Precise beam energy measurement in collider experiments.

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Physical motivation.

Precise beam energy detrmination in experiments at **e+e–** colliders is important for

- Particles masses and widths measurements
- Study of interference effects in the cross sections
- Measurements of cross sections themselves

Examples.

- ***Z***-boson mass **m_Z=91187.6±2.1 MeV**. Common LEP energy error lead to uncertainty **1.7 MeV**.
- In order to measure the **$e^+e^- \to \pi^+\pi^-$** cross section below **1 GeV** (center-of-mass energy) with accuracy about **0.5%**, the beam energy should be measured with error **$\delta E/E \sim 10^{-4}$**.

Beam energy determination methods.

- **E(MeV) = 300Bρ+Δ$_{corr}$**, B is magnetic field, **ρ** is radius of the dipole magnet, **Δ$_{corr}$** is nonlinear corrections. **δE/E>10^{-3}**.
- Beam energy determination by measurement of the momentum of particles in collinear events. Example **$e^+e^-\to\phi(1020)\to K^+K^-$**. $E=\sqrt{p_K^2+m_K^2}+\Delta_{corr}$, **$p_K$** is average momentum of **K^+K^-**, **Δ$_{corr}$** is correction due to kaon energy losses inside the detector, radiative losses of initial electrons, ... **δE/E~5×10^{-5}** (CMD-2 at VEPP-2M).
- Beam energy determination using positions of the narrow and precisely measured resonances peaks (**ω**, **φ**, **ψ**, **ϒ**).
- Resonance depolarization. **δE/E~10^{-6}**.

$$E=\left(\frac{\Omega}{\omega_s}-1\right)\frac{\mu_0}{\mu'}m_e c^2, \quad \omega_d \pm k\omega_s=\Omega\,(k\in\mathbb{Z}).$$

The polarized beam is necessary.
- Compton backscattering (CBS) of laser photons on the collider beam **δE/E~10^{-4}-10^{-5}**.

Resonance depolarizaton.

The beam energy determination is based on the relation between the electron energy and frequency Ω of its spin precession during the motion of the particlein the transverce magnetic field with a revolution frequency ω_s:

$$E = \left(\frac{\Omega}{\omega_s} - 1 \right) \frac{\mu_0}{\mu'} m_e c^2 ,$$

μ' and μ_0 are anomalous and normal parts of the electron magnetic momentum.

The frequency Ω can be obtained through resonant depolarization of the polarized beam due to impact by an external electromagnetic field with frequency ω_d :

$$k \omega_s \pm \omega_d = \Omega \left(k \in \mathbb{Z} \right).$$

Resonance depolarizaton.

The beam is polarized due to the Sokolov-Ternov effect (radiation polarization): self-polarization of electrons moving in magnetic field for a long time through the emission of synchrotron radiation:

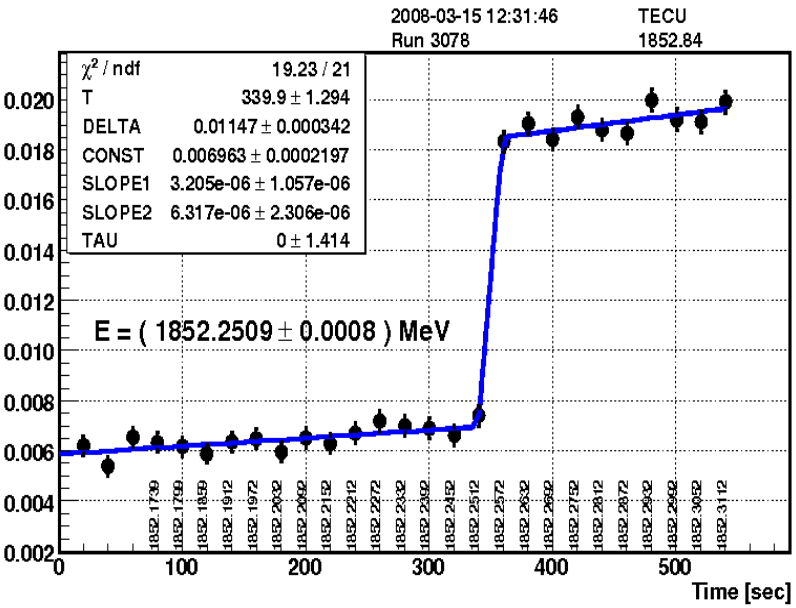
$$\zeta(t) = \frac{8}{5\sqrt{3}}\left(1 - e^{-t/\tau_p}\right), \qquad \frac{1}{\tau_p} = \frac{5\sqrt{3}}{8}\alpha\left(\frac{\lambda_e}{R}\right)^2 \gamma^5 \omega_s.$$

The destruction of polarization is provided by a high-frequency depolarizer. The moment of depolarization is detected by the process which cross-section depends on the depolarization degree.

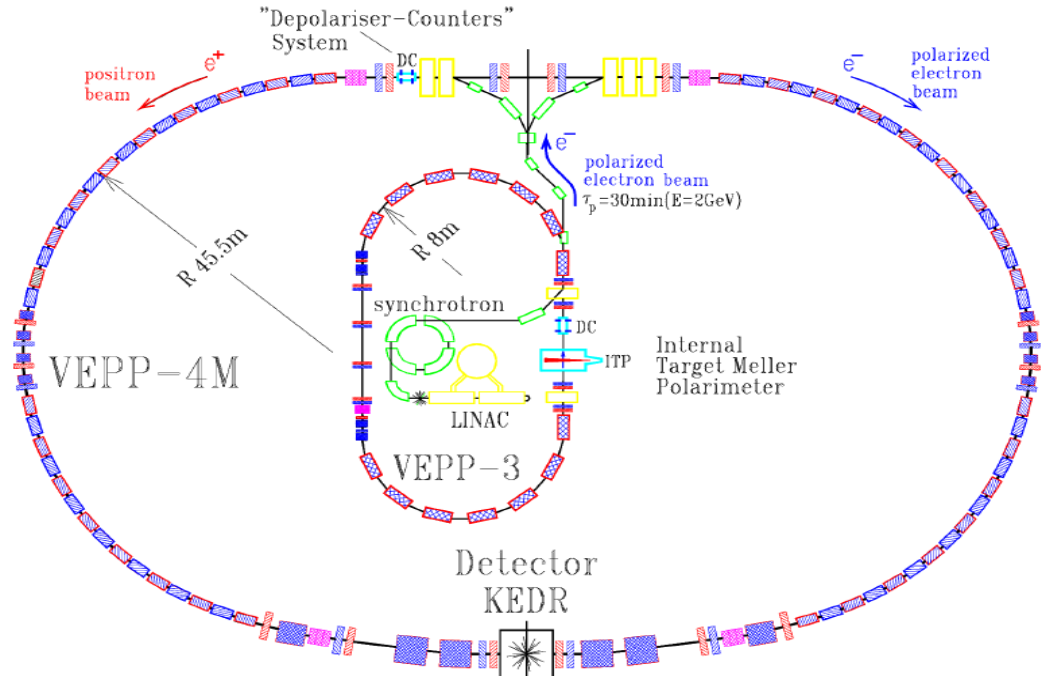
Example. Intrabeam scattering (Toushek effect):

$$d\sigma = d\sigma_0\left(1 - \zeta^2 \frac{\sin^2\theta}{1 + 2\cos^2\theta}\right)$$

Resonance depolarizaton at VEPP-4M.



Counting rate for Touschek electrons.



$\delta E/E$ for single measurement is 10^{-6}.

