Precise ILC Beam Energy Measurement using Compton backscattering

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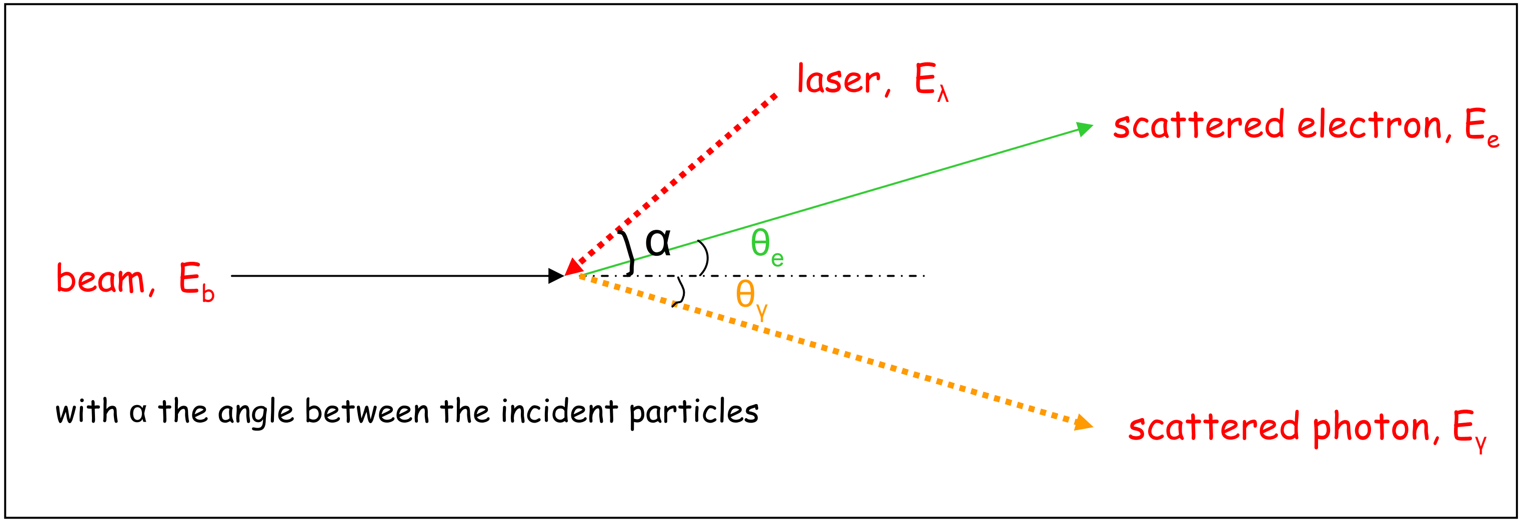
Process : $\boxed{e_b + \gamma_L \rightarrow e' + \gamma'}$

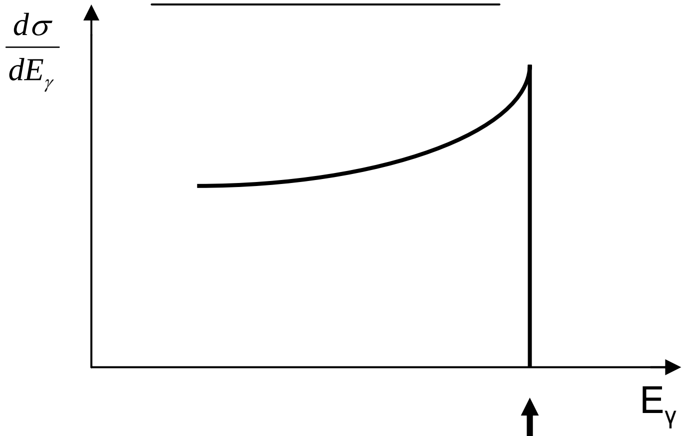


with α the angle between the incident particles

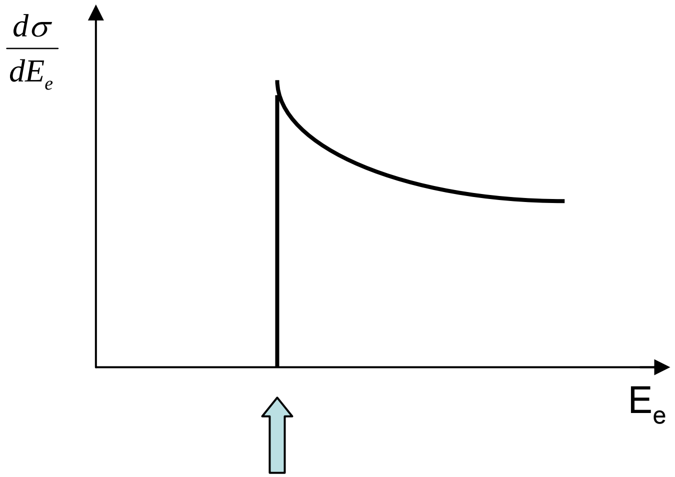
Basic properties (kinematics) of scattered photon resp. electron:

- ***sharp edge*** in the energy distribution
- both particles are ***strongly forward collimated***
- the ***position of the edge is not dependent on the initial polarization state***

in the lab frame



by energy conservation



$$E_\gamma^{\max} = \frac{2E_b}{2 + \frac{1}{k_i}}$$

with $k_i = 2\gamma E_\lambda / m_e$

$$\gamma = E_b / m_e$$

varies with the beam energy, E_b

$$\boxed{\Delta E_e < \Delta E_b}$$

The ***energy of the edge electrons*** depends

- on the primary ***beam energy*** (E_b = 250 GeV (45 … 500 GeV)
- the laser wavelength resp. the ***laser energy, E_L*** (~ eV)
- the ***angle*** **α**, the angle between the incoming particles (which should be chosen to be very small)

These quantities determine whether the edge electrons (photons) have a large or small energy; once E_L and α are fixed ➔ access to the beam energy E_b

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Our basic requirement of ***$\Delta E_b/E_b = 10^{-4}$*** means to note an absolute shift of the beam energy of ***ΔE_b=25 (50) MeV at E_b=250 (500) GeV***

!

