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Physics and Experiments with Linear e^+e^- Colliders

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INTRODUCTION TO $\gamma\gamma, \gamma$e AT LINEAR COLLIDERS

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Abstract

Short review of problems in obtaining $\gamma\gamma, \gamma e$–beams at linear colliders is given. A method of a measurement of the $\gamma\gamma$–luminosity and polarization is discused.

1. Introduction

Future linear colliders [1] offer unique opportunities to study $\gamma\gamma$ and γe–interactions. Unlike the situation in storage rings, in linear colliders each bunch is used only once. This makes it possible to "convert" electrons to high energy photons and to obtain colliding $\gamma\gamma, \gamma$e–beams [2]. This possibility was considered in Ref.[2–11] and other works. The best method of e $\to \gamma$ conversion is Compton scattering of laser light on high energy electrons[12]. The scattered photons have the energy close to that of the initial electrons and follow their directions. A small bunch size in linear colliders makes it possible to get a conversion coefficient $k \equiv N_\gamma/N_e \sim 1$ at a laser flash energy of a few Joules. In $\gamma\gamma$–collisions a luminosity higher than in e^+e^-–collisions is possible due to the absence of some collision effects. Monochromaticity of collisions $\Delta W_{\gamma\gamma}/W_{\gamma\gamma} \sim 10\%$ can be obtained. Photons may have various polarizations, which is very advantageous for experiments.

The detailed consideration of the conversion, photon spectra and monochromatization of collisions can be found in Ref.[4]. The polarization effects have been considered in Ref.[6]. Collision effects restricting the luminosities, the scheme of interaction region, requirements to accelerators, attainable luminosities and other aspects of obtaining $\gamma\gamma, \gamma$e–collisions have been considered in Ref.[9,10]. Physical problems, which can be studied in $\gamma\gamma, \gamma$e–collisions were discussed in many papers, see Ref.[11] and references therein.

Recently D.Bauer et al.[13] have proposed a photon collider to study $\gamma\gamma$ physics in the region $W_{\gamma\gamma} \sim$ 1–3 GeV. V.Balakin and I. Ginzburg have a talk at this Workshop about the possible Photon Collider with c.m.s. energy in the range 100-200 GeV. Such collider offers a unique opportunity to search for and study the Higgs boson, which according to some models have a mass below $\sim$ 120 GeV.

2. Compton scattering

2.1. Kinematics

The Compton kinematics is characterized by the variable

$$x = \frac{4E_0\omega_0}{m^2c^4} = 15.3\left[\frac{E_0}{\mathrm{TeV}}\right]\left[\frac{\omega_0}{\mathrm{eV}}\right],$$

where ω_0 is the energy of a laser photon, E_0 – is the electron initial energy. The maximum energy of the scattered photons $\omega_m = xE_0/(x+1)$.

The energy spectrum of the scattered photons is defined by the Compton cross section, which can be found in convenient form elsewhere [4,6].

For the polarized beams the spectrum only varies, if both electron mean helicity λ_e ($|\lambda_e| \leq 1/2$) and that of the laser photons (P_c) are nonzero. At $2\lambda_e P_c = -1$ and x>2 the relative number of hard photons nearly doubles (Fig.1), improving significantly the monochromaticity of the photon beam.

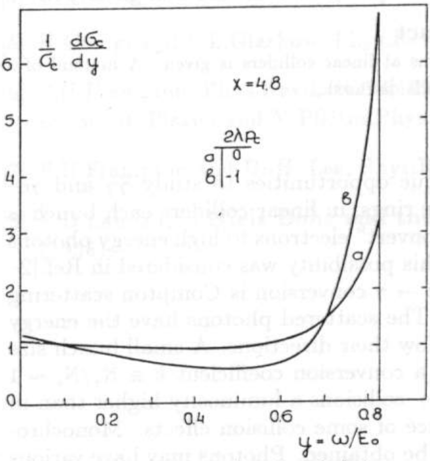

Fig.1.Energy spectrum of scattered photons

2.2. Choice of a laser wave length

With increasing the energy of laser photons the maximum energy of scattered photons also increases and monochromaticity improves. However, besides the Compton scattering, in the conversion region the process of e^+e^-–pair creation becomes possible in a collision of a laser photon with a high energy (scattered) photon [4,9,10]. The threshold of this reaction is x≈4.83. Due to this fact the conversion coefficient at large x is limited by 25–30%. For these reasons it is preferable to work at x<4.8.

