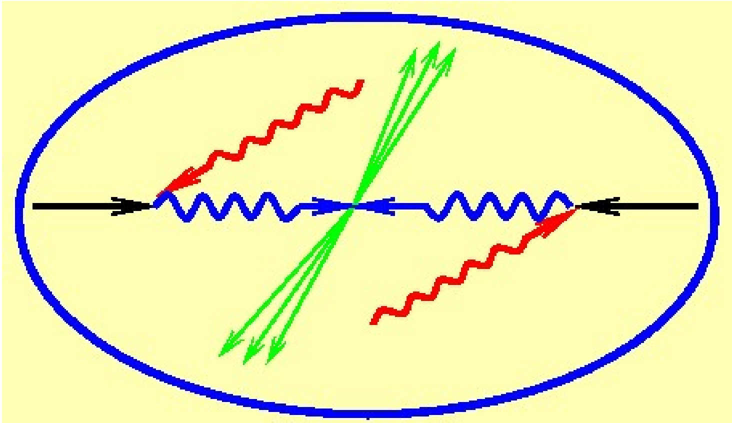

γγ collider on the energy W<12 GeV based on European XFEL as a precursor of PLC at ILC

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LCWS-2019, 29.10.2019, Sendai, Japan

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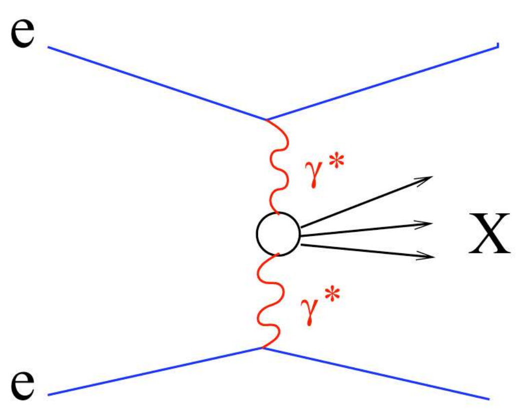
  - Property of beams, luminosities
  - Laser system
  - Physics

$\gamma\gamma$-colliders

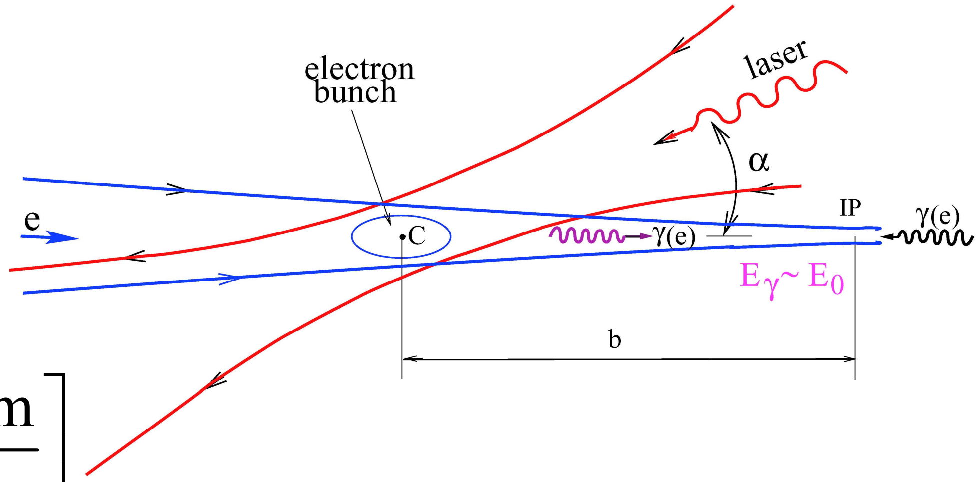
Gamma-gamma collisions have already long history.

Since 1970 two-photon processes were studied at e^+e^- storage rings in collisions of virtual (almost real) photons (γ^*). In the case of resonance production in $\gamma\gamma$ its charge parity C=+ (like π_0, H(125)), while in e+e- it is C=- (like $J/\psi, \Upsilon$). So, physics is complementary.

The number of such photons per one electron is rather small: $dn_\gamma \sim 0.035\, d\omega/\omega$, therefore $L_{\gamma\gamma} << L_{e+e-}$.



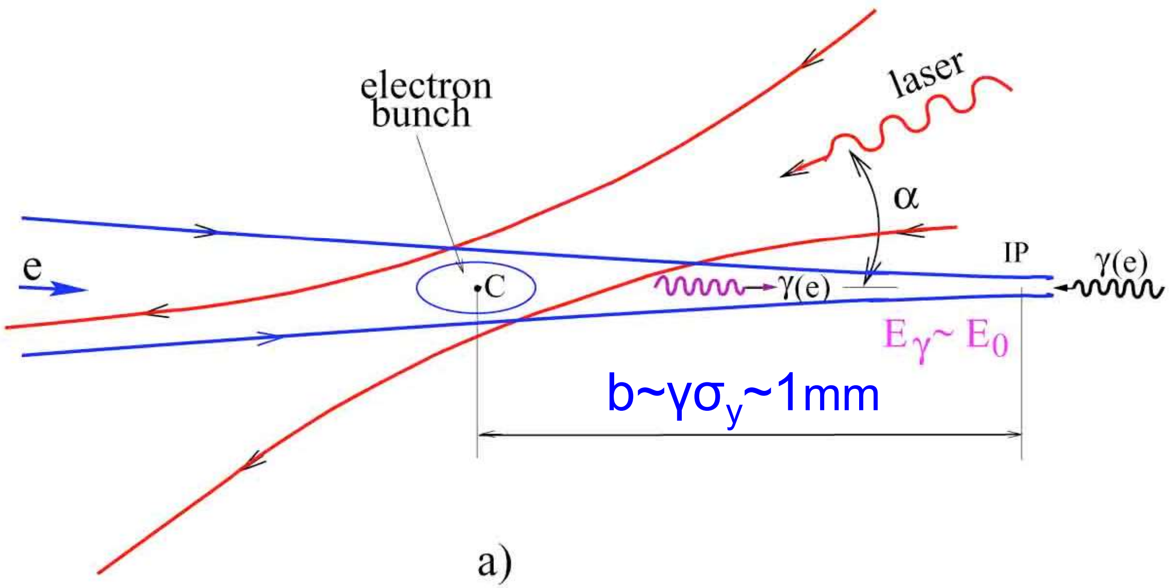
At future e^+e^- linear colliders beams are used only once which make possible $e \to \gamma$ "conversion" using Compton back scattering of laser light (1981). For E_0=250 GeV and $\lambda = 1\ \mu m$ ($x = 4.75$) the max. energy $E_\gamma \sim 0.8 E_0$



$$E_\gamma = \frac{x}{x+1} E_0, \qquad x \approx \frac{4 E_0 \omega_0}{m^2 c^4} = 19 \left[\frac{E_0}{\mathrm{TeV}}\right]\left[\frac{\mu \mathrm{m}}{\lambda}\right]$$

The required flash energy for $k = N_\gamma / N_e \sim 0.65$ is ~5-10 J and ps duration

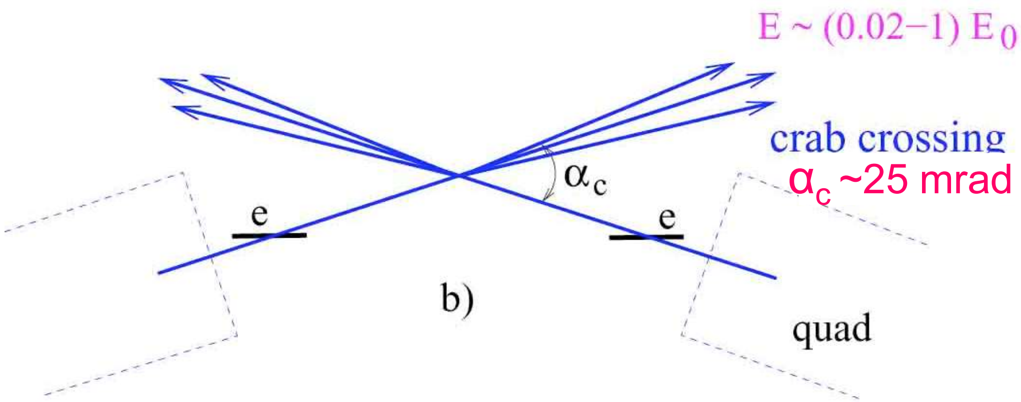
Scheme of $\gamma\gamma$, γe collider



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

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

$E_0 = 250$ 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.

