

## GAMMA-GAMMA, GAMMA-ELECTRON COLLIDERS: PHYSICS, LUMINOSITIES, BACKGROUNDS.

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This report on Photon Colliders covers the following “physics” issues: physics motivation, possible luminosities, backgrounds, plans of works and international cooperation. More technical aspects such as accelerator issues, new ideas on laser optics, laser cooling, and interaction region layout are discussed in my second talk at this Workshop.

### 1 Introduction

In addition to  $e^+e^-$  collisions, linear colliders provide a unique possibility to study  $\gamma\gamma$  and  $\gamma e$  interactions at energies and luminosities comparable to those in  $e^+e^-$  collisions.<sup>1-6</sup> High energy photons for  $\gamma\gamma$ ,  $\gamma e$  collisions can be obtained using laser backscattering. Modern laser technology presents the real possibility for construction of the laser system for  $\gamma\gamma$ ,  $\gamma e$  collider (‘photon collider’). This option is now included in the pre-conceptual design of the NLC (North American)<sup>7</sup>, TESLA (European)<sup>8</sup> and JLC (Asian)<sup>9</sup> linear collider projects in the energy range of a few hundred GeV to about 1.5 TeV. These teams have intent so submit full conceptual design reports in 2001-2002. However, in our time of tight HEP budgets the physics community needs a very clear answer to the following question: a) can  $\gamma\gamma, \gamma e$  collisions give new physics information in addition to  $e^+e^-$  collisions that could justify an additional collider cost ( $\sim 15\%$ , including detector); b) is it technically feasible; c) is there enough people who are ready to spend a significant part of their career for the design and construction of a photon collider, and exploiting its unique science?

Shortly, my answers are the following:

a) Certainly yes. There are many predictions of extremely interesting physics in the region of the next linear colliders. If something new will be discovered (Higgs, supersymmetry or ... quantum gravity with extra dimensions), to understand better the nature of these new phenomena they should be studied in different reactions which give complementary information.

b) There are no show-stoppers. There are good ideas on obtaining very high luminosities, on laser and optical schemes. It is clear how to remove the disrupted beams and there is an understanding of backgrounds. However, much remains to be done in terms of detailed studies and experimental tests. Special efforts are required for the development of the laser and optics which are the key elements of photon colliders.

c) This is a new direction and it has to pass several natural phases of development. In the last almost two decade, a general conception of photon colliders has been developed and has been discussed at many workshops, the bibliography on  $\gamma\gamma$ ,  $\gamma e$  physics now numbers over 1000 papers, mostly theoretical. The next phase will require much wider participation of the experimental community.

To this end, it was recently decided to initiate an International collaboration on Photon Colliders. This Collaboration does not replace the regional working groups, but rather supports and strengthens them. The Invitation letter, signed by Worldwide Study contact persons on photon colliders: V.Telnov (Europe), K. Van Bibber (North America), T.Takahashi (Asia) will be send to you shortly.

## 2 Physics

### 2.1 Higgs

The Higgs boson will be produced at photon colliders as a single resonance. This process goes via the loop and its cross section is very sensitive to all heavy (even super-heavy) charged particles which get their mass via the Higgs mechanism. The mass of the Higgs most probably lies in the region of  $100 < M_H < 250$  GeV. The effective cross section is presented in Fig. 1.<sup>10</sup>

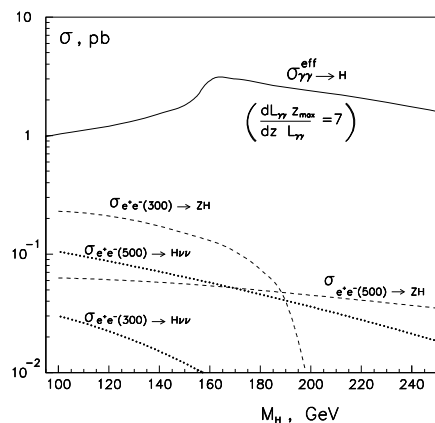


Figure 1: Cross sections for the Standard model Higgs in  $\gamma\gamma$  and  $e^+e^-$  collisions.

