BASICS OF A PHOTON COLLIDER* **

Valery G. Serbo

Novosibirsk State University, 6300090 Novosibirsk, Russia

This small review is devoted to $\gamma\gamma$ collisions including methods of creating the colliding $\gamma\gamma$ beams of high energy and physical problems which can be solved or clarified in such collisions.

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1. Introduction

1.1. The subject

This small review is based on papers [1–3]. It deals with high-energy $\gamma\gamma$ collisions, which is a new and promising area in high-energy physics related to fundamental problems of strong and electro-weak interactions.

Our knowledge about elementary particles and their interactions is mainly obtained from particle collisions. Accelerators with colliding beams are now called *colliders*. Most of the fundamental results in particle physics have been obtained from experiments at the pp, $p\bar{p}$, $e^{+}e^{-}$ and ep colliders.

The principal characteristics of colliders are:

1. The *energy* in the center-of-mass system (c.m.s) E_{cm};
2. *Luminosity* of a collider L which determines collision rate $\dot{N}$ of events with the cross section σ by relation $\dot{N} = L\,\sigma$;
3. *Types* of colliding particles.

The progress in high-energy colliders can be seen from Table I. Up to now and in the nearest future, the pp and $p\bar{p}$ colliders are the machines with the highest energy. That is why such epochal discoveries as W and Z bosons

(responsible for weak interaction) and t quark have been performed at the S$p\bar{p}$S and the TEVATRON, respectively. It is not excluded that at future pp collider, the LHC, the Higgs boson H (thought to be responsible for the origin of the particle masses) will be discovered.

TABLE I

High energy colliders.

Collider	Type	E_{cm}, TeV	Start date
S$p\bar{p}$S	$p\bar{p}$	0.6	1981
TEVATRON	$p\bar{p}$	2	1987
LHC	pp	14	2007
HERA	ep	0.31	1992
SLC	e^+e^-	0.1	1989
LEP-I	e^+e^-	0.1	1989
LEP-II	e^+e^-	0.2	1999
Linear collider	e^+e^-	0.5	2010?
Photon collider	$\gamma\gamma$, γe	0.4	2010+?
Muon collider	$\mu^+\mu^-$	$0.1 \div 3$	??

For detailed study of new phenomena, the important factor is not only the energy but also types of colliding particles. The e^+e^- colliders, being less energetic than pp colliders, have certain advantages over proton colliders due to much lower background and simpler initial state. Well known example is the study of Z boson. It was discovered at $p\bar{p}$ collider S$p\bar{p}$S where about 100 events with Z bosons were found among about 10^{11} background events, while the detailed study of Z boson had been performed at the e^+e^- colliders LEP and SLC which provided us with more than 10^7 Z-events with a very low background.

About thirty years ago a new field of particle physics — photon–photon interactions — has appeared [4–7]. Up to now $\gamma\gamma$ interactions were studied in collisions of virtual (or equivalent) photons at e^+e^- storage rings. A lot of interesting results have been obtained. However, the number of the equivalent photons is by two orders of magnitude less than the number of electrons.

A new possibility in this field is connected with high-energy $e^{\pm}e^-$ linear colliders which are now under development. The electron bunches in these colliders are used only once. This makes possible to "convert" electrons to real high-energy photons, using the Compton back-scattering of laser light, and thus to obtain $\gamma\gamma$ and γe colliders with real photons [8–10]. The luminosity and energy of such colliders will be comparable to those of the basic $e^{\pm}e^-$ colliders.

Physical problems, which are now investigated in the $\gamma\gamma$ collisions, are mainly connected with strong interaction at large $\sim \hbar/(m_\pi c)$ and moderate small distances $\sim \hbar/p_\perp$, where $p_\perp \lesssim 10\,\text{GeV}/c$. In the future it will be a continuation of the present day experiments plus the physics of gauge $(W^\pm,\ Z)$ bosons and Higgs H bosons, *i.e.* the problems of the electro-weak interactions, Standard Model and beyond, search of new particles and new interactions. In other words, physics at high-energy $\gamma\gamma$ and γe collisions will be very rich and no less interesting than at pp or e^+e^- collisions. Moreover, some phenomena can best be studied at photon collisions.

At the end of this subsection it will be appropriate to cite some words from the article "Gamma-Ray Colliders and Muon Colliders" of the former President of the American Physical Society, Sessler in *Physics Today* [11]:

> In high-energy physics, almost all of the present accelerators are colliding-beam machines.
>
> In recent decades these colliders have produced epochal discoveries: Stanford SPEAR electron–positron collider unveiled the charmed-quark meson and τ lepton in 1970s. In the realm of high-energy proton–antiproton colliders, the Super Proton Synchrotron at CERN gave us the $W^\pm$ and Z^0 vector bosons of electroweak unification in 1990's, and in 1999's the Tevatron at Fermilab finally unearthed the top quark, which is almost 200 times heavier than the proton.
>
> . . . What about other particles? Beam physicists are now actively studying schemes for colliding photons with one another and schemes for colliding a beam of short-lived μ^+ leptons with a beam of their μ^- antiparticles.
>
> If such schemes can be realized, they will provide extraordinary new opportunities for the investigation of high-energy phenomena.
>
> These exotic collider ideas first put forward in Russia more that 20 years ago . . .

1.2. Interaction of photons in the Maxwell theory and QED

The Maxwell's equations are linear in the strengths of the electric and magnetic fields. As a result, in the classical Maxwell theory of electromagnetism, the rays of light do not interact with each other. In quantum electrodynamics (QED) photons can interact via virtual e^+e^- pairs. For example, an elastic $\gamma\gamma$ scattering is described by Feynman diagrams of Fig. 1. The maximal value of the cross section is achieved at the c.m.s. photon energy $\omega \sim m_e c^2$ and is large enough:
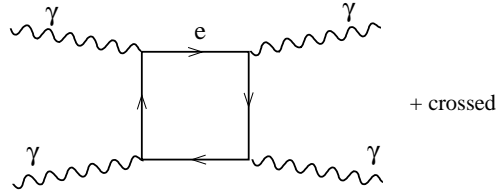
Fig. 1. Feynman diagrams for the elastic $\gamma\gamma$ scattering in QED.

$$\max \ \sigma_{\gamma\gamma\to\gamma\gamma} \sim \alpha^4 \left(\frac{\hbar}{m_e c}\right)^2 = \alpha^2 r_e^2 \sim 4 \times 10^{-30} \ \text{cm}^2 \,. \qquad (1)$$

However, at low energies, $\omega \ll m_e c^2$, this cross section is very small

$$\sigma_{\gamma\gamma\to\gamma\gamma} = 0.031 \alpha^2 r_e^2 \left(\frac{\omega}{m_e c^2}\right)^6 \,. \qquad (2)$$

For example, for visible light, $\omega \sim 1\,\text{eV}$,

$$\sigma_{\gamma\gamma\to\gamma\gamma} \sim 10^{-65} \ \text{cm}^2 \,. \qquad (3)$$

