Two photon physics. Personal recollection

Ilya F. Ginzburg $^{a,b}$

$a$ Sobolev Inst. of Mathematics, av. Koptyug, 4, Novosibirsk, 630090, Russia
$b$ Novosibirsk State University, Pirogova str., 2, Novosibirsk, 630090, Russia
e-mail: Ginzburg@math.nsc.ru

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Abstract

The term two–photon processes is used for the reactions in which some system of particles is produced in collision of two photons, either real or virtual. In the study of these processes our main goal was to suggest an approach, allowing to extract from the data information on proper two–photon process separating it from mechanism which responsible for the production of photons.

Here I present my view for history of two–photon physics. I don’t try to give complete review, concentrating mainly on works of our team (which cover essential part of the topic) and some colleagues. My citation is strongly incomplete. I cite here only papers which were essential in our understanding of the problems. The choice of presented details is the result of my discussions with Gleb Kotkin and Valery Serbo.

1 Prehistory

• 30-th-60-th. High order processes of QED.

The processes which called now as two-photon ones were discussed after discovery of positron by Anderson (1932), when a necessity is appeared to find out the process in which positrons are generated. In 1934 studying $e^+e^-$ pair production in collision of ultrarelativistic charged particles $A_1$ and $A_2$ Landau and Lifshitz [1] have ascertained that the two photon channel of Fig. 1 is dominated in this reaction. They calculated the cross section of the process $A_1A_2 \rightarrow A_1A_2 e^+e^-$ in the leading logarithmic approximation. Almost simultaneously Bethe and Heitler [2] considered $e^+e^-$ pair production by photon in the field of a nuclei, $\gamma A \rightarrow e^+e^- A$. These processes contain subprocess $\gamma\gamma \rightarrow e^+e^-$, like Fig. 1.
The leading log result of [1] was improved by Racah [3] who have calculated the corresponding cross section with an accuracy \( \sim (M/E)^2 \) where \( E \) and \( M \) are energy and mass of incident nuclei. The process \( \gamma A \rightarrow e^+e^- A \) was included in the theory of wide atmospheric showers in cosmic rays [4] and in the description of the energy losses of fast muons in matter [5].

The hadron production by two photons was considered for the first time by Primakoff [6] suggested in 1951 to measure the \( \pi^0 \) life–time in the reaction \( \gamma A \rightarrow \pi^0 A \). The new interest to such processes was appeared when the construction of \( e^+e^- \) colliders become close to a reality. In 1960 Low [7] pointed out that the \( \pi^0 \) life–time can be measured also in the \( e^+e^- \rightarrow e^+e^- \pi^0 \) process. Simultaneously the two-photon reaction \( e^+e^- \rightarrow e^+e^- \pi^+\pi^- \) (for point–like pions) was considered [8]. However, the calculated rates seemed unmeasurable small and no further work was done at that time.

In 1969–1970 new generation of papers appeared with the goal to cover possible set of final states of \( e^+e^- \) colliders as complete as possible. Authors considered \( e^+e^- \) collisions with final states \( e^+e^- \pi^0 \), \( e^+e^- \eta \) and \( e^+e^- \pi^+\pi^- \), \( e^+e^- K^+K^- \) (in the latter two cases for the point-like pions and kaons) [9]. Some of these processes for point-like hadrons just as \( e^+e^- \rightarrow e^+e^- \mu^+\mu^- \) were considered in more detail by Paris [10] and Novosibirsk BINP [11] groups. These papers did not provoke high interest in particle physics community since they were in line with numerous calculations of various processes at \( e^+e^- \) colliders, having small cross section (for the contemporary machines). They don’t try to suggest method of extraction of information about \( \gamma\gamma \rightarrow \pi\pi \), \( \gamma\gamma \rightarrow KK \) subprocesses.

- End of 60-th. Popular problems.

In the 60-th the study of different processes of hadron collisions was of main interest for community. In addition to the collisions initiated by proton and deuton beams, the processes, initiated by pion beams, kaon beams, antiproton beams, hyperon beams (experiment and theory) were of great interest for community providing new types of final states and new field for the Regge theory developed at that time. In this respect the study of deep inelastic \( ep \) scattering was a hot point in particle physics provided new type of collided hadron (photon) with variable mass and helicity.

One more popular field of studies was the coupled channel problem in the low energy scattering – description of \( \pi\pi \rightarrow \pi\pi \) and \( \pi\pi \rightarrow KK \) scattering.
Two photon processes at $e^+e^-$ colliders

Novosibirsk. 1969-1970.