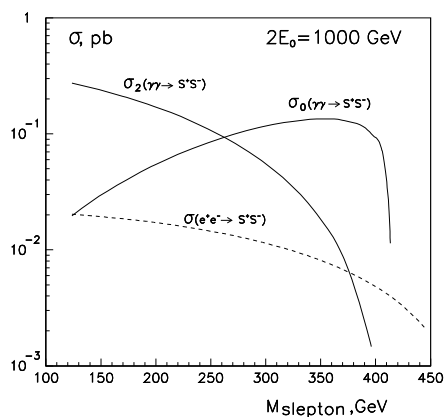


Figure 2: Cross sections for charged scalars production in  $e^+e^-$  and  $\gamma\gamma$  collisions at  $2E_0 = 1$  TeV collider (in  $\gamma\gamma$  collision  $W_{max} \approx 0.82$  TeV,  $x = 4.6$ );  $\sigma_0$  and  $\sigma_2$  correspond to the total  $\gamma\gamma$  helicity 0 and 2.

Note that here  $L_{\gamma\gamma}$  is defined as the  $\gamma\gamma$  luminosity at the high energy luminosity peak ( $z = W_{\gamma\gamma}/2E_e > 0.65$  for  $x = 4.8$ ) with FWHM about 15%. For comparison, the cross sections of the Higgs production in  $e^+e^-$  collisions are shown. We see that for  $M_H = 120$ – $250$  GeV the effective cross section in  $\gamma\gamma$  collisions is larger than that in  $e^+e^-$  collisions by a factor of about 6–30. If the Higgs is light enough, its width is much less than the energy spread in  $\gamma\gamma$  collisions. It can be detected as a peak in the invariant mass distribution or can be searched for by energy scanning using the very sharp ( $\sim 1\%$ ) high energy edge of luminosity distribution.<sup>10</sup> The total number of events in the main decay channels  $H \rightarrow b\bar{b}, WW(W^*), ZZ(Z^*)$  will be several thousands for a typical integrated luminosity of  $10 \text{ fb}^{-1}$ . The scanning method also enables the measurement of the Higgs mass with a high precision.

## 2.2 Charge pair production

The second example is the charged pair production. It could be  $W^+W^-$  or  $t\bar{t}$  pairs or some new, for instance, supersymmetric particles. Cross sections for the production of charged scalar, lepton, and top pairs in  $\gamma\gamma$  collisions are larger than those in  $e^+e^-$  collisions by a factor of approximately 5–10; for WW production this factor is even larger, about 10–20. The corresponding graphs can be found elsewhere.<sup>4,8,10</sup>

The cross section of the scalar pair production (sleptons, for example) in collision of polarized photons is shown in Fig.2. One can see that for heavy scalars the cross section in collisions of polarized photons is higher than that in  $e^+e^-$  collisions by a factor of 10–20. The cross section near the threshold is very sharp (in  $e^+e^-$  it contains a factor  $\beta^3$ ) and can be used for measurement of particle masses. Note that for scalar selectrons the cross section in  $e^+e^-$  collisions is not described by the curve in Fig.2 due to the existence of an additional exchange diagram (exchange by neutralino). Correspondingly the cross section is not described by pure QED (as it takes place in  $\gamma\gamma$ ). Measurement of cross sections in both  $e^+e^-$  and  $\gamma\gamma$  channels give, certainly, complementary information.

## 2.3 Accessible masses

In  $\gamma e$  collisions, charged supersymmetric particles with masses higher than those in  $e^+e^-$  collisions can be produced (a heavy charged particle plus a light neutral).  $\gamma\gamma$  collisions also provide higher accessible masses for particles which are produced as a single resonance in  $\gamma\gamma$  collisions (such as the Higgs boson).

## 2.4 Quantum gravity effects in Extra Dimensions.

This new theory<sup>11</sup> is very interesting though beyond my imagination. It suggests a possible explanation of why gravitation forces are so weak in comparison with electroweak forces. According to this theory the gravitational forces are as strong as electroweak forces at small distances in space with extra dimensions and became weak at large distances due to “compactification” of these extra dimensions. It turns out that this extravagant theory can be tested at linear colliders and according to T.Rizzo<sup>12</sup> ( $\gamma\gamma \rightarrow WW$ ) and K.Cheung<sup>13</sup> ( $\gamma\gamma \rightarrow \gamma\gamma$ ) photon colliders are sensitive up to a factor of 2 higher quantum gravity mass scale than  $e^+e^-$  collisions.

