Compton polarimeter on CEPC

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极化讨论会议

Outline

- 1. Motivation
- 2. Layout of Compton polarimeter on CEPC
- 3. Physics of Compton polarimeter
- 4. Measurement results
- 5. Discussion of statistical and systematic uncertainty

The motivation

- A beam is considered to be polarized: there is an asymmetry in the orientation of the particle spins

$$P = \frac{N^{+} - N^{-}}{N^{+} + N^{-}} \neq 0$$

$N^{+(-)}$: number of particles with spin oriented along the +(-) direction

- **Transverse polarization:**
  an electron spin orientation is perpendicular to the beam momentum.

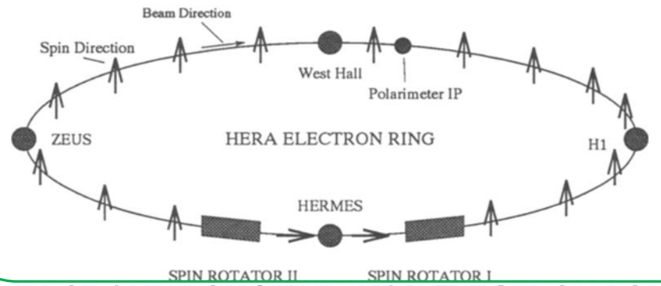
Electrons in storage rings become naturally transversely polarized due to the *Sokolov-Ternov effect*

$$P(t) = -92.4\%(1 - e^{-t/\tau_P})$$

A.A. Sokolov, I.M. Ternov, Sov. Phys. Dokl. 8 No.12 (1964) 1203

- **Longitudinal polarization:**
  an electron spin orientation either parallel or antiparallel to the beam momentum.

Siberian Snake, Spin rotator



Michael D U. TRANSVERSE AND LONGITUDINAL ELECTRON POLARIZATION AT HERA[J].

The motivation

	Vertical Polarization in the ARC		Longitudinal Polarization at IPs
Purpose	Energy calibration (Accuracy 10^{-6} for CEPC)		Collision
Goal	5%~10%		$P \geq 50\%$
Benefits	calibrate beam energy with RDP	①Z mass	anomalous couplings (electroweak physics)
		②momentum compaction factor	
		③monitor machine stability	
	CP violation (new physics)		suppressing background in new physics searches
	indirect searches for massive gravitons		

[1]Zhe Duan, CEPC Z-pole Polarization Study Status, CEPC Day Feb 25, 2021. https://indico.ihep.ac.cn/event/13810/

【ELSA】Measurement of momentum compaction factor via depolarization resoances at ELSA_2015

【ESRF】Mesurements of the monmentum compaction factor og the ESRF storage ring

【ALS】energy calibration of the electron beam of the ALS using resonant depolarization_2000

【CP 2004】CP violation at a linear collider with transeverse polarization_2004

【4】L. Arnaudon, et al., “Accurate determination of the LEP beam energy by resonant depolarization,” Zeitschrift für Physik C Particles and Fields 66, 45–62 (1995).

【G. MOORTGAT-PICK.etl】The role of polarized positrons and electrons in revealing fundamental interactions at the Linear Collider

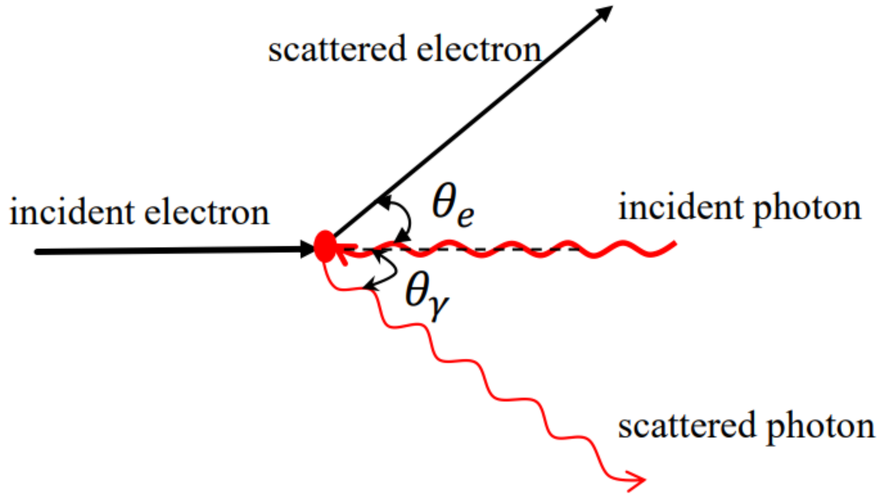
【Gudrid Moortgat-Pick, Herbert Steiner2001】Physics opportunities with polarized e− and e+ beams at TESLA,2001

Electron Polarimetry Techniques

➤ Common techniques for measuring electron beam polarization

- Mott scattering: $\vec{e} + Z \rightarrow e$
  - this polarimeter can measure transverse polarization
  - Useful at MeV-scale energies
- Moller scattering: $\vec{e} + \vec{e} \rightarrow e + e$
  - Can be used at MeV to GeV energies---rapid and precise measurements
  - electron current is about a few µA to avoid depolarization effect, however the electron current is 461mA in Z mode on CEPC.

- Compton scattering: $\vec{e} + \vec{\gamma} \rightarrow e + \gamma$
  - Easiest at high energy
  - Non-destructive
  - Can be time consuming

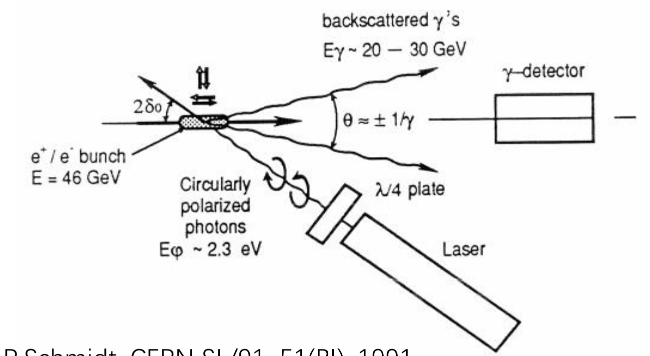


➤ Other polarimetry techniques

- Spin-light polarimetry---use analyzing power from emission of synchrotron radiation
- Touscheck lifetime measurement

