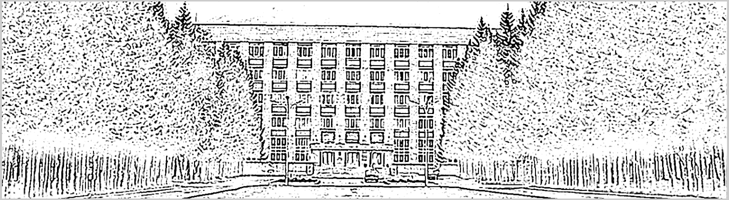
Instrumentation for Colliding Beam Physics - 2017



Laser backscattering for beam energy calibration in collider experiments

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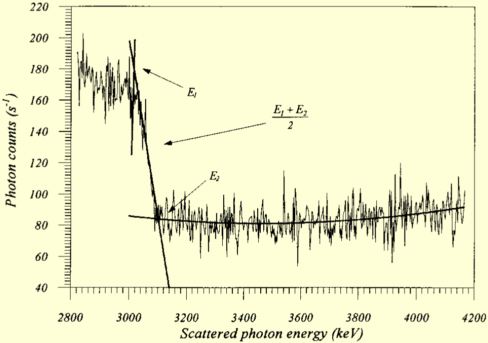
Laser backscattering for beam energy calibration

First experiment in 1996

Taiwan Light Source
CO_2 laser & HPGe detector



$E = 1305.8 \pm 1.7$ MeV
Phys. Rev. E v.54 (5) 1996

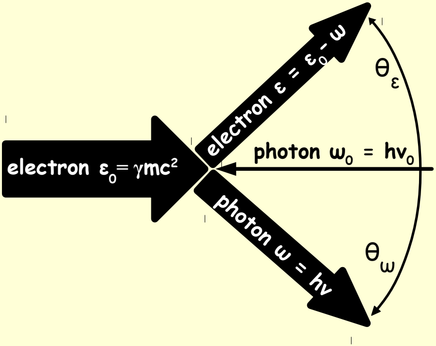
STORAGE RINGS

- 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

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 photon energy $(u = \kappa,\ \theta_\omega = \theta_\varepsilon = 0)$: $\boxed{\omega_{max} = \frac{\varepsilon_0\kappa}{1+\kappa}}$

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

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

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

- Optics: e. g. 10P20 CO_2 laser line $\omega_0 = 0.117065228$ eV
- γ-lines from radioactive isotopes as a good reference for ω_{max}:

Laboratoire National Henri Becquerel http://www.nucleide.org

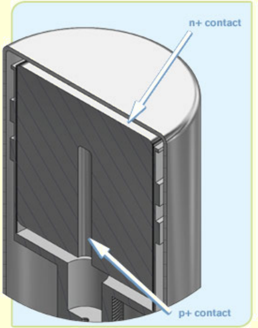
^{137}Cs	$\tau_{1/2} \simeq 30.07$ y	$E_\gamma = 0661.657 \pm 0.003$ keV
^{60}Co	$\tau_{1/2} \simeq 5.27$ y	$E_\gamma = 1173.228 \pm 0.003$ keV
		$E_\gamma = 1332.422 \pm 0.004$ keV
^{208}Tl	$\tau_{1/2} \simeq 3$ m	$E_\gamma = 2614.511 \pm 0.013$ keV
^{16}O*	^{232}Pu$\rightarrow \alpha \rightarrow ^{13}$C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

(www.ortec-online.com)

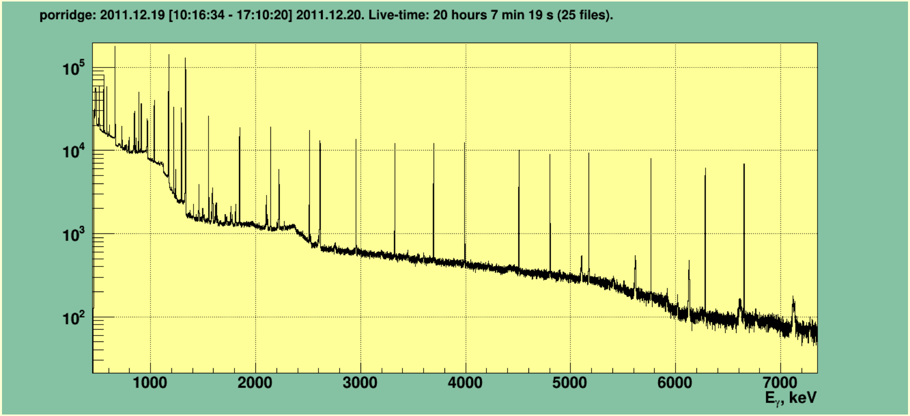
Pulse Generator
BNC PB-5

integral nonlinearity

$\pm$ 15 ppm

(www.berkeleynucleonics.com)

