Precise ILC Beam Energy Measurement using Compton backscattering

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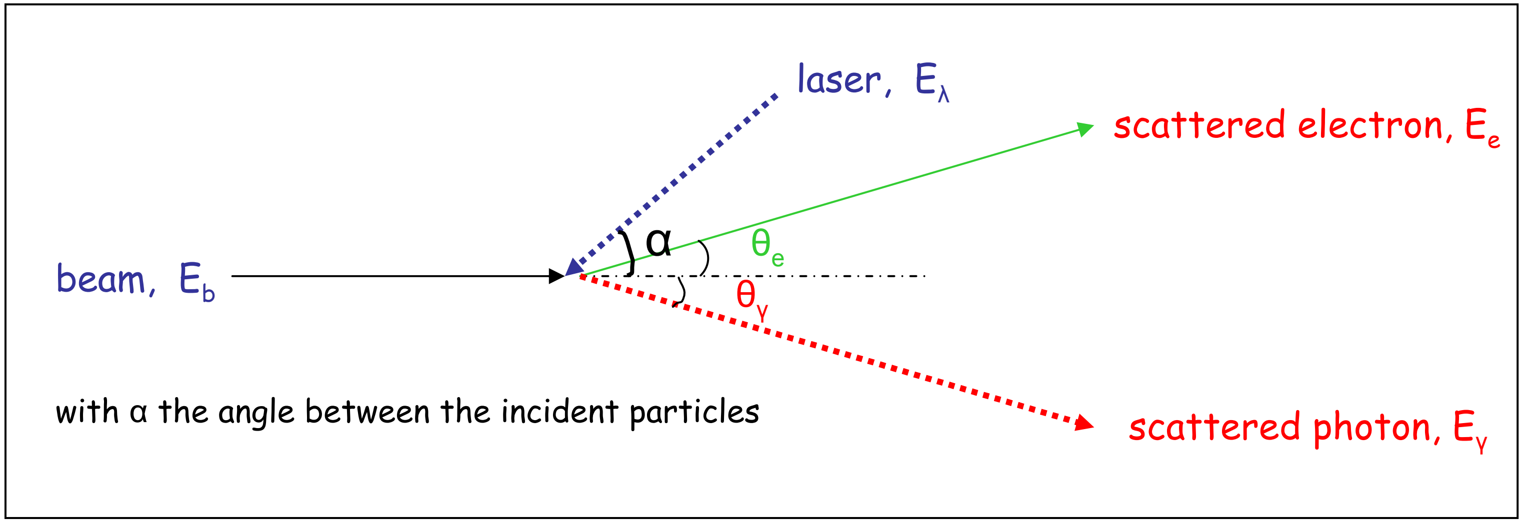
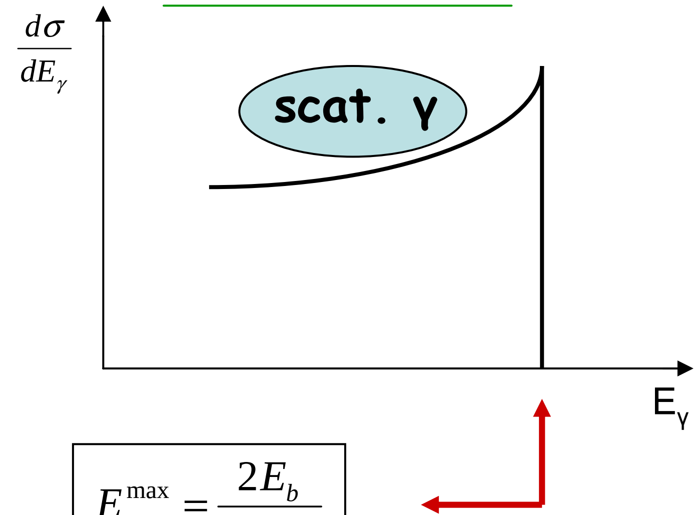
Process : $e_b + \gamma_L \rightarrow e' + \gamma'$



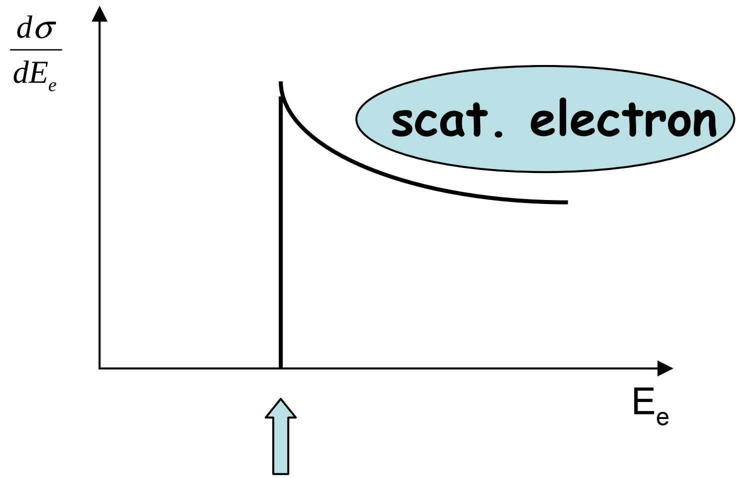
Basic properties (kinematics) of scattered photon resp. electron:

- ***sharp edges*** in the energy distribution of scattered photon and electron, with beam energy position variation
- both particles are ***strongly forward collimated***
- the ***position of the edges is not dependent on the initial polarization***

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

but $\Delta E_e < \Delta E_b$

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 (if chosen to be very small ➔ insensitive !)

