Photon Colliders in a Future Collider Program

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Subjects of discussion

1. Different scenarios
2. Higgs window to a New Physics
3. Anomalies in the interactions of gauge and Higgs bosons, t–quarks
4. Some problems of $\mathcal{MSSM}$.
5. Some problems in QCD and hadron physics.
6. *By-product*: Production of axions, etc. from region of conversion $e \to \gamma$.

1 Different scenarios

Photon Colliders in the widespread scenario. When discussing the program for future high energy colliders, the basic point is usually that *Nature is so favorable to us to dispose the essential fraction of new particles and the thresholds of new interactions* (e.g., effects of new higher dimensions, compositeness, etc.) *within the LHC operation domain.*

In this case, main discoveries will be made at the Tevatron and the LHC. The e^+e^- Linear Colliders (LC) in their first stages will be machines for measuring precise values of coupling constants and exploring in detail supersymmetry. The high luminosity expected for e^+e^- Linear Colliders provides opportunity to obtain parameters of models realized with very high accuracy, see, e.g., [1].

With the Photon Collider mode of LC [2] having roughly the same luminosity as that for e^+e^- mode [3] these results will be improved. Indeed,

• The thresholds for the production of some new particles in γe collisions are lower than those in e^+e^- collisions.

• The cross sections of production of pairs of charged particles in the $\gamma\gamma$ collision are $5 \div 8$ times higher than that in the e^+e^- collision in its maxima; this ratio increases with growth of energy.

• The set of final states at a Photon Collider is richer than that at in an e^+e^- mode.

• One can vary polarizations of photon beams relatively easily (*circular* $\to$ *transverse*).

Unfortunately, this Photon Collider opportunity was not explored by the community in necessary detail. It can be assured that the forthcoming studies of many physicists with detailed simulation will show an exceptional potential for the Photon Collider mode in both new problems and all problems considered till now.

$\mathcal{SM}$ – like scenario. It can also happen that the opposite scenario will be realized:
No new particles and interactions will be discovered at the Tevatron, LHC and e^+e^- LC, except one Higgs boson. If additionally Higgs coupling constant squared to quarks and gauge bosons will be close to their values in the $\mathcal{SM}$, we find a $\mathcal{SM}$ like picture of the World. It can be realized both if our World is really described by simple $\mathcal{SM}$ up to very small distances and if some other model is realized and New Physics is *round the corner.* In this case, the main goal of studies at new colliders will be the hunting for indirect signals of New Physics – deviations of observed quantities from $\mathcal{SM}$ predictions.
Photon Colliders are the best machines for the hunting for signals of New Physics if the $\mathcal{SM}$ like scenario is realized.

2 Higgs window to a New Physics

The study of Higgs-boson couplings with photons ($h\gamma\gamma$ and $hZ\gamma$) is a very promising tool for resolving of models of New Physics.

• These couplings are absent in the $\mathcal{SM}$ at the tree level, appearing only at the loop level. Therefore, the background for signals of New Physics will be relatively lower here than in other processes which are allowed at the tree level of the SM.

• All fundamental charged particles contribute to these effective couplings. The whole structure of the theory influences the corresponding Higgs-boson decays.

• The expected accuracy in the two-photon width is $\approx 2\%$ at $M_h \le 150$ GeV and even at the luminosity integral ~ 40 fb^{-1} in the high energy peak of the luminosity spectrum [4].

In **the $\mathcal{SM}$ like scenario** *only one Higgs boson is observed, its basic couplings squared (to W, Z, quarks and leptons) g_i^2 are close to the $\mathcal{SM}$ values. In the $2\mathcal{HDM}$ and $\mathcal{MSSM}$, the observed Higgs boson will be either the lightest scalar Higgs boson h or the heavier one H. The other Higgs bosons can easily avoid observation at LHC and e^+e^- LC due to small couplings to standard matter or (and) if they are very heavy.* Table 1 present the set of possible realizations of $\mathcal{SM}$ like scenario in $2\mathcal{HDM}$ [6].

