PHYSICAL PROGRAM FOR PHOTON COLLIDERS

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Ilya F. Ginzburg
Institute of Mathematics. 630090. Novosibirsk. Russia.
E-mail: ginzburg@math.nsk.su

Abstract

The physical program for the photon linear colliders (PLC) is discussed. We consider the problems in electroweak theory, hadron physics and QCD, new particles and interactions. We arrange this program for the main stages of PLC, which are the parts of an entire program for linear colliders. Some important unsolved problems are listed.

1 Main expected features of photon colliders

We believe now that

Most of future linear colliders (LC) will be $e^+e^- / e\gamma / \gamma\gamma$ complexes. The entire project of a LC should have an ambitious goal, e.g., to achieve energy about 2 TeV. Its total realization will be a long and expensive task. However the specific features of LC’s provide an opportunity to do this job step by step, depending on present day reserves of funds and time. The stops along the way will be the separate colliders with ever higher beam energies and with new and higher physical potentials.

The idea of Photon Linear Colliders (PLC) based on $e^+e^-$ LC was proposed and developed in papers [1]. Some details of design and some separate phenomena in PLC were considered in the subsequent papers [2–5]. The relation to the modern projects of LC’s is discussed in the Telnov’s talk at this Workshop [3].

We will denote below: $E$ – initial electron energy, $E_\gamma$ – photon energy, $E_{\gamma\gamma}$ or $E_{e\gamma}$ – c.m. energy of photon–photon or electron–photon system.

Modern studies show that one can expect the following parameters of PLC:

- Characteristic photon energy is $E_\gamma \approx 0.8E$.
- Mean energy spread is $< \Delta E_{\gamma\gamma} / E_{\gamma\gamma} > \approx 0.1$ (monochromatic variant).
- Photons will be polarized, with mean helicity $< \lambda > \approx 0.95$. 
• There is no special physical reasons for observations at small angles, except details of design.

• One can expect annual luminosity $10 \div 20 \, \text{fb}^{-1}$ in the monochromatic variant. It is about 20% from that for the basic $e^+e^-$ LC. This value can be obtained on the basis of modern LC projects, optimized for the $e^+e^-$ mode. If one optimize these projects from beginning for $\gamma\gamma$ mode, one can hope for luminosities, which are higher by an factor $\gtrsim 10$.

• In each case one can organize nonmonochromatic variant with $\gamma\gamma$ luminosity $\sim 5$ times higher with wide energy spectrum (and with almost the same high energy part of spectrum as in the monochromatic variant). The additional, more soft photons are almost unpolarized in this case.

• One can organize, in principle, the supermonochromatic variant with $E_\gamma \approx 0.95E$, $\langle \lambda \rangle \approx 0.95$; $\langle \Delta E_{\gamma\gamma}/E_{\gamma\gamma} \rangle \approx 0.015 \div 0.02$ but with luminosity which is about $10 \div 20$ times less\footnote{Variation from monochromatic variant to the nonmonochromatic one seems to be possible during operations; going to the supermonochromatic variant demands for new optical technique.}. Besides, the conversion region is (very nonsymmetrical) $e\gamma$ and $\gamma\gamma$ collider with a small c.m. energy ($E_{e\gamma} \approx 1.2 \, \text{MeV}$, $E_{\gamma\gamma} \approx 1 \, \text{MeV}$), but with a huge luminosity $10^6 \div 10^8 \, \text{fb}^{-1}$ per year. It provides new opportunities to hunt for the very light particles [7, 4].

We discuss below physical program for PLC. The separate programs for different stages of PLC (PLC0 – PLC3) are considered briefly in the end of the text. Some stages of such program for $e^+e^-$ LC’s were considered in refs. [8]–[13]. Some points related to PLC have been discussed in refs. [12]–[14],[5].

2 Hadron Physics and QCD

The hadron physics and QCD are the traditional problems for two photon experiments. These experiments provide new type of collisions and with the simplest quark structure of the pointlike initial state. The PLC’s will spread these studies to quite new regions. Here these studies will be no less informative than those at other colliders. The results from PLC’s together with those from the Tevatron and HERA, will produce the entire set of complementing data related to a factorized (in the old Regge sense) set of processes. In this respect, HERA acquires a new importance of a bridge between PLC’s and Tevatron/LHC.

Basic problems in Hadron Physics and QCD at PLC (In more details see, e.g., [15, 16].)

