Linear accelerator - Photon collider

Seminar

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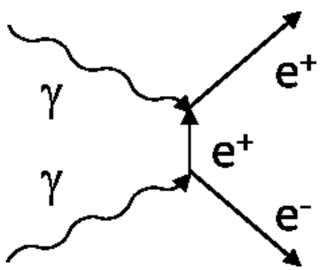
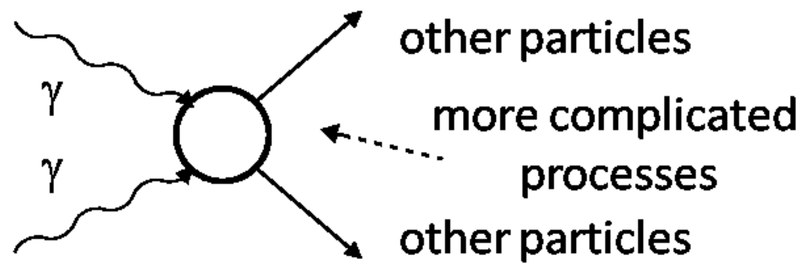
Introduction

- Visible light does not interact with visible light (Maxwell equations).
- However when frequency and intensity of photon beams is high enough, pairs of electrons and positrons are produced, at even higher frequency and intensity, elementary particles are produced through quantum effects.



("Feynman diagram")



- Idea of photon colliders is to collide intense beams of gamma rays to produce elementary particles.
- Method: gamma rays produced by compton scattering of laser light on high energy electrons.

Introduction

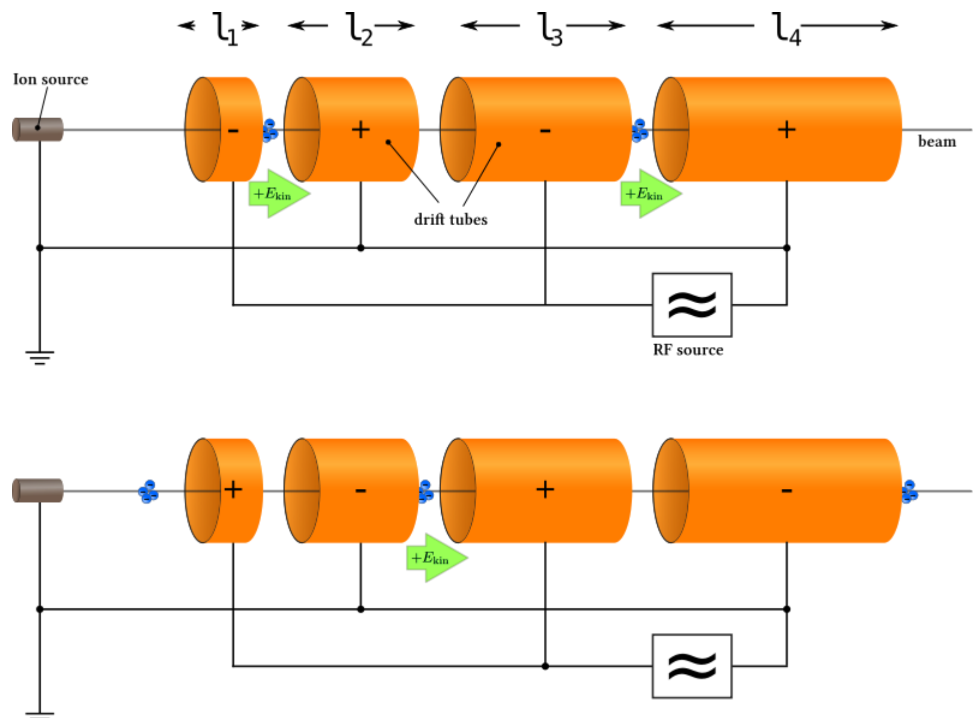
- Idea of colliding photons known since 1930s, first tested in 1963.
- Idea became realistic in the 1980s when powerful and fast lasers became available.
- High energy electrons needed $\rightarrow$ particle accelerators.
- Problem: energies above 500 GeV cannot be reached by standard circular accelerators (radiation loss) $\rightarrow$ high energy linear accelerators.
- Photon colliders are not built yet.