Once in the winter 1969-1970 my PhD student Victor Budnev was informed me about observation in Novosibirsk BINP the process $e^+e^- \rightarrow e^+e^- e^+e^-$ in the group including my former student Vladimir Balakin [12], [13]. Relatively high cross section of this 4-th order process of QED was explained by small virtuality of photons coupled with the initial and scattered electrons. I immediately understood that similar mechanism is suitable also for the production of hadron systems, not only for $e^+e^-$. During few months I reported in different groups in the Moscow institutes and in the JINR about new opportunity found by experimentalists of BINP. My first proposal was to study process $\gamma\gamma \rightarrow \pi\pi$ using the methods developed for the $\pi\pi \rightarrow KK$. I had not received a response for these proposals. And once someone told me – "you know, you find a new opportunity".

I understood that high energy $e^+e^-$ colliders really provide us by opportunity to study new type of processes, yet unknown for community – the production of particles in collisions of two photons (I had in mind mainly production of hadrons). The study of such process continues investigations of deep inelastic $ep$ scattering to the new region of parameters and final states with two new variable parameters – virtualities of each photon.

I invite for writing paper V. Budnev and V. Balakin. We tried to present the paper which contained the description of processes as well as the method of extracting the information from the data.

Fortunately, I had no experience in the QED calculations and did not know the Weizsäcker-Williams method (to the moment, mainly qualitative descriptions were spread). We started our calculations from Feynman diagrams, from the very beginning. This way allow us to skip inaccuracies widely spread in the description of similar processes even many years later.

We understand that the calculation of cross sections is more preferable than calculation of amplitudes. Our important point was to introduce useful objects for investigation, similar to those in $ep$ DIS but more physically motivated. We find that the differential distribution is roughly $\frac{d\sigma}{dq_1^2 dq_2^2} \propto \sigma_{exp}^\gamma (s, q_1^2, q_2^2)$ (more accurate form is (1)) with kinematically determined lower limits $q_{min}^2 \sim m_e^2 (m_e/E)^2$. In accordance with experience in the hadron physics, we understood that cross section $\sigma_{exp}^\gamma$ decreases with growth of photon virtualities like form-factor. The scale of this decreasing $\Lambda$ depends on the nature of produced system. For the most of processes of hadron production $\Lambda \sim m_\rho \sim 770$ MeV, for the production of kaons $\Lambda \sim m_\phi \sim 1$ GeV, for the production of $\mu^+\mu^-$ pairs $\Lambda \sim m_\mu \sim 100$ MeV, for the production of discovered later charmed particles $\Lambda \sim m_\Psi \sim 3$ GeV, etc. In our estimates we approximated $q_i^2$ dependence by step function $\theta(\Lambda^2 - q_i^2)\theta(\Lambda^2 - q_i^2)$.

In the result we found that the main contribution into the cross section...
appears from the region of small photon virtualities $q_i^2 < \Lambda^2$. In this region for the most of interesting processes the cross section $\sigma_{\gamma \gamma}$ coincides with its mass shell value $\sigma_{\gamma \gamma}(\hat{s})$. The description of differential cross sections within this region has high accuracy $q^2/\Lambda^2$, in the description of total cross sections it turns out to the accuracy $\sim 1/\ln(\Lambda^2/q^2) \sim 1/\ln(\Lambda^2 E^2/m_e^4) \lesssim 0.03$.

We found here also estimate for high energy total cross section

$$
\sigma_{\gamma \gamma \to \text{hadrons}} \sim \sigma^2(\gamma p)/\sigma(pp) \sim 0.3 \mu b,
$$

it is in accord with modern (2015) measurements.

Based on all these estimates, we found that the experiments at $e^+e^-$ colliders open new experimental field in the particle physics – the possibility to extract from the data an information about process $\gamma^* \gamma^* \to \text{hadrons}$, etc, and present necessary algorithm. We submitted our paper to the Pis'ma ZhETF at May 4, 1970 and it was published there (in Russian) at June 5, 1970 [14], Fig.2, English translation (JETP Lett) appeared 1 or 2 months later; the abstract of this paper was published (in English) on July in the book of abstracts for XV Rochester (in Kiev) 1970 conference (26.08-04.09) [13] where paper was reported by Budnev[3].

![Figure 2: V.E. Balakin, V.M. Budnev, I.F. Ginzburg, "Possible experiment of hadron production by two photons from threshold to extremely high energies", published June 5, 1970, submitted May 4, 1970, Pisma Zh.Eksp.Teor.Fiz. (in Russian), transl. in JETP Lett.](image)

The paper contains also the equations for extraction of two-photon cross sections from the data at small electron scattering angles in the form which is

