Institute of High Energy Physics
Chinese Academy of Sciences

CEPC 环形正负电子对撞机 Circular Electron Positron Collider

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Study of beam energy measurement using inverse Compton scattering approach

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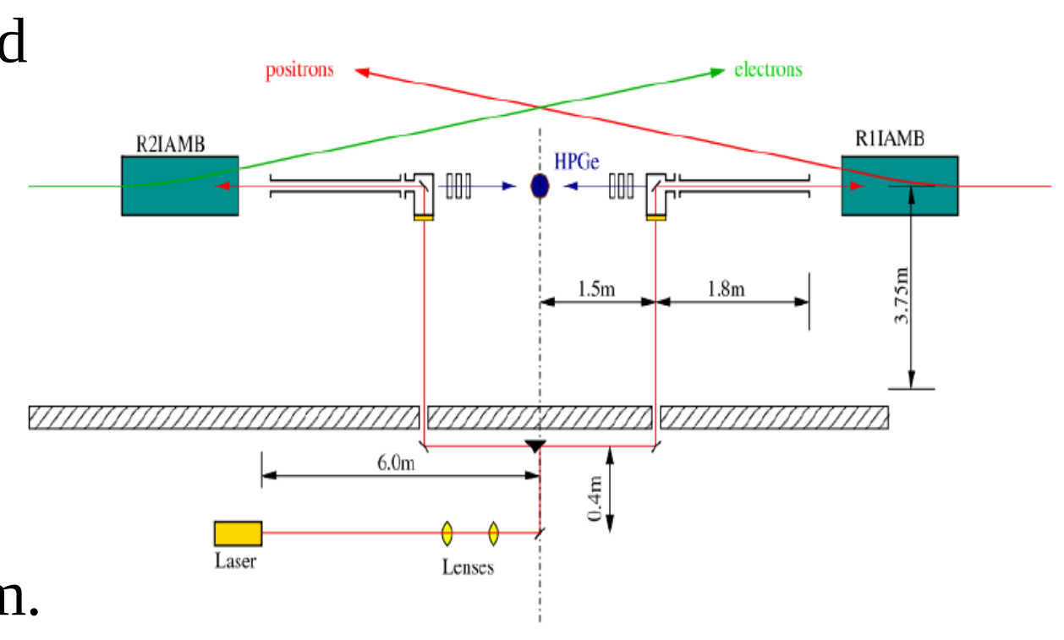
We discuss some schemes for measuring beam energy in a hundred-GeV collider using inverse Compton scattering approach. One is adjusting be in the collision angle or the incident photon frequency, the maximum energy of scattered photons could be in the range between 9 and 20 MeV. The systematic uncertainty of the beam energy could be in the range 2.1 to 8.1 MeV. The other is measuring the scattered lepton positions. Depending on whether the beam positions is measured directly, the systematic uncertainty could range from 1 MeV to 100MeV.

1. Introduction

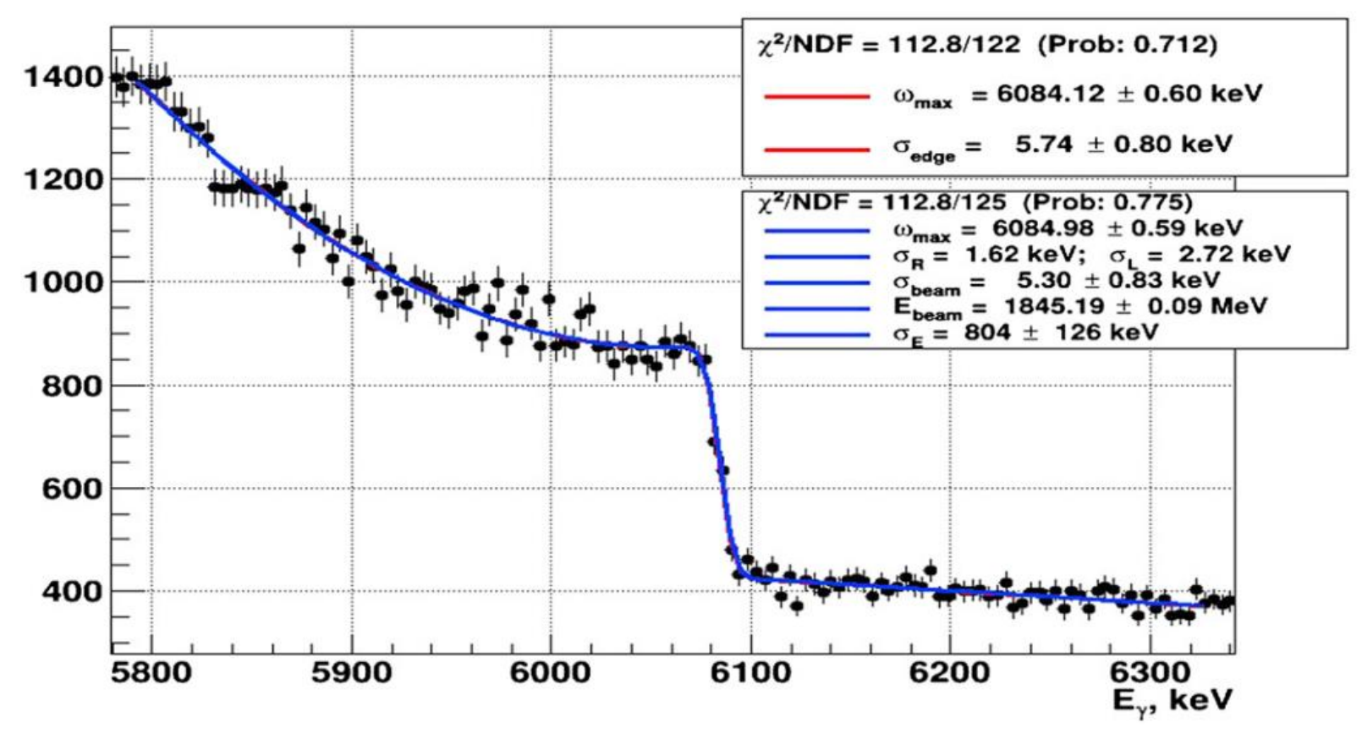
- There are a lot of experiences in the world to measure beam energy from 1 GeV to 90 GeV, with accuracy 10^{-4}~10^{-5}. For the future lepton collider, beam energy measurement is a essential component.