Example: E_b = 250 GeV, α = 0., CO_2 laser (E_L=0.117 eV)

➔ ***E_e(edge) = 173 GeV and ΔE_e = 11.9 MeV for ΔE_b=25 MeV***

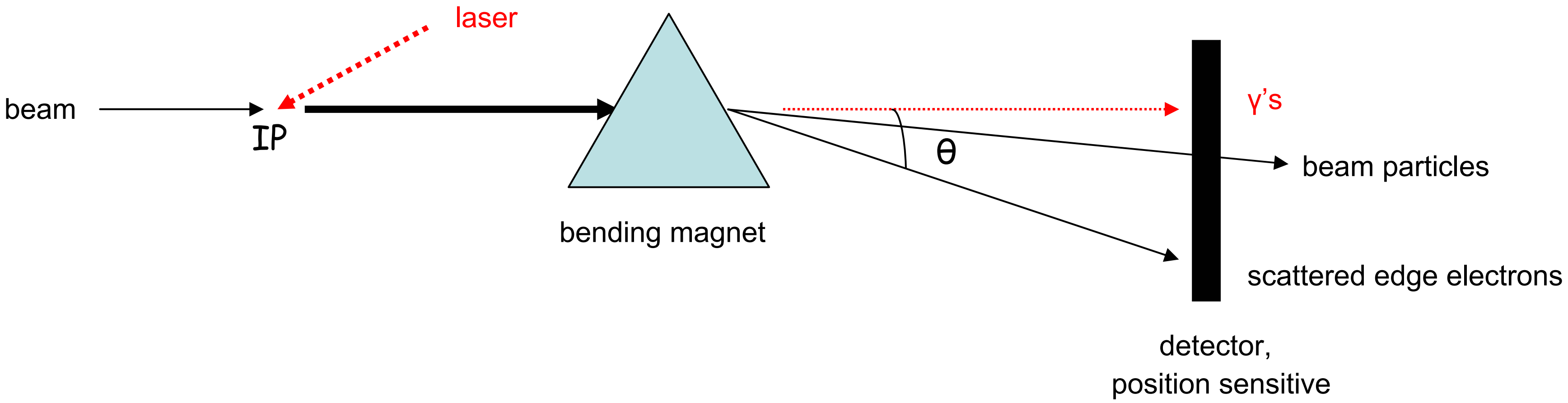
Nd:YAG (green, E_L=2.33 eV)

➔ ***E_e(edge) = 25 GeV and ΔE_e = 0.254 MeV***

lasers with large wavelength are preferred

Sketch of possible experiment

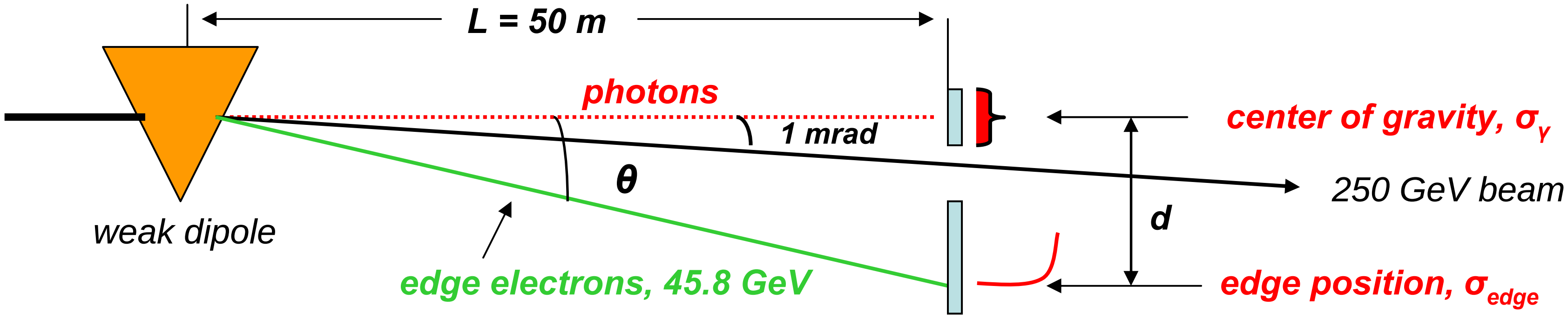
- The beam electrons interact with the laser photons at very small angle α, so that downstream of the IP untouched beam particles (most of them), scattered electrons and photons exist. All these particles are overlaid and strongly collimated in the forward direction.
- By a dipole magnet these particles are divided into through-going photons, less deflected beam particles and scattered electrons with some larger bending angles.
- The electrons with the largest bending angle are the edge electrons and their position in the detector should be carefully measured.



