Letter of Interest for Snowmass 2021

Gamma-gamma collider with $W_{\gamma\gamma} \leq 12\,\text{GeV}$ based on the 17.5 GeV SC linac of the European XFEL

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Abstract

We propose a $\gamma\gamma$ collider with $W_{\gamma\gamma} \leq 12$ GeV which can be added to the European XFEL with a minimal disruption to its main program. High-energy photons will be obtained by Compton scattering of $0.5\,\mu$m laser photons on the existing 17.5 GeV electron beams. Such a $\gamma\gamma$ collider would be an excellent place for the development and application of modern technologies: powerful lasers, optical cavities, superconducting linacs, and low-emittance electron sources — as well as training the next generation of accelerator physicists and engineers. The physics program would include spectroscopy of $C = +$ resonances in various J^P states ($b\bar{b}, c\bar{c}$, four-quark states, quark molecules and other exotica) in a mass range barely scratched by past and not covered by any current or planned experiments. Variable circular and linear polarizations will help in the determination of quantum numbers and measurement of polarization components of the $\gamma\gamma$ cross section ($\sigma_\perp$, $\sigma_\parallel$, σ_0, σ_2).

Gamma-gamma collisions have a long history: since the 1970s, they have been studied at e^+e^- storage rings in collisions of virtual photons (γ^*).

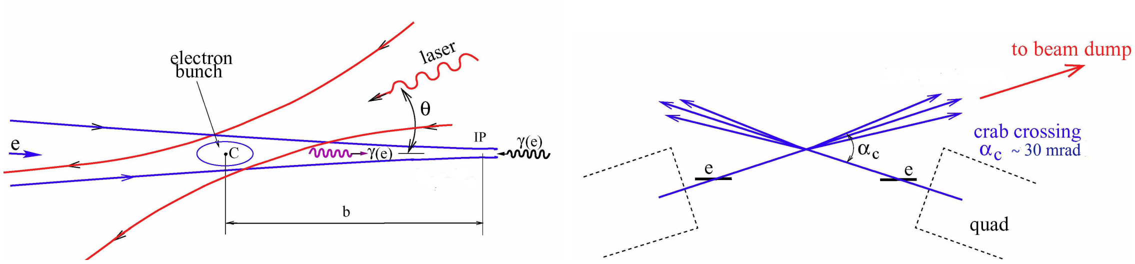

FIG. 1. *(left)* The general scheme of a $\gamma\gamma$, γe photon collider. *(right)* A crab-crossing collision scheme for the removal of disrupted beams from the detector to the beam dump.

At future e^+e^- linear colliders beams will be used only once, which makes possible $e \to \gamma$ conversion by Compton backscattering of laser light just before the interaction point, thus obtaining a $\gamma\gamma$,γe collider (a *photon collider*) with a luminosity comparable to that in e^+e^- collisions [1, 2]. The general scheme of the photon collider is shown in Fig. 1.

The maximum energy of scattered photons

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

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, the most powerful solid-state lasers with a 1 μm wavelength are perfectly suited for a photon collider based on a $2E_0$ =100–1000 GeV e^+e^- linear collider, which have been actively developed since the 1980s (VLEPP, NLC, JLC, TESLA-ILC, CLIC). A $\gamma\gamma$ collider would require a laser with pulses of picosecond duration and an energy of a few joules, and a pulse structure similar to that of the e^-e^- collider it is based on. The required laser system is within reach of modern laser technology.

Since the late 1980s, $\gamma\gamma$ colliders have been considered a natural part of all linear collider proposals; a number of detailed conceptual and pre-technical designs [3] have been published. The photon collider is considered as one of the Higgs factory options [4]; a dozen variants of stand-alone $\gamma\gamma$ Higgs factories have been proposed in addition to those based on ILC and CLIC.

If a linear collider, either ILC or CLIC, is ever built, its first stage will offer only e^+e^- collisions; a photon collider is at least 30–40 years away. Obviously, such an outlook cannot inspire people who want to do something exciting and groundbreaking right now.

In 2017, at ICFA Mini-Workshop on Future $\gamma\gamma$ Collider in Beijing I proposed that a photon collider be built on the basis of the electron linac of an existing or future free-electron laser [5]. The first candidate is the European XFEL, which has been in operation since 2017. By pairing its 17.5 GeV electron beam with a 0.5 μm laser, one can complement the European XFEL with a photon collider with a center-of-mass energy $W_{\gamma\gamma} \leq 12$ GeV. While the $W_{\gamma\gamma} < 4$–5 GeV region can be studied at the e^+e^- Super B-factory at KEK (in $\gamma^*\gamma^*$ collisions), in the $W_{\gamma\gamma} = 5$–12 GeV region this photon collider would have no competition. The addition of circular and linear polarizations would make such a photon collider a unique machine for the study of $\gamma\gamma$ physics in the $b\bar{b}$ energy region, with many new states, including exotic, accessible for discovery and detailed study. This suggestion was further reported at several conferences [6] and the paper [7].

Possible parameters of $\gamma\gamma$ collider based on the European XFEL are presented in Table I.

$2E_0$	GeV	35
N per bunch	10^{10}	0.62
Collision rate	kHz	13.5
σ_z	μm	70
$\varepsilon_{x,n}/\varepsilon_{y,n}$	mm $\cdot$ mrad	1.4/1.4
β_x/β_y at IP	μm	70/70
σ_x/σ_y at IP	nm	53/53
Laser wavelength λ	μm	0.5
Parameters x and ξ^2		0.65, 0.05
Laser flash energy	J	3
Laser pulse duration	ps	2
f# $\equiv F/D$ of laser system		27
Crossing angle	mrad	~ 30
b (CP–IP distance)	mm	1.8
$\mathcal{L}_{ee,\mathrm{geom}}$	$10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.45
$\mathcal{L}_{\gamma\gamma}\,(z > 0.5z_m)$	$10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.19
$W_{\gamma\gamma}$ (peak)	GeV	12

TABLE I. Parameters of the proposed photon collider based on the European XFEL.

