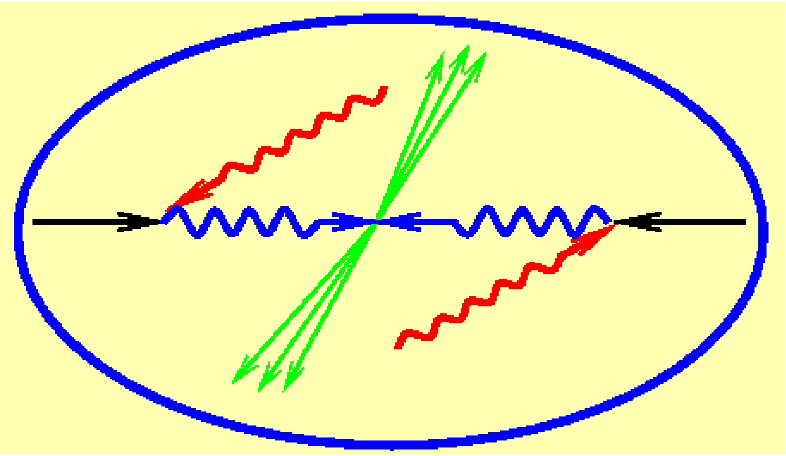

Perspectives of γγ colliders, physics potential and limits

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Budker INP and Novosibirsk State Univ.

Snowmass 2021 AF1 Physics Limit of Ultimate Beams Workshop, Feb. 19, 2021

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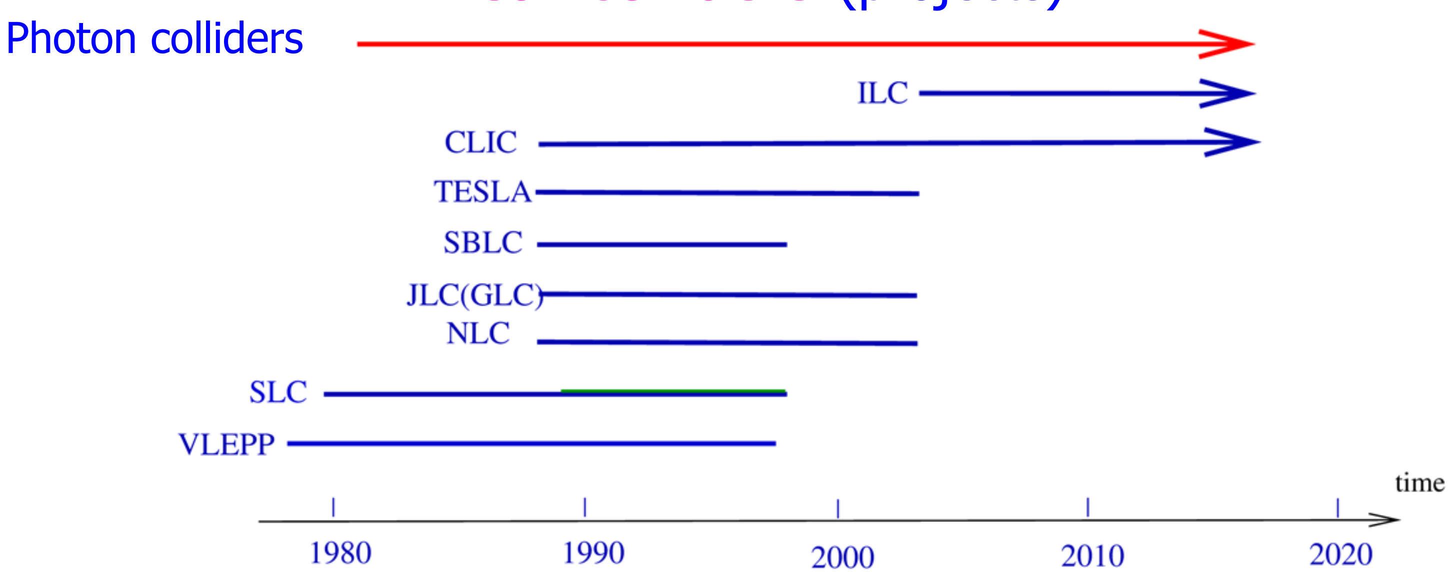
Idea of the photon collider (1981) based on one pass linear colliders

The idea of the high energy photon collider was proposed at the first workshop on physics at linear collider VLEPP (Novosibirsk, Dec. 1980) and is based on the fact that at linear e^+e^- (e^-e^-) colliders electron beams are used only once which makes possible to convert electron beam to high energy photons just before the interaction point.

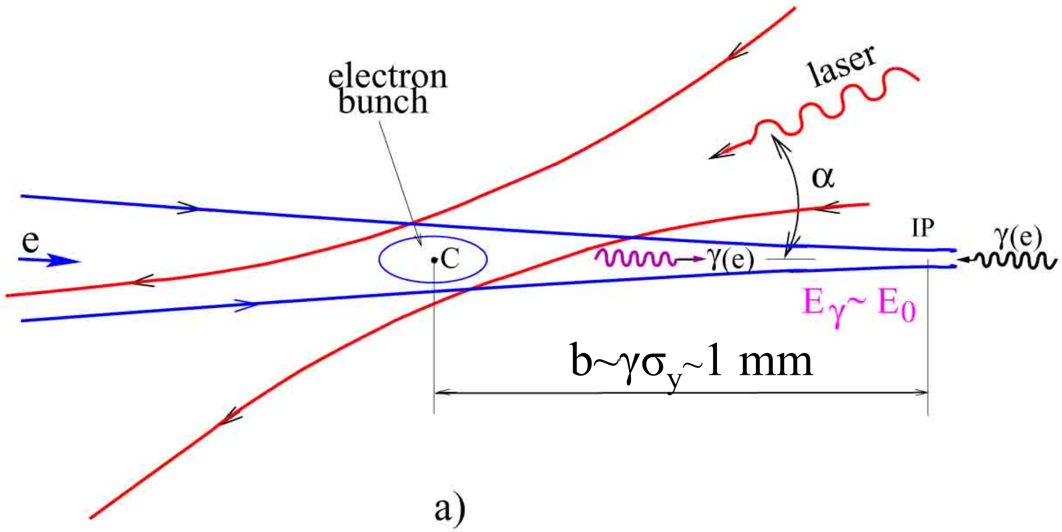
The best way of $e \to \gamma$ conversion is the Compton scattering of the laser light off the high energy electrons (laser target). Thus one can get the energy and luminosity in $\gamma\gamma$, γe collisions close to those in e+e- collisions: $E_\gamma \sim E_e$; $L_{\gamma\gamma} \sim L_{e\text{-}e\text{-}}$

Linear colliders (projects)



Scheme of $\gamma\gamma$, γe collider

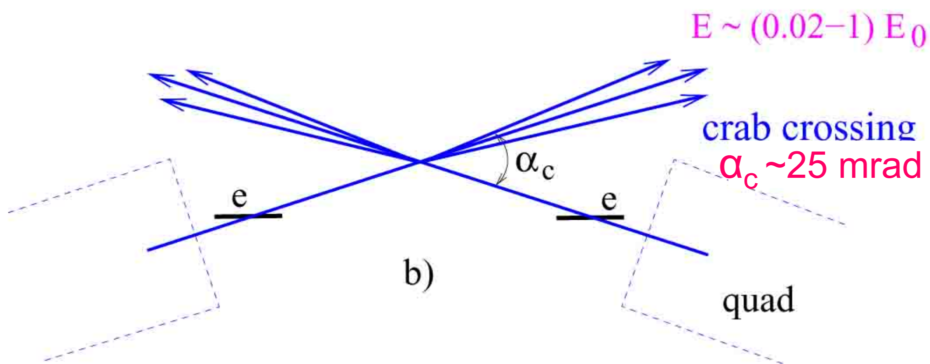
GKST 1981



$$\omega_m = \frac{x}{x+1} E_0$$

$$x \approx \frac{4E_0\omega_0}{m^2c^4} \simeq 15.3 \left[\frac{E_0}{\mathrm{TeV}}\right]\left[\frac{\omega_0}{\mathrm{eV}}\right]$$

$E_0 = 250$ GeV, $\omega_0 = 1.17$ eV
($\lambda = 1.06\ \mu$m) $\Rightarrow$
x=4.5, ω_m=0.82E_0=205 GeV



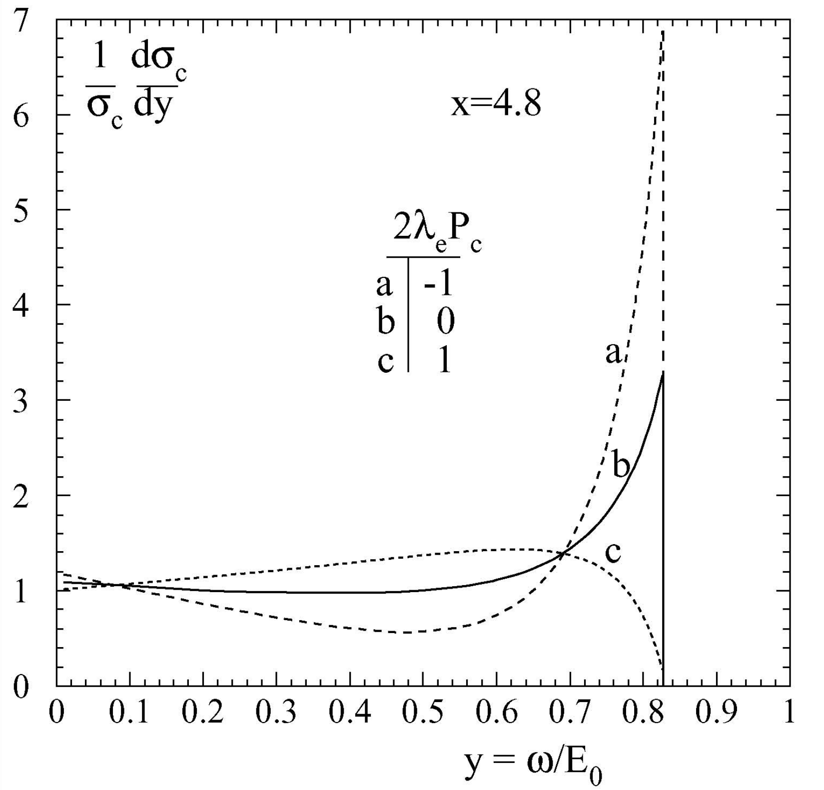
$x = 4.8$ is the threshold for $\gamma\gamma_L \to e^+e^-$ at conv. reg.

$\omega_{max} \sim 0.8\ E_0$

$W_{\gamma\gamma,\ max} \sim 0.8 \cdot 2E_0$
$W_{\gamma e,\ max} \sim 0.9 \cdot 2E_0$

Electron to Photon Conversion

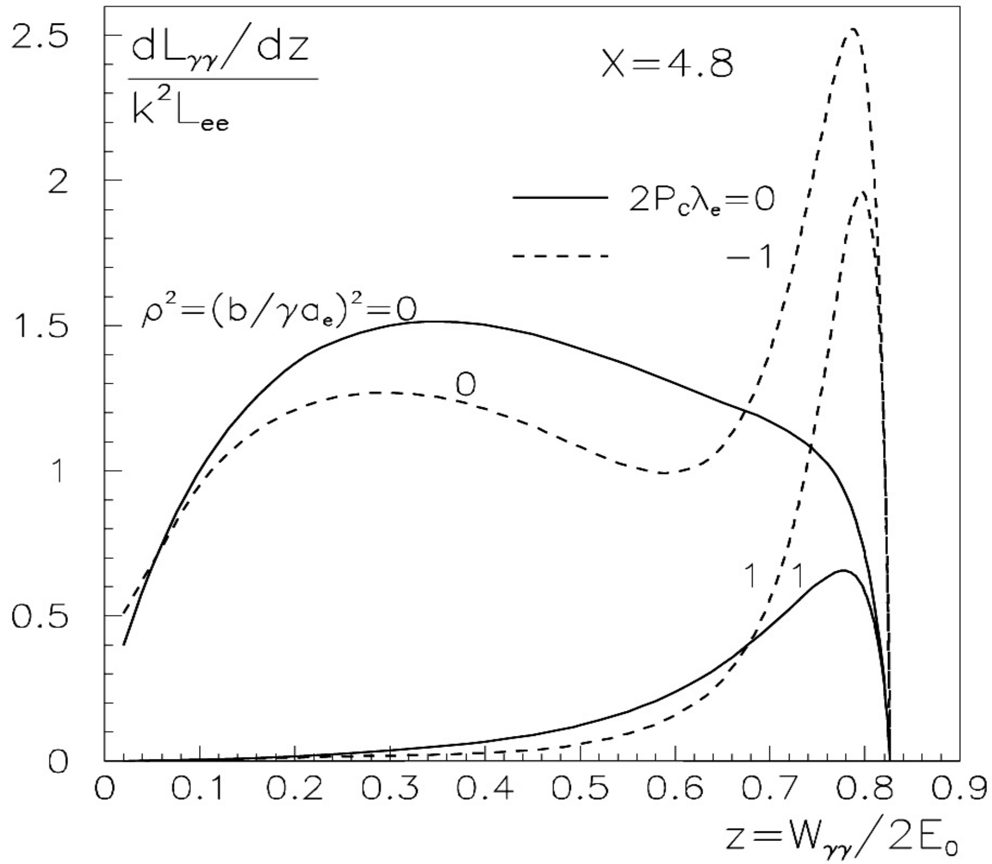
Spectrum of the Compton scattered photons



λ_e – electron longitudinal polarization
P_c – helicity of laser photons, $x \approx \frac{4E_0\omega_0}{m^2c^4}$

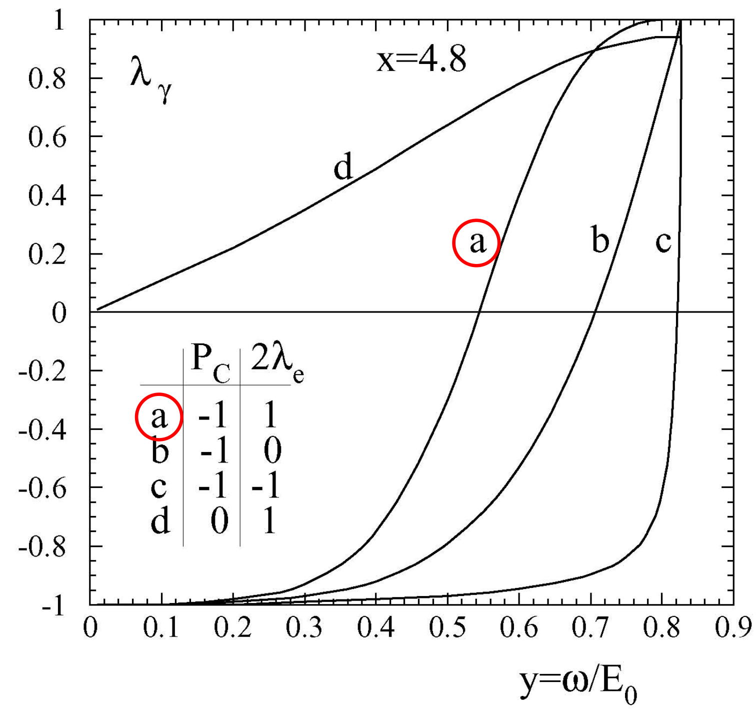
The electron polarization increases the number of high energy photons nearly by factor of 2).

