



38th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

AUGUST 3 - 10, 2016
CHICAGO

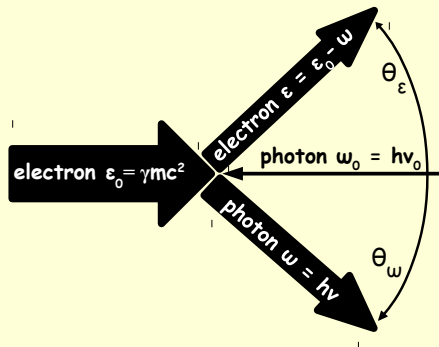
Review of the laser backscattering as an approach for the electron beam energy measurement

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Inverse Compton Scattering



$$u = \frac{\omega}{\varepsilon} = \frac{\theta_\varepsilon}{\theta_\omega} = \frac{\omega}{\varepsilon_0 - \omega}$$

$$u \in \left[0 : \kappa = \frac{4\omega_0\varepsilon_0}{m^2} \right]$$

$$\theta_\omega = \frac{1}{\gamma} \sqrt{\frac{\kappa}{u} - 1}$$

$$\theta_\varepsilon = \frac{4\omega_0}{m} \sqrt{\frac{u}{\kappa} \left(1 - \frac{u}{\kappa} \right)}$$

Maximum energy of photon ($u = \kappa$, $\theta_\omega = \theta_\varepsilon = 0$):

$$\omega_{max} = \frac{\varepsilon_0 \kappa}{1 + \kappa}$$

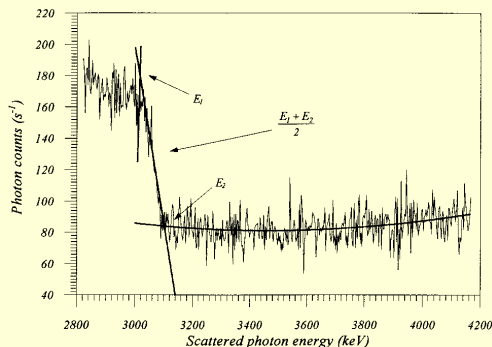
If ω_0 is a laser photon and we measure ω_{max} :

$$\varepsilon_0 = \frac{\omega_{max}}{2} \left(1 + \sqrt{1 + m^2/\omega_0\omega_{max}} \right) \simeq \frac{m}{2} \sqrt{\frac{\omega_{max}}{\omega_0}}.$$

Laser backscattering for beam energy calibration

First experiment in 1996

Taiwan Light Source
CO₂ laser & HPGe detector



$$E = 1305.8 \pm 1.7 \text{ MeV}$$

Phys. Rev. E v.54 (5) 1996

STORAGE RINGS

- BESSY-I – 1998
- BESSY-II – 2002
- VEPP-3 – 2008
- NewSUBARU – 2009
- ANKA – 2015

e^+/e^- COLLIDERS

- VEPP-4M – 2005
- BEPC-II – 2010
- VEPP-2000 – 2012

Accurate energy scale transfer: eV $\rightarrow$ MeV $\rightarrow$ GeV

- IR optics: e. g. 10P20 CO₂ laser line $\omega_0 = 0.117065228$ eV
- γ -lines from radioactive isotopes as a good reference for ω_{max} :

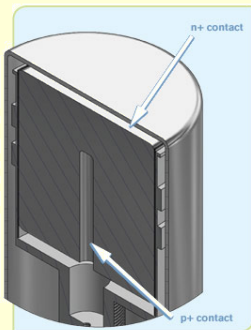
¹³⁷ Cs	$\tau_{1/2} \simeq 30.07$ y	$E_\gamma = 0661.657 \pm 0.003$ keV
⁶⁰ Co	$\tau_{1/2} \simeq 5.27$ y	$E_\gamma = 1173.228 \pm 0.003$ keV
		$E_\gamma = 1332.422 \pm 0.004$ keV
²⁰⁸ Tl	$\tau_{1/2} \simeq 3$ m	$E_\gamma = 2614.511 \pm 0.013$ keV
¹⁶ O*	²³² Pu $\rightarrow \alpha \rightarrow$ ¹³ C	$E_\gamma = 6129.266 \pm 0.054$ keV

- Narrow resonances checkpoints (requires colliding beams)

