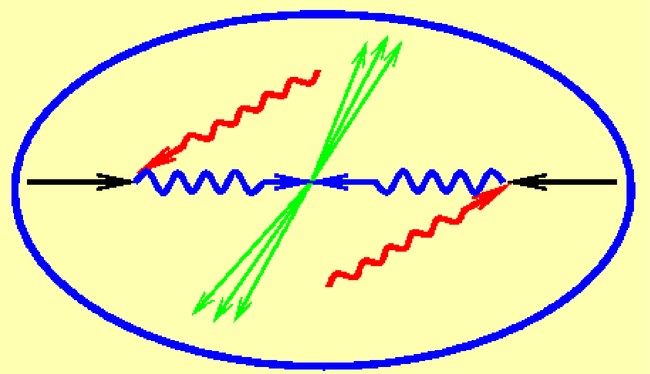


Photon collider at ILC

(overview)

Valery Telnov

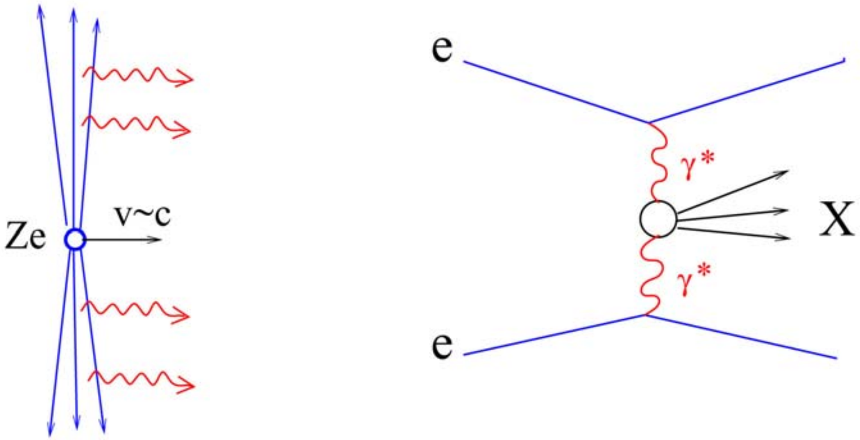
Budker INP, Novosibirsk

High-energy $\gamma\gamma$ collision at LHC,
CERN, April 23, 2008

Contents

- Basic principles and properties the $\gamma\gamma$, γe collider
- Conversion and Interaction regions issues
- Lasers, optics
- Physics motivation
- The Photon collider at ILC, current status
- Conclusion

Colliding $\gamma^*\gamma^*$ photons



Landau-Lifshitz process

Physics in $\gamma^*\gamma^*$ is quite interesting, though can not compete with e^+e^- collisions because the number of equivalent photons is rather small and their spectrum soft

$$dn_\gamma \approx \frac{2\alpha}{\pi}\frac{dy}{y}\left(1-y+\frac{1}{2}y^2\right)\ln\frac{E}{m_e} \sim 0.035\,\frac{d\omega}{\omega}\,;$$

$L_{\gamma\gamma}(z>0.1) \sim 10^{-2}\, L_{e+e-}$

$L_{\gamma\gamma}(z>0.5) \sim 0.4\cdot 10^{-3}\, L_{e+e-}$

$z=W_{\gamma\gamma}/2E_0$

Idea of the photon collider

The idea of the high energy photon collider is based on the fact that at linear 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 (it is not possible at storage ring where bunches are used many times).

The best method of the $e \longrightarrow \gamma$ 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 $\gamma\gamma$ collisions close to those in e+e- collisions:

$$E_\gamma \sim E_e \;; \qquad L_{\gamma\gamma} \sim L_{e+e-}$$

Laser e→γ conversion

The method of the Compton scattering of laser light off high energy electrons was known since 1964 (Arutyunian, Tumanian, Milburn) and was used since 1966 at SLAC and other labs with $k=n_\gamma/n_e \sim 10^{-6}$.

For the photon collider one needs k~1 !

The required laser flash energy is about 1-10 J and ~1-3 ps durations and rep.rate similar to the linear collider (~10 kHz).

In 1981 we believed that it will be possible just extrapolating the progress in the laser technique (beside rep.rate was only 10-100 Hz).

In 1985 D.Strickland and G.Mourou invented the chirped pulse technique which made the photon collider realistic.

For the supercondicting ILC one can use the external optical cavity which considerably decreases the required laser power and together with other modern laser techniques (diode pumping, adaptive optics, multilayer mirrors) makes the photon collider really technically feasible.

The history of the photon collider and major steps is described in

V.I. Telnov, Photon colliders: The First 25 years.
Acta Physica Polonica B 37 (2006) 633, physics/0602172.

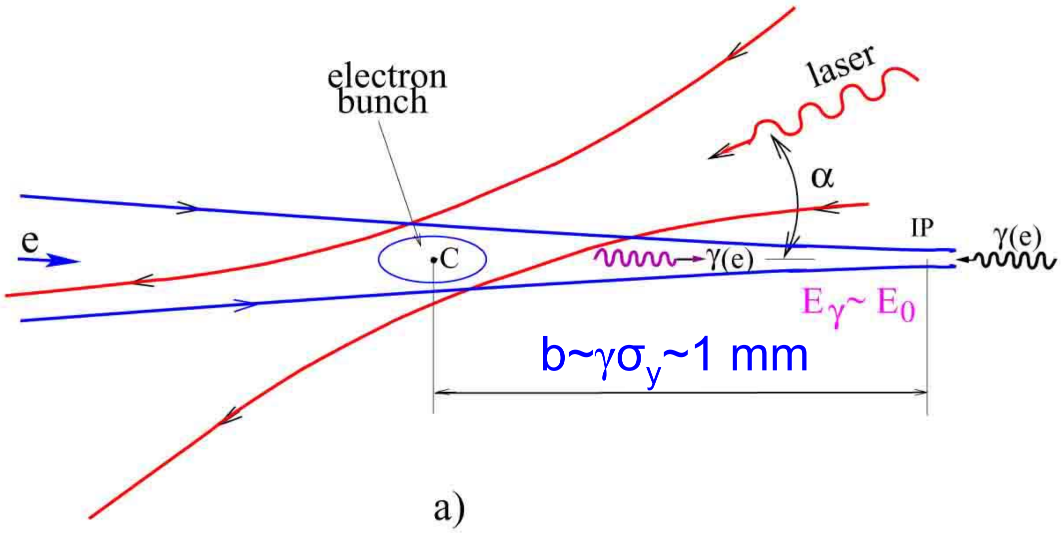
Most full description of the PLC (up to now)

Badelek et al., Photon collider at TESLA (TESLA TDR, 2001),
Int. J. Mod.Phys.A19: 5097-5186, 2004.

+more recent works (crossing angle, beamdump, optical scheme)

Scheme of $\gamma\gamma$, γe collider

GKST,1981

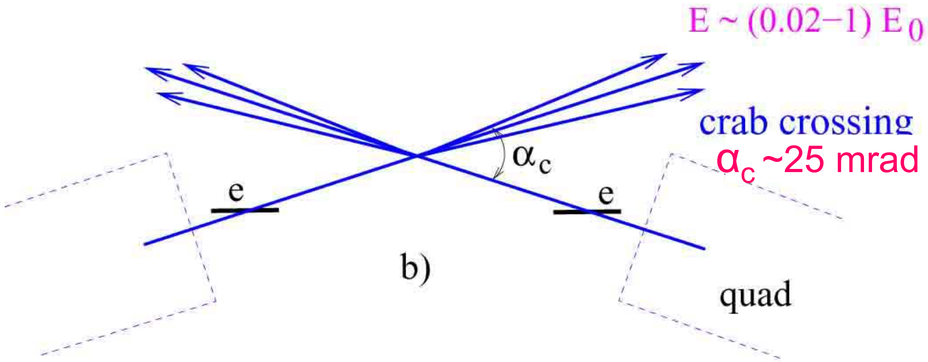


$$\omega_m = \frac{x}{x+1}E_0$$

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

$(\omega = 4\gamma^2\omega_0$ at $\omega << E)$

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



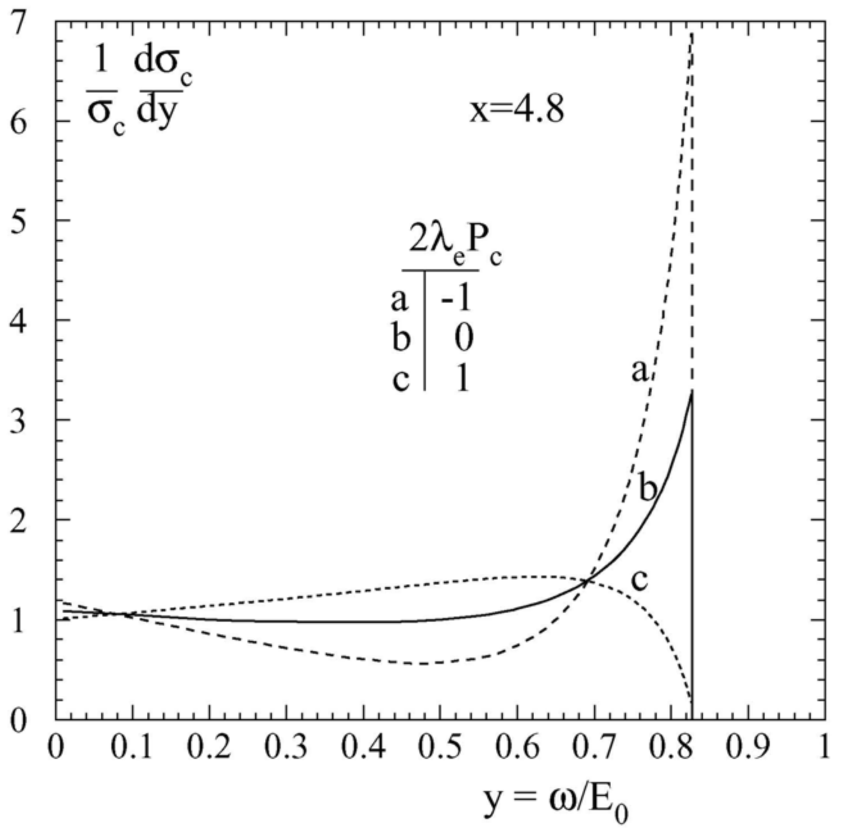
$x = 4.8$ is the threshold for
$\gamma\gamma_L \to e^+e^-$ at conv. reg.

