Instrumentation for Colliding Beam Physics (INSTR'20)

Center-of-mass energy calibration in BES-III & VEPP-2000 experiments

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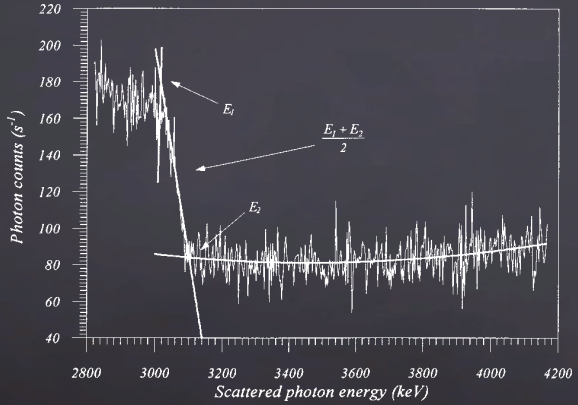
Laser backscattering for beam energy calibration

Taiwan Light Source: 1996
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

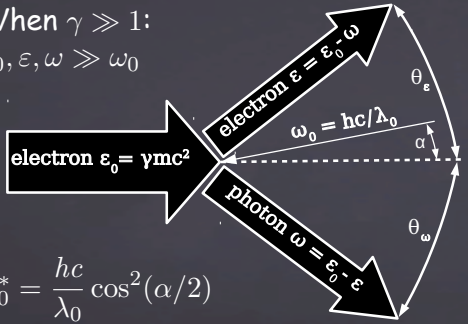
e^+e^- COLLIDERS

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

Inverse Compton Scattering

When $\gamma \gg 1$:

$\varepsilon_0, \varepsilon, \omega \gg \omega_0$



$$\omega_0^* = \frac{hc}{\lambda_0}\cos^2(\alpha/2)$$

Universal scattering parameter:

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

is in the range

$$0 \le u \le \kappa, \text{ where } \kappa = \frac{4\omega_0^* \varepsilon_0}{(mc^2)^2}.$$

$\kappa \simeq 0.0153$ for $\varepsilon_0 = 1$ GeV and $\omega_0^* = 1$ eV

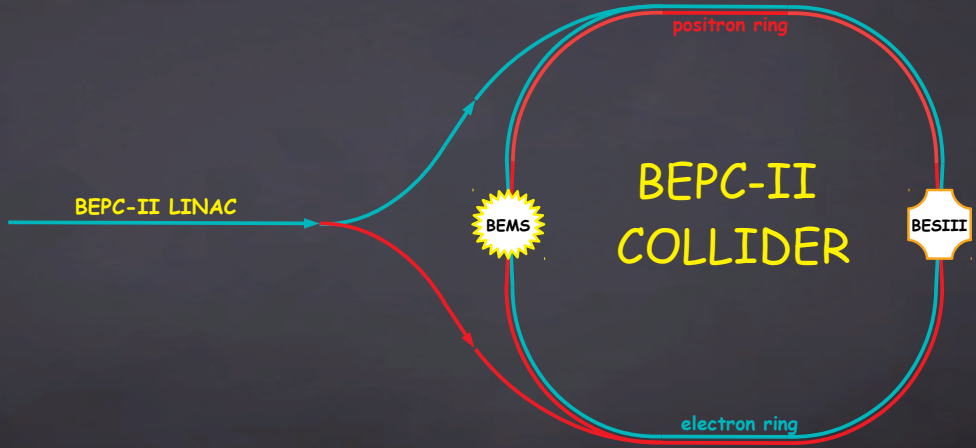
Scattering energies:

$$\max(\omega) = \kappa \cdot \varepsilon_0/(1+\kappa)$$
$$\min(\varepsilon) = \varepsilon_0/(1+\kappa)$$

Scattering angles: $\gamma\theta_\omega = \sqrt{\kappa/u - 1}; \quad \theta_\varepsilon = u\theta_\omega$

