Physics at a $\gamma\gamma$, $e\gamma$ and e^-e^- Option for a Linear Collider

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Abstract

This report presents a review of the studies made in the working group on "$\gamma\gamma$ and $e\gamma$ physics" of the ECFA/DESY workshop on linear collider physics. It reports on several new physics studies, in particular s-channel Higgs production. A summary of R&D activities for the interaction region is presented. The merits of e^-e^- collisions are briefly recalled.

INTRODUCTION

A future e^+e^- linear collider (LC) offers excellent new opportunities for the study of high energy particle collisions. The idea to convert the electron beams of a LC into photon beams, by laser backscattering, and thus create a photon collider (PC), was first discussed about 20 years ago in [1]. Projects for a future LC collider are studied in Europe (TESLA,CLIC), the US (NLC) and Asia (JLC), and all consider a PC as a possible additional option. Recently, in the context of the ECFA-DESY LC study, a detailed discussion of the physics and design of a PC was presented in the TESLA-TDR [2] and in [3]. This paper reviews the work done during the last two years in the study group "$\gamma\gamma$ and $e\gamma$ physics" of the extended ECFA/DESY workshop on physics and detectors at a linear collider.

A plethora of new and exciting measurements become accessible with a PC, in particular Higgs boson studies, but also searches for new physics and electroweak, top and QCD measurements can be made often in a complementary way compared to e^+e^- collisions. The precision reached at a PC is competitive if sufficiently high luminosities can be reached.

Examples of advantages of a PC include:

- Higher cross sections for charged particles than in e^+e^-.
- Different J^{PC} states than for e^+e^-.
- Higgs can be s-channel produced as a resonance.
- CP analysis opportunities for Higgs bosons
- Precise test of the coupling to photons
- Possible higher mass discovery range for e.g. H, A, and sleptons

Note that a PC needs no positron drive beam but electron beams, which can be produced with relatively high polarisation, are sufficient.

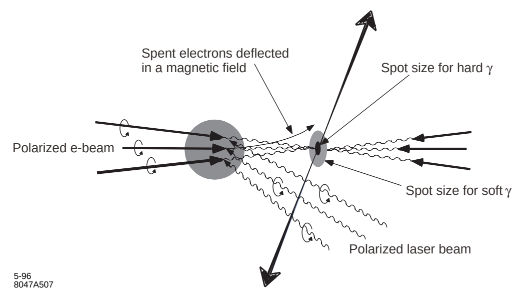

Figure 1: A sketch of the creation of a photon beam by Compton backscattering of laser photons off beam electrons.

The proposed technique for a PC consists of using laser backscattering as shown in Fig. 1. A low energy (typically 1 eV) laser beam of photons collides with the high energy (typically 250-500 GeV) electron beam and is backscattered receiving a major fraction of the incoming electron energy. The maximum energy of the generated photons is given by $E_\gamma^{max} = xE_e/(1+x)$, with E_e the electron beam energy and $x = 4E_eE_L\cos^2(\theta/2)/m_e^2c^4$ with E_L and θ the laser photon energy and angle between the electron and laser beam. The distance of the conversion to the interaction point is in the range of several mm. A typical value for x is 4.8, which leads to photon spectra which peak around $0.8E_e$. The energy distribution depends on the polarisation of the photon (P_c) and electron beam (λ_e), the most peaked spectrum is obtained when $P_c\lambda_e = -1$. In reality, due to the maximum polarizability of the electron beam a value close to $P_c\lambda_e = -0.8$ can be reached. Sometimes it is advantageous to have a broader spectrum, e.g. to discover particles with unknown masses, in which case the configuration $P_c\lambda_e = +0.8$ will be more useful.

The polarization of both beams can be further used to produce interactions with the same ($J_z = 0$) or opposite ($J_z = 2$) photon helicities, useful e.g. for Higgs studies. Higher geometrical luminosities can be achieved

*The work reported in this talk was done by the members of the "$\gamma\gamma$ and $e\gamma$ physics" working group of the Extended ECFA/DESY Study; D. Anipko (Nowosibirsk), E. Asakawa (Tokyo U.), D. Asner (Cornel), I. Bozovic (VINCA Belgrade), W. Da Silva (Paris VI), A. De Roeck (CERN), A. Finch (Lancaster), I. Ginzburg (Nowosibirsk), R. Godbole (Bangalore), J. Gronberg (LLNL Livermore), C. Heusch (Santa Cruz), G. Klemz (DESY-Zeuthen), M. Krämer (Edinburgh), F. Kraus (Dresden), M. Krawczyk (Warsaw), J. Kwiecinski (Krakow), V. Makarenko (NC PHEP Minsk), I. Marfin (NC PHEP Minsk), S. Maxfield (Liverpool), D. Miller (CERN), K. Moenig (DESY-Zeuthen), M. Mühlleitner (PSI), F. Nagel (Uni Heidelberg), P. Niezurawski (Warsaw), A.V. Pak (Novisibirsk), D.V. Pavluchenko (Novisibirsk), S.S. Petrosyan (Novisibirsk), A. Rosca DESY-Zeuthen), S. Schumann (Dresden), J. Sekaric (DESY Zeuthen), V.G. Serbo (Novisibirsk), T. Shishkina (NC PHEP Minsk), S. Soeldner-Rembold (Manchester), A. Stahl (DESY Zeuthen), V. Telnov (Novisibirsk), M. Velasco (Northwestern), M. Wing (Bristol Univ. & DESY), A.F.Żarnecki (Warsaw), for photon colliders than for genuine e^+e^- colliders, due to the absence or strong reduction of beamstrahlung in the interaction region. The 'luminosity' is usually defined to be the luminosity corresponding to the region $\sqrt{s_{\gamma\gamma}} > 0.8\sqrt{s_{\gamma\gamma,max}}$ and is typically 10% of the geometrical e^+e^- luminosity. For the TESLA parameters, but including a smaller horizontal β function at the interaction point namely 1.5 mm in x, compared to 15 mm for the e^+e^- beam design, and reducing the horizontal emittance from 553 nm to 140 nm, leads to $L_{\gamma\gamma}(\sqrt{s_{\gamma\gamma}} > 0.8\sqrt{s_{\gamma\gamma,max}}) \sim \frac{1}{3}L_{e+e-}$. This gives event samples corresponding to $O(100)$ fb^{-1} per year for the PC. A PC

- needs a second interaction point
- needs a cross angle
- has a rather peaked but somewhat smeared centre of mass system (CMS) energy spectrum

Both high energy $e\gamma$ and $\gamma\gamma$ interactions can be provided, depending on whether only one or both lepton beams are converted.

