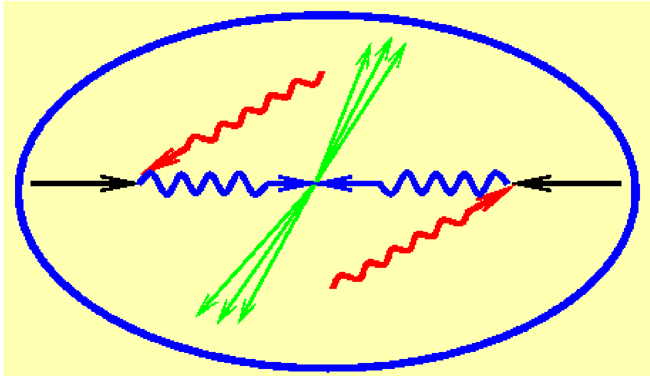


Фотон-фотонные взаимодействия и коллайдеры

(из первых рук)

В.И.Тельнов

ИЯФ и НГУ

Семинар ФФ НГУ, 08.12.2020

План

- ✓ Введение, упругое рассеяние фотонов

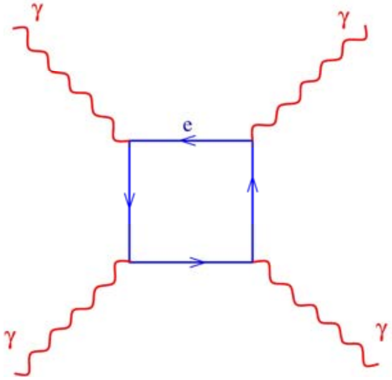
$\gamma^*\gamma^*$

- ✓ Изучения $\gamma^*\gamma^*$-процессов на e+e- коллайдерах

$\gamma\gamma,\gamma e$ -colliders

- ✓ Идея $\gamma\gamma$, γe коллайдера в высокой энергией и светимостью на базе однопролетных e^+e^- коллайдеров, где фотоны получаются путем комптоновского рассеяния лазерных фотонов
- ✓ Разработка концепции $\gamma\gamma$, γe коллайдера, проекты
- ✓ Физика на $\gamma\gamma$, γe коллайдерах

Упругое $\gamma\gamma$ рассеяние



Полное сечение (H.Euler,1936)

$$\sigma = 0.031\alpha^2 r_e^2 \left(\frac{\hbar\omega}{mc^2}\right)^6, \qquad \hbar\omega \ll mc^2$$

$$\sigma = 4.7\alpha^4 \left(\frac{c}{\omega}\right)^2, \qquad \hbar\omega \gg mc^2$$

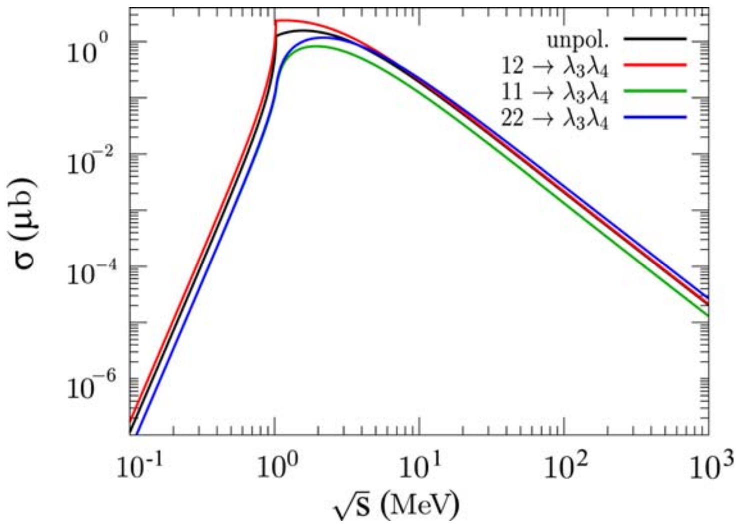
Для оптических фотонов, $E_\gamma=2$ эВ

$$\sigma = 5\cdot 10^{-64}\ \text{см}^2$$

При столкновении коротких лазерных сгустков, 1 Дж в импульсе, частота повторения 10^4 Гц, сечении пучка 10^{-8} см^2 частота реакций

$$\dot{n} = \frac{N^2 f}{S}\sigma = 5\cdot 10^{-15}\ \text{с}^{-1}$$

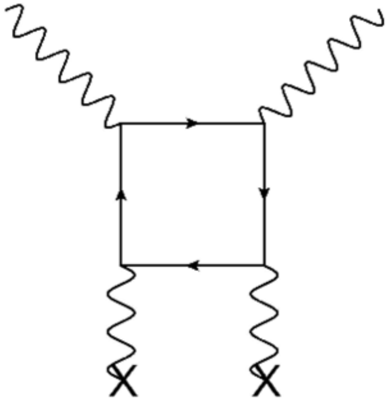
~1 событие рассеяния за 10 млн. лет



При энергии 1 МэВ сечение большое $\sigma \sim 10^{-30}$см^2, но пока прямых измерений не было (готовятся в Китае)

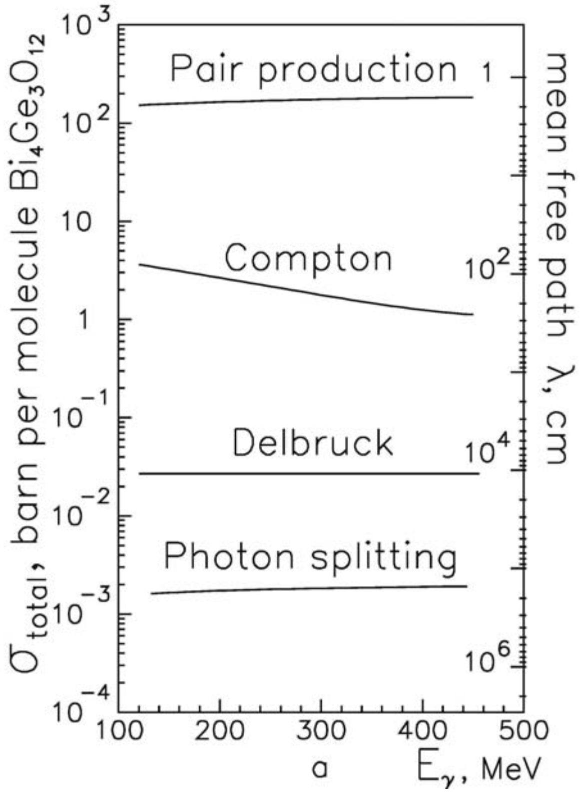
Рассеяние и расщепление фотона на ядре

дельбрюковкое рассеяние

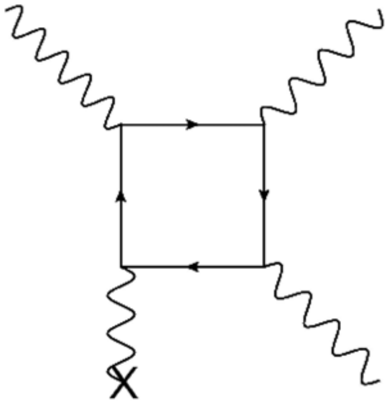


$$\sigma^{\mathrm{Delb}}_{\omega\to\infty} = \frac{98 Z^4 \alpha^4 r_e^2}{81\pi}$$

Эксперимент ИЯФ, 1998
(наблюдался ранее,
здесь детальное измерение)



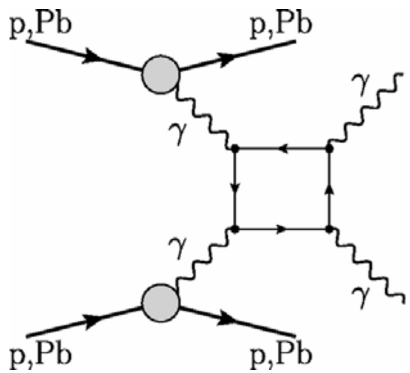
расщепление фотона

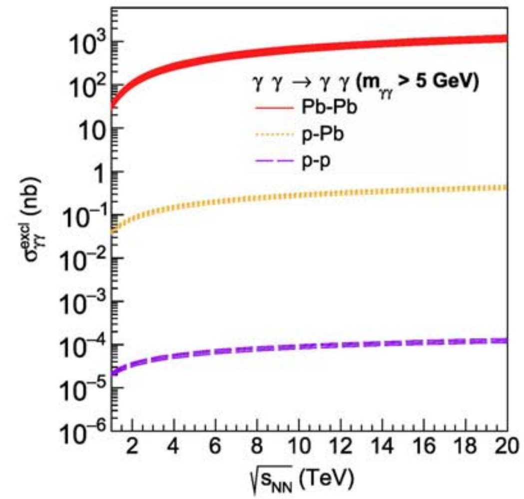


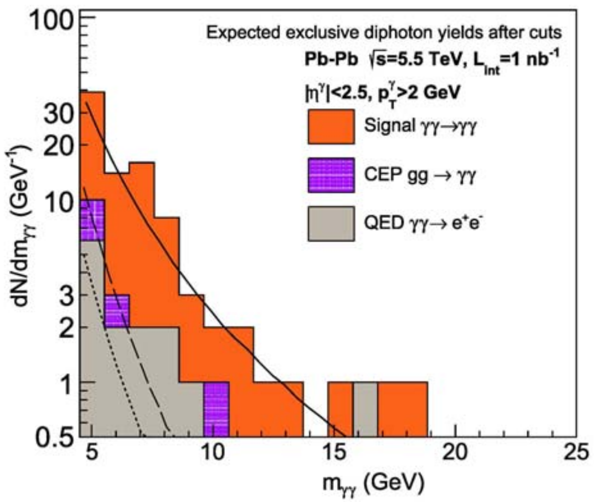
$$\sigma^{\mathrm{split}}_{\omega\to\infty} = 0.7 Z^2 \alpha^3 r_e^2$$

Эксперимент ИЯФ, 2002
(наблюден впервые)

Observing Light-by-Light Scattering at the Large Hadron Collider [Phys. Rev. Lett. 111, 080405 (2013)]





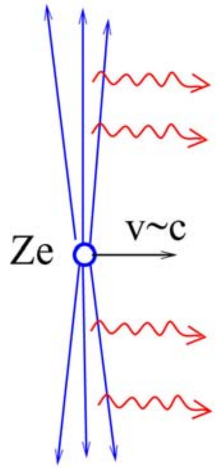


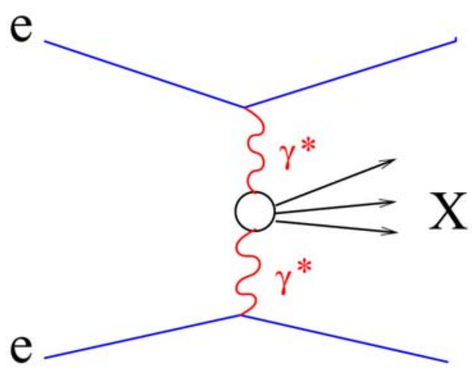
Prehistory: colliding $\gamma^*\gamma^*$ photons

(γ^* -virtual, quasi-real photon)

The idea to study some physics in photon-photon collisions is about 75 years old. The problem: a source of high energy photons.

In 30-th, Fermi-Weizsacker-Williams noticed that the field of a charged particle can be treated as the flux of almost real photons.





Such two-photon processes have been discovered and studied at all e^+e^- storage rings since 1970th

Landau-Lifshitz processes (X=e+e-) ,1934

Physics in $\gamma^*\gamma^*$ is quite interesting, though it is difficult to compete with e^+e^- collisions because the number of equivalent photons is rather small and their spectrum soft

$$dn_\gamma \approx \frac{2\alpha}{\pi}\frac{dy}{y}(1-y+\frac{1}{2}y^2)\ln\frac{E}{m_e} \sim 0.035\frac{d\omega}{\omega};\qquad m_{\gamma^*} > \omega/\gamma,\quad \gamma = E_0/mc^2$$

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

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

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

$\gamma^*\gamma^*$

1970 $e^+e^- \to e^+e^-e^+e^-$ Новосибирск, ВЭПП-2

EVIDENCE FOR ELECTRON-POSITRON PAIR ELECTROPRODUCTION

V. E. BALAKIN, A. D. BUKIN, E. V. PAKHTUSOVA, V. A. SIDOROV and A. G. KHABAKHPASHEV
Nuclear Physics Institute, Novosibirsk, USSR

Received 25 February 1971

The process of pair electroproduction has been observed in the electron-positron interaction at the energy 2×510 MeV. The work has been done with the colliding beam machine VEPP-2 in Novosibirsk. The cross section of this process and the azimuth angular distribution for large out-of-flight angles of the produced particles have been measured.