Once these quantities are fixed ➔ access to the beam energy E_b via the energy of edge electrons

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

➔ ***E_e(edge) = 173 GeV and a ΔE_b=25 MeV resuts to ΔE_e = 11.9 MeV***

or Nd:YAG (green, E_L=2.33 eV)

$\Delta E_b/E_b = 10^{-4}$

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

lasers with large wavelength are preferred

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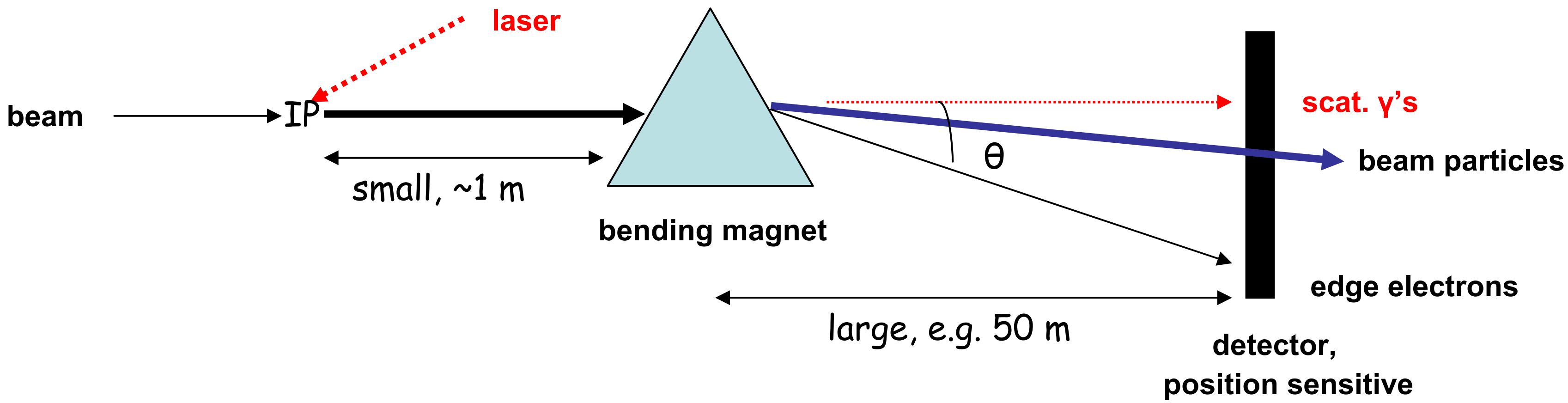
Sketch of possible experiment

- 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.

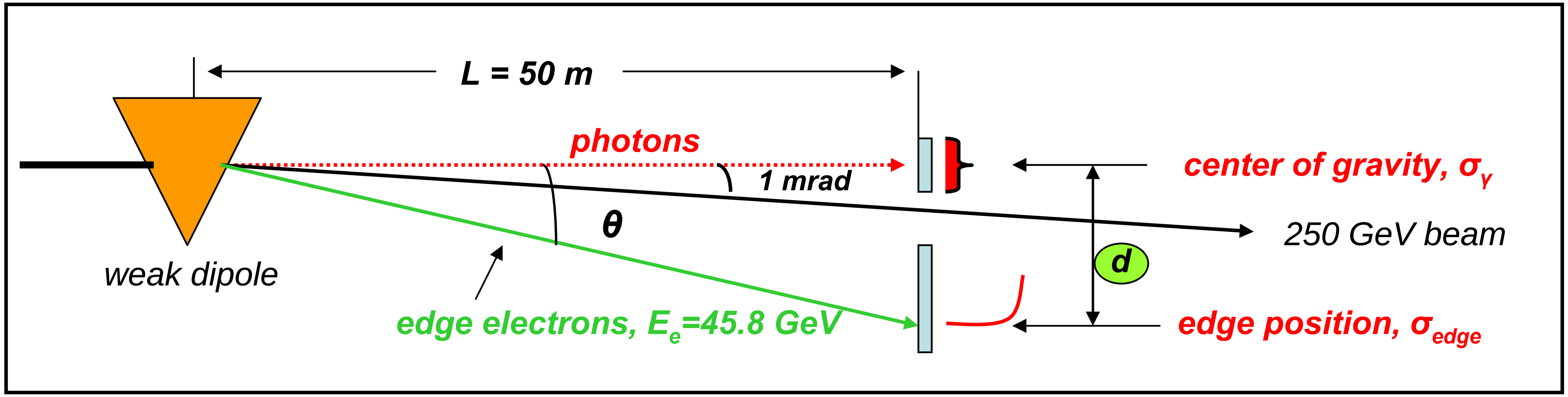
- The electrons with the largest bending angle are the edge electrons and their position in the detector should be carefully measured.



