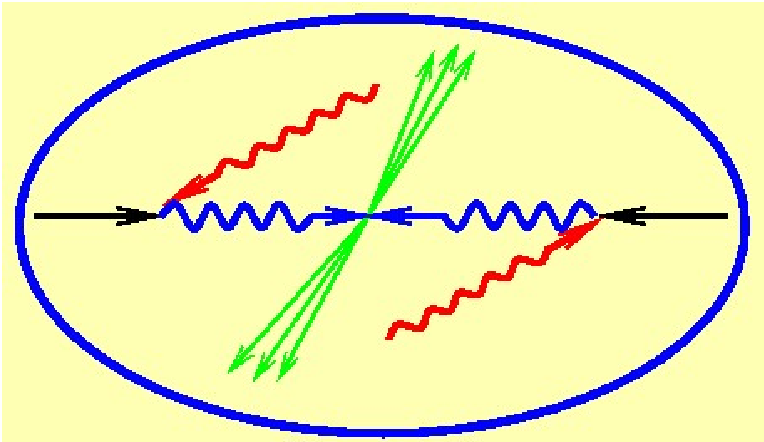

$\gamma\gamma$ collider on the energy W<12 GeV based on European XFEL

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Probing strong-field QED in electron-photon interactions
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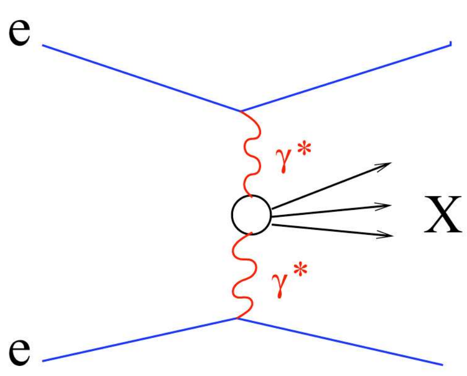
γγ-colliders

Gamma-gamma collisions have already long history.

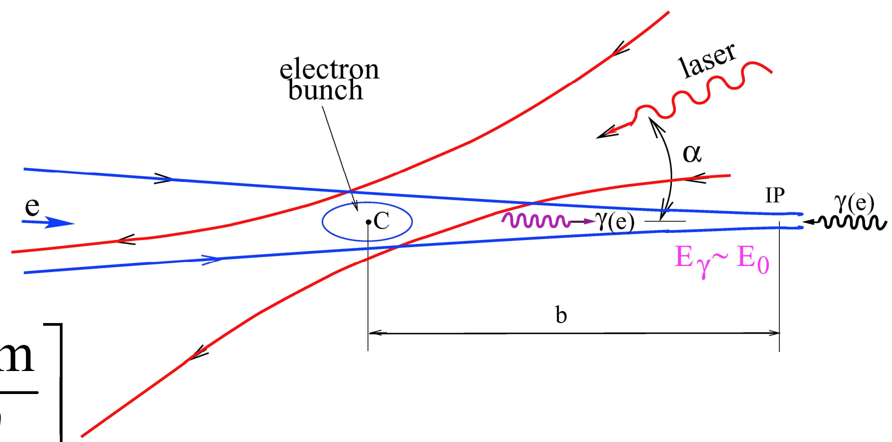
Since 1970 two-photon processes were studied at e^+e^- storage rings in collisions of virtual (almost real) photons (γ^*). In the case of resonance production in γγ its charge parity C=+ (like π_0, H(125)), while in e+e- it is C=- (like J/ψ,ϒ). So, physics is complementary.

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⟶γ "conversion" using Compton back scattering of laser light (1981). The max. energy $E_\gamma \sim 0.8 E_0$ for E_0=250 GeV and $\lambda = 1\ \mu m$ (x=4.75)

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

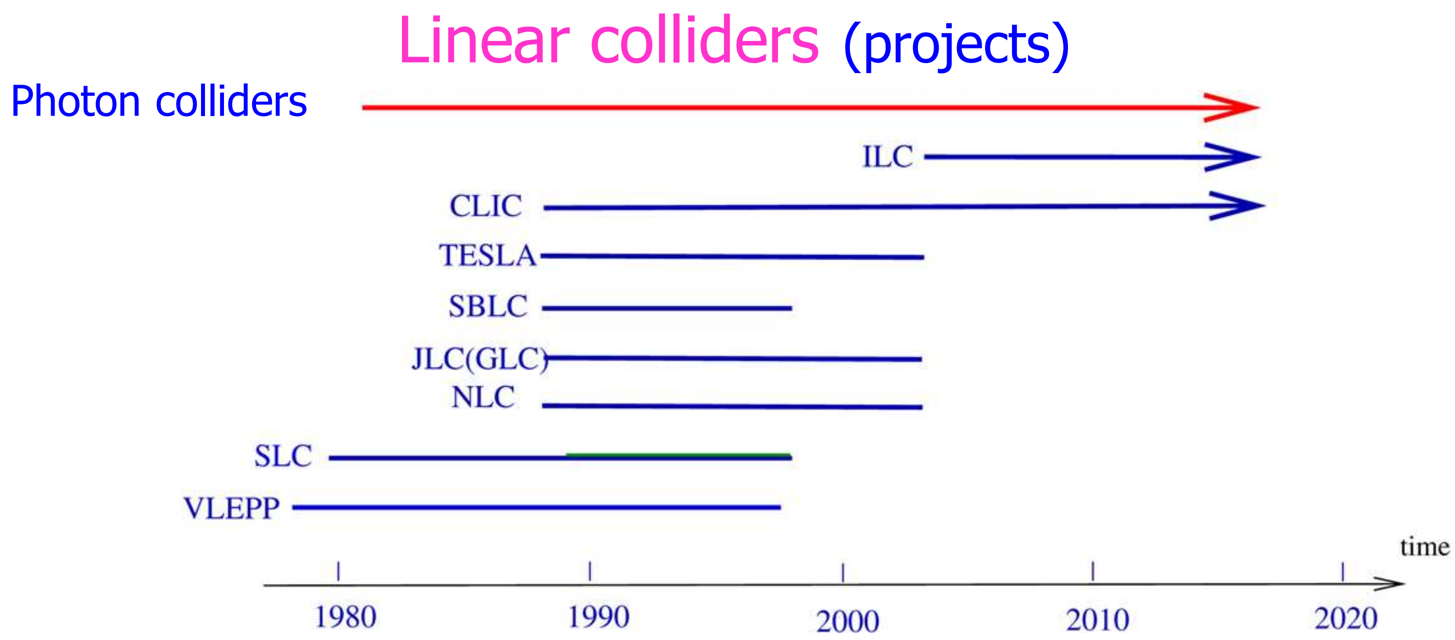


The required flash energy for $k = N_\gamma / N_e \sim 0.65$ is ~5-10 J and ps duration