<table>
<tr><th></th><th>observed Higgs boson</th><th>χ_V</th><th colspan="2">$\tan\beta$</th><th>constraint</th></tr>
<tr><td rowspan="4">$A_{\phi\pm}$:
$\chi_V \approx \chi_u \approx \chi_d$</td><td rowspan="2">h</td><td rowspan="2">$\approx +1$</td><td rowspan="4">$= \sqrt{\left\vert\frac{\epsilon_d}{\epsilon_u}\right\vert}$</td><td>$> 1$</td><td rowspan="4">$\epsilon_V = -\frac{\epsilon_u \epsilon_d}{2}$</td></tr>
<tr><td>< 1</td></tr>
<tr><td>h</td><td>≈ -1</td><td>$\gg 1$</td></tr>
<tr><td>H</td><td>≈ -1</td><td>> 1</td></tr>
<tr><td rowspan="3">$B_{\phi\pm d}$:
$\chi_V \approx \chi_u \approx -\chi_d$</td><td>h</td><td>$\approx +1$</td><td colspan="2" rowspan="3">$= \sqrt{\frac{2}{\epsilon_V}} > 1$</td><td rowspan="3">$\epsilon_u = -\frac{\epsilon_V \epsilon_d}{2}$</td></tr>
<tr><td>h</td><td>≈ -1</td></tr>
<tr><td>H</td><td>≈ -1</td></tr>
<tr><td>B_{h+u} :
$\chi_V \approx \chi_d \approx -\chi_u$</td><td>h</td><td>$\approx +1$</td><td colspan="2">$= \sqrt{\frac{\epsilon_V}{2}} < 1$</td><td>$\epsilon_d = -\frac{\epsilon_V \epsilon_u}{2}$</td></tr>
<tr><td colspan="6">$\chi_i = \frac{g_i}{g_i^{SM}} = \pm(1-\epsilon_i)$ with
$i = V(\equiv Z, W)$ or $i = u(\equiv t, c)$ or $i = d, \ell(\equiv b, \tau)$.
$\epsilon_V > 0$, $\epsilon_u \epsilon_d < 0$</td></tr>
</table>

Table 1: Realizations of SM-like scenario in the $2\mathcal{HDM}$ (II)

Even in these cases, the models can be distinguished well via precise measurement of two–photon width of observed $\mathcal{SM}$ like Higgs boson [6]. The two photon width is calculated via the Higgs couplings with the matter measurable at an e^+e^- LC. For solutions A and $B_{\phi\pm d}$, deviation from $\mathcal{SM}$ is mainly due to contribution of charged Higgs. For solution B_{h+d}, this difference is due to change of sign of t quark contribution. For solutions A this width depend on parameter λ_5 which is not fixed by theory and other data.

The results are shown in Fig. 1 for $M_{H^\pm} = 800$ GeV. Here the shaded zones correspond to uncertainties in couplings of Higgs boson to W, Z, quarks and leptons, expected in the experiments at e^+e^- LC estimated for $M_h = 120$ GeV [5]. Table 2 presents all loop-induced widths for $M_h = 120$ GeV for the case $|\chi_i| = 1$ (central lines in Figure). For solutions A, all numbers are given for $\lambda_5 = 0$. Deviation of the two two-photon width from the $\mathcal{SM}$ value for solution A depends on λ_5 as $1 - R_{\gamma\gamma}(1 - \lambda_5/\lambda_4)$ with $\lambda_4 = M_{H^\pm}^2/2v^2)$ and $v = 246$ GeV v.e.v. of Higgs field. For solutions B, all considered widths are practically independent of λ_5. One can see that in the general case the two-photon width differs from its $\mathcal{SM}$ value by about 10% or more. It is several times larger than the expected experimental inaccuracy. Therefore, measurement of the two-photon width at a Photon collider can resolve these models reliably.

solution	basic couplings	$\lvert\chi_{\gamma\gamma}\rvert^2$	$\lvert\chi_{Z\gamma}\rvert^2$	$\lvert\chi_{gg}\rvert^2$
$A_{h\pm}$; A_{H-}	$\chi_V \approx \chi_d \approx \chi_u \approx \pm 1$	0.90	0.96	1.00
$B_{h\pm d}$; B_{H-d}	$\chi_V \approx -\chi_d \approx \chi_u \approx \pm 1$	0.87	0.96	1.28
B_{h+u}	$\chi_V \approx \chi_d \approx -\chi_u \approx 1$	2.28	1.21	1.28