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

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

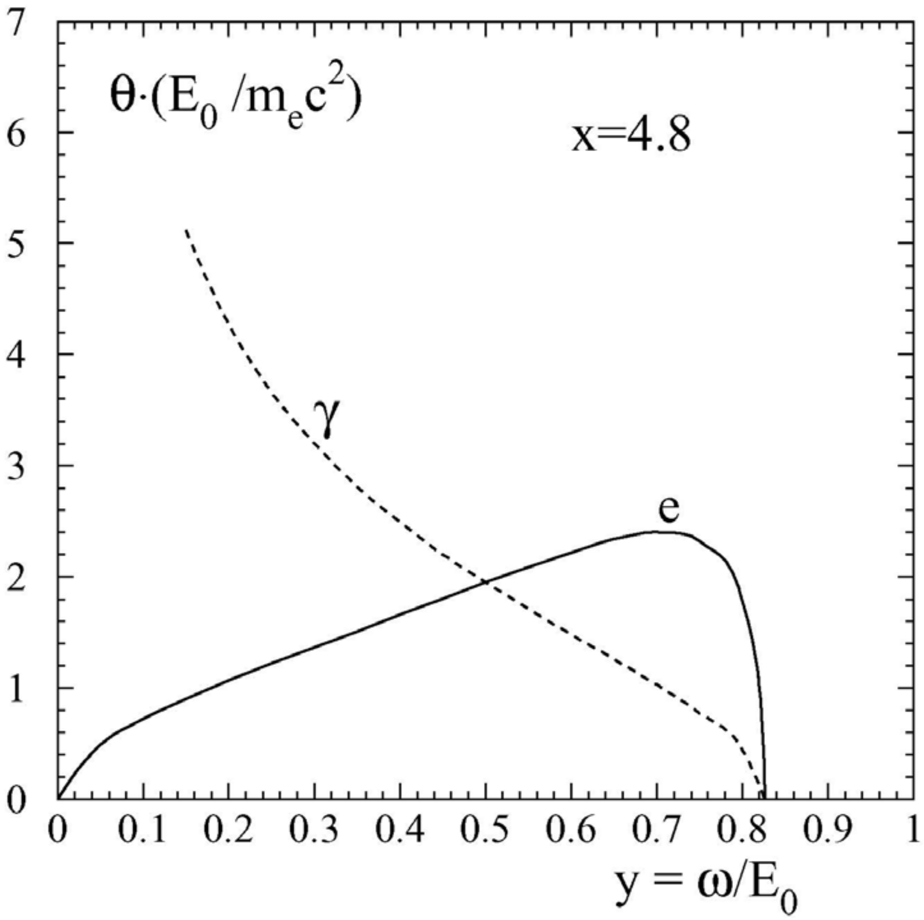
Electron to Photon Conversion

Spectrum of the Compton scattered photons

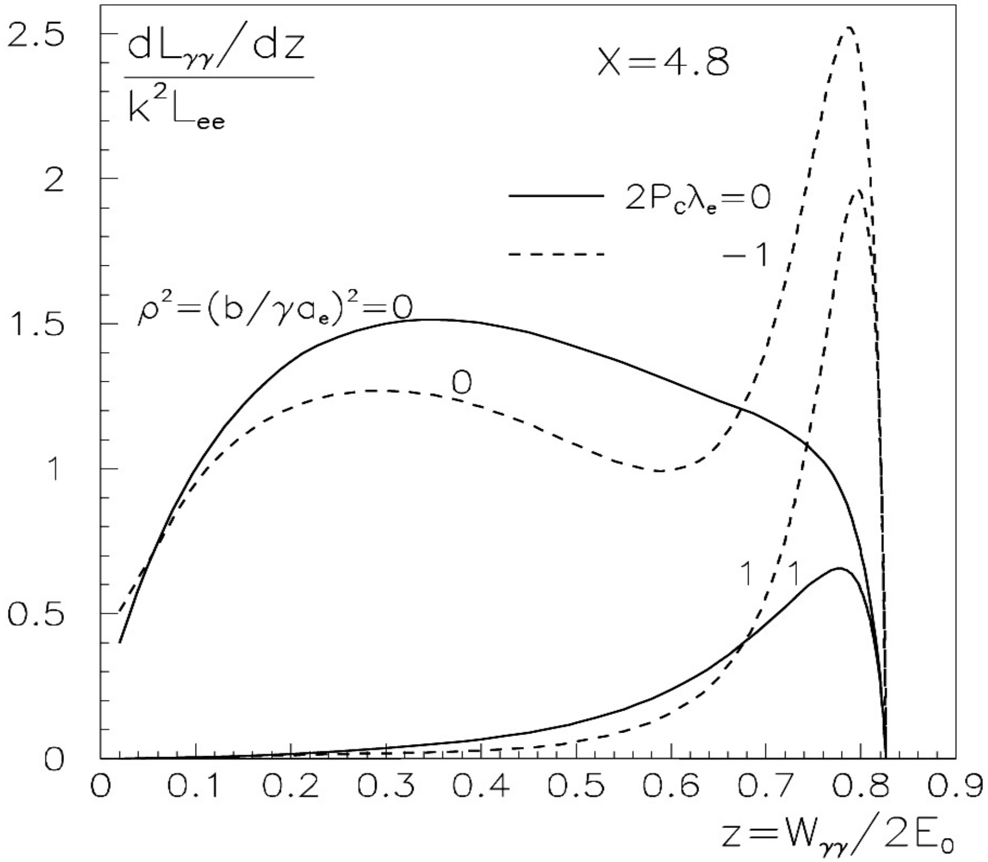


λ_e – electron longitudinal polarization
P_c – helicity of laser photons, $x \approx \frac{4E_0\omega_0}{m^2c^4}$

Angle-energy correlation for photons

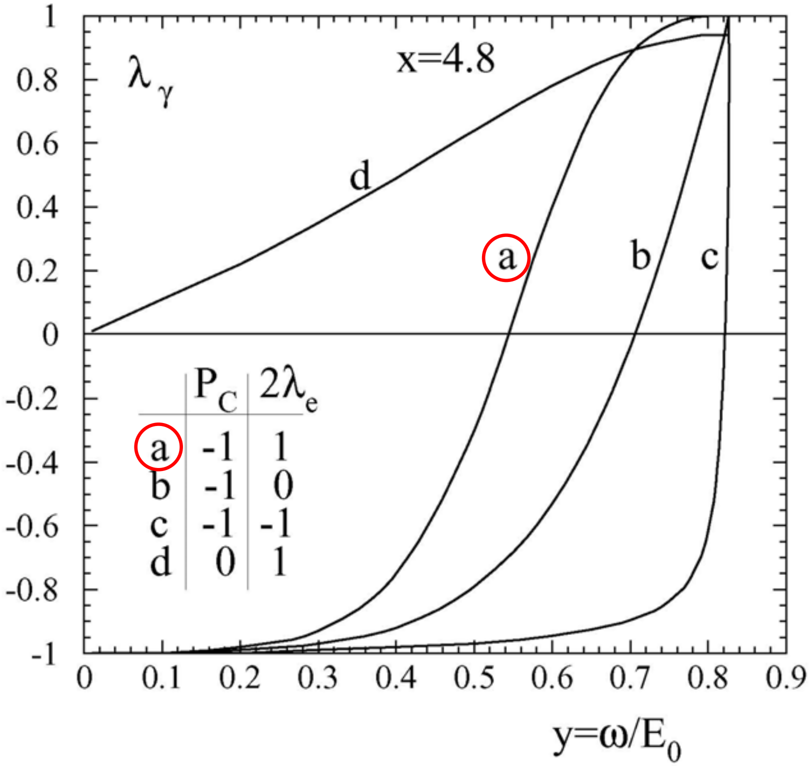


Ideal luminosity distributions, monohromatization



Due to angle-energy correlation high energy photons collide at smaller spot size, providing monohromatization of γγ collisions. This happends at $b/\gamma > a_e$, (a_e is the radius of the electron beam at the IP)

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



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

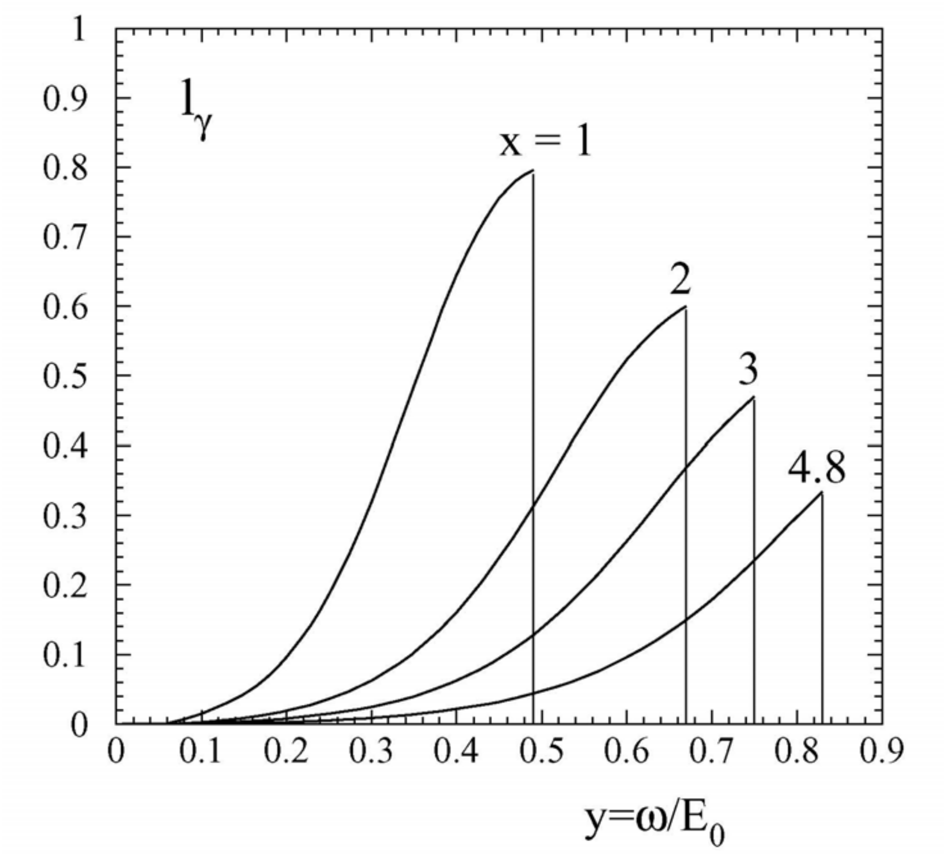
The cross section of the Higgs production