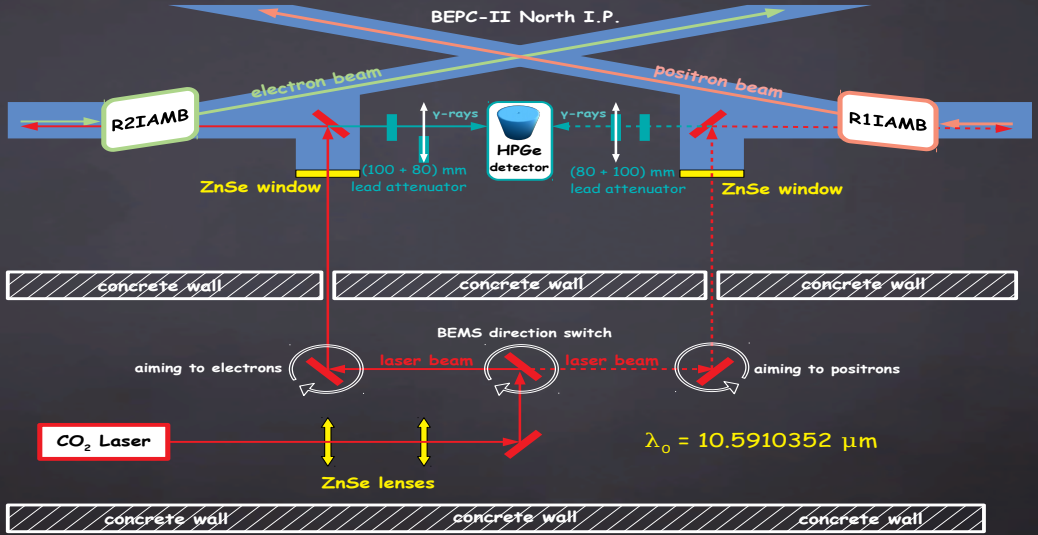
$\max(\theta_\varepsilon) = 2\omega_0^*/mc^2$ ($\simeq 10$ urad for green light).

BEPC-II Collider

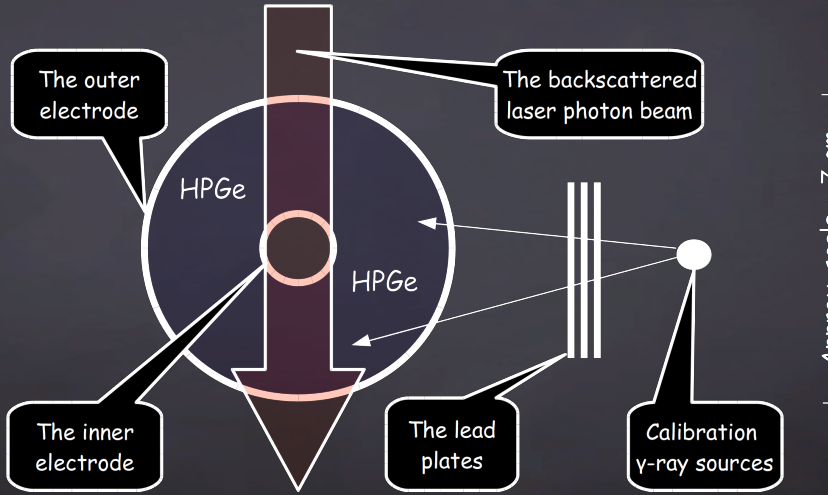


- SR losses: $E_{\text{ip}} = E_{\text{BEMS}} + 4.75 \cdot 10^{-6} \, (E_{\text{BEMS}})^4$ [GeV]
- IP angle: $E_{\text{cm}} = 2\cos(0.011)\sqrt{E_{\text{ip}}^{e^+} \; E_{\text{ip}}^{e^-}}$