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

and infrared Nd:YAG laser (E_L = 1.165 eV)



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

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

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

with (feasible) $\Delta L/L = 5\ 10^{-6}$, $\Delta \int Bdl / \int Bdl = 10^{-5}$

one needs a precision for the distance **d** of ➔ ***Δd = 5 μm !***

to recognize a 25 MeV shift of the beam energy

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GEANT SIMULATIONS

included

- beam size 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 horizontal (x) direction; ↔
- 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

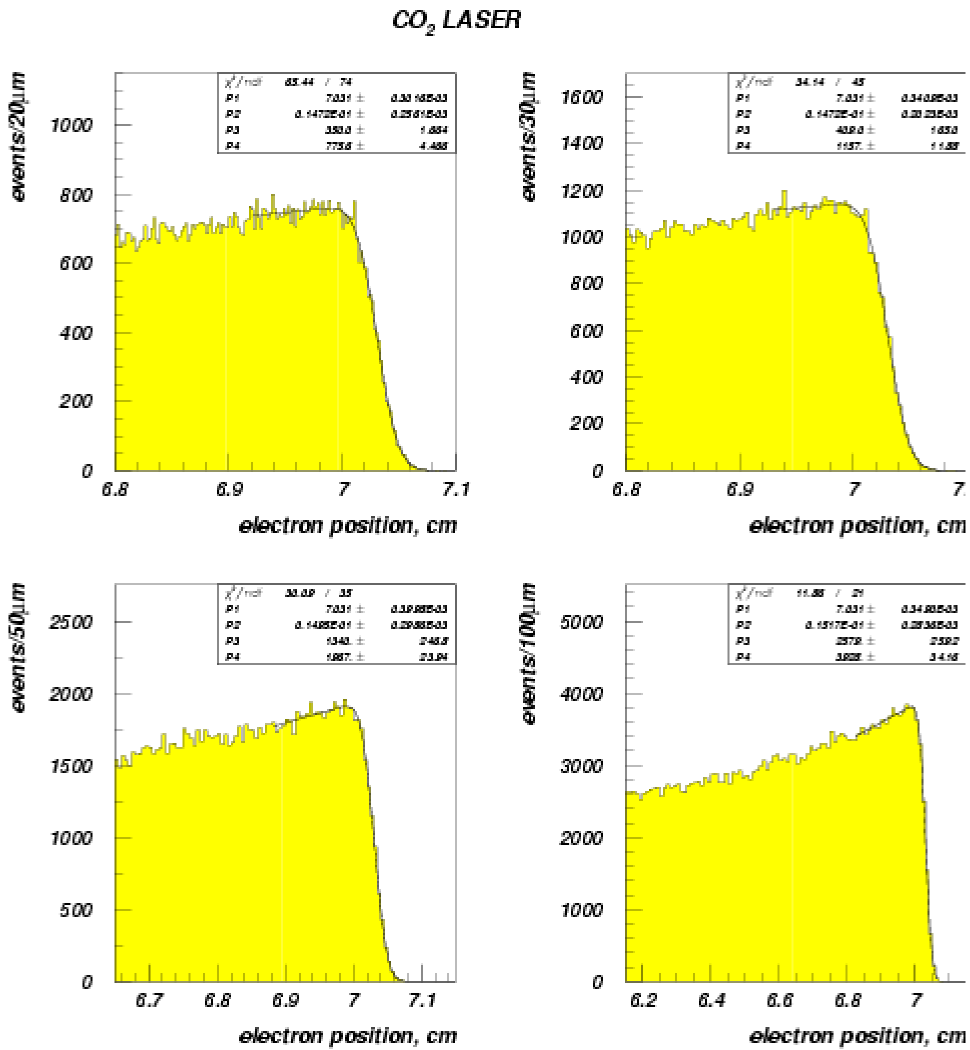
- IP position according to beam sizes in x and y
- direction of beam according to beam dispersion
- energy of beam according to beam energy spread
- direction of laser according to laser dispersion
- angle between the incoming beam and laser
  according to beam and laser directions
- laser energy according 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

Multiple photon-beam particle interactions and non-linear effects which occur during the beam-laser overlap were independently studied

(results will be discussed somewhat later)

So far, NO detector effects



The curves in the plots are the results of a fit to estimate the **endpoints of the SR fan**

