

BASICS OF A PHOTON COLLIDER

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Based on papers:

V. Budnev, I. Ginzburg, G. Meledin and V. Serbo “The Two-Photon Particle Production Mechanism”, Physics Reports 15C (1975) 181;

I. Ginzburg, G. Kotkin, V. Serbo and V. Telnov “Photon Colliders”, review for Physics Reports (under preparation)

“The Photon Collider at TESLA”, IJMP A 19 (2004) 5097

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1. Introduction

1.1. The subject

This small review

is devoted to $\gamma\gamma$ collisions

including methods of creating the colliding $\gamma\gamma$ beams of high energy and physical problems which can be solved or clarified in such collisions.

It is a new and promising area in high energy physics connected with the fundamental problems of

strong and electro-weak interactions.

Our knowledge about elementary particles and their interactions is mainly obtained **from particle collisions**.

Most of fundamental results in particle physics has been obtained from experiments at the pp , $p\bar{p}$, e^+e^- and ep colliders.

Principal characteristics of colliders are:

the energy in the center-of-mass system (c.m.s) E_{cm} ;

luminosity of a collider L which determines collision rate \dot{N} of events with the cross section σ by relation:

$$\dot{N} = L \sigma ;$$

types of colliding particles.

The progress on high-energy colliders can be seen from the Table:

Collider	Type	E_{cm} , TeV	Start date
$Spp\bar{S}$	$p\bar{p}$	0.6	1981
TEVATRON	$p\bar{p}$	2	1987
LHC	pp	14	2007
HERA	ep	0.31	1992
SLC	e^+e^-	0.1	1989
LEP-I	e^+e^-	0.1	1989
LEP-II	e^+e^-	0.2	1999
Linear collider	e^+e^-	0.5	201?
Photon collider	$\gamma\gamma, \gamma e$	0.4	201?+?
Muon collider	$\mu^+\mu^-$	0.1 ÷ 3	??

Up to now and in the nearest future, **the pp and $p\bar{p}$ colliders are the machines with the highest energy**. That is why such epochal discoveries as W and Z bosons (responsible for weak interaction) and t quark had been performed at the $Spp\bar{S}$ and the TEVATRON, respectively.

For detail study of new phenomena, **it is important not only the energy but also types of colliding particles.**

The e^+e^- colliders, being **less energetic** than pp colliders, have **some advantages** over proton colliders due to **much lower background and simpler initial state.** Well known example — the study of Z boson.

About thirty years ago a new field of particle physics has appeared —

photon-photon interactions

Since that time the two-photon physics is actively investigated in a number of accelerators.

A. Sessler “Gamma-Ray Colliders and Muon Colliders”

Physics Today (March 1998, p. 48)

“In high-energy physics, almost all of the present accelerators are colliding-beam machines.

In recent decades these colliders have produced epochal discoveries: Stanford SPEAR electron-positron collider unveiled **the charmed-quark meson and τ lepton in 1970s. In the realm of high-energy proton-antiproton colliders, the Super Proton Synchrotron at CERN gave us **the W^\pm and Z^0 vector bosons** of electroweak unification in 1990s, and in 1999s the Tevatron at Fermilab finally unearthed **the top quark**, which is almost 200 times heavier than the proton.”**

“...What about other particles? Beam physicists are now actively studying schemes **for colliding photons with one another** and schemes for colliding a beam of short-lived μ^+ leptons with a beam of their μ^- antiparticles.

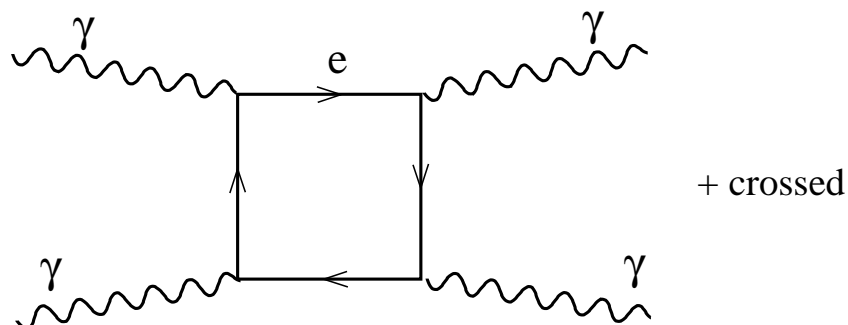
If such schemes can be realized, they **will provide extraordinary new opportunities** for the investigation of high-energy phenomena.

These exotic collider ideas first put forward in Russia more than 20 years ago...”

1.2. Interaction of photons in the Maxwell theory and QED

In the classical Maxwell theory of electromagnetism, **photons do not interact with each other.**

In quantum electrodynamics (QED) photons **can interact via virtual e^+e^- pairs.** For example, an elastic $\gamma\gamma$ scattering is described by Feynman diagrams of the following Fig.



At **low energies**, $\omega \ll m_e c^2$ where ω is the photon c.m.s. energy, this cross section is very small

$$\sigma_{\gamma\gamma \rightarrow \gamma\gamma} = 0.031 \alpha^2 r_e^2 \left(\frac{\omega}{m_e c^2} \right)^6 .$$

The maximal value of the cross section is achieved at the c.m.s. photon energy $\omega \sim m_e c^2$ and is large enough:

$$\max \sigma_{\gamma\gamma \rightarrow \gamma\gamma} \sim \alpha^4 \left(\frac{\hbar}{m_e c} \right)^2 = \alpha^2 r_e^2 \sim 4 \cdot 10^{-30} \text{ cm}^2.$$

At high energies, $\omega \gg m_e c^2$, this cross section decreases

$$\sigma_{\gamma\gamma \rightarrow \gamma\gamma} \sim 4.7 \alpha^2 r_e^2 \left(\frac{m_e c^2}{\omega} \right)^2.$$

For example, **for visible light**, $\omega \sim 1 \text{ eV}$,

$$\sigma_{\gamma\gamma \rightarrow \gamma\gamma} \sim 10^{-65} \text{ cm}^2.$$

It is too small to be measured even with the most powerful modern lasers, though there were **such attempts** [D. Bernard, 2000].

Search for low (eV) energy photon-photon scattering in vacuum

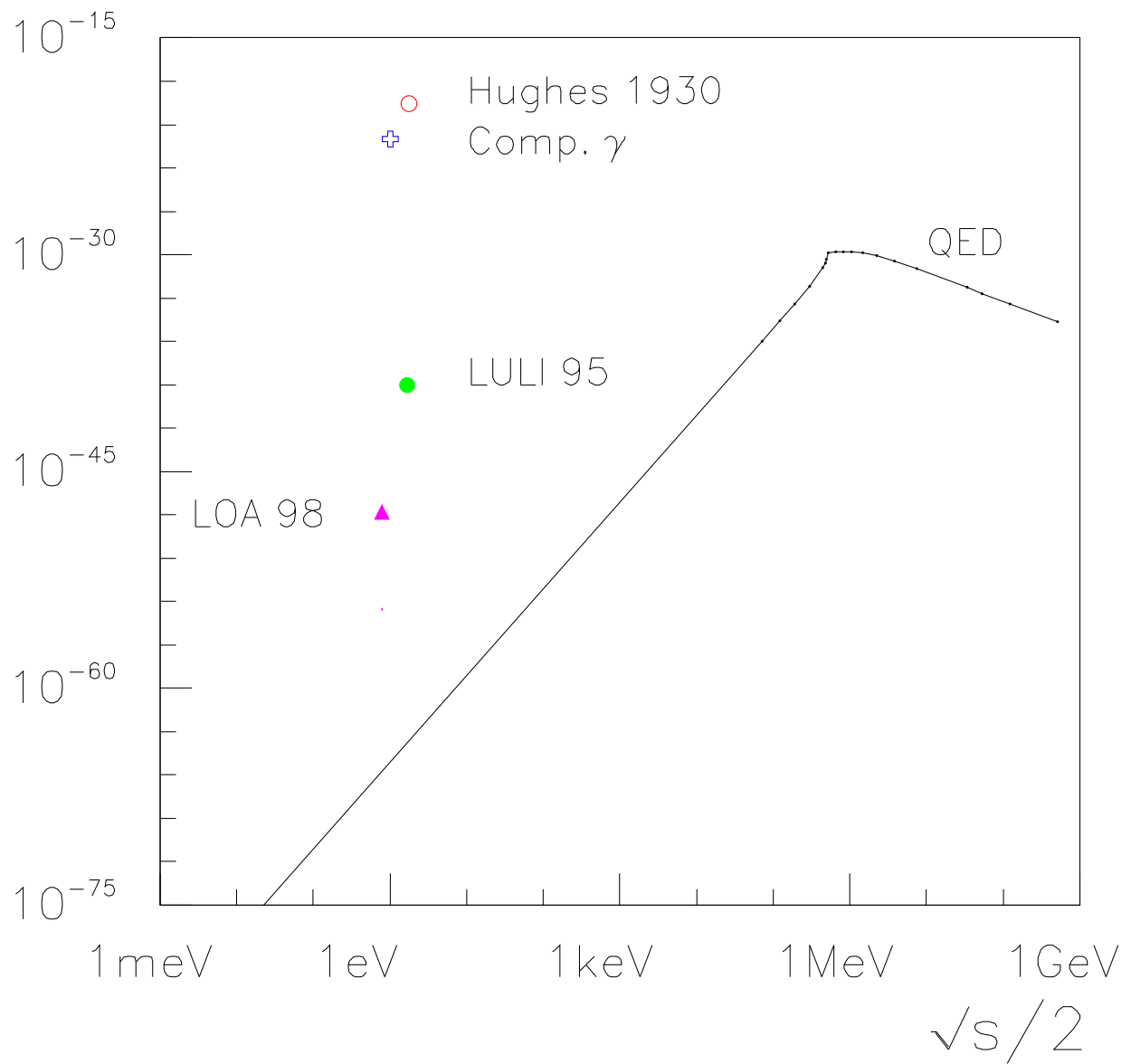
$$\gamma_1 \gamma_2 \rightarrow \gamma_3 \gamma_4$$

- Explore possible low energy photon interactions (eg : composite photons theory)
- Ultimate BG : photon scattering in QED
- 2 beam experiment (LULI, 1995)
- 3 beam experiment (LOA, 1998)
- Prospects