HPGe scale calibration: initial spectrum



HPGe scale calibration: photo-peaks fits

HPGe response function we describe by bifurcated Gaussian:

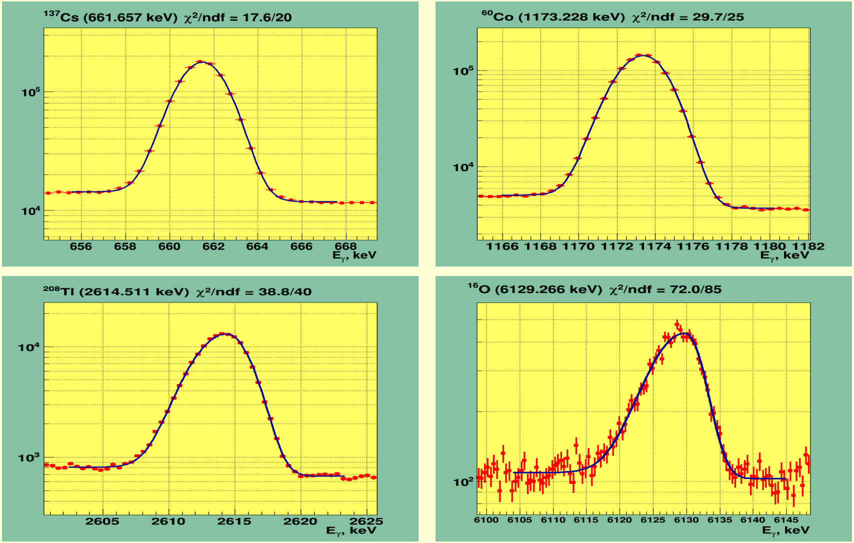
$$f(x) = \frac{\sqrt{2}}{\sqrt{\pi}(\sigma_R + \sigma_L)} \begin{cases} \exp\left[-0.5(x/\sigma_R)^2\right] & \text{if } x = (\omega - \omega_0) > 0; \\ \exp\left[-0.5(x/\sigma_L)^2\right] & \text{if } x = (\omega - \omega_0) \leq 0. \end{cases}$$

The spikes from radio-nuclide γ-rays are then fitted by:

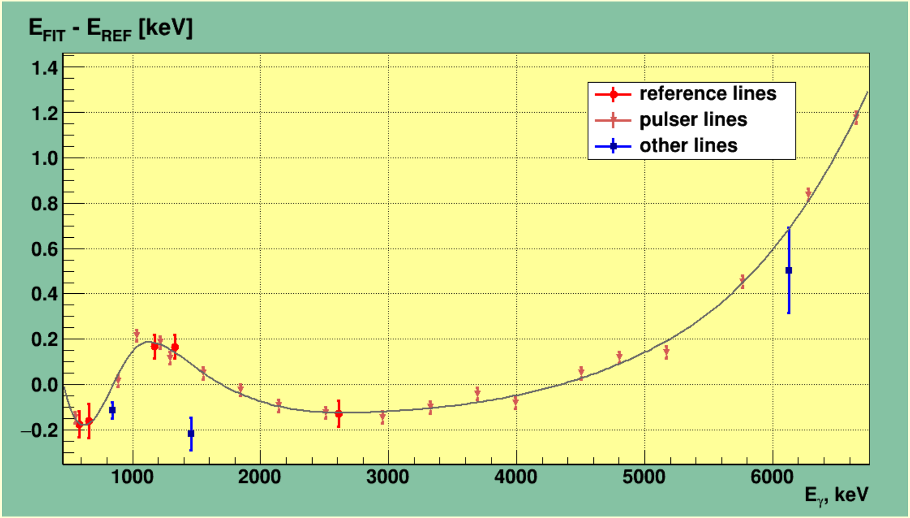
$$g(x) = B + A \cdot \begin{cases} f(x) & \text{if } x = (\omega - \omega_0) > 0; \\ C + (1 - C) f(x) & \text{if } x = (\omega - \omega_0) \leq 0. \end{cases}$$

where A – amplitude, B – background and C is due to Compton scattering in the material between the source and the detector.

