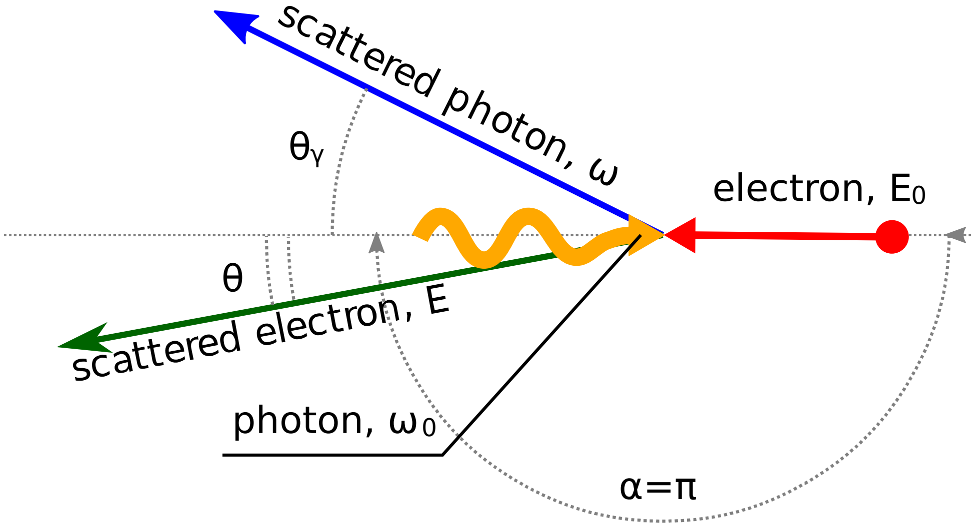

Fast and Precise Beam Energy Measurement Using Compton Backscattering at e^+e^- Colliders

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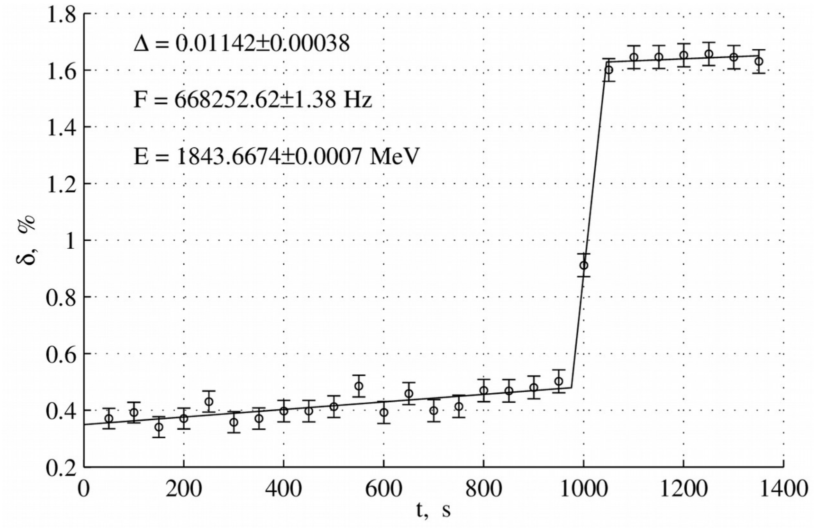
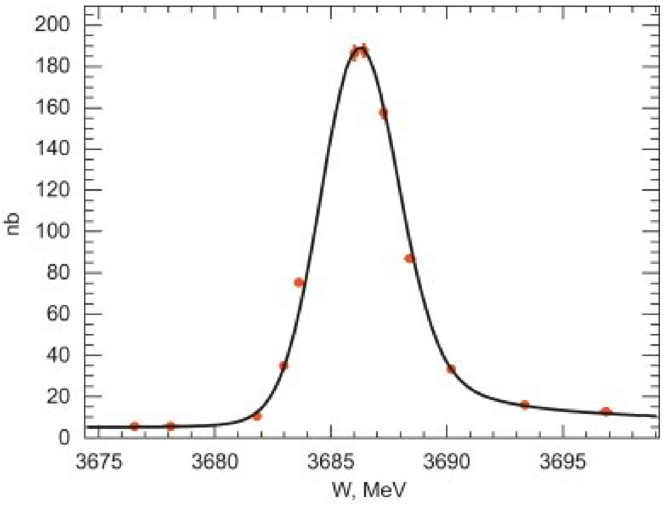
Motivation

- For precision experiments at colliders an accurate beam energy measurement is needed.

- Extremely precise method: resonant depolarization (see talk by Ivan Nikolaev). Accuracy ~10^{-6} of the beam energy. VEPP-2, VEPP-4, LEP, etc.
  - Toushek polarized/unpolirized rate asymmetry vs. time and the moment of depolarization at VEPP-4 →

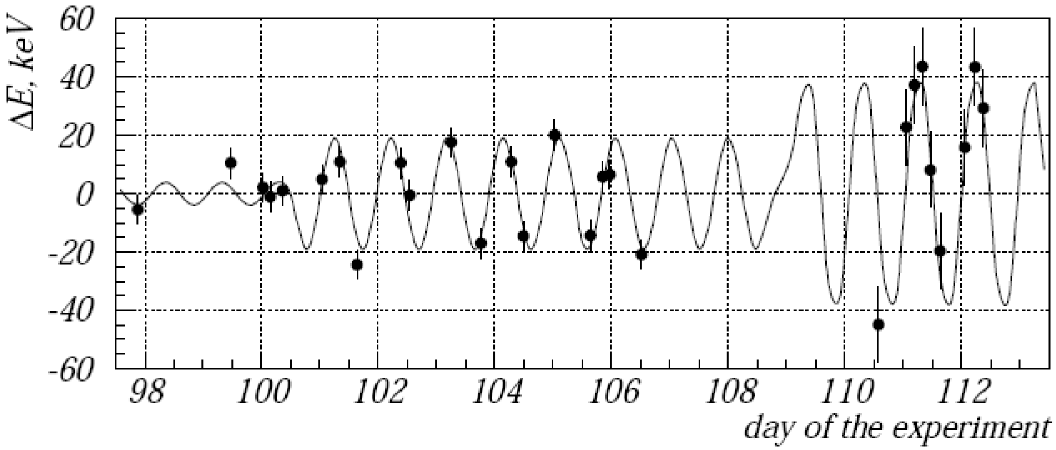


- Collider energy scale calibration using well-known narrow resonanses. Accuracy ~10^{-5}.
  - $e^- e^+ \to$ *hadrons* cross-cection near ψ(2S) (*m* = 3686.09 ± 0.04 MeV) at BEPC-II →