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2I cannot took part in this conference since I was in the hospital after a car accident in the July in Yakutia.
used for this aim up to now,

\[
\frac{d\sigma}{dE_1 dE_2 d\Omega_1 d\Omega_2} = \left( \frac{\alpha}{2\pi^2} \right)^2 \frac{1}{q_1^2 q_2^2} \frac{E_1 E_2 (E_2^2 + E_1^2)(E_2^2 + E_2^2)}{(E - E_1)(E - E_2)} \sigma_{\gamma\gamma}^{\gamma\gamma},
\]

\[
\sigma_{\gamma\gamma}^{\gamma\gamma} = \sigma_T^T + \varepsilon_1 \sigma_S^ST + \varepsilon_2 \sigma_T^S + \varepsilon_1 \varepsilon_2 \sigma_{SS} + \varepsilon_1 \varepsilon_2 \tau \cos 2\phi / 2 + \varepsilon_3 \tau ST,
\]

\[
\varepsilon_1 = \frac{2E E_1}{E^2 + E_1^2}, \quad \varepsilon_2 = \frac{2E E_2}{E^2 + E_2^2}, \quad \varepsilon_3 = \frac{\varepsilon_1 \varepsilon_2 (E + E_1)(E + E_2)}{32 E \sqrt{E_1 E_2}} \cos \phi.
\]

\(E\) and \(E_i\) are the energies of initial and scattered electrons, \(\phi\) is the angle between scattering planes of electrons, other notations was not practically changed during 45 years.) The numerical estimates of anticipated cross sections were done and it was found that the observable cross section grows fast with beam energy. Besides, the sketch of experimental program was formulated. More detail calculations were published soon \[15\].

The paper \[14\] contains also the Balakin’s proposal to supplement future detectors by transverse magnetic field in the collision region. It allows to detect the scattered forward electrons for the detail observation of \(e^+e^- \rightarrow e^+e^- f\) process. This idea was realized on detector MD-1 of BINP \[16\].

- **Brodsky, Kinoshita, Terazawa, 1970.** 3 month after publication \[14\] S. Brodsky, T. Kinoshita & S. Terazawa have submitted to Physical Review Letters their paper, published October 5, 1970 \[17\] (Fig.3). They consider two-photon production of \(e^+e^-, \mu^+\mu^-, \pi^0, \eta\) and point-like \(\pi^+\pi^-\) in \(e^+e^-\) and \(e^-e^-\) colliding beams. They found that these cross sections grow with beam energy and described some features of the angular distributions of produced pions. Analogously to \[14\], these results had shown that two-photon physics provides a large field for theoretical studies and experimentation but without discussion of method of extraction information about two-photon subprocess. Unfortunately they used the Weizsäcker–Williams method without analysis of its applicability, with essential mistake. At the language of virtualities, they did not take into account the decreasing of cross sections of subprocess with virtual photons due to formfactor, and used in fact for the scale \(\Lambda\) mentioned above, the kinematical limit \(\Lambda \sim E\). It enhances spectra of equivalent photons by factor about 2 for each photon. Many authors of subsequent papers reproduced this inaccuracy (I have met papers with such mistaken spectra even in the end of 90-th).

- **First experiments.**
In 1971 VEPP-2 (BINP, Novosibirsk \[12\], \[13\]) and in 1972 ADONE (Frascati, Italy) \[18\] reported about the observation of \(e^+e^- \rightarrow e^+e^- e^+e^-\) process.

- **1970-th.**
The papers \[14\], \[17\], \[12\], \[18\] open door for stream of publications devoted to two-photon physics.

Our group continue basic analysis to understand main features of two-photon processes which are independent on the nature of produced system. In this stage
the important member of our team becomes Valery Serbo. The first results were summarized in review [19] containing all necessary equations for data preparation and set of equations useful for different estimates. It contains also detail description of equivalent photon (Weizsäcker–Williams) method, including estimate of its accuracy in different situations. In 1974 we did not think about possibility of longitudinal electron polarization at $e^+e^-$ storage rings and did not consider this case in basic equations. This lacuna in [19] was closed in [20].

The physical problems related to the separate $\gamma\gamma$ processes, details of data extraction, backgrounds and QED processes were discussed by many authors at that time. Most of papers of 70-th devoted to hadron physics in $\gamma\gamma$ collisions were reproductions of results and ideas considered earlier for other hadronic systems. Some of these results were reported in review [19].

In 1973 series of conferences devoted to these processes was started in Paris as the International Colloquium on Photon-Photon Collisions at Electron-Positron Storage Rings. I cannot took part in the eight first conferences since Soviet state stopped my attempts despite the regular invitations. My first visit was in 1992 at the 9-th San Diego conference from modern Russia.

The real experimental activity in this field started, in fact, in 1979 by SLAC experiment in which it was demonstrated that two-photon processes can be suc-
cessfully studied at the modern detectors without recording of the scattered electron and positrons – via the separation of events with the small total transverse momentum of produced system and effective mass $\ll 2E$ \cite{21} (this approach was initiated by V. Telnov \cite{22}). After this work, the experimental investigation of two-photon processes became the essential component of physical program at each $e^+e^-$ collider. One of the first review of the experimental data has been summarized in the book of Kolanoski \cite{23}. Many results obtained till now are collected in the Particle Data Review \cite{24}.