LETTERS 12 April 1971

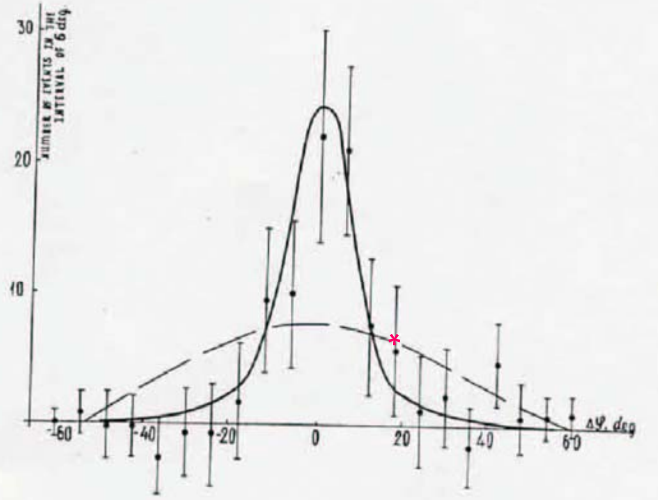


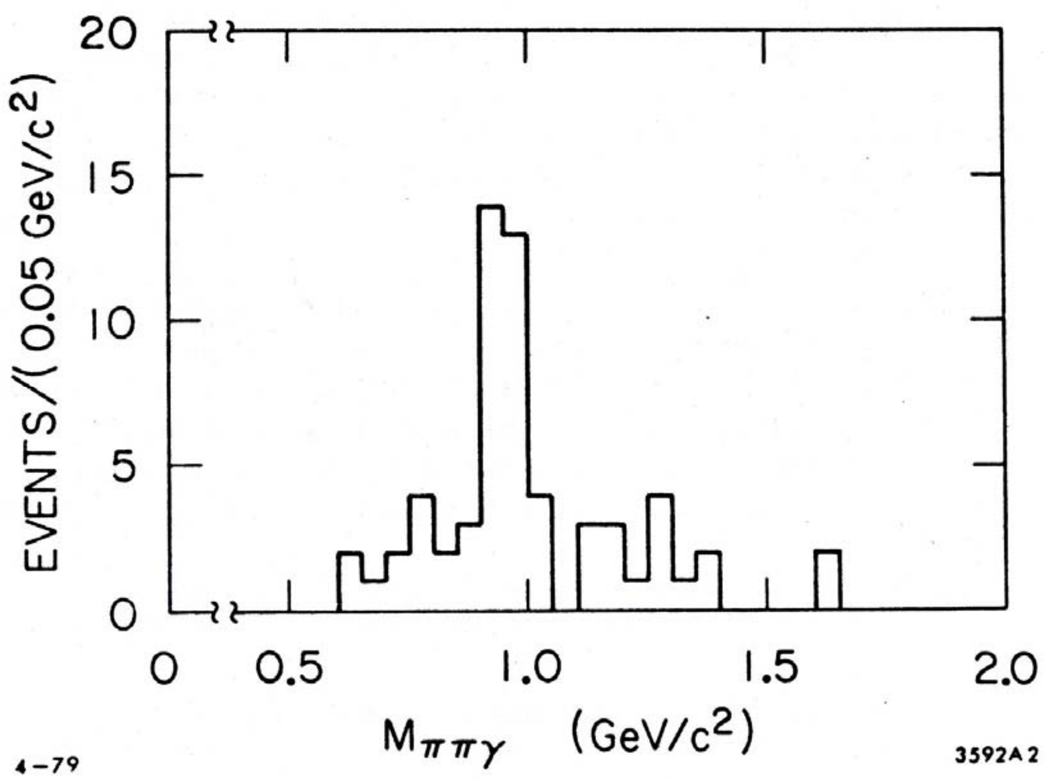
Fig.1. Pair electroproduction events distribution with respect to angle $\Delta\varphi$. Solid curve is obtained with the Baier and Fadin formulas. Dashed one represents the computed distribution for the process with independent and isotropic particle distribution.

В детекторе наблюдались компланарные e+e- пары ($\Delta\varphi \sim 180^o$)

Первое наблюдение $\gamma^*\gamma^* \to C+$ частиц (адронов)

$$\gamma^*\gamma^* \to \eta' \to \rho\gamma \to \pi^+\pi^-\gamma$$

(V. Telnov, e+e- collider SPEAR, SLAC, 1979)



PRL, May 1979

$\Gamma_{\gamma\gamma}(\eta') = 5.9 \pm 1.6 \pm 1.2$ keV

(на малой статистике, 5.5 pb^{-1})

Theory:

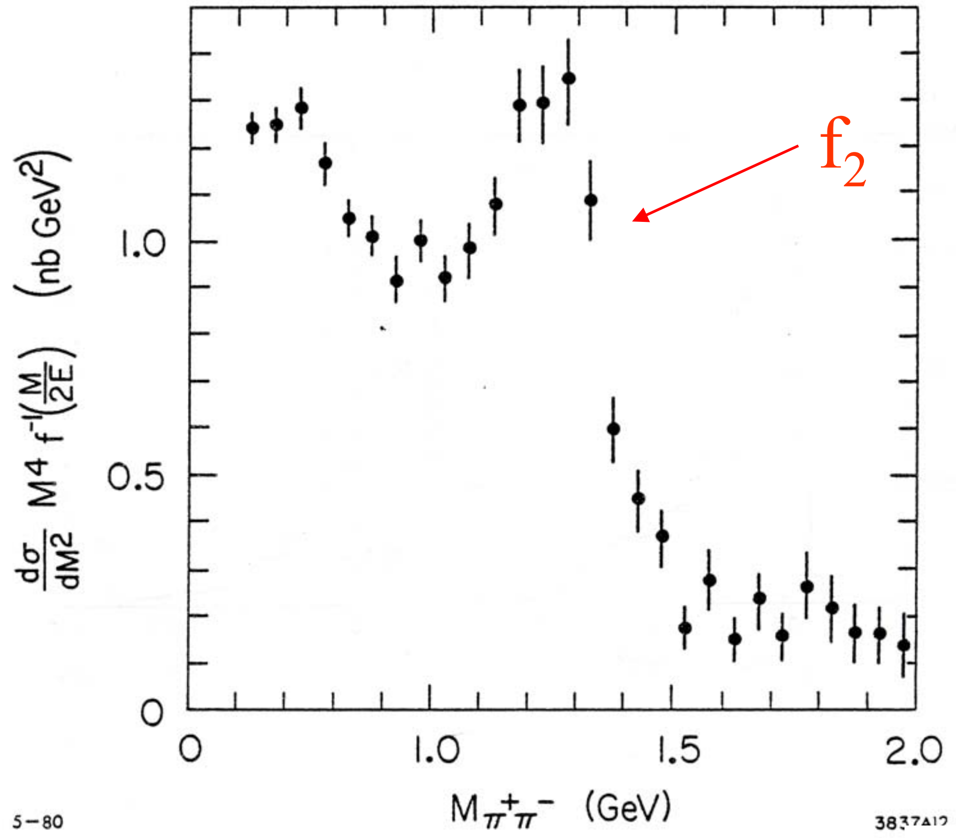
Han-Nambu - 25 кэВ

Gell-Mann - 6 кэВ

$\gamma^*\gamma^* \rightarrow \pi^+\pi^-$

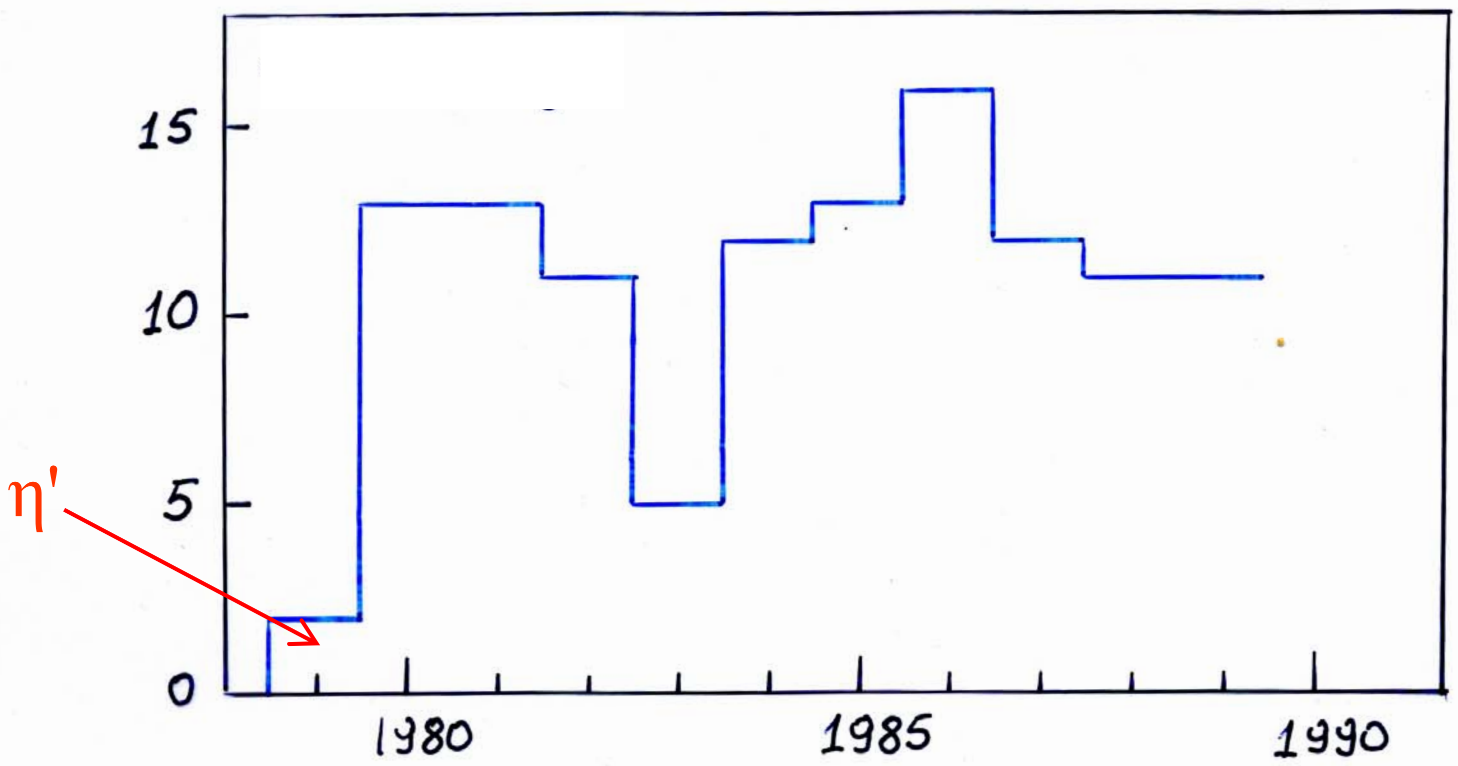
Первое наблюдение двухфотонного рождения f_2

V. Telnov, SLAC, 1979

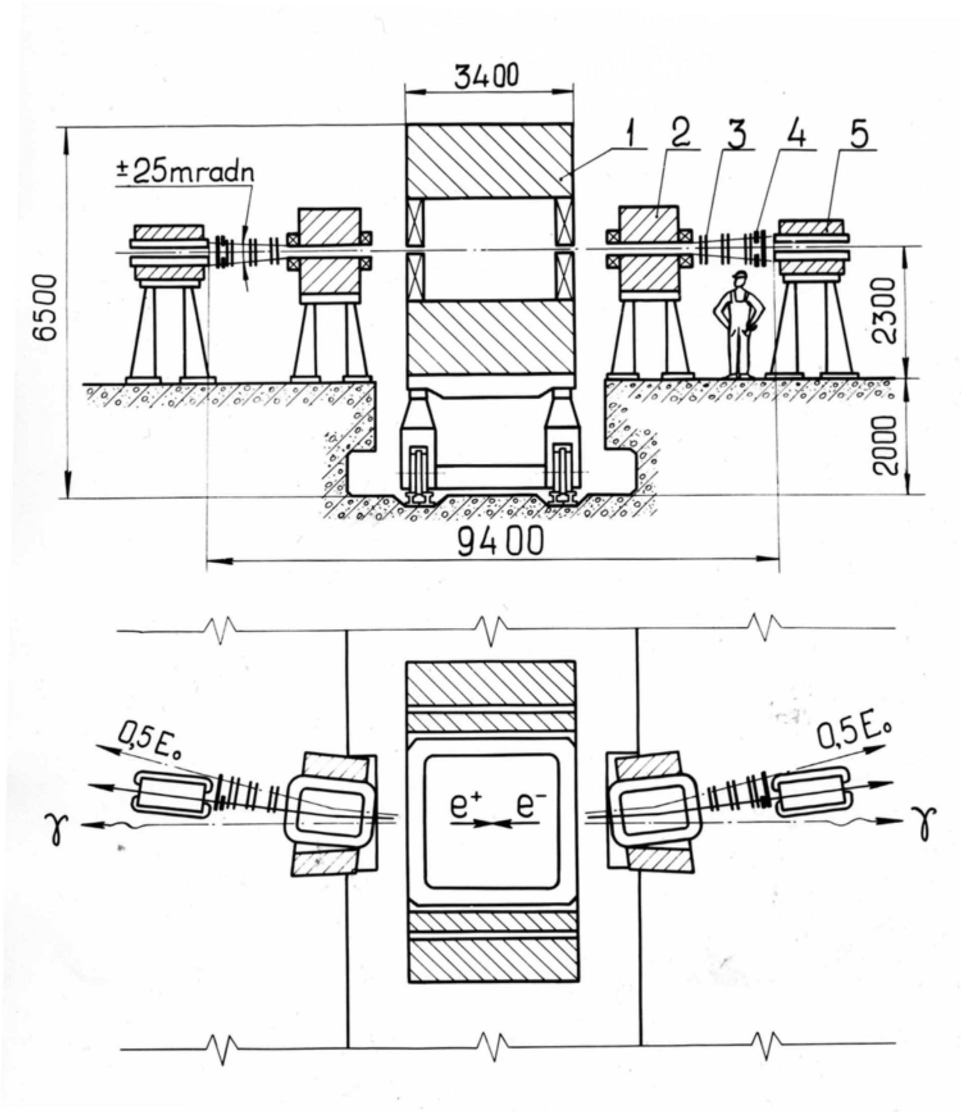


Результат по η' со SPEAR и был неожиданным, вызвал всплеск активности по $\gamma\gamma$-физике на всех $e+e-$ коллайдерах, положил начало систематическому изучению двухфотонных процессов в мире.