Having precise information on the bending angle θ of the edge electrons and the B-field integral, the beam energy (for each bunch ?) can be determined -- ***how well ?***

Example: Aim: $\boxed{\Delta E_b/E_b = 10^{-4}}$

infrared Nd:YAG laser (E_L = 1.165 eV)



in this example, Θ is 5.46 mrad
resulting to d = 27.3 cm

Note, if E_b changes by 25 MeV,

and ΔL = 0.1 mm, $\Delta \int Bdl / \int Bdl = 10^{-5}$

one needs a precision for the distance **d** of

➔ $\boxed{\Delta d = 5\ \mu m\ !}$

to recognize a 25 MeV shift
of beam energy

Using a CO_2 laser with E_Λ = 0.117 eV and the same set-up

→ energy of the edge electrons 172.6 GeV
with an offset in the detector d = 7.2 cm

→ **Δd = 7-8 μm**

$$\frac{\Delta E_b}{E_b} = \sqrt{\left(\frac{\Delta B}{B}\right)^2 + \left(\frac{\Delta\theta}{\theta}\right)^2}$$

$$\frac{\Delta\theta}{\theta} = \sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta d}{d}\right)^2}$$

independent on laser

For fixed B-field and distance L (magnet -> detector)
the relative error on d

→ Δd/d (CO_2) = 5.4·Δd/d (Nd:YAG)

due to the small value of d in the CO_2 case

↷ non-trivial task to select the best suitable laser
in conjunction with many other parameters
(B-field, L, detector, …)

GEANT SIMULATIONS

included

- beam sizes of the electron bunches (σx = 20 µm, σy = 2 µm, σz = 300 µm)
- beam dispersion of 5 µrad in x and y
- beam energy spread of 0.15 % of the nominal energy of 250 GeV
- # of electrons/bunch = 2 10^{10} , unpolarized

- bending magnet of 3 m length with B-field of 2.75 kG; fringe field included, bending in vertical (y) direction; ↔ flat horizontal beam
- synchrotron radiation ON
- distance between magnet and detector L = 50 m
- scattering angle in the initial state α = 8 mrad; vertical beam crossing

- infrared Nd:YAG laser (E_Λ = 1.165 eV) resp. CO_2 laser (E_Λ = 0.117 eV) used
- laser dispersion of 5 mrad in x and y, i.e. the laser is focused to the IP
- Nd:YAG laser: spot size at IP of 45 µm, power/pulse = 2 mJ
  and a pulse duration of 10 psec (with a spacing of 337 nsec)
- CO_2 laser: spot size at IP of 100 µm, power/pulse = 1 mJ
  and a pulse duration of 10 psec (with a spacing of 337 nsec)
  - → laser monochromaticity of 3 10^{-3} resp. 3 10^{-2} for YAG and CO_2 laser

- perfect overlap of both beams

Gaussian smearing

- IP position according to beam sizes in x and y
- direction of beam according to beam dispersion
- energy of beam according to beam energy spread
- direction of laser according to laser dispersion
- angle between the incoming beam and laser according to beam and laser directions
- laser energy according to laser duration ($d\omega/\omega \sim \lambda/(c\cdot t)$)
- B-field according to its error

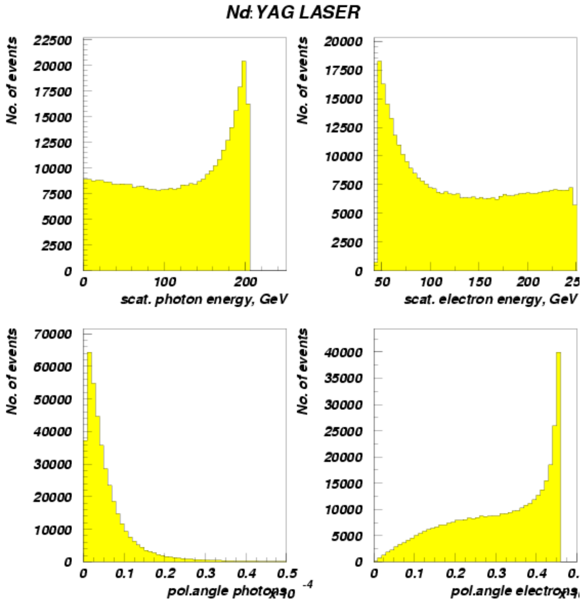
Synchrotron radiation (a stochastic process) in GEANT was switched on all the time

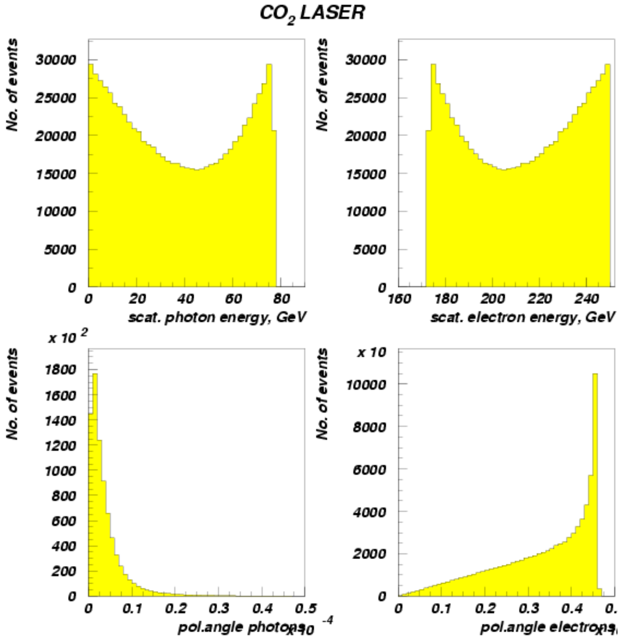
In simulation studies, individual Gaussian smearing can be ON or OFF
→ most important effects can be realized and accounted for

So far, non-linear effects which occur during the beam-laser interaction and which disturb the scattered electron edge behavior NOT taken into account
→ expected to be small or negligible due to small laser power ?