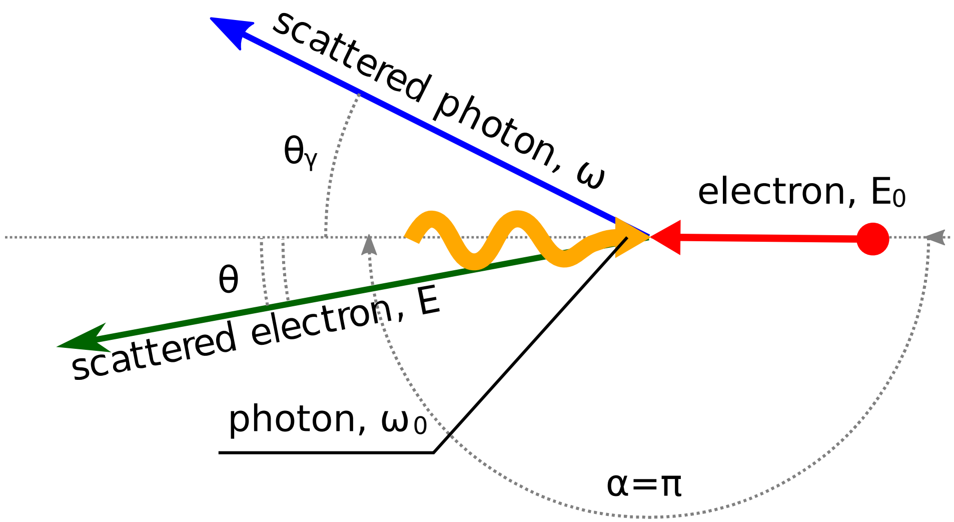
Motivation

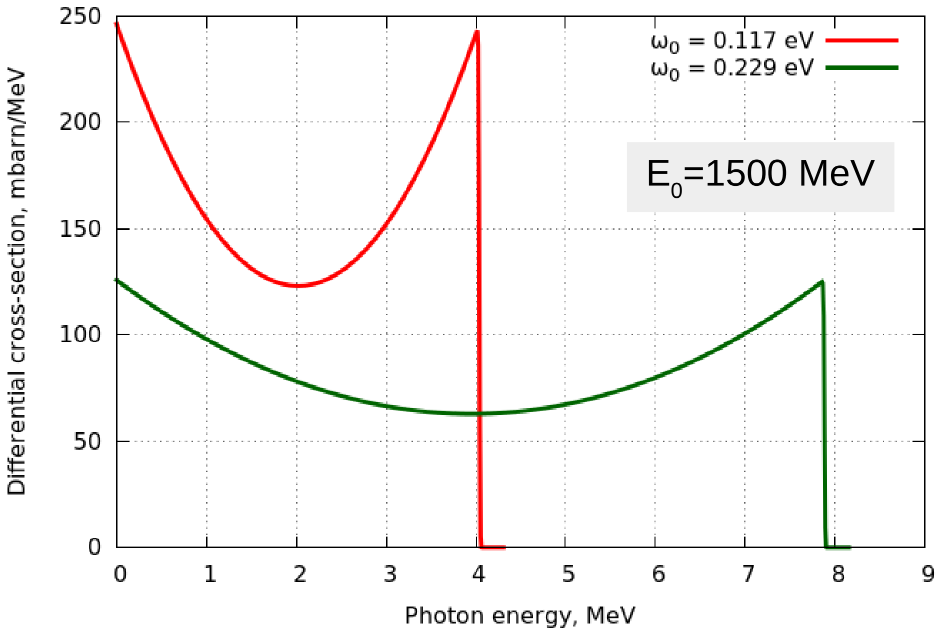
- Fast method: field measurement by NMR and consequent energy calculation. Accuracy: $\sim 10^{-2}$, thought after calibration and with field and temperature correction provides $\sim 10^{-3} \ldots 10^{-4}$ within some period of time
  - Calculation of VEPP-4M beam energy based on NMR field measurements, sextupole fields, temperature, and calibrated with resonant depolarization technique



- Fast and precise method: measuring maximum Compton backscattering photon energy. Accuracy $20 \ldots 4 \cdot 10^{-5}$ within 20...60 minutes.

Compton backscattering



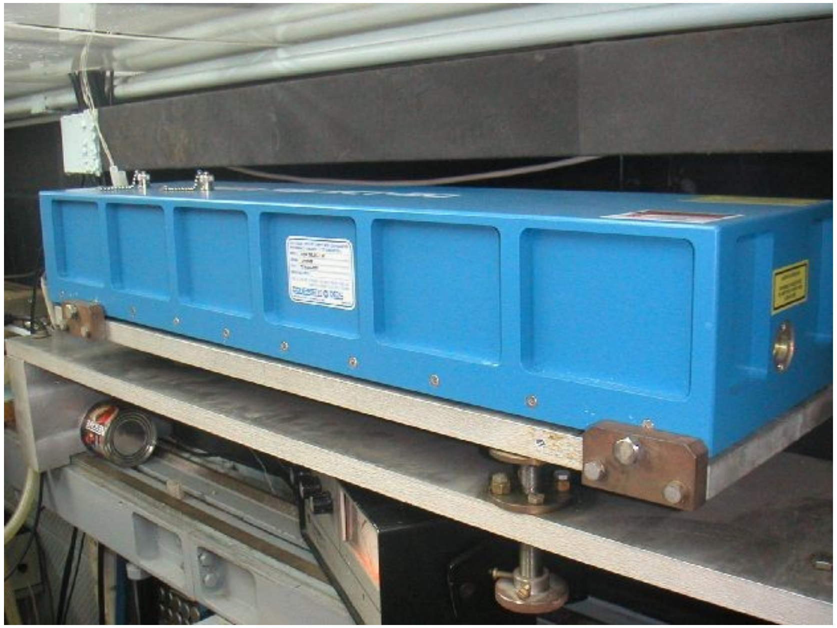


- Energy of the scattered photon strictly depends on scattering angle θ_γ.
- When θ_γ=0 energy of the photon is maximal (and energy of the electron is minimal):

$$\omega_{max} = \frac{E_0 \lambda}{1+\lambda} \overset{E_0 \gg \omega_0 \ll m}{\approx} 4\gamma^2 \omega_0 \qquad \lambda = \frac{4 E_0 \omega_0}{m^2} \qquad E_{min} = \frac{E_0}{1+\lambda}$$

Concept

- Mid-IR laser beam interacts with the electron beam (or positron beam)



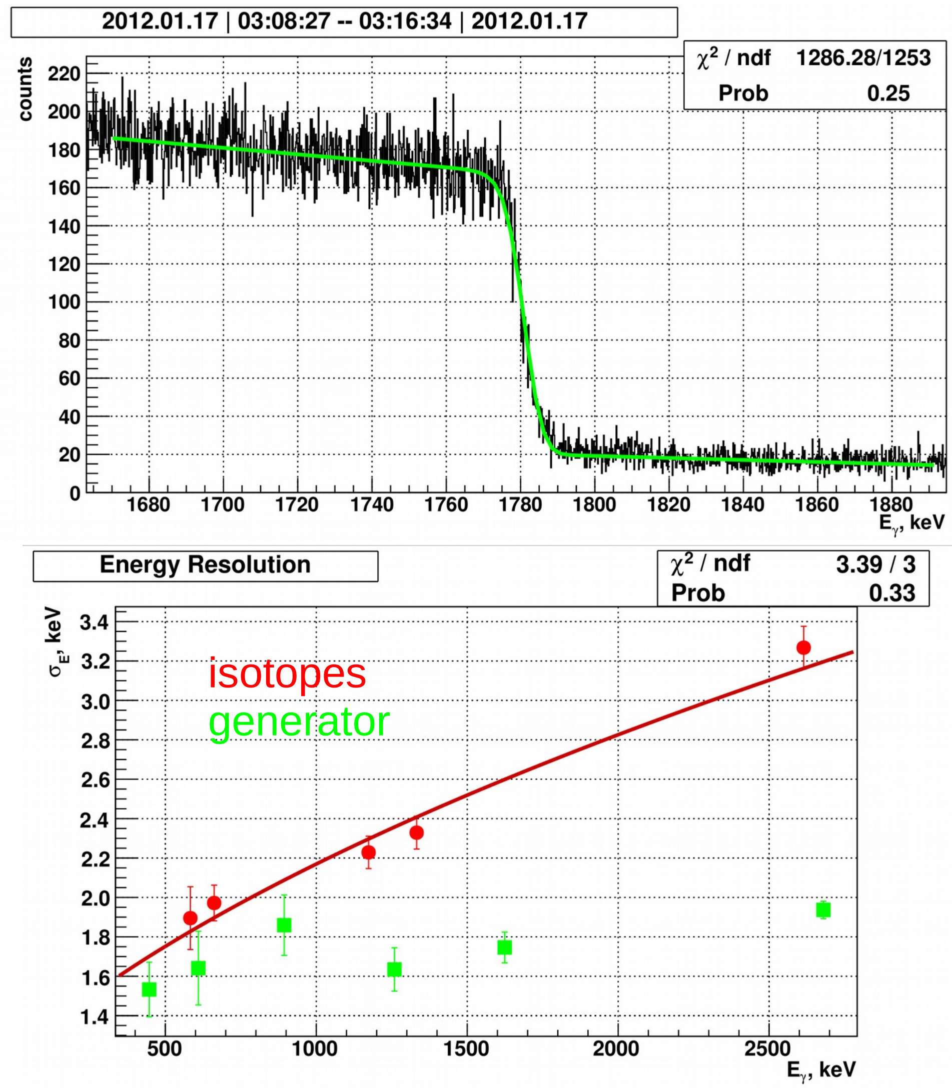
CO_2 laser:
$\lambda = 10.56\ \mu m$, $\omega_0 = 0.117$ eV, $P = 50$ W
(was used at VEPP-4M)

Concept

- Compton back-scattered photons (few MeV) are registered by high-purity germanium (HPGe) detector with excellent energy resolution.