# 3 Luminosity of photon colliders in current designs.

## 3.1 0.5–1 TeV colliders

Some results of simulation of  $\gamma\gamma$  collisions at TESLA, ILC (converged NLC and JLC) and CLIC are presented below in Table 1. Beam parameters were taken the same as those in  $e^+e^-$  collisions with the exception of the horizontal beta function at the IP which is taken (quite conservatively) equal to 2 mm for all cases, that is several times smaller than that in  $e^+e^-$  collisions due to the absence of beamstrahlung. The conversion point(CP) is situated at distance  $b = \gamma\sigma_y$ . It is assumed that electron

beams have 85% longitudinal polarization and laser photons have 100% circular polarization.

Table 1: Parameters of  $\gamma\gamma$  colliders based on Tesla(T), ILC(I) and CLIC(C).

	T(500)	I(500)	C(500)	T(800)	I(1000)	C(1000)
no deflection, $b = \gamma\sigma_y, x = 4.6$						
$N/10^{10}$	2.	0.95	0.4	1.4	0.95	0.4
$\sigma_z$ , mm	0.4	0.12	0.05	0.3	0.12	0.05
$f_{rep} \times n_b$ , kHz	15	11.4	30.1	13.5	11.4	26.6
$\gamma\epsilon_{x,y}/10^{-6}$ , m-rad	10/0.03	5/0.1	1.9/0.1	8/0.01	5/0.1	1.5/0.1
$\beta_{x,y}$ , mm at IP	2/0.4	2/0.12	2/0.1	2/0.3	2/0.16	2/0.1
$\sigma_{x,y}$ , mm	200/5	140/5	88/4.5	140/2	100/4	55/3.2
b, mm	2.4	2.4	2.2	1.5	4	3.1
$L(geom)$ , $10^{33}$	48	12	10	75	20	19.5
$L_{\gamma\gamma}(z > 0.65)$ , $10^{33}$	4.5	1.1	1.05	7.2	1.75	1.8
$L_{\gamma e}(z > 0.65)$ , $10^{33}$	6.6	2.6	2.8	8	4.2	4.6
$L_{ee}$ , $10^{33}$	1.2	1.2	1.6	1.1	1.8	2.3
$\theta_x/\theta_{y,max}$ , mrad	5.8/6.5	6.5/6.9	6/7	4.6/5	4.6/5.3	4.6/5.5

We see that  $\gamma\gamma$  luminosity in the hard part of the spectrum  $L_{\gamma\gamma}(z > 0.65) \sim 0.1L(geom)$ , numerically it is about  $(1/6)L_{e^+e^-}$ . Note, that the coefficient 1/6 is not a fundamental constant. The  $\gamma\gamma$  luminosity in these projects is determined only by “geometric” ee-luminosity. With some new low emittance electron sources or with laser cooling of electron beams after the damping ring (or photo-guns) one can get, in principle,  $L_{\gamma\gamma}(z > 0.65) > L_{e^+e^-}$ . The limitations and technical feasibility are discussed in the next section and my second talk at this workshop.

Beside  $\gamma\gamma$  collisions, there is considerable  $\gamma e$  luminosity (see table) and it is possible to study  $\gamma e$  interactions simultaneously with  $\gamma\gamma$  collisions.

The normalized  $\gamma\gamma$  luminosity spectra for a 0.5 TeV TESLA are shown in Fig.3(left). The luminosity spectrum is decomposed into two parts, with the total helicity of two photons 0 and 2. We see that in the high energy part of the luminosity spectra photons have a high degree of polarization, which is very important for many experiments. In addition to the high energy peak, there is a factor 5–8 larger low energy luminosity. It is produced by photons after multiple Compton scattering and beamstrahlung photons. Fortunately, these events have a large boost and can be easily distinguished from the central high energy events. In the same Fig.3(left) you can see the same spectrum with an additional “soft” cut on the longitudinal momentum of the produced system which suppresses low energy luminosity to a negligible level.