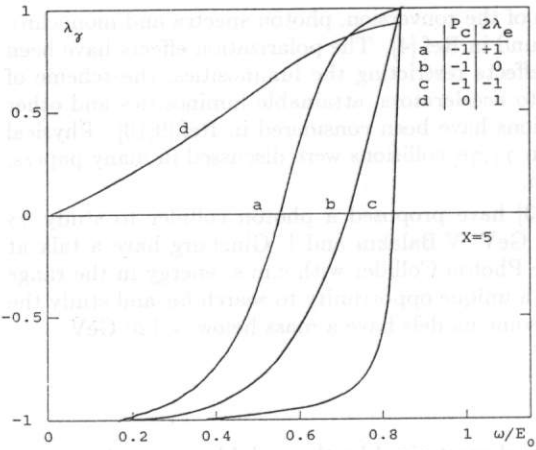

Fig.2. The circular polarization degree of photons vs ω/E for various polarization of laser photons and electrons.

2.3. Conversion coefficient

The conversion coefficient depends on the energy of the laser flash A as $k = N_\gamma/N_e \approx 1 - \exp(A/A_0)$. The value of A_0 is determined by the diffraction and nonlinear effects in the conversion region [4,9,10]. Consideration of the diffraction and nonlinear effects give the following requirements to the laser [9,10] ($k \sim 1$, x=4.8):

$$P_0 \sim \frac{\pi \hbar c^2}{2\sigma} \sim 0.75\ \mathrm{TW},$$

$$c\tau = \max(l_e, 0.15 \cdot E_0[\mathrm{TeV}]), \mathrm{cm}.$$

For various projects $A_0 \sim$ 1–4 J, $\tau \sim$ 1–5 ps.

2.4. Polarization

If electrons or laser photons are longitudinally polarized, the scattered high energy photons have circular polarization too [6]. The degree of polarization is shown in Fig.2 for various helicities of electron and laser beams. In the case of $2P_c\lambda_e = -1$ all the photons in the high energy peak have a high degree like-sign polarization. Photon polarization is crucial for some experiments.

3. Spectral luminosity

The spectrum of scattered photons is very broad, but because of energy–angle correlation in the Compton scattering it is possible to have much better monochromaticity of $\gamma\gamma$– and γe– collisions [4,6,9]. A spectral luminosity distribution depends on the variable $\rho = b/\gamma a$, where b is the distance between interaction point (i.p.) and conversion region, a — is the r.m.s. radius of the electron beam at i.p. In Fig.3 the plots of spectral luminosities are shown for round, unpolarized and polarized beams ($2P_c\lambda_e = -1$ for both beams). A possible helicity of two colliding photons is 0 or 2, therefore dL/dz can be decomposed in two parts dL_0/dz and dL_2/dz. These luminosities are shown in Fig.4 for x=4.8, P_c=1 and $2\lambda_e = -1, -0.5, 0$ (equal for both beams). The dependence of the ratio L_0/L_2 in the region $0.75<z<z_{max}$ on the λ_e is shown in Fig.4d. For a 100% electron polarization $L_0/L_2 \sim 60$. This is of great importance for Higgs measurements, because $N_{\gamma\gamma\to H} \propto 1+\lambda_{\gamma1}\lambda_{\gamma2} \propto L_0$, while for main background $N_{\gamma\gamma\to q\bar{q}} \propto 1+\lambda_{\gamma1}\lambda_{\gamma2} \propto L_2$ (see talk of D.Borden at this Workshop).