Linear accelerator

- Invented in 1928 by Rolf Wideroe.
- For acceleration of charged subatomic particles or ions.
- Particles subjected to a series of oscillating electric potentials along a straight line.

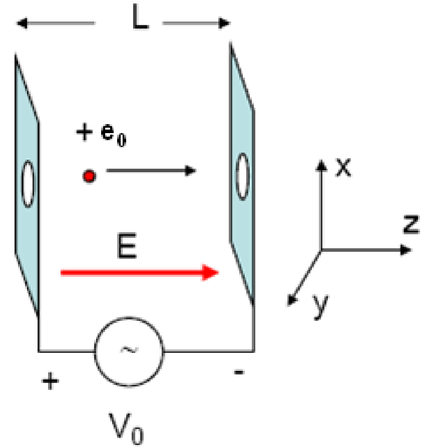
- Made of following parts:
  - Source of particles
  - Hollow vacuum waveguide
  - High voltage generator
  - Isolated cylindrical electrodes
  - Target

• 50 MeV proton Linac at CERN (left) and schematic view of a linac (right):



Basics of acceleration

Consider infinite parallel plates separated by a distance L with sinusoidal voltage applied, assume uniform E-field in gap (neglect holes).



$$E_z(t) = E_0 \cos(\omega t(z))$$

Approximately: $$t(z) = z/v + t_0$$

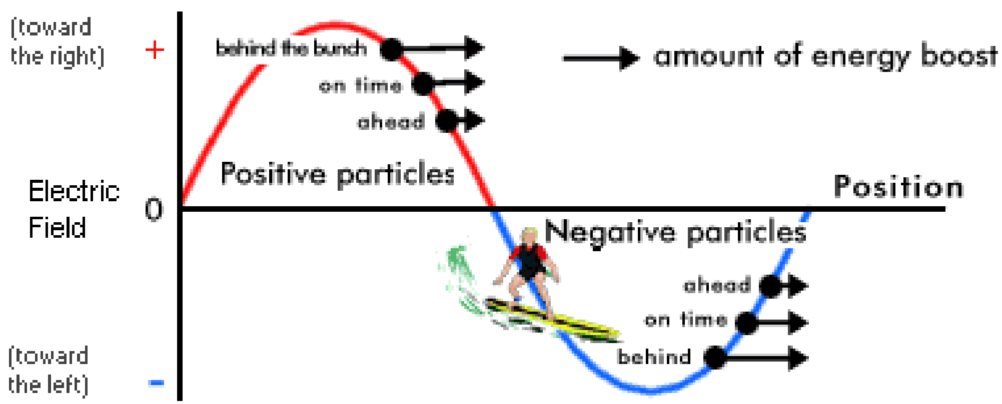
The energy gain of a particle with charge e_0 in the accelerating gap is:

$$\Delta W = e_0 \int_{-L/2}^{L/2} E_z(t)\,dz = e_0 E_0 \int_{-L/2}^{L/2} (\cos(\omega z/v + \omega t_0))\,dz =$$

