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GAMMA-GAMMA COLLIDER WITH $W_{\gamma\gamma} \leq 12$ GEV BASED ON EUROPEAN XFEL

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Abstract

Using Compton scattering of 0.5 μm laser photons on existing 17.5 GeV electron beams from European XFEL one can obtain a $\gamma\gamma$ collider with $W_{\gamma\gamma} \leq 12$ GeV. Such a collider will be a nice place for application of modern technologies: powerful lasers, optical cavities, superconducting linacs and low-emittance electron sources. Physics program: spectroscopy of $C = +$ resonances in various J^P states ($b\bar{b}$, four quark states, quark molecules and other exotica). Variable circular and linear polarizations will help to determine quantum numbers and to measure separately polarization components of the $\gamma\gamma$ cross section $(\sigma_\perp, \sigma_\parallel, \sigma_0, \sigma_2)$.

1 Introduction

Gamma-gamma collisions have already long history. Since 1970 two-photon processes were studies at e^+e^- storage rings in collisions of virtual photons (γ^*). Physics here is interesting and complementary to that in e^+e^-, but not competitive because the number of virtual photons per one electron is rather small: $dn_\gamma \sim 0.03\, d\omega/\omega$, therefore $L_{\gamma\gamma} \ll L_{e^+e^-}$.

At future e^+e^- linear colliders beams are used only once which makes possible $e \to \gamma$ conversion using Compton back scattering of laser light just before the interaction point and thus obtaining $\gamma\gamma$,γe collider (or the photon collider) with a luminosity comparable with that in e^+e^- collisions. [1, 2] The maximum energy of scattered photons

$$\omega_m = \frac{x}{x+1} E_0; \quad x \approx \frac{4E_0\omega_0}{m^2c^4} \simeq 15.3 \left[\frac{E_0}{\text{TeV}}\right] \left[\frac{\omega_0}{\text{eV}}\right] = 19 \left[\frac{E_0}{\text{TeV}}\right] \left[\frac{\mu\text{m}}{\lambda}\right]. \tag{1}$$

For example: $E_0 = 250$ GeV, $\omega_0 = 1.17$ eV ($\lambda = 1.06\ \mu m$) $\Rightarrow x = 4.5$ and $\omega_m/E_0 = 0.82$. So, most powerful solid-state lasers with $1\,\mu$m wavelength are perfectly suited for e^+e^- linear colliders with the energies $2E_0$ =100–1000 GeV, which are actively developed since 1980s (VLEPP, NLC, JLC, TESLA-ILC, CLIC). For the $\gamma\gamma$ collider one needs lasers with ps duration, several Joules flash energy and the pulse structure similar to that of a basic e^-e^- collider. Modern laser technology allows to build the required laser system, though it is not easy.

Since the late 1980s $\gamma\gamma$ colliders are considered as a natural part of all linear collider projects, conceptual [4, 6, 5] and pre-technical designs [7, 8] have been published. Just after the Higgs discovery the photon collider was considered as one of Higgs factory options, [9, 10] a dozen variants of $\gamma\gamma$ Higgs factories were proposed beside those based on ILC and CLIC. The photon collider is attractive because it does not need positrons and the energy required to produce the Higgs is somewhat lower that in e^+e^- collisions. However, e^+e^- colliders are better for the Higgs study due to the unique reaction $e^+e^- \to$ ZH which allows to detect almost all Higgs decays, even invisible (by missing mass).

If the linear collider (ILC or CLIC) is ever built, at first it will work in the e^+e^- mode, so the photon collider can appear only in 3–4 decades. Such perspective cannot inspire people who want to do something interesting already now.