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

The cross section for main backgound

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

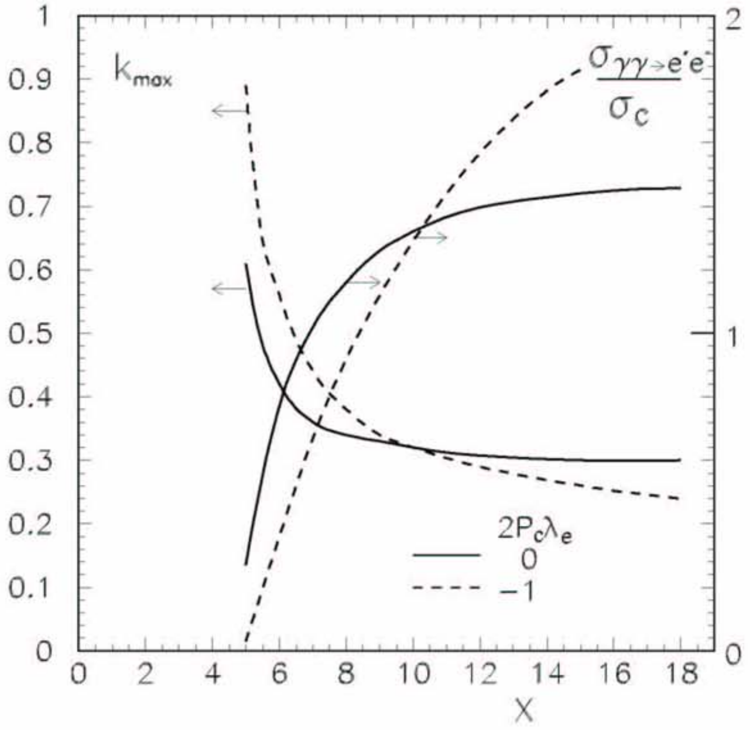
Linear polarization of photons



$\sigma \propto 1 \pm l_{\gamma 1} l_{\gamma 2} \cos 2\varphi$ ± for CP=±1

Linear polarization helps to separate H and A Higgs bosons

e^+e^- pair creation in the collisions of laser and high energy photons

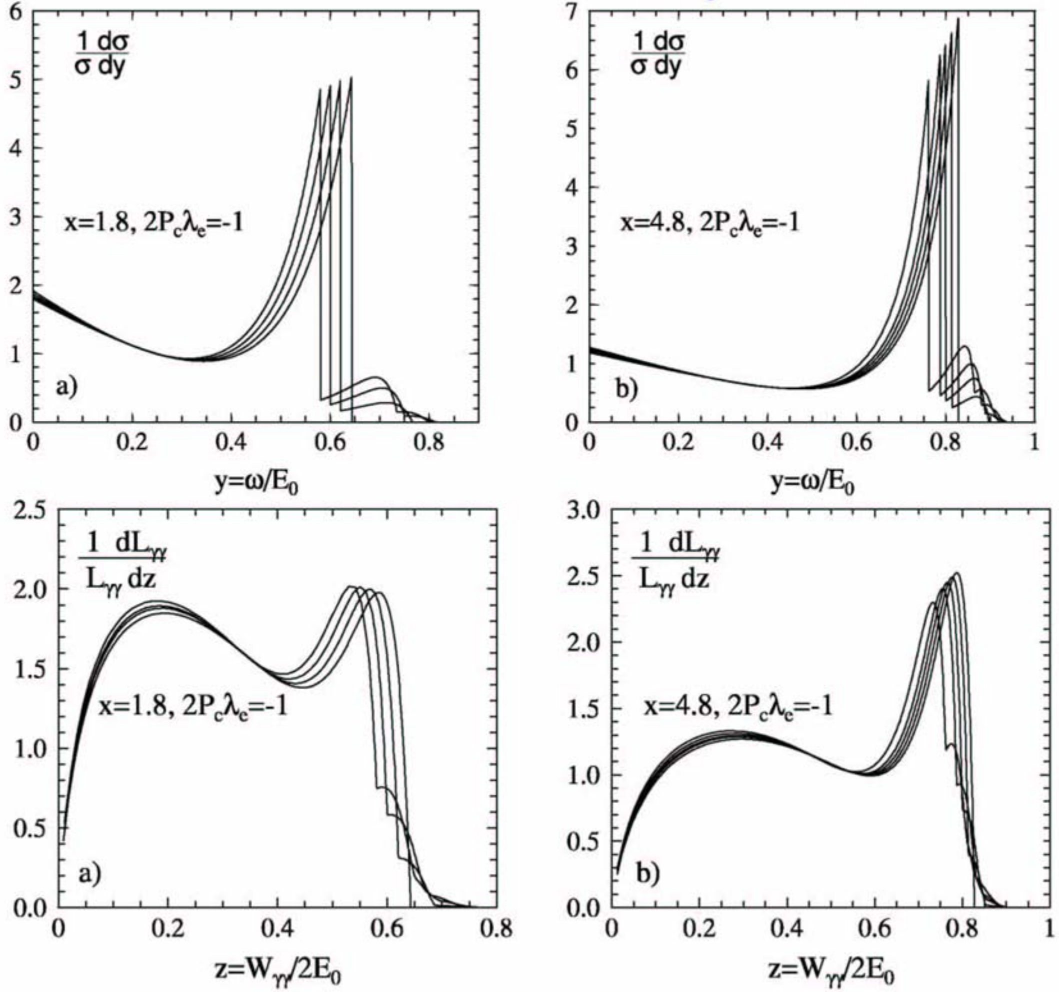


The threshold of e^+e^- creation: $x = 4.8$, the optimum value.
Corrsponding wavelength $\lambda = 4.2 E_0[\text{TeV}]\,\mu\text{m}$.

$E_{\gamma,max}/E_0 \sim x/(x+1) \sim 0.82$

Nonlinear effects in Compton scattering

$$\xi^2 = \frac{e^2 \bar{F}^2 \hbar^2}{m^2 c^2 \omega_0^2} = \frac{2 n_\gamma r_e^2 \lambda}{\alpha}$$



Photon spectra

$\gamma\gamma$ luminosity spectra

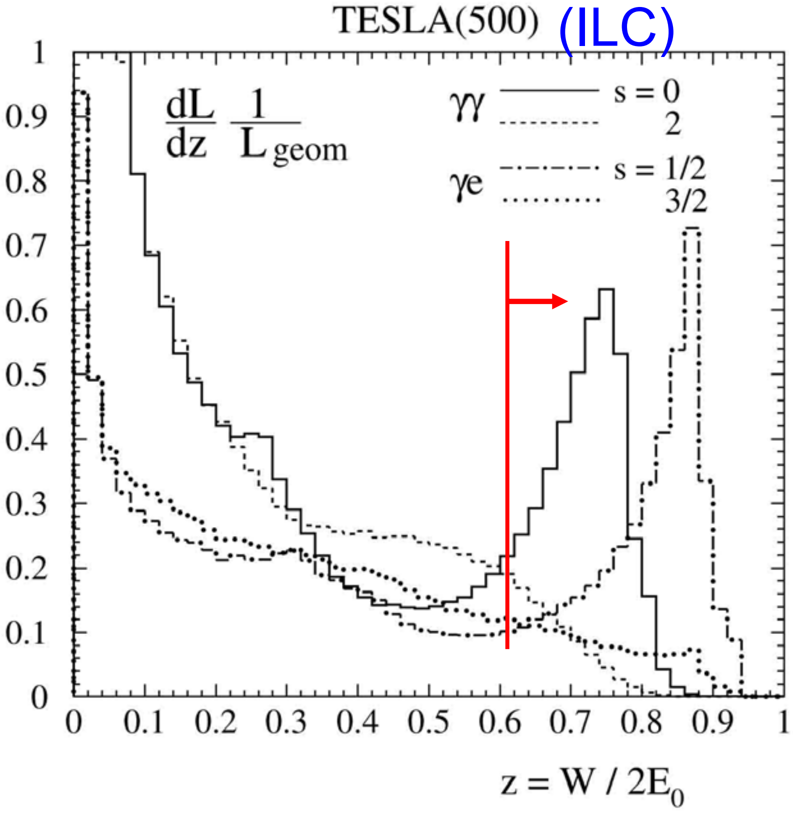
(Curves from right to left: $\xi^2 = 0, 0.1, 0.2, 0.3, 0.5$)

$\xi^2 \leq 0.2$-0.3 is required

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

(with account multiple Compton scattering, beamstrahlung photons
and beam-beam collision effects)

(decomposed in two states of J_z)



(ILC)

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

For ILC conditions

$L_{\gamma\gamma}(z>0.8z_m)$ ~(0.17-0.55) L_{e+e-}(nom)
~ (0.35-1) $\cdot 10^{34}$ cm^{-2} s^{-1}

(but cross sections in $\gamma\gamma$ are larger by one order!)

First number - nominal beam emittances
Second - optimistic emittances
(possible, needs optimization of DR for $\gamma\gamma$)

For γe it is better to convert only one electron beam, in this case it will be easier to identify γe reactions, to measure its luminosity (and polarization) and the γe luminosity will be larger.