It is too small to be measured even with the most powerful modern lasers, though there were such attempts. In a recent paper [12] an upper limit of the cross section of $\sigma(\gamma\gamma \to \gamma\gamma)_{\text{Lim}} = 1.5 \times 10^{-48}\,\text{cm}^2$ for the photon c.m.s. energy $0.8\,\text{eV}$ was obtained (see Fig. 2 from [12]).
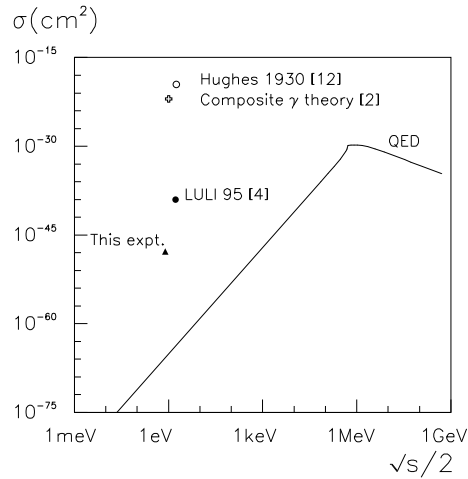

Fig. 2. Elastic photon cross section as a function of photon c.m.s. energy.

At energies $\omega > mc^2$, two photons can produce a pair of charged particles. The cross section of the characteristic process $\gamma\gamma \to \mu^+\mu^-$ (Fig. 3(a)) is equal to

$$\sigma_{\gamma\gamma\to\mu^+\mu^-} = 4\pi r_e^2 \frac{m_e^2 c^4}{s} \ln \frac{s}{m_\mu^2 c^4} , \qquad \text{at} \qquad s = (2\omega)^2 \gg 4m_\mu^2 c^4 . \qquad (4)$$

It is larger than the "standard" cross section for the production of the same pair in the e^+e^- collisions (Fig. 3(b) via a virtual photon only)

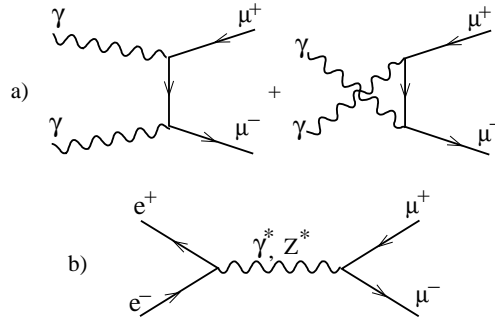$$\sigma_{e^+e^-\to\mu^+\mu^-} = \frac{4}{3} \pi r_e^2 \frac{m_e^2 c^4}{s} . \qquad (5)$$

Fig. 3. Feynman diagrams for (a) $\gamma\gamma \to \mu^+\mu^-$ and (b) $e^+e^- \to \mu^+\mu^-$.

1.3. Collisions of equivalent photons at e^+e^- storage rings

Unfortunately, there are no sources of intense high-energy photon beams (such as lasers at low energies). However, there is an indirect way to get such beams, namely to use equivalent photons which accompanied fast charged particles. Namely these methods were used during last three decades for investigation of two-photon physics at e^+e^- storage rings. The essence of the equivalent photon approach can be explained in the following way [13,14] (see also [15] §99). The electromagnetic field of an ultra-relativistic electron is similar to the field of a light wave. Therefore, this field can be described as a flux of the *equivalent* photons with energy distribution $dn_\gamma/d\omega$. The number of these photons per one electron with the energy E is

$$dn_\gamma \sim \frac{2\alpha}{\pi} \ln \frac{E}{\omega} \frac{d\omega}{\omega} \qquad (6)$$

or approximately

$$dn_\gamma \sim 0.03 \, \frac{d\omega}{\omega} \,. \tag{7}$$

At the e^+e^- colliders the equivalent photons also collide and can produce some system of particles X (see Fig. 4(a), γ^* denotes the equivalent photon)

$$e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X \,. \tag{8}$$

Thus, this process is directly connected with the subprocess $\gamma^*\gamma^* \to X$. Strictly speaking, the equivalent photons are not real photons, they are virtual ones. The 4-momentum squared q_i^2 of such a photon (which is equal to m^2c^2 for usual particle) is not equal zero, $q_i^2 \neq 0$. But for large part of the cross section $|q_i^2|$ is very small, therefore, the most of equivalent photons are almost real.

The cross section for two-photon production of e^+e^- in collisions of two fast particles with charges Z_1e and Z_2e, *i.e.* for the $Z_1Z_2 \to Z_1Z_2e^+e^-$ process, was calculated by Landau and Lifshitz [16] in 1934 (see also [15] §100). In fact, it was the Ph.D. Thesis of E.M. Lifshitz.

At first sight, the cross sections of the two-photon processes at e^+e^- colliders (Fig. 4(a)) are very small since they are the fourth-order processes: $\sigma_{\mathrm{two-phot}} \propto \alpha^4$, while for the annihilation processes of Fig. 4(b) the cross sections $\sigma_{\mathrm{annih}} \propto \alpha^2$. However, the annihilation cross sections decrease with increase of the energy (compare with (5))

$$\sigma_{\mathrm{annih}} \sim \alpha^2 \, \frac{\hbar^2 c^2}{s} \,, \qquad s = (2E)^2 \,, \tag{9}$$

while the two-photon cross sections increase

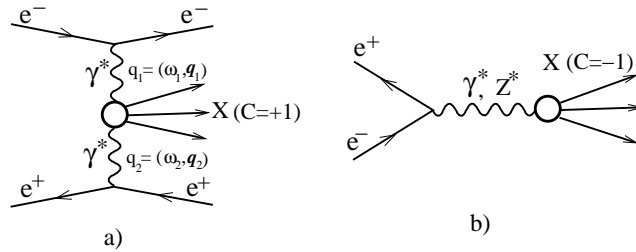$$\sigma_{\mathrm{two-phot}} \sim \alpha^4 \, \frac{\hbar^2}{m_{\mathrm{char}}^2 c^2} \, \ln^n s \,. \tag{10}$$

Fig. 4. Production of system X (a) by two equivalent photons γ^* with 4-momenta (energies) q_1 (ω_1) and q_2 (ω_2) emitted by an electron and a positron and (b) in the annihilation process $e^+e^- \to X$.

Here $n = 3 \div 4$, depending on the process, and the characteristic mass m_{char} is constant (for example, $m_{\mathrm{char}} \sim m_\mu$ for $X = \mu^+\mu^-$ and $m_{\mathrm{char}} \sim m_\pi$ for $X = hadrons$). As a result, already at $\sqrt{s} > 2$ GeV

$$\sigma_{e^+e^- \to e^+e^-\mu^+\mu^-} > \sigma_{e^+e^- \to \mu^+\mu^-}. \tag{11}$$

Another example: at the LEP-II electron–positron collider with the energy $\sqrt{s} = 200$ GeV, the number of events for two-photon production of hadrons with the c.m.s. energy $W_{\gamma\gamma} > 2$ GeV is by three orders of magnitude larger than that in the annihilation channel (Fig. 5).

