Photon Collider for Energy of 1–2 TeV

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Abstract—We discuss a photon collider based on the linear collider with energy 1–2 TeV in cms (ILC, CLIC, ...), TeV PLC. Earlier, this energy range was considered hopeless for the experiment in the foreseeable future. We discuss a realization TeV PLC based on modern lasers. A small modification of the laser-optical system constructed for the photon collider with energy 1 TeV will be sufficient if the parameters are chosen optimally. The high-energy part of the photon spectrum does not depend on design details and is well separated from the low-energy part. That is a narrow band near the upper boundary, about 5% wide. The high-energy integrated $\gamma\gamma$ luminosity is about 1/5 and the maximum differential luminosity is about 1/4 of the corresponding values for the photon collider with $E = 250\text{ GeV}$.

INTRODUCTION

Two-Photon Processes—Virtual Photons

The processes now called two-photon processes have been studied since 1934 [1]. It was the production of a $e^+e^-$ pair in a collision of ultrarelativistic charged particles, $A_iA_j \to A_iA_j + X$ with $X = e^+e^-$. In the next 35 years, different authors have considered similar processes with $X = \mu^+\mu^-$, or $\pi^0$, or $\pi^+\pi^-$ (point-like) (see references in review [2]).

In 1970, it was noted that the observation of processes $A_iA_j \to A_iA_j + X$ at colliders (initially, at $e^+e^-$-colliders) would allow studying processes $\gamma\gamma \to X$ with two quasi-real photons and different final systems $X$ at very high energies $M_X$ ([3], [4], and a little later [5]).

The general description of such processes given in review [2] is still relevant today. The collision of particles $A_i$ with masses $M_i$, electric charge $Z_i$, and energy $E_i$ generates a pair of virtual (quasi-real) photons with energies $\omega_i$. Their fluxes (per one initial particle $A_i$) are

$$f(\omega) d\omega_i = \frac{Z_i^2 G_i(\omega_i/E_i)}{\pi} \frac{d\omega_i}{\omega_i} \log \theta(\log \omega_i),$$

where the shape of the functions $g_i(x)$ $\leq$ 1 depends on the type of colliding particles, and the parameter $\lambda_q$ also depends on the properties of the system $X$.

The study of processes with quasi-real photons has become an important field of experiments at colliders (for example, see [6]). The results of these experiments significantly added to our knowledge of resonances and the details of hadron physics. However, such experiments cannot compete with experiments at other colliders when studying the problems of New Physics. Indeed, the luminosity of collisions of virtual photons in the high-energy region is 3–5 orders of magnitude lower than the luminosity of current $e^+e^-$ or $pp$ colliders. For collisions of heavy nuclei (RHIC, LHC), the effective energy spectrum of quasi-real photons is bounded from above, and difficulties with the signature of $\gamma\gamma$ events at high photon energies are added here.

Photon Colliders with Real Photons—PLC

Another approach, which allows one to study the collisions of real high-energy photons was proposed in 1981 when discussing the capabilities of the linear $e^+e^-$ collider ($e^+e^-$ LC). In a linear collider, each electron bunch is used once. Therefore, one can try to convert a significant part of the initial electrons into photons with energies close to the energy of the initial electrons so that the collisions of these photons will compete with the main collisions both in energy and luminosity. The way to implement these ideas (photon linear collider, PLC) was proposed in [7–9].

A well-known scheme of PLC is shown in Fig. 1. In the conversion region $CR$ preceding the interaction region $IR$, the electron beam ($e^-$ or $e^+$; for definiteness, we discuss the case when two initial beams are electron beams $e^-$) of the conventional LC encounters a photon beam (a flash of a powerful laser). Compton
scattering of a laser photon by an LC electron (with energy $E$)\(^1\) generates a photon with energy close to $E$

$$e_0\gamma_o \rightarrow e\gamma.$$  \hspace{1cm} (2)

These photons are focused in the interaction region (IR) into a spot of about the same size as expected for electrons without laser conversion. In the IR, these photons collide with photons from the opposite conversion region ($\gamma\gamma$ collision) or with electrons of the counter-propagating beam ($e\gamma$ collision).

The ratio of the number of high-energy photons to that of electrons in LC is called the conversion coefficient $k$; for the standard PLC, $k = 1 - 1/e = 0.63$ typically.

Many PLC studies (for example, see [10, 11, 15]) discuss many important technical details\(^2\), but they all retain the original scheme of Fig. 1.

The main properties of the basic Compton process are characterized by the parameter

$$x = 4E\omega_0/m_e^2,$$ \hspace{1cm} (3)

where $E$ is energy of the electrons in the beam; $\omega_0$ is energy of the laser photon. (To simplify text, we set $\omega_0 = 0$ in Fig. 1).

In 1981, to construct PLC, it was proposed to use a laser with neodymium glass or garnet, for which $\omega_0 = 1.17 \text{ eV}$ [7–8]. For electrons with energy of $E \leq 250 \text{ GeV}$, this choice remains optimal until now. Using such a laser, we have

$$2E = 0.5 \text{ TeV} \Rightarrow x = 4.5;$$
$$2E = 1 \text{ TeV} \Rightarrow x = 9;$$
$$2E = 2 \text{ TeV} \Rightarrow x = 18;$$
$$2E = 11 \text{ TeV} \Rightarrow x = 100.$$ \hspace{1cm} (4)

The first three lines correspond to different stages of the ILC and CLIC projects; the fourth line is some asymptotics.

The considered scheme in its pure form works only for $x < 2[(1 + \sqrt{2}) = 4.8$ (for $E < 270 \text{ GeV}$ using the considered laser). For large values of $x$, which will be realized in the subsequent stages of ILC, CLIC, ..., some of the high-energy photons are lost producing $e^+e^-$ pairs in collisions with photons from the tail of the laser pulse

$$\gamma_o \rightarrow \text{(killing process).}$$ \hspace{1cm} (5)

This fact was considered as limiting the implementing a PLC based on an LC with high electron energies [7, 8].

Two ways to overcome this difficulty are discussed.

1) Use a new laser with a lower value of $\omega_0$ for $x \leq 4.8$.

2) Use the existing laser, resigned to the decrease in $\gamma\gamma$ luminosity.

\(\triangleright\) The results of [7–9] are directly applicable for the first way. However, a new laser is required for each new energy of electrons; so far, such lasers with the required parameters have not been developed.

\(\triangleright\) This work is devoted to the study of the second way with a guiding idea to get almost monochromatic photon collisions at a cost acceptable reduction in luminosity. This possibility is noted in [22, 23] and partially developed in [22]. Unfortunately, the method of optimizing the conditions for conversion $e \rightarrow \gamma$ used in [22] gives an inaccurate result for some beam polarizations. The analysis of the spectra of final photons without considering the polarization of particles distorts the spectra and the luminosity distribution. The result is obtained only for a certain configuration of the facility. It is not clear what changes should be expected when the engineering solution for beam collision changes. We correct these inaccuracies below and find out to what extent the results can be applied to any engineering solution for beam collisions. We call the corresponding photon collider the TeV PLC.