Число экспериментальных статей по 2γ-физике



Эксперимент МД-1 на ВЭПП-4 по двухфотонной физике (1980-1985)



Результаты МД-1 по 2γ-физике

$\gamma\gamma \to$ hadrons (double tag)

$\gamma\gamma \to e^+e^-$, $\mu^+\mu^-$, $\pi^+\pi^-$, η, η', a_2,, f_2

Система регистрации рассеянных электронов в реакции e+e-→e+e-X определяет энергии виртуальных фотонов ($\omega_i = E_0 - E_i$), откуда находится инвариантная масса рожденной системы

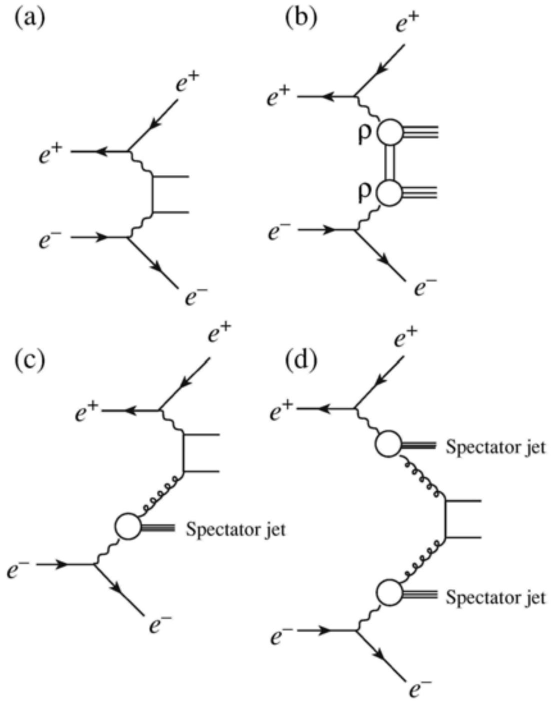
$$W_{\gamma\gamma} \approx 4\omega_1\omega_2$$

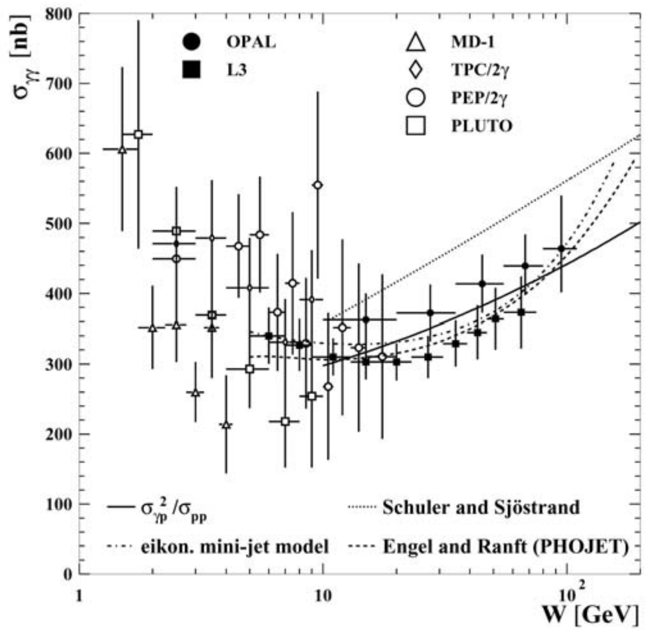
Особенности $\gamma\gamma$ взаимодействий

В e+e- аннигиляции рождаются C=-1 резонансы (кван. числа фотона), сечения падают с увеличением энергии, $\sigma \propto 1/W^2_{e+e-}$

В $\gamma\gamma$ столкновениях конечное состояние имеет C=+1, рождаются C-четные резонансы, фотон ведет себя одновременно и как точечная частица (с $\sigma \propto 1/W^2_{\gamma\gamma}$) , а с некоторой вероятность как виртуальный адрон с .

$$\sigma(\gamma\gamma \to \text{hadrons}) \approx (300\text{-}500)10^{-33}\text{cm}^2 \sim \text{const}$$





Physics in $\gamma^*\gamma^*$ is quite interesting, though it is difficult to compete with e^+e^- collisions because the number of equivalent photons is rather small and their spectrum soft

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

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

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

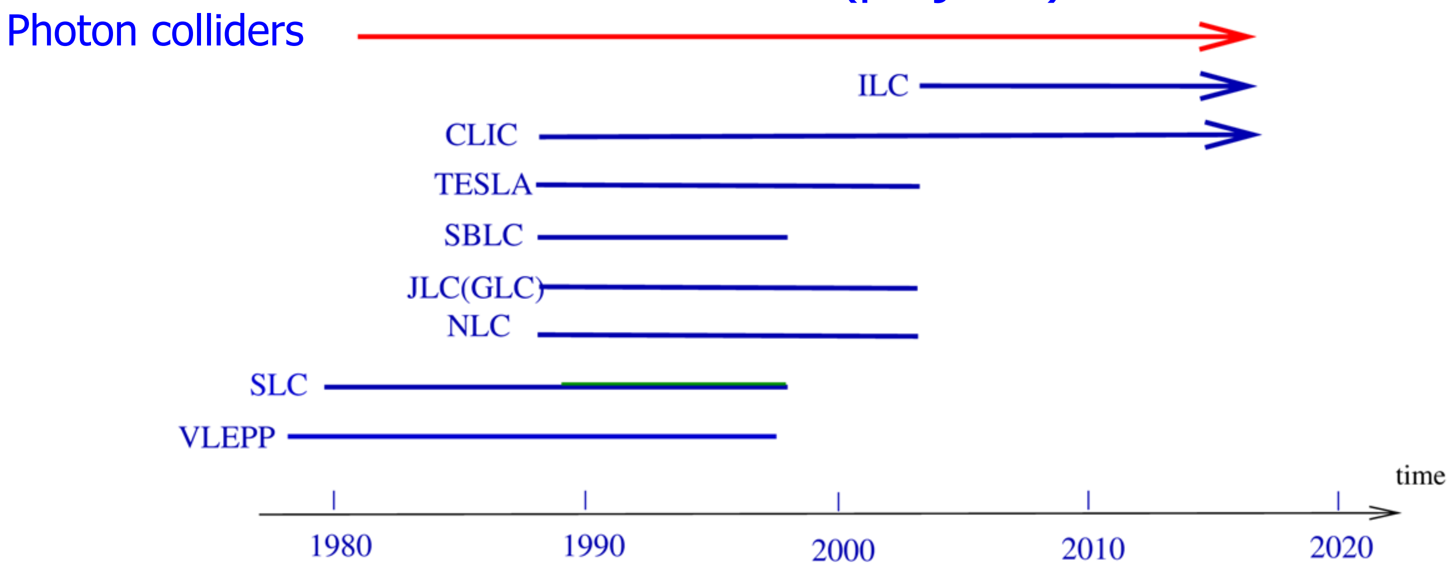
$L_{\gamma\gamma}(z>0.5) \sim 0.4\cdot10^{-3}\, L_{e+e-}$

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

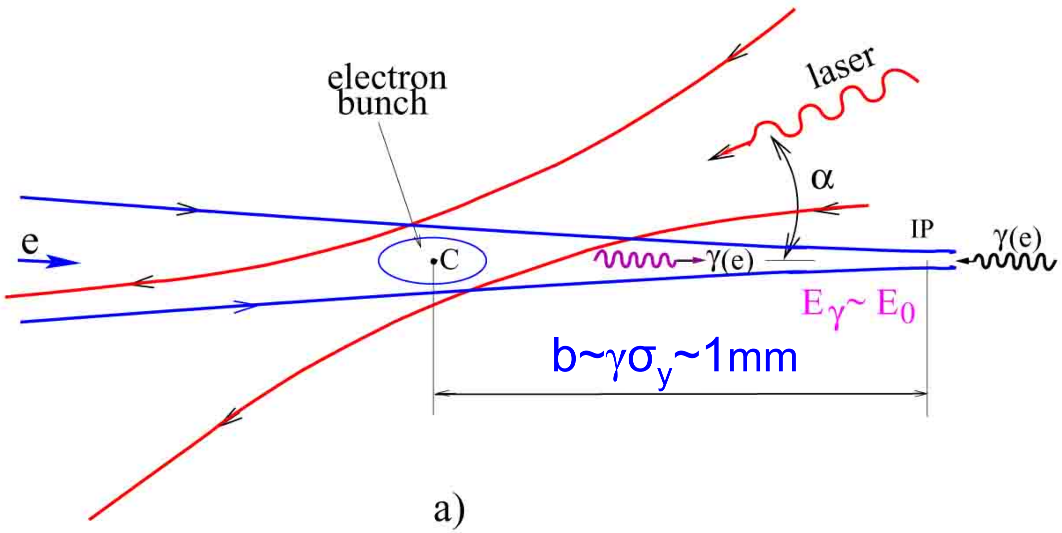
The idea of the high energy photon collider was proposed at the first workshop on physics at linear collider VLEPP (Novosibirsk,Dec.1980) and is based on the fact that at linear e^+e^- (e^-e^-) colliders electron beams are used only once which makes possible to convert electron beam to high energy photons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

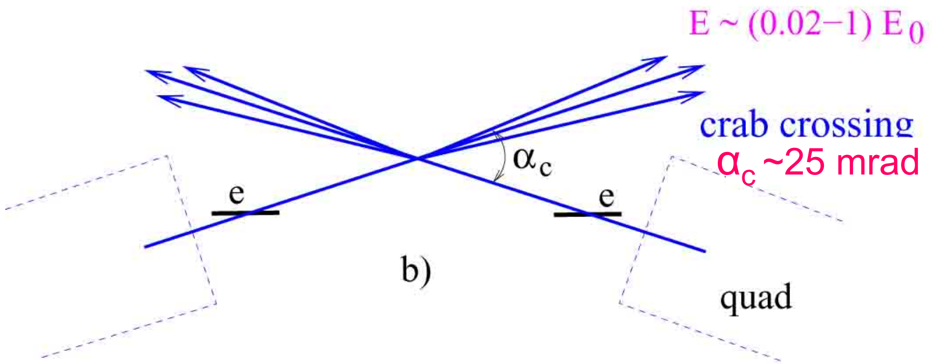


a)

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

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

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



b)

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

ω_{max}~0.8 E_0

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

Laser $e \rightarrow \gamma$ 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 superconducting 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.

First publications

1. I.Ginzburg, G.Kotkin, V.Serbo, V.Telnov, On posibility of obtaining gamma-gamma, gamma-electron beams with high energy and luminosity, Preprint INP 81-50, Feb.1981, Pizma ZhETF 34 (1981) 514; JETP Lett. 34 (1982) 91(265citations)
2. I.Ginzburg, G.Kotkin, V.Serbo, V.Telnov, Nucl.Insr.and Meth 205(1983) 47; (770c)
3. I.Ginzburg, G.Kotkin, S.Panfil, V.Serbo, V.Telnov, Nucl.Insr.&Meth A219 (1984) 5; (620c) (2 and 3 – detailed description of PLC principles: kinematics, polarization effects, luminosity spectra e.t.c.)

Very important

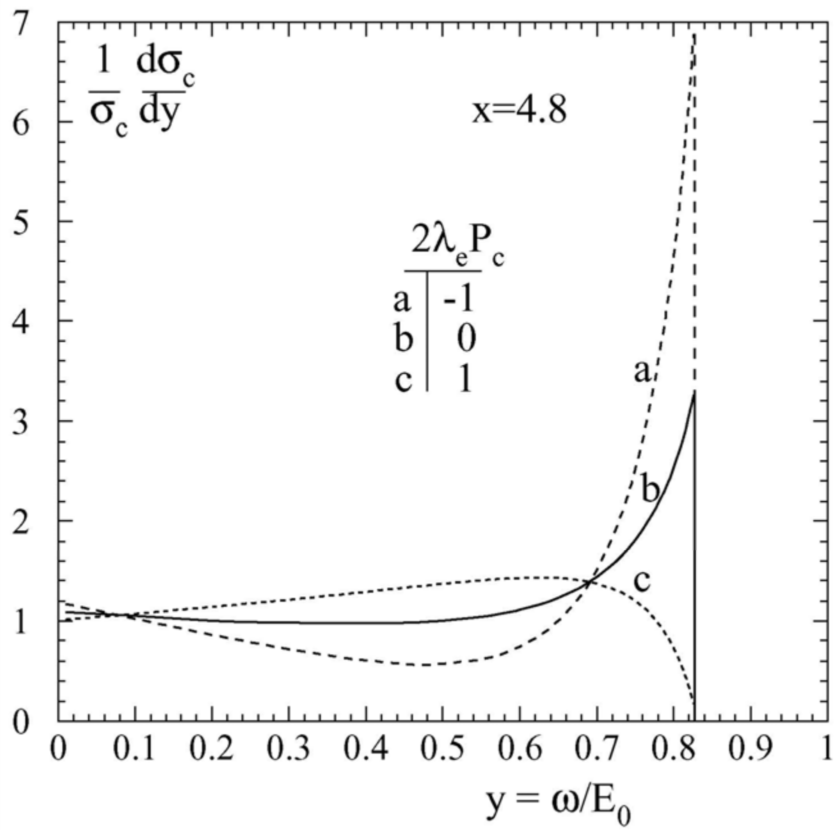
1. V.Telnov, Problems of obtaining $\gamma\gamma$,γe at lin.coll., Nucl.Insr.&Meth A294 (1990) 72; (390c) (Removal of beams (crab crossing), beam collision effects)
2. V.Telnov, Status of gamma gamma, gamma electron colliders (PHOTON99, May1999) Nucl.Phys.Proc.Suppl.82:359-366,2000. (“External” optical cavity for PLC at TESLA has been suggested)

Most full description of the PLC up to now

Badelek et al., Photon collider at TESLA (TESLA TDR), Int.J.Mod.Phys.A19: 5097-5186, 2004 (290c).