Idealistic luminosity distributions, monohromatization



Due to angle-energy correlation high energy photons collide at smaller spot size, providing monohromatization of $\gamma\gamma$ collisions. This happends at $b/\gamma > a_e$.

Mean helicity of the scattered photons ($x = 4.8$)



Highest energy scattered photons are polarized even at λ_e=0 (see (b))

(in the case a) photons in the high energy peak have $\lambda_\gamma \approx 1$)

The cross section of the Higgs production

$$\sigma(\gamma\gamma \to h) \propto 1 + \lambda_1\lambda_2$$

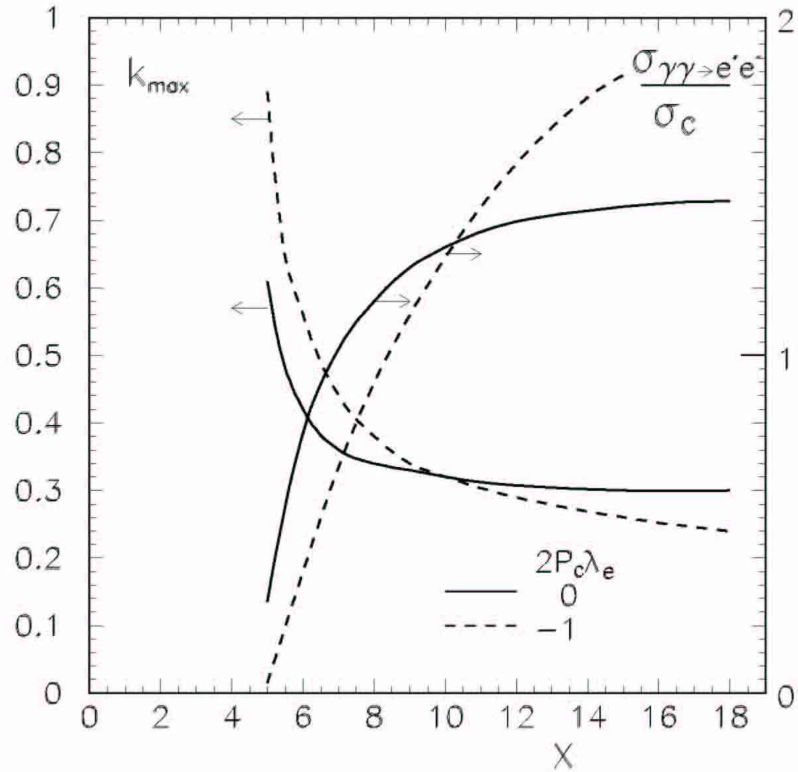
The cross section for main backgound

$$\sigma(\gamma\gamma \to b\bar{b}) \propto 1 - \lambda_1\lambda_2$$

The electron polarization makes the region with a high polarization at ω~$\omega_{m)}$ wider (compare a and b).

e^+e^- pair creation

in the collisions of laser and high energy photons



The threshold of e^+e^- creation: $x = 4.8$, the optimum value.
Corrsponding wavelength $\lambda = 4.2 E_0[\text{TeV}]\,\mu\text{m}$.

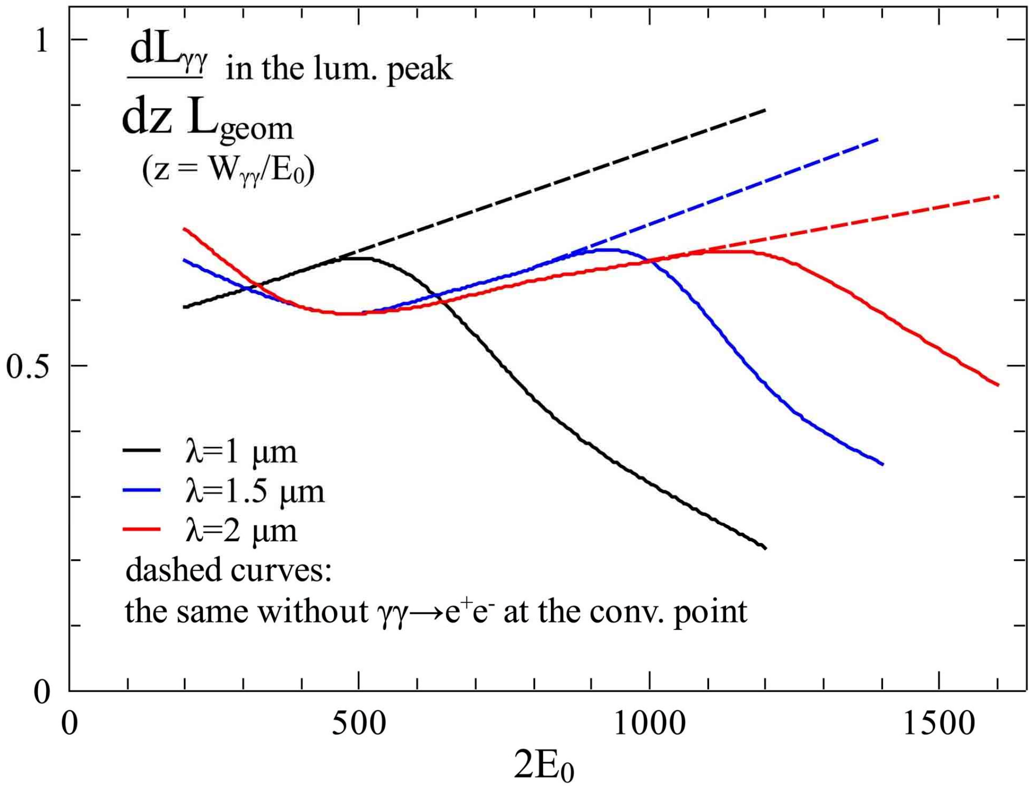
The optimum laser wavelength

The maximum energy of photons after the Compton scattering

$$\omega_{\max} \approx \frac{x}{x+1} E_0, \quad x = \frac{4E_0\omega_0}{m^2c^4}$$

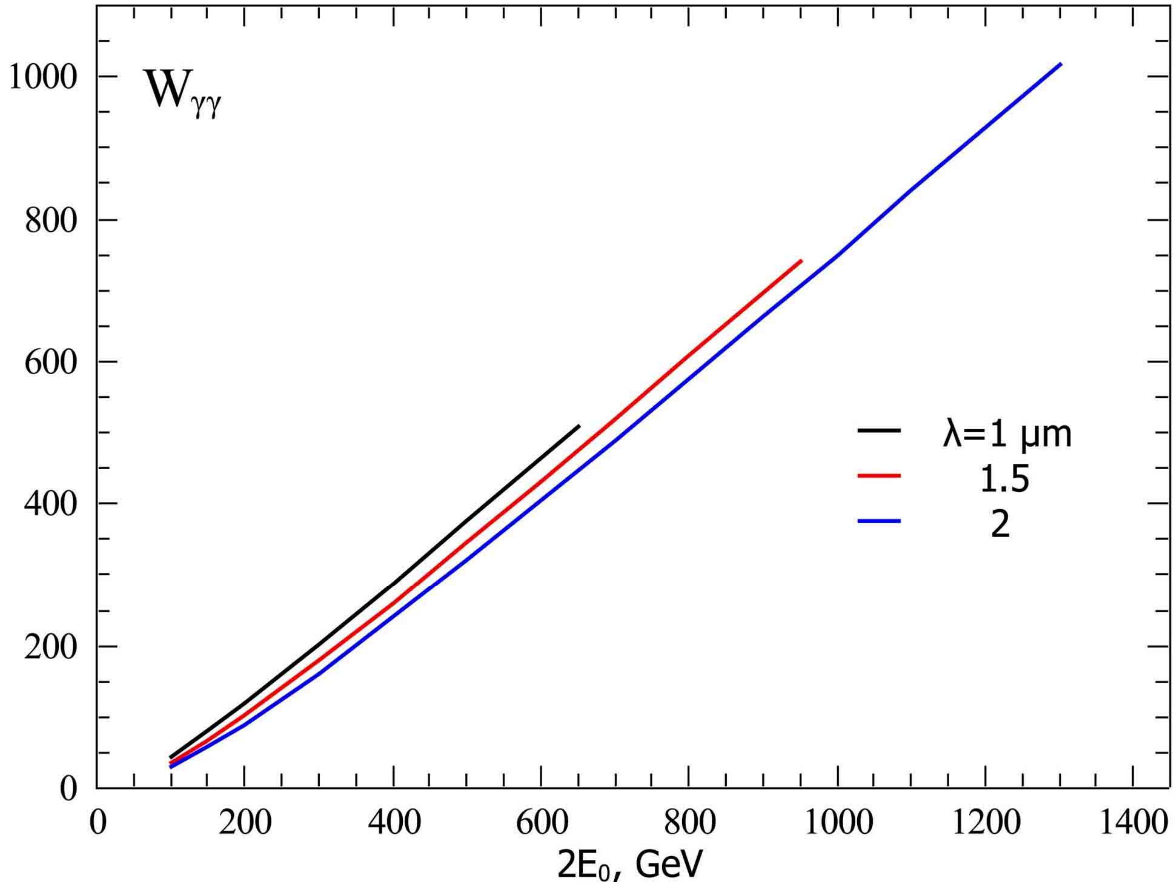
For x>4.8 the luminosity in the high energy lum. peak decreases due to e+e- pair creation in collision of laser and high energy photons at the conversion point.
For the maximum collider energy E_0 the optimum laser wave length (x=4.8) is

$$\lambda\ [\mu m] \approx 4E_0[\text{TeV}]$$



λ=1 μm for $2E_0$<500-600 GeV,
λ=2 μm for $2E_0$<1.2 TeV

The dependence of $W_{\gamma\gamma}$ on the laser wavelengh



Here $W_{\gamma\gamma}$ corresponds to the peak of lum. spectra

Laser flash energy

For $e \rightarrow \gamma$ conversion one needs thickness (t) of laser target equal about one Compton collision length ($p = t/\lambda_C \sim 1$). The required flash energy is determined by σ_c , geometric properties of laser and electron beams and by nonlinear effects in Compton scattering described by parameter $\xi^2 = \frac{e^2 \overline{F}^2 \hbar^2}{m^2 c^2 \omega_0^2} = \frac{2 n_\gamma r_e^2 \lambda}{\alpha}$ which should be kept small,

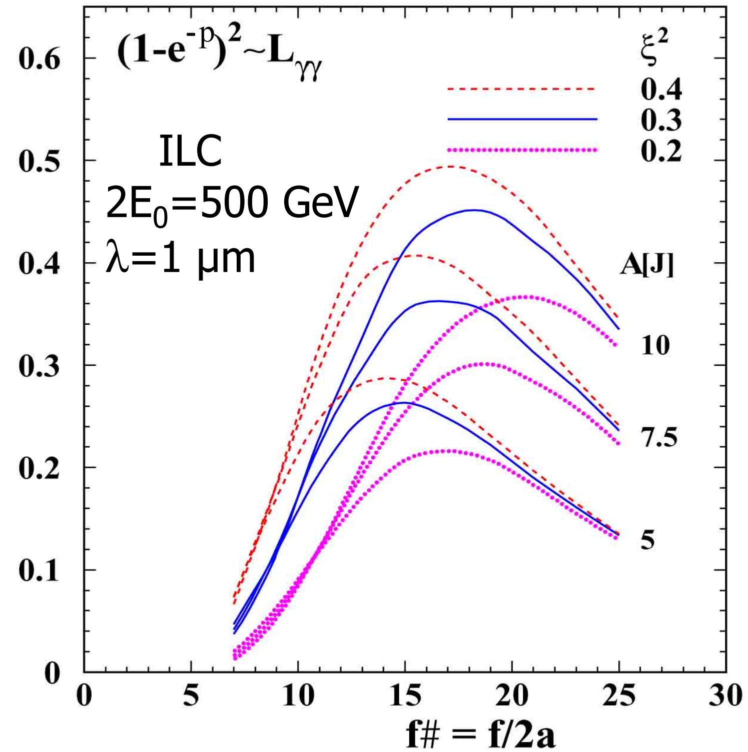
because $\omega_m = \frac{x}{x+1+\xi^2} E_0$.

