Measurement of $\gamma\gamma$, γe luminosities and polarizations at photon colliders

+ general remarks on photon colliders

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PHOTON2003, Frascati, April 7-11, 2003

General features
of luminosity distributions:

1. Broad
2. Can not be described by some equivalent photon spectra (because the photon energy depends on the scattering angle)
3. Photon have various polarizations

For $\gamma\gamma$ collisions

$$d\sigma_{\gamma\gamma\ \to X} = \sum_{i,j=0}^{3} \xi_i \tilde{\xi}_j d\sigma_{ij},$$

where ξ_i are Stokes parameters, ξ_2 - the circular polarization, $l = \sqrt{\xi_1^2 + \xi_3^2}$ - the linear polarization, $\xi_0 \equiv 1$.

$$d\dot{N}_{\gamma\gamma\ \to X} = dL_{\gamma\gamma} \sum_{i,j=0}^{3} \langle \xi_i \tilde{\xi}_j \rangle \sigma_{ij}$$

So, in general case, one has to to measure $\dfrac{d^2 L_{ij}}{d\omega_1 d\omega_2}$ − 16 two-dimensional distributions !

However, after averaging over final spin states and azimuthal angles only 3 from 16 σ_{ij} do not vanish

$$\sigma \equiv \sigma_{00} = \frac{1}{2}(\sigma_{\parallel} + \sigma_{\perp}) = \frac{1}{2}(\sigma_0 + \sigma_2)$$

$$\tau^c \equiv \sigma_{22} = \frac{1}{2}(\sigma_0 - \sigma_2)$$

$$\tau^l \equiv \frac{1}{2}(\sigma_{33} - \sigma_{11}) = \frac{1}{2}(\sigma_{\parallel} - \sigma_{\perp})$$

$$d\dot{N}_{\gamma\gamma\,\to X} = dL_{\gamma\gamma}(d\sigma + \langle \xi_2 \tilde{\xi_2} \rangle d\tau^c + \langle \xi_3 \tilde{\xi_3} - \xi_1 \tilde{\xi_1} \rangle d\tau^l)$$

Substituting $\xi_2 \equiv \lambda_\gamma$, $\tilde{\xi_2} \equiv \tilde{\lambda}_\gamma$, $\xi_1 \equiv l_\gamma \sin 2\gamma$, $\tilde{\xi_1} \equiv -\tilde{l}_\gamma \sin 2\tilde{\gamma}$, $\xi_3 \equiv l_\gamma \cos 2\gamma$, $\tilde{\xi_3} \equiv \tilde{l}_\gamma \cos 2\tilde{\gamma}$ and $\Delta\phi = \gamma - \tilde{\gamma}$ (azimuthal angles for linear polarizations are defined relative to one x axis), we get

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

$$\equiv dL_{\gamma\gamma}\, d\sigma^{np} + (dL_0 - dL_2) d\tau^c + (dL_{\parallel} - dL_{\perp})\, d\tau^l$$

$$\equiv dL_0 d\sigma_0 + dL_2 d\sigma_2 + (dL_{\parallel} - dL_{\perp})\, d\tau^l$$

$$\equiv dL_{\parallel}\, d\sigma_{\parallel} + dL_{\perp}\, d\sigma_{\perp} + (dL_0 - dL_2)\, d\tau^c$$

where

$$dL_0 = dL_\gamma (1 + \lambda_\gamma \tilde{\lambda}_\gamma)/2$$

$$dL_2 = dL_\gamma (1 - \lambda_\gamma \tilde{\lambda}_\gamma)/2$$

$$dL_{\parallel} = dL_\gamma (1 + l_\gamma \tilde{l}_\gamma \cos 2\Delta\phi)/2$$

$$dL_{\perp} = dL_\gamma (1 - l_\gamma \tilde{l}_\gamma \cos 2\Delta\phi)/2$$

So, one should measure (not only in a general case) $dL_{\gamma\gamma}$, $\langle \lambda_\gamma \tilde{\lambda}_\gamma \rangle$, $\langle l_\gamma \tilde{l}_\gamma \rangle$
or alternatively $dL_0, dL_2, dL_\parallel, dL_\perp$.
If both photon beams have no linear polarization or no circular polarization, the luminosity can be decomposed in two parts: L_0 and L_2, or $L_\parallel$ and $L_\perp$, respectively.