TOOLS

During this workshop major progress was made on the development and completion of the tools to study physics at a $\gamma\gamma$ collider. These tools have now reached a high level of maturity.

Luminosity spectra at photon colliders can not be described completely by effective photon spectra due to the energy-angle correlation in Compton scattering and beam collision effects. Fully detailed luminosity distributions were obtained by a complete simulation of beam collisions, resulting in 'collision events' that contain the types of colliding particles (photon, electron, positron), their energies and polarizations. The PHOCOL program [4] was used to generate these collision events for several e^-e^- CMS energies and laser configurations. PHOCOL includes nonlinear corrections and contributions of higher order processes. An example of a $\gamma\gamma$ CMS energy distribution is shown in Fig. 2. The event files can be used by the CIRCE program [5]. These luminosity spectra are also used to tune a simple model based on analytical formulae for the Compton scattering (CompAZ [6]). The results of such a tune are shown in Fig. 2 as well. While being an approximation, these spectra are nevertheless extremely convenient for studies e.g. at different energies other than the (few) ones for which event files were produced.

A version of the fast detector simulation package SIMDET, including modifications for the PC interaction point (IP) has been used. Overlap events from the QCD background can be added to the signal events. For TESLA luminosities, we expect typically on average about one overlaying event at low energy ($\sqrt{s_{ee}} \sim 200$ GeV, also called the Higgs mode since it would be best suited for the study of a light Higgs with mass ~ 120 GeV) and two events at nominal energy ($\sqrt{s_{ee}} \sim 500$ GeV).

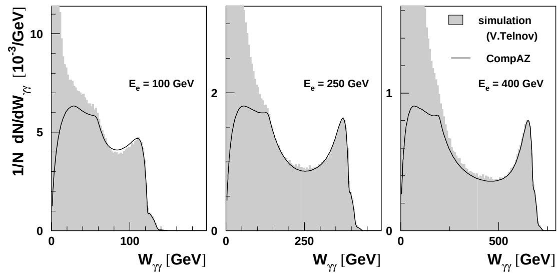

Figure 2: Comparison of the center of mass energy distribution obtained from full simulation of the luminosity spectrum [4] with results from CompAZ, for three electron beam energies [6]

Background studies [7] have been made for incoherent and coherent e^+e^- pair production. A new two-mask design in the IP reduces the background by a factor 2-3 with respect to the previous layout; the details are still being optimized. Tracks in the TPC and hits in the vertex detector from incoherent and coherent pairs were found to be tolerable and similar to the expected background at an e^+e^- collider interaction region. Hence there is now evidence that a similar vertex detector as for an e^+e^- collider detector can be used for a PC detector, and therefore a similar quality in b-tagging can be achieved. The neutron background is still under study but the first results show that it is tolerable as well [8].

During this workshop we also had direct contact with MC developers which resulted in getting requirements implemented in e.g. the new SHERPA generator [9], and getting good MC parameter tunes for PYTHIA and HERWIG (using mostly HERA γp data) from the JETWEB team [10].

On the web page of the working group a link directing to the page with the tools can be found: http://www-h1.desy.de/~maxfield/ggcol/lcgg.html.

LUMINOSITY

One of the topics studied in detail is the precision with which the luminosity can be measured. The following processes are proposed for the $\gamma\gamma$ mode [11, 12]:

- $ee \to ee\,(\mu\mu)$
- $ee \to ee\gamma\,(\mu\mu\gamma)$
- $ee \to$ 4 leptons

The cross sections for these channels are shown in Fig. 3. The first channel can give the highest precision $\sim 0.1\%$ (stat) but cannot be used for $J_z = 0$, i.e. for the Higgs study, because it is suppressed as m_l^2/s, with m_l the lepton mass. In that case, however, the second channel can be used. For two years of running the statistical precision for

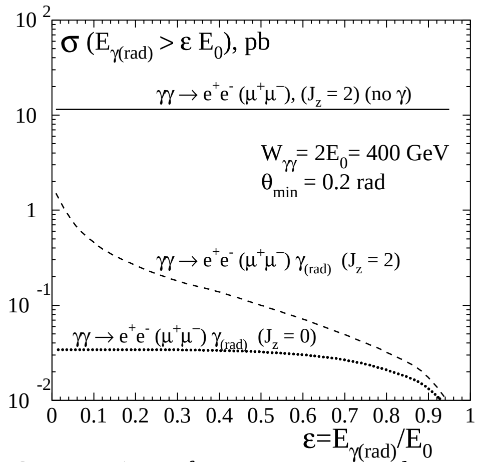

Figure 3: Cross sections of processes proposed to measure luminosity at a $\gamma\gamma$ collider [12].

the channel $ee \to ee\gamma$, using realistic detector cuts, is

$$\frac{\Delta L}{L}(\sqrt{s} > 0.8\sqrt{s_{\gamma\gamma,max}}) = 0.4\% \qquad (1)$$

$$\frac{\Delta L}{L}(m_H \pm 2\text{GeV}) = 1.0\% \qquad (2)$$

For $e\gamma$ collisions the following processes are suggested:

- $e\gamma \to e\gamma, eZ$
- $e\gamma \to eee.$

The statistical precision that can be achieved is better than 1% for one year of running.

PHYSICS TOPICS

Two-photon physics is not new. Most e^+e^- colliders have or had a program of two-photon physics, by using the photons emitted from the lepton beams, which follow the well known WWA [13] energy dependence. The known disadvantage is the rapidly decreasing photon flux with photon energy: for collisions with a fractional energy $\sqrt{s_{\gamma\gamma}}/2E_e^{beam}$ larger than 0.1 (0.5) the $\gamma\gamma$ luminosity is reduced by a factor 100 (10000) with respect to the e^+e^- luminosity. Hence the PC opens a new opportunity for truly *high* energy two-photon physics, which is not limited to QCD but competes in searches for new physics and measurements of Higgs properties.