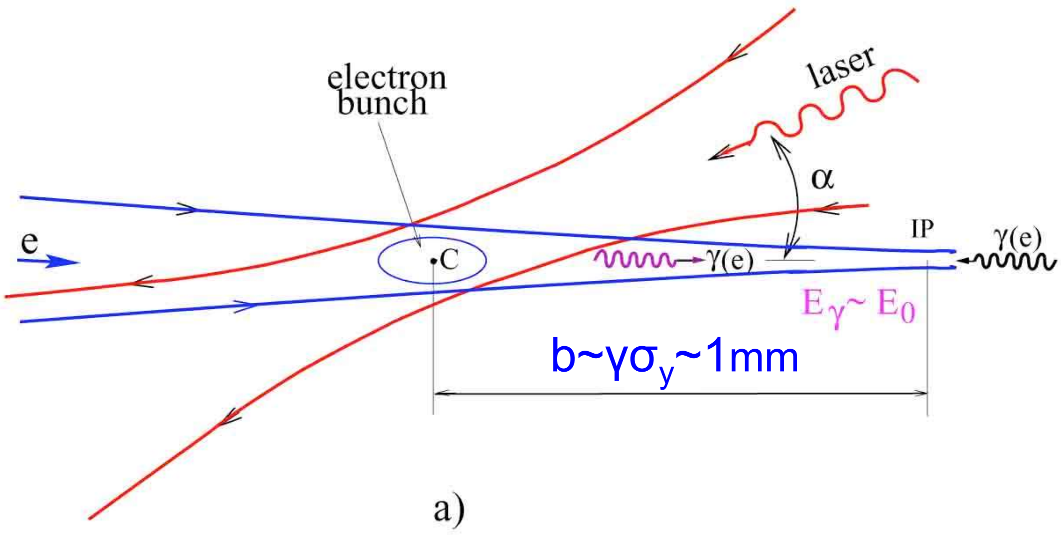
Idea of the photon collider (1981) based on one pass linear colliders

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: $E_\gamma \sim E_e$; $L_{\gamma\gamma} \sim L_{e\text{-}e\text{-}}$



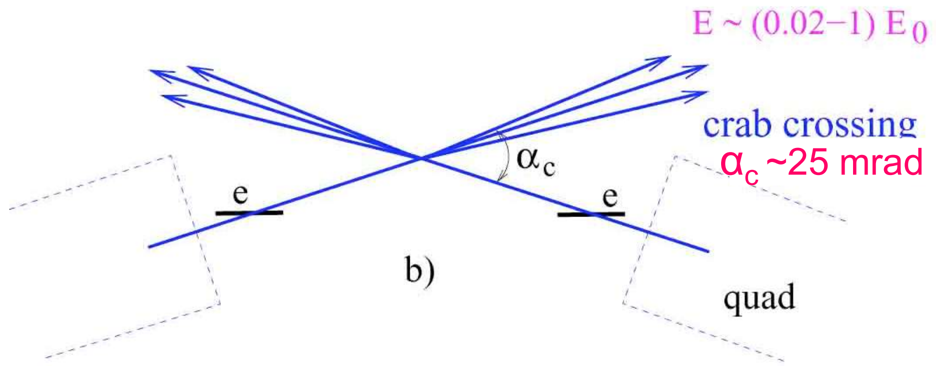
Scheme of $\gamma\gamma$, γe collider



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

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

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



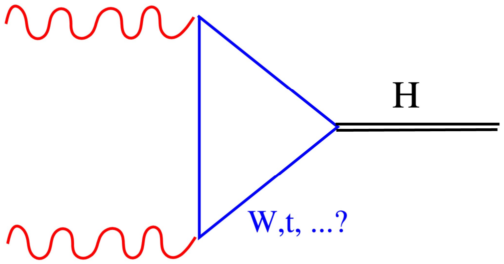
$x = 4.8$ is the threshold for
$\gamma\gamma_L \to e^+e^-$ at conv. reg.

ω_{max}~0.8 E_0

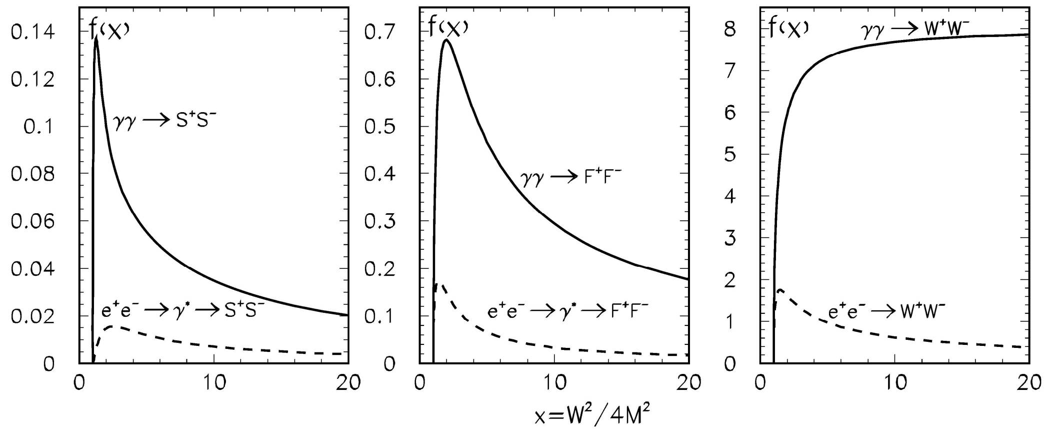
$W_{\gamma\gamma,\ max} \sim 0.8 \cdot 2E_0$
$W_{\gamma e,\ max} \sim 0.9 \cdot 2E_0$