$$= e_0 E_0 L_0 \sin(L/L_0 + \omega t_0); \qquad L_0 = 2v/\omega$$

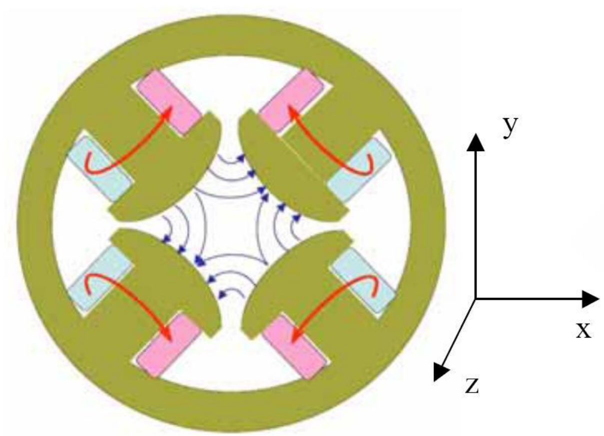
Phase stabilisation

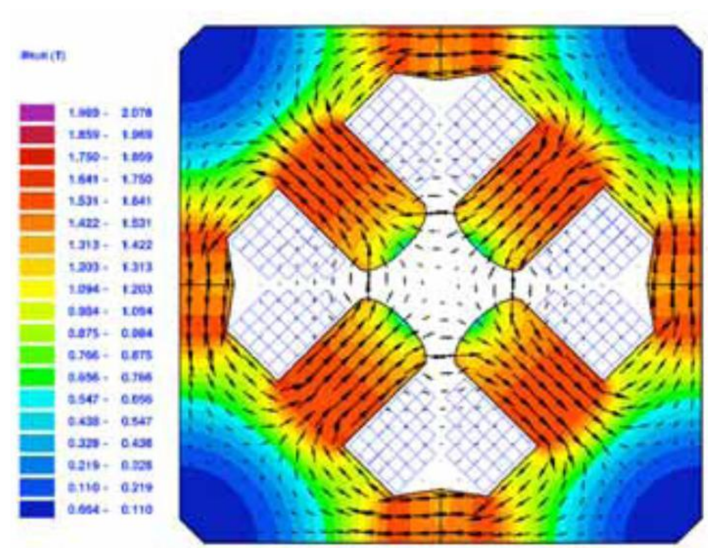
- Oscillatory field used not only to speed up particles, but also to concentrate them in bunches.
- $\Delta W > 0$ if injected when field is increasing.
- Particles that reach the gap too early are less accelerated than particles that come too late.

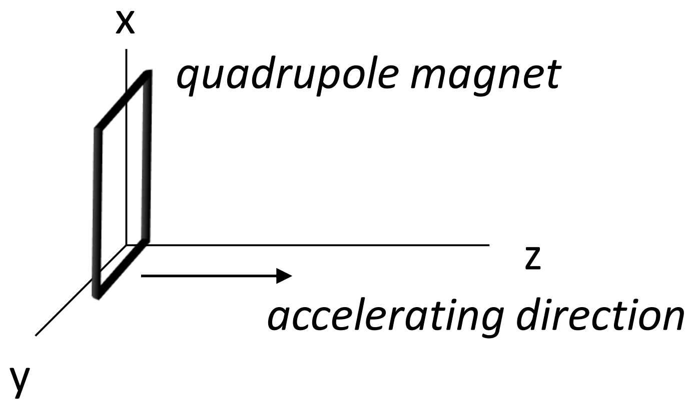


Focusing

- Bunches must be squeezed to increase the probability of interaction.
- Quadrupole magnets work as lens.
- Focus in y direction, defocus in x direction.







$$\vec{F} = e_0 \vec{v} \times \vec{B}$$

- In first approximation B is linear function of distance.

$$B_x = -ay, \qquad B_y = -ax$$

Equations of motion: $m\dfrac{d^2x}{dt^2} = e_0 vax, \qquad m\dfrac{d^2y}{dt^2} = -e_0 vay$

$$v \approx const. \Rightarrow z = vt \Rightarrow \frac{d^2x}{dt^2} = \frac{d^2x}{dz^2}v^2, \quad \frac{d^2y}{dt^2} = \frac{d^2y}{dz^2}v^2$$

$$x = \frac{x'(0)}{K}\sinh Kz + x(0)\cosh Kz, \quad y = \frac{y'(0)}{K}\sin Kz + y(0)\cos Kz; \quad K = \sqrt{\frac{e_0 a}{mv}}$$

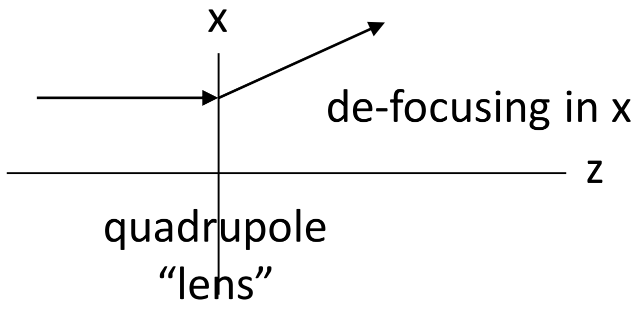
x’ = dx/dz, y’ = dy/dz;