At e^+e^- storage rings the first two-photon processes $e^+e^- \to e^+e^-e^+e^-$ had been observed in 1970 (Novosibirsk [4]). The importance of two-photon processes for the lepton and hadron production at e^+e^- storage rings had been emphasized in the papers by Jaccarini, Arteage-Romero, Parisi and Kessler [5], Balakin, Budnev and Ginzburg [6] and Brodsky, Kinoshita and Terazawa [7]. In the papers [6] it was shown that e^+e^- colliding beam experiments can give information about a new fundamental process $\gamma^*\gamma^* \to$ *hadrons* and the necessary formulae and estimations were obtained.

At that time there was a lot of theoretical investigations of various aspects of two-photon physics, but only few experimental results [4, 17] have been obtained related mainly to the processes $\gamma\gamma \to e^+e^-$, $\gamma\gamma \to \mu^+\mu^-$. This period of two-photon physics was summarized in a review by Budnev, Ginzburg, Meledin and Serbo [1].
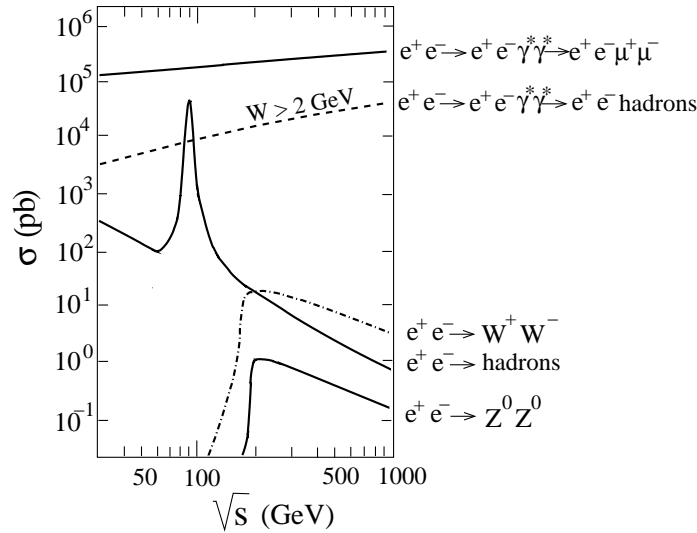

Fig. 5. Cross sections for some annihilation and two-photon processes in e^+e^- collisions.

A few years later (approximately from 1977) it was shown in a number of theoretical papers that the two-photon processes are very convenient for the test and detailed study of the Quantum Chromodynamics (QCD) including investigation of

- the photon structure function (Witten [18]),

- jet production in the $\gamma\gamma$ collisions (Llewelyn Smith [19]; Brodsky, De Grand, Gunion and Wise [20]; Baier, Kuraev and Fadin [21]),

- the $\gamma\gamma \to c\bar{c}c\bar{c}$ process and the problem of the perturbative Pomeron (Balitskij and Lipatov [22]).

A new wave of experimental activity in this field was initiated by the experiment at SLAC [23] which demonstrated that two-photon processes can be successfully studied without detection of the scattered electrons and positrons. After that there was a flow of experimental data from almost all detectors at the e^+e^- storage rings. It should be mentioned a special detector MD-1 in Novosibirsk with a transverse magnetic field in the interaction region and system of registration of scattered at small angles electrons which was developed for two-photon experiments (see review [24]). This period was reviewed by Kolanoski [25].

2. Results obtained in virtual $\gamma^*\gamma^*$ collisions

In experiments at e^+e^- storage rings a lot of interesting results about $\gamma^*\gamma^*$ collisions have been obtained (see reviews [25–27] and Proceedings of Workshops on Photon–Photon Collisions), among them:

- production in $\gamma^*\gamma^*$ collisions of C-even resonances, such as π^0, η, η', f_2, $a_2, \eta_c, \chi_c, \ldots$ and measurement of their $\gamma\gamma$ width;
- measurement of the total $\gamma\gamma \to hadrons$ cross section up to c.m.s. energy $W_{\gamma\gamma}$ of about $150\,\mathrm{GeV}$;
- measurement of the total $\gamma^*\gamma^* \to hadrons$ cross section with large values of $W_{\gamma\gamma}^2$ and photon virtualities $-q_1^2 \sim -q_2^2 \sim 10\,(\mathrm{GeV}/c)^2$;
- a number of exclusive reactions: $\gamma^*\gamma^* \to \pi\pi$, $K\bar{K}$, $p\bar{p}$, $\rho\rho$, $\rho\omega$, $etc.$;
- investigation of the photon structure function in the collision of almost real photon and highly virtual photon with $-q^2$ up to about $1000\,(\mathrm{GeV}/c)^2$;
- jet production in $\gamma\gamma$ collisions.

As an example, let us present the beautiful result (Fig. 6) for the study of two-photon process $\gamma\gamma \to \eta_c$ at CLEO (Cornell).
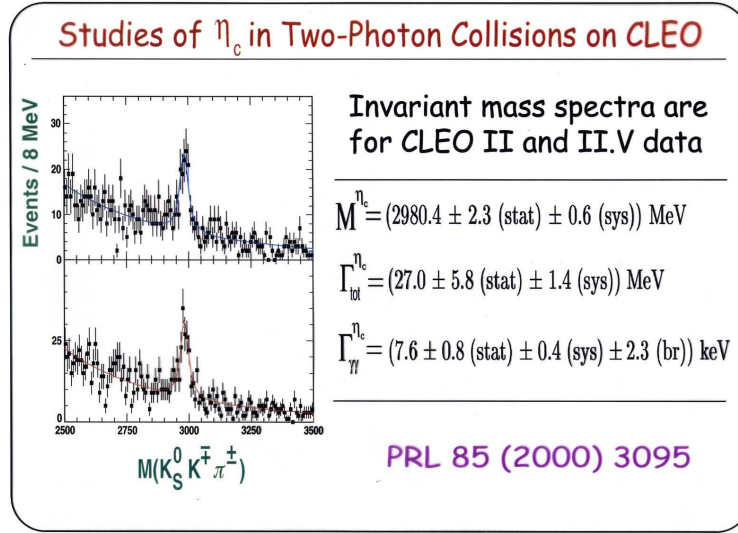
Fig. 6. Results for the process $\gamma\gamma \to \eta_c$.

Unfortunately, the number of equivalent photons per one electron is rather small, and correspondingly the $\gamma^*\gamma^*$ luminosity is about $3 \div 4$ orders of magnitude smaller than that in e^+e^- collisions. Therefore, it is not surprising that the most important results at e^+e^- storage rings were obtained in the e^+e^- annihilation.