The cross sections for charged particle pair productions are considerably larger in $\gamma\gamma$ collisions than for e^+e^- collisions and decrease more slowly with energy. Hence one can study new particles far from threshold with higher rate. E.g. WW pair production in $\gamma\gamma$ at 500 GeV is a factor 20 larger than in e^+e^-. Cross sections for charged scalars, lepton and top pairs are a factor $5-10$ higher at a PC, compensating for the reduced luminosity compared to e^+e^-.

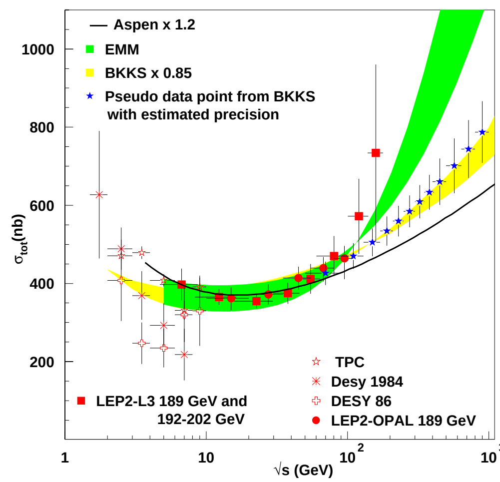

Figure 4: The total $\gamma\gamma$ cross-section as function of the $\gamma\gamma$ collision energy, compared with model calculations [17]: BKKS band (upper and lower limits correspond to different photon densities) and EMM band (Eikonal Minijet Model for total and inelastic cross-section, with different photon densities and different minimum jet transverse momentum).

QCD

First we consider the QCD aspects of two-photon collisions in the reaction $\gamma\gamma \to$ hadrons. The nature of the photon is complex. A high energy photon can fluctuate into a fermion pair or into a bound state, i.e. a vector meson with the same quantum numbers as the photon $J^{PC} = 1^{--}$. These quantum fluctuations lead to the so-called hadronic structure of the photon.

Many QCD studies of photon-photon collisions were made for the TDR [2] and will not be repeated here. During this workshop we got new paramterizations of the energy dependence of the total cross section [14, 15], and new LO parametrizations of the photon structure functions [16].

As an example the total $\gamma\gamma$ cross-section is briefly discussed, a quantity that is not yet understood from first principles. Fig. 4 shows the present photon-photon cross-section data in comparison with recent phenomenological models [14]. All models predict a rise of the cross-section with the collision energy, $\sqrt{s_{\gamma\gamma}}$, but the amount of the rise differs and predictions for high photon-photon energies show noticable differences. *Proton-like-models* follow closely the rise of the proton-proton cross-section, while in *QCD based* models, a stronger rise is predicted using the eikonalized pQCD jet cross-section.

The figure demonstrates that large differences between the models become apparent in the energy range of a future 0.5-1 TeV e^+e^-collider. An overview of new model predictions is reported in [14]. The absolute precision with which these cross-sections can be measured ranges from

5% to 10%, where the largest contributions to the errors are due to the control of the diffractive component of the cross-section, Monte Carlo models used to correct for the event selections, the absolute luminosity and knowledge on the shape of the luminosity spectrum [17]. These prospects for measurement have been updated to the TeV range and are shown in Fig. 4.

Higgs Studies

The quest for the Higgs particle(s) and the measurement of its properties will be one of the most important topics for high energy collider physics in the coming years. The PC is an ideal place to study the Higgs boson since it can be produced as an s-channel resonance. The mass reach of the PC is up to 80% of the CMS energy of the e^-e^- collider. A detailed study of the $\gamma\gamma H$ vertex is only possible at a PC. Accurate measurements of mass and width are extremely important and can be used to compare the SM predictions with those of alternative models e.g. based on SUSY. Since the two-photon decay width of the Higgs is sensitive to all heavy charged particles which acquire mass via the Higgs mechanism, the partial width could be modified by 5-10% in these models.

For a light Higgs, the most promising channel is $\gamma\gamma \to H \to b\bar{b}$. A first study based on detector simulation, showed that a 2% statistical precision for the partial width could be reached [18], for a Higgs with mass of 120 GeV. During this workshop we have

- Revisited the $H \to b\bar{b}$ channel in detail
- Studied the $H \to WW, ZZ$ channels
- Studied analysis methods for the spin and CP properties of the Higgs
- Studied the model separation power
- Studied the MSSM higgs

Members of the US PC study group have been reporting to us on their Higgs analyses as well, in particular H, A production and discovery, the $H \to \gamma\gamma$ decay mode, and charged Higgs studies.

First we discuss the $H \to b\bar{b}$ studies. Selecting $J_z = 0$ strongly suppresses the (Leading Order) contributions of $b\bar{b}$ and $c\bar{c}$ production, but a good tagging of bottom quarks with simultaneous rejection of charm quarks is needed. During this workshop two new complete analyses were finalized [19, 20]. The two studies use a different approach for the background process, but come to the same conclusions. The simulated mass spectrum for a Higgs particle with mass of 120 GeV, is shown in Fig. 5 for signal and background. The PC will determine the quantity $\Gamma(H \to \gamma\gamma) \cdot BR(H \to b\bar{b})$. A feasibility study for a light Higgs, using a parametrized simulation of the detector, has confirmed that the quantity above can be determined with a typical statistical accuracy of about 2-3%, as shown in Fig. 6. These studies use as before the NLO QCD backgrounds [21]. New in these studies are the use of a more realistic photon spectrum, inclusion of overlap background QCD events (on average one event per bunch crossing), b-tagging using a neural net, and using a correction method for the reconstructed Higgs mass, accounting for escaping neutrinos from the heavy flavour decays.