It is reasonable to keep

$$\Delta\omega_m / \omega_m \approx \xi^2 / (x+1) < 0.05$$

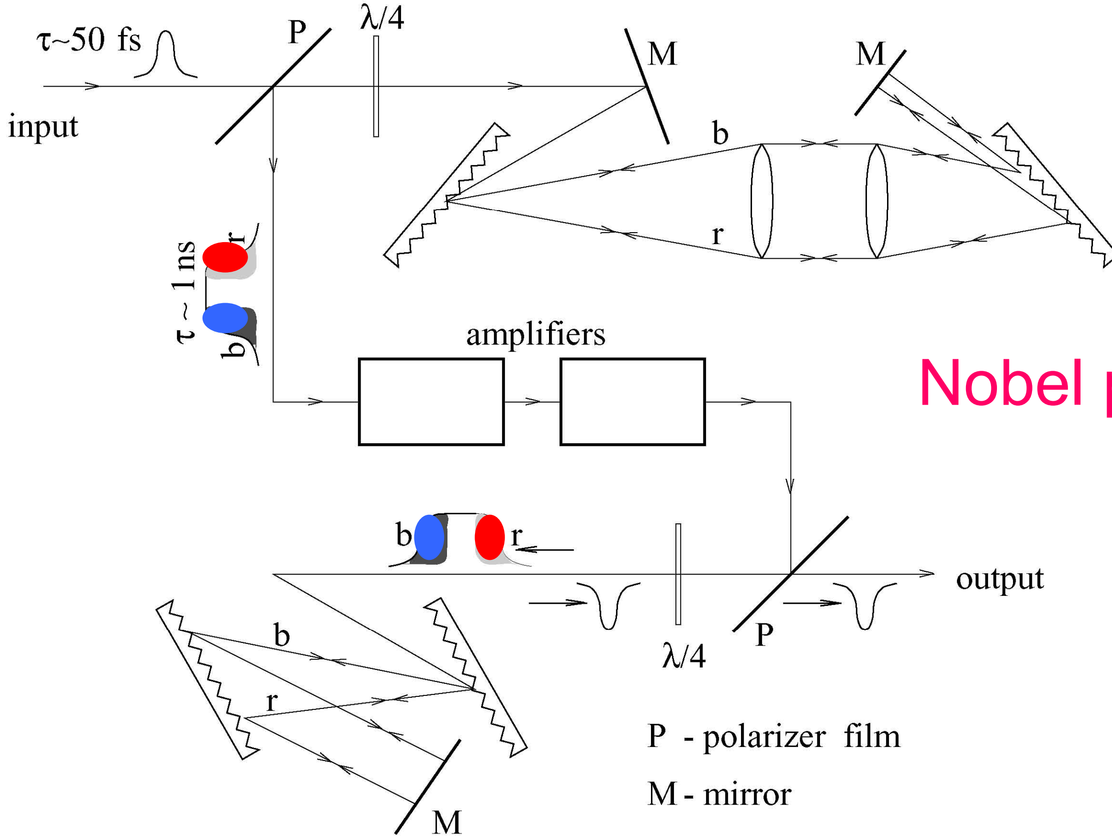
then for x=4.8 $\xi^2 < 0.3$

For $\lambda = 1$ µm ($2E_0 = 500$ GeV) the required flash energy is about A~10 J and it increases for larger λ (or E_0) due to the nonlinear effect.



Chirped pulse laser technique (D.Strickland, G.Mourou, 1985) made photon colliders idea really feasible

Stretching-amplification-compression allows to avoid nonlinear effects (self-focusing) during amplification and thus to increase laser a power by a factor of 1000! Tens Joule pulses of ps duration became a reality.



Nobel prize (2018)!

Other technologies important for the photon collider: diode pumping, adaptive optics, high reflective multilayer mirrors for high powers – all is available now.

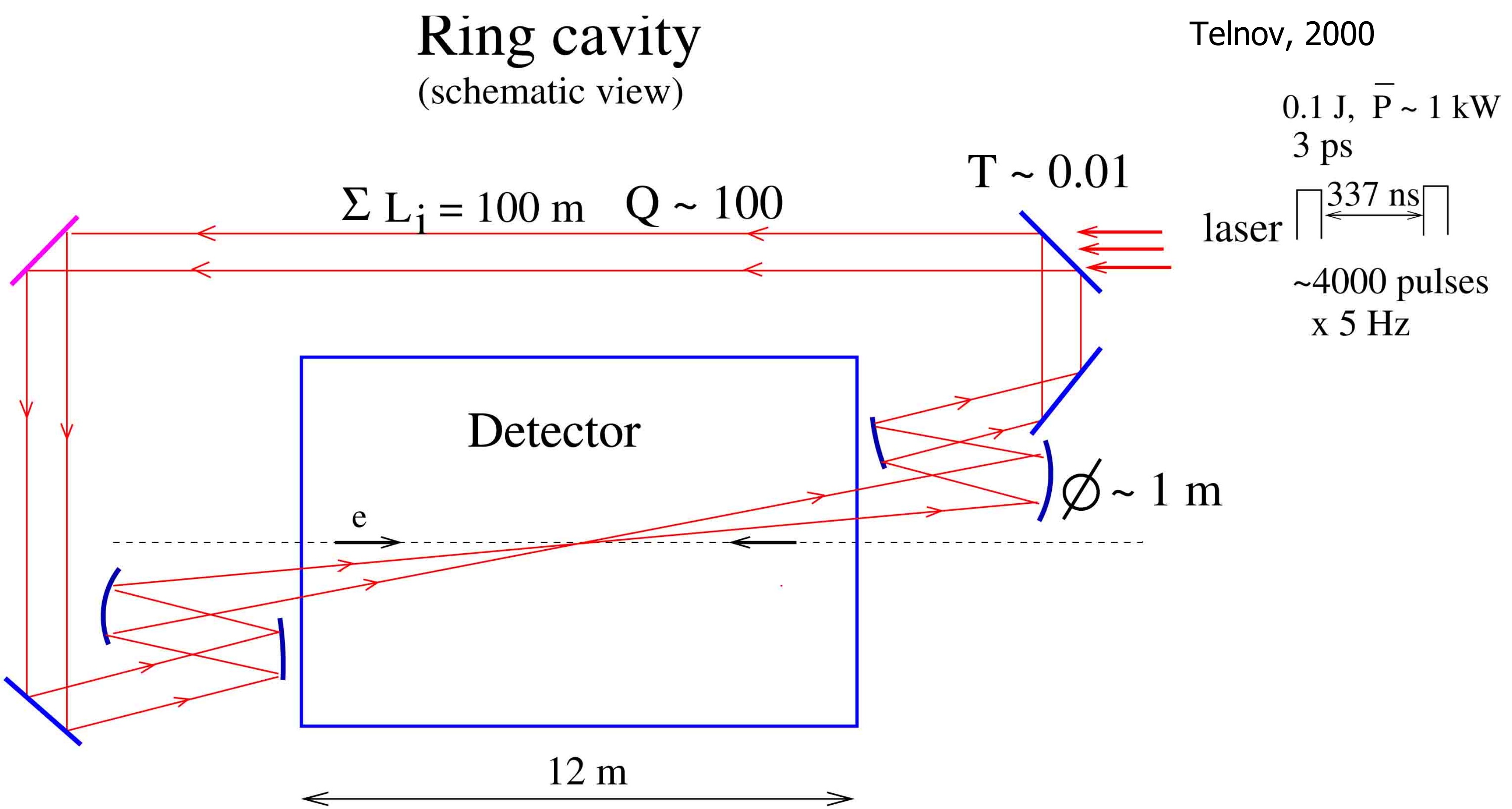
Requirements for the ILC laser system

- Wavelength ~1 μm (good for 2E<0.8 TeV)
- Time structure Δct~100 m, 3000 bunch/train, 5 Hz
- Flash energy ~5-10 J
- Pulse dutation ~1-2 ps

If a laser pulse is used only once, the average required power is P~150 kW and the power inside one train is 30 MW! Fortunately, only 10^{-9} part of the laser photons is knocked out in one collision with the electron beam, therefore the laser bunch can be used many times.

The best is the scheme with accumulation of very powerful laser bunch is an external optical cavity. The pulse structure at ILC (3000 bunches in the train with inter-pulse distance ~100 m) is very good for such cavity. It allows to decrease the laser power by a factor of 100-300.

Laser system

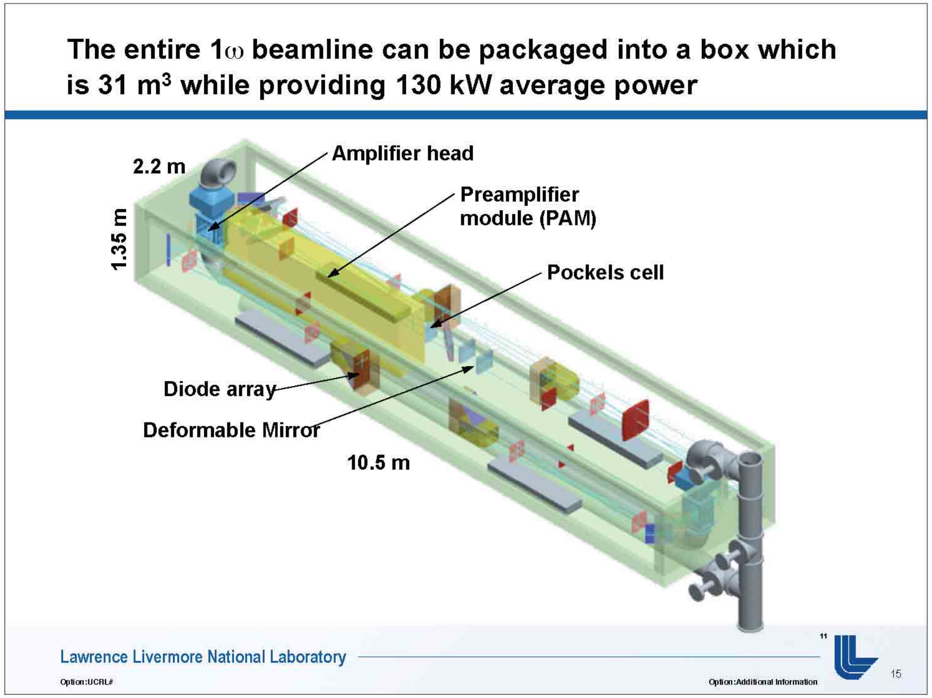


The cavity includes adaptive mirrors and diagnostics. Optimum angular divergence of the laser beam is ±30 mrad, A≈9 J (k=1), $\sigma_t \approx 1.3$ ps, $\sigma_{x,L} \sim 7$ μm

Recently new option has appeared, one pass laser system, based on new laser ignition thermonuclear facility

Project LIFE, LLNL 16 Hz, 8.125 kJ/pulse, 130 kW aver. power

(the pulse can be split into the ILC (or CLIC) train)

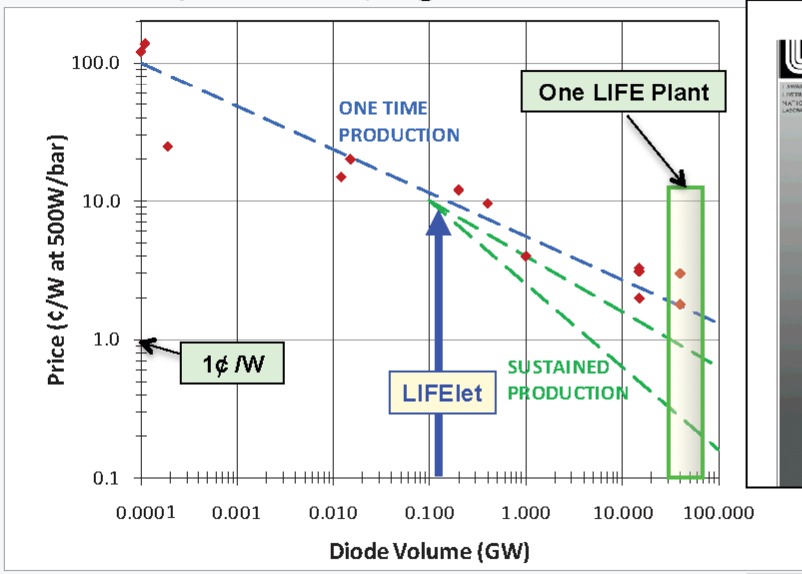


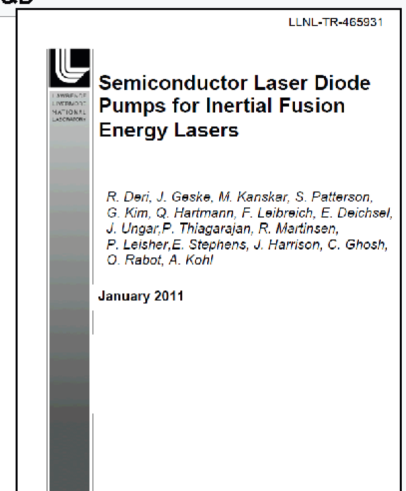
Laser diodes cost go down at mass production, that makes one pass laser system for PLC at ILC and CLIC realistic!