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

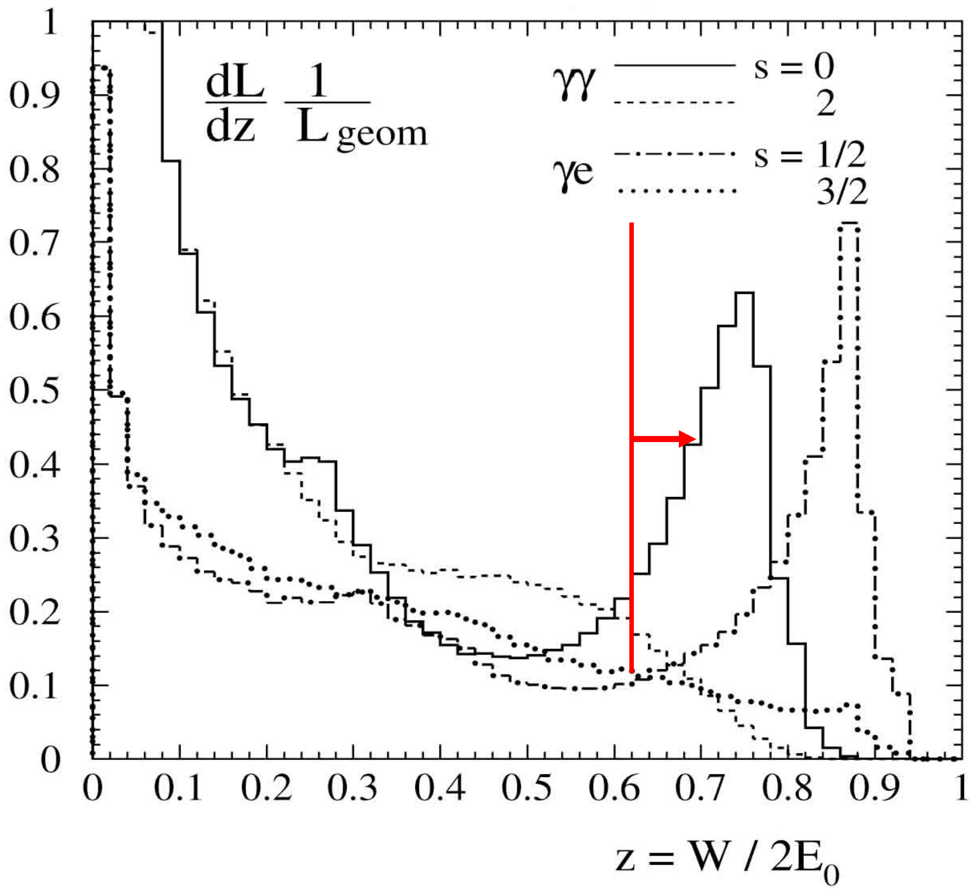
$W_{\gamma\gamma,\ max} \sim 0.8 \cdot 2E_0$
$W_{\gamma e,\ max} \sim 0.9 \cdot 2E_0$

The crossing angle at ILC for γγ option should be >20-25 mrad (now 14 mrad), do not forget to increase it (after the ILC approval)

Typical γγ, 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)

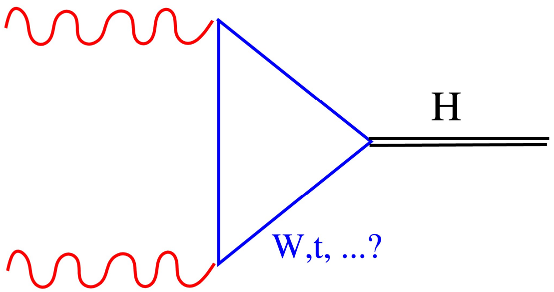


Luminosity spectra and their polarization properties can be measured using QED processes

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

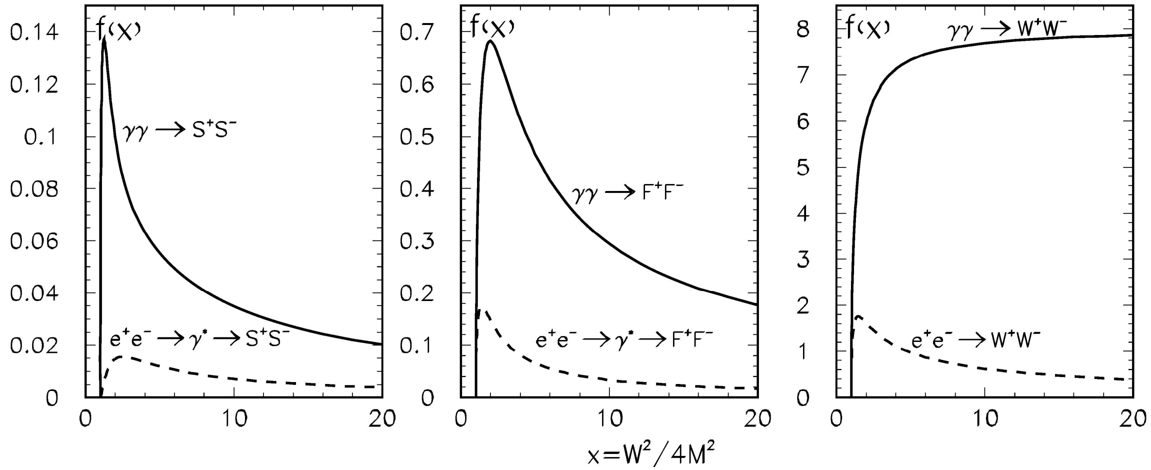
γγ physics at high energy linear colliders

resonance Higgs production

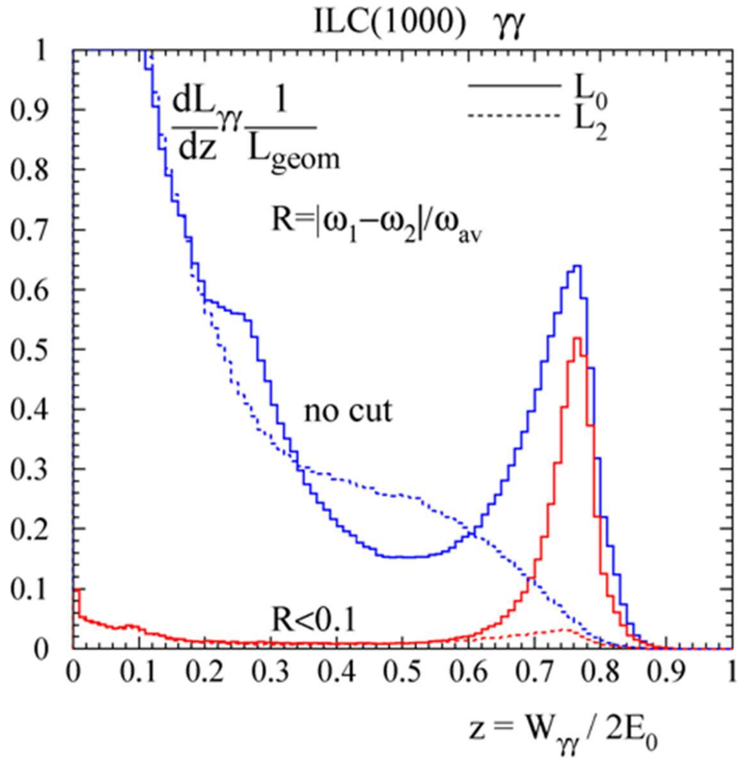


$\Gamma_{\gamma\gamma}(H)$ can be measured much better (~8 times) than in e^+e^-

Any charge pairs production



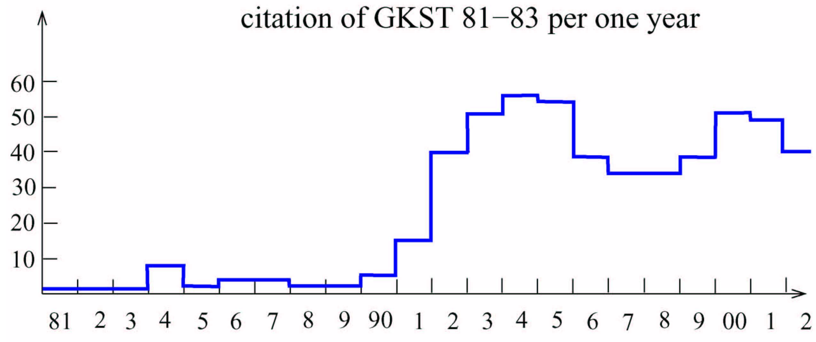
Unfortunately only H(125) is found at the LHC, but surprises are not excluded.



γγ, γe luminosity spectra at the ILC(1000) (for λ=2 μm)

Such collider would be best for study of the (fake) diphoton peak seen at the LHC at 750 GeV.