At May 2 of 1980, Victor Budnev died during rafting. Since that our two-photon theoretical team from Sobolev IM-NSU consists of three key persons – Valery Serbo, Gleb Kotkin and me.

3 Photon colliders

• Important fact from 60-th. In 1970 we read with great interest about photo-nuclear experiments in SLAC \cite{25}. The laser photons collided with electrons of SLAC beam producing via backward Compton scattering the high-energy photons. The latter have the energy determined by production angle. Then these tagged photons collided with fix-target. Thus it is appeared an opportunity to study collisions of photons having high and precisely known energy with proton. The typical conversion coefficient (ratio of number of high energy photons to the number of incident electrons) was about $10^{-7}$. The typical photon energy was about 10% from an initial electron energy. (After 1981, we were informed about another similar experiments.)

• Working group at Workshop 1981. Basic idea.

In the winter 1980-1981, BINP was organized the first Workshop devoted to the Linear $e^+e^-$ colliders (LC) with beam energy $E = 100$ GeV, named as VLEPP. At this Workshop I presented the review about two-photon physics. I concluded there that the two-photon option at $e^+e^-$ colliders will be the essential part of physical program at LC but not central point there, these studies will give substantial supplement to the future hadron and $e^+e^-$ data with improved values of parameters but without discovery of new phenomena of the first line (except two points discussed in sect. 4).

During discussions of the working group at two-photon section Valery Telnov proposed a very new idea.

In the LC each electron is used only once. Therefore, one can try to convert almost each electron into the high energy photon.

If we can do it, one hope to obtain $\gamma\gamma$ and $e\gamma$ collisions of real photons with luminosity about 1000 times more than for $e^+e^-$ collider and with considerable higher energies.

Unfortunately, the particular ideas suggested for realization of this proposal did not look very perspective. We discussed there (i) bremsstrahlung on a
solid target; (ii) the radiation in the undulator (wiggler); (iii) beamstrahlung radiation in the collision with strong electromagnetic field of collided beam.

Common feature of these proposals giving large number of produced photons was very soft energetic spectrum of these photons, large background and relatively wide angular distribution. These roads had been recognized as unpromising in the discussion of the working group.

At the end of discussions in the working group, Gleb Kotkin proposed to consider the laser photon backscattering on the electron of LC beam in spirit of forgotten ideas of 60-th [25]. I mentioned this proposal among others unpromising ideas in the final report of the working group. This idea was accepted by participants with big scepticism. They referred to the mentioned experiments (and other experiments, known to them) in which the photon energy was much lower than $E$ and the corresponding conversion coefficient was extremely small. Nevertheless, Serbo and me asked Kotkin to discuss with laser experimentalists this opportunity. In one or two days he informed us that experts consider the necessary laser flash energy to be unacceptably high (some orders of magnitude higher than that of existed lasers). We were impressed that the intense high energy photon beam is only a dream.

- **Laser photon backscattering. First proposal.**

The idea of laser backscattering looked very attractive for us (GKS). We understood that in our case the kinematical properties of obtained photons will be better than in old works, in particular, the photons will move mainly along initial electron direction and their energy will be high enough.

Few days after Workshop during our walking with Serbo I suggested: "Let us check statements of Gleb" (we know that he may be impressed by the opinion of a good person and give up after the first objection). During walk we estimated necessary laser flash energy. Our estimate was very simple. We were known the size of electron beam of VLEPP near the collision point $S$. For complete conversion of electrons to photons the laser target should be opaque for electrons. Therefore, the necessary number $N$ of laser photons in flash is $S/\sigma_C$, where $\sigma_C$ is Compton cross section. For the first oral estimate we took for $\sigma_C$ the Tomson limit value. For the laser photon energy $\omega_o \sim$ few eV (visible light) we estimated the necessary laser flash energy $\omega_o N \sim 10$ J. This value seemed realistic for us. One half hour later Serbo at home reproduced this estimate with pen.

After that we three were connected with laser specialist Folin about possible type of laser suitable for our problem. He showed us laser from neodimium glass or garnet with laser photon energy $\omega_o = 1.17$ eV (*this choice turned out to be the best up to now*). He informed us about existence such lasers with the necessary flash energy and repetition rate (about 100 Hz) – separately. He told us that with suitable budget even middle laser group can construct laser with necessary flash energy and repetition rate for about 3 year. We understood that the desirable conversion can be possible.

The scheme of $e \rightarrow \gamma$ conversion was evident for us from the very beginning (Fig. 4). At the conversion point $C$, preceding the interaction point $IP$, the electron ($e^-$ or $e^+$) beam of basic Linear Collider (LC) meets the photon flash
from powerful laser containing photons $\gamma_0$, having energies $\omega_0$ (We neglect below difference of the angle $\alpha_0$ in Fig. 4 from 0.). The Compton backscattering of laser photons on electrons from LC $\gamma_0 e \rightarrow \gamma e$ produces high energy photons $\gamma$, having energies $\omega$, with energy spectrum limited by the kinematically determined upper limit $\sim E$. With the suitable choice of laser one can obtain the photon beam with the photon energy close to that of the basic electron. The ratio of number of high energy photons to that of electrons – the conversion coefficient $k \sim 1$.

