HIGH-PRECISION CEPC ENERGY CALIBRATION

TANG Guangyi
On behalf of CEPC Energy Calibration Group
June 22, 2018

CEPC ENERGY CALIBRATION GROUP

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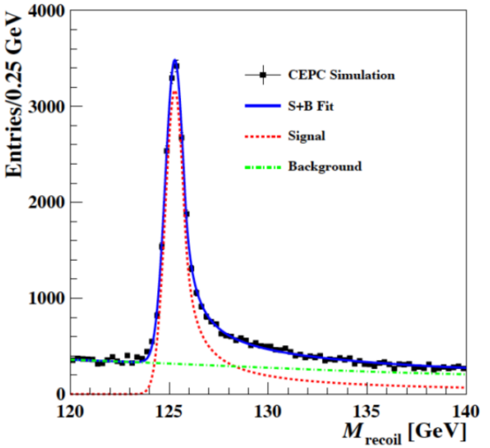
- CWNU(西华师范):
  - LAN Xiaofei.
- …
- Thank Muchnoi for his helpful discussion.

OUTLINE

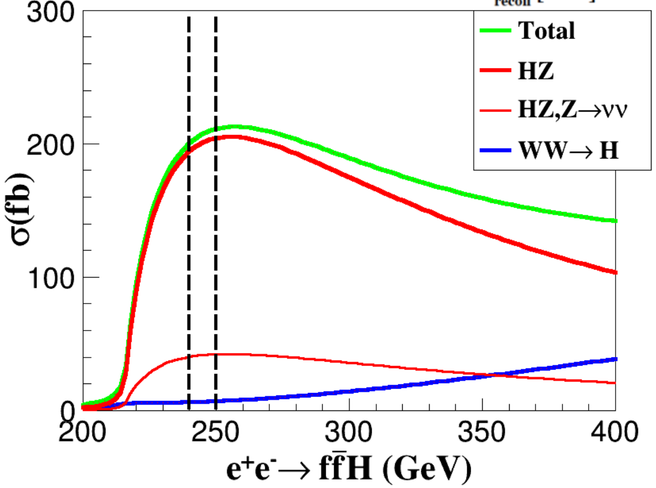
To show the feasibility of Compton scattering method.

- Introduction
  - Common method
  - Experience @BEPCII
- Compton scattering method
  - Scattering with infrared laser, measure scattered photon energy.
  - Scattering with micro-wave, measure scattered photon energy.
  - Scattering with infrared laser, measure bending angle.
- summary

PHYSICAL AIM



- Higgs Mass from Recoil Mass method
  - If we require $\delta M_{recoil} < 1\text{MeV}$, than,$\delta E_B < 0.25\sim1.35$MeV.
- $\sigma(ZH)$ measurement
  - Find Left/Right Shift with 0.5% $\sigma(ZH$b) =200.5fb@240GeV 200.5f×(1$\pm$0.5%)~@240$\pm$0.5GeV than,$\delta E_{cm} < 500\text{MeV}$.



- No significant impact on other Higgs programs
  - Event/Background selection efficiency.
  - Branching ratio (Br(H->bb)) requires δm_H<130MeV.
- WW threshold & Z pole:

  at least δE_B<1MeV ~ LEP precision 2×10^{-5}
  - Try to do it better, δE_B<100keV

COMMON METHOD

- $\mu\mu\gamma$ events
  - Uncertainty ~ 40-50MeV (CM energy, by Qinglei)
- Resonant depolarization technique (@Z-pole, LEP)
  - Uncertainty ~ 2×10^{-5} (relative, beam energy)
- Compton scattering method. (beam energy)
- Others:
  - J/ψ production with extra beams. (beam energy)
  - ...

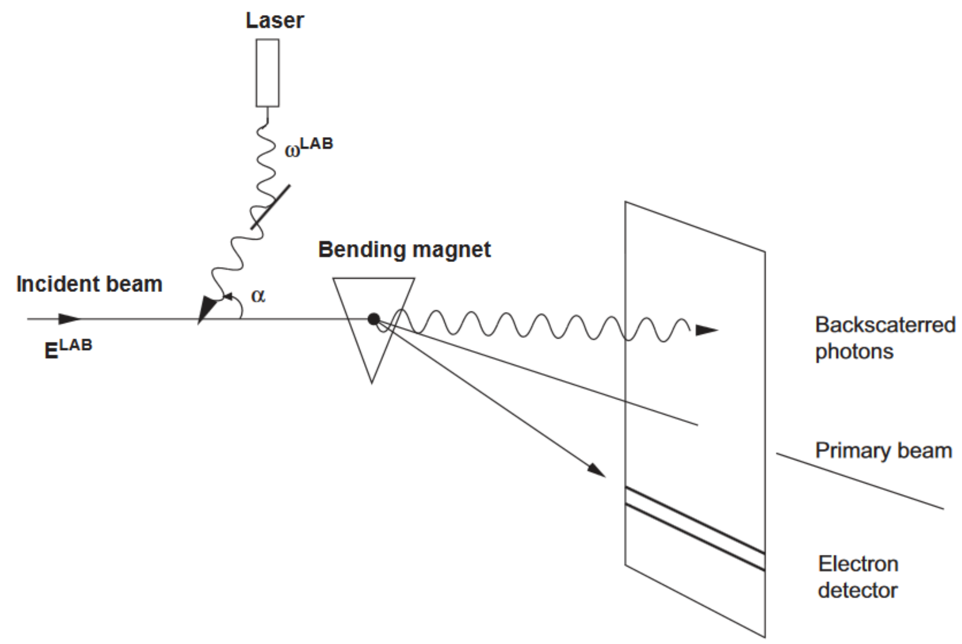


Fig. 8. Scheme of the proposed energy spectrometer based on Compton backscattering.

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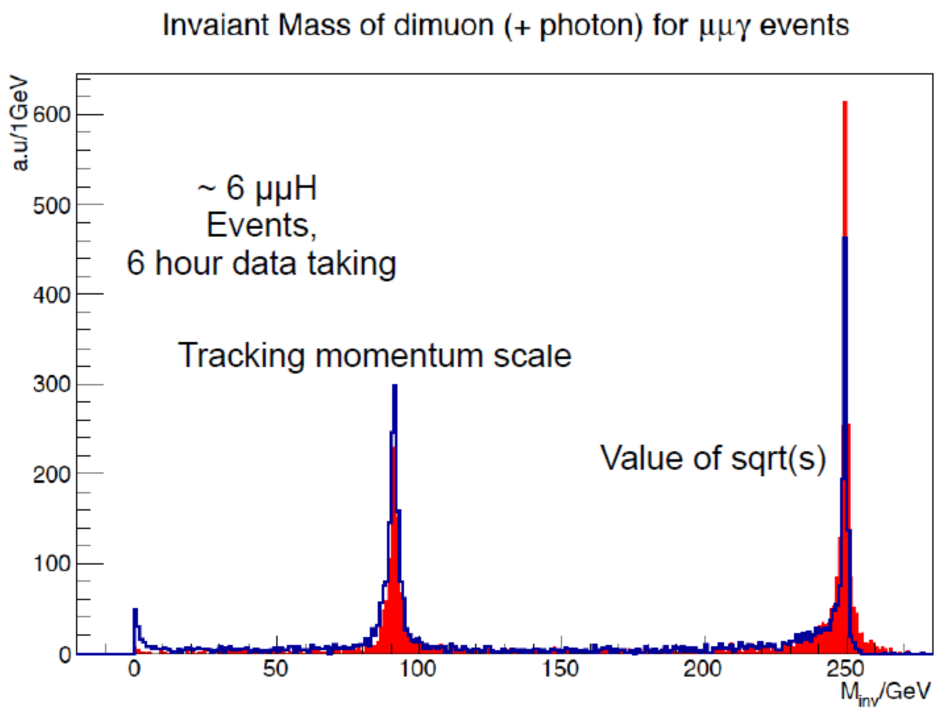
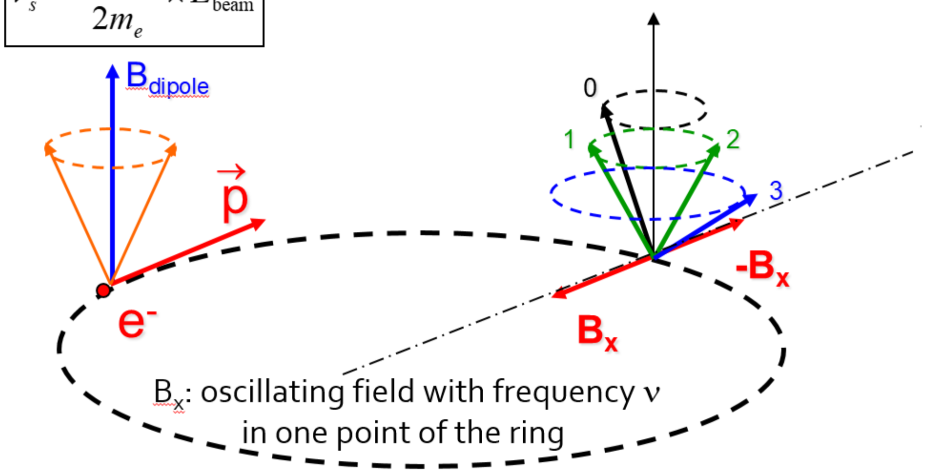
COMMON METHOD