In April 2017, Chinese physicists organized ICFA Mini-Workshop on Future $\gamma\gamma$ Collider with invitation of world experts in particle, laser and accelerators physics to discuss what can be made reasonable in this direction. In my review talk, I have proposed to construct a photon collider based on electron linacs of existing (or future) free electron lasers. [11] The first candidate is the European XFEL with 17.5 GeV electron beams which is in operation since 2017. Using 0.5 μm laser one can obtain compliment it with a photon collider on the energy $W_{\gamma\gamma} \leq 12$ GeV. The region $W_{\gamma\gamma} < 4$–5 GeV can be studied at e^+e^- Super B-factory (in $\gamma^*\gamma^*$ collisions), but in the region $W_{\gamma\gamma} = 5$–12 GeV the photon collider has no competitors. Possible circular and linear polarizations make such photon collider an unique machine for the study of $\gamma\gamma$ physics in the $b\bar{b}$ energy region with many new states, including exotic. Beside the Mini-Workshop in China [11] this suggestion was reported at several recent conferences-workshops, [12, 13] the present paper is the first one on this subject.

2 Possible parameters of $\gamma\gamma$ collider based on European XFEL

The European XFEL has the following parameters of electron beams: [14] beam energy $E_0 = 17.5$ GeV, the number of particles in the bunch $N = 0.62 \cdot 10^{10}$ (1 nC), the bunch length $\sigma_z = 25$ μm, the normalized transverse emittance $\epsilon_n = 1.4$ mm·mrad, the bunch rate 27 kHz (trains 10 Hz, 2700 bunches in one train, about 100 m between bunches in the train). To obtain the photon collider, the electron beams from the XFEL should be sequentially deflected into two arches with a radius of about 100 m and then converted by lasers to high-energy photons just before the interaction point.

The general scheme of the photon collider is shown in Fig. 1. Laser photons scatter on electrons at the distance $b \sim \gamma\sigma_y$ which is about 2 mm for the considered project. Increasing of $\rho = b/\gamma\sigma_y$ leads to some degree of monochromatization and suppression of low energy collisions. After crossing the conversion region, electrons have a broad energy spectrum and large disruption angles due to deflection of low-energy electrons in the field of the opposing beam. The "crab crossing" scheme of collisions solves the problem of the beam removal without hitting final quads.

In order to have the energy of Compton scattered photons close to the electron energy the parameter x should be optimally somewhat below $x = 4.8$ (when $\omega_m = 0.82E_0$) or $\lambda = 4.2E_0[\text{TeV}]$ μm. [7] It is $\lambda \approx 0.074$ μm for $E_0 = 17.5$ GeV. In this case the maximum $W_{\gamma\gamma}$ would be $35 * 0.8 = 28$ GeV. We do not consider such ultimate case because 1) such a short wavelength laser system with the required peak (TW) and average (100 kW) power is technically unfeasible and 2) there is no interesting physics in the region

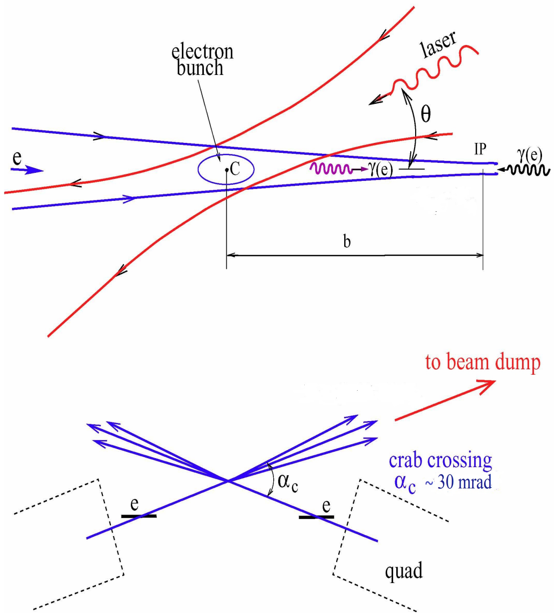

Figure 1: *(top)* The general scheme of a $\gamma\gamma$ γe photon collider. *(below)* A crab-crossing collision scheme for the removal of disrupted beams from the detector to the beam dump.