Desirability of Magnetic Deflection of the Electrons at the CR–IR Way

In papers [7–9], it was proposed to remove electrons that survived after conversion from the interaction region using a transverse magnetic field along the CR–IR path. For $x < 4.8$, the problem was to obtain the maximum conversion coefficient so that after passing through the CR, only a small part of the electrons retained their initial energy, and most of electrons decrease energy and scatter away at small angles similar to photons. This effect increased the total spread of electrons in the transverse plane. In addition, when using colliding $e^+e^-$ beams, residual electrons in the IR are repulsed by Coulomb forces so that the interaction of these electrons with each other and with the resulting photon beams becomes insignificant. Therefore, it is possible to dispense with the inclusion of a transverse magnetic field [10]. The PLC projects discussed since than [11–16] do not have such a magnetic field.

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\(^1\) We distinguish an electron of a collider bunch $e_0$ and a scattered electron $e$ and a photon of a laser flash $\gamma_o$ and a produced photon $\gamma$.

\(^2\) A recent example is optimization of the beam crossing angle for $e^+e^-$ and $\gamma\gamma$ collisions in LC [16].
For $x > 4.8$, in the optimal situation (see below), about half of the electrons pass through the CR freely (without interaction with photons). In the absence of a magnetic field, it would be wrong to neglect their interaction with counter propagating photons and electrons. To eliminate this interaction, electrons must be removed from the interaction region using a transverse magnetic field along the CR–IR path, as it was suggested in [7–9]. Further, we assume for $x > 4.8$, that when studying $\gamma\gamma$ collisions the magnetic field is turned on for both beams, and when studying $e^+\gamma$ collisions the magnetic field is turned on for one beam (converted to photon).

The Organization of the Subsequent Text is as Follows

Section 1 contains basic notation and a description of the Compton process in the studied parameter range with examples for $x = 4.5$. It also introduces the important concept of the optical length of a laser flash for high-energy electrons.

In Section 2, we discuss the sources of photons falling into the interaction region. It is shown that the energy spectrum of these photons and the corresponding luminosities are naturally divided into two parts that are well separated from each other. The high-energy part, which is most interesting for studying the problems of New Physics, admits a universal description independent of the details of the experimental facility. There is no such universal description for the low-energy part. The basic notations related to the distribution of high-energy luminosity are also introduced in this section.

In the main part of the work, we discuss the case of $x > 4.8$ and the main characteristics of high-energy $\gamma\gamma$ and $e^+\gamma$ collisions considering the modifications introduced by new processes in CR. We consider the cases of $x = 9.18$ Key: [9, 18] (ILC, CLIC) in detail and give some examples for $x = 100$. After a brief discussion of the basic Compton effect for $x > 4.8$ (Section 3.1), Section 3.2 discusses the killing process $\gamma\gamma \rightarrow e^+e^-$, which was not discussed in detail earlier, because it takes place only for $x > 4.8$. In Section 3.3, we write down the balance equations for the number of photons produced in the Compton process and lost within the conversion region due to the killing process. The polarizing properties of the killing process turn out to be very important.

The next step is to choose the optimal value for the laser flash energy or, in other words, the optical length of the laser flash. We chose as a criterion, the requirement to obtain the maximum number of photons for the physical problems of interest (Section 4).

Section 5 contains a description of the resulting high-energy spectra for $e^+\gamma$ and $\gamma\gamma$ collisions.

A brief description of the results is given in SUMMARY.

Appendix A.1 discusses the case of a “bad” choice of initial polarization. Appendix A.2 shows that study with linear polarization of a high-energy photon is almost impracticable using TeV PLC. The most important background source is discussed in Appendix A.3. In Appendix A.4, we discuss the Bethe–Heitler process that could reduce the number of produced photons and show that this phenomenon is insignificant up to very high energies.

In Appendix B, we list some of the important New Physics problems that can be explored using TeV PLC and cannot be studied using the LHC and $e^+e^-$ colliders.

1. SOME NOTATIONS: COMPTON EFFECT ON A HIGH-ENERGY ELECTRON

For definiteness, we consider $e^−e^−$ LC (not $e^+e^−$). We neglect the effects of high photon density in the conversion region (nonlinear QED effects).

1. Notation

- $\gamma_o$, $\omega_o$, and $\lambda_o$—the laser photon, its energy, and helicity; usually, $\omega_o \sim eV$.
- $e_o$, $E$, and $\lambda_e$—an initial electron, its energy, and helicity ($2|\lambda_e| \leq 1$).
- $\gamma$, $\omega$, and $\lambda$—a photon produced in the Compton process, its energy, and helicity.
- $\sigma_{o} = \pi\alpha^2/m_e^2 = 2.5 \times 10^{-25}$ cm$^2$.
- $b$—the distance between the conversion region CR and the interaction region IR (Fig. 1).
- $\Lambda_C = 2\lambda_e\lambda_o$—polarization parameter of the process.
- $y = \omega/E$—relative energy of the photon.
- $y_M = x/(x + 1)$—the maximum value of $y$ for the given $x$.
- $y_{\min}$—the position of the minimum $y$ in distribution $d\sigma/dy$ for the Compton process for $\Lambda_C = -1$.
- $w_{\gamma\gamma} = \sqrt{4\omega_1\omega_2/2E} = \sqrt{y_1y_2y_M}$ and $w_{e\gamma} = \sqrt{4E\omega_o/2E} = \sqrt{y_1y_M}$ are ratios of $\gamma\gamma$ and $e\gamma$ cms energies to $\sqrt{s}$.

2. Compton scattering. We give the basic information about the process in question in the kinematic region of interest according [7–9] with the addition of some details that were not discussed earlier. In this section, numerical examples are given for $x = 4.5$, which is close to the upper limit of the domain of applicability of the initial studies.

3 This value is determined for $x \geq 3$; it depends on $x$. For $\Lambda_C < -0.75$, it is found that the total fraction of photons with $y > y_{\min}$ is 0.55 or more and weakly depends on $\Lambda_C$. For calculations, it is more convenient to define $y_{\min}$ in the form of Eq. (8) (the definition of $y_{\min}$ does not require high accuracy, since $f(x, y = y_{\min}) \ll f(x, y_M)$ is a very small value).
The total cross section for the Compton effect is well known (Table 1)

\[ \sigma_c = \frac{2\sigma_0}{x} [F(x) + \Lambda_c T(x)]; \]
\[ F(x) = \frac{1}{x} \left( 1 - \frac{4}{x} - \frac{8}{x^2} \right) \ln(x + 1) + \frac{1}{2} - \frac{1}{2(x + 1)}, \]
\[ T(x) = \frac{1}{x} \left( 1 + \frac{2}{x} \right) \ln(x + 1) - \frac{5}{2} + \frac{1}{x + 1} - \frac{1}{2(x + 1)^2}. \]