- $\mu\mu\gamma$ events (by Qinglei)
  - Uncertainty ~ 40-50MeV (CM energy)



- Resonant depolarization technique (@Z-pole, LEP)
  - Uncertainty ~ 2×10^{-5} (relative, beam energy)
- CEPC: @Z-pole√, but @ZH?

$$\nu_s = \frac{g_e - 2}{2m_e} \times E_{\text{beam}}$$



Patrick Janot, lecture gave in the 2014 Frascati Spring school

COMMON METHOD

- Compton scattering method. (beam energy)
  - $E_{beam} \sim f(\alpha, \omega, \omega')$;
  - α: crossing angle; ω: laser photon energy; ω': maximum energy of outgoing photon.
  - Or, $E_{beam} = \frac{(mc^2)^2}{4\omega} \frac{\Delta\theta}{\theta_0}$;
- Experiences @BEPCII.

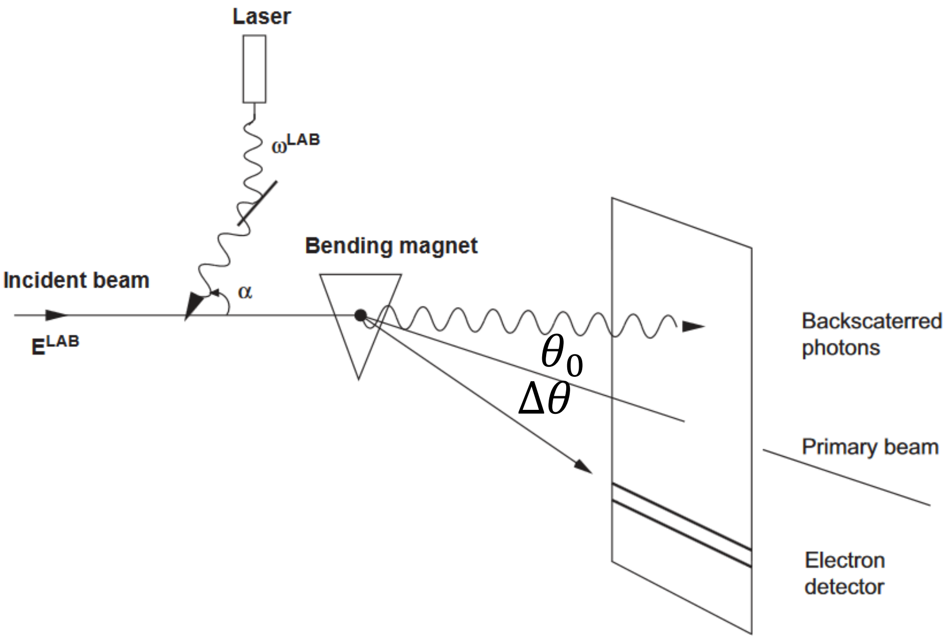


Fig. 8. Scheme of the proposed energy spectrometer based on Compton backscattering.

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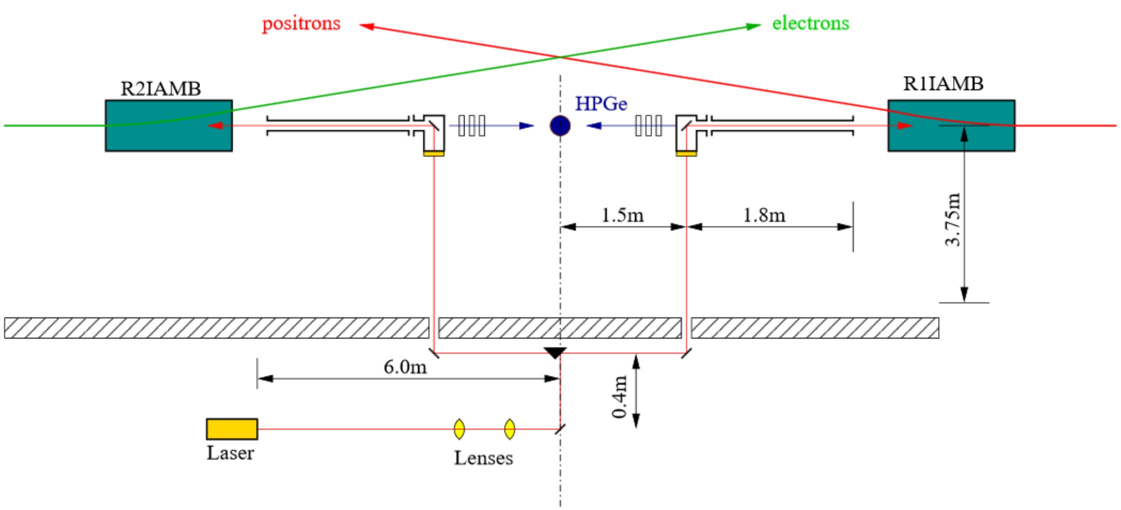
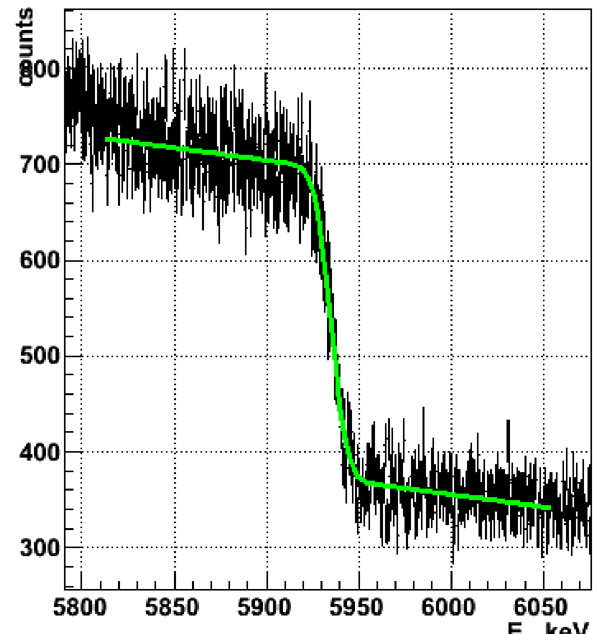
ENERGY CALIBRATION @BEPCII

