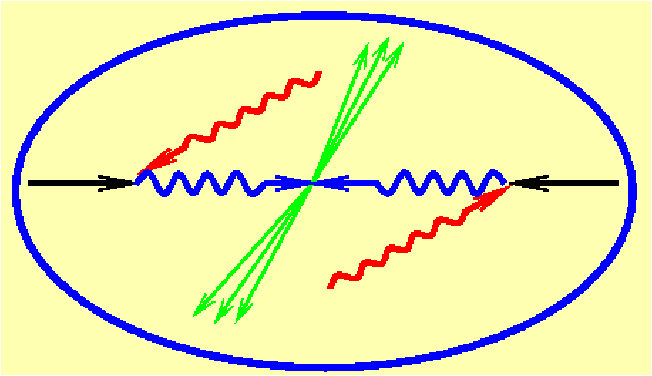

Calibration of energies at the photon collider

Valery Telnov

Budker INP, Novosibirsk

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The problem of the energy calibration at the photon collider was not discussed until now because did not seem difficult. Luminosity spectra at a PLC are quite broad and an ultimate accuracy is not required. Nevertheless, the detector should be calibrated in some way and energies of sharp edges of luminosity spectra should be known with a rather good accuracy as they can be used in kinematical reconstruction.

From e+e- storage rings we know that knowledge of the absolute beam energy is very useful and allows to determine particle masses with fantastic precision, practically independent of the detector resolution and its systematic errors. The method of the resonance depolarization at storage rings has allowed to measure

M_z with a relative accuracy 2.3×10^{-5} (CERN)

$M_{J/\psi}$ 4×10^{-6} (Novosibirsk) (σ_M =12 keV !)

At linear colliders in e+e- mode there is a desire to determine the absolute beam energy with an accuracy about 10^{-4} or even better. It can be achieved using a special spectrometer upstream the IP.

What accuracy of the energy is needed for the photon collider?

How the energy can be calibrated?

When the energy calibration is required?

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At the LHC and Tevatron the precise knowledge of the beam energy is not too important because E_{cm} is not used as a constrain in kinematical reconstruction, more important is the energy calibration of detectors. In ATLAS the EM calorimeter will be calibrated with an accuracy 0.02% using $Z \to e^+e^-$.

e^+e^-

At linear e^+e^- colliders the beam energy spread is about 0.15%. During the beam collision a large fraction of beam particles emit beamstrahlung and ISR photons, nevertheless the narrow spike in the luminosity spectrum remains. It can be used for measurement of particle masses and fine structures in cross sections, such as t-quark threshold, SUSY thresholds, Z-prime e.t.c.. By scanning energy with a narrow luminosity spectrum one can measure masses much better than they can be measured by the detector. That is because the width of the luminosity spectrum is narrower than the detector resolution and a systematic errors are smaller (if the beam energy is calibrated in some way).

What is a situation in the photon collider?

The maximum photon energy

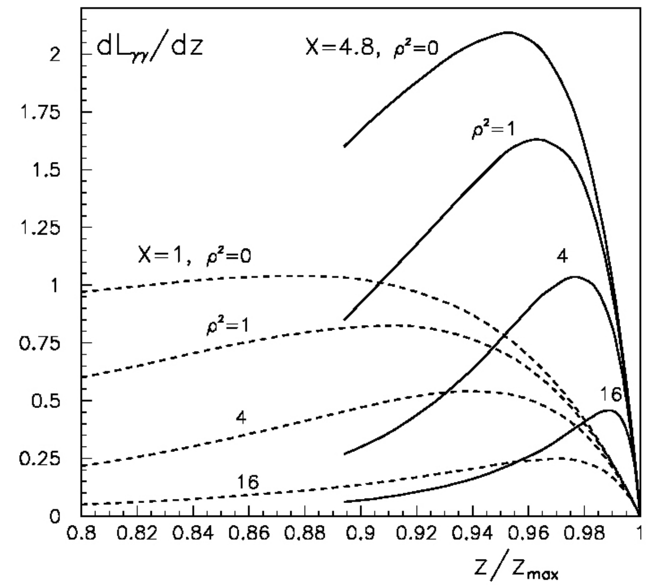
$$\omega_m = E_0 \frac{x}{x+1}, \qquad x = \frac{4E_0\omega_0}{m_e^2c^4} \qquad (x\sim 2\text{-}5)$$

Due to nonlinear QED effects in a strong field in the laser focus $m_e \to m_e(1+\xi^2)$, where ξ^2 is proportional to the laser photon density.