Denis Bernard
Photon'99
Freiburg im Breisgau
Germany
27 may 1999

$\sigma(\text{cm}^2)$



1.2 Photon splitting.



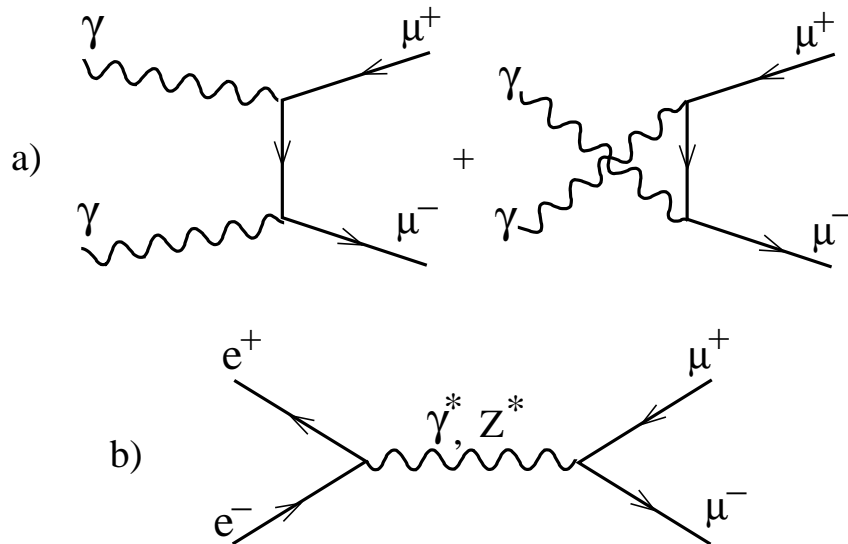
$$\sigma = \frac{Z\alpha^2}{\pi} \ln(183z^{-1/3}) \cdot 10^{-29} \text{ cm}^2$$

Baier et al., 1974.

$$\sigma \simeq 0.6 \cdot 10^{-27} \text{ cm}^2 \quad \text{at } Z = 83 \text{ (Bi)}.$$

- Coulomb corrections are not very important ($\sim 20\%$ only).
- Details of theoretical calculations can be found in :
R. N. Lee, A. I. Milstein, and V. M. Strakhovenko,
Phys. Rev. A57 (1998) 2325.
- Photon splitting was observed at the first time at
VEPP-4M (*Sh. Zh. Akhmadaliev et al., 1998*).

At energies $\omega > mc^2$, two photons can produce a **pair of charged particles**. The cross section of the characteristic process $\gamma\gamma \rightarrow \mu^+\mu^-$ (Fig. a)



is equal to (at $s = (2\omega)^2 \gg 4m_\mu^2c^4$)

$$\sigma_{\gamma\gamma \rightarrow \mu^+\mu^-} = 4\pi r_e^2 \frac{m_e^2 c^4}{s} \ln \frac{s}{m_\mu^2 c^4}.$$

It is **larger** than the “standard” cross section for the production of the same pair in the e^+e^- collisions via a virtual photon only (Fig. b)

$$\sigma_{e^+e^- \rightarrow \mu^+\mu^-} = \frac{4\pi r_e^2}{3} \frac{m_e^2 c^4}{s}.$$

Brown et al.

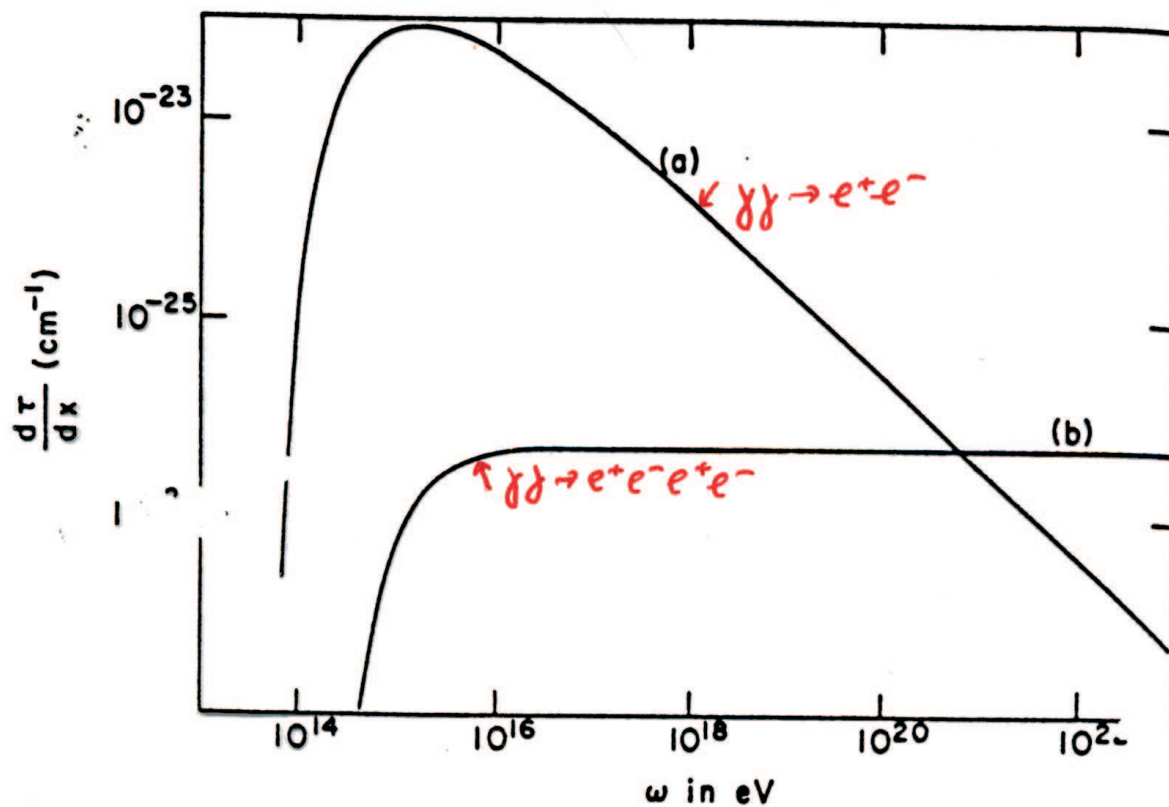


FIG. 10. Absorption probability per unit length as a function of γ -ray energy ω . The curves (a) and (b) correspond to absorption through single and double electron pair creation, respectively. The black-body temperature is 3 °K.

2. Collisions of equivalent photons at e^+e^- storage rings

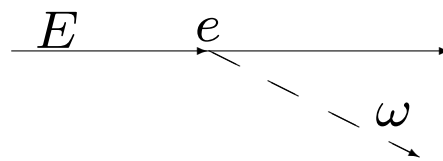
Unfortunately, there are no sources of intense high-energy photon beams (like lasers at low energies). However, there is indirect way to get such beams — to use **equivalent photons** which accompanied fast charged particles.

Namely this methods was used during last three decades for investigation of two-photon physics at e^+e^- storage rings.

The essence of the equivalent photon approach can be explained in the following way:

Fermi (1924); Weizsäcker and Williams (1934)

The electromagnetic field of an ultra-relativistic electron is similar to the field of a light wave. Therefore, **this field can be described as a flux of the equivalent photons** with energy distribution $dn_\gamma/d\omega$. The number of these photons per one electron with the energy E is determined by diagram of virtual bremsstrahlung



and it is equal to

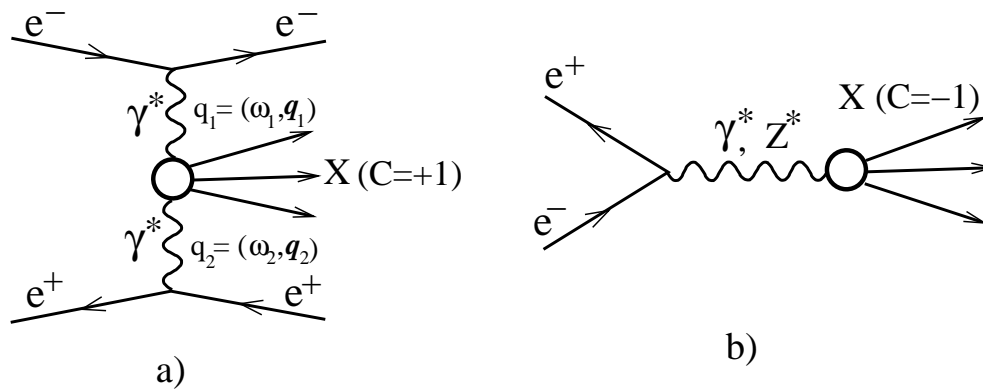
$$dn_\gamma \sim \frac{2\alpha}{\pi} \ln \frac{E}{\omega} \frac{d\omega}{\omega}$$

or approximately

$$dn_\gamma \sim 0.03 \frac{d\omega}{\omega}.$$

At the e^+e^- colliders the equivalent photons also collide and can produce some system of particles X (see Fig. a, where γ^* denotes the equivalent photon)

$$e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-X.$$



Thus, this process is directly connected with the subprocess $\gamma^* \gamma^* \rightarrow X$.

Strictly speaking, **the equivalent photons are not real photons, they are virtual ones.** The 4-momentum squared of such a photon q_i^2 (which is equal to $m^2 c^2$ for usual particle) **is not equal zero, $q_i^2 \neq 0$, but it is very small.** For large part of the cross section $|q_i^2| \ll m_e^2 c^2$, therefore, **the most of equivalent photons are almost real.**

The cross section for two-photon production of $e^+ e^-$ in collisions of two fast particles with charges $Z_1 e$ and $Z_2 e$, i.e. for the $Z_1 Z_2 \rightarrow Z_1 Z_2 e^+ e^-$ process, was calculated by **Landau and Lifshitz in 1934.**