Electron to Photon Conversion

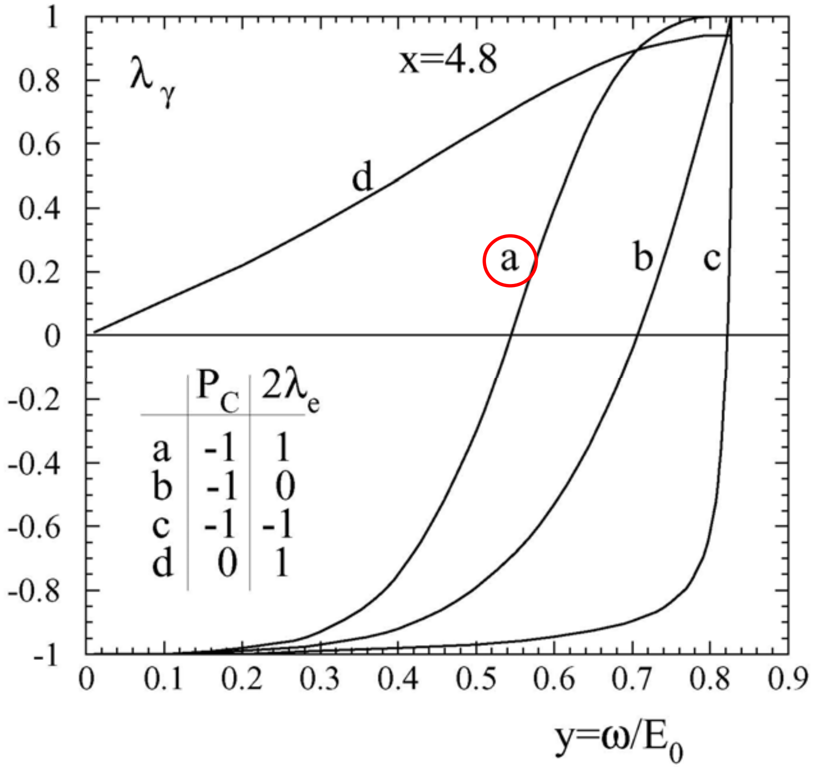
Spectrum of the Compton scattered photons



λ_e – electron longitudinal polarization

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

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



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

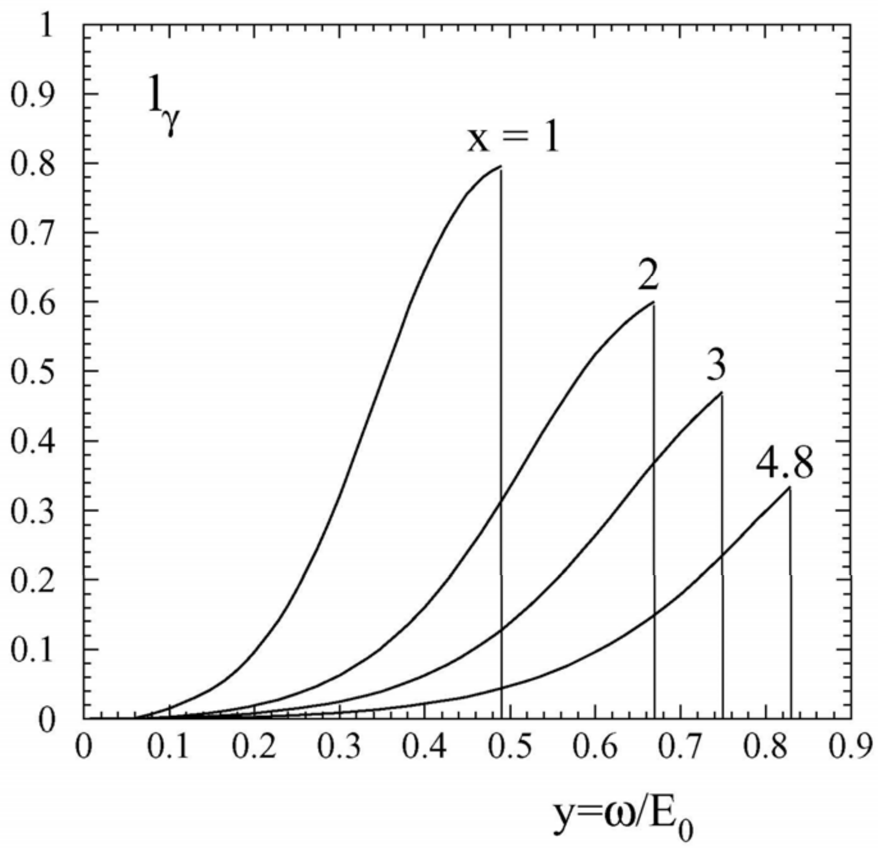
The cross section of the Higgs production

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

The cross section for main backgound

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

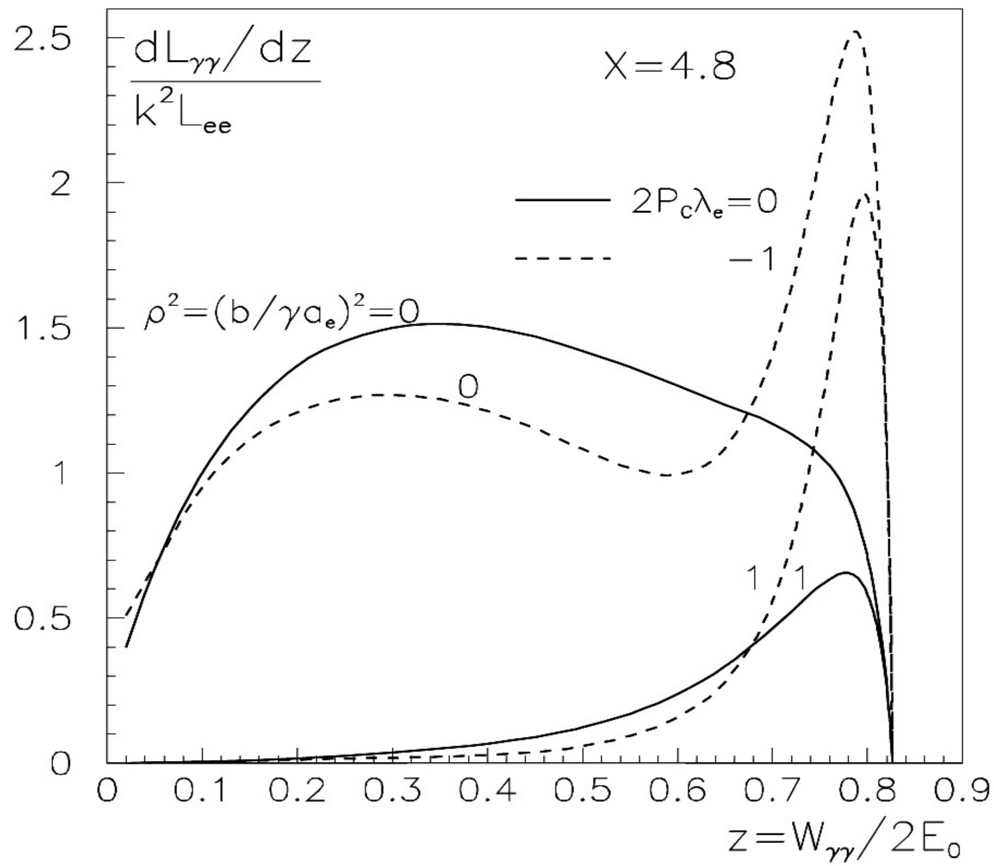
Linear polarization of photons



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

Linear polarization helps to separate H and A Higgs bosons

Ideal luminosity distributions, monohromatization



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

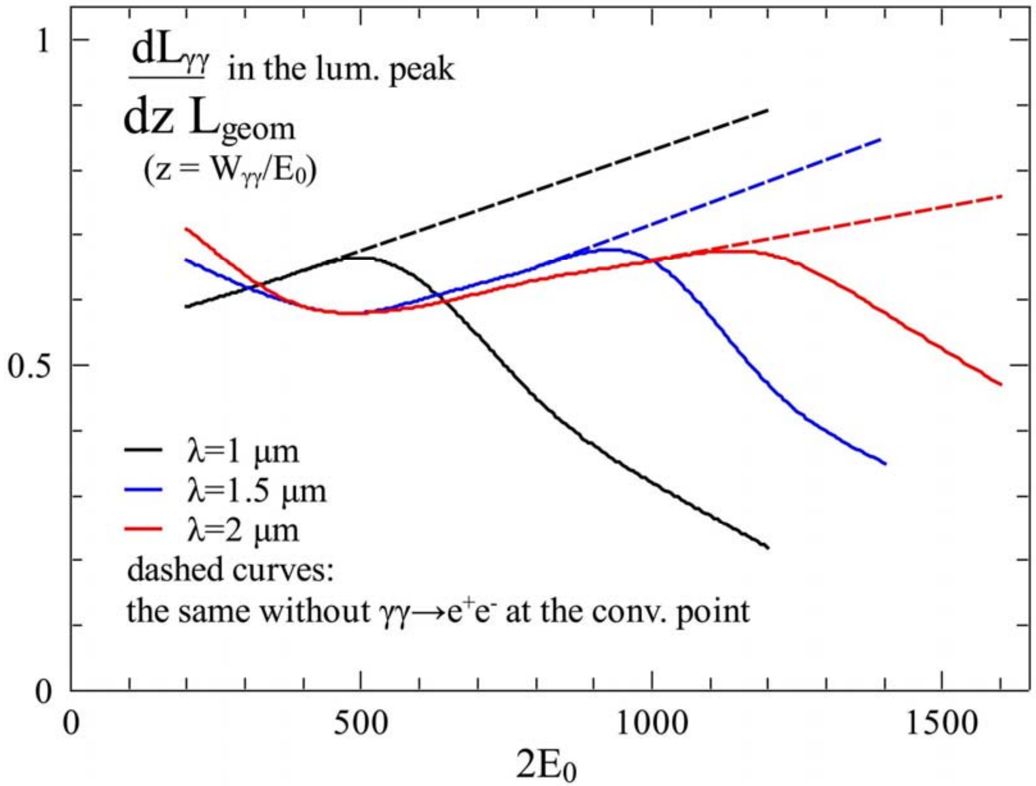
The optimum laser wavelength

The maximum energy of photons after the Compton scattering

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

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

$$\lambda\ [\mu m] \approx 4E_0[TeV]$$



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

Laser flash energy

For $e \to \gamma$ 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 (0.15-0.3),

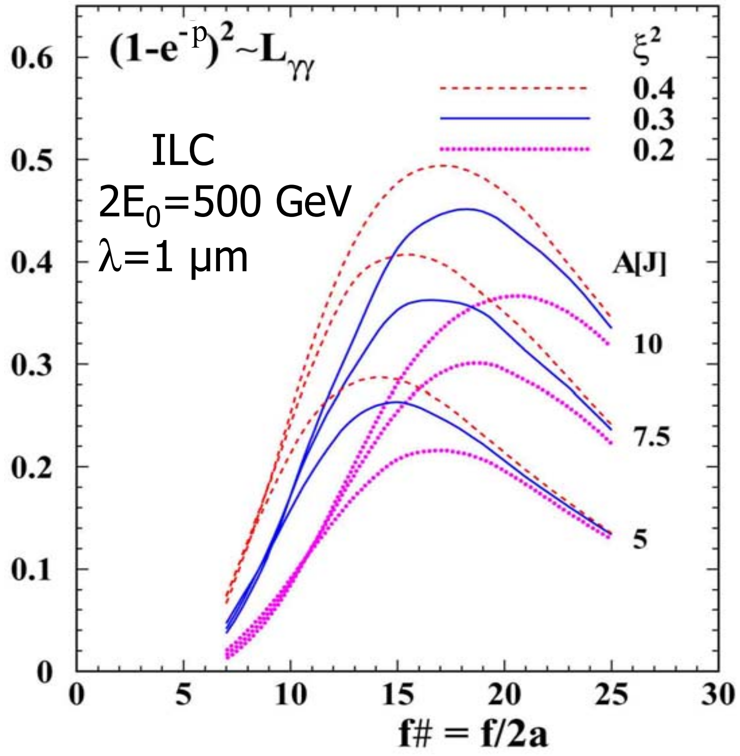
because $\omega_m = \frac{x}{x+1+\xi^2} E_0$.

It is reasonable to keep

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

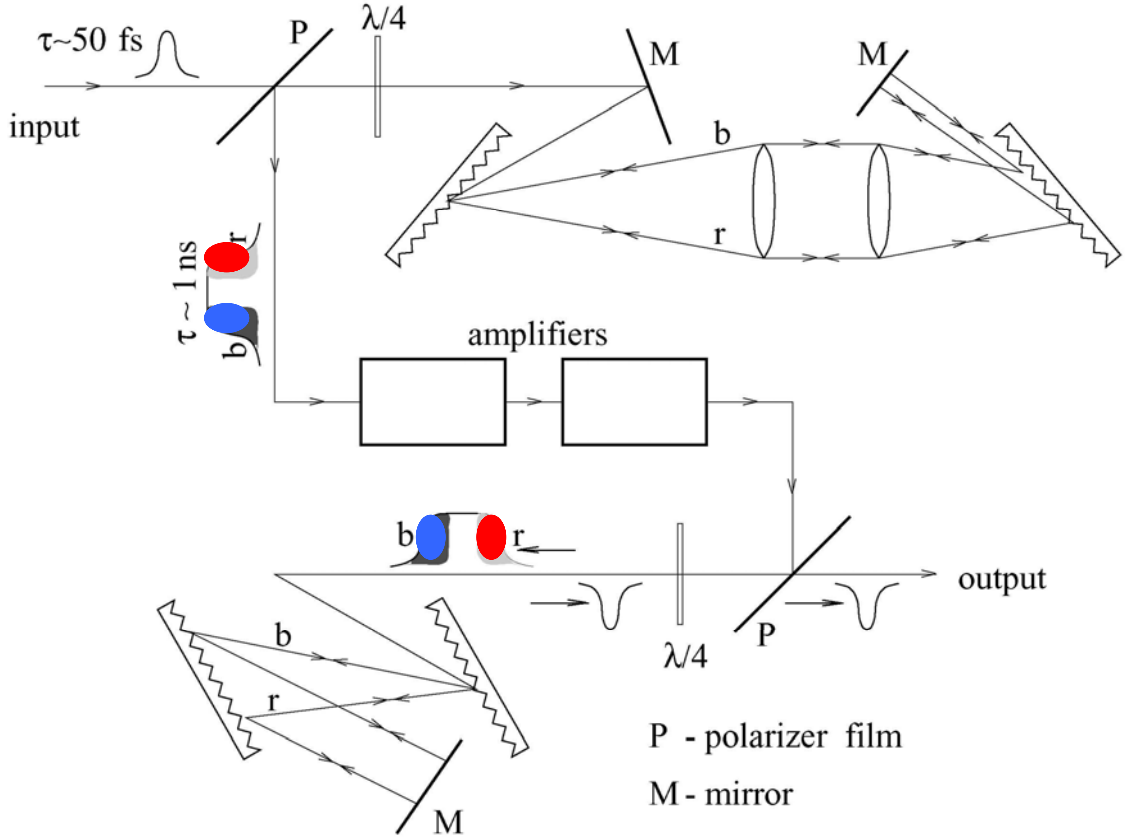
then for $x = 4.8$ $\xi^2 < 0.3$

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.
It is determined by laser diffraction and geometric beam parameters at short λ and by nonlinear effects at large λ (multiTeV collider).