Fig.3 (right) shows the same spectrum with a stronger cut on the longitudinal momentum. In this case, the spectrum has a nice peak with FWHM about 7.5%. On first sight such cut is somewhat artificial because one can directly select events with high invariant masses. The minimum width of the invariant mass distribution depends only on the detector resolution. However, there is a very important example when one can obtain a “collider resolution” somewhat better than the “detector resolution”; this is the case of only two jets in the event when one can restrict

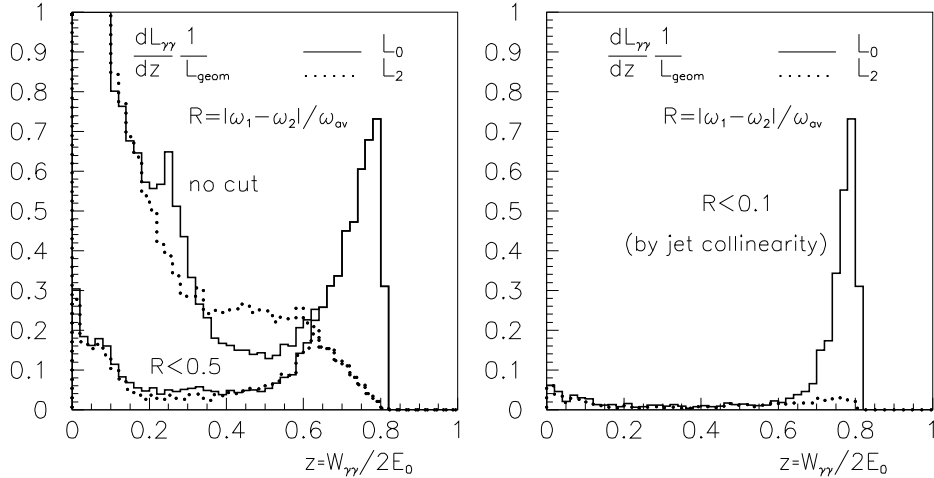


Figure 3:  $\gamma\gamma$  luminosity spectra at TESLA(500) for parameters presented in Table 1. Solid line for total helicity of two photons 0 and dotted line for total helicity 2. Upper curves without cuts, two lower pairs of curves have cut on the relative difference of the photon energy. See comments in the text.

the longitudinal momentum of the produced system using the acollinearity angle between jets ( $H \rightarrow b\bar{b}, \tau\tau$ , for example).

A similar table and distributions for the photon collider on the c.m.s. energy 130 GeV (Higgs collider) can be found in ref.<sup>16</sup>

#### 4 Ultimate $\gamma\gamma, \gamma e$ luminosities

The  $\gamma\gamma$  luminosities in the current projects are determined by the “geometric” luminosity of the electron beams. Having electron beams with smaller emittances one can obtain a much higher  $\gamma\gamma$  luminosity.<sup>15</sup> Fig.4 shows dependence of the  $\gamma\gamma$  (solid curves) and  $\gamma e$  (dashed curves) luminosities on the horizontal beam size. The vertical emittance is taken as in TESLA(500), ILC(500) projects (see Table 1). The horizontal beam size was varied by change of horizontal beam emittance keeping the horizontal beta function at the IP constant and equal to 2 mm.

One can see that all curves for  $\gamma\gamma$  luminosity follow their natural behavior:  $L \propto 1/\sigma_x$ , with the exception of ILC at  $2E_0 = 1$  GeV where at small  $\sigma_x$  the effect of coherent pair creation<sup>14,4</sup> is seen.<sup>a</sup> This means that at the same collider the  $\gamma\gamma$  luminosity can be increased by decreasing the horizontal beam size at least by one order ( $\sigma_x < 10$  nm is difficult due to some effects connected with the crab crossing). Additional increase of  $\gamma\gamma$  luminosity by a factor about 3 (TESLA), 7(ILC) can be obtained by a further decrease of the vertical emittance.<sup>16</sup> So, using beams with smaller emittances, the  $\gamma\gamma$  luminosity at TESLA, ILC can be increase by almost 2 orders of magnitude. However, even with one order improvement, the number

<sup>a</sup>This curve has also some bend at large  $\sigma_x$  that is connected with synchrotron radiation in quads (Oide effect) due to a large horizontal emittance. One can avoid this effect by taking larger  $\beta_x$  and smaller  $\epsilon_{nx}$ .