The required laser flash energy is smaller when ξ^2 is larger, however large ξ^2 leads to the decrease of the maximum photon energy and appearance of higher harmonics in the photon energy spectrum:

$$\omega_m = E_0 \frac{x}{x+1+\xi^2}, \qquad \frac{\Delta\omega_m}{\omega_m} = -\frac{\xi^2}{x+1}$$

$L_{\gamma\gamma}$ high energy edge, $\rho=(b/\gamma)/\sigma_y$



the "width" of the edge of the $\gamma\gamma$ luminosity spectrum is about 2-3% (without nonlinear effects)

The 5% shift corresponds to ξ^2 ~0.3 at x=4.5.

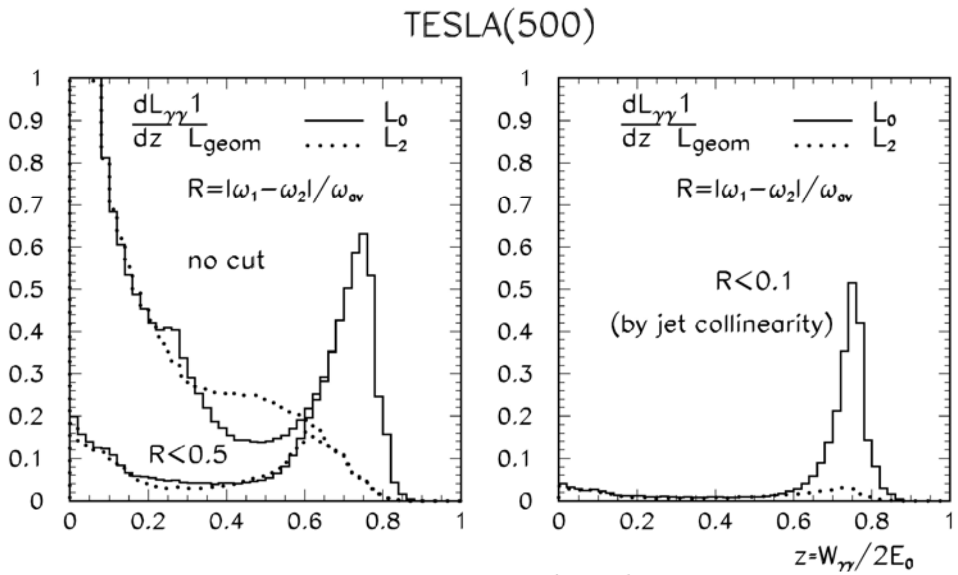
Beside, the density in the laser focus varies that gives the spread $\sigma_{\xi 2}$ ~0.4 $<\xi^2>$, where $<\xi^2>$~$0.7\xi^2(0)$. If the average shift is 4%, then the additional r.m.s. energy spread is 1.5% So the high energy edge of $\gamma\gamma$ luminosity spectrum is not sharp (width~3-4%) and the maximum energy is unstable due possible variation of the laser focus geometry (displacement, change of the spot size).

In γe collisions the high energy edge is sharp (such process would be the best for detection of e*), but due to nonlinear effects in Compton scattering it gets about 1.5% energy spread and plus some additional spread due to possible variation of the laser intensity in the focus.

Resume:

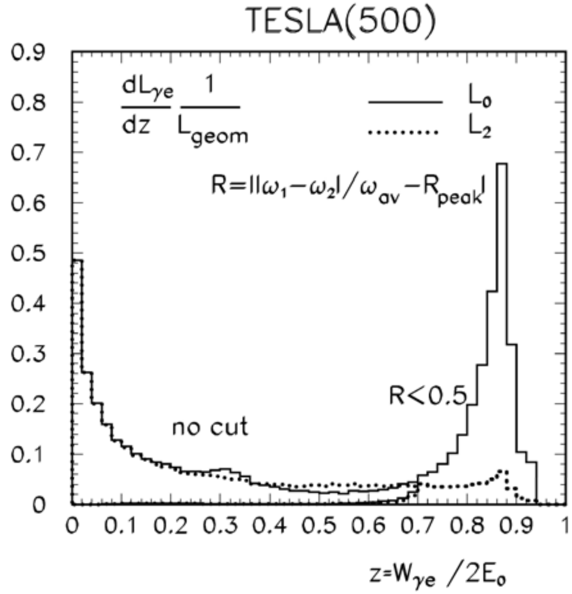
1) At the photon collider the main uncertainty in the energy of colliding particles (position of the edge) is connected with uncontrolled variation of the laser intensity in the conversion region.
2) The characteristic spread (width) of the high energy edge of luminosity spectra is larger than 3-4%, that is larger than the detector resolution (~0.3% at E=100 GeV). The luminosity spectrum can be measured using QED processes ($\gamma\gamma \to e^+e^-$, $\gamma e \to \gamma e$, $\gamma e \to eZ$, etc).
3) The absolute energy calibration of the detector is needed.