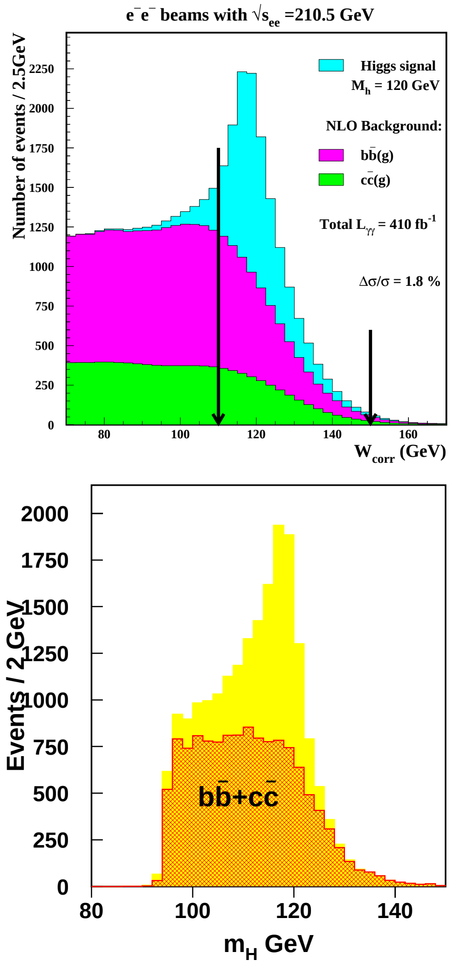

Figure 5: Reconstructed invariant mass distribution, W_{rec} (top [19]) and M_H (below[20]), for selected $b\bar{b}$ events. Contributions for background and signal are shown separately. In the top plot the arrows show the optimized mass window for the partial width measurement.

Since the $b\bar{b}$ branching ratio can be measured at an e^+e^- collider with a precision of 1-2%, $\Gamma(H \to \gamma\gamma)$ can be determined with a statistical accuracy of approx. 2% for an integrated luminosity of 85 fb^{-1}, i.e one year running.

In [22] the processes $\gamma\gamma \to H \to WW$ and $\gamma\gamma \to H \to ZZ$ have been studied for the region 180 GeV $< m_H <$ 350 GeV via $q\bar{q}q\bar{q}$ decays for the WW channel and $llq\bar{q}$ decays for the ZZ channel. Typical mass plots are shown in Fig. 7. Due to the interference with the standard model background the processes $\gamma\gamma \to$ Higgs $\to WW/ZZ$ turn out to be also sensitivity to the phase

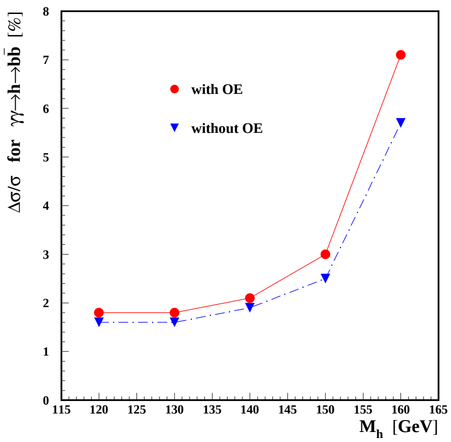

Figure 6: Statistical precision of $\Gamma(h \to \gamma\gamma) Br(h \to b\bar{b})$ measurements for the SM Higgs boson with mass 120-160 GeV, with and without overlaying events (OE). The lines are drawn to guide the eye [19].

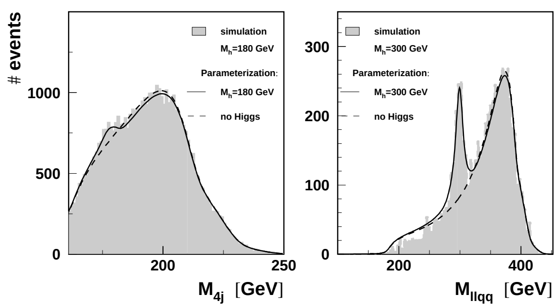

Figure 7: Distribution of the reconstructed invariant mass $\gamma\gamma \to WW, ZZ$ for Higgs mass/electron beam of 180/152.5 GeV and 300/250 GeV respectively [22].

of the $\gamma\gamma \to$ Higgs coupling, $\phi_{\gamma\gamma}$. The measurement of both the phase and partial width gives powerful tools to discriminate a SM Higgs from that of an extended model. A plot showing the sensitivity that can be reached on the partial two-photon width and the phase versus the mass of the Higgs is given in Fig. 8, using the same simulation tools as for the light Higgs discussed above. Over a large region a sensitivity of 3-5% can be achieved. The deviation from the SM prediction expected by a Higgs in a 2HDM is also indicated [22]

Furthermore the CP structure of the Higgs boson can be verified by studying the decay into ZZ, WW and measuring the azimuthal angle $\Delta\phi$ between the decay planes of the two Z, W bosons. An example of the sensitivity of the angle $\Delta\phi$ is shown in Fig. 9 for the decay channels $H \to ZZ, WW$, using a realistic simulation and for one year of data taking. In [22] one can find a very extensive discussion on sensitivities to CP properties using this and other variables, showing that a PC is an excellent tool for

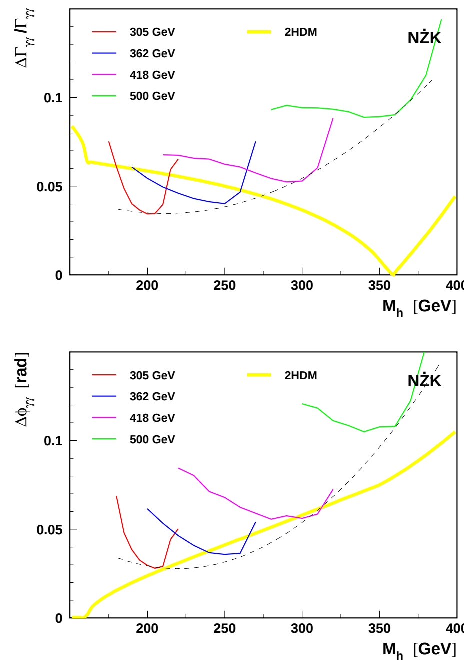

Figure 8: Statistical determination of the Higgs boson width (upper plot) and phase (lower plot) from the combined fit to the observed WW and ZZ mass spectra as a function of M_H [22]. The yellow (thick) line shows the size of the deviation expected in the SM-like 2HDM II [23], with an additional charged Higgs of 800 GeV. The dashed line is to guide the eye.

such analyses.