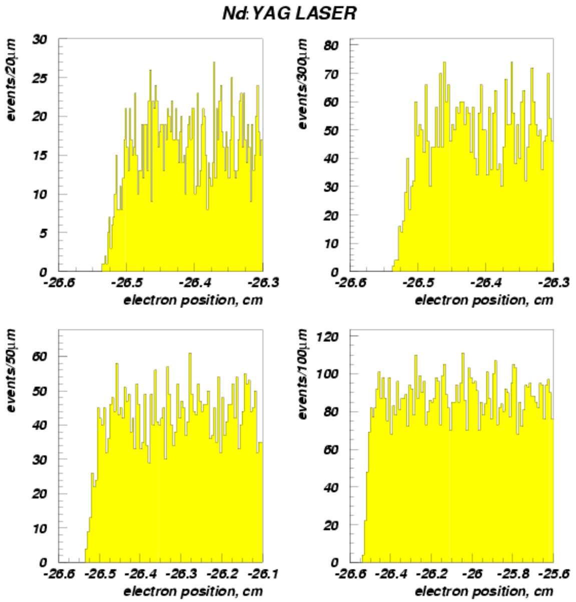
NO detector effects

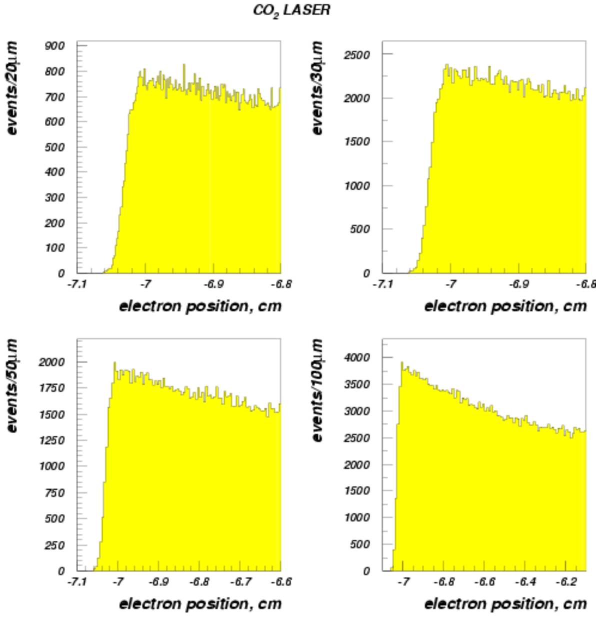
Characteristics of scattered particles (complete smearing):





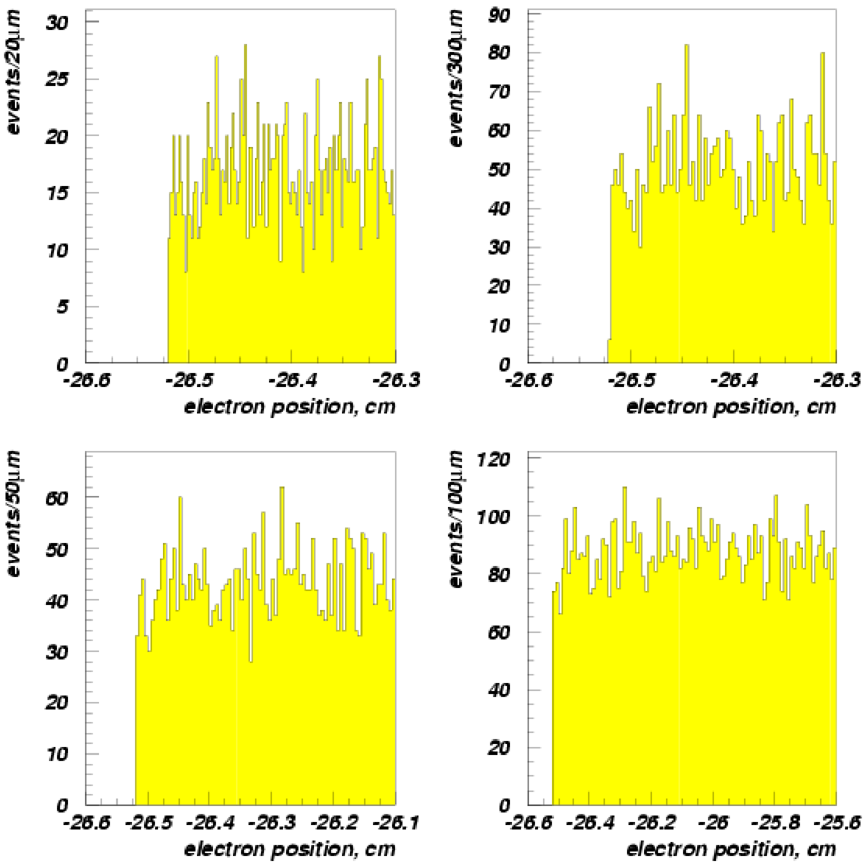
Position of the edge electrons in the detector (complete smearing)