ϕ	1019.461 ± 0.019 MeV	PDG - 2014
J/ψ	$3096.900 \pm 0.002 \pm 0.006$ MeV	KEDR - 2015
$\psi(2S)$	$3686.099 \pm 0.004 \pm 0.009$ MeV	KEDR - 2015

Hardware

HPGe coaxial
detector,
p-type or n-type



(image: www.canberra.com)

Multichannel Analyzer
ORTEC® DSPEC Pro™



integral nonlinearity

 $\pm 250 \text{ ppm}$

(www.ortec-online.com)

Pulse Generator BNC PB-5

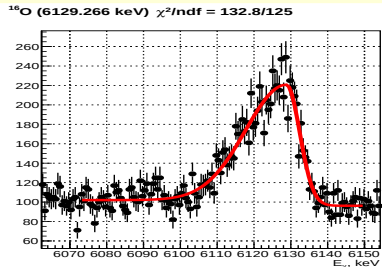
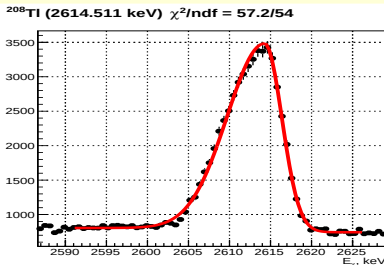
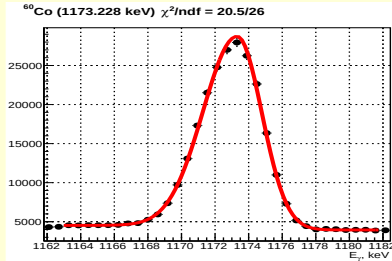
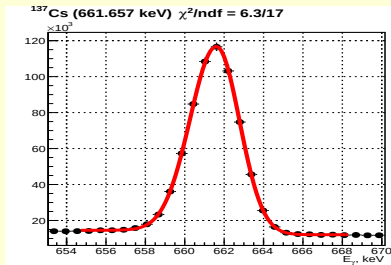


integral nonlinearity

± 15 ppm

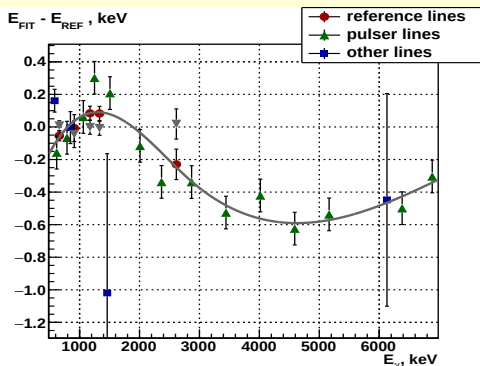
(www.berkeleyneutronics.com)

HPGe calibration: photo-peaks fits (BEPC-II 2016)



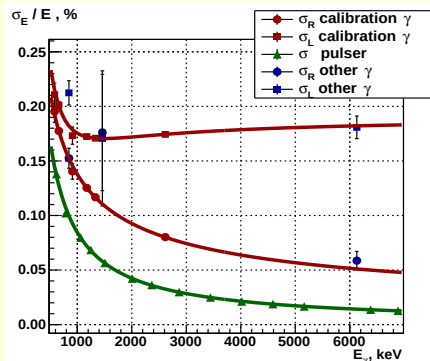
HPGe energy scale & resolution (BEPC-II 2016)

Residual Scale Nonlinearity:



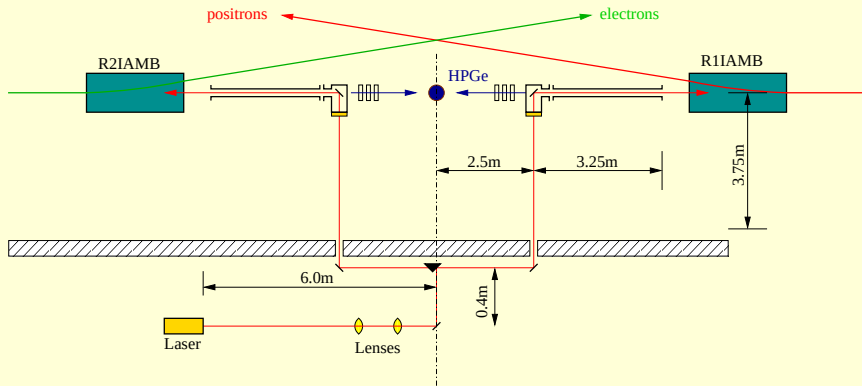
Use of pulser eliminates the MCA nonlinearity down to ~ 50 ppm