At first sight, the cross sections of the two-photon processes at e^+e^- colliders (Fig. a) are **very small** since they are the 4-order processes:

$$\sigma_{\text{two-photon}} \propto \alpha^4,$$

while for the annihilation processes of (Fig. b) the cross sections

$$\sigma_{\text{annih}} \propto \alpha^2.$$

However, **the annihilation cross sections decrease with increase of the energy**

$$\sigma_{\text{annih}} \sim \alpha^2 \frac{\hbar^2 c^4}{s}, \quad s = (2E)^2,$$

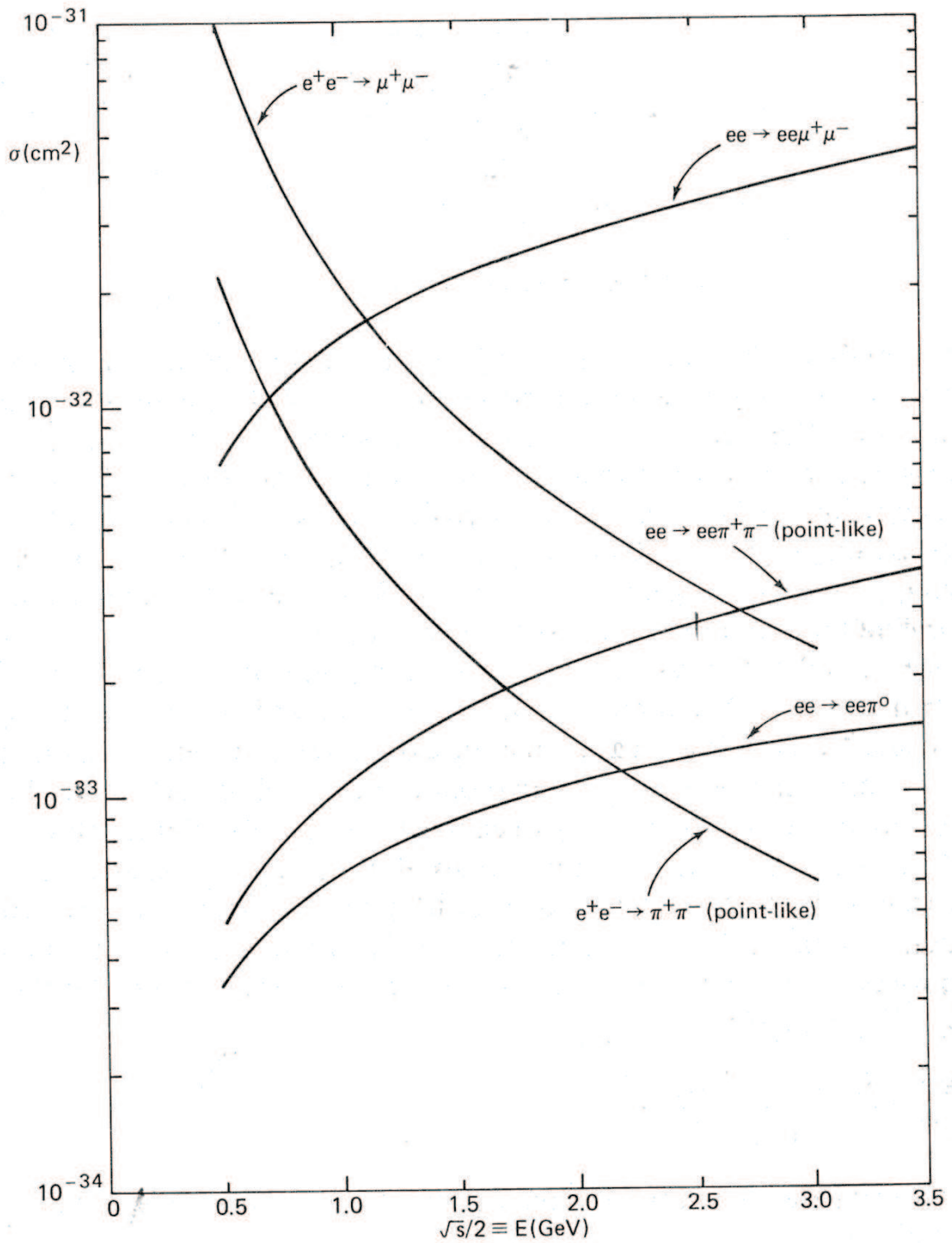
while the two-photon cross sections **increase**

$$\sigma_{\text{two-photon}} \sim \alpha^4 \frac{\hbar^2}{m_{\text{char}}^2 c^2} \ln^n s.$$

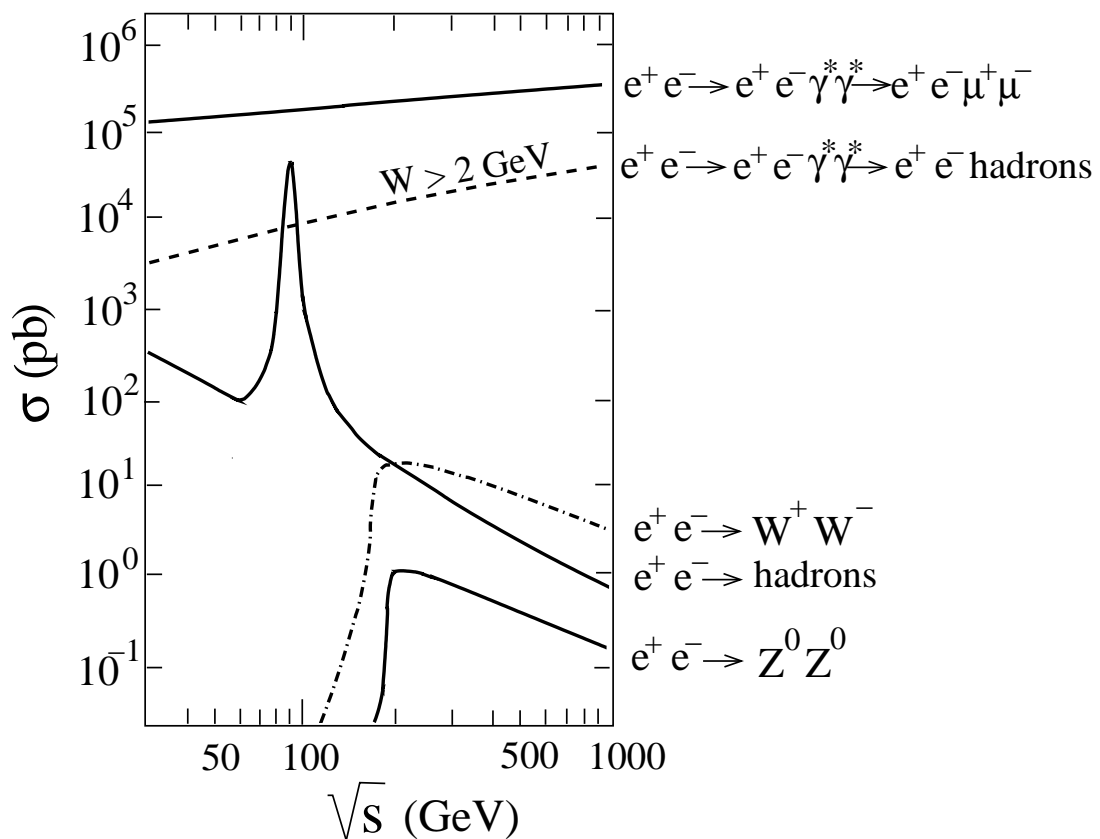
Here $n = 3 \div 4$ depending on the process, and the characteristic mass m_{char} is constant (for example, $m_{\text{char}} \sim m_\mu$ for $X = \mu^+\mu^-$ and $m_{\text{char}} \sim m_\pi$ for $X = \text{hadrons}$).

As a result, already at $\sqrt{s} > 2 \text{ GeV}$

$$\sigma_{e^+e^- \rightarrow e^+e^- \mu^+\mu^-} > \sigma_{e^+e^- \rightarrow \mu^+\mu^-}.$$



Another example, at **the LEP-II** electron-positron collider with the energy $\sqrt{s} = 200$ GeV, the number of events for two-photon production of hadrons with the invariant mass $W_{\gamma\gamma} > 2$ GeV was by **a three order of magnitude larger** than that in the annihilation channel:



At e^+e^- storage rings the two-photon processes

$$e^+e^- \rightarrow e^+e^-e^+e^-$$

had been observed for the first time in 1970 (Novosibirsk).

The importance of two-photon processes for the lepton and hadron production at e^+e^- storage rings had been emphasized in the papers:

Arteage-Romero, Jaccarini, Kessler and Parisi (1969, Paris);

Balakin, Budnev and Ginzburg (1970, Novosibirsk);

Brodsky, Kinoshita and Terazawa (1970, SLAC).

In the papers Balakin, Budnev and Ginzbur it was shown that e^+e^- colliding beam experiments can give information about a new fundamental process $\gamma^*\gamma^* \rightarrow hadrons$ and the necessary formulae and estimations were obtained.

At that time there were a lot of theoretical investigations of various aspects of two-photon physics, but only a few experimental results [Novosibirsk, Frascati] have been obtained related mainly to the processes $\gamma\gamma \rightarrow e^+e^-$, $\gamma\gamma \rightarrow \mu^+\mu^-$ and $\gamma\gamma \rightarrow \mu^+\mu^-$.

This period of two-photon physics was summarized in review by

Budnev, Ginzburg, Meledin and Serbo [Phys. Rep. 1975].

A few years later (approximately from 1977) it was shown in a number of theoretical papers that the two-photon processes are **very convenient for the test and detailed study of the Quantum Chromodynamics (QCD)** including investigation of:

- a photon structure function (**Witten , Zerwas**);
- a jet production in the $\gamma\gamma$ collisions (**Llewellyn Smith; Brodsky, De Grand, Gunion and Weis; Baier, Kuraev and Fadin**);
- the $\gamma\gamma \rightarrow c\bar{c}c\bar{c}$ process and the problem of the perturbative Pomeron (**Balitsky and Lipatov**).

A new wave of experimental activity in this field was initiated by the experiment at **SLAC (1979)** which demonstrated that two-photon processes can be successfully studied **without detection of the scattered electrons and positrons**.

After that there was **a flow of experimental data from almost all detectors** at the e^+e^- storage rings.

This period was reviewed by **Kolanoski, 1984**.