HPGe scale calibration: photo-peaks fits

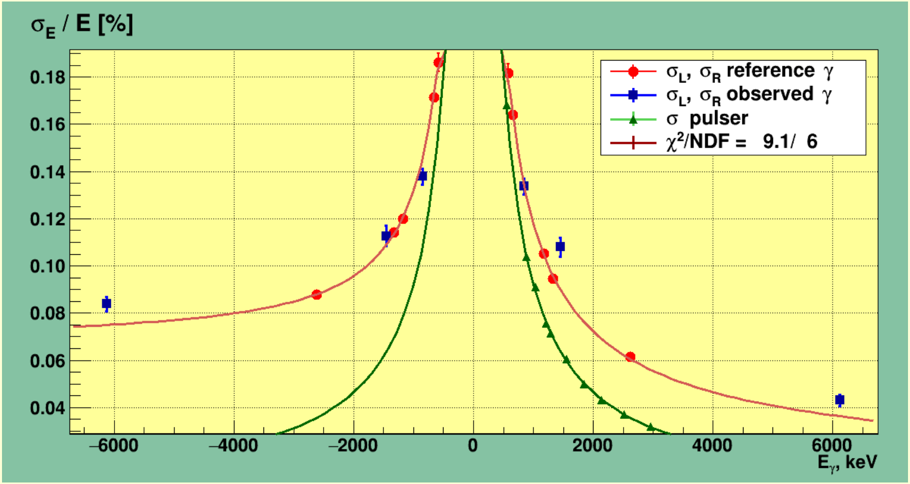


Residual Scale Nonlinearity



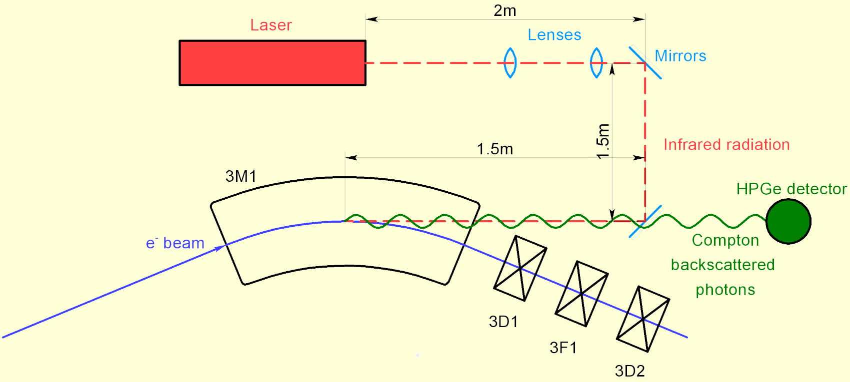
Use of pulser eliminates the MCA nonlinearity down to $\lesssim$ 50 ppm

Energy Resolution (g=2.96 eV)



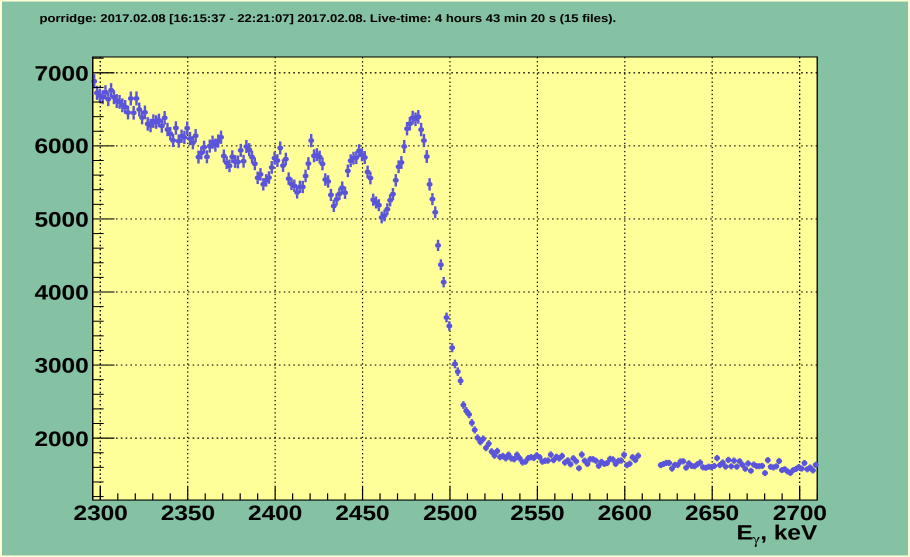
$$\sigma_E = \begin{cases} \sqrt{p_0^2 + p_1 \mathrm{g}|E_\gamma|} & \text{if } E_\gamma > 0; \\ \sqrt{p_0^2 + p_1 \mathrm{g}|E_\gamma| + p_2(p_3 - |E_\gamma|)^2} & \text{if } E_\gamma < 0. \end{cases}$$