KEDR results on ψ masses.

particle	$\frac{\Delta m}{m} \cdot 10^6$ (PDG avg.)
p	0.1
n	0.1
e	0.1
μ	0.1
$\pi^\pm$	2.5
J/ψ	3.5
π^0	4.5
$\psi(2S)$	9.2

Energy interpolation between measurements is necessery:

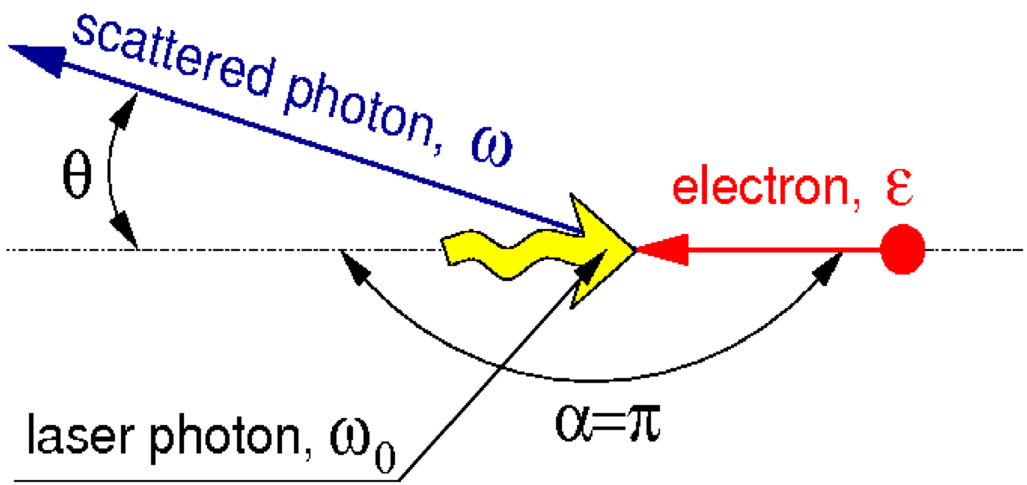
$$E = E_{RD} + \sum \alpha_i P_i(t).$$

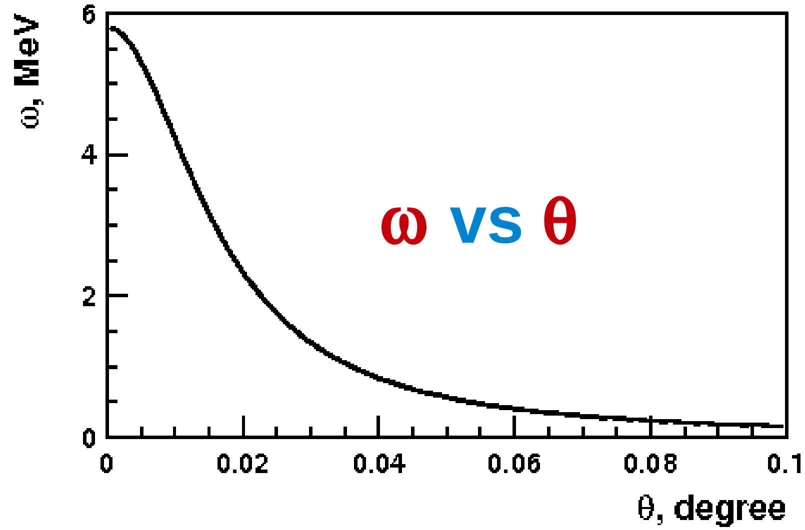
$P_i(t)$ are collider's parameters (B-field, temperature, etc),

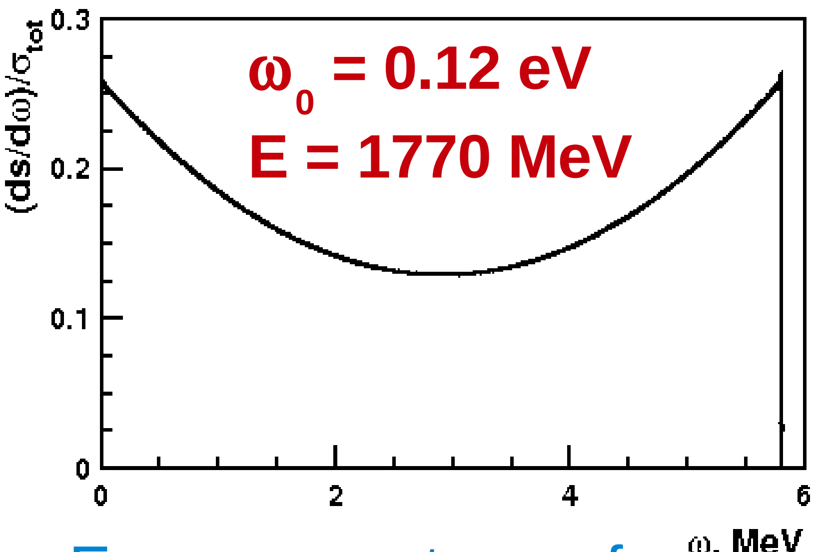
α_i are empirically found coefficients.

Compton backscattering.

CBS of laser light on electron beams is a well known method of generation of quasimonochromatic photon beams.







Energy spectrum of scattered photons.

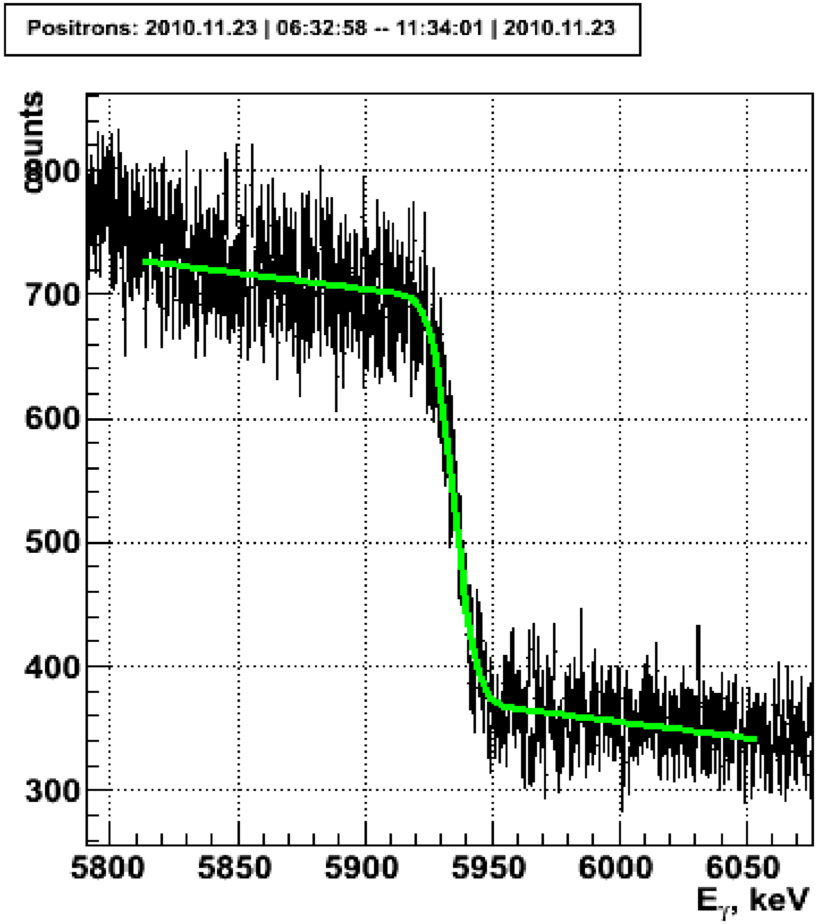
The maximal energy of backscattered photon $\omega_{max} = \frac{E^2}{E + m_e^2/4\omega_0}$

If one have measured ω_{max} then the electron energy can be obtained as

$$E = \frac{\omega_{max}}{2}\left[1 + \sqrt{1 + \frac{m_e^2}{\omega_0 \omega_{max}}}\right]$$

Brief description of the CBS method

- The monochromatic laser radiation is put in collisions with the beam.
- The energy of the backscattered photons is measured with High Purity Germanium (HPGe) detector.
- The beam energy **E** is calculated from the maximum energy ω_{max}.



The fit to the edge of the photons backscattered at BEPC-II.

CBS method

- provides rather high accuracy,
- provides measurements in a wide energy region,
- allows to measure beam energy during data taking.

Application of the CBS method.