Comparison of the two-photon Higgs(150) production at LHC, ILC(e+e-) and PLC

$$N_H \propto (1+\lambda_1\lambda_2)\ dL/dW\ _{W=150}$$

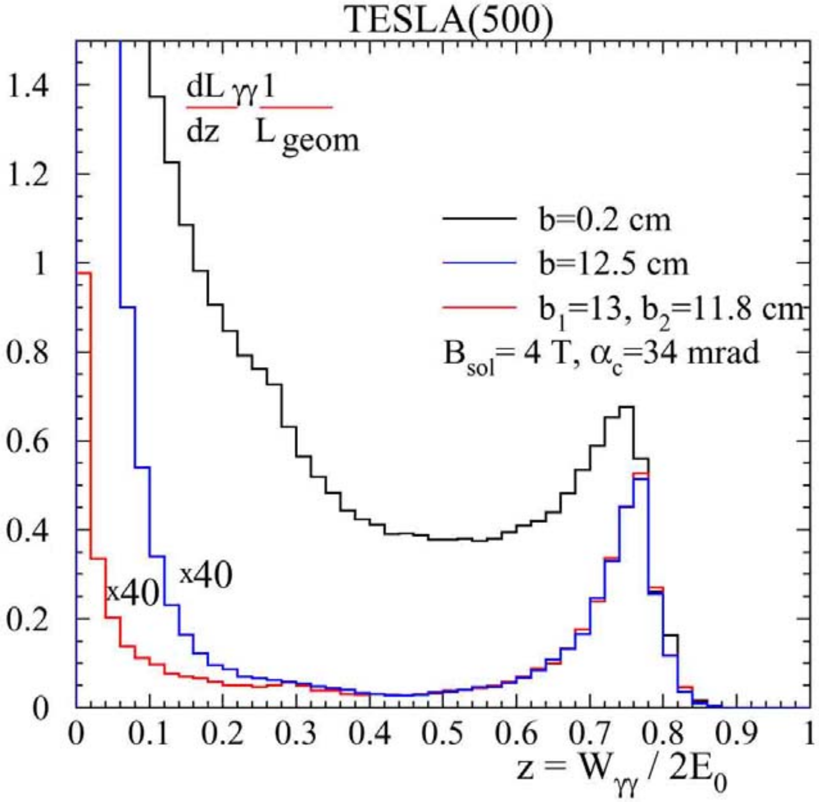
LHC : ILC : PLC ~ 1 : 8 : 1000

$L = 10^{34}$ $2 \cdot 10^{34}$ $3 \cdot 10^{34}$(geom)

In addition, at PLC the Higgs boson is produced almost in rest, backgrounds are suppressed using photon polarization.

γ γ- luminosity spectrum for QCD study

For measurement of the total cross section or QCD study one needs lower luminosity (to decrease overlaping of events (about 1 hadronic event at the nominal luminosity), but more monochromatic. This can be achieved by increasing CP-IP distance.



Owing to the crossing angle and the detector field electron beams are deflected after the conversion point and do not collider, if b1≠b2 (red).

Measurement of $\gamma\gamma$ γe luminosities and polarizations

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

For measurement of luminosities and polarizations

one can use QED processes

$\gamma\gamma \rightarrow l^+l^-$ $(l = e, \mu)$

$\gamma\gamma \rightarrow l^+l^-\gamma$ $(l = e, \mu)$

$\gamma\gamma \rightarrow l^+l^-l^+l^-$ $(l = e, \mu)$

γe $\rightarrow \gamma$e

γe $\rightarrow e^-e^+e^-$

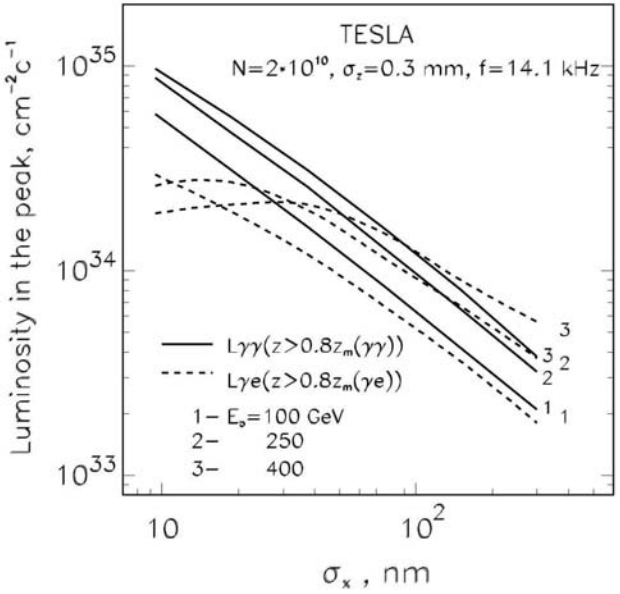
Processes for measurement of luminosity were considered in
A.V.Pak et al., Nucl. Phys.Proc.Suppl.126 (2004) 379б hep-ex/0301037;
V. Makarenko et al.,Eur.Phys.J.C32:SUPPL1143-150,2003, hep-ph/0306135

Factors limiting $\gamma\gamma$,γe luminosities

Collisions effects:

- Coherent pair creation
- Beamstrahlung
- Beam-beam repulsion

On the right: dependence of $\gamma\gamma$ and γe luminosities in the high energy peak on the horizontal beam size:



For the TESLA electron beams $\sigma_x \sim 100$ nm at $2E_0 = 500$. Having beams with smaller emittances one could have by one order higher $\gamma\gamma$ luminosity.

γe luminosity in the high energy peak is limited due to the beam repulsion and beamstrahlung

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

Some interaction region issues

1. For removal of the disrupted beams the crossing angle at one of the interaction regions should be about 25 mrad.

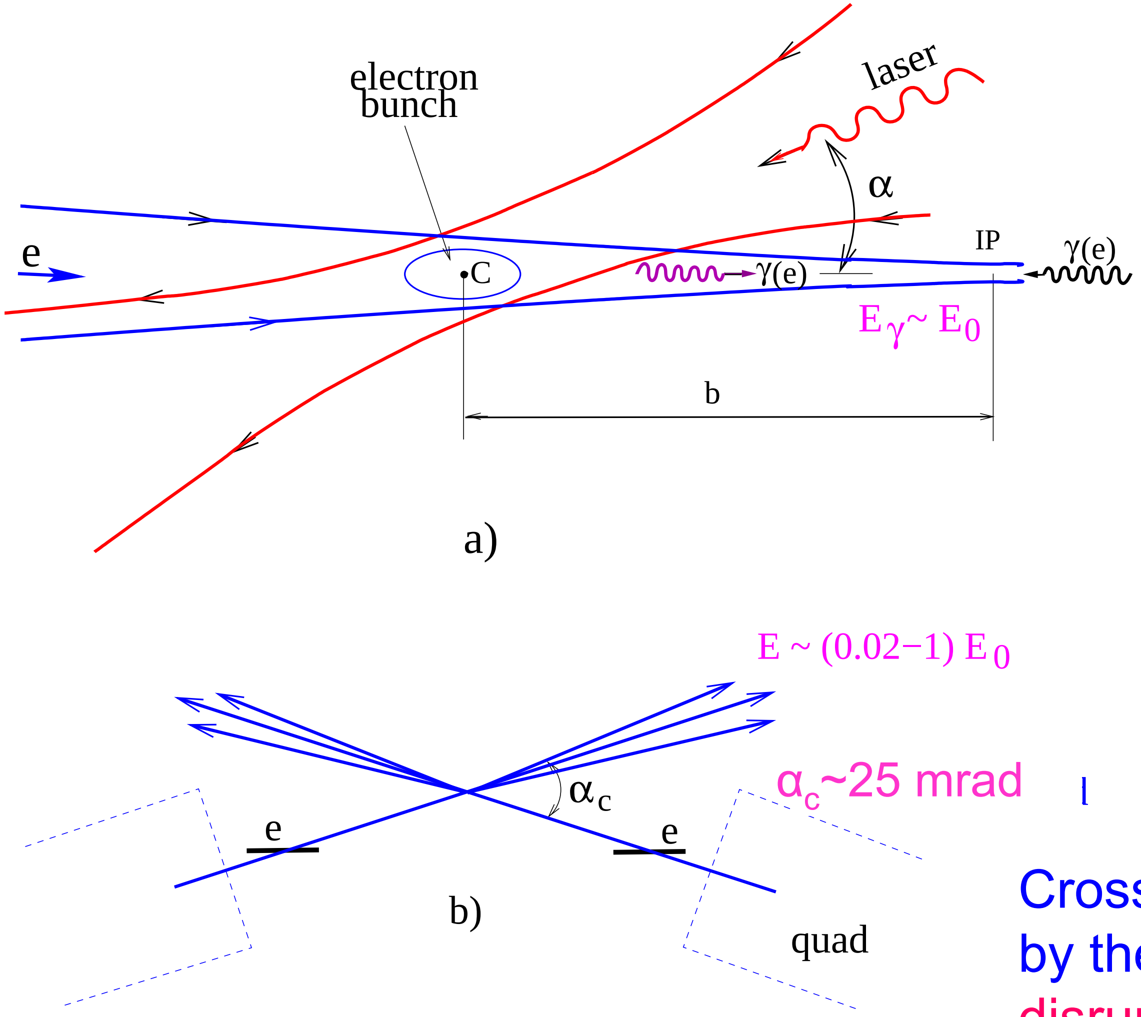
2. The $\gamma\gamma$ luminosity is almost proportional to the geometric e-e- luminosity, therefore the product of horizontal and vertical emittances should be as small as possible (requirements to damping rings and beam transport lines);

3. The final focus system should provide a spot size at the interaction point as small as possible (the horizontal β-functions can be smaller by one order of magnitude than that in the e+e- case);

4. Very wide disrupted beam should be transported to the beam dump with acceptable losses; the beam dump should withstand absorption of very narrow photon beam after Compton scattering;