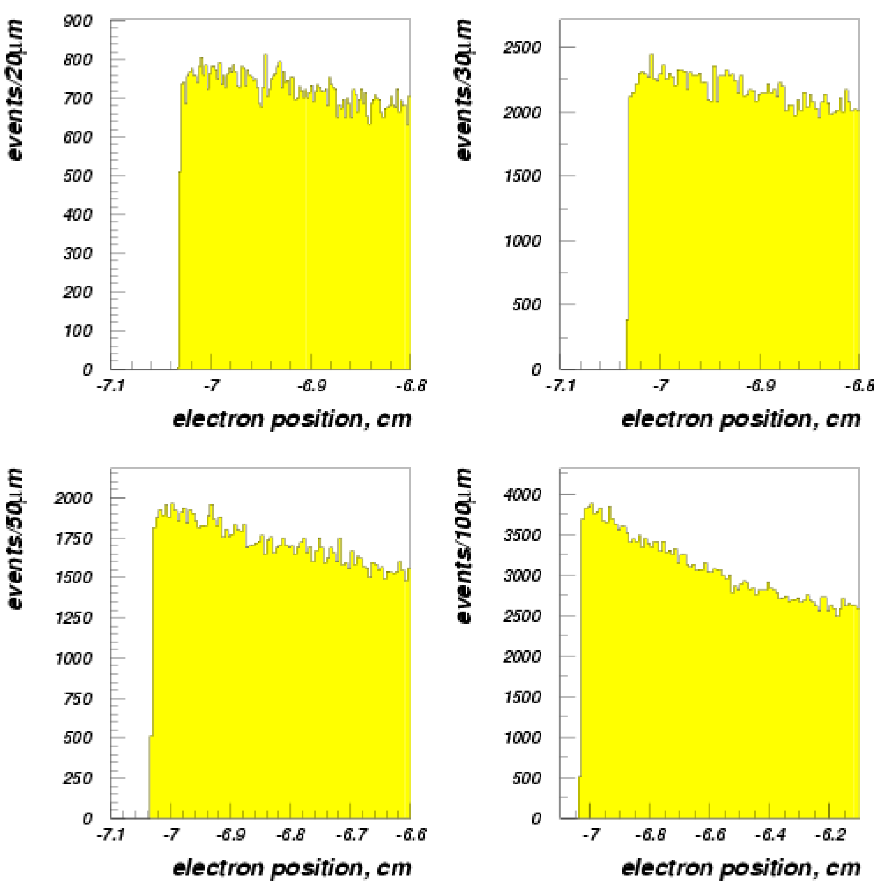


Position of the edge electrons in the detector (NO smearing, except SR):

Nd:YAG LASER



CO$_2$ LASER



From simulations with several smearing effects ON or OFF

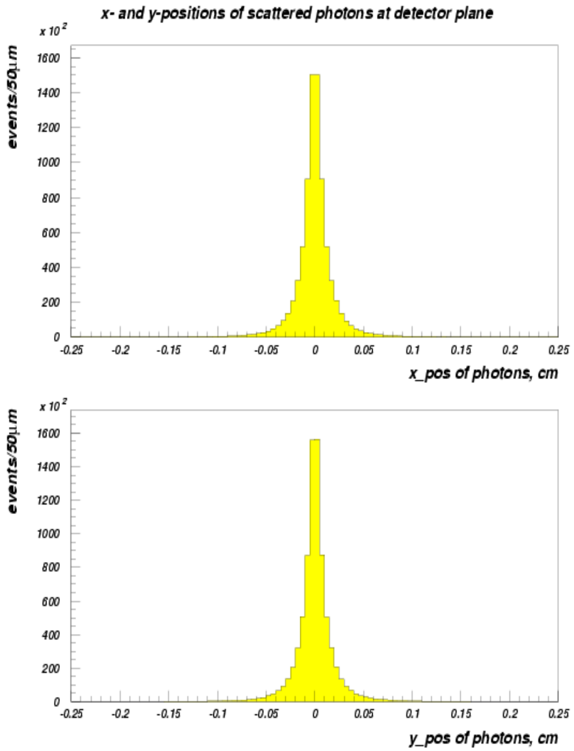
→ beam and laser energy uncertainties are most important for the electron edge behavior

for e- beam: both beam energy uncertainties contribute with about equal weights

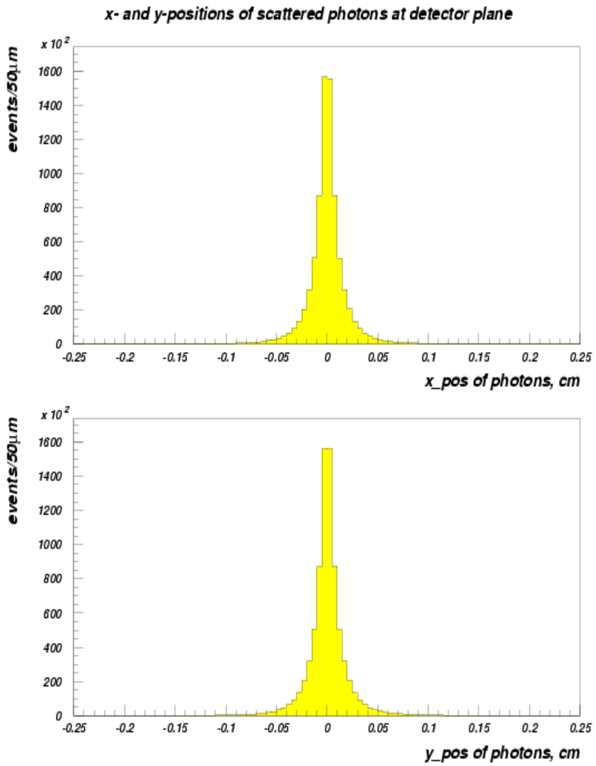
e+ beam: the uncertainty of the laser energy is dominant and governs the edge