γγ physics at high energy linear colliders

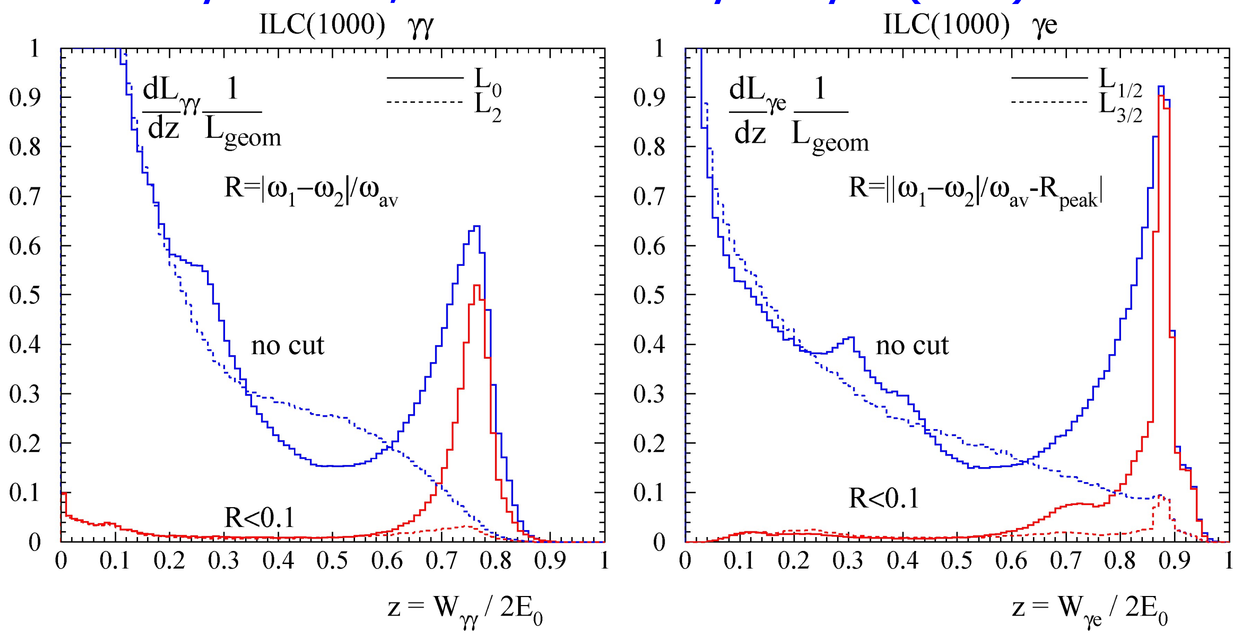
resonance Higgs production



Any charge pairs production



and many others, unfortunately only H(125) is found at LHC and linear colliders.



γγ, γe luminosity spectra at the ILC(1000).
Such collider would be best for study of the (fake) diphoton peak seen at the LHC at 750 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 $W_{\gamma\gamma}$=6-12 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.

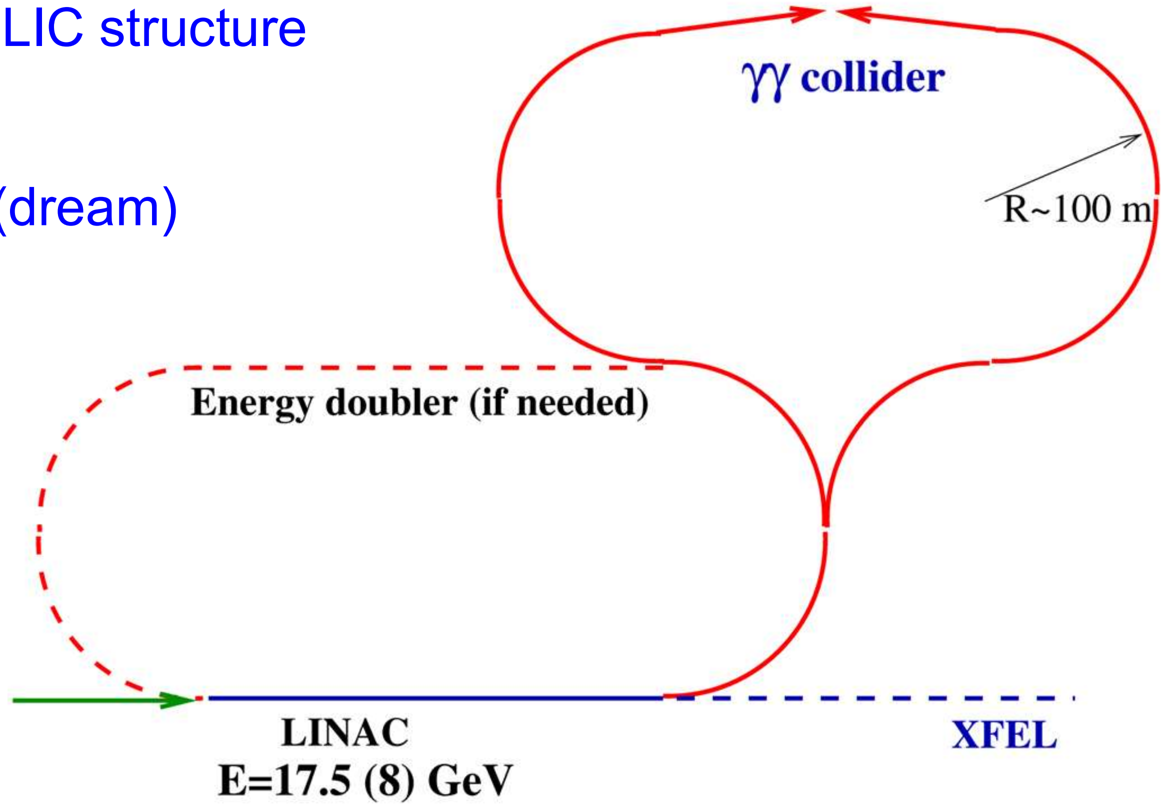
Two real photons will produce resonance states with Q = 0 , C = +,
J^P= 0^+, 0^-, 2^+, 2^-, 3^+, 4^+, 4^-, 5^+ … $(\text{even})^\pm$, $(\text{odd} \neq 1)^+$
as well as numerous 4-quark (or molecule) states similar to those observed in e+e-.