1) TOTAL CROSS SECTION $\sigma_{\gamma\gamma \rightarrow \text{hadrons}}$. It is important to study the energy dependence of this cross section (together with the $Q^2$ dependence — in $\gamma e$ collisions). Its comparison with $\sigma_{pp}(\sigma_{p\bar{p}})$ and $\sigma_{pp}$ will allow us to understand the nature of the increase

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1 I am grateful to V.Balakin and A.Skrinsky who clarify me this opportunity.

2 Variation from monochromatic variant to the nonmonochromatic one seems to be possible during operations; going to the supermonochromatic variant demands for new optical technique.
in the hadron cross sections with energy. The crucial problem is to test the possible factorization of these cross sections (this factorization is assumed in ref. [18]). (This cross section is expected to be $\sim 0.3 \mu b$ in the SLC energy region, and $\sim 0.5 \div 1 \mu b$ at $E_{\gamma\gamma} \sim 2$ TeV [18]). How can we measure this cross section?

2) The same questions can be posed for the DIFFRACTION LIKE PROCESSES IN SOFT REGION with production of neutral vector mesons $V$ (Pomeron) and pseudoscalar $P$ or tensor $T$ mesons (Odderon). That are the processes

$$\gamma\gamma \rightarrow M + M'; \quad \gamma\gamma \rightarrow M + X \text{ with rapidity gap } \quad (M = V \text{ or } T/P). \quad (1)$$

(X is the hadronic system separated from meson $M$ by large enough rapidity gap).

The cross section of process $\gamma\gamma \rightarrow \rho^0\rho^0$ is expected to be $\sim 0.1\sigma_{tot}$ (see [22]). The processes $\gamma\gamma \rightarrow \pi^0\pi^0, \gamma\gamma \rightarrow \pi^0a_2, \ldots$ are described only by Odderon exchange. These present a unique opportunity for Odderon study. The real role of Odderon in hadron collisions is unknown today. This is in contrast with the fact that the Pomeron and the Odderon have the identical status in pQCD. But where is the Odderon in the data?

3) PHOTON STRUCTURE FUNCTION is discussed widely at this Workshop. At PLC it will be studied in new region and with high accuracy (target energy is roughly known). Modern studies show that the real influence of the hadronic component of the photon is very important over a wide region of parameters [19]. It is expected that at the higher values of $Q^2$ the pointlike component of photon [20] becomes dominant. The small $x$ region is related to the Pomeron in pQCD (perturbative Pomeron) [21].

Table 1: Positions of different colliders in discussed problems of hadron physics

| nature of $\sigma_{tot}^{had}$ growth | PLC | HERA, LEP+LHC | Tevatron, LHC | $e^+e^-$ LC |
|--------------------------------------|-----|---------------|---------------|-------------|
| Pert. Pomeron and odderon            |     | the best      |               | —           |
| Photon structure function            |     | Comparison    |               | —           |
| large angle jets for discovery of New Physics |     | second        | specific      | the best    |
| t quark, threshold phenomena         |     | second        | —             | the best    |
| t quark, properties                  |     | the best      | —             | second      |

4) Three mechanisms of LARGE ANGLE JET production [17] are substantial:

QUARK EXCHANGE is described by the simplest pQCD diagram with two quarks (jets) in the final state. The corresponding cross section is $d\sigma^q \propto 1/(s p^2_\perp)$.

Diagrams with GLUON EXCHANGE between two pairs of quark (jets) give the cross section $d\sigma^g \propto 1/(p^2_\perp)^2$.

The W PRODUCTION mechanism is $\gamma\gamma \rightarrow W^+W^-$ reaction with subsequent decay of W’s into quark jets (at $\sqrt{s} > 160$ GeV).

At $p^2_\perp \sim s$ W production dominates, $d\sigma^W > d\sigma^q > d\sigma^g$. When $p_\perp$ decreases, the relative value of quark exchange decreases as $p^2_\perp/s$ in comparison with other mechanisms.
and gluon exchange become dominant. (In the $e\gamma$ collisions W production through process $e\gamma \rightarrow W\nu$ provides dominant part of produced quark jets for almost all $p_\perp$.)

The NEW PHYSICS can manifest itself as anomalous large angle jet production, obliged by anomalous interaction like $\gamma\gamma q\bar{q}$.

5) THE SEMIHARD PROCESSES are those, for which the characteristic value of transverse momentum is small in comparison with total energy but large in comparison with the strong interaction scale $\mu \sim 300$ MeV: $s \gg p_\perp^2 \gg \mu^2$ (THE SMALL ANGLE JET PRODUCTION, THE DIFFRACTION LIKE PROCESSES (1), THE PHOTON STRUCTURE FUNCTION AT SMALL $x$, etc.). These phenomena provide us information about perturbative Pomeron and odderon, mechanisms of shadowing in pQCD, etc.