fit function: step function folded by a Gaussian

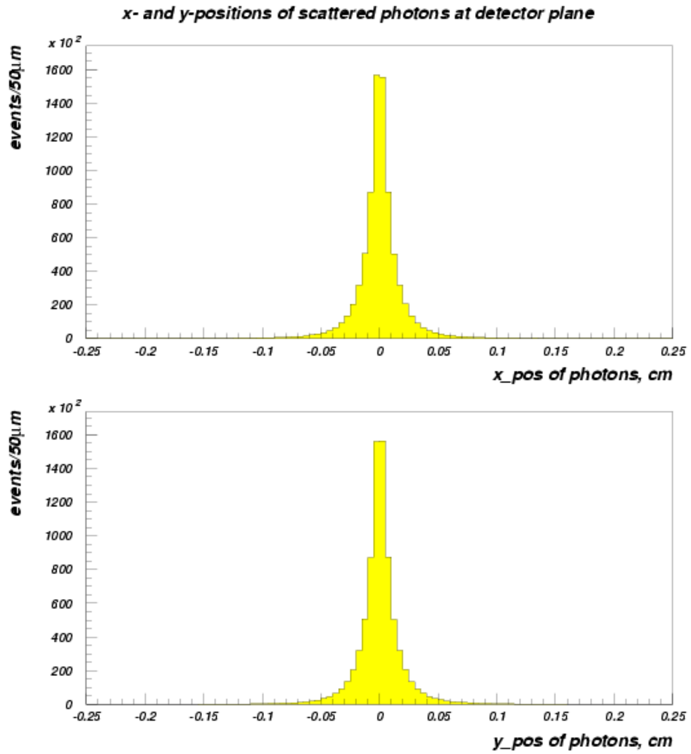
$$f(x, p_1 \ldots p_4) = \frac{1}{2}(p_2(x-p_0)+p_3) + erf\left[\frac{x-p_0}{\sqrt{2}p_1}\right] - \frac{p_1 p_2}{\sqrt{2\pi}} \cdot \exp\left[-\frac{(x-p_0)^2}{2p_1^2}\right] - p_4(x-p_0)$$

with p0 - edge position;
p1 – edge width;
p2 – slope left;
p3 – edge amplitude;
p4 – edge right

➔ **stable, robust result for p0**

Detector positions of the scattered photons (for CO_2 case):

complete smearing



no difference between smeared and non-smeared cases visible

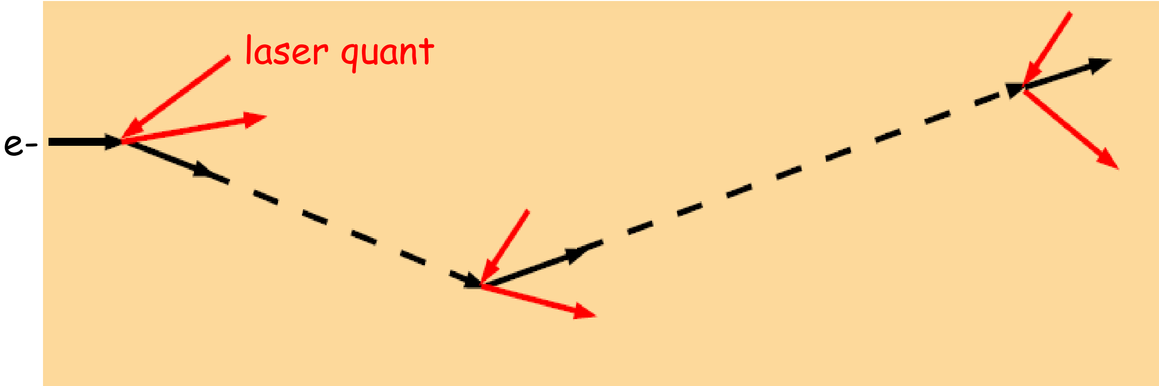
→ position of scattered photons in detector insensitive to input parameters

→ good news

So far, multiple interactions and non-linear effects which occur during the beam-laser overlap might disturb the scattered electron edge behavior NOT considered

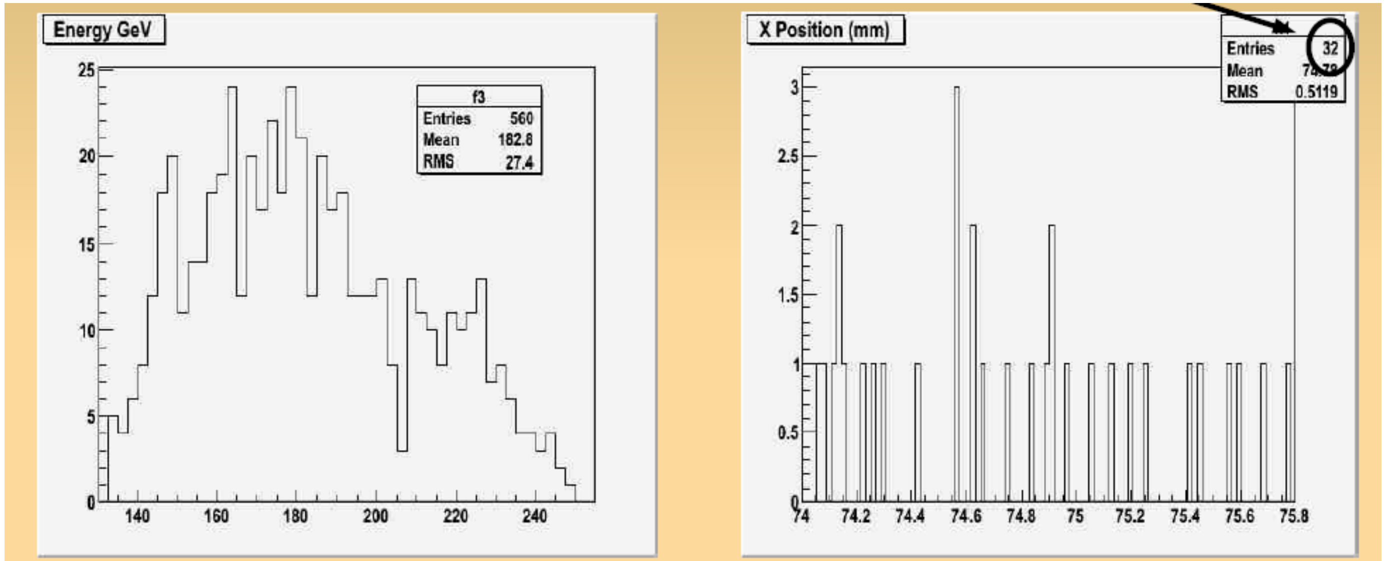
→ significant or negligible ?