The required electron beam energy E_0~17-23 GeV (for λ=0.5 and 1 μm), 10 time smaller than ILC, so 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)

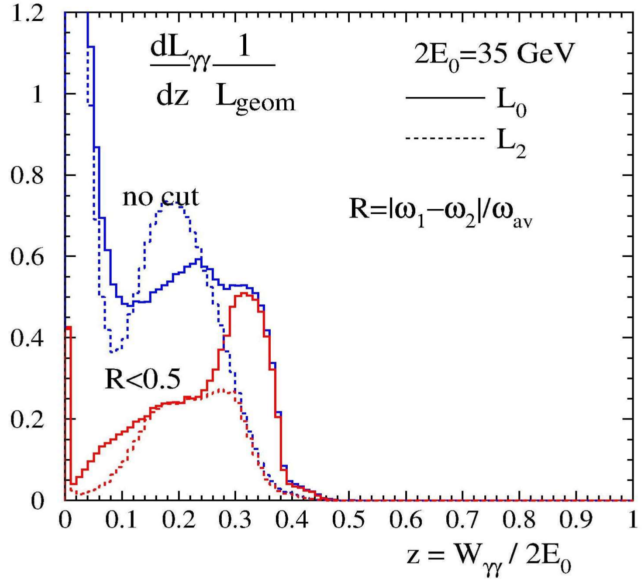


(Linac not in scale)

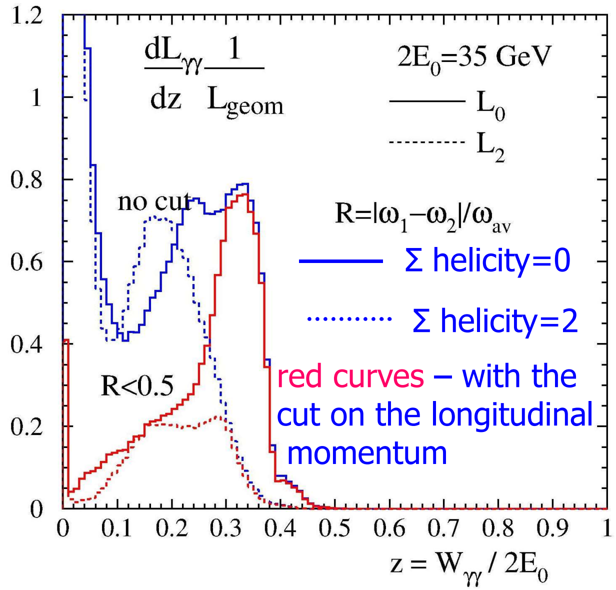
European Superconducting XFEL has started operation in 2017. Its e-beam parameters: E_0=17.5 GeV, N=0.62·10^{10} (1 nQ), σ_z=25 μm, ε_n=1.4 mm mrad, f≈30 kHz

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=$\gamma\sigma_y$=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}=2.3·10^{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: $\gamma\gamma \to \eta_b$.

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 $\Gamma_{\gamma\gamma}(\eta_b) = 0.5\ \mathrm{keV},\ E_0 = 17.5\ \mathrm{GeV},\ \mathrm{M}(\eta_b) = 9.4\ \mathrm{GeV},\ \lambda_{1,2} = 1, L_{ee} = 1.6 \cdot 10^{33} - 2.3 \cdot 10^{34},$

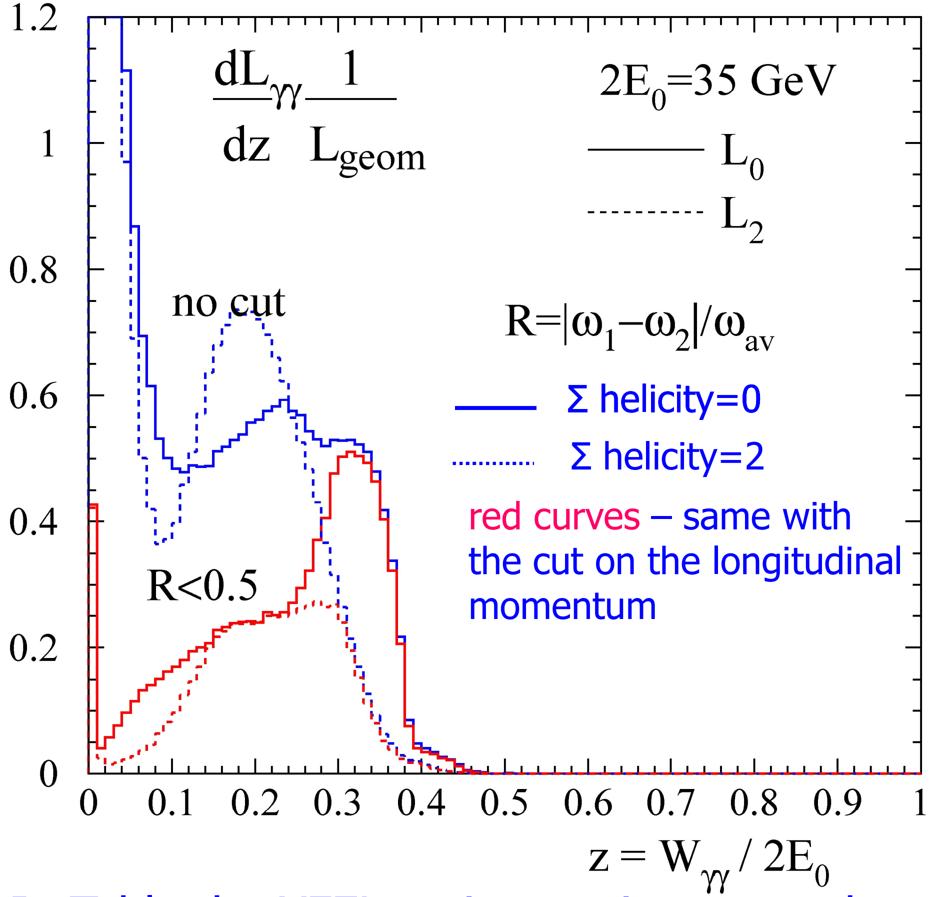
$t = 3 \cdot 10^7\, s$ we get $N(\eta_b) \approx 1.5 \cdot 10^5 - 2 \cdot 10^6$ and can measure its $\Gamma_{\gamma\gamma}$