Further interesting CP studies include the study of the channel $\gamma\gamma \to t\bar{t}$, measuring asymmetries composed of the initial lepton beam polarization and the decay lepton charge [24]. A sensitivity plot is shown in Fig. 10.

Our US colleagues have reported to us on studies of $\gamma\gamma \to H \to \gamma\gamma$ and charged Higgs production. The first channel is quadratically sensitive to the two photon Higgs partial width. The event rate is however small and an excellent calorimeter is need for the signal to be observable. In the analysis a calorimeter energy resolution $\sigma_e/E = ((0.015/\sqrt{E})^2 + (0.0045)^2)^{1/2}$ was assumed which is better than the CMS experiment EM calorimeter resolution. This would be also a different calorimeter than what is currently envisaged for the TESLA detector. The signal for one year of running is shown in Fig. 11. The mass resolution on the peak is 0.4 GeV, allowing for a measurement of $\Delta m_H \sim 100$ MeV and $\Delta\sigma/\sigma$ of 24%. A crucial issue will be the understanding of the background.

An analysis of the production of charged Higgses, which appear in extended Higgs doublet models, is reported in [25]. The cross section is about a factor 20 larger than for e^+e^- collisions. Taken into account the branching ratios, for a charged Higgs below 200 GeV generally the channel $\gamma\gamma \to H^+H^- \to \tau\nu\tau\nu$ is the most promising. With suitable cuts (albeit with a very low efficiency of a few %) a

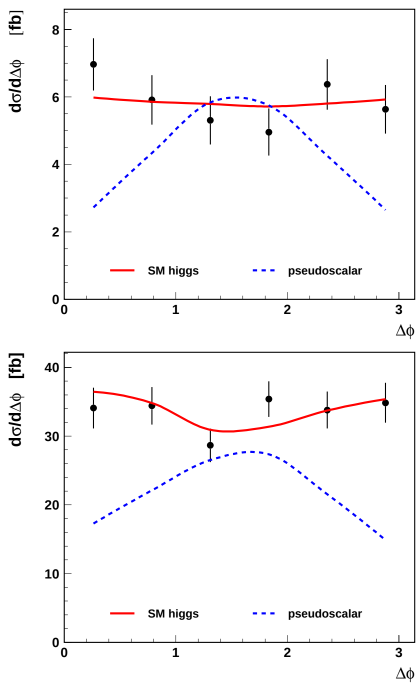

Figure 9: Statistical error on the determination of the azimuthal angle $\Delta\phi$, as explained in the text, for $H \to WW$ and $H \to ZZ$.

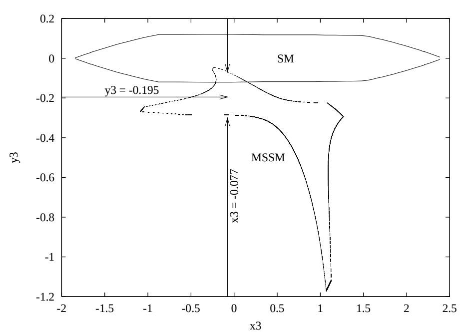

Figure 10: The boundaries of blind regions in the parameter space at 95% C.L. in the $x_3 - y_3$ plane for a luminosity of 100 fb^{-1} for E_B = 310 GeV, given for both the SM and an example of a MSSM point. Details on this analysis and definitions of the x_3, y_3 variables can be found in [24].

S/B of about 3 can be achieved. This decay mode does not allow to reconstruct the mass. To get mass information the channel $H^+H^- \to \tau\nu q\bar{q}$ is under study. More PC studies of the US group are reported in [25, 26].

An important "golden" channel for the PC is the production $\gamma\gamma \to H, A$. Indeed, a PC may help to discover H, A bosons in the MSSM SUSY extension of the SM when these are inaccessible by other machines. For example the LHC cannot extract the H, A signals out of the background

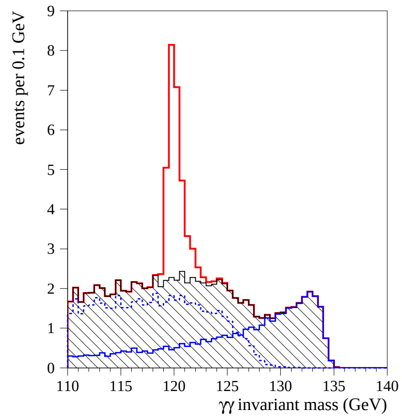

Figure 11: The $\gamma\gamma$ invariant mass distribution including backgrounds from $\gamma\gamma \to \gamma\gamma$ (dashed lines) and $e\gamma \to e\gamma$ (heavy solid line) as well as the Higgs signal peak [25]. The hatched histogram shows the sum of the background contributions.

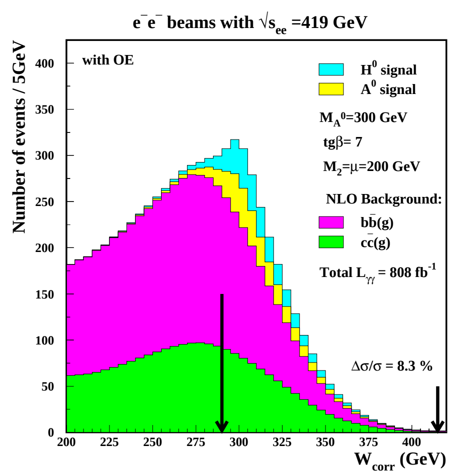

Figure 12: Reconstructed invariant mass, W_{rec}, distribution for selected $b\bar{b}$ events for H, A. Contributions for background and signal are shown separately. The arrows show the optimized mass window for the partial width measurement [28].