In this region, a new parameter appears in the pQCD series, $\alpha_s(p_\perp^2)\ln(s/p_\perp^2) \approx \alpha_s(p_\perp^2)\eta$ or $\alpha_s(Q^2)\ln(1/x)$, that becomes large while $s$ increases. Therefore, the entire pQCD series should be taken into account, and studies here provide opportunity to test the inner structure of pQCD in all orders. Due to the simple pointlike nature of photons, the nontrivial results in pQCD could be obtained almost without model assumptions. Unfortunately, the influence of hadronlike component of photon is expected to be relatively small at large enough $p_\perp$ only. For example, for the diffraction like processes (1) it is expected to be at $p_\perp > 7$ GeV.\footnote{The cross sections of some processes, integrated over this range of $p_\perp$ and with large enough rapidity gap, are estimated from below as: $\sigma_{\gamma\gamma \rightarrow \rho \chi} \approx 1$ pb, $\sigma_{\gamma\gamma \rightarrow \pi \chi} \approx 0.4$ pb [24, 25]. The first quantity should be multiplied by the growing BFKL factor (see [26, 27]).}

Where is the corresponding boundary for the jet production with rapidity gap?

Where are the real bounds for the description of $s/p_\perp^2$ dependence with perturbative Pomeron or odderon?

What is the nature of shadowing effects?

6) MINIJETS. The number of minijets within some definite angular interval (e.g., $1^\circ - 179^\circ$, $5^\circ - 175^\circ$) should be weakly dependent on energy [17]. Hence, the energy dependence of transverse energy flow will show us the energy dependence of mean transverse momentum for single minijet.

The threshold effects will be investigated both at $e^+e^- 500$ and its $\gamma\gamma$ modification [28].

The strong dependence on photon helicities provides opportunity to see delicate details of $t\bar{t}$ interaction near the threshold.

The PLC provides the best opportunity for study of $t$–quark properties themselves. Indeed, the cross section of $t\bar{t}$ production in the $\gamma\gamma$ collision is larger and it decreases more slowly with energy than that in $e^+e^-$ collision (Fig. 2). Therefore, relatively far from the threshold one can expect at PLC about $10^5$ $t\bar{t}$ pairs/year, and their decay products are overlapped weakly. Some rare $t^\pm$–decays could be studied here.

### 3 Higgs Boson Physics

1) THE DISCOVERY OF HIGGS BOSON (Higgs) seems to be the most important problem of modern particle physics. The result of competition between different colliders
depends on both Higgs mass and the time of beginning of operations there. In any case, the SM Higgs with \( M_H \leq 90 \text{ GeV} \) will be either found or prohibited at the LEP2.

If \( M_H > 2M_Z \), the Higgs will be detected at the LHC in the decay mode \( H \rightarrow ZZ \). This Higgs will be seen at PLC2 through this very decay mode if its mass is less than \( 400 \div 500 \text{ GeV} \). (The upper bound is obliged by 1) compensation of t quark and W boson loop contributions into the Higgs two photon width and 2) large background due to \( \gamma \gamma \rightarrow ZZ \) process \( [29] \).

The PLC1 seems to be the best machine for the discovery of Higgs with mass \( 80 \div 180 \text{ GeV} \) \( [30] \). The process \( \gamma \gamma \rightarrow H \rightarrow b \bar{b} \) with QED background \( \gamma \gamma \rightarrow b \bar{b} \) was considered in \( [32] \), these results are refined in ref. \( [33, 34] \). It is follows from these results, that with using of monochromatic variant of PLC with zero total initial photon pair helicity, one can observe Higgs with mass \( 80 < M_H < 150 \text{ GeV} \), based on the luminosity integral about \( 3 \text{ fb}^{-1} \).

The mass interval \( 150 \text{ GeV} < M_H < 2M_Z \) is the most difficult one for the Higgs discovery. Indeed, the decay \( H \rightarrow WW \) dominates here strongly, but the WW production cross section via Higgs is much less than that without this intermediate state. The new opportunity follows from the recent result \( [35] \). It was noted there, that the total width of the heavy Higgs will by high enough to resolve details of WW spectrum within this width interval. Besides, the amplitude of the \( \gamma \gamma \rightarrow H \rightarrow WW \) process is complex with the phase, which varies fast:

\[
M \propto \Gamma(\gamma \gamma \rightarrow H) \frac{1}{s - M_H^2 + i\Gamma_H M_H} \Gamma(H \rightarrow WW)
\]

(The first factor here is also complex.) Therefore, the interference of this amplitude with that for QED process \( \gamma \gamma \rightarrow W^+ W^- \) is high enough. The paper \( [35] \) shows the spectacular curves for \( 180 \text{ GeV} < M_H < 400 \text{ GeV} \). The special simulation work is necessary to understand, how are requirements imposed on either PLC (monochromatization degree) or detector (accuracy of W decay products momenta measurements), to see Higgs in the widest mass interval.