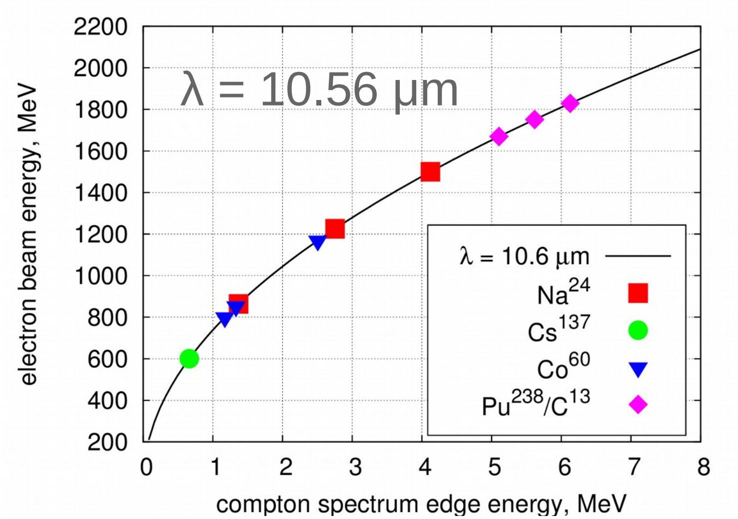
HPGe detector: energy resolution 1-2 keV at 1 MeV, photon energies up to 6 MeV (was used at VEPP-4M)

Multichannel analyser ORTEC® DSPEC PRO™
Integral nonlinearity ±250 ppm
(www.ortec-online.com)

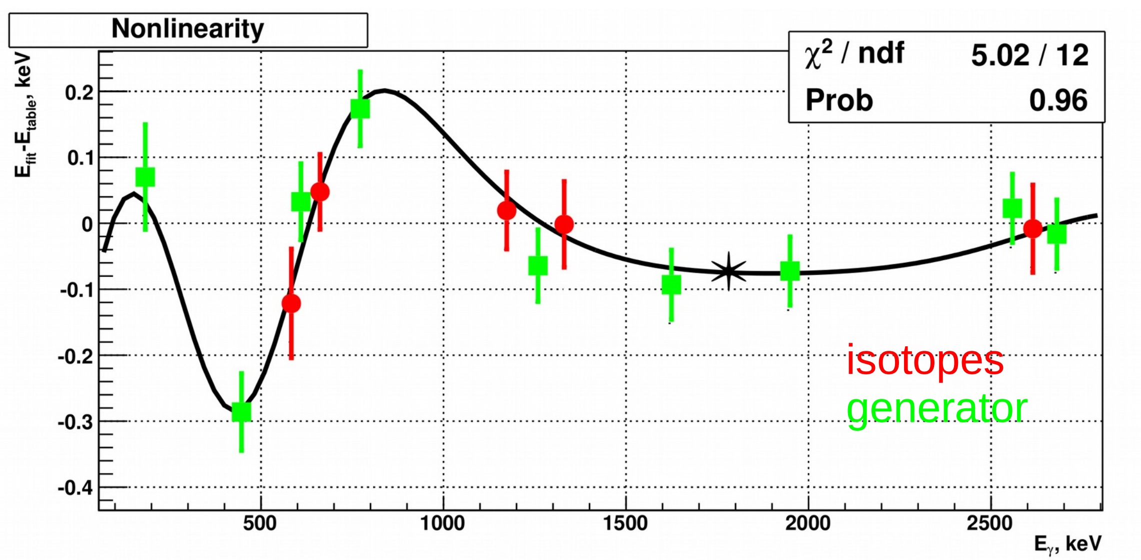


Concept

- HPGe detector energy scale is calibrated using photons with well-known energies from γ-active isotopes and precision pulse generator.



Precision pulse generator
BNC PB-5
Integral nonlinearity ±15 ppm
(www.berkeleynucleonics.com)



Why HPGe detector?
Ultimate resolution + possibility of calibration

Concept

- The energy of Compton spectrum edge is found and the beam energy is calculated.

$$E_0 = \frac{\omega_{max}}{2}\left(1+\sqrt{1+\frac{m^2}{\omega_0\,\omega_{max}}}\right) \approx \frac{m}{2}\sqrt{\frac{\omega_{max}}{\omega_0}}$$

  - Remark: local beam energy is measured (unlike resonant depolarization technique)

- Uncertainty:

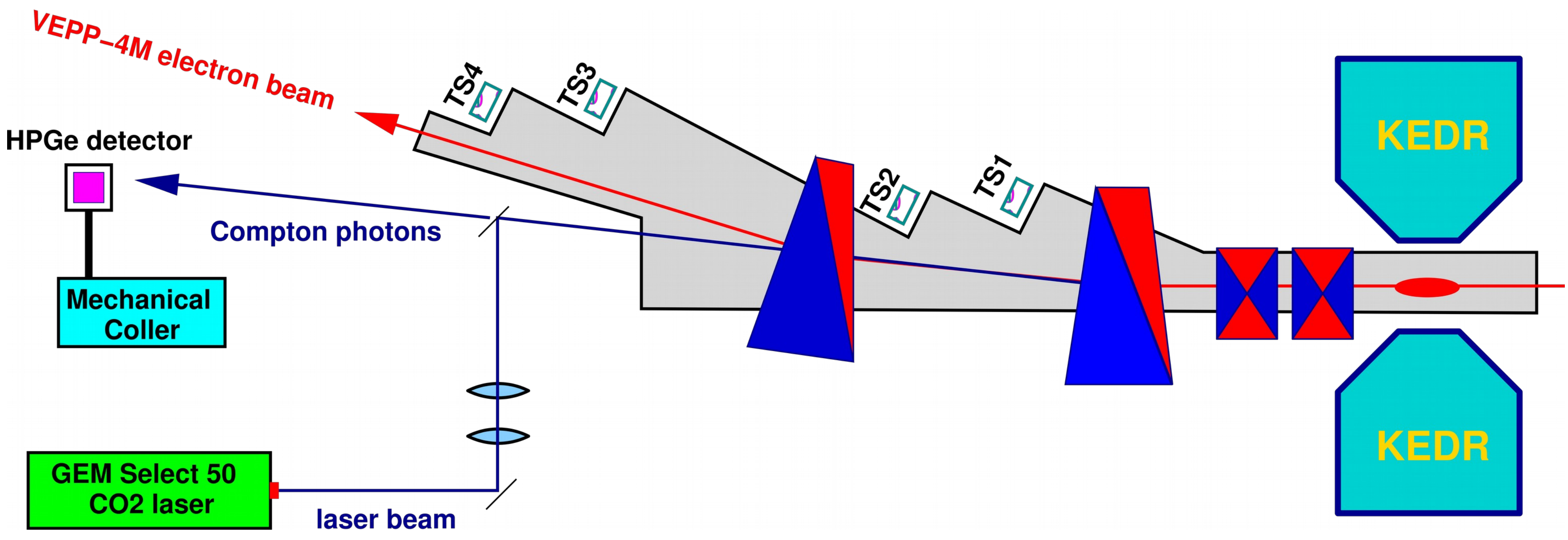
$$\Delta\frac{E_0}{E_0} \simeq \underbrace{\frac{1}{2}\frac{\Delta\,\omega_{max}}{\omega_{max}}}_{\substack{\textit{detector resolution},\\ \textit{calibration},\\ \textit{beam energy spread},\\ \textit{etc}.}} \oplus \underbrace{\frac{1}{2}\frac{\Delta\,\omega_0}{\omega_0} \oplus \frac{\Delta m}{m}}_{<10^{-7}}$$

- Typically $5\cdot10^{-5}$
- Beam energy spread can be also measured (10% accuracy)

Implementation: history

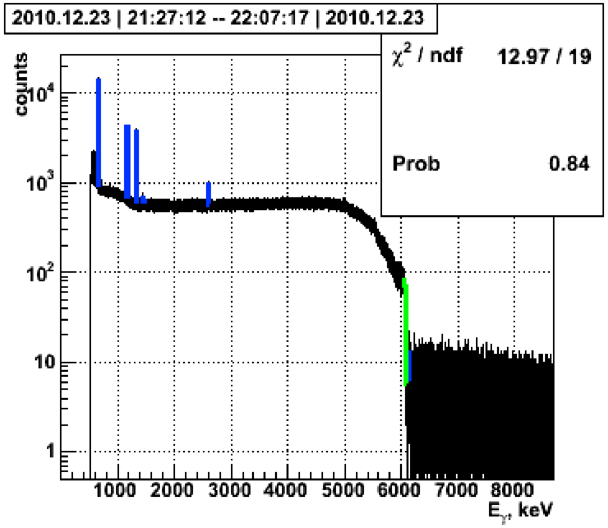
- «Taiwan Light Source», 1996: E_0 ~ 1300 MeV, $\Delta E_0/E_0$ ~ 0.1%. *Hsu et al. Phys.Rev. E 1996, 54-5*.
- BESSY-I, BESSY-II (Berlin), : E_0 ~ 1720 MeV, $\Delta E_0/E_0 \sim 3{\cdot}10^{-5}$. *Klein et al. J.Synchrotron.Radiat. 5 (1998) 392-394; Klein et al. NIM A 486 (2002) 3 545–551.*
- Why not use the method at colliders?