Laser diodes cost go down at mass production, that makes one pass laser system for PLC at ILC and CLIC realistic!

Diode costs are the main capital cost in the system

- White paper co-authored by 14 key laser diode vendors
- 2009 Industry Consensus: 3¢/W @ 500 W/bar, with no new R&D





LLNL-TR-465931

Semiconductor Laser Diode Pumps for Inertial Fusion Energy Lasers

R. Deri, J. Geske, M. Kanskar, S. Patterson, G. Kim, Q. Hartmann, F. Leibreich, E. Deichsel, J. Ungar, P. Thiagarajan, R. Martinsen, P. Leisher, E. Stephens, J. Harrison, C. Ghosh, O. Rabot, A. Kohl

January 2011

- Power scaling to 850 W/bar provides \$0.0176/W (1st plant)
- Sustained production of LIFE plants reduces price to ~\$0.007/W
- Diode costs for first plant: \$880M
- Diode costs for sustained production: \$350M

Diode costs for 1 beamline ~ \$2.3M

LIFElet (1st beamline) \$0.1/W diodes for 1 beamline \$13M

Laser system for CLIC

Requirements to a laser system for PLC at CLIC (500)

Laser wavelength	~ 1 μm (5 for 2E=3000 GeV)
Flash energy	A~5 J, τ~1 ps
Number of bunches in one train	354
Length of the train	177 ns=53 m
Distance between bunches	0.5 ns
Repetition rate	50 Hz

The train is too short for the optical cavity, so one pass laser should be used.

The average power of one laser is 90 kW (two lasers 180 kW).

One pass laser system, developed for LIFE (LLNL) is well suited for CLIC photon collider at 2E<500 GeV.

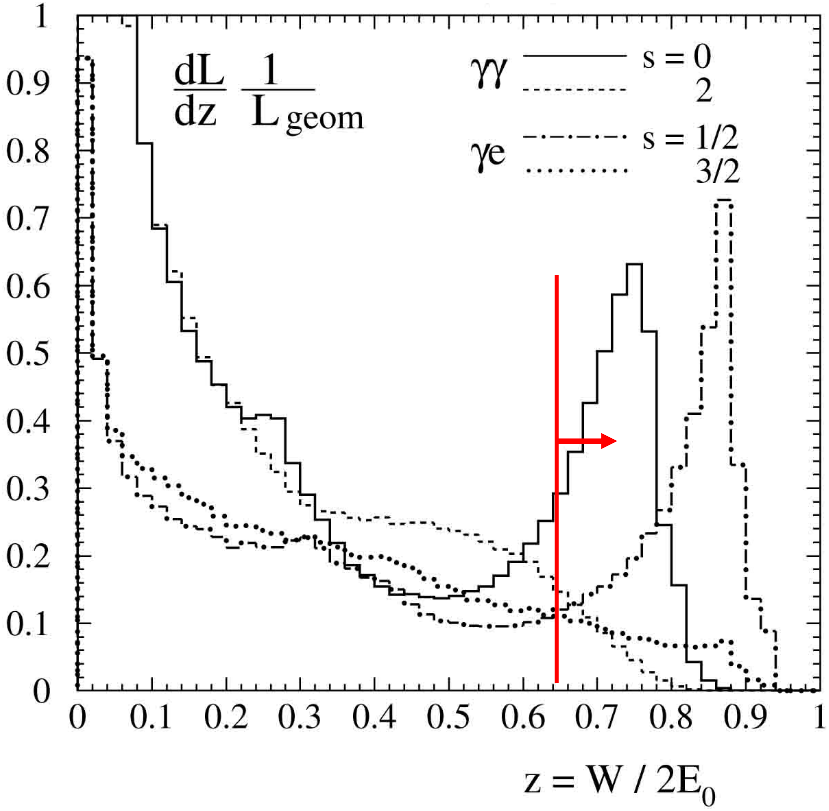
MultiTeV CLIC needs lasers with longer wavelength: $\lambda \approx 4E_0$[TeV], μm

Realistic luminosity spectra ($\gamma\gamma$ and γe)

(with account multiple Compton scattering, beamstrahlung photons, coherent pair creation, polarization and beam-beam collision effects)

(decomposed in two states of J_z)

ILC(500)



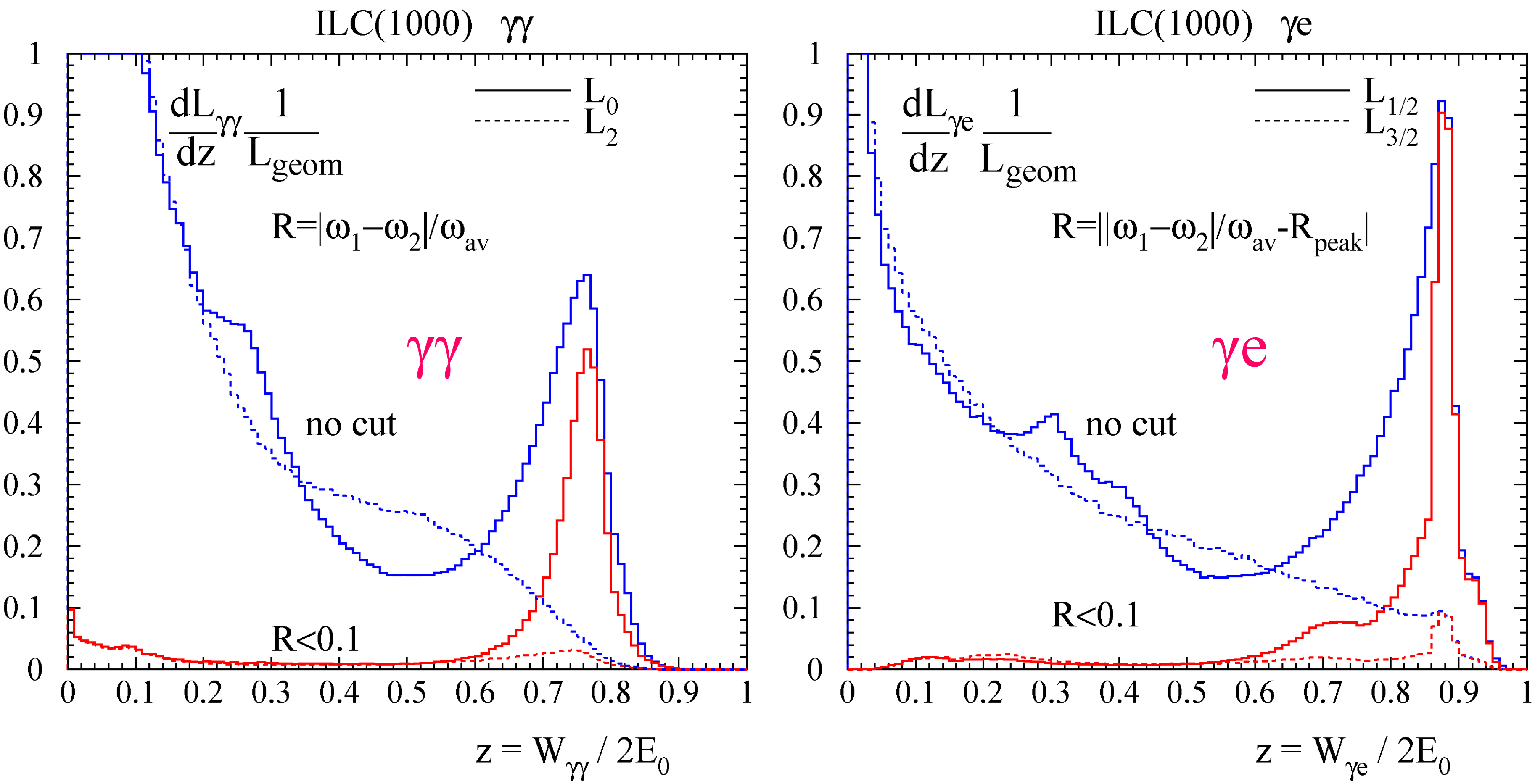
Usually a luminosity at the photon collider is defined as the luminosity in the high energy peak, $z>0.8z_m$.

For ILC conditions

$L_{\gamma\gamma}(z>0.8z_m) \sim 0.1\ L_{ee} \sim 3\cdot10^{33} \sim 0.15\ L_{e+e-}$
(for 2600 bunches in the train, σ_x=250 nm, σ_y=5 nm)

Luminosity spectra at ILC(1000) with λ=2 μm

(red curves with restriction on longitudinal momentum of produced system)



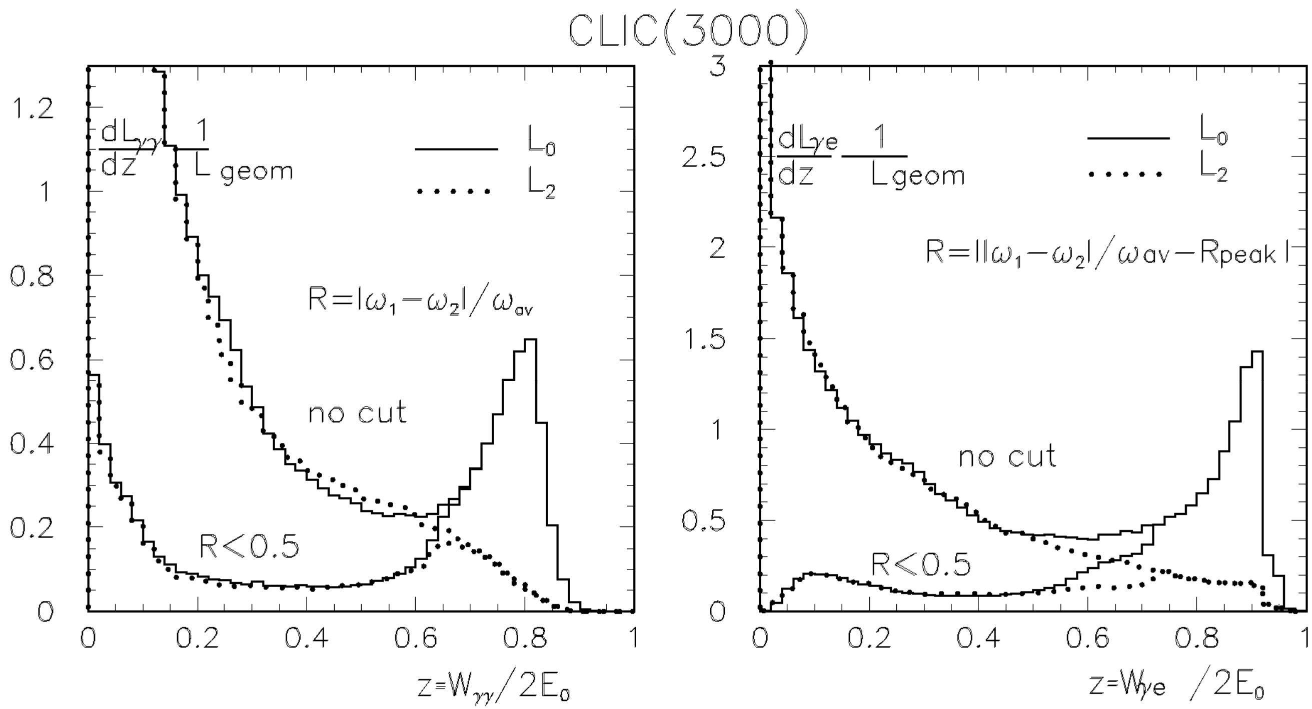
Such γγ collider would be the best option for study of X(750)

(fake γγ peak observed at LHC in 2015-2016)

Luminosity spectra for CLIC(3000)

Here the γγ luminosity is limitted by coherent pair creation (the photon is converted to e+e- pair in the field of the opposing beam). The horizontal beam size can be only 2 times smaller than in e+e- collisions.

λ=4.5 μm



$L_{\gamma\gamma}(z>0.8z_m)$ ~$(4\text{-}8)\cdot 10^{33}$

Physics motivation for the photon collider at LC
(shortly, independent on a physics scenario)

In $\gamma\gamma$, γe collisions compared to e^+e^-

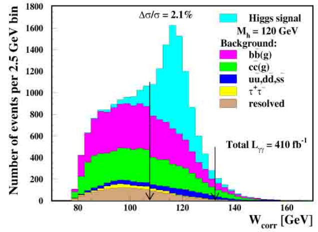
- the energy is smaller only by 10-20%
- the number of interesting events is similar or even higher
- access to higher particle masses (H,A in $\gamma\gamma$, charged and light neutral SUSY in γe)
- higher precision for some phenomena ($\Gamma_{\gamma\gamma}$, CP-proper.)

  $\Gamma(H\to\gamma\gamma)$ width can be measured with statistics ≈ 60 times higher than in e+e- collisions.
- different types of reactions (different dependence on theoretical parameters)

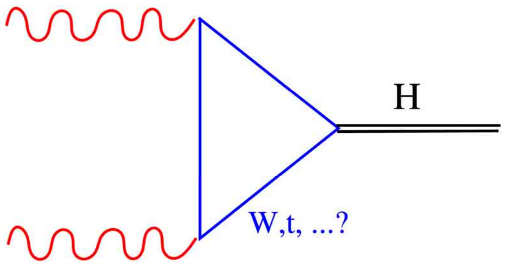
It is the unique case when linear colliders allow to study new physics in several types of collisions at the cost of very small additional investments

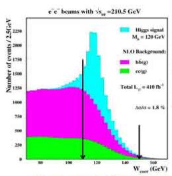
Unfortunately, the physics in LC region is not so rich as expected, by now LHC found only light Higgs boson.