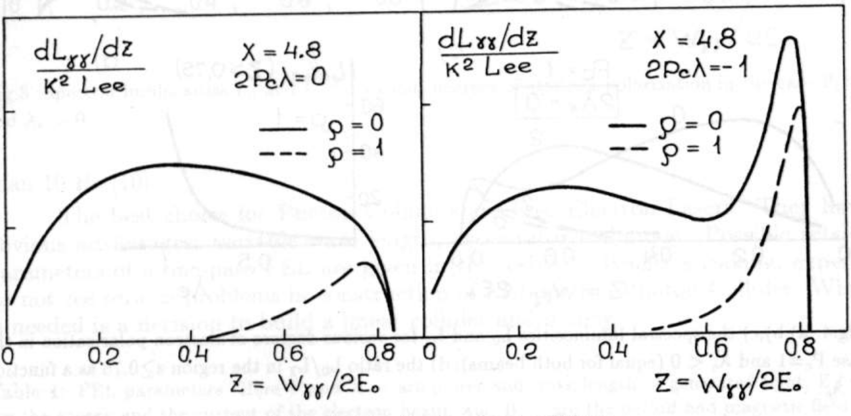

Fig.3. Spectral luminosity of $\gamma\gamma$–collisions.

We have seen that for $2P_c\lambda_e \sim -1$ the ratio L_0/L_2 is large in the high energy peak. In this case one can work at $\rho \geq 1$ i.e. with a good monochromaticity. For the other case, $2P_c\lambda_e \sim +1$, the ratio L_0/L_2 is large in the wide range of invariant masses(see Fig.5), that is convenient for purpose of search for the Higgs. But in this case in order to have a broad spectrum one has to work at $\rho \ll 1$. However in this regime the $\gamma\gamma$–luminosity may be much lower than at $\rho \gg 1$. Indeed, at fixed distance b between i.p. and the conversion region (sufficient to provide beam separation to avoid γe–collision and e^+e^-–pair production) $L_{\gamma\gamma}(\rho \gg 1)/L_{\gamma\gamma}(\rho \ll 1) \approx (b/\gamma)^2/a_e^2 = \rho^2 \gg 1$. If the electron beam spot size is sufficiently small and does not restrict the $\gamma\gamma$–luminosity, then we naturally obtain $\rho \geq 1$. To get $\rho \sim 0$ (at fixed b) one has to increase a_e that leads to considerable loss of the luminosity.