Energy Resolution:



Resolution asymmetry is due to neutron damage of HPGc

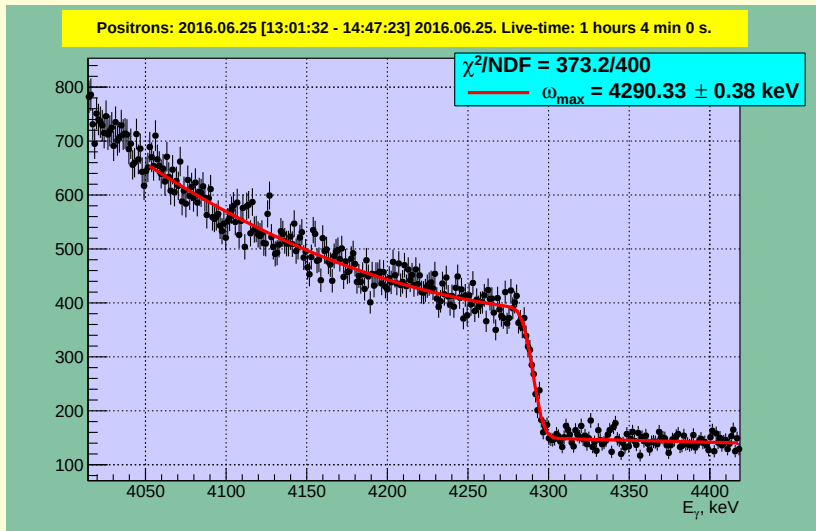
BEPC-II Beam Energy Measurement System



- Size of HPGe detector $D \simeq 4$ cm
- Distance between HPGe and $\gamma e^+/\gamma e^-$ scattering area $L \simeq 8$ m
- Beams orbit angles should be “zero” within $D/L \simeq \pm 2.5$ mrad

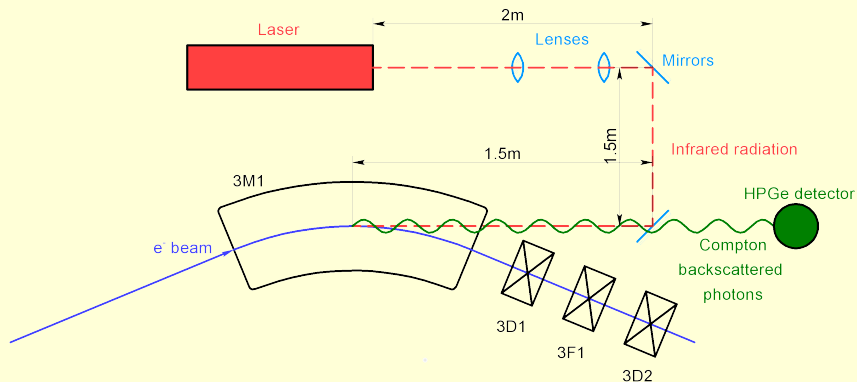
$$m_\tau = 1776.91 \pm 0.12^{+0.10}_{-0.13} \text{ MeV. Phys. Rev. D90 (2014) 012001}$$

BEPC-II 2016 spectrum edge (example)



$$E_{\text{beam}} = 1549.113 \pm 0.072 \text{ MeV}; \sigma_E = 787 \pm 99 \text{ keV}$$

VEPP-2000 Beam Energy Measurement System



Beam orbit radius in the VEPP-2000 dipole $R = 140$ cm

Interference of scattered photons / PRL 110 2013 140402

Since $\theta_{int} \gg \theta_{rad}$, only $\phi = 0$ case is a matter of interest

Time for electron $A \rightarrow B \rightarrow C$:

$$t_e = \frac{2R\theta}{\beta c}$$

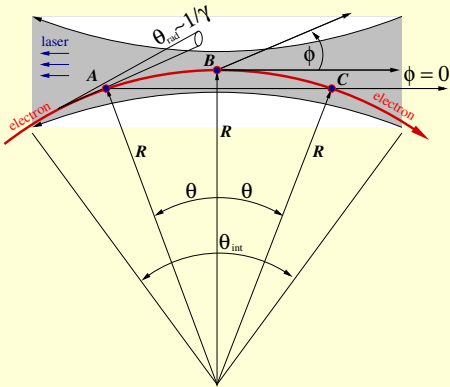
Time for photon $A \rightarrow C$:

$$t_\gamma = \frac{2R \sin \theta}{c} \cos \psi$$

Phase shift:

$$\Delta\Phi = 2\pi c \left(\frac{t_e}{\lambda} - \frac{2t_e}{\lambda_0} - \frac{t_\gamma}{\lambda} \right),$$

where λ_0 is the laser wavelength.



