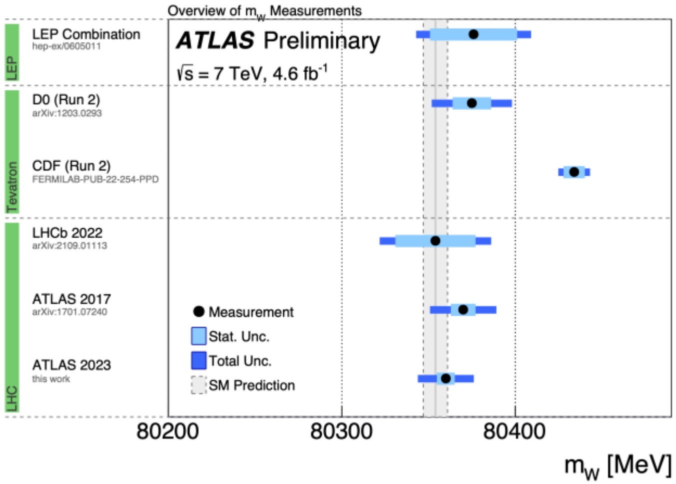
Compton polarimeters

Aurélien MARTENS (IJCLab Orsay)
On behalf of FCC-ee FS EPOL group
https://indico.cern.ch/category/8678/

Physics requirements



Observable	statistics	$\Delta\sqrt{s}_{\mathrm{abs}}$ 100 keV	$\Delta\sqrt{s}_{\mathrm{syst-ptp}}$ **40 keV**	calib. stats. $200\,\mathrm{keV}/\sqrt{N^i}$	$\sigma_{\sqrt{s}}$ $85 \pm \mathbf{0.05}$ MeV
$\mathrm{m_Z}$ (keV)	4	100	**28**	1	–
Γ_Z (keV)	4	2.5	**22**	1	**10**
$\sin^2\theta_\mathrm{W}^{\mathrm{eff}} \times 10^6$ from $A_{\mathrm{FB}}^{\mu\mu}$	2	–	**2.4**	0.1	–
$\frac{\Delta\alpha_{\mathrm{QED}}(\mathrm{m_Z^2})}{\alpha_{\mathrm{QED}}(\mathrm{m_Z^2})} \times 10^5$	3	0.1	**0.9**	–	**0.1**

Required accuracy of <1ppm

Blondel et al., arXiv:1909.12245

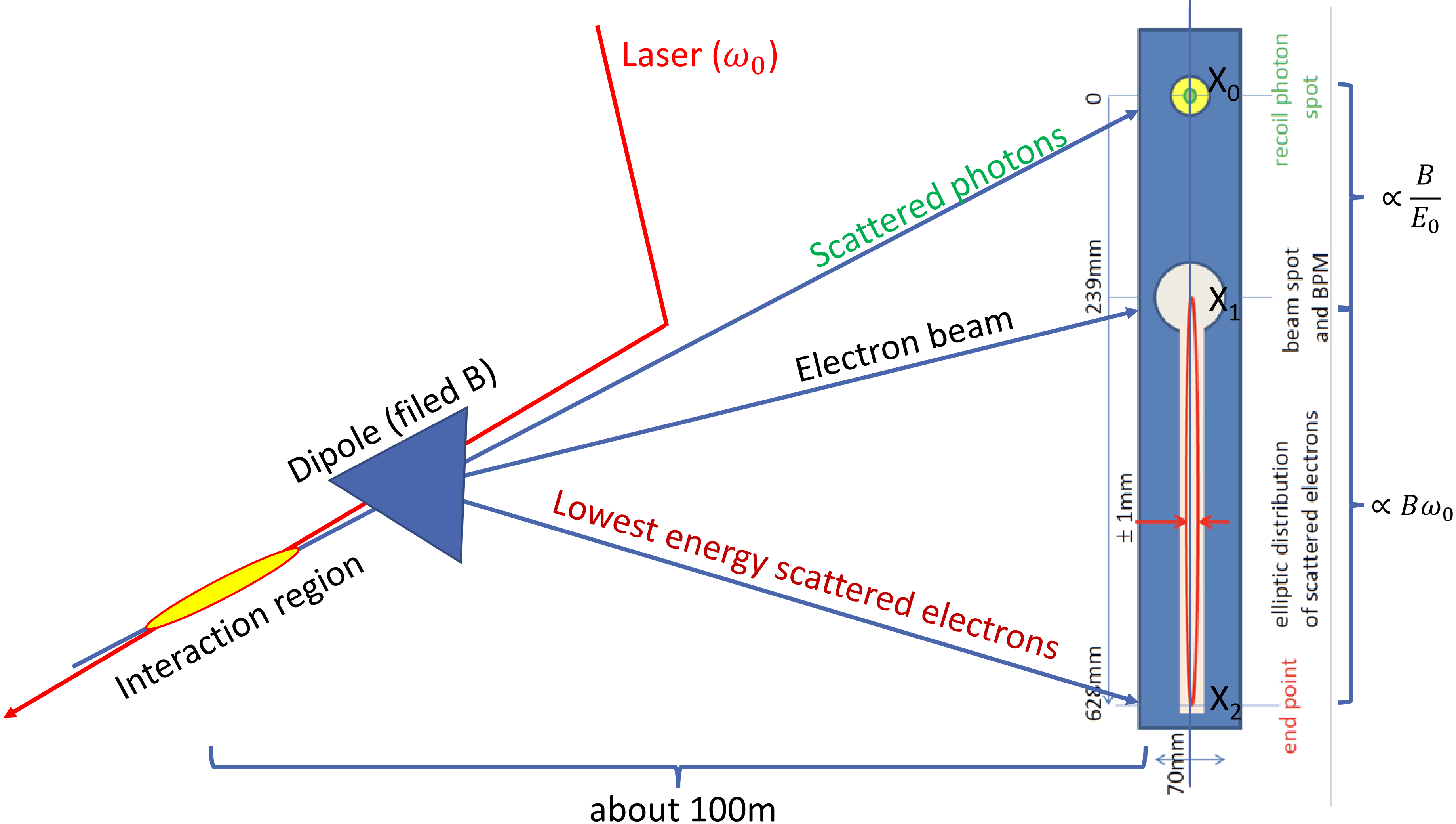
High reproductibility of measurements for various sqrt(s) is critically needed