At \( E \gg \omega_0 \), the photon energy \( \omega = yE \) is bounded from above by the value \( \omega_M = x/(x + 1) \) (\( \omega_M = 0.82 \) for \( x = 4.5 \)); the energy distribution of photons strongly depends on \( x \) and on polarization of the process (here, \( r = y/[x(1 - y)] \leq 1 \))

\[ f(x, y) = \frac{1}{\sigma_c} \frac{d\sigma_c}{dy} = \frac{U(x, y)}{F(x) + \Lambda_c T(x)}, \]
\[ U(x, y) = \frac{1}{1 - y} + 1 - y - 4r(1 - r) - \Lambda_c x r(2 - y)(2r - 1). \]

When \( \Lambda_c \approx -1 \), the energy spectrum of photons grows up to the upper limit \( y = y_M \) and the peak sharpens as \( x \) increases; if \( \Lambda_c = 1 \), the spectrum is much flatter (Fig. 2). For \( x > 3 \) and \( \Lambda_c = -1 \), the high-energy part of this distribution is concentrated in a narrow band below the upper limit; the band contains more than half of the produced photons. We characterize this band by its lower limit \( y_{\text{min}} \) and the sharpness parameter \( \tau \) (see Table 2)

Alternative definition \( y_{\text{min}} : \int_{y_{\text{min}}}^{y_M} f(x, y)dy = 0.55 \);

Definition \( \tau : f(x, y = y_M(1 - \tau)) = f(x, y_M)/2. \)

The mean circular polarization of the produced photon (helicity) is

\[ \lambda(y) = \frac{\lambda_0 A + 2 \Lambda_c B}{U(x, y)}; \]
\[ A = (1 - 2r) \left[ \frac{1}{1 - y} + 1 - y \right]; \]
\[ B = x r \left[ 1 + (1 - y)(2r - 1)^2 \right]. \]

For \( \lambda_0 = \pm 1 \), the ratio is simplified

\[ \lambda(y) = -\lambda_0 \left[ (2r - 1) + \frac{(2r - 1) - \Lambda_c x r}{U(x, y)} [4r(1 - r)] \right]. \]

Maximum-energy photons are well polarized with the same direction of spin as laser photons, i.e., \( \lambda(y = y_M) = -\lambda_0 \). They move in the direction of the initial electron. The emission angle of a photon increases as its energy decreases

\[ \theta(y) = \frac{m_e}{E} \sqrt{1 + \frac{y_M}{y} - 1}. \]

Due to the increase in the angular spread on the distance \( b \) from the conversion region \( CR \) to the interaction region \( IR \), softer photons are distributed over a wider region and collide less frequently than hard photons; their relative contribution to the luminosity decreases. As a result, the high-energy part of the resulting photon spectrum is better and better separated from the low-energy part as the distance \( b \) increases together with decreasing total luminosity; this separation is enhanced with increasing energy \( E \) of the collider electrons.

3. Optical length of a laser flash for electrons. The laser flash is assumed to be wide enough so that the inhomogeneity of the electron density inside the electron bunch is insignificant.

The optical length of the laser flash for electrons is expressed in terms of the longitudinal photon density in the flash (i.e., laser flash energy \( \tilde{A} \) divided by its cross section \( \sigma_c \) and the total cross section of the Compton process \( \sigma_c(x, \Lambda_C) \))

\[ z = \frac{A}{\omega_0 S_L} - \frac{\sigma_c(x, \Lambda_C)}{\tilde{A} \sigma_c(x = 4.5, \Lambda_C = -1)}. \]

In the last form of this relation, we introduced \( \tilde{A} \), the laser flash energy necessary to obtain \( z = 1 \) for \( x = 4.5 \) and \( \Lambda_C = -1 \).

![Fig. 2. Photon energy spectrum \( f(x, y) \) for \( x = 4.5, \Lambda_C = -1 \) (solid line), and \( \Lambda_C = 1 \) (dashed line).](image-url)
When electrons cross the laser flash, their number decreases as
\[ n_e(z) = n_e e^{-z}. \]  
(12)

2. PHOTONS IN THE INTERACTION REGION

We list the sources of photons in the interaction region.

The highest energies have photons produced in the main Compton effect. One can see that the number of such photons with energies greater than \( y_{\text{min}}E \) is about 15% of the number of initial electrons after the loss of some of the photons in the killing process for \( \lambda_c = -1 \) and for moderate distances from the conversion region to the interaction region under optimal conversion conditions (see below).

In addition, a significant number of photons of a different origin cross the interaction region.

(A) Photons produced from the scattering of the tail of the laser pulse on (i) electrons, which slow down in the main Compton effect (rescattering) or on (ii) positrons (electrons) produced in the killing process.

These photons primarily had lower energies, and their angular distribution is wider than that of the initial Compton photons.

(B) Photons produced from magnetic lenses focusing beams and from synchrotron radiation with magnetic deflection of beams along the CR–IR beam path. Almost all of these photons have energies \( \omega < y_{\text{min}}E \).

(C) Photons produced from the interaction of electrons with each other, which survived in conversion (beamstrahlung). When using magnetic deflection, the number of such photons with energy greater than \( E/2 \) is small.

• Two regions of energy distribution. Thus, the luminosity spectrum of \( \gamma \gamma \) collision is naturally divided into two regions: they are a high-energy region for \( w_{\gamma\gamma} > y_{\text{min}}E \) and a low-energy region for lower values \( w \). These regions are well separated from each other.

The magnitude and shape of the low-energy luminosity obviously depend on the details of the experimental facility. They are not discussed in this work.

High-energy luminosity and selection of events. For the problems of New Physics, which are in the range of our interests, high-energy photons \( \omega \sim E \) are important. We study the high-energy luminosity only, considering the selection of events, which include the states with total energy\(^4\) of \( e > E_{\text{lim}} \sim E \). This part of the luminosity spectrum is formed by photons produced in the main Compton effect (2), some of them disappear in the killing process (5).

\(^4\) The limit value \( E_{\text{lim}} \) should be determined more accurately when simulating a real facility. Note that the total energy of the \( \gamma \gamma \) collision products can be close to \( 2E \). According to our estimates, the value \( E_{\text{lim}} \) may turn out to be even less than \( E \) in some cases.

• We consider the relative luminosities \( L \) and the high-energy integrated luminosity
\[ L_{\text{exp}}(w) = L(w) L_{\text{geom}}, \]
\[ L_{\text{h.e.}} = \int_{y_{\text{min}}}^{1} L(w) dw \quad (w = w_\gamma \text{ or } w_{\gamma\gamma}). \]

Here, \( L_{\text{geom}} \) is the luminosity of a \( e^- e^- \) collider designed for \( \gamma \gamma \) collision. In the nominal ILC option, that is, at an electron energy of \( E = 250 \text{ GeV} \), the geometric luminosity can reach \( L_{\text{geom}} = 12 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \), which is about four times the expected \( e^- e^- \) luminosity\(^5\).