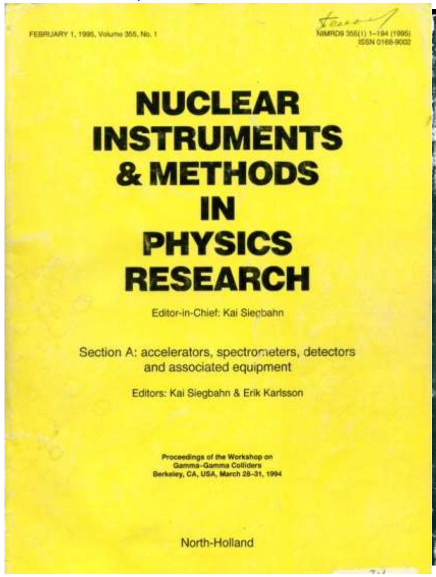
Activity on photon colliders



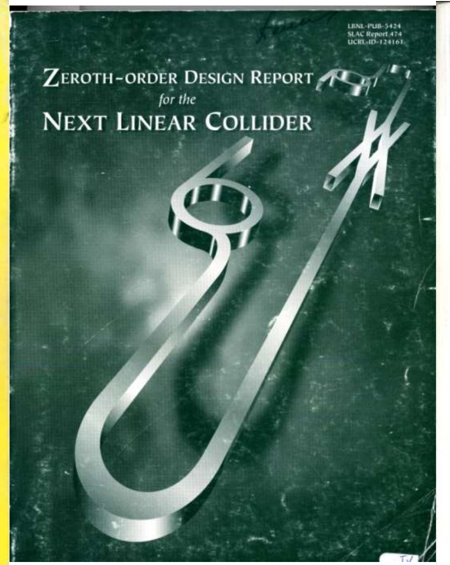
(total number of publications is larger by a factor of 2)

→ about 2 papers/week

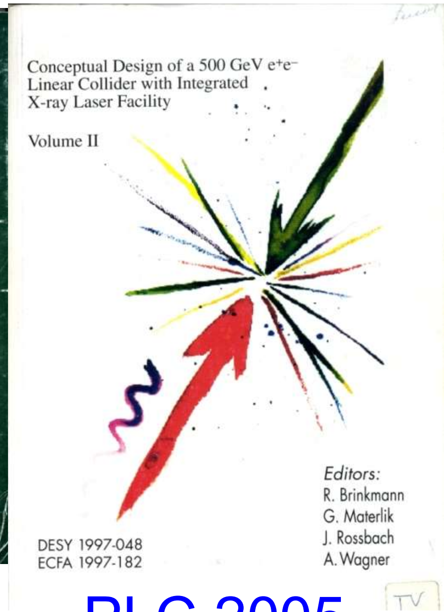
Gamma-gamma workshop LBL, 1994



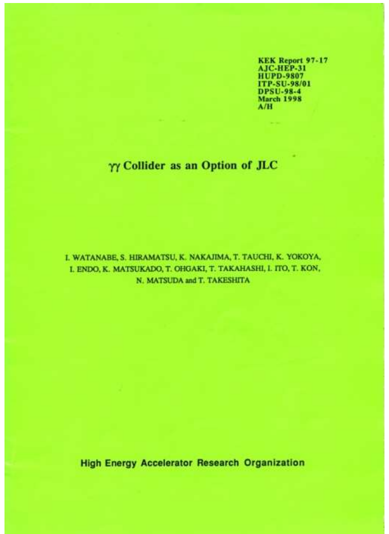
NLC



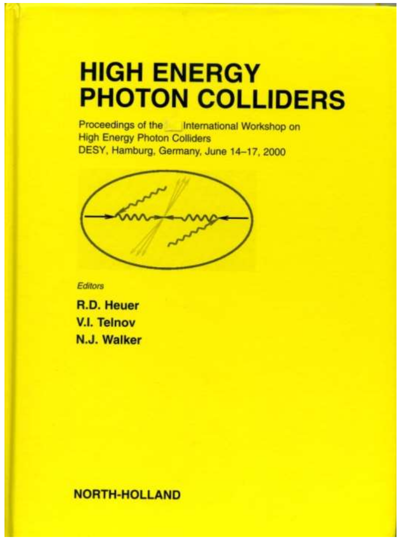
TESLA CDR



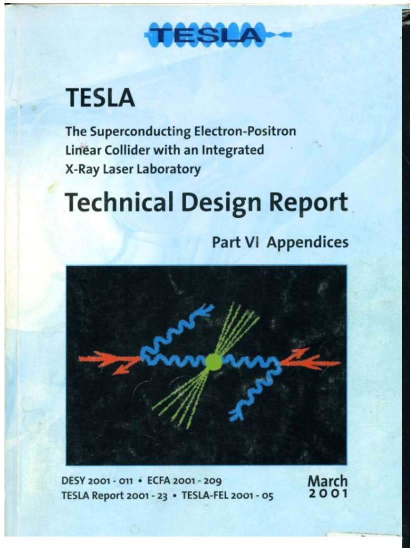
γγ at JLC



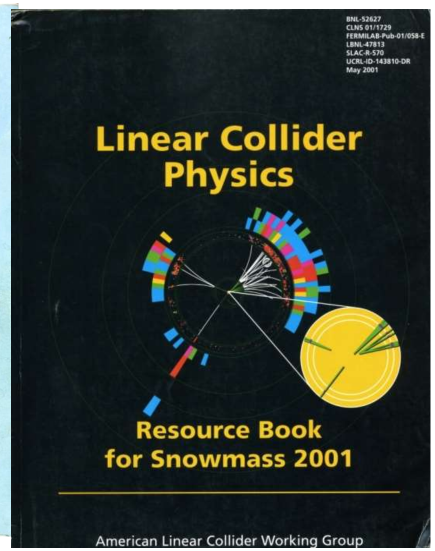
γγ workshop at DESY



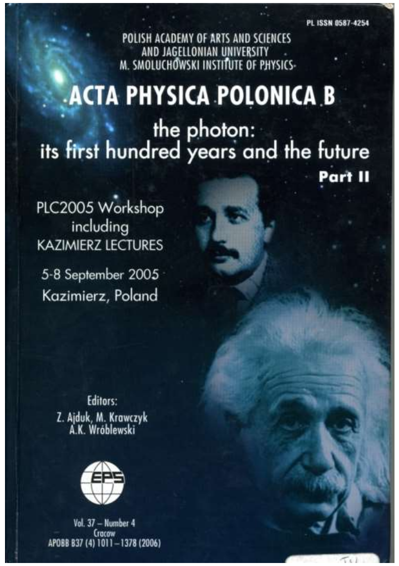
TESLA TDR



γγ NLC



PLC 2005



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

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, but people want to do something interesting just now, during their life, they need some facility for application of their technologies (accelerators, laser, plasma,etc).

It has sense to consider a $\gamma\gamma$ collider on the energy $W_{\gamma\gamma}$=3-12 GeV

c-b-$\gamma\gamma$-factory (V.Telnov, 2017)

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 e^+e^- B-factories can not study $\gamma\gamma$ collisions at $W_{\gamma\gamma}$=5-12 GeV (too low $\gamma^*\gamma^*$ luminosity).

The LHC is not good for $\gamma\gamma$ physics due to very large background (such as pomeron-pomeron interactions) with very similar final states.

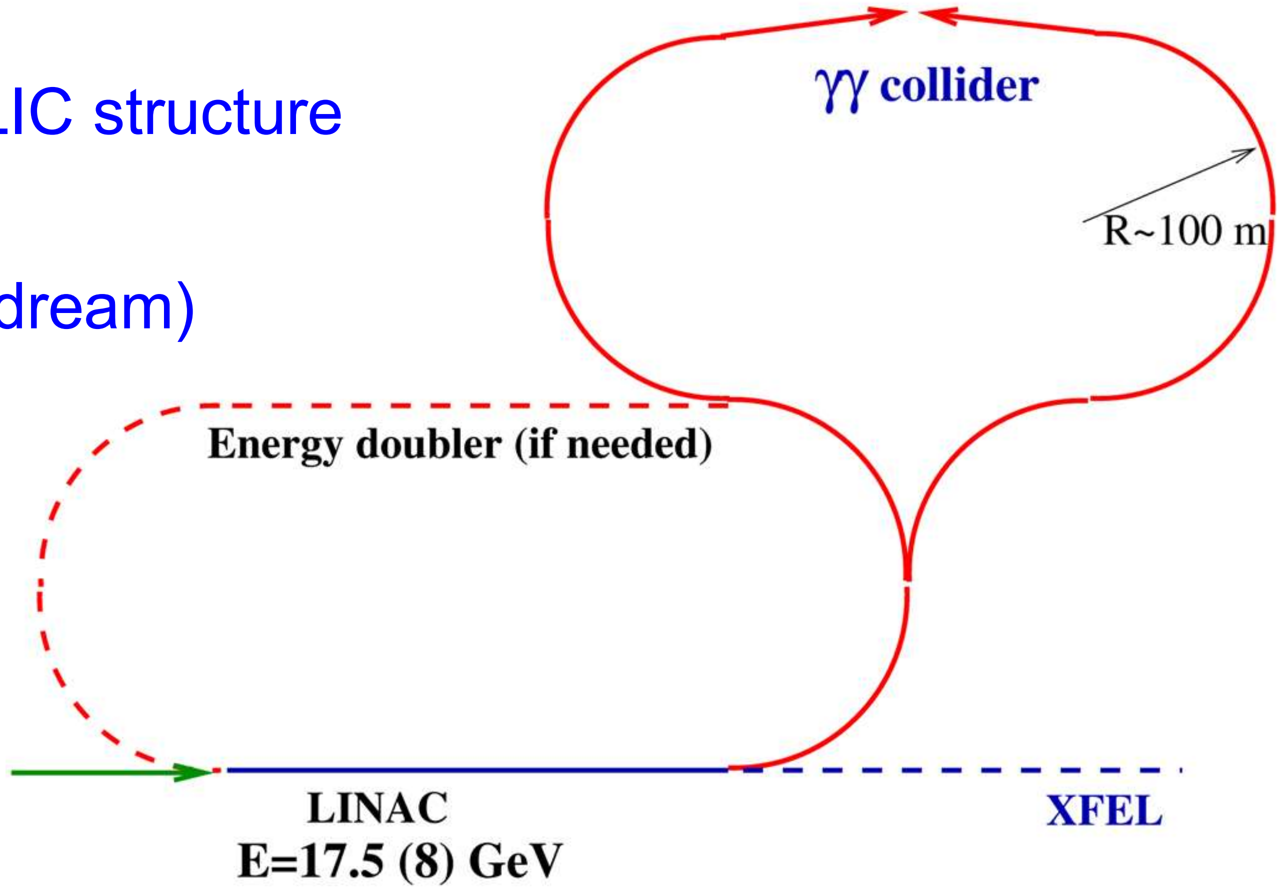
Two real photons will produce resonance states with Q = 0 , C = +,
J^P= 0^+, 0^-, 2^+, 2^-, 3^+, 4^+, 4^-, 5^+ … $(\text{even})^{\pm}$, $(\text{odd} \neq 1)^+$
as well as numerous 4-quark (or molecule) states, similar to those observed in e+e-.

