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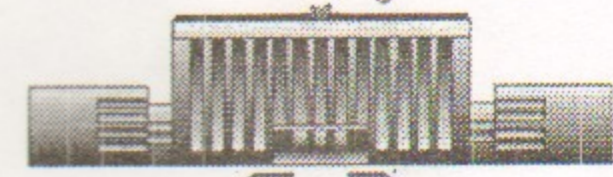
A.V. Pak, D.V. Pavluchenko, S.S. Petrosyan,  
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MEASUREMENT OF  $\gamma\gamma$  and  $\gamma e$  LUMINOSITIES  
AT PHOTON COLLIDERS

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Introduction

Abstract  
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Initial electrons and laser photons and energy of proton in electron-positron colliders are generated naturally by Compton scattering of laser photons on relativistic electrons. This is not a simple problem because photon have broad spectra and various energy electrons in linear colliders are considered. This is not a simple problem because photon have broad spectra and various energy electrons in linear colliders are considered. This is not a simple problem because photon have broad spectra and various energy electrons in linear colliders are considered.

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Talk given at International Workshop Linear Colliders (LCWS 2003), JINR, Dubna, Moscow, 26-30 Aug 2003  
2003

# Measurement of $\gamma\gamma$ and $\gamma e$ luminosities at photon colliders<sup>1</sup>

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## Abstract

Methods of  $\gamma\gamma$ ,  $\gamma e$  luminosities measurement at photon colliders based on Compton scattering of laser photons on high energy electrons at linear colliders are considered. This is not a simple problem because photons have broad spectra and various kind of polarizations.

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## 1 Introduction

In addition to  $e^+e^-$  physics, linear colliders provide a unique opportunity to study  $\gamma\gamma$  and  $\gamma e$  interactions at high energies and luminosities [1, 2]. High energy photons can be obtained using Compton backscattering of laser light off high energy electrons. This option is included in Conceptual and Technical Design of the linear collider TESLA [3, 4] and is considered for all other projects of linear colliders [5, 6, 7]. At present three projects TESLA, NLC and JLC are almost ready for construction and, hopefully, a decision about construction of one international linear collider will be made soon.

Spectrum of photons after Compton scattering is a broad with characteristic peak at maximum energies. Photons can have circular or linear polarizations depending on their energies and polarizations of initial electrons and laser photons. Angle and energies of photons in Compton scattering are correlated, therefore the  $\gamma\gamma$  luminosity can not be described by convolution of some photon spectra. Due to complexity of processes in the conversion and interaction regions an accuracy of prediction by simulation will be rather poor, therefore one should measure all luminosity properties experimentally.

Below we consider some general features of  $\gamma\gamma$ ,  $\gamma e$  processes, give example of luminosity spectra and then consider methods for measurement of  $\gamma\gamma$ ,  $\gamma e$  luminosities.

## 2 General features of luminosities and cross sections

In general case the number of events in  $\gamma\gamma$  collision is given by [2]

$$d\dot{N}_{\gamma\gamma \rightarrow X} = dL_{\gamma\gamma} \sum_{i,j=0}^3 \langle \xi_i \tilde{\xi}_j \rangle \sigma_{ij}, \quad (1)$$

where  $\xi_i$  are Stokes parameters,  $\xi_2 \equiv \lambda_\gamma$  is the circular polarization,  $\sqrt{\xi_1^2 + \xi_3^2} \equiv l_\gamma$  the linear polarization and  $\xi_0 \equiv 1$ . Since photons have wide spectra and various polarizations, in general case one has to measure 16 two dimensional luminosity distributions  $d^2L_{ij}/d\omega_1 d\omega_2$ ,  $dL_{ij} = dL_{\gamma\gamma} \langle \xi_i \tilde{\xi}_j \rangle$ , where the tilde sign marks the second colliding beam.

Among 16 cross sections  $\sigma_{ij}$  there are three most important which do not vanish after averaging over spin states of final particles and azimuthal angles, that are [2]

$$\begin{aligned} \sigma^{np} &\equiv \sigma_{00} = \frac{1}{2}(\sigma_{\parallel} + \sigma_{\perp}) = \frac{1}{2}(\sigma_0 + \sigma_2) \\ \tau^c &\equiv \sigma_{22} = \frac{1}{2}(\sigma_0 - \sigma_2) \\ \tau^l &\equiv \frac{1}{2}(\sigma_{33} - \sigma_{11}) = \frac{1}{2}(\sigma_{\parallel} - \sigma_{\perp}) \end{aligned} \quad (2)$$

Here  $\sigma_{\parallel}, \sigma_{\perp}$  are cross sections for collisions of linearly polarized photons with parallel and orthogonal relative polarizations and  $\sigma_0$  and  $\sigma_2$  are cross sections for collisions of photons with  $J_z$  of two photons equal 0 and 2, respectively.