Production rate is higher than was at LEP-2 (in central region) ~ $700 - 10^4$ 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	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

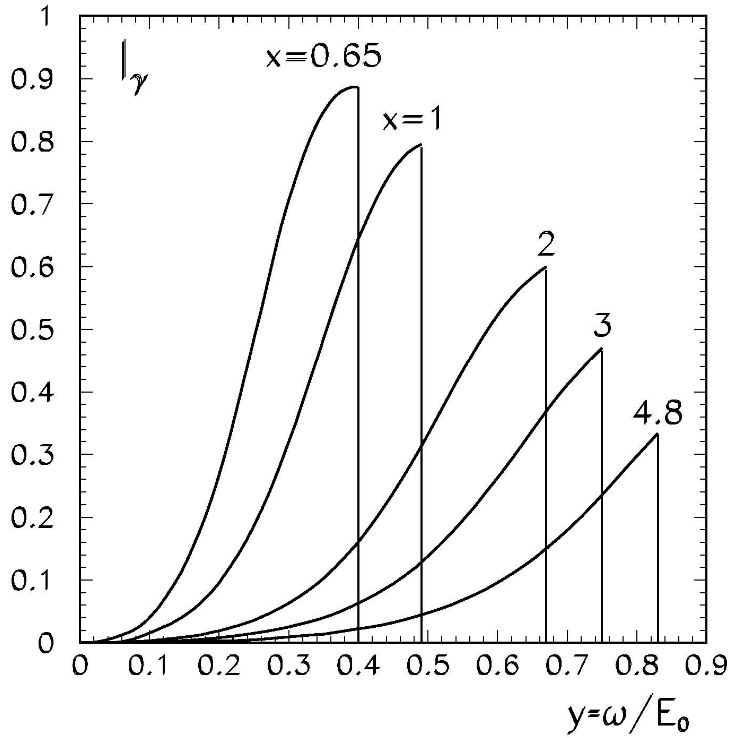


In Table the XFEL emittance is assumed. With promised plasma gun the luminosity can be larger ~15 times.

Linear polarization

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

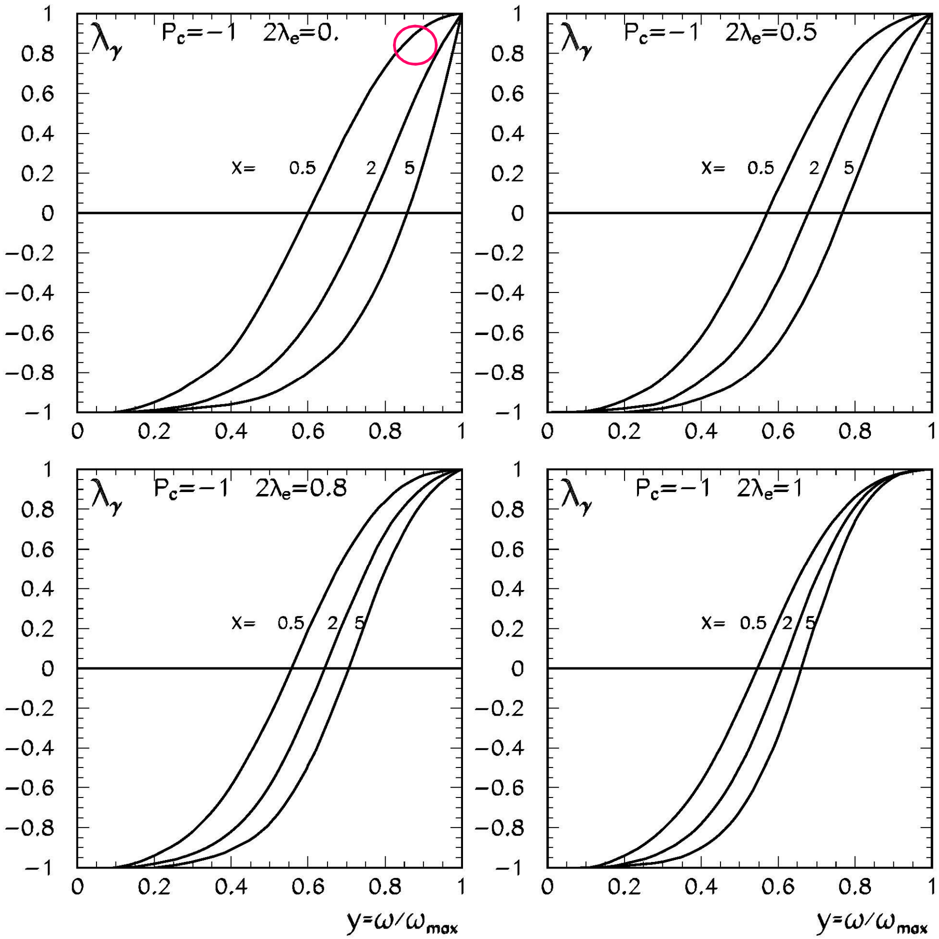
$$\sigma \propto 1 \pm l_{\gamma 1} l_{\gamma 2} \cos 2\varphi \qquad \pm \text{ for CP}=\pm 1$$



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.