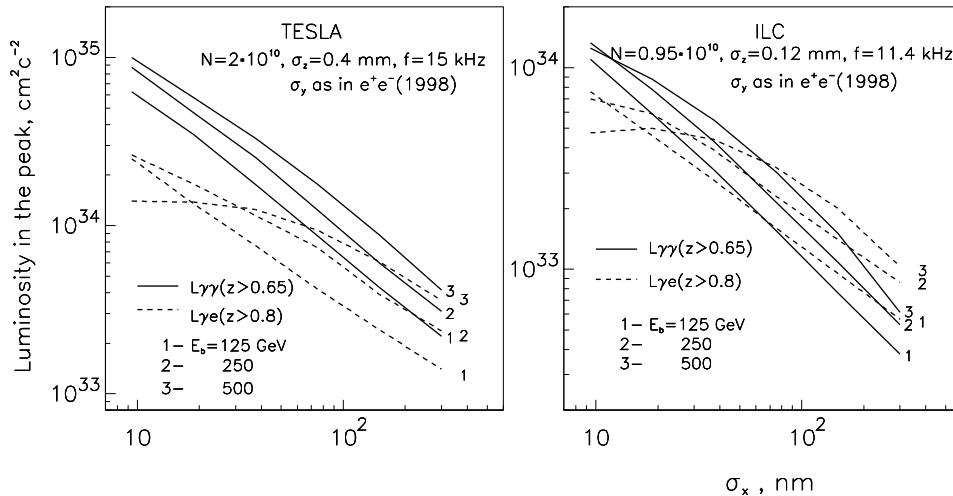


Figure 4: Dependence of  $\gamma\gamma$  and  $\gamma e$  luminosities in the high energy peak on the horizontal beam size for TESLA and ILC at various energies. See also comments in the text.

of “interesting” events (the Higgs, charged pairs) at photon colliders will be larger than that in  $e^+e^-$  collisions by about one order. This is a nice goal and motivation for photon colliders.

In  $\gamma e$  collision (Fig.4, dashed curves), the behavior of the luminosity on  $\sigma_x$  is different due to additional collision effects: beams repulsion and beamstrahlung. As a result, the luminosity in the high energy peak is not proportional to the “geometric” luminosity.

There are several ways of decreasing the transverse beam emittances (their product): optimization of storage rings with long wigglers, development of low-emittance RF or pulsed photo-guns with merging many beams with low charge and emittances. Here some progress is certainly possible. Moreover, there is one method which allows further decrease of beam cross sections by two orders in comparison with current designs. It is a laser cooling,<sup>17,18</sup> see my second talk at this workshop.

## 5 Backgrounds

Sometimes one hears that photon colliders are closer to pp than to  $e^+e^-$  colliders because the process  $\gamma\gamma \rightarrow hadron$  connected with the hadronic component of the photon, which has a cross section by about 5 orders of magnitude larger than that of electromagnetic production of charged pairs. Continuing this logics line one should say that  $e^+e^-$  colliders are, in fact, rather photon colliders than  $e^+e^-$  because the cross section of the two-photon process  $e^+e^- \rightarrow e^+e^- e^+e^-$  is 10–11 orders higher than any of  $e^+e^-$  annihilation processes. This is obviously a misleading philosophy.

It is more correct to evaluate the seriousness of background by the problems which it causes for experimentation: recording of data (trigger), their analysis (underlying background processes, overlapping of interesting and background events)

and radiation damage of detector. The proton collider LHC has approximately the same luminosity as a photon collider, but the hadronic background rate is 5 orders magnitude higher; this causes radiation damage of detector components. In this respect photon colliders are much cleaner, practically the same as  $e^+e^-$  LC. Nevertheless, the background is a serious issue for both  $e^+e^-$  and  $\gamma\gamma$  modes at an LC. This is connected mainly with the high luminosity and relatively low beam collision rate that causes many background reactions per each beam collisions.