Important example is the Higgs production

$$\sigma(\gamma\gamma \to h_0) \propto 1 + \lambda_\gamma \tilde{\lambda}_\gamma \pm l_\gamma \tilde{l}_\gamma \cos 2\Delta\phi$$

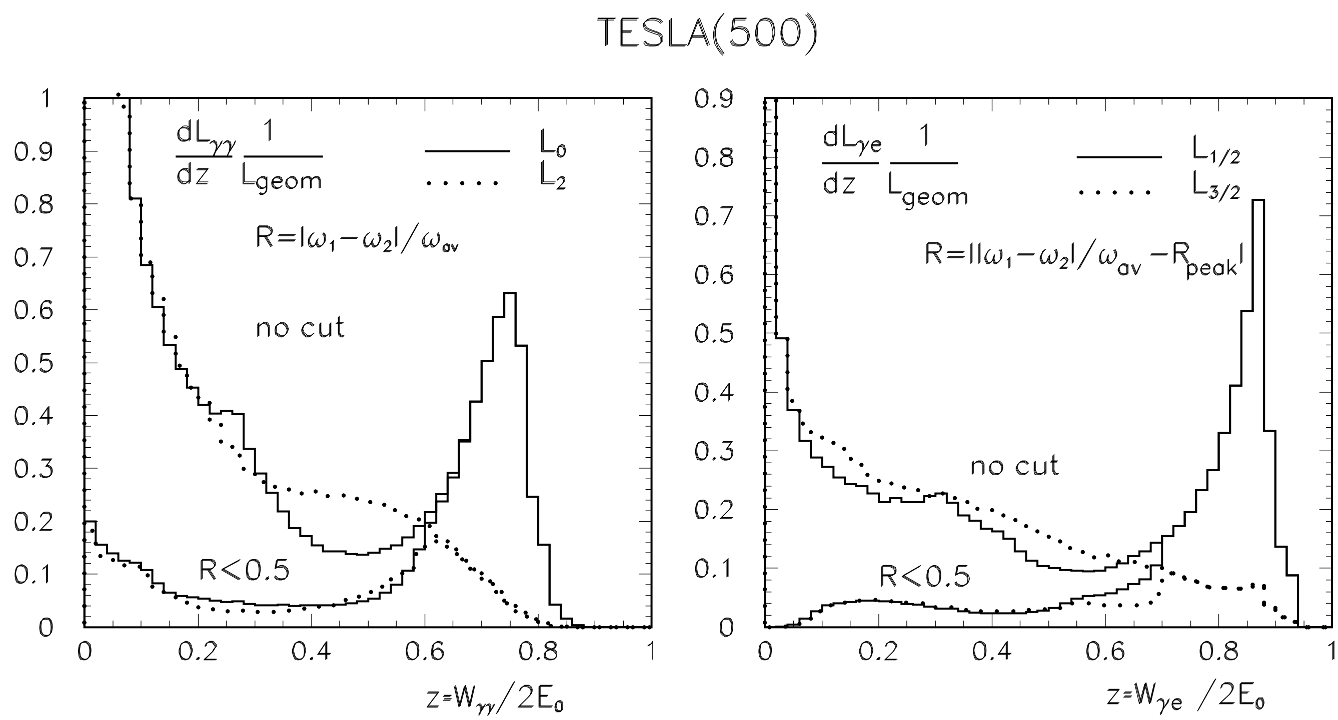
which needs measurement of $dL_0, dL_2, dL_\parallel, dL_\perp$

In γe collisions the picture is quite similar, there are also 16 independent luminosity distributions, though in practice not all are equaly important.