Multiple Compton scattering



Using the package ***CAIN***
the fraction of electrons
with multiple interactions
is $f \sim 1 \cdot 10^{-4}$

Based on 1 Million interactions
➔ energy distribution ➔ detector position
of electrons with multiple interactions

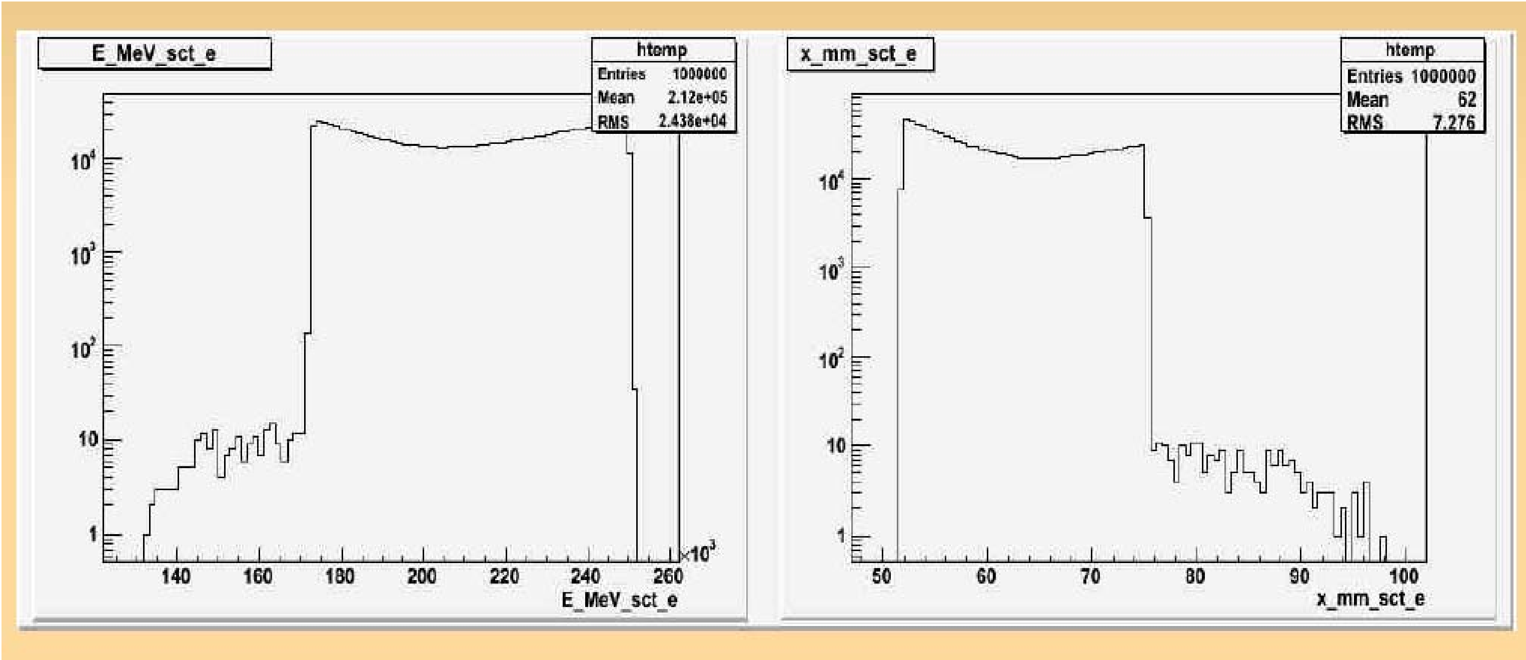


Accounting for all events

energy distribution

position in the detector

logarithmic scale



Fitting the endpoint → with multiple interactions: $X_{Edge}^{Mul} = (75.1191 \pm 0.0022)\ mm$