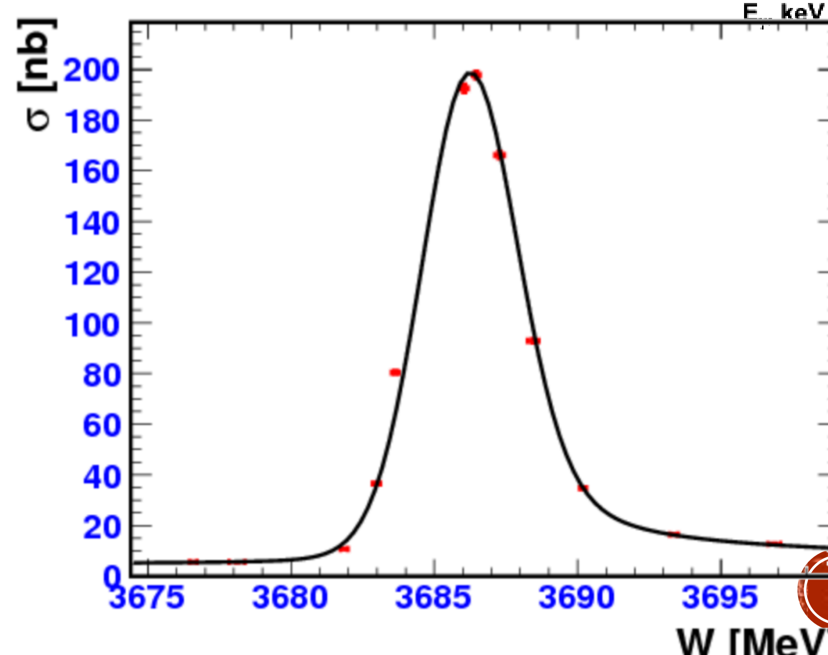
- Compton Back-scattering:
  - $E_{beam} = \frac{\omega'}{2}\sqrt{1 + \frac{m_e^2}{\omega\,\omega'}}$
- Hardware: locate at north IP of BEPCII
  - CO_2 Laser (ω=0.117eV, 50W) and optical system.
  - High purity germanium detector: 16384 channels.
  - Pulse generator and isotopes (Cs, Co, …).
  - Data acquisition system.
- Side-by-side measurement.



ENERGY CALIBRATION @BEPCII

- Compton Back-scattering:
  - $E_{beam} = \frac{\omega'}{2}\sqrt{1 + \frac{m_e^2}{\omega\ \omega'}}$
- Calibration with isotopes and pulse generator.
- Fit of maximum photon energy (Compton edge).
- Performance studied by comparison of $\psi(2S)$
  - relative uncertainty~2×10^{-5}

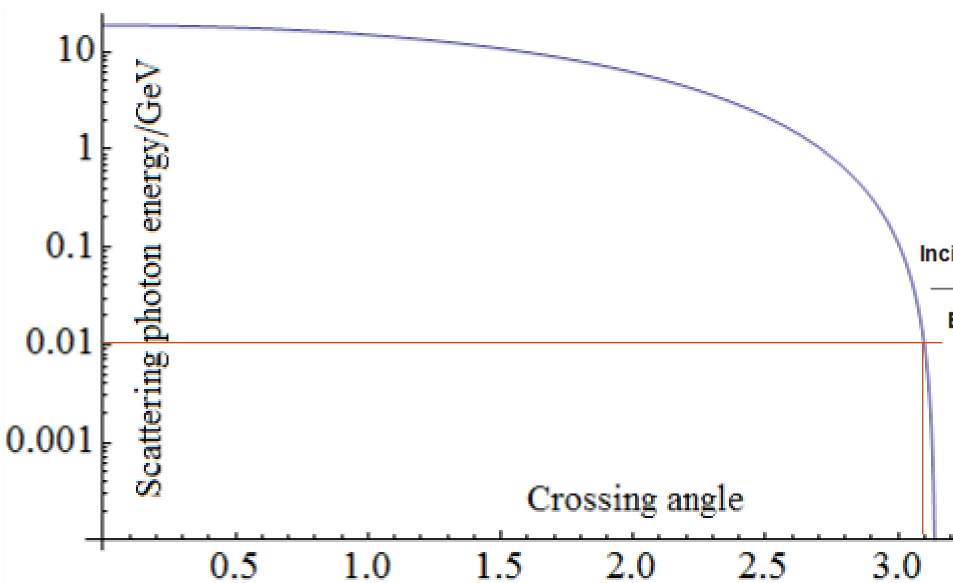


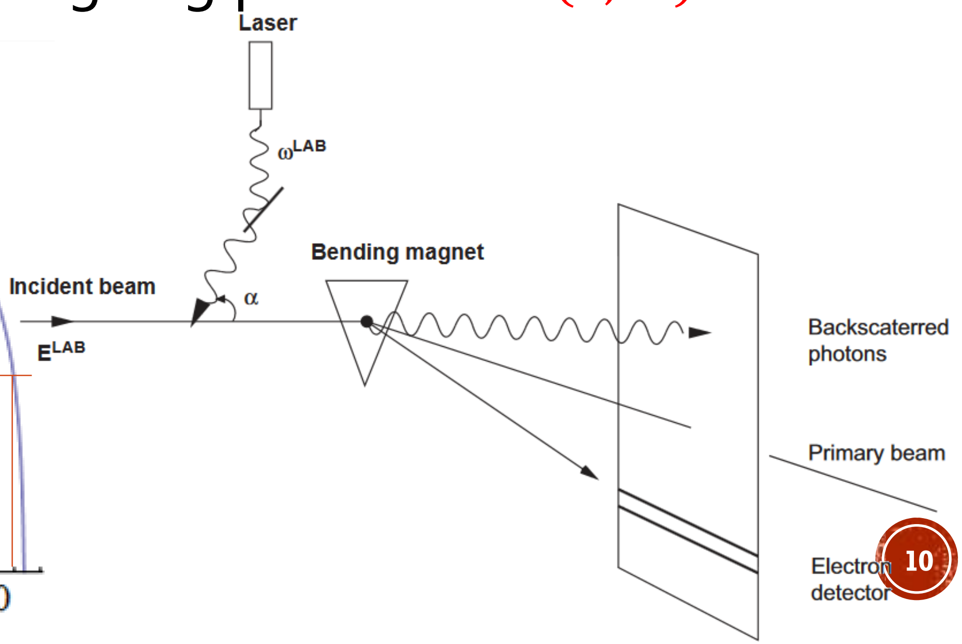


JINST 12 (2017) no.07, C07019

BEAM ENERGY CALIBRATION

- If we do the same work @CEPC
  - 120GeV(beam) + 0.11eV(CO_2 laser)→20GeV (maximum scattering photon energy). Too large to be measured precisely.
  - Change crossing angle, $\alpha \in (3.06, 3.13)$rad. → Scattering with infrared laser, measure scattered photon energy.
  - Or, change the laser frequency $\nu \sim 20$GHz, and crossing angle. → Scattering with micro-wave, measur scattered photon energy.
  - The maximum energy of outgoing photon $\omega' \in (1{,}40)$MeV.





BEAM ENERGY CALIBRATION

- If we do the same work @CEPC
  - 120GeV(beam) + 0.11eV(CO_2 laser)→20GeV (maximum scattering photon energy). Too large to be measured precisely.
  - The maximum energy of outgoing photon $\omega' \in (1,40)$MeV.