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.

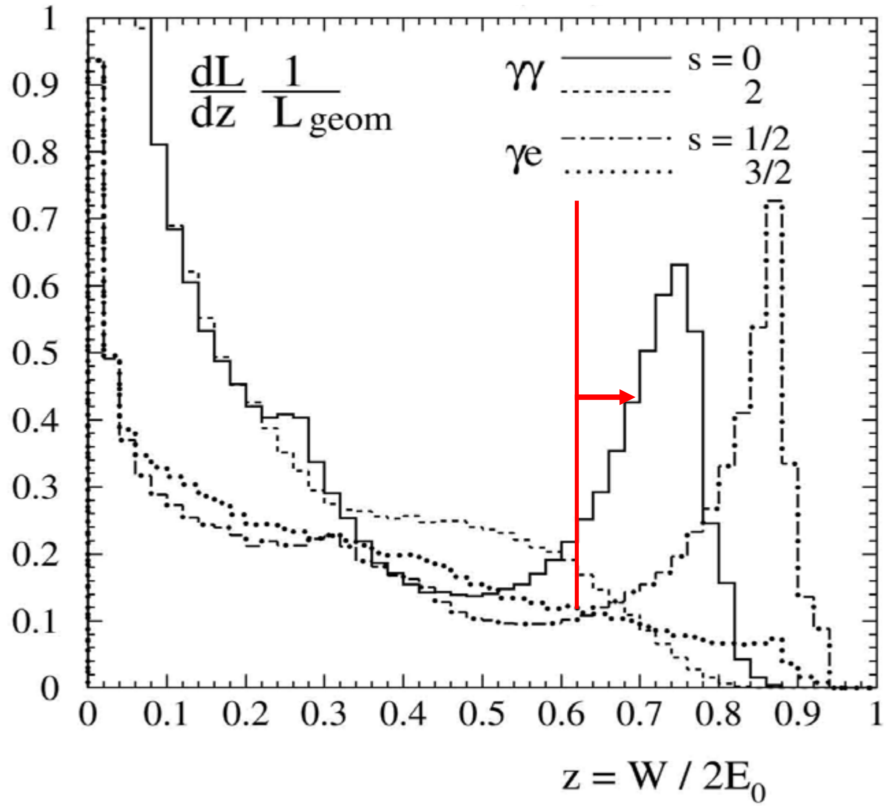


Other technologies important for the photon collider: diode pumping, adaptive optics, high reflective multilayer mirrors for high powers – all is available now.

Typical $\gamma\gamma$, γe luminosity spectra

simulation with account all important effect at CP and IP regions:
multiple Compton scattering in CP, beamstrahlung, coherent pair creation, beam repulsion e.t.c.

ILC(500)

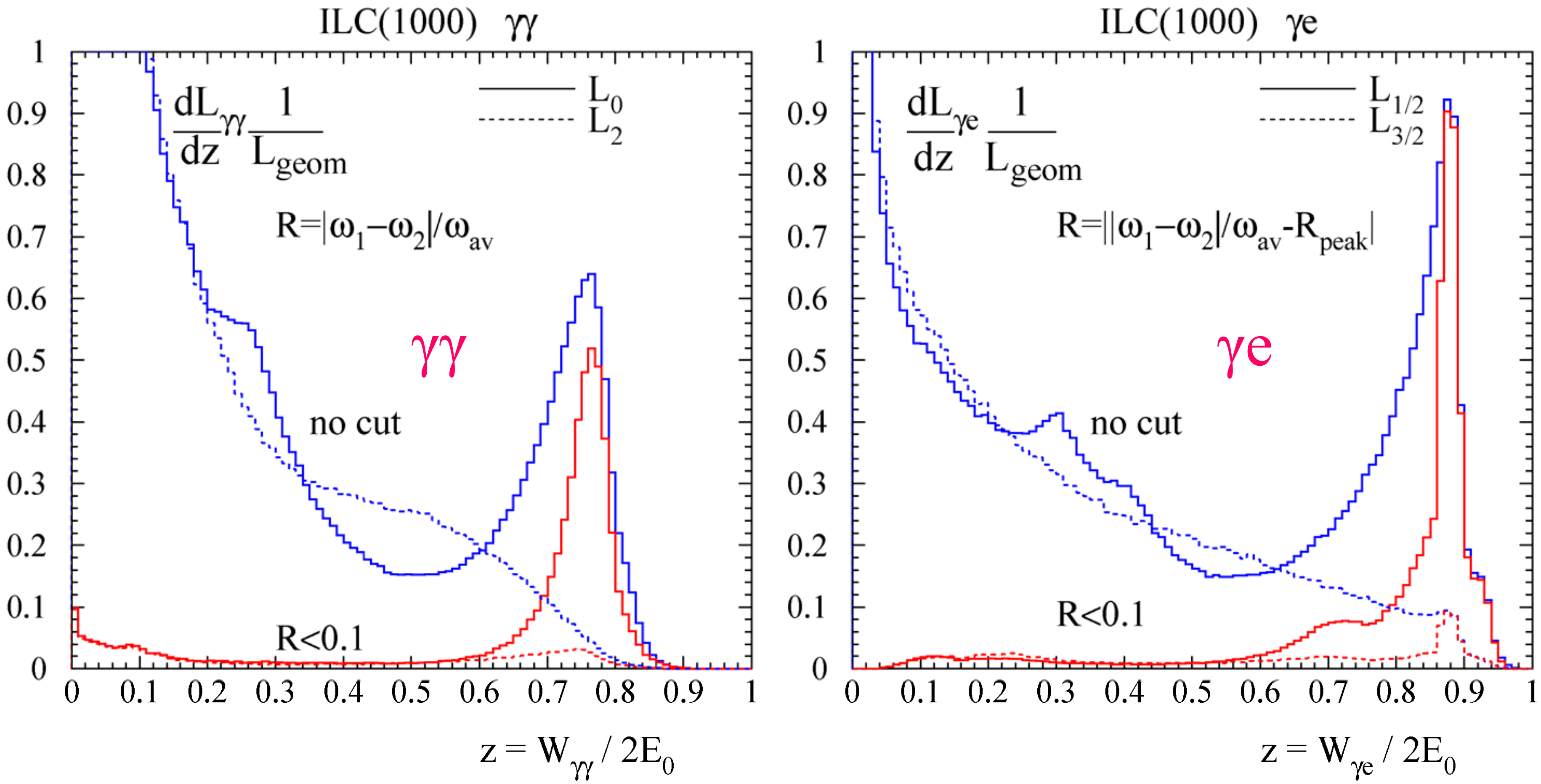


Luminosity spectra and their polarization properties can be measured using QED processes

$L_{\gamma\gamma}(z>0.8z_m) \sim 0.1\ L_{e\text{-}e\text{-}}(\text{geom})$

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)

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

Main collision effects at the IP:

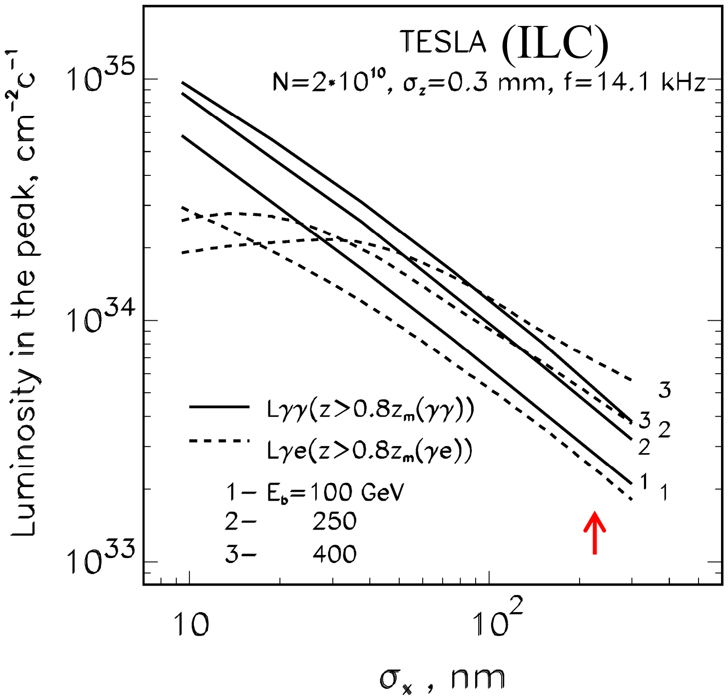
$\gamma\gamma$	•coherent pair creation
$\gamma\gamma$, γe	•beamstrahlung
γe,ee	•beam-beam repulsion

Coherent pair creation:

high energy photons convert to e+e- pair on the field of the opposing electron beam, it is the only collision effect limiting γγ-luminosity, important for multi-TeV colliders and short beams.

$$\gamma B > B_S = m^2c^3/e\hbar = 4.4\cdot10^{13}\ \text{Гс}$$

(B_S-поле Швингера)

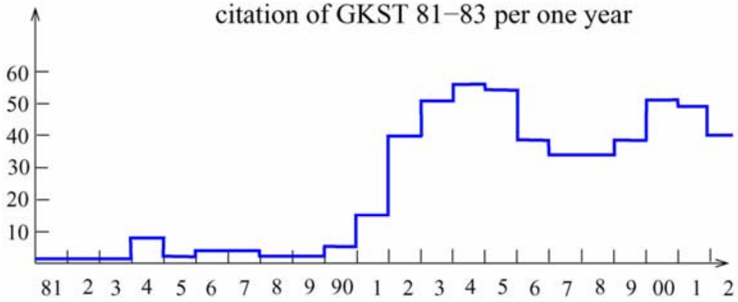


At ILC σ_x~200-300 μm (limited by emittance). This figure shows that one order higher luminosity is possible with smaller beam sizes.

For 2E<1 TeV the $\gamma\gamma$-luminosity is determined only by geometric e-e- luminosity, which depends on beam emittances: $L \propto 1/\sqrt{\varepsilon_{nx}\varepsilon_{nx}}$.

At present electron guns give the product of emittances several times larger than with damping rings, further improvements (combining, cooling) of electron sources (polarization is very desirable) are needed for photon colliders without damping rings.

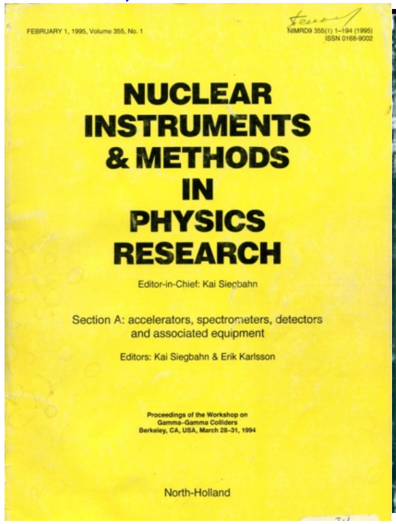
Activity on photon colliders



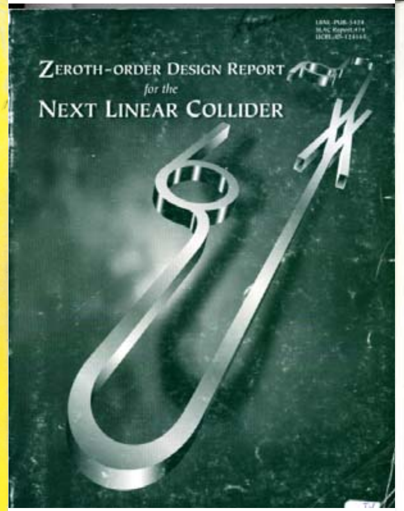
(total number of publications is larger by a factor of 2)