3. Results obtained in virtual $\gamma^*\gamma^*$ collisions

In experiments at e^+e^- storage rings a lot of interesting results about $\gamma^*\gamma^*$ collisions have been obtained (see collections of data in reviews Morgan, Pennington and Whalley (1994) and Proceedings of Workshops on Photon-Photon Collisions), among them:

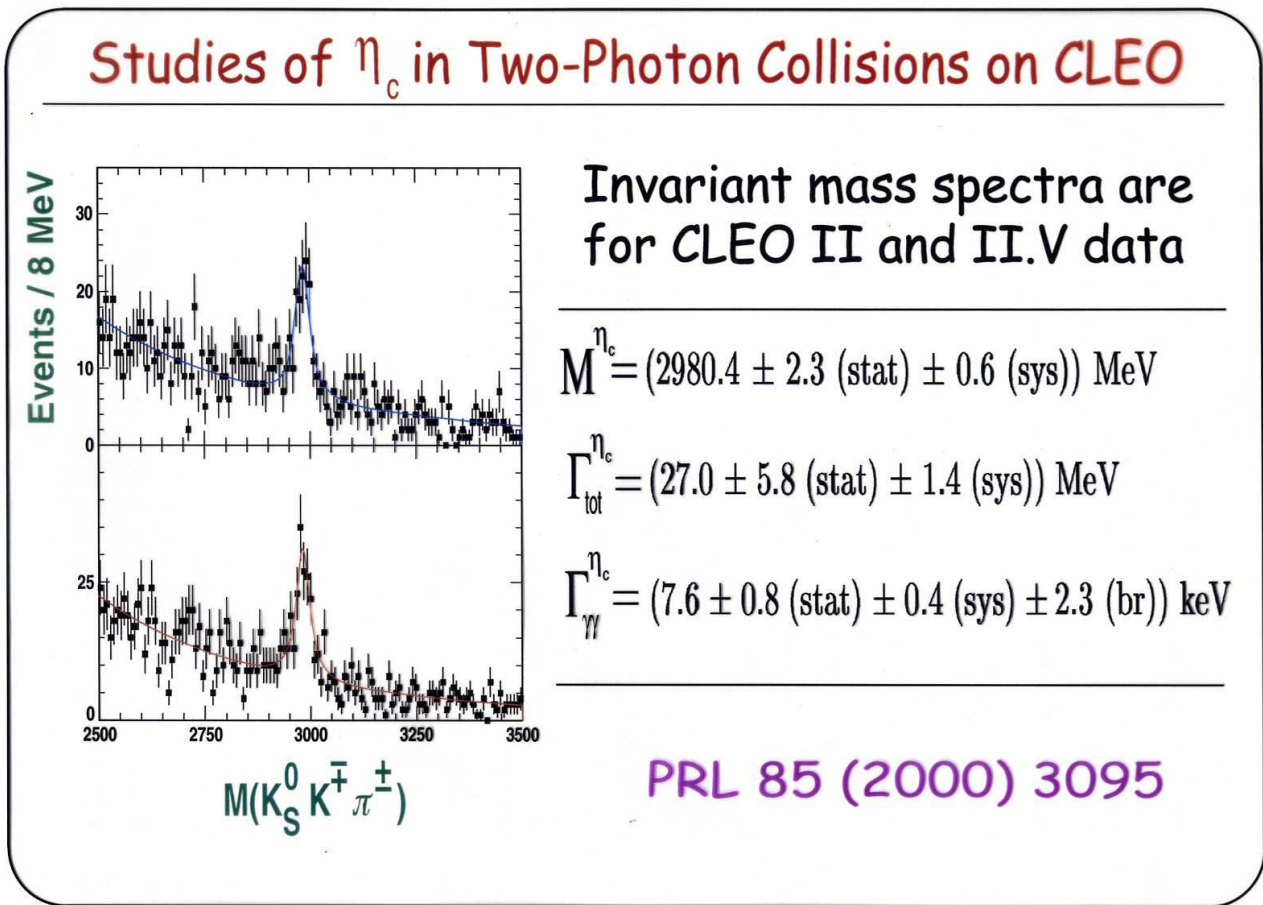
- production of **C -even resonances** in $\gamma^*\gamma^*$ collisions, such as π^0 , η , η' , f_2 , a_2 , η_c , χ_c , ... and measurement of their $\gamma\gamma$ width;
- measurement of **the total $\gamma\gamma \rightarrow hadrons$ cross section** up to c.m.s. energy $W_{\gamma\gamma}$ about 150 GeV;
- measurement of **the total $\gamma^*\gamma^* \rightarrow hadrons$ cross section** with large values of $W_{\gamma\gamma}^2$ and photon virtualities $-q_1^2 \sim -q_2^2 \sim 10 \text{ (GeV/c)}^2$;

- a number of **exclusive reactions**:

$$\gamma^* \gamma^* \rightarrow \pi\pi, K\bar{K}, p\bar{p}, \rho\rho, \rho\omega, \text{ etc.};$$

- investigation of **the photon structure function** in the collision of almost real photon and highly virtual photon with $-q^2$ up to 600 (GeV/c)^2 ;
- **jet production** in $\gamma\gamma$ collisions.

Example: $\gamma\gamma \rightarrow \eta_c$ production - Fig.



Unfortunately, the number of equivalent photons per one electron is rather small, and correspondingly the $\gamma^*\gamma^*$ luminosity is about 3 ÷ 4 orders of magnitude smaller than that in e^+e^- collisions. Therefore, it is not surprising that the most important results at e^+e^- storage rings were obtained in the e^+e^- annihilation.

4. Linear $e^{\pm}e^{-}$ collider

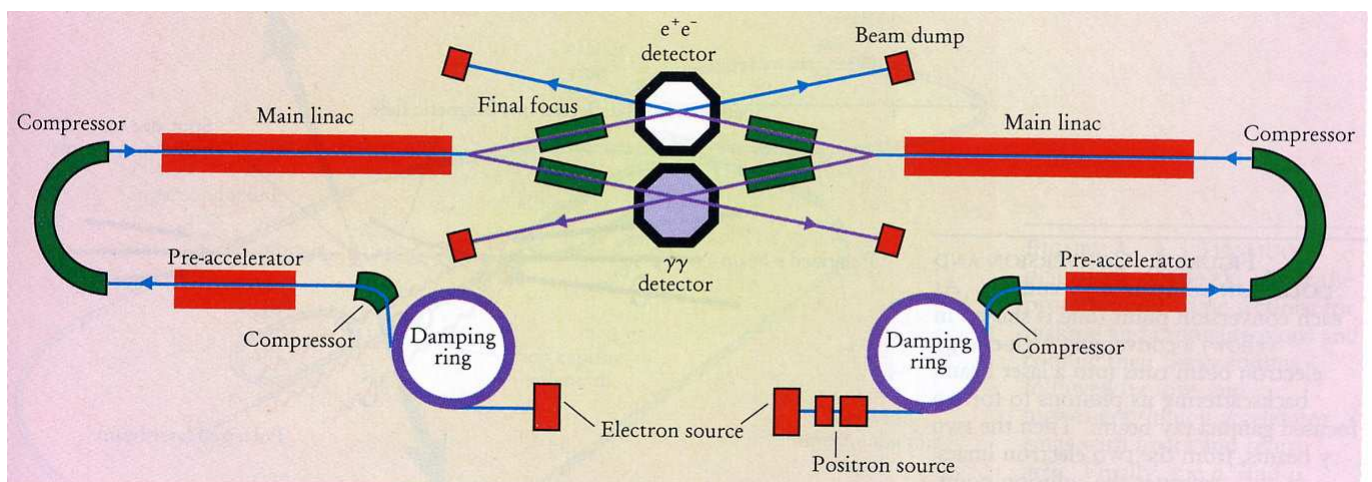
New opportunities for two-photon physics are connected with **future linear $e^{\pm}e^{-}$ colliders**. Projects of such accelerators are now under development in several laboratories.

Since 1988 this field is developed in a very tight international collaboration of physicists from many countries. In 1996-97 three projects NLC (North America), JLC (Asia), TESLA (Europe) have published their **Conceptual Design Reports** of the linear colliders in the energy range about 500 GeV; in 2001 the TESLA **Technical Design Report** has been published.

One team at CERN is working now on the conception of multi-TeV Compact Linear Collider (CLIC).

A linear collider consists of several main systems (see Fig.):

**electron injectors,
pre-accelerators,
a positron source,
two damping rings,
bunch compressors,
main linacs,
interaction regions,
a beam dump.**



Current parameters of these projects are presented in Table. Parameters of the projects NLC and JLC are presented in one column since their teams developed a common set of parameters.

		NLC	TESLA
C.m.s. energy $2E_0$	[TeV]	0.5	0.5
Luminosity L	$[10^{34}/(\text{cm}^2\text{s})]$	2.2	3
Repetition rate f_r	[Hz]	120	5
No. bunch/train n_b		190	2820
No. particles/bunch N_e	$[10^{10}]$	0.75	2
Collision rate ν	[kHz]	22.8	14.1
Bunch spacing Δt_b	[ns]	1.4	337
Accel. gradient G	[MeV/m]	50	~ 25
Linac length L_l	[km]	10	20
Beams power $2P_b$	[MW]	14	22.5
IP beta-function β_x/β_y	[mm]	8/0.1	15/0.4
R.m.s. beam size at IP σ_x/σ_y	[nm]	245/2.7	555/5
R.m.s. beam length σ_z	$[\mu]$	110	300

Now the project of

International Linear Collider (ILC)

is under development.

LUMINOSITY

$$L = \nu \frac{N_{e^+} N_{e^-}}{S_{\text{eff}}},$$

where

$$S_{\text{eff}} \sim \sigma_x \sigma_y.$$

Collider	$2E_e$, GeV	L , 10^{33} $1/(\text{cm}^2\text{s})$	ν , kHz	N_{e^\pm} , 10^{10}	σ_x , μ	σ_y , nm
LEP-II	200	0.05	45	30	200	8000
NLC	500	22	22.8	0.75	0.245	2.7
TESLA	500	30	14.1	2	0,555	5

NOTE: transverse bunch sizes

$$\text{LEP - II} \quad \sigma_x \sigma_y \sim 10^{-5} \text{cm}^2$$

$$\text{TESLA} \quad \sigma_x \sigma_y \sim 3 \cdot 10^{-11} \text{cm}^2$$

So, it is likely that a first linear collider will have energy about **500 GeV** with some possible extension up to 1.5 TeV.

Compared to the SLC, these colliders of the so called next generation are designed on **one order** higher energy and **four orders** of magnitude higher luminosity!

5. Photon collider on a base of a linear $e^{\pm}e^{-}$ collider

5.1. Idea of high-energy $\gamma\gamma$ and γe colliders with real photons

Unlike the situation in storage rings, *in linear colliders each e^{\pm} bunch is used only once*. It makes possible to “convert” electrons to high-energy photons and to obtain the $\gamma\gamma$ or γe colliding beams **with approximately the same energy and luminosity as in the basic $e^{\pm}e^{-}$ collisions**. Moreover, $\gamma\gamma$ luminosity may be even larger due to absence of some collisions effects.

This idea was put forward by Novosibirsk group in 1981–1984

Ginzburg, Kotkin, Serbo and Telnov

and was further developed in detail.

Among various methods of $e \rightarrow \gamma$ conversion (bremsstrahlung, undulator radiation, beamstrahlung and so on), the best one is **the Compton scattering of laser light on high-energy electrons**. In this method a laser photon is scattered backward taking from the high-energy electron a large fraction of its energy. The scattered photon travels along the direction of the initial electron with an additional angular spread $\theta \sim 1/\gamma_e$.

This method was known long time ago

Arutyunian and Tumanian (1963); Milburn (1963)

and has been realized in a number of experiments:

FIAN (1964); SLAC (1969); Novosibirsk (1997).

However, the conversion coefficient of electrons to high-energy photons $k = N_\gamma/N_e$ was **very small** in all these experiments. For example, in the SLAC experiment it was $\sim 10^{-7}$.

In our papers it was shown that at future linear $e^\pm e^-$ colliders it will be possible to get $k \sim 1$ at a quite reasonable laser flash energy of a few Joules.