1MeV 10MeV 20MeV 40MeV

- 1MeV–10MeV:
  - Easy to calibrate and detect
  - High SR background
- 10MeV–20MeV:
  - (p, γ) reaction to calibrate
- 20MeV–40MeV:
  - Difficult to calibrate and detect
  - Low SR background

- We choose 15MeV photon as the optimized value.

SCATTER WITH INFRARED LASER

- Example: crossing angle $\alpha = 3.108\text{rad}$, (scatter maximal 15MeV photon)
  - $\delta E_{beam} \sim \sqrt{(3.5 \times 10^6 \times \delta\alpha)^2 + (4.0 \times 10^3 \times \delta\omega')^2}$
  - If $\delta E_{beam} < 1\text{MeV}$, $\delta\alpha < 2.8 \times 10^{-7}$ and $\delta\omega' < 2.5 \times 10^{-4}\text{keV}$.
- Impact on $\delta\alpha$:
  - Beam orbit, variance of beam momentum $\delta\vec{p}$;
  - Laser alignment.
- Impact on $\delta\omega'$:
  - Detector calibration;
  - Statistic error.

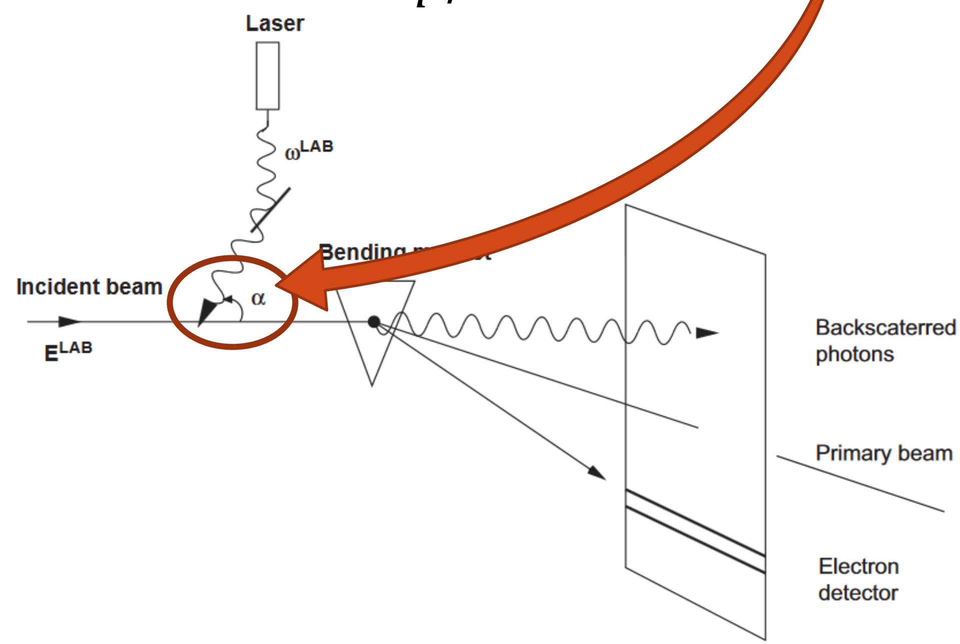


Fig. 8. Scheme of the proposed energy spectrometer based on Compton backscattering.

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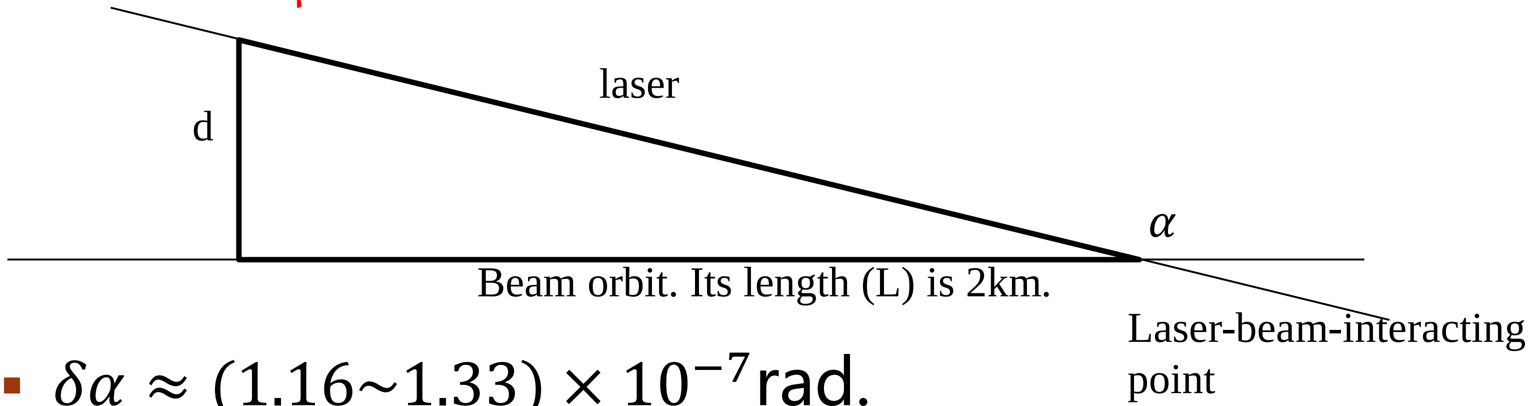
  - Beam orbit, variance of beam momentum $\delta\vec{p}$;
  - Laser alignment.
- Impact on $\delta\omega'$:
  - Detector calibration;
  - Statistic error.
- Beam position monitor + long linear orbit
- Long laser path

SCATTER WITH INFRARED LASER

- Beam position monitor + long linear orbit.

$$\pi - \alpha = \text{ArcTan}(d/L).$$

  - linear orbit 2km; BPM precision 0.1mm; alignment uncertainty 40~100μm.



- $\delta\alpha \approx (1.16\text{~}1.33) \times 10^{-7}$rad.

  $< 2.8 \times 10^{-7}$rad.

- It is crucial to input beam parameters.

SCATTER WITH INFRARED LASER

- Example: crossing angle $\alpha = 3.108\text{rad}$, (scatter maximal 15MeV photon)
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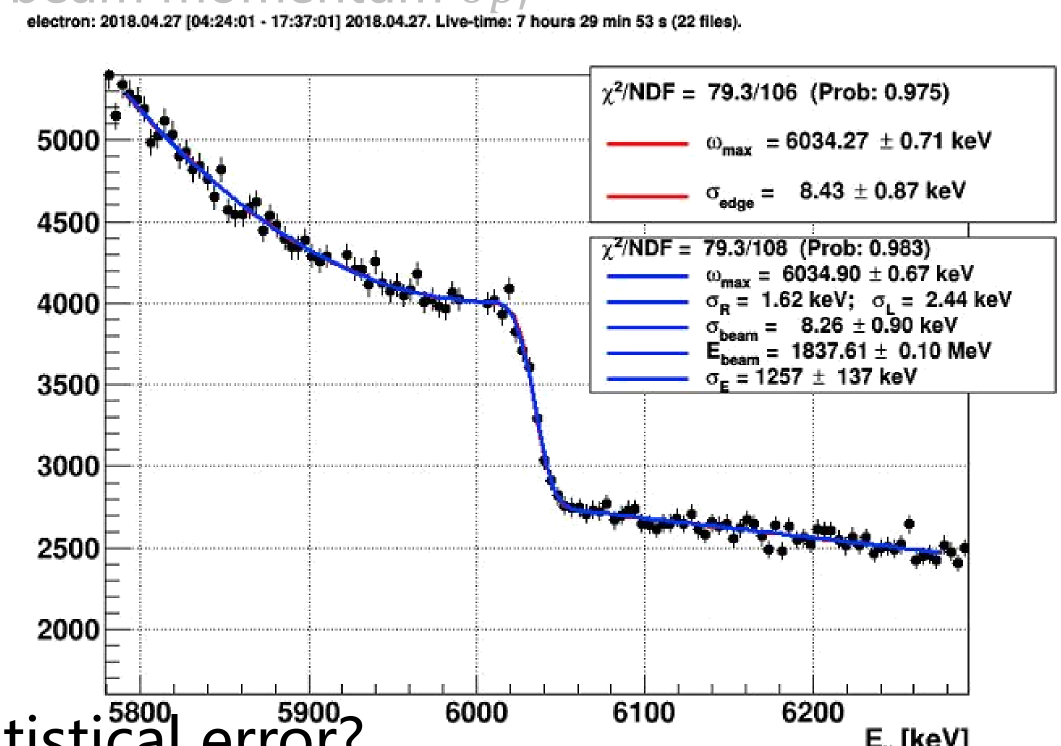
- Impact on $\delta\alpha$:
  - Beam orbit, variance of beam momentum $\delta\vec{p}$;
  - Laser alignment.
- Impact on $\delta\omega'$:
  - Detector calibration;
  - Statistical error.
- $\frac{\delta\omega'}{\omega'} \sim 10^{-4}$, $\delta\omega' \sim 1.5\text{keV}$
- Total beam energy uncertainty~6.1MeV.