To describe phenomenon we introduce variables $x = 4E\omega_0/m_e^2$ and $y = \omega/E$, so the squared Compton cms energy $s_C = (x+1)m_e^2$. Simple kinematic calculation showed that $y$ is limited from above by quantity $y_m = x/(x+1)$. Using the well known QED results for the considered case, we found that the energy spectrum of photons is concentrated near upper limit $y_m$, Fig. 5.

We were lucky with the numbers. Indeed, at the considered electron energy $E = 100$ GeV the parameter $x \approx 1.8$. Therefore, the maximal photon energy is equal to $\omega_m = 0.64E$ (while at earlier experiments, for example, at $E = 10$ GeV we had $x = 0.18$ and $\omega_m = 0.15E$, as what mentioned by participants of Workshop. The choice of lasers with reasonable high power flash allows in principle to reach conversion coefficient $\sim 1$, in contrast with $10^{-7}$ in experiments [25].

Since cm energy of $\gamma_0 e$ system is $m_e \sqrt{x+1}$, the transverse momentum of produced photon is $\lesssim m_e \sqrt{x} \lesssim 1$ MeV, and the photon escape angle $\theta$ is typically very small ($\sim m_e/E$) and depends on the escape angle as $y = y_m/(1+(\theta/\theta_0)^2)$, where $\theta_0 = m_e \sqrt{x+1}/E \lesssim 10^{-5}$. Therefore, the produced photons move almost along momenta of incident electrons and focus approximately in the same spot, as it is expected for electrons without laser conversion. Hence, the total luminosity provided by these photons will be close to that expected for initial $e^+ e^-$ or $e^- e^-$ collision. And the repetition rate for VLEPP project (100 Hz) seemed realistic for laser community.

In the IP the obtained photon beam collides with either opposite non-converted electron beam ($e\gamma$ collisions) or with photon beam ($\gamma\gamma$ collisions). Later on this scheme was called Photon Linear Collider — PLC.

In few days we reach complete understanding. At this stage Valery Telnov
joined us. It became clear that the opportunity is realizable and the paper with the corresponding proposal should be written as soon as possible. Our joint studies were published in Refs. [26, 27, 28].

We develop together the concept of the differential luminosity spectrum. It is given by convolution of individual photon spectra with geometric factor determined by the energy dependent angular spread. At the shift of conversion point C from the interaction point IP on the distance $b$ (Fig. 4), the photons of smaller energies spread for more wide region, and their contribution into luminosity become relatively lower, i.e. total luminosity decreases, but luminosity spectra become more monochromatic – quality of $\gamma\gamma$ collisions improves, Fig. 6 (L. Barkov suggested us to underline this fact.).

The dependence of luminosity spectrum on the distance $b$ for the case of the round electron beam is determined by parameter, expressed via the radius of this beam $\sigma$ in the IP for the case without conversion:

$$\rho = b m_e/(\sigma E).$$  \hspace{1cm} (2)

- The important remaining problem is the following: The length of electron bunch is finite. Within this length it is necessary to provide the density of laser photons sufficient for conversion. We understood that the density of laser flash decreases with the growth of distance from the focal plane. Kotkin suggested to use the Gaussian laser beams providing the maximal length of region of highest density of photons. Simple estimate gave the optimistic result. Serbo confirmed it by direct calculation with these beams. It transformed our preliminary estimates into reliable calculation.

In these papers we suggested to remove residual electrons from IP by magnetic field $\sim 1$ Tl, acting between conversion point and IP. 10 years later Telnov [29], [30] offered to abandon the use of the magnetic field.

- We note in this basic paper that the quality of $\gamma\gamma$ collisions (degree of monochromaticity) improves with increase of $x$. However, with the growth of $x$ the new phenomenon stops improvements. At large enough $x$ the number of output high energy photons is diminishes due to their death in the collisions with laser photons from the tail of laser flash, produced $e^+e^-$ pairs. Therefore, the "optimal" laser photon energy is limited from above by the threshold of $\gamma_0\gamma \rightarrow e^+e^-$ process $x > 2(1 + \sqrt{2}) \approx 4.8$ (for the considered laser at $E = 250$ GeV we have almost optimal $x = 4.5$).

In two or three months after sending of preprint [26] in different centers including SLAC, we receive preprint [31] with similar in form proposal for $e\gamma$ collisions but with incorrect estimate of necessary laser flash energy. After our message pointing this inaccuracy author stops his activity.