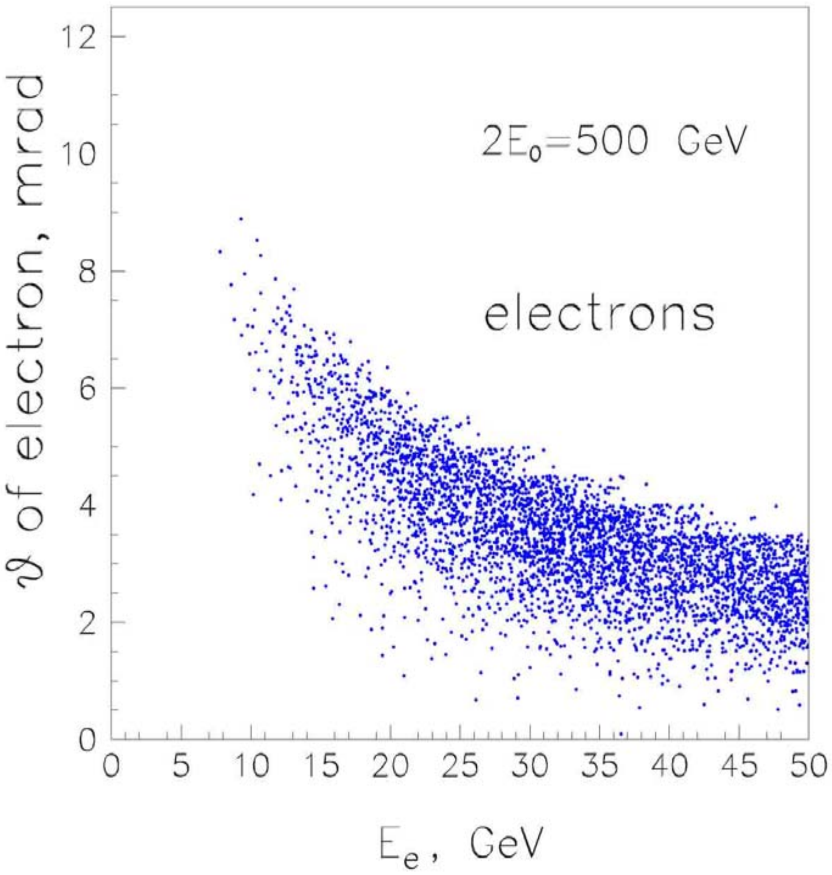
5. The detector design should allow replacement of elements in the forward region (<100 mrad);

Crab-crossing angle



Crossing angle is determined by the angular spread in the disrupted beam and the radius of the first quad

Properties of the beams after CP,IP



Electrons:

E_{min}~6 GeV,
$\theta_{x\ max}$~8 mrad
$\theta_{y\ max}$~10 mrad

practically same for
E_0=100 and 250 GeV

For low energy particles the deflection in the field of opposing beam

$$\vartheta \propto 1/\sqrt{E\sigma_z}$$

An additional vertical deflection, about ±4 mrad, adds the detector field

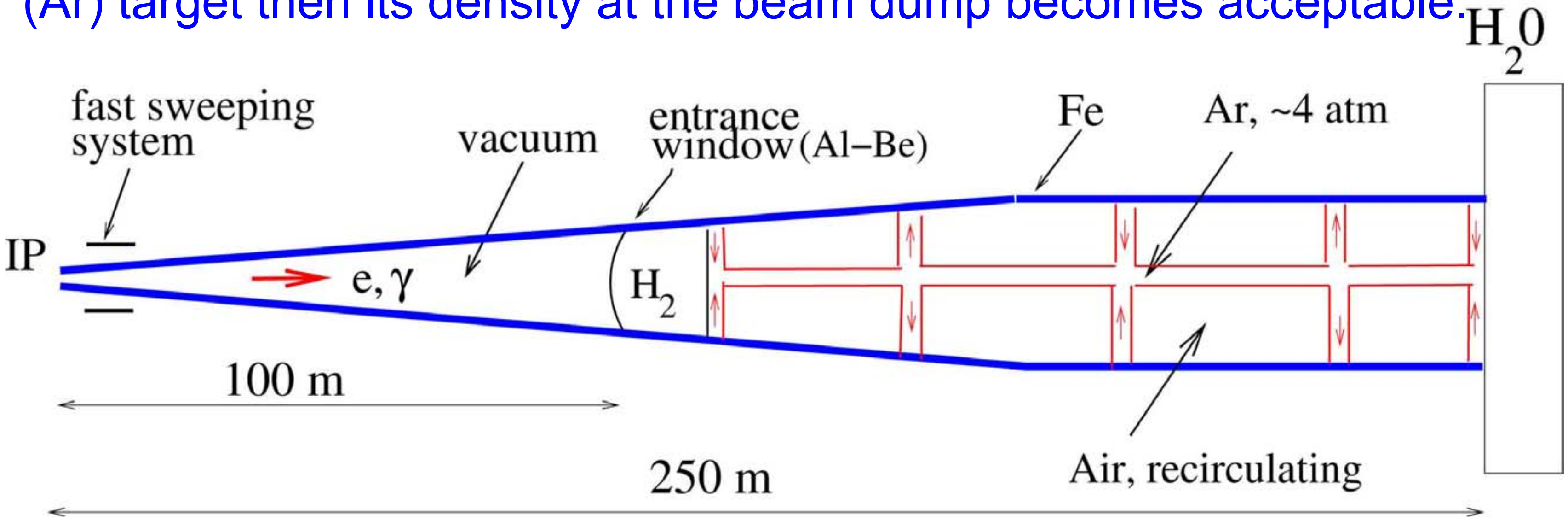
$$\alpha_c = (5/400)\ (\text{quad}) + 12.5 \cdot 10^{-3} (\text{beam}) \sim 25\ \text{mrad}$$

Problem of the beam dump

The angular distribution of photons after Compton scattering is very narrow, equal to the angular divergence of electron beams at the IP:

$\sigma_{\theta x} \sim 4 \cdot 10^{-5}$ rad, $\sigma_{\theta y} \sim 1.5 \cdot 10^{-5}$ rad, that is 1 x 0.35 cm^2 and beam power about 10 MW at the beam dump. No one material can withstand with such average power and energy of one ILC train.

Possible solution: the photon beam produces a shower in the long gas (Ar) target then its density at the beam dump becomes acceptable.



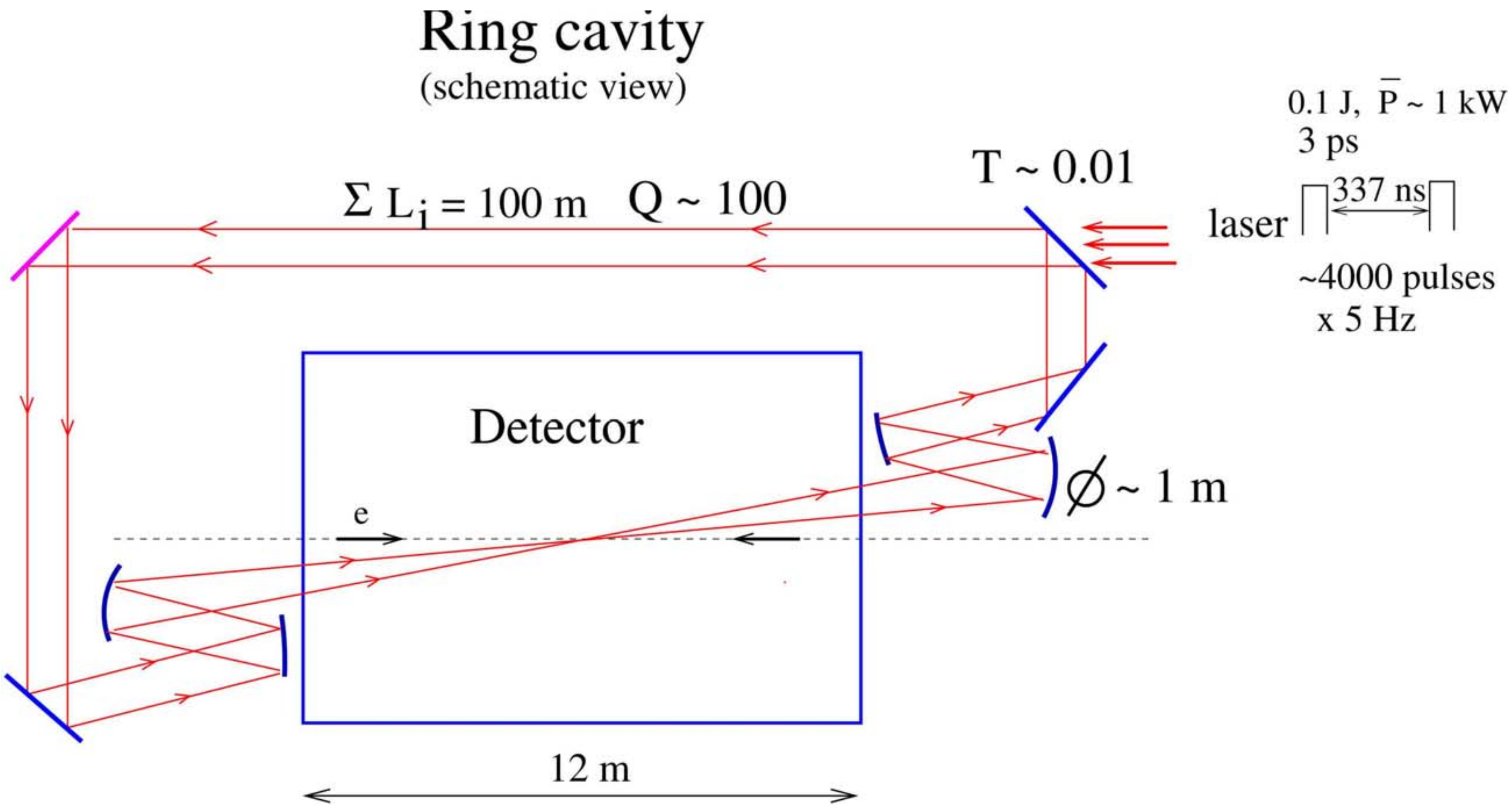
Requirements for laser

• 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 length	~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, but even in this case the pumping laser should be very powerful.