VEPP-2000 Beam Energy Measurement System



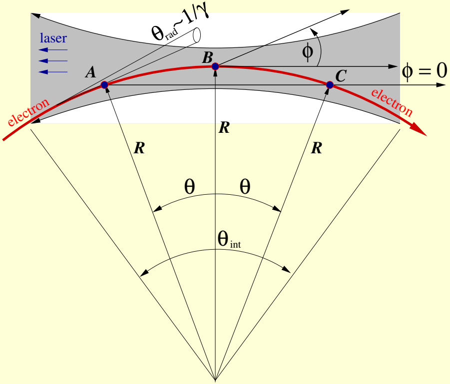
- Laser 1: PL-3 CO by Edinburgh Instruments $\lambda = 5.426463\ \mu$m.
- Laser 2: Ytterbium fiber by Inversion Fiber $\lambda = 1.064966\ \mu$m.
- Beam orbit radius in the VEPP-2000 dipole $R = 140$ cm

A spectrum (2017, $E = 850$ MeV, $\lambda = 5.43\ \mu$m)



Electron - laser beams interaction area

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



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

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

Time for photon $A \to C$:

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

Phase shift for a wavelength λ:

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

where λ_0 is the laser wavelength.

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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 $\overline{AC} \simeq 10^{-2}$cm $\simeq 10^8\lambda$!

Interference of scattered field / PRL 110 2013 140402

Since $\theta, \psi, 1/\gamma \ll 1$:

$$\Delta\Phi(\theta) \simeq \frac{\omega R}{c}\left(\theta\left(\frac{1}{\gamma^2} - \frac{4\omega_0}{\omega} + \psi^2\right) + \frac{\theta^3}{3}\right).$$

The scattered field amplitude is:

$$U(\omega,\psi) \propto \omega \int\limits_0^\infty \left(e^{i\frac{\Delta\Phi(\theta)}{2}} + e^{-i\frac{\Delta\Phi(\theta)}{2}}\right)d\theta = 2\omega \int\limits_0^\infty \cos\frac{\Delta\Phi(\theta)}{2}d\theta.$$

Change of the integration variable $\theta \to \xi = \theta\big(\omega R/2c\big)^{1/3}$ gives:

$$U(\omega,\psi) \propto \omega^{2/3}\,\mathrm{Ai}(x),\ \text{where } x = \left(\frac{\omega R}{2c}\right)^{2/3}\left(\frac{1}{\gamma^2} - \frac{4\omega_0}{\omega} + \psi^2\right),$$

and $\mathrm{Ai}(x) = \dfrac{1}{\pi}\displaystyle\int\limits_0^\infty \cos\left(xt + \frac{t^3}{3}\right)dt$ is the Airy function.

The intensity of the scattered wave is: $I = |U|^2 \propto \omega^{4/3}\,\mathrm{Ai}^2(x)$.

The spectrum shape

The photon spectrum is:

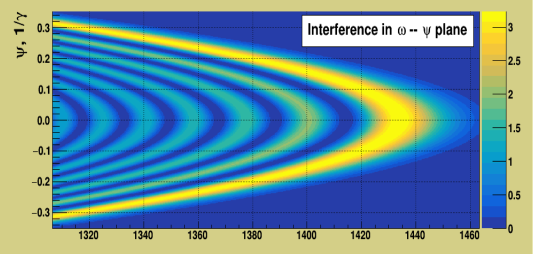
$$\frac{d\dot{N}_\gamma}{d\hbar\omega\, d\psi} \propto \omega^{1/3}\,\mathrm{Ai}^2(x).$$