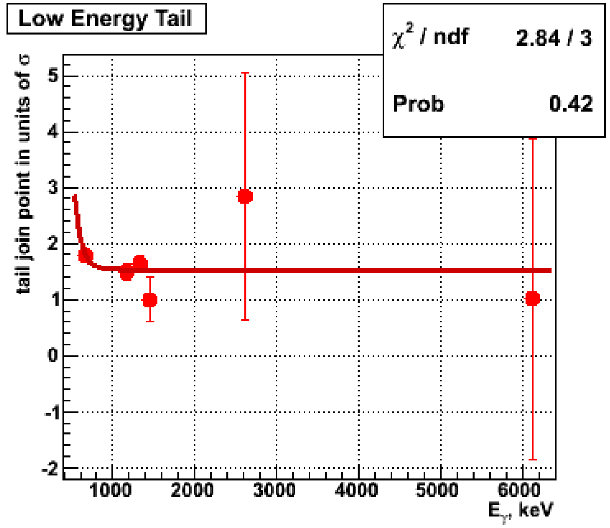
Implementation: VEPP-4M (BINP) / 2005-2014

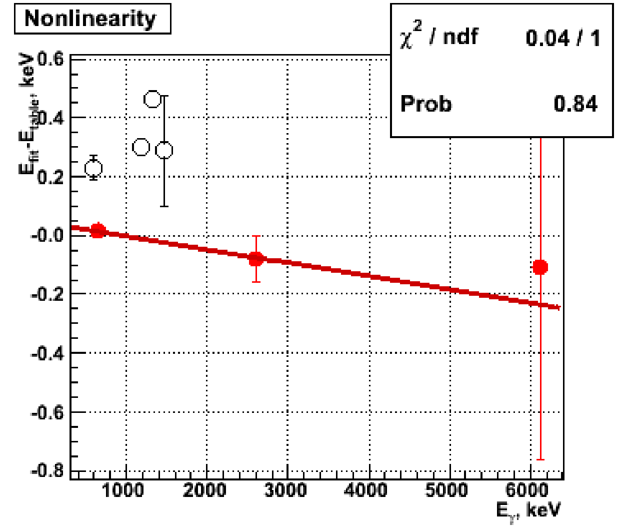


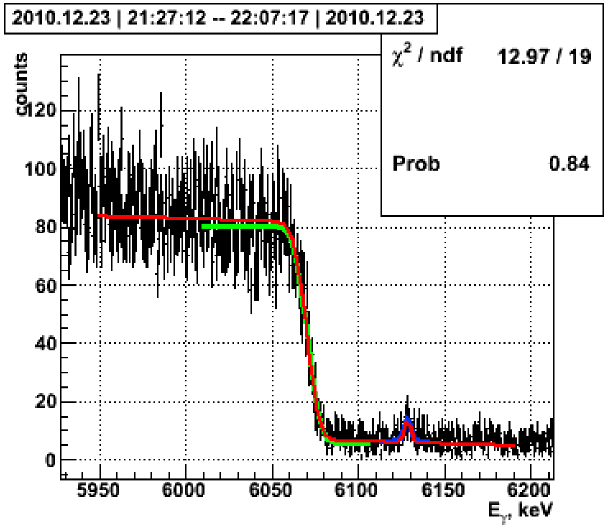
- Precise τ, J/ψ, ψ(2S), ψ(3770) masses and *R* measurement with KEDR detector.
- Electron beam energy from 1.5 to 2 GeV (positrons move in the same ring).
- CO_2 laser: $\lambda = 10.56$ μm, $\omega_0 = 0.117$ eV, 50 W.
- Best accuracy $2{\cdot}10^{-5}$ (1.5 h), typical $4{\cdot}10^{-5}$ (20 min). Accuracy was confirmed using resonant depolarisation technique.

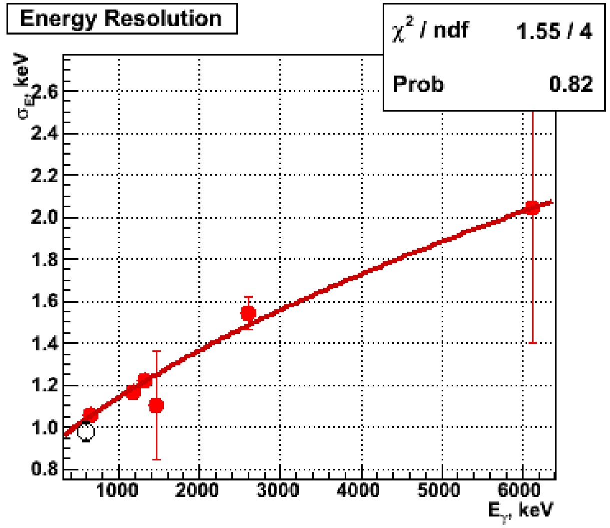
Implementation: VEPP-4M











Zero = 0.81189 keV

Gain = 0.52942 keV/Ch

"Fano" = 0.189 ± 0.018

"Noise" = 0.740 ± 0.046 keV

$E_{edge} = 6070.120 \pm 0.324$ keV

$\sigma_{E_{edge}} = 5.48 \pm 0.42$ keV

$E_{beam} = 1842.855 \pm 0.049$ MeV

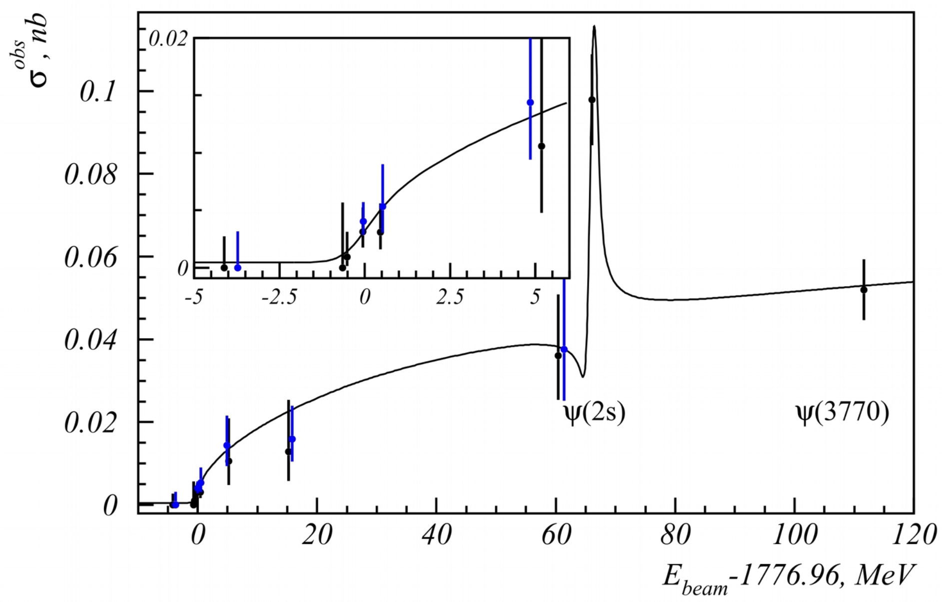
$\sigma_{E_{beam}} = 831.8 \pm 64.5$ keV

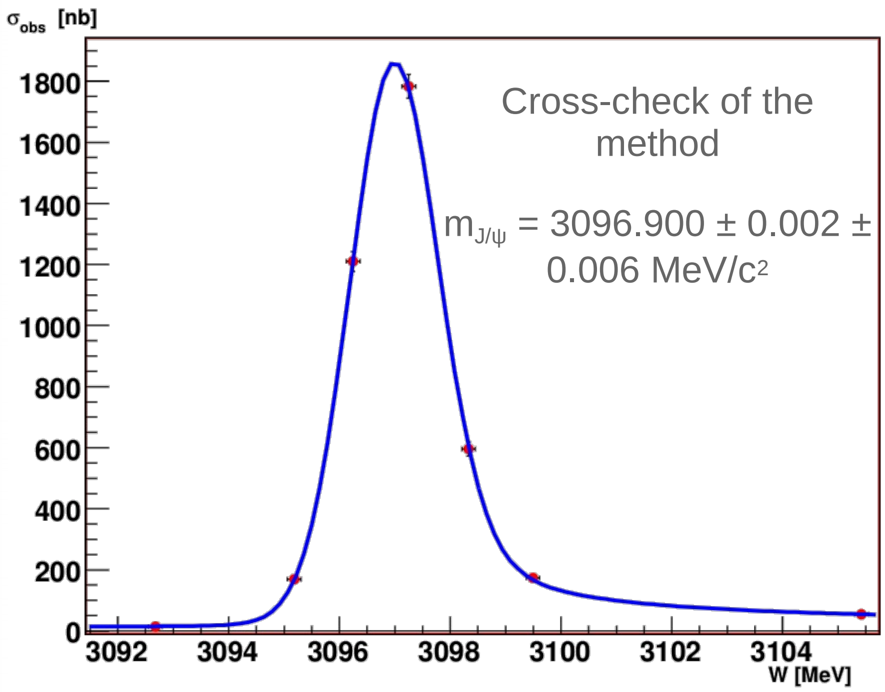
time from: 21:27:12 / 2010.12.23

time upto: 22:07:17 / 2010.12.23

- Similar data processing for other experiments.