Compton backscattering has been proposed as a diagnostic tool for electron beam energy in *T. Yamazaki et. al., IEEE Trans. on Nucl. Sci., Vol. NS-32, No 5, 1985.*

First measurement of the beam energy $E \approx 1.3$ GeV at storage ring of Taiwan Light Source with error $\delta E/E \sim 10^{-3}$ was reported in *Ian C. Hsu, et al., Phys. Rev. E 54 (1996).*

The accuracy of the measurements was improved at SR sources BESSY-I and BESSY-II (Berlin):

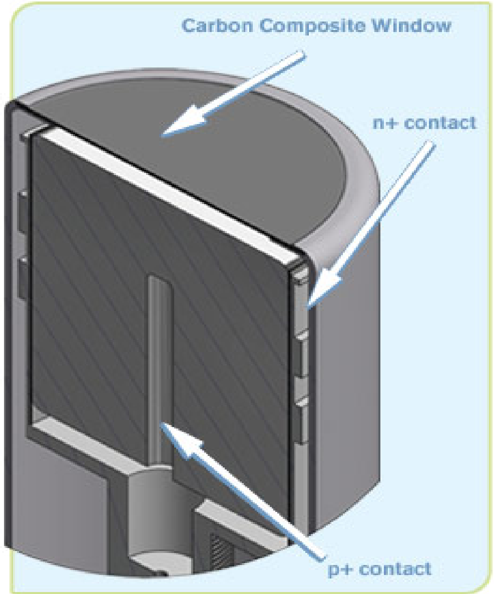
$\delta E/E \sim 2\times10^{-4}$, $E \approx 0.8$ GeV, $\delta E/E \sim 3\times10^{-5}$, $E \approx 1.7$ GeV.

It was proved by comparison with results of resonance depolarization method.

In collider experiments CBS was first applied at VEPP-4M (Novosibirsk) $E = 1–2$ GeV.

Then at τ–charm factory BEPC-II (Beijing) $E = 1–2$ GeV and at VEPP-2000 (Novosibirsk), $E < 1$ GeV.

High Purity Germanium (HPGe) detector.



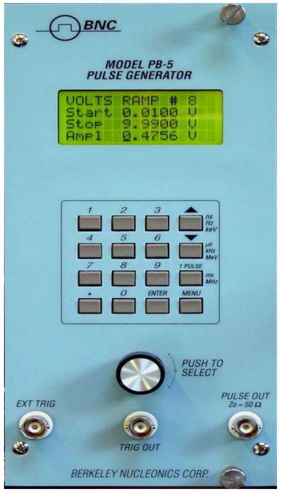
HPGe detector can measured the γ–quanta with energy below **10 MeV**.

Typical parameters of coaxial HPGe detector:

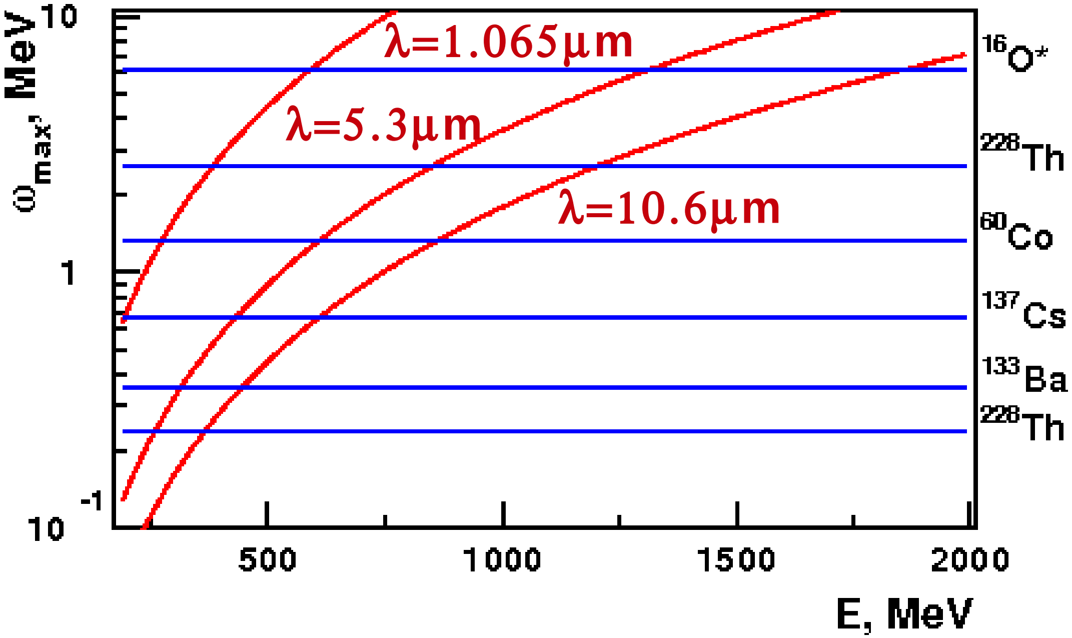
- **∅ 5 – 6 cm**, height **5 – 7 cm**
- Energy resolution $\boldsymbol{\delta\omega/\omega \sim 10^{-3}}$.
- Operating temperature **≈100K**

The detector is connected to multichannel analyzer with integrated nonlinearity **±250 ppm** (ORTEC DSPEC Pro™).

Precise calibration pulse generator BNC model BP-5 integral nonlinearity **±15 ppm** jitter **±10 ppm**.



Laser – the source of initial photons.



Relation between ω_{max} and E for different laser wavelength.

The main requirements:

- the single generated line,
- high stability of parameters,
- easy maintance,
- **$\omega_{max} \approx 0.2 – 6$ MeV** (posibility of detection and calibration using γ−active radionuclides.)

λ≈ 1.065 μm – solid state laser is used at low energy region **E<0.5 GeV** (VEPP-2000).

λ≈ 5.3 μm – CO laser is used below **1 GeV**.

λ≈ 10.6 μm – CO_2 laser is used in the energy region **1<E<2 GeV**.

HPGe detector calibration.

The statistical accuracy of beam energy measurement about **$5\times(10^{-4} - 10^{-5})$** can be achived in a reasonable time (**≤ 1 hour**).

The systematic accuracy is mostly defined by calibration of the detector.
The nonlinearity of multichannel analyzer's scale is calibrated using the precise pulse generator.
The accurate absolute calibration could be done by using the γ−active radionuclides.

Radiative sources for HPGe calibration:

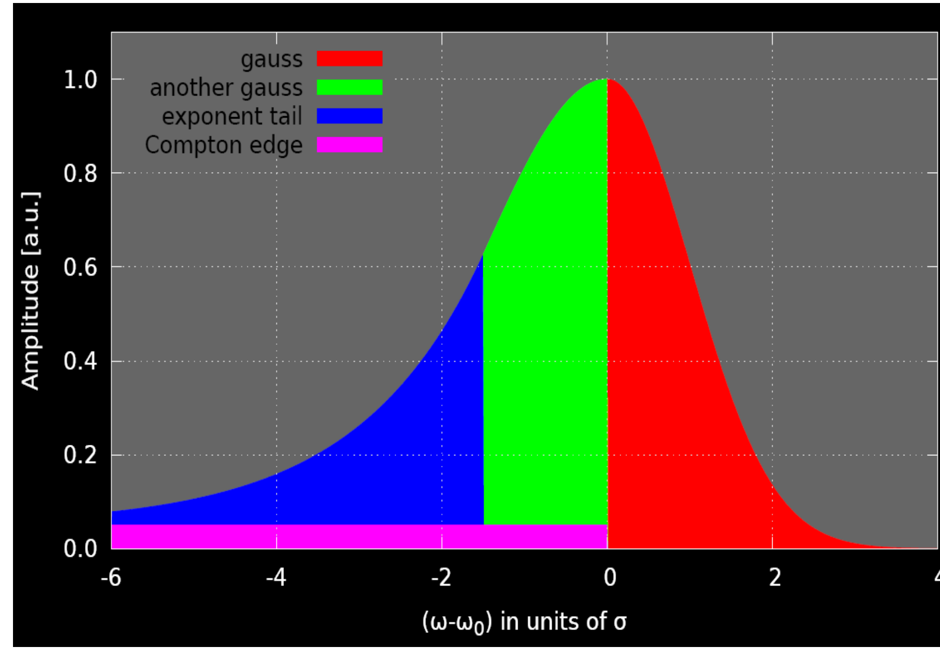
- **^{228}Th E_γ = 583.191 ± 0.002 keV**
- **^{137}Cs E_γ = 661.657 ± 0.003 keV**
- **^{60}Co E_γ = 1173.237 ± 0.004 keV**
- **^{60}Co E_γ = 1332.501 ± 0.005 keV**
- **^{228}Th E_γ = 2614.553 ± 0.013 keV**
- **^{16}O* E_γ = 6129.266 ± 0.054 keV**