All subsequent calculations are performed for good polarization of colliding electrons and photons \( \Lambda_c = -1 \) in two versions (\( \Lambda_c = -1 \) and \( \Lambda_c = -0.86 \)).

We discuss luminosities \( L \) for different values of the total helicity \( J = [\lambda_1 - \lambda_2] \) of the initial state (these are \( L_{1/2} \) and \( L_{3/2} \) for \( e\gamma \) collisions and \( L_0 \) and \( L_2 \) for \( \gamma \gamma \) collisions). We found that one of the helicities dominates in the high-energy part of the spectrum. Therefore, below we discuss the total luminosity (the sum over both helicities) and indicate how much of it is made up of states with a nonleading total luminosity.

In addition to the notations in Section 1, we define quantities depending on \( x, \Lambda_c \), and \( b \).

• \( L_{\text{h.e.}} \) —the total luminosity in the high-energy peak (13).

• \( L_{m} = L(w_m) \) —maximum value of \( L(w) \).

• \( w_m \) —the position of the maximum in the dependence \( L(w) \).

• \( w_\pm \) —the solutions of equation \( L(w_\pm) = L_m/2 \).

• \( \gamma_w = (w_+ - w_-)/w_m \) —the relative width of the peak.

(For \( e\gamma \) collision, the quantity \( w_+ = w_m = \sqrt{y_M} \); \( L_m \) does not depend on distance \( b \); \( \gamma_w = 1 - w_-/w_m \).)

• Luminosities of \( \gamma \gamma \) and \( e\gamma \) collisions are given by the convolution of the spectrum of a high-energy photon with the spectrum of a counter-propagating photon or electron, considering in the calculations transverse widening of the photon beam on the way from the conversion region CR to the interaction region IR. Real beams of electrons in LC are elliptical in the transverse direction; we denote by \( \sigma_x \) and \( \sigma_y \) the semi-axes of the ellipse in the interaction region. Therefore, it is not possible to directly use formulas from [7–9], and many authors use direct simulation for each studied option of the intersection (for example, see [10–16]).

\(^5\) In an \( e^- e^- \) collider, radiation from collisions of \( e^- e^- \) bunches in IR (beamstrahlung) limits the limiting densities of colliding beams. In PLC, there is no such problem. This allows \( L_{\text{geom}} \) to be larger than the expected luminosity of the conventional \( e^- e^- \) collider.
In [25], we found that the effect of beam broadening on the way from CR to IR is described (at \( y > y_{\text{min}} \)) with good accuracy by a single parameter (as for a round beam)

\[
\rho^2 = \left( \frac{b}{(E/m_\gamma)\sigma_x} \right)^2 + \left( \frac{b}{(E/m_\gamma)\sigma_y} \right)^2. \tag{14}
\]

In this approximation, the luminosities are expressed in terms of the energy distributions of photons by the formulas, where \( \phi = \frac{\sqrt{y_M/y_\rho} - 1}{I_0(z)} \) is the modified Bessel function, [7–9]

\[
\frac{dL^Y_{\gamma\gamma}}{dy} = n_e n_b(y,z)e^{-\frac{\rho^2+\rho^2_{\gamma\gamma}}{r^2}}; \tag{15}
\]

\[
\frac{dL^{2\lambda\lambda}_{\gamma\gamma}}{dy_1dy_2} = n_e n_b(y_1,z)n_b(y_2,z)I_0(\rho^2\phi_1\phi_2)e^{-\frac{\rho_1^2+\rho_2^2}{r^2}}. \tag{16}
\]

The energy distributions in the center-of-mass system are obtained by substitution \( w = \sqrt{y} \) for \( e\gamma \) luminosity or \( w = \sqrt{y_1y_2} \) with simple integration for \( \gamma\gamma \) luminosity.

Thus, the shape of the high-energy part of the luminosity distribution is determined in a universal way regardless of the details of experimental facility.

For \( x \leq 4.8 \), every lost electron produces a photon. Consequently, for \( z = 1 \) and \( \rho = 0 \), the total \( e\gamma \) and \( \gamma\gamma \) luminosities are

\[
\mathcal{L}_{e\gamma} = (1-1/e) = 0.63, \quad \mathcal{L}_{\gamma\gamma} = (1-1/e)^2 = 0.4. \tag{17}
\]

Figure 3 and the first lines of Tables 4 and 5 show the distributions of \( \gamma\gamma \) and \( e\gamma \) luminosities in their cms at \( z = 1 \) and \( \Lambda_c = -1 \) for \( \rho = 1 \) and 5.

3. WHAT HAPPENS AT \( x \geq 4.8 \)

3.1. Basic Spectra

The energy spectrum of photons from the main Compton effect (7) for \( x = 9 \) is shown on the left in Fig. 4. It can be seen that the spectrum for \( \Lambda_c = -1 \) is concentrated near the upper limit much more strongly than a similar spectrum for \( x = 4.5 \) in Fig. 2. For \( x = 18 \), a similar calculation reveals that the spectrum for \( \Lambda_c = -1 \) is concentrated in an even narrower band of 0.85 < \( y \equiv \omega/E < 0.95 \).

For \( \Lambda_c = 1 \), the spectrum is almost flat; there is a minimum instead of a peak near the upper limit.

3.2. Killing Process \( \gamma\gamma \rightarrow e^+e^- \)

The killing process is responsible for the disappearance of Compton high-energy photons in their collisions with laser photons from the tail of the laser pulse by producing \( e^+e^- \)-pairs. This process is turned on for \( x > 4.8 \). For a photon with energy \( \gamma E \), the squared energy of the killing process in the cms is

\[
w_k^2 = 4\omega_m/m_e^2 = xy > 4.
\]

Its cross section is

\[
\sigma_{\text{kill}}(w_k^2,\lambda,\lambda) = \frac{4\sigma_0}{w_k^2} \Phi_{\gamma\gamma}(w_k^2,\lambda,\lambda),
\]

\[
\Phi_{\gamma\gamma}(w_k^2,\lambda,\lambda) \left( 1 + \frac{4}{w_k} - \frac{8}{w_k^2} \right) L - \left( 1 + \frac{4}{w_k} \right) v - \lambda,\lambda(L-3v),
\]

\[
v = \sqrt{1-4/w_k^2}, \quad L = 2\ln\left( \frac{w_k}{2}(1+v) \right).
\]
Note that
$$\frac{\sigma_{\text{kill}}(\lambda > 0)}{\sigma_{\text{kill}}(\lambda < 0)} > 1 \text{ for } w_k^2 < 15;$$
$$\frac{\sigma_{\text{kill}}(\lambda > 0)}{\sigma_{\text{kill}}(\lambda < 0)} < 1 \text{ for } w_k^2 > 15.$$  \hspace{1cm} (19)

3.3. Equations

The balance of high-energy photons is given by their production in the Compton process (2) and their disappearance at the production of $e^+e^-$ pairs in the killing process (5).