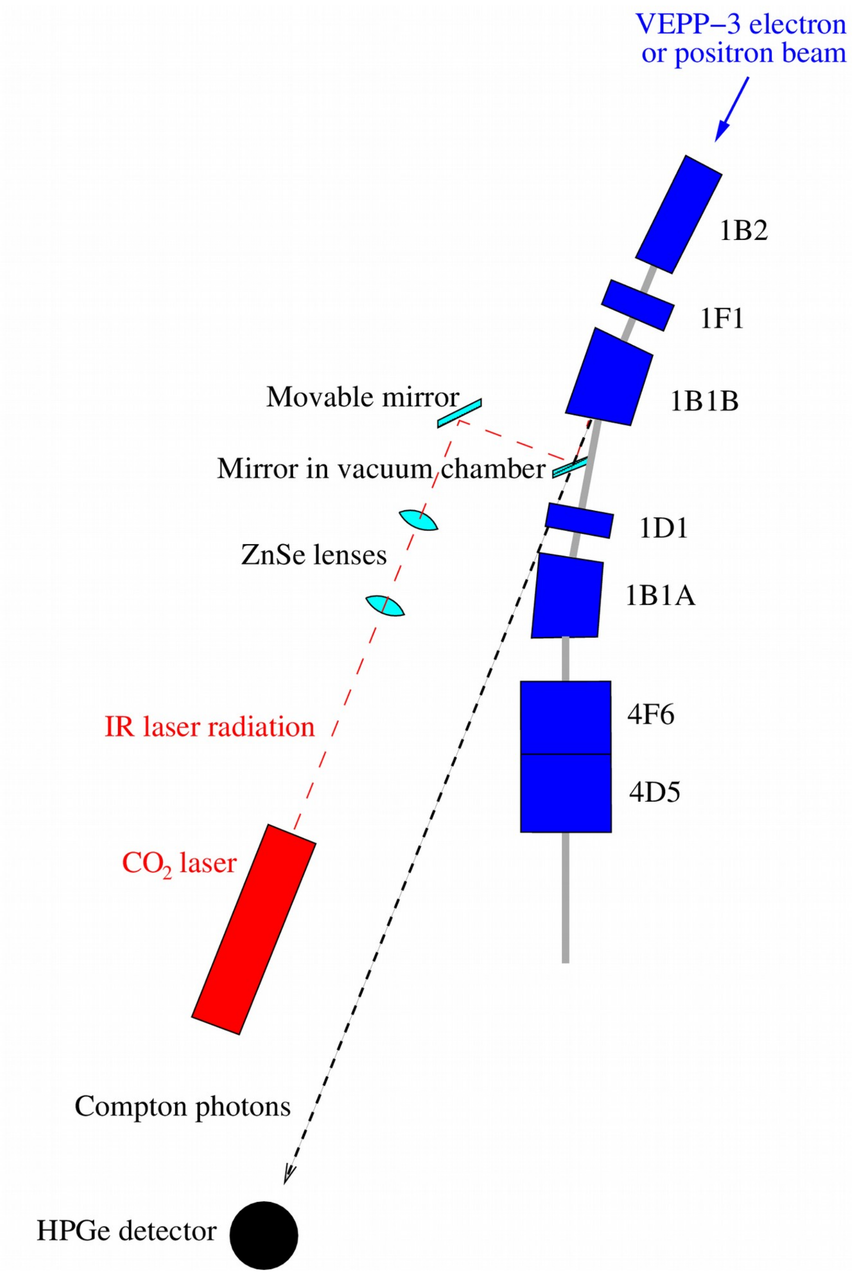
Implementation: VEPP-4M





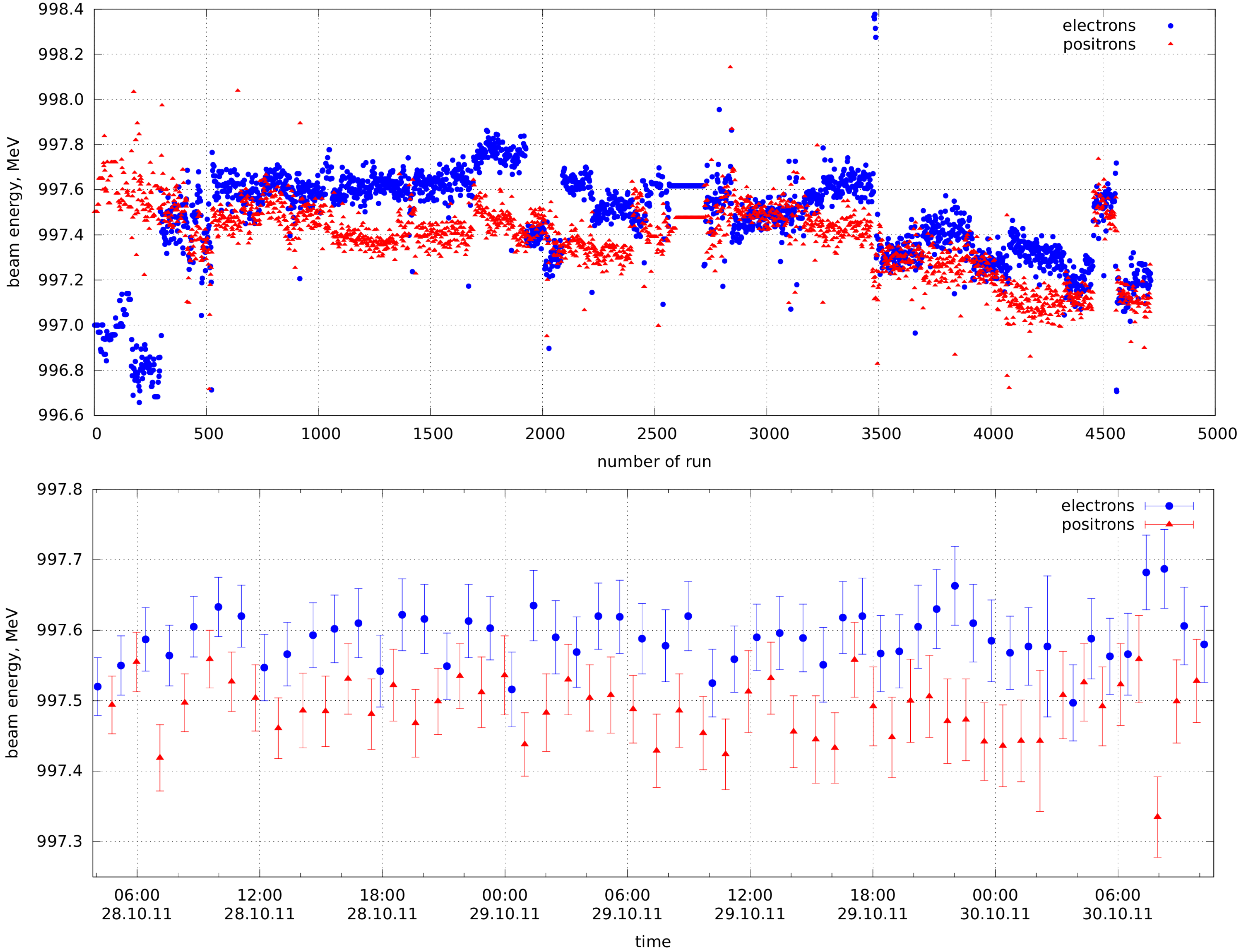
- $m_\tau = 1776.69^{+0.17}_{-0.19} \pm 0.15$ MeV/c^2
- Some results: *Eidelman et al. (KEDR collaboration) Nucl. Phys. B 218(2011)-1 pp 155-159*
- Method: *Blinov et al. ICFA Beam Dynamics Newsletter No. 48 (April 2009), p. 195.*

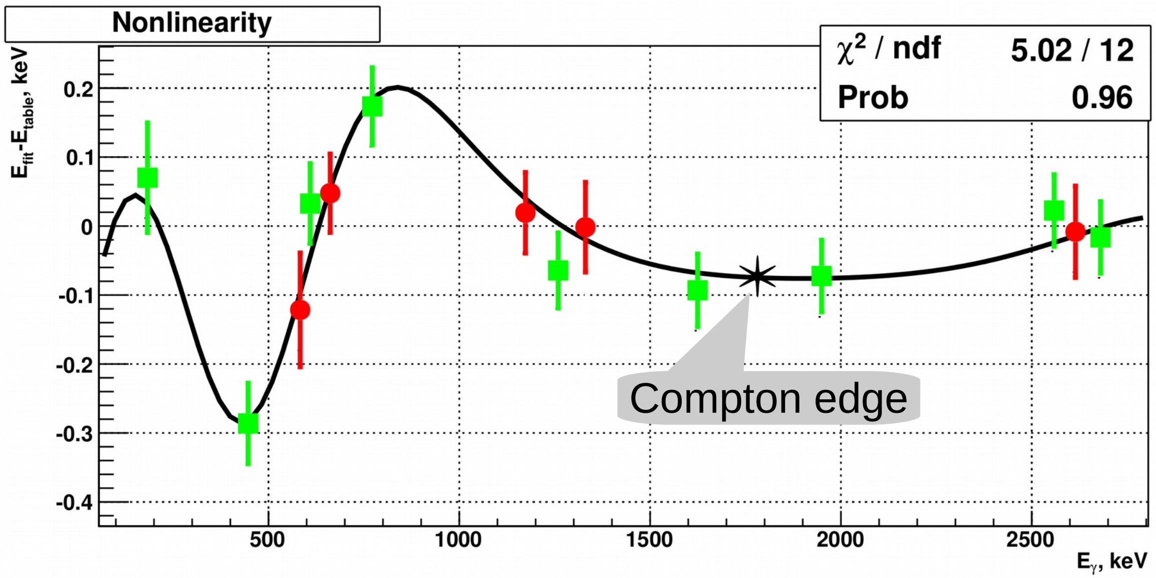
Implementation: VEPP-3 (BINP) / 2009-2012