[^{238}Pu^{13}C]: $\alpha + {}^{13}C \rightarrow n + {}^{16}O^*$

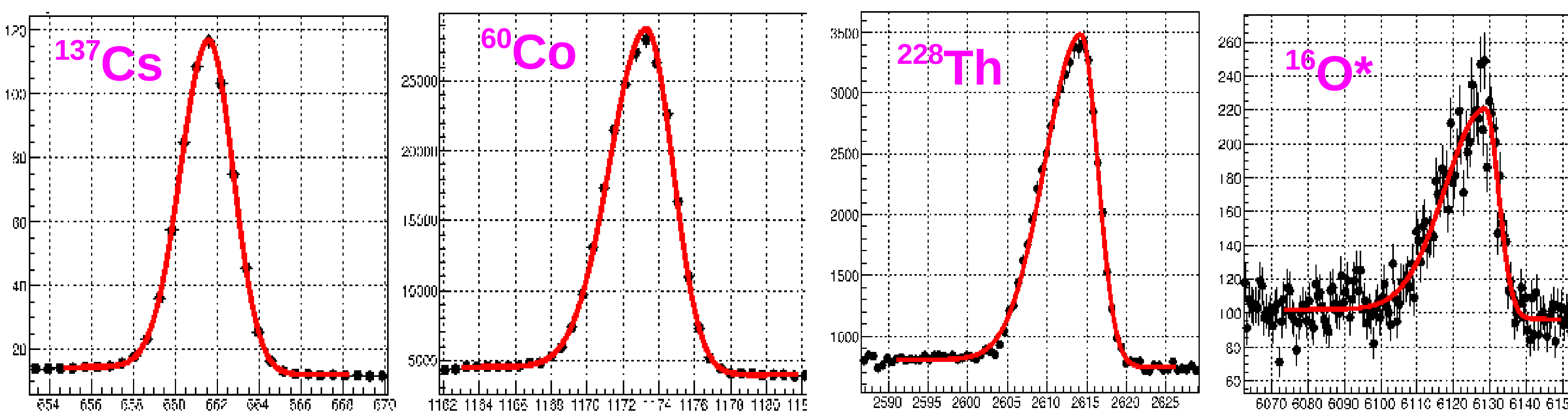
HPGe calibration.

The goals of calibration:

- To obtain the coefficients for conversion of ACD counts to corresponding energy deposition in the units of MeV.
- Determination of the parameters of the detector responce function.



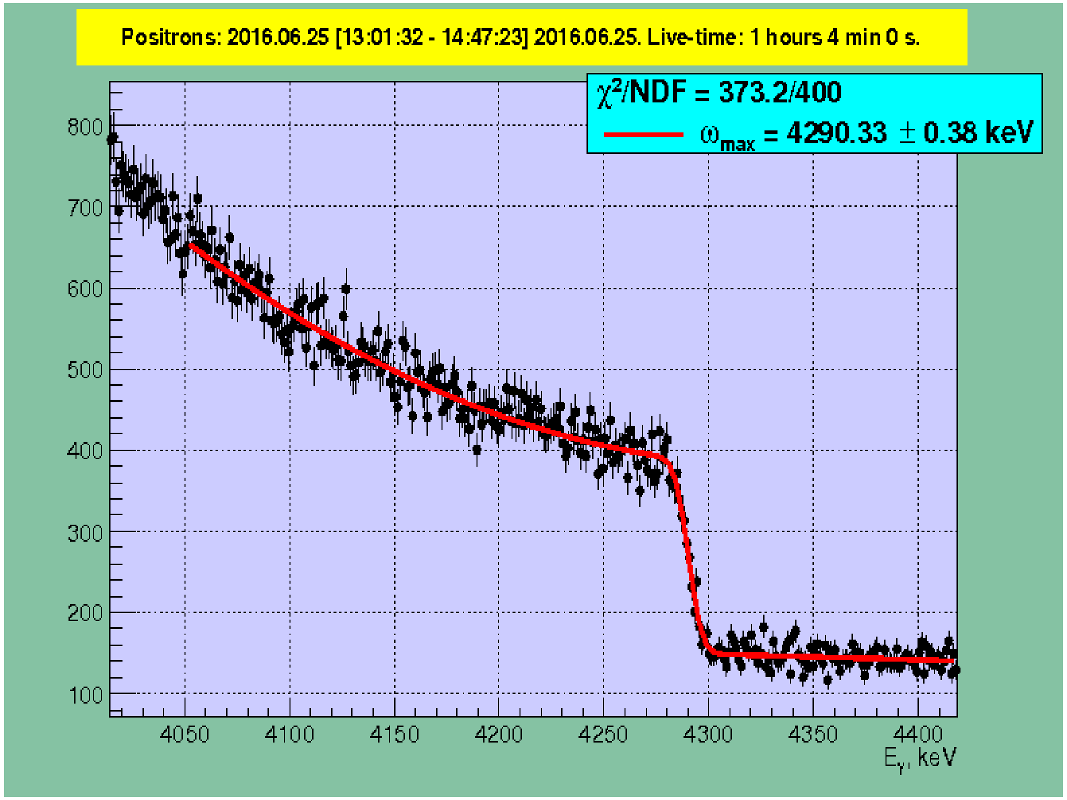
The fits of the photo-peaks.



Energy of γ–quanta, keV.

The fit of backscattered photons spectrum.

Actually the width of spectrum edge depends on the HPGe detector resolution and the electron beam energy spread.



The fit to the edge of the photons backscattered at BEPC-II.

The spectrum edge is fitted by the function, which takes into account:

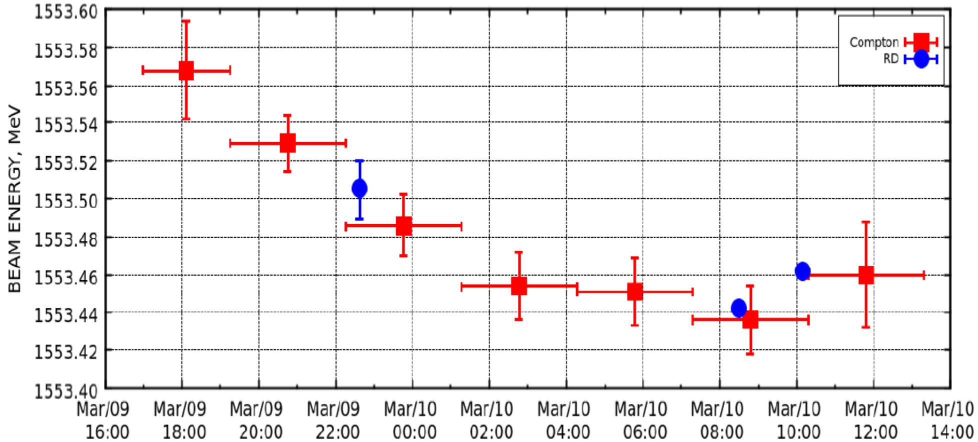
- the «pure» edge shape,
- detector responce function,
- energy spread of scattered photons due to the energy distribution of the collider beam.