Therefore, **two principal facts**, which make possible a photon collider, are:

- linear colliders are **single-pass accelerators**, the electron beams are used here only once;
- obtaining of conversion coefficient $k \sim 1$ is **technically feasible**.

It should be noted that **positrons are not necessary for photon colliders**, it is sufficient and much easier to use **the electron-electron** colliding beams.

The problems of the $\gamma\gamma$ and γe colliders were discussed on many conferences. **Very rich physics, potentially higher than in e^+e^- collisions luminosity, simplification of the collider (positrons are not required) are all attractive to physicists.** Progress in development of linear e^+e^- colliders and high power lasers (both conventional and free-electron lasers) makes it possible to consider photon colliders as very perspective machines for investigation of elementary particles.

This option **has been included** in Conceptual Designs of all linear colliders and in the Technical Design Report of the TESLA colliders. **All these projects foresee the second interaction regions for the $\gamma\gamma$ and γe collisions.**

5.2. Scheme of a photon collider

To create a $\gamma\gamma$ or γe collider with parameters comparable to those in e^+e^- colliders, the following requirements should be fulfilled:

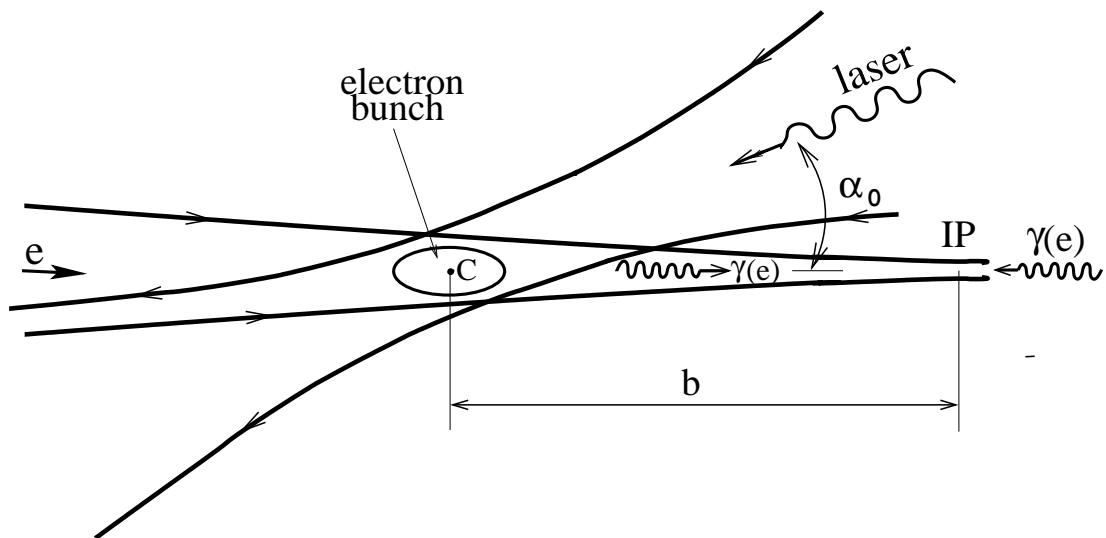
(i) **the photon energy** $\omega \approx E_e \sim 100 \div 1000$ GeV;

(ii) **the number of photons** $N_\gamma \sim N_e \sim 10^{10}$;

(iii) **photon beams should be focused** on the spot with transverse sizes close to those which electron bunches would have at the interaction point $\sigma_x \times \sigma_y \sim 10^{-5}$ cm $\times 10^{-7}$ cm.

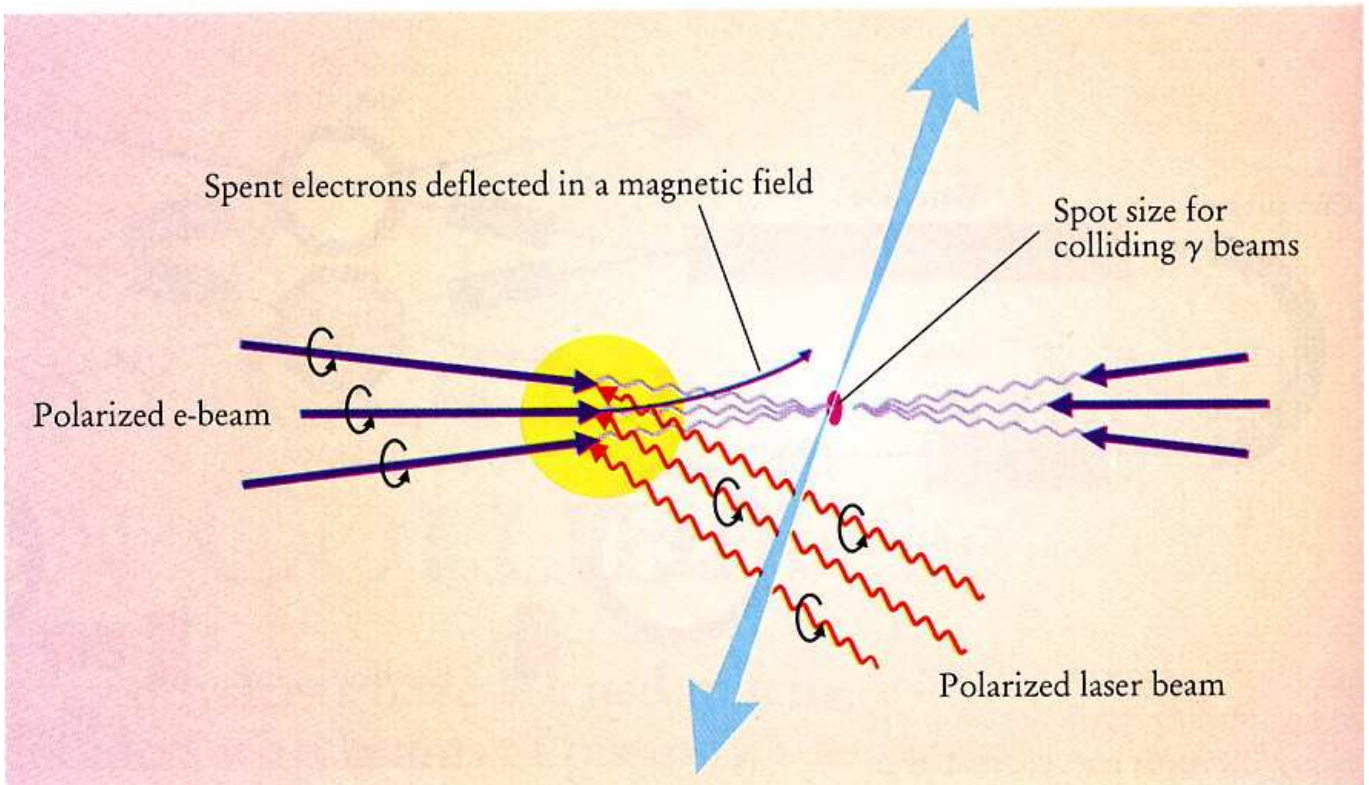
The best solution for this task is to use a linear $e^\pm e^-$ collider as a basis and convert the e^\pm beams into γ beams by means of the backward Compton scattering.

The scheme proposed in our papers is shown in Fig.:



An electron beam after the final focus system is traveling towards **the interaction point IP**. At the distance $b \sim 0.1 \div 1$ cm from the interaction point, the electrons collide with the focused laser beam in **the conversion region C**. The scattered high-energy photons follow along the initial electron trajectories (with small additional angular spread $\sim 1/\gamma_e$), hence, **they are also focused at the interaction point IP**. The produced γ beam collides downstream with the oncoming electron or a similar γ beam.

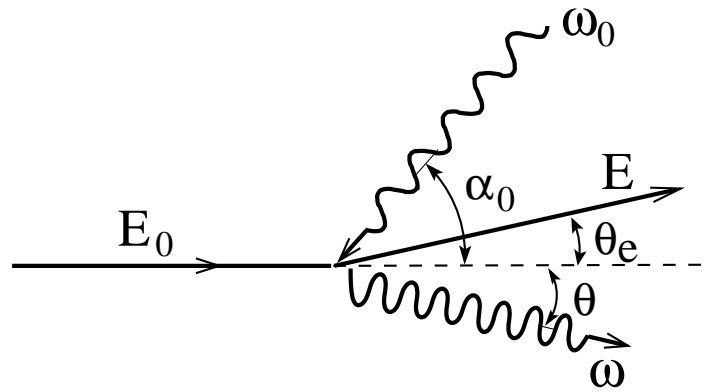
Conversion region:



It is very important that modern laser technology allows **to convert most of electrons to high-energy photons**. This means that the $\gamma\gamma$ luminosity will be close to the luminosity of the basic $e^{\pm}e^{-}$ beams.

5.3. Compton scattering

In the conversion region a laser photon with energy $\omega_0 \sim 1$ eV scatters on an electron with energy $E_0 \sim 100$ GeV at a small collision angle α_0 (see Fig.) and produces a final photon with the energy ω and the emission angle θ :



Kinematics of the backward Compton scattering

$$e(p_0) + \gamma_0(k_0) \rightarrow e(p) + \gamma(k)$$

is characterized by **two dimensionless variables**:

$$x = \frac{4E_0\omega_0}{m^2c^4} \cos^2 \frac{\alpha_0}{2}, \quad y = \frac{\omega}{E_0}$$

The maximum energy of the scattered photon

ω_m and the maximum value of the parameter y are:

$$\omega \leq \omega_m = \frac{x}{x+1} E_0, \quad y \leq y_m = \frac{x}{x+1} = \frac{\omega_m}{E_0}.$$