$\gamma\gamma$ and γe luminosity spectra at TESLA(500)

with various cuts on the longitudinal momentum;
0 and 2 are the total helicities of colliding photons
(1/2 and 3/2 in the case of γe collisions)

$\gamma\gamma$ γe



Measurement of $\gamma\gamma$ luminosity using $\gamma\gamma \to l^+l^-(l = e, \mu)$

The cross section

$$\frac{d\sigma}{d(\cos\theta)} = \frac{2\pi\alpha^2}{{W_{\gamma\gamma}}^2}\left[(1-\lambda_\gamma\tilde{\lambda}_\gamma)\frac{(1+\cos^2\theta)}{(1-\cos^2\theta)} - l_\gamma\tilde{l}_\gamma\cos(4\phi - 2(\gamma+\tilde{\gamma}))\right]\frac{d\phi}{2\pi}$$

$\lambda, \tilde{\lambda}$ and $l, \tilde{l}$ are circular and linear polarizations
ϕ asimuthal angle of decay plane
$\gamma, \tilde{\gamma}$ asimuthal angle of linear polarization.

If photons have only circular polarization

$$d\sigma_2 = \frac{4\pi\alpha^2}{{W_{\gamma\gamma}}^2}\;\frac{(1+\cos^2\theta)}{(1-\cos^2\theta)}\,d(\cos\theta)$$

$$d\sigma_0 = 0$$

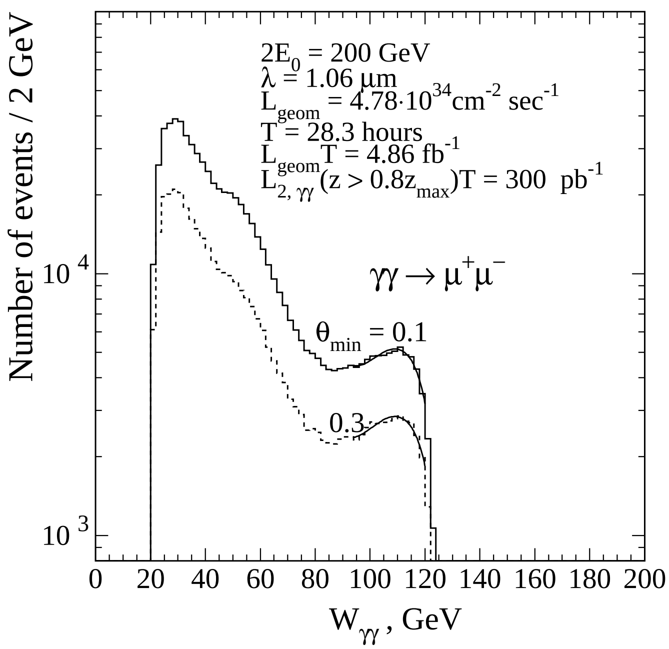
Pair are produced only in collisions of photons with total helicity 2, therefore one can measure only L_2.

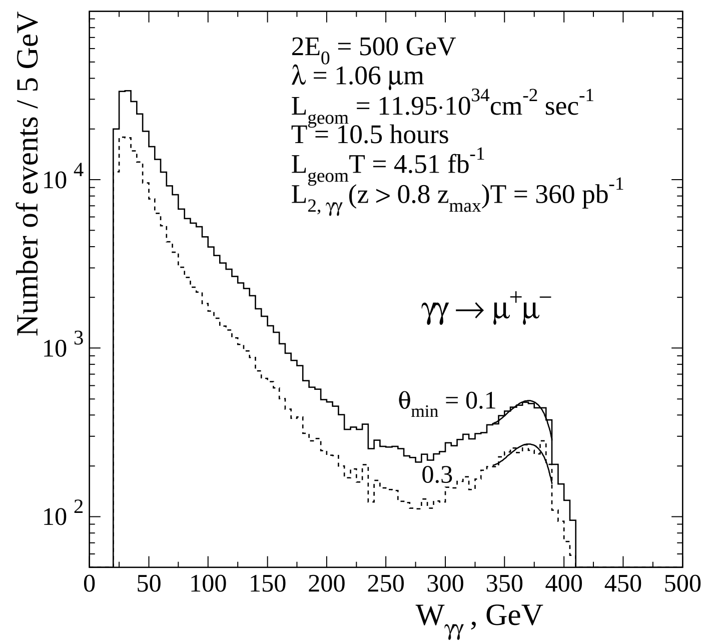
To measure L_0 one has to change polarization of one beam to opposite (part of time)(V.T., LCWS, 1993)

Linear polarizations ($l_\gamma\tilde{l}_\gamma$) can be measured by the azimuthal variation of the cross section at large angles.