→ without multiple interactions: $X_{Edge} = 75.1191 \pm 0.0022\ mm$

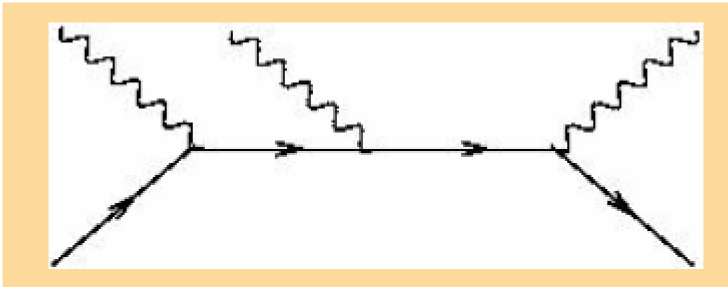
no difference

Non-linear effects

When the density of the laser resp. the field in the laser is very high the electrons can interact **simultaneously** with more than one laser photon

$$e(p) + n\gamma(k) \rightarrow e^{'}(p^{'}) + \gamma^{'}(k^{'}) \qquad (n > 1)$$

In form of an intuitive picture, the effect can be represented by Feynman diagrams like



The **strength** of the non-linear effect is usually characterized by the **quantity ξ**

$$\xi^2 = \frac{2 n_\gamma r_e^2 \lambda}{\alpha}, \; n_\gamma \; laser\ photon\ density, \; \lambda \; laser\ wavelength$$

$$r_e^2 \; classical\ electron\ radius, \; \alpha \; fine\ structure\ constant$$

i.e. by the photon density for a given laser

The impact of non-zero ξ^2 values on the backscattered photon edge behaviour is of two fold:

- it moves the position of the maximum photon energy, ω_{max}, to smaller values
- and adds some contributions in form of a small bump at energies > ω_{max}

both effects are more pronounced as larger ξ is !

for the electrons a mirror-reflected behaviour is expected

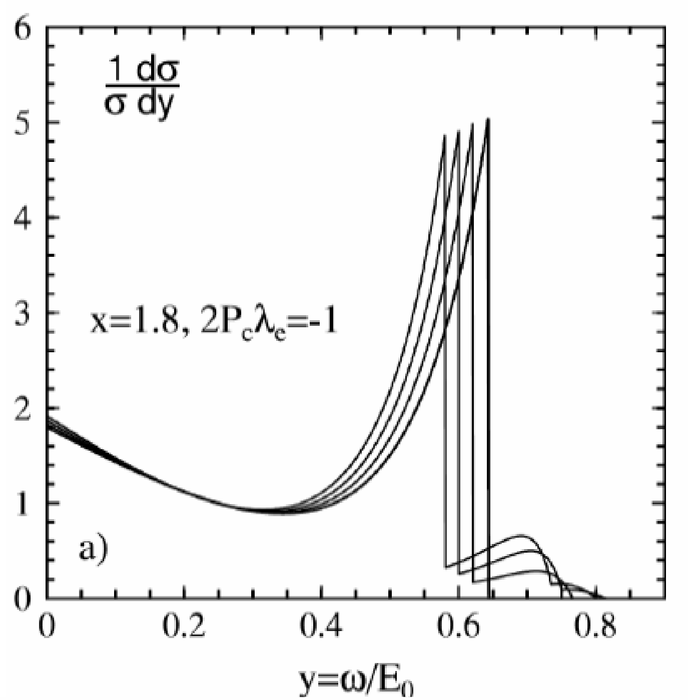


Figure taken from the TESLA Technical Design Report, Part VI

Figure 1.3.5: *Compton spectra for various values of the parameter ξ^2. Left figure is for $x = 1.8$, right for $x = 4.8$. Curves from right to left correspond to $\xi^2 = 0, 0.1, 0.2, 0.3, 0.5$ (the last for $x = 4.8$, only).*

For our laser parameters $0 \leqslant \xi^2 \leqslant 1.04 \cdot 10^{-5}$ i.e. it is very small

Hence, the ratio of the cross sections with 2 photon absorption to 1 photon absorption is estimated as

$$\frac{\sigma_2}{\sigma_1} < 10^{-5}$$

For 1 Million of events less than 10 electrons scatter absorbing 2 photons!!!

or, for the **max. value of ξ^2** the change of the electron edge energy is **~$2 \cdot 10^{-6}$ MeV**

which has no impact on the electron edge position in the detector !

