On polarimeter study for CEPC

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On behalf of CEPC Beam Polarization Working Group

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Outline

- Motivation
- Technique to measure the polarization
- Compton scattering physics
- Compton polarimeter simulation
- Layout discussion
- Conclusion

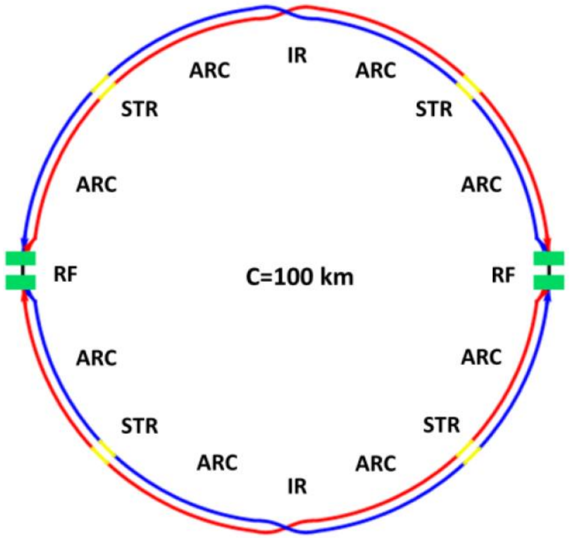
Motivation

➢ Polarization of spin-1/2 particles

- Spin is an intrinsic property of particles
- For electron/positron, Quantum number of spin is : $\pm 1/2$
- Relation to Anomalous magnetic moment(G) and nuclear physics, nuclear structure
- Beam polarization is an observable and is the ensemble average of a beam of spin-1/2 particles, e+, e-, etc.
- The degree of the polarization is defined:

$$\mathrm{P} = \left| \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} \right|$$

$N_{\uparrow}$ $N_{\downarrow}$:is the "up" and "down" state



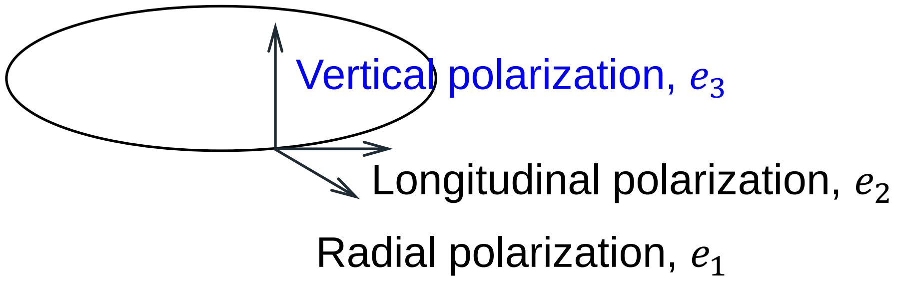


Fig. Sketch of the coordinate basis for a planar ring

Ref: CEPC-CDR; CEPC pre-CDR; K. Oide, arXiv:1610.07170; M. Zobov et al, Phys. Rev. Lett. 104, 174801(2010); A. Milanese, PRAB 19, 112401 (2016);

Ref: Rep. Prog. Phys. 68 (2005) 1997–2265

Motivation

➢ Vertically polarized beams in the arc

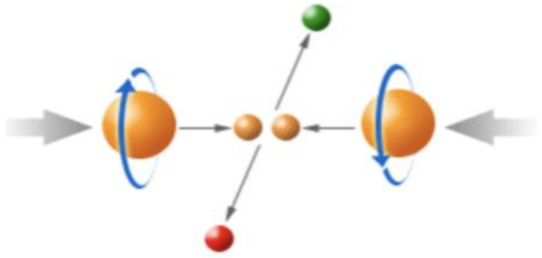
- Beam energy calibration via the resonant depolarization technique
- Essential for precision measurements of Z and W properties
- At least 5% ~ 10% vertical polarization, for both e+ and e- beams

Ref: Soviet Physics Uspekhi **14** (1972) 695.

➢ Longitudinally polarized beams at IPs

– Beneficial to colliding beam physics programs at Z, W and Higgs

– ~50% or more longitudinal polarization is desired, for one beam, or both beams



Ref: Zhe Duan, "Longitudinal polarized colliding beams at CEPC", 65th ICF Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders (eeFACT2022), September 12-15 2022

Introduction of polarization

- spin dynamics in circular accelerators

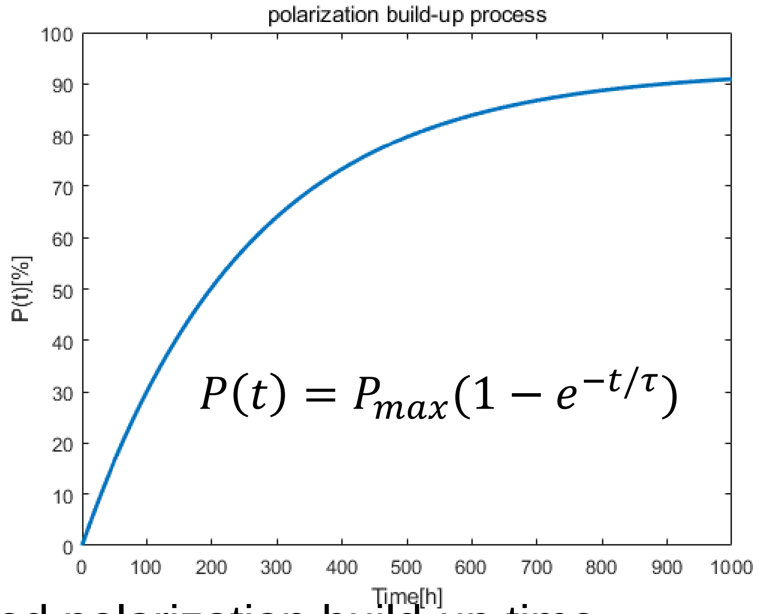
  - The maximum achievable polarization level in a planar ring without imperfections is given by:

$$P_{ST} = \left|\frac{W_{\uparrow\downarrow} - W_{\downarrow\uparrow}}{W_{\uparrow\downarrow} + W_{\downarrow\uparrow}}\right| = \frac{8}{5\sqrt{3}} = 92.38\%$$

Sokolov-Ternov effect: electrons gradually polarized in storage rings due to sustained transverse acceleration while orbiting. The mechanism is the emission of spin-flip synchrotron radiation.