If only these three cross sections are of interest than (1) can be written as

$$d\dot{N}_{\gamma\gamma \rightarrow X} = dL_{\gamma\gamma} (d\sigma^{np} + \langle \xi_2 \tilde{\xi}_2 \rangle d\tau^c + \langle \xi_3 \tilde{\xi}_3 - \xi_1 \tilde{\xi}_1 \rangle d\tau^l). \quad (3)$$

Substituting  $\xi_2 \equiv \lambda_\gamma$ ,  $\tilde{\xi}_2 \equiv \tilde{\lambda}_\gamma$ ,  $\xi_1 \equiv l_\gamma \sin 2\gamma$ ,  $\tilde{\xi}_1 \equiv -\tilde{l}_\gamma \sin 2\tilde{\gamma}$ ,  $\xi_3 \equiv l_\gamma \cos 2\gamma$ ,  $\tilde{\xi}_3 \equiv \tilde{l}_\gamma \cos 2\tilde{\gamma}$  and  $\Delta\phi = \gamma - \tilde{\gamma}$  (azimuthal angles for

linear polarizations are defined relative to one  $x$  axis), we get

$$\begin{aligned} d\dot{N} &= dL_{\gamma\gamma} (d\sigma^{np} + \lambda_\gamma \tilde{\lambda}_\gamma d\tau^c + l_\gamma \tilde{l}_\gamma \cos 2\Delta\phi d\tau^l) \\ &\equiv dL_{\gamma\gamma} d\sigma^{np} + (dL_0 - dL_2) d\tau^c + (dL_{\parallel} - dL_{\perp}) d\tau^l \\ &\equiv dL_0 d\sigma_0 + dL_2 d\sigma_2 + (dL_{\parallel} - dL_{\perp}) d\tau^l \\ &\equiv dL_{\parallel} d\sigma_{\parallel} + dL_{\perp} d\sigma_{\perp} + (dL_0 - dL_2) d\tau^c, \end{aligned} \quad (4)$$

where

$$\begin{aligned} dL_0 &= dL_\gamma \frac{1 + \lambda_\gamma \tilde{\lambda}_\gamma}{2}; & dL_2 &= dL_\gamma \frac{1 - \lambda_\gamma \tilde{\lambda}_\gamma}{2}; \\ dL_{\parallel} &= dL_\gamma \frac{1 + l_\gamma \tilde{l}_\gamma \cos 2\Delta\phi}{2}; & dL_{\perp} &= dL_\gamma \frac{1 - l_\gamma \tilde{l}_\gamma \cos 2\Delta\phi}{2}. \end{aligned}$$

So, one should measure (not only in a general case)  $dL_{\gamma\gamma}$ ,  $\langle \lambda_\gamma \tilde{\lambda}_\gamma \rangle$ ,  $\langle l_\gamma \tilde{l}_\gamma \rangle$  or alternatively  $dL_0, dL_2, dL_{\parallel}, dL_{\perp}$ . If both photon beams have no linear polarization or no circular polarization, the luminosity can be decomposed in two parts:  $L_0$  and  $L_2$ , or  $L_{\parallel}$  and  $L_{\perp}$ , respectively.

For example, for scalar resonances such as the Higgs boson,  $\sigma_2 = 0$ , while  $\sigma_{\parallel} = \sigma_0$ ,  $\sigma_{\perp} = 0$  for  $CP = 1$  and  $\sigma_{\perp} = \sigma_0$ ,  $\sigma_{\parallel} = 0$  for  $CP = -1$ , then

$$d\dot{N} = dL_{\gamma\gamma} d\sigma^{np} (1 + \lambda_\gamma \tilde{\lambda}_\gamma \pm l_\gamma \tilde{l}_\gamma \cos 2\Delta\phi). \quad (5)$$

In  $\gamma e$  collisions general formulae are similar to (1) but Stokes parameters for the second particle are replaced by the electron spin vector  $\zeta$  (the double mean electron helicity  $2\lambda_e = \zeta_3$ ). Besides  $dL_{\gamma e}$  the most important characteristic is  $\langle \lambda_e \lambda_\gamma \rangle$  (as function of  $E_e$  and  $E_\gamma$ ), but in some cases  $\lambda_e$  and  $\lambda_\gamma$  should be known separately, in the process  $\gamma e \rightarrow W\nu$ , for instance.