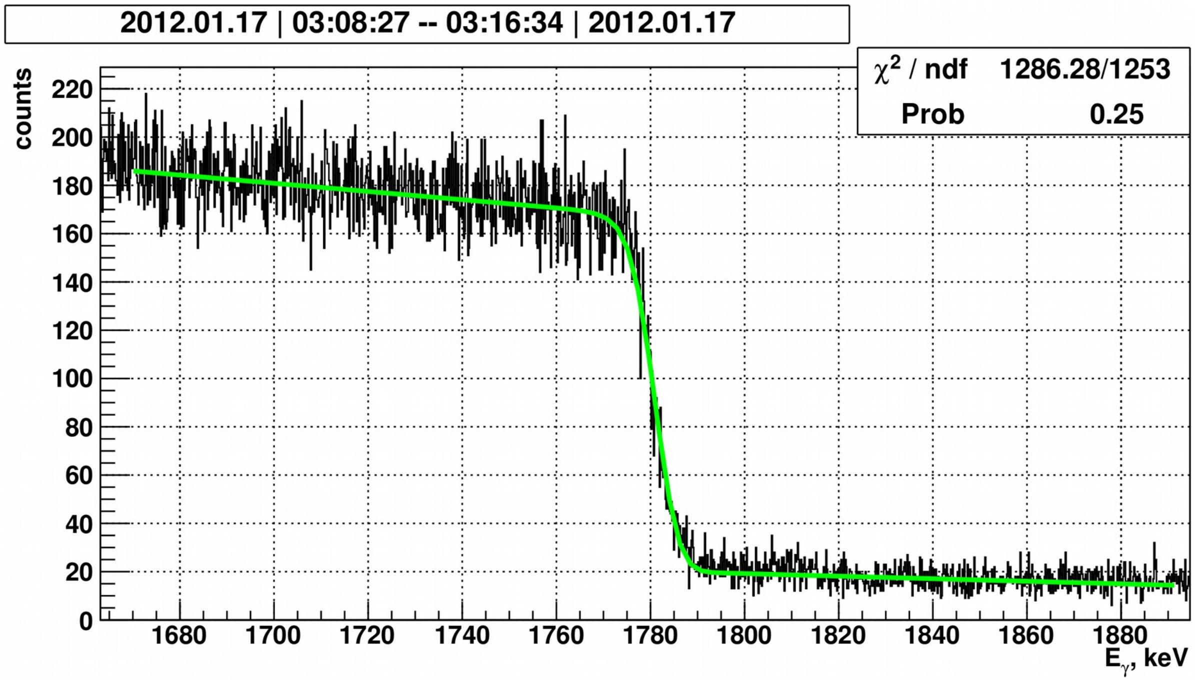


- Fast control of electron and positron beam energies for study of EM proton form factors: two-photon contribution in $e^{\pm}p$ scattering.
- Beam energies 1 GeV, 1.6 GeV.
- CO_2 laser: λ=10.56 μm, ω_0=0.117 eV, 50 W.
- High background, including neutrons.
- Typical accuracy $5 \cdot 10^{-5}$