Method	Accuracy	Facility	Energy range
$\gamma\mu\mu$	10^{-3}~10^{-4}	BESIII/Belle	3 ~ 11 GeV (CM energy)
Beam position monitor + magnet field measurement (BPM based)	10^{-4}	LEPII CLIC, ILC	45 ~ 500 GeV
Resonant depolarization (RDP)	10^{-5}~10^{-6}	LEP/LEPII, VEPP-4M, FCC-ee	1.5 ~ 90 GeV
Wire Imaging SR Detector (WISRD)	10^{-4}	SLC, ILC	45 ~ 500 GeV
Inverse Compton scattering (ICS)	10^{-5}	BEPCII, VEPP-4M, VEPP-2000	1.5~ 2 GeV

- Right figure illustrates a diagram of this system at the BEPCII . The green line, running from top-left side to top-right and the red line, running from top-right to top-left represent the beam directions passing through two bending magnets The CO_2 laser propagates along the red line in the middle of the diagram. Various optical devices are utilized to ensure an appropriate optical path. The scattered photons mainly travel in the horizontal direction . As the beam passes through the bending magnet and changes direction, the scattered photons maintain their original trajectory, allowing them to separate from the beam.



- The scattered photons are detected using a high purity Germanium (HPGe) detector is chosen for its superior energy resolution in the MeV energy region. The detected photon energy spectrum is depicted in the bottom figure. The beam energy is determined using three parameters: the angle α shown in the right figure below, the energy of the laser photon ω and the maximum energy of the scattered photons ω'. At the BEPCII, $\alpha = 0,\ \omega = 0.117$ eV, $\omega' \sim 6$ MeV. The accuracy of the beam energy is on the order of 10^{-5}.



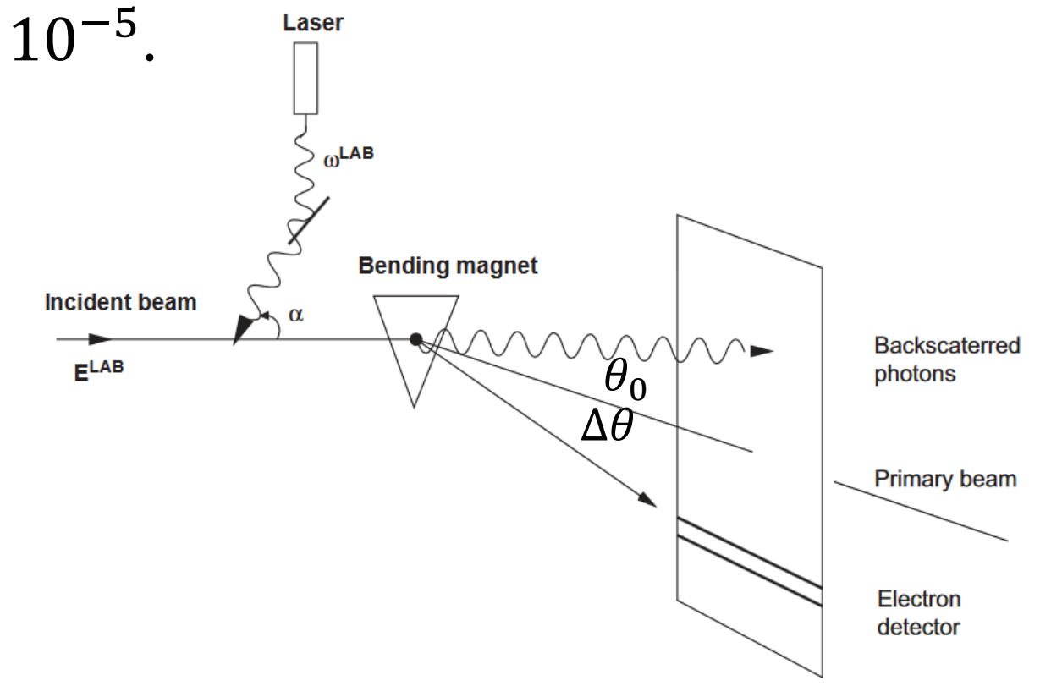


Fig. 8. Scheme of the proposed energy spectrometer based on Compton backscattering.