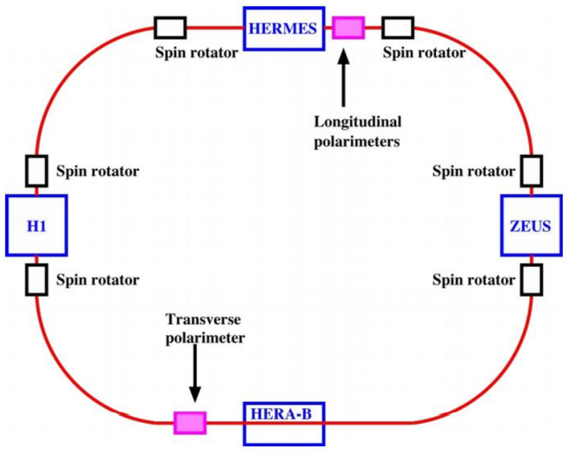
Compton polarimeter

CERN LEP 46GeV



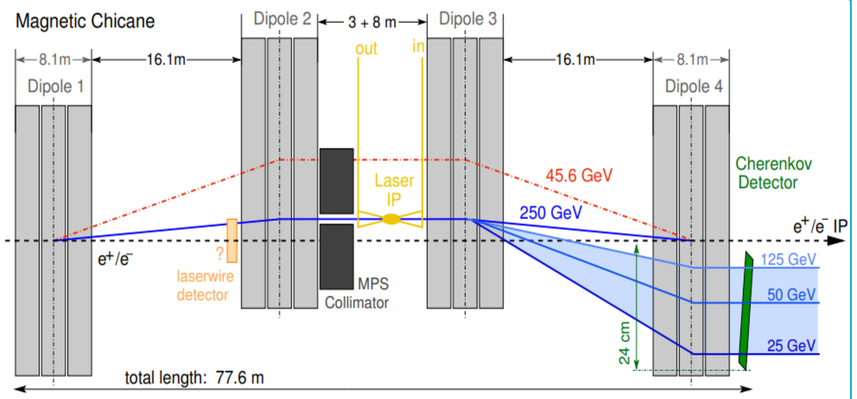
R.Schmidt. CERN SL/91-51(BI), 1991.

HERA 27GeV



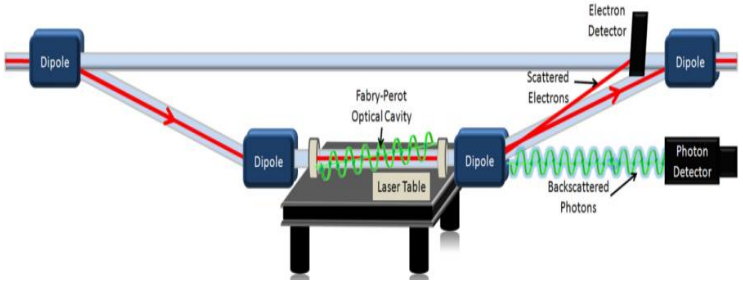
S.Schmitt, HERA polarimeter review

ILC 45.6GeV



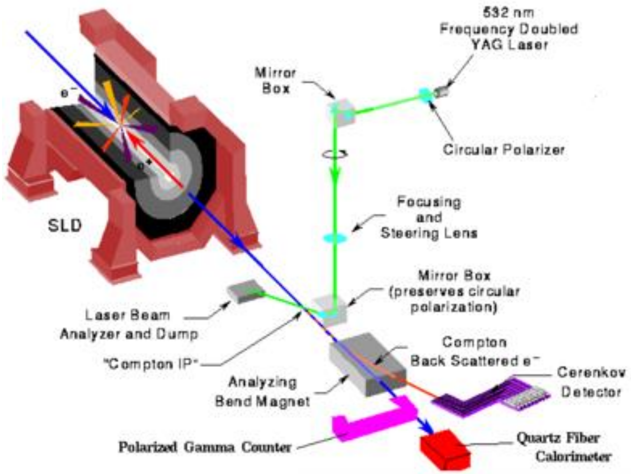
Jenny List, ILC Polarimetry,2020

JLab Hall C 1.16GeV



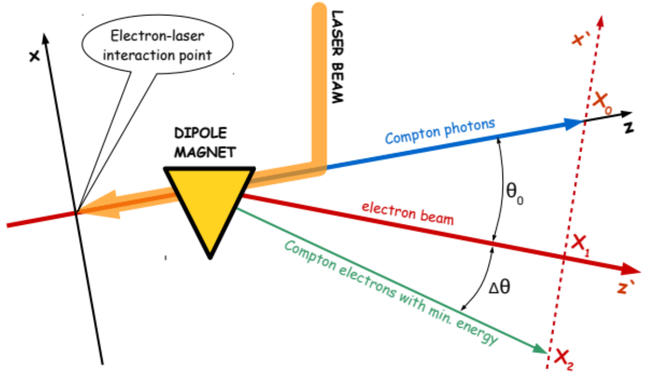
Donald Jones, Hall C Compton Polarimetry, PSTP 2013.

SLD at SLAC 45.6GeV



M.Wood. SLAC, 2003.