1 MeV photon has $\lambda = 1.24 \cdot 10^{-12}$ m. For $R = 140$ cm, $E = 1$ GeV,
 $\Delta\Phi = 2\pi$ when $\theta \simeq 0.1/\gamma$ and $\overline{AC} \simeq 10^{-2}\text{cm} \simeq 10^8\lambda$!

Interference of scattered photons / PRL 110 2013 140402

The photon spectrum is:

$$\frac{d\dot{N}_\gamma}{d\hbar\omega d\psi} \propto \omega^{1/3} \text{Ai}^2(x),$$

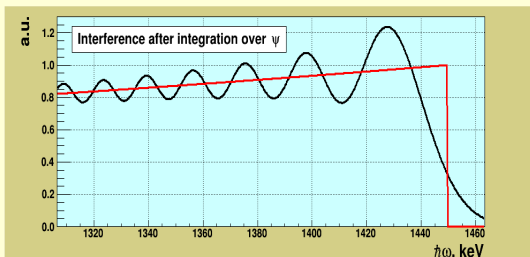
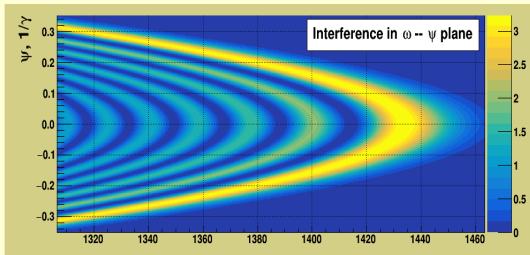
where

$$x = \left[\frac{\omega R}{2c} \right]^{2/3} \left[\frac{1}{\gamma^2} - \frac{4\omega_0}{\omega} + \psi^2 \right]$$

and

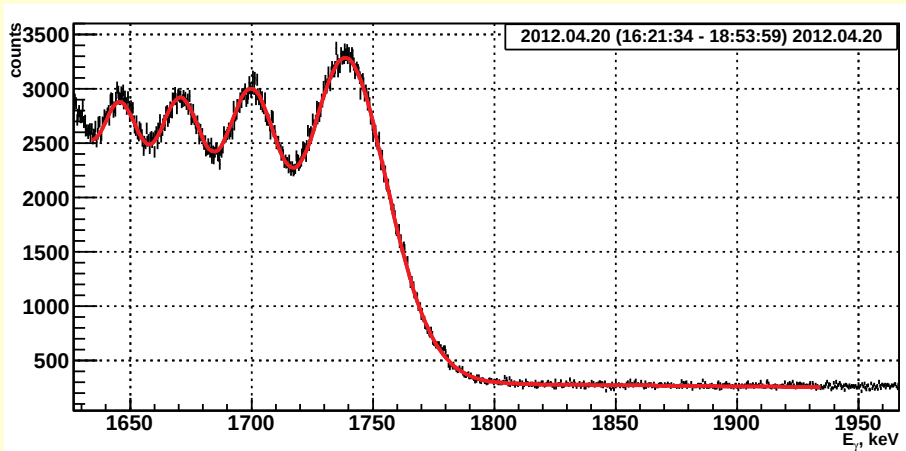
$$\text{Ai}(x) = \frac{1}{\pi} \int_0^\infty \cos\left(xt + \frac{t^3}{3}\right) dt$$

is the Airy function.



$$(\omega_0=0.117 \text{ eV}, E_e = 900 \text{ MeV}, R=140 \text{ cm})$$

Experimental spectrum & fit / PRL 110 2013 140402

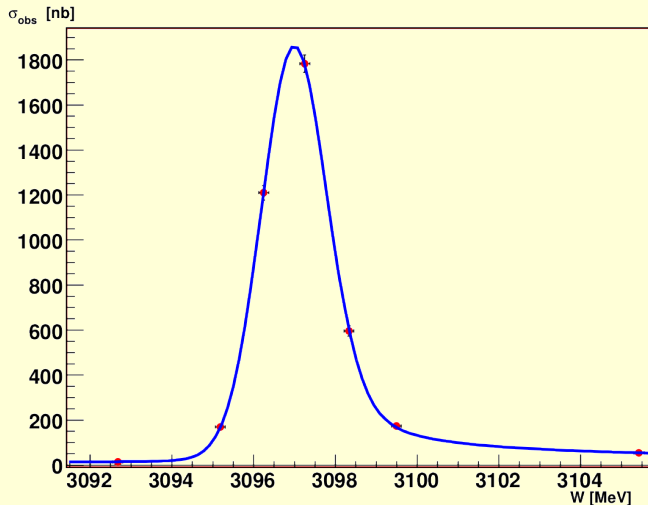


The edge of the energy spectrum with the fit result:

$$\chi^2/NDF = 773.0/745, \text{ Prob.} = 0.231,$$

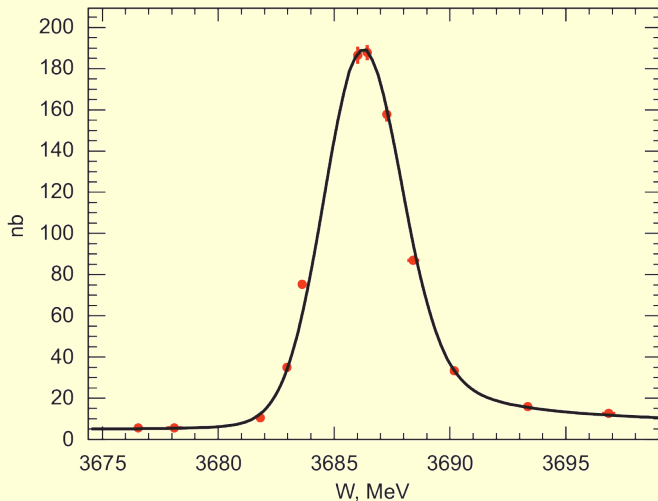
$$E = 993.662 \pm 0.016 \text{ MeV}, B = 2.3880 \pm 0.0044 \text{ T}, \sigma = 810 \pm 40 \text{ keV}.$$

Cross section $e^+e^- \rightarrow \text{hadrons}$, KEDR (2010)



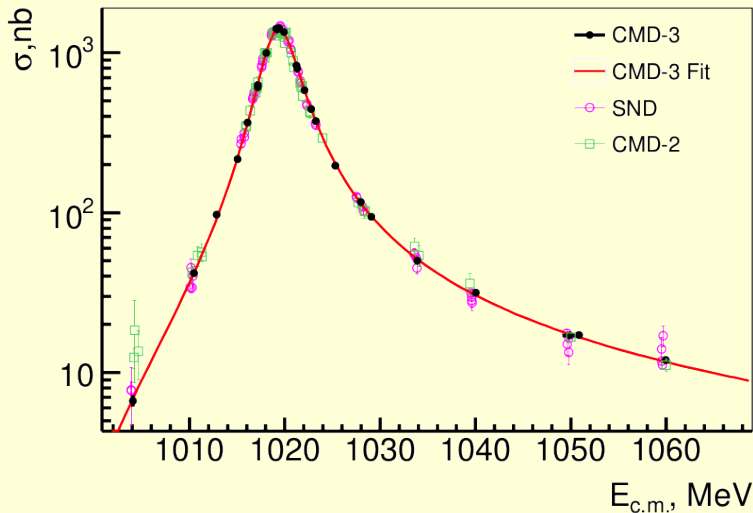
$$m_{J/\psi} - m_{J/\psi}^{PDG} = 1.2 \pm 14.7 \text{ keV}$$

Cross section $e^+e^- \rightarrow \text{hadrons}$, BES-III (2011)



$$m_{\psi(2S)} - m_{\psi(2S)}^{PDG} = 1 \pm 72 \text{ keV}$$

Cross section $e^+e^- \rightarrow K_S K_L$, CMD-3 (2013)



$$m_\phi - m_\phi^{PDG} = -8 \pm 20 \text{ keV}$$

Conclusion

- The beam energy measurement systems were implemented successfully at three e^+/e^- colliders.
- The best accuracy achieved is at the level of $\Delta E/E \lesssim 5 \cdot 10^{-5}$.
- High accuracy measurements always requires careful continuous studies of the system performance, calibration, etc.
- There is not enough time to discuss here the extensions of the approach to higher energies. Please refer to my talk "Polarization Free Methods for Beam Energy Calibration."

THANK YOU!