Simulation $\gamma\gamma \to l^+ l^-$

$2E_0 = 200(500)$ GeV, other parameters from TESLA TDR. The distribution of detected pairs on invariant mass for 28.3 (10.3) hours runs



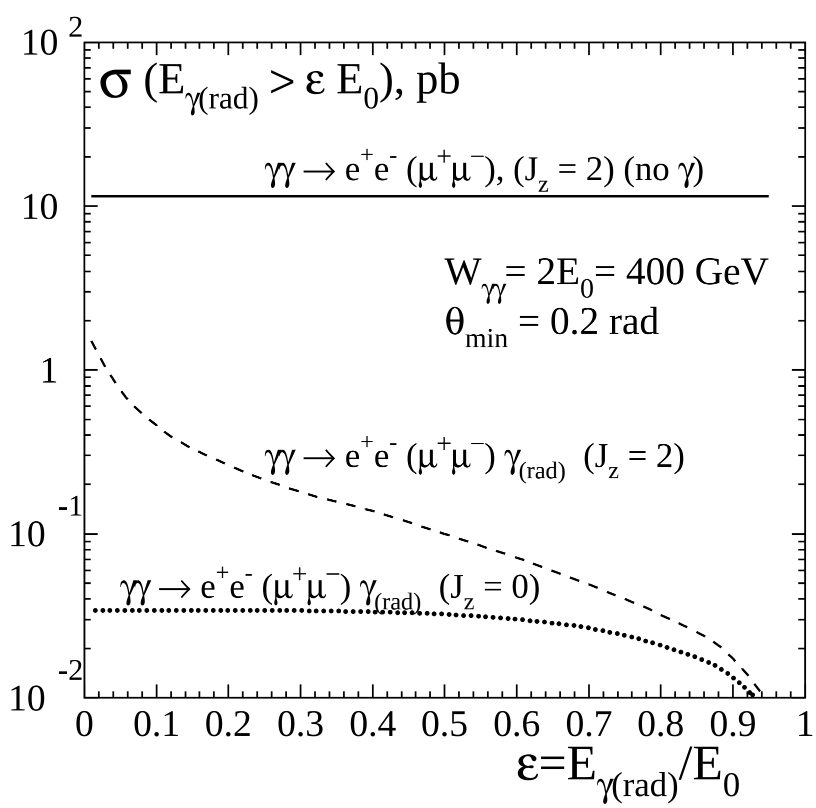


Stat. accuracy of $\frac{dL}{dW_{\gamma\gamma}}$ in the peak (important for the Higgs) is about 0.07–0.14 % ($2E_0 = 200 - 500$ GeV) for one year (10^7 s).

The expected accuracy for SM Higgs $\frac{\sigma(\Gamma_{\gamma\gamma})}{\Gamma_{\gamma\gamma}} \sim$ 1.5%, not limited by (statistical) luminosity uncertainty.