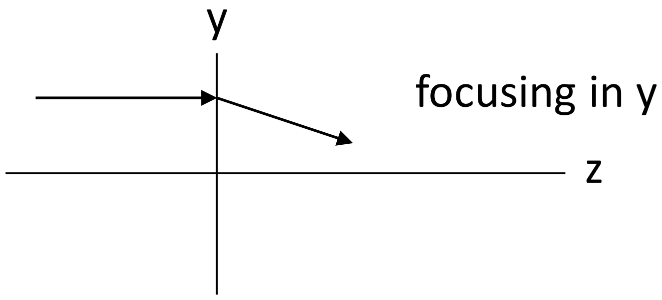
in matrix form:

$$\begin{bmatrix} x(z) \\ x'(z) \end{bmatrix} = \begin{bmatrix} \cosh Kz & 1/K \sinh Kz \\ K \sinh Kz & \cosh Kz \end{bmatrix} \cdot \begin{bmatrix} x(0) \\ x'(0) \end{bmatrix} \quad \begin{bmatrix} y(z) \\ y'(z) \end{bmatrix} = \begin{bmatrix} \cos Kz & 1/K \sin Kz \\ -K \sin Kz & \cos Kz \end{bmatrix} \cdot \begin{bmatrix} y(0) \\ y'(0) \end{bmatrix}$$

- Short quadrupole: Kz <<1

$$\boxed{\begin{aligned} x(z) &\approx x(0) + zx'(0), \quad x'(z) \approx K^2 zx(0) + x'(0) \\ y(z) &\approx y(0) + zy'(0), \quad y'(z) \approx -K^2 zy(0) + y'(0) \end{aligned}}$$





2 quadrupoles shifted in phase by 90° needed.

Photon collider at ILC

- This year the construction of the International Linear Collider (ILC) is planned to start.
- A proposed linac with collision energy of 500 GeV.
- It will be possible to upgrade it to 1000 GeV.
- It will collide e^+ with e^-.
- Between 30 and 50 km long (longest linac ever built).
- Has a γ interaction region included.

Why photon collider

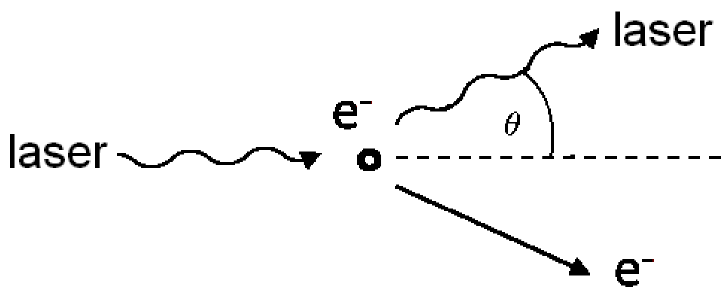
- Some reactions can be studied at photon colliders better than anywhere, for example Higgs boson properties.

- Cross sections for the pair production of various known as well as undiscovered particles are larger in $\gamma\gamma$ collisions than those in e^+e^- collisions by an order of magnitude.

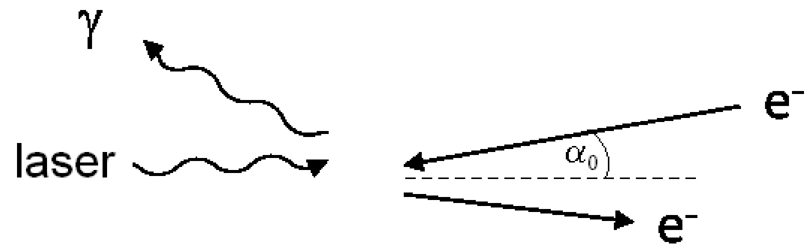
- Linear colliders are very expensive facilities and they should be used in the best way. Two detectors (one for e^+e^- and the other for $\gamma\gamma$) can give much more results than the simple doubling of statistics in e^+e^- collisions with one detector.

Collision scheme

- Photon colliders use Compton scattering of laser light on high energy electrons for producing gamma rays.