We denote by $n_t(y, z, \lambda)$ the flux of photons (per one electron) with energy $yE$ with polarization $\lambda$ after passing through the laser beam with the optical length $z$. For calculations, it is convenient to split this flux into the sum of fluxes of right-polarized photons $n_{\gamma^+}(y, z)$ and left-polarized photons $n_{\gamma^-}(y, z)$, so that the total flux of photons $n_t(y, z)$ and their mean polarization $\lambda$ are written as
$$n_t(y, z) = n_{\gamma^+}(y, z) + n_{\gamma^-}(y, z),$$
$$\langle \lambda(y, z) \rangle = \frac{n_{\gamma^+}(y, z) - n_{\gamma^-}(y, z)}{n_{\gamma^+}(y, z) + n_{\gamma^-}(y, z)}. \hspace{1cm} (20)$$

Naturally, $\langle \lambda(y, z \to 0) \rangle \to \lambda(y)$ from Eq. (9).

The variation of in these fluxes during the passage through a laser beam is described by the equations
$$\frac{dn_{\gamma^+}(y, z)}{dz} = \frac{1}{2} (1 \pm \lambda(y)) f(x, y)n_t(z) + n_{\gamma^+}(y, z) \sigma_{\text{kill}}(xy, \pm \lambda_0) \sigma_C(x).$$
$$\hspace{1cm} (21)$$

The numbers of photons and their mean polarization are expressed in terms of auxiliary quantities $v_\pm$
$$n_{\gamma^\pm}(y, z) = f(x, y)v_{\pm}(z, y), \quad \langle \lambda \rangle = \frac{v_+(z, y) - v_-(z, y)}{v_+(z, y) + v_-(z, y)}.$$

Equation (21) can be easily solved
$$n_{\gamma^\pm}(y, z) = f(x, y)n_t(y, z);$$
where $v_\pm(y, z) = \left\{ \frac{1 \pm \lambda_C(y)}{1 - \zeta_\pm} \right\} e^{-\zeta_\pm y} - e^{-z}; \hspace{1cm} (22)$
$$\zeta_\pm = \frac{\sigma_{\text{kill}}(xy, \pm \lambda_0)}{\sigma_C(x)}.$$

For subsequent discussions, it is also convenient to determine the ratio of the number of killed photons of a given energy to the number of remaining photons (see Table 3).

In Fig. 4, we compare the energy spectrum of Compton photons (left panel) with what remains after the passage of a laser beam with an optical length of 0.7 (right panel).

One can see that
(i) The shape of high-energy part of the spectrum is very similar to that for the pure Compton effect$^6$.
(ii) The killing process “eats” away photons from the middle part of the energy spectrum (improving the separation of the high-energy and low-energy parts of the spectrum).
(iii) The separation of the high-energy and low-energy parts of the spectrum increases with increasing $\rho$.
(iv) The part of the spectrum corresponding to $xy < 4$ is relatively enhanced, since there is no killing process with these $xy$.

4. OPTIMIZATION

For $x < 4.8$, an increase in the optical length of the photonic target leads to a monotonic (but limited) rise in the number of photons with a simultaneous increase in the background. For $x > 4.8$, the killing process stops this rise, and for very large $z$, it kills almost all photons.

$^6$ That is due to the relationship between the spin structures of processes (2) and (5). Neglecting this structure for process (5), as was done in [22], one arrives at an erroneous conclusion about a strong “sharpening” of the resulting spectrum.
high-energy photons. The dependence of the number of photons $n(y, z)$ on $z$ has a maximum for some $z = z_m(y)$. This can be interpreted as the optimal value of $z$. There is a question: what criterion should be used for the optimal choice?

The simplest approach is to study the balance only for photons of maximum energy for $y = y_M$ [22]. In our opinion, it is more reasonable to use the dependence on $z$ for the total luminosity within the high-energy peak $L_{h.e.}$ \(^{(13)}\) and \(^{(8)}\).

A typical dependence of the high-energy luminosity $L_{h.e.}$ on $z$ is shown in Fig. 5. Curves for other $x$ and $\rho$ are similar. The optimal value of the optical length of the laser flash corresponds to the position of the maximum on these curves $z_m$. These values are given in Table 3. We have found it useful to define a value of $z_{0.9}$ that provides luminosity 10% less than the maximum luminosity. Note that $z_{0.9}$ is noticeably less than $z_m$. It turned out that dependence of these quantities on $\rho$ is negligibly weak for $\Lambda_C = −1$. In addition, Table 3 contains the value of the threshold energy $A(z)$ \(^{(11)}\) necessary to obtain this optical length (evaluated relative to the threshold energy $A_0$ needed for obtaining $z = 1$ for $x = 4.5$), a fraction of photons producing $e^+e^−$ pairs with respect to the highest energy photons obtained in the main Compton effect $r_k(z, y_M)$, and a fraction of electrons freely passing through the laser beam $d(z)$.

Table 3. The optical lengths $z_m$ and $z_{0.9}$ necessary for $z$ laser flash energies, the fraction of killed photons $r_k(z, y_M)$, and the fraction of electrons freely passed through the laser beam $d(z)$ for $\Lambda_C = −1$

| $x$ | $y_{\text{min}}$ | $z$ | $A(z)/A_0$ | $r_k(z, y_M)$ | $d(z) = e^{-z}$ |
|-----|----------------|-----|-------------|---------------|----------------|
| 9   | 0.7            | $z_m = 0.704$ | 1.15         | 0.22          | 0.495          |
|     |               | $z_{0.9} = 0.49$ | 0.8          | 0.13          | 0.61           |
| 18  | 0.75           | $z_m = 0.609$ | 1.70         | 0.43          | 0.54           |
|     |               | $z_{0.9} = 0.418$ | 1.17         | 0.28          | 0.66           |
| 100 | 0.94           | $z_m = 0.48$  | 6.3          | 0.62          |                |
|     |               | $z_{0.9} = 0.32$ | 4.2          | 0.73          |                |

Fig. 5. Integrated $\gamma\gamma$ luminosity $L_{h.e.}$ as a function of $z$ for $\rho = 1$ and $\Lambda_C = −1$. The dots correspond to $z_m$ and $z_{0.9}$.

Tables 4 and 5 present the properties of the high-energy peak in $\gamma\gamma$ and $e^+e^−$ luminosity spectra at $z = z_m$ for $\Lambda_C = −1$ and $\Lambda_C = −0.86$ for $x = 9$ and 18. The table rows for $(x = 4.5, z = 1)$ and $(x = 100, z = z_m)$ are shown for comparison.

Let us list the main properties of these distributions at $x = 9$ and 18.

1. High-energy luminosity for $\rho = 1$:
   $L_{h.e.}^{\gamma\gamma} = 0.02L_{\text{geom}}$ (it is 5.5–7 times less than for $x = 4.5$);
   $L_{h.e.}^{e^+e^-} = 0.15L_{\text{geom}}$ (it is 2.5 times less than for $x = 4.5$).