→ about 2 papers/week

Gamma-gamma workshop LBL, 1994

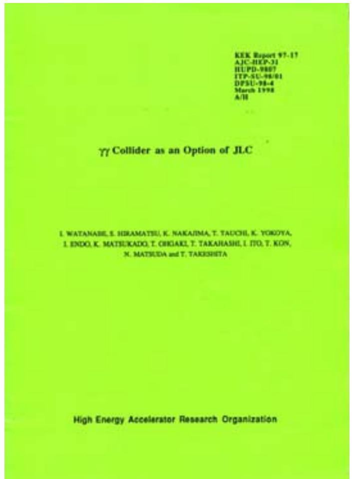


NLC

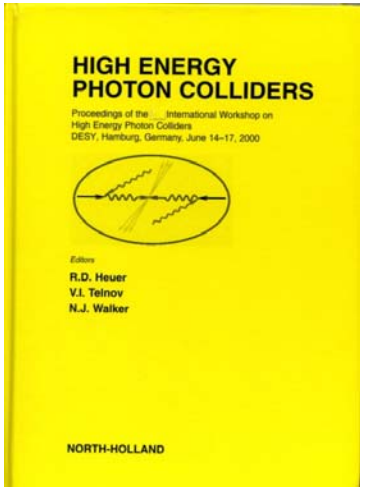


TESLA CDR

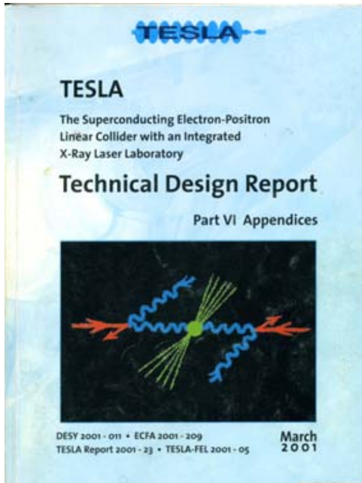
γγ at JLC



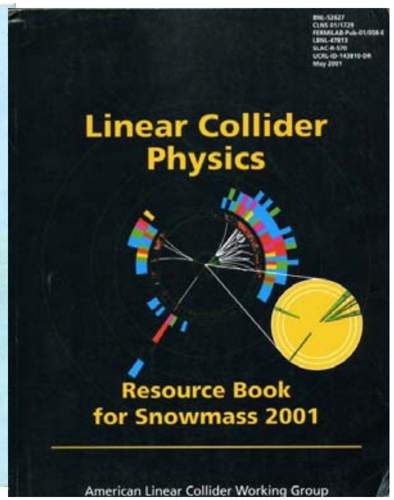
γγ workshop at DESY



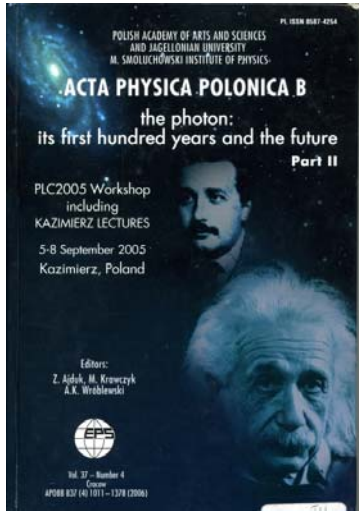
TESLA TDR



γγ NLC

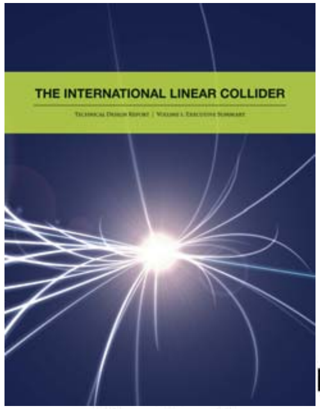


PLC 2005



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

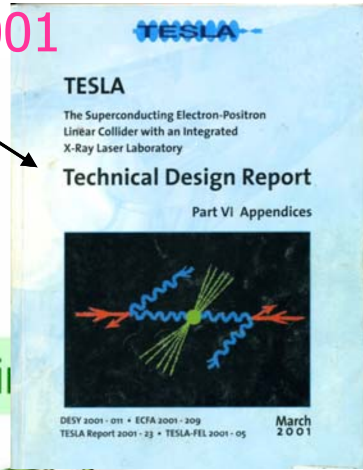
Photon colliders at ILC and CLIC

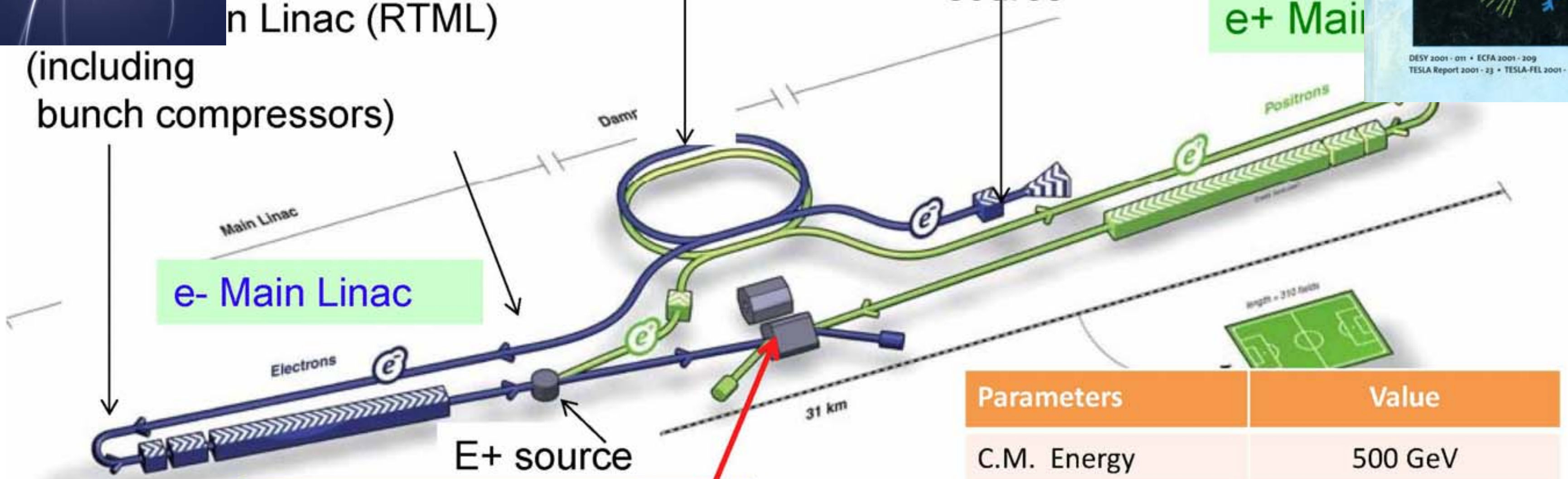


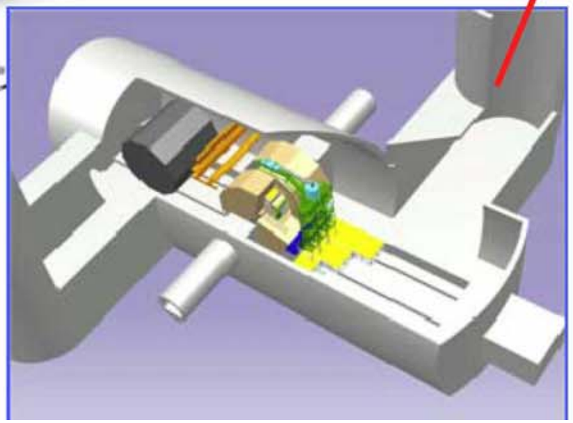
ILC TDR
6.2013

ILC TDR Layout

PLC at TESLA, 2001





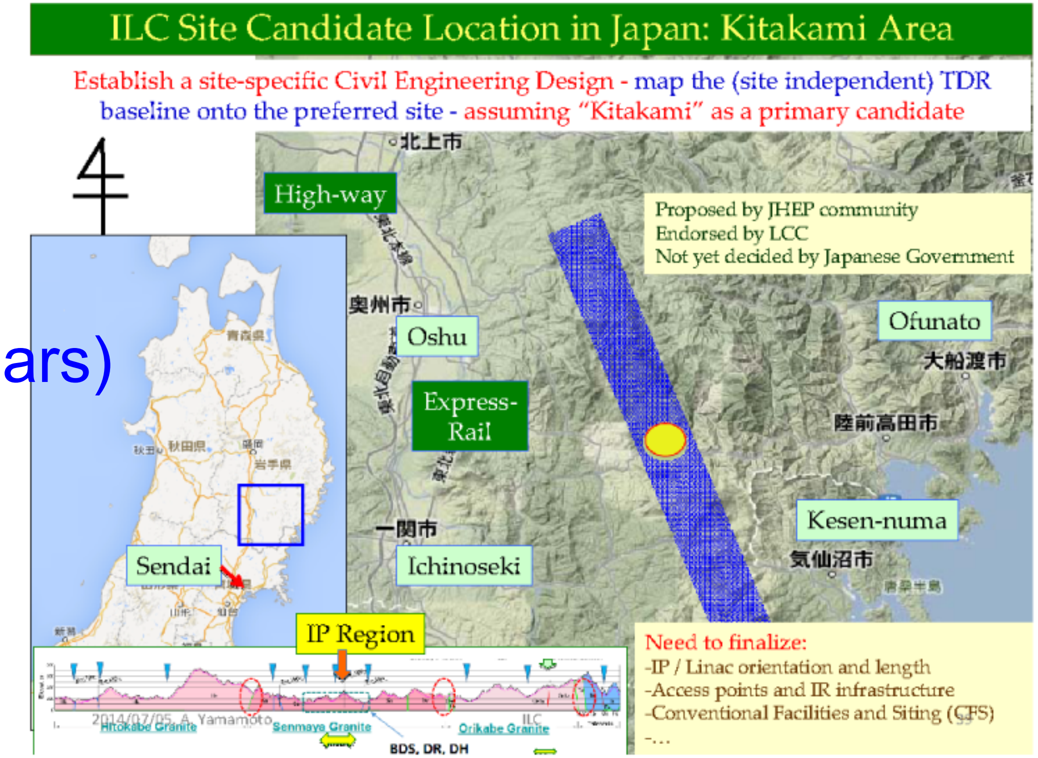


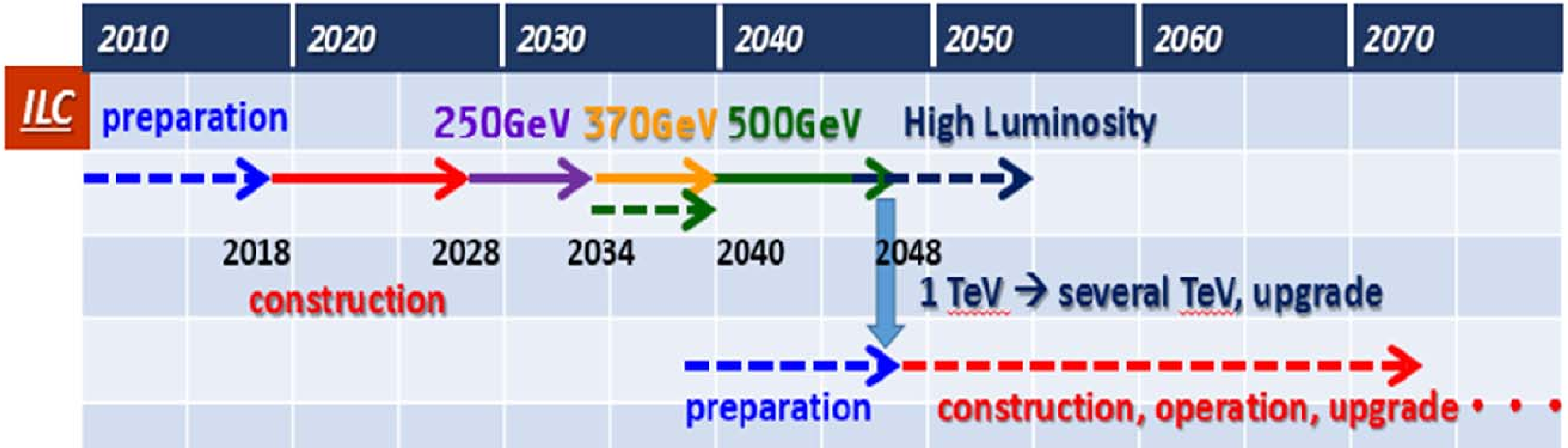
Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} cm^{-2}s^{-1}
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
E gradient in SCRF acc. cavity	31.5 MV/m +/-20% Q_0 = 1E10

2E=250-500 GeV, upgradable to 1000 GeV

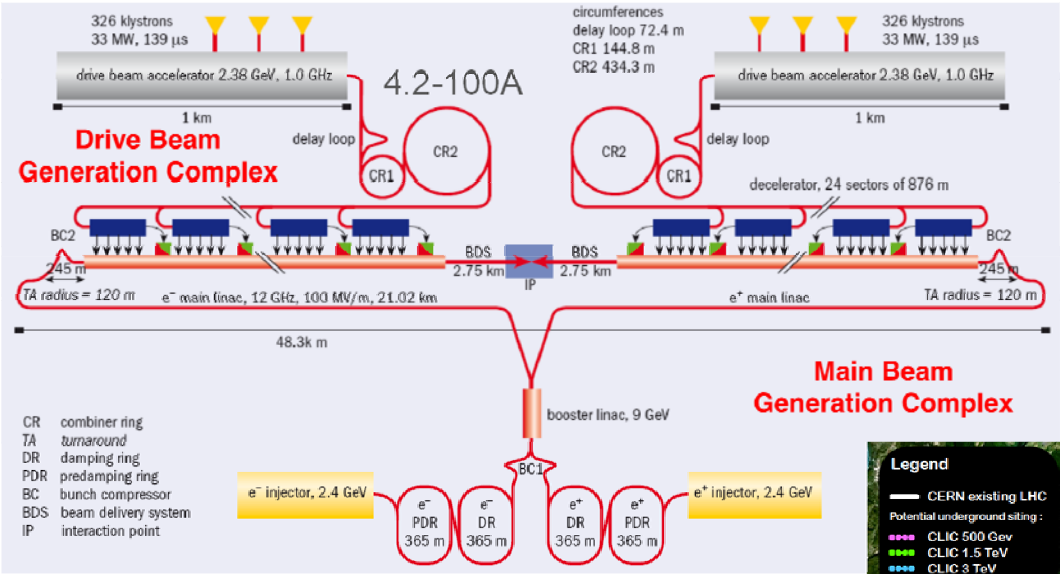
Japan is interested to host
-decision ~2018???
-construction ~2019?? (~10 years)
-physics ~2030???

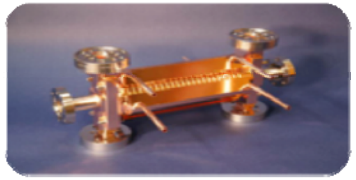
Unfortunately in this scenario the photon collider is possible here only in 40 years



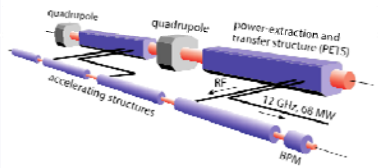


Compact LInear Collider (CLIC)

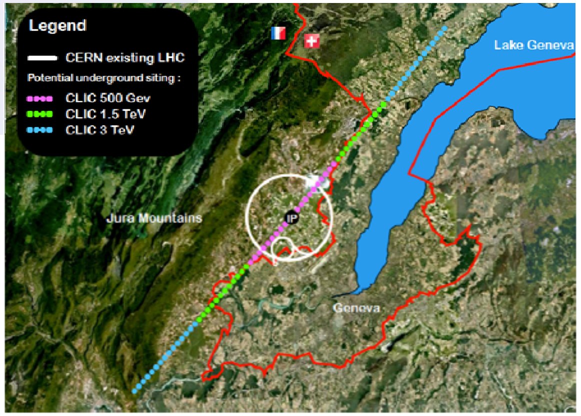




G_a ~ 100 MV/m



- CLIC
  - e+e- 500 - 3000 GeV
  - x-band accelerator technology
  - 2-beam acceleration
  - $\mathscr{L} \sim 2\text{-}6 \times 10^{34}$



0.5 TeV: 8,300 MCHF ($\mathcal{L} \sim 1.4 \times 10^{34}$)

In best case construction can start in 2024-25???; commissioning in ~2033???.