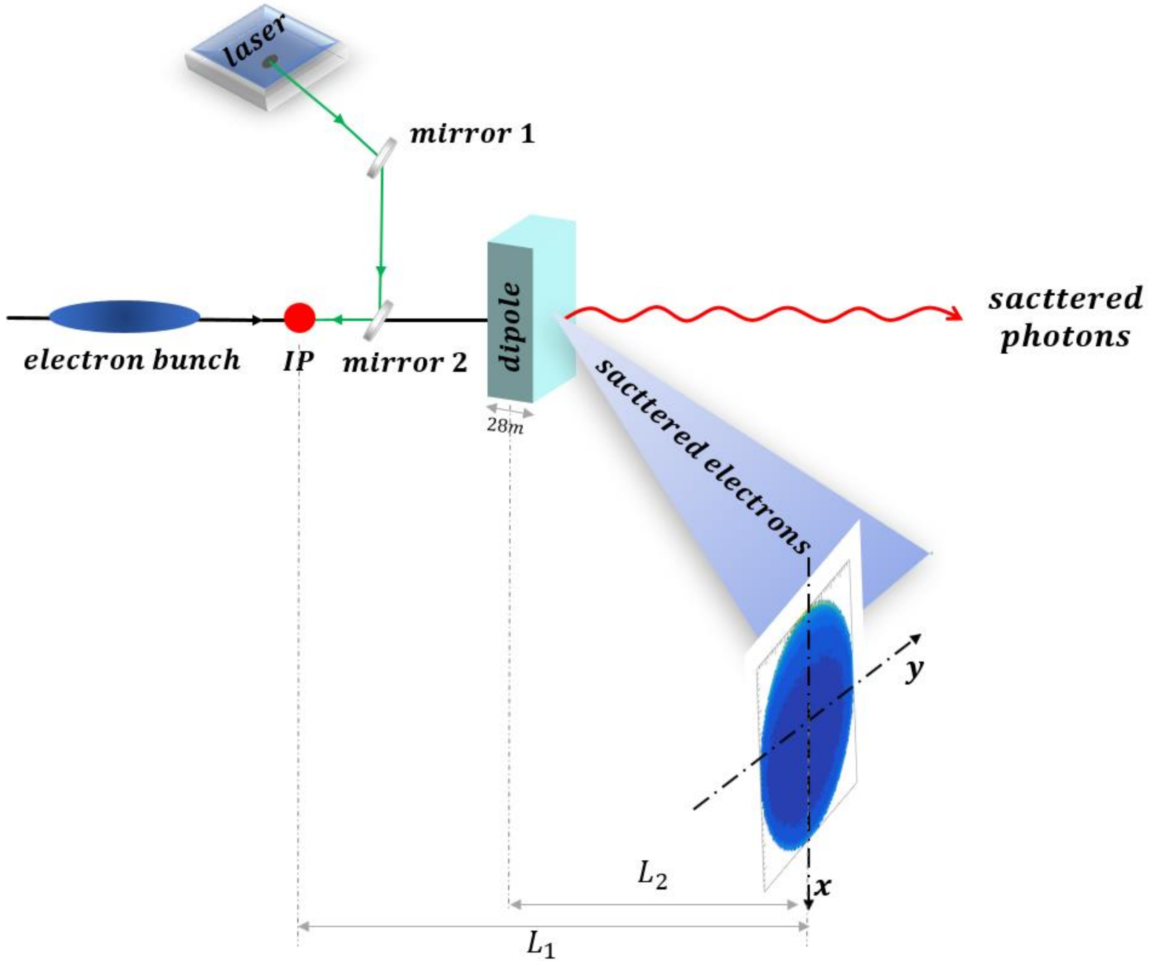
FCC-ee 45.6GeV



Nickolai Muchnoi, 2018

Compton Polarimeter for CEPC(Z pole)

➢ Layout of CEPC Compton polarimeter



Prospects for the Compton polarimeter system:

- Arranged in previous or next **straight sections** near the physical IP.
- The last dipole in the **CEPC arcs** is used to bend electron beams.
- Based on **Inverse Compton scattering process**
- Aim to measure the distribution of **scattered electrons in the detector.**

Layout parameter	
Beam energy(Z pole)	$45.5GeV$
Laser	$\omega = 1.24eV; E_{laser} = 2.8mJ;$ $pulse\ length = 28ps$
Dipole	Magnetic length: $l = 28.686m$ Magnetic strength: $B = 70.7904Gs$
Beam vacuum tube	31mm(Outer radius)
Drift distance	$L_1 = 60m$; $L_2 = 40m$
$\mathfrak{L}$	$6.9676 \times 10^{33} m^{-2} \cdot s^{-1}$
Max. scattering rate	$2.742 \times 10^5 s^{-1}$

Compton backscattering cross section

$$d\sigma = d\sigma_0 + d\sigma_{||} + d\sigma_{\perp}$$

unpolarized cross section — longitudinal electron polarization — transverse electron polarization

✓ At the (u,φ) plane:

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

$$\frac{d\sigma_{||}}{dud\varphi} = \frac{\xi_\circlearrowleft \zeta_\circlearrowleft r_e^2}{\kappa^2(1+u)^3}\mathrm{u}(u+2)(\kappa-2u)$$

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

u is the ratio of scattered energy of photons and electrons;
φ is the azimuthal angle in the detector.

✓ At the (x, y) plane:

$$\frac{d\sigma_0}{dxdy} = \frac{r_e^2}{(1+u)^3\sqrt{1-x^2-y^2}}\left(1+(1+u)^2-4\frac{u}{\kappa}(1+u)\right)$$

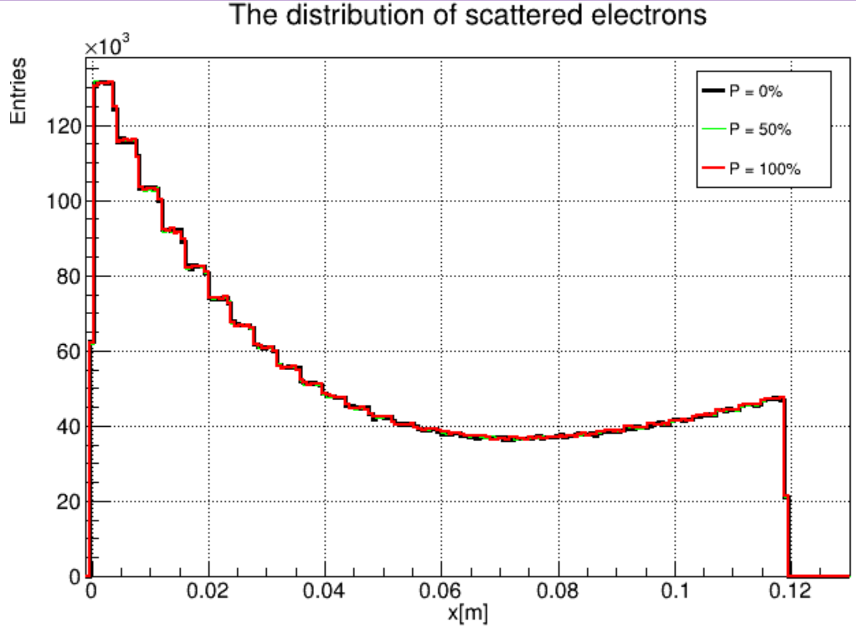
$$\frac{d\sigma_{||}}{dxdy} = \frac{\xi_\circlearrowleft \zeta_\circlearrowleft r_e^2}{\kappa(1+u)^3\sqrt{1-x^2-y^2}}\mathrm{u}(u+2)\left(1-2\frac{u}{\kappa}\right)$$

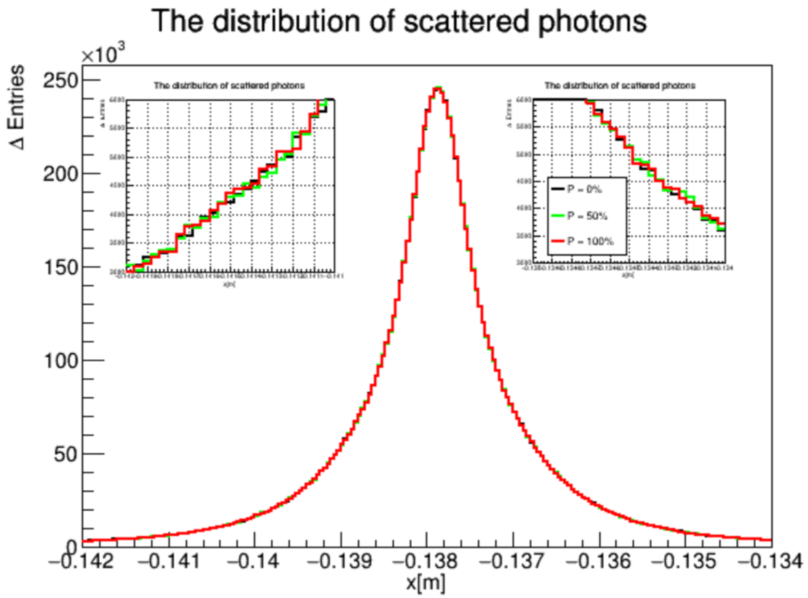
$$\frac{d\sigma_\perp}{dxdy} = -\frac{\xi_\circlearrowleft \zeta_\perp r_e^2}{(1+u)^3\sqrt{1-x^2-y^2}}uy$$