$W_{\gamma\gamma} = 12$–28 GeV. In our consideration we assume the laser wavelength $\lambda = 0.5$ μm, having in mind the laser system with an external optical cavity like at the ILC photon collider, [8] pumped by a frequency doubled 1 μm laser. In this case the parameter $x = 0.65$ and the ratio $\omega_m/E_0 = x/(x+1) \approx 0.394$. The laser intensity in the conversion region is limited by nonlinear effects in Compton scattering, described by the parameter ξ^2 (see ref. [7]). We assume $\xi^2 = 0.05$, which reduces ω_m/E_0 by 3%, down to 0.38. In this case $W_{\gamma\gamma,\max} = 13.3$ GeV (peak at 12 GeV), that covers the region with b-quark resonances.

In calculation of an the optimal pulse duration and flash energy we assume the laser system similar to that at the ILC based $\gamma\gamma$ collider (optical resonator, laser mirrors outside electron beams). [8] The required flash energy is smaller than in the ILC case by a factor of 3 due to larger Compton cross section at smaller x.

One of serious problems at $\gamma\gamma$ colliders is removal of used beams which are disrupted by the opposing electron beam. The disruption angle is proportional to $\sqrt{N/\sigma_z}$. In order to keep disruption angles acceptable we assume the electron bunch length longer than at XFEL, 70 μm instead of 25 μm.

Simulation of processes at the interaction and collision points was done by my code used since 1995 for simulation of photon colliders at the NLC, CLIC, TESLA-ILC. [7] We consider both unpolarized electron beams (existed at the XFEL) and 80% longitudinally polarized (here low emittances is a problem to be solved). The laser beam is circularly polarized, $P_c = \pm 1$ (when circularly polarized high energy photons are needed). Collisions of linearly polarized photons is also interesting for physics, for that linearly polarized laser beams should be used. The degree of polarization in the high energy part of spectrum is almost 100% for circular polarization and about 85% for linear polarization (in the considered case of $x = 0.65$).

The $\gamma\gamma$ luminosity spectra for non-polarized and longitudinally polarized electrons are shown in Fig. 2. Spectra are decomposed to the states with total helicity of the colliding photons $J_z = 0$ or 2. The total luminosity is the sum of the two spectra. The luminosities with the cut on the relative longitudinal momentum of produced systems are also shown. This cut suppress boosted collisions of Compton and beamstrahlung photons with very different energies. Luminosity distributions similar to those in Fig. 2 but for various distances between the conversion and interaction points are shown in Fig. 3. One can see that with the increase of ρ the luminosity spectra become more cleaner and energetic at at the cost of some reduction in luminosity. Resulting parameters of the photon collider are given in Table 1.

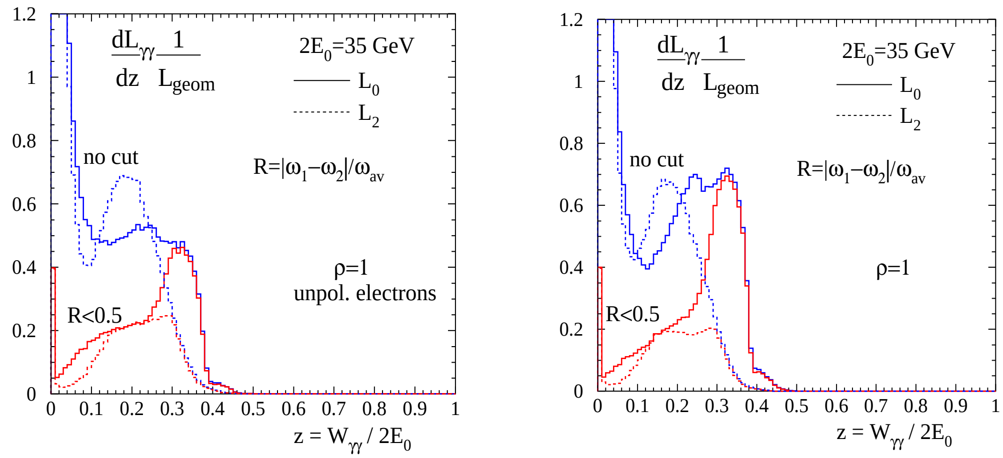

Figure 2: $\gamma\gamma$ luminosity distributions. Left: unpolarized electrons; right: longitudinal electron polarization $2\lambda_e = 0.8$ (80%). In both cases laser photons are circularly polarized, $P_c = -1$. Solid lines for J_z of two colliding photons equal to 0, dotted lines for $J_z = 2$. Red curves are luminosities with the cut on longitudinal momentum.

