High energy Photon Collider

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Few words about linear e^+e^- colliders

The advantage of e^+e^- colliders vs hadronic colliders (like LHC) are:

• the ratios of cross sections under interest to the background don't contain small parameter α as it takes place at hadronic colliders (like LHC),

• entire beam energy is used for elementary process, kinematical picture of process is very simple,

The disadvantage of e^+e^- colliders

♦ Much lower cross sections.

♦ Lower beam energy.

The motion of electrons along a curved trajectory is accompanied by a significant synchrotron radiation $\Rightarrow$ at high energy and reasonable size of set up energy loss at one circle can reach initial beam energy – circular collider become impossible.

Conclusion – next generation of e^+e^- colliders should be linear one – linear e^+e^- colliders are discussed since mid of 70-th. Detailed developed project – TESLA (earlier 2000), now 2 main projects are discussed – ILC (perhaps – in Japan) and CLIC (in CERN).

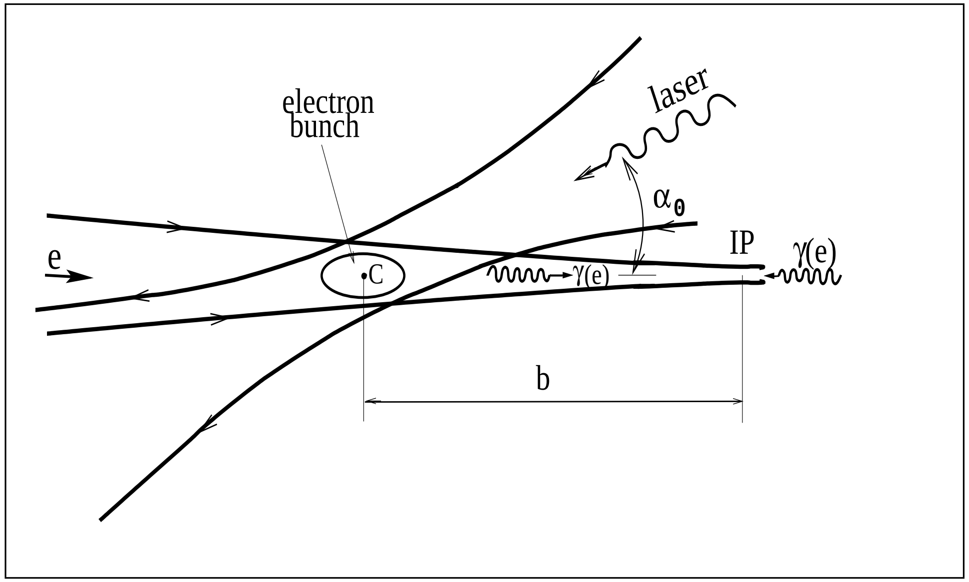
Essential feature of LC – each $e^\pm$ bunch is used here only once.

Real e^+e^- collision can be treated as two step process, first – collided $e^\pm$ radiate photons, physically interesting collision is second step process. Therefore, real energy of electrons, collided in physically interested process is lower than initial beam energy, corresponding spectra of this initial state radiation (ISR) are well known, The averaged spread of the energies of the colliding electrons due to ISR reaches 10% at beam energy about 100-200 GeV.
(This effect is universal for all e^+e^- colliders, both circular and linear).

Technical demand – to have necessary luminosity, sizes of bunches should be low $\Rightarrow$ electromagnetic fields in collision are strong – collective influence for collided beam – one more mechanism of beam energy loss – beamstrahlung (BS), dependent on detail of construction of set up. One can reach energy spread due to BS in few % (in addition to ISR).

Basics

Standard scheme of obtaining photon beam for PLC with laser backscattering (I.F.G., G.L. Kotkin, V.G. Serbo, V.I. Telnov, 1981)



γ_o, ω_o, λ_o – laser photon, its energy and helicity;
e_o, E, λ_e – incident electron, its energy and helicity ($2|\lambda_e| \le 1$).
γ, $\omega \equiv yE$, λ – produced photon, its energy and helicity.

$$x = \frac{4E\omega_0}{m_e^2}, \qquad y < y_m = \frac{x}{x+1}$$

$$w = \sqrt{\frac{4\omega_1\omega_2}{4E^2}} \equiv \sqrt{y_1 y_2}$$ – ratio of the $\gamma\gamma$ cms energy to $\sqrt{s}$.

WIDESPREAD MISTAKE

Differential Luminosity is written as product 2 photon fluxes:

$$L(y_1, y_2 = f_1(y_1) f_2(y_2) \quad ---WRONG$$

In fact, photons of lower energies scatter for larger angles ($\sim 1/\gamma$) and with the growth of distance between b collide more rare than more energetic photons. This effect is easily included in the calculations.

With the growth of distance b between conversion point C and interaction point IP luminosity decreases but monochromaticity improves. In the high energy part these effects are described – even for elliptic beams – single parameter $\rho^2 = \left(\frac{b}{\gamma\sigma_x}\right)^2 + \left(\frac{b}{\gamma\sigma_x}\right)^2$ (I.F.G., Kotkin. Eur. Phys. J. **C 13** (2000) 295).