(except perhaps for SUSY decay modes of the H, A) if the mass is larger than about 200-300 GeV at medium $\tan\beta$. Fig. 12 shows the mass distribution of the H, A in the $b\bar{b}$ decay channel. This mass distribution [28] was estimated using exactly the same tools as for the light Higgs $H \to b\bar{b}$ analysis [19]. Fig. 13 shows the region that could be covered by a PC for several years of running (assuming a 630 GeV collider) [27] in the $b\bar{b}$ decay mode. The e^+e^- mode of that collider can reach $M_{H,A}$ masses up to about 300 GeV only. The PC essentially closes the wedge left by the LHC, up to masses of 500 GeV. Fig. 14 shows the precision with which the cross section can measured for M_A in the range of 200-350 GeV and $\tan\beta$ = 7, with and without

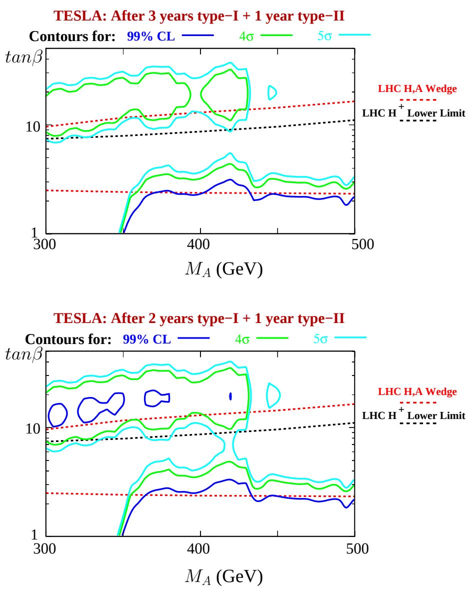

Figure 13: Regions in M_A, $\tan\beta$ where the LHC has problems discovering the heavy Higgs, A and H, with the statistical sensitivity at a PC based on a 630 GeV e^+e^- collider, after several years of running [27].

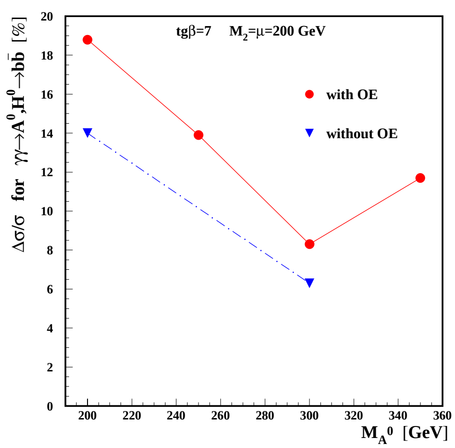

Figure 14: Statistical error on the determination of the $\sigma(\gamma\gamma \rightarrow A, H \rightarrow b\bar{b})$ measurements shown for $M_A = 200 - 350$ GeV and $\tan\beta = 7, M_2 = \mu = 200$ GeV, with and without overlaying events (OE) [28]. The lines are to guide the eye.

overlaying events.

Standard Model

Due to the large cross sections, several precise measurements of SM parameters or particle properties can be made at a PC.

Triple gauge couplings were studied in detail, using realistic luminosity spectra and detector simulation [29]. The WHIZARD [30] Monte Carlo was used for the signal. The

(GeV) $\int L\Delta t$ ΔL	$\sqrt{s_{e\gamma}}$= 450 $110 fb^{-1}$ 0.1%	$\sqrt{s_{\gamma\gamma}}$= 400 $110 fb^{-1}$ 0.1 %	$\sqrt{s_{ee}}$= 500 $500 fb^{-1}$
ΔK_γ $\Delta\Lambda_\gamma$	$9.9 \cdot 10^{-4}$ $2.6 \cdot 10^{-4}$	$6.7 \cdot 10^{-4}$ $(6.0) \cdot 10^{-4}$	$3.1 \cdot 10^{-4}$ $4.3 \cdot 10^{-4}$

Table 1: Precision achievable on triple gauge couplings for a $\gamma\gamma$, $e\gamma$ and ee collider.

study shows that these couplings can be measured at a PC with a precision similar to the one achieved at an e^+e^- collider, see Table 1. The sensitivity is proportional to the momentum of the particles involved in the triple gauge boson vertex. The analysis [29] includes detector simulation and 3D fits including the azimuthal decay angle (not yet done for the $\gamma\gamma$ study).

Top quark production was studied in [3]. The $e\gamma$ scattering gives a good sensitivity to the anomalous top couplings, as detailed in that report. The reaction $\gamma\gamma \rightarrow t\bar{t}$ allows for an extraction of the electric dipole moment: for 20 fb^{-1} and an electron beam energy of 250 GeV a sensitivity on the dipole moment of $1.3 \cdot 10^{-16}$ ecm can be achieved, when assuming a realistic luminosity spectrum [31].

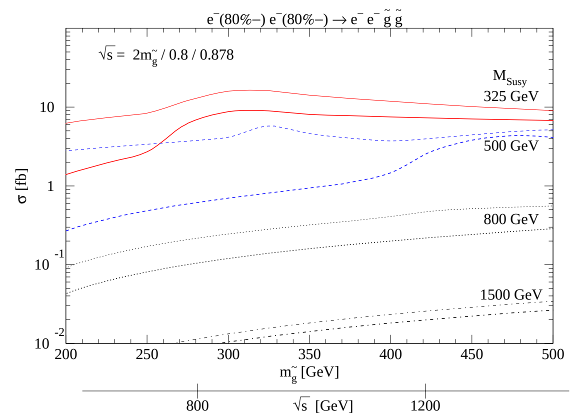

Figure 15: Cross section for gluino production in $\gamma\gamma$ collisions versus the gluino mass and for different squark masses [33] (maximal stop mixing (thin lines) and no mixing (thick lines)).

Beyond the Standard Model

Supersymmetry is presently the most popular theory for physics beyond the standard model. A few examples are given where a PC can make significant contributions.

If the LSP is light, the process $e\gamma \rightarrow \tilde{e}\chi_1^0 \rightarrow e\chi_1^0\chi_1^0$ can extend the range of discovery for heavy sleptons. Indeed LHC has difficulties discovering sleptons for masses above 300-350 GeV, and the e^+e^- collider has to pair produce sleptons, hence its range is limited to $\sqrt{s}_{ee}/2$. In case of a $e\gamma$ collider the reach is $0.9 \cdot \sqrt{s}_{ee} - m_{\chi_1^0}$, e.g. 350 GeV for 250 GeV electron beams and a LSP of 100 GeV [32].