Measurement of $\gamma\gamma$ luminosity with $J_z = 0$ using $\gamma\gamma \to l^+l^-\gamma(l = e, \mu)$

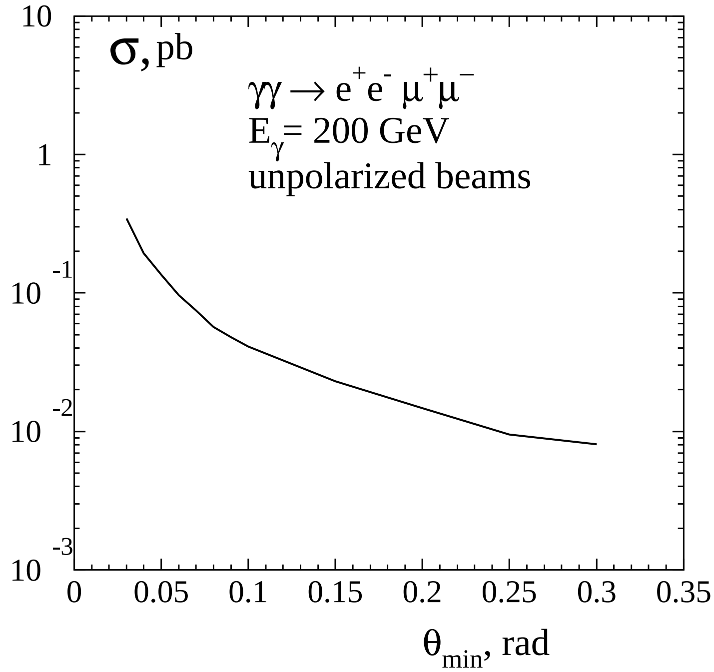
Due to $\sigma_{\gamma\gamma\to l^+l^-} \approx 0$ and necessity of spin-flip for measurement of $L_{\gamma\gamma}(J_z = 0)$ it was of interest to look the same process with additional photon. Calculation was done using ComHEP:



The cross section $\gamma\gamma \to l^+l^-\gamma(J_z = 0)$ is not neglegible, but 300 times lower than allowed proccess $\gamma\gamma \to l^+l^-(J_z = 2)$. Spin-flip of the later process looks much more attractive for measuement of $L_{\gamma\gamma}(J_z = 0)$.

Measurement of $\gamma\gamma$ luminosity using $\gamma\gamma \to l^+l^-l^+l^-(l = e, \mu)$

This process is 4-th order on α but the total cross section is large because proportional to $1/m_l^2$ (instead of $1/E^2$ for $\gamma\gamma \to l^+l^-$). For small angles $\sigma(\gamma\gamma \to l^+l^-l^+l^-) \propto 1/(E\theta)^2$. Calculation was done using ComHEP:



At small angles main contribution gives the peripheral diagram and the cross section is prop. to $1/\theta^2$.
At large angles (above 0.1 rad) main contibution gives the diagram where the second pair is emitted by one of leptons of the first pair.

The region $\theta \geq 20$ mrad with detection of final electrons in the forward calorimeter looks attractive, but obtaining of small systematic errors is problematic.

Resume on measurement of $\gamma\gamma$ luminosity.

The process $\gamma\gamma \to l^+l^-$ has the cross section

$$\sigma \approx \frac{0.95}{W_{\gamma\gamma}{}^2(\text{TeV})}(1 - \lambda_\gamma \tilde{\lambda}_\gamma) \ \text{pb}$$

is the best process for measurement of $\gamma\gamma$ luminosity.

For $\gamma\gamma \to l^+l^-\gamma \ \ (J_z = 0, \ \theta > 0.2)$

$$\sigma \approx \frac{5 \times 10^{-3}}{W_{\gamma\gamma}{}^2(\text{TeV})} \ \text{pb}$$

For $\gamma\gamma \to l^+l^-l^+l^-$

$$\sigma(\theta > 0.15) \sim \frac{3 \times 10^{-3}}{W_{\gamma\gamma}{}^2(\text{TeV})} \ \text{pb}$$

$$\sigma(\theta > 0.02) \sim \frac{0.1}{W_{\gamma\gamma}{}^2(\text{TeV})} \ \text{pb}$$

and it is very large at small angles which are occupied by beam backgrounds.