With the growth of x quality of high energy photon collision improves.

For the most suitable to the moment laser with $\omega_o \approx 1$ eV at $E = 250$ GeV we have $x = 4.5$.

So – many studies on details of design and using of PLC at $x < 5$

In the first papers (GKST 1981,)

$x = 4.8$ – boundary, at higher x some of produced photons γ disappear in the killing process $\gamma\gamma_o \to e^+e^-$.

How to come to larger energy?

Two possible ways: 1) To use new laser with correspondingly lower photon energy, e.g. FEL

2) To use existent laser material with some reduction of $\gamma\gamma$ luminosity. We discuss second way

(was mentioned: Telnov, NIMR (2001), I.F.G., Kotkin (Photon2009))

Main point:

To leave idea about obtaining maximal luminosity in favor of quality of photon collisions.

Using relatively small conversion coefficient,

we will have reasonable luminosity with sharp energy distribution.

Below laser beam is supposed to be wide enough, i.e. uniform in entire electron bunch. Optical length of laser bunch for electrons is expressed via density of photons n_L and total cross of Compton scattering $\sigma_C(x, \Lambda_0)$,

$$\boxed{\Lambda_0 = 2\lambda_o\lambda_e}, \quad \boxed{z = 2c\sigma_C(x, \Lambda_0)n_L}.$$

The number of electrons $n_e(z)$ decreases with the growth of z

$$n_e(z) = n_{eo}e^{-z}$$

We express luminosity via L_{geom} – luminosity of e^+e^- collider improved for $\gamma\gamma$ mode.

At $x \leq 4.8$

At $\Lambda_0 = -1$ energy spectrum is shifted to high energy bound $\omega = y_m E$, $y_m \leq 0.83$, high energy photons are mainly polarized with the same direction of spin as laser photons.
At $z = 1$ total luminosity $L_{\gamma\gamma} = \left[(1 - e^{-1})^2 = 0.4\right] L_{geom}$.
At not too small z low energy part of photon spectrum is modified due to rescatterings – production of photons in the collision of electron after first collision with the next laser photon.
Increase of ρ decreases the low energy part of luminosity.
At $x = 4.8$ and $\rho = 1$ the high energy photon luminosity

$$L_{\gamma\gamma}(w > 0.6, \Lambda_0 = -1, \rho = 1) = 0.12 L_{geom}.$$

With the growth of ρ this quantity decreases fast,

$$L_{\gamma\gamma}(w > 0.6, \Lambda_0 = -1, \rho = 5) = 0.03 L_{geom}.$$

At $\Lambda_0 = 1$ high energy fraction of cross section is much smaller.

At $x \geq 4.8$

Main processes:

(I) $e_o\gamma_o \to e\gamma$ (main process),

(II) $e\gamma_o \to e\gamma$ (rescattering)

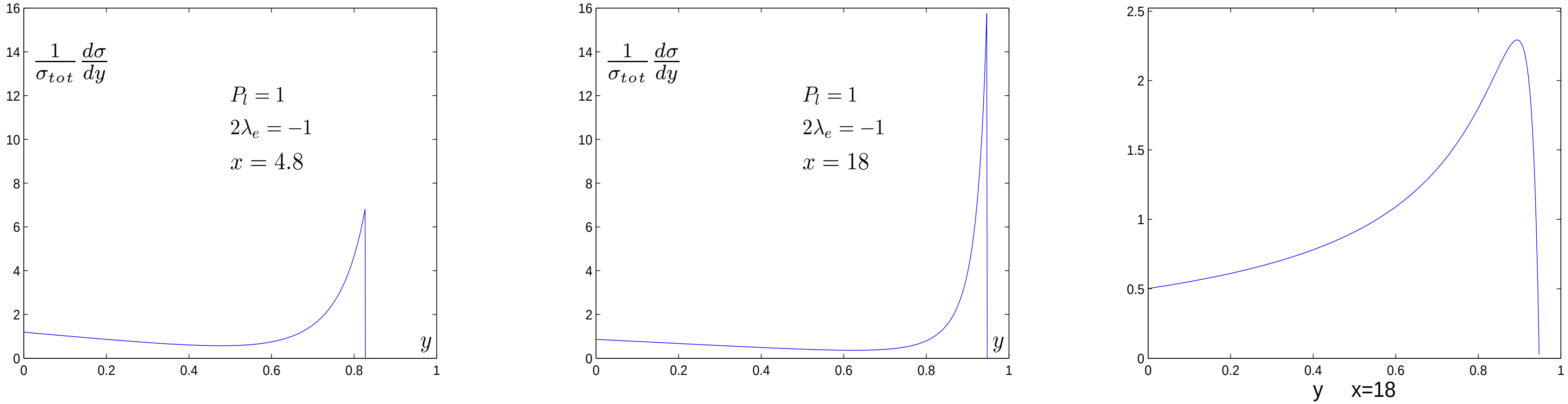
(III) $\gamma\gamma_o \to e^+e^-$ (killing process),

(IV) $e^\pm\gamma_o \to e^\pm\gamma$ (parasitic process).