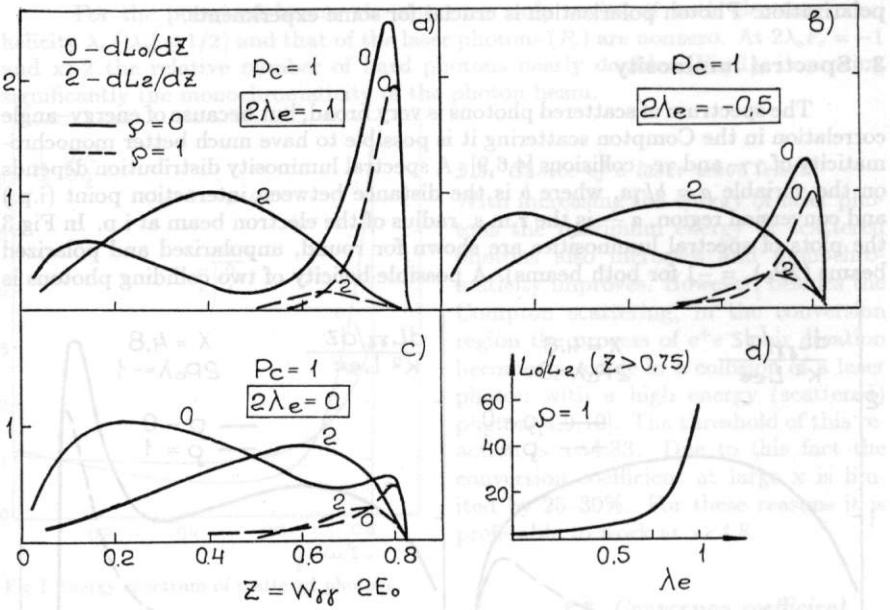

Fig.4. a),b),c) the spectral luminosities L_0 and L_2 for various degrees of electron polarization in the case $P_c=1$ and $\lambda_e < 0$ (equal for both beams); d) the ratio L_0/L_2 in the region $z \geq 0.75$ as a function of λ_e.

4. Measurement of $\gamma\gamma$–luminosity

A system produced in a $\gamma\gamma$–collision is characterized by it's invariant mass $W_{\gamma\gamma} = \sqrt{4\omega_1\omega_2}$ and rapidity $\eta = 0.5\ln(\omega_1/\omega_2)$. We should have a method to measure 1) $d^2L/dWd\eta$ and 2)$\lambda_{\gamma 1}\lambda_{\gamma 2}$ or, in other words, $dL_0/dWd\eta$ and $dL_2/dWd\eta$ (0,2—total helicity of the system). These can be measured using the process $\gamma\gamma \to e^+e^-$. The cross section of this process can be found elsewhere [14–15].

When $\beta \to 1$, then $\sigma_0/\sigma_2 \sim m^2/s$ (excluding the region of small angles). Therefore, the measurement of this process will give us $dL_2/dzd\eta$. How to measure $dL_0/dzd\eta$? This can be done by inversion of the helicity(λ_γ) of the one photon beam by means of changing simultaneously signs of helicities of the laser beam used for $e \to \gamma$ conversion and that of the electron beam. In this case the spectrum of scattered photons does not change while the product $\lambda_{\gamma 1}\lambda_{\gamma 2}$ changes its sign. In other words, what was before L_0 is now L_2, which we can measure. The cross section for this process $\sigma(|\cos\Theta| < 0.9) \approx 10^{-36}/s[\mathrm{TeV}^2],\mathrm{cm}^2$. This process is very easy to select due to a zero coplanarity angle.

5. Lasers

Obtaining Joule pulses of the picosecond duration is not a problem for solid state and gas lasers, but there are not much hopes to get a repetition rate more

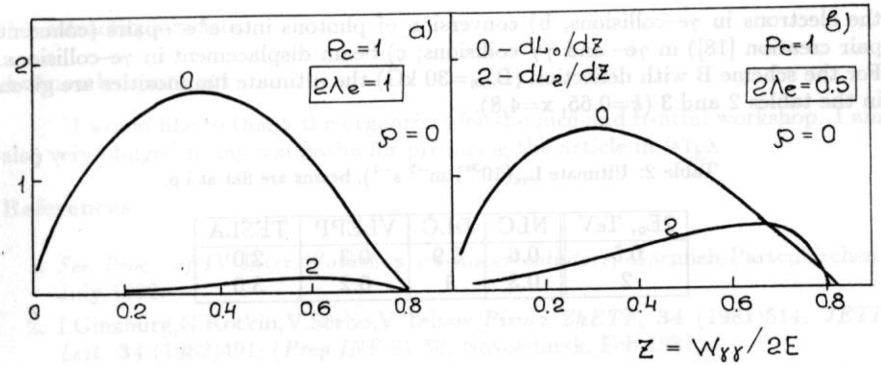

Fig.5. Spectral luminosities L_0 and L_2 for various degrees of electron polarization in the case $P_c=1$ and $\lambda_e > 0$.

than 10 Hz [10].