Nucl.Instr.Meth.A607 (2009) 340

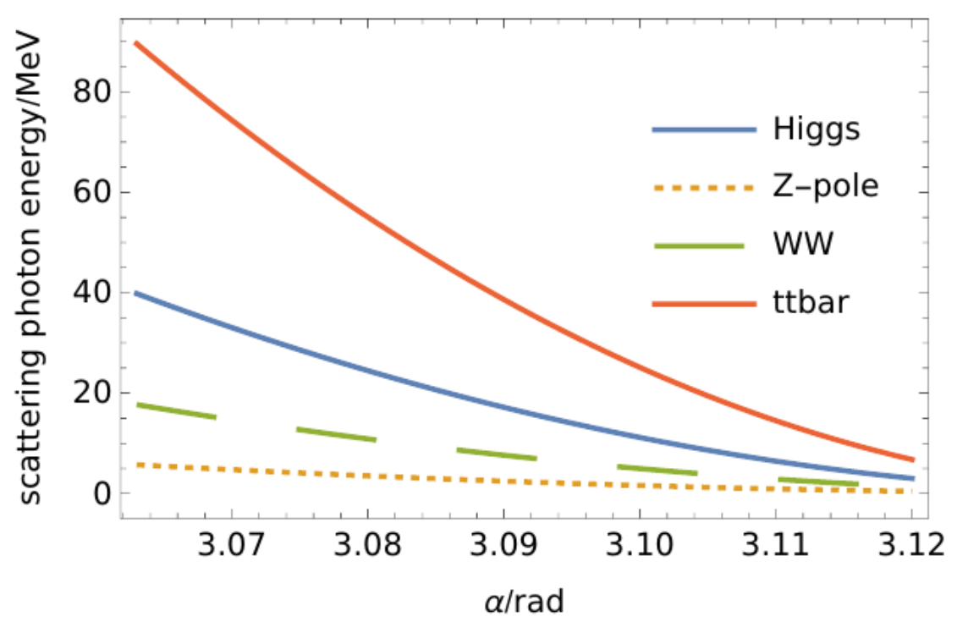
- If we were to directly implement this system in a hundred GeV accelerator, the scattered photon energy would be in the range of several tens of GeV. However, accurately measuring such high energies and calculating the beam energy with a small uncertainty would be impossible. It is evident that there are three approaches to reduce the scattered photon energy:

method	Estimated accuracy
Adjusting the collision angle	2.1 ~ 8.1 MeV
Decreasing the laser photon energy	6 MeV
Measuring scattered lepton positions	1 MeV (beam position measured)
	108 MeV (without measuring beam position)

2. Adjusting the crossing angle

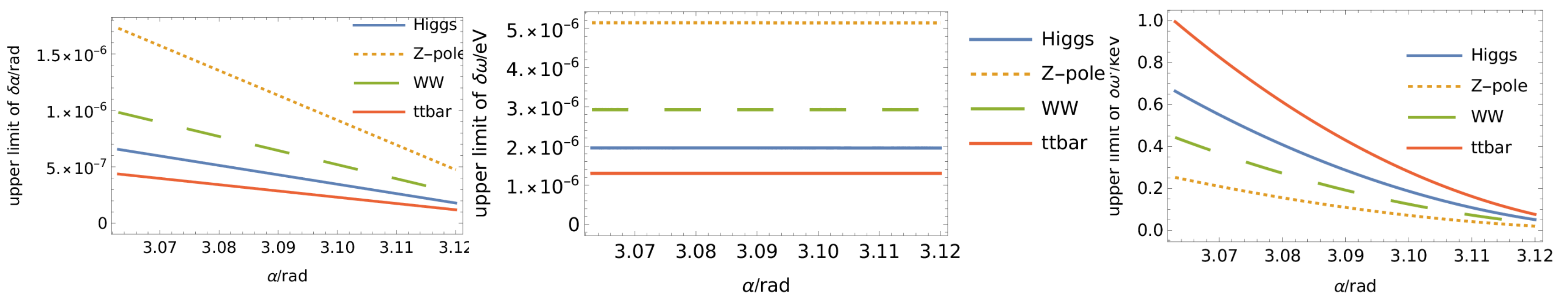
- The maximum energy of scattered photons as a function of angle α is shown in the figure below. The uncertainty of the beam energy propagates as follows:

$$\delta E_{beam} = \sqrt{\left(\frac{dE_{beam}(\alpha,\omega,\omega')}{d\alpha}\right)^2 (\delta\alpha)^2 + \left(\frac{dE_{beam}(\alpha,\omega,\omega')}{d\omega}\right)^2 (\delta\omega)^2 + \left(\frac{dE_{beam}(\alpha,\omega,\omega')}{d\omega\prime}\right)^2 (\delta\omega')^2}$$