3. Linear $e^\pm e^-$ collider

New opportunities for two-photon physics are connected with future linear $e^\pm e^-$ colliders. Projects of such accelerators are now under development in several laboratories. A linear collider consists of several main systems (see Fig. 7 from [11]): electron injectors, pre-accelerators, a positron source, two damping rings, bunch compressors, main linacs, interaction regions, a beam dump.

Since 1988 this field is developed in a very close international collaboration of physicists from many countries. In 1996–97 three projects NLC (North America), JLC (Asia) and TESLA (Europe) have published their Conceptual Design Reports [28] of the linear colliders in the energy range from a few hundred GeV to about one TeV; in 2001 the TESLA Technical Design Report [3, 29] has been published. One team at CERN is working now on the conception of multi-TeV Compact Linear Collider (CLIC). Current parameters of these projects are presented in Table II. Parameters of the projects NLC and JLC are presented in one column since their teams developed a common set of the collider parameters.
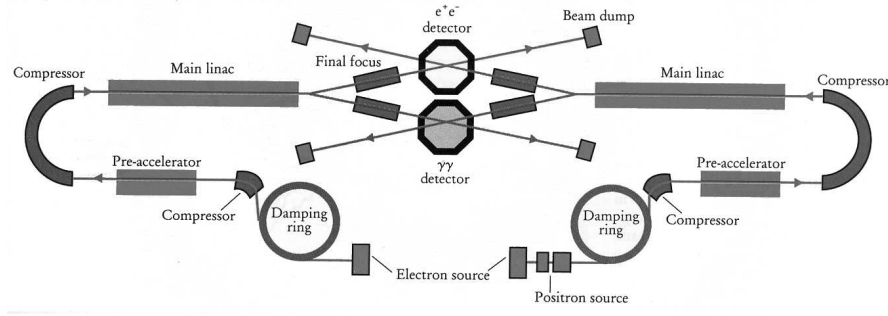
Fig. 7. Schema of a linear e^+e^- collider.

TABLE II

Some parameters of the linear colliders NLC/JLC and TESLA.

		NLC/JLC	TESLA
C.m.s. energy $2E_0$	[TeV]	0.5	0.5
Luminosity L	$[10^{34}/(\text{cm}^2\text{s})]$	2.2	3
Repetition rate f_r	[Hz]	120	5
No. bunch/train n_b		190	2820
No. particles/bunch N_e	$[10^{10}]$	0.75	2
Collision rate ν	kHz	22.8	14.1
Bunch spacing Δt_b	[ns]	1.4	337
Accel. gradient G	[MeV/m]	50	~ 25
Linac length L_l	[km]	10	20
Beams power $2P_b$	[MW]	14	22.5
IP beta-function β_x/β_y	[mm]	8/0.1	15/0.4
R.m.s. beam size at IP σ_x/σ_y	[nm]	245/2.7	555/5
R.m.s. beam length σ_z	$[\mu]$	110	300

Now the project of International Linear Collider (ILC) is under development.

A few special words have to be said about the luminosity of linear colliders, which is determined as

$$L = \nu \, \frac{N_{e^+} \, N_{e^-}}{S_{\text{eff}}} \,, \tag{12}$$

where the effective transverse bunch area $S_{\text{eff}} \sim \sigma_x\sigma_y$. In the next table we present a comparison of the storage ring LEP-II and linear collider:

Collider	$2E_e$	L	ν	$N_{e\pm}$	σ_x	σ_y
	GeV	$10^{33} \times 1/(\text{cm}^2\text{s})$	kHz	10^{10}	μ	nm
LEP-II	200	0.05	45	30	200	8000
NLC/JLC	500	22	22.8	0.75	0.245	2.7
TESLA	500	30	14.1	2	0,555	5

Note the transverse bunch sizes

$$\text{LEP-II}: \qquad \sigma_x\sigma_y \sim 10^{-5}\text{cm}^2\,,$$
$$\text{TESLA}: \qquad \sigma_x\sigma_y \sim 3 \times 10^{-11}\text{cm}^2\,.$$

So, it is likely that the first linear collider will have energy of about 500 GeV with some possible extension up to 1.5 TeV. Compared to LEP, these colliders of the so called next generation are designed for 2.5–7 times higher energy and four orders of magnitude higher luminosity!

4. Photon collider on a base of a linear $e^{\pm}e^-$ collider

4.1. Idea of high-energy $\gamma\gamma$ and γe colliders with real photons

Unlike the situation in storage rings, *in linear colliders each $e^{\pm}$ bunch is used only once.* It makes possible to "convert" electrons to high-energy photons and to obtain the $\gamma\gamma$ or γe colliding beams with approximately the same energy and luminosity[1] as in the basic $e^{\pm}e^-$ collisions. Moreover, $\gamma\gamma$ luminosity may be even larger due to absence of some collisions effects.

This idea was put forward by Novosibirsk group in 1981–1983 (Ginzburg, Kotkin, Serbo and Telnov [8,9]) and was further developed in detail.

Among various methods of $e \to \gamma$ conversion (bremsstrahlung, ondulator radiation, beamstrahlung and so on), the best one is the Compton scattering of laser light on high-energy electrons. In this method a laser photon is scattered backward, taking from the high-energy electron a large fraction of its energy. The scattered photon travels along the direction of the initial electron with an additional angular spread $\theta \sim 1/\gamma_e$ where $\gamma_e = E/(m_ec^2)$ is the Lorentz factor of the electron. This method was known long time ago [30] and has been realized in a number of experiments, *e.g.* [31,32]. However, the conversion coefficient of electrons to high-energy photons $k = N_\gamma/N_e$ was

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[1] This cannot be done at usual e^+e^- storage rings where high luminosity is provided by large number of collisions ($\sim 10^9$–10^{11}) of the same e^+ and e^- bunches. Conversion of the electron and positron bunches into the γ bunches at the storage ring gives only a single collision of gamma bunches. The resulting luminosity will be very low because obtaining of new e^+ and e^- bunches at storage rings takes long time.

very small in all these experiments. For example, in the SLAC experiment [32] it was $\sim 10^{-7}$.

In our papers [8,9] it was shown that at future linear $e^{\pm}e^{-}$ colliders *it will be possible to get $k \sim 1$ at a quite reasonable laser flash energy of a few Joules.*

Therefore, two principal facts, which make a photon collider possible, are:

- linear colliders are single-pass accelerators, the electron beams are used here only once;
- obtaining of conversion coefficient $k \sim 1$ is technically feasible.

It should be noted that *positrons are not necessary for photon colliders*; it is sufficient and much easier to use the electron–electron colliding beams.

The problems of the $\gamma\gamma$ and γe colliders were discussed on many conferences: Photon–Photon Collisions, Linear Colliders, and dedicated $\gamma\gamma$ Workshops [33,34]. Very rich physics, luminosity potentially higher than in $e^{+}e^{-}$ collisions, simplification of the collider (positrons are not required) are all attractive to physicists. Progress in development of linear $e^{+}e^{-}$ colliders and high power lasers (both conventional and free-electron lasers) makes it possible to consider photon colliders as very perspective machines for investigation of elementary particles.