The best choice for Photon Colliders are Free Electron Lasers. They have obvious advantages: variable wave length, accelerator technique. Possible sets of parameters of a one-pass FEL are given in the Table 1. Briefly speaking, experts do not see serious problems in construction of FEL for the Photon Collider. What is needed is a decision to build a linear collider and money.

Table 1: FEL parameters. Here P and λ — are power and wave length of generated light; E,I — are the energy and the current of the electron beam; λ_W, B — are the period and magnetic field of the ondulator.

P, TW	$\lambda, \mu m$	E, Gev	I, kA	λ_W, cm	B, kG	Reference
0.5	4	2	2.5	20	13	E.Saldin et al [16]
1	1	0.45	20	5	20	A. Sessler [17]

6. Scheme of $\gamma\gamma$,γe–collision, ultimate luminosity

These questions were discussed in Ref.[9,10]. Two schemes were considered:

Scheme A. The conversion region is situated close to the interaction point(i.p) at the distance $b \geq 2\sigma_z$. After conversion all particles travel directly to the i.p.

Scheme B. After conversion at some distance b from the interaction region, particles pass through the region with a transverse magnetic field, where "used" electrons are swept aside. Thereby one can get more or less clean $\gamma\gamma$– or γe– collisions.

The first scheme is simpler, but background conditions are much worse (mixture of $\gamma\gamma$, γe, ee collisions, larger disruption angles).

The ultimate luminosity is restricted by collision effects. A strong field of opposing electron beam (deflected and not deflected) leads to: a) energy spread of the electrons in γe–collisions; b) conversion of photons into e^+e^-–pairs (coherent pair creation [18]) in γe– and $\gamma\gamma$–collisions; c) beam displacement in γe–collisions. For the scheme B with deflection (B_{defl}=30 kG) the ultimate luminosities are given in the tables 2 and 3 (k=0.65, x=4,8).

Table 2: Ultimate $L_{\gamma e}(10^{34})\text{cm}^{-2}\,\text{s}^{-1}$), beams are flat at i.p.

$2E_0$, TeV	NLC	DLC	VLEPP	TESLA
0.5	0.6	0.9	0.3	2.0
2	0.3	1	0.2	3.0

Table 3: Ultimate $L_{\gamma\gamma}(10^{34}\ \text{cm}^{-2}\text{s}^{-1})$, 2E=500 GeV, beams are round at i.p. Here a_γ — is photons spot size at i.p., x_0 — the deflection of "used" beam.

	NLC	DLC	VLEPP	TESLA
$L_{\gamma\gamma}$	3	12	6	50
a_γ, nm	10	9	25	12
b, cm	0.5	0.5	1.3	0.6
x_0, nm	40	40	300	60

Resume. In $\gamma\gamma$–collisions the collision effects do not restrict the luminosity for the energies 2E≤1 TeV. In γe–collision the luminosity is sufficient for 2E=500 GeV, but there will be problems at higher energies. Real luminosities will depend not only on collision effects, but also on the emittance of electron beams.

At the energies 2E≥1 TeV the screening effect [9,10] owing to the presence of e^+e^-–pair at the i.p. can be used to increase the $\gamma\gamma$–luminosity. The estimations show that $L_{\gamma\gamma} > 10^{35-36}\cdot E^2$[TeV], $\text{cm}^{-2}\text{s}^{-1}$ is possible (if beam emittances are sufficiently small).

7. Backgrounds in $\gamma\gamma$–collisions

One of the serious problems for $\gamma\gamma,\gamma$e–colliders is the removal of disrupted beams from the interaction region. How to do this was discussed in Ref.[9]. Besides this "machine" backgrounds, there is physical background – the reaction $\gamma\gamma \to$ hadrons with a large cross section. This problem will be discussed at this workshop in many talks.