Processes (I) and (II) are the same at all x, processes (III) and (IV) are new.

Processes (II) and (IV) influence only for low energy part of spectrum, their impact not very high at considered small conversion coefficients.

Process $e\gamma \to ee^+e^-$ (Bethe-Heitler) is dominant at $x > 100 \div 300$



Compton spectra of photons. Left – $x = 4.8$ $\Lambda_0 = -1$, center – $x = 18$, $\Lambda_0 = -1$, right – $x = 18$, $\Lambda_0 = 1$.

At $x = 18$, $\Lambda_0 = -1$ the spectrum is concentrated in the narrow region $0.85 < y \equiv \omega/E < 0.95$, initial monochromaticity $\Delta\omega/\omega_m < 0.05$.

At $x = 18$, $\Lambda_0 = 1$ it is even more flat than that in the "classical case" $x = 4.8$, $\Lambda_0 = -1$

Basic equations (processes I and III) – at fixed x and Λ_0

Evolution of number of electrons: $n_e(z) = n_{eo}e^{-z}$

Denote $f(x,y) = \dfrac{d\sigma_c/dy}{\sigma_C}$ and $\lambda_C(y)$ – polarization of photon in Compton:

$$\frac{dn^2_{\gamma\pm}}{dzdy} = \frac{1}{2}\left(1 \pm \lambda_C(y)\right) f(x,y) n_e(z) - \frac{dn_{\gamma\pm}}{dy}\frac{\sigma_{\gamma\gamma_0\to e^+e^-}(xy, \pm\lambda_0)}{\sigma_C(x)}$$

Solution:

$$\frac{dn_{\gamma\pm}}{dy} = f(x,y) n_{e0} \nu_\pm(z,y); \quad \nu_\pm(z,y) = \frac{1}{2}\left(1 \pm \lambda_C(y)\right) \cdot \frac{e^{-\zeta_\pm z} - e^{-z}}{1-\zeta_\pm};$$

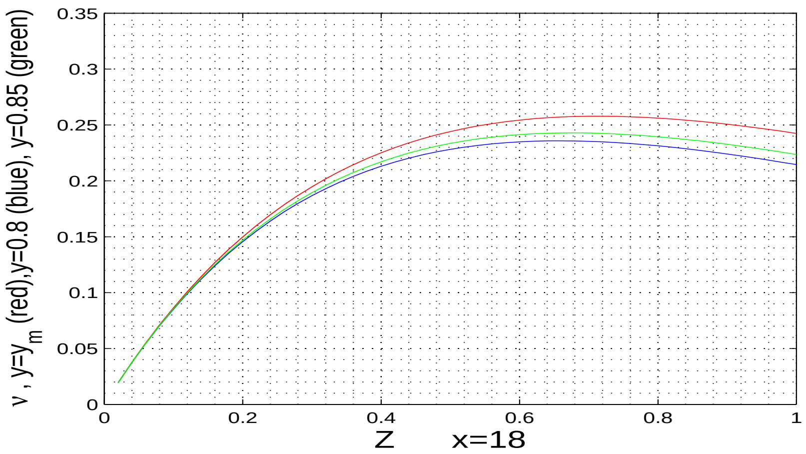
$$\text{where } \zeta_\lambda = \frac{\sigma_{\gamma\gamma_0\to e^+e^-}(xy, \lambda\lambda_0)}{\sigma_C(x)}, \;\; \lambda = \pm$$

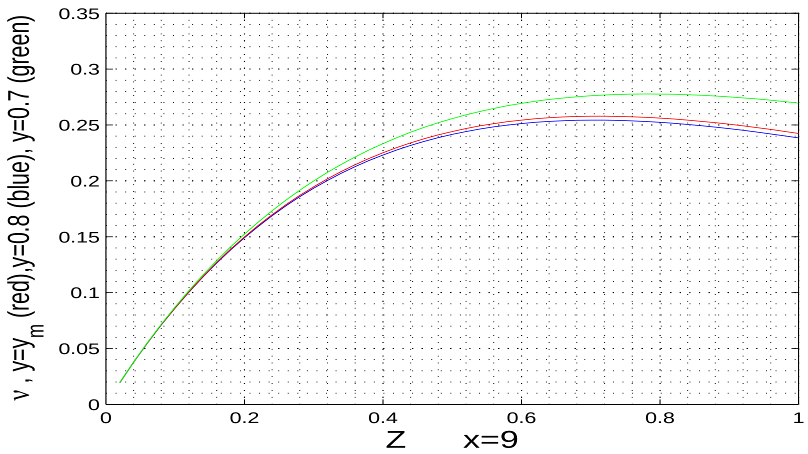
Number of photons and their mean polarization are

$$\frac{dn_\gamma}{dy} = f(x,y)\nu(z,y); \;\; \nu(z,y) = \nu_+(z,y) + \nu_-(z,y),$$