This option has been included in Conceptual [28] and Technical [29] Designs of linear colliders. All these projects foresee the second interaction regions for the $\gamma\gamma$ and γe collisions.

4.2. Scheme of a photon collider

To create a $\gamma\gamma$ or γe collider with parameters comparable to those in $e^{+}e^{-}$ colliders, the following requirements should be fulfilled:

- the photon energy $\omega \approx E_0$ from 100 GeV to several TeV;

- the number of high-energy photons $N_\gamma \sim N_e \sim 10^{10}$;

- photon beams should be focused on the spot with transverse sizes close to those which electron bunches would have at the interaction point $\sigma_x \times \sigma_y \sim 10^{-5}$ cm $\times 10^{-7}$ cm.

The best solution for this task is to use a linear $e^{\pm}e^{-}$ collider as a basis and convert the $e^{\pm}$ beams into γ beams by means of the backward Compton scattering [8–10].

The principal scheme is shown in Fig. 8. An electron beam after the final focus system is traveling towards the interaction point IP. At the distance $b \sim 0.1 \div 1$ cm from the interaction point, the electrons collide with the
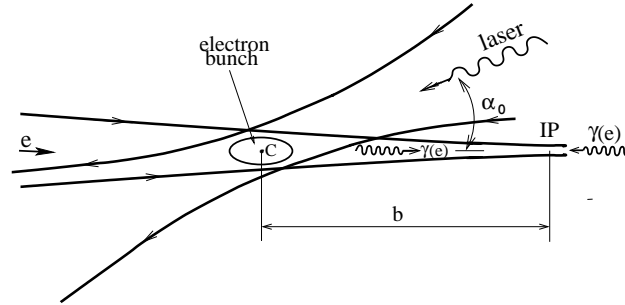
Fig. 8. A principal scheme of a photon collider. High-energy electrons scatter on laser photons (in the conversion region C) and produce high-energy γ beam which collides with similar γ or e beam at the interaction point IP.

focused laser beam in the conversion region C. The scattered high-energy photons follow along the initial electron trajectories (with small additional angular spread $\sim 1/\gamma_e$), hence, **the high-energy photons are also focused at the interaction point IP**. This very feature is one of the most attractive points in the discussed scheme. The produced γ beam collides downstream with the oncoming electron or a similar γ beam[2].

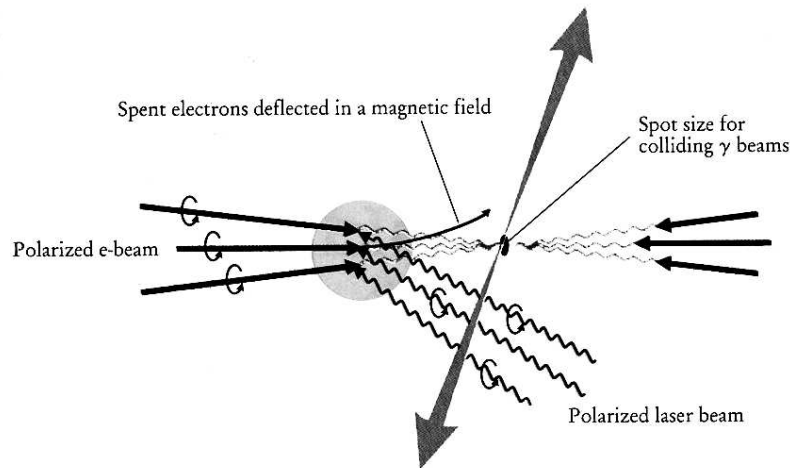More details about the conversion region are shown in Fig. 9 from [11].

Fig. 9. Conversion region.

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[2] To reduce background, the "used" electrons can be deflected from the interaction point by an external magnetic field. In the scheme without magnetic deflection, the background is somewhat higher, but such scheme is simpler and allows to get higher luminosity.

It is very important that modern laser technology allows to convert most of electrons to high-energy photons. This means that the $\gamma\gamma$ luminosity will be close to the luminosity of the basic $e^{\pm}e^{-}$ beams.

4.3. Compton scattering as a basic process for $e \to \gamma$ conversion

Properties of the linear and non-linear Compton scattering are considered in detail in [10, 35, 36]. In the conversion region a laser photon with energy $\omega_0 \sim 1$ eV scatters on an electron with energy $E_0 \sim 100$ GeV at a small collision angle α_0 (Fig. 10) and produces a final photon with the energy ω and the emission angle θ. Kinematics of the backward Compton scattering

$$e(p_0) + \gamma_0(k_0) \to e(p) + \gamma(k) \tag{13}$$

is characterized by two dimensionless variables x and y:

$$x = \frac{2p_0 k_0}{m^2 c^2} \approx \frac{4E_0\omega_0}{m^2 c^4} \cos^2 \frac{\alpha_0}{2}, \qquad y = \frac{kk_0}{p_0 k_0} \approx \frac{\omega}{E_0}. \tag{14}$$

The maximum energy of the scattered photon ω_{m} and the maximum value of the parameter y are:

$$\omega \le \omega_{\mathrm{m}} = \frac{x}{x+1} E_0, \qquad y \le y_{\mathrm{m}} = \frac{x}{x+1} = \frac{\omega_{\mathrm{m}}}{E_0}. \tag{15}$$

The energy of the scattered electron is $E = (1-y)E_0$ and its minimum value is $E_{\min} = E_0/(x+1)$.

Typical example: in collision of the photon with $\omega_0 = 1.17$ eV ($\lambda = 1.06 \, \mu$m — the region of the most powerful solid state lasers) and the electron with $E_0 = 250$ GeV, the parameter $x = 4.5$ and the maximum photon energy

$$\omega_{\mathrm{m}} = 0.82E_0 = 205 \, \text{GeV} \tag{16}$$

is close enough to the initial electron energy E_0.

A photon emission angle is very small, $\theta \sim 1/\gamma_e = 2 \times 10^{-6}$.

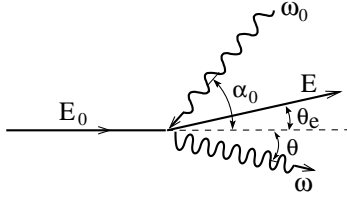Fig. 10. Kinematics of the backward Compton scattering.