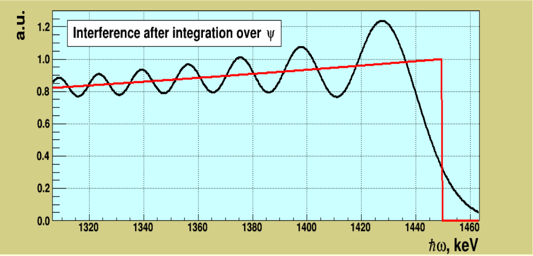
Integration over ψ yields:

$$\frac{d\dot{N}_\gamma}{d\hbar\omega} \propto \int_z^\infty \mathrm{Ai}(z')dz',$$

where

$$z = \left(\frac{\omega R}{c}\right)^{2/3}\left(\frac{1}{\gamma^2} - \frac{4\omega_0}{\omega}\right)$$





(ω_0=0.117 eV, E_e = 900 MeV, R=140 cm)

Electron recoil

For electron recoil account we do: $\omega \to \omega \cdot E/(E - \hbar\omega)$.
Let's perform $R \to E/cB$ substitution and introduce new variables:

$$u = \frac{\hbar\omega}{E - \hbar\omega}, \quad \kappa = \frac{4E\hbar\omega_0}{m^2}, \quad \chi = \frac{E}{m}\frac{B}{B_0},$$

$B_0 = m^2c^2/\hbar e = 4.414 \cdot 10^9$ [T] is the Schwinger field strength.

$$z = \left(\frac{\omega R}{c}\right)^{2/3}\left(\frac{1}{\gamma^2} - \frac{4\omega_0}{\omega}\right) \ \to \ z = (u/\chi)^{2/3}(1 - \kappa/u) \ .$$

Similar result was obtained in 1971 by QED calculations:

V. Ch. Zhukovsky and I. Herrmann. Journal of Nuclear Physics 14 1 (1971) 150-159

Compton effect and Induced Compton Effect in Constant Electromagnetic Field.

Beam energy spread & detector response

$$\omega_{max} = E_0 \frac{\kappa}{1+\kappa} \quad \left(\kappa = \frac{4\omega_0 E_0}{m^2}\right) \Rightarrow \sigma_{\omega_{max}} = \frac{(2+\kappa)\kappa}{(1+\kappa)^2}\sigma_{E_0}.$$

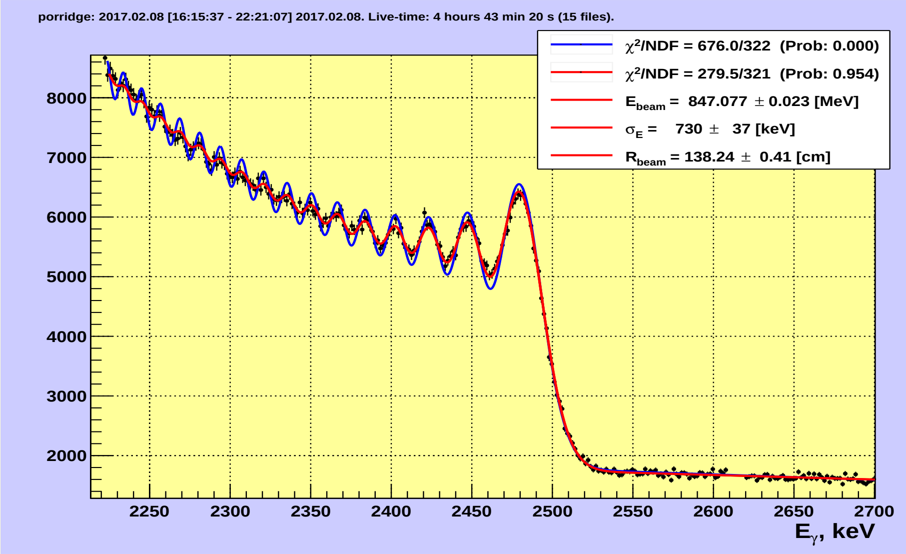
Convolution of beam energy spread impact σ_ω and HPGe detector response function $f(x, \sigma_R, \sigma_L)$ yields: $S(x, \sigma_R, \sigma_L, \sigma_\omega) =$

$$= \frac{\sigma_R \exp\left[\frac{-x^2/2}{\sigma_R^2+\sigma_\omega^2}\right] \mathrm{erfc}\left[\frac{-x\sigma_R/\sigma_\omega}{\sqrt{2(\sigma_R^2+\sigma_\omega^2)}}\right]}{(\sigma_R+\sigma_L)\sqrt{2\pi(\sigma_R^2+\sigma_\omega^2)}} + \frac{\sigma_L \exp\left[\frac{-x^2/2}{\sigma_L^2+\sigma_\omega^2}\right] \mathrm{erfc}\left[\frac{x\sigma_L/\sigma_\omega}{\sqrt{2(\sigma_L^2+\sigma_\omega^2)}}\right]}{(\sigma_R+\sigma_L)\sqrt{2\pi(\sigma_L^2+\sigma_\omega^2)}}.$$