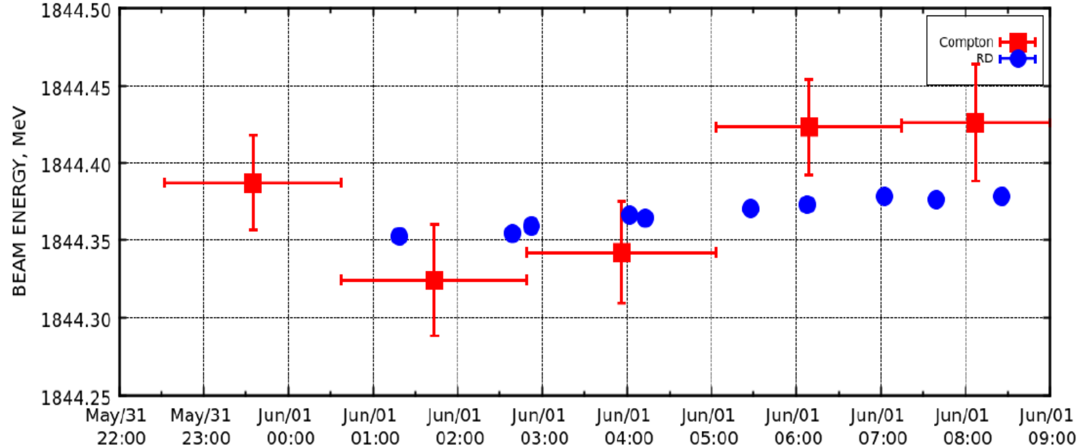
The edge position ω_{max} and the photons energy spread σ_ω are obtained from the fit.

The beam energy E and energy spread σ_E are calculated from ω_{max} and σ_ω.

Comparison of CBS and RD methods.

Direct comparison at VEPP-2M. CBS-red and RD-blue points.

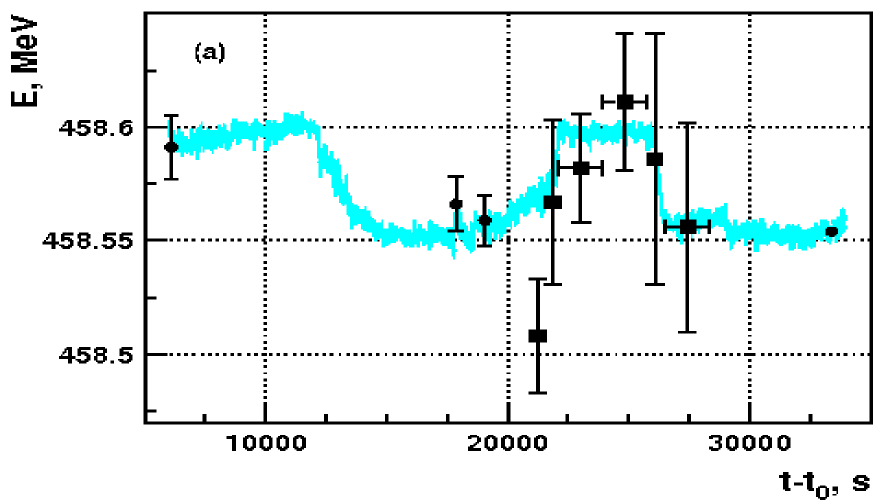


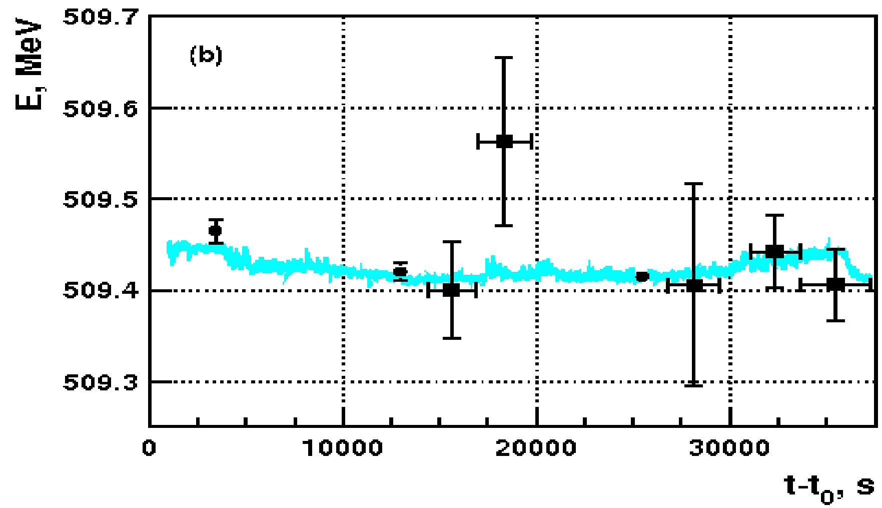


Beam energy E=1553 MeV. No systematical bias between RD and CBS results. $\delta E/E=1.3\times10^{-5}$.

Beam energy E=1844 MeV. $E_{RD} - E_{CBS}$=13±38 keV. $\delta E/E=2\times10^{-5}$.

Comparison at VEPP-2000. CBS-squares and RD-dots points.

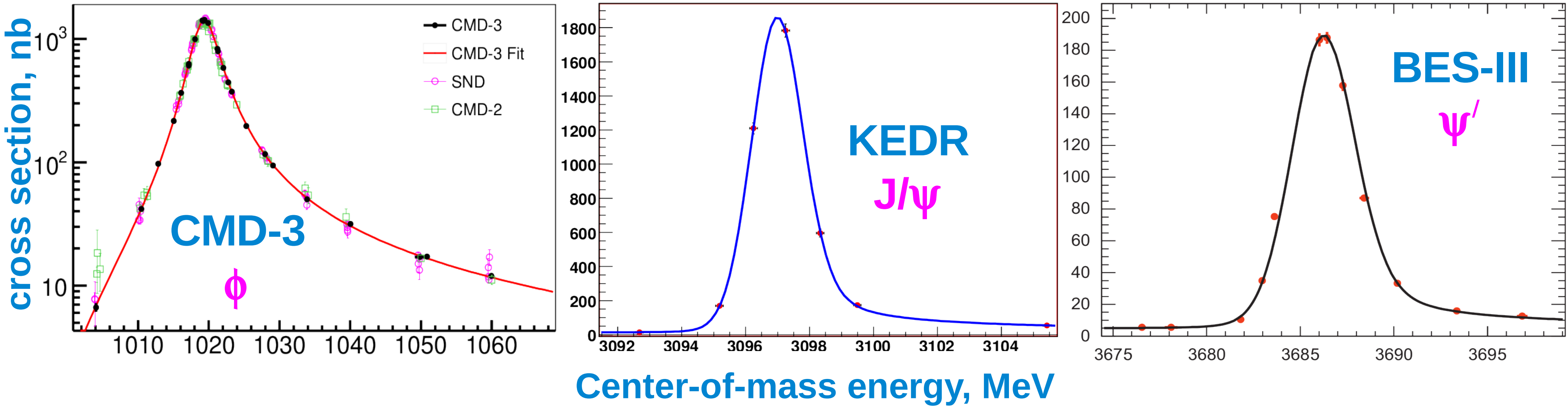




The line shows the energy calculated using magnetic field of the collider, which was measured by NMR sensors. $\delta E/E\approx 6\times10^{-5}$.

Tests of CBS method using narrow resonances peaks.

The masses of narrow resonances (ϕ, J/ψ, ψ) obtained using CBS method are compared with their PDG values.