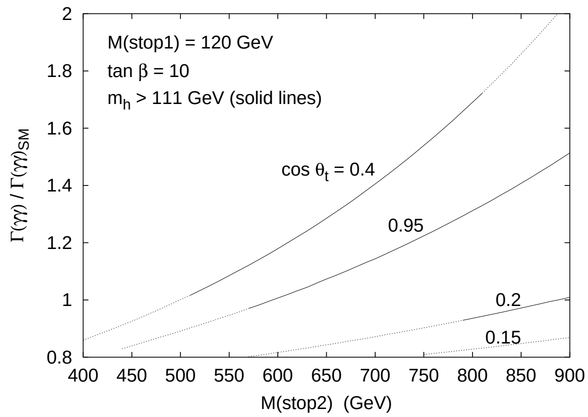

Figure 16: Dependence of the partial two photon width of the Higgs on $M_{\tilde{t}_2}$ for various values of $M_{\tilde{t}_1}$. Here M_A is 1 TeV, $\tan\beta = 10$ and $M_2 = -\mu = 200$ GeV, other SUSY mass parameters are set to 1 TeV [25].

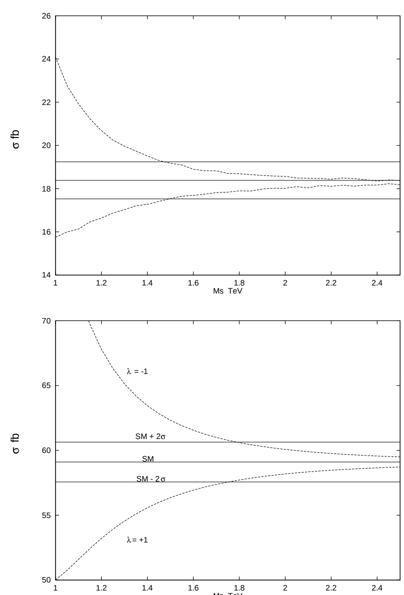

Figure 17: The sensitivity to ADD extra dimensions in the channel $\gamma\gamma \rightarrow t\bar{t}$, for an ideal Compton spectrum (top) and for a realistic one using CompAZ (bottom).

Another channel of interest at a PC is $\gamma\gamma \rightarrow$ gluinos. This reaction is only accessible at an e^+e^- collider if the squarks are heavier than the gluinos and the decays $\tilde{q} \rightarrow \tilde{g}q$ are open. Photons couple to squarks and quarks and can produce gluinos via box diagrams. The yield is shown in Fig. 15. Typically 2000 gluinos pairs can be produced/year for light quarks (325 GeV) [33]. It remains to be seen what one can learn more at a PC than what is known from the LHC at that point.

Measuring the two photon width at a PC can also help to pin down masses of sparticles which cannot be directly produced at the e^+e^- collider. An example is shown in Fig. 16, where we assume a scenario of large mass splitting between the $\tilde{t_1}$ and $\tilde{t_2}$. If the $\tilde{t_1}$ mass and $\tilde{t}$ mixing angle are known from e^+e^- studies then using a precise measurement of the two-photon partial width of the Higgs one can constrain the mass of $\tilde{t_2}$ as shown in the Figure [26].

Other new theories propose the existence of extra dimensions. It appears that the reaction $\gamma\gamma \rightarrow WW$ is very sensitive to ADD type of effects [34]. The sensitivity scales with a CMS energy as 11 $\sqrt{s}$. For $e^+e^- \rightarrow f\overline{f}$ the sensitivity is 6.5 $\sqrt{s}$, and for the LHC using the process $pp \rightarrow jj$ it is 9 TeV for 100 fb^{-1}. A new study shows the sensitivity to ADD extra dimensions in the channel $\gamma\gamma \rightarrow t\bar{t}$ in Fig. 17 [35]: the top figure takes the ideal Compton spectrum while the lower figure includes the luminosity via CompAZ. The sensitivity is reduced from $M_s = 1.7$ TeV to 1.4 TeV for one year of running.

TECHNOLOGY FOR A PC

A photon collider IP introduces new challenges: The laser part, the optics, stability and control in the IP (to 1 nm), length control in case of a cavity, beam extraction line, etc. Both the European and the US groups have an R&D effort on the hardware part.

Europe is developing a scheme for an optical cavity, shown in Fig. 18 [36], and plans are considered to make a 1:9 scale model. The use of a cavity allows multi-passing of the laser signal and thus reduces the required laser power. The US group of LLNL follows a full power laser design, as the short bunch distance at the NLC is less favourable to benefit from such a cavity option.

The US group has commissioned a laser with 20 J pulses at 10 Hz. The full power (100 Hz at 10 Hz) is expected to be reached next year. In total 10 of these lasers would be required. They have also studied interferometry for alignment, built a half-size focusing optics setup in the lab, studied a beam-beam deflection feedback system, and are preparing a proposal for a PC testbed at SLAC, using the SLC and perhaps even parts of the SLD [37]. A picture of the set-up of the optics is shown in Fig. 19.

In all there is progress but funding is presently certainly and issue to continue the R&D. The developments during the coming years will be of vital importance.

E-E- COLLISIONS

The PC will be based on e^-e^- collisions. These collisions can be of great interest by itself. No new studies have been presented in the context of this workshop, but an excellent overview paper can be found in the proceedings of the LCWS2002 [38]. Here we recall on a few of the outstanding advantages of e^-e^-

- Large polarization for both beams, hence (almost) pure e_L, e_R initial states.

- Excellent discovery potential for states with exotic quantum numbers (e.g such as H^{--})

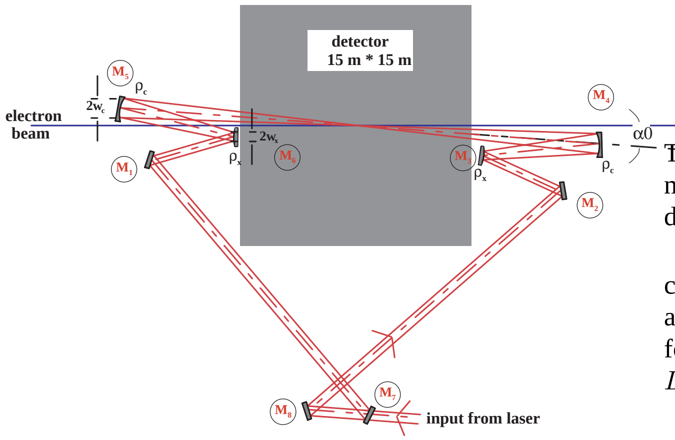

Figure 18: The optical cavity for the TESLA PC IP design.