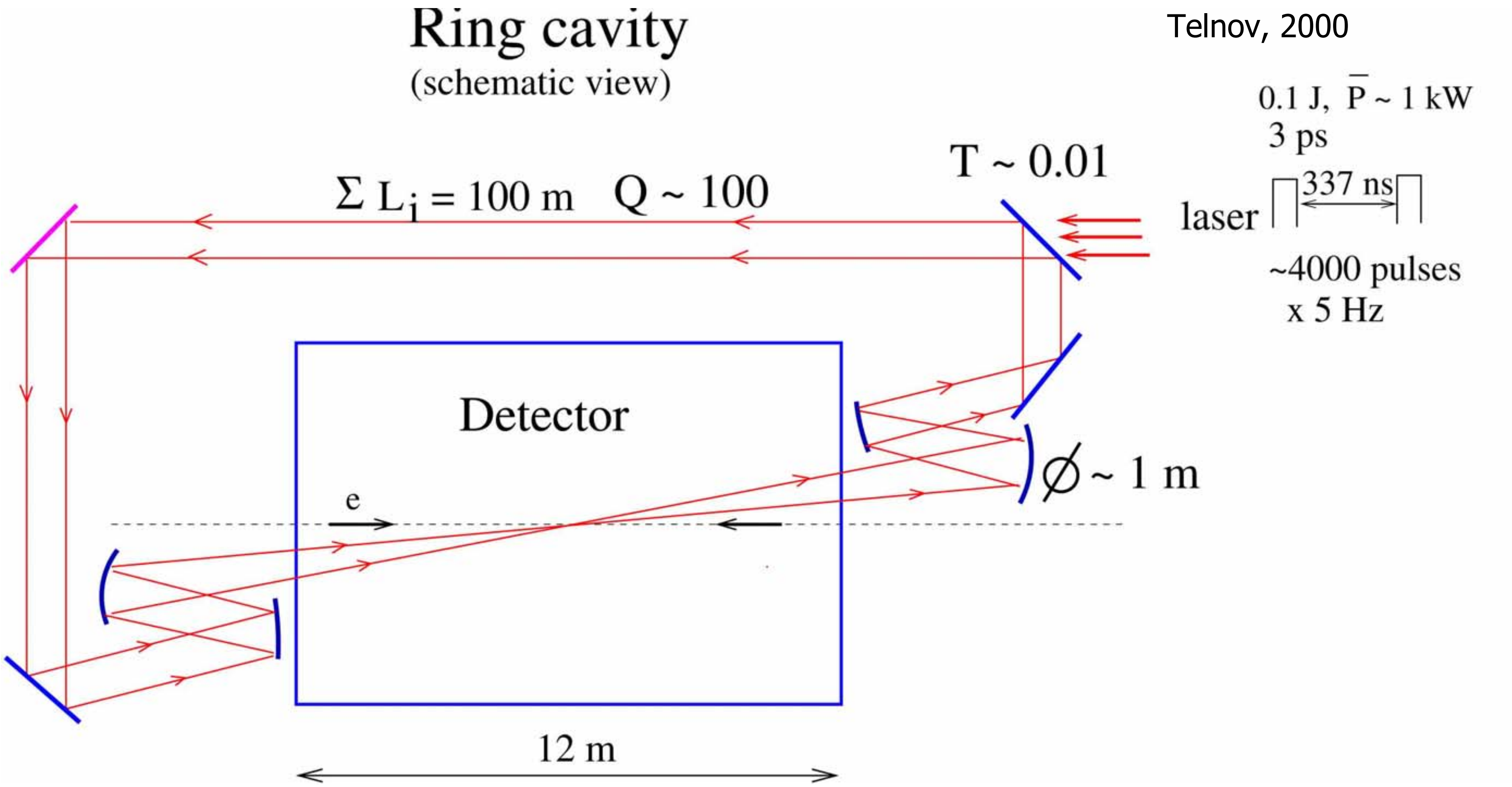
Requirements for the ILC laser system

- 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

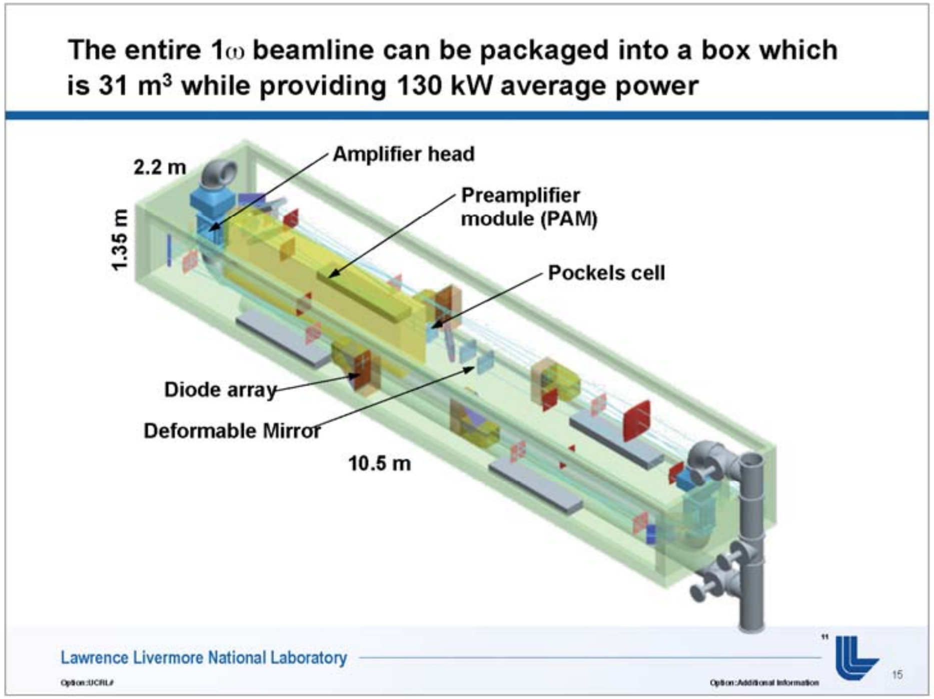


The cavity includes adaptive mirrors and diagnostics. Optimum angular divergence of the laser beam is ±30 mrad, A≈9 J (k=1), $\sigma_t \approx 1.3$ ps, $\sigma_{x,L}$~7 μm

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 train)



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

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

The discovery of the Higgs boson in 2012 has triggered several proposal of photon collider Higgs factories (without e+e-):

Photon collider Higgs factories

γγ Higgs factories appeared in 2012-2013 years

CERN

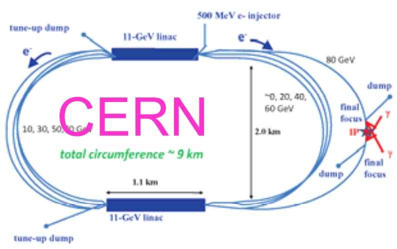
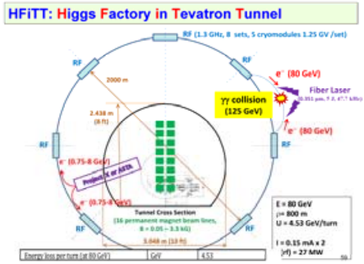


Figure 3: Sketch of a layout for a γγ collider based on recirculating superconducting linacs – the SAPPHiRE concept.

SLAC

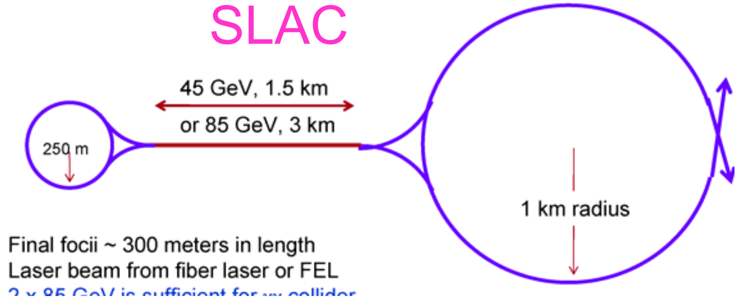


FNAL

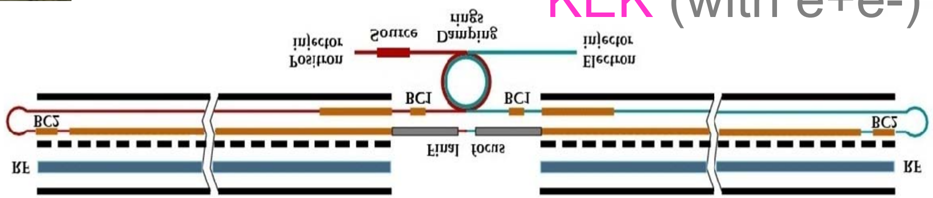
JLAB

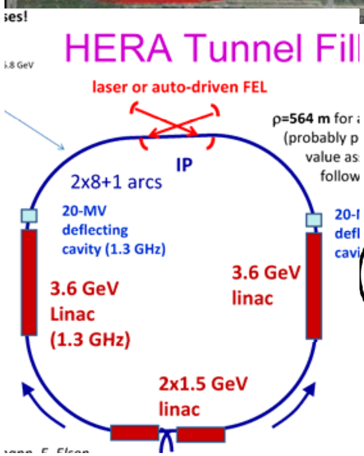
FNAL

SLAC

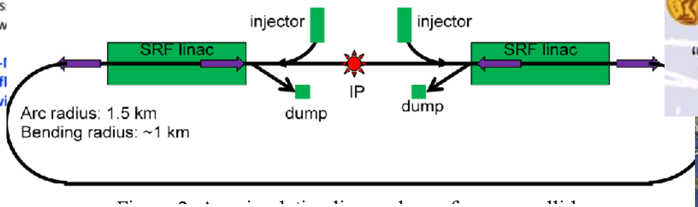


KEK (with e+e-)





JLAB



Turkey

Laser for HFiTT

Fiber Lasers -- Significant breakthrough

Gerard Mourou et al., *"The future is fiber accelerators," Nature Photonics, vol 7, p.258 (April 2013).*

ICAN – International Coherent Amplification Network

Figure 2: Principle of a coherent amplifier network (CAN) based on fiber laser technology. An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of ~1 mJ at a high repetition rate (4). All the channels are combined coherently, compressed (5) and focused (6) to produce a pulse with an energy of >10 J at a repetition rate of 10 kHz (7). [3]

10 J, 10 kHz

Very good approach for equal spacing between bunches and problematic for collider with bunch trains, such as ILC, CLIC, because need very high diode peak power.

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.)

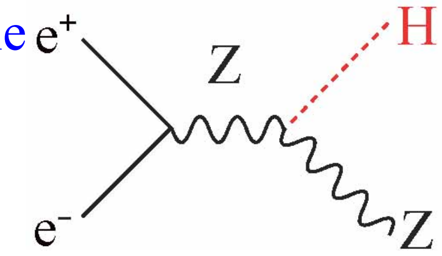
  $\Gamma(H \to \gamma\gamma)$ width can be measured with statistics ≈ 60 times higher than in e+e- collisions.
- different types of reactions (different dependence on theoretical parameters)

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.

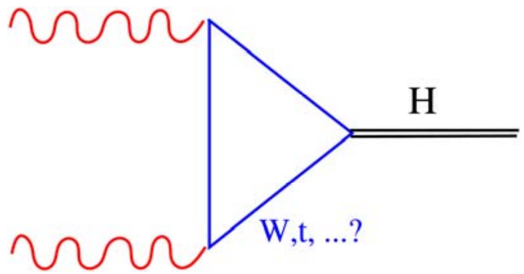
Known physics, ILC stages

In e+e-



- 2E=250 GeV Higgs boson, Br(bb, cc, gg, ττ, μμ, invisible
  Γtot, Z tagging
- 350 top quark
- 500 ZHH –Higgs self coupling
- 500 and higher ttH - top Yukawa coupling
- 1000 and higher Beyond

In γγ

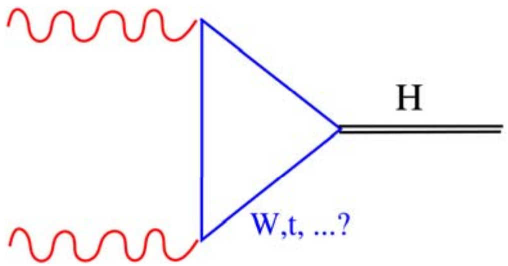


$\Gamma_{\gamma\gamma}$(H) is determited by contributions of all charge particles (even with $M>2E_0$), therefore this process is most sensitive to new physics!

In γγ collisions the Γ(H→γγ) width can be measured with statistics ≈ 60 times higher than in e+e- collisions. This is the most important argument for the photon collider .

However, e+e- beams are much better for Higgs study (due to Z tagging). Therefore PLC has sense only in combination with e+e-: parallel work or second stage.

Хиггсовский бозон



Сечение очень чувствительно к новым частицам в петле

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

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

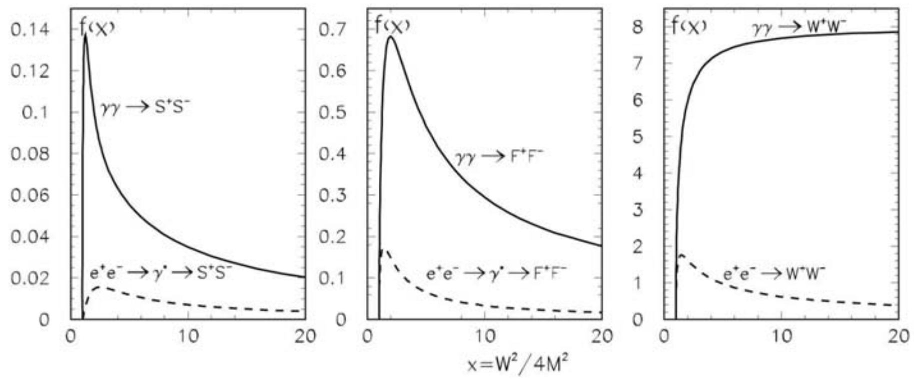
На фотонном коллайдере точность измерения $\Gamma_{\gamma\gamma}$ (H) в ~8 раз выше, чем в e+e- (при одном времени набора статистики)

Some examples of Physics

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)



Сечения рождения пары заряженных частиц в 5-10 раз выше, чем в е+е-, другие диаграммы

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.