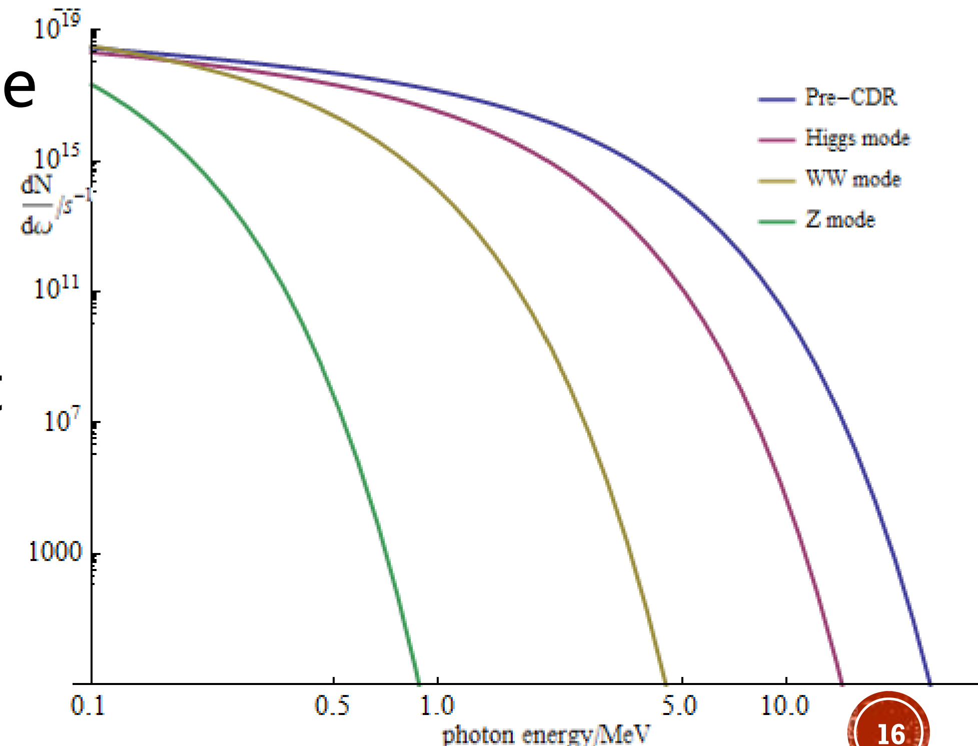
- Signal-noise ratio? Statistical error?

SCATTER WITH INFRARED LASER

- Compare between different energy region:

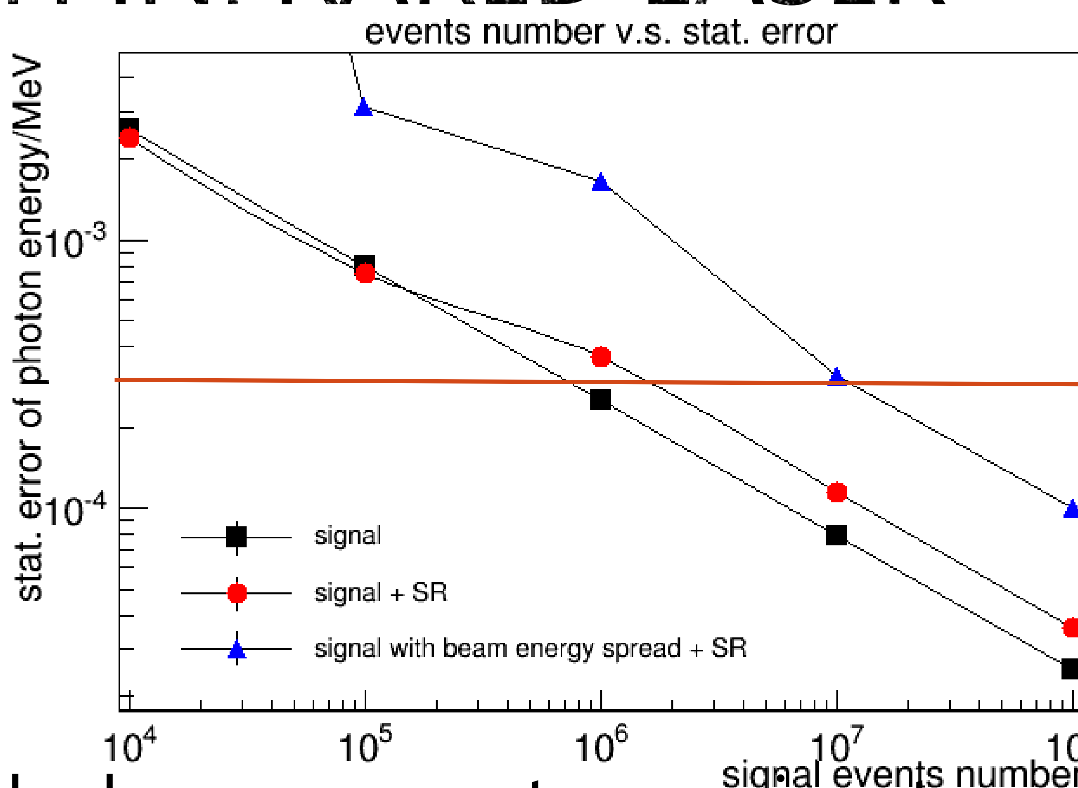
$\frac{dN}{d\omega}/s$		@3MeV	@10MeV	@20MeV	@40MeV
SR	Pre-CDR	10^{15}	10^{10}	2000	10^{-11}
	Double ring	10^{13}	10^{4}	10^{-7}	10^{-32}
CS		$10^{3}\sim10^{4}$ (integrated)			

- SR background of double ring is smaller than that of pre-CDR.
- Balance SN ratio against calibration.