The total Compton cross section is

$$\sigma_{\rm c} \;=\; \sigma_{\rm c}^{\rm up} \;+\; 2\lambda_e^{(0)} P_{\rm c}\,\tau_{\rm c}\,,$$

where $\lambda_e^{(0)}$ is the mean helicity of the initial electron, $P_{\rm c}$ is that of the laser photon and

$$\sigma_{\rm c}^{\rm up} \;=\; \frac{2\sigma_0}{x}\left[\left(1 - \frac{4}{x} - \frac{8}{x^2}\right)\ln(x+1) + \frac{1}{2} + \frac{8}{x} - \frac{1}{2(x+1)^2}\right]\,,$$

$$\tau_{\rm c} \;=\; \frac{2\sigma_0}{x}\left[\left(1 + \frac{2}{x}\right)\ln(x+1) - \frac{5}{2} + \frac{1}{x+1} - \frac{1}{2(x+1)^2}\right]\,,$$

$$\sigma_0 \;=\; \pi r_e^2 = 2.5 \times 10^{-25}\ {\rm cm}^2\,. \tag{17}$$

Note, that polarizations of initial beams influence the total cross section (as well as the spectrum) only if both their helicities are nonzero, *i.e.* at $\lambda_e^{(0)} P_{\rm c} \neq 0$. The functions $\sigma_{\rm c}^{\rm up}$, corresponding to the cross section of unpolarized beams, and $\tau_{\rm c}$, determining the spin asymmetry, are shown in Fig. 11. In the region of interest $x = 1 \div 5$ the total cross section is large enough

$$\sigma_{\rm c} \sim \sigma_0 = 2.5 \times 10^{-25}\ {\rm cm}^2 \tag{18}$$

and depends only slightly on the polarization of the initial particles, $|\tau_{\rm c}|/\sigma_{\rm c}^{\rm up} < 0.1$.
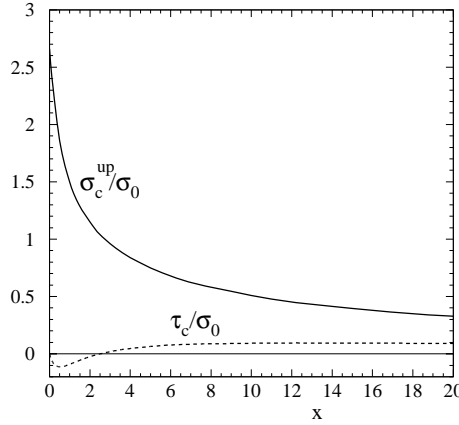

Fig. 11. Cross section $\sigma_{\rm c}^{\rm up}$ for unpolarized photons and $\tau_{\rm c}$, related to spin asymmetry (see (17)).

On the contrary, the energy spectrum does essentially depend on the value of $\lambda_e^{(0)} P_{\rm c}$. The energy spectrum of scattered photons is defined by the differential Compton cross section:

$$\frac{d\sigma_c}{dy} = \frac{2\sigma_0}{x}\left[\frac{1}{1-y}+1-y-4r(1-r)-2\lambda_e^{(0)}P_c\,\frac{y(2-y)}{1-y}\,(2r-1)\right]. \qquad (19)$$

It is useful to note that $r = y/[x(1-y)] \leq 1$ and $r \to 1$ at $y \to y_m$.

The "quality" of the photon beam, *i.e.* the relative number of hard photons, is better for the negative value of $\lambda_e^{(0)}P_c$. For $2\lambda_e^{(0)}P_c = -1$ the peak value of the spectrum at $\omega = \omega_m$ nearly doubles which improves significantly the monochromaticity of the γ beam (*cf.* curves a and b in Fig. 12).
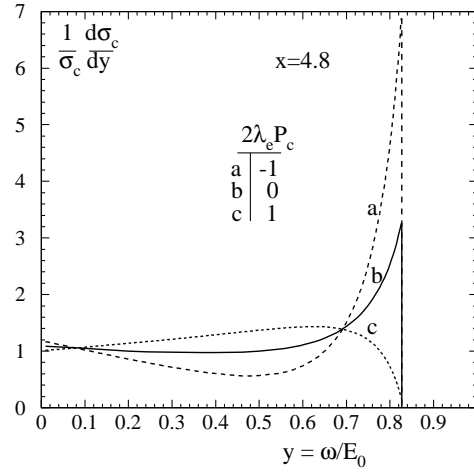

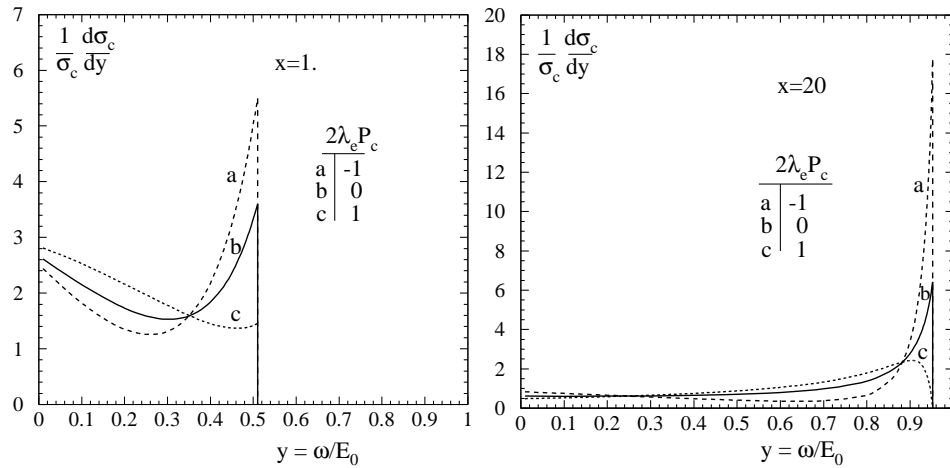Fig. 12. Energy spectrum of scattering photons at $x = 4.8$.

Fig. 13. Energy spectrum of scattering photons at $x = 1$ (left figure) and $x = 20$ (right figure).

In order to increase the maximum photon energy, one should use the laser with larger frequency. This also increases the fraction of hard photons (*cf.* Figs. 12 and 13). Unfortunately, at large x the high energy photons disappear from the beam producing e^+e^- pairs in collisions with laser photons. The threshold of this reaction, $\gamma\gamma_{\mathrm{L}} \to e^+e^-$, corresponds to $x \approx 4.8$. Therefore, it seems that the value $x \approx 5$ is the most preferable.

4.3.1. Angular distribution

The energy of a scattered photon depends on its emission angle θ as follows:

$$\omega = \frac{\omega_{\mathrm{m}}}{1 + (\theta/\theta_0)^2}; \qquad \theta_0 = \frac{mc^2}{E_0}\sqrt{x+1}. \tag{20}$$

Note, that photons with the maximum energy ω_{m} scatter at zero angle. The angular distribution of scattered protons has a very sharp peak in the direction of the incident electron momentum.