Table 1: Key Parameters of Self Polarization

Storage ring	Circumference (km)	Bending radius(km)	E (GeV)	τ_P (hour)
LEP	27	3.1	45	5.8
CEPC	100	10.7	45.5	256
CEPC	100	10.7	80	15.2
CEPC	100	10.7	120	2



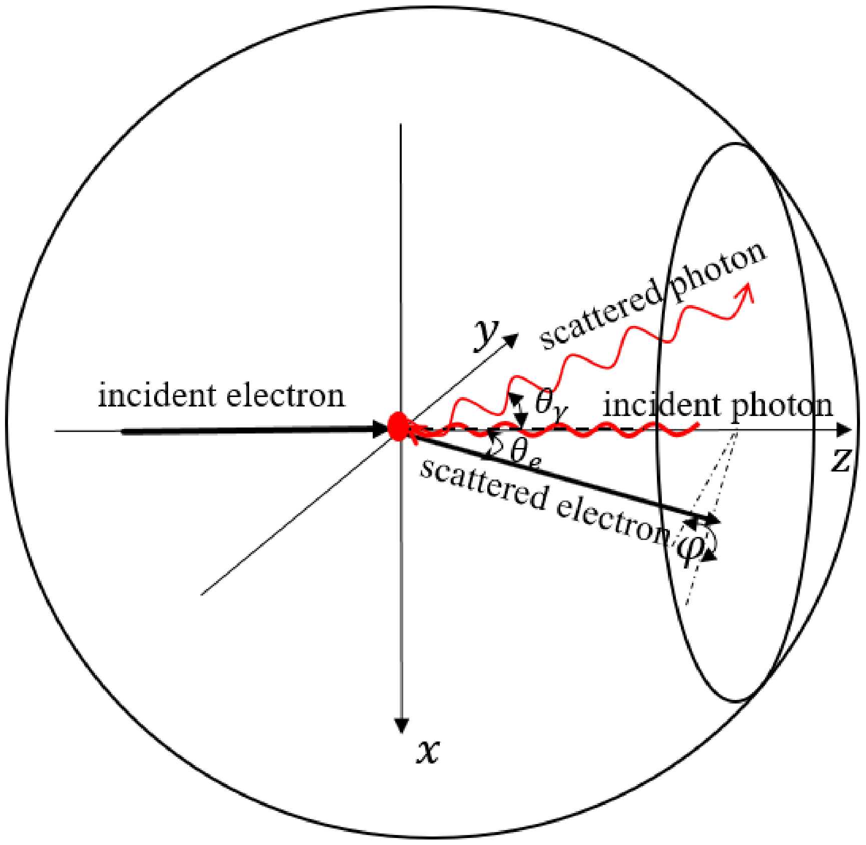
- To generate sufficient beam polarization for RD requires a much reduced polarization build-up time
- The wiggler can be used to speed up the polarization build-up time.

Ref: [1] arXiv:2204.12718. [2] Y. Derbenev,et.al., Radiative polarization at ultra-high energies, Particle Accelerators 9, 247 (1979).

Techniques

Technique	Principle	Requirements	Device
Touscheck lifetime measurement	$\frac{\tau_t(P)-\tau_t(0)}{\tau_t(P)} = -\frac{< aF(\xi) >}{< aC(\xi) >}P^2$	• A highly stable and repeatable machine of the polarized and unpolarized beam • A more accurate measurement of the change of the lifetime	Duke storage ring
"spin-light" polarimeter	Measure the total SR power (transverse polarization) or the spatial asymmetry of the SR (longitudinal-spin dependent)	• Best suited for the 4 - 20 GeV energy range, for current less than mA	VEPP-4 JLab
Mott polarimeter	Elastic scattering asymmetry of electron incident on the nuclei of a thin target foil	• Operate in beam energy below 10 MeV	CEBAF, MAMI
Moller polarimeter	$e+e \rightarrow e+e$	• Low beam current • Suitable for energy 100 MeV ~ 50 GeV.	MAMI, SLAC(E143), TJNAF(hall A)
Compton polarimeter	$e+\gamma \rightarrow e+\gamma$	• In theory, the scattered electrons and photons can be independently measured to obtain the polarization • " non-invasive " cross-section is small	TRISTAN, NIKHEF, HERA, LEP, JLab(Hall C), ILC, FCC

Compton scattering physics



- The Compton differential scattering cross section was first theoretically obtained by Klein and Nishina in 1929

$$\frac{d^2\sigma}{du d\varphi} = \Sigma_0 + \xi_{\circlearrowright}\zeta_{\circlearrowright}\Sigma_{\parallel} + \xi_{\circlearrowright}\zeta_{\perp}\Sigma_{\perp} sin\varphi$$

- $\xi_{\circlearrowright}$: circular polarization of laser
- $\zeta_{\circlearrowright}$, $\zeta_{\perp}$: longitudinal & transverse electron beam polarization

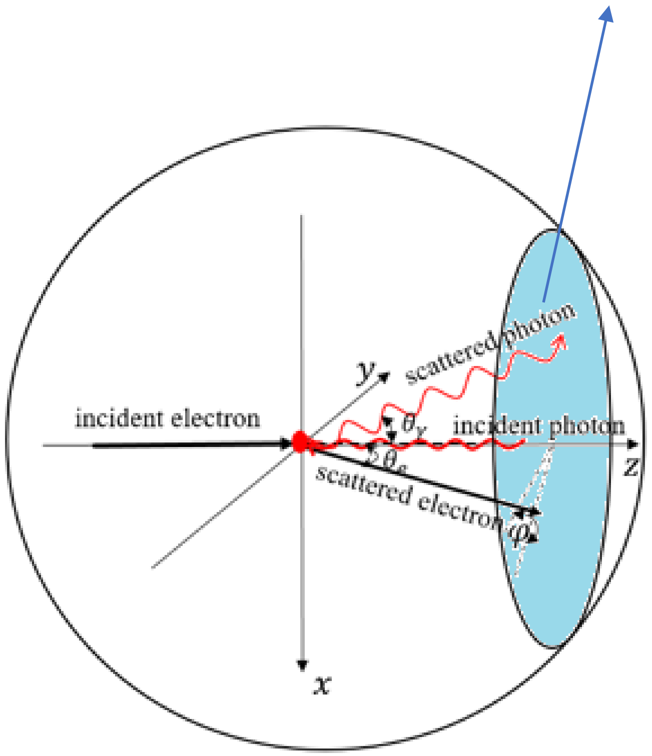
- kinematics described by 2 variables:
  polar angle θ => u (u is the ratio of the energy of the scattered photons and the scattered electrons)
  azimuthal angle φ => y (vertical position)

Ref: N. Y. Muchnoi, et al., Performance of the FCC-ee polarimeter, Proceedings of eeFACT 18 (2019) 157–164

Compton scattering physics

- The spatial position distribution of the scattered photons and the scattered electrons