Realistic luminosity spectra at the PLC



$\gamma\gamma$

b =2 mm



γe

b =1 cm

(one beam is converted $e\to\gamma$)

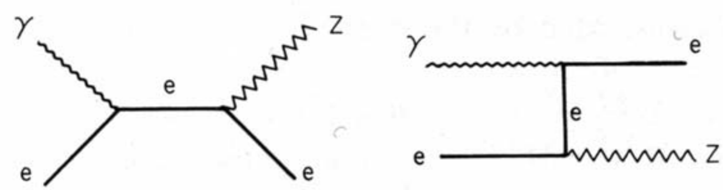
Calibration of the detector

$\gamma e \to \gamma e$

In order to measure energy one needs some value with a dimension of a mass. On first sight, one can use γe collisions (the energy scale is given by the electron mass m). The scattering angles in collisions of the electrons with an energy E_0 and a photons with edge energy ω_m allow to determine $x=4E_0\omega_0/(m^2c^4)$ and thus to find E_0. However this measurement gives $x/(1+\xi^2)$ and due to large uncertainty in ξ^2 the accuracy of the beam energy measurement will be very pure:

$$\frac{\sigma_{E_0}}{E_0} \sim \frac{\sigma_{\xi^2}}{1+\xi^2} \sim O(1\%)$$

$\gamma e \to eZ$ (the energy scale is given by M_z).



Diagrams for $\gamma e \to Ze$

The second diagram dominates, Z-boson travels predominantly in the direction of the initial electron, the final electron escapes the detector. In most cases only Z decay products are detected.

a) If the initial electron has the energy E_0, then using angles on final leptons in Z decay one can find the ratio

$$\sqrt{\frac{s'}{s}} = x = \sqrt{\frac{\sin(\theta_{\mu^+}) + \sin(\theta_{\mu^-}) - |\sin(\theta_{\mu^+}+\theta_{\mu^-})|}{\sin(\theta_{\mu^+}) + \sin(\theta_{\mu^-}) + |\sin(\theta_{\mu^+}+\theta_{\mu^-})|}},$$

The peak in the distribution gives the ratio M_Z and E_0. The similar method was used successfully at LEP-2: $e^+e^- \to Z\gamma$ (practically the same diagram)

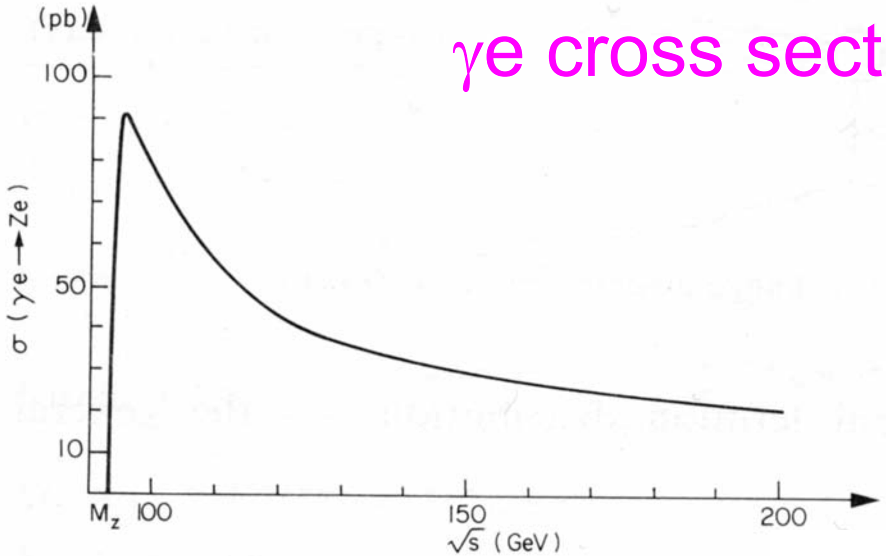
b) If the initial electron has $E \neq E_0$ (there are a lot of such electrons in mixed $\gamma\gamma,\gamma e$ collisions) and Z-boson is detected, then one can use leptons from Z for calibration of the tracking system, by to introducing corrections which shift the Z-peak to the right M_Z mass.

c) if all three final leptons are detected, then using only angles one can find energies of these particles and thus to calibrate the momenta up to almost maximum energies. Such kinematics, when Z and e scatter at large angle allows to calibrate at any collider energy. The cross section for such events smaller than the total by about one order of magnitude.