The resonance Higgs production is one of the gold-plated processes for PLC

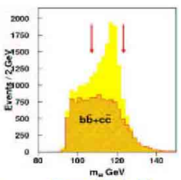


Very sensitive to high mass particles in the loop

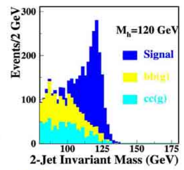




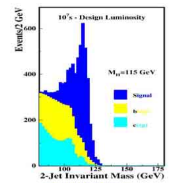
Niezurawski(TESLA)



Rosca(TESLA)



Asner(NLC)



Asner(Cliche)

$$\dot{N}_H = L_{ee} \times \frac{dL_{0,\gamma\gamma}}{dW_{\gamma\gamma} L_{ee}} \frac{4\pi^2 \Gamma_{\gamma\gamma}}{M_H^2} (1 + \lambda_1\lambda_2 + CP * l_1 l_2 cos2\varphi) = L_{ee}\sigma$$

$$\sigma = \frac{0.98 \cdot 10^{-35}}{2E_0[\mathrm{GeV}]} \frac{dL_{0,\gamma\gamma}}{dz L_{ee}} (1 + \lambda_1\lambda_2 + CP * l_1 l_2 cos2\varphi),\ \mathrm{cm}$$

For realistic ILC conditions $\sigma(\gamma\gamma\to H)\approx 75$ fb, while $\sigma(e^+e^-\to HZ)\approx 290$ fb

in e+e- N($H\to\gamma\gamma$)∞ L $\sigma(e^+e^-\to HZ)$*Br($H\to\gamma\gamma$), where Br($H\to\gamma\gamma$)=0.0024

in $\gamma\gamma$ N($H\to\gamma\gamma$)∞ L $\sigma(\gamma\gamma\to H)$*Br($H\to bb$), where Br($H\to bb$)=0.57

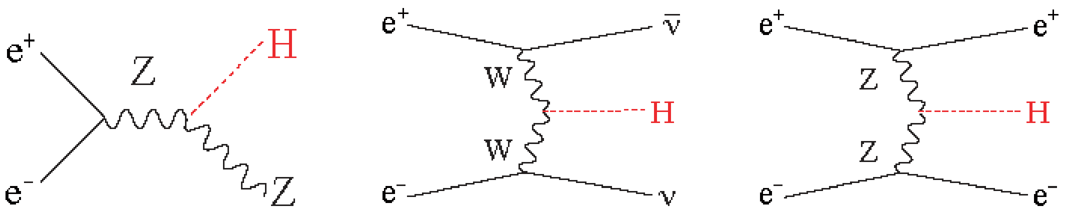
Conclusion: in γγ collisions the $\Gamma(H\to\gamma\gamma)$ width can be measured with statistics (75*0.57)/(290*0.0024)=60 times higher than in e+e- collisions.

That is one of most important argument for the photon collider.

Remark on Photon collider Higgs factories

Photon collider can measure
$\Gamma(H\to\gamma\gamma)$*$Br(H\to bb, ZZ, WW)$, $\Gamma^2(H\to\gamma\gamma)/\Gamma_{tot}$, Higgs CP properties (using photon polarizations). In order to get $\Gamma(H\to\gamma\gamma)$ one needs $Br(H\to bb)$ from e+e-(accuracy about 1%). As result the accuracy of $\Gamma(H\to\gamma\gamma)$ is about 1.5-2% after 1 years of operation. Other Higgs decay channels will be unobservable due to large QED background.

e+e- can also (in addition) measure Br(bb, cc, gg, ττ, μμ, invisible), Γ_{tot}, less backgrounds due to tagging of Z.



Therefore PLC is nicely motivated in only in combination with e+e-: parallel work or second stage.

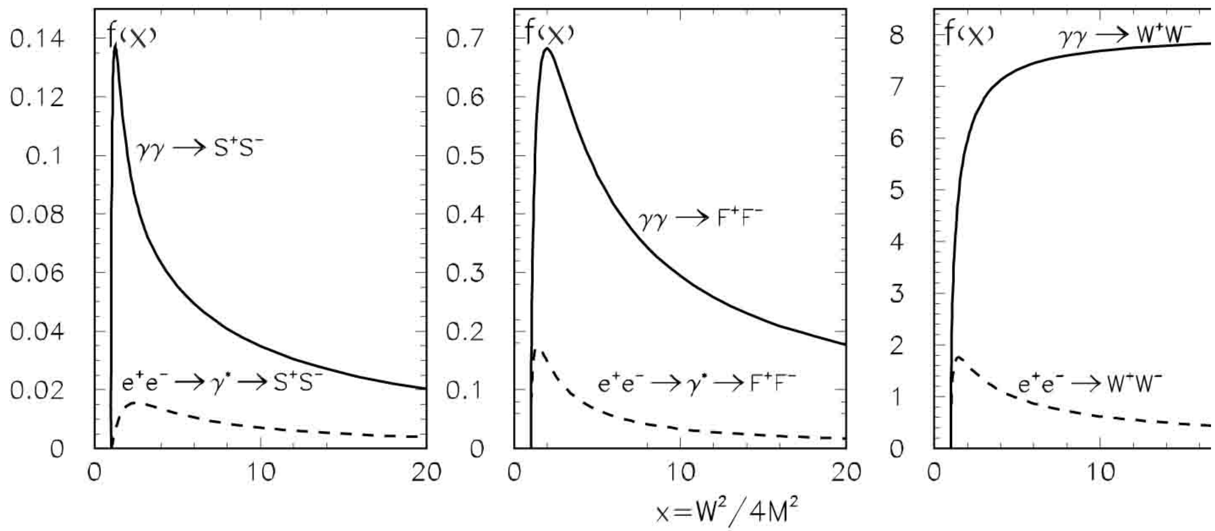
Some examples of Physics (in addition to H(125))

Charged pair production in e^+e^- and $\gamma\gamma$ collisions.

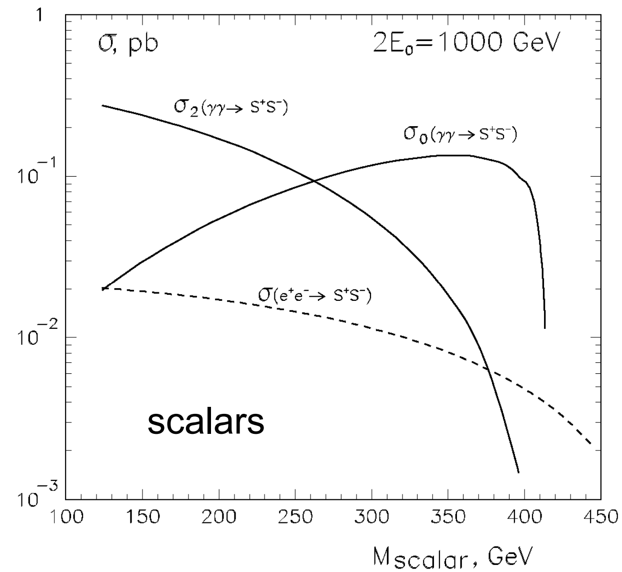
unpolarized beams

(S (scalars), F (fermions), W (W-bosons);

$\sigma = (\pi\alpha^2/M^2) f(x)$, beams unpolarized)



polarized beams



So, typical cross sections for charged pair production in $\gamma\gamma$ collisions is larger than in e^+e^- by one order of magnitude (circular polarizations helps)

Not seen at LHC

Supersymmetry in $\gamma\gamma$

In supersymmetric model there are 5 Higgs bosons:

h^0 light, with $m_h < 130$ GeV

H^0, A^0 heavy Higgs bosons;

H^+, H^- charged bosons.

$M_H \approx M_A$, in e$^+$e$^-$ collisions H and A are produced in pairs (for certain param. region), while in $\gamma\gamma$ as the single resonances, therefore:

in e$^+$e$^-$ collisions $M_{H,A}^{max} \sim E_0$ (e$^+$e$^-$ $\rightarrow H + A$)
in $\gamma\gamma$ collisions $M_{H,A}^{max} \sim 1.6 E_0$ ($\gamma\gamma \rightarrow H(A)$)

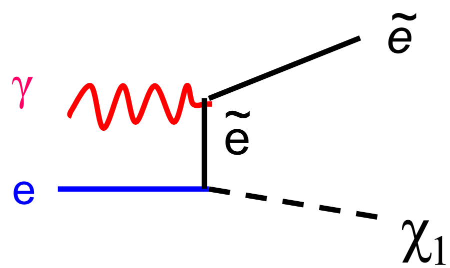
For some SUSY parameters H,A can be seen only in $\gamma\gamma$
(but not in e+e- and LHC)

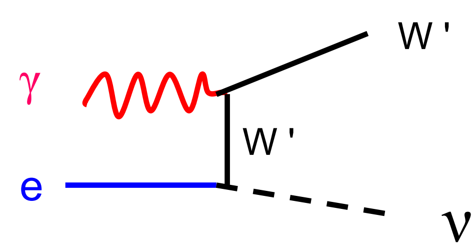
Not seen at LHC

Supersymmetry in γe

At a γe collider charged particles with masses higher than in e^+e^- collisions at the same collider can be produced (a heavy charged particle plus a light neutral one, such as a new W' boson and neutrino or supersymmetric charged particle plus neutralino):

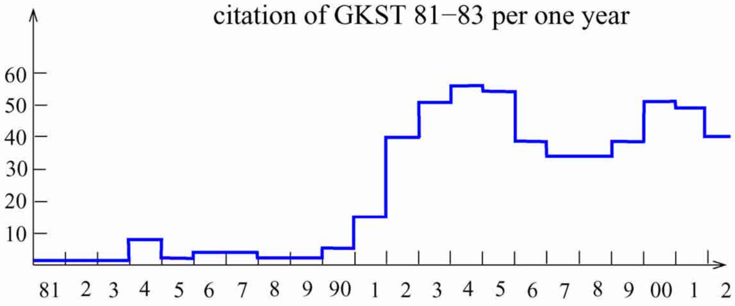
$$m_{\tilde{e}^-} < 0.9 \times 2E_0 - m_{\tilde{\chi}_1^0}$$





Not seen at LHC

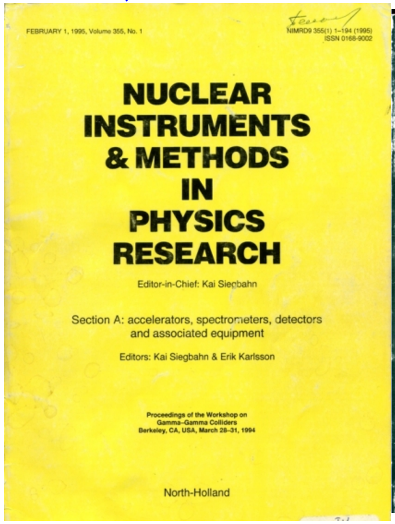
Activity on photon colliders



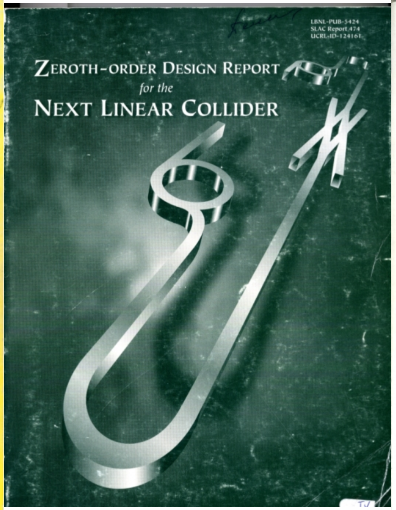
(total number of publications is larger by a factor of 2)

→ about 2 papers/week

Gamma-gamma workshop LBL, 1994

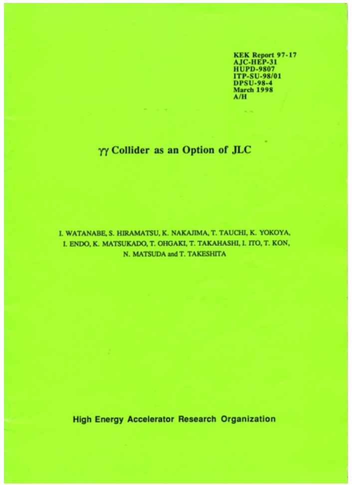


NLC

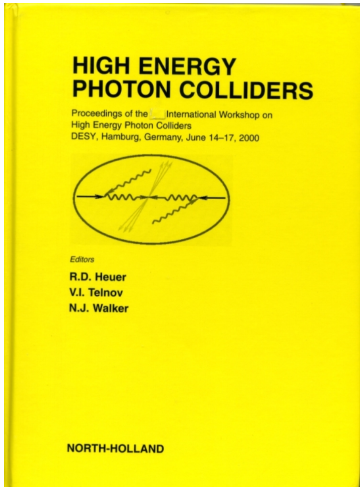


TESLA CDR

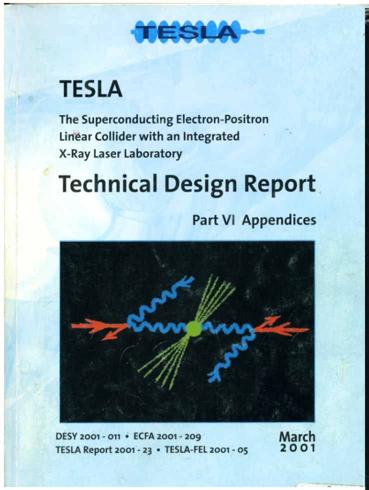
γγ at JLC



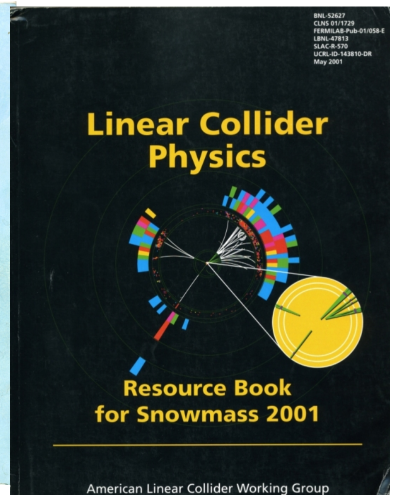
γγ workshop at DESY



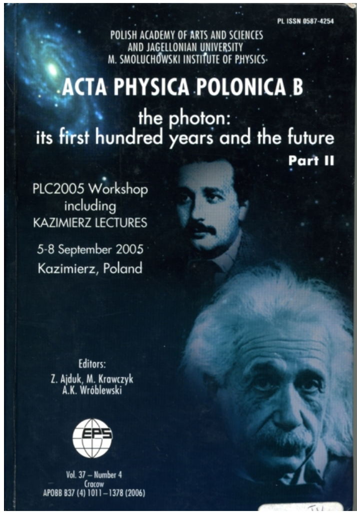
TESLA TDR



γγ NLC



PLC 2005



Photon colliders were suggested in 1981 and since ~1990 are considered as a natural part of all linear collider projects.