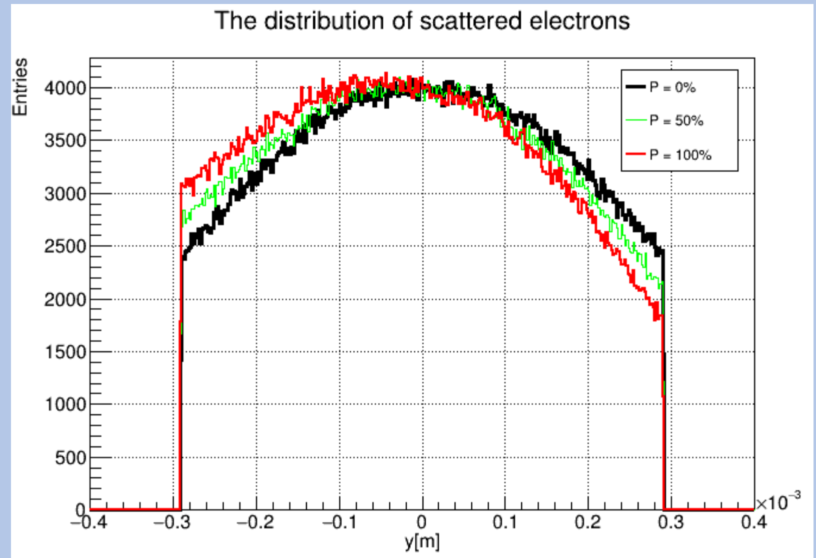
(x,y) is the *position of* scattered electrons