The cross section of the process $\gamma e \to eZ$ is large (the next slide). The total cross section is smaller than $\gamma e \to \gamma e$ by a factor of 3. However, for detection of $\gamma e \to \gamma e$ the scattering angle should be large enough that reduces the observation cross section by a factor of $L = 2\ln(W/m_e) \sim 20$, while $\gamma e \to eZ$ is detected (Z-boson) even at zero scattering angle!

Moreover, practically all events are useful for the calibration!

γe cross section



Integrated cross-section $\sigma(\gamma e \to Z e)$

$$\sigma_{\gamma e \to Z^0 e} = \frac{\tilde{\sigma}}{x}\left[\left(1 - \frac{2}{x} + \frac{2}{x^2}\right)L + \frac{1}{2}\left(1 - \frac{1}{x}\right)\left(1 + \frac{7}{x}\right)\right], \qquad x = \frac{s_{\gamma e}}{M_Z^2},$$

$$\tilde{\sigma} = \frac{\pi\alpha^2}{2M_Z^2 \sin^2 2\theta_W}\left[1 + \left(4\sin^2\theta_W - 1\right)^2\right] = 5.9\ \text{pb},$$

$$L = \ln\frac{\left(s_{\gamma e} - M_Z^2\right)^2}{m_e^2 s_{\gamma e}} \approx 24 + \ln\frac{(x-1)^2}{x}.$$

The dominant term in the angular distribution

$$\frac{d\sigma}{d\cos\theta_e} \propto \frac{1}{1 + \cos\theta_e + 2m_e^2 / W^2}$$

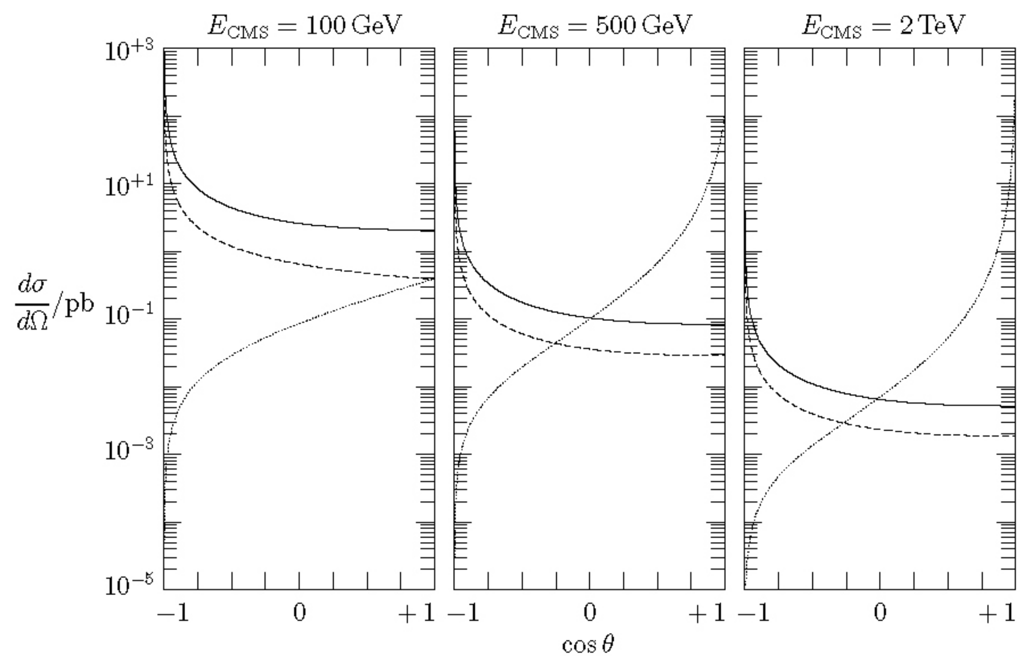


Figure 1: Differential lowest-order cross-sections for unpolarized particles: ——— $e^-\gamma \to e^-\gamma$, − − − $e^-\gamma \to e^-Z$, · · · · · · $e^-\gamma \to W^-\nu_e$.

Conclusion

- At the photon collider the edge energy of the photon spectra and the electron beam energy E_0 are not strictly connected due to nonlinear effects in the Compton scattering (dependence on the laser intensity).
- The luminosity spectra at PLC are wide enough and can be measured by the detector tracking system with a required precision.
- The absolute energy calibration of the detector can be done using the process $\gamma e \to eZ$ (during normal runs in γe mode or mixed $\gamma\gamma$ and γe mode).
- Some energy spectrometer upstream the IP will be useful for monitoring the stability of the energy and its controllable variations (during the energy scan) and, of course, for tuning of the LC.
- The absolute energy calibration by the spectrometer would be useful as a cross check of the detector calibration.