The first journal publication [27] meet unexpected objection of deputy editor of JETP Letters – "publication is unsuitable since necessary lasers don’t
exist now”. The overcome of this unfair objection delays publication for 4 or 5 months.

- Polarization.

During Workshop we have learned about the possibility to obtain longitudinally polarized electrons in the project of LC. Laser light is easily polarized.

We known that the polarization effects can give only little changes for high energy hadron and $e^+e^-$ collisions. We believed that the same is also true for the $\gamma\gamma$ collisions. As a result, the study of such effects at the $\gamma\gamma$ collisions looks for us as useful but not important problem.

Nevertheless, our theory group (GKS) started to calculate the polarization effects. The first analysis gave us the surprising result. The energy spectrum of photons changes strongly for longitudinally polarized collided particles. This spectrum depends on the product of longitudinal polarization of electron (helicity) $\lambda_e$ and degree of laser circular polarization $\lambda_L$. At $2\lambda_e\lambda_L = -1$ the number of photons with the maximal energy is almost doubled as compare with the case of nonpolarized photons. On the other hand, at $2\lambda_e\lambda_L = 1$ photons with the maximal energy almost disappear (see Fig. 7). (The total cross section depends on polarization weakly at $x \lesssim 8$).

This observation was the reason for more detail study of problem. First, we observed that the circular polarization of laser photons is transferred to that of high energy photons $\lambda$. At $y = y_m$ we have $\lambda = -\lambda_L$ due to angular momentum conservation. At smaller $y$ value of $\lambda$ decreases, depending on both $y$ and the parameter $2\lambda_e\lambda_L$ for the incident beam. Therefore, it is useful to consider two different $\gamma\gamma$ luminosities, dependent on the initial laser photon polarization – the luminosity $L_0$ for high-energy photons having identical helicity (total helicity of final state $\lambda_1 - \lambda_2 = 0$) and $L_2$ for photons having opposite helicity (total helicity of final state $|\lambda_1 - \lambda_2| = 2$). At the suitable choice of initial helicities $L_0 > L_2$ (see Fig. 8).
The natural next problem was to study transverse polarization of photons. To the moment we did not know detail equation for Compton effect with all polarization. Besides, at the subsequent stage we meet important technical difficulty. The scattering planes, which are useful for description of transverse polarizations in the individual Compton process, are different for each Compton scattering. In the description of beam polarization the suitable averaging becomes necessary. Some delicate effects appear at this averaging. My recent PhD student Shimon Panfil took part in the corresponding calculations. The results were published in [32]. These complete description of polarization phenomena was presented in the paper prepared together with V. Telnov [33].

Let us summarize some results of this study for collision of longitudinally polarized electron beam and polarized laser beam. The photons with the highest energy \( y \sim y_m \) can be made circularly polarized with high degree of polarization using the circularly polarized laser light. Degree of this polarization increases with the growth of \( \rho \). The sizable transverse polarization of high energy photons can be obtained using the transversally polarized laser light, but only at moderate \( x < 2 \) and \( y \lesssim y_m/2 \). Degree of this polarization is not high and it decreases with the growth of \( \rho \).

The papers [28] and [32], [33] gave the complete description of basics of PLC. Beginning from 90-th many physicists considered different problems related to construction of PLC, but in fact these investigations added some details which changed basic results only weakly.

After these basic researches, our team (GKS) studied the physical processes at PLC with some works devoted to PLC itself, while Telnov concentrated efforts on the technical problems [30]. His activity in the various audiences ensured the inclusion of PLC mode in all projects of LC’s. The challenges for the PLC project were given by strong increasing of repetition rate as compare with the original VLEPP project, strong decreasing of beam size of LC and corresponding electromagnetic field of laser bunch, choice of geometry of collision, etc. Telnov answered to the most of these challenges with the goal to obtain the highest \( \gamma \gamma \) luminosity of the best quality.

Beginning from 90-th Photon Collider become substantial part of Linear Collider projects [34], [35].

- **The attempt to use infrared lasers. Nonlinear QED effects.** The next problem interested for us after first studies was the following.

  At \( E = 100 \text{ GeV} \) we have \( x \approx 1.8 \) which is far from optimal value \( x \approx 4.8 \).

  \textbf{How to obtain photons with higher energy?}

  We did not know about perspectives to construct powerful laser with photon energy about \( 2.5 \div 3 \text{ eV} \) which give necessary \( x \). The using of a free electron laser with the regulated frequency demands one more complex equipment. However, another idea looks attractive for the first glance.