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)

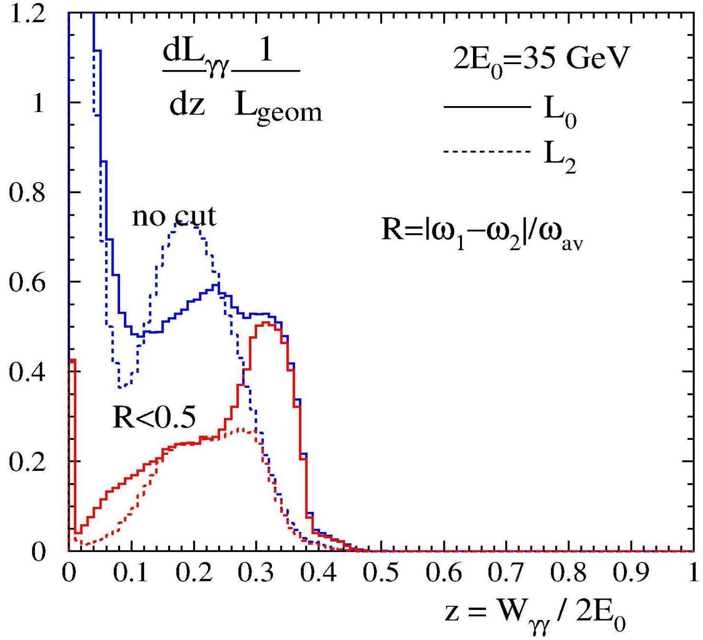
Main (most expensive) part of the photon collider is already in operation since 2017

There is enough place left for the photon collider

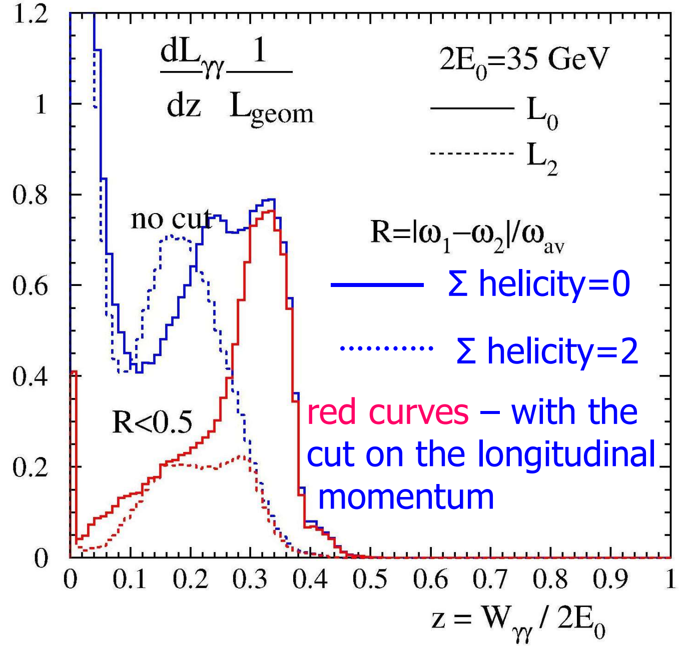
European Superconducting XFEL has started operation in 2017. Its e-beam parameters: E_0=17.5 GeV, $N=0.62\cdot10^{10}$ (1 nQ), σ_z=25 μm, ε_n=1.4 mm mrad, f≈30 kHz

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 $b=\gamma\sigma_y$=1.8 mm)

Unpolarized electrons, $P_c=-1$



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



$L_{geom}=1.6\cdot10^{33}$

$W_{\gamma\gamma}$ 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: $\gamma\gamma \to \eta_b$.

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

$$N = \frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}} \frac{4\pi^2 \Gamma_{\gamma\gamma}(1+\lambda_1\lambda_2)(\hbar c)^2}{(Mc^2)^2} t \approx 8\cdot 10^{-27} \frac{\Gamma_{\gamma\gamma}}{E_0 M_x^2 [\mathrm{GeV}^2]} (L_{ee} t)$$

where for $\gamma\gamma$ collider $$\frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}} \frac{2E_0}{L_{ee}} \simeq 0.5$$

For $\Gamma_{\gamma\gamma}(\eta_b) = 0.5$ keV, $E_0 = 17.5$ GeV, $\mathrm{M}(\eta_b) = 9.4$ GeV, $\lambda_{1,2} = 1, L_{ee} = 1.6\cdot 10^{33}$,

$t = 10^7 s$ we gets N(η_b) ≈ 50000 .

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

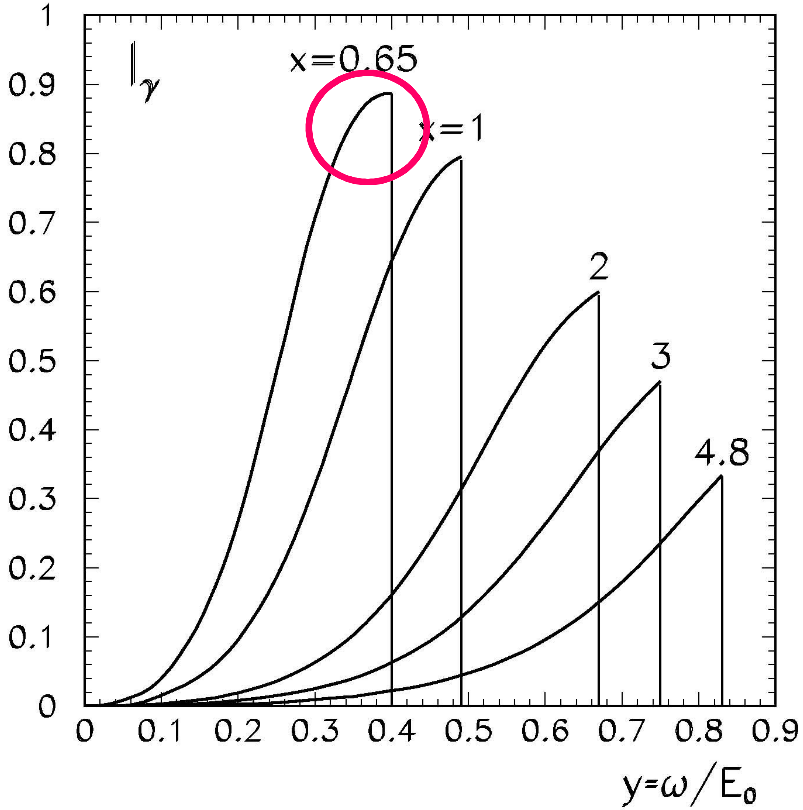
In order to have the same number of events (in central region) with $W_{\gamma\gamma}$=10 GeV at 100 GeV e^+e^- collider its luminosity should be about L_{e+e-}~10^{35} $cm^{-1}s^{-1}$ or about 70 times higher that the geometric L_{ee} at the considered photon collider.

However $\gamma\gamma$ collider has an additional advantage – polarization (linear and circular).

Linear polarization

Gamma beams have high degree of circular or linearly polarization at maximum energies that allows to measure easily C and P-parity of resonances (C=+)