Measurement of γe luminosity using

$\gamma e \rightarrow \gamma e$

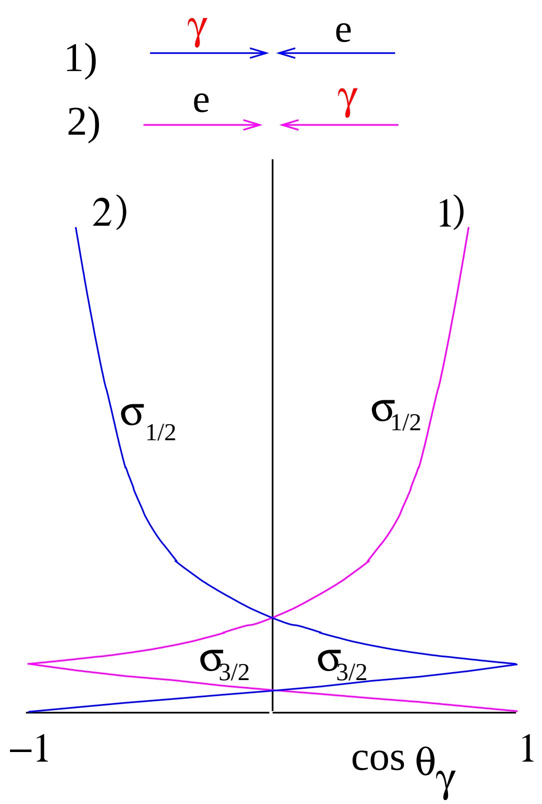
Cross section at $\theta \gg 1/\gamma$

$$\frac{d\sigma}{d\cos\theta_\gamma} = \frac{\pi\alpha^2}{2{W_{\gamma e}}^2}\left[(1-2\lambda_e\lambda_\gamma)(1-\cos\theta_\gamma)+(1+2\lambda_e\lambda_\gamma)\frac{4}{1-\cos\theta_\gamma}\right]$$

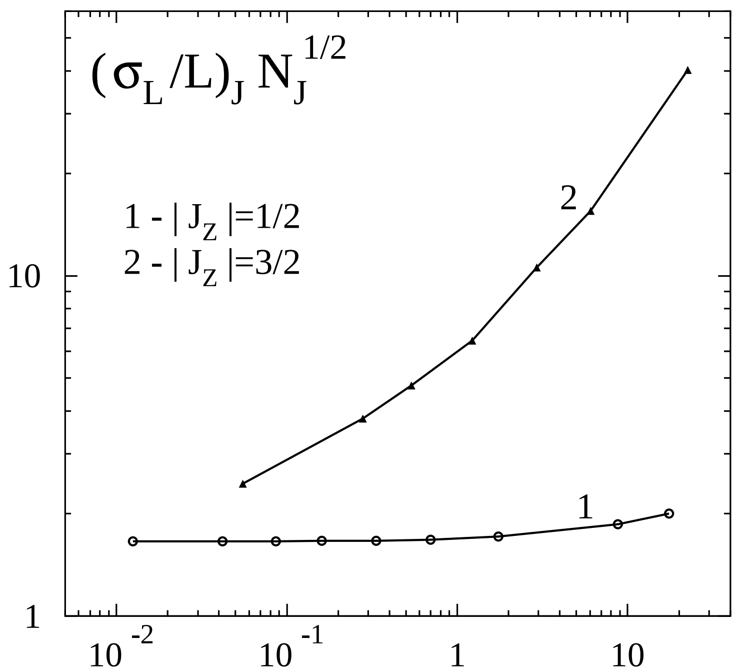
λ_γ circular polarization of the photon
λ_e the electron helicity
z-axis is along the initial direction of the electron
One can see that

$$d\sigma_{3/2} \propto const \times (1-\cos\theta) \quad \ll \quad d\sigma_{1/2} \propto const \times \frac{4}{1-\cos\theta}$$

Additional problem: there are two combinations of γe collisions, these luminosities should be measured separately



The cross section with $J_z = 3/2$ is much lower than for $J_z = 1/2$ at all angles. They can be separated using the angular distribution but statistical accuracy for $J_z = 3/2$ will rather poor:

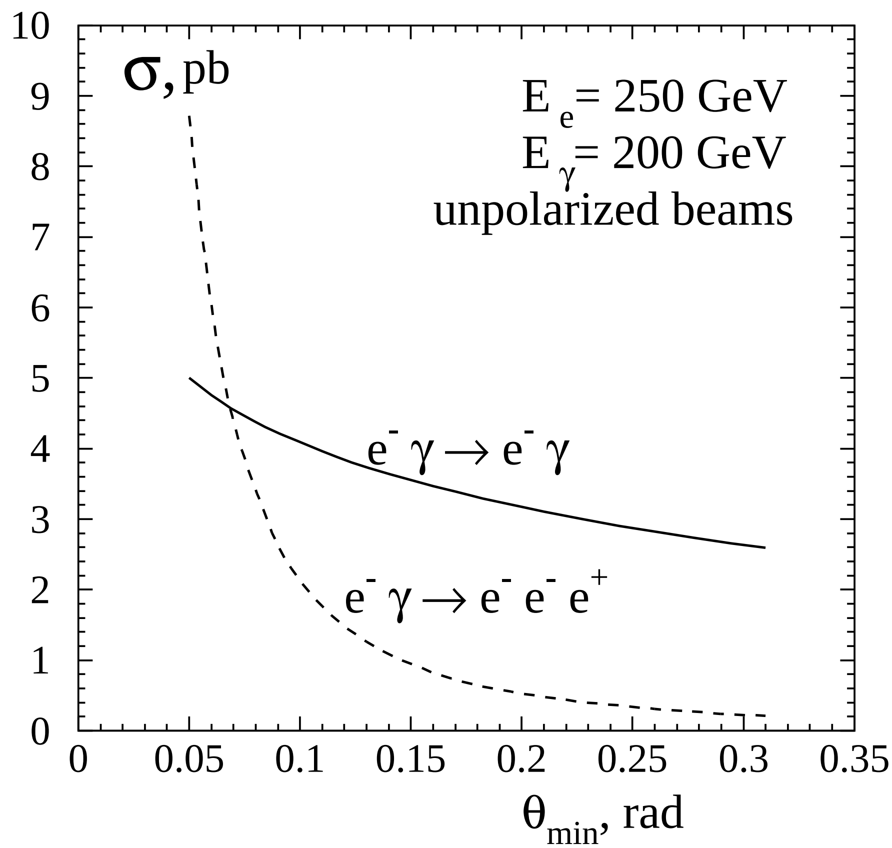


For TESLA(500) and $t = 10^7$ sec $N_{1/2} = 3 \times 10^5$, $N_{3/2} = 5 \times 10^3$. The luminosities $L_{1/2}$ and $L_{3/2}$ are measured with accuraces 0.3% and 20%, respectively.

After inversion of polarization for one of beams $N_{1/2} = 5 \times 10^4$, $N_{3/2} = 3 \times 10^4$ and the accuracies for $L_{1/2}$ and $L_{3/2}$ are 0.8% and 1.8%, respectively. Thus, the measurement with inverted polarization allows to improve the accuracy for $L_{3/2}$ from 20% to 0.8%.

Measurement of γe luminosity using γe $\to e^- e^+ e^-$

The cross section (see below) at $\theta < 70$ mrad is larger than for $\gamma e \to \gamma e$



Together with $\gamma e \to \gamma e$ it allows to measure $L_{3/2}$ with sufficiently good accuracy without the inversion of beam polarizations or can be used for the cross check.

Resume on γe $\to$ γe: studing angular distribution of γe system in c.m.s. system for each $\Delta E_1 \Delta E_2$ bin, one can find the γe luminosities for both mirror combinations, but the accuracy of $L_{3/2}$ will be much worse than for $L_{1/2}$.

One of solutions: similarly to $\gamma\gamma$ collisions the inversion of the polarization for one beam allows to measure $L_{1/2}$ and $L_{3/2}$ with comparable accuracy.

Second solution: to use simultaneously the process γe $\to$ e e^+e^- which depends on polarization differently and very weakly.

Unsolved problem: how to measure λ_e and λ_γ separately?