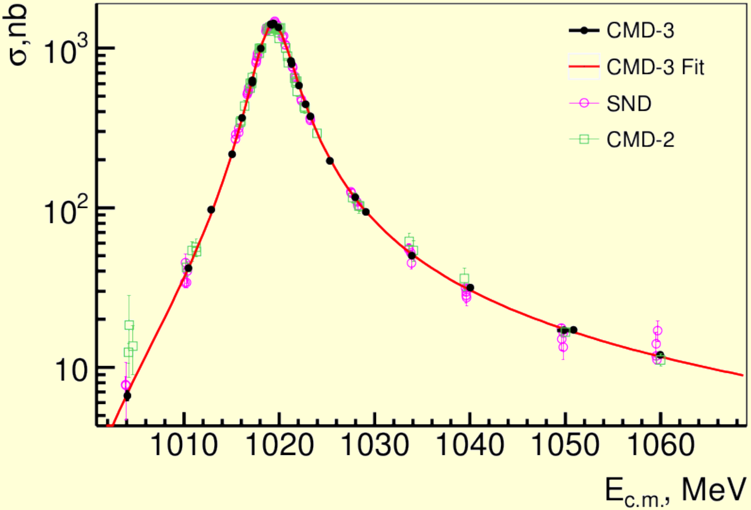
$$F_1(\omega) = A(1 + A'\Delta_\omega + A''\Delta_\omega^2) \int\limits_{z(E_0,B)}^{\infty} \mathrm{Ai}(z')dz' + B(1 + B'\Delta_\omega),$$

where $\Delta_\omega = (\omega - \omega_{max})$. The final fit will be: $F_2(\omega) = (F_1 * S)(\omega)$

Experimental spectrum & fits by F_1 and F_2



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



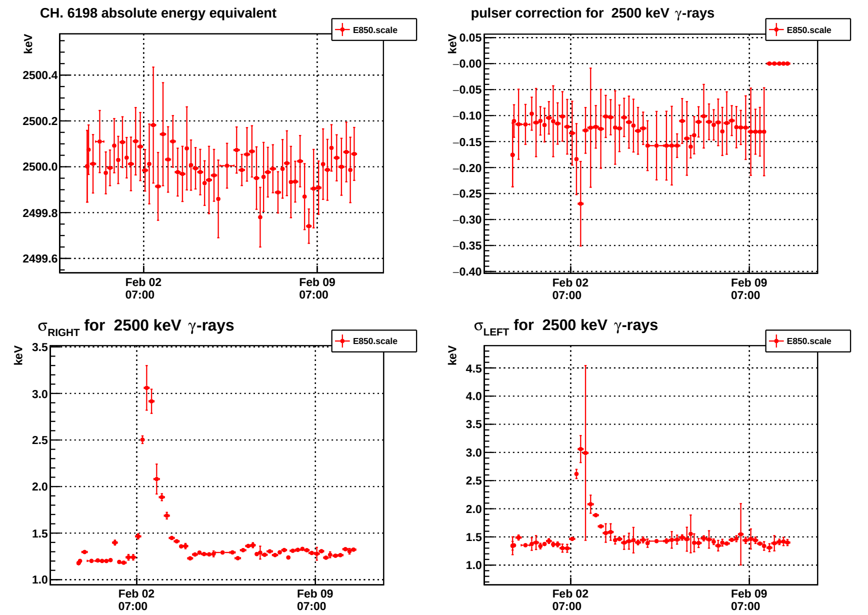
$$m_\phi - m_\phi^{PDG} = -8 \pm 20 \text{ keV}$$

Summary

- The beam energy measurement systems were successfully implemented at VEPP-4M, BEPC-II & VEPP-2000 colliders.
- The accuracy achieved is at the level of $\Delta E/E \simeq 3 \cdot 10^{-5}$.
- First observation of inverse Compton scattering in presence of the external field agrees with theoretical predictions.
- The unusual shape of the energy spectrum in this case allows to measure the magnetic field in the area of scattering.
- High accuracy measurements require careful studies of the system performance, calibration, etc. along the experiment.

THANK YOU.

One-week scale calibration



One week history