Expected  $\gamma\gamma$ ,  $\gamma e$  luminosities at TESLA(500) are presented in Table 1. The luminosities in the high energy peaks are about  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  both for  $\gamma\gamma$  and  $\gamma e$  collisions [4] that is about 1/3 of  $e^+e^-$  luminosity (the last line). That is good because cross sections in  $\gamma\gamma$  collisions are typically higher than in  $e^+e^-$  collisions by one order of magnitude. The  $\gamma\gamma$ ,  $\gamma e$  luminosity spectra for the beam energy  $2E_0 = 500 \text{ GeV}$  are presented in Fig.1 [8, 4, 9].

Table 1: Luminosities at the photon collider at TESLA

$2E_0, \text{GeV}$	200	500	800
$L_{ee}(\text{geom}) [10^{34} \text{ cm}^{-2} \text{ s}^{-1}]$	4.8	12	19
$L_{ee}(z > 0.65)$	0.03	0.07	0.095
$W_{\gamma\gamma, \text{max}} (\text{GeV})$	122	390	670
$L_{\gamma\gamma}(z > 0.8z_{m, \gamma\gamma}) [10^{34}]$	0.43	1.1	1.7
$W_{\gamma e, \text{max}} (\text{GeV})$	156	440	732
$L_{\gamma e}(z > 0.8z_{m, \gamma e}) [10^{34}]$	0.36	0.94	1.3
$L_{e^+e^-} [10^{34} \text{ cm}^{-2} \text{ s}^{-1}]$	1.3	3.4	5.8

TESLA(500)

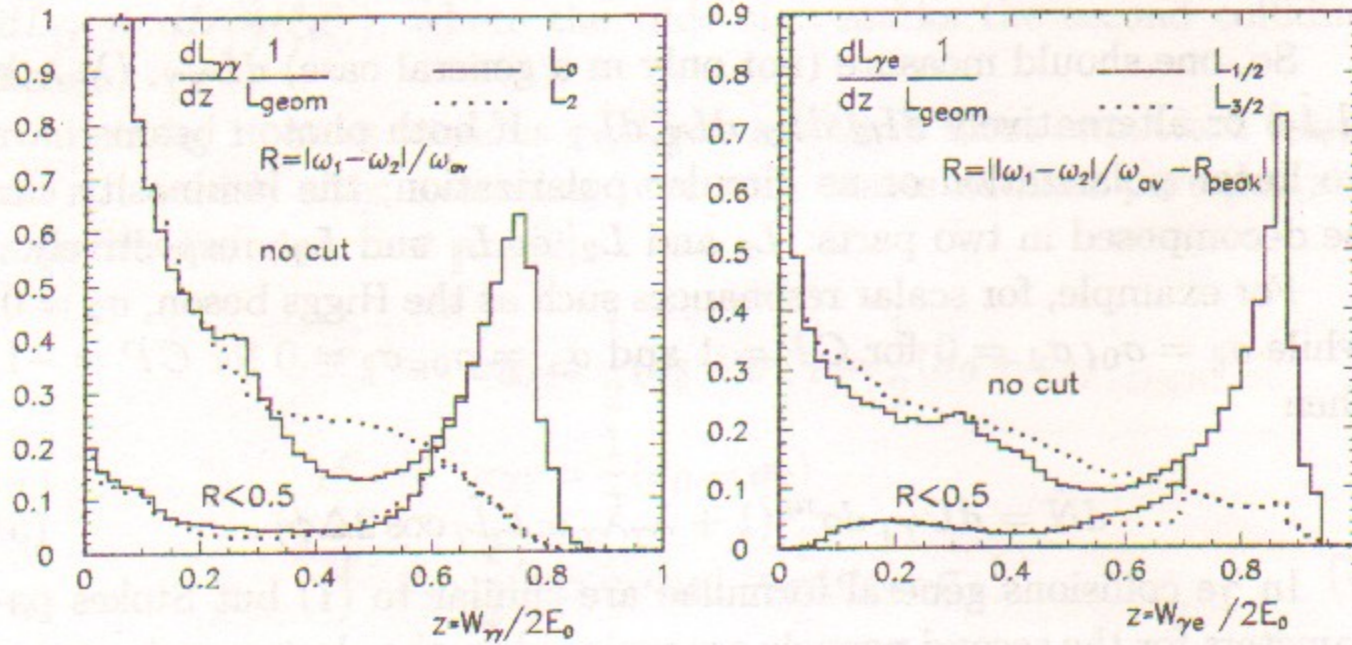


Figure 1: Left:  $\gamma\gamma$  luminosity spectra; right:  $\gamma e$  luminosity spectra at TESLA. Solid lines for  $J_z$  of two colliding photons equal to 0, dotted lines for  $J_z = 2$  (1/2 and 3/2 in case of  $\gamma e$  collisions).