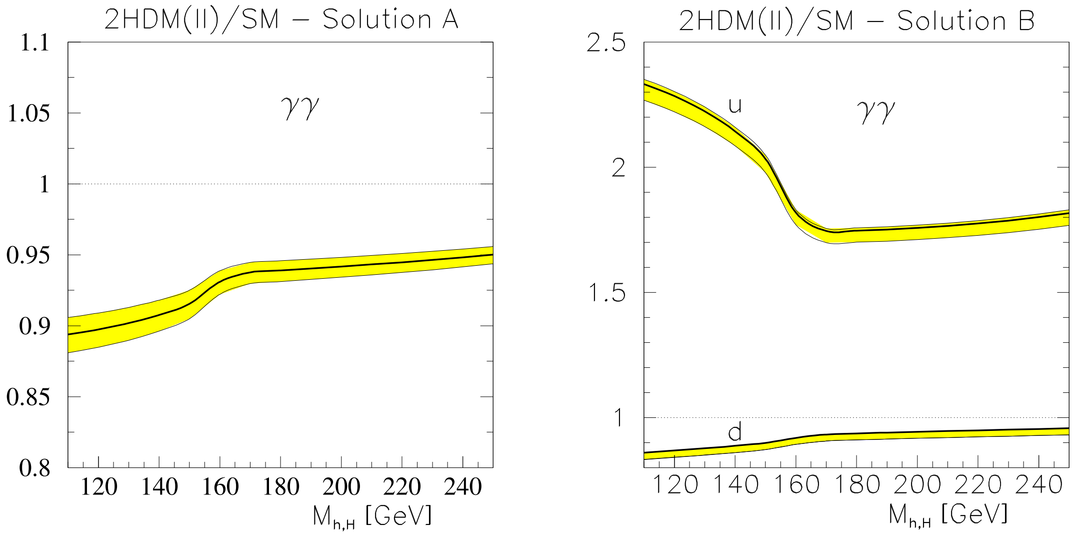

Figure 1: *The ratio of two–photon width of Higgs boson in $2\mathcal{HDM}$ to its $\mathcal{SM}$ value.*

Table 2: *Ratios of the $\gamma\gamma$, $Z\gamma$ and two gluon (gg) width of the observed Higgs boson to their $\mathcal{SM}$ values in the $\mathcal{SM}$ like scenario.*

In the $\mathcal{MSSM}$ the lightest Higgs boson is decoupled from superpartners and other members of Higgs multiplet, if they are very heavy [7]. More detailed calculations will give us the upper bounds for masses of superparticles which can influence the photon widths so that the difference will be seen in the experiment. Preliminary estimates show that these values are higher than the discovery limits at LHC.

In many variants of $2\mathcal{HDM}$ or $\mathcal{MSSM}$ the masses of heavy scalar Higgs H and Higgs pseudoscalar A are close each other. In some other variants they are mixed ($\mathcal{CP}$ violated scenarios). The observations at LHC and e^+e^- Linear Collider cannot often resolve these opportunities due to low resolution for these bosons. The polarization asymmetries in Higgs boson production at a Photon Collider can resolve these variants, i.e. establish whether $\mathcal{CP}$ parity at Higgs level is violated or not.

3 Anomalies in the interactions of gauge and Higgs bosons, t–quarks

Before discovery new heavy particles, New Physics reveals itself at lower energies as some anomalies in the interactions of known particles. Our goal is to find these anomalies and discriminate them as best as possible. *The correlation between coefficients of different anomalies will be the key for understanding what is the nature of New Physics.*

$\otimes$ **Interactions of gauge bosons.** Practically the unique process under study in the e^+e^- mode is $e^+e^- \to W^+W^-$. At suitable electron polarization, the neutrino exchange contribution (having small interest) disappears, and the residual cross section (due to photon and Z boson exchange) has a maximum about 2 pb within the LEP operation interval and decreases at higher energies. Cross sections of other processes with W production ($e^+e^- \to e^+e^- WW$, $e^+e^- \to e\nu W$, ...) are small at $\sqrt{s} < 1$ TeV.