$$\langle\lambda\rangle = \frac{\nu_+(z,y) - \nu_-(z,y)}{\nu(z,y)}.$$

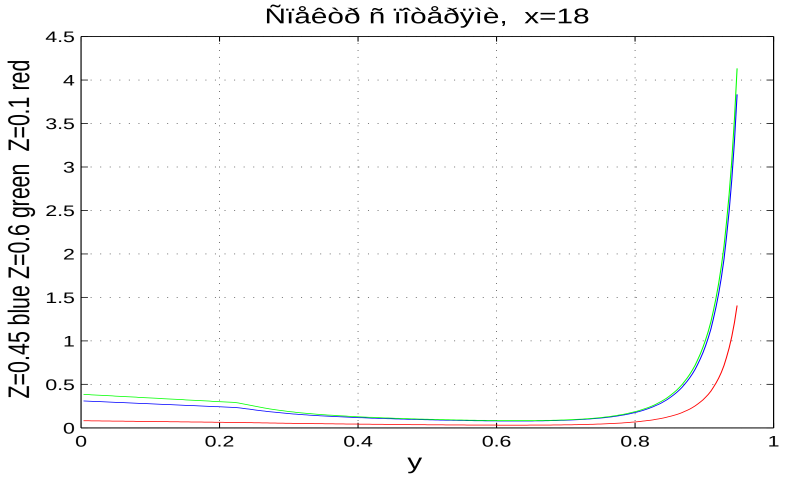
Since at $x = 18$, $\Lambda_0 = -1$, the spectrum is concentrated in the narrow region $0.85 < y \equiv \omega/E < 0.95$, to find optimal optical length it is sufficient to consider spectra a y near y_m only. (At $\Lambda_0 = 1$ another approach is necessary.)





1) Curves have maximum; 2) very flat near maximum
3) at $x = 18$ optimal $z \approx 0.6$, $z \approx 0.45$ is also not bad,
at $x = 9$ optimal $z \approx 0.7$.

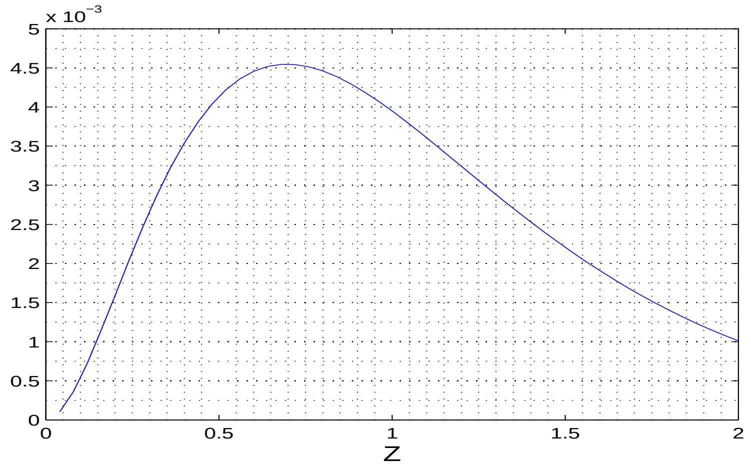
Photon energy spectrum with Compton backscattering and killing process at $z = 0.6,\ 0.45,\ 0.1$.
(That is also luminosity spectrum for $e\gamma$ collisions.)

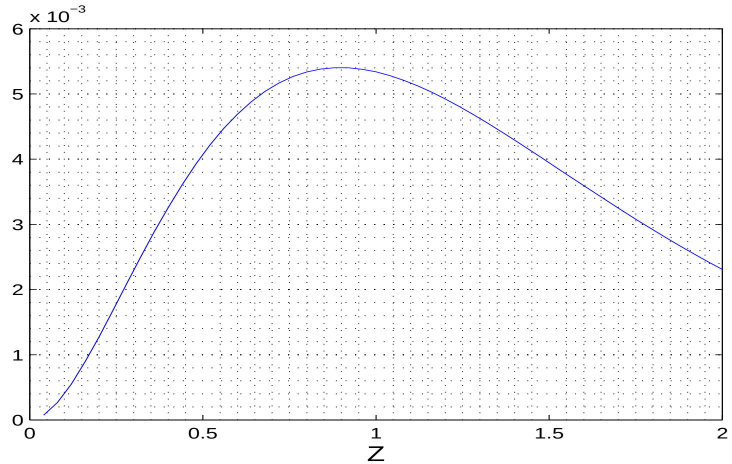


Other processes (rescattering and parasitic process) influenced only to soft part of spectrum, their effect is relatively small due to small number of electrons collided with laser photons ($0.44 n_{eo}$) and have more wide angular distribution, what results in additional decreasing of small part of luminosity spectrum.

$\gamma\gamma$ luminosity

To find the best for luminosity optical length, we consider dependence on $\gamma\gamma$ luminosity on z at typical $\rho = 1$.





$(x = 18, \Lambda_0 = -1, \rho = 1, w > 0.8)$. $(x = 18, \Lambda_0 = 1, \rho = 1, w > 0.6)$.