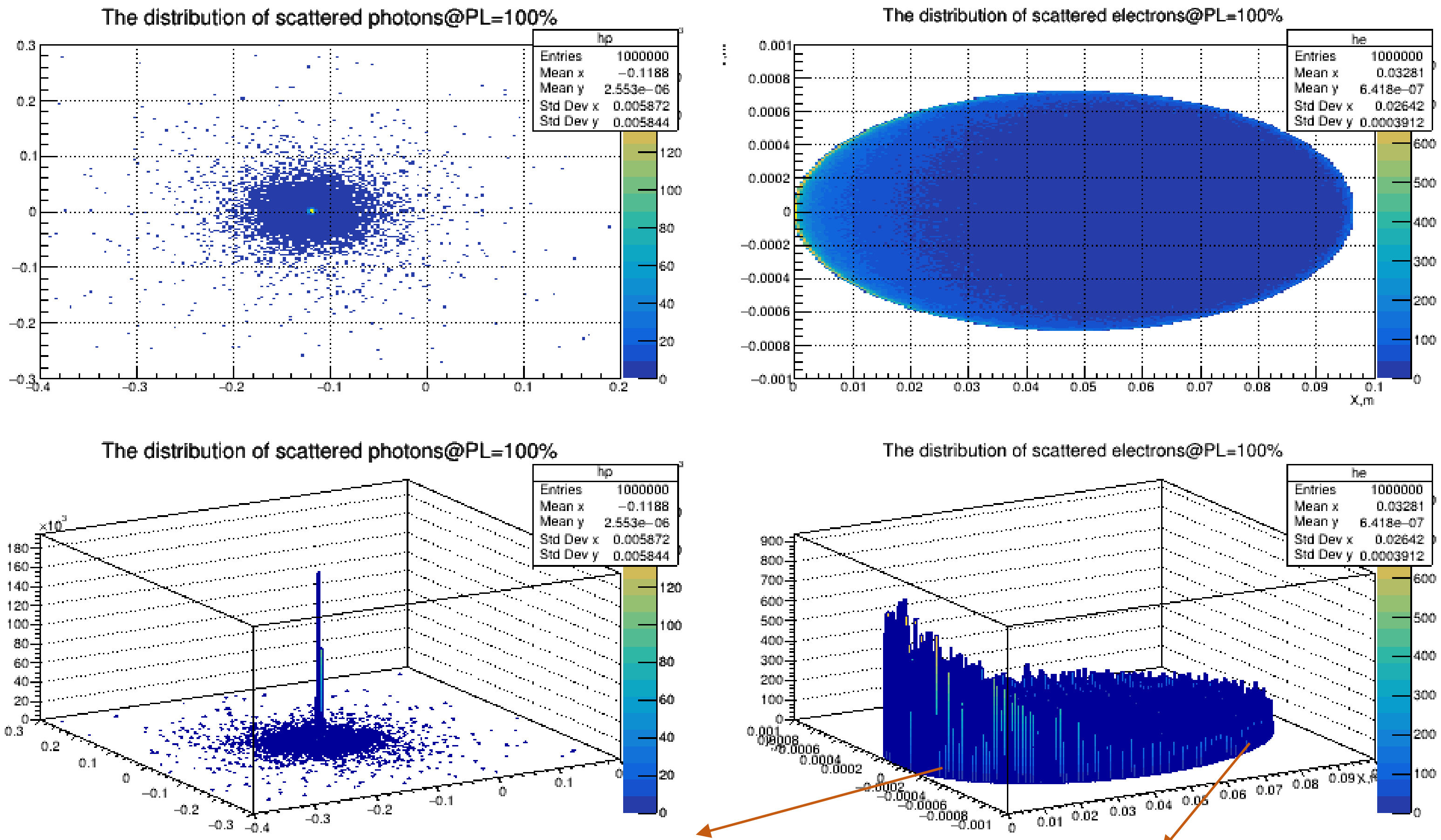
The detector plane



add dipole magnet to simulate

Scattered photons

Scattered electrons



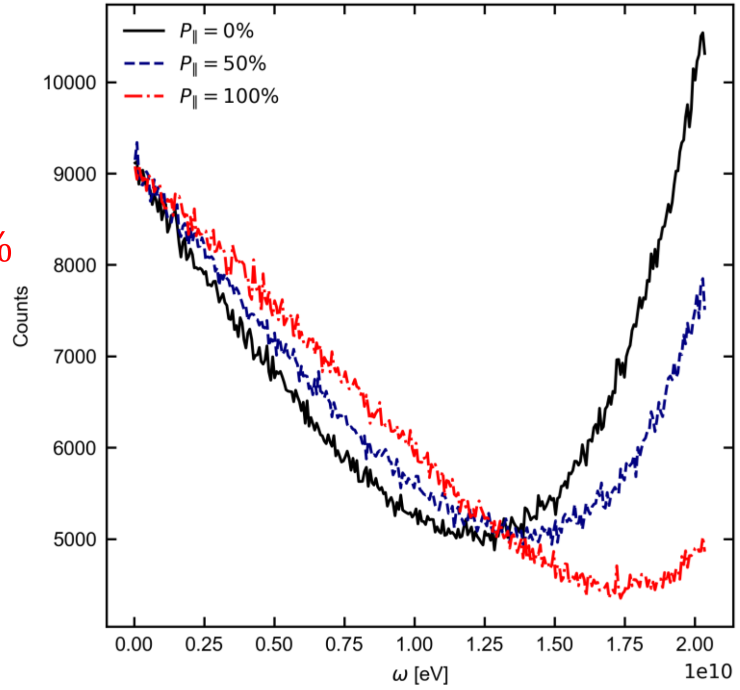
Electron main beam

Scattered electrons with the minimum energy.

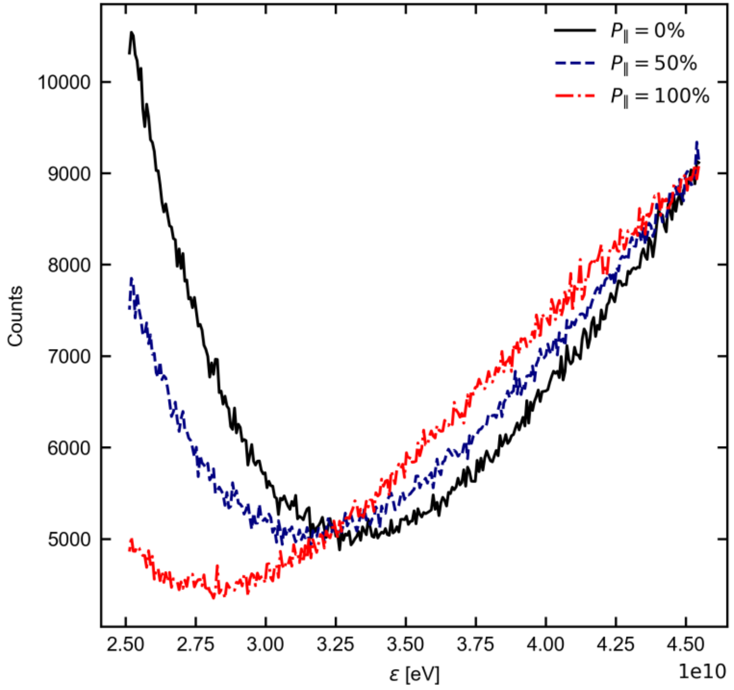
The longitudinal polarization vs the scattered energy

$P_\perp = 0\%$
$P_\perp = 50\%$
$P_\perp = 100\%$

Scattered energy of the photons



Scattered energy of the electrons



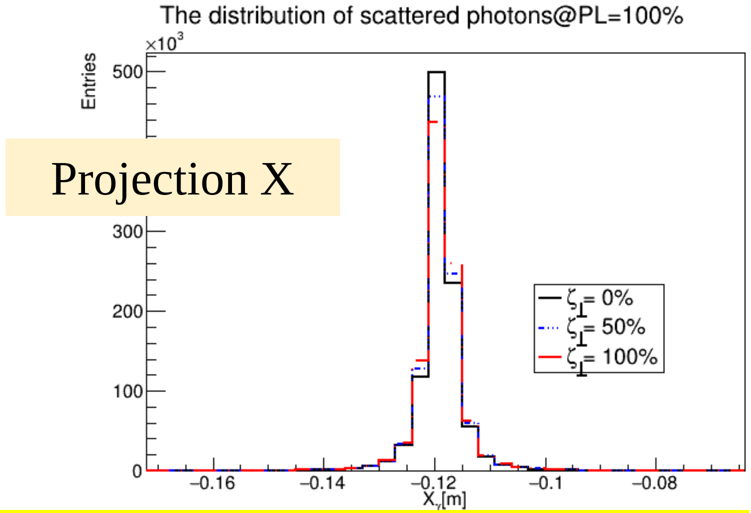
- The longitudinal polarization of the electrons can be obtained by measuring the energy spectrum of the scattered photons.