8. Physics in $\gamma\gamma,\gamma$e–collisions

The number of paper on $\gamma\gamma,\gamma$e–physics at linear colliders is growing exponentially in the last two years (may be the announcement about this Workshop in Hawaii has stimulated authors?). It is already clear that physics in $\gamma\gamma,\gamma$e–collisions is as rich as in e^+e^-–collisions. Potentially higher than in e^+e^-–collision luminosity, high polarization, simplification of the collider (positrons are not required) — all this attracts physicists.

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THE POSSIBLE PHOTON COLLIDER WITH CMS ENERGY IN THE RANGE 100-200 GEV AND ITS PHYSICAL POTENTIAL

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ABSTRACT

We propose to construct the photon-photon (photon-electron) collider with cms energy 100-200 GeV for two main targets.

The first target relates to the modern situation in particle physics. The central problem here is the discovery of the Higgs. The modern data give a hint that the most probable mass of Higgs is 100-150 GeV. In this region photon collider seems to be the best machine for Higgs hunting and investigation.

The second target relates to the modern situation with the activity in linear colliders – both in accelerator problems and the political ones.

We propose to construct the Photon Linear Collider ($\gamma\gamma$ or γe) – PLC.

23 years ago we reported at the Kiev conference (15 Rochester) the paper "The possibility of experiments with production of hadrons by two photons from threshold to the extremely high energies"[1]. It was one of the papers which gave start for the modern investigations of photon collisions at e^+e^- colliders. In some sense the present proposal is directed for this very goal.

1. Linear Colliders

Discussion of methods for creating of the lepton colliders has been held more than two decade ago[2]. The concept of new colliders – the linear ones – with an analysis of problems and possible decisions was first reported at the Budker Memorial International Seminar, 1978[3].*

Among the problems relating to these colliders one can mention the creation of multimegawatt pulse RF sources (100 MW), the development of the high gradient (50-100 MV/m) accelerating structures, generation of the low emittance bunches for their injection into the main linac, the damping of the bunch instabilities, precision alignment (less than 1 mkm) of the elements of the accelerator with maintaining of the linac position independent of seismic and technical vibrations, temperature variations etc.

Nowadays the possibility for realization of the linear collider project with the parameters given in refs.[2,3] are doubtless: the power achieved for RF sources power is close to those required, the necessary gradients of accelerating structures are attained, an ability to

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***In the middle of 70's Ugo Amaldi also proposed linear collider which coincides with one from variants discussed in ref.[3].**

align the elements of lattice by means "adaptive system" was shown. Method of damping bunch instabilities has been proved at SLC etc. (see e.g. Proceedings of Workshops on Linear Colliders – LC 88 (SLAC), LC 90 (KEK), LC 91 (Protvino), LC 92 (Garmish)). However, the final development of all the components and units up to the stage of their industrial manufacturing will take a few years.

Research and design work for the linear colliders are being carried out with wide international collaboration. The natural way to continue this efforts seems to prepare the appropriate project and to construct the international linear collider.

1.1. Photon Collider – PLC

Twelve years ago it was proposed[4] to transform $e^{\pm}e^{-}$ linear colliders into the γe or $\gamma\gamma$ colliders with approximately the same energies and luminosities using the Compton backscattering of laser light on electrons of the basic e beams. The additional cost for this transformation seems to be relatively small. This possibility was discussed widely at above annual Workshops on Linear Colliders and it is doubtless nowadays that photon colliders should be an essential part of future very high energy linear colliders.

The our proposal is based on the following reasons:

1) Taking into account a little experience of Physics Community in the construction of the facilities of this scale, it seems important to make first **international** collider to be as small as possible, inexpensive facility, since, otherwise, the management – bureaucratic problems might be dominating.

2) This collider can begin operates after LEP II. However it should give additional physical information.

It is the reason why we propose to construct such linear collider as photon one based on $e^{-}e^{-}$ collider (without positrons) with the electron beam energy 100 GeV.