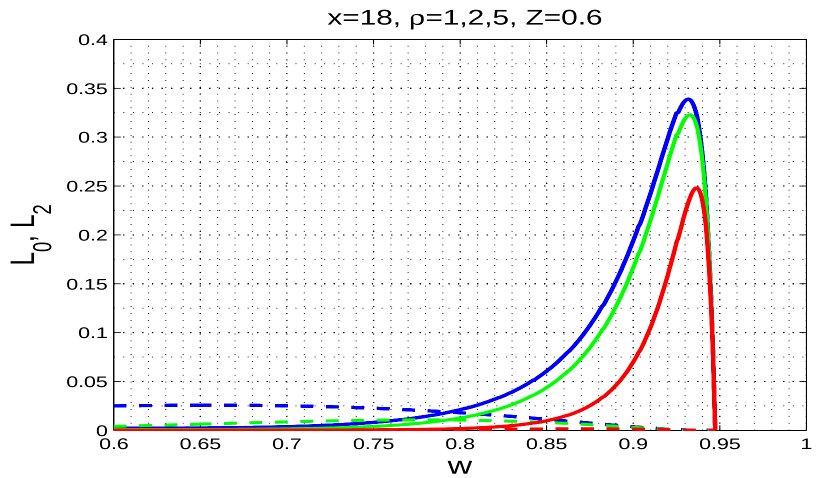
At $\Lambda_0 = -1$ the luminosity maximum is reached at approximately the same z, as it was found for spectra.

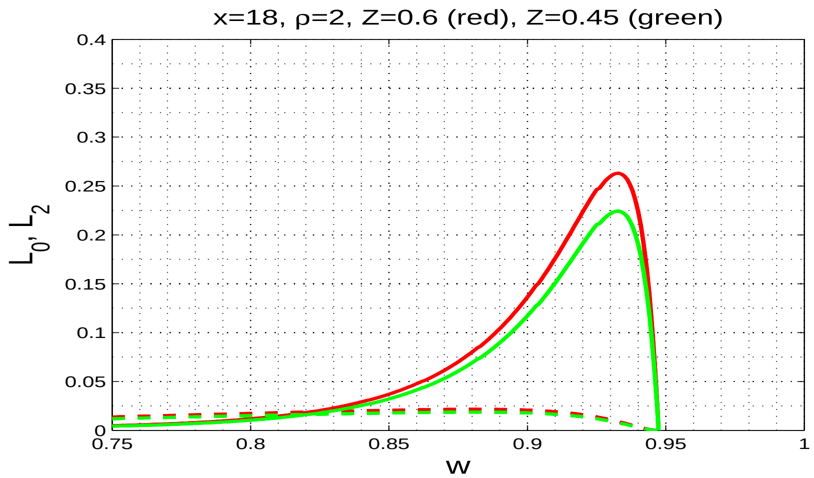
At $\Lambda_0 = 1$ the luminosity maximum is reached at larger value $z \approx 0.9$, it demands larger laser flash energy.

x	w_{min}	z_m	$z_{0.9}$	$A(z_m)/A_0$	$A(z_{0.9})/A_0$
9	0.7	0.704	0.49	1.15	0.8
18	0.75	0.609	0.418	1.7	1.17
100	0.94	0.48	0.32	6.3	4.2

Optimized optical length and necessary laser flash energy at $\Lambda_C = -1$

Luminosity distributions L_0 (full) and L_2 (dotted) at $\Lambda_0 = -1-$ in L_{geom}





Left $\rho = 1$ – blue, $\rho = 2$ – green, $\rho = 5$ – red;
right $\rho = 2$ $z = 0.6$ (red) and $z = 0.45$ (green)

We discuss luminosity integral $L_y(x, \rho, z) \equiv \int_y^{y_m} L^{0,2}(x, z) dy$ and maximal luminosity $L_m(x)(x, z) \equiv max\left(L^{0,2}(x, z)\right)$

In the tables below

$\mathcal{L}(w_{min}) = \int\limits_{w_{min}}^{1} L(w)dw$ – total luminosity of high energy peak,

$L_m = L(w_m)$ – maximal differential luminosity,

w_m – position of maximum in luminosity,

$w_\pm$ – solutions of equation $L(w_\pm) = L(w_m)/2$,

$\gamma_w = (w_+ - w_-)/w_m$ – relative width of obtained peak.

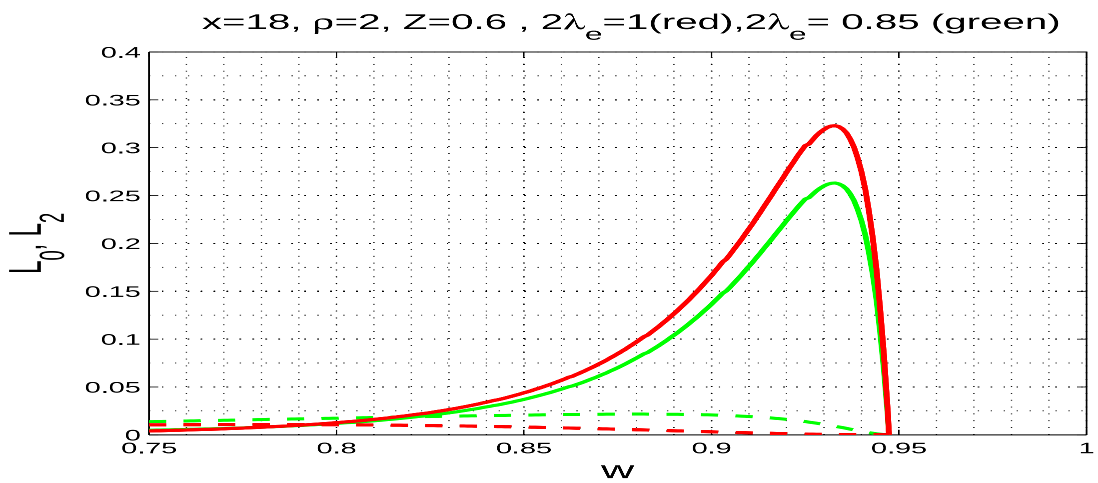
L_2/L – fraction of contribution with non-leading total helicity 2.