Let us enumerate the main sources of background at photon colliders:

- *Disrupted beams.* Low energy electrons after the multiple Compton scattering are deflected on opposing electron beam. The maximum disruption angle is about 10 mrad and the energy spread  $(0.02 - 1)E_0$ . Solution: all these particles can be removed from the IP using the crab crossing collisions with  $\alpha_c \sim 30$  mrad.

- *Electron-positron pairs.* This pairs are produced in the processes  $\gamma\gamma \rightarrow e^+e^-$ ,  $\gamma e \rightarrow e^+e^-$ ,  $ee \rightarrow ee + e^+e^-$ . There are unavoidable hard large angle particles with acceptable rate and many rather low  $P_t$  electrons produced at very small angle and then kicked by the opposing electron beam. Due to solenoidal magnetic field these particles are confined in the region<sup>8</sup>  
 $r^2[cm^2] < 0.12(N/10^{10})(z[cm]/\sigma_z[mm])B[T]$ .

The vacuum pipe should have larger radius. The level of  $e^+e^-$  background (mainly in the vertex detector) at photon colliders is approximately the same as in  $e^+e^-$  collisions though some additional study taking into account “reflection” of particles from the mirrors is necessary .

- *Large angle Compton scattering.* The energy of these photon is  $\omega = 4\omega_0/\theta^2$  at  $\theta \gg 1/\gamma$ , where  $\omega_0$  is the energy of laser photons ( $\sim 1$  eV). At a distance  $L$  the flux of photons  $dn/ds \propto N/\gamma^2 L^2 \theta^4$ . The main contribution comes from Compton scattering on low energy electrons. The simulation for  $2E = 500$  GeV gives:  $P \sim 10^{-7}$  W/cm<sup>2</sup>,  $\omega \sim 40$  keV at  $\theta = 10$  mrad (the edge of mirrors).

- *Large angle beamstrahlung.* The simulation shows that X-ray photons have a wide spectrum,  $P \sim 10^{-6}$  W/cm<sup>2</sup>,  $\bar{\omega} \sim 1.5$  keV at  $\theta = 10$  mrad.

X-rays may cause radiation damage problems for multilayer dielectric mirrors. For our case this problem is not sufficiently studied yet. In principle, there are dielectrical mirrors with very high radiation damage thresholds, sufficient for our task, it should be checked that they have simultaneously high reflectivity. In any case, one can use metal mirrors near the beam, for  $1 \mu m$  wave length the reflectivity is more than 99 %. Other problems with mirrors: change of the shape due to overheating and carbon deposits due to residual gas. Note, that the X-ray power density on the mirrors is proportional to  $1/\theta^6$  and, if necessary, the minimum angle can be increased (it is very easy when the mirrors are place outside the beam).

- *Halo of X-rays from final quads.* This is a problem for  $e^+e^-$  colliders as well. The solution here is the scraping of electron beam tails by collimators before final focusing. This is not a simple problem, especially if some halo arises after collimation.

- $\gamma\gamma \rightarrow hadrons$ . Its cross section is  $\sigma_{tot} \sim 500$  nb.<sup>-1</sup> For a typical case  $L_{\gamma\gamma} \sim 10^{34}$ ,  $\nu \sim 10^4$  the background rate is 0.5 events/ bunch crossing. Hadronic background was studied in TESLA CDR.<sup>8</sup> It will make problems for certain processes with jets at small angles (such as various QCD processes), however, for the

“main” physics, where products usually have large angles, it should be no serious problem even at maximum expected luminosities (one order higher than at the “nominal” TESLA). It is important to develop algorithms of jet reconstruction which have low sensitivity to “smooth” hadronic background. Influence of hadronic background on quality of reconstruction of various physics processes is one of important tasks of our Study.

## 6 Conclusion

Prospects of photon colliders for particle physics are great; the physics community should not miss this unique possibility.

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