Dreams on γγ colliders

Factors limiting luminosity

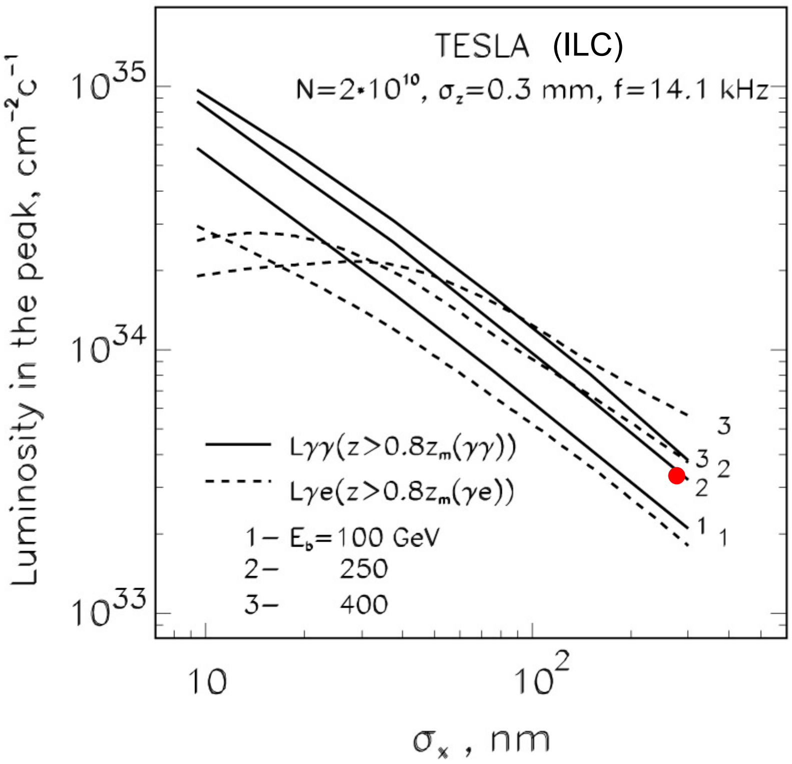
Factors limiting $\gamma\gamma,\gamma e$ luminosities

Telnov,1998

Collision effects:

- Coherent pair creation ($\gamma\gamma$)
- Beamstrahlung (γe)
- Beam-beam repulsion (γe)

On the right figure: the dependence of $\gamma\gamma$ and γe luminosities in the high energy peak vs the horizontal beam size (σ_y is fixed).



At the ILC nominal parameters of electron beams σ_x ~ 250-300 nm is only available at $2E_0$=500 GeV. Limitations due to horiz. emittance and chromo-geometric aberrations ($\beta_{x,min}$~5mm, while σ_z=0.5mm)

At e^+e^- the luminosity is limitted by collision effects (beamstrahlung, instability),while in $\gamma\gamma$ collsions only by available beam sizes or geom. e^-e^- luminosity (for at $2E_0$<1 TeV).

So, one needs: ε_{nx}, ε_{ny} as small as possible and β_x , β_y ~ σ_z

Coherent pair creation in the field of the opposing beam: γ→e$^+$e$^-$

P.Chen, V.Telnov, 1989

Considerations below V. Telnov *AIP Conf.Proc.* 397 (1997) 1, 259-273, physics/9706003

The probability/cm $\mu(\kappa) = \frac{\alpha^2}{r_e}\frac{B}{B_S}T(\kappa), \quad \kappa = \frac{\omega}{mc^2}\frac{B}{B_S}, \quad B_S = m^2c^3/e\hbar = 4.4\cdot 10^{13}\ \mathrm{Gs}, \quad r_e = e^2/mc^2.$

$$
\begin{aligned}
T(\kappa) &\approx 0.16\kappa^{-1}K_{1/3}^2(4/3\kappa) \\
&\approx 0.23\exp(-8/3\kappa) \qquad \kappa<1 \\
&\approx 0.1 \qquad \kappa = 3-100 \\
&\approx 0.38\kappa^{-1/3} \qquad \kappa > 100
\end{aligned}
$$

$$\omega \approx 0.8E_0 \quad \rightarrow \quad \kappa \sim \Upsilon \equiv \gamma B/B_S, \qquad |B| = |B_b| + |E_b| \sim 2eN/\sigma_x\sigma_z$$

The probability/collision $p \approx \mu\sigma_z = \frac{\alpha^2\sigma_z}{r_e\gamma}\Upsilon T(\Upsilon).$

The value of Y(p)

$$
\begin{aligned}
\Upsilon_{\mathrm{m}} &\approx 2.7/\ln(0.1/p_1) \qquad p_1<0.01 \\
&\approx 1.2 + 9p_1 \qquad 0.01<p_1<4 \\
&\approx 4.5p_1^{3/2} \qquad p_1>4
\end{aligned}
$$

where

$$p_1 = p\frac{\gamma r_e}{\alpha^2\sigma_z} \approx p\cdot 0.1\frac{E[\mathrm{TeV}]}{\sigma_z[\mathrm{mm}]}$$

Now we can find the minimum σ_x, corresponding to γ→e+e- probability *p* (optimally p>1)

$$\sigma_x > \frac{1.6N\gamma r_e^2}{\alpha\sigma_z\Upsilon_{\mathrm{m}}}$$

4.1 Flat beams

The field of the beam with the r.m.s horizontal size σ_x and the length σ_z is $B \equiv |B|+|E| \sim 2eN/\sigma_x\sigma_z$. From the condition $\kappa \sim 0.8\gamma B/B_0 < \Upsilon_m$ we get

$$\sigma_x > \frac{1.6N\gamma r_e^2}{\alpha\sigma_z\Upsilon_m} = \frac{1.6N\gamma r_e^2}{\alpha\sigma_z(1.2+9pr_e\gamma/\alpha^2\sigma_z)} \sim \frac{40\cdot\left[\frac{N}{10^{10}}\right]}{p+1.3\frac{\sigma_z[\mathrm{mm}]}{E[\mathrm{TeV}]}} \ \mathrm{nm} \tag{7}$$

The $\gamma\gamma$ luminosity at $z > 0.65$

$$L_{\gamma\gamma} \sim \frac{0.5k^2N^2f}{4\pi(b/\gamma)\sigma_x} \sim \frac{0.025\alpha N\sigma_z f k^2}{br_e^2}\left[1.2+9p\frac{r_e\gamma}{\alpha^2\sigma_z}\right]e^{-p}, \tag{8}$$

where the coefficient 0.5 follows from the simulation for $\sigma_y = b\gamma$. It has its maximum at

$$I: \quad \tilde{p}=0 \quad \text{at} \quad a = \frac{7.5r_e\gamma}{\alpha^2\sigma_z} = \frac{0.75E[TeV]}{\sigma_z[\mathrm{mm}]} < 1 \ ;$$

$$II: \quad \tilde{p} = 1-1/a \quad \text{at} \quad a > 1 \ .$$

The corresponding luminosities for these two cases are the following

$$L_{\gamma\gamma} \sim 0.03\frac{\alpha k^2Nf\sigma_z}{br_e^2} = 2.8\cdot 10^{33}\left(\frac{N}{10^{10}}\right)\frac{f[kHz]}{b[\mathrm{cm}]}k^2\sigma_z[\mathrm{mm}], \ \mathrm{cm}^{-2}\mathrm{s}^{-1}; \tag{9}$$

$$L_{\gamma\gamma} \sim 0.23\frac{Nf\gamma k^2}{\alpha br_e}e^{-\tilde{p}} = 2.2\cdot 10^{33}\left(\frac{N}{10^{10}}\right)\frac{f[kHz]}{b[\mathrm{cm}]}k^2E[\mathrm{TeV}]e^{-\tilde{p}}, \ \mathrm{cm}^{-2}\mathrm{s}^{-1}. \tag{10}$$

Optimum horizontal beam sizes in these two cases are

$$I: \quad \sigma_x \sim \frac{1.3Nr_e^2\gamma}{\alpha\sigma_z} = 28\frac{E[\mathrm{TeV}]\left(\frac{N}{10^{10}}\right)}{\sigma_z[\mathrm{mm}]}, \ \mathrm{nm} \ ; \ \text{at} \ a<1 \ ; \tag{11}$$

$$II: \quad \sigma_x \sim 0.18\alpha Nr_e = 37\left(\frac{N}{10^{10}}\right), \ \mathrm{nm} \quad \text{at} \ a>1 \ . \tag{12}$$

The minimum value of the distance between the conversion (CP)) and the interaction regions b is determined by the length of the conversion region which is equal approximately to $b = 0.08E[\mathrm{TeV}]$, cm (see section 6.1). For further estimation we assume that

$$b = 3\sigma_z + 0.04E[\mathrm{TeV}], \quad \mathrm{cm}.$$

- distance needed for the conversion

Let us take $N = 10^{10}$, $\sigma_z = 0.2$ mm, $f = 10\ kHz$, $k^2 = 0.4$ (one conversion length) that corresponds at $E > 0.25$ TeV to the case II. For $2E = 5$ TeV we get

$$L_{\gamma\gamma} \sim 6 \cdot 10^{34}\ \mathrm{cm^{-2}s^{-1}} \quad \text{at } \sigma_x \sim 40 \text{ nm} \quad \text{and } \sigma_y \sim b/\gamma = 0.3 \text{ nm.} \quad \text{at} \quad p_{opt} \approx 1$$

For a very high energy $L_{max} \sim 8 \cdot 10^{34}$ $\mathrm{cm^{-2}s^{-1}}$ for a chosen parameters corresponding to the beam power $P = 15E[\mathrm{TeV}]$ MW per beam. In the next section we will compare these approximate results with the results of simulation.

Summary of estimates (flat beams):
for flat beams in wide range of parameters the ultimate γγ-luminosity does not depend on σ_z, optimal $\sigma_x \sim 40(N/10^{10})$ nm,
for $Nf=10^{14}$ $L_{\gamma\gamma}(z>0.65) \sim 6 \cdot 10^{34}$

simulation results later

4.2 Influence of the beam-beam repulsion on the coherent pair creation

During the beam collision electrons get displacement in the field of the opposing beam

$$r \sim \sqrt{\frac{\sigma_z r_e N}{8\gamma}}. \tag{15}$$

This estimate is obtained from the condition that at the impact parameter equal to the characteristic displacement the additional displacement is equal to the initial impact parameter.

The field at the axis (which influences on the high energy photons) $B \sim 2eN/r\sigma_z$. Then the corresponding field parameter

$$\Upsilon \sim \gamma\frac{B}{B_0} = \frac{\gamma B r_e^2}{\alpha e} \sim 5\frac{r_e\gamma}{\alpha\sigma_z}\sqrt{\frac{\gamma r_e N}{\sigma_z}} \tag{16}$$

According to eq.(6), in the transition regime $\Upsilon_m = 1.2 + 9pr_e\gamma/\alpha^2\sigma_z$. From $\Upsilon = \Upsilon_m$ we can find the maximum beam energy when the coherent pair creation is suppressed due to the beam repulsion.