### 3 Measurement $\gamma\gamma$ luminosity

The best process for the measurement of the  $\gamma\gamma$  luminosity is  $\gamma\gamma \rightarrow l^+l^-$  ( $l = e, \mu$ ) [2, 10, 11, 4]. Another QED process with large cross section is  $\gamma\gamma \rightarrow l^+l^-l^+l^-$  [1, 13]. The process  $\gamma\gamma \rightarrow W^+W^-$  was also suggested for the luminosity measurement [12], but at first its

cross section has to be measured as it may differ from prediction of the Standard Model and presents a special physics interest by itself.

#### 3.1 $\gamma\gamma \rightarrow l^+l^-$

The cross section at not too small angles [4]

$$d\sigma = \frac{2\pi\alpha^2}{W_{\gamma\gamma}^2} \left[ (1 - \lambda_\gamma \tilde{\lambda}_\gamma) \frac{(1 + \cos^2 \theta)}{(1 - \cos^2 \theta)} - l_\gamma \tilde{l}_\gamma \cos(4\varphi - 2(\gamma + \tilde{\gamma})) \right] \frac{d\varphi}{2\pi} d(\cos \theta), \quad (6)$$

where  $\lambda_\gamma, \tilde{\lambda}_\gamma$  the circular polarizations,  $l_\gamma, \tilde{l}_\gamma$  linear polarizations of photons,  $\gamma, \tilde{\gamma}$  azimuthal angles of photon linear polarizations,  $\varphi$  the azimuthal angle of the lepton plane. One can see that the cross section is zero for  $\lambda_\gamma = \tilde{\lambda}_\gamma = \pm 1$  (or  $J_z = 0$ ). Thus, lepton pairs are produced only in collisions of photons with total  $J_z = 2$ . The suppression factor for  $J_z = 0$  is  $m_l^2/W_{\gamma\gamma}^2$  [4]. This process can measure only  $L_2$ , for measurement of  $L_0$  one can change the polarization of one beam to opposite for part of the time [10, 11]. The product of linear polarizations  $\langle l_\gamma \tilde{l}_\gamma \rangle$  can be measured by azimuthal variation of the cross section at the large angles  $\theta$ . The total cross section

$$\sigma_2(|\cos \theta| < a) \approx \frac{4\pi\alpha^2}{W_{\gamma\gamma}^2} \left[ 2 \ln \left( \frac{1+a}{1-a} \right) - 2a \right], \quad (7)$$

$\sigma(|\cos \theta| < 0.9) \approx 10^{-36}/W_{\gamma\gamma}^2 [\text{TeV}] \text{ cm}^2$ . For examples, at TESLA(500) for  $10^7$  sec one can expect about  $10^6$  of  $e^+e^-$  and  $\mu^+\mu^-$  events in the high energy peak.

The invariant mass spectrum of  $\mu^+\mu^-$  pairs in the detector is shown in Fig.2. For the minimum detection angle  $\theta = 0.3$  rad and  $10^7$  sec run the expected statistical accuracy of the peak value of  $dL/dW_{\gamma\gamma}$  is about 0.07 % and 0.14 % for  $2E_0 = 200$  and 500 GeV, respectively. This is much better than necessary for the Higgs study where the accuracy for branchings not better than 1% is expected.