Extract as much information as possible from physics experiments themselves (crossing angle, luminosity, sqrt(s) spread)

Beam-based measurements in real time, including beams energy with resonant depolarization

24/7 operable measurement of (de-)polarization

Compton polarimeter layout



Blondel et al., arXiv:1909.12245; Muchnoi, INST 17 P10014 (2022)

New concept (N. Yu Muchnoi) to measure all polarization parameters → 3D polarimeter

Integration

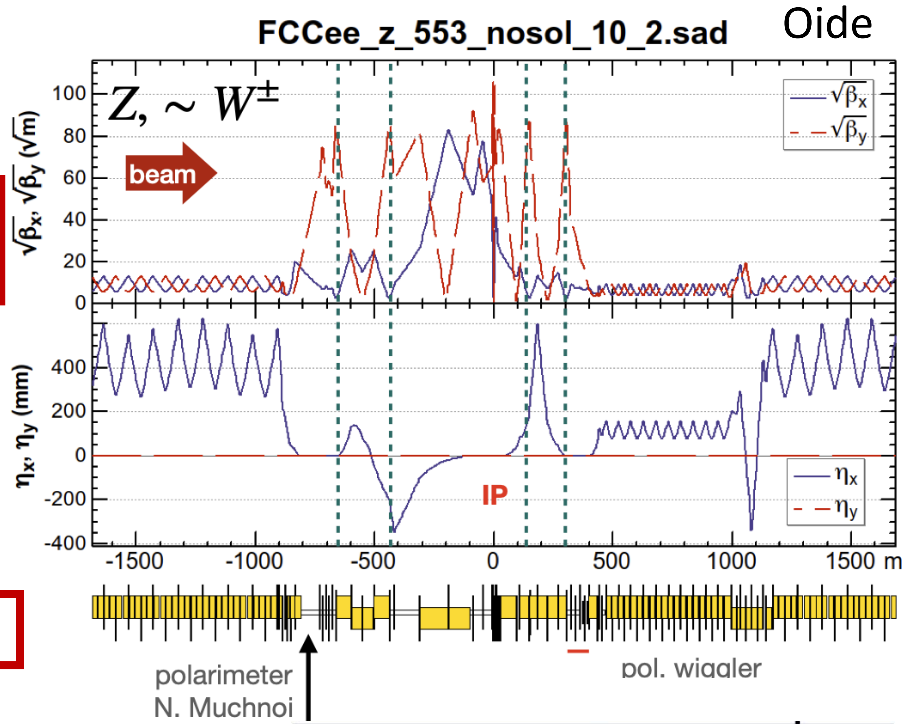
Polarimeter integrated close to experiments IP
1/beam (baseline)

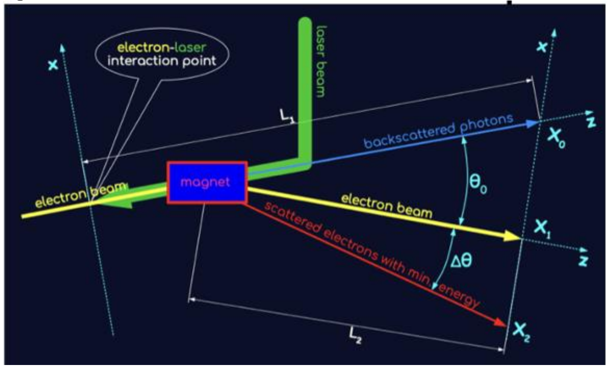
e-beam size at Compton IP :
~500µm (horizontal)

Robust laser technology is available nowadays

Demanding operational constraints
→ laser room in the parallel technical gallery
→ 24/7 access to the laser system and related electronics