2. Peak differential luminosity: $L_{\gamma\gamma}^{\text{d}} = L_{e^+e^-}^{\text{d}}(x = 4.5)$ and does not depend on $\rho$; $L_{\gamma\gamma}^{\text{d}}(x = 4.5) = (1/4)L_{e^+e^-}^{\text{d}}(x = 4.5)$.

3. As $\rho$ increases, the integrated luminosity $L_{h.e.}$ and the peak value $L_{\gamma\gamma}^{\text{d}}$ decrease, but this decrease is slower than for $x = 4.5$.

4. The photons within the peak under consideration are well polarized. The fraction of luminosities $L_{\gamma\gamma}$ and $L_{3/2}$ in the total luminosity is very small; for $\rho = 5$, there is almost no contribution \(^8\).

5. The energy distribution of luminosity is very narrow: for $\gamma\gamma$ collisions, the peak width $\gamma_w$ is comparable to the peak width in the main $e^+e^−$ collision mode (considering the radiation in the initial state (ISR) and beam radiation (beamstrahlung, BS)). For $e^+e^−$ collisions, the peak width $\gamma_w$ is even narrower than in the basic $e^+e^−$ collision (considering ISR and BS).

6. The rapidities of the $e^+e^−$ and $\gamma\gamma$ collisions produced in the collider system are in narrow intervals determined by the spread of photon energies within high-energy peak \(^8\).

---

\(^7\) For $\Lambda_C = −1$, the spectrum is concentrated near the upper boundary, and the criteria differ little from each other. For $\Lambda_C = 1$, the initial spectra are flat, and the method from [22] gives a result that is not optimal in terms of the luminosity criterion.

\(^8\) A simultaneous change in the signs of the helicity of one of the electrons and a laser photon colliding with it leads to substitutions $L_0 \leftrightarrow L_2$, $L_{1/2} \leftrightarrow L_{3/2}$. 

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7. Imperfect polarization of the initial electrons $2\lambda_x = -0.86$ rather than $-1$ only weakly degrades the spectrum.

**SUMMARY**

(1) The LC with electron energy $E \leq 1$ TeV allows one to construct a photon collider (TeV PLC) using the same laser and optical system as those designed for construction PLC at $E \leq 250$ GeV. In comparison with this case, the required laser flash energy should be increased by no more than 70–20%.

(2) For TeV PLC two complements compared to the $x < 4.8$ case seem to be very desirable:

(a) the magnetic deflection of electrons after conversion,

(b) the selection of events with total observed energy of reaction products $\sum_i E_i > E_{lim} \sim E$.

(3) When using an LC with $E = 1$ TeV in a TeV PLC, the maximum photon energy is $\omega_m = 0.95$ TeV ($\sqrt{s_{\gamma\gamma}} = 1.9$ TeV), the $\gamma\gamma$ luminosity is concentrated in a narrow band with a width of 5% near the upper limit. Almost all photons have the same helicity (+1 or −1,

Table 4. Properties of high-energy $\gamma\gamma$ luminosity

| $\rho$ | $\Lambda_C$ | $\mathcal{L}_{h.c.}$ | $L_2/L$ | $L_m$ | $w_M$ | $w_-$ | $w_+$ | $\gamma_w$ |
|-------|-------------|-----------------|-------|------|------|------|------|----------|
| 1     | -1          | 0.121           | 0.143 | 0.933| 0.779| 0.689| 0.89  | 0.154    |
|       | -0.86       | 0.114           | 0.215 | 0.82 | 0.778| 0.672| 0.809 | 0.177    |
| 5     | -1          | 0.031           | 0.041 | 0.464| 0.799| 0.760| 0.814 | 0.067    |
|       | -0.86       | 0.0275          | 0.086 | 0.40 | 0.7985| 0.0758| 0.813 | 0.069    |
|       | x = 4.5, $z = 1$, $\eta \in (\tau, \tau)$, $\sum_i E_i > E_{lim} \sim E$. |
| 1     | -1          | 0.0214          | 0.079 | 0.222| 0.872| 0.814| 0.894 | 0.092    |
|       | -0.86       | 0.0201          | 0.164 | 0.195| 0.871| 0.806| 0.894 | 0.100    |
| 5     | -1          | 0.0072          | 0.021 | 0.137| 0.885| 0.854| 0.896 | 0.048    |
|       | -0.86       | 0.064           | 0.074 | 0.118| 0.885| 0.852| 0.896 | 0.050    |
|       | x = 9, $z = z_m = 0.704$, $\eta = \sqrt{s_{\gamma\gamma}}$. |
| 1     | -1          | 0.0178          | 0.089 | 0.2615| 0.9317| 0.8932| 0.9436 | 0.054    |
|       | -0.86       | 0.0178          | 0.228 | 0.229| 0.931| 0.886| 0.9436 | 0.062    |
| 5     | -1          | 0.0074          | 0.021 | 0.190| 0.9365| 0.9138| 0.9447 | 0.033    |
|       | -0.86       | 0.069           | 0.144 | 0.164| 0.936| 0.912| 0.9447 | 0.035    |
|       | x = 18, $z = z_m = 0.609$, $\eta \in (\tau, \tau)$, $\sum_i E_i > E_{lim} \sim E$. |
| 1     | -1          | 0.0093          | 0.017 | 0.527| 0.9867| 0.9771| 0.9890 | 0.012    |
|       | -0.86       | 0.0070          | 0.009 | 0.519| 0.9867| 0.9793| 0.9890 | 0.0097    |
| 5     | -1          | 0.0093          | 0.017 | 0.527| 0.9867| 0.9771| 0.9890 | 0.012    |

Fig. 6. Luminosity spectra $dL/\omega$ for $x = 18$, $\Lambda_C = -1$, and $z = 1$. Solid lines are total luminosities for $\rho = 1$ (upper line) and $\rho = 5$ (lower line). Dashed lines are luminosities for final states with total helicity of 3/2 ($\gamma e$ collisions) or 2 ($\gamma\gamma$ collisions).
in accordance with the choice of the experimenter). In other words, photons are monochromatic with good accuracy in both energy and polarization. The total integrated luminosity in this high-energy part of the spectrum is about \((10 \text{ fb per year})\); this is only five times less than for the option of \(E = 250 \text{ GeV}\). For \(E = 250 \text{ GeV}\), the spread of effective \(\gamma \gamma\) masses is much higher. The maximum differential \(\gamma \gamma\) luminosity in the TeV PLC is more than 25% of the maximum luminosity for \(E = 250 \text{ GeV}\).

(4) The low-energy part of the photon spectrum includes photons from all channels mentioned above. This part is highly dependent on the details of experimental facility. The integrated luminosity can be large [31]. This part of the spectrum can be used to study rather traditional problems (for example, see [32]).