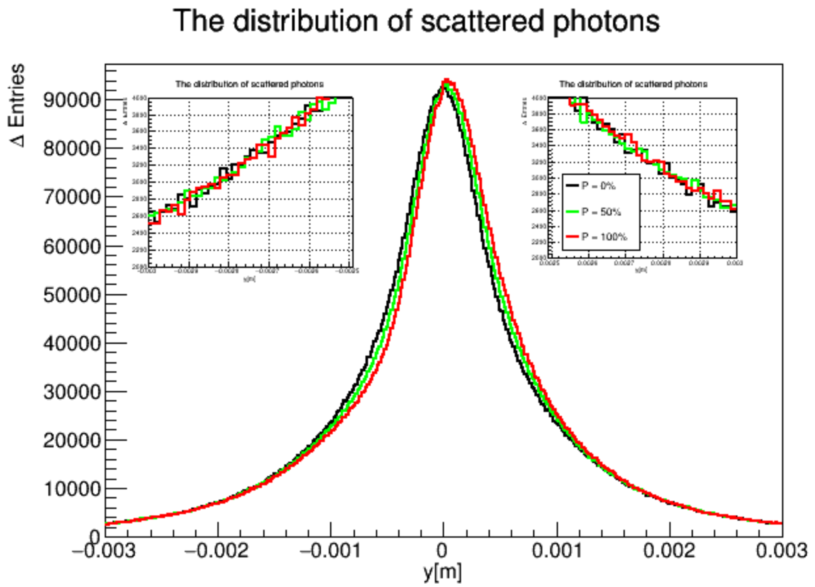
Transverse polarization

Asymmetry vs position

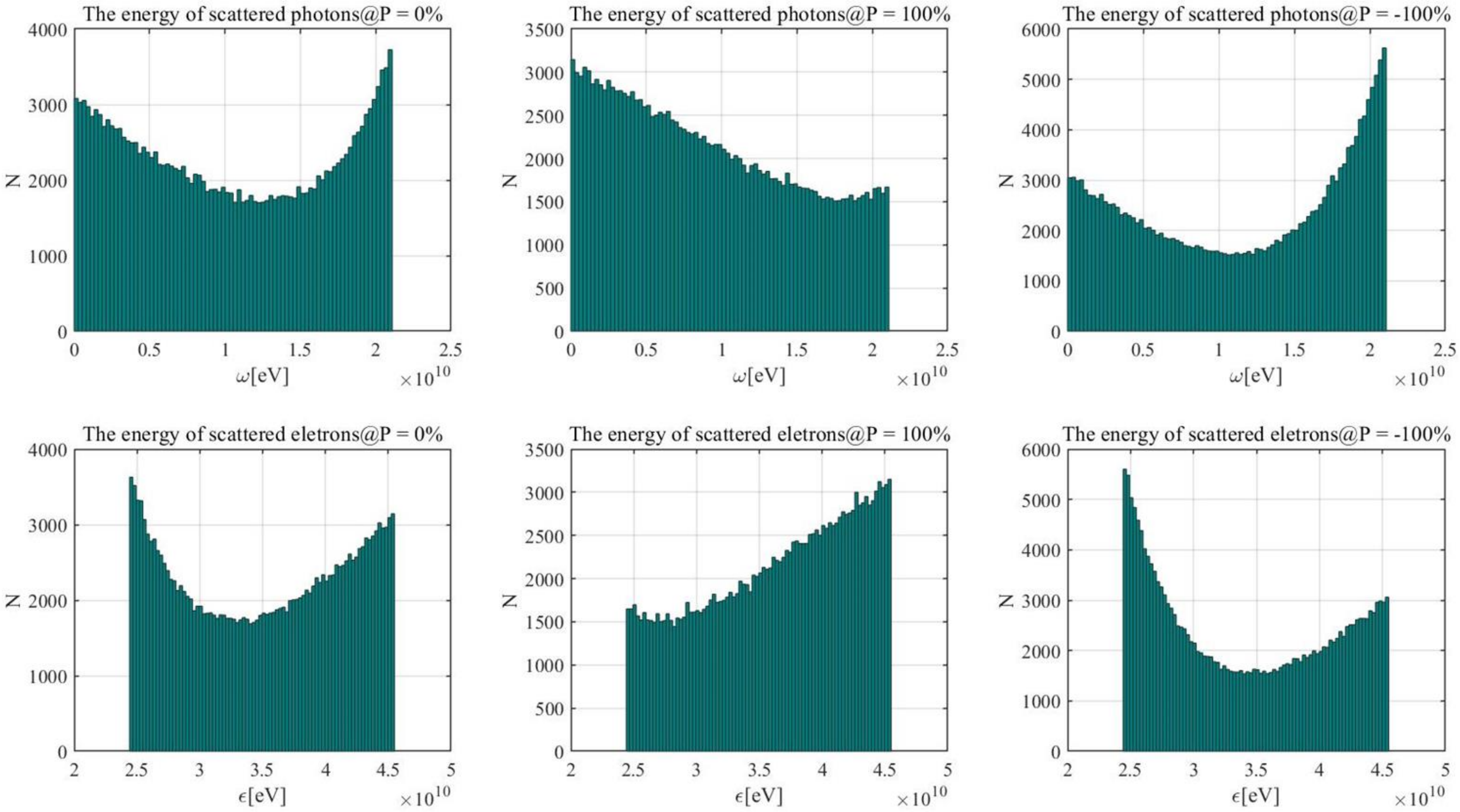








Asymmetry vs energy



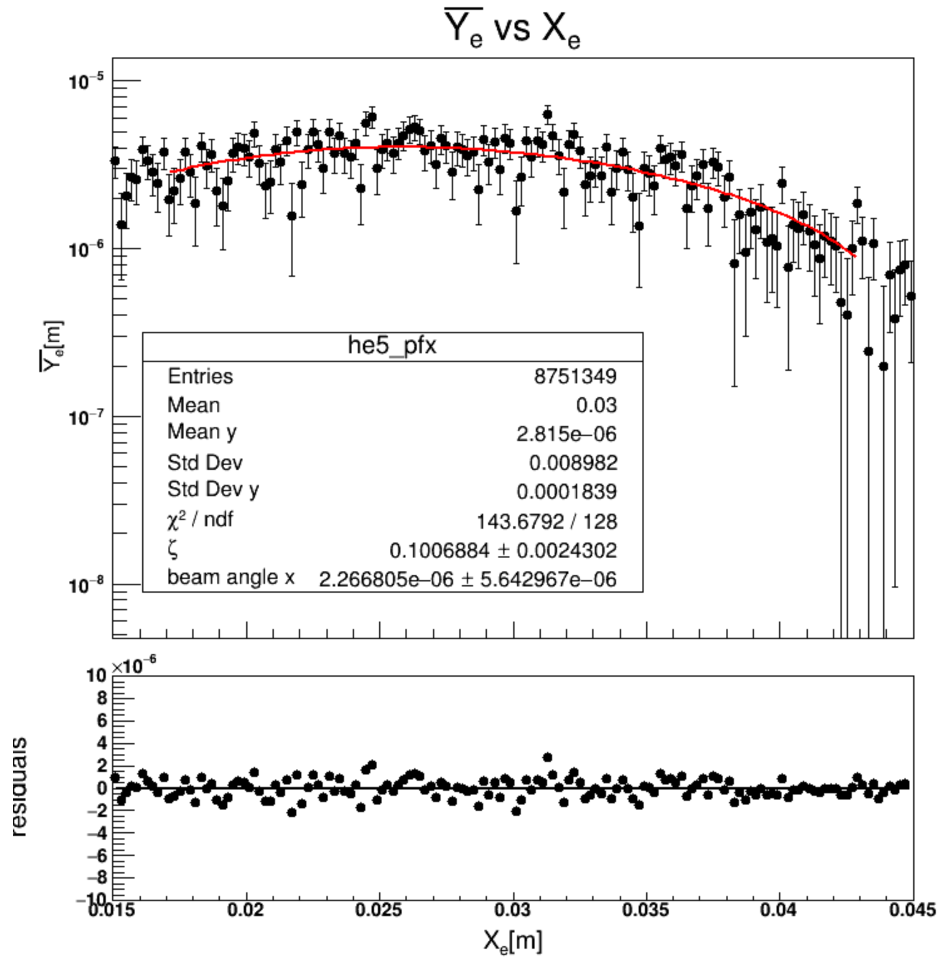
Compton Polarimeter for CEPC(Z pole)

- **For example: 10% polarization electron beam**
  - Fit result: $P_{\perp} = 0.1007 \pm 0.0024$
  - Statistical error: $\frac{\Delta P}{P} \approx 2.43\%$ for 32s.
    $\frac{\Delta P}{P} \approx 1.63\%$ for 67s.
  - Systematic uncertainty can be controlled to be 0.6%.

Sources of systematic uncertainties	Δ	$\left\lvert\frac{\Delta P}{P}\right\rvert$
Dipole strength	$7.07904 \times 10^{-7} T$	0.0404%
L1=60m (Ip to detector)	1cm	0.0168%
L2=40m (Dipole to detector)	1cm	0.1008%
Beam energy uncertainty	100keV	0.000093676%
Detector resolution	$7\mu m \times 7\mu m$	0.428%
Total		0.6%