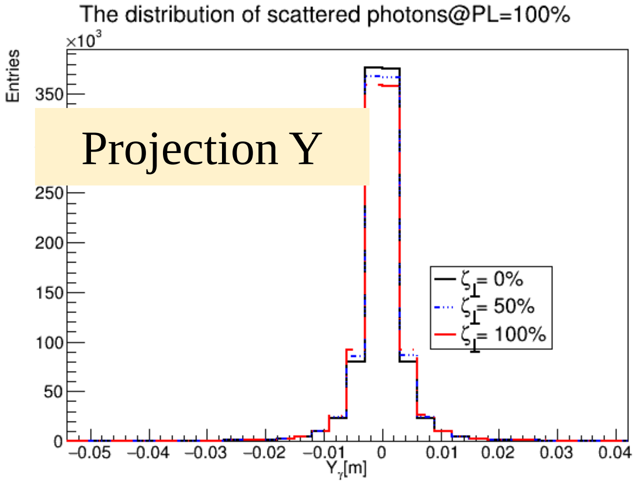
[1] Phys. Rev. Lett. 66 (1991) 1697.
[2] Nucl. Instrum. Meth. A 414 (1998) 446 [physics/9902011].
[3] Nucl. Instrum. Meth. A 479 (2002) 334 [physics/0009047].

TRISTAN, NIKHEF, HERA(LPOL)

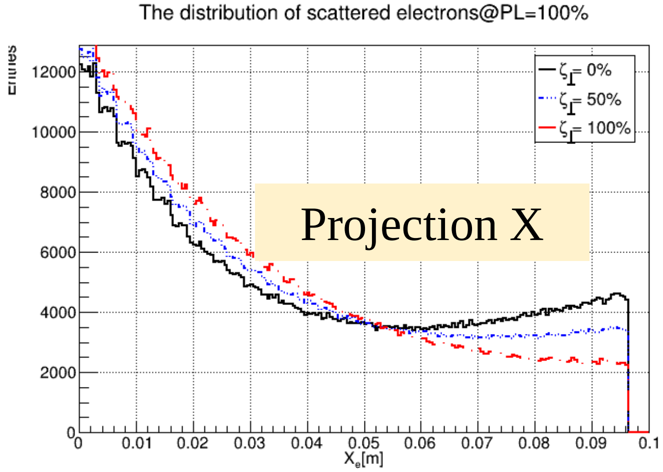
The longitudinal polarization vs the position of the scattered particles

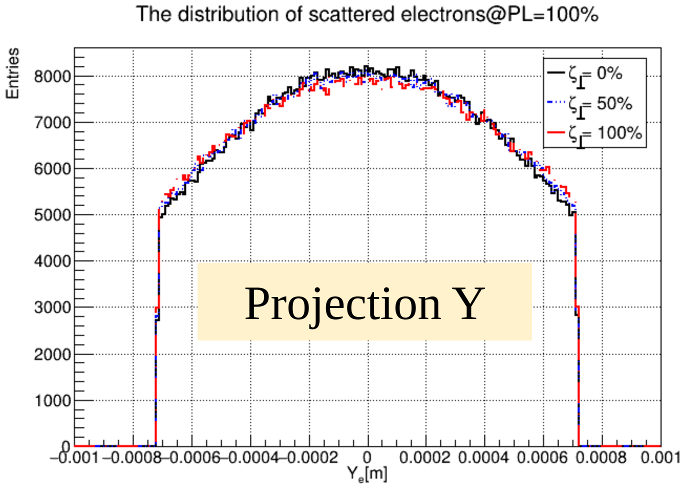
projection of the scattered photons





projection of the scattered electrons





- The longitudinal polarization of the electrons can be obtained by measuring the rate asymmetry of Compton-scattered electrons

[1] [hep-ex/9611005]
[2] Phys. Rev. X 6 (2016) 011013 [arXiv:1509.06642].

JLab(Hall C), SLC

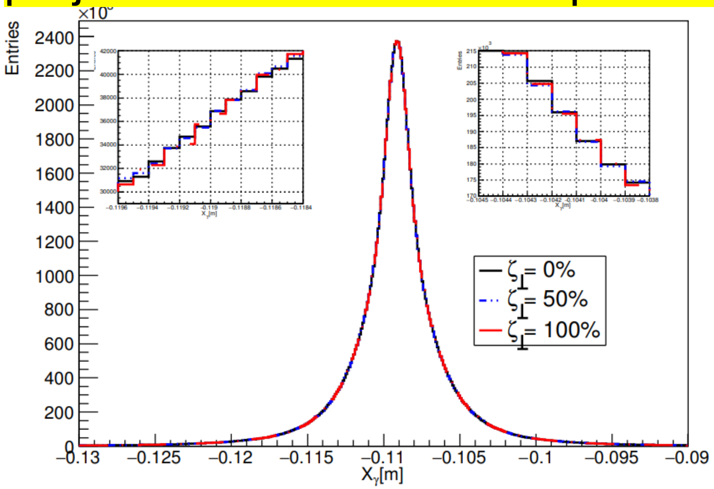
Vertical polarization vs the position

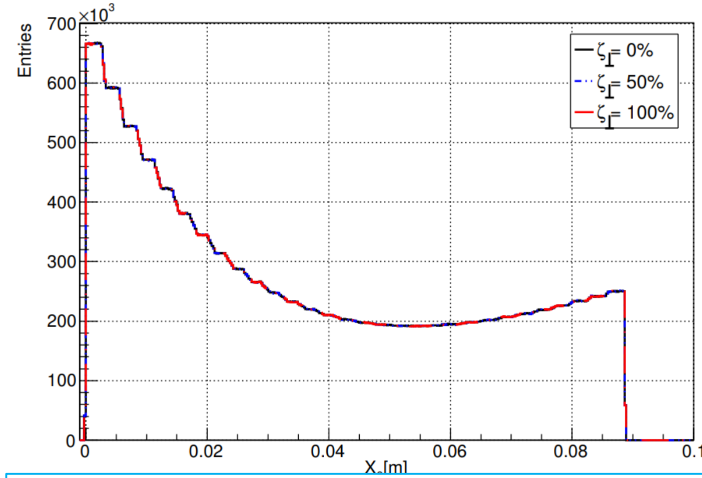
Vertical polarization	Vertical angular asymmetry of scattered photons	LEP, TRISTAN, SPEAR, ELSA, HERA(TPOL)
	Spatial distribution of scattered electrons	ILC, FCC