### APPENDICES

#### A. SOME BACKGROUND PROCESSES AND RELATED ISSUES

##### A.1. “Bad” Initial Helicity: \(\Lambda_C = 1\)

For \(\Lambda_C = 1\), the spectrum of basic Compton photons is much flatter than in the “good” case of \(\Lambda_C = -1\) (see Fig. 4). Therefore, the lower limit of integrated luminosity (13) \(\gamma_{\text{min}} = 0.6\) should be used. The optimal optical length turns out to be larger than in the good case \(\Lambda_C = -1\). In particular, for \(\rho = 1\), one has \(z_m(x = 18, \Lambda_C = 1) = 0.827\) and \(z_m(x = 100, \Lambda_C = 1) = 1.07\) for \(x = 100\). In this case, the laser flash energy is slightly higher than in the good case.

The most important difference is the high-energy part of the luminosity spectrum. It is significantly flatter than the one shown in Fig. 6. The position of its smeared maximum shifts toward much smaller values of \(w\). A simple one-parameter description of the spectrum with a change in \(b\) (14)–(16) becomes unacceptable; the details of the facility become significant at all photon energies; and the high-energy and low-energy parts of the spectrum are barely separated.

##### A.2. Linear Polarization of High-Energy Photons

The linear polarization of high-energy photons is expressed through the linear polarization of laser photons \(P_0\) by the well-known relation \((N/D)\) (see [9]), in which \(|N| \leq |2P_0|\) and \(D \propto f(x, y)\). For the high-energy luminosity to be large, the denominator \(D\) must be large. Therefore, for high \(\gamma \gamma\) luminosity, the linear polarization of the high-energy photon can only be small. We cannot hope to observe these effects at the TeV PLCs under discussion.

##### A.3. Collisions of Positrons with Electrons of the Counter-Propagating Beam

Collisions of positrons produced in the killing process with electrons of the counter-propagating beam give rise to physical states similar to some states generated in \(\gamma \gamma\) collisions. This could be an important background process for TeV PLC.

#### Table 5. Properties of high-energy \(e \gamma\) luminosity

| \(\rho\) | \(\mathcal{L}_{\text{h.e.}}\) | \(L_m\) | \(L_{3/2}/L\) | \(\gamma_w\) | \(\mathcal{L}_{\text{h.e.}}\) | \(L_m\) | \(L_{3/2}/L\) | \(\gamma_w\) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.38 | 7.626 | 0.135 | 0.0296 | 0.372 | 7.034 | 0.182 | 0.031 |
| 5 | 0.143 | 0.007 | 0.0141 | 0.134 | 0.079 | 0.014 |
| \(\Lambda_C = -1\) | \(\Lambda_C = -0.86\) | \(x = 4.5, z = 1, w_M = 0.9045\) | \(x = 9, z = 0.7047, w_M = 0.949\) |
| 1 | 0.153 | 4.837 | 0.069 | 0.0176 | 0.149 | 4.32 | 0.116 | 0.018 |
| 5 | 0.074 | 0.05 | 0.0105 | 0.068 | 0.063 | 0.011 |
| \(\Lambda_C = -1\) | \(\Lambda_C = -0.86\) | \(x = 18, z = 0.609, w_M = 0.973\) | \(x = 100, z = 0.477, w_M = 0.995\) |
| 1 | 0.136 | 7.015 | 0.0625 | 0.0098 | 0.138 | 6.439 | 0.12 | 0.01 |
| 5 | 0.08 | 0.0059 | 0.007 | 0.076 | 0.077 | 0.007 |
| \(\Lambda_C = -1\) | \(\Lambda_C = -0.86\) | \(x = 100, z = 0.477, w_M = 0.995\) |
| 1 | 0.099 | 22.905 | 0.0086 | 0.002 | 0.1085 | 21.905 | 0.108 | 0.002 |
| 5 | 0.083 | 0.0042 | 0.0018 | 0.088 | 0.103 | 0.0018 |
General. According to Table 3, for \( x = 18 \) and \( z = z_m \), the number of killed photons (that is produced \( e^+e^- \) pairs) is less than \( 3/4 \) of the number of remaining photons. This ratio decreases with decreasing \( x \). Only half of these photons produce high energy positrons. Therefore, the luminosity of these collisions is \( \mathcal{L}_{e^+e^-} \) half of that of the \( \gamma\gamma \) collisions. To verify this, consider the energy distribution of positrons produced by photons with energy \( \omega = Ey \) and polarization \( \lambda \). We use notation (18) and denote the positron energy by \( E_+ = y_+\omega \equiv y_+yE \). The kinematic constraints are

\[
\begin{align*}
\frac{1 + v}{2} & \geq y_+ \geq \frac{1 - v}{2}, \\
\frac{1 - \sqrt{1 - 4/w^2}}{2} & \geq y_+ \geq \frac{1 + \sqrt{1 - 4/w^2}}{2},
\end{align*}
\] (24a)

so

\[
\begin{align*}
y_+ & \leq 0.77 \rightarrow E_+ \leq 0.693E \text{ at } x = 9, \\
y_+ & \leq 0.888 \rightarrow E_+ \leq 0.841 \text{ at } x = 18.
\end{align*}
\] (24b)

As a result, the rapidities of the system produced in the \( e^+e^- \) collisions are

\[
\eta_{e^+e^-}(x = 9)0.153, \quad \eta_{e^+e^-}(x = 18)0.08.
\] (25)

These values do not overlap with the rapidity interval for \( \gamma\gamma \) system (23) and (8). Therefore, when all the final products of \( e^+e^- \) and \( \gamma\gamma \) reaction are observed, the events are clearly distinguishable.

In general, a more detailed description is needed. The energy distribution of positrons produced in \( \gamma\gamma \) collisions is

\[
\frac{dn_+(y_+; w^2, \lambda\lambda_\omega)}{dy_+} = \frac{(u - 2)(1 + c\lambda\lambda_\omega) + s^2}{\Phi_{\gamma\gamma}(w^2, \lambda\lambda_\omega)},
\] (26)

\[
u = \frac{1}{y_+(1 - y_+)}, \quad c = \frac{2u}{w^2} - 1, \quad s^2 = 1 - c^2.
\]

At the highest energy of positrons \( c = 1 \), one has \( dn = 0 \) (for \( \lambda\lambda_\omega = -1 \)). This means that the physical positron flux is even more constrained than in Eq. (24).

When moving away from the specified end points, distribution (26) over \( y_+ \) changes slightly in the entire range of \( y_+ \) variation. Therefore, the \( e^+e^- \) luminosity is widely distributed over the entire domain of possible variation. As a result, the differential luminosity is

\[
\frac{dL^{e^+e^-}}{dw} \ll \frac{dL^{\gamma\gamma}}{dw_{peak}}.
\]

Apart from the differences in the luminosity distribution, important differences in the produced systems at the same energies should be noted.

1. With increasing energy, all cross sections in the \( e^+e^- \) mode decrease as \( 1/s \). In \( \gamma\gamma \) collisions, the cross sections of many processes do not decrease.