Implementation: VEPP-3

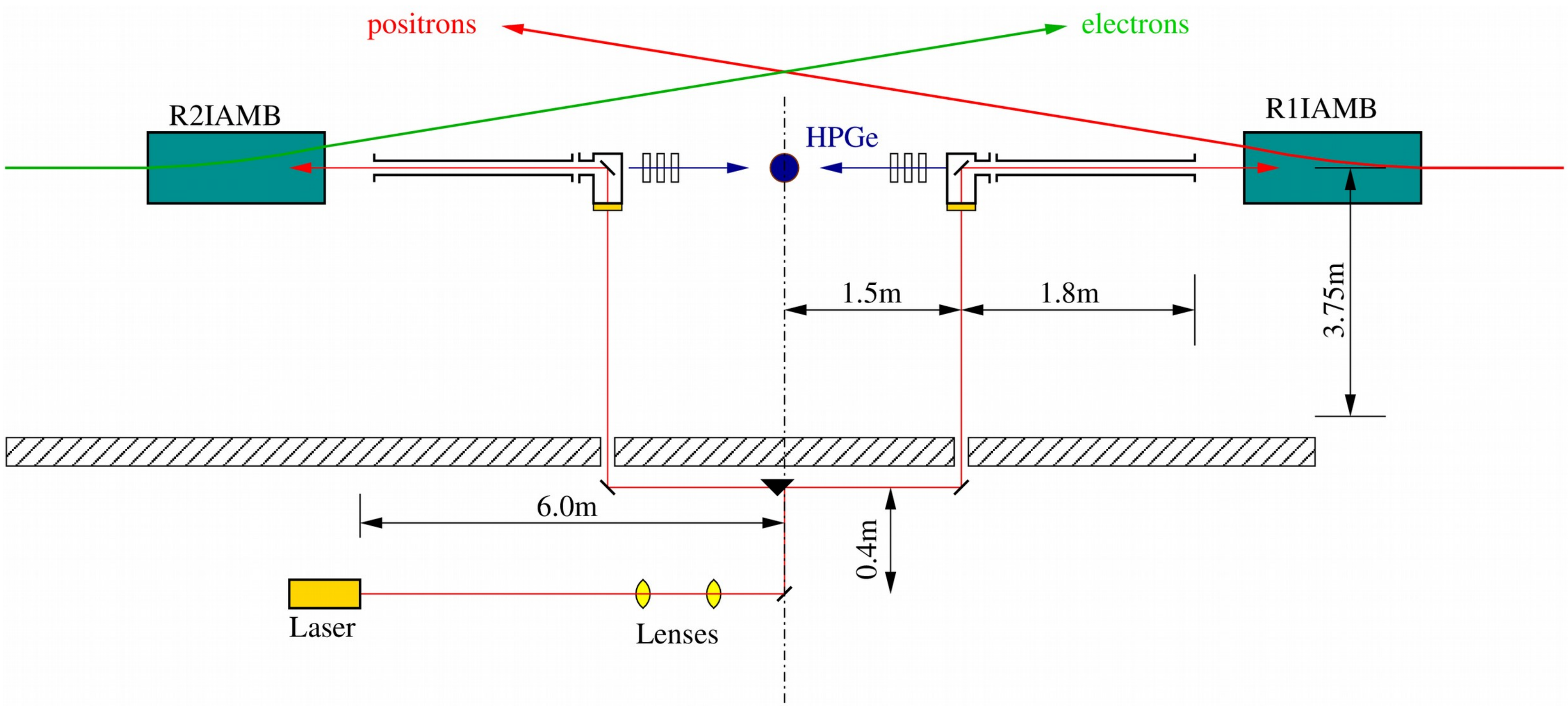




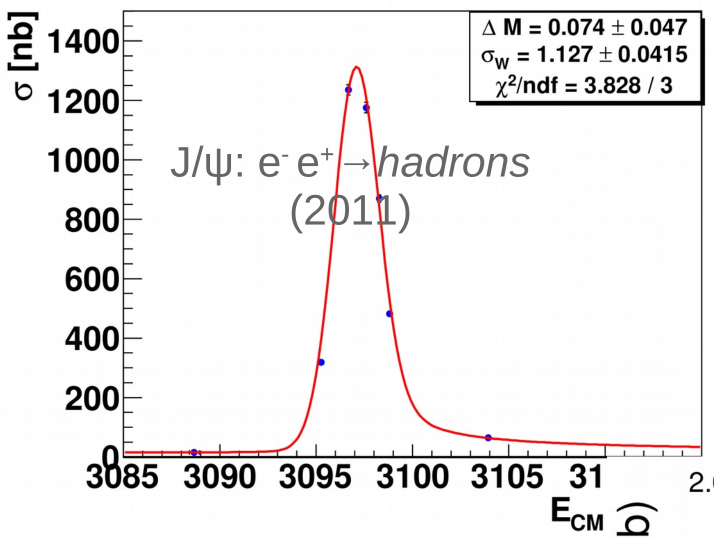


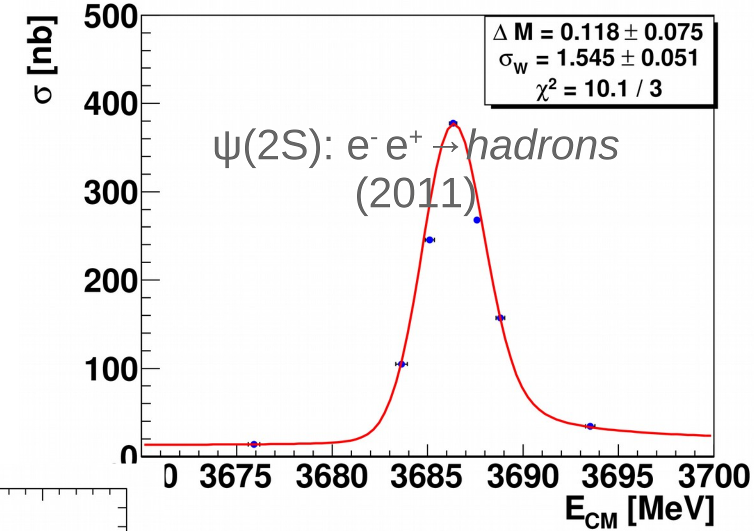
- HPGe detector calibration: isotopes + precision pulse generator (first applied). Calibration precision $<10^{-4}$.
- Method: *Kaminskiy et al. 2014 JINST 9 T06006*
- Results of the experiment: *Rachek et al. Physica Scripta 2015-T166*

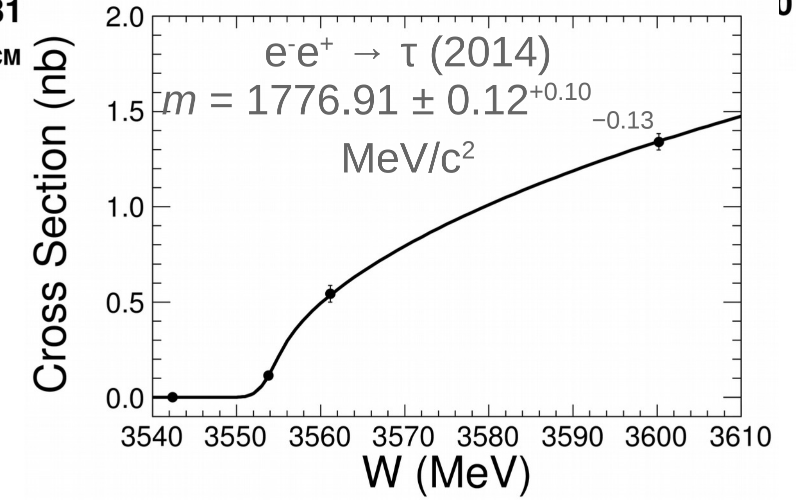
Implementation: BEPC-II (IHEP, Beijing) / since 2010



- Precise τ lepton, J/ψ, ψ(2S) measurements with BES-III detector.
- Separate electron and positron beamlines, alternating e^- and e^+ energy measurement up to 2 GeV:
  - one CO_2 laser: λ_0=10.84 μm, ω_0=0.114 eV, 50 W
  - one HPGe-detector.
- Typical accuracy $5{\cdot}10^{-5}$



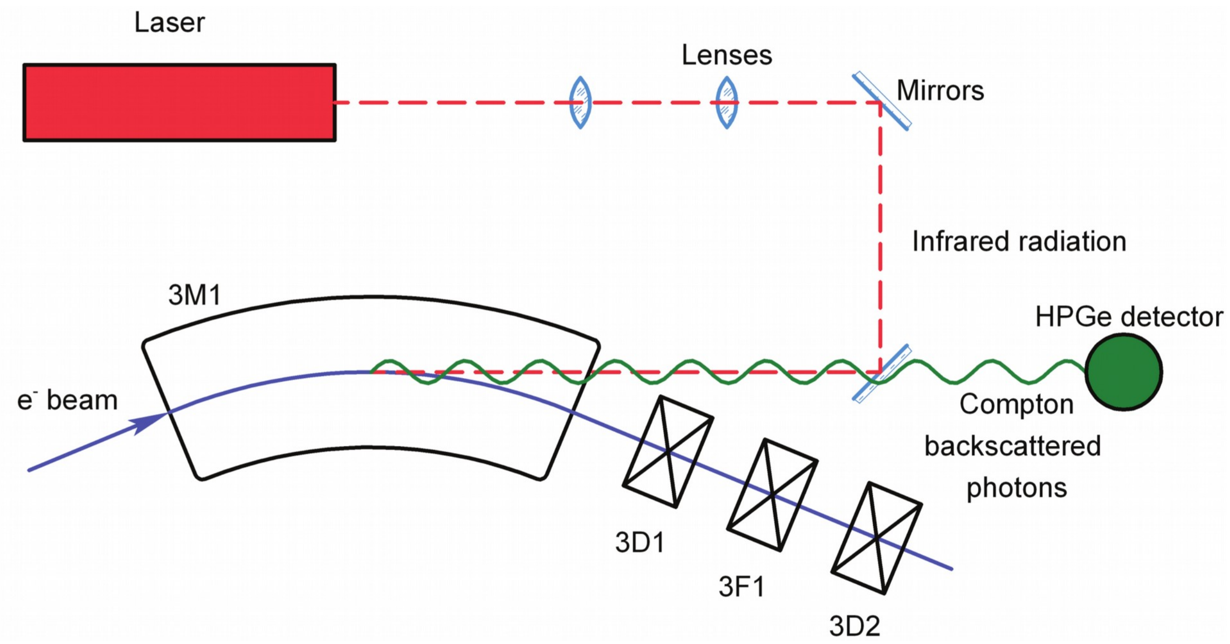




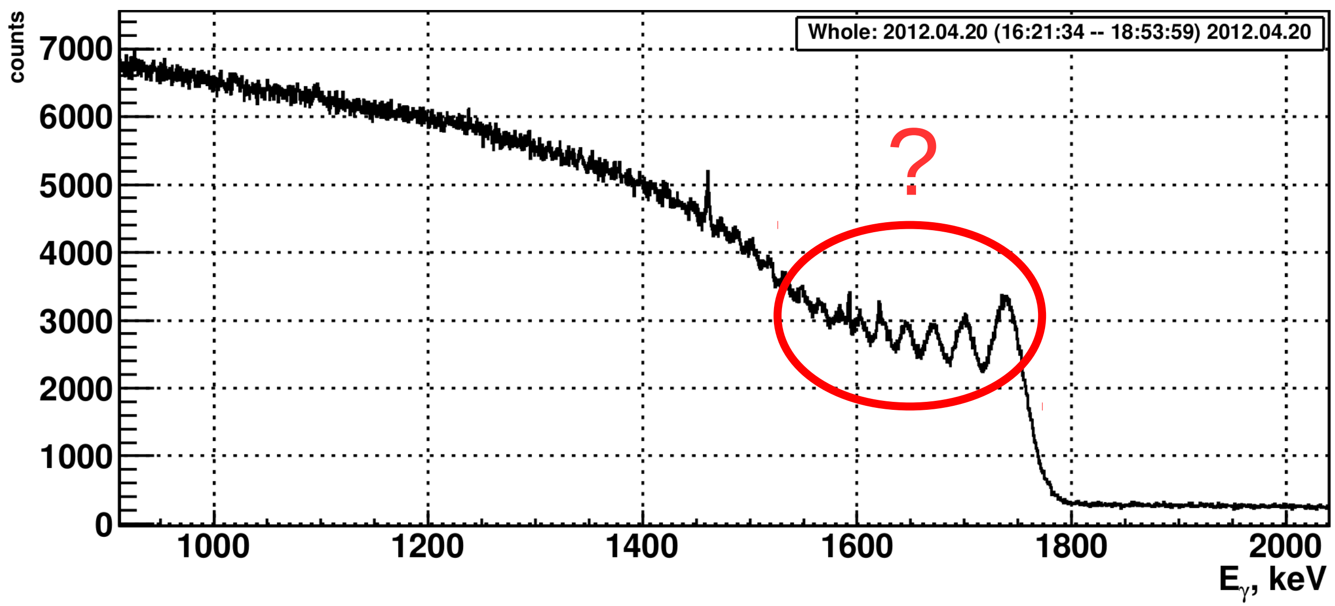
- Some results: *Ablikim et al. (BESIII Collaboration) Phys. Rev. D 90, 012001*
- Method: *Abakumova et al. NIM A 659-1 (2011) p21-29*