Detector positions of the scattered photons (CO_2):

complete smearing



no smearing



no difference between the two cases visible

→ **position of scattered photons in detector insensitive to input parameters**

(good news)

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- Clear, the CO_2 laser provides more electrons close to the edge than the Nd:YAG laser due to larger cross section and somewhat better kinematics in the edge region.
- With assumed laser and electron beam parameters and scattering angle α

  → # of Compton scatters **$4 \ 10^5$** for the Nd:YAG laser, while **$8 \ 10^5$** for the CO_2 laser

  negligible event rate w.r.t. the total bunch intensity → **method is nondestructive,**

  and the large ILC bunch spacing should allow for **single bunch measurements**

- Optimization of the experiment not trivial, in particular the selection of the laser, to be sensitive on a tiny beam energy jump of 25 MeV or less.
- Including further information e.g. from the scattered photons has to be considered.
- Do we need some further beam line elements in the set-up ?
- Whatever we do, the emittance of the beam should not be diluted;
  if however an emittance grow cannot be avoided → think about on a dedicated measuring scheme.

Summary (preliminary)

- Laser: ongoing laser activities
  - Nd:YAG laser (infrared)
    e.g. at TTF Nd:YLF laser (λ = 1.047 μm) → 3 MHz repetition rate
    and peak/power of 140 μJ
    → a factor ~10 off our needs
  - CO_2 laser
    polarized positron source collaboration (see e.g. NIM A 500 (2003) 232)
    proposed a CO_2 laser with 121 pulses with 2.8 nsec spacing
    and a pulse power of 250 mJ

    resp. recent Snowmass proposal (physics/0509016)
    → 3.6 10^4 pulses with 3 psec rms bunch duration and power/pulse of 2.1 mJ

  → **CO_2** laser advantageous (needs more studies), but **does not exist**
  → infrared **Nd:YAG** (Nd:YLF) promising, power increase needed **no showstopper**

- Magnet:
  - a field error of 2 10^{-5} today achievable → very close to our needs (1-1.5) 10^{-5}
  - vertical bending preferred since σy << σx (flat beam), also background smaller (?),
    what about emittance in y-direction ?, check horizontal bending !
- Detector for scattered photons, electrons
  - measure the distance d with a precision of 5-8 μm, bunch by bunch (?) → CHALLENGING
    === silicon strip detector ===
- set-up also usable for (crude) beam profile determination, using the photon spatial distributions in the detector

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Further items to be studied

- decision on the best suitable laser and a laser line design
- detector has to be designed and implemented into simulation studies
- optimization of parameters of the set-up
- detailed GEANT simulation
- background ?
- account for experiences and results from low-energy experiments
- partners are very welcome
- . . .

With all that, including further ideas, a conceptual design report in ~ 1 year

With some optimism and further suggestions it seems possible

to achieve $\Delta E_b/E_b = 10^{-4}$ or better

by Compton backscattering of laser light

The idea to use Compton backscattering for beam energy determination
has been refreshed in discussions with Amour Margaryan during a visit
of Yerevan in autumn 2004

statement ' laser with low energy resp. large wavelength is preferred' was questioned (N. Muchnoi):

Max. scattered photon energy, $E_\gamma(\max)$, vs. laser energy E_laser

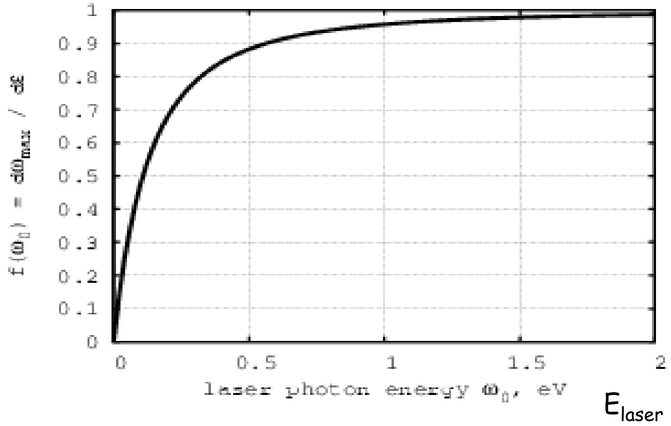
$$\boxed{E_\gamma^{\max} = E_{beam}\frac{\lambda}{1+\lambda}}$$

with

$$\boxed{\lambda = \frac{4E_{laser}E_{beam}}{m^2}\sin^2\frac{\alpha}{2}}$$

derivative $\dfrac{dE_\gamma^{\max}}{dE_{beam}} \longrightarrow$

(α = π and E_beam= 250 GeV)