$\mathcal{L}(w_{min})$	L_2/L	L_m	w_m	w_-	w_+	γ_w
$\gamma\gamma$: $x = 4.5$, $z = 1$, $w_{min} = 0.6$						
0.121	0.143	0.933	0.779	0.689	0.809	0.154
0.031	0.041	0.464	0.799	0.760	0.814	0.067
$\gamma\gamma$: $x = 9$, $z = 0.704$, $w_{min} = 0.7$						
0.0214	0.079	0.222	0.872	0.814	0.894	0.092
0.072	0.021	0.137	0.885	0.854	0.896	0.048
$\gamma\gamma$: $x = 18$, $z = 0.609$, $w_{min} = 0.75$						
0.0178	0.089	0.2615	0.9317	0.8932	0.9436	0.055
0.074	0.021	0.190	0.365	0.9138	0.9447	0.033
$\gamma\gamma$: $x = 100$, $z = 0.477$, $w_{min} = 0.94$						
0.0093	0.017	0.527	0.9867	0.9771	0.9890	0.012
0.0070	0.009	0.519	0.9867	0.9793	0.9890	0.0097

Properties of high energy $\gamma\gamma$ luminosity for different x and $\Lambda_C = -1$, data for $\rho = 1$ (up) and $\rho = 5$ (down).

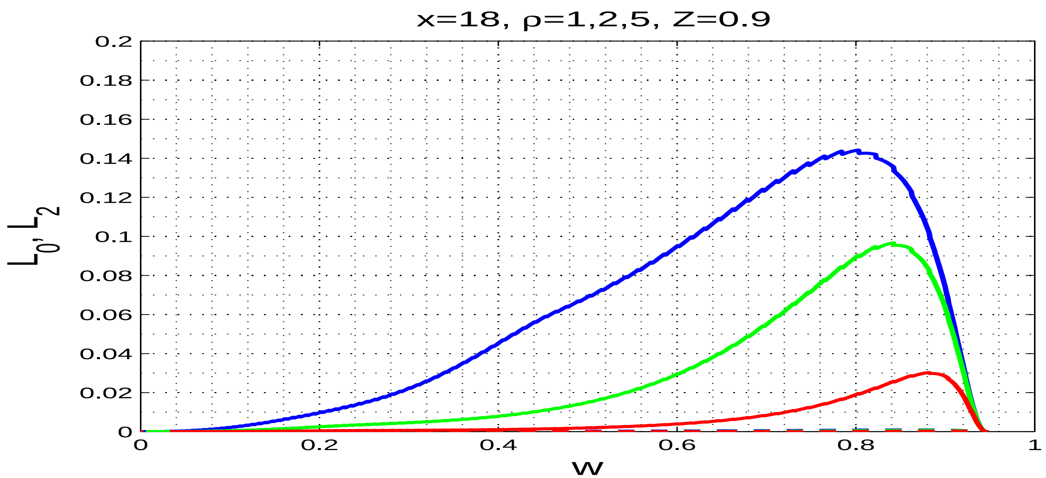
Main observations

1. At $\rho = 1$ for total helicity 0, luminosity integral is only 6 times less than that for $x = 4.8$, $z = 1$ and more wide interval of y, $L_{0.6}(4.8, z = 1)$, maximal luminosity $L_m(18, z = 0.6) = 0.339$ is only 3.5 times less than that for $x = 4.5$, contribution of total helicity 2 is much lower.
2. With the growth of ρ the $\gamma\gamma$ collisions become monochromatic in both energy and polarization (at $\rho = 5$ contribution L_2 disappears practically). Decrease of luminosity with ρ is weaker than that at smaller x.
3. Luminosity decreases weakly at decreasing z from 0.6 to 0.45 (decreasing necessary laser flash energy from $1.6A_0$ to $1.2A_0$.)



Luminosity distributions L_0 at $x = 18$, $\rho = 2$, $\Lambda_0 = -1$ (red) and $\Lambda_0 = -0.85$ $\Downarrow$.

Non-ideal polarization of initial electron reduces luminosity markedly



Luminosity distributions $L_0 + L_2$ at $\Lambda_0 = 1$,
$\rho = 1$ – blue, $\rho = 2$ – green, $\rho = 5$ – red.

The maximal value of luminosity is reached at $z = 0.9$, which needs laser flash energy $1.7A_0$.