Absence of e+e induced backgrounds

At e+e- colliders, after emission of ISR e+e- can produce C=- resonances which looks similar to $\gamma\gamma$ resonances.

At e-e- based $\gamma\gamma$-collider there are no such backgrounds

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

  a) for SC XFEL linac Δct~100 m, 3000 bunch/train, 5 Hz

  b) for CLIC linac Δct~15 cm, 350 bunch/train, 50 Hz

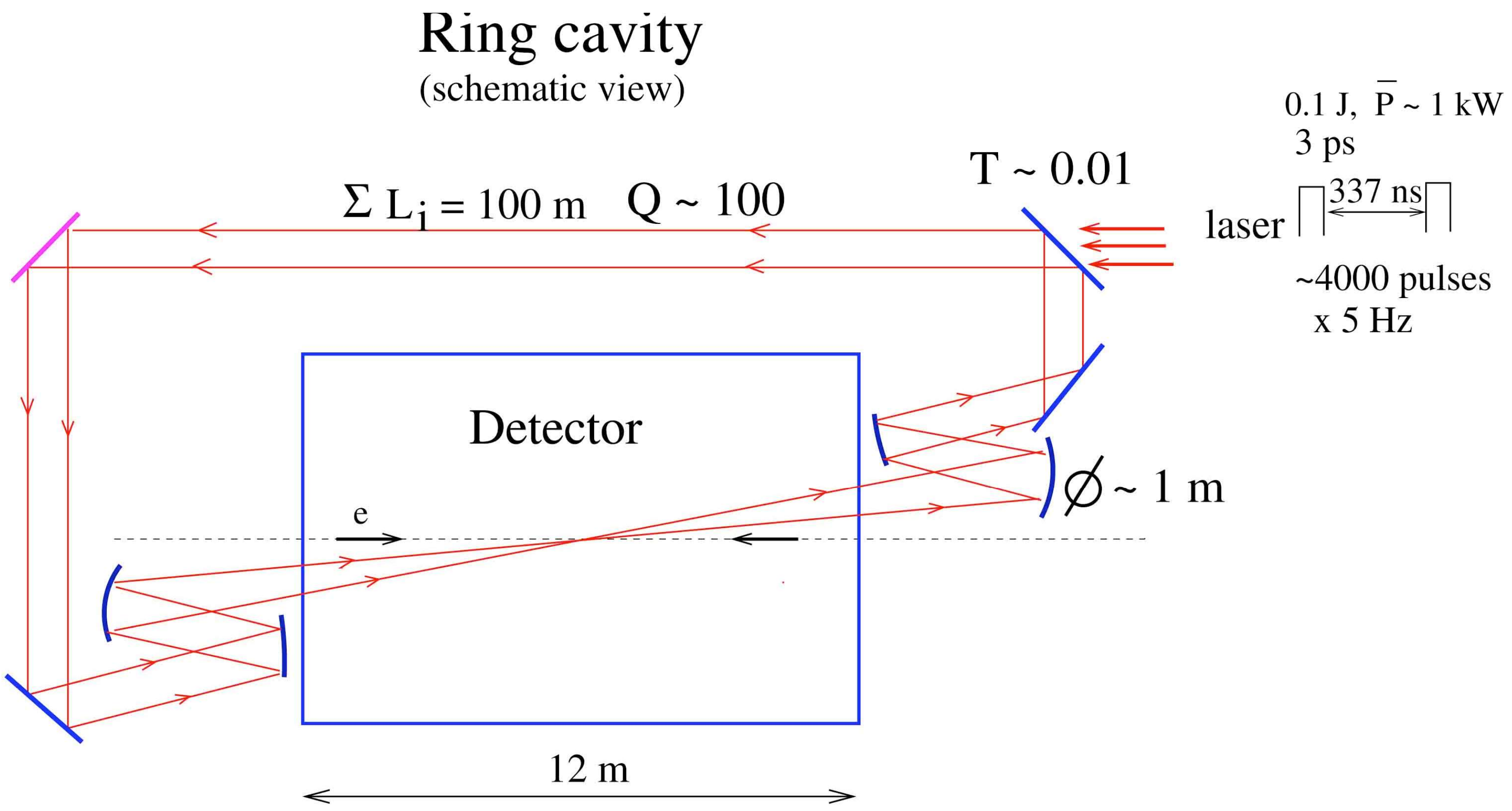
  c) plasma linac equidistantly 30 kHz

For the case a) a ring external optical cavity can be used which can reduce the laser power by a factor of 100-300.

For the case b) a linear cavity can be used which can reduce the laser power by a factor of 10 (or less).

The case c) needs the largest average power, but the minimum peak diode power.

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 low energy collider the Compton cross section is larger by a factor of 3, so flash energy is smaller correspondingly (A~3 J).