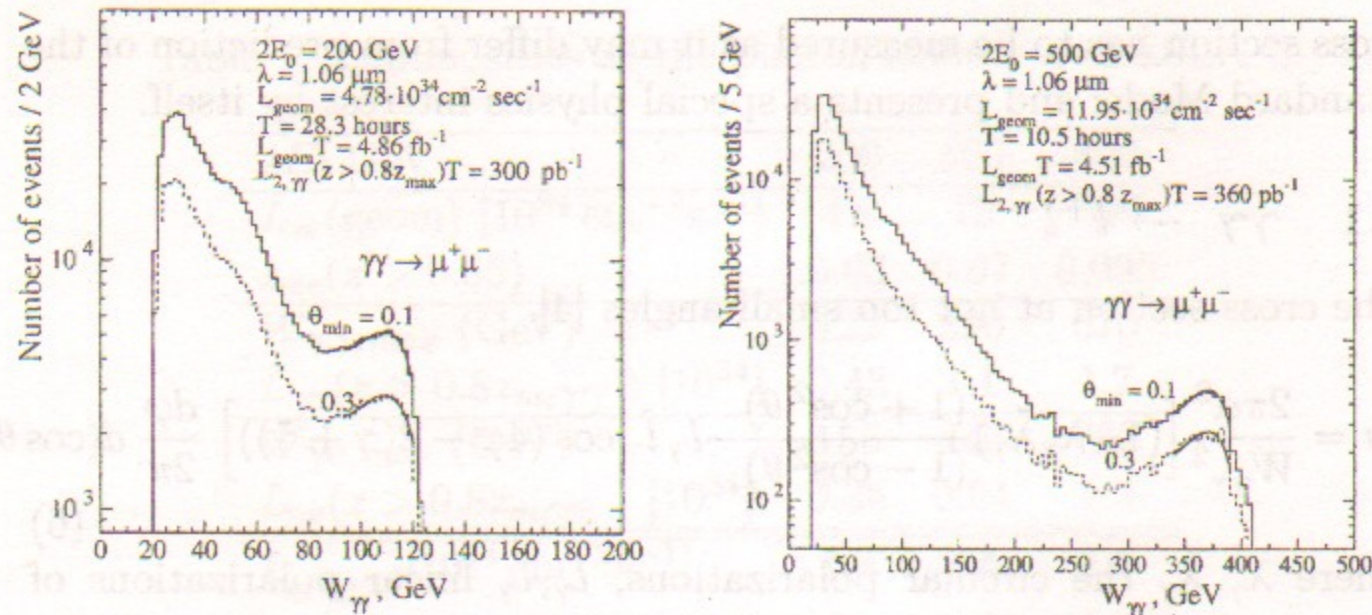


Figure 2: Distribution of pairs on the invariant mass in the process  $\gamma\gamma \rightarrow \mu^+\mu^-$ ; left:  $2E_0 = 200$  GeV, right:  $2E_0 = 500$  GeV.

### 3.2 $\gamma\gamma \rightarrow l^+l^-\gamma$

This process is of interest because the photon emission removes the suppression of the lepton production in the case of  $J_z = 0$ . The cross section for this process as a function of the minimum photon energy obtained by the ComHEP code [14] is presented in Fig.3. Indeed, the cross section for this case is not negligible, but lower than for  $J_z = 2$  without photons by a factor of 300.

### 3.3 $\gamma\gamma \rightarrow l^+l^-l^+l^- (l = e, \mu)$

This process is of interest [1, 13] because it has large total cross section and weakly depends on photon polarizations, therefore it could be used together with  $\gamma\gamma \rightarrow l^+l^-$  for measurement of  $L_0$  and  $L_2$  simultaneously. Unfortunately, at large angles, where particle momenta can be measured with a high accuracy, the cross section is rather small. The cross section obtained by ComHEP for the process  $\gamma\gamma \rightarrow e^+e^-\mu^+\mu^-$  at the photon energies  $2 \times 200$  GeV is shown in Fig. 4 and it changes with the energy as  $1/E^2$ . At small angles main contribution gives the peripheral diagram and the cross section depends on the minimum angle as  $1/\theta^2$ . At the angles above 0.1 rad main contribution give diagrams where the

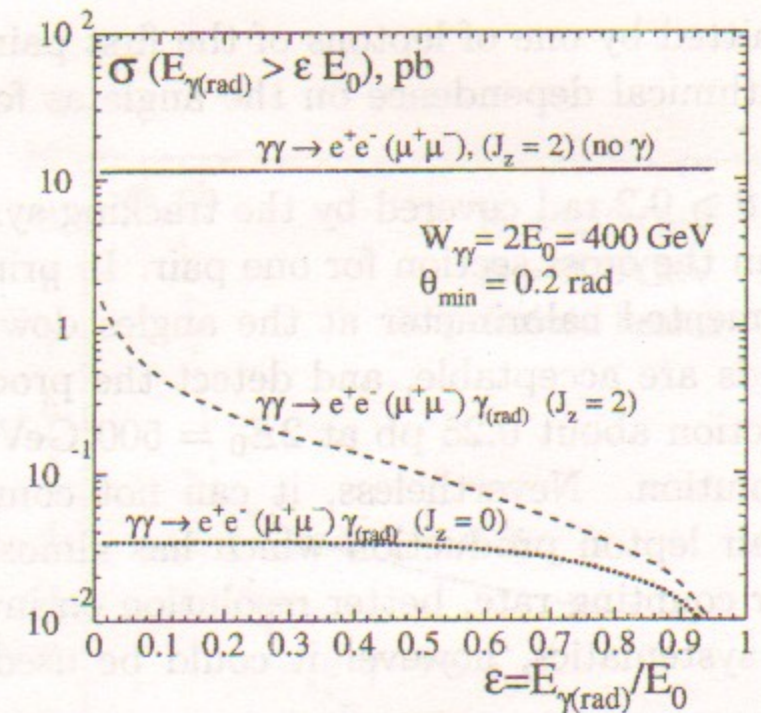


Figure 3: The cross section of the process  $\gamma\gamma \rightarrow l^+l^-\gamma$  vs the minimum energy of the emitted photons.