Laser system

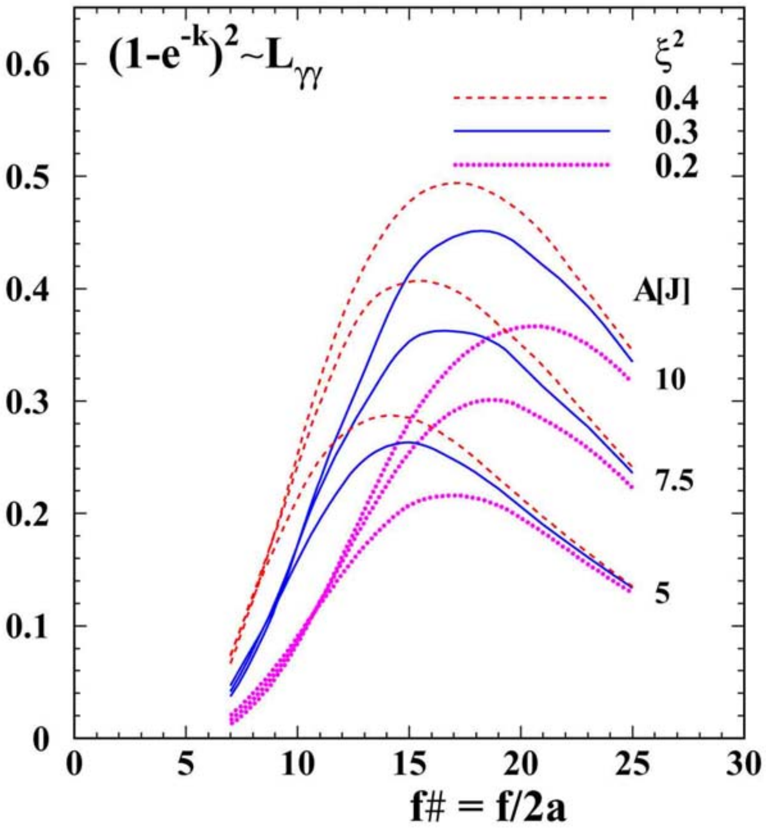


The cavity includes adaptive mirrors and diagnostics. Optimum angular divergence of the laser beam is ±30 mrad, A≈9 J (k=1), $\sigma_t \approx 1.3$ ps, $\sigma_{x,L} \sim 7$ μm

Parameters of the laser system

The figure shows how the conversion efficiency depends on the f# of the laser focusing system for flat top beams in radial and Gaussian in the longitudinal directions

T.V.



f- focal distance
a – mirror radius

The parameter $$\xi^2 = \frac{e^2B^2}{m^2c^2\omega^2} = \frac{2n_\gamma r_e^2\lambda}{\alpha}$$

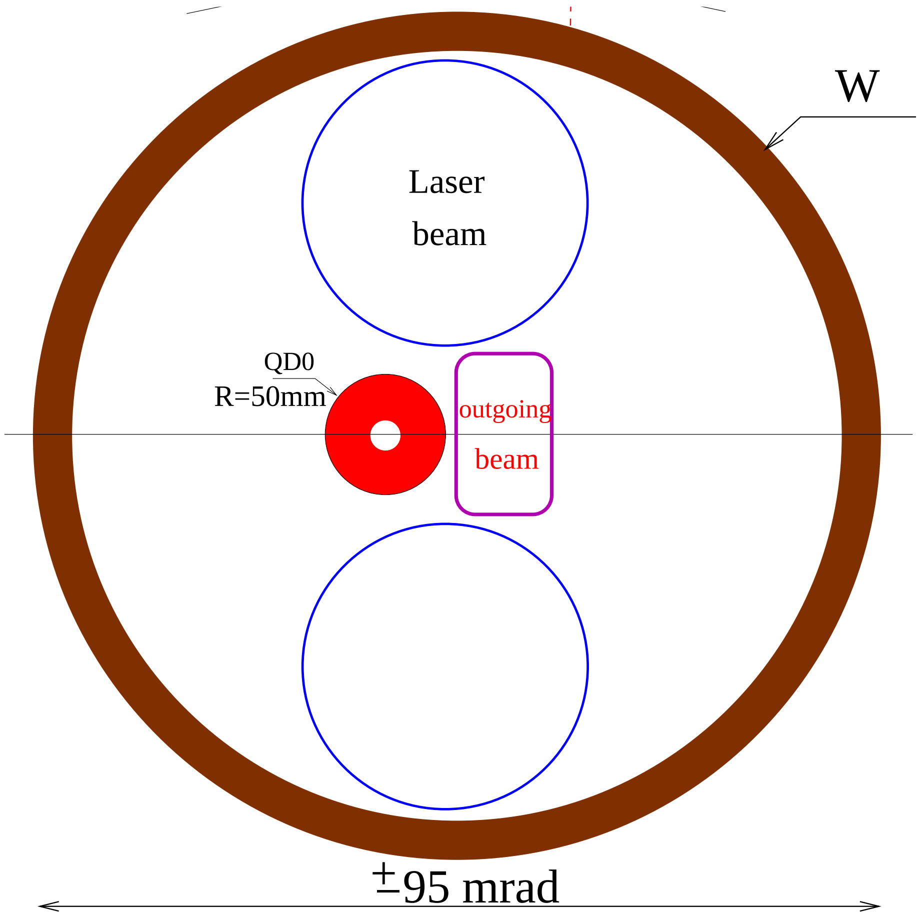
characterizes the probability of Compton scattering on several laser photons simultaneously, it should be kept below 0.2-0.4, depending on the par. x)

For ILC beams, α_c=25 mrad, and θ_{min}=17 mrad (see fig. with the quad) the optimum $f_\#$ =f/2a ≈ 17, A≈9 J (k=1), σ_t ≈ 1.3 ps, $\sigma_{x,L}$~7 μm.

So, the angle of the laser beam is ±1/2$f_\#$ = ±30 mrad,

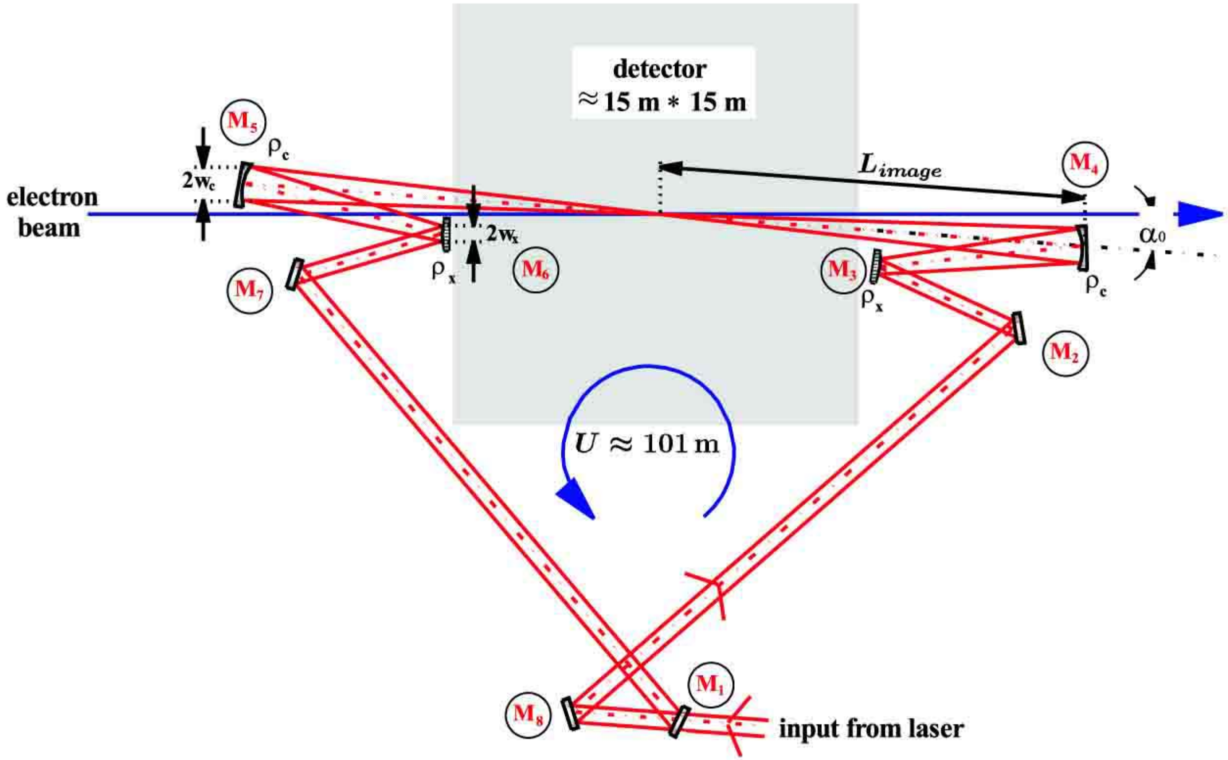
The diameter of the focusing mirror at L=15 m from the IP is about 90 cm.

Layout of the quad, electron and laser beams at the distance 4 m from the interaction point (IP)