$c\bar{c}$

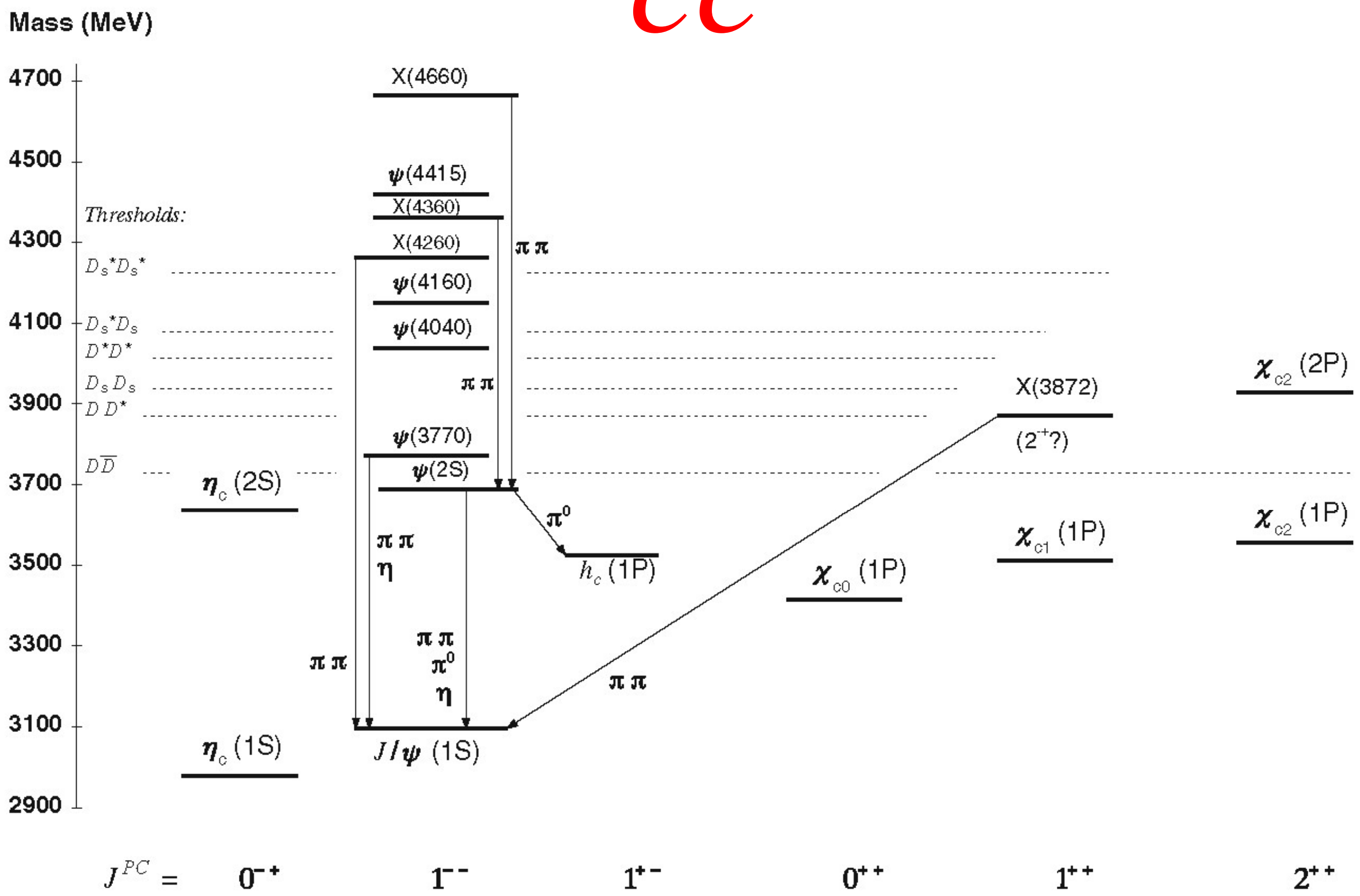


Fig. 2.1 The experimentally observed charmonium states. The states labelled X, the nature of which is unknown, are not thought to be conventional charmonium states. Figure from Ref. [1]