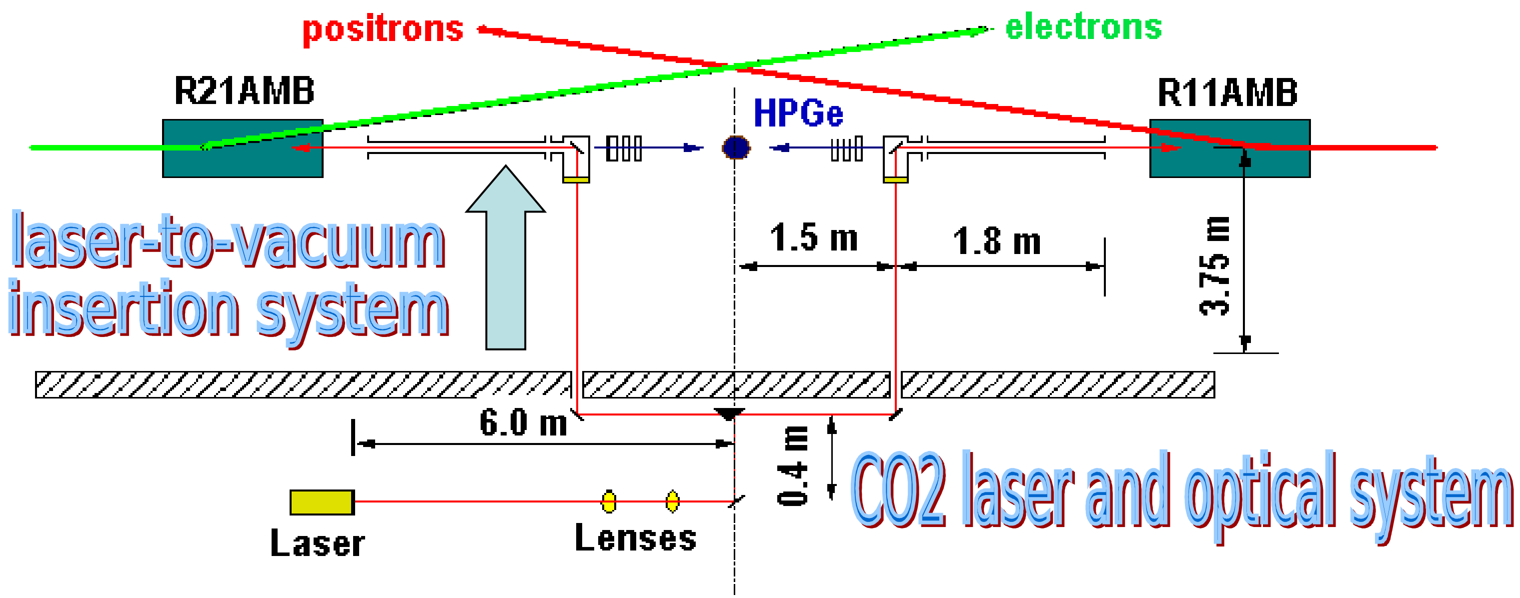
Mass difference
$\Delta m = m_{CBS} - m_{PDG}$
is used to estimate the error of beam energy measurement
$\Delta E = \Delta m / 2$.

Scan		ΔE, keV	δE/E
$\phi(1020)$,	CMD-3	-8 ± 20	2×10^{-5}
J/ψ,	KEDR	$0{,}6 \pm 7{,}4$	5×10^{-6}
J/ψ,	BES-III	74 ± 57	6×10^{-5}
ψ',	BES-III	118 ± 79	7×10^{-5}
ψ',	BES-III	1 ± 36	2×10^{-5}

BEPC-II beam energy measurement system.

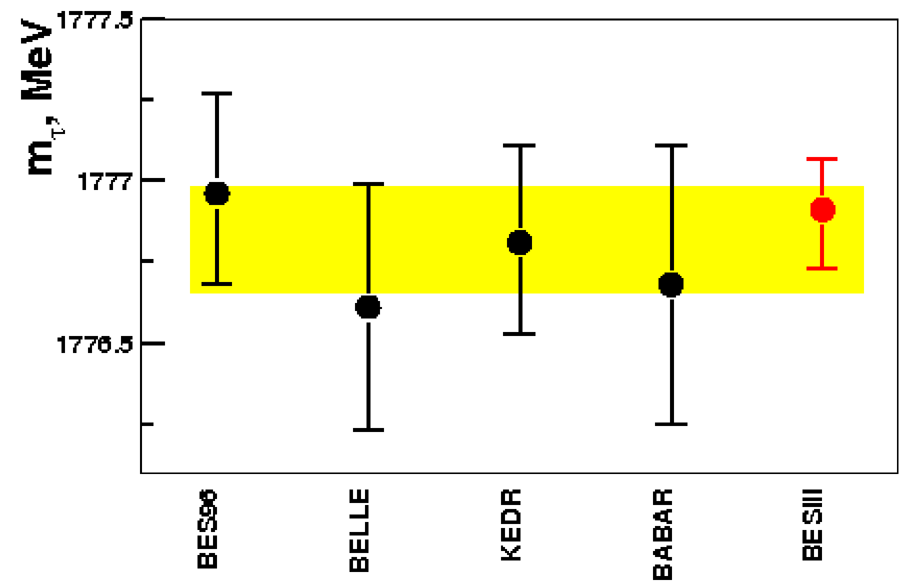
Layout of BEPC-II beam energy measurement system.

The energy of the electron and positron beams are measured one after another, in turn.



In December 2011 BESIII have collected **25 pb^{-1}** at τ threshold.

m_τ=1776,91 ±0,12 $\pm^{0,10}_{0,13}$ MeV.
[*Phys. Rev. D90, 012001 (2014)*]

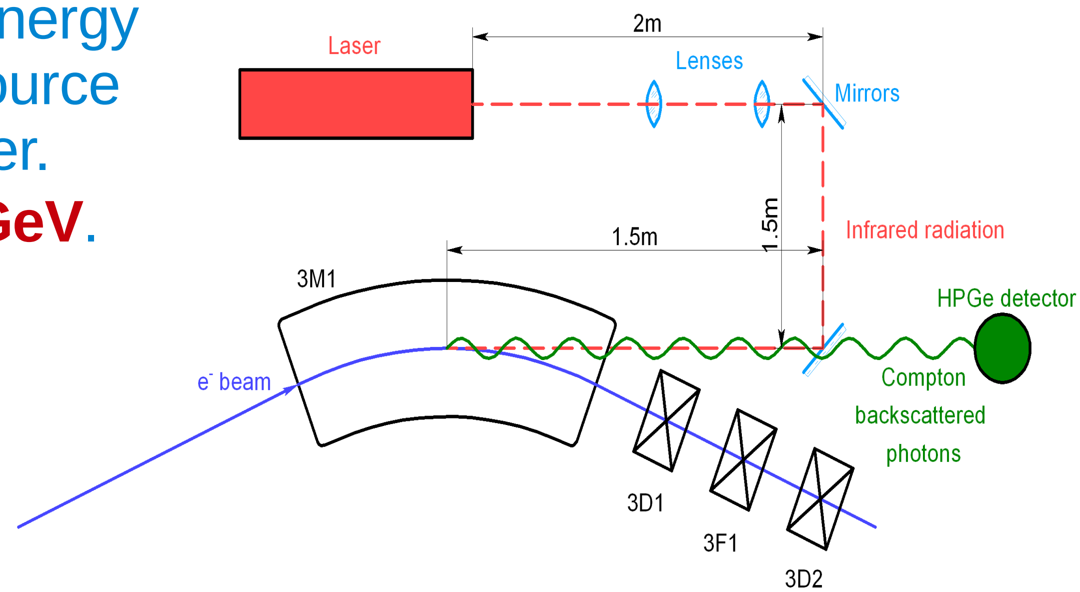


The plan is to collect **100 pb^{-1}** and try to reach the error of **50 keV** of mass determination.

VEPP-2000 beam energy measurement system.

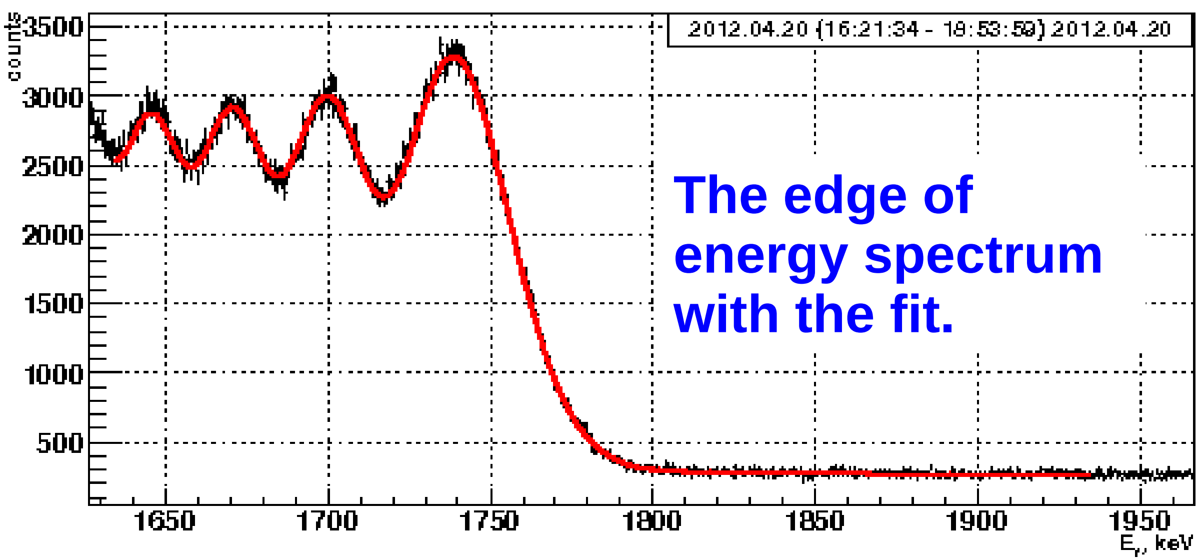
Layout of VEPP-2000 beam energy measurement system. The source of initial photons is CO laser.