This distribution is much more flat than that at $\Lambda_0 = -1$.
$\Rightarrow$ Luminosity integral for more wide interval $L_{0.6}(18, \rho, z = 0.9)$ is larger than that for $\Lambda_0 = -1$ ($L_{0.6}(18, \rho = 1, z = 0.9) = 0.038$; $L_{0.6}(18, \rho = 2, z = 0.9) = 0.0215$; $L_{0.6}(18, \rho = 5, z = 0.9) = 0.0966$).
However maximal luminosity $L_m(x = 18, \rho, z = 0.9)$ is smaller than that for $\Lambda_0 = -1$, $z = 0.6$ ($L_m(x = 18, \rho = 1, z = 0.9) = 0.125$, $L_m(x = 18, \rho = 2, z = 0.9) = 0.0966$,
$L_m(x = 18, \rho = 5, z = 0.9) = 0.0302$.

Summary I

1. LC with beam energy E above 250 GeV allows to construct photon collider (PLC) with the aid lasers and optical systems used for construction PLC at $E \leq 250$ GeV - HE PLC.

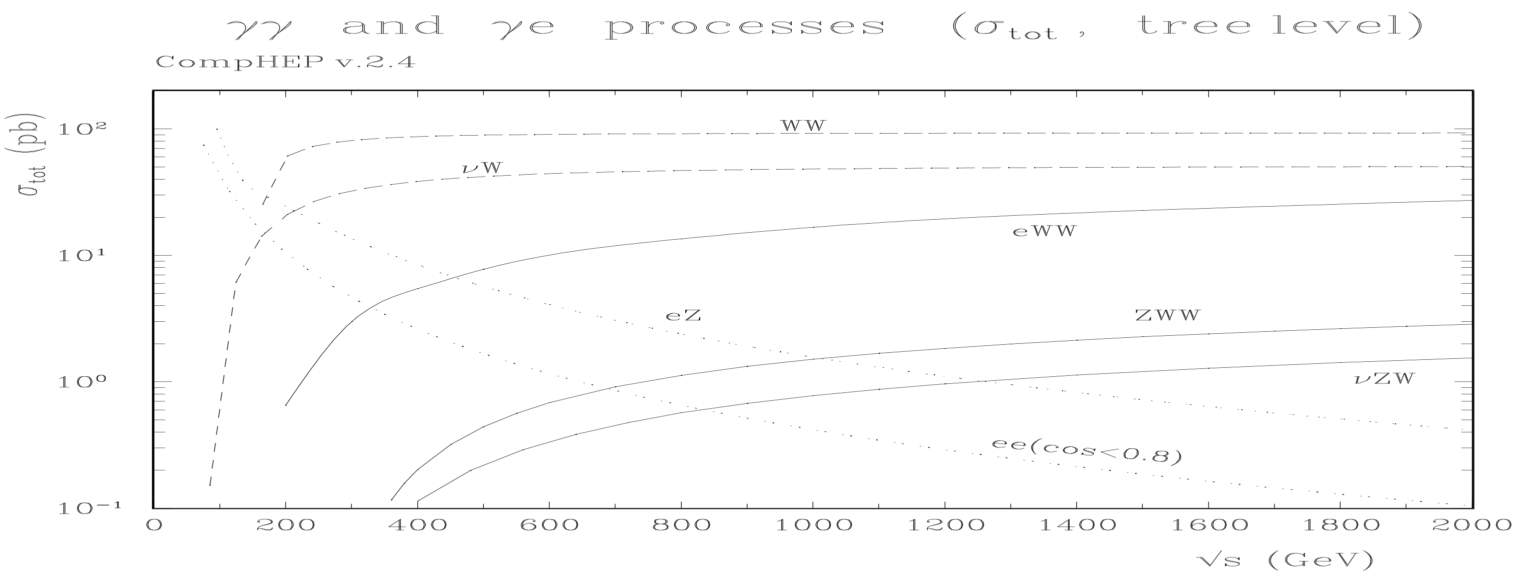
2. In HE PLC at electron beam energy $E = 1$ TeV maximal photon energy $\omega_m = 0.95$ TeV, the $\gamma\gamma$ luminosity distribution is concentrated near upper bound with accuracy 5%, almost all photons have identical helicity (+1 or -1). Total luminosity integral for this high energy part of spectrum is about $0.02 L_{geom}$ (annual > 10 fb^{-1}), what is only 5 times less than that for "regular case" $E = 250$ GeV but integrated for much more wide region of effective $\gamma\gamma$ masses. Maximal $\gamma\gamma$ luminosity of this HE PLC is only triple lower than that for "regular case" $E = 250$ GeV. The necessary laser flash energy is $1.6 A_0$, where A_0 is that for "regular case" $E = 250$ GeV.