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

$b\bar{b}$

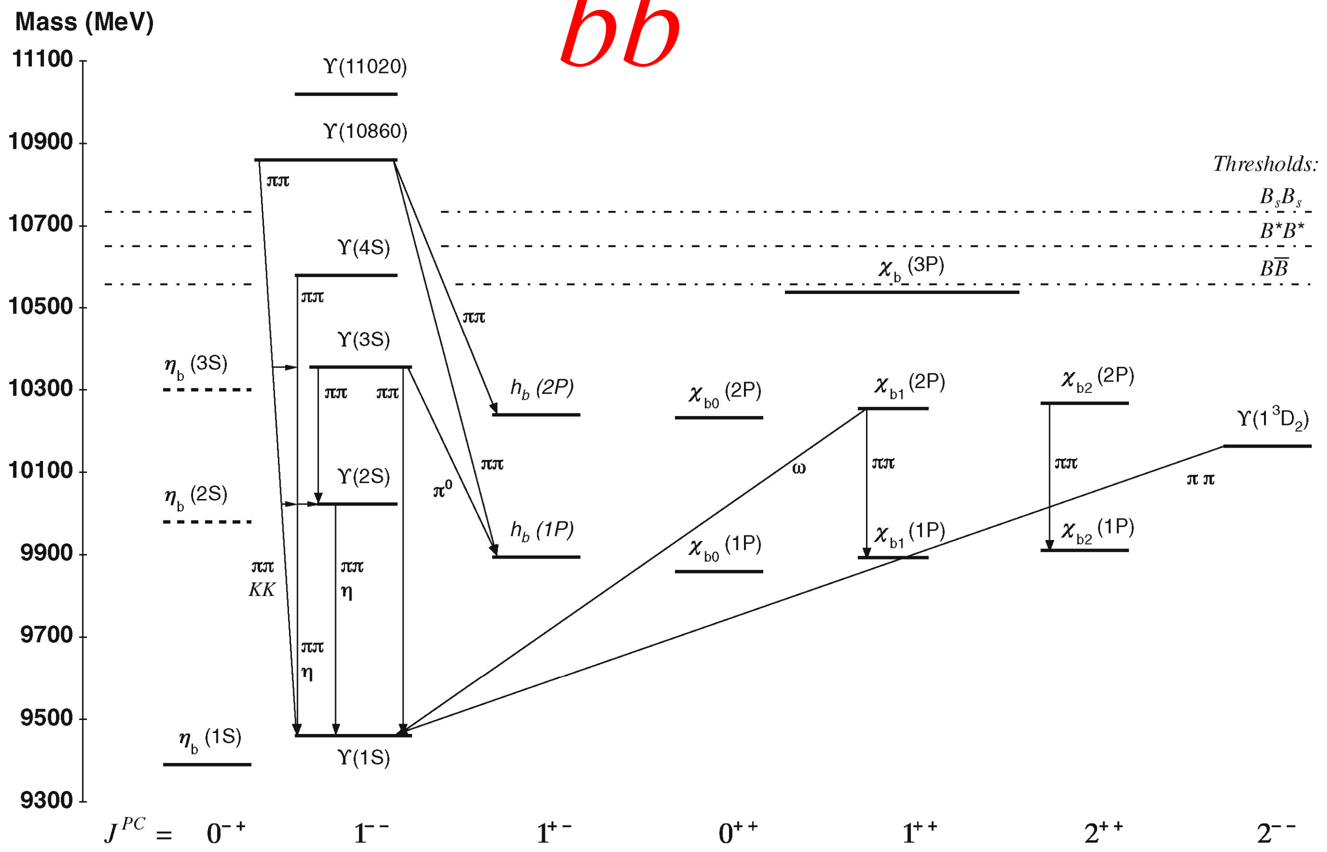


Fig. 2.2 The experimentally observed and theoretically expected bottomonium states. *Dashed lines* denote unobserved or unconfirmed states (an unconfirmed experimental candidate for the $\eta_b(2S)$ state has been observed by the Belle experiment [6]). Figure from Ref. [1]

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

At e+e- colliders C+ states above DD and BB thresholds are not observed yet because they are detected in radiative decays of Ψ and Υ excited states, which become broad above the threshold (and radiative branching becomes very small).

In $\gamma\gamma$-colliisons these resonances will be produced directly. Production rate in $\gamma\gamma$-collisions is proportional to $\Gamma_{\gamma\gamma}$ and does not depend on their total widths.

Comparison of the $\gamma\gamma$ factory and LHC for study $\gamma\gamma$-physics in bb region

At $\gamma\gamma$ factory $$\frac{dL_{\gamma\gamma}}{dW} \approx \frac{0.015 L_{ee}}{\text{GeV}}$$

At LHC $$\frac{dL_{\gamma\gamma}}{dW} \approx \frac{0.0025\,\Delta\eta}{W} L_{pp} \approx \frac{0.0002\Delta\eta}{\text{GeV}} L_{pp} \sim 3\cdot 10^{-4} L_{pp} \quad \text{for } \Delta\eta = 1.5$$

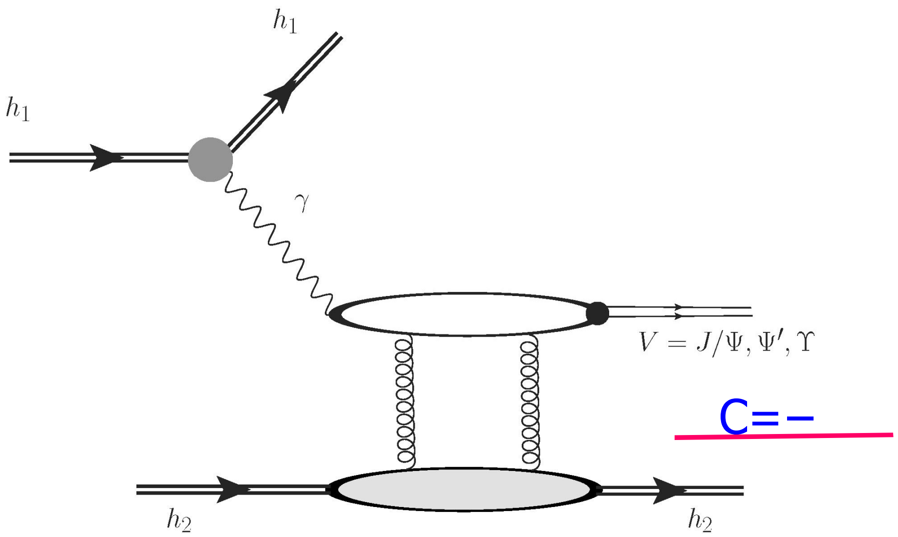
$$\frac{(dL/dW)_{\gamma\gamma-factory}}{(dL/dW)_{LHC}} \sim 50 \frac{L_{ee}}{L_{pp}}$$

Important:
in pp (or heavy ion-ion) collisions there is a huge background from diffractive processes (pomeron-pomeron, photon-pomeron) interactions that makes the study of $\gamma\gamma$ processes very problematic.

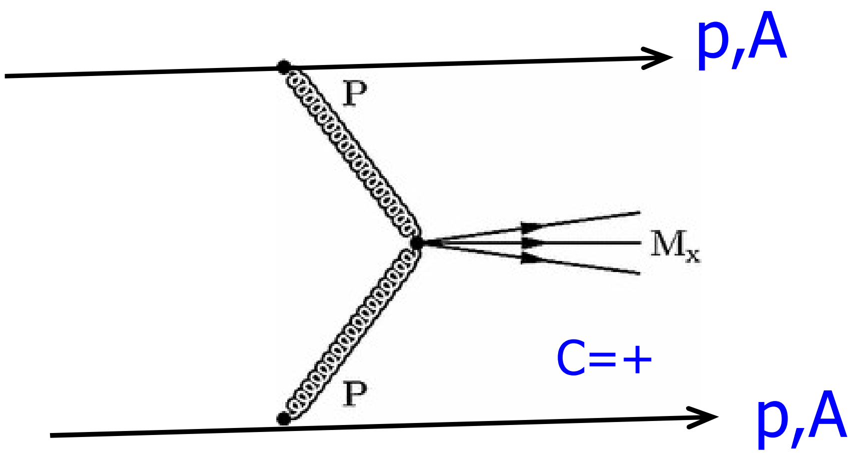
For example, at LHC in photon-pomeron(P) collision C=– resonances are produced which are forbidden in γγ-collisions

P – Pomeron - multigluon state

γP



PP



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

So, LHC can't compete in study of γγ-processes with a clean γγ-collider

Conclusion

- Photon colliders have sense as a very cost effective addition for e+e- linear colliders. 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 ~40 year.
- It has sense to construct a smaller photon 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 outstanding 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. The same electron linacs can be used simultaneously for XFELs.
- European XFEL is a primary candidate for such photon collider