ω_{max}≈0.2–2.0 MeV for **E<1 GeV**.



The interaction of laser photons with electrons occurs inside bending magnet (**ρ=140 cm**) at the curvulinear part of orbit.

In this case the spectrum of backscattered photons differs from that defined by the Klein-Nishina cross section and scattering kinematics of free electrons.

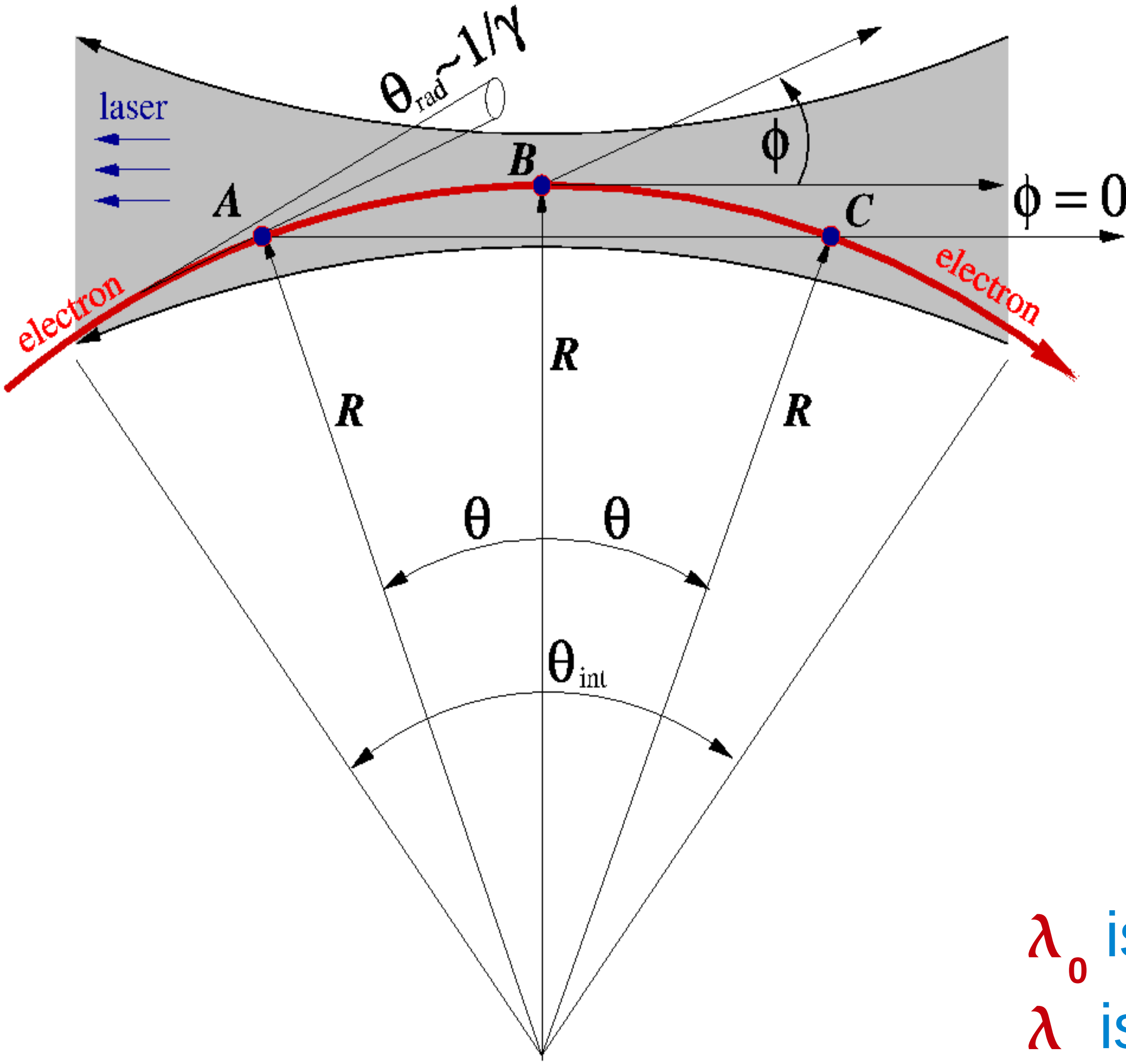


The interference of scattered photons is observed in the energy spectrum.

[*E.V. Abakumova, et.al., Phys. Rev. Lett., 100, 140402 (2013)*]

Interference of scattered photons.

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



Time for electron to pass A→B→C:

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

Time for photon to pass A→C:

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

ψ is the vertical angle with respect to the orbit plate.

Phase shift:

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

λ_0 is a laser wavelength

λ is a scattered photon wavelength.

Interference of scattered photons.

The photon spectrum:

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

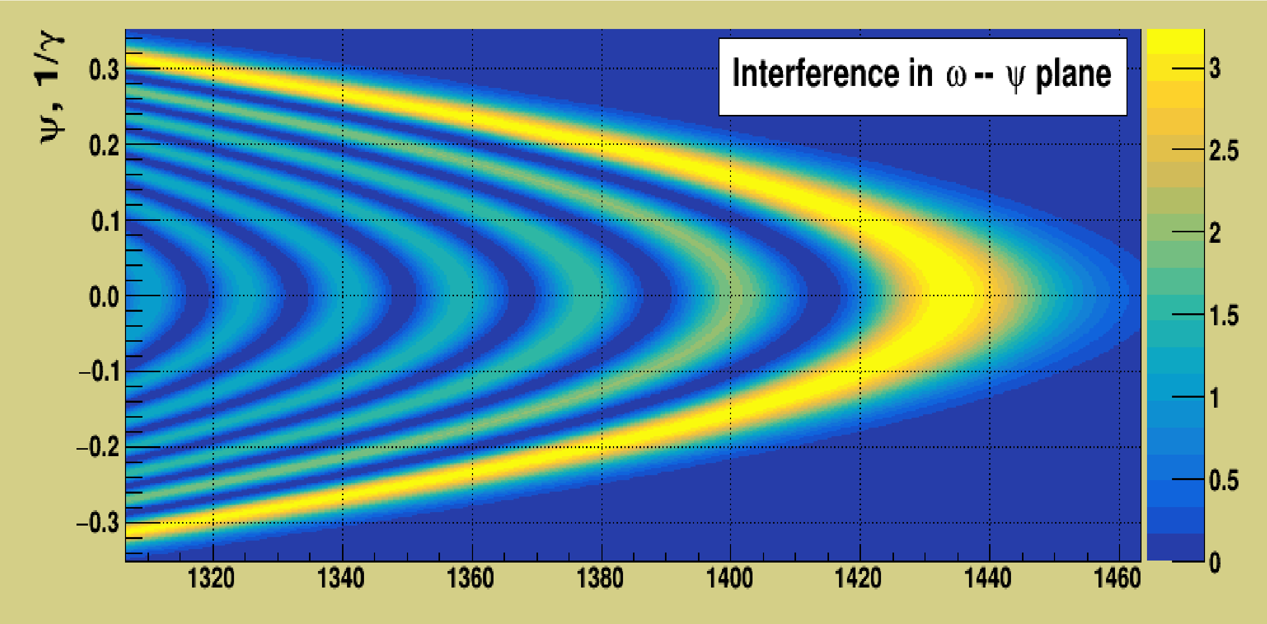
where

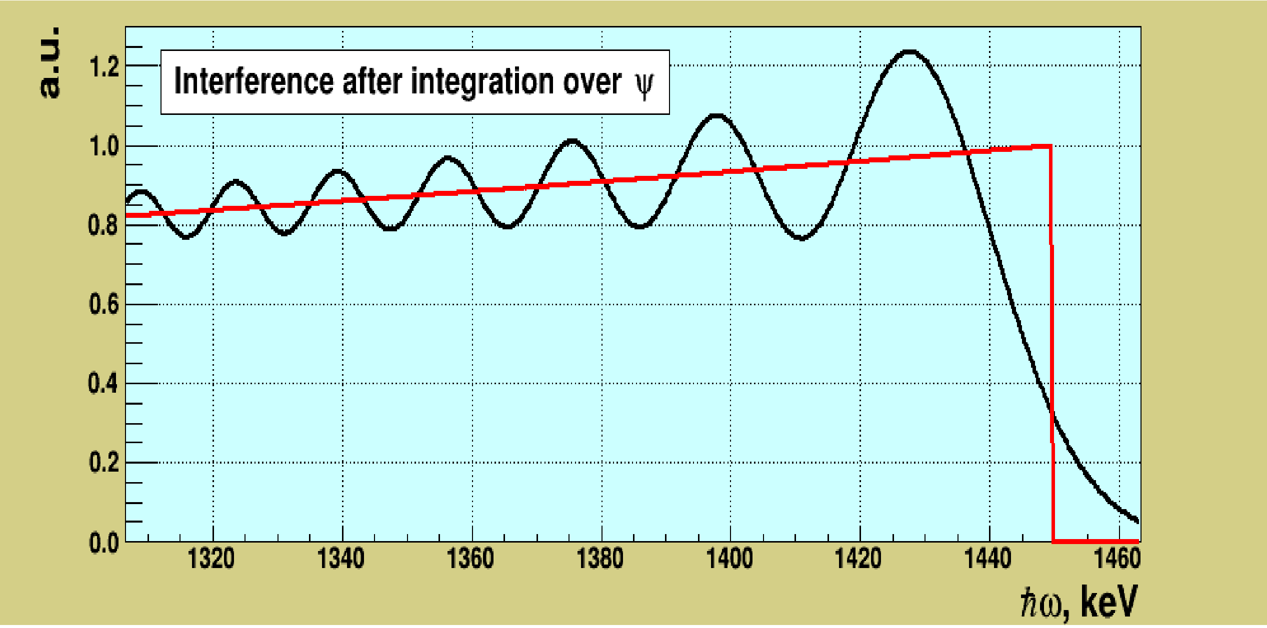
$$x = \left[\frac{\omega R}{2c}\right]^{2/3} \left[\frac{1}{\gamma^2} - \frac{4\omega_0}{\omega} + \psi^2\right]$$

and

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

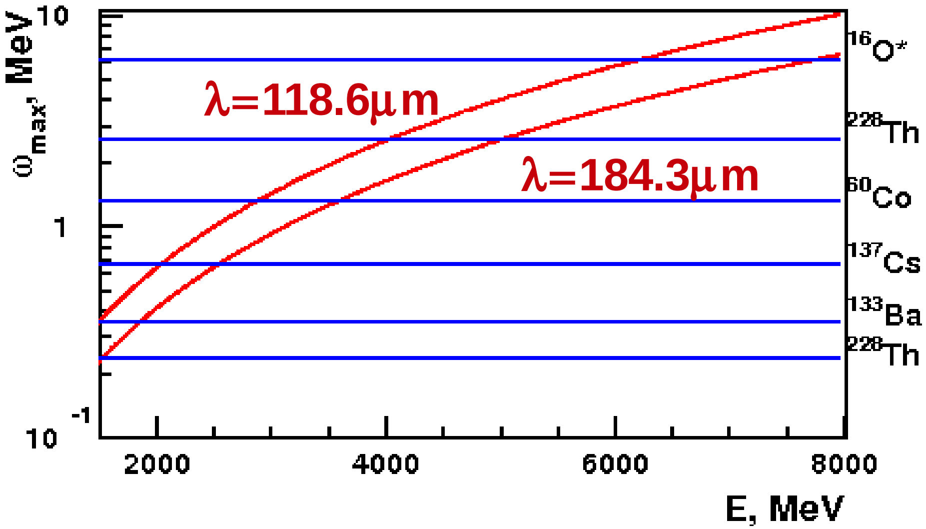
is the Airy function.





ω_0 =0.117 eV, E_e=900 MeV, R=140 cm.

CBS for beam energies above 2 GeV ?



Relation between ω_{max} and E for FIR laser.

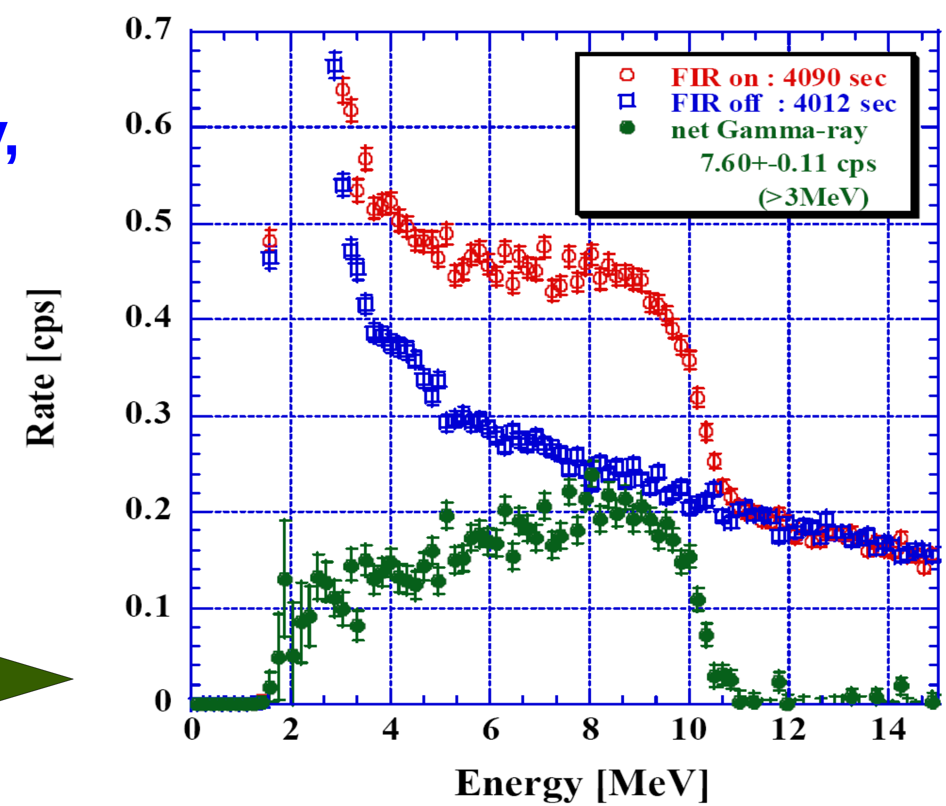
Edinburgh Instruments.

FIRL 100 far infrared output specification

λ(μm)	FIR Molecule	CO_2 pump line	Typical Power
96.5	CH_3OH	9R10	60mW
118.8	CH_3OH	9P36	150mW
184.3	CH_2F_2	9R32	150mW
432.6	HCOOH	9R20	30mW
513.0	HCOOH	9R28	10mW

Spring-8 synchrotron radiation facility, beam energy E=8 GeV. FIR laser 119 μm, P=1W.

Scattered photons energy spectrum measured by LYSO:Ce scintillator.



Conclution.

The RD and CBS methods is precise and effective tools for collider energy beam measuring and monitoring.

The CBS method can be applied for the electron beam energy upto **2 GeV**.

The relative accuracy of the CBS method is **$\delta E/E \approx 10^{-4} - 10^{-5}$**.

The FIR laser can be used for CBS method for the beams with energy **2 – 8 GeV**. Special studies are necessary.