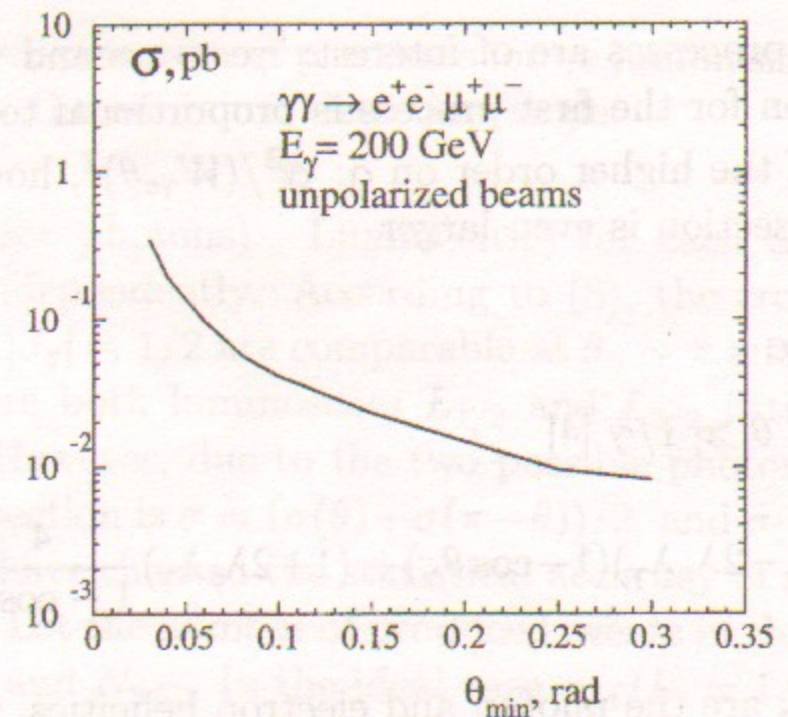


Figure 4: The cross section of the process  $\gamma\gamma \rightarrow e^+e^-\mu^+\mu^-$  vs the minimum polar angle of all final particles. For the processes  $\gamma\gamma \rightarrow e^+e^-e^+e^-$  and  $\gamma\gamma \rightarrow \mu^+\mu^-\mu^+\mu^-$  the cross sections are smaller by a factor of 2 due to identity of the lepton pairs.

second pair is emitted by one of leptons of the first pair, here one can expect the logarithmical dependence on the angle as for the one pair production.

In the region  $\theta > 0.2$  rad covered by the tracking system it is 1000 times smaller than the cross section for one pair. In principle, one can install a fine segmented calorimeter at the angles down to 20 mrad, where backgrounds are acceptable, and detect the process  $e^+e^-e^+e^-$  with the cross section about 0.25 pb at  $2E_0 = 500$  GeV with a rather good energy resolution. Nevertheless, it can not compete with the process of one pair lepton production which has almost two order of magnitude higher counting rate, better resolution on invariant masses and much lower systematics, however it could be used for the cross check.

#### 4 Measurement of $\gamma e$ luminosity

Here two QED processes are of interest:  $\gamma e \rightarrow \gamma e$  and  $\gamma e \rightarrow e^-e^+e^-$ . The cross section for the first process is proportional to  $\alpha^2/W_{\gamma e}^2$ , the second one is of the higher order on  $\alpha$ :  $\alpha^3/(W_{\gamma e}\theta)^2$ , however at small angles its cross section is even larger.

##### 4.1 $\gamma e \rightarrow \gamma e$

Cross section at  $\theta \gg 1/\gamma$  [4]

$$d\sigma = \frac{\pi\alpha^2}{2W_{\gamma e}^2} \left[ (1-2\lambda_e\lambda_\gamma)(1-\cos\theta_\gamma) + (1+2\lambda_e\lambda_\gamma)\frac{4}{1-\cos\theta_\gamma} \right] d(\cos\theta_\gamma), \quad (8)$$

where  $\lambda_\gamma$  and  $\lambda_e$  are the photon and electron helicities, z-axis is along the initial direction of the electron. The first term corresponds to the case when helicities of the electron and photon have opposite signs, i.e.  $|J_z| = 3/2$ , the second, dominant term, to  $|J_z| = 1/2$ . The cross section for unpolarized beams is shown in Fig. 5.