2. In the \( e^+e^- \) mode, most of the processes are annihilation ones (via \( \gamma \) or \( Z \) in the intermediate state). The products of these processes have wide angular distributions. In \( \gamma\gamma \) collisions, a significant part of the reaction products move along the collision axis with a moderate transverse momentum.

A.4. Bethe–Heitler Process \( e^-\gamma_0 \rightarrow e^+e^- \)

This process starts at \( x = 8 \). This is a process of the next order in \( \alpha \), but (in contrast to the Compton effect) its cross section does not decrease with increasing energy

\[
\sigma_{BH} = \frac{(28/9\pi)\alpha\sigma_{\gamma\gamma}(\ln x - 109/42)}{x} \quad \text{for } x \gg 1.
\]

Because of this process, the flux of high-energy photons is effectively reduced by \( K_{BH} \) times

\[
K_{BH} = \frac{\sigma_c(x)}{\sigma_c(x) + \sigma_{BH}(x)},
\] (27)

and \( \gamma\gamma \) luminosity decreases by \( K_{BH}^2 \) times. The numerical values of this factor are given in Table 6. It shows that the Bethe–Heitler process can be neglected for \( x < 100 \); the decrease in the photon flux becomes unacceptably strong for \( x > 300 \).

B. SOME PHYSICAL PROBLEMS FOR TeV PLC

We expect the LHC and \( e^+e^- \) colliders to yield many new results. Of course, TeV PLC will complement these results and improve the measurement accuracy of some of the fundamental parameters. However, there are also important problems of fundamental physics that cannot be studied using the LHC and \( e^+e^- \) colliders or require very great efforts to study, but they can find a solution using TeV PLC. We discuss just such problems below.

Beyond the Standard Model (BSM). In the extended Higgs sector, a scenario can be realized in which the observed Higgs boson \( h \) is similar to the Higgs boson in the Standard Model (SM-like, or aligned), while the model contains other scalars, some of which interact strongly. It was previously discussed (in the model with one Higgs boson) that the nature of such a strongly interacting sector could be similar to the nature of low-energy pion physics. Such a system can have resonances similar
to $\sigma$, $\rho$, and $f$ with spin of 0, 1, and 2 (according to estimates, with a mass of $M \leq 1$–2 TeV). The high monochromaticity of TeV PLC will make it possible to observe these resonance states with spin 0 and 2 in $\gamma\gamma$ collisions.

Likewise, it will be possible to observe excited electrons with spin of 1/2 or 3/2 in $e\gamma$ collisions.

• **Gauge boson physics.** The electroweak theory has now been tested at the tree level for the simplest processes and at the one-loop level for the $Z$ peak. The ability to test the effects of this model in more complex processes and for off-peak loop effects is very important. A TeV PLC will provide us with a unique opportunity to explore these problems.

Processes $\gamma\gamma \to WW$ and $e\gamma \to WW$ have huge cross sections by the standards of physics of TeV energies; for large $s$, we have [26–30]

$$\sigma(\gamma\gamma \to WW) \equiv \sigma_{\gamma} = 8\pi\alpha^2/M_W^2 = 86\rho b, \quad (28a)$$

$$\sigma(e\gamma \to WW) = \left(1 - \lambda_\gamma\right)\sigma_{\gamma}. \quad (28b)$$

Measurement of these processes will allow testing the structure of the electroweak theory with an error of about 0.1% (one loop and partially two loops). To describe the results with such accuracy, a quantum field theory with unstable particles should be constructed. Sensitivity to possible anomalous interactions (operators of higher dimensions), i.e., to the signals of the new physics will be enhanced [26].

Processes $\gamma\gamma \to ZZ$ and $\gamma\gamma \to ZZ$ will be the first well-measured processes induced by the loop contributions alone [27] and [29]. The energy dependence of the $\gamma\gamma \to ZZ$ process cross section is shown in Fig. 7. Note that $\sigma(\gamma\gamma \to ZZ)/3$ [30].

> Processes with multiple productions of gauge bosons using the TeV PLC have relatively large cross sections (Fig. 8)\(^1\). These cross sections are sensitive to details of the gauge interaction (which cannot be seen otherwise) and to possible anomalous interactions. Nothing of the kind is being discovered using other colliders. These relatively large cross sections are due to the contributions of the diagrams with the exchange of gauge bosons in the $t$ channel, which do not decrease with increasing energy [33]. These cross sections increase logarithmically with the factors $L = \ln(s/m^2)$ for the exchange with photons and $\ell = \ln(s/M_W^2)$ for the $W(Z)$ exchange

$$\sigma(e\gamma \to eWW) - \alpha\sigma_W L, \sigma(e\gamma \to eWW) - \alpha^2\sigma_W L\ell, \quad (29)$$

$$\sigma(e\gamma \to WW) - \alpha^2\sigma_W \ell, \sigma(\gamma\gamma \to ZWW) - \alpha^2\sigma_W \ell, \quad (29)$$

$$\sigma(\gamma\gamma \to WWZZ) - \alpha^2\sigma_W \ell^2, \quad (29)$$

For processes $e\gamma \to eWW$ and $e\gamma \to eWWZ$, we present cross sections for well-observed electron transverse momenta ($p_{te} > 30$ GeV). The study of the dependence of these cross sections on the transverse momentum of the electron will make it possible to measure the electromagnetic form factor $W$ in process $\gamma\gamma \to WW$, and to isolate the contribution of process $Z\gamma \to WW$, $Z\gamma \to WWZ$ ($p_{te} > 30$ GeV). The study of process $e\gamma \to WWZ$ will provide the first information about subprocess $W^*\gamma \to WZ$.

• **Hadron physics and QCD.** Our understanding of hadron physics is twofold. We are confident that we understand the basic theory (QCD) with its asymptotic freedom. However, the results of QCD calculations are applied to the description of the data only using phenomenological assumptions (often confirmed by many years of practice). This leads to poorly controlled uncertainties in the description of data.

> In some respects, the PLC can be considered as a hadronic machine with a cleaner initial state. This means that the PLC can be used for detailed studies of high-energy QCD processes such as diffraction, total cross sections, odderon, etc. The results of the experiments can be compared with the results of the experiments with uncertainties smaller than those when using the LHC.

Studying the photon structure function $W_\gamma$ (in $e\gamma$ collision) will provide a unique QCD test. This function can be represented as the sum of the point-like $W_\gamma^p$ and hadronic $W_\gamma^h$ contributions. The latter is sim-

\(^{10}\)Possible contributions from additional Higgs bosons are not considered.
Fig. 8. Cross sections of the multiple production of gauge bosons calculated using CalcHEP software package.

ilar to the structure function of the proton and is described by a similar phenomenology. On the contrary, the point-like contribution $W_{pl}$ is described without phenomenological parameters \[34\]. Ratio $W_h/W_{pl}$ decreases with increasing $Q^2$ approximately as $(\ln Q^2)^{-1/3}$. The hadronic contribution dominates in the currently accessible range of parameters. The point-like contribution should become dominant with increasing $Q^2$ for $e\gamma$ collision in TeV PLC.

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