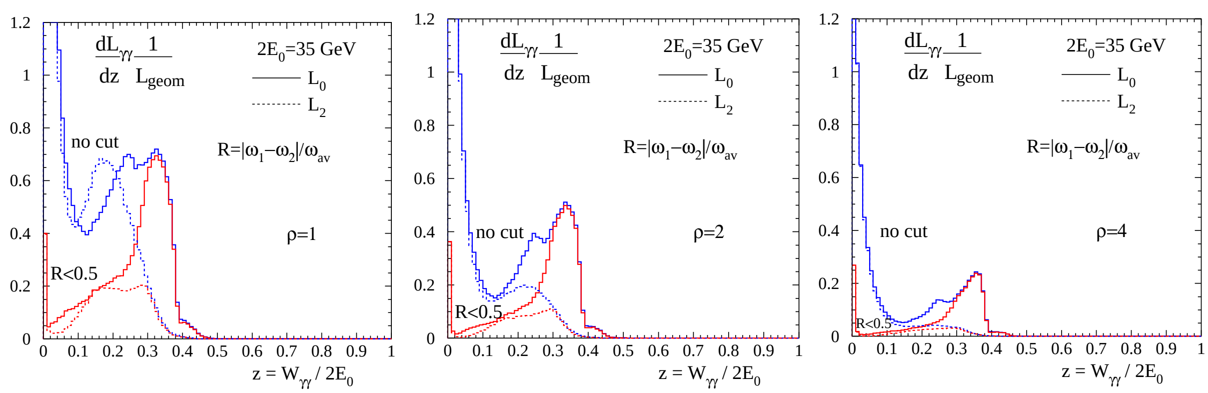

Figure 3: $\gamma\gamma$ luminosity distributions on invariant mass $W_{\gamma\gamma}$ for various distances b between conversion and interaction points (characterized by the parameter $\rho = b/(\gamma\sigma_y)$. See other explanations in Fig. 2.

3 Physics at a 0.1-12 GeV photon collider

A photon, like an electron, is a point-like particle participating in electromagnetic interactions. The cross section for a lepton pair production in $\gamma\gamma$ collisions is $\sigma_{\gamma\gamma} \approx (q/e)^4/W^2_{\gamma\gamma}[\,\mathrm{GeV}^2] \cdot 10^{-30}$ cm^2 for $W_{\gamma\gamma} \gg mc^2$ and $|cos\theta| < 0.9$ while in e^+e^- collisions $\sigma_{e^+e^-} \approx 0.085(q/e)^2/W^2_{e^+e^-}[\,\mathrm{GeV}^2] \cdot 10^{-30}$ cm^2.

Beside, photons spends some time in the form of virtual lepton pairs, quark pairs (or vector mesons) and behaves in $\gamma\gamma$ collisions as a hadron. The cross section $\sigma(\gamma\gamma \to hadrons)$ =(0.4–0.6)$\cdot 10^{-30}$ cm^2 (at

Table 1: Parameters of the photon collider.

$2E_0$	GeV	35
N per bunch	10^{10}	0.62
Coll. rate	kHz	15
σ_z	μm	70
$\epsilon_{x,n}/\epsilon_{y,n}$	mm-mrad	1.4/1.4
β_x/β_y at IP	μm	70
σ_x/σ_y at IP	nm	53/53
Laser λ	μm	0.5
Parameters x and ξ^2		0.65, 0.05
Laser flash energy	J	3
Laser pulse duration	ps	2
f# of laser system		27
Crossing angle	mrad	~ 30
b,(CP-IP distance)	mm	1.8
$L_{\rm ee,geom}$	10^{33} cm^{-2}s^{-1}	1.6
$L_{\gamma\gamma}(z > 0.5z_m)$	10^{33} cm^{-2}s^{-1}	0.21
$W_{\gamma\gamma}$(peak)	GeV	12

$W_{\gamma\gamma} > 1\,$GeV) does not decrease with the energy and exceeds the point like quark pair production cross section.