projection of the scattered photons

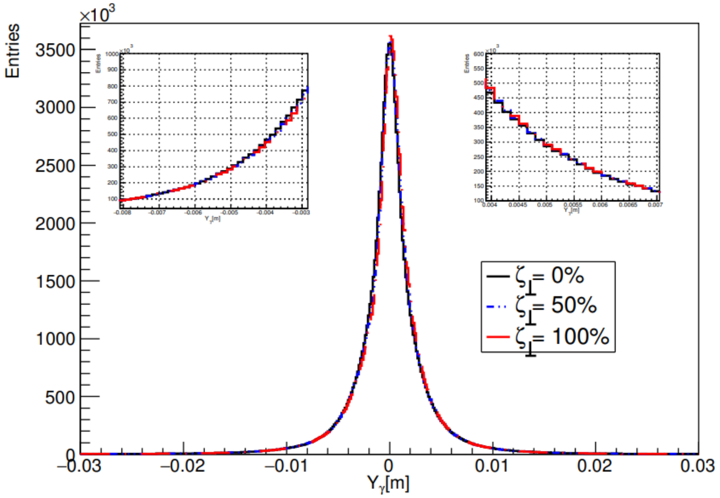
projection of the scattered electrons

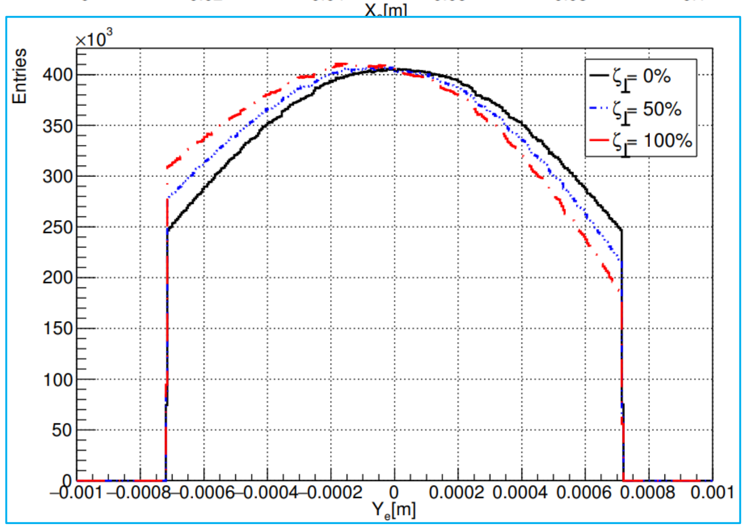
Projection X





Projection Y





Compton polarimeter

- Schematic drawing of the Compton polarimeter

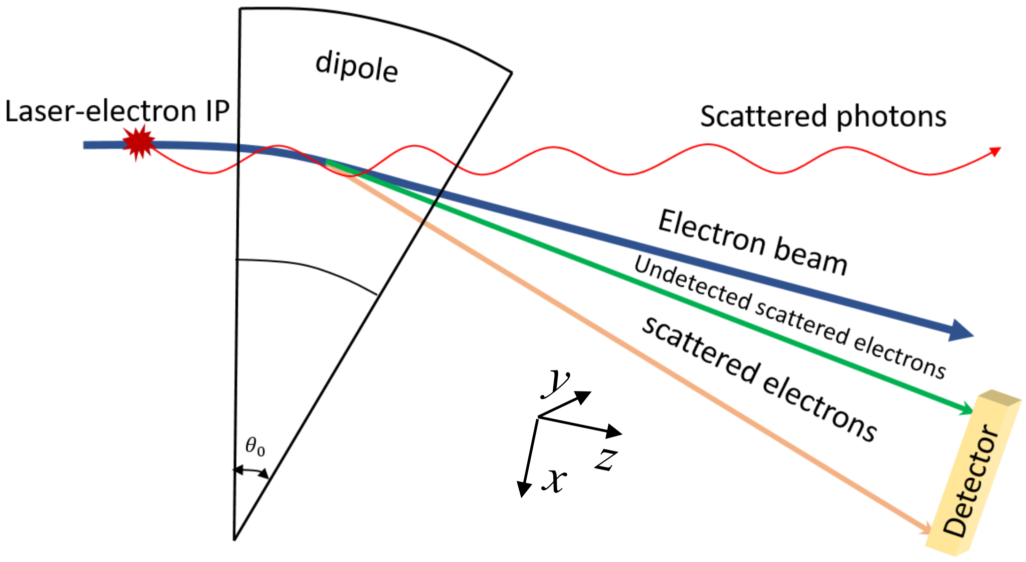


Table 3: Polarimeter parameters (Z pole)

Parameter	value
Beam energy, E	45.5 GeV
Laser wavelength, λ	1064 nm
Laser power, P_L	0.1 GW
Magnet bending angle	0.97 mrad
Maximum energy of scattered photons, w_{max}	20.34 GeV
Minimum energy of scattered electrons, ε_{min}	25.16 GeV
Maximum electron scattering angle, $\theta_{e\,max}$	4.54 μrad

- A vertically polarized electron bunch collide with circularly polarized laser pulse
- **A dipole** is arranged to separate the scattered particles from the electron beam.
- CEPC Compton polarimeter: detecting the spatial distribution of the scattered electrons to measure the vertical polarization of electron beam.

JINST 17, P08005, (2022)

The method to measure the vertical polarization

- Fit the spatial distribution of the scattered electrons by analyzing power (Π)

$$A = \bar{Y_e}|_{X_e} = P_{\perp}\Pi$$

A : Experimental value of the asymmetry

Π: Theoretical value of the asymmetry

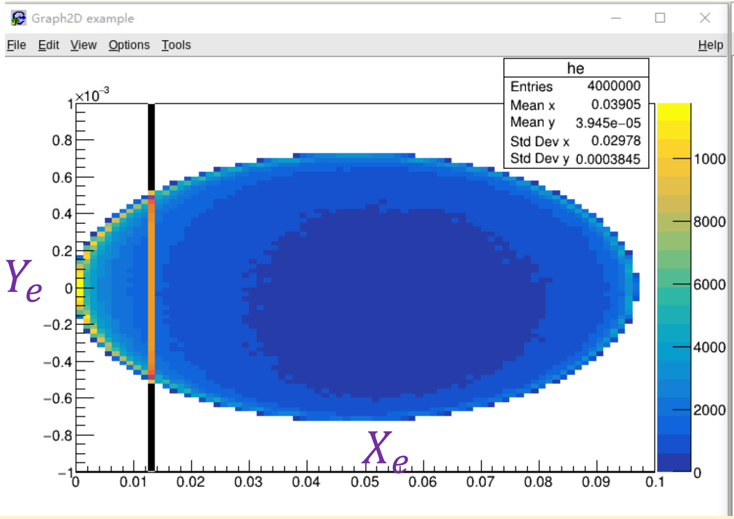
$P_{\perp} = \xi_{\circlearrowright}\zeta_{\perp}$ ($\zeta_{\perp}$ is vertical polarization)

$$Y_e|_{X_e} = \frac{\sum_{i=0} Y_e}{n_i}$$

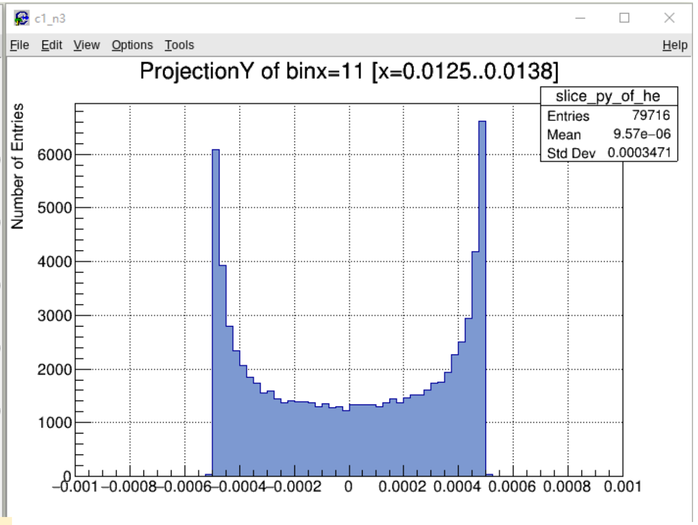
Represents the relationship of the Ye mean value in the i_{th} x-axis bin and the n_i is the counts number of the per x-bin.