Oide

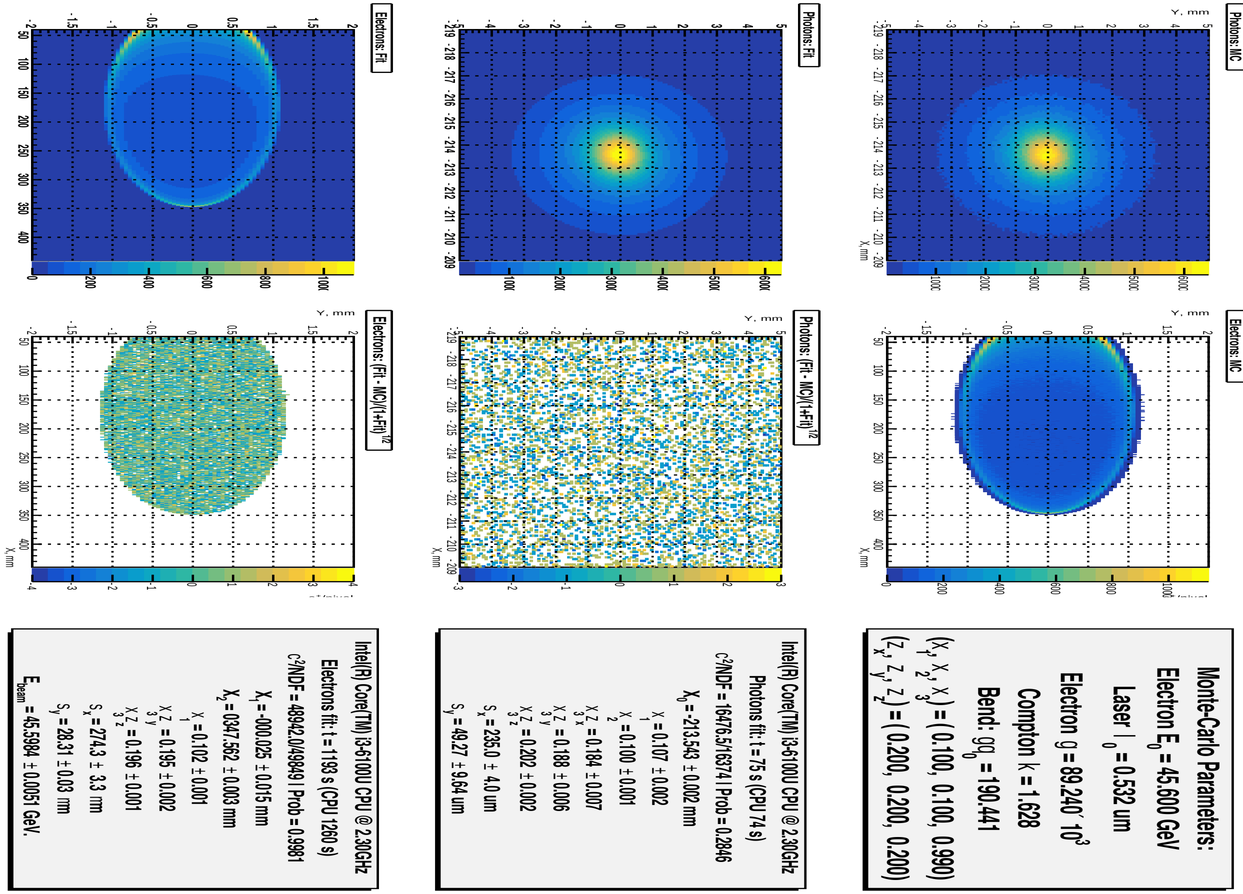




Typically obtained in 30s for a single bunch

Transverse distributions

Based on measurement of scattered particles transverse distributions (pixelized detectors)



All components extracted with ~0.001 precision in few seconds

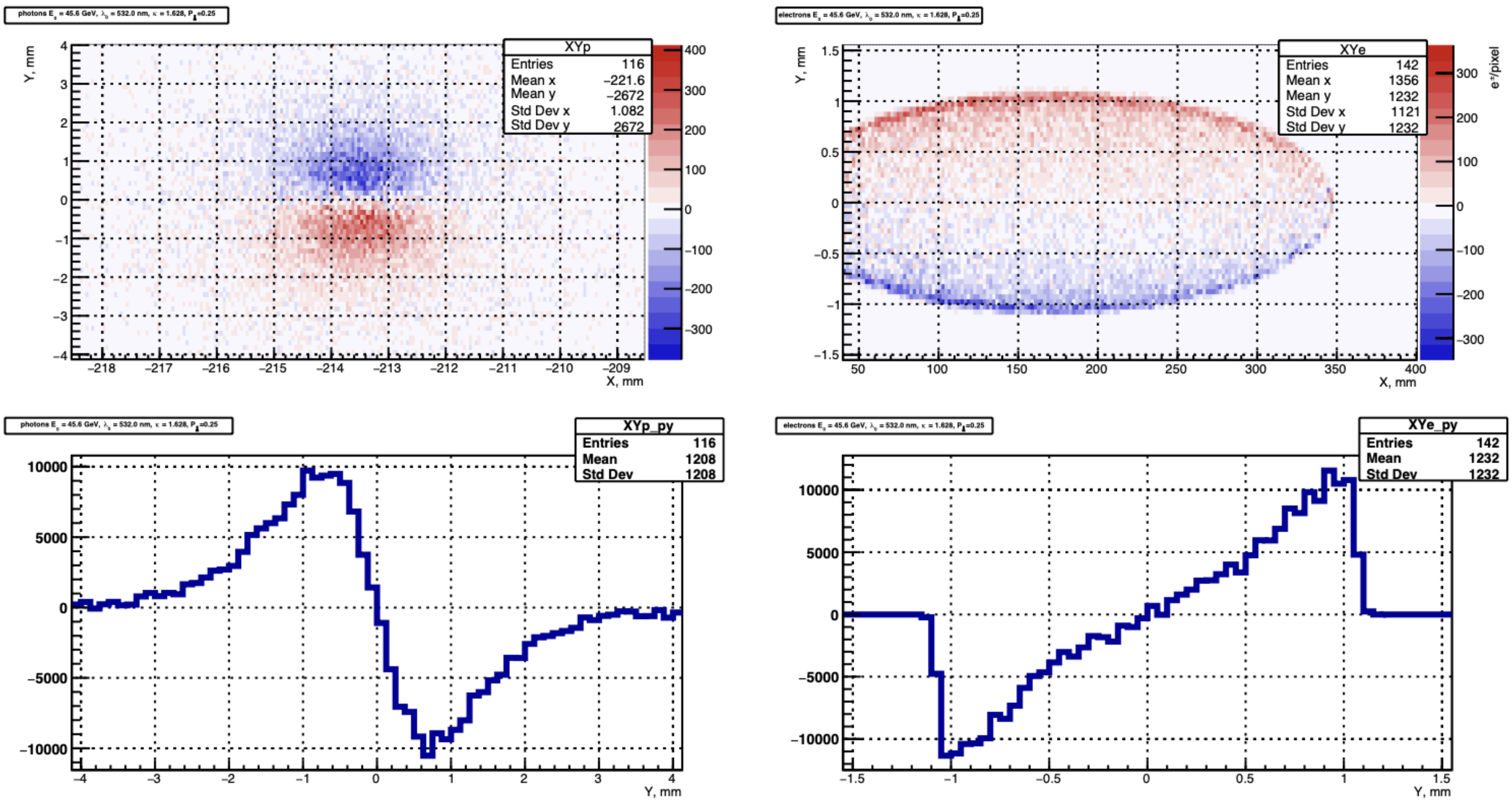
Beam energy may be extracted too! → redundancy with RDP