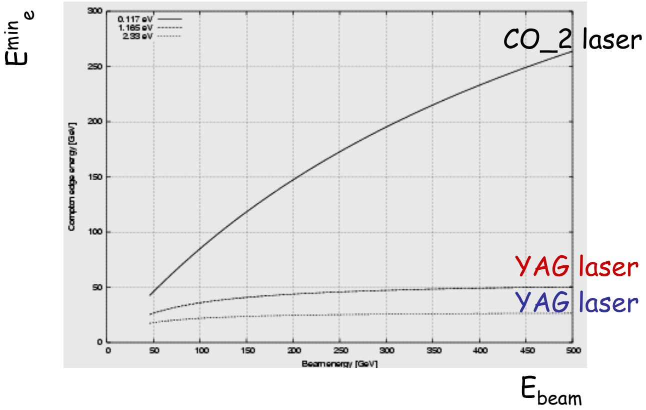
→ laser with shorter wavelength or larger energy → preferred

(α = 0)

while Hannu Paukkunen (sommerstudent)

claimed the opposite for $E_e(\min)$!

$$\boxed{E_e^{\min} = \frac{1}{1/E_{beam} + 2E_{laser}(1+\cos\alpha)/m^2}}$$



→ laser with larger wavelength or smaller energy → preferred

→ SOLUTION ?

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Solution:

- Energy conservation:

$$\boxed{E_{beam} + E_{laser} = E_e^{\min} + E_\gamma^{\max}}$$

↷

$$\boxed{\frac{dE_e^{\min}}{dE_{beam}} = 1 - \frac{dE_\gamma^{\max}}{dE_{beam}}}$$

and since dE^{max}/dE_{beam} is rising from 0 to 1 with increasing E_{laser}

the quantity $(1 - dE^{max}/dE_{beam})$ becomes smaller with increasing E_{laser}

→ ergo, both are right !

Since we are primary interested on measuring the low-energy edge of the scattered electrons

→ a laser with low energy resp. large wavelength is preferred

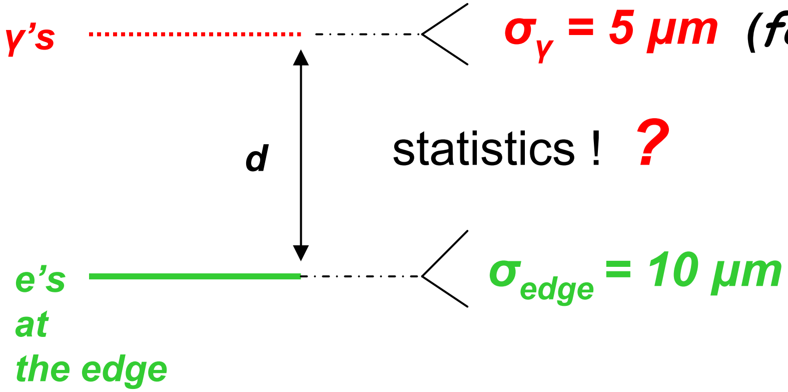
CO_2 !

(first guess !)

$$\frac{\Delta E_b}{E_b} = \sqrt{\left(\frac{\Delta B}{B}\right)^2 + \left(\frac{\Delta \theta}{\theta}\right)^2}$$

$$\frac{\Delta \theta}{\theta} = \sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta d}{d}\right)^2}$$

Assume



$\sigma_\gamma = 5\ \mu m$ *(for centre of gravity)*

statistics ! **?** ➔ $\boxed{\Delta d/d = 3.3\ 10^{-4}}$

$\sigma_{edge} = 10\ \mu m$

i.e. a factor 8.5 off (3.9 10^{-5} !)

Possible way out: 5 µm → 3 µm and 10 µm → 5 µm

➔ $\Delta d/d = 1.7\ 10^{-4}$

or increase L to 30 m ➔ $\Delta d/d = 2.2\ 10^{-4}$

or do both ➔ $\Delta d/d = 1.1\ 10^{-4}$

i.e. we are a factor 2.6 off

With some optimism and further ideas/suggestions to improve the set-up it seems possible to achieve $\Delta E_b/E_b = 5\ 10^{-5}$

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The task may be divided into three steps:

Step No. 1

Fix the kinematics and understand the Compton scattering cross section w.r.t.

- the angle α, the laser wavelength, the laser polarization for
  - a) unpolarized beam electrons at E_b = 250 GeV (46 (Z pole), 500 GeV)
  - b) polarized beam electrons (longitudinal and transverse pol.)
- include the luminosity to estimate the rate of the Compton process in a detector