$$A = \frac{\bar{Y_e}|_{X_e}(left\ helicity) - \bar{Y_e}|_{X_e}(right\ helicity)}{2}$$

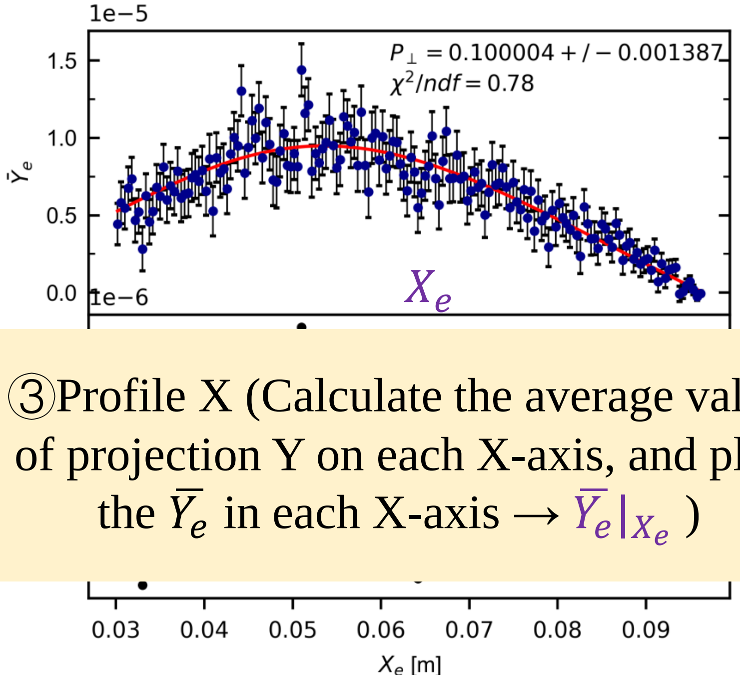
- The Monte Carlo simulation to obtain the Experimental value of the asymmetry



①The 2D spatial position distribution of the scattered electrons



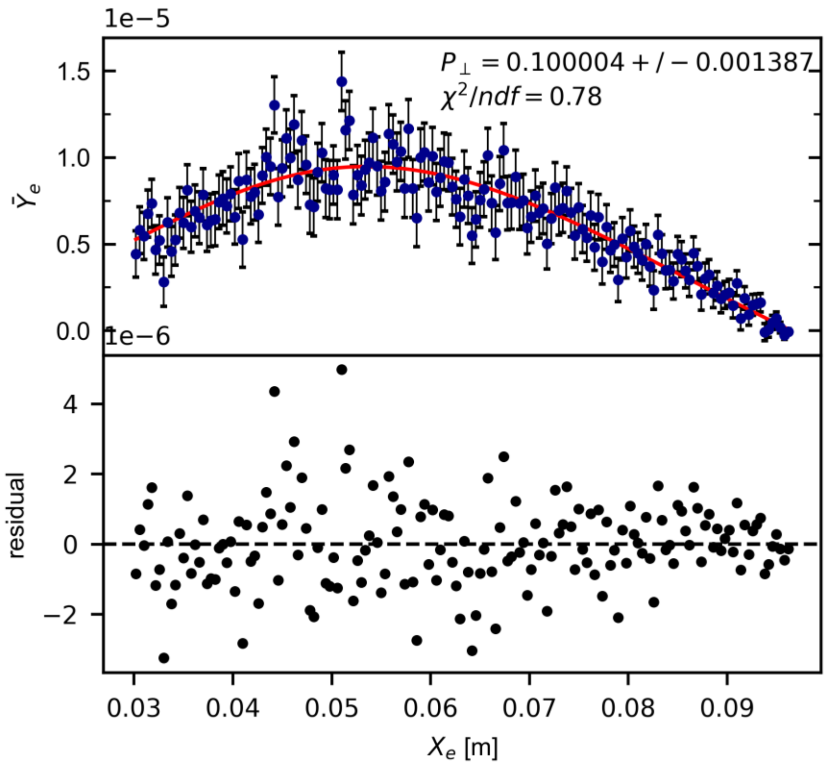
②Projection Y on each X-bin

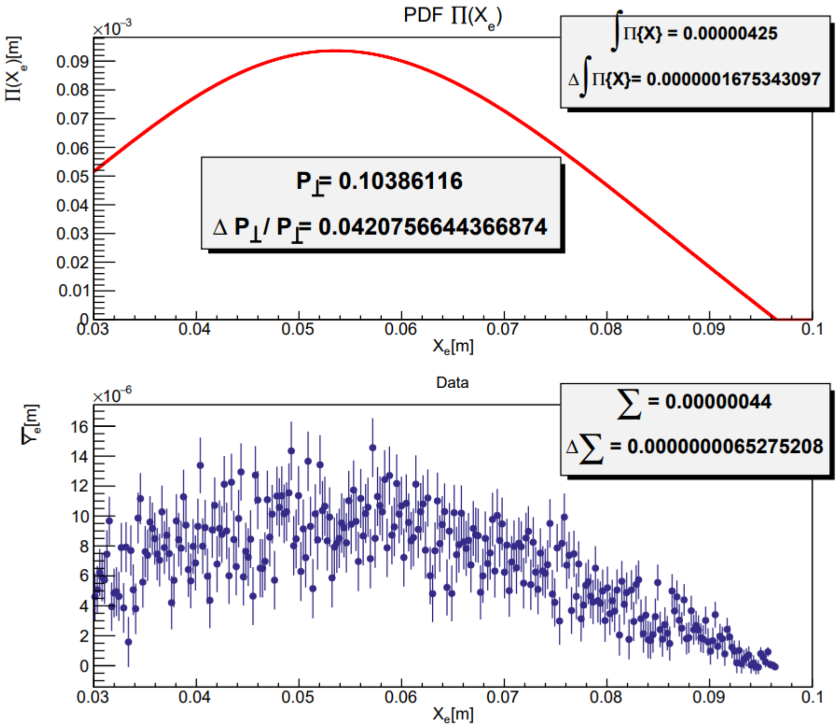


③Profile X (Calculate the average value of projection Y on each X-axis, and plot the $\bar{Y_e}$ in each X-axis → $\bar{Y_e}|_{X_e}$)

The results

- Method 1: Fit by the analyzing power $A = \bar{Y}_e|_{X_e} = P_{\perp}\Pi$
- Method 2: the polarization is equal to the ratio of the integral of the distribution of the Experimental value A and the Theoretical value Π





- Assume that the polarization of the initial electron beam is 10%

Estimation of statistical error

The luminosity

$$\mathfrak{L} = \frac{N_e N_\gamma \cos(2\alpha)}{2\pi\sqrt{(\sigma_{e,y}^2 + \sigma_{\gamma,y}^2)}\sqrt{(\sigma_{e,x}^2 + \sigma_{\gamma,x}^2)cos^2(\alpha/2) + (\sigma_{e,z}^2 + \sigma_{\gamma,z}^2)sin^2(\alpha/2)}}$$