2) At the PLC only, one can measure precisely the HIGGS TWO PHOTON WIDTH. This width is the counter for SM particles heavier than a Higgs.

3) The investigation of HIGGS COUPLING WITH MATTER is necessary to obtain whether the observed particle is actually a Higgs of the SM or something else. It will be an essential test for the Higgs nature of quark masses and (as some alternative) possible SUSY Higgs.

If \( M_H < 150 \text{ GeV} \), one could investigate Higgs decay into \( \tau \bar{\tau} \) or \( c \bar{c} \) with SM branching ratios \( \sim 0.06 \) or \( 0.04 \) (cf. \( [34] \)). These opportunities need for new work with simulation.

If \( M_H > 2M_Z \), one can compare Higgs coupling with Z and W (by comparison of Higgs production via reaction \( \gamma \gamma \rightarrow H \rightarrow ZZ \) and via interference in \( \gamma \gamma \rightarrow W^+ W^- \) reaction).

If \( M_H \sim 2M_t \), the interference between QED process \( \gamma \gamma \rightarrow t \bar{t} \) and resonant one \( \gamma \gamma \rightarrow H \rightarrow t \bar{t} \) can be used to see the value of Higgs coupling with t-quark \( [35] \).

3) THE ANOMALOUS INTERACTIONS OF HIGGS The SM Higgs with \( M > 500 \text{ GeV} \) will be invisible in a photon–photon collision. Therefore, any Higgs signal at a PLC

\[4\] The modern activity about observation of such Higgs at the LHC shows very questionable possibilities here. The \( e^+ e^- 300 \text{ LC} \) will covers mass interval below \( 150 \text{ GeV} \), but it will be built later than PLC1.

\[5\] The amplitude of this interference is higher at lower \( s \), since W's from Higgs decay are polarized longitudinally and the fraction of longitudinal W's from \( \gamma \gamma \rightarrow W^+ W^- \) process decreases with \( s \).
Table 2: Higgs physics at various colliders

|                  | PLC1, $\sqrt{s} < 180$ GeV | PLC$_1$, next stages | $e^+e^- \text{ LC}$ | LHC |
|------------------|-----------------------------|----------------------|---------------------|-----|
| $80 < M_H < 150$ | discovery $(bb)$, $??$-study $(\tau\bar{\tau})$ | $??$ | discovery | $??$ |
| $150 < M_H < 180$ | discovery $(WW)$? | ?? | discovery | $??$ |
| $180 < M_H < 400$ | study | weakly | good | $??$ |
| $400 < M_H < 800$ | If anomalies? | | discovery | $??$ |
| $H^3$ vertex | weakly | good | $+$ | accuracy? |
| anomalies in Higgs sector | $\pm$ | | | |

In this region manifests the existence of either some heavier SM particles or nonstandard interactions of Higgs, having the scale about a few TeV [37, 15].

4 Gauge boson physics

Modern data show that the Standard Model is the theory of our world. Meanwhile both the checkings up of this theory in new areas and the observation of some (now unknown) features seem to be necessary. After LEP study of $Z$ peak, photon colliders will be the best laboratory for this aim.

The sketch of THE MAIN PROCESSES WITH W AND Z PRODUCTION at PLC within SM is given in refs. [38, 39]. The scale of these phenomena at PLC is given by the quantity $\sigma_W = 8\pi\alpha^2/M_W^2 \approx 81$ pb, which is the cross section of $\gamma\gamma \rightarrow W^+W^-$ process at high enough energies. This very process (together with $e\gamma \rightarrow W\nu$) determines PLC as $W$ factory with $10^6 \div 10^7 W$'s per year.

The cross sections of processes $e\gamma \rightarrow W\nu$ and $\gamma\gamma \rightarrow W^+W^-$ with their dependence on helicities of photon $\lambda_\gamma$ and electron $\lambda_e$ are considered in ref. [40]. The $e\gamma$ cross sections at $Ee\gamma < 200$ GeV and the $\gamma\gamma$ cross sections at $Ee\gamma < 300$ GeV are varied strongly with variation of photon helicities. The more detail study of this dependence taking into account finite $W$ width is desirable. Perhaps, this provides additional opportunity to see the admixture of gauge boson interactions or decays which violate $C\ P$ invariance. This dependence on photon polarization vanishes at large enough energies.