Typical example: in collision of the photon with $\omega_0 = 1.17$ eV ($\lambda = 1.06$ μm — the region of the most powerful solid state lasers) and the electron with $E_0 = 250$ GeV, the parameter $x = 4.5$ and **the maximum photon energy**

$$\omega_m = 0.82E_0 = 205 \text{ GeV}$$

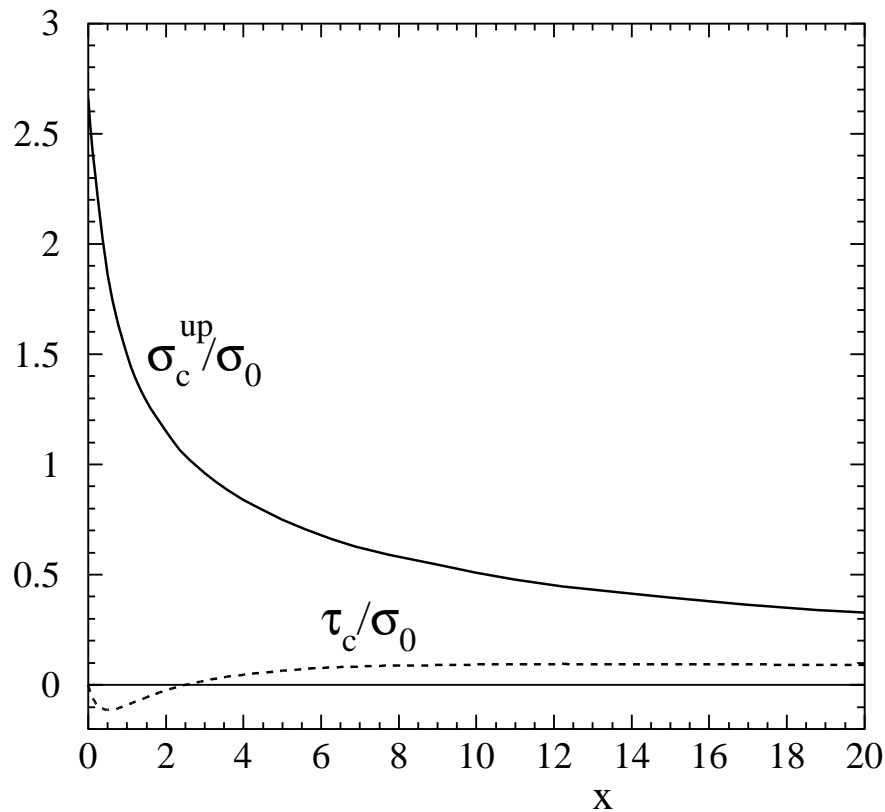
is close enough to the initial electron energy E_0 .

A photon emission angle $\theta \sim 1/\gamma_e = 2 \cdot 10^{-6}$.

The total Compton cross section is

$$\sigma_c = \sigma_c^{\text{up}} + 2\lambda_e^{(0)} P_c \tau_c,$$

where $\lambda_e^{(0)}$ is the mean helicity of the initial electron and P_c is that of the laser photon:

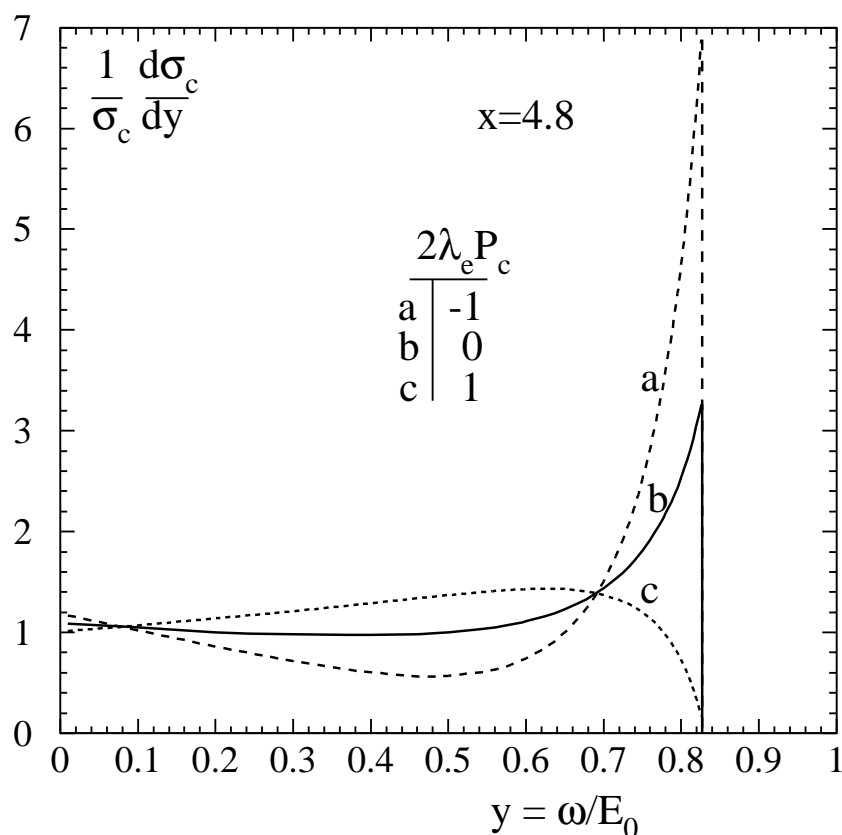


In the region of interest $x = 1 \div 5$ the total cross section is **large enough**

$$\sigma_c \sim \sigma_0 = 2.5 \cdot 10^{-25} \text{ cm}^2$$

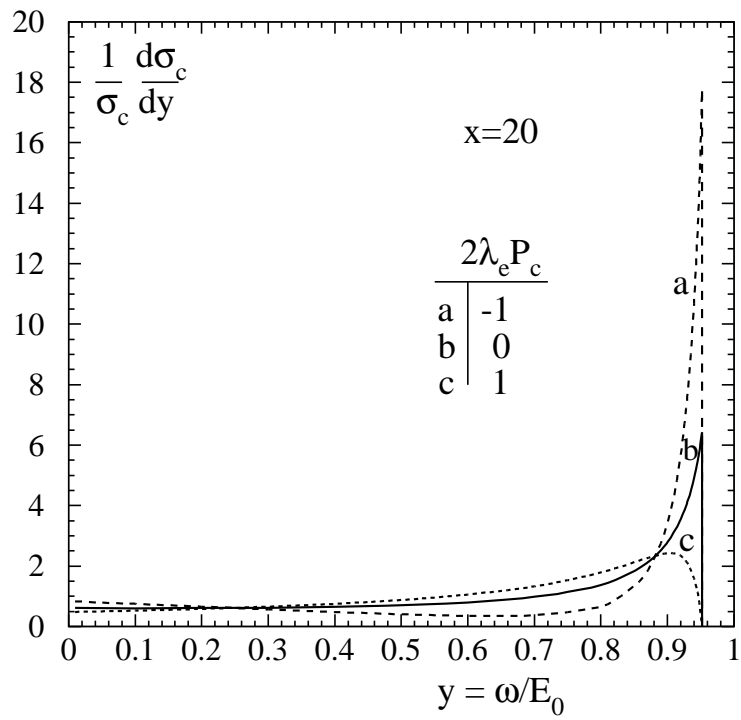
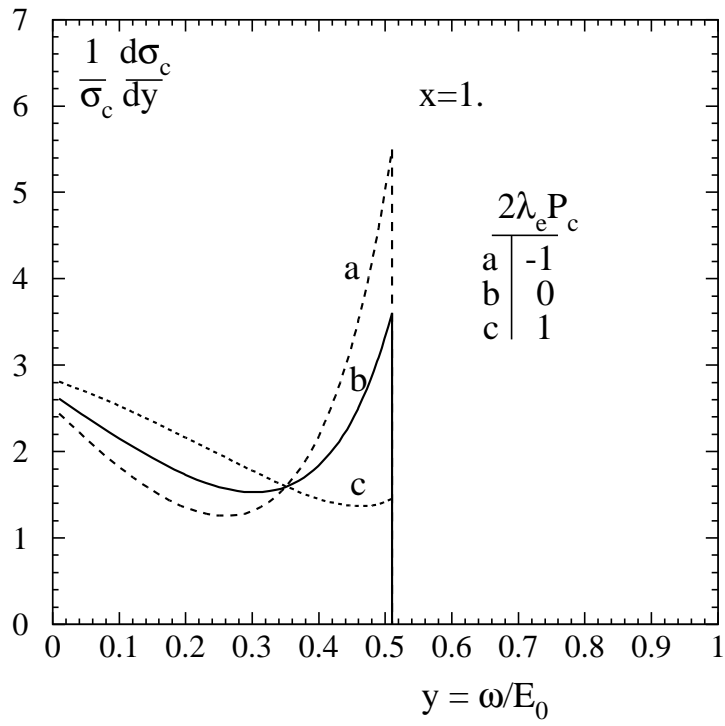
and **only slightly depends on the polarization of the initial particles**, $|\tau_c|/\sigma_c^{\text{up}} < 0.1$.

On the contrary, **the energy spectrum does essentially depend** on the value of $\lambda_e^{(0)} P_C$:



The “quality” of the photon beam, i.e. the relative number of hard photons, is better for the negative value of $\lambda_e^{(0)} P_C$. For $2\lambda_e^{(0)} P_C = -1$ the peak value of the spectrum at $\omega = \omega_m$ **nearly doubles** improving significantly the monochromaticity of the γ beam (cf. curves *a* and *b* in Fig.)

In order to **increase the maximum photon energy**, one should use the laser with larger frequency. This also increases a fraction of hard photons (cf. Figs. at $x = 1$ and $x = 20$).



Unfortunately, at large x **the high energy photons disappear from the beam** producing e^+e^- pairs in collisions with laser photons. The threshold of this reaction, $\gamma\gamma_0 \rightarrow e^+e^-$, corresponds to $x \approx 4.8$.

Therefore, it seems that the value $x \approx 5$ is the most preferable.

Angular distribution

The energy of a scattered photon depends on its emission angle θ as follows:

$$\omega = \frac{\omega_m}{1 + (\theta/\theta_0)^2}; \quad \theta_0 = \frac{mc^2}{E_0} \sqrt{x + 1}.$$

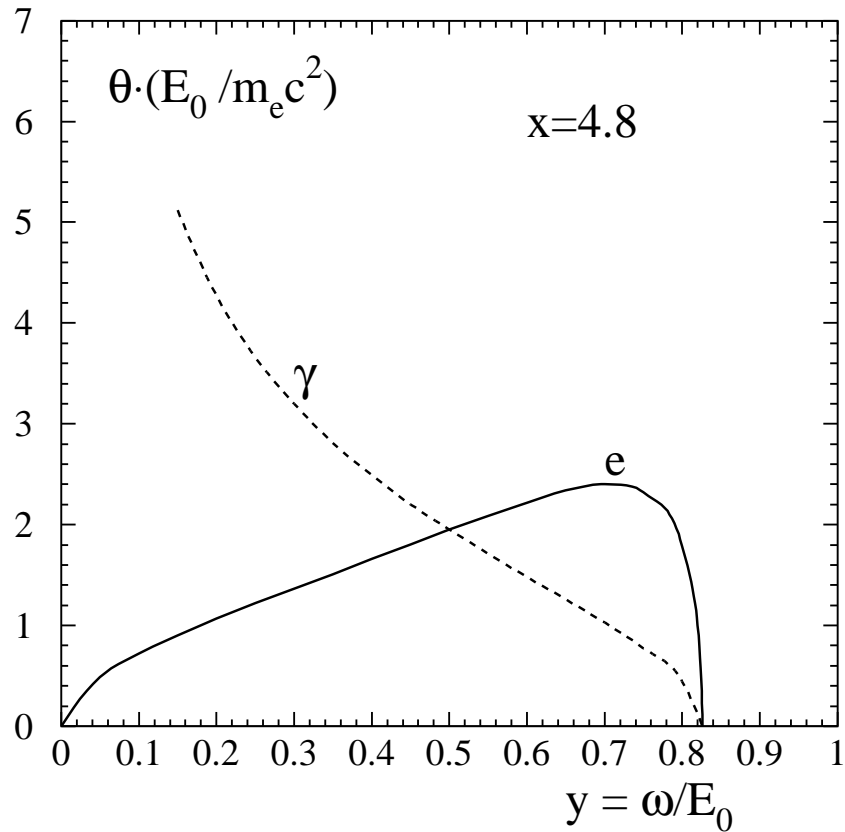
Note, that photons with the maximum energy ω_m scatter at zero angle.