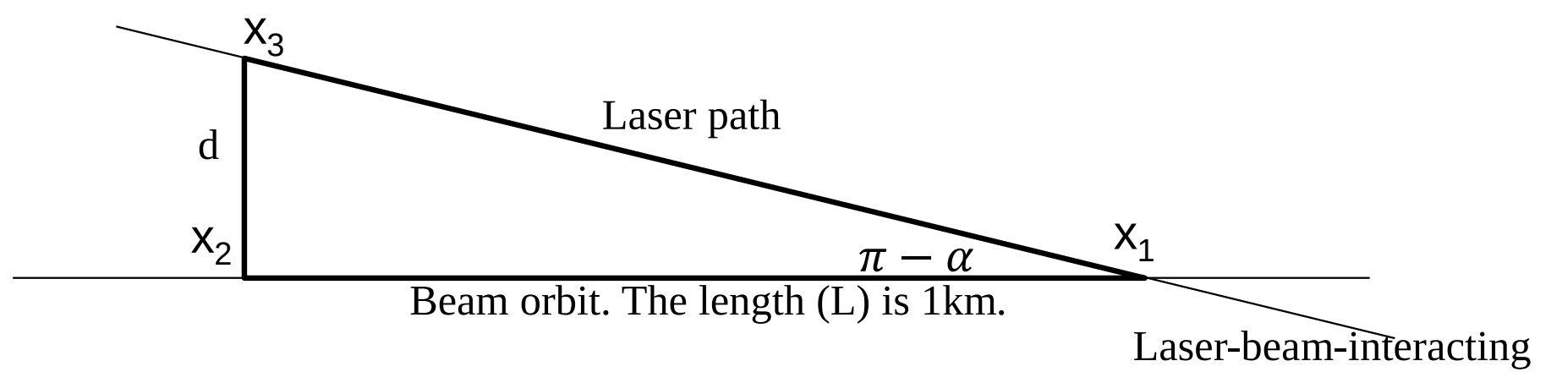


E_{beam}/GeV	α/rad	ω'/MeV	$\delta\alpha$/rad	$\delta\omega$/eV	$\delta\omega'$/keV
120	3.12	3.008	1.6×10^{-7}	1.95×10^{-6}	0.05
	3.102	10.629	3.0×10^{-7}		0.16
	3.093	15.230	4.1×10^{-7}		0.25
	3.086	19.932	4.6×10^{-7}		0.33

- We choose $\alpha < 20$ MeV, because of the range of HPGe detector. Assuming δE_{beam} = 1 MeV, and considering $\delta\omega = 0$ and $\delta\omega‘ = 0$, the uncertainties $\delta\alpha$ as a function of the angle α. Similarly, assuming $\delta\alpha = 0$, $\delta\omega' = 0$ and $\delta\alpha = 0$, $\delta\omega = 0$, we can obtain the uncertainties $\delta\omega$ and $\delta\omega'$ as functions of the angle α. These uncertainties are presented in Figures below. We have selected a series value for Higgs operation in Table above.