The $\gamma\gamma$ luminosity spectra for non-polarized and longitudinally polarized electrons are shown in Fig. 2. See details in ref.[7].

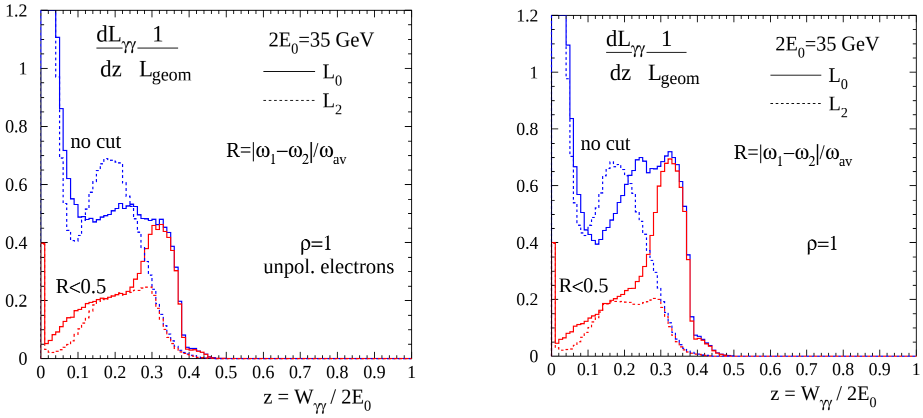

FIG. 2. $\gamma\gamma$ luminosity distributions vs the invariant mass $W_{\gamma\gamma}$: *(left)* unpolarized electrons; *(right)* longitudinal electron polarization $2\lambda_e = 0.8$ (80%). In both cases the laser photons are circularly polarized, $P_c = -1$. Solid lines are for the total helicity of the two colliding photons $J_z = 0$, dotted lines for $J_z = 2$. Red curves are luminosities with a cut on the longitudinal momentum.

A nice feature of both e^+e^- and $\gamma\gamma$ collisions is the single resonance production of hadrons. At e^+e^- colliders, resonances with the photon quantum numbers, $J^{PC} = 1^{--}$, can be single-produced, which includes the J/ψ and Υ families. On the other hand, two real photons can single-produce $C = +$ resonances with the following quantum numbers: $J^P = 0^+$, 0^-, 2^+, 2^-, 3^+, 4^+, 4^-, 5^+, etc., the forbidden numbers being $J^P = 1^\pm$ and (odd $J)^-$. Therefore, the

$\gamma\gamma$ collider presents a much richer opportunity for the study of hadronic resonances. The production rate of resonances with $M = 10$ GeV/c^2 at this $\gamma\gamma$ collider will be about 1000 times higher than it was at LEP-2 (in the central region) with $\mathcal{L}_{ee}$ (LEP2) $= 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

Photon polarization is characterized by the photon helicity λ_γ, the linear polarization l_γ, and the direction of the linear polarization. The $\gamma\gamma$ cross has three components $\sigma^{np} = (\sigma_\parallel + \sigma_\perp)/2 = (\sigma_0 + \sigma_2)/2$, $\tau^c = (\sigma_0 - \sigma_2)/2$, and $\tau^l = (\sigma_\parallel - \sigma_\perp)/2$. The number of events $\mathrm{d}\dot{N} = \mathrm{d}\mathcal{L}_{\gamma\gamma}(\mathrm{d}\sigma^{np} + \lambda_\gamma\tilde{\lambda}_\gamma\ \mathrm{d}\tau^c + l_\gamma\tilde{l}_\gamma \cos 2\Delta\phi\ \mathrm{d}\tau^l)$, where $\Delta\phi$ is the angle between the directions of the linear polarizations of the two colliding photons. Scalar particles are produced when linear polarizations of the colliding photons are parallel; pseudoscalars are produced when the polarizations are orthogonal. Availability of circular and linear photon polarizations is of great value in the determination of J^P of the produced resonances and allows one to measure all important polarization components of the $\gamma\gamma$ cross sections.

In conclusion. Photon colliders are highly cost-effective additions to future e^+e^- linear colliders. Unfortunately, the outlook for high-energy linear colliders has been uncertain for many decades. It therefore makes sense to build a photon collider for a smaller energy, $W_{\gamma\gamma} < 12\,\mathrm{GeV}$, which would offer excellent coverage of the $b\bar{b}$ and $c\bar{c}$ production regions. The $\gamma\gamma$ physics in this energy range is very rich, much of it not accessible otherwise. The required linear accelerator already exists: it is the superconducting 17.5 GeV linac of the European XFEL. The photon collider can use the "spent" electron beams, which currently are sent to the beam dump (although for some experiments time sharing would be desirable). This $\gamma\gamma$ collider would be a nice place for the application and further development of cutting-edge accelerator and laser technologies. It does not need positrons or damping rings. The required laser system is identical to that needed for the photon collider at the ILC. While it cannot be guaranteed that the proposed $\gamma\gamma$ collider would yield any breakthrough discoveries (which applies to all other projects as well), there are many arguments (scientific, technical, financial and social) in favor of such a collider of a brand new type.

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