Besides, the process $e\gamma \rightarrow W\nu$ is switched on or off entirely with variation of electron helicity ($\sigma_{e\gamma} \rightarrow W\nu = (1-2\lambda_e)(\sigma + \lambda_e\tau$). This means, that this process is very sensitive to admixture of right–handed currents in $W$ coupling with matter.

The angular distribution of produced $W$’s for both processes is more favorable for $W$ recording than that in process $e^+e^- \rightarrow W^+W^-$. The $\gamma\gamma \rightarrow W^+W^-$ cross section tends fast to its asymptotic value $\sigma_W$. At large enough energies we have $\sigma_{e\gamma} \rightarrow W\nu =$
$\sigma_W / 8\sin^2 \Theta_W \approx 43 \text{ pb}$.

When the energy increases, the cross sections of a number of higher–order processes become large enough. The catalogue of such processes of third order in SM was obtained with CompHEP package [11], see Fig. 1. I will don’t enumerate all papers, devoted to separate processes here.

The different processes (and different kinematical regions for one process) are sensitive in different manner to various possible anomalous gauge boson interactions. Therefore, the comparative detail study of different processes provides opportunity to study various anomalies separately. The special work is necessary to present detail program in this field.

Among the processes of highest interest is the process $e\gamma \to eW^+W^-$ with high cross section. The large enough fraction of this cross section is given by region, which is very sensitive to the $\gamma ZWW$ interaction [12].

In fourth order processes we can see subprocesses with heavy gauge boson scattering. The SM cross sections for the processes $\gamma\gamma \to WWWW$ and $\gamma\gamma \to WWZZ$ are $\sim 0.3 \div 0.1 \text{ pb}$ [13]. The cross section of the process $e\gamma \to eWWZ$ is of the same order of value:

$$(\alpha/\pi)^2 \ln(s/m_e^2) \cdot \ln^2(s/4M^2_W) \sigma_{\gamma\gamma} \to W^+W^-.$$  

Some process of fifth and sixth order will be observable at high enough energies, for example, $e\gamma to e^-e^+WW$, $e\gamma \to e^+e^-\nu WZ$, $\gamma \gamma \to e^+e^-\mu\bar{\mu}WW$, etc.

| Table 3: Gauge boson physics at different colliders |
|--------------------------------------------------|
| parameters of W                                   | PLC will be W factories with $\sim 10^6 \div 10^7$ W’s per year |
| right hand currents in $W \to e\bar{\nu}$          | LHC (only $M_W$) $\to$ LEP200 $\to$ PLC |
| multiple $W$ production                           | PLC1 $\to$ PLC ($e\gamma \to W\nu$) |
| Testing of deep properties of QFT (quantization of theory with unstable particles) | PLC better than $e^+e^-\text{LC}$ and LHC |
| CKM matrix elements measuring                     | PLC only (necessary accuracy $\sim \alpha(M) \sim 10^{-3}$) |
| QCD effects in WW interactions                    | PLC better than $e^+e^-\text{LC}$ |
| Testing of EW SM perturbation theory, $\alpha \ln^2(s/M_W^2)$ summation | PLC2 TeV only |

4.1 Problems in gauge boson physics

Insertion of finite $W$ width

To describe gauge boson production with real final states of the $W$ decay, one should use the $W$ propagator near its physical pole. To avoid divergence, it is necessary to insert in this propagator the $W$ width $\Gamma_W$, for example,

$$\frac{1}{k^2 - M_W^2 - i\varepsilon} \Rightarrow \frac{1}{k^2 - M_W^2 - i\Gamma_W}.$$  

(2)
This simple substitution can violate gauge invariance and unitarity. The naive recipes used here results in inaccuracy’s $\sim (1 \div 3)\Gamma/M$. The more likely recipes (which unknown until now) should eliminate the above violations. Nevertheless, this requirement gives no unambiguous recipe. One can expect that the ambiguity of the result when using the different recipes, both unitary and gauge invariant, without genuine theory will be $\sim \alpha\Gamma/M (\sim 10^{-3} \text{ or larger})$, i.e. the accuracy of such recipes seems to be deficient for description of data. Therefore, the well–known fundamental problem of quantum field theory becomes of practical importance here (see e.g. [45]):

It is necessary to construct a genuine theory of unstable gauge bosons. The key place is in the quantization of unstable fields.

**Radiative corrections (RC)**

To understand the future data from PLC’s, the RC to the discussed cross sections should be calculated. These RC can be subdivided for 3 types: those caused by finite width of W and Z, those caused by initial state radiation, and the ”proper” RC.