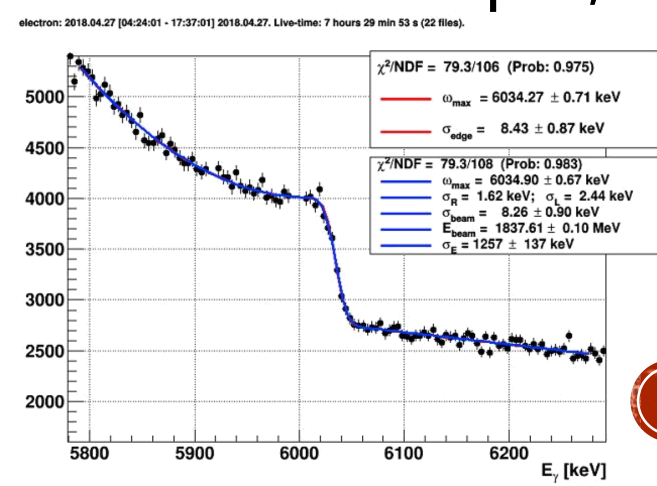


SCATTER WITH INFRARED LASER

- The more statistics are, the smaller the statistical error is.
  - Efficiency
  - Laser power
  - Duration
- Depends on the details of fits.



- The more precisely the beam parameters are input, the better fit we obtain.
  - Energy spread, orbit, emittance…



SCATTER WITH MICRO-WAVE

- Example: frequency $\nu \sim 20$GHz, $\alpha = 0.873$rad, (scatter maximal 15MeV photon)
  - $\delta\alpha \sim 9.5 \times 10^{-6}$, $\delta\omega < 8.3 \times 10^{-11}$eV and $\delta\omega' \sim 1.5$keV.
  - Total beam energy uncertainty~6.1MeV.
- Cross section

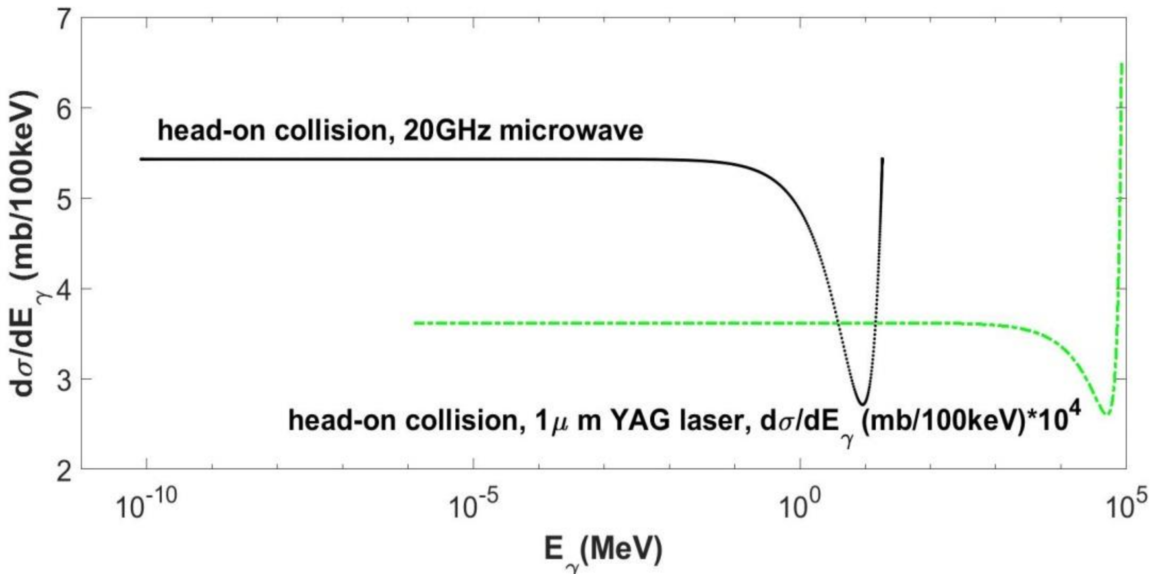


图2-15微波与电子束对撞微分截面与YAG激光与电子束对撞微分截面比较。绿色虚线是YAG激光散射截面*10^4；黑色实线是20GHz微波散射的截面。

OUTLINE

To show the feasibility of Compton scattering method.

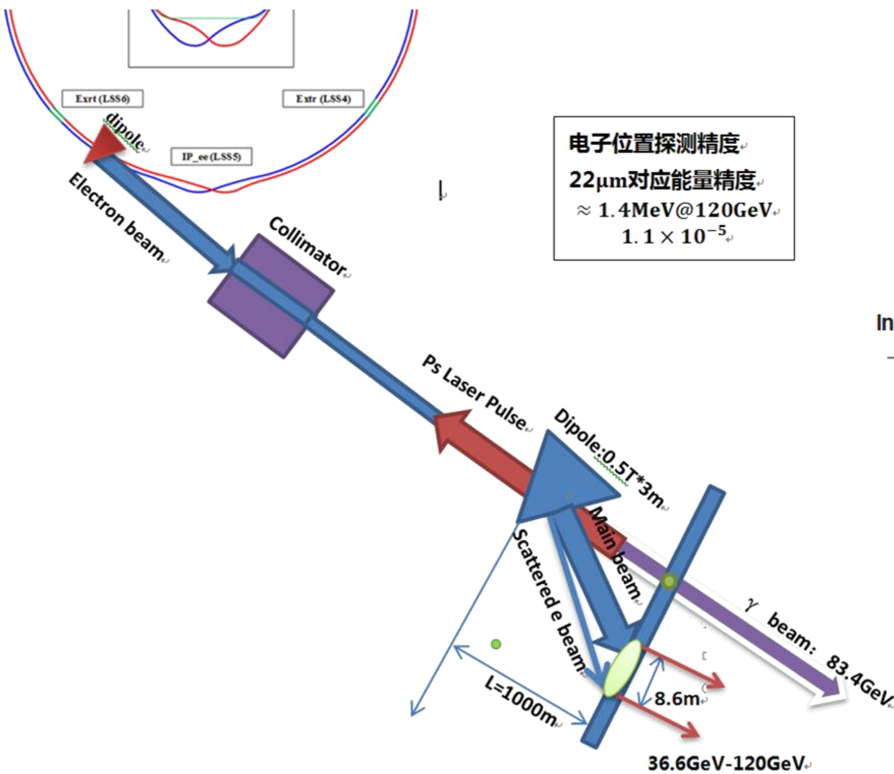
- Introduction
  - Common method
  - Experiences @BEPCII
- Compton scattering method
  - Scattering with infrared laser, measure scattered photon energy.
  - Scattering with micro-wave, measure scattered photon energy.
  - Scattering with infrared laser, measure bending angle.
- summary

MEASURE BENDING ANGLE

- If α=0, and the orbit difference of particles with different energy in dipole and the synchrotron radiation are omitted.

$$E_{beam} = \frac{(mc^2)^2}{4\omega}\frac{\Delta\theta}{\theta_0}.$$

- The magnetic induction B is 0.5T and the length of dipole is 3m. The drift distance between the dipole and detector is 1km.