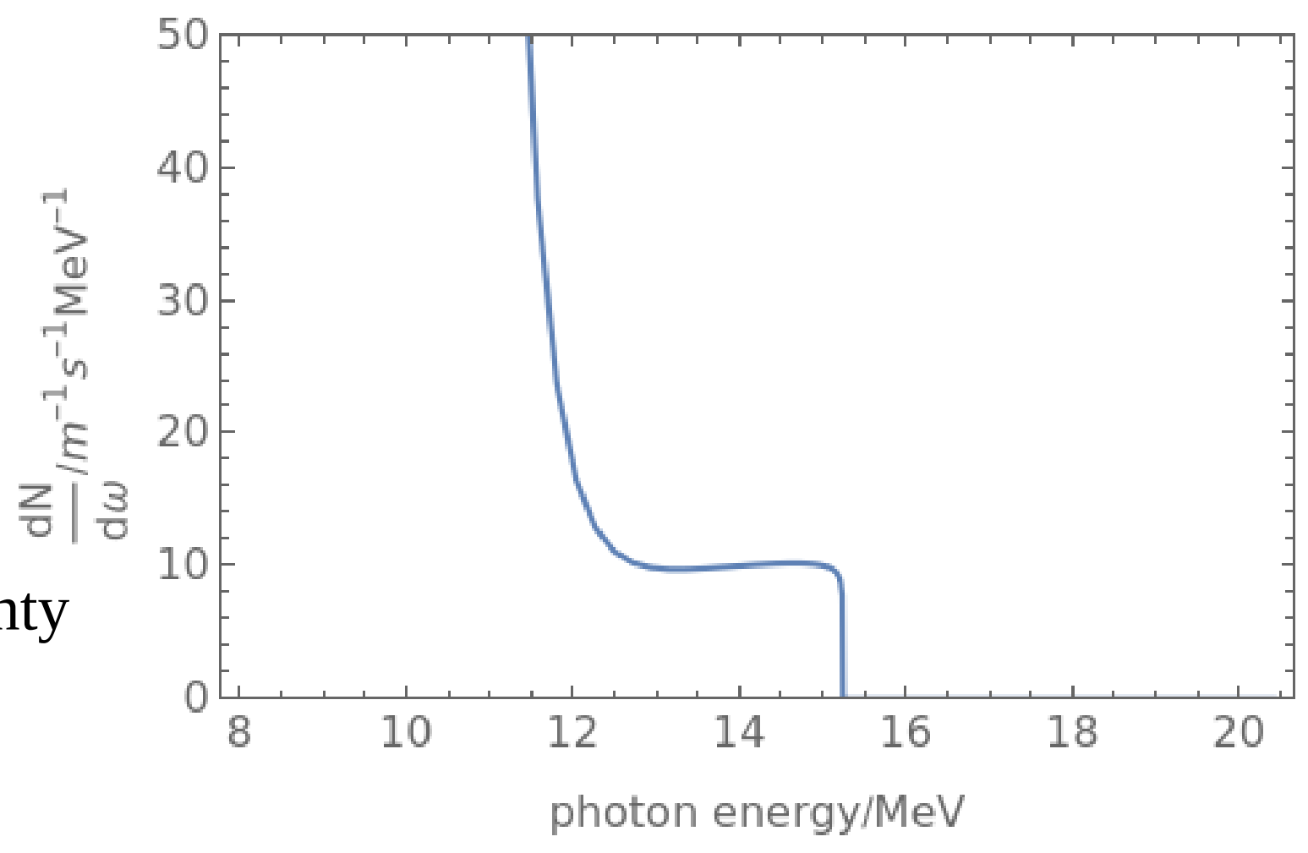
- The uncertainty of α would be control using a long beam orbit and a long laser path.
  - x_1, x_2, x_3 are the vertex
  - linear orbit 1km; BPM accuracy 100um; alignment uncertainty 50~100µm.



Beam orbit. The length (L) is 1km.

Laser-beam-interacting point

- $\delta\alpha \approx 1.42 \times 10^{-7}$rad.
  $< 4 \times 10^{-7}$rad.
  contribute a 0.5 MeV systematic uncertainty of the beam energy.
- Use beam and laser paras.: Laser Power: 50W; Photon energy: 0.117eV; Waist radius: 100um; Beam: 16.7mA, $\sigma_{x/y}$: 100/10um. Photon energy spectrum of SR and Compton scattering can be obtained in the figure below.
  - example: $\alpha = 3.093$



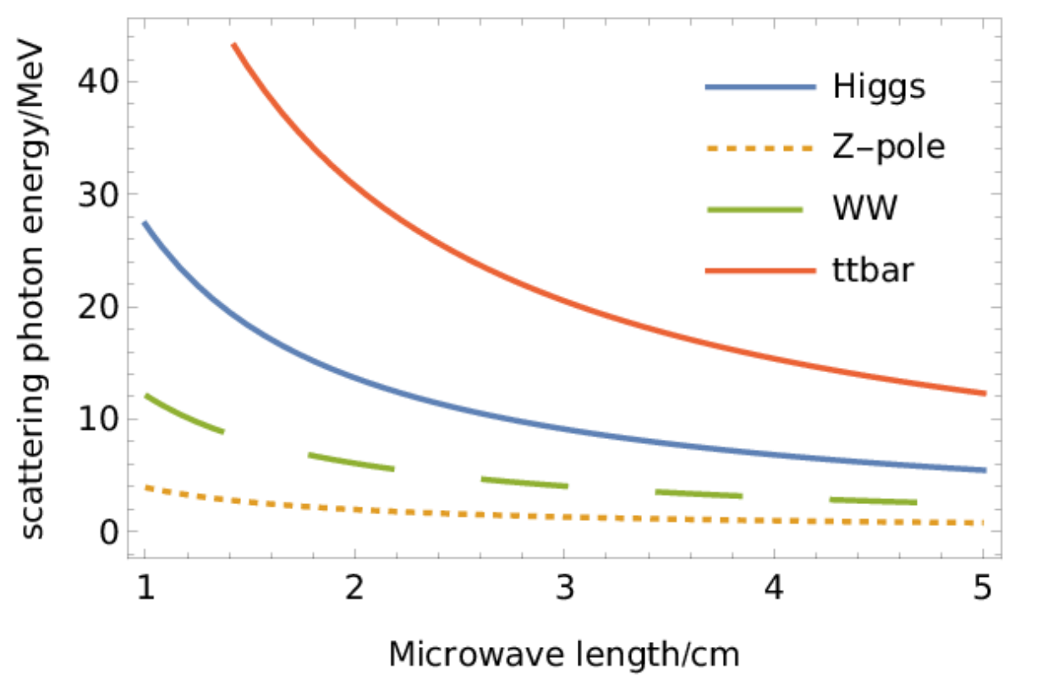
- HPGe Detector efficiency can be evaluated using Geant4.