Simulation of the ring optical cavity in DESY-Zeuthen

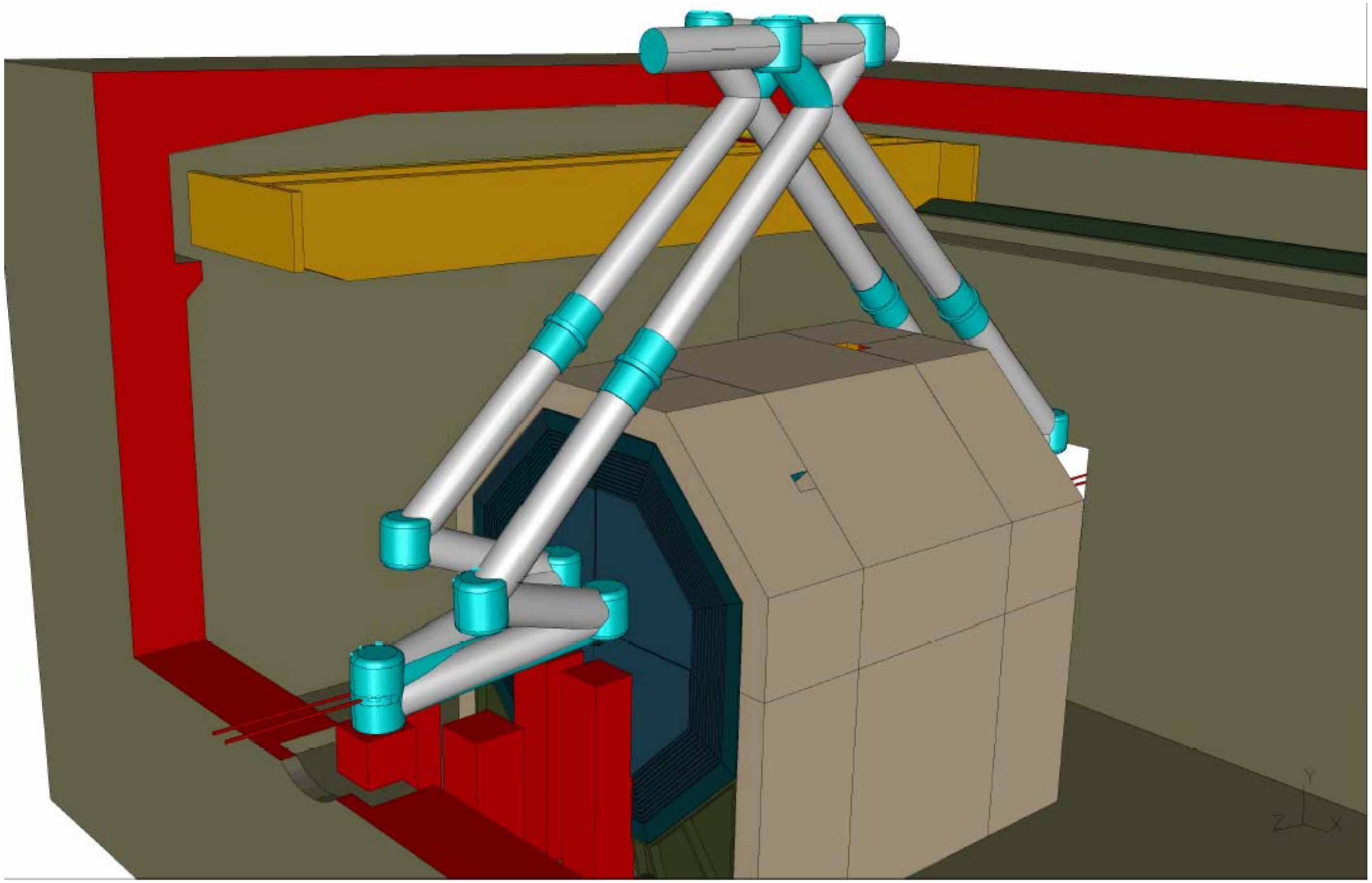
Optimization was done at the wave level with account of diffraction losses (which are negligibly small). Obtained numbers are close to that for flat-top beams (shown above).



View of the detector with the laser system

(just the very first approach)

Klemz, Monig…



The above scheme does not fit the ILC experimental hall

Laser experts considered requirements to the optical cavity for the photon collider and by now have not revealed any stoppers.

At present there is very big activity on development of the laser pulse stacking cavities at Orsay, KEK, CERN, BNL, LLNL for

ILC polarimetry
Laser wire
Laser source of polarized positrons(ILC,CLIC,Super-B)
X-ray sources

All these developments are very helpful for the photon collider.

Some problems with laser optics

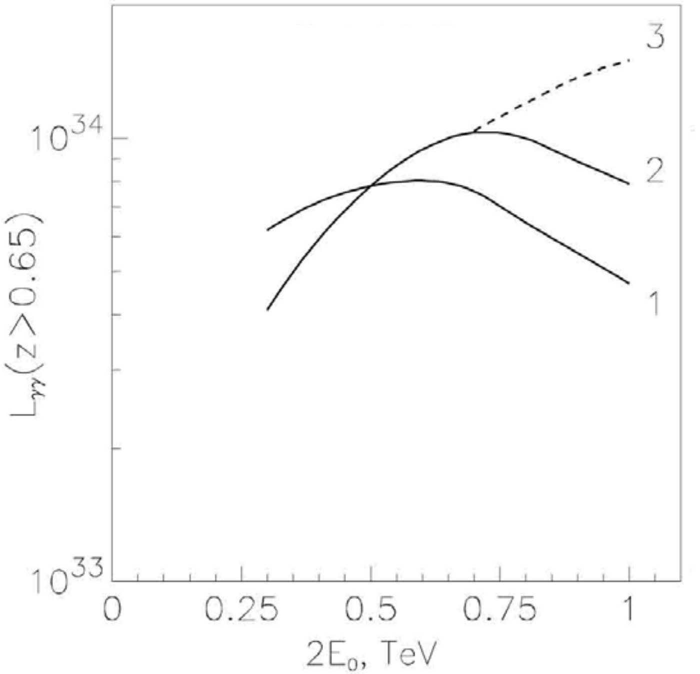
- If the final mirror is outside the detector at the distance ~15 m from the center, its diameter is about d~90 cm, very large (other mirrors in the loop can be of smaller diameter).
- Detectors have holes in forward direction ±33-50 mrad (see next slide) while the photon collider needs ±95 mrad, so there should be special removable parts in ECAL, HCAL and the yoke.

Another solution: mirrors inside the detector

There problem is still to be considered.

Dependence of the γγ luminosity on the energy due to laser parameters

V.Telnov, LCWS04, physics/0411252



1- k=0.64 at 2E=500, A = const, ξ^2 = const, λ = 1.05 μm

2- k=0.64 at all energies, $\xi^2 \propto$ A, λ =1.05 μm

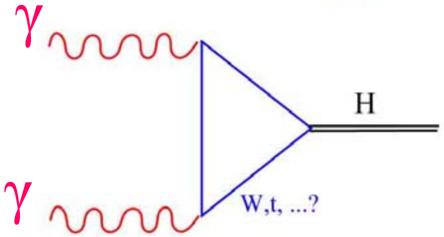
3- k=0.64 at all energies, $\xi^2 \propto$ A, λ =1.47 μm (to avoid pair creation)

If the laser wave length is fixed, the Compton cross section decreases with increasing the energy, consequently the conversion coefficient decreases. Moreover for $x > 4.8$, the e^+e^- pair creation in the conversion region is possible which leads to large decrease of the conversion coefficient at large x. Laser with $\lambda \sim 1.05$ μm (most developed powerful lasers) can be used up to the energy of about $2E_0 = 750 - 800$ GeV. For $2E_0 = 1$ TeV it is desirable to use lasers with $\lambda \sim 1.5$ μm.

Some examples of physics at PLC

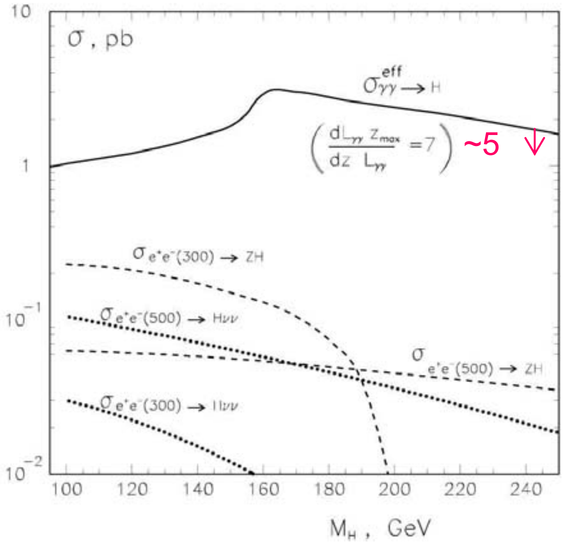
(details see in A. De Roeck's talk)

Higgs boson



Very sensitive to heavy charge particles in the loop.

Cross sections of the Higgs boson in $\gamma\gamma$ and e^+e^- collisions



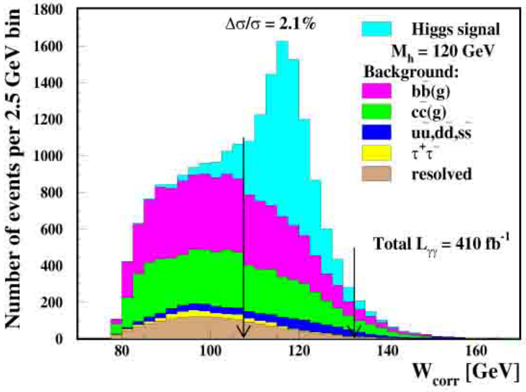
$$\dot{N}_{\gamma\gamma\to H} = L_{\gamma\gamma}\times\frac{dL_{\gamma\gamma}M_H}{dW_{\gamma\gamma}L_{\gamma\gamma}}\frac{4\pi^2\Gamma_{\gamma\gamma}(1+\lambda_1\lambda_2)}{M_H^3}$$

At ILC

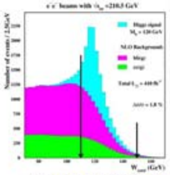
$$\frac{N(\gamma\gamma\to H)}{N(e^+e^-\to H+X)}\sim 1-10$$

For M_H=115-250 GeV

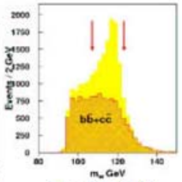
realistic simulation P.Niezurawski et al



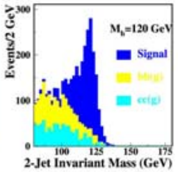
(previous analyses)



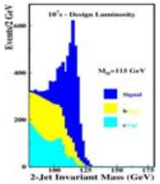
Niezurawski(TESLA)



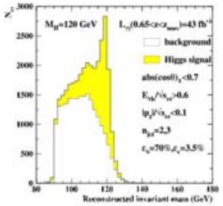
Rosca(TESLA)



Asner(NLC)



Asner(Cliche)