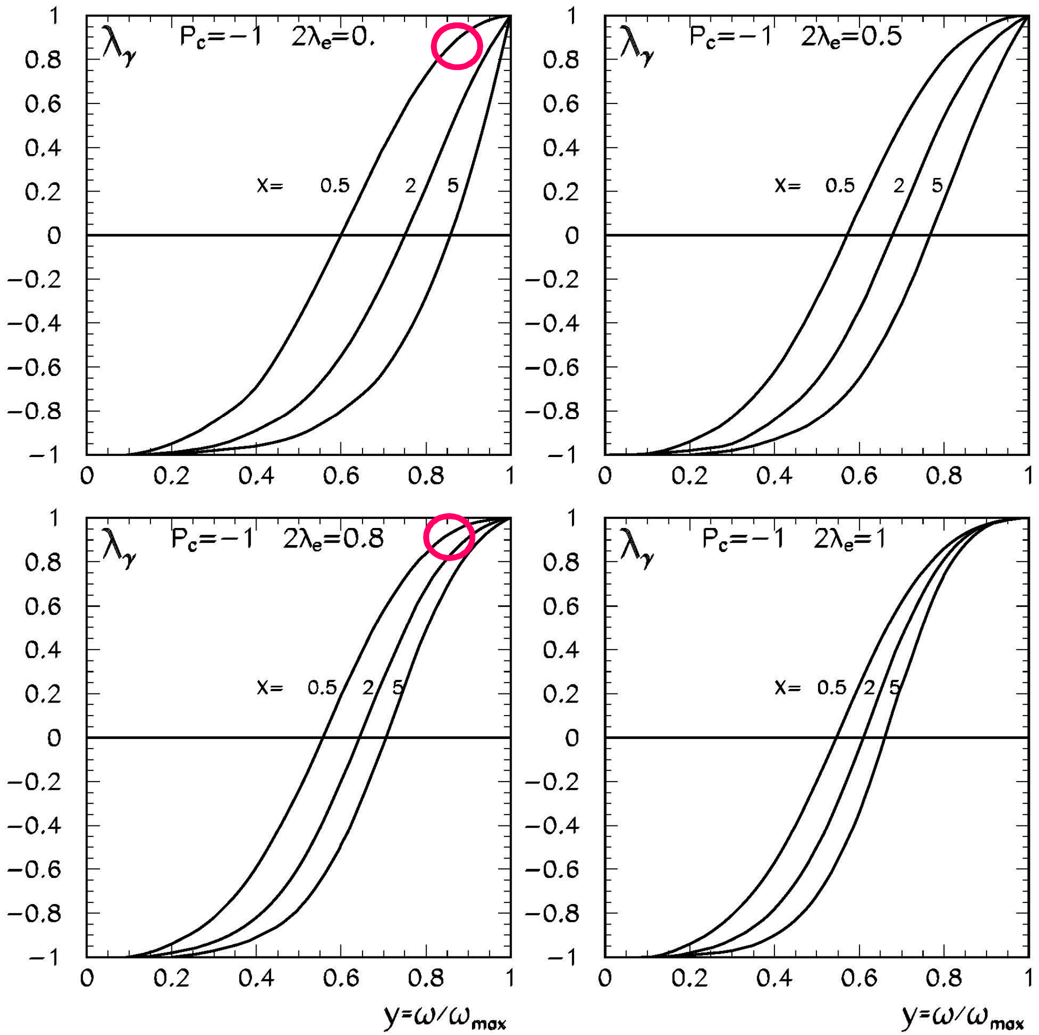
$$\sigma \propto 1 \pm l_{\gamma 1} l_{\gamma 2} \cos 2\varphi \qquad \pm \text{ for CP}=\pm 1$$



Varying the angle φ between linear polarization planes one can distinguish scalar and pseudo-scalar resonances or even to measure CP violation (if it exist, like in the Higgs).

For the considered collider the parameter x~0.65 and the degree of linear polarization in the high energy part of spectrum is very high, about 85%.

Circular polarization



The circular polarization in the high energy part of spectrum is very high (x~0.65 for the considered collider), one need a circular polarized laser, longitudinal electron polarization helps only a little.

The cross section for scalar resonances

$$\sigma \sim 1+\lambda_1\lambda_2,$$

while for light quark pairs

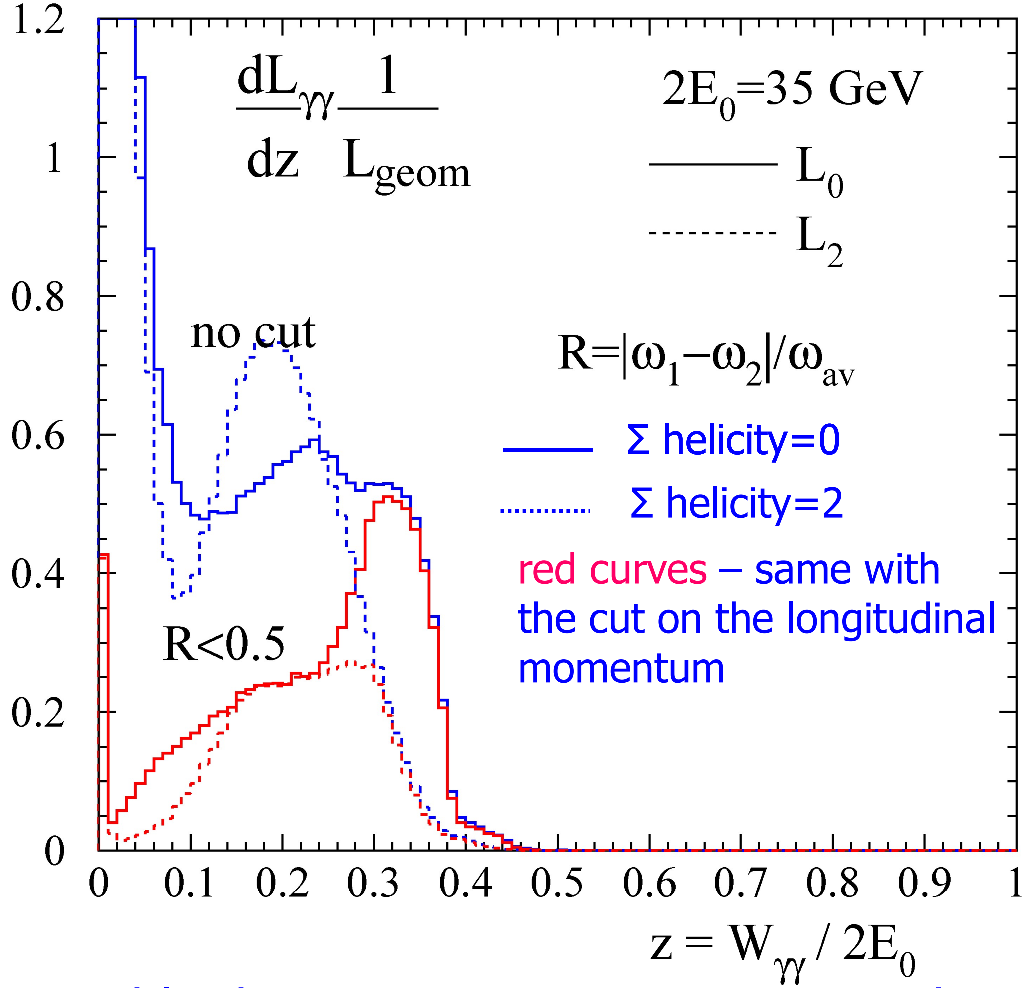
$$\sigma \sim 1-\lambda_1\lambda_2$$

Variable helicities is a powerful instrument in study of particle physics, spin properties of cross sections, allows to enhance or suppress processes.