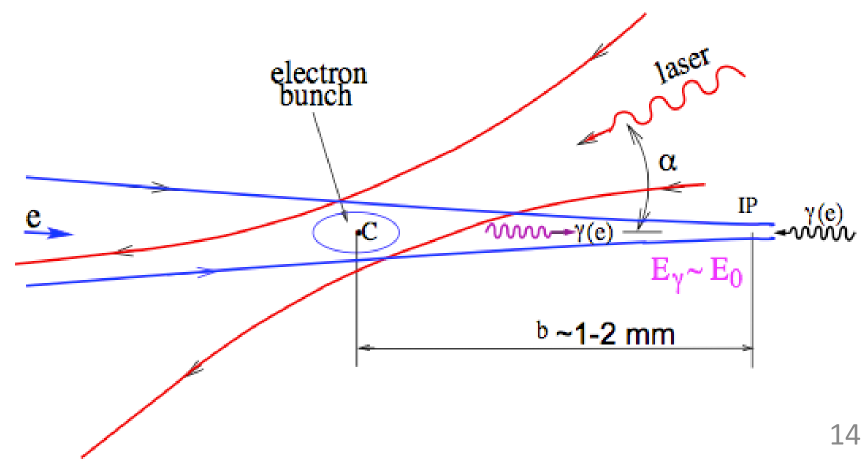
Compton scattering with e^- at rest



Compton scattering with accelerated e^-

Gamma rays are then collided

- Collision (C) and interaction point (IP)



Compton scattering

- Compton backscattering on relativistic electron.
- Assuming head on collisions (α_0 = 0), we can write:

$$(E_0, cp_0, 0, 0) \quad \rightarrow \quad (E, cp, 0, 0)$$

$$(\hbar\omega_0, -\hbar\omega_0, 0, 0) \quad \rightarrow \quad (\hbar\omega, \hbar\omega, 0, 0)$$

- Conservation of energy:

$$E_0 + \hbar\omega_0 = E + \hbar\omega$$

- Conservation of momentum:

$$cp_0 - \hbar\omega_0 = -cp + \hbar\omega$$

- Using $E_0 \approx cp_0$ and $E = \sqrt{m^2c^4 + c^2p^2}$ we get:

$$\hbar\omega \approx cp_0 - \frac{m^2}{4\hbar\omega_0}$$ energy of scattered photon

- If collisions are not colinear, we get a more general equation:

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

$\hbar\omega_m$ - maximal energy of scattered photon

$$x = \frac{4E\hbar\omega_0}{m^2c^4}\cos^2\frac{\alpha_0}{2}$$

- Typical values:

$$E_0 = 250\,GeV,\ \hbar\omega_0 = 1.17\,eV \Rightarrow x = 4.5,\ \hbar\omega_m / E_0 = 0.82$$

- Above x=4.8 photons may be lost (creation of e^+e^- pairs in collision between gamma and laser photons).

Important parameters

- Luminosity is the most important parameter of a collider. More particles through a smaller area means more collisions.

$$L = \frac{N_1 N_2 \nu}{4\pi\sigma_x\sigma_y}$$

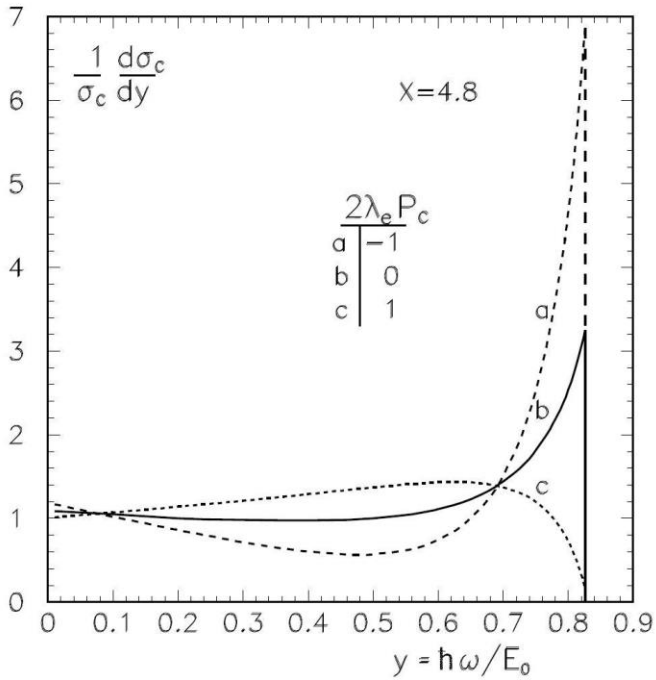
- The event rate is proportional to luminosity and interaction cross section. Rare processes need lots of luminosity.