An additional problem in  $\gamma e$  collisions is connected with the fact that the photon can come from two directions (if both electron beams

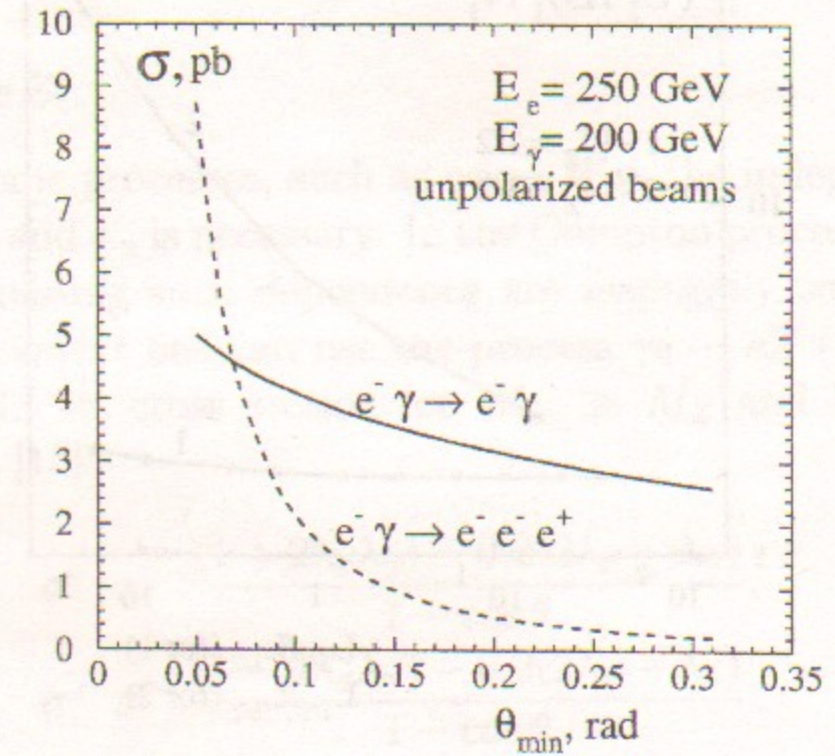


Figure 5: The cross section of processes for  $\gamma e$  luminosity measurement as a function of the minimum detection angle.

collide with laser photons). Luminosities for each direction should be measured independently. According to (8), the cross section with  $|J_z| = 3/2$  and  $|J_z| = 1/2$  are comparable at  $\theta_\gamma \sim \pi$  and, it seems, that one can measure both luminosities  $L_{1/2}$  and  $L_{3/2}$  fitting the angular distributions. However, due to the two possible photon directions the effective cross section is  $\sigma = (\sigma(\theta) + \sigma(\pi - \theta))/2$ , and  $\sigma_{1/2}$  dominates at all angles. We have checked the statistical accuracy of measurement of  $L_{1/2}$  and  $L_{3/2}$ . Let the number of produced events in these polarization states be  $N_{1/2}$  and  $N_{3/2}$ . In the ideal case  $\sigma_{Li}/L_i = 1/\sqrt{N_i}$ , in reality the accuracies depend on the ratio of luminosities as shown in Fig. 6. One can see that  $L_{3/2}$  can be measured with an accuracy close to  $1/\sqrt{N_i}$  only when  $L_{1/2} \ll L_{3/2}$ . For the measurement of both  $L_{1/2}$  and  $L_{3/2}$  with a high accuracy one should invert polarization of one beam to opposite in the same way as for  $\gamma\gamma$  collisions. For  $\gamma e$  luminosity spectra at TESLA(500) (see Fig.1) and beams with equal polarizations the number of events in the high energy peak for  $10^7$  sec is  $N_{1/2} = 3 \times 10^5$