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

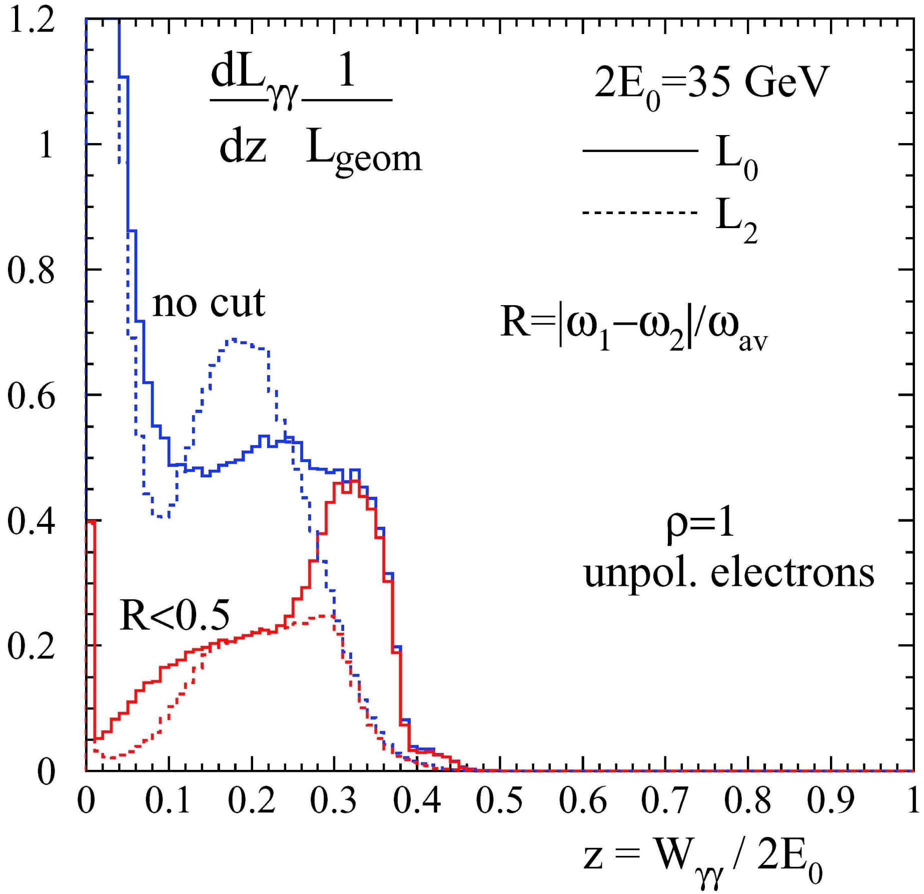
Unpolarized electrons, P_c=-1



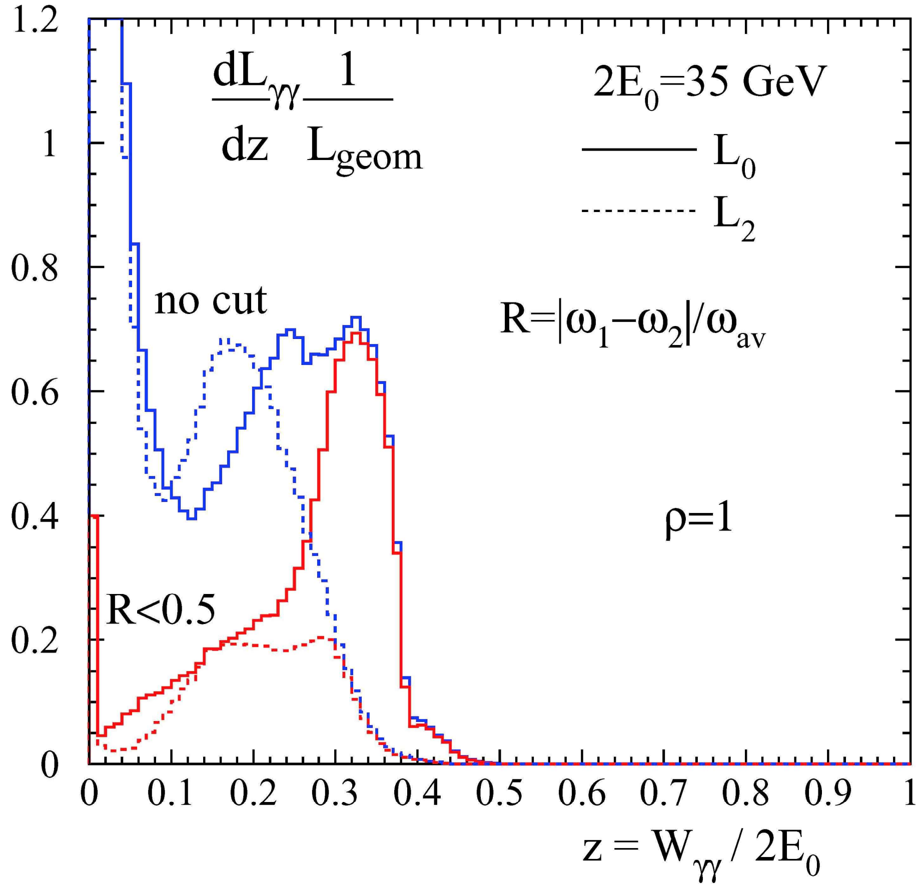
In Table the XFEL emittance is assumed. With promised plasma gun the luminosity can be larger ~10 times.

$\gamma\gamma$ luminosity spectra for $\rho=b/\gamma\sigma_y=1$

Unpolarized electrons, P_c=-1

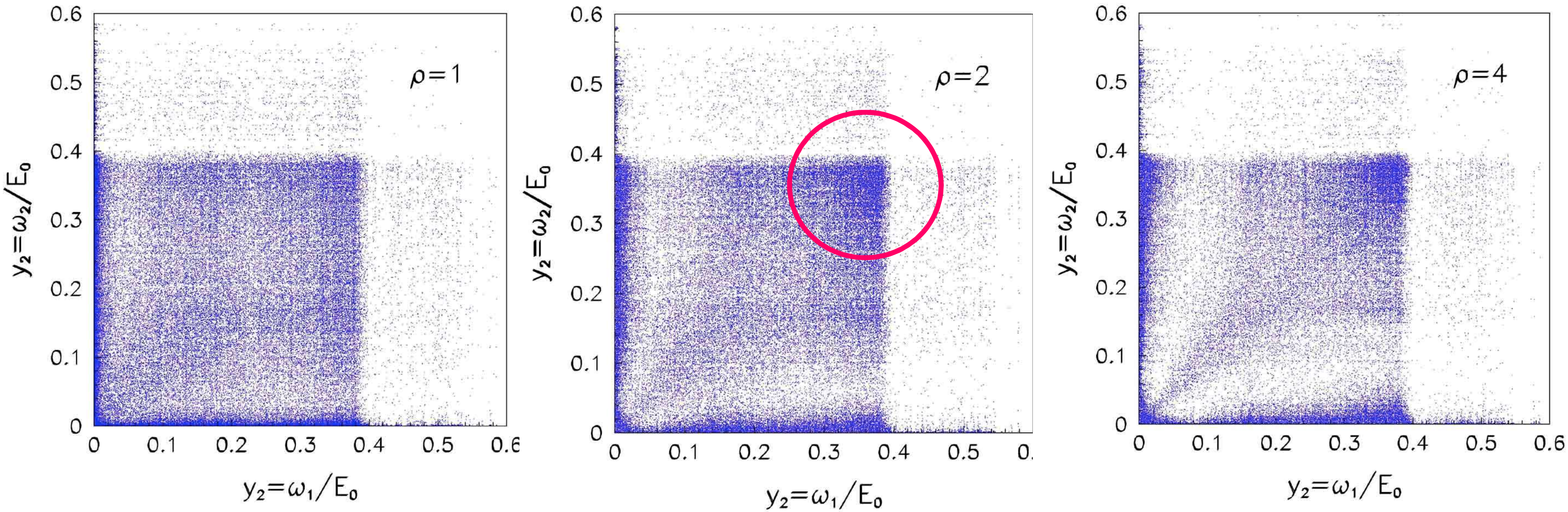


Polarized electrons, $2\lambda_e P_c$=-0.85



XFEL uses unpolarized electron beams, for the photon collider
it is preferable to use polarized electron source

2D-luminosity spectra for various ρ

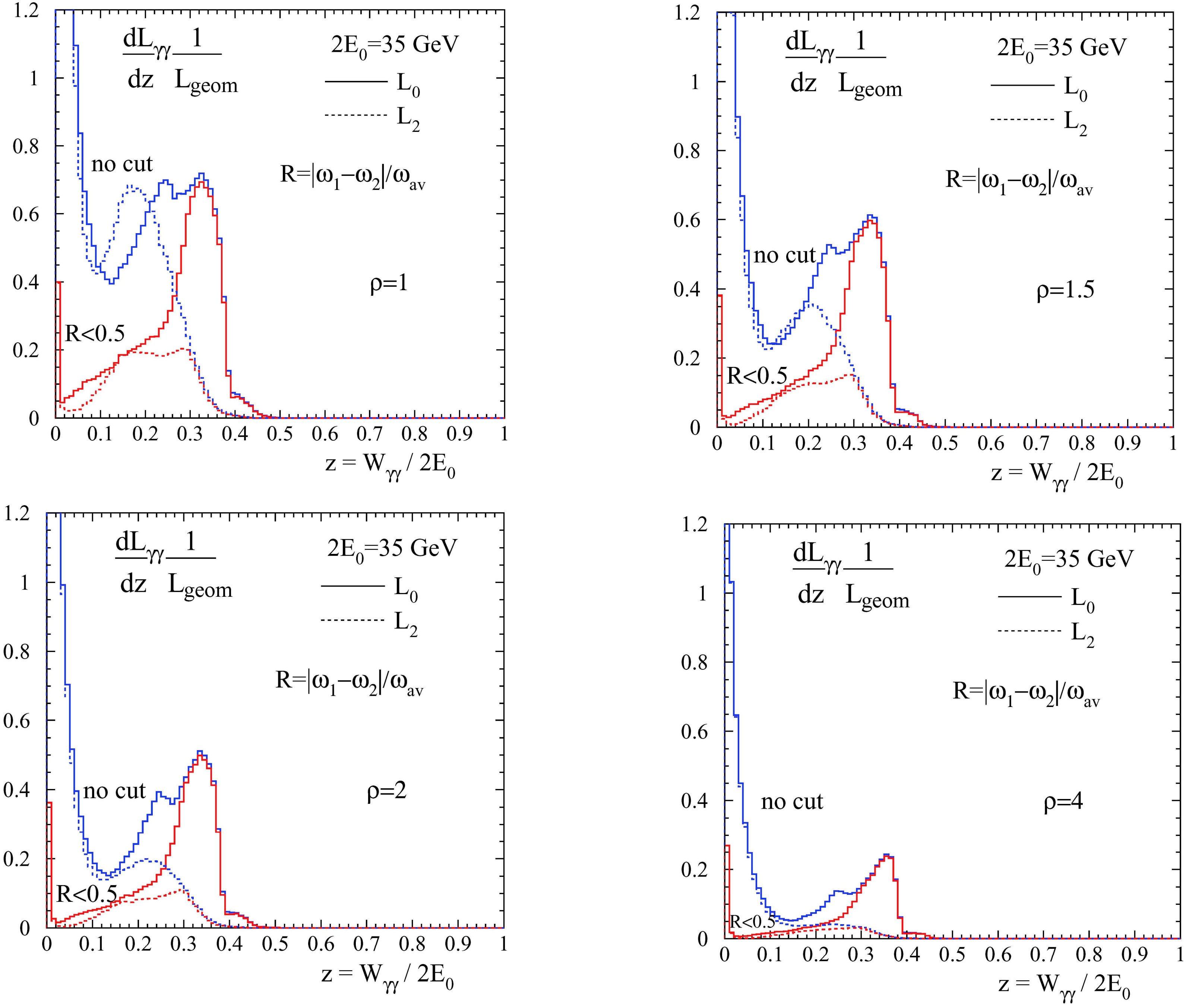


Spectra are more monochromatic for larger ρ, but luminosity decreases.

For search of resonances one needs maximum L and ρ=1 is OK.

For measurement of γγ cross sections (with polarization) one should use ρ~2-4 (more peaked spectra) and use for analyses events with invariant masses W~(0.85-1)W_{max} where high degree of polarizations.