➔ optimize the event rate

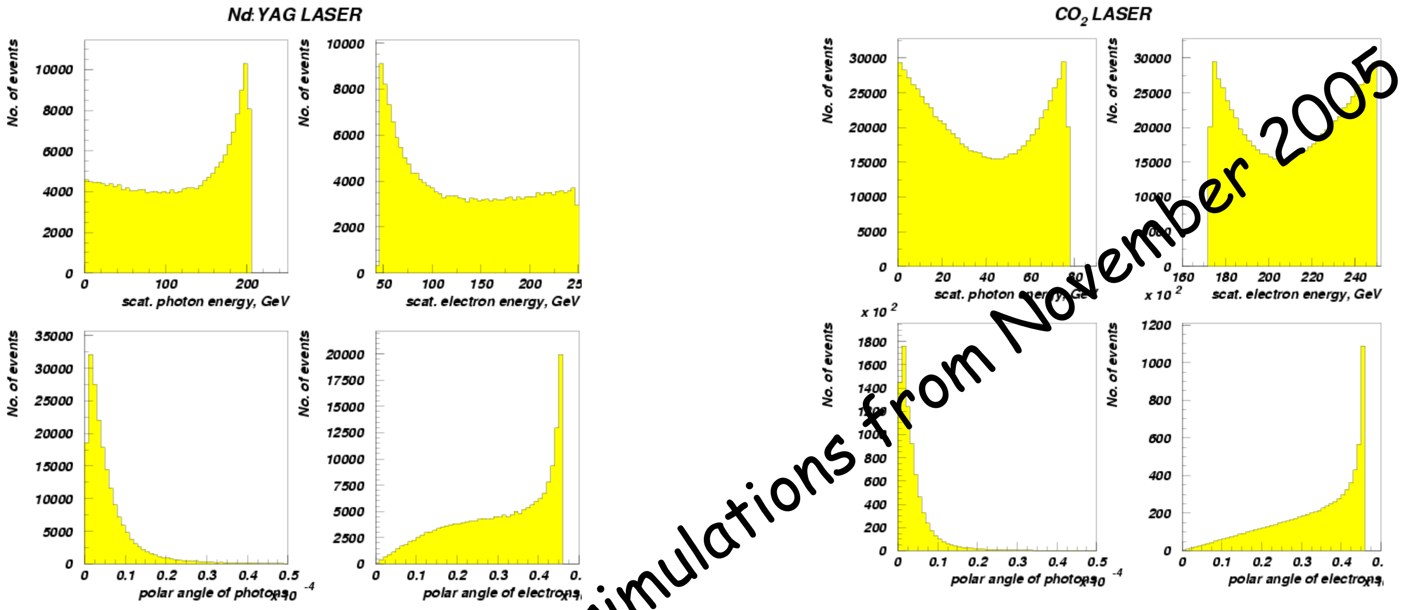
Step No. 2

Based on the results from Step No.1, design an experimental layout for precise beam energy measurement, for each bunch crossing

Step No. 3

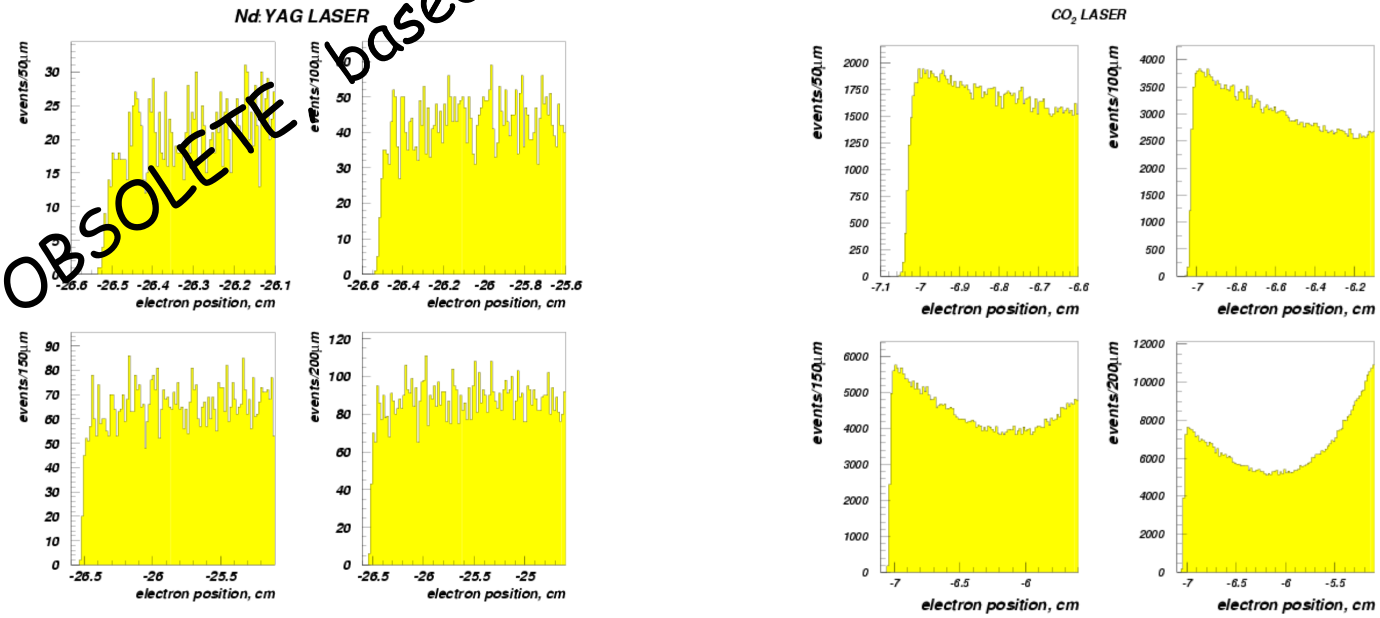
Try to have a first simulation of the experiment with GEANT

Characteristics of scattered particles:



OBSOLETE, based on simulations from November 2005

Position of the edge electrons in the detector



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Nikolai Muchnoi, May 2006, dE_γ_max/dE_laser vs. E_laser, for E_beam = 250 GeV and α = pi