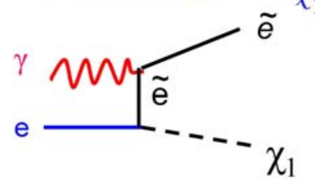
$M_H \approx M_A$, in e^+e^- collisions H and A are produced in pairs (for certain param. region), while in $\gamma\gamma$ as the single resonances, therefore:

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

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):

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



В $\gamma\gamma$,γe можно родить частицы большей массы, чем в е+е-

Физическая мотивация $\gamma\gamma$ коллайдера
(независимо от теории)

In $\gamma\gamma$, γe столкновениях по сравнению с e^+e^-

1. Энергия ниже только 10-20%
2. Число интересных событий примерно такое же и даже выше
3. Возможность зарегистрировать частицы большей массы.
4. Более высокая точность для некоторых процессов.
5. Другие реакции (другая зависимость от теор. параметров)

Это уникальная возможность, когда один (линейный) коллайдер может изучать физику не только в e^+e^- столкновениях, но еще и в $\gamma\gamma$, γe за совсем небольшую (в %) дополнительную цену.

Главное, чтобы была новая физика в области 100-2000 ГэВ

A new proposal (2017)

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

(or other new FEL with E_0=8 GeV with energy doubling)

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

$\boxed{\text{c-b-}\gamma\gamma\text{-factory}}$

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.

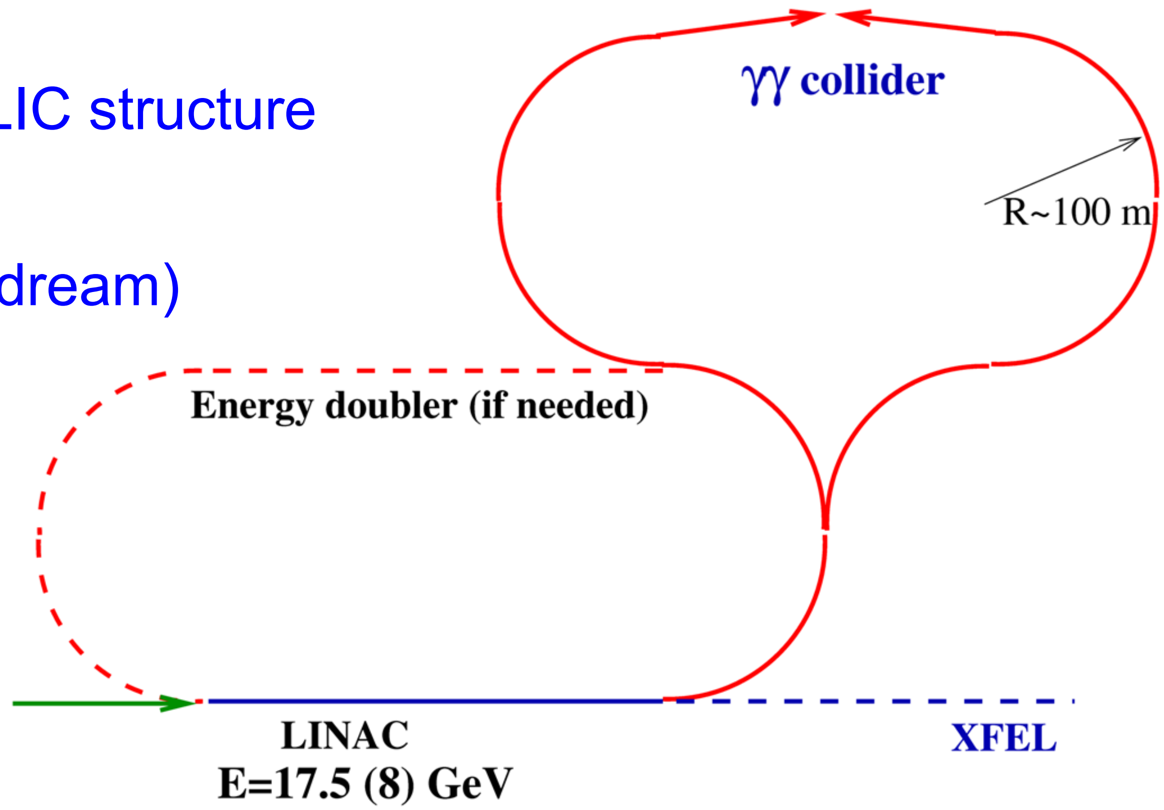
Two real photons will produce resonance states with Q = 0 , C = +, J^P= 0^+, 0^-, 2^+, 2^-, 3^+, 4^+, 4^-, 5^+ … $(\text{even})^\pm$, $(\text{odd} \neq 1)^+$
as well as numerous 4-quark (or molecule) states similar to those observed in e+e-.

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)

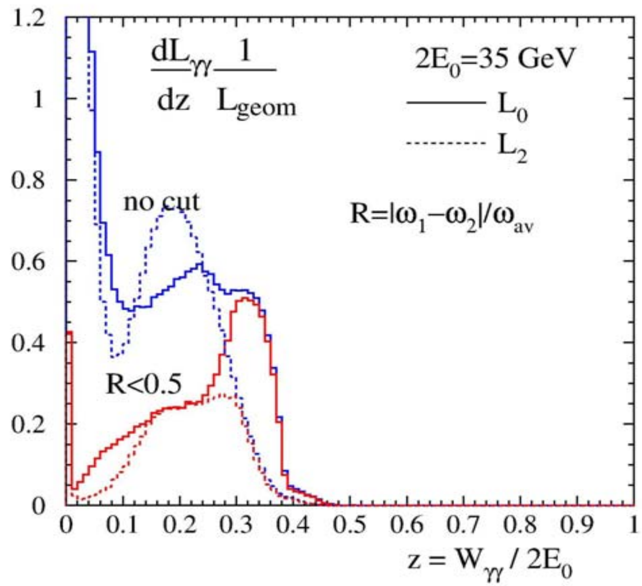


(Linac not in scale)

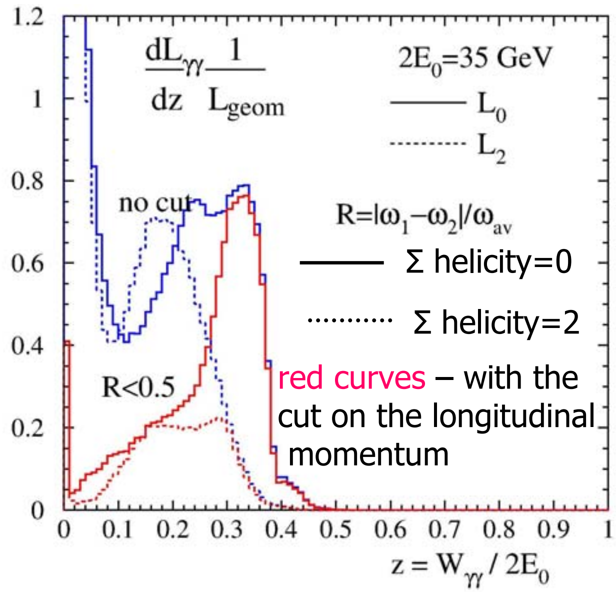
European Superconducting XFEL has started operation in 2017. Its e-beam parameters: E_0=17.5 GeV, N=0.62·10^{10} (1 nQ), σ_z=25 μm, ε_n=1.4 mm mrad, f≈30 kHz

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}=1.6·10^{33}
(XFEL beams)
↓
L_{geom}=1.6·10^{34}
(with low emittance plasma source)

$W_{\gamma\gamma}$ 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 $\dfrac{dL_{\gamma\gamma} 2E_0}{dW_{\gamma\gamma} L_{ee}} \simeq 0.5$, 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, $\lambda_{1,2} = 1, L_{ee} = 1.6 \cdot 10^{33} - 1.6 \cdot 10^{34}$,

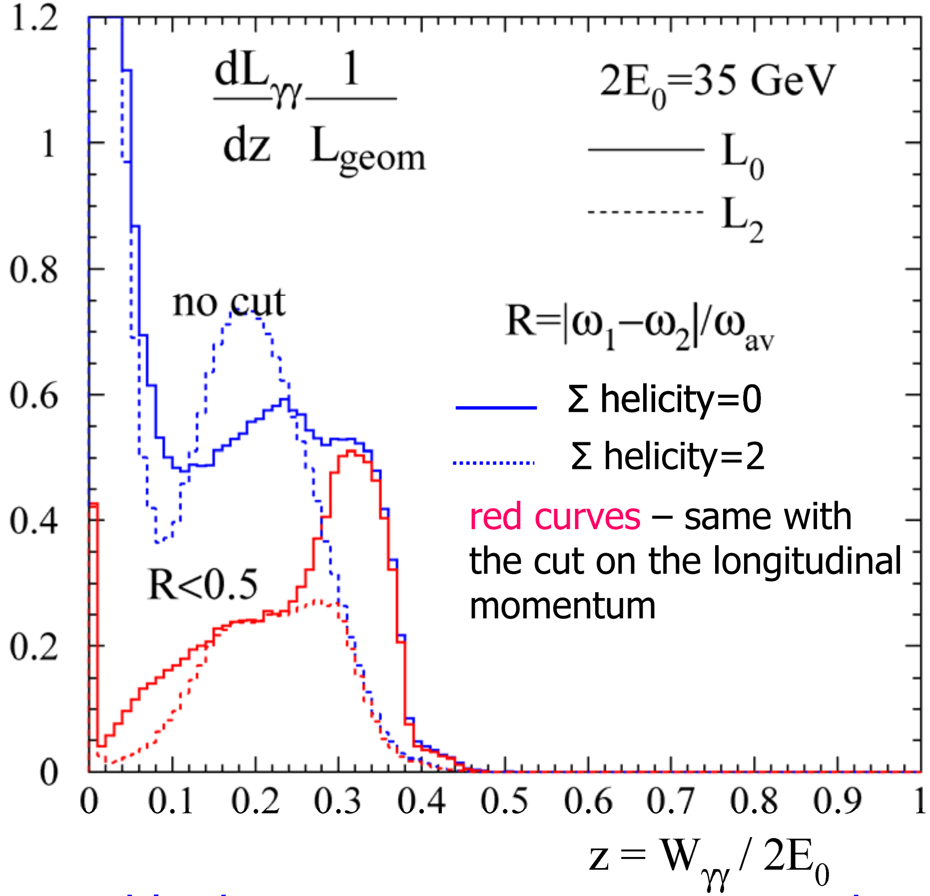
$t = 3 \cdot 10^7 s$ we get $N(\eta_b) \approx 1.5 \cdot 10^5 - 1.5 \cdot 10^6$ and can measure its $\Gamma_{\gamma\gamma}$

Production rate is higher than was at LEP-2 (in central region) ~ 700 - 7000 times!

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

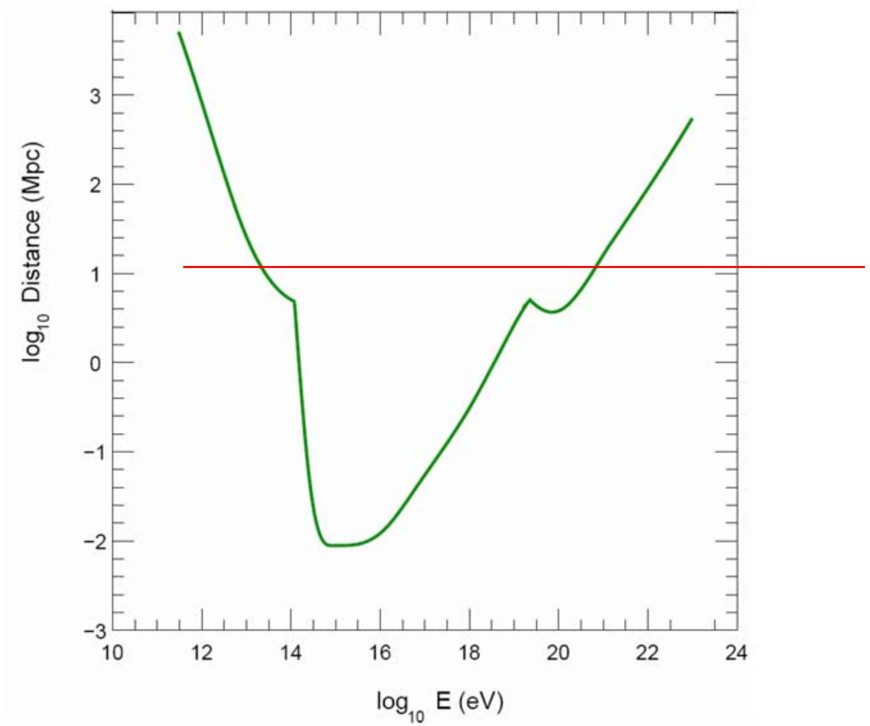
Unpolarized electrons, P_c=-1



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

$\gamma\gamma$ процессы во Вселенной

Пробег высокоэнергичных фотонов за счет столкновения с фотонами реликтового излучения (и от звезд и др.)



Размер видимой Вселенной 10^4 Mpc

Аналогичный эффект на Земле:

Время жизни пучка в e+e- коллайдере LEP(50-100 ГэВ) определяется комптоновским рассеянием электронов на тепловых (black-body) фотонах (около 20 часов), ожидалось τ~200 часов из-за рассеяния на остаточном газе). V.I. Telnov, 1987.

Thank you!