A nice feature of both e^+e^- and $\gamma\gamma$ collisions is a single resonance production of hadrons. In e^+e^- these resonances have the photon quantum numbers: $J^{PC} = 1^{--}$, that are $\dots J/\Psi, \Upsilon \dots$. Two real photons can produce $C = +$ resonances with the following states: [16] $J^P = 0^+, 0^-, 2^+, 2^-, 3^+, 4^+, 4^-, 5^+ \dots$ ($\pi^0, \eta \dots, H-$boson), forbidden numbers are $J^P = 1^\pm$ and (odd $J)^-$. So, the $\gamma\gamma$ collider presents much richer possibility for study of hadronic resonances.

Cross sections of resonance production in $\gamma\gamma$ collisions depend on the total helicity of two photons $J_z = 0$ or 2. If C and P-parities conserve, then resonances are produced only in certain helicity states: [16] $J_z = 0$ for $J^P = 0^\pm$, (even $J)^-$; $J_z = 2$ for (odd$J \neq 1)^+$; $J_z = 0$ or 2 for J^P=(even $J)^+$. The value of J_z is set in the experiment by varying the laser photon helicities (and the longitudinal electron beam polarization, if it is not zero).

Photon polarization is characterized by the photon helicity λ_γ, the linear polarization l_γ and the direction of the linear polarization. Any $\gamma\gamma$ process is described by 16 cross sections, but only three most important which do not vanish after averaging over spin states and azimuthal angles of final particles [3, 15], that are $\sigma^{np} = 0.5(\sigma_\parallel + \sigma_\perp) = 0.5(\sigma_0 + \sigma_2)$; $\tau^c = 0.5(\sigma_0 - \sigma_2)$; $\tau^l = 0.5(\sigma_\parallel - \sigma_\perp)$.

The number of events

$$d\dot{N} = dL_{\gamma\gamma}(d\sigma^{np} + \lambda_\gamma\tilde{\lambda}_\gamma\, d\tau^c + l_\gamma\tilde{l}_\gamma \cos 2\Delta\phi\, d\tau^l)\ , \tag{2}$$

where the tilde sign marks the second colliding beam, $\Delta\phi$ is the angle between directions of linear polarizations of colliding photons. For example, for $J = 0$ resonance always $\sigma_2 = 0$, while $\sigma_\parallel$ and $\sigma_\perp$ depend on CP-parity: for $CP = 1$ $\sigma_\parallel = \sigma_0$, $\sigma_\perp = 0$, for $CP = -1$ resonances $\sigma_\parallel = 0$, $\sigma_\perp = \sigma_0$. The cross section in this case

$$\sigma \propto 1 + CP \cdot l_{\gamma,1} l_{\gamma,2} \cos 2\Delta\phi. \tag{3}$$

Scalar particles are produced when photon lineaar polarizations are parallel, while pseudoscalar scalars are produced when polarization are perpendicular. So, the circular and linear photon polarizations help a lot for J^P determination and allow to measure all important polarization components of $\gamma\gamma$ cross sections.

Photon colliders have broad luminosity spectra with complicated polarization properties. All this characteristics can be measured and calibrated experimentally using QED processes with known cross section. [7, 15]

At $\gamma\gamma$ collider in $W < 12$ GeV, (u, d, s, c, b-quarks energy region), a high degree of circular and linear polarizations of scattered photons is available. It is determined mainly by the polarization of the laser. Longitudinal polarization of electrons (there are sources with 85% polarization) is desirable to enhance photon helicities and make larger ratio L_0/L_2 (or opposite), see Fig. 2.

Observation of $\gamma\gamma$ resonances is one of most interesting task for the $\gamma\gamma$ collider. The cross section for a resonance production is proportional to its partial width $\Gamma_{\gamma\gamma}$, which says a lot about its structure and nature. Most of observed $\gamma\gamma$ resonances are $q\bar{q}$ states, there are also several candidates for 4-quark states. Glueballs, composed from two gluons, are predicted but not observed yet.