	Dimension (mm)		Efficiency	
	Diameter	Length	9MeV	15MeV
Type I	57	62	1.4%	1.1%
Type II	80	82	4.5%	1.7%

- Detect 200 events/hour. If assuming the same uncertainty of the Compton edge, it contributes a 2 ~ 8 MeV uncertainty of the beam energy
- Difficulty:
  - Higher power laser, smaller bunches, higher efficiency
  - Survived in Neutron-rich environment

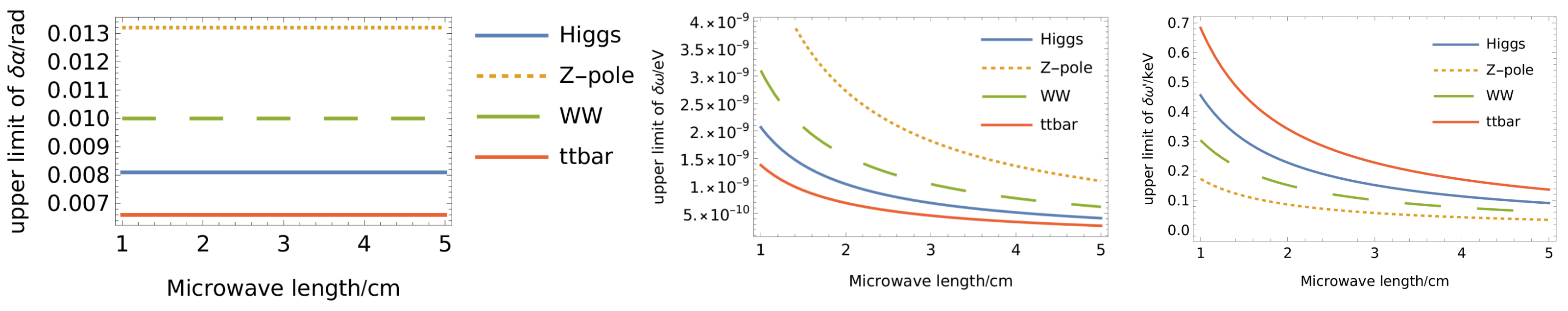
3. Decreasing the photon energy (frequency)

- The maximum energy of scattered photons as a function of the wave length of the micro wave is shown in the figure below. We can select a series value for Higgs operation in Table below.



E_{beam}/GeV	Wave length/cm	ω'/MeV	$\delta\alpha$/rad	$\delta\omega$/eV	$\delta\omega'$/keV
120	9.10	3.005	0.008	2.27×10^{-10}	0.05
	3.04	8.996		6.79×10^{-10}	0.16
	2.30	15.192		1.15×10^{-9}	0.25
	1.37	19.969		1.51×10^{-9}	0.33

- These uncertainties are presented in Figures below. The uncertainty of the beam energy is estimated in Ref. Nucl. Instrum. Meth. A, 1026:166216, 2022.



- The wave length is in the microwave band and we should find a suitable source. Notice that the existence of a Compton edge relies on the on-shell (plane-wave) photon and the energy-momentum conservation. The micro wave in a wave guide or cavity may not appropriate