The total Compton cross-section

$$\sigma_t = \pi r_e^2 a[\frac{2a^2 + 12a + 2}{(1-a)^2} + a - 1 + \frac{6a^2 + 12a - 2}{(1-a)^3}\ln a]$$

$$a = \frac{1}{1 + 4\gamma\omega_0/m_e}$$

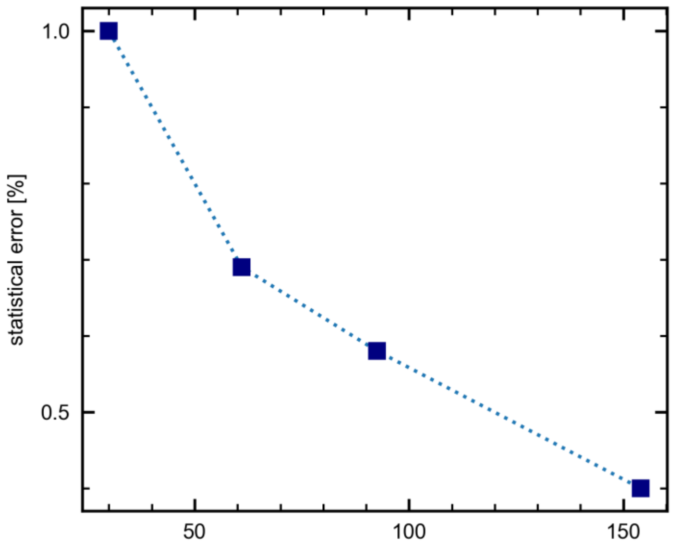


Figure: Statistical errors for several samples for different measurement periods (based on CDR)

Table 4: Electron beam and laser beam properties used in simulation (based on CDR)

symbol	meaning	Unit
E_b	Electron beam energy	120 eV
ω_0	Laser photon energy	1.24 eV
$\sigma_{\gamma,x}$ $/\sigma_{\gamma,y}$	Laser focus radius	160 μm
N_e	Bunch population	8×10^{10}
N_γ	Laser photon population	1.5×10^{16}
α	Cross angle = π-collision angle	2.35 mrad
$\mathfrak{L}$	luminosity	$7\times10^{33}\ \mathrm{m^2 s^{-1}}$
σ_t	Total Compton cross-section	402 mb

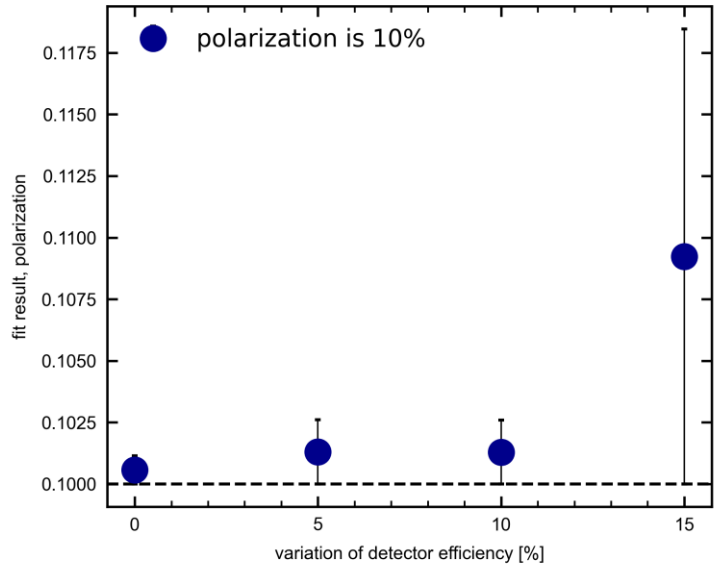
- Statistical error 1% within tens of seconds in Z pole can be achieved.

Estimation of systematical uncertainties

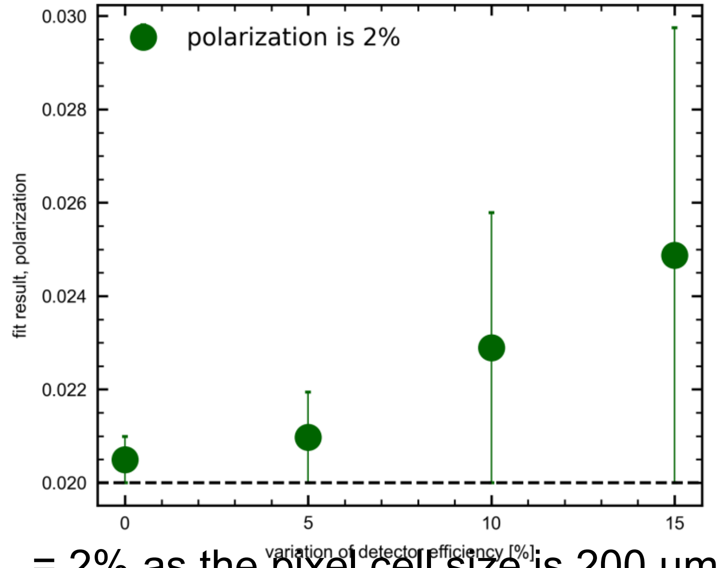
Table 5: polarimeter-related systematic uncertainties (polarization is 10%)

Sources of systematic uncertainties	Uncertainty	$\|\Delta P_\perp/P_\perp\|\%$
Dipole strength	3.3×10^{-7} T	0.062%
L1(Ip-to-detector)	1cm	0.007%
L2 (magnet-to-detector)	1cm	0.051%
Beam energy spread	100 keV	0.0001%
Detector resolution	115μm×7μm	0.278%
Laser polarization	0.2%	0.2%
Total		0.6%

- Response of the efficiency detector variation was simulated.
- The fit result for $P_\perp$ = 10% and $P_\perp$ = 2% fitted by the analyzing power.
- The deviation between the fitting result and the theoretical value shows that variation less than 10% could be considered to be acceptable.



(a) $P_\perp$ = 10% as the pixel cell size is 400 μm×25 μm.