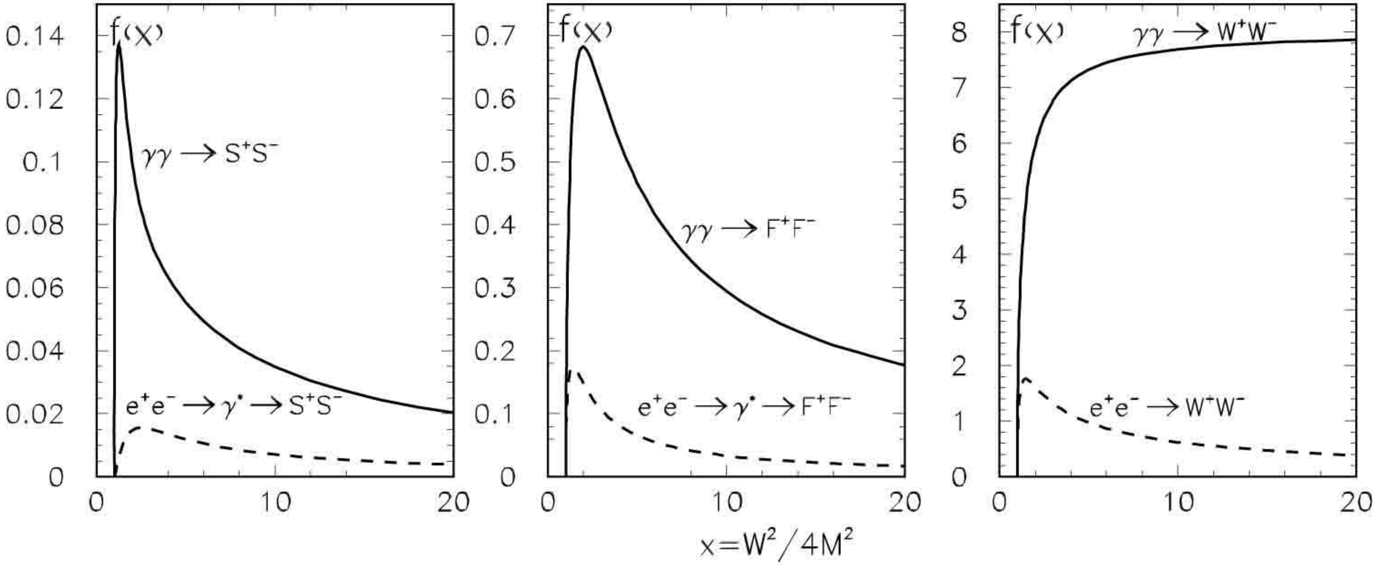
S.Soldner-Rembold

At nominal luminosities the number of Higgs in $\gamma\gamma$ will be similar to that in e+e-

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

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

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



unpolarized beams

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

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:

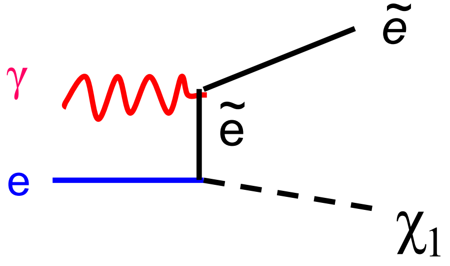
in e$^+$e$^-$ collisions $M_{H,A}^{max} \sim E_0$ (e$^+$e$^-$ $\to H + A$)
in $\gamma\gamma$ collisions $M_{H,A}^{max} \sim 1.6 E_0$ ($\gamma\gamma \to H(A)$)

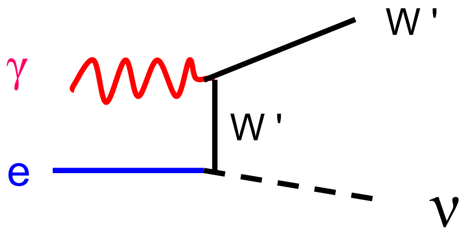
For some SUSY parameters H,A can be seen only in $\gamma\gamma$
(but not in e+e- and LHC)

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):

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





Physics motivation: summary

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

1. the energy is smaller only by 10-20%
2. the number of events is similar or even higher
3. access to higher particle masses
4. higher precision for some phenomena
5. different type of reactions (different dependence on theoretical parameters)

It is the unique case when the same collider allows to study new physics in several types of collisions at the cost of rather small additional investments

Status of the ILC

International linear collider ILC is not approved yet, main problem is a high cost, ~6.5B$ in minimum configuration (only e+e- 2E=500 GeV, one IP). However, other sources give a larger cost: 15-28 B$!, because the GDE number does not include lab personel costs, inflation, contingency, detectors, physics support buildings, and R&D in support of construction as usually calculated in US.

GDE Plans (in mid. 2007):

2007-RDR -reference design report
2007-2010-Technical design report
2010-2012 site selection, first results from LHC
2012-2019 construction (very optimistic plan)

However, DOE officials expect a delay and start of operation in the late 2020s.

In 12.2007 UK has stopped support of ILC, two weeks later US congress cut almost to zero financing of the ILC.

Hopefully, the situation can change, if new physics below 0.5 TeV is found at the LHC, then the construction can start (somewhere) with a little delay.

Status of the photon collider at ILC

The PLC is "the option" at ILC (all except e+e-(500) are options) However, it is important to make design decisions on the baseline project not prohibitive or unnecessarily difficult for the photon collider, which allow to reach its ultimate performance and rather easy transition between e^+e^- and $\gamma\gamma$, γe modes.

The PLC needs (now):

- the IP with the crossing angle ~ 25 mrad (the upgrades should not require new excavation);
- place for the beam dump and the laser system;
- detector, which can be easily modified for $\gamma\gamma$ mode;
- DR with as small as possible beam emittances.

Status (continue)

Unfortunately, in the RDR (2007) only one IP with 14 mrad crossing angle is assumed with two detectors working in pull-push mode. Driven by a need to reduce the initial ILC cost, the RDR team considered (in the accelerator book) only e+e- mode (assuming that options can be added later). So, the layout of IR in RDR is not compatible with the photon collider which needs 25 mrad crossing angle, e.t.c..

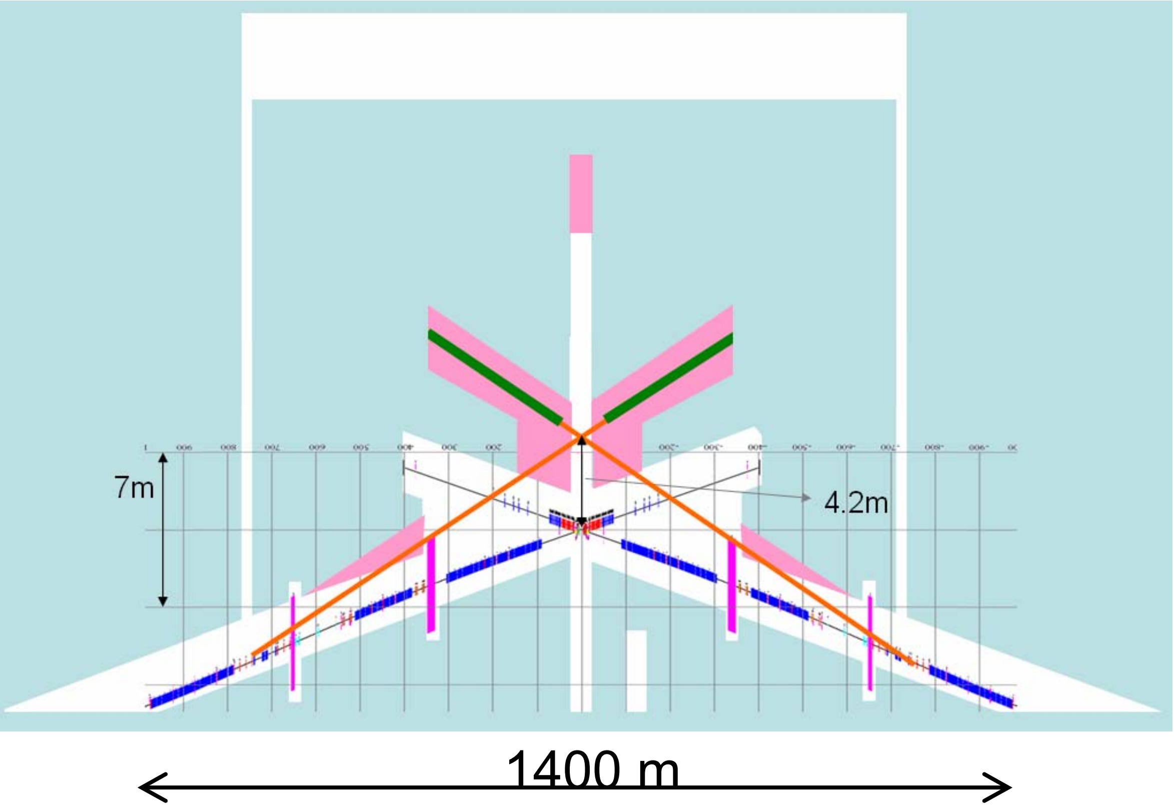
It is obvious that the total cost is minimum when all underground construction works (excavations) are done at once. Moreover, such excavation in the IP region in the middle of the ILC run will be technologically or politically impossible.

In Sept.2007 the GDE has agreed that the ILC Technical Design should include the photon collider. It was decided to correct the layout of the interaction-region area in order to make it compatible with $\gamma\gamma$ collisions, the underground space will be reserved for an upgrade to the 25 mrad crossing angle.

The scheme of upgrade from 14 to 25 mrad

(just principle, numbers will be changed somewhat)

14mr => 25mr



- additional angle is 5.5mrad and shift of detector by about 3-4 m

Upgrade 14 mr (e^+e^-) to 25 mr ($\gamma\gamma$)

- Tunnel in FF area may need to be wider
- For transition from e+e- to $\gamma\gamma$ one should shift the detector by about 0.0055*600=3.3 m as well as to shift 600 m of the upstream beam line or (better) to construct an additional final transformer and doublet. In that case the transition between e+e- and $\gamma\gamma$ modes will be faster.
- Two extra 250 m tunnels for $\gamma\gamma$ beam dump.
- Somewhat wider experimental hall. Different position of shielding walls.

Next steps on the photon collider (in frame of TDR):

- to make the IR design compatible with the PLC;
- to find an optimum way for transition from 14 to 25 mrad;
- to consider space requirements for the PLC laser system (allocation of the laser optics in and around the detector, space (the room) for the laser);
- to start a preliminary study with detector groups on possible modification of the detector for gamma-gamma (not clear which detector)
- to start a development of the laser system

Conclusion

The physics expected in the 0.1-1 TeV region is very exciting, and the ILC is a unique machine for the study physics in this energy region.

Answers to the mysteries of the origin of mass and the nature of the dark matter in the Universe would give excitement to several generations; from this perspective, $10B or even $30B is a negligible price to pay for these breakthroughs.

There is no doubt that, if e+e- linear collider is built, the photon collider should be build as well. I hope that this will happen sometime and

e+e-, e-e-, γγ, γe

collider will help to understand better our world!