The angular distribution of scattered photons has **a very sharp peak** in the direction of the incident electron momentum.

The photon and electron scattering angles (θ and θ_e) are unique function of the photon energy:

$$\theta(y) = \theta_0 \sqrt{\frac{y_m}{y} - 1}, \quad \theta_e = \frac{\theta_0 \sqrt{y(y_m - y)}}{1 - y}.$$

For $x = 4.8$ these functions are plotted in Fig.



It is remarkable that electrons are **only slightly deflected from their original direction and scatter into a narrow cone:**

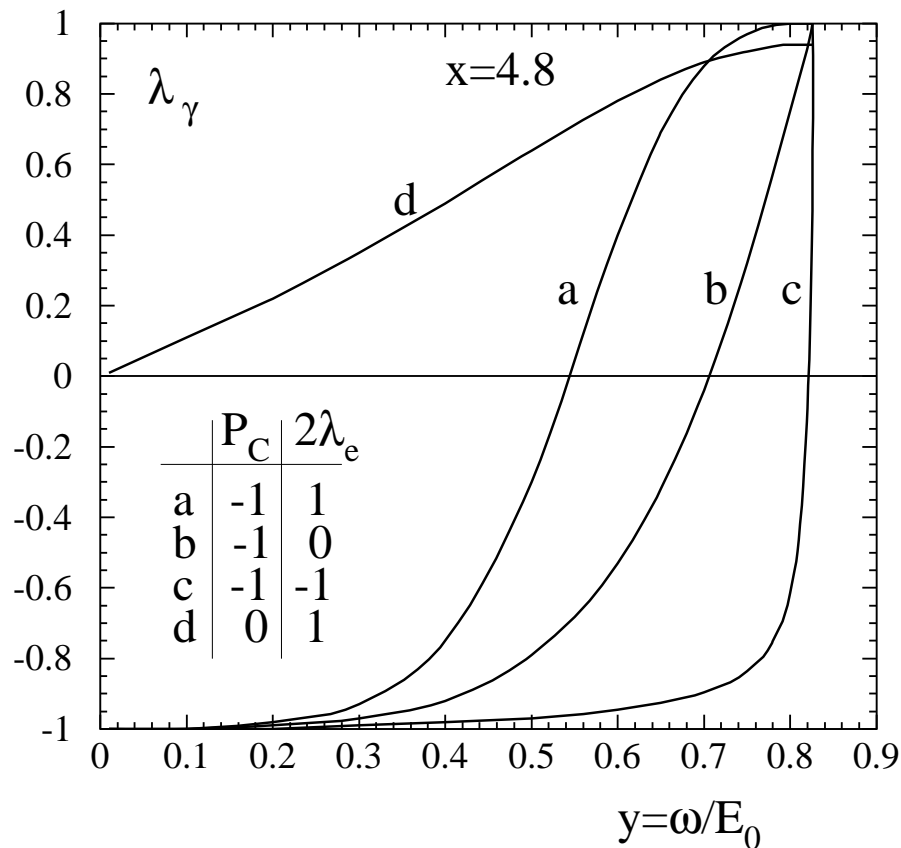
$$\theta_e \leq \frac{x}{2\gamma} = \frac{2\omega_0}{mc^2}.$$

Polarization of final photons

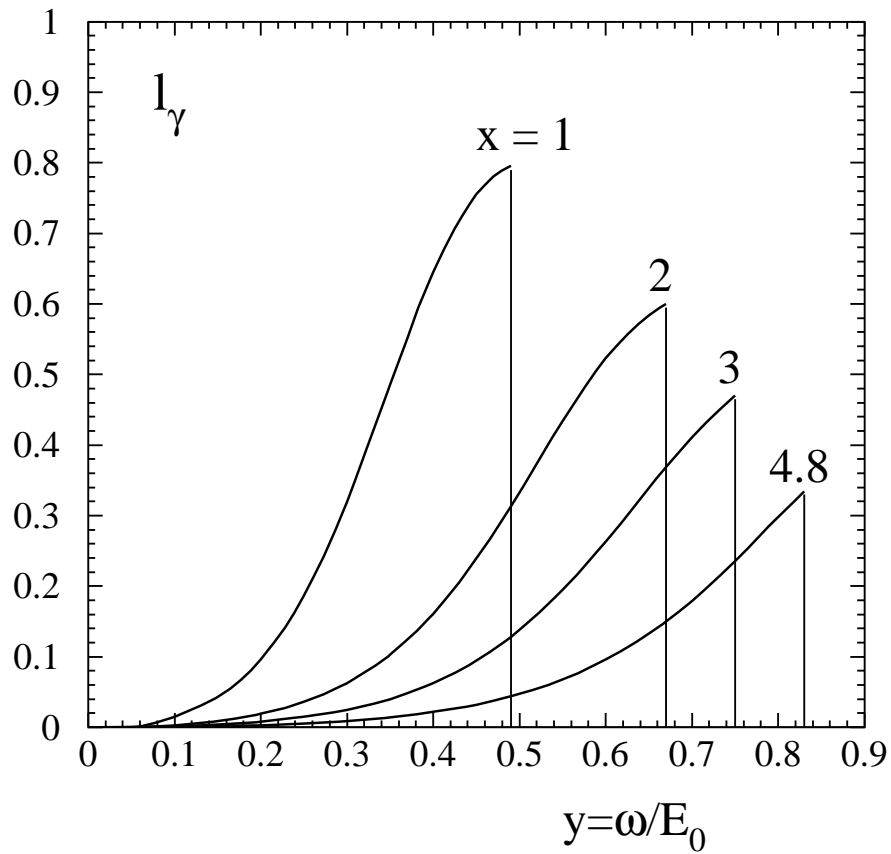
Using the polarized initial electrons and laser photons, one can obtain the high-energy photons with various polarization.

Examples:

The mean helicity of the final photon λ_γ vs. ω/E_0 for various laser photon helicities P_C and electron helicities λ_e at $x = 4.8$:



Average linear polarization of the final photon
 $\langle l_\gamma \rangle$ vs. ω/E_0 at $x = 1, 2, 3$ and 4.8 (the degree of linear polarization of the laser photon $P_l = 1$):



6. Physics of $\gamma\gamma$ interactions

Physical potential of such $\gamma\gamma$ and γe colliders will be

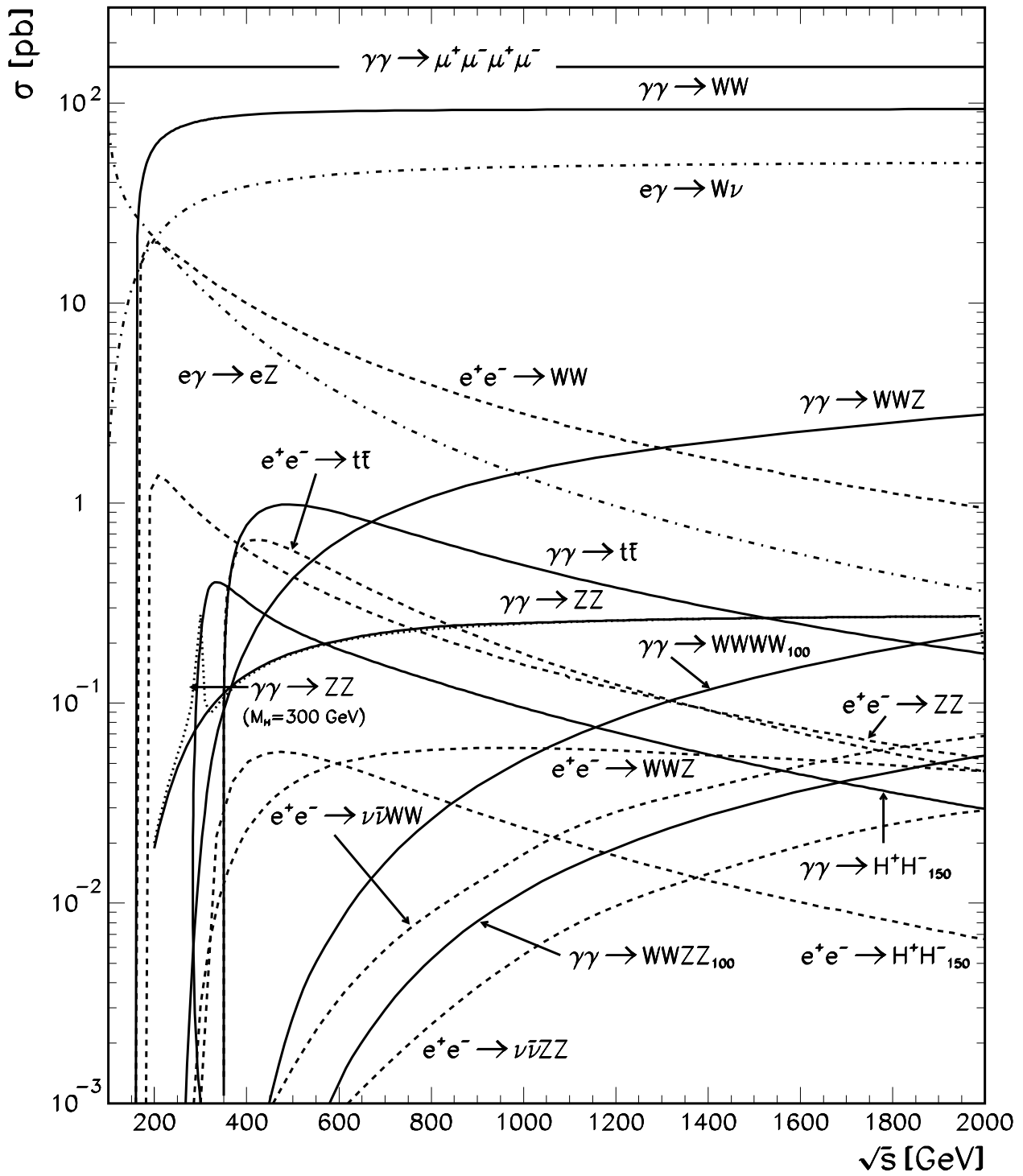
on the same level

with future e^+e^- and pp colliders.