At Photon collider, the main processes are – $\gamma\gamma \to W^+W^-$, $e\gamma \to \nu W$. Their cross sections are about 80 pb and are energy independent at $\sqrt{s} > 200$ GeV. These are at least 40 times higher than for e^+e^- collisions, and yield about $(1 \div 5) \cdot 10^7$ W's per year, comparable with Z production at LEP. Due to high magnitudes of these basic cross sections, many processes of 3-rd and 4-th order have large enough cross sections:
$\boldsymbol{\gamma e \to eWW}$, $\boldsymbol{\gamma\gamma \to ZWW}$, $\boldsymbol{\gamma e \to \nu WZ}$, $\boldsymbol{\gamma\gamma \to WWWW}$, $\boldsymbol{\gamma\gamma \to WWZZ}$, etc. Large variety of these processes permit us to discover and separate well anomalies in specific processes and (or)

distributions. This subject needs studies of all processes discussed with details of behavior in different regions of phase space and polarization dependence.

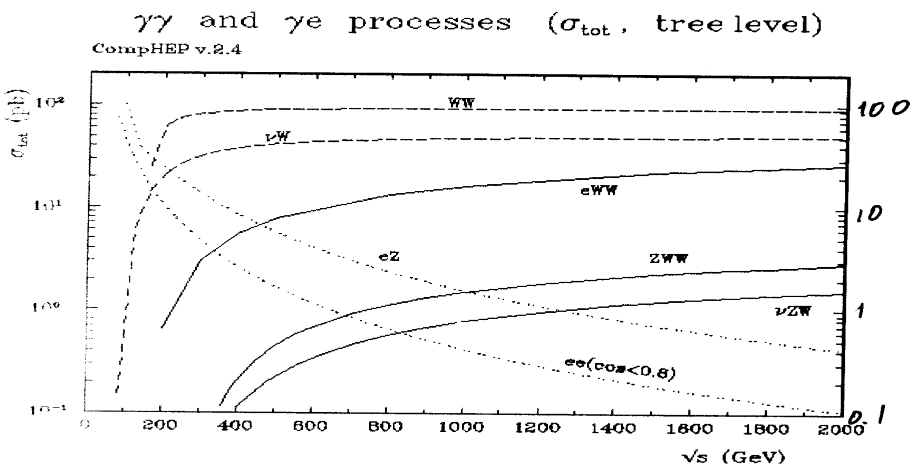

Figure 2: *Some processes of gauge boson production at γe and $\gamma\gamma$ colliders*

• For example, the following line of procedures is almost evident:
(a) To extract γWW anomalies from $\gamma e \to \nu W$.
(b) To extract ZWW anomalies from $e^+e^- \to W^+W^-$.
(c) To extract $\gamma\gamma WW$ anomaly from $\gamma\gamma \to W^+W^-$.
• $\boldsymbol{e\gamma \to \nu W}$. The cross section of the process is $\propto (1-2\lambda_e)$; it is switched on or off with variation of electron helicity λ_e. It gives precise test of the absence of right handed currents in the interaction of W with the matter.
• $\boldsymbol{\gamma e \to eWW}$**.** The cross section of theprocess at $\sqrt{s} = 500$ GeV is about 10 pb; corresponding counting rate is few millions events per year.
⋆ In events with transverse momentum of scattered electron $p_\perp \geq 30$ GeV one can study here anomaly γZWW.
⋆ The charge asymmetry of produced W's looks like most sensitive key for the study of strong interaction in Higgs sector.
• $\boldsymbol{\gamma\gamma \to W^+W^-}$ **and** $\boldsymbol{e\gamma \to \nu W}$. The two–loop radiative corrections to these processes are measurable and involve the problems:
⋆ *construction of S–matrix of theory with unstable particles;*
⋆ *gluon corrections like Pomeron exchange between quark components of W's.*