  We knew about the very powerful gaseous laser with \( \omega_o \approx 0.2 \text{ eV} \) (e.g. on \( \text{CO}_2 \)) and good repetition rate. Therefore, it seemed attractive to use such laser with the very high flash energy. In this case the laser photon density will be so high that the typical process will be not the ordinary Compton scattering, but
the collision of an electron with a few laser photons simultaneously. It will be the non-linear QED (NQED) process like \( e + 5\gamma_o \rightarrow \gamma + e \) (see \( \text{[36]} \) for the basic description). Our first naive expectation was that in this way one can reach necessary high energy of the final photons. Kotkin, my PhD student Polityko and me consider this problem\(^3\). We found that the desirable parameters can be obtained on the existent lasers. Nevertheless, the real situation appeared far from our expectations due to new effects in the strong electromagnetic field. These effects are determined by the parameter

\[
\xi^2 = \frac{e^2 F^2}{(mc\omega_o)^2} = \frac{4\pi\alpha \hbar}{m^2 c\omega_o n_L}.
\]

Here \( F \) is electric field strength in the laser wave and \( n_L \) is the laser photon density in the conversion region. At low and moderate \( \xi \) the probability of process with simultaneous collision of \( k \) laser photons \( e + k\gamma_o \rightarrow \gamma e \) is proportional to \((\xi^2)^k\) (with small numerical factor). However, the transverse motion of electron enhances its effective mass as \( m^2 \rightarrow (m^*)^2 = m^2(1 + \xi^2) \). The maximal photon energy decreases as \( y_m = kx/(1 + kx + \xi^2) \). At \( \xi \gg 1 \) the new parameter \( \chi = \xi \) becomes important. At \( \chi \gg 1 \) the energy distribution of produced photons is roughly similar to that for virtual photons \( \text{[37]} \).

As a result, at any \( \xi \) the fraction of photons with really high energy will be very low, therefore, this approach is unsuitable for construction of PLC.

20 years later D. Ivanov, G. Kotkin and V. Serbo presented the complete description all polarization effects in the non-linear Compton scattering which is used now for simulation of high-energy photon production in the conversion region \( \text{[39]} \).

- Measuring and simulation of luminosity.

In the papers \( \text{[26]}-\text{[28]} \), \( \text{[33]} \) we noted that the future luminosity distributions will differ from those, calculated in our papers, and experimental calibration is necessary. We had in mind corrections obliged by non-round geometrical form of electron bunches, rescatterings and other processes in the conversion and collision regions. We also think about inaccuracy in the aiming of beams. Telnov present simulation of all effects except inaccuracy in the aiming and to publish "realistic spectra of luminosity" \( \text{[40]} \). The method for measuring this distribution via processes \( \gamma\gamma \rightarrow e^+e^-, \mu^+\mu^- \), \( e^+e^-\gamma, \mu^+\mu^-\gamma, e^+e^-\mu^+\mu^- \) was presented by Serbo, Telnov et al. in \( \text{[41]} \).

- Flat electron beams.

In modern projects the electron beam for LC will be very flat (in the would be interaction point this beam presents ellipse with half-axes \( \sigma_x \) and \( \sigma_y \), where \( \sigma_x/\sigma_y \lesssim 100 \)). It leads to changes in the luminosity spectra for \( \gamma\gamma \) collisions, especially in low energy part. In the paper \( \text{[42]} \) Kotkin and me consider the high

\(^3\)Simultaneously we consider production of \( e^+e^- \) pairs in the NQED processes like \( e + 5\gamma_o \rightarrow e^+e^- + e \). This process can be used as the signal of observation of NQED processes \( \text{[38]} \).
energy part of these spectra (which in addition weakly changes by rescatterings). We found that this high energy part with good accuracy is described by the same equation as for the round beam with the natural replacement of $x$ to

$$
\rho^2 = (b/(E/m_e)\sigma_x)^2 + (b/(E/m_e)\sigma_y)^2.
$$

(4)

**The case $x > 4.8$.**

The most suitable modern lasers with neodymium glass or garnet allow to realize the basic scheme in its pure form only for the electron energy $E \leq 250$ GeV (the first stage of ILC). At $x > 2(1 + \sqrt{2}) \approx 4.8$ (at $E > 270$ GeV with the same laser), some of produced high energy photons are died out, producing $e^+e^-$ pairs in the collisions with laser photons from the tail of laser bunch. This fact was treated as limiting one for realization of PLC based on LC with higher electron energy [20]-[28].

The opportunity to use standard scheme at $x > 4.8$ with lower conversion coefficient was mentioned in [43, 44] but without detailed description. In the ref. [45] Kotkin and me found that using the same laser system with almost the same laser flash energy as was prepared for $E = 250$ GeV allows to obtain PLC with $E \leq 1$ TeV and luminosity concentrated in the high energy part only, with $\Delta\hat{s}/\langle\hat{s}\rangle \sim 3 \div 5\%$. The total luminosity at suitable $\rho$ is 0.25 ÷ 0.2 from that for high energy part of luminosity at $x = 4.5$ ($E = 250$ GeV).