At the energy $E > 1$ TeV and bunches short enough, one can neglect the first term and get

$$\gamma_{max} \sim 3\frac{p^2\sigma_z}{\alpha^2 r_e N} \quad \text{or} \quad E_{max} \sim p^2\frac{\sigma_z[\text{mm}]}{N/10^{10}}, \ \text{TeV}\ . \tag{17}$$

The $\gamma\gamma$ luminosity is equal

$$L_{\gamma\gamma}(z > 0.65) \sim 0.35\frac{N^2 f k^2}{4\pi(b/\gamma)^2}e^{-p} \sim 0.1(Nf)\frac{\sigma_z\gamma p^2 k^2}{\alpha^2 r_e b^2}e^{-p}, \tag{18}$$

where the numerical factor 0.35 follows from the simulation. It has its maximum at p=2 when

$$L_{\gamma\gamma} \sim 0.05(Nf)\frac{\sigma_z\gamma k^2}{\alpha^2 r_e b^2} \sim 7\cdot 10^{33}\left(\frac{N}{10^{10}}\right)\frac{\sigma_z[\text{mm}]}{b^2[\text{cm}]}E[\text{TeV}]f[\text{kHz}]k^2 \quad . \tag{19}$$

We have separated the factor (Nf) because it is a beam power. Taking in the previous example $Nf = 10^{14}$ Hz, $\sigma_z = 0.2$ mm, $k^2 = 0.4$, $b = 3\sigma_z + 0.04E[\mathrm{TeV}]$, cm, $E = 2.5$ TeV we obtain

$$L_{\gamma\gamma}(z > 0.65) \sim 6 \cdot 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}. \quad (20)$$

The optimum number of particles in the beam for an energy considered (eq.(17)) is $N \sim 0.8 \cdot 10^{10}$.

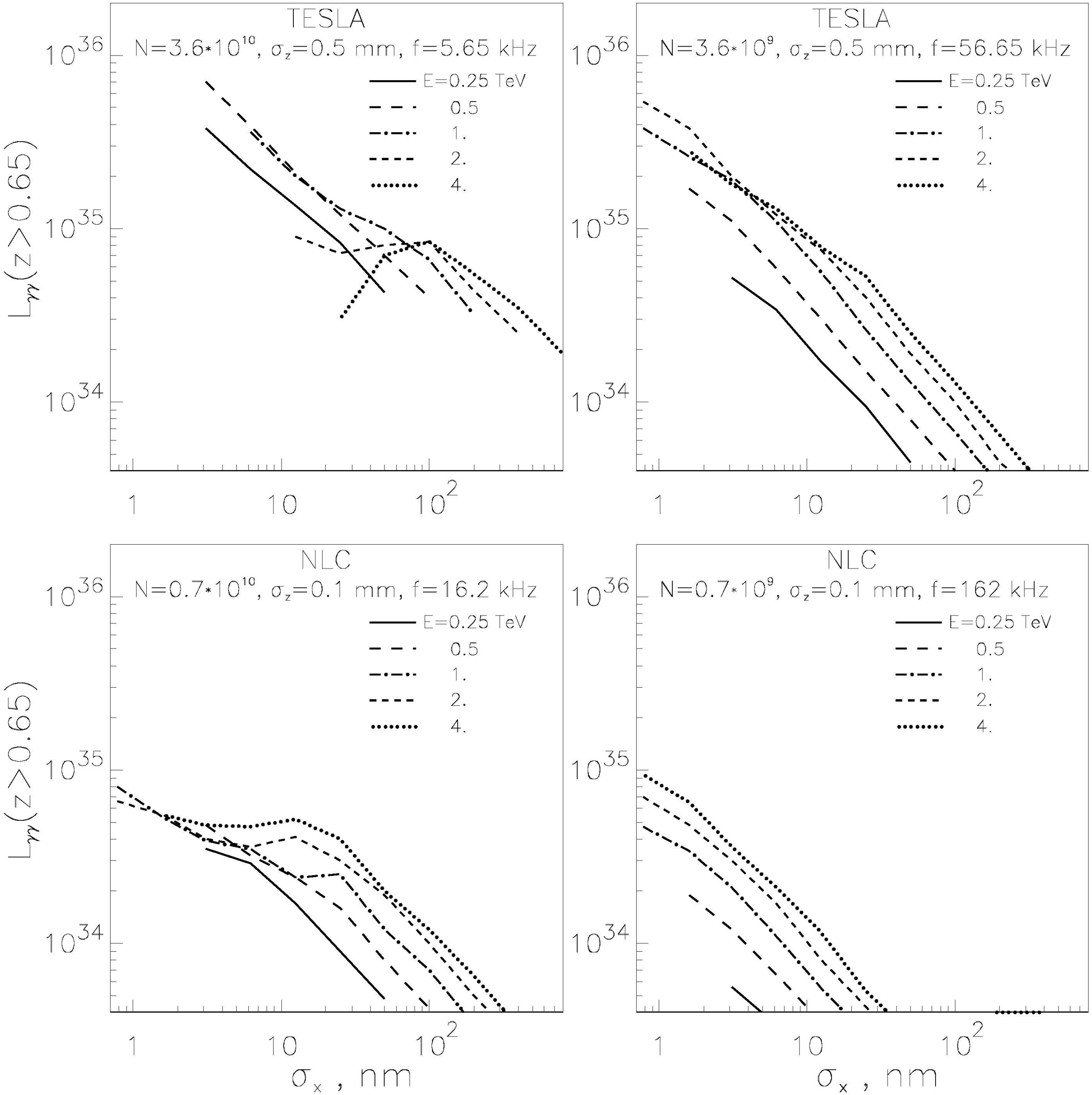
From (19) $$L \propto \frac{\sigma_z E}{b^2} = \frac{\sigma_z E}{\left(3\sigma_z + 0.04E[\mathrm{TeV}]\right)^2}$$

$L_{\max}$ at $\sigma_z[\mathrm{cm}] = (0.04/3)\,\mathrm{E}[\mathrm{TeV}]$

Result: $L_{\gamma\gamma}(z>0.65) \sim 6 \cdot 10^{35}$ for $Nf=10^{14}$

Here we assumed infinitely narrow electron beams, which get sizes due to the beam repulsion. The resulting luminosity is 10 times larger than without disruption.

Simulation results

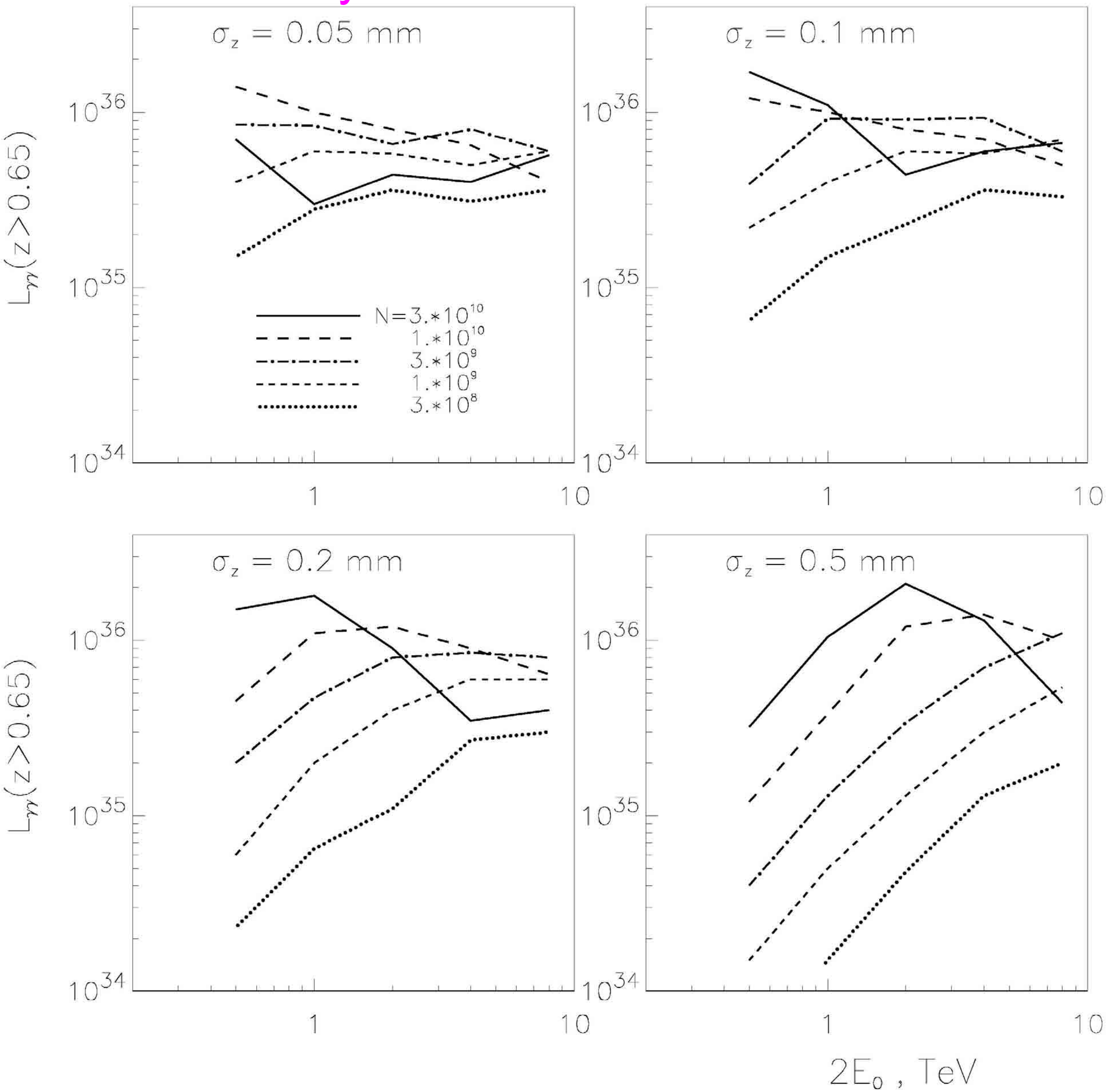


σ_x is varied

one can see zigzags due to pair creation at high energy

Simulation results

for infinitely narrow beams



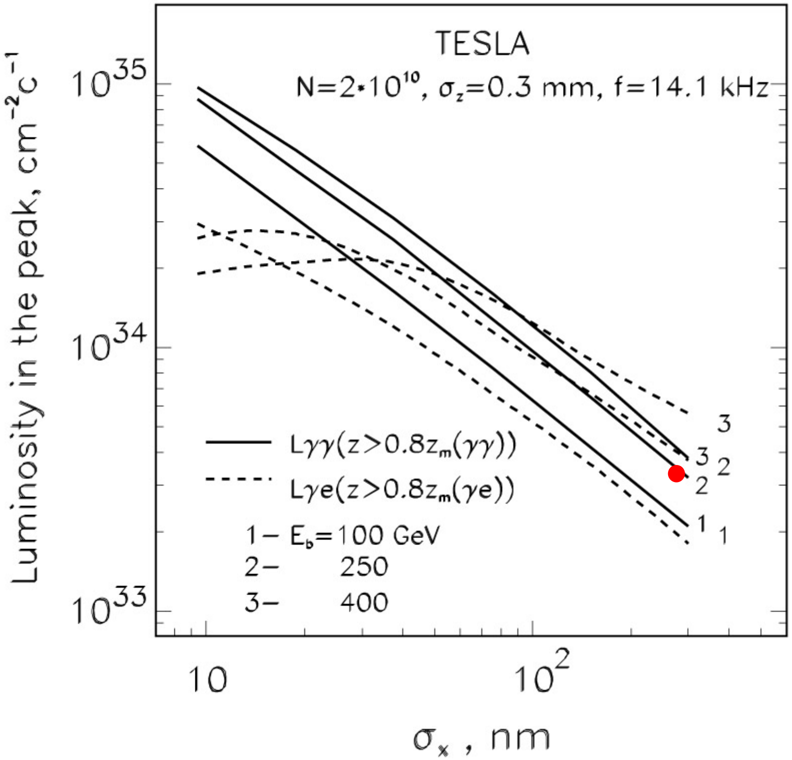
N,σ_z,E are varied

Nf=10^{14}=const

L near to the prediction:

$L_{\gamma\gamma}(z>0.65)\sim 6\cdot 10^{35}$

It was shown before, just to remind



Resume on possible luminosities:

It can be high at all LC energies (2E<10 TeV), significant influence of coherent pair production at multi-TeV energies

For ILC parameters we just need beams with smaller transverse (horizontal) emittances.

γγ-collider does not need positrons, therefore it attractive to use guns without damping rings. Longitudinal polarization is very desirable, but not obligatory.

One idea: method based on longitudinal emittances

V.Telnov, LWLC10, CERN

Let us compare longitudinal emittances needed for ILC with those in RF guns.

At the ILC $\sigma_E/E \sim 0.3\%$ at the IP (needed for focusing to the IP), the bunch length $\sigma_z \sim 0.03$ cm, $E_{min} \sim 75$ GeV that gives the required normalized emittance

$$\varepsilon_{nz} \approx (\sigma_E/mc^2)\sigma_z \sim 15 \text{ cm}$$

In RF guns $\sigma_z \sim 0.1$ cm (example) and $\sigma_E \sim 10$ keV, that gives $\varepsilon_{nz} \sim 2 \cdot 10^{-3}$ cm, or 7500 times smaller than required for ILC!

So, photoguns have much smaller longitudinal emittances than it is needed for linear collider. One can combine many low charge, low emittance bunches in longitudinal phase space!

No time to discuss.

Problems with lasers

Lasers for energies 2E<700 GeV exists, $\lambda \sim 1$ μm

For higher energy longer wave length is needed, larger flash energy due to larger nonlinear effect.

In principle one can use $\lambda \sim 1$ μm for all energies (using $2P_c\lambda_e=+1$, instead of -1. In this case x~50 and $\xi^2 \sim 1$, e+e- coherent creation in laser wave is possible, need to study.

Beam removal

At ILC the disruption angles are about 10 mrad, the crossing angle >20 mrad is need.

The disruption angle $\theta \propto \sqrt{\frac{N}{\sigma_z E_{\min}}}$. One should take this into account..