⊗ **Interactions of Higgs boson with light (** $\boldsymbol{\gamma\gamma \to h,\ \gamma e \to eh}$**).** All observable anomalous $\mathcal{CP}$ – even and $\mathcal{CP}$ – odd interactions of Higgs boson with light are summarized in the form of an effective Lagrangian:

$$\begin{gathered}\Delta\mathcal{L} = 2Hv\left(\theta_\gamma \frac{F_{\mu\nu}F^{\mu\nu}}{2\Lambda_\gamma^2} + \theta_Z \frac{Z_{\mu\nu}F^{\mu\nu}}{\Lambda_Z^2} + \right. \\ \left. i\theta_{P\gamma}\frac{F_{\mu\nu}\tilde{F}^{\mu\nu}}{2\Lambda_{P\gamma}^2} + i\theta_{PZ}\frac{Z_{\mu\nu}\tilde{F}^{\mu\nu}}{\Lambda_{PZ}^2}\right), \quad \left(\theta_i = e^{i\xi_i}\right).\end{gathered} \tag{1}$$

Here $F^{\mu\nu}$ and $Z^{\mu\nu}$ are the standard field strengths for the electromagnetic and Z field, $\tilde{F}^{\mu\nu} = \varepsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}/2$ and ξ_i *are the phases of couplings*, generally different from 0 or π even in the C–even case (due to possible anomalous contributions of some light particles) [8].

While $\mathcal{CP}$ -even anomalies can be seen via the values of measured cross sections, the $\mathcal{CP}$ anomalies will be seen via the polarization asymmetries ("longitudinal" – variation of cross sections with the change of sign of helicities of collided photons, or "transverse" variation of cross section as a function of the angle between directions of linear polarization of collided photons). The effects are large enough to see them at reasonable values of anomaly scales Λ_i and phases ξ_i (see Fig. 2).

A particular example of anomaly presents $\mathcal{CP}$ -violating mixing in Higgs sector of $2\mathcal{HDM}$ (scalar –

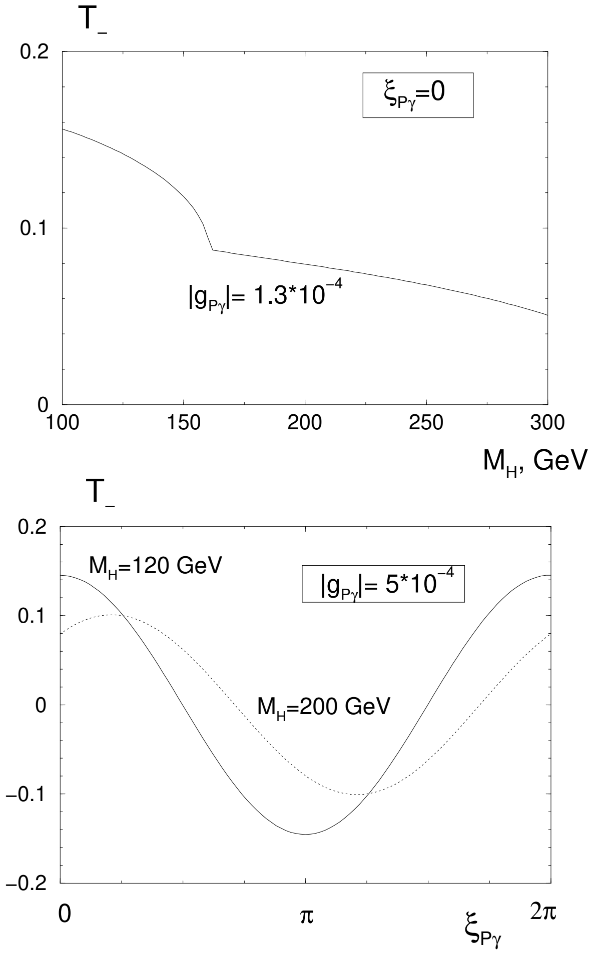

Figure 3: *"Longitudinal" asymmetry for $\gamma\gamma \to H$ process*

pseudoscalar) with mixing angle α_2. We present results in Fig. 3 fixing other model parameters to be close to the $\mathcal{SM}$ case.