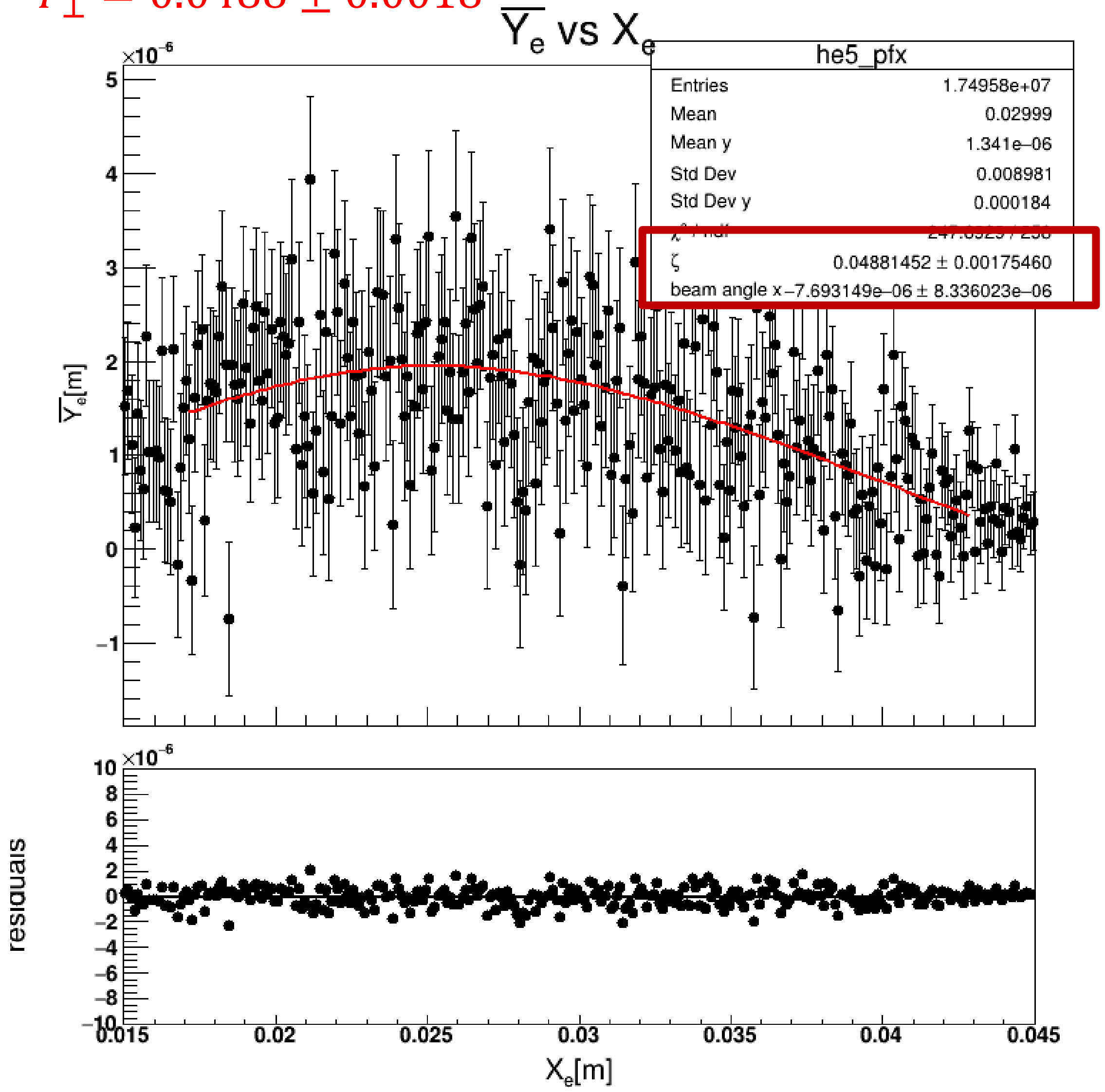
The measurement result

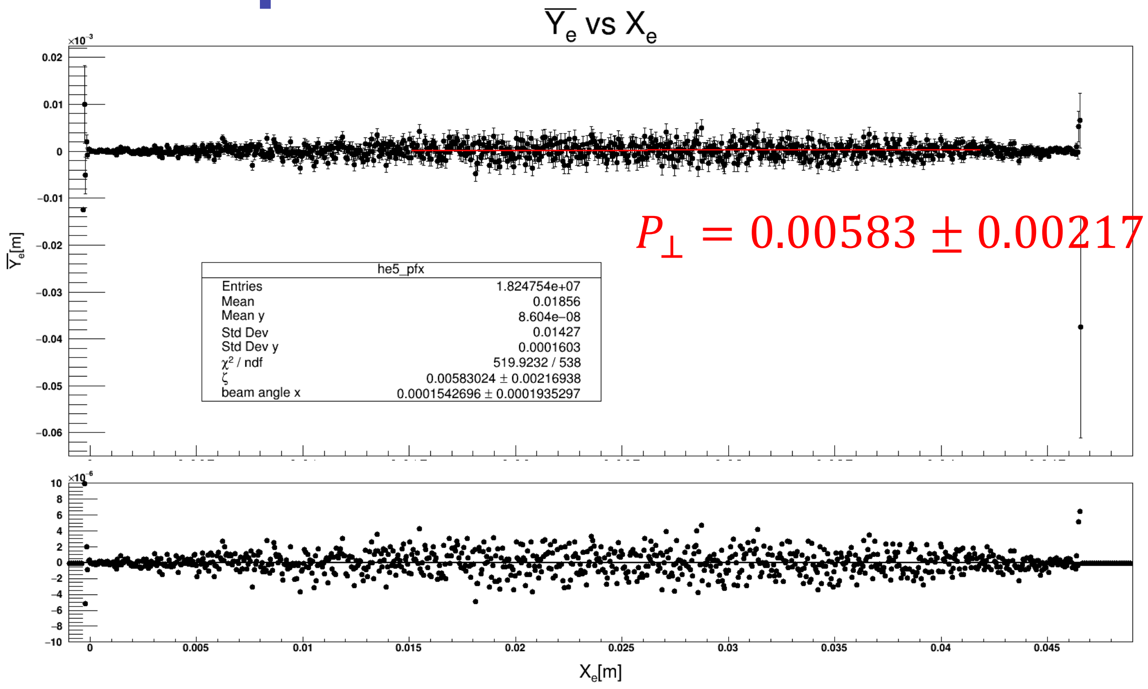
Measuring the asymmetry position distribution of scattered electrons