**Change of photon polarization. Vacuum birefringence.**

The scattering of high energy photon on laser photon from the tail of laser bunch after conversion can result in an interesting effect, considered by Kotkin and Serbo [46]. At $x > 4.8$ this collision results in production of $e^+e^-$ pairs, discussed above.

At $x < 4.8$ the main interaction is the elastic $\gamma\gamma$ scattering with negligibly small cross section ($< \alpha^4/m_e^2$). Therefore, the laser bunch is practically transparent for such $\gamma$-quanta. On the other hand, the variation in polarization for the $\gamma$-quantum traversing the bunch is determined by the interference of the incoming wave and the wave scattered at zero angle. In other words, for such a variation it is responsible not the cross section (which is proportional to square of the light-light scattering amplitude of the order of $\alpha^4$), but the scattering amplitude itself $\sim \alpha^2$. As a result, in this case the essential variation in the $\gamma$-quantum polarization can occur practically without loss in intensity of $\gamma$-quanta – vacuum birefringence. Fortunately, this effect weakly influences for the photons of highest energies for the case with longitudinally polarized incident beams. However, it should be taken into account at intermediate $y$ and for transverse polarization.

4 Notes on physical program

The physical program for photon collisions has huge literature.

**e±e− colliders.** Energies and luminosities of $\gamma\gamma$ subprocesses are much lower than those of parent colliders. Therefore, the two-photon studies at these
colliders provide substantial supplement to the future hadron and $e^+e^-$ data with improved values of parameters but without discovery of new phenomena of the first line.

- **The photon colliders** will be built only in far future. No doubts, measurements at these colliders will improve accuracy of results obtained at hadron and $e^+e^-$ colliders. I skip these problems here.

Below I discuss only several processes in which two-photon mechanism can provide information unavailable in other collisions or machines. For $e^+e^-$ collisions that are points (A) and (B) below, for PLC – points (B)-(G).

(A) At relatively low $\gamma\gamma$ energy the interference between two-photon and bremsstrahlung mechanism of production of simple systems like $\pi^+\pi^-$ allows to measure relative phases of s- and p-waves (d- and p-waves) of $\pi\pi$ scattering, not available in other approaches [47].

(B) The most important for photon collisions at $e^+e^-$ colliders and very important for PLC is the study of the structure function of the photon. Witten found that it is an unique quantity in particle physics which can be determined from QCD at large enough $Q^2$ and $s$ completely without phenomenological parameters, it is determined by point-like component of photon [48]. The test of this result at future experiments is necessary to verify that QCD is indeed a theory of strong interactions. At modern parameters of $e^+e^-$ machines the hadron-like component of photon dominates.

![Figure 9: Cross sections of some processes at PLC in pb. Unpolarized photons. Subscript 100 means that it is calculated for $m_h = 100$ GeV](image)

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The study of semi-hard processes like $\gamma\gamma \rightarrow \rho\rho$ provides an opportunity to measure the Pomeron of QCD with high accuracy. We presented one of the first calculations in this field [49]. Now this topic has huge literature.

The next group form processes with production of gauge $W$ and $Z$ bosons. In 1983 we consider the basic processes of gauge boson production in $\gamma\gamma$ and $\gamma e$ collisions [50]. The important observation was that the cross sections of these processes don’t decrease with the growth of collision energy, reaching large enough value $\sigma_W \sim 80 \div 90$ pb. (That is due to dominance of vector – $W/Z$ – exchange in t-channel). It allows to perform the high energy measurements with high enough accuracy. It opens the door for the test of high order electroweak radiative corrections, which cannot be studied at another machines with reasonable accuracy. The relevant field provides an opportunity to observe the multiple production of gauge bosons in processes like $\gamma\gamma \rightarrow WWZ$, $e\gamma \rightarrow eWW$, $e\gamma \rightarrow WZ\nu$ with cross sections $\sim \alpha\sigma_W$ and $\gamma\gamma \rightarrow WWWW$, $\gamma\gamma \rightarrow WWZZ$, $\gamma\gamma \rightarrow eWWZ$, $e\gamma \rightarrow eWZ\nu$ with cross sections $\sim \alpha^2\sigma_W$ [51] (see Fig. 4).

The study of resonances with spin 0 or 2 in the processes $\gamma\gamma \rightarrow WW$, $\gamma\gamma \rightarrow ZZ$ which can appear due to possible strong interaction in Higgs sector allowed by modern data in the multi-Higgs models.

The study of Higgs productions at PLC has huge literature. The probing of possible violation of CP in the extended models of Higgs sector is very difficult task for LHC. It can be solved in the study of process $\gamma\gamma \rightarrow h$ with polarized photons [52].

Unfortunately, we can hope now that these measurements will give only refinements of data obtainable at LHC and future LC. I don’t expect that these refinements would be crucial in the understanding of general picture. Moreover, observations of production of possible heavier neutral Higgs bosons at PLC look difficult task [53].

Who knows?

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