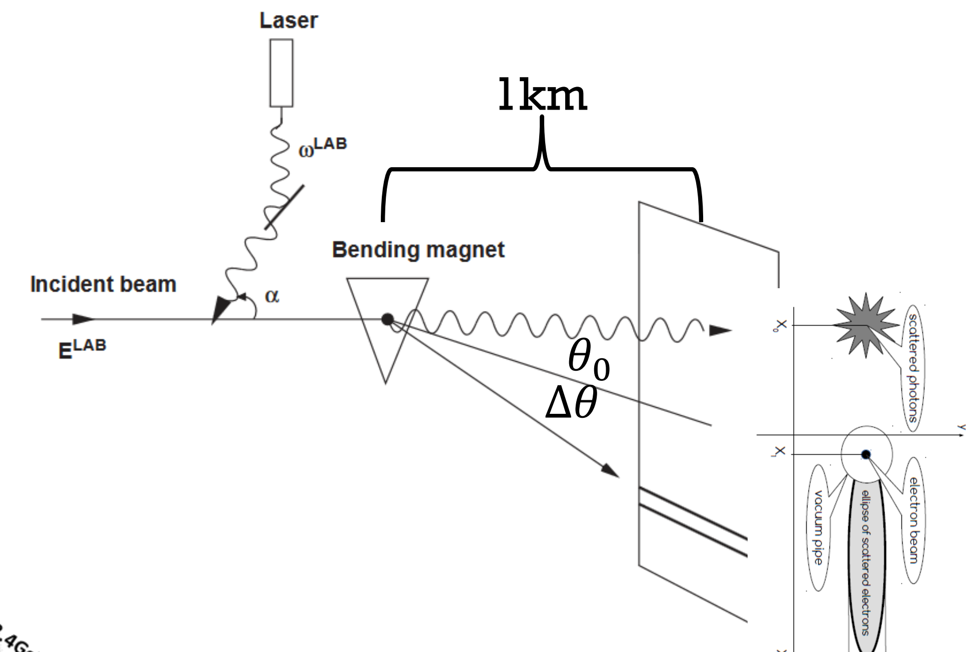


Fig. 8. Scheme of the proposed energy spectrometer based on Compton

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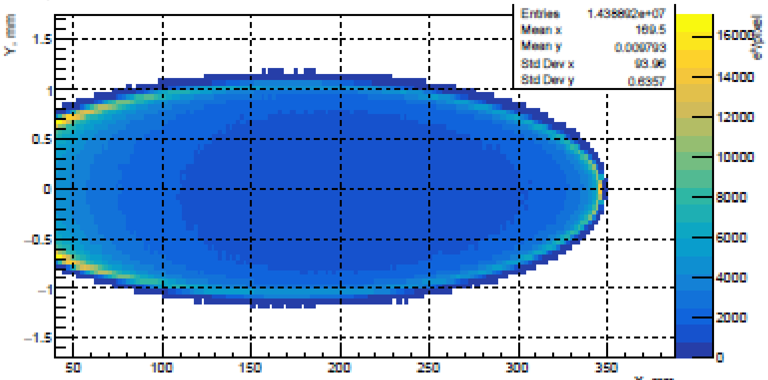
MEASURE BENDING ANGLE

- Three positions should be measured:
  - backscattered photon position, X_γ (which is set as the axis origin).
  - the beam position, X_{beam}.
  - the position of the lepton with minimum energy after scattering, X_{edge}.

Beam energy	δX_{edge} corresponding to the case $\delta E_{beam} = 1$MeV	δX_{beam} corresponding to the case $\delta E_{beam} = 1$MeV	δX_γ corresponding to the case $\delta E_{beam} = 1$MeV
120GeV	72μm	22μm	32μm

- If the uncertainty of position measurement is 6μm, the beam energy uncertainty is 1MeV.

arXiv: 1803.09595



MEASURE BENDING ANGLE

- The IO check shows 11.7MeV difference because of orbit differences.
- And this residue is stable while magnet, drift length and beam energy change.
- The positions with and without SR energy loss are nearly same and would not introduce measurable uncertainty.

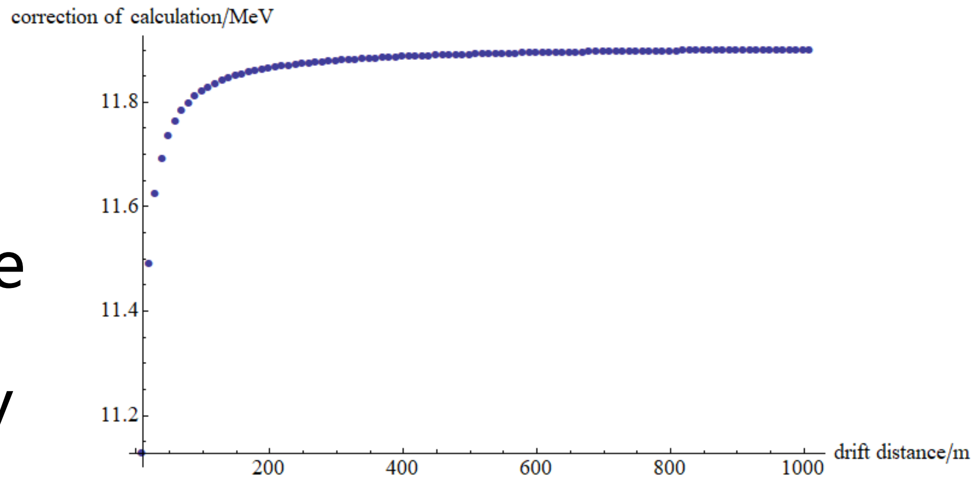


Figure 1 residue vs. drift distance

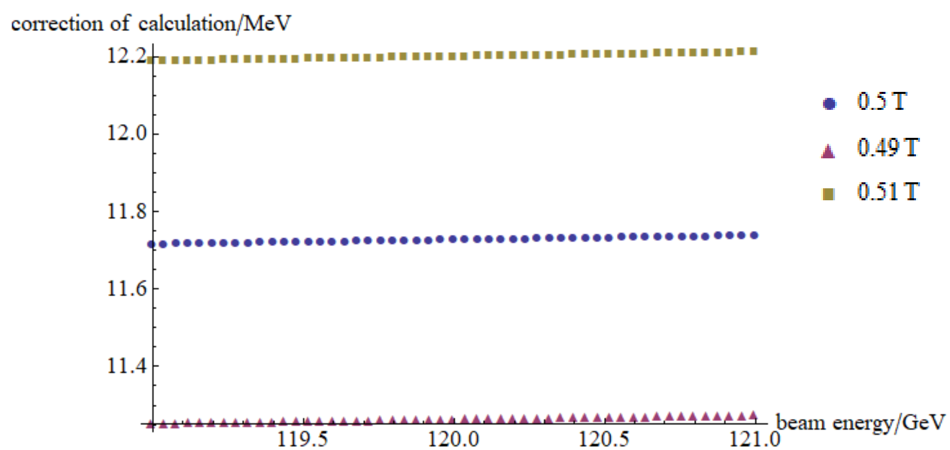


Figure 3 residue vs. and beam energy with B=0.5T, 0.49T and 0.51T

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SUMMARY

- Three schemes:
  - Scattering with infrared laser, measure scattered photon energy. → ~6MeV
  - Scattering with micro-wave, measure scattered photon energy. → ~6MeV
  - Scattering with infrared laser, measure bending angle. → ~1MeV
- Systematic error:
  - ~6MeV
  - ~6MeV
  - ~1MeV
- Still more topics should be discussed.

SUMMARY

- Beam energy could be measured precisely (error 1~10MeV, or even smaller).

Uncertainty of crossing angle α can be handled.

- beam orbit
- beam momentum

→ discuss with accelerator experts to understand bunch property.

- laser alignment → optics system with long light path.

Additional hardware is compatible with accelerator.

- Extract bunches
- Interface between micro-wave and accelerator (beam pipe)

Calibrate HPGe detector.

- isotopes → neutron capture or proton resonance reactions
- detector damage by (SR) radiation?

Statistical error is small enough.

- detector efficiency?
- fit scheme?
- laser power → pulse laser or multiple reflection

(Interface between micro-wave and accelerator, detector damage, detector efficiency) → study on detector and simulate.