(i) Corrections caused by the finite width of W or Z. Finite width results in some enlargement of the final phase space. This enlargement can be used to extract some parameters of W more precisely. For example, one can use the $e^+e^- \rightarrow WW$ process below threshold to obtain more precise values of the width and mass of W [40, 46]. The above discussion shows the ambiguity in such description of these parameters.

(ii) The RC, caused by the initial state radiation in the $e\gamma$ collisions are often calculated by the method from ref. [47]. These very large nonspecific RC can be treated as the nonmonochromaticity of the initial electron energy [48].

(iii) The ”proper” RC due to electroweak interaction are of more interest for they are sensitive to additional heavy particles or violations of the SM (cf. [49]).

In the study of real processes it is necessary to calculate the RC due to interaction of W decay products. The largest RC of this type are related to the strong interaction between quarks (jets) from the decay of different W’s. The Pomeronlike effects can intensify these RC at $s \gg M_W^2$.

**Some other problems at PLC’s**

Let us list some problems in gauge boson physics, which was not discussed above.

1) The underlying interactions could manifest itself as the deviations from the SM in some ANOMALOUS INTERACTIONS OF GAUGE BOSONS. These anomalies are described by some effective Lagrangian. The standard approach is to consider here operators of lower dimension – 4 and 6 (e.g. an anomalous magnetic moment, quadruple moment, etc.). Usually, these effects increase with energy, the larger energy is the better for their detection. Some results had been obtained for the $e^+e^-500 \text{ LC (including PLC)}$ [50, 51, 52].

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6 It appears here first as a practical one in particle physics. Indeed, the same problem for Z peak is solved for the unique object produced without other W’s or Z’s; therefore in this case the gauge invariant recipe is sufficient. The description of last stages of hadron reactions contains some phenomenological models; therefore, any contradictory recipe is suitable here. For $\mu$ and $\tau$, the $\Gamma/M$ ratio is less than the corresponding coupling constant $\alpha$.  
The values of anomalous coupling constants, which can be considered, are limited from below by condition, that the anomalous contribution into cross section should be larger than RC in SM (see Appendix for more details). At PLC we expect to meet these bounds.

2) One can look for THE POSSIBLE CP VIOLATION IN THE W BOSON DECAYS, e.g., $\text{BR}(W^- \rightarrow e^-\bar{\nu}) \neq \text{BR}(W^+ \rightarrow e^+\nu)$. In this problem, the additional opportunities should be considered, which given by the initial photon state with total helicity 0.

3) One can measure THE ELEMENTS OF THE CABIBBO–KOBAYASHI–MASKAWA MIXING MATRIX on the mass shell of $W$. Their comparison with those obtained in the update experiments (far from $W$ mass shell) can give an idea about their dependence on $W$ boson virtuality.

4) The STRONG INTERACTION IN HIGGS SECTOR seems to be very probable one at $\sqrt{s} \gtrsim 1$ TeV independent on Higgs mass, since the interaction Higgs t quark is strong one. It could manifest itself at PLC3 as new effects in gauge boson interactions, like resonances in the gauge boson systems, unusual energy dependence, multiple W production, etc. Its first signals could be obtained in the production of longitudinal W’s and Z’s. (For more details, see a number of papers, e.g., [54]). Therefore, this is a problem for gauge boson physics too.

The SM cross section $\gamma\gamma \rightarrow Z_L Z_L$ is small [29]. However, experience in pion physics permits us to expect here the large effects due to some heavy states (like $\omega$ in the $t$-channel for $\gamma\gamma \rightarrow \pi\pi$). The relatively large contribution from the transverse W loop has no analogy in the pion world.

At the large enough energies, one can expect to see the strong interaction of transverse W’s driven by the strong Higgs self–interaction. Where does this energy region begin?

5 New Physics

Two opportunities are considered, when we speak about New Physics effects — the discovery of NEW PARTICLES and NEW NONSTANDARD INTERACTIONS of known particles.

PLC’s provide the best place to discover many new particles — in comparison with other colliders, having similar energy. The reasons for this statement are:

1) The signal to background (S/B) ratio at PLC is often much better than that at hadron colliders (see in more detail ref. [17]).

2) The photons are "democratic" respective to all charged particles. Therefore, the analyses of new particles production have no additional ambiguities due to production mechanism at PLC (which exists in collisions with hadrons).[9]

3) The cross sections of charged particles production at $\gamma\gamma$ PLC are larger than those at $e^+e^-$ LC (see Fig. 2). Even if PLC luminosity is 5 times less than that for basic $e^+e^-$ LC

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[7] The value of this effect in the "most optimistic" case can run into $10^{-3}$ [53].