The modern results achieved at the preparation of linear colliders permit to expect that the main parameters of such a facility can be as follows:

$$E = 2 \times 100 \text{ GeV}; \quad l = 2 \times 2 \text{ km}; \quad L \sim 10^{3}4cm^{-2}s^{-1}$$

Taking into account that the main parameter of the device, its length, is close to that of SLC one can assume that its cost would not exceed much the cost of SLC facility.

2. Physics potential

What are the physical motivation for this collider which will operate after LEP II and, perhaps, simultaneously with LHC and SSC?

2.1.Higgs boson

Status. The discovery of Higgs boson (Higgs) and subsequent investigation of its properties seems to be the most important problem of modern particle physics.

The modern data[5] show that the most probable position of Higgs is around 130 GeV, i.e. within energy range discussed. Besides, in the minimal supersymmetry model mass of lightest Higgs between two ones (with account of radiative corrections) should be less than $2M_Z$ in the most probable case.

The SM Higgs with a mass below ~ 80 GeV will be either found or ruled out at LEP II. For Higgs masses above ~ $2M_Z$ almost certain detection seem assured at the LHC and

SSC in the decay $H \to ZZ \to 4$ leptons. The most probable intermediate mass region – from 80 to 180 GeV is the most difficult one for all these accelerators. The modern activity about observation this intermediate Higgs at LHC and SSC show very questionable possibilities here. Therefore the discussed photon colliders seems to be necessary for discovery of most probable Higgs and investigation of its properties.

The SM predicts very narrow Higgs in this interval (5 MeV $< \Gamma <$ 8 MeV). The SM two photon Higgs width can be found e.g. in ref.[6].

Higgs hunting. The discovery of intermediate Higgs at photon collider was discussed in Borden report here[7]. He had shown that the intermediate Higgs can be discovered via $\gamma\gamma \to H \to b\bar{b}$ channel at nonspecific photon collider based on the electron collider with beam energy E = 150 GeV and the luminosity distribution with wide tail below 80 GeV.

Preliminary estimations show that for this aim one can use the photon collider with upper cms energy which varies from 80 to 160 GeV (electron beam energy up to 100 GeV) and with luminosity $\approx 3 \cdot 10^{32}\text{cm}^{-2}\text{s}^{-1}$.

Investigation of Higgs. The investigation of Higgs after its discovery is important to understand whether the observed particle is actually Higgs of SM or something else [†]. At the photon collider one can measure precisely the Higgs two photon width which is – in SM – the counter for particles which are heavier than Higgs.

Besides, with the appropriate luminosity integral one could to test that the particle get their masses due to Higgs in SM or (as some alternative) in SUSY. For this aim it is necessary to measure $Br(H \to c\bar{c})$ and $Br(H \to \tau\bar{\tau})$ which should be 0.04 and 0.06 in SM. If Higgs mass is near 150 GeV one can measure additionally $Br(H \to WW)$ (with one W far from its mass shell).

2.2. W physics[‡]

The $\gamma e \to W\nu$ process is of great interest here. It is very sensitive to possible admixture of right handed currents in $We\nu$ vertex. In SM its cross section is doubled at $\zeta_e = -1$ in comparison with that for unpolarized electrons; it is switched off at $\zeta_e = 1$. he above admixture should be tested here. The possible difference with the results obtained at the investigation of β decay could manifest existence of additional heavy W bosons.

Besides, near the threshold (just in our region) the variation of photon helicity is switched on or off practically the contribution of diagram with electron exchange. At $\lambda_\gamma = 1$ the cross section contains the contribution of W exchange only, $\sigma \propto (s - M^2)^2$; at $\lambda_\gamma = -1$ the cross section observed $\propto (s - M^2)^4$.

The amplitude for W production in the backward direction is zero (with accuracy up to RC). The checking up of this radiation amplitude zero will be good test for some anomalous $WW\gamma$ interactions since they can smooth this zero.

$e^-e^- \to e^-W^-\nu$; $\gamma\gamma \to WW$ etc, threshold behavior.

$\gamma\gamma \to WW$ below and near threshold.