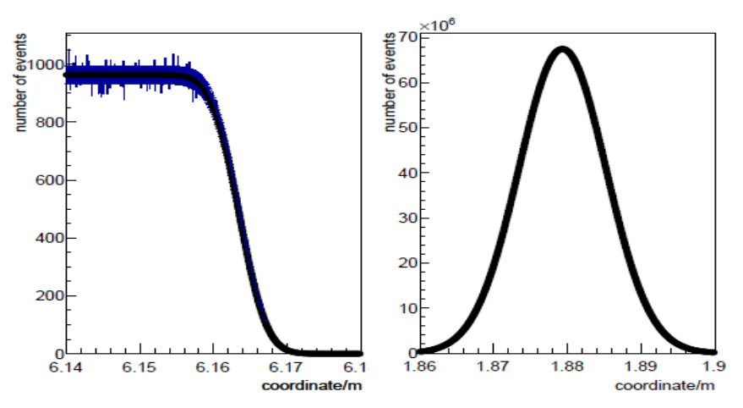
4. Measuring scattered lepton positions

- Extract some bunches; Magnet field: 0.5T; the length of dipole: 3m; the drift distance between the bending magnet and detector: 500m. Three positions should be measured:
  - Backscattered photon position, X_γ (which is set as the axis origin).
  - Beam position, X_beam.
  - Position of the lepton with minimum energy after scattering, X_edge.
- If α=0, $E\_beam \sim \frac{(mc^2)^2}{4\omega}\frac{\Delta\theta}{\theta_0} \sim \frac{(mc^2)^2}{4\omega}\frac{X_{edge}-X_{beam}}{X_{beam}-X_\gamma} + O(\left(\frac{X_{edge}-X_{beam}}{X_{beam}-X_\gamma}\right)^2 + \cdots$
  - $O\left(\left(\frac{X_{edge}-X_{beam}}{X_{beam}-X_\gamma}\right)^2\right) \sim 11.5MeV;$
- If requiring δE_{beam}<1MeV, the upper limits of positions measurement are listed above.

Beam energy	δX_{edge}	δX_{beam}	δX_γ
120GeV	$36\mu m$	$22\mu m$	$32\mu m$

- In Ref. RSI 91.3 (2020): 033109. A preliminary simulation shows the uncertainty of the beam energy is smaller than 1 MeV.

X_{edge}/m	$6.163503 \pm 2.6 \times 10^{-5}$
X_{beam}/m	$1.879339 \pm 6 \times 10^{-8}$
X_γ/m	0 (fixed)
E_{beam}/GeV	119.9993 ± 0.0010



- Difficulty: How to measure bunch position?
  Diamond detector? BPM?

- To avoid the measurement of the bunch position, 2D fit is proposed in Ref. Nucl.Instr.Meth.A607 (2009) 340 and JINST 17 (2022) 10, P10014. Not only the beam energy but also the beam polarization can be measured.
  - Uncertainty of the beam energy @Z-pole ~ 10^{-4}