[8] One should remind in this respect that a number of modern limitations to masses of new particles were obtained with some additional hypotheses, which are often not so natural. For example, the modern limitation to a mass of leptoquark from HERA data was obtained, assuming its coupling with electron and quark, is not small. There are models, in which this $G_{\ell q}$ is of order of ratio of sum of mass, consisting leptoquark to a Higgs v.e.v. $v \approx 250$ GeV: $G_{\ell q} \sim S_{\ell q}(m_\ell + m_q)/v$. Here the $S_{\ell q}$ is the corresponding mixing matrix element. Therefore, the coupling of electron with some u or d or s quark should be very weak in such a model, and the corresponding leptoquark could not be seen at HERA even if it is light enough.)
(standard monochromatic variant), the number of produced pairs at $e^+e^-$ collider is no greater than that at $\gamma\gamma$ collider. Besides, this production in $\gamma\gamma$ collision decrease with energy more slow than that in $e^+e^-$ collision. This provides an opportunity to study new particles relatively far from threshold with a good enough rate. In this region, the decay products of these new particles are overlapped weakly. Therefore, theirs detailed study should become more feasible.

4) The $\gamma\gamma$ collisions produce often the pairs of identical particles with identical decays (e.g., $\gamma\gamma \rightarrow \tilde{\mu}\bar{\mu}$). This makes easier the analysis of events with missed $p_\perp$.

5) In contrast with hadrons, a photon is pointlike, its quark content is well known. Entire photon energy is used to see the small distance phenomena of interest.

6) In some cases $e\gamma$ collisions are preferable (for example, reactions $e\gamma \rightarrow e^*$, $e\gamma \rightarrow W\nu^*$, $e\gamma \rightarrow \tilde{e}\bar{\gamma}$.)

On the contrary, gauge invariance is constrained strongly interactions of matter with photons. Therefore, the effects of some new interactions are suppressed here. On the other hand, it means that the origination of observed effects would be separated easily.

The discovery potential of PLC for new particles and interactions was considered in numerous papers (see also reviews [13, 50]):

- SUSY particles [55]:
  
  \[ \tilde{W}^\pm, \tilde{Z} : \ e\gamma \rightarrow \tilde{W}\bar{\nu}, \ \gamma\gamma \rightarrow \tilde{W}^+\tilde{W}^- ; \ e\gamma \tilde{Z}\tilde{e} ; \ \tilde{P} \equiv \tilde{\ell}, \ \tilde{H}^\pm, \ \tilde{u}, \ \tilde{d} : \ \gamma\gamma \rightarrow \tilde{P}\bar{\tilde{P}}. \]

- Excited leptons and quarks [56]:
  
  \[ e^* : \ e\gamma \rightarrow e^* ; \ \ell^* : \ \gamma\gamma \rightarrow \ell^*\bar{\ell} ; \ \nu^* : \ e\gamma \rightarrow \nu^*W ; \ q^* : \ \gamma\gamma \rightarrow q^*\bar{q}. \]

- Leptoquarks [57].

- Charged Higgses.

- Composite scalars and tensors.

- Dirac–Schwinger monopoles with mass $\lesssim 10E$ [58].

- Invisible axion (from the conversion region) [7, 4].

- Higgs nonstandard interactions [37].

### 6 Main stages of PLC program

To see for discussed problems from more practical point of view, we consider briefly the opportunities of various stages of entire program for LC. We will point in this list the points only with the known now energy scale. Certainly, one should study hadron physics and hunt for new particles and interactions at all PLC’s.
6.1 PLC0 — Photon collider, based on SLC.

Stanford Linear Collider (SLC) – the sole Linear Collider, which works now, can provide a realistic test bed for a high energy PLC [12]. The characteristic energy for such – preliminary stage – PLC will be $E_{\gamma\gamma} \approx 70 \div 80$ GeV, and its annual luminosity can be $\sim 1 \text{ pb}^{-1}$ (or $\sim 100 \text{ pb}^{-1}$ if rather large variations in SLC design will be realized[9]).

These numbers show that such collider could be only used for the study of hadron physics and QCD. It will be the substantial step in comparison with modern studies at $e^+e^-$ colliders (which were discussed at this Workshop). The specific problems for this PLC are ([13]):

TOTAL CROSS SECTIONS, DIFRACTIVE PROCESSES, PHOTON STRUCTURE FUNCTION, JETS.

To use the potential of this PLC as whole as possible, the small angle detector is necessary.

6.2 PLC1 — with $e\gamma\gamma \leq 180 \div 190$ GeV

This stage PLC was proposed in [30]. It needs no positron beams, since this energy interval will be covered by LEP2.