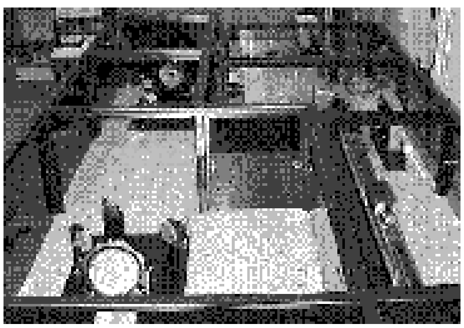

Figure 19: The optics setup at LLNL.

- Larger sensitvity (for identical luminosity) than e^+e^- e.g. for contact interactions, non-commutative scales (via Moller scattering)
- Special processes can be very clean, e.g. $e^-e^- \rightarrow e^-e^-H$
- Sharper onset of e.g. the slepton production threshold

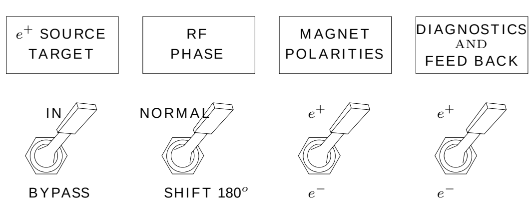

Figure 20: Since the e^-e^- collider requires only minor changes to the hardware of the e^+e^- machine and detector, its programme could be pursued during the first face of the facility...” International Linear Collider Technical Review Committee Report- 1995 [38].

than in e^+e^-

- Possibility to identify TeV level Majorana neutrinos through the lepton number violation reaction $e^-e^- \rightarrow W^-W^-$

To be fully convincing these studies need to reach the same maturity as for the e^+e^- collider or PC studies: i.e. include detector simulation, backgrounds, beamstrahlung, ...

On the downside there are of course no classical s-channel processes in e^-e^-, and since the beams show an anti-pinch effect, the luminosity in general is lower than for e^+e^-. One finds typically numbers in the ball-park of $L_{e^-e^-} = 0.15 - 0.3 \cdot L_{e^+e^-}$ [39].

Unlike for the PC there are however no major changes required in the interaction region or accelerator. The e^-e^- option is the extra option which for TESLA would be most easily to realize. Fig. 20 shows how easy it could be for the machine shift leader to switch from e^+e^- to e^-e^- collisions: just four switches to turn... Clearly we must keep it on the roadmap and the future new physics will decide how valuable this option will be for us.

CONCLUSION

An $\gamma\gamma$ and $e\gamma$ collider will provide exciting physics opportunities, many of which have been developed in detail during the last two years. The development of specific PC study tools has allowed that several of the studies have now reached the necessary maturity.

At the LCWS2002 in Jeju a panel discussion was organized on the PC option [40]. The conclusion was a clear plea to continue the R&D and physics studies such that we can be in a good position to incorporate a PC in the overall planning of a LC, when that day comes. A PC will be largely complementary to its drive LC and will therefore strengthen the case for such an e^+e^- collider. A PC option should be considered from the onset within the planning of the project. A vigorous R&D plan for a PC will need to be put in place, preferably on a world-wide level.

Finally an (updated) short list of processes which are considered to be most important for the physics program of the photon collider option of the LC, is presented in Table 2, taken from ref. [3]. Additionally to this list are the processes $e\gamma \rightarrow e^*$, leptoquark production, strong WW scattering and $e\gamma \rightarrow eH$. It summarizes the rich physics program that becomes accessible at a Photon Collider!

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Reaction	Remarks
$\gamma\gamma \to H, h \to bb$	SM/MSSM Higgs, $M_{H,h} < 160$ GeV
$\gamma\gamma \to H \to WW(*)$	SM Higgs, 140< $M_H < 190$ GeV
$\gamma\gamma \to H \to ZZ(*)$	SM Higgs, 180< $M_H < 350$ GeV
$\gamma\gamma \to H \to \gamma\gamma$	SM Higgs, 120< $M_H < 160$ GeV
$\gamma\gamma \to H \to t\bar{t}$	SM Higgs, $M_H > 350$ GeV
$\gamma\gamma \to H, A \to bb$	MSSM heavy Higgs, interm. $\tan\beta$
$\gamma\gamma \to \tilde{f}\bar{\tilde{f}},\ \tilde{\chi}_i^+\tilde{\chi}_i^-$	large cross sections
$\gamma\gamma \to \tilde{g}\tilde{g}$	measurable cross sections
$\gamma\gamma \to H^+H^-$	large cross sections
$\gamma\gamma \to S[\tilde{t}\bar{\tilde{t}}]$	$\tilde{t}\bar{\tilde{t}}$ stoponium
$e\gamma \to \tilde{e}^-\tilde{\chi}_1^0$	$M_{\tilde{e}^-} < 0.9 \times 2E_0 - M_{\tilde{\chi}_1^0}$
$\gamma\gamma \to \gamma\gamma$	non-commutative theories
$e\gamma \to eG$	extra dimensions
$\gamma\gamma \to \phi$	Radions
$e\gamma \to \tilde{e}\tilde{G}$	superlight gravitions
$\gamma\gamma \to W^+W^-$	anom. W inter., extra dimensions
$e\gamma \to W^-\nu_e$	anom.W couplings
$\gamma\gamma \to 4W/(Z)$	WW scatt., quartic anom. W,Z
$\gamma\gamma \to t\bar{t}$	anomalous top quark interactions
$e\gamma \to \bar{t}b\nu_e$	anomalous Wtb coupling
$\gamma\gamma \to$ hadrons	total $\gamma\gamma$ cross section
$e\gamma \to e^-X, \nu_e X$	NC and CC structure functions
$\gamma g \to q\bar{q},\ c\bar{c}$	gluon in the photon
$\gamma\gamma \to J/\psi\, J/\psi$	QCD Pomeron

Table 2: Update of the Gold–plated processes at photon colliders.

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