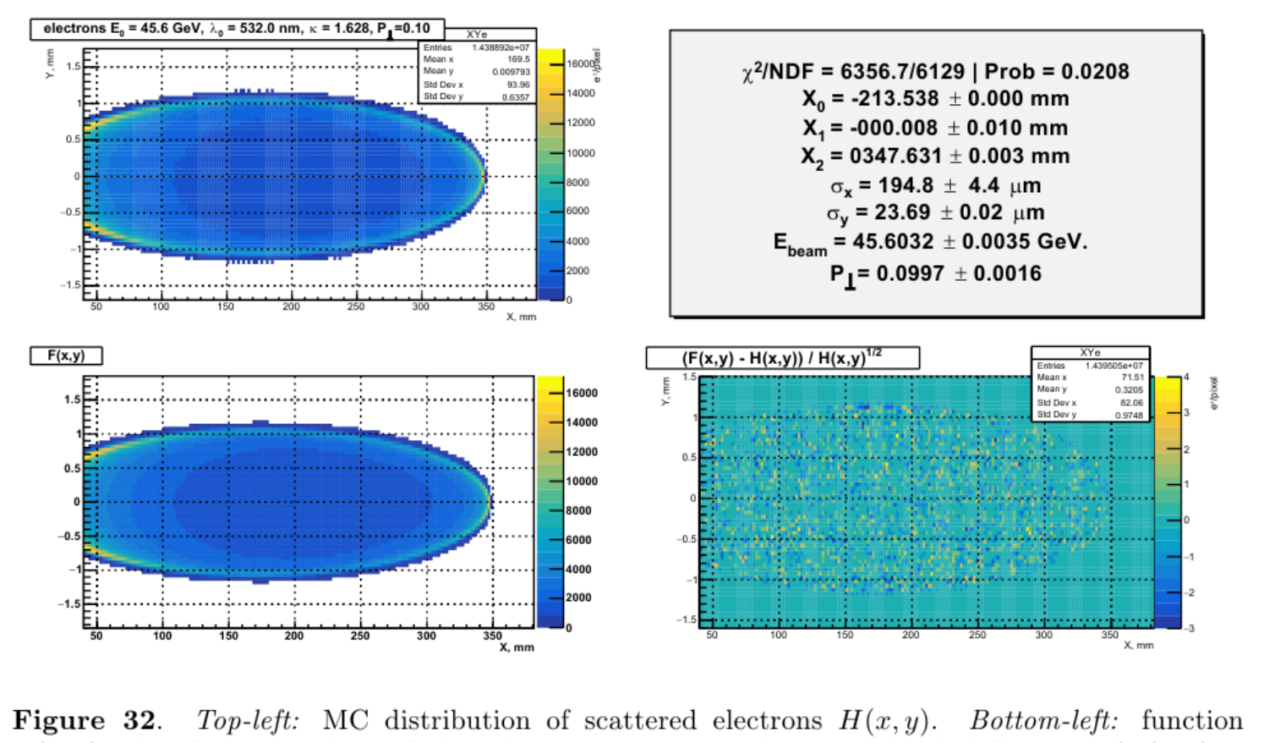
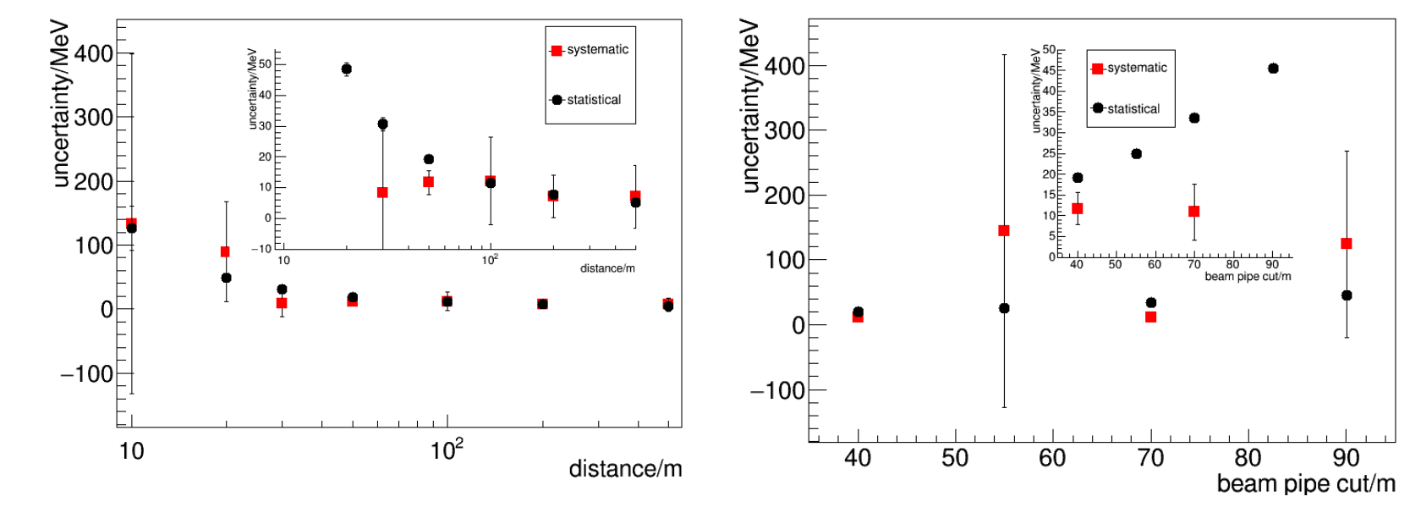
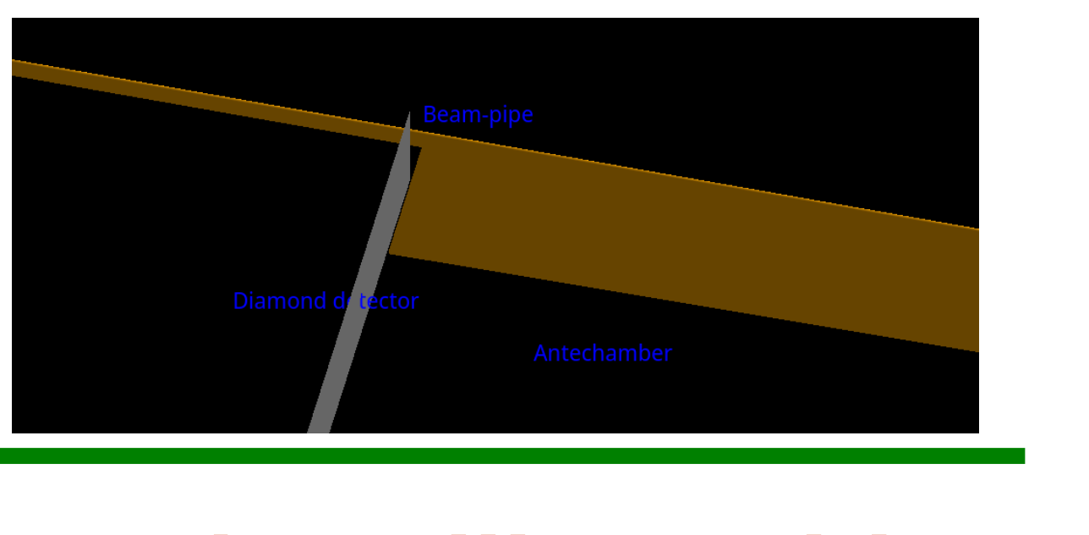


Figure 32. *Top-left:* MC distribution of scattered electrons $H(x,y)$. *Bottom-left:* function $F(x,y)$ after fitting to the MC distribution. *Bottom-right:* normalized difference: $(F(x,y) - H(x,y))/\sqrt{H(x,y)}$. *Top-right:* $F(x,y)$ parameters obtained from the fit, only the mean x value of the scattered photons distribution (X_0) was fixed).

- We optimize the parameters, then uncertainty of the beam energy @Higgs ~30 MeV (3×10^{-4})



- A preliminary Geant4 simulation using optimized paras. is done.
  - Uncertainty ~ $\pm 87(stat.) - 108(sys.)$ MeV.



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