Particles with $C = +$ are observed at e^+e^- colliders in decays of other heavier particles ($J/\Psi, \Upsilon$ and their excited states. Decay branchings are not small only in decays of narrow states. $J/\Psi(\Upsilon)$ excited states with masses above $D\bar{D}(B\bar{B})$ thresholds are broad therefore their branching to $C = +$ states are very small. Photon collider allows not only to observe directly $C = +$ states but also simultaneously to measure their $\Gamma_{\gamma\gamma}$.

One example. The $\eta_b(9398)$ $C = +$ state was observed at B-factories in radiative decay of $\Upsilon(1S)$, but its $\Gamma_{\gamma\gamma}$ width is unknown yet because its expected branching to $\gamma\gamma$ is less then 10^{-4}. At the photon collider the production rate of a resonance with $J = 0$ is

$$\dot{N} = \frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}} \frac{4\pi^2\Gamma_{\gamma\gamma}(1+\lambda_1\lambda_2)(\hbar c)^2}{(Mc^2)^2} \approx 8 \cdot 10^{-27} \frac{\Gamma_{\gamma\gamma} L_{ee}}{E_0 M^2 [\,\mathrm{GeV}^2]}, \tag{4}$$

where we put $(dL_{\gamma\gamma}/dW_{\gamma\gamma})(2E_0/L_{ee}) \approx 0.5$ (see Fig. 2 for unpolarized electrons), photon helicities $\lambda_{1,2} = 1$. For $E_0 = 17.5$ GeV, $\Gamma_{\gamma\gamma}(\eta_b) = 0.5$ keV, $M_{\eta_b} = 9.4$ GeV, $L_{ee} = 1.6 \cdot 10^{33}$ cm^{-2}s^{-1} and $t = 10^7$ s we get 40000 events. Electron polarization increase the production rate by factor of 1.5.

The collider LEP-2 had enough energy to produce η_b in $\gamma^*\gamma^*$ collisions but it was not observed because the production rate at $L_{e^+e^-}$(LEP-2) $= 10^{32}$ cm^{-2}s^{-1} was about 700 times lower than at considered $\gamma\gamma$ collider. In order to have the same production rate of $\gamma\gamma$ states in central region at e^+e^- collider with $2E_0 \sim 100$ GeV its luminosity should be approximately $L_{e^+e^-} \sim 10^{35}$ or 70 times higher than the geometric luminosity $L_{ee} \sim 1.6 \cdot 10^{33}$ at the $\gamma\gamma$ collider.

Observation of single $C = +$ resonances in $\gamma\gamma$ collisions needs detection of all final particles that can be checked by requiring the total transverse momentum to be near to zero. These events will be central with more or less isotropic distribution of particles. The non-resonance hadronic background is large but can be suppressed using a cut on $\sum |p_{i,\perp}|$ and particle identification (b, c-quark tagging). Note, at the photon collider only the high energy part of the luminosity spectra has good polarization properties. In order use these good properties in a whole energy region one has to do an energy scan by changing the electron beam energy.

4 Conclusion

Photon colliders are very cost effective additions for e^+e^- linear colliders. However perspectives of the high energy linear colliderss are unclear already many decades. It makes sense to build a photon collider on smaller energy, $W_{\gamma\gamma} < 12$ GeV (b,c regions). The $\gamma\gamma$ physics here is very rich. The required linac already exist, it is SC linac of European XFEL with the energy 17.5 GeV. The photon collider can use electron beams after XFEL which now are sent to the beamdump (though for some experiments time sharing will be desirable). Such $\gamma\gamma$ collider will be a nice place for application of modern outstanding accelerator and laser technologies. It does not need positrons and damping rings. The required laser system is identical to that needed for the photon collider at the ILC. One can not promise some breakthrough discoveries at this collider (this applies to other projects as well), but there are many arguments (scientific, technical, financial and social) in favor of such collider of a new type.

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