Realistic detector specifications (still) to be drawn

With the constraints of being tolerant to radiations

Blondel et al., arXiv:1909.12245; Muchnoi, INST 17 P10014 (2022)

Laser helicity asymmetries

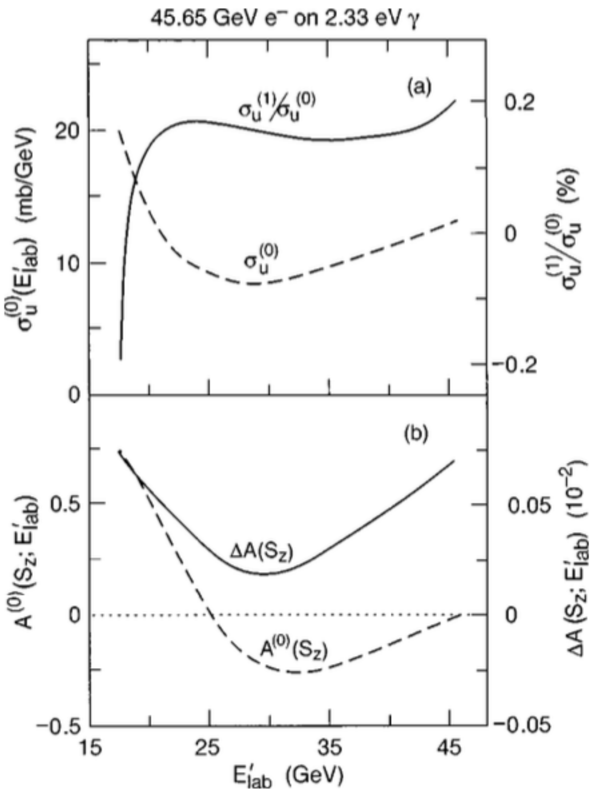


Reproductible and well known laser helicity flip is required

Blondel et al., arXiv:1909.12245

QED corrections

Studied in details at SLD



PHYSICAL REVIEW D, VOLUME 58, 014010

Complete order-α^3 calculation of the cross section for polarized Compton scattering

Morris L. Swartz
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309
(Received 24 November 1997; published 28 May 1998)

The construction of a computer code to calculate the cross sections for the spin-polarized processes $e^-\gamma \to e^-\gamma, e^-\gamma\gamma, e^-e^+e^-$ to order α^3 is described. The code calculates cross sections for circularly polarized initial-state photons and arbitrarily polarized initial-state electrons. The application of the code to the SLD Compton polarimeter indicates that the order-α^3 corrections produce a fractional shift in the SLC polarization scale of -0.1% which is too small and of the wrong sign to account for the discrepancy in the Z-pole asymmetries measured by the SLD Collaboration and the CERN LEP Collaborations.
[S0556-2821(98)03413-4]

Measurement of transverse polarization at FCCee :

photons $\frac{\delta P}{P} \approx 1 \times 10^{-3}$ (0.5×10^{-3}) at 45 (80) GeV

electrons $\frac{\delta P}{P} \approx 4 \times 10^{-3}$ (10×10^{-3}) at 45 (80) GeV

Measurement of longitudinal polarization at FCCee :

$\frac{\delta P}{P} \approx 1 \times 10^{-3}$ at 45 GeV

If and only if laser helicity asymmetries are measured

Denner & Dittmaier Nucl. Phys. B 540 (1999) 58, Swartz Phys. Rev. D 58 014010 (1998), Veltman Phys. Rev. D 40 2810 (1989), Veltman Phys. Rev D 42 1856E (1990);
A. Martens et al 2023 JINST 18 P10001

Magnetic field tolerancing

Many potential sources of 'bending angle' uncertainties (for instance genuine inhomogeneities of B-field, short-/long-term fluctuations of currents, temperatures, alignments)

Over the useful aperture of the magnet: $$\frac{\sigma(\int B_y dl)}{\int B_y dl} \ll 2 \times 10^{-4}$$

Fringe fields also may affect performance of polarimeter

$$\int B_x dl \ll \frac{\sigma_y \gamma}{L_2} \frac{mc}{q} \approx 1.1 \times 10^{-4} \text{ T.m and}$$
$$\int B_z dl \ll \frac{\sigma_y \gamma}{L_2 \kappa \theta_0} \frac{mc}{q} \approx 3.2 \times 10^{-2} \text{ T.m.}$$

Nominal vertical field for reference:

$$\int B_y dl = \theta_0 \gamma \frac{mc}{q} \approx 0.3 \text{ T.m.}$$

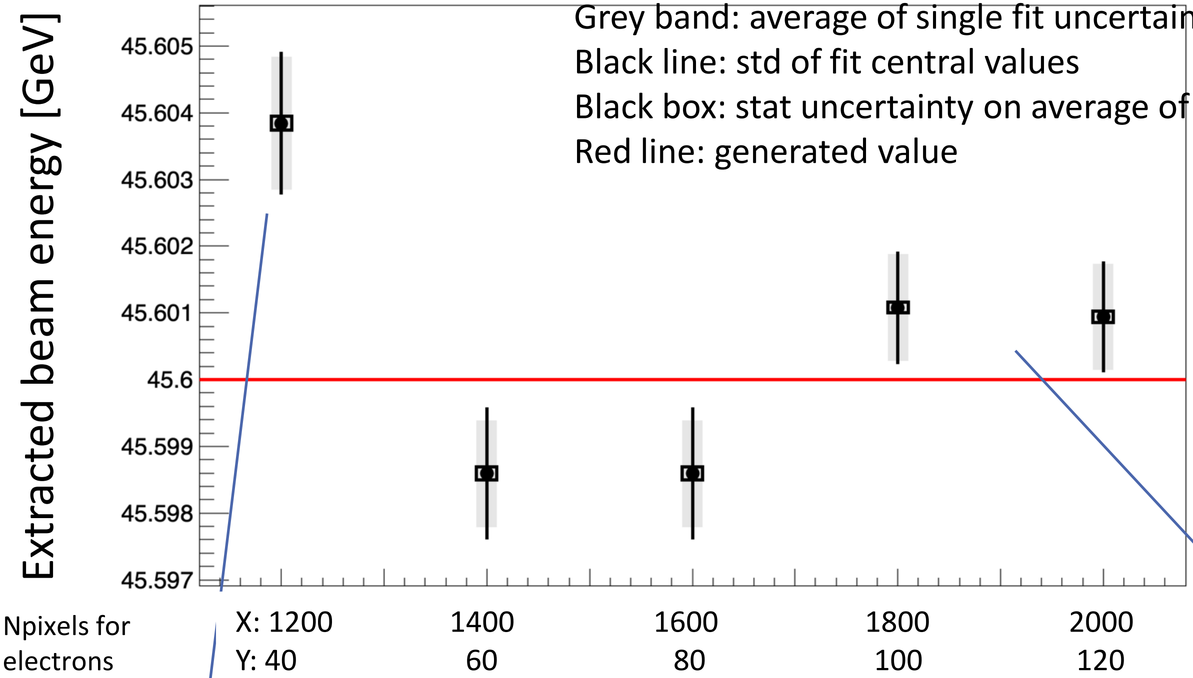
By product: angular alignment $$\delta_B \ll \frac{\sigma_y \gamma}{L_2 \int B_y dl} \frac{mc}{q} \approx 370\ \mu\text{rad.}$$

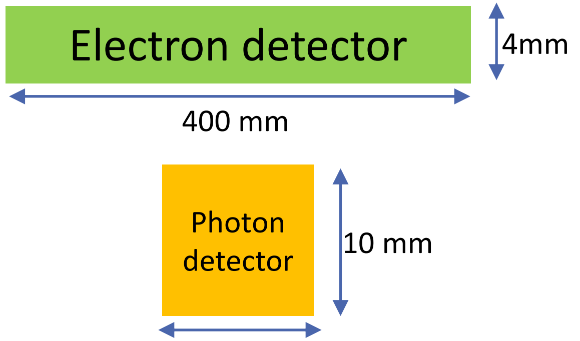
NB: Requirements not met → not a show-stopper but detailed studies required

Preliminary study of pixel size

A toy MonteCarlo procedure is applied (100 experiments, 10^8 events each)
Fit results for few different pixel sizes

Dot: average of fit central values
Grey band: average of single fit uncertainties
Black line: std of fit central values
Black box: stat uncertainty on average of fit central values
Red line: generated value



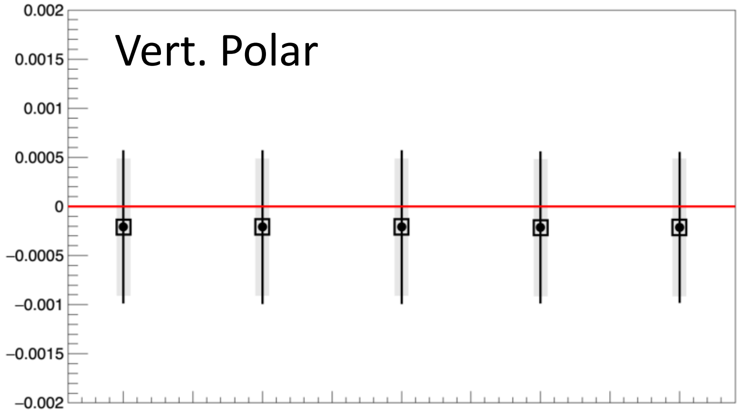


Biased extrapolation of the 'beam' position

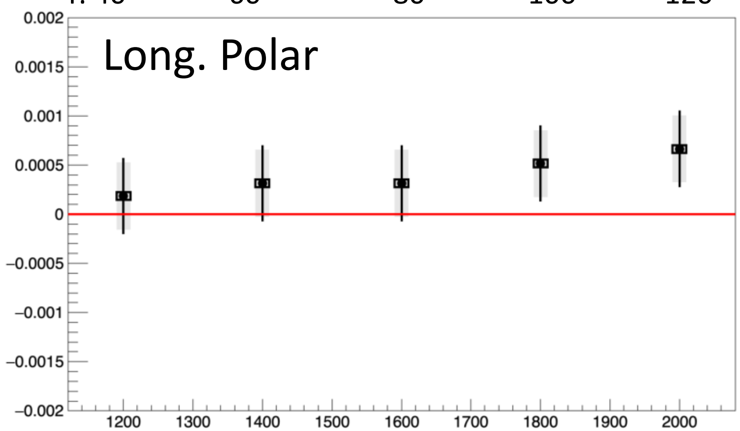
The fit ellipse gets larger & the beam spread gets smaller → likely inconsistency between model and data (some approx. made for the fit)