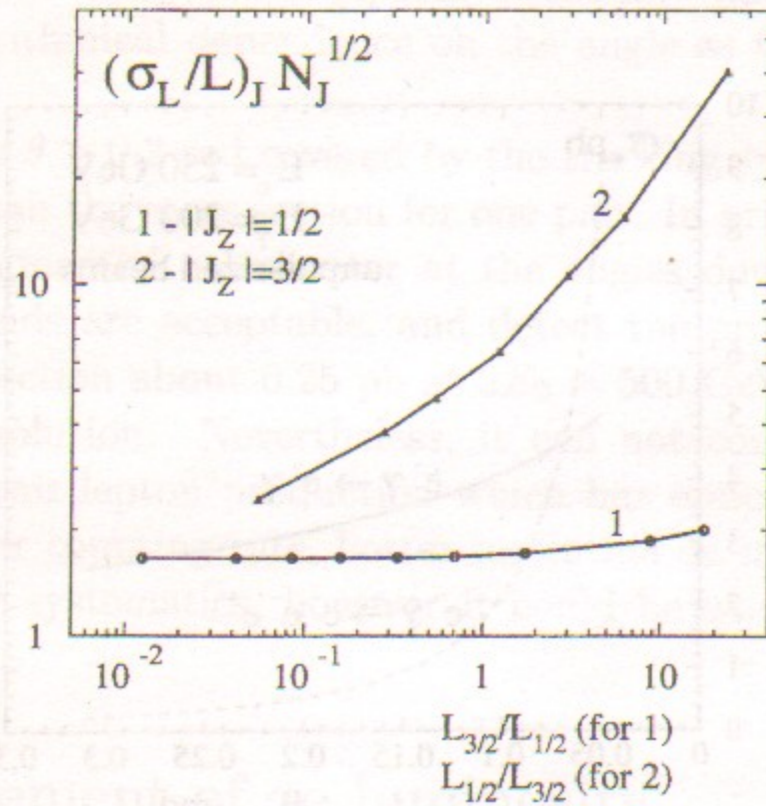


Figure 6: Statistical accuracy of  $L_{1/2}$  and  $L_{3/2}$  as a function of the luminosities ratio.

and  $N_{3/2} = 5 \times 10^3$ . The luminosities  $L_{1/2}$  and  $L_{3/2}$  are measured with accuracies 0.3% and 20%, respectively. After inversion of polarization for one beam, distributions for  $L_{1/2}$  and  $L_{3/2}$  replace each other and new number of events are  $N_{1/2} = 5 \times 10^4$ ,  $N_{3/2} = 3 \times 10^4$  and the accuracies for  $L_{1/2}$  and  $L_{3/2}$  are 0.8% and 1.8%, respectively. Thus, the measurement with inverted polarization improves the accuracy for  $L_{3/2}$  (that was before the inversion) from 20 % to 0.8%.

#### 4.2 $\gamma e \rightarrow e^- e^+ e^-$

The cross section of the Bethe-Heitler process for the case when all three final particles have angles above  $\theta_{\min}$  was obtained by ComHEP code and is shown in Fig. 5. As it was mentioned before, at  $\theta \leq 70$  mrad it is larger than that for  $\gamma e \rightarrow \gamma e$ . It is not small even in the region above 0.15–0.2 rad where detectors measure precisely parameters of all particles. The cross section of this process only weakly depends on the polarization of initial particles. Together with the process  $\gamma e \rightarrow \gamma e$

it allows to measure  $L_{3/2}$  with sufficiently good accuracy without the inversion of beam polarizations or can be used for the cross check.

#### 4.3 $\gamma e \rightarrow eZ$

For study of some processes, such as  $\gamma e \rightarrow W\nu$ , the independent measurement of  $\lambda_e$  and  $\lambda_\gamma$  is necessary. In the Compton process at  $\theta \gg 1/\gamma$  the terms containing such dependence are negligibly small (see [4]). For the measurement one can use the process  $\gamma e \rightarrow eZ$  (may be there is better one?). Its cross section for  $W_{\gamma e} \gg M_Z$  and  $W_{\gamma e} \sim M_Z$ , respectively, is [15]

$$\sigma \propto \frac{(1 + 2\lambda_e\lambda_\gamma) - 0.2(2\lambda_e + \lambda_\gamma)}{1 - \cos\theta},$$

$$\sigma \propto \frac{(1 - 2\lambda_e\lambda_\gamma) - 0.2(2\lambda_e - \lambda_\gamma)}{1 - \cos\theta}. \quad (9)$$

One can see that it is possible to extract the electron and photon polarization separately assuming that their product is measured by  $\gamma e \rightarrow \gamma e$  with a high accuracy.

### 5 Discussion and conclusion

The  $\gamma\gamma$  luminosity for circular and linear polarized beams can be measured using the process  $\gamma\gamma \rightarrow l^+l^-$ . Since this cross section is negligible for  $J_z = 0$ , to measure of  $L_0$  one has to invert the polarization of one beam for part of the time. The processes  $\gamma\gamma \rightarrow l^+l^-\gamma$  is sensitive to  $J_z = 0$  but has too small cross section. The process  $\gamma\gamma \rightarrow l^+l^-l^+l^-$  has too small cross section in the large angle part of the detector with good measurement of particle momenta. Detection of this process in the region of small angles (above 20 mrad) may be useful.

In  $\gamma e$  collisions the luminosity and product  $\lambda_e\lambda_\gamma$  can be measured with a high accuracy by means of the process  $\gamma e \rightarrow \gamma e$ . In order to measure both helicity combinations, inversion of the polarization for one of beams is necessary. The Bethe-Heitler process  $\gamma e \rightarrow e^-e^+e^-$  has also sufficiently large cross section, it can provide independent check of



the first method and allows to improve the accuracy of  $L_{3/2}$  without inversion of beam polarizations.

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**Measurement of  $\gamma\gamma$  and  $\gamma e$  luminosities  
at photon colliders**

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В.С. Сербо, В.И. Тельнов**

**Измерение  $\gamma\gamma$  и  $\gamma e$  светимостей  
на фотонных коллайдерах**

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