Some physical problems for HE PLC

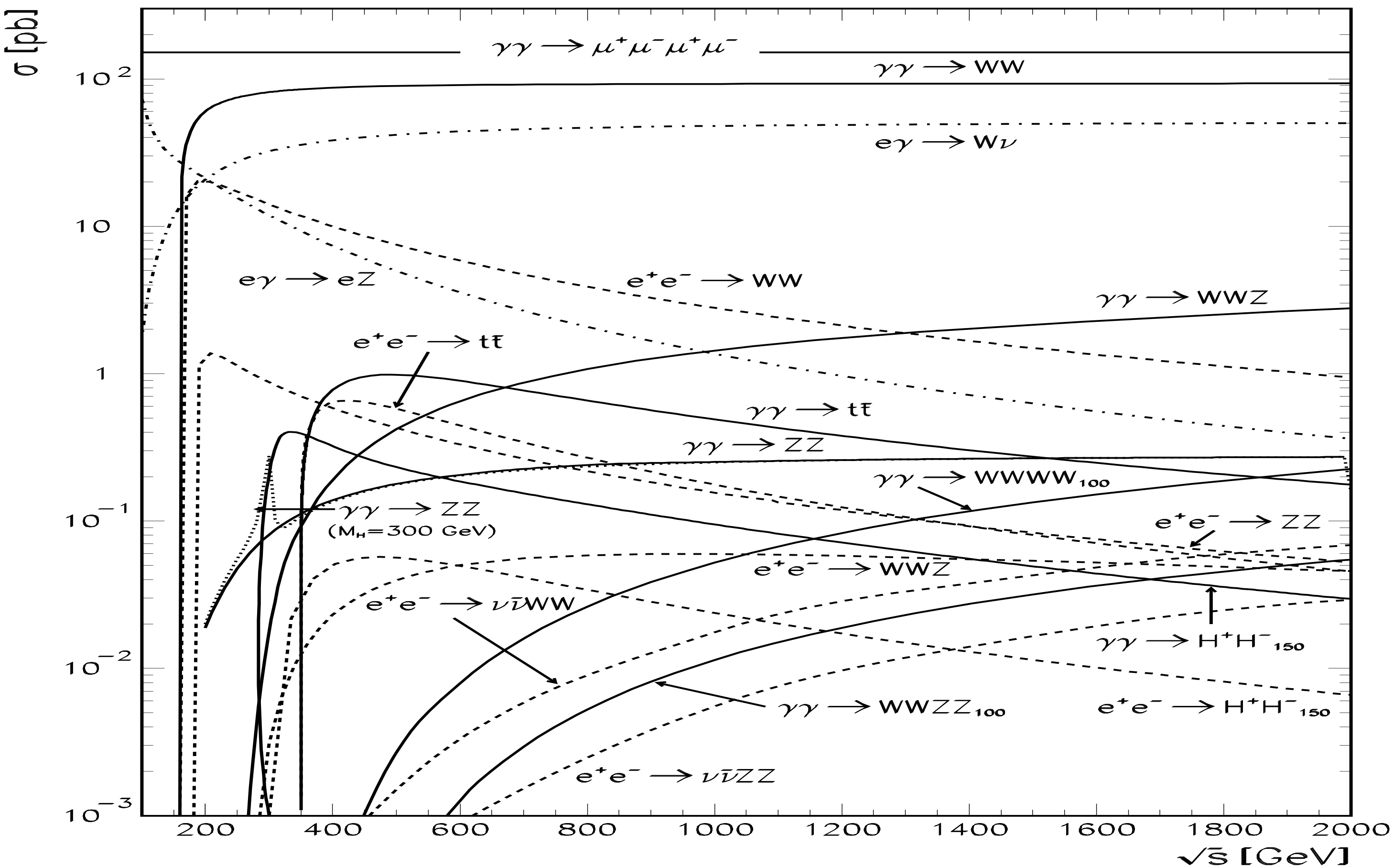
(operated AFTER LHC and e^+e^- LC)

1. LHC and e^+e^- LC will obtain many results for Higgs physics, gauge boson physics. PLC complement these results and improve precision of some fundamental parameters. If some new particles would be discovered, PLC allow improve precision in the knowledge of their properties (see report of Krawczyk for Higgs, in particular),

2. Multiple production of gauge bosons have relatively large cross sections, these processes are sensitive to inner details of gauge boson interactions (which cannot be seen in another way) and possible anomalous interactions. Nothing similar can be seen at other colliders.



Processes of 2-nd and 3-rd order



Processes of 2-nd, 3-rd and 4-th order

3. Photon structure function W_γ (in $e\gamma$ mode). At large enough Q^2 point-like part should dominate. Here theory predict quantities, measurable WITHOUT PHENOMENOLOGICAL PARAMETERS (Witten, 1977). (In the modern studies accuracy is very low, and hadron-like part dominates.) That is unique test of QCD, without phenomenological assumptions.

4. In a number of extended models for Higgs sector, allowing modern data (including models for Higgs-like Dark Matter – IDM) some of Higgs-like scalars can interact strong. In this case strongly interacting Higgs-like sector can generate resonances similar to pions (well known theories of strongly interacting Higgs sector). In particular, in such case resonances with spin 0 and 2 and mass $1\div 2$ TeV can exist. The HE PLC can separate such resonances at suitable choice of direction of polarization of initial electron and laser photon.

Summary II

The HE PLC have field of important studies which cannot be covered other machines