After the Compton scattering, both electrons and photons travel essentially along the original electron beam direction. The photon and electron scattering angles (θ and θ_e) are unique functions of the photon energy:

$$\theta(y) = \theta_0\sqrt{\frac{y_{\mathrm{m}}}{y} - 1}, \qquad \theta_e = \frac{\theta_0\sqrt{y(y_{\mathrm{m}} - y)}}{1 - y}. \tag{21}$$

For $x = 4.8$ these functions are plotted in Fig. 14. It is remarkable that electrons are only slightly deflected from their original direction and scatter into a narrow cone:

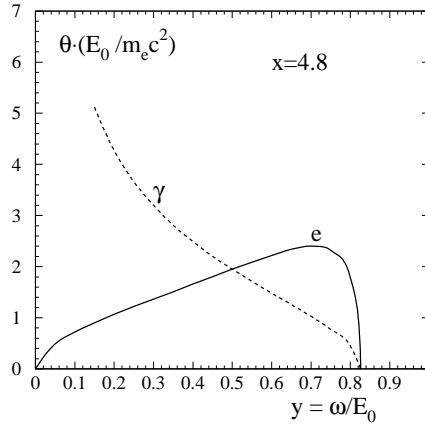$$\theta_e \le \frac{x}{2\gamma} = \frac{2\omega_0}{mc^2}. \tag{22}$$

Fig. 14. Photon and electron scattering angles *vs.* the photon energy ω at $x = 4.8$.

4.3.2. Polarization of final photons

Using the polarized initial electrons and laser photons, one can obtain the high-energy photons with various polarization. Let us present two typical examples. The mean helicity of the final photon λ_γ in dependence on the final photon energy ω is shown in Fig. 15. Curves a, b and c in Fig. 15 correspond to spectra a, b and c in Fig. 12. In the case of $2\lambda_e^{(0)} P_{\rm c} = -1$ (the case of good monochromaticity — see curves a in Fig. 12) almost all high-energy photons have a high degree of circular polarization. In case b the electrons are unpolarized, and the region, where high-energy photons have a high degree of polarization, is much narrower.
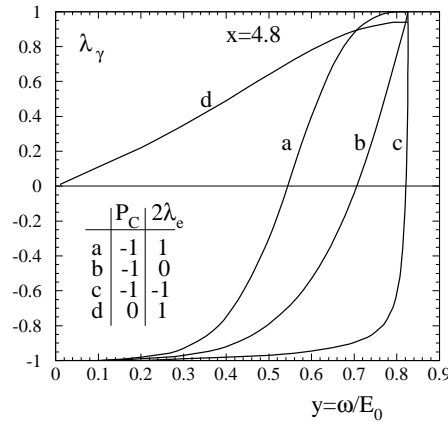

Fig. 15. Mean helicity of the scattered photons λ_γ vs. ω/E_0 for various laser photon helicities $P_{\rm c}$ and electron helicities λ_e at $x = 4.8$.
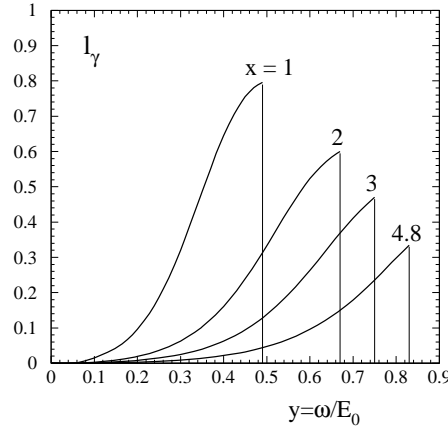

Fig. 16. Average linear polarization of the scattered photons l_γ vs. ω/E_0 at $x = 1$, 2, 3 and 4.8 (the degree of linear polarization of the laser photon $P_l = 1$).

If the laser light has a linear polarization, then high-energy photons are polarized in the same direction. The average degree of the linear polarization of the final photon l_γ in dependence on the final photon energy ω is shown in Fig. 16. The linear polarization of the colliding photons is very important for the study of the nature of the Higgs boson.

5. Physics of $\gamma\gamma$ interactions

Physics potential of such $\gamma\gamma$ and γe colliders will be on the same level as future e^+e^- and pp colliders. Moreover, there is a number of problems in which photon colliders are beyond competition. The comparison of cross sections in the e^+e^-, $\gamma\gamma$ and γe colliders is given in Fig. 17.

Photon collider (PC) makes it possible to investigate both problems of new physics and of "classical" hadron physics and QCD.
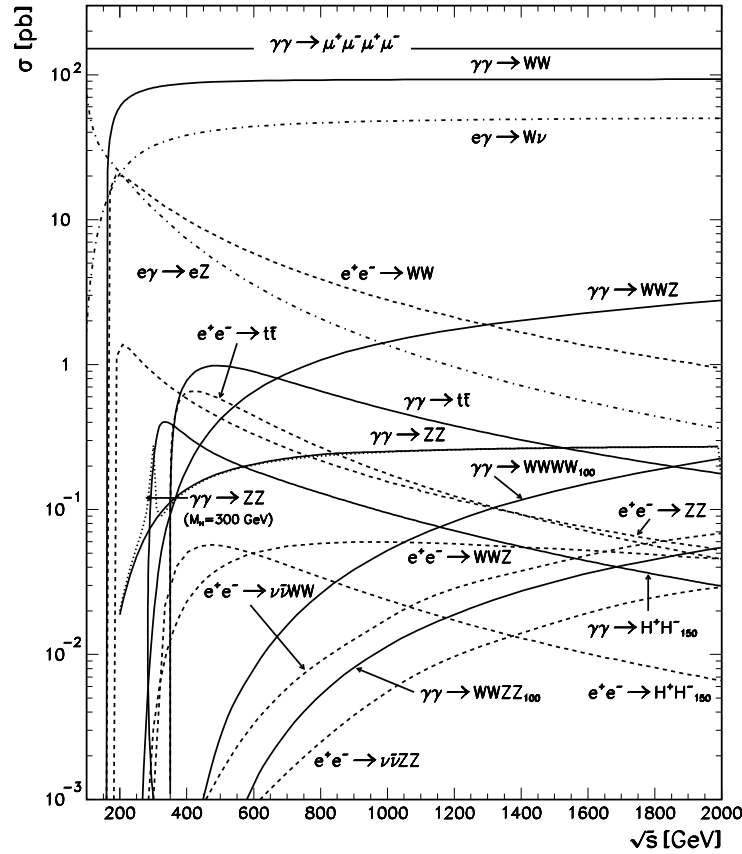

Fig. 17. Cross sections for some interesting processes in e^+e^-, γe and $\gamma\gamma$ collisions.

Since photons couple directly to all fundamental charged particles — leptons, quarks, W bosons, super-symmetric particles, *etc.* — a PC can provide a possibility to test every aspect of the Standard Model (SM) and beyond.

Besides, photons can couple to neutral particles (gluons, Z bosons, Higgs bosons, *etc.*) through charged particles box diagrams (Fig. 18).
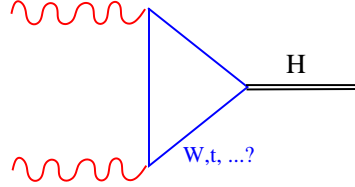

Fig. 18. Higgs boson production in $\gamma\gamma$ collision.