$$\frac{dN}{dt} = L\,\sigma_{\text{int}}$$

- Helicity is the projection of spin on momentum.

$$h = \vec{J}\cdot\hat{p}; \quad \hat{p} = \frac{\vec{p}}{|\vec{p}|}$$

Compton spectrum



λ_e – electron helicity
P_c – helicity of laser photon

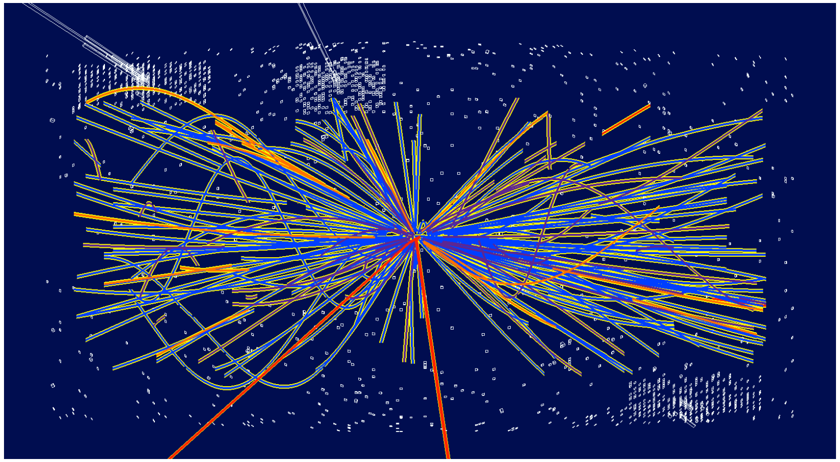
More highest energy photons if product of electron and photon helicities negative
$\rightarrow$ need polarized electron and laser beams.

Laser system

- We need a powerful laser system for e $\rightarrow \gamma$ conversion.
- Several J flash energy and pulse duration $\approx$ 1 ps required.
- Problem: high repetition rate, about 10-15 kHz.
- Pulse structure repeating the time structure of electron bunches.

Examples of particle physics

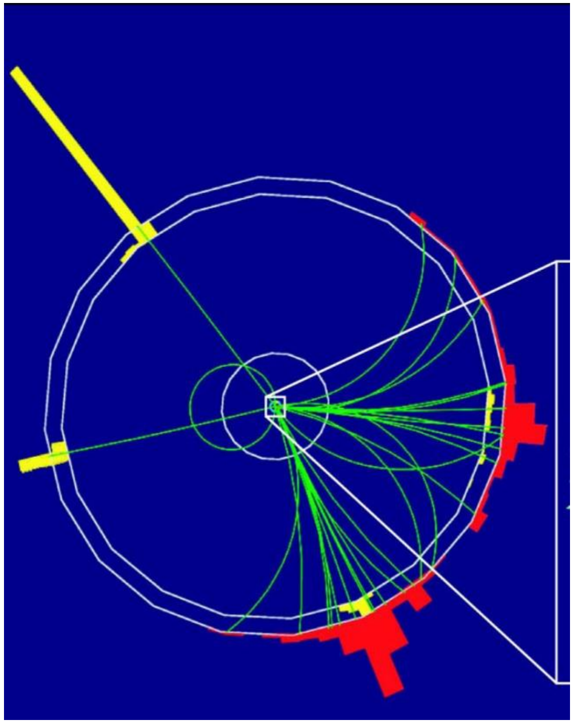
- Higgs boson – hypothetical particle predicted by the Standard Model of particle physics. From recent experiments at the Large Hadron collider (LHC) it is estimated has a mass between 115 GeV/c^2 and 135 GeV/c^2. The existence of Higgs boson, if confirmed will explain why elementary particles have mass.
- Hadron colliders such as the LHC are extremely capable machines to search for undiscovered particles in a wide range of high energies, the e^+e^- colliders and their extension to $\gamma\gamma$ colliders are more appropriate for detailed studies of individual particle properties.