For example:

$$\sigma_{\gamma\mathrm{e}\to W\nu} \propto (1 - 2\lambda_e)(a + b\lambda_\gamma).$$

The process γe $\to \gamma$e depends on all the photon and electron polarizations, but only at $\theta \sim m_e/E$

One can use γe $\to$ eZ (may be there is better one?)

$W_{\gamma e} \gg M_Z$ $\qquad\qquad$ $W_{\gamma e} \sim M_Z$

$$\sigma \propto \frac{(1 + 2\lambda_e\lambda_\gamma) - 0.2(2\lambda_e + \lambda_\gamma)}{1 - \cos\theta}; \ \sigma \propto \frac{(1 - 2\lambda_e\lambda_\gamma) - 0.2(2\lambda_e - \lambda_\gamma)}{1 - \cos\theta}$$

($\lambda_e\lambda_\gamma$ is known from γe $\to \gamma$e and γe $\to$ e e^+e^-)

How to measure linear polariazations of laser photons in γe collisions? Is it necessary?

Note, photons participating in γe collisions and $\gamma\gamma$ collisons are not the same !

Conclusions

1. $\gamma\gamma$ lumonosity (most important polariazation combinations) can be measured by the process $\gamma\gamma \to l^+l^-(l = \mathrm{e}, \mu)$, inversion of the polarization for one beam is required for measurement of L_0.

The processes $\gamma\gamma \to l^+l^-\gamma$ and $\gamma\gamma \to l^+l^-l^+l^-$ are sensitive to L_0, but the cross sections are rather small.

2. γe luminosity (and the product $\lambda_e\lambda_\gamma$) can be measured using $\gamma \mathrm{e} \to \gamma \mathrm{e}$ and $\gamma \mathrm{e} \to \mathrm{ee^+e^-}$. The first process with spin inversion for one beam is sufficient, then the second one can be used for cross check.

For separate measurement of $\lambda_e, \lambda_\gamma$ one can use the process $\gamma \mathrm{e} \to \mathrm{e}Z$ though the accuracy here will be worser than for the product.

Conclusion remarks,

$\gamma\gamma$ physics: past, present and future

past and present:

$\gamma^*\gamma^* \to X$ at e^+e^- storage rings

$$dn_\gamma \sim 0.03\frac{d\omega}{\omega}$$

$$L_{\gamma\gamma} \ll L_{e^+e^-}$$

$$W_{\gamma\gamma} \ll 2E_0$$

1970 $e^+e^- \to e^+e^-\ e^+e^-$ at Novosibirsk

1972 $\mu^+\mu^-$ at Frascati

1979 η' at SLAC

1980–now — several $\times$ 100 experimental papers from all e^+e^- colliders and detectors. Physics is quite interesting, though no great discoveries.

Future

$\gamma\gamma$,γe at linear colliders

$$n_\gamma \sim n_e$$

$$L_{\gamma\gamma} \sim L_{\mathrm{e^+e^-}}$$

$$W_{\gamma\gamma} \sim W_{\mathrm{e^+e^-}}$$

1973-76	beginning of works on e^+e^- LC at Novosibirsk
1981	idea of photon colliders
1986	Conceptual Design of VLEPP
1988	beginning of Intern. study on LC
1991	beg. of Intern. study on physics and detectors at L
1996	ZERO Design of NLC
1997	Conceptual Dessign of TESLA and JLC
2001	Technical Design of TESLA
2001	Snowmass 2001, LC is the next HEP project
2003(now)	-TESLA has not been approved by German government, future of LC is quite uncertain.

There are 3 regional projects: TESLA, NLC, JLC, (CLIC is next-to next)

Questions: **which one ? where ? when?**

Choice of technology	2004–2005
Choice of place	2005-2006
Beginning of construction	2007-2008
Beginning of e^+e^- experiments	2013-2015
Beginning of $\gamma\gamma$ experiments	2016-2018

It seems, a Linear Collider e^+e^-, $\gamma\gamma$, γe collider is a dream for several generations. Hopefully it will be materialized faster than Leonardo da Vinci's idea of a helicopter.