[†] This investigation seems to be very hard for LHC or SSC where only the quantity $\sigma(pp \to H + ...) \cdot Br(H \to ZZ)$ can be found and the first factor here has large uncertainty since it include badly determined product of quark densities.

[‡] See in more details report[8].

Background processes: $\gamma e \rightarrow Ze$; $\gamma\gamma \rightarrow Zee$.

2.2. Beyond SM[§]

The advantage of the photon colliders in comparison with the e^+e^- ones is obliged by the democracy of photons with respect to flavors. Therefore here e.g. the discovery mass intervals for both exited μ and τ and their superpartners are almost identical.

Besides, the γe collider will be the best machine for the discovery of e^*.

2.3. Hadron physics. QCD

The photon colliders provide the unique possibility to investigate the hadron physics and QCD in the new type of collisions and with the simplest structure of initial state. The set of problems in this field in many respects is similar to one discussed by Bjorken for SSC[10]; the essential difference can arise due to pointlike nature of colliding photons. The comparison of results from different types of colliders seems to be very promising. It will be the test for a number of models. In this respect HERA becomes a bridge between photon collider and LHC/SSC; therefore the correlation with the physical program of LHC/SSC seems to be important despite the difference in energies.

The exact value of photon energy is nonspecific for these problems.

Hard and semihard processes. In the hard processes the characteristic values of $p_\perp \sim \sqrt{s}$, they are large angle processes. The specific of photon collisions (in comparison with e^+e^-) seems to be not too essential here.

The semihard processes are those with production of particles and jets under constraints: $s \gg p_\perp^2 \gg \mu^2$; $(\mu = 0.3\, GeV)$. That are the processes with relatively large cross sections which will be observed well.

These processes evolve at small distances $\sim (1/p_\perp) \ll (1/\mu)$, i.e. the nonperturbative effects are small, and the effective QCD coupling constant $\alpha_s\,(p_\perp^2)$ is small. It allows one to use pQCD here. These processes give the unique possibility to investigate the region when both the perturbative QCD is applicable with high accuracy and the observable phenomena are described by whole perturbation series (which sensitive to the inner properties of QCD – they does not tested up to now).

The problems related with jets were reported here[11].

Jets. Large angles. Quark nature; angular correlations; comparison with annihilation. Contact interactions.

Jets. Semihard parton region. $p_\perp$ dependence. Growth of cross sections. Polarization dependence. Angular distribution of jets. Shadowing.

Jets. Semihard nonparton region. (Problems). Distribution on jets in $p_\perp$ and rapidity. Separation of minijets. Energy dependence.

Semihard production of neutral mesons[12] and investigation of perturbative Pomeron – pP ($\gamma\gamma \rightarrow \rho^0\rho^0$) & Odderon –pO ($\gamma\gamma \rightarrow\ pi^0\pi^0,\ \gamma\gamma \rightarrow \pi^0 a_2, \ldots$). Energy dependence, polarization dependence. Dependence on virtuality ($e\gamma$ collisions). Comparison of pP and pO. Shadowing. Small x phenomena.

Photon structure function. Polarization dependence. Testing of QCD. Choice of hadron component. Small x region and region of $x \rightarrow 1$.

[§] See in more details ref.[9].

Soft processes – large distance physics. The investigation of $\sigma^{tot}_{\gamma\gamma\to hadrons}$ energy dependence (together with Q^2 dependence in γe collisions) in comparison with the data in $pp(p\bar{p})$ and γp collisions (from HERA) is important in order to understand the nature of the growth of hadron cross sections with energy.

The diffractive processes.

Multiproduction. $< n(s) >, < p_\perp >$, minijets, hot spots. It seems to be useful to collate the multiproduction at $pp(p\bar{p})$ and $\gamma\gamma$ collisions. One of the additional questions is: what is the real significance of fragmentation at high energies?

3. Acknowledgments

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