Simulation of collision between two protons in CMS detector at the LHC. The red paths come from Higgs boson decay, all the others come from other products generated in the collision at high energy.

Examples of particle physics

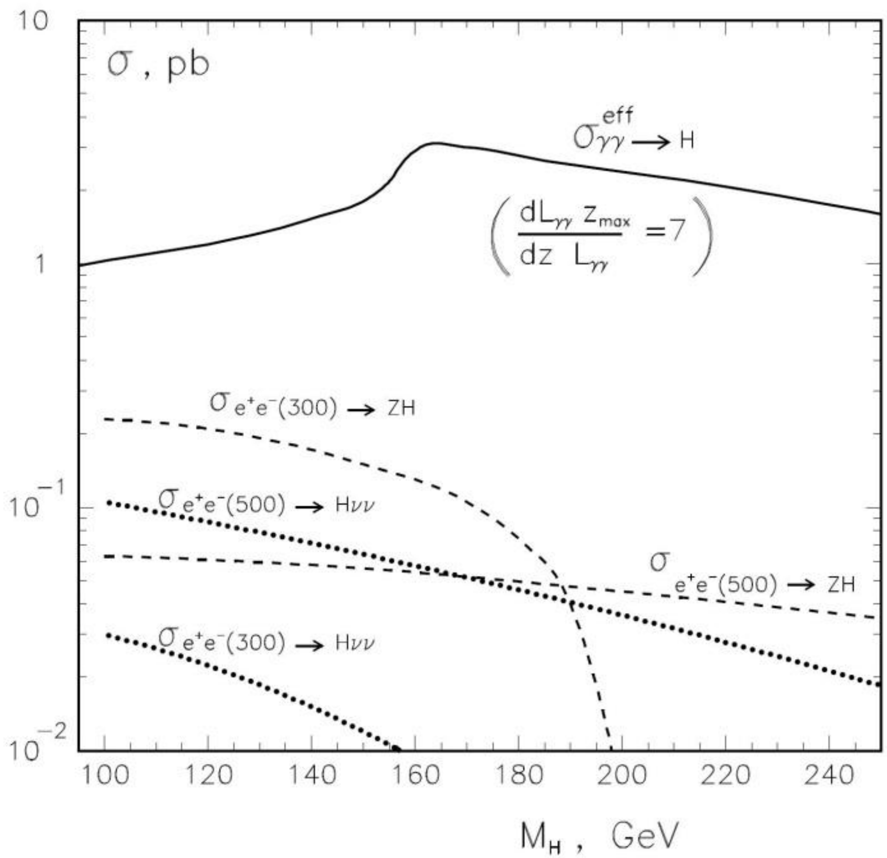
- If the Higgs boson will be discovered at the Large Hadron Collider (LHC), photon colliders will be very useful to produce enough amounts of this particle to study it in detail.



Computer simulation of Higgs boson decay at ILC;
If we study a large number of such decays we can accurately measure Higgs boson properties.

Cross sections

- Cross sections σ for production of pairs of various particles are all significantly larger in $\gamma\gamma$ collisions compared with e^+e^- collisions.



Cross section for Higgs boson production at $\gamma\gamma$ collider is about 100 times larger than in e^+e^- collisions.

Summary

- Photon colliders use Compton scattering of laser light on high energy electrons to produce elementary particles.
- Photon colliders give a possibility to study reactions above energy 500 GeV.
- Collisions between γ photons have less background than collisions between protons or e^+e^-.
- Adding a γ interaction region to a linear e^+e^- collider nearly doubles the possible reactions that can be studied.
- If Higgs boson is discovered at LHC, photon colliders will offer an opportunity to study this particle in detail.
- A photon collider has not yet been built. It is intended to be a part of the international linear collider project.

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