The Photon collider based on European XFEL with $E_0 \approx 17.5$ GeV

(or any one linac with similar energy)

for study $\gamma\gamma$ physics in c, b quark energy region $W_{\gamma\gamma}=3\text{-}12$ GeV

Linear colliders on 0.3-1.5 TeV energies are still not approved (due to high cost and uncertain physics case), beside the photon collider based at ILC (CLIC) can appear as the second stage in 3-4 decades, therefore it has sense to consider a $\gamma\gamma$ collider on the energy $W_{\gamma\gamma}$=3-12 GeV

c-b-$\gamma\gamma$-factory

It is a natural choice, because it is the region of b-quark bound states (and there is nothing interesting between 12 and 125 GeV).

This energy region was studied in e^+e^- collisions at B-factories and will be further studied at SuperB-factory. However these e+e- factories can not study $\gamma\gamma$ collisions at $W_{\gamma\gamma}$=5-12 GeV (too low $\gamma^*\gamma^*$ luminosity).

The LHC is not suited for detailed study of $\gamma\gamma$ physics because there is very large background due to strong interactions (such as pomeron-pomeron interactions) with very similar final states.

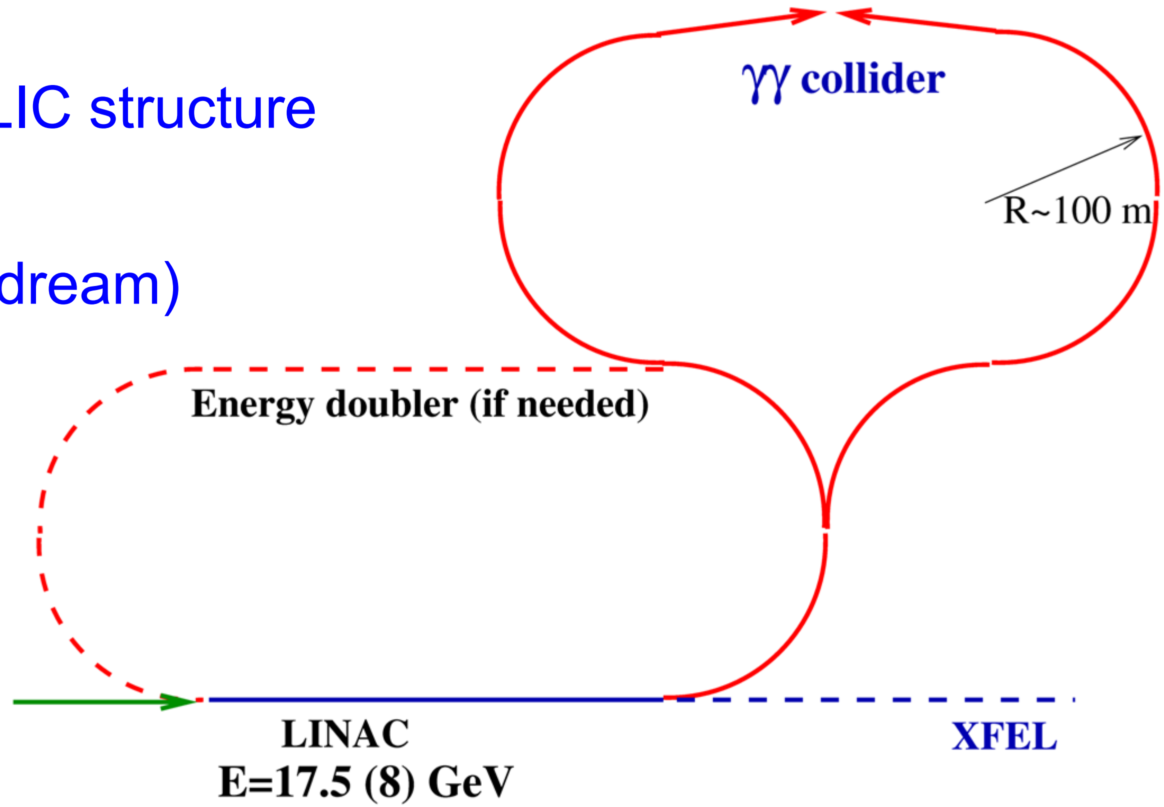
Two real photons will produce resonance states with Q = 0 , C = +,
$J^P = 0^+, 0^-, 2^+, 2^-, 3^+, 4^+, 4^-, 5^+ \ldots (\text{even})^{\pm}, (\text{odd} \neq 1)^+$
as well as numerous 4-quark (or molecule) states similar to those observed in e+e-.

The required electron beam energy E_0~17-23 GeV (for λ=0.5 and 1 μm), 10 times smaller than at the ILC, the cost will be smaller accordingly.

Scheme of the collider

There are several possible electron "drivers" for c-b-$\gamma\gamma$-collider:

1) SC European 17.5 GeV XFEL (used beams?)
2) Warm cavity linac (CLIC structure with klystrons)
3) Plasma accelerator (dream)

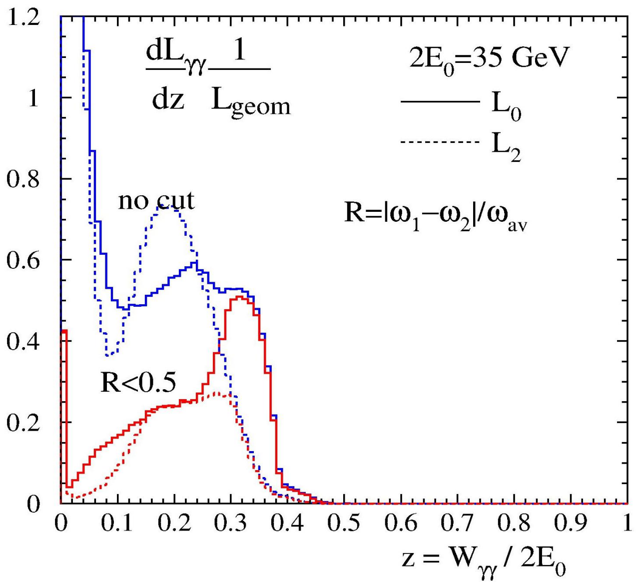


(Linac not in scale)

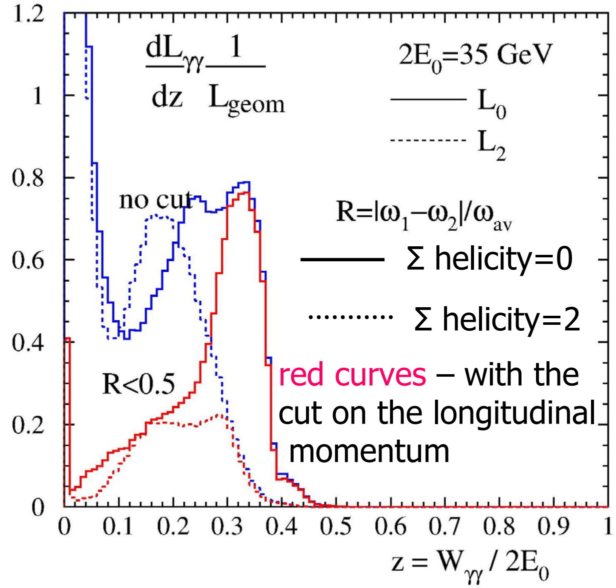
European Superconducting XFEL has started operation in 2017. Its e-beam parameters: E_0=17.5 GeV, N=0.62·10^{10} (1 nQ), σ_z=25 μm, ε_n=1.4 mm mrad, f≈30 kHz

Using arcs we can get the photon collider with f=15 kHz. Other parameters for γγ collider: β^*=70 μm, σ_z=70 μm, laser wavelength λ=0.5 μm (parameter x~0.65). Corresponding γγ luminosity spectra (for b=γσ_y=1.8 mm)

Unpolarized electrons, P_c=-1



Polarized electrons, $2\lambda_e P_c$=-0.85



L_{geom}=1.5·10^{33} (XFEL beams)

$W_{\gamma\gamma}$ peak at 12 GeV, covers all bb-meson region. Electron polarization is desirable, but not mandatory (improvement <1.5 times). Easy to go to lower energies by reducing the electron beam energy.

By increasing the CP-IP distance the luminosity spectrum can be made more narrow and cleaner

One example: $\gamma\gamma \to \eta_b$. M=9.4 GeV

There was attempt to detect this process at LEP-2 (2E=200 GeV, L=10^{32}, but only upper limit was set.

$$N = \frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}} \frac{4\pi^2 \Gamma_{\gamma\gamma}(1+\lambda_1\lambda_2)}{M_x^2} \left(\frac{\hbar}{c}\right)^2 t$$

For $\gamma\gamma$ collider $\frac{dL_{\gamma\gamma}\, 2E_0}{dW_{\gamma\gamma} L_{ee}} \simeq 0.5$, so

$$N \sim \frac{\pi^2 \Gamma_{\gamma\gamma}(1+\lambda_1\lambda_2)}{E_0 M_x^2} \left(\frac{\hbar}{c}\right)^2 (L_{ee} t) \sim 8 \cdot 10^{-27} \frac{\Gamma_{\gamma\gamma}}{E_0 M_x^2 [\mathrm{GeV}^2]} (L_{ee} t)$$

For $\Gamma_{\gamma\gamma}(\eta_b) = 0.5$ keV, $E_0 = 17.5$ GeV, $\mathrm{M}(\eta_b) = 9.4$ GeV, $\lambda_{1,2} = 1, L_{ee} = 1.5 \cdot 10^{33} - 1.5 \cdot 10^{34}$,

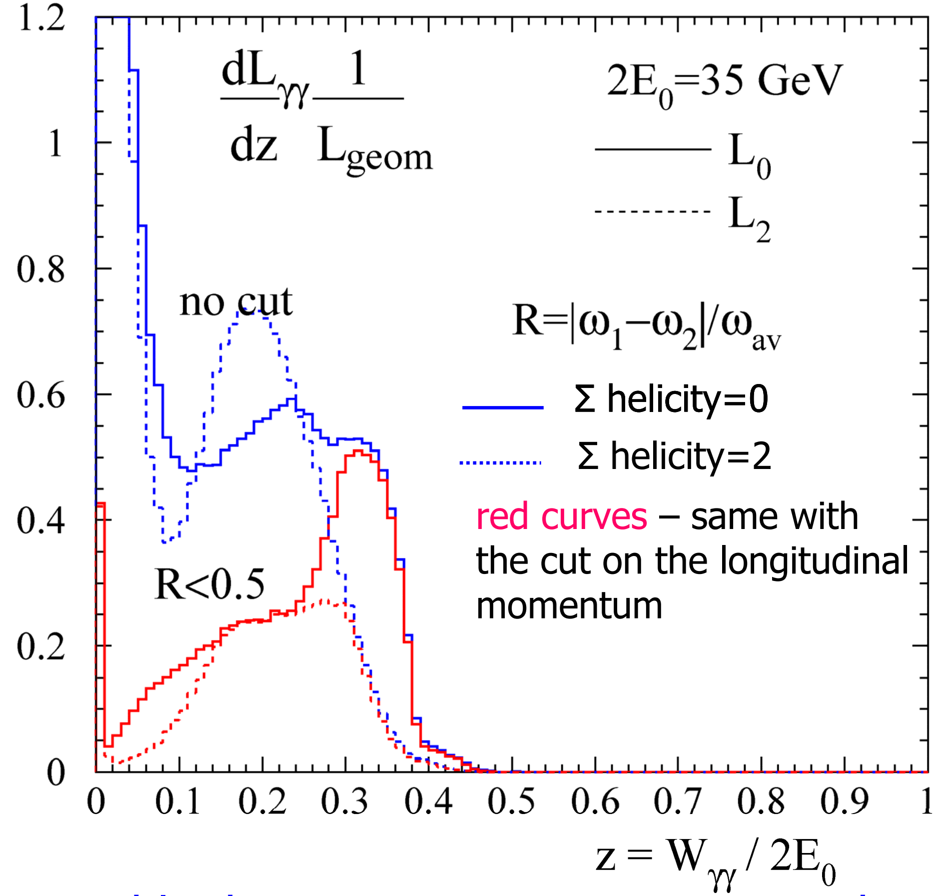
$t = 10^7 s$ we get $N(\eta_b) \approx 4 \cdot 10^4$ and can measure its $\Gamma_{\gamma\gamma}$

Production rate is higher than was at LEP-2 (in central region) ~ 700!

Parameters of photon collider for bb-energy region (W<12 GeV)

E_0, GeV	17.5 (23)
$N/10^{10}$	0.62
f, kHz	15
σ_z, µm	70
$\varepsilon_{nx}/\varepsilon_{ny}$, mm mrad	1.4/1.4
β_x/β_y, µm	70/70
σ_x/σ_y, nm	53/53
laser λ, µm (x≈0.65)	0.5 (1)
laser flash energy, J	3 (ξ^2=0.05)
f#, τ, ps	27, 2
crossing angle, mrad	~30
b, (CP-IP dist.), mm	1.8
L_{ee}, 10^{33}	1.6
$L_{\gamma\gamma}(z>0.5z_m)$, 10^{33}	0.21
$W_{\gamma\gamma}$(peak), GeV	12

Unpolarized electrons, P_c=-1



In Table the XFEL emittance is assumed. With promised plasma gun the luminosity can be larger ~10 times.

Conclusion

Linear e+e- collider + γγ collider was most exiting direction of particle physics in 1988-2001 years. Unfortunately …..

People tired to wait, necessary to built something interesting