5% & 0.5% transverse polarization

$P_{\perp} = 0.0488 \pm 0.0018$

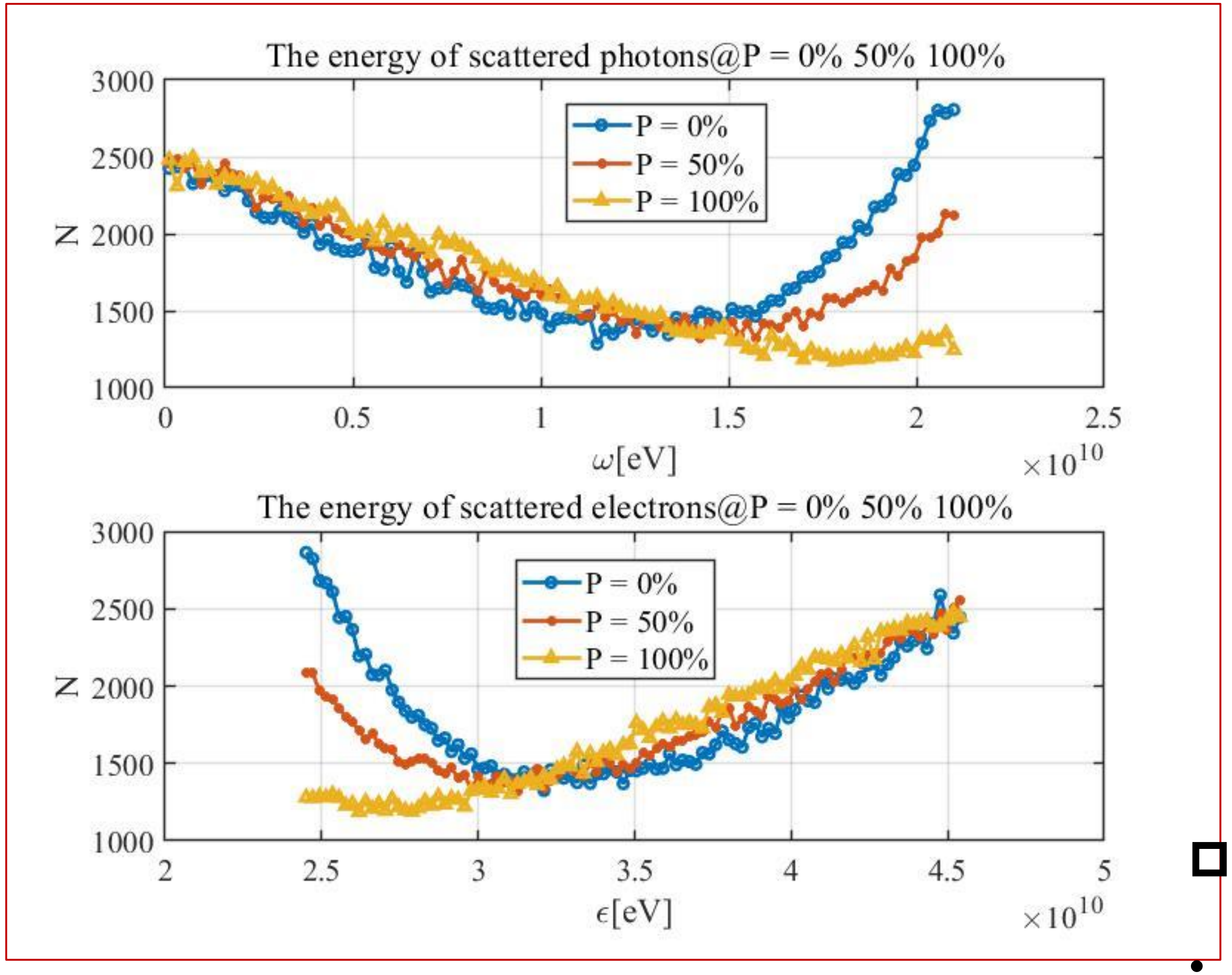


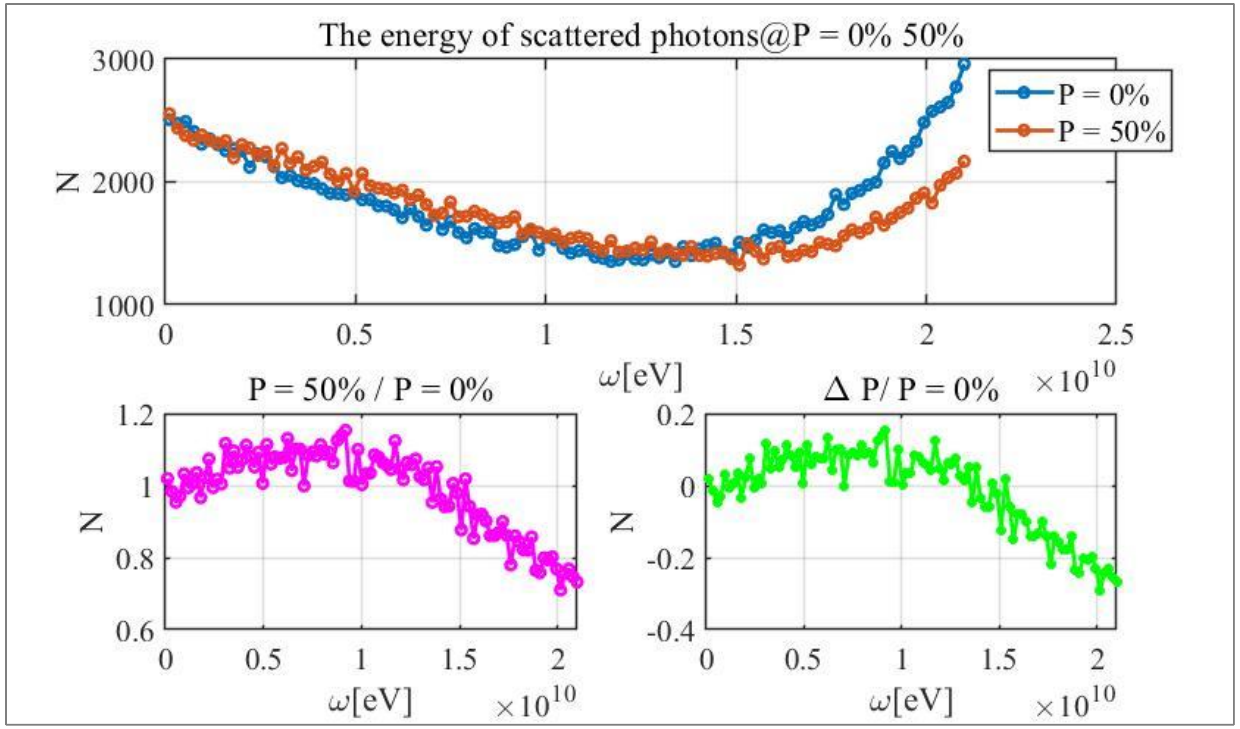


$P_{\perp} = 0.00583 \pm 0.00217$

- The relative error 3.6% for 5% polarization is observed at about one minute.
- The longer taken-time:
  - detector ?
- The higher laser power:
  - To avoid the ionization of the vacuum tube by the laser pulse?
- Considering the requirement of RDP & the time of polarization change

Measurement of longitudinal polarization





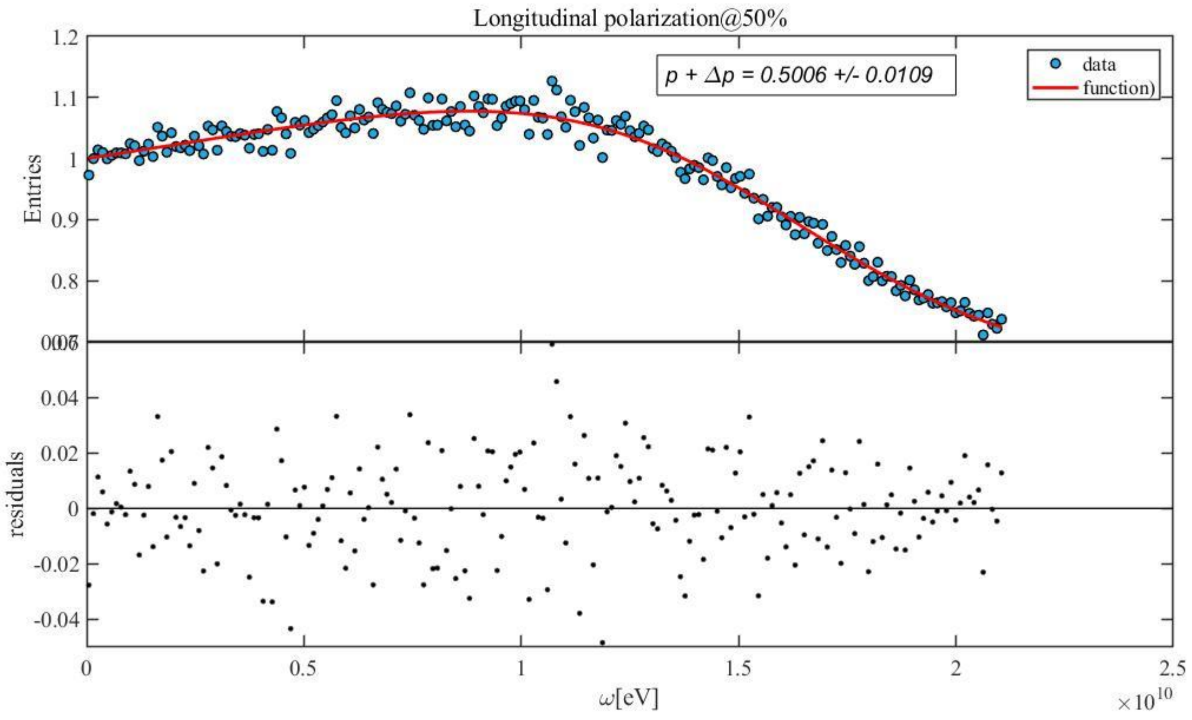
- **Fit function:**
  - $$\frac{P_{\parallel}(50\%)}{P_{\parallel}(0\%)} = \frac{\frac{d\sigma_0}{d\omega}+\frac{d\sigma_{\parallel}}{d\omega}}{\frac{d\sigma_0}{d\omega}} = \frac{\left(\kappa\left(1+(1+u)^2\right)-4\frac{u}{\kappa}(1+u)(\kappa-u)\right)+P_{\parallel}u(u+2)(\kappa-2u)}{\kappa\left(1+(1+u)^2\right)-4\frac{u}{\kappa}(1+u)(\kappa-u)}$$
  - $$\frac{P_{\parallel}(50\%)-P_{\parallel}(0\%)}{P_{\parallel}(0\%)} = \frac{\frac{d\sigma_{\parallel}}{d\omega}}{\frac{d\sigma_0}{d\omega}} = \frac{P_{\parallel}u(u+2)(\kappa-2u)}{\kappa\left(1+(1+u)^2\right)-4\frac{u}{\kappa}(1+u)(\kappa-u)}$$