$\gamma\gamma$ luminosity spectra for various ρ, $2\lambda_e P_c = -0.85$

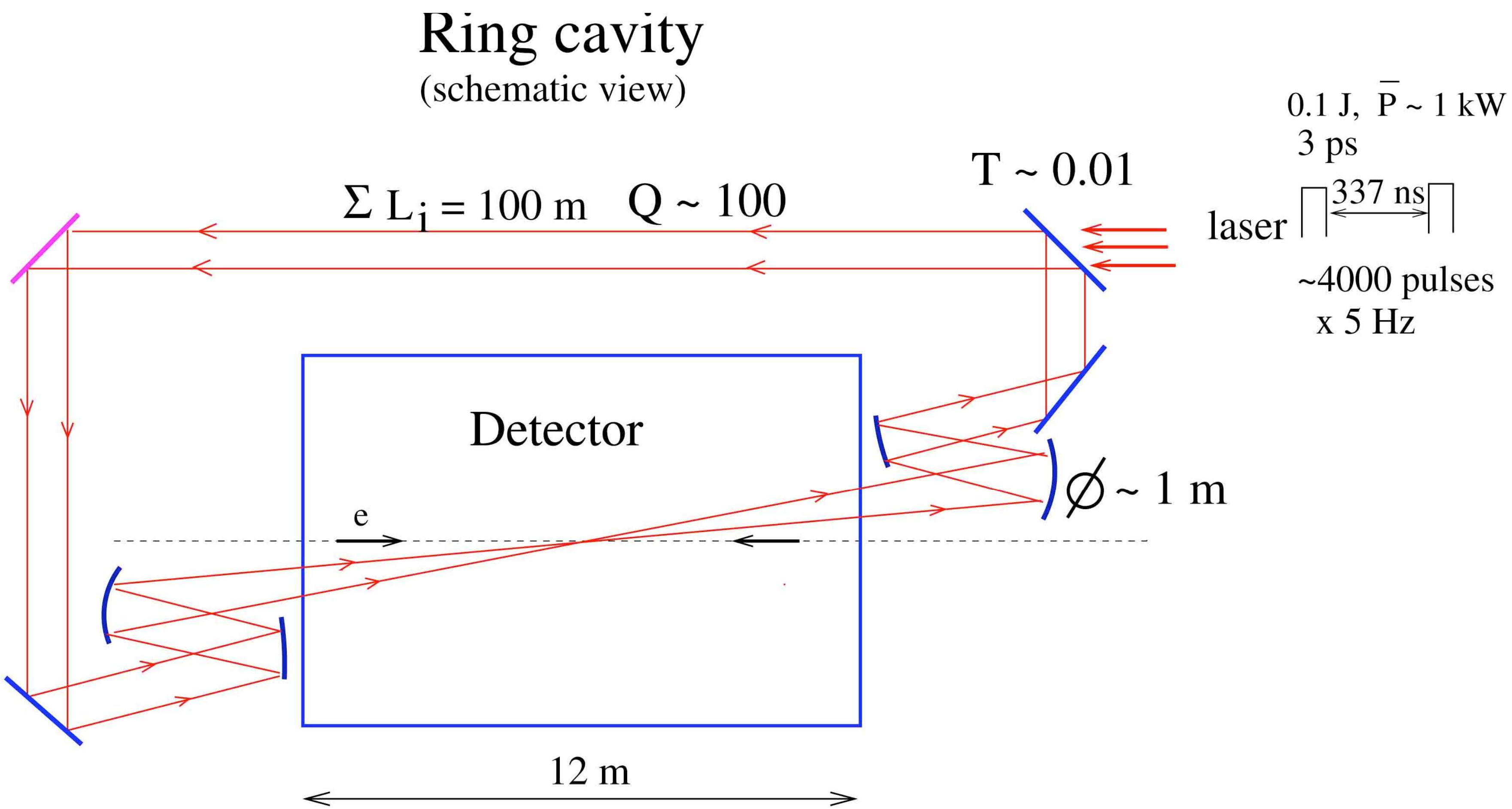


Requirements for the laser system

- Wavelength ~0.5-1 μm (1 μm needs 30% high electron energy)
- Flash energy ~3 J
- Pulse duration ~2 ps
- Time structure same as electron linac
  Δct~100 m, 3000 bunch/train, 5 Hz

The ring external optical cavity can be used which can reduce the laser power by a factor of 100-300 (or more?).

Laser system for ILC



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

For the considered ~10 GeV γγ collider all is similar, only the wavelength is 2-3 times shorted, Compton cross section is larger, therefore the flash energy is smaller (A~3 J)

$c\bar{c}$

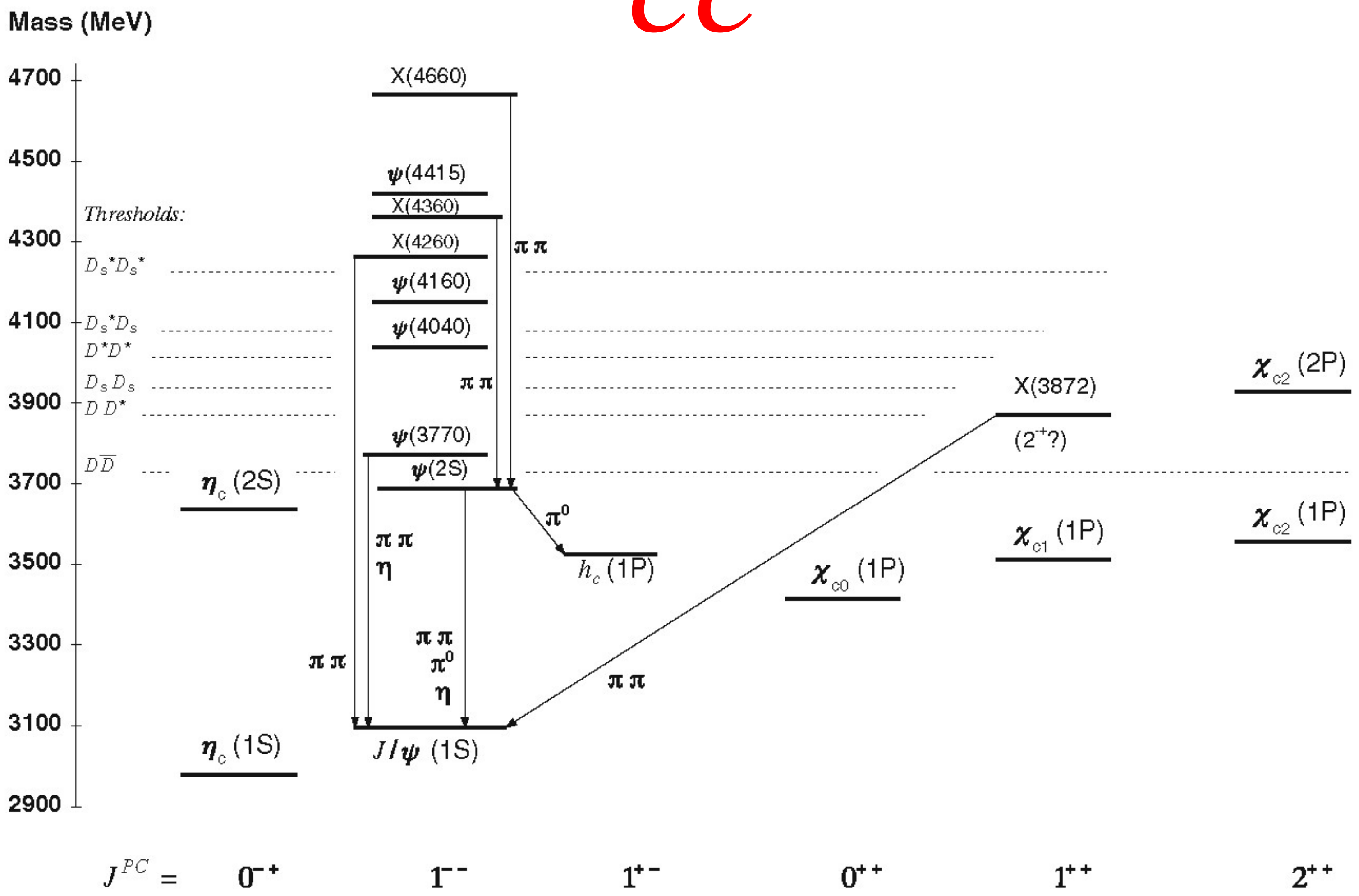


Fig. 2.1 The experimentally observed charmonium states. The states labelled X, the nature of which is unknown, are not thought to be conventional charmonium states. Figure from Ref. [1]

Almost all charmonium states below DD threshold have been observed experimentally, but there exotic X,Y,Z,X',X"states, measurement of $\Gamma_{\gamma\gamma}$ can help to understand their nature.