谢谢！

THANKS FOR YOUR ATTENTION！

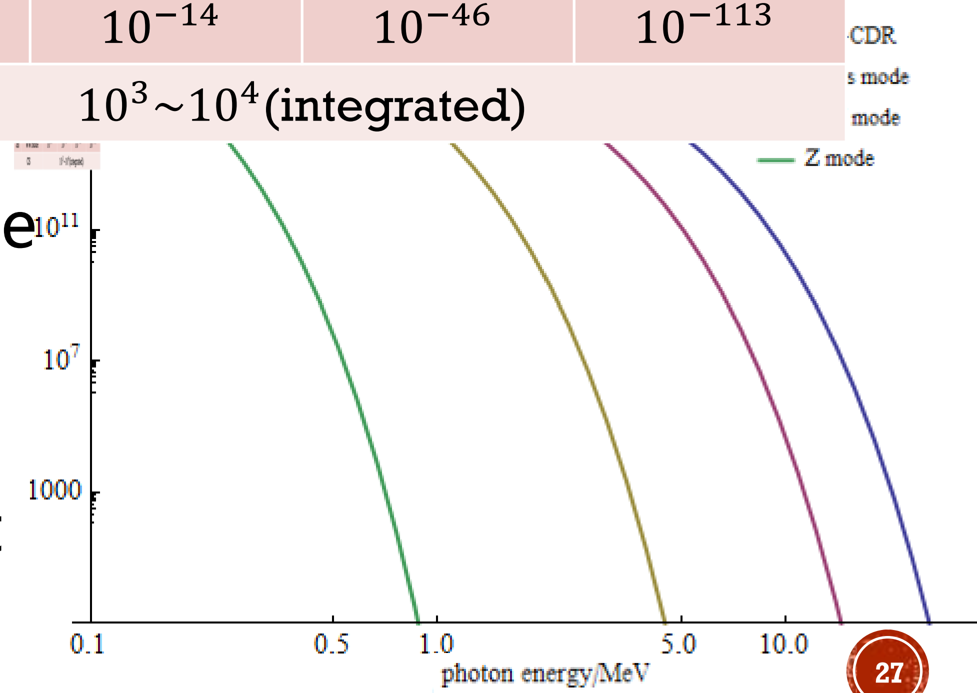
BACKUP

SIGNAL-NOISE RATIO

- Compare between different energy region:

$\frac{dN}{d\omega}/s$		@1MeV	@4MeV	@9MeV	@20MeV
SR	WW mode	10^{12}	10^{-2}	10^{-20}	10^{-54}
CS		$10^3 \sim 10^4$ (integrated)			

$\frac{dN}{d\omega}/s$		@0.4MeV	@1.4MeV	@2.8MeV	@5.7MeV
SR	Z mode	10^{10}	10^{-14}	10^{-46}	10^{-113}
CS		$10^3 \sim 10^4$ (integrated)			



- SR background of double ring is smaller than that of pre-CDR.
- Balance SN ratio against calibration.

RESONANT DEPOLARIZATION

- How to measure polarimetry?

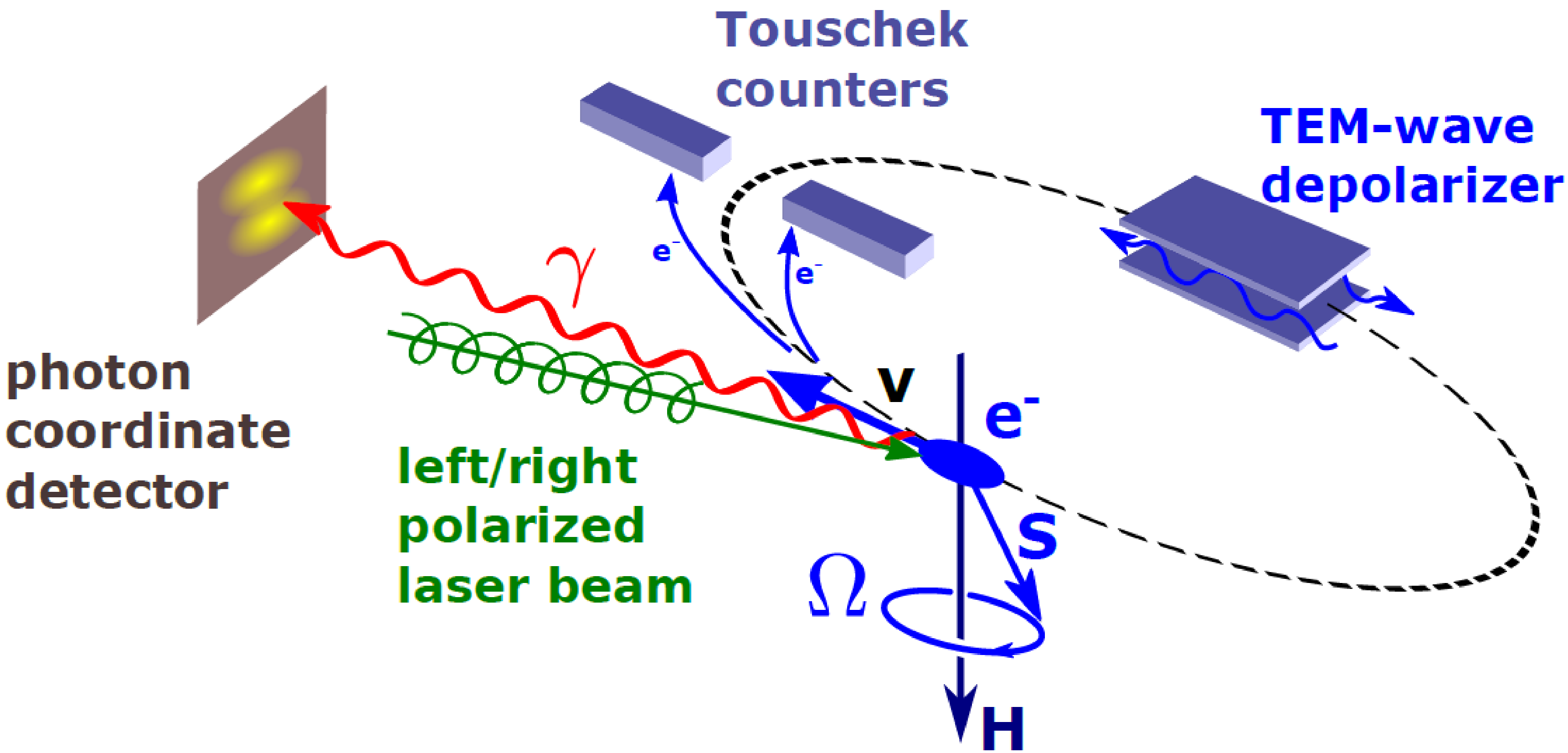


Fig. 2: Scheme of the resonant depolarization method with Touschek and Compton polarimeters

NIKOLAEV, Ivan et al. **CERN Proceedings**, [S.l.], v. 1, p. 109, jun. 2017. ISSN 2518-315X.

RESONANT DEPOLARIZATION

Polarimetry

The external modulation frequency can destroy the beam polarization when it is in resonance with spin precession. One needs to measure the beam polarization degree while scanning this frequency. In different experiments the beam polarization was measured in different ways:

- Touschek effect (BINP, BESSY ...)
- Compton backscattering (BINP, CERN, DESY ...)
- Møller scattering (SLAC, JLAB, BINP ...)
- SR intensity spin-dependence (BINP)
- ...

N. Muchnoi, talks in th 10th international conference on instrumentation for colliding

BEAM ENERGY MEASUREMENT @e^+e^- COLLIDERS

	Beam energy	**Relative acurancy**	
LEP II	80-104GeV	$(1.1\sim2.0)\times10^{-4}$	NMR model calibrated by RDP
LEP	45GeV	2.4×10^{-5}	Resonant depolarization (RDP)
BEPC II	<2.5GeV	$2\ \times10^{-5}$	Compton back-scattering
CESR	5GeV	$< 1.4\ \times10^{-5}$	RDP
VEPP4M	1-5.5GeV	$\sim10^{-6}$	RDP
		5×10^{-6}	Compton back-scattering
DORIS	5GeV	$2\ \times10^{-5}$	RDP