Moreover, there is

a number of problems in which photon colliders are beyond competition.

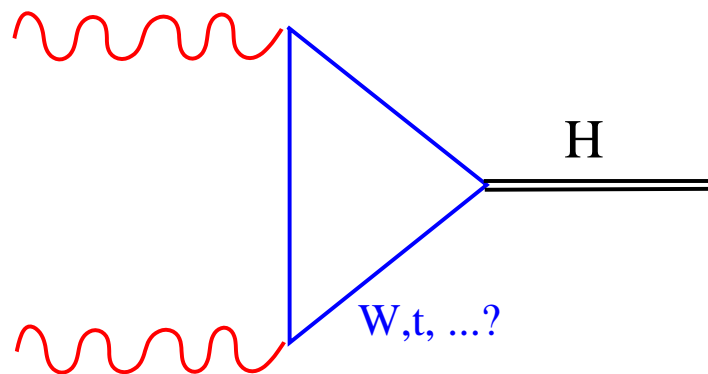
The comparison of cross sections — see Fig.



Photon collider makes it possible to investigate **both problems of new physics and of “classical” hadron physics and QCD.**

Since photon couple directly to all fundamental charged particles — leptons, quarks, W bosons, super-symmetric particles, etc. — a PC can provide a possibility **to test every aspect of the Standard Model (SM) and beyond.**

Besides, photons can couple to **neutral particles** (gluons, Z bosons, **Higgs bosons**, etc.) through charged particles box diagrams.

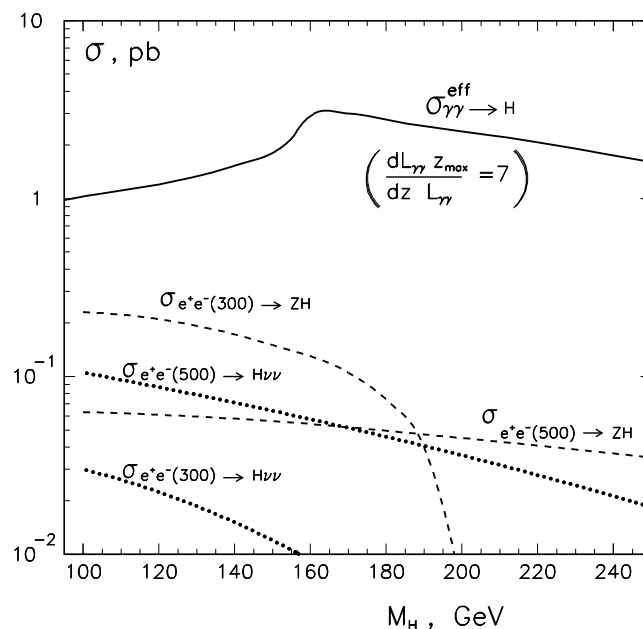


On the other hand, in a number of aspects **photons are similar to hadrons**, but with simpler initial state. Therefore, PC will be perfect in studying of QCD and other problems of hadron physics.

Let us list the problems in which the photon colliders have a high potential or some advantages:

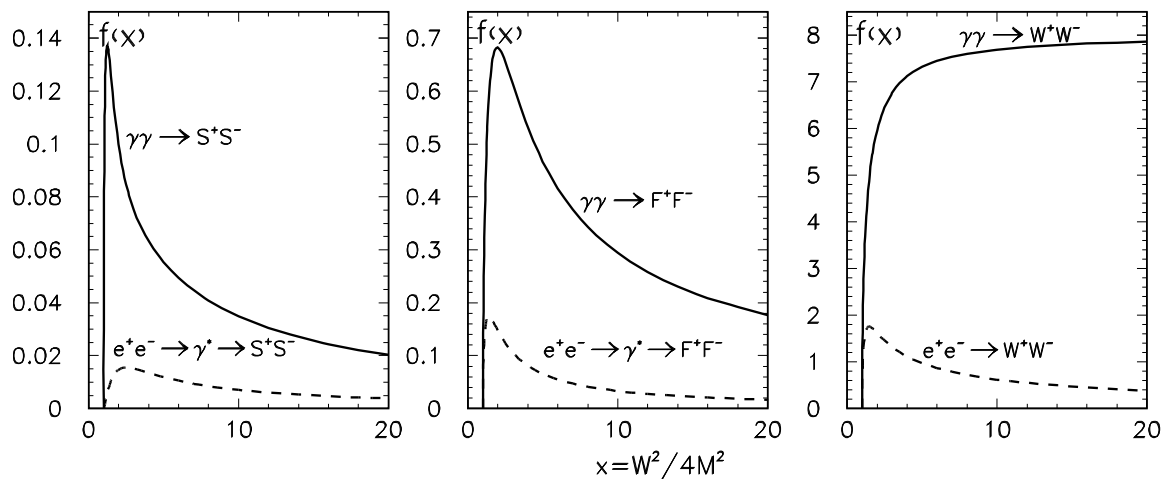
Higgs hunting and investigation. PC provides the opportunity to observe the Higgs boson at the smallest energy as a resonance in the $\gamma\gamma$ system. PC seems to be the best machine for Higgs hunting if its mass is within interval $80 \div 150$ GeV. Moreover, PC is out of competition in the testing of Higgs nature.

Fig. Total cross section of the Higgs boson production in $\gamma\gamma$ and e^+e^- collisions



Beyond SM. PC provides the excellent opportunities for finding of various particles beyond the SM: SUSY partners, charged Higgses, excited leptons and quarks, leptoquarks,... In particular, γe collider will be the best machines for discovery of **selectron or excited electron.**

Fig. Charged pair production: S – scalars, F – fermions, $\sigma = (\pi\alpha^2/M^2) f(x)$



Electroweak gauge boson physics. The electroweak theory is the substantial part of the SM which pretend for precise description like QED. **PC will be W factories with a rate about 10^7 W bosons per year.** In addition, the $\gamma e \rightarrow W\nu$ process will produce single W s which is very attractive for W decay's study. Thus, PCs provide the best — in comparison with other colliders — opportunity to test the precise predictions of the electroweak theory.

QCD and hadron physics. The photon colliders provide the unique possibility to investigate the problems of hadron physics and QCD in the new type of collisions and with the simplest structure of initial state. The principal topics here are the following:

- the $t\bar{t}$ production in different partial waves;
- the photon structure functions;
- the semihard processes;
- the mechanisms of shadowing;
- jets;
- the total $\gamma\gamma \rightarrow \text{hadrons}$ cross section.

To clarify many of these points it will be very useful **to compare** results from $\gamma\gamma$, γe , ep and pp colliders.

Besides the high-energy $\gamma\gamma$ and γe collisions, PCs provide *some additional options*:

(i) The region of conversion $e \rightarrow \gamma$ can be treated as $e\gamma_0$ collider (here γ_0 is the laser photon) with c.m.s. energy ~ 1 MeV but with **enormous luminosity** $\sim 10^{38} \div 10^{39} \text{ cm}^{-2}\text{s}^{-1}$. It can be used, for example, for search of weakly interacting light particles, like invisible axion.

(ii) In the conversion region one can test **nonlinear QED processes**, like the e^+e^- pair production in collision of high-energy photon with a few laser photons.

(iii) The used high-energy photon beams can be utilized for fixed-target experiments, etc.

7. Conclusions

Table of gold-plated processes from TESLA TDR, 2001

Table 3. Gold-plated processes at photon colliders.

Reaction	Remarks
$\gamma\gamma \rightarrow h^0 \rightarrow b\bar{b}$	SM (or MSSM) Higgs, $M_{h^0} < 160$ GeV
$\gamma\gamma \rightarrow h^0 \rightarrow WW(WW^*)$	SM Higgs, $140 \text{ GeV} < M_{h^0} < 190$ GeV
$\gamma\gamma \rightarrow h^0 \rightarrow ZZ(ZZ^*)$	SM Higgs, $180 \text{ GeV} < M_{h^0} < 350$ GeV
$\gamma\gamma \rightarrow H, A \rightarrow b\bar{b}$	MSSM heavy Higgs, for intermediate $\tan\beta$
$\gamma\gamma \rightarrow \tilde{f}\tilde{f}, \tilde{\chi}_i^+ \tilde{\chi}_i^-, H^+ H^-$	large cross-sections, possible observations of FCNC
$\gamma\gamma \rightarrow S[\tilde{t}\tilde{t}]$	$\tilde{t}\tilde{t}$ stoponium
$\gamma e \rightarrow \tilde{e}^- \tilde{\chi}_1^0$	$M_{\tilde{e}^-} < 0.9 \times 2E_0 - M_{\tilde{\chi}_1^0}$
$\gamma\gamma \rightarrow W^+ W^-$	anomalous W interactions, extra dimensions
$\gamma e^- \rightarrow W^- \nu_e$	anomalous W couplings
$\gamma\gamma \rightarrow WWWW, WWZZ$	strong WW scatt., quartic anomalous W, Z couplings
$\gamma\gamma \rightarrow t\bar{t}$	anomalous top quark interactions
$\gamma e^- \rightarrow \bar{t} b \nu_e$	anomalous Wtb coupling
$\gamma\gamma \rightarrow \text{hadrons}$	total $\gamma\gamma$ cross-section
$\gamma e^- \rightarrow e^- X$ and $\nu_e X$	$\mathcal{N}\mathcal{C}$ and $\mathcal{C}\mathcal{C}$ structure functions (polarized and unpolarized)
$\gamma g \rightarrow q\bar{q}, c\bar{c}$	gluon distribution in the photon
$\gamma\gamma \rightarrow J/\psi, \psi, J/\psi$	QCD Pomeron

“**To summarize**, the Photon Collider will allow us to study **the physics of the EWSB** in both the weak-coupling and strong-coupling scenario.

Measurements of the two-photon Higgs width of the h , H and A Higgs states provide a strong physics motivation for developing the technology of the $\gamma\gamma$ collider option.

Polarized photon beams, large cross sections and sufficiently large luminosities allow **to significantly enhance the discovery limits of many new particles** in SUSY and other extensions of the Standard Model.

Moreover, they will **substantially improve the accuracy of the precision measurements of anomalous W boson and top quark couplings**, thereby complementing and improving the measurements at the e^+e^- mode of TESLA.

Photon colliders offer **a unique possibility for probing the photon structure and the QCD Pomeron.**”