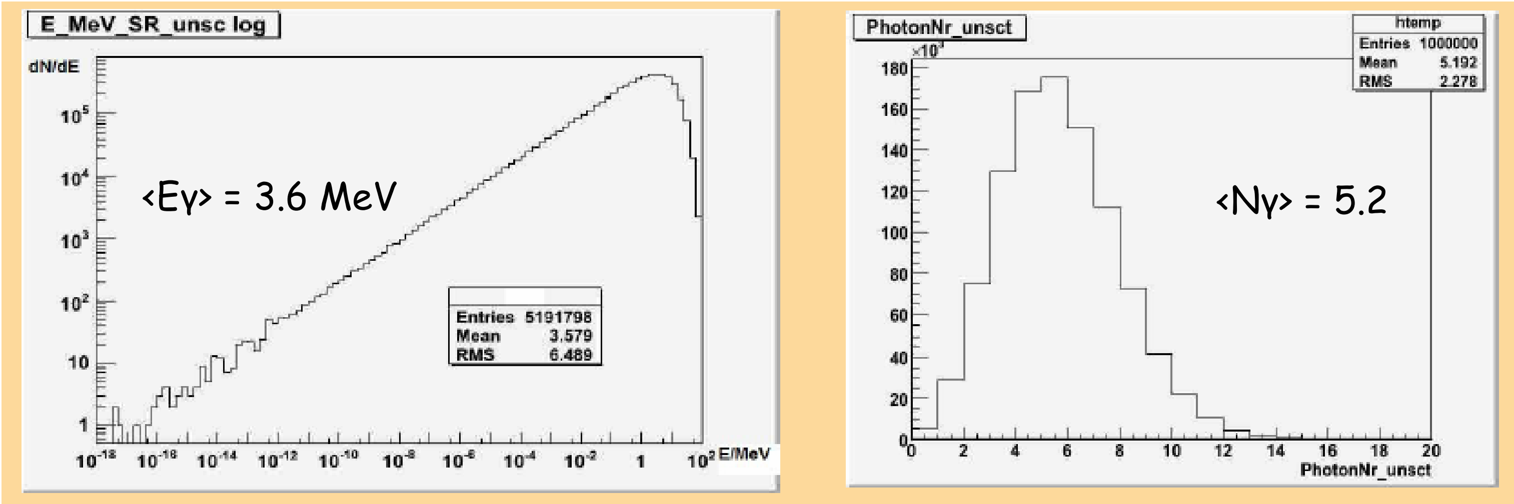
Photon detection capability

(we need the center of gravity of Compton scattered photons)

Due to the bending magnet ➔ synchrotron radiation (SR) ➔ background !

Basic properties of SR:

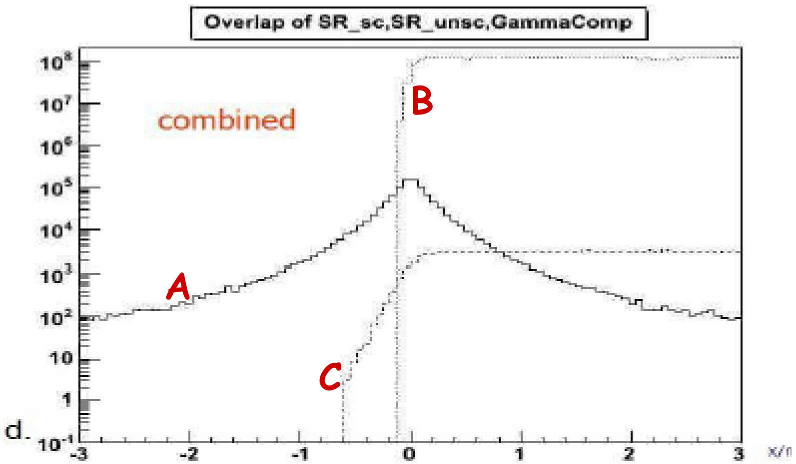
energy distribution # of photons/electron



In the detector

- backscattered Compton photons, **A**
- SR photons from unscat. beam particles, **B**
- SR photons from scattered electrons, **C**

➔ **overwhelming # of SR photons, B**



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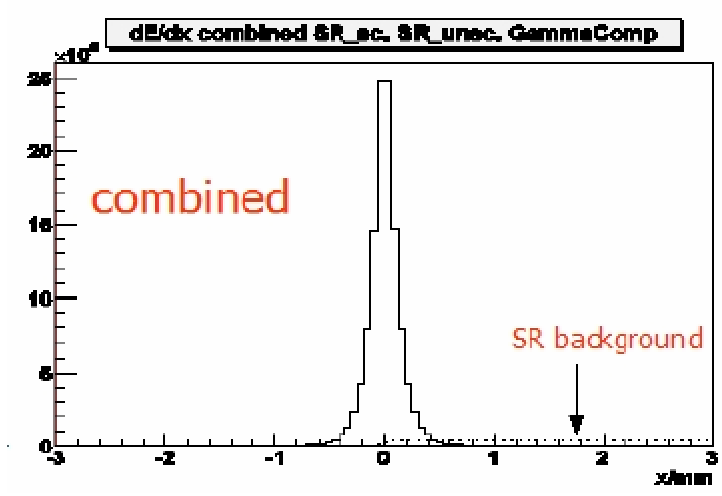
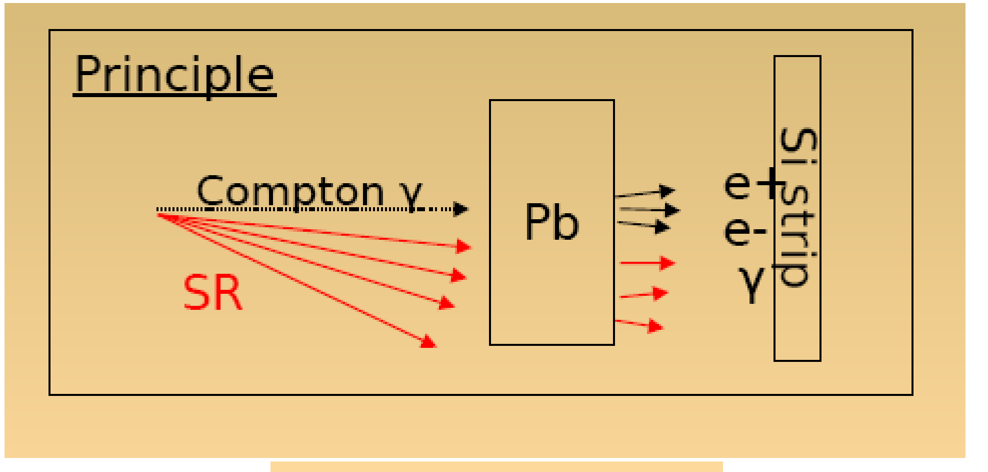
But if dE/dx is plotted