On the other hand, in a number of aspects photons are similar to hadrons, but with simpler initial state. Therefor, PC will be perfect for studying of QCD and other problems of hadron physics.

Let us list the problems in which the photon colliders have a high potential or some advantages:

Higgs hunting and investigation. PC provides the opportunity to observe the Higgs boson at the smallest energy as a resonance in the $\gamma\gamma$ system, moreover, PC is beyond competition in the testing of Higgs nature.

Beyond SM. PC provides the excellent opportunities for finding various particles beyond the SM: SUSY partners, charged Higgses, excited leptons and quarks, leptoquarks, ... In particular, γe collider will be the best machine for discovery of a selectron or an excited electron. Cross sections for the charged pair production in $\gamma\gamma$ collisions are larger than in e^+e^- collisions — see Fig. 19.
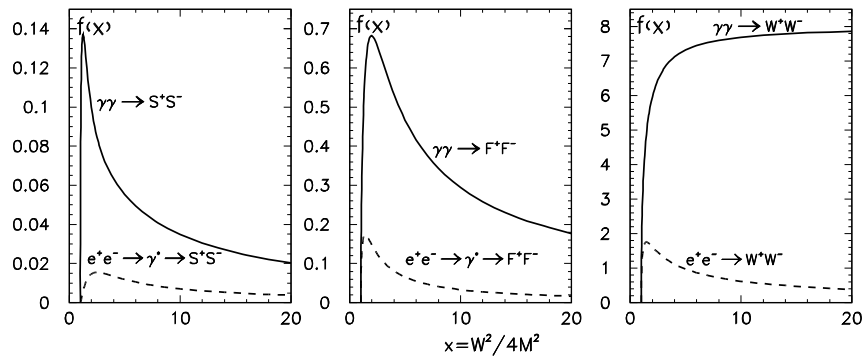

Fig. 19. Cross sections for charged pair production in e^+e^- and $\gamma\gamma$ collisions: here S — scalars, F — fermions, $\sigma = (\pi\alpha^2/M^2)\, f(x)$.

Electroweak gauge boson physics. The electroweak theory is the substantial part of the SM which pretend to have precise description like the QED. Photon colliders will be W factories with a rate about 10^7 W bosons per year. In addition, the $\gamma e \to W\nu$ process will produce single Ws which is very attractive for W decay's study. Thus, PCs provide one of the best opportunity to test the precise predictions of the electroweak theory.

QCD and hadron physics. The photon colliders provide the unique possibility to investigate the problems of hadron physics and QCD in the new type of collisions and with the simplest structure of initial state. The principal topics here are the following:

- the $t\bar{t}$ production in different partial waves;

- the photon structure functions;

- the semihard processes;

- the jet production;

- the total $\gamma\gamma \to hadrons$ cross section.

To clarify many of these points it will be very useful to compare results from $\gamma\gamma$, γe, ep and pp colliders.

Besides the high-energy $\gamma\gamma$ and γe collisions, PCs provide *some additional options*:

(i) The region of conversion $e \to \gamma$ can be treated as $e\gamma_\mathrm{L}$ collider (here γ_L is the laser photon) with c.m.s. energy $\sim 1\,\mathrm{MeV}$ but with enormous luminosity $\sim 10^{38} \div 10^{39}$ cm^{-2}s^{-1}. It can be used, for example, for a search of weakly interacting light particles, such as invisible axion.

(ii) In the conversion region one can test non-linear QED processes, like the e^+e^- pair production in collision of high-energy photon with a few laser photons.

(iii) The used high-energy photon beams can be utilized for fixed-target experiments.

6. Concluding remarks

6.1. Summary from TESLA TDR

The TESLA Technical Design Report [29] contains the part devoted to the high-energy photon collider [3]. It will be useful to cite the Physics Summary from this part:

> To summarize, the Photon Collider will allow us to study the physics of the electroweak symmetry breaking in both the weak-coupling and strong-coupling scenario.

Measurements of the two-photon Higgs width of the h, H and A Higgs states provide a strong physics motivation for developing the technology of the $\gamma\gamma$ collider option.

Polarized photon beams, large cross sections and sufficiently large luminosities allow to significantly enhance the discovery limits of many new particles in SUSY and other extensions of the Standard Model.

Moreover, they will substantially improve the accuracy of the precision measurements of anomalous W boson and top quark couplings, thereby complementing and improving the measurements at the e^+e^- mode of TESLA.

Photon colliders offer a unique possibility for probing the photon structure and the QCD Pomeron.

6.2. Prediction of Andrew Sessler [11] in 1998

At present, Europe has the lead in electron colliders (LEP), hadron colliders (LHC) and hadron–electron colliders (HERA). Stanford and Japan's High Energy Research Organization (KEK) are jointly working on a TeV e^+e^- collider design, as in DESY. Japan and/or Germany seem to be the most likely location for the next-generation e^+e^- machine. Looking broadly, and also contemplating what the US will do in high-energy physics, one may imagine a $\mu^+\mu^-$ collider in the US, early in the next century.

6.3. Conclusion of Karl von Weizsäcker for young scientists

I would like to tell you a little real story. In 1991 the International Conference on Physics devoted to Andrej Sakharov was held in Moscow. A number of great men have participated in this Conference including a dozen of Nobel prize winners. Among them was Karl von Weizsäcker.

I personally was very interested in application of the Weizsäcker–Williams method to the two-photon processes at colliding beams and I even have published a few articles on this subject. So, I wanted to see the author of this method and speak with him. At the beginning of our conversation, Weizsäcker told me a history of this invention.

In 1934 Weizsäcker was in Copenhagen as an assistant of Prof. Niels Bohr. And just at that moment there was some international Conference on Physics in the Niels Bohr Institute. Williams was the first who suggested the idea of the equivalent photon approximation for QED processes. But the final result appeared only after a lot of heated discussions in which Weizsäcker, Williams, Niels Bohr, Lev Landau, Edward Teller and some others participated.

After the Conference all people, but Weizsäcker, went back to their home institutes. So, it was quite natural that some day Bohr invited Weizsäcker and said: "And you, young man, you should write a paper on the discussed subject".

And Weizsäcker did and brought the paper to Bohr. A few days after that Bohr invited him to discuss the work. "At the beginning of this meeting — Weizsäcker told me — I was young and excited, but Professor seemed to me old and tired".

Bohr said: "It is an excellent work, a very clean and perfect paper, but . . . I have a small remark about the second page". So they have discussed this small remark. After that they have discussed another remark, and another remark, and another . . .

"After four or five hours of discussion — Weizsäcker continued — I was young and tired, but Professor was old and excited". At the end Bohr said: "Now I see that you wrote quite contrary to what you think, you should rewrite your paper".

Weizsäcker's conclusion was: "I think that it is the best way for a young scientist to study physics: you should have a good problem and a possibility to discuss this problem during hours with a great man".

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