• It can happen that the masses of heavy scalar Higgs H and pseudoscalar A are so close to each other that they cannot be resolved in the mass spectrum. The study of decay products cannot distinguish this overlapping from the case of their mixing with $\mathcal{CP}$ violation. In the case when these Higgses overlap in the true mass spectrum, the correlations in the decay products will be identical, if $\mathcal{CP}$ -violated mixing exists or not. The study of polarization asymmetries in the Higgs boson production at Photon Colliders distinguish between these two opportunities well.

$\bigotimes$ ***t*–quarks**. In addition to the usually discussed problems related to t-quarks, the specific one is the study of axial anomaly in the process $\gamma e \to et\bar{t}$. It was found that at small transverse momenta of scattered electrons $p_\perp$, the cross section of subprocess $Z_L\gamma \to t\bar{t}$ with longitudinally polarized Z does not disappear as happens with photons, but diverges as $M_t^2/p_\perp^2$ [9].

4 $\mathcal{MSSM}$

Here I present only few examples in which Photon Colliders look absolutely necessary.

• If masses of selectron $\tilde{e}$ or chargino $\tilde{\chi}^\pm$ are within mass interval 250-350 GeV, and other superparticles are heavy enough, SUSY can escape discovery at LHC and e^+e^- LC 500. In this case, at least one of these particles can be discovered, and respectively SUSY will be found in the γe collider mode via reaction

$$\gamma e \to \tilde{e}\tilde{\gamma}\,, \quad \gamma e \to \tilde{\chi}^-\tilde{\nu} \tag{2}$$

in dependence of what from neutrals, fermion $\tilde{\gamma}$ or scalar $\tilde{\nu}$ is LSP (lightest superparticle).

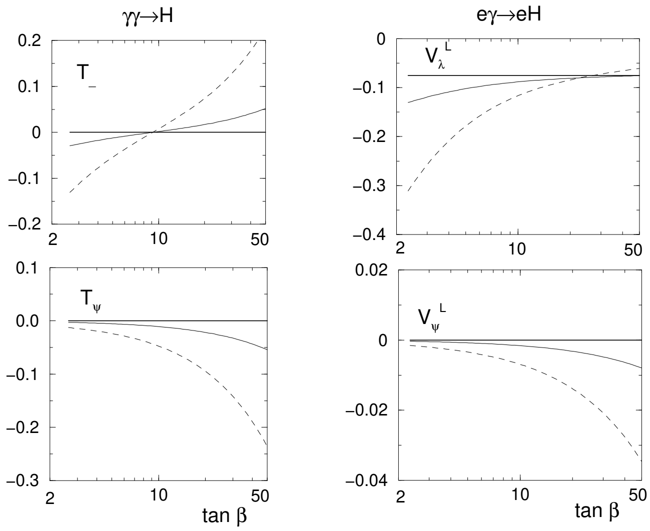

Figure 4: *Polarization asymmetries in* $\gamma\gamma \to h$ *and* $\gamma e \to eh$ *processes due to scalar-pseudoscalar mixing in 2$\mathcal{HDM}$ (II),* $M_h = 110$ *GeV; for* $e\gamma \to eH$ *process* $E_{tot} = 1.5$ *TeV. The thick solid lines show the* $\mathcal{SM}$ *values; thin solid and dashed lines refer to* $\sin\alpha_2 = 0.1$ *and* 0.5 *respectively* (α_2 *is light scalar–pseudoscalar mixing angle).*

Other points supplement possible SUSY discovery at Tevatron, LHC and e^+e^- LC.

• Due to high values of the basic cross sections for the production of pairs of charged particles, Photon Colliders promise to be an excellent place for observation of (even small) possible flavor non-conservation in the neutral currents with superparticles.

• If the stop squark is not very heavy, the atom-like stoponium with mass 200-400 GeV should also exists. It will be very narrow and hard to observe at hadron collider and e^+e^- Linear Colliders. However, it can be clearly seen at $\gamma\gamma$ collider with cross section averaged over photon spectrum $\boldsymbol{< \sigma > \approx 10 - 50}$ **fb** and clear enough signature [10].

• Gaugino discovery. The expected discovery limit for gaugino at LHC is about 170 GeV in the variants of MSSM which looks the most probable now. It can be enhanced till 450 GeV in the "less probable" variants of MSSM.