1) HIGGS HUNTING AND STUDY will be the central idea of this stage PLC.

The discovery of Higgs boson with $M_H < 150$ GeV via $\gamma\gamma \rightarrow H \rightarrow b\bar{b}$ reaction at a PLC in a monochromatic variant demands about $3 \text{ fb}^{-1}$ integrated luminosity [22, 32]. Perhaps, it is possible to see Higgs decay to $\tau\bar{\tau}$ or $c\bar{c}$ in supermonochromatic variant? Perhaps, it is possible to discover Higgs with mass $150 < M_H < 180$ GeV via interference of $\gamma\gamma \rightarrow H \rightarrow WW$ process with QED process $\gamma\gamma \rightarrow W^+W^-$ [35]?

2) In the process $e\gamma \rightarrow W\nu$ (with $10^4 \div 10^5$ W’s per year – depending on beam energy) we will see the SINGLE W. The (Coulomb) interaction with other produced particles will be absent. In the almost all channels the interference with nonpole diagrams will be very small, i.e., problems with gauge invariance at incorporation of total width will be also absent. Therefore, these experiments will give us more precise and unambiguous values for W PARAMETERS.

This process is switched on or off with variation of basic electron helicity. Therefore, it provides the best place for THE TESTING OF ADMIXTURE OF RIGHT–HANDED CURRENTS IN THE $W\nu$ VERTEX (in quite other point than modern $\mu$ decay).

3) The $\gamma\gamma \rightarrow W^+W^-$ process near the threshold depends strongly on photon helicities. Its study with finite W width should be made. Perhaps, these polarization phenomena are sensitive to some anomalous gauge boson interactions?

6.3 PLC2 — based on $e^+e^- 500$

1) This stage PLC begin new era — era of PLC as a SPECIAL COLLIDER FOR A STUDY OF GAUGE BOSON PHYSICS. Both $\gamma\gamma$ and $e\gamma$ PLC’s become W factories with about $10^6 \div 10^7$ W’s per year. The entire set of problems related to EW SM bosons will be solved here with high precision.

2) The study of t QUARK PRODUCTION near the threshold (in the states with different polarizations).

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[9] I am grateful to V. Balakin, who tell me about this opportunity.
3) HIGGS HUNTING AND STUDY if $M_H < 400$ GeV.

6.4 PLC3 — with energy up to 2 TeV

1) The main problem for SM physics here are the study of both the basic processes $\gamma\gamma \to W^+W^-$, $e\gamma \to W\nu$ with high accuracy and processes of the third and fourth order (multiple gauge boson production), in particular $e\gamma \to eWW$. In the processes $e\gamma \to eWWZ$, $\gamma\gamma \to W^+W^-$ $WW$, $\gamma\gamma \to W^+W^- ZZ$, one can study subprocesses with heavy gauge boson scattering.

2) Hunting for effects from strong interaction in the Higgs sector.

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Appendix. Anomalies and RC

The RC with anomalies are divergent. To kill these divergencies, one should introduce counter-terms of higher orders. Therefore, the Lagrangian with operators of dimension, e.g., up to 6 should be added by items of 8-h order, etc. (That is standard picture for the nonrenormalizable theory). It means that the calculation of RC with anomalies is beyond the accuracy of basic approximarion with effective Lagrangian.

In practice, one can introduce some formfactors of anomalies. The values of RC depend on the scale of these formfactors. Therefore, the effective Lagrangian should be added by some additional prescriptions that include both the scales of anomalies and the relation between these scales in different ”directions”. Besides, some additional constant items from operators of higher degrees and dimensions can vary results strongly.

Therefore, (i) the RC are out of accuracy of approximation used when anomalous interactions taken into account. The calculations with anomalies have sense if only these anomalies are large enough to standard RC could be invisible in comparison with anomalies. (ii) The calculation of RC with anomalies could have sense if only we know much enough about the structure of underlying theory, for which the EW theory is low energy limit.

Figure captions

Figure 1: The cross sections of some processes in $\gamma\gamma$ and $e\gamma$ collisions.

Figure 2: The cross sections for charged pair particles (P) production in $\gamma\gamma$ and $e^+e^-$ collisions, $\sigma = (\pi\alpha^2/M^2)f_P(x)$, where M is particle mass, $x = s/4M^2$. The functions $f_P(x)$ are shown for P=S (scalars), F (fermions) or W (vector gauge bosons).
\( \gamma \gamma \) and \( \gamma e \) processes (\( \sigma_{\text{tot}}, \text{tree level} \))

Compgen 2.4
Figure 2.