(b) $P_\perp$ = 2% as the pixel cell size is 200 μm×25 μm

Discussion of the Compton polarimeter layout

- The discussion is based on the CDR lattices

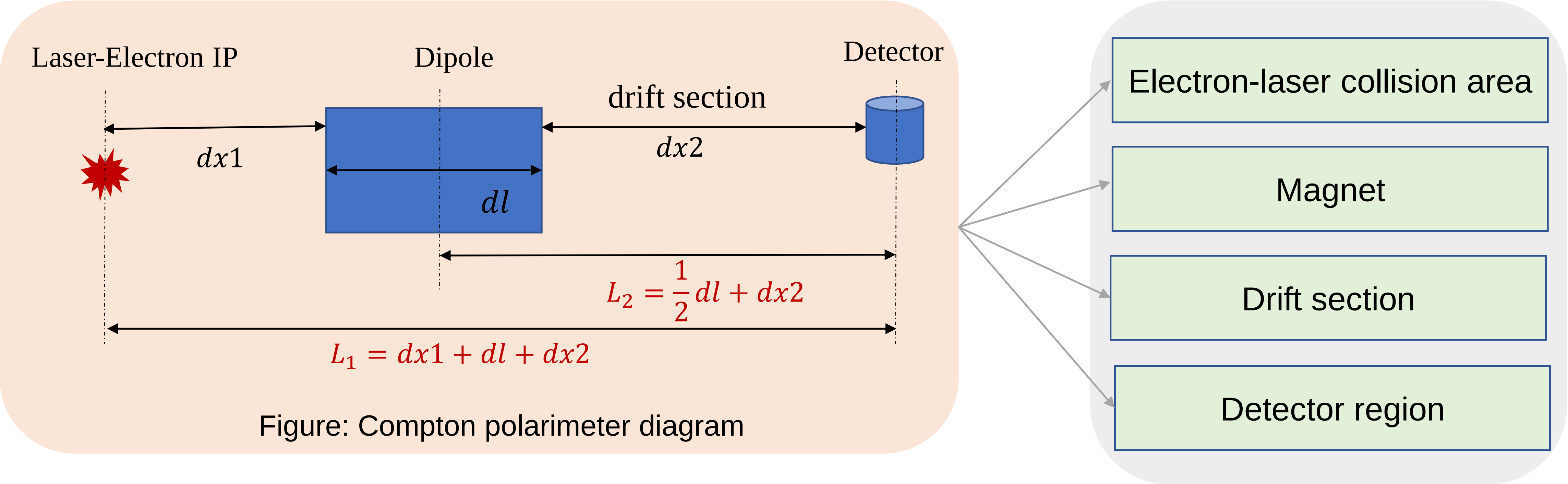


Figure: Compton polarimeter diagram

- The polarimeter requirements for lattice
  - The aim is to measure the most of the scattered electrons. (energy range is about the 25 GeV ~ 40 GeV)
  - The drift out of the beam tube is 31 mm (beam pipe inner radius is 28 mm + wall thickness 3 mm)
  - Requirement:

$$L_2\theta_0 > 0.2255m$$

L_2 is the distance between the dipole center and the detector

θ_0 is the dipole bending angle

  - On the basis that the laser wavelength is 1064 nm

Summary and discussion

- Polarization can be obtained by measuring the position or energy of scattering particles by Compton scattering.
- CEPC Compton polarimeter aim to deduce the beam polarization through the asymmetry of the scattered electron position distribution.
- Monte Carlo simulation has been conducted based on CDR
- The layout on the collider ring is under discussion

backup

Cross-section

- Compton scattering total cross-section

$$\sigma_t = \frac{2\pi r_e^2}{\kappa}\left(\left[1 - \frac{4}{\kappa} - \frac{8}{\kappa^2}\right]\log(1+\kappa) + \frac{1}{2}\left[1 - \frac{1}{(1+\kappa)^2}\right] + \frac{8}{\kappa}\right)$$

- Compton scattering differential cross-section

$$d\sigma_0 = \frac{r_e^2}{\kappa^2(1+u)^3}\left(\kappa(1+(1+u)^2) - 4\frac{u}{\kappa}(1+u)(\kappa-u)\left[1 - \xi_\perp\cos\left(2(\varphi-\varphi_\perp)\right)\right]\right) du\,d\varphi$$

$$d\sigma_\parallel = \frac{\xi_\circlearrowright \zeta_\circlearrowright r_e^2}{\kappa^2(1+u)^3}\mathrm{u}(u+2)(\kappa-2u) \qquad du\,d\varphi$$

$$d\sigma_\perp = -\frac{\xi_\circlearrowright \zeta_\perp r_e^2}{\kappa^2(1+u)^3}2u\sqrt{u(\kappa-u)}\cos(\varphi-\phi_\perp) \qquad du\,d\varphi$$

Ref: N. Y. Muchnoi, et al., Performance of the FCC-ee polarimeter, Proceedings of eeFACT 18 (2019) 157–164

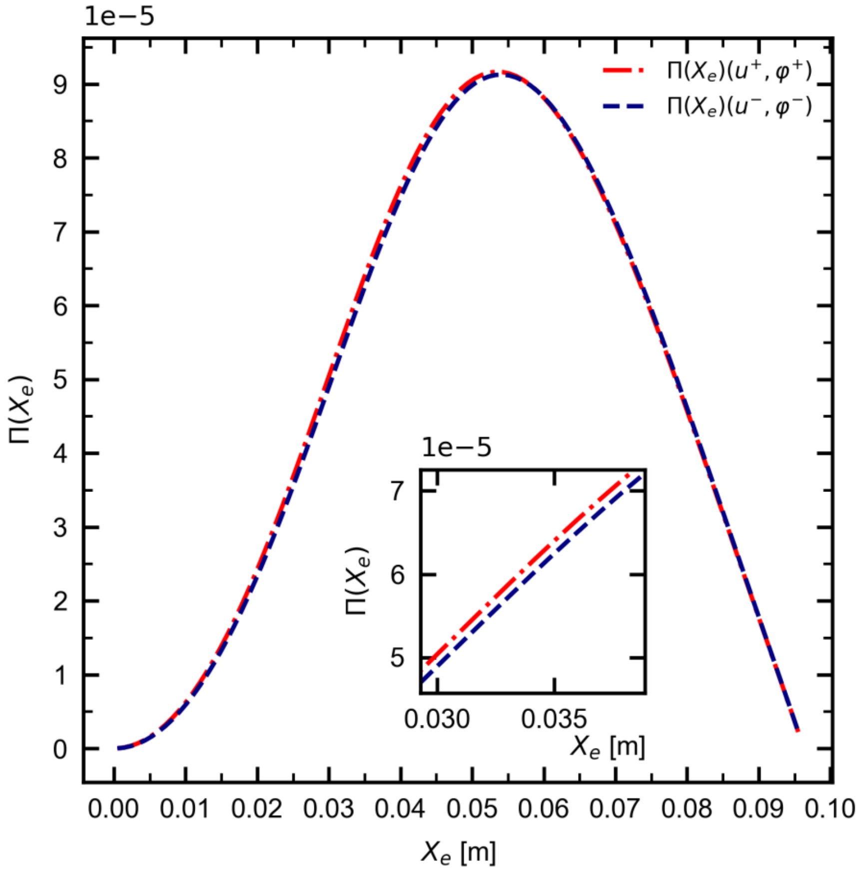
Analyzing power

- The analyzing power reflects the asymmetry in theory.
- It can be obtained by the cross-section, and the variable can be the position or the scattered energy.

$$A(Y_e) = \bar{Y_e}|_{X_e} = P_{\perp}\Pi(X_e)$$

$$A(Y_e) = \frac{\bar{Y_e}|_{X_e}(left\ helicity) - \bar{Y_e}|_{X_e}(right\ helicity)}{2}$$

$$\Pi(X_e) = \frac{\int Y_e \frac{d\sigma}{dX_e dY_e} dY_e}{\int \frac{d\sigma}{dX_e dY_e} dY_e}$$



Polarimeter

➢ 讨论磁铁参数和漂移段长度

- <u>Case:</u> CEPC Z mode & 激光入射光子的波长取1064 nm

- 保证能量区间在25.11 GeV ~ 40 GeV的散射电子偏移出束管，$L_2\theta_0$ 应满足：
- 则：

$$L_2\theta_0 > 0.2255m$$

$$\left(\frac{1}{2}dl + dx2\right)\cdot\frac{dl\cdot B\cdot ec}{E_b} > 0.2255m$$

其中, dl： dipole 长度, $dx2$： 自由漂移段(磁铁末端至探测器距离)，θ_0： 磁铁偏转角

- 三个参数变量：磁铁长度dl， 磁铁强度B， 自由漂移动段长度 $dx2$