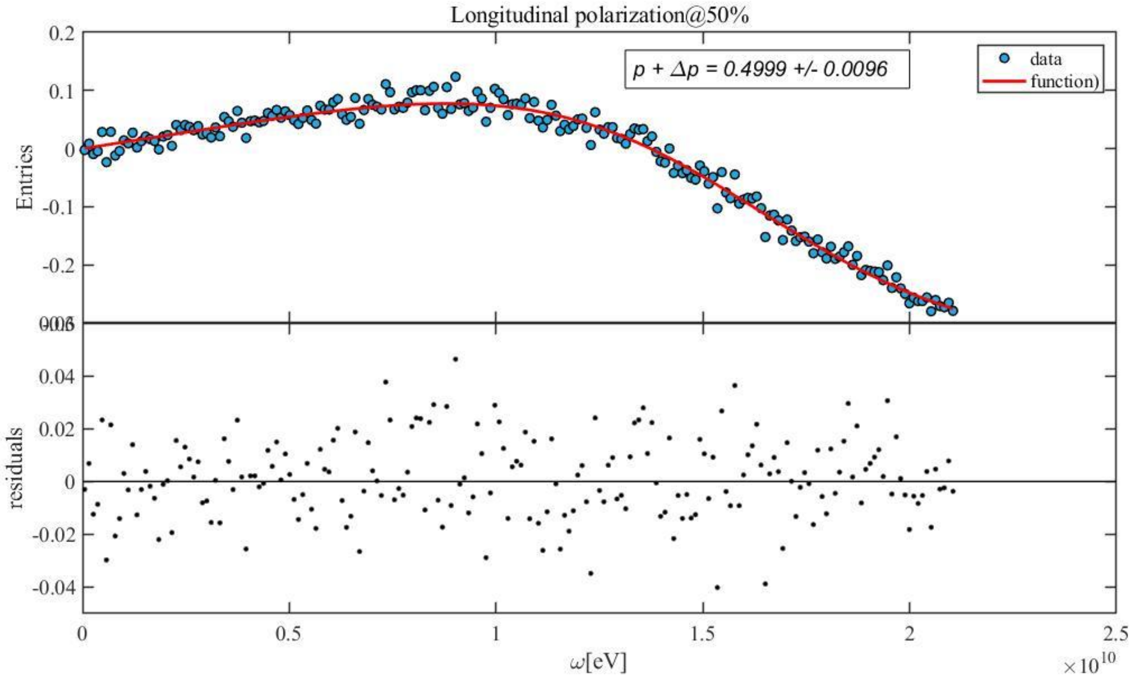
CEPC Z mode

Measurement of longitudinal polarization

$$\frac{P_{\parallel}(50\%)}{P_{\parallel}(0\%)}$$

$$\frac{P_{\parallel}(50\%) - P_{\parallel}(0\%)}{P_{\parallel}(0\%)}$$





Technical issues:

- **测光子能谱：**
  - 能谱的background?
  - 同步辐射造成的影响（单光子接受?）
- **测电子能谱：**
  - （位置→能谱）（Xe, Ye）→ u
  - Systematical uncertainties

- Layout…
- BEPC 上横向极化度/纵向极化度的相关研究…

Discussion and Summary

- Compton Polarimeter is the clear technique of choice for electron polarization at CEPC
  - High precision (~2.5%) has been achieved in 33s time
  - The measurement of polarization has low requirements for detector(different from calibrate the beam energy)

- The systematic error (0.6%) come from :①the uncertainty of beam energy; ② layout of drift distance and magnet; ③ The Angle of collision between laser beam and electron beam; ④ error from detector (A full simulation by Geant4 would be desirable to study the systematics uncertainty.

- The measurement of longitudinal polarization by Compton polarimeter are going on.

Backup

Calculation of scattering rate

➢ The maximum rate of pulsed laser and electron bunch

- The luminosity of 1 pulse laser with 1 electron bunch:

$$\mathfrak{L} = \frac{N_e N_\gamma}{2\pi\sigma_{x\gamma}\sigma_{y\gamma}} = \frac{8\times10^{10}\times1.4\times10^{16}}{2\pi\times(160\mu m\times160\mu m)} = 6.967\times10^{33} m^{-2}\cdot s^{-1}$$

- The ICS cross section is :

$$\sigma(\kappa) = \frac{2\pi r_e^2}{\kappa}\left[\left(1-\frac{4}{\kappa}-\frac{8}{\kappa^2}\right)\log(1+\kappa)+\frac{1}{2}\left(1-\frac{1}{(1+\kappa)^2}\right)+\frac{8}{\kappa}\right] = 393.5mb$$

- Compton scattering event rate:

$$N = \mathfrak{L}\sigma = 6.967\times10^{33} m^{-2}\cdot s^{-1}\times393.5mb = 2.742\times10^5\ \text{pulse}^{-1}$$

Note that: The laser is 1HZ.

IP： 1 bunch 1 second $v = \frac{3\times10^8 m/s}{100km} = 3000$次

1s内 electron 共有12000(CEPC CDR bunch nember)*3000个束团经过IP点，但是Laser无法匹配那么高的频率，设置 laser 的频率为1Hz, 则 1s内 仅仅发生一次 pulsed laser collider with 1 electron bunch

- ➢ timing system 可以给laser一个合适的trigger，保证laser同指定的一个bunch相互作用, timing system 里面有每个bunch的时间戳
- ➢ 正常情况下，polarization 演化的时间尺度在小时以上，甚至到几十小时，1min内的变化可以忽略。 如果是进行共振退极化实验，可以对一个指定束团，扫描一次depolarizer的频率，即进行一次resonant depolarization run，然后测量一下该束团极化度的情况，主要是看扫描depolarizer频率前后，该束团极化度有没有变化，不关心测量过程中的极化度变化