➔ SR background is negligible

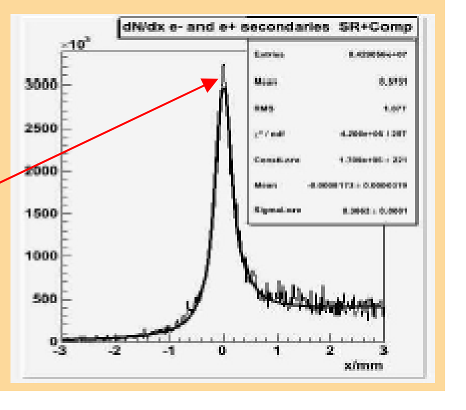
➔ calorimeter with very fine granularity, Δx = 50-100μm, is needed, **challenging**



Different approach by implementing an absorber, e.g. Pb of ~20 mm thickness, and measure the e-/e+ by Si strip detector



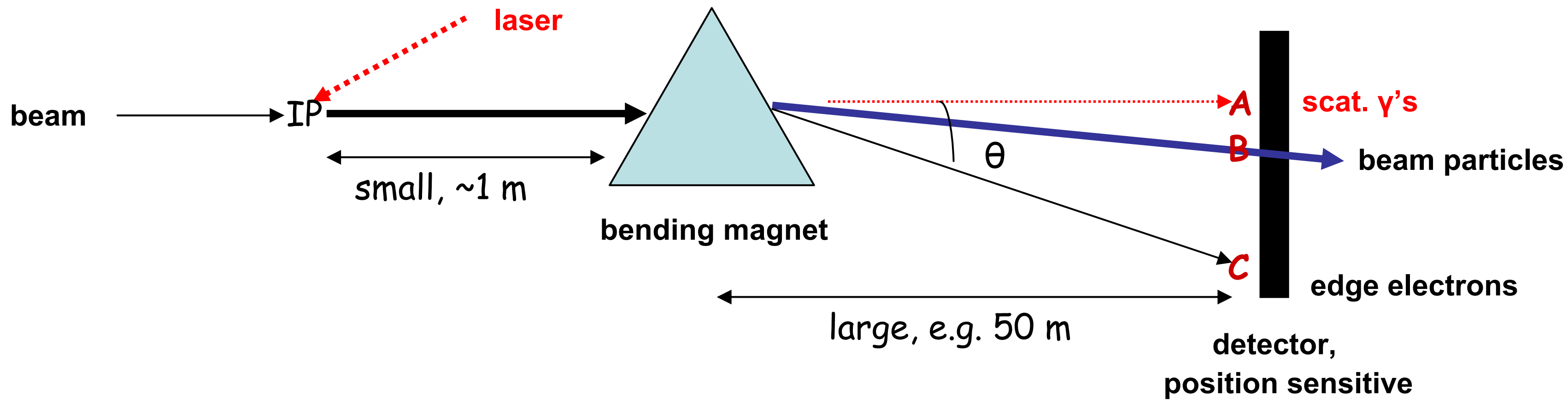
➔# of e+/e- particles in the Si detector with 50 μm pitch for 10^6 Compton scatters



The original photon peak position X_{peak} can be reproduced better than 0.5 μm

So far, we rely on measuring the **energy of the edge electrons** using precise B-field, the distance between the magnet and detector and the position difference between the scattered photons and the edge electrons

Other option:



Measure position of
- Compton photons, **A**
- position of unaffected beam particles (dedicated BPM), **B**
- position of edge electrons, **C**

the ratio of the distances **R = (A – C)/(B – C)** - linear prop. to the beam energy !

provides access to the E_b:

$$E_b = (R-1) \cdot m_e^2 / 4E_L$$

no dependence on B-field, distance 'magnet-detector' and length of magnet

Accounting for the numbers given in the example above
and a BPM position resolution of **1 μm**

→ $$\frac{\Delta E_b}{E_b} = 4 \cdot 10^{-5}$$!

Summary

- **Compton backscattering seems a promising,nondestructive and feasible option to measure the beam energy with high precision**

- promising laser options are either a CO_2 or Nd:YAG laser;
  - whether higher harmonics of the laser are advantageous has to be studied
  - Nd:YAG laser power needed is only a factor 10 off of existing lasers
  - CO_2 laser needs significant R&D !

- magnet - no problem

- detector option: Si strip detector with absorber; calorimeter (presently not promising)

- cavity BPM allows for better than 1 μm beam position measurements