5 QCD and Hadron Physics

All problems studied at HERA and LEP will be studied at Photon Colliers, but in much more wide interval of parameters and with much better accuracy. Among them I underline those which look most interesting now.

• Study of photon structure function(s) at small x.

• Nature of growth of **total cross sections**. The widespread concepts assume standard Regge type factorization and universal energy behavior for different processes. With Photon Colliders –*for the first time in particle physics*– one can have the set of mass shell cross sections of very high-energy processes, appropriate for the testing of factorization or the level of its violation. They are σ_{pp}, measured at Tevatron and LHC, $\sigma_{\gamma p}$, measured at HERA, $\sigma_{\gamma\gamma}$, measurable at Photon Collider. For this goal, *the preliminary stage of operations with low luminosity can be used* to observe large enough cross sections at small scattering angles.

• In this very low luminosity stage the study of events with particle production in the center of rapidity scale and with rapidity gaps for two vector mesons or dijets originated from initial photons will be crucial for the understanding of **double Pomeron effects** having no reliable explanation till now.

• The study of **charge asymmetry of produced hadrons** in $\gamma\gamma$ collisions will give quite new information about quark–gluon matter at small distances. The charge asymmetry of the produced hadrons in the γe collisions with transverse momentum of scattered electron $p_\perp \geq 30$ GeV will show in explicit form the relation between hadron states produced by vector and axial current.

6 Conversion region – γe collider

The conversion region in γe collider with c.m.s. energy about 1.2 MeV, but with luminosity about 0.1 fb^{-1}/sec! It will be unique source of light Goldstone particles (axions, majorons, etc.) LGP, expected in numerous schemes [11].
The production processes are

$$e\gamma_0 \to e(LGP)\,, \quad \gamma\gamma_0 \to (LGP)\,. \tag{3}$$

The energy of LGP is limited from above as

$$E_{LGP} \leq \frac{x + a^2 + \sqrt{(x-a^2)^2 - 4a^2}}{2(x+1)} E, \quad a = \frac{m_a}{m_e}. \tag{4}$$

The angular spread of these LGP's is even more narrow than that of high energy photons. In comparison with neutrinos produced by photons in the final wall, the main part of these "axions" is concentrated in a $10^6 \div 10^8$ times more narrow solid angle.

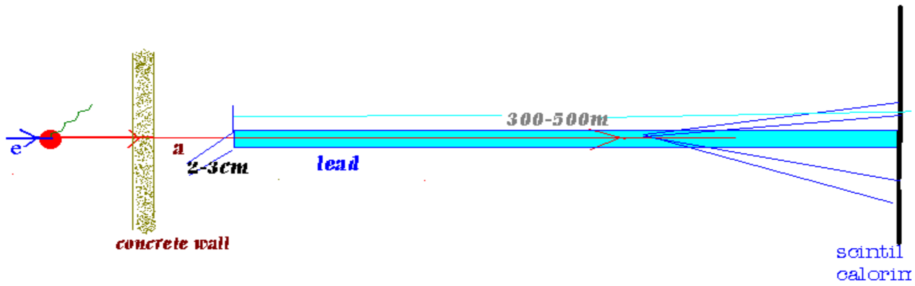

Figure 5: Possible scheme for recording of the "axion"

These LGPs interact with matter very weakly. So, the registration scheme can be of the type shown in Fig. 4: the produced LGP after concrete wall travel to the detector inside $L = 300 - 500$ m long lead wire of diameter 3-5 cm. Here it can interact with hadrons in the nucleus of lead and produce hadrons with typical mean transverse momentum about 300-500 MeV. They can be detected in scintillator-like devices of diameter 3-5 m in the end of wire.

7 Conclusion

This discussion shows that *R&D for Photon collider mode should be performed simultaneously with those for e^+e^- mode of TESLA, etc. Final decision about the turn of different stages of Linear collider should be made only* **AFTER** *first operations of LHC.* It is possible that the Photon collider mode will be switched on before e^+e^- mode. The advantages are:
• The basic electron energy is lower.
• Positron beam is unnecessary.

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