Note, $\gamma\gamma$ collider can produce C+resonances with any J≠1

$b\bar{b}$

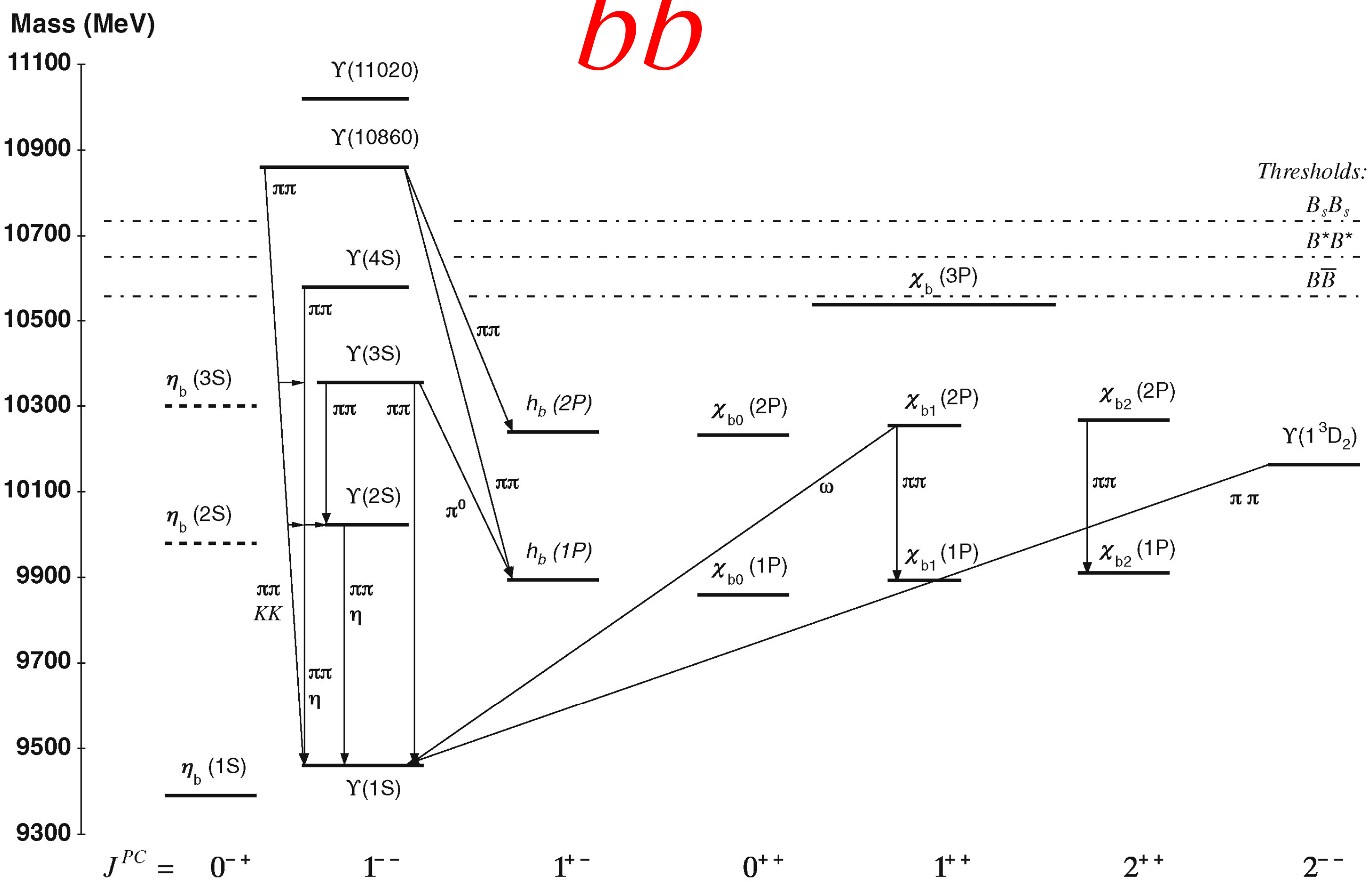


Fig. 2.2 The experimentally observed and theoretically expected bottomonium states. *Dashed lines* denote unobserved or unconfirmed states (an unconfirmed experimental candidate for the $\eta_b(2S)$ state has been observed by the Belle experiment [6]). Figure from Ref. [1]

Many of these bottomonium states below BB threshold have been observed experimentally, with exception of $\eta_b(3S)$, $h_b(3P)$ and most D-wave bottomonium. Many exotics states are observed (4-quark, molecules ??)

Beside study of resonances one can measure for the first time $\gamma\gamma$ cross sections with polarized beams:

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

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

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

The number of events

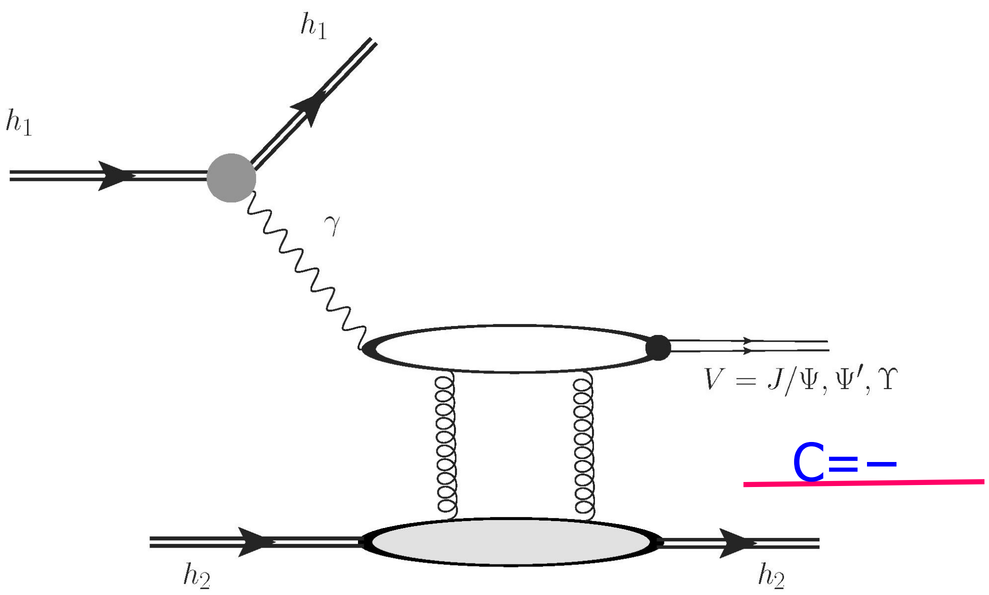
$$d\dot{N} = dL_{\gamma\gamma}(d\sigma^{np} + \lambda_\gamma \tilde{\lambda}_\gamma d\tau^c + l_\gamma \tilde{l}_\gamma \cos(2\Delta\phi) d\tau^l),$$

All these cross sections can be measured at W<12 GeV

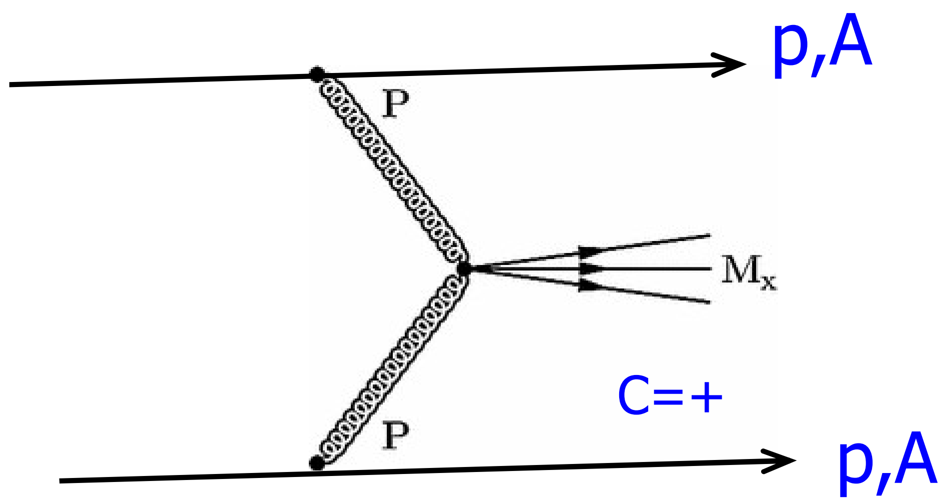
For example, at LHC in photon-pomeron(P) collision C=− resonances are produced which are forbidden in $\gamma\gamma$-collisions

P – Pomeron - multigluon state

γP



PP



final states are quite similar to those in $\gamma\gamma$-collisions, only wider transverse momentum distribution

So, LHC can't compete in study of $\gamma\gamma$-processes with a clean $\gamma\gamma$-collider with polarized (linearly and circularly) photon beams

Conclusion

- Photon collider has sense as a very cost effective addition for e+e- linear collider. However perspectives of high energy LCs are unclear already many decades, photon colliders are considered as the second stage, so they can appear only in ~30-40 year.
- It has sense to construct a smaller $\gamma\gamma$ collider on the energy $W_{\gamma\gamma} \leq 12$ GeV (b,c regions). $\gamma\gamma$ physics here is very rich.
- Such $\gamma\gamma$ collider will be a nice place for application of modern advanced accelerator, laser and plasma technologies (linacs (SC, plasma-based), low-emittance electron sources (incl. plasma), powerful laser systems, optical cavities). It does not need positrons and damping rings. European XFEL (its linac) is a perfect base for a such $\gamma\gamma$ collider.
- The optical system is identical to that needed for the PLC at ILC (only the wavelength is shorter, 0.5 μm instead of 1-2 μm), therefore such photon collider can be considered as a precursor of $\gamma\gamma$ collider at the ILC.