Implementation: VEPP-2000 (BINP) / since 2012

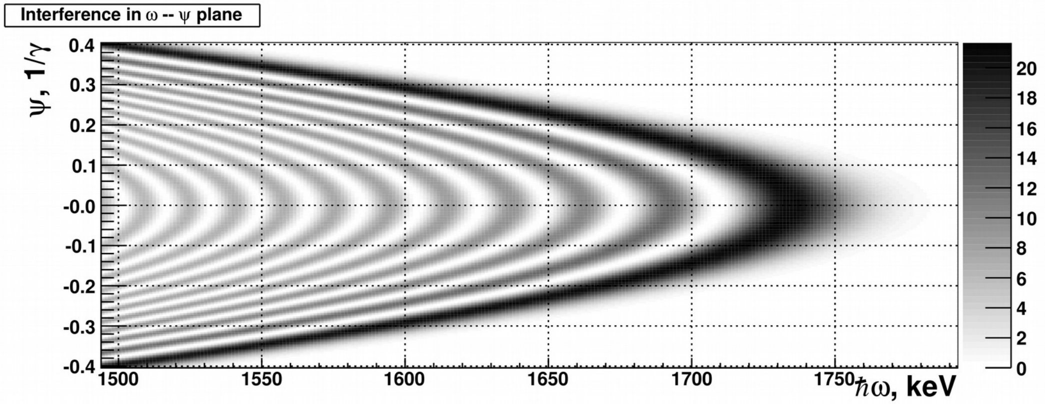
- Precise experiments in the beam energy range 0.5...1.0 GeV with CMD-3 and SND detectors.
- CO_2 (0.12 eV) and CO (0.22 eV) lasers.
- Interaction occurs in dipole magnet.

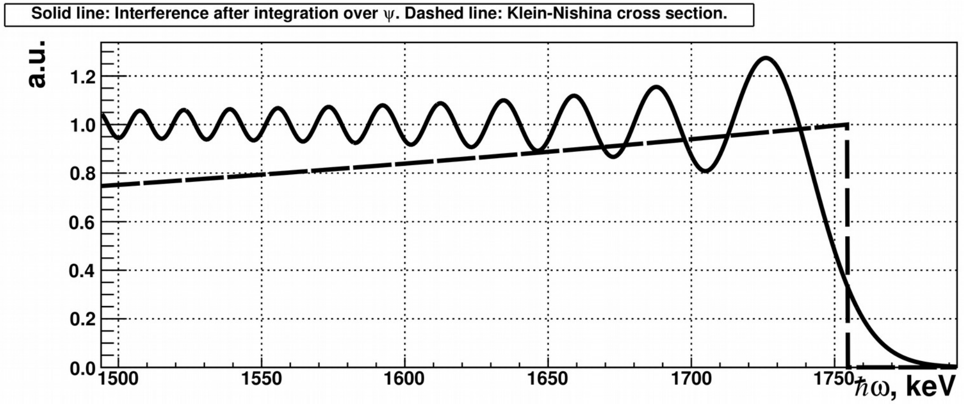


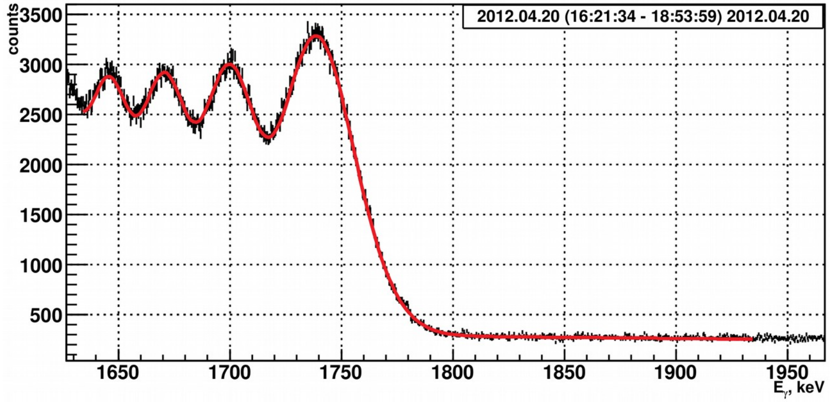
- Something gone wrong…



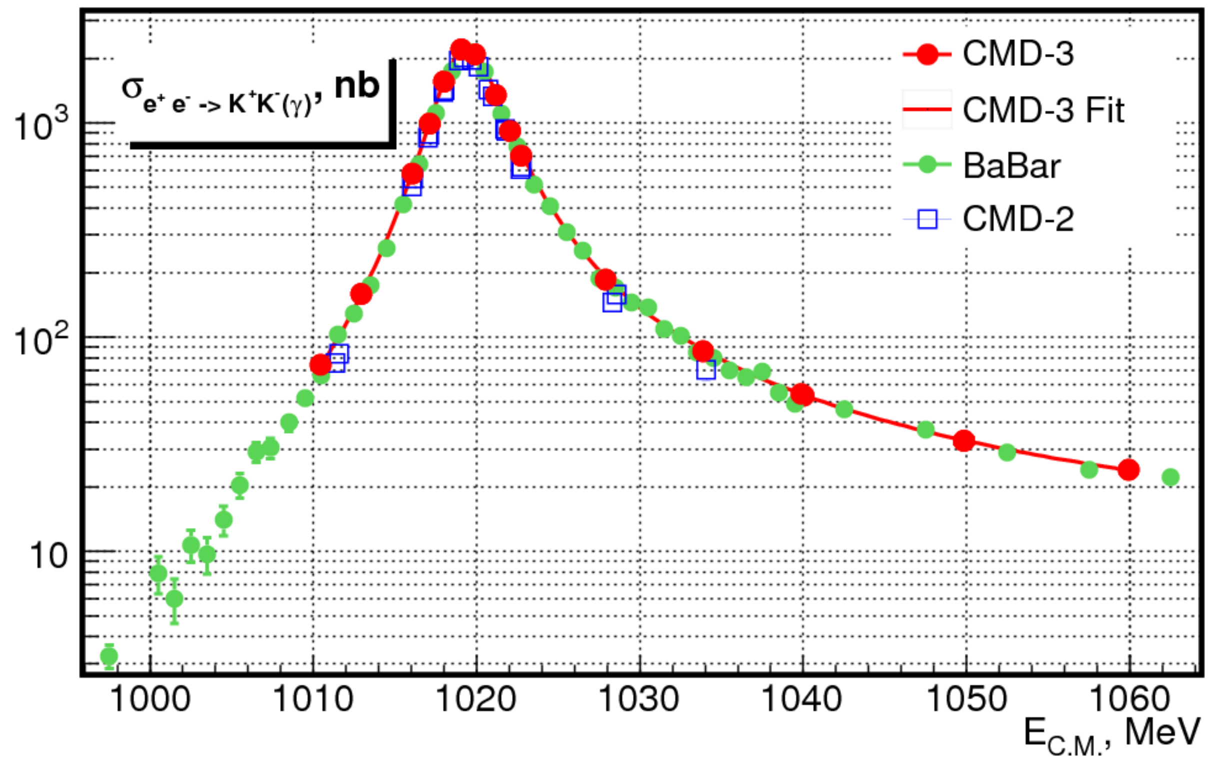
- Interaction of a low-energy photon and electron in magnetic field (bounded electron!).
- Can be described both in quasi-classical and quantum approaches. Difference <10^{-6}.
- Quasi-classical:
  - interference of MeV-range photons emitted at arc electron trajectory, or
  - an electron goes throught superimposed μm-size undulator and uniform transverse field
- Quantum: EM radiation of an electron in alternating field *Zhukovsky/Herrmann J.Nucl.Phys. 14-150 (1971)*.







Implementation: VEPP-2000



- Method: *Abakumova et al. PRL 110-140402 (2013)*
- Some results: *Kozyrev et al. Phys. Atom. Nuclei (2015) 78: 358*

HOWTO

- Points to start (technological limits):
  - HPGe detector can operate properly up to 6 MeV photon energies.
  - Reliable and powerful lasers: 1...10 μm (CO_2, CO, Nd:YAG…).
- Accelerator energies 200...2000 MeV. Note linear dependence ω_{max}~ω_0.
- A set of calibration isotopes, generator and HPGe detector calibration procedure.
- Motorized and automated optical system.
- BINP team has a large experience.

Conclusion

- Beam energy measurement using Compton backscattering photons spectrum edge was successfully implemented at various accelerators and colliders: VEPP-4M, VEPP-3, VEPP-2000, BEPC-II. BINP team has a large experience.
- The method is fast, precise, non-invasive and does not require special beam conditions.
- The method has accuracy 2...20$\cdot 10^{-5}$ of the beam energy achievable within 20..60 minutes data-taking.
- The method can be applied at various ("low-energy") $e^{\pm}$ accelerators, including Super Charm-Tau Factory.
- MeV-range photons interference was observed.

Thank you for attention!

Questions are welcome.