Polarization extraction: performance

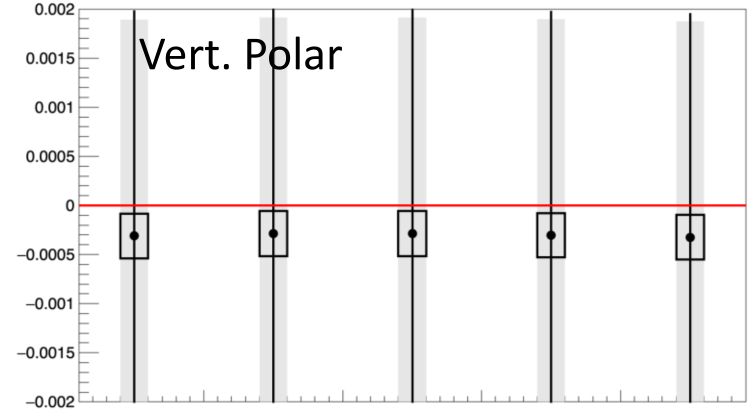
Electron detector



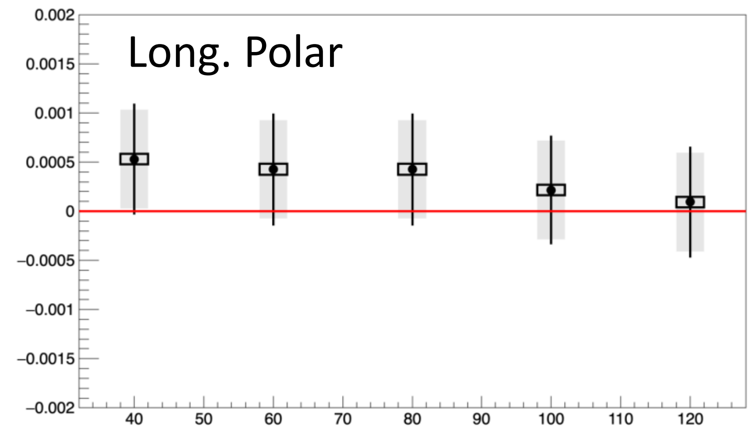
Pixels: X: 1200 1400 1600 1800 2000
Y: 40 60 80 100 120



Photon detector



Pixels: X: 40 60 80 100 120
Y: 40 60 80 100 120



Bias (~2-6 10^{-4}) → work in progress to understand

Conclusion & prospects

High accuracy and precision beam energy measurement with pilots
24/7 operable Compton polarimeters (1/beam)

Versatile industrial and robust laser system

Ability to access lasers during operations

Laser beam transport

Real time laser polarization monitoring

R&D

Magnet tolerancing

Magnet design

Pixel detectors tolerancing

Pixel detectors design

Just starting

Assessment of systematic uncertainties

Started, but huge task

backup

Physics requirements cont'd

Wilkinson at EPOL workshop https://indico.cern.ch/event/1181966

Importance of longitudinal polarisation measurement

Any residual longitudinal-polarisation will bias cross sections & forward-backward asymmetries (indeed, high longitudinal polarisation is actually useful, but we assume we are not in that regime – rather longitudinal polarisation is a nuisance).

Consider forward-backward asymmetry of $b\bar{b}$ at Z pole: $A^b_{\rm FB} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_b$

where in the SM $\mathcal{A}_e \approx 0.15, \quad \mathcal{A}_b \approx 0.95 \Longrightarrow A^b_{\rm FB} \approx 0.11$

Now, if there is longitudinal polarisation, asymmetry becomes: $(A^b_{\rm FB})^{/} = \frac{3}{4}\mathcal{A}^{/}_e\mathcal{A}_b$

where $\mathcal{A}^{/}_e = -\left(\frac{\mathcal{A}_e - P}{1 - \mathcal{A}_e P}\right)$ with $P = \frac{(P_z)_{e^-} - (P_z)_{e^+}}{1 - (P_z)_{e^-}(P_z)_{e^+}}$

and $(P_z)_{e^\pm}$ the longitudinal polarisation of the $e^\pm$.

21/9/22 EPOL requirements at FCC-ee Guy Wilkinson 17

Importance of longitudinal polarisation measurement

Any residual longitudinal-polarisation will bias cross sections & forward-backward asymmetries (indeed, high longitudinal polarisation is actually useful, but we assume we are not in that regime – rather longitudinal polarisation is a nuisance).

So, if $(P_z)_{e^-} = (P_z)_{e^+}$ (no reason to be so) = 10^{-5} (ballpark guess)

$$P = 2 \times 10^{-5} \quad \Longrightarrow \quad \frac{(A^b_{FB})^{/} - A^b_{FB}}{A^b_{FB}} = 1.3 \times 10^{-4}$$

Statistical uncertainty on $A^b_{\rm FB}$ around 2 x 10^{-5} (relative), and QCD uncertainty which will probably be larger. Still, to be safe we would want to control P_Z to < 10^{-5}.

How is this to be done ? Measurements must be made on colliding bunches, where scattering rates are lower. Can we sample all bunches ? Will it prove necessary to depolarise the physics bunches ? If so, we will still need to monitor residual effects. And what are the systematics on an absolute measurement ?

Note also, that calculations required to transport the measurement of 3-vector at polarimeter to P_Z value at the interaction points. How can this be cross checked ?

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High accuracy longitudinal polarization measurement is needed

→ Naturally small at IPs but with what accuracy ?

→ Measure it !

Compton cross-section

Fig. 1. Tree diagrams for $e^- \gamma \rightarrow e^- \gamma$

Berestskii & Lfshitz QED textbook

$$x = \frac{2E_0 \omega_0}{m^2}(1 + \cos\alpha) \qquad y = \frac{E_\gamma}{E_0}$$

The Compton cross-section averaged over scattered particles spins:

Differential cross-section

Transverse laser polarisation: nuisance parameter to minimize and keep under control

Transverse electron beam polarisation: intervenes as an asymmetry in the transverse plane

$$\frac{d\sigma}{dy d\varphi_{obs}}(x,y) = \frac{d\sigma_0}{dy}(x,y) + \frac{d\sigma_\perp}{dy}(x,y)\cos\big(2(\varphi_{obs} - \varphi_{las})\big)\mathcal{P}_L^{las} + \frac{d\sigma_\parallel}{dy}(x,y)\mathcal{P}_C^{las}\big(P_T f_T(x,y)\cos(\varphi_{obs} - \varphi_{elec}) + P_z f_z(x,y)\big)$$

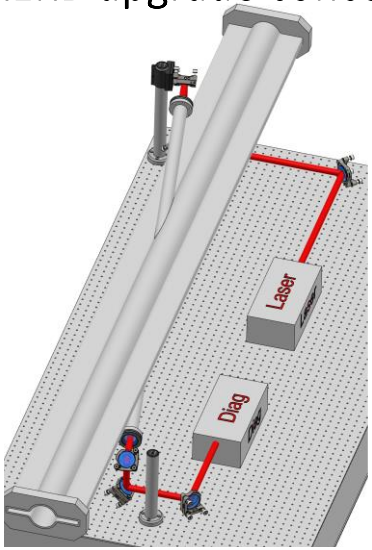
Electron beam polarization independent

Electron beam polarization dependent

⚠ But small opening angle of scattered particles:

- Electrons → spectrometer
- Photons → difficult to measure asymmetric distribution of a narrow spot → long lever arm needed

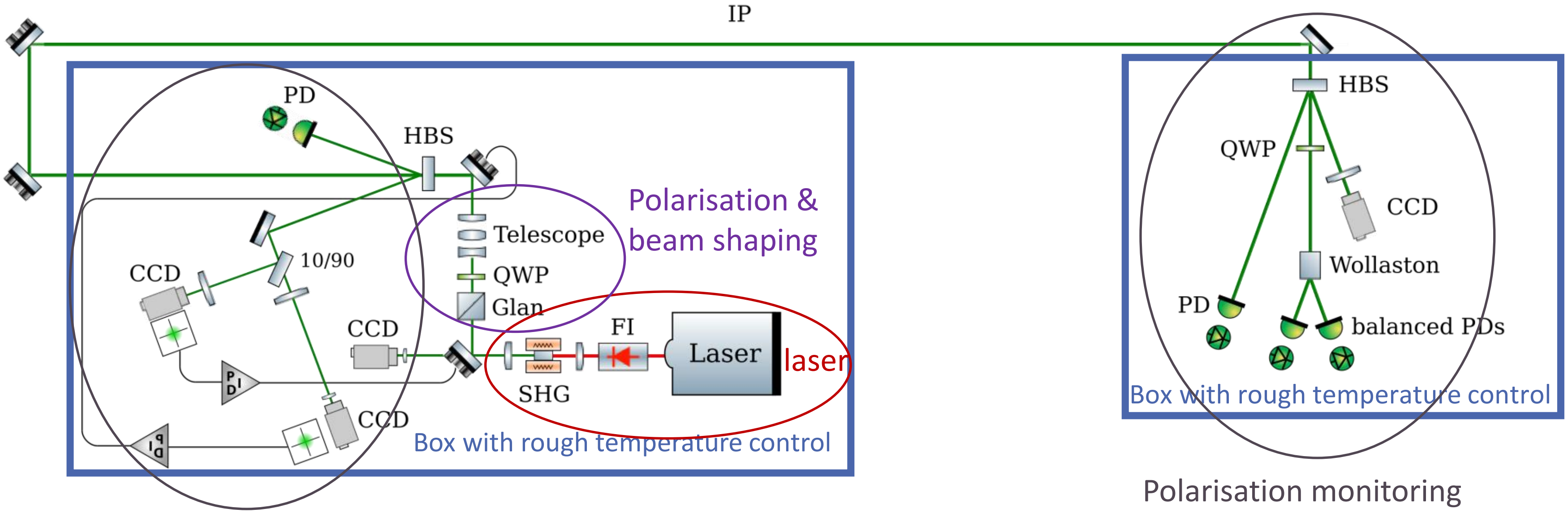
SuperKEKB upgrade concept



Laser integration

Some constraints

- Small crossing angles are preferred (cross-section, beam jitters) few mrad typically
- Beams crossing plane neither horizontal nor vertical
- beam impedance
- beam induced currents in metallic parts ← avoid
- mechanical stability
- ease of maintenance works



Position, pointing control and monitoring
Polarisation independent intensity monitoring
Optical spectrum monitoring possible

Polarisation monitoring
Duplicated at injection
Add Position and pointing monitoring
R&D needed to reach required perf.

24/7 operable laser system, with full monitoring, remote control

Some laser systems

Nikolai's baseline (Q-switch Nd-YAG)

Versatile Yb system

Laser param.	1 pilot	1 pilot v2	All colliding bunches (at Z)
Repetition rate	3 kHz	3 kHz	30 kHz
Pulse energy	1 mJ	1 mJ	10x0.05mJ
Pulse duration	3 ns	30 ps (**)	30 ps
Average power	3 W	3 W	15 W (***)
Scattering rate	3×10^5/s (*)	3×10^5/s (****)	4×10^7/s (****)
Scattering rate per bunch	3×10^5/s (*)	3×10^5/s	4×10^5/s

adaptable

Same oscillator may be used but two different amplification schemes

(*) crossing angle ~ 2mrad
(**) related to optical bandwidth ← constrains resolution of 'direct' energy measurement from polarimeter
(***) Can be increased to typically ~100W (nowadays) but requires operational validation
(****) not limited by Piwinski contribution → can be several degrees without affecting rate

Scattering rates

Laser-beam single pulse energy

Compton cross-section

Electron bunch charge
(25nC for colliding bunches,
1.5nC for pilots)

Geometrical factor

Photon rate $n = \sigma_C \frac{\mathcal{E}}{E_\lambda} \frac{Q}{q} \frac{\mathcal{F}}{2\pi\sigma_y\sigma_x}$

- $\mathcal{F}^{-1} = \sqrt{1 + \left(\frac{\sigma_z}{\sigma_x}\tan\frac{\theta_0}{2}\right)^2}$
- $\theta_0 \sim 2mrad$

Laser photon energy
(2.4eV for 0.5µm wavelengths)

Transverse beam sizes:

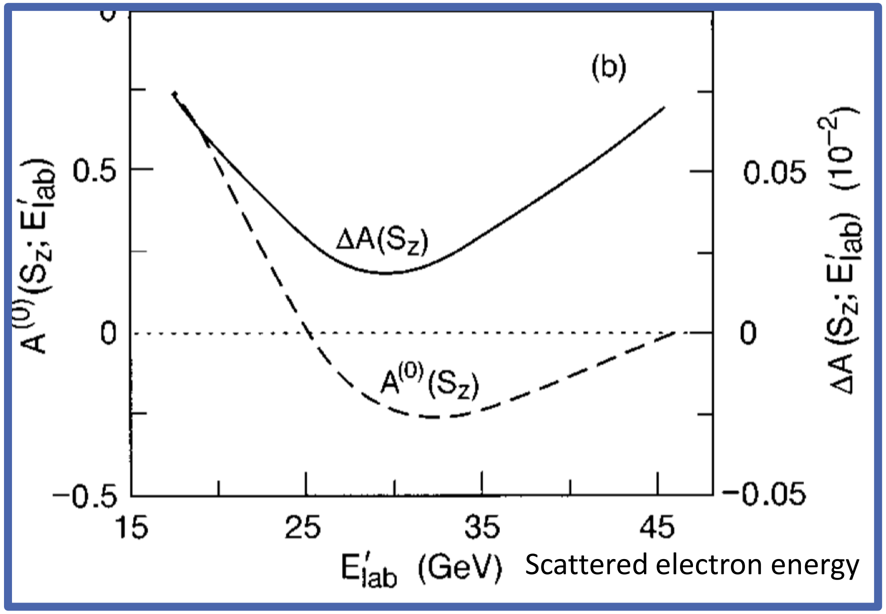
- $\sigma_{x,y,z} = \sqrt{\sigma^2_{x,y,z,laser} + \sigma^2_{x,y,z,e-}}$
- $\sigma_{x,laser} = \sigma_{y,laser}$=1000µm
- $\sigma_{x,e-}$ = 500µm, $\sigma_{y,e-}$=10µm, $\sigma_{z,e-}\sim$10mm

Involved processes eγ→ eγ, eγ→eee, eγ→ eγγ

QED corrections

$$\frac{d\sigma}{dE'}(E') \cong \frac{d\sigma_0}{dE'}(1+\delta)\left[1+\mathcal{P}_z\mathcal{P}_{C,las}(A+\Delta A)\right]$$

QED corrections<0.001 @ 45 GeV

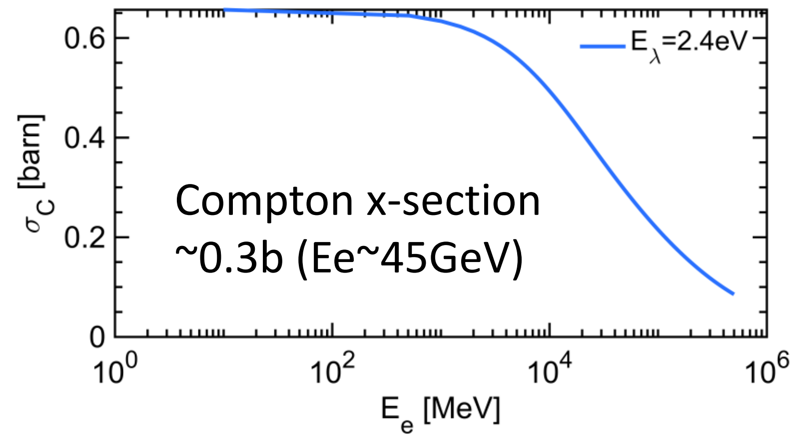


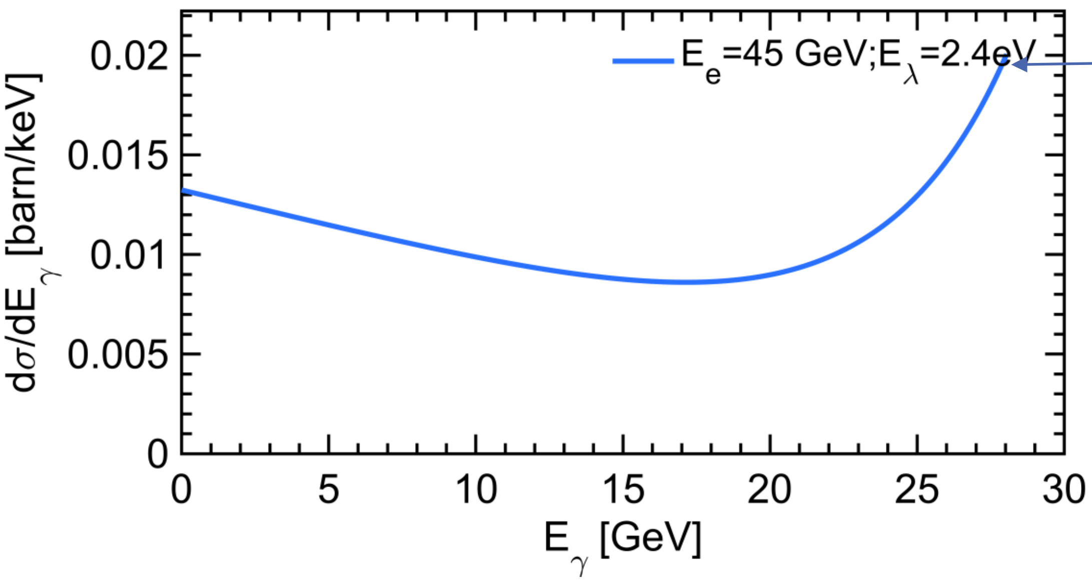
Need to be eventually included in simulations…

Denner & Dittmaier Nucl. Phys. B 540 (1999) 58, Swartz Phys. Rev. D 58 014010 (1998), Veltman Ophys. Rev. D 40 2810 (1989), Veltman Phys. Rev D 42 1856E (1990)

The Compton process

Fig. 1. Tree diagrams for $e^- \gamma \to e^- \gamma$





Kinematic edge

Klein O. and Nishina Y., Z. Phys. 52(1929) 853; Ginzburg I. et al., Nucl. Instr. Methods in Phys. Research 219 (1984) 5, V. B. Berestetskii, E. M. Lifshitz, L. P. Pitaevskii (1982). Quantum Electrodynamics. Vol. 4 (2nd ed.)