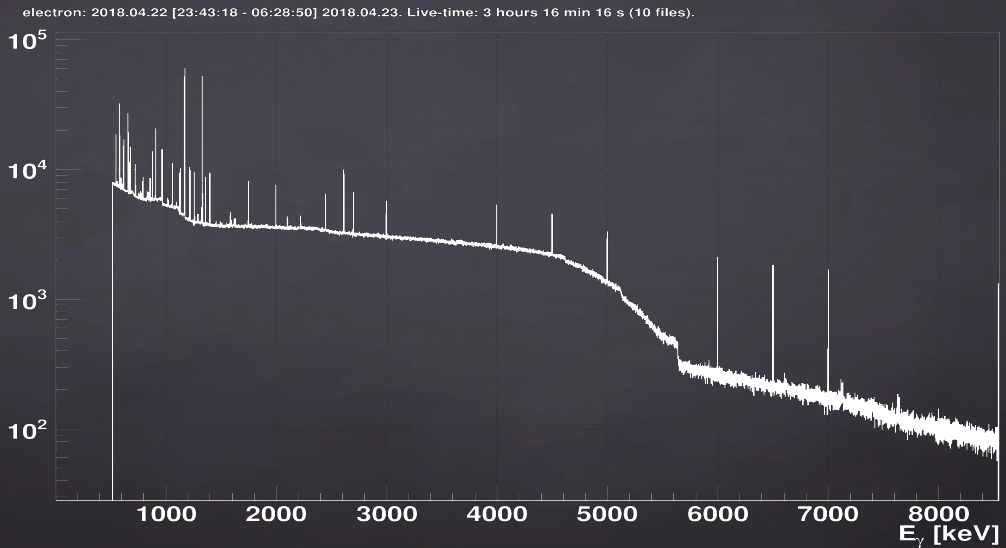
Beam Energy Measurement System



γ-rays detection



γ-rays spectrum example

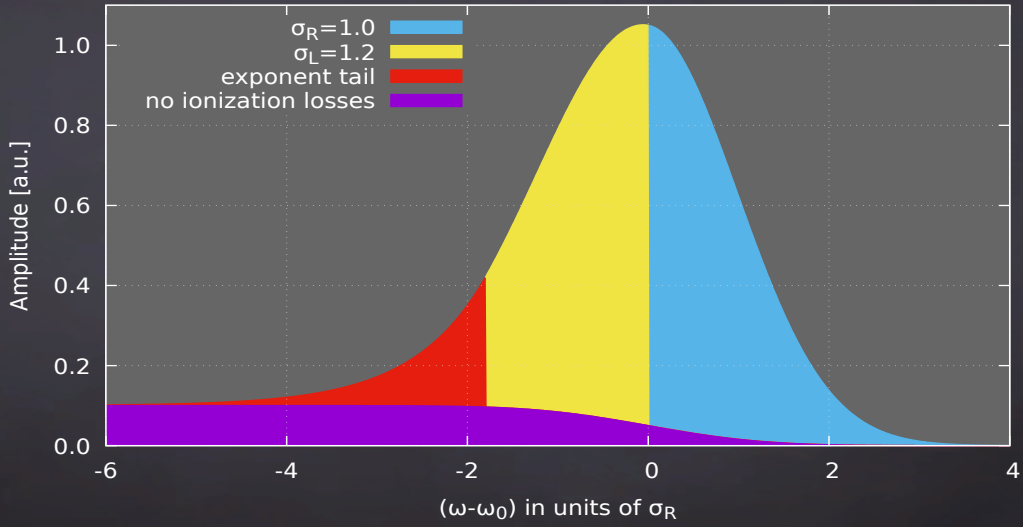


Absolute Scale Calibration

Source	γ-rays energies, keV	Reference *
^{137}Cs	661.657 ± 0.003	vol.4, 2008
^{60}Co	1173.228 ± 0.003 1332.492 ± 0.004	vol.4, 2008
^{228}Ac (^{232}Th)	911.209 ± 0.006	vol.6, 2011
^{212}Bi (^{232}Th)	727.330 ± 0.030 1620.740 ± 0.010	vol.2, 2004
^{208}Tl (^{232}Th)	583.187 ± 0.002 860.560 ± 0.030 2614.511 ± 0.010	vol.2, 2004

* Table of Radionuclides, Bureau International des Poids et Mesures
https://www.bipm.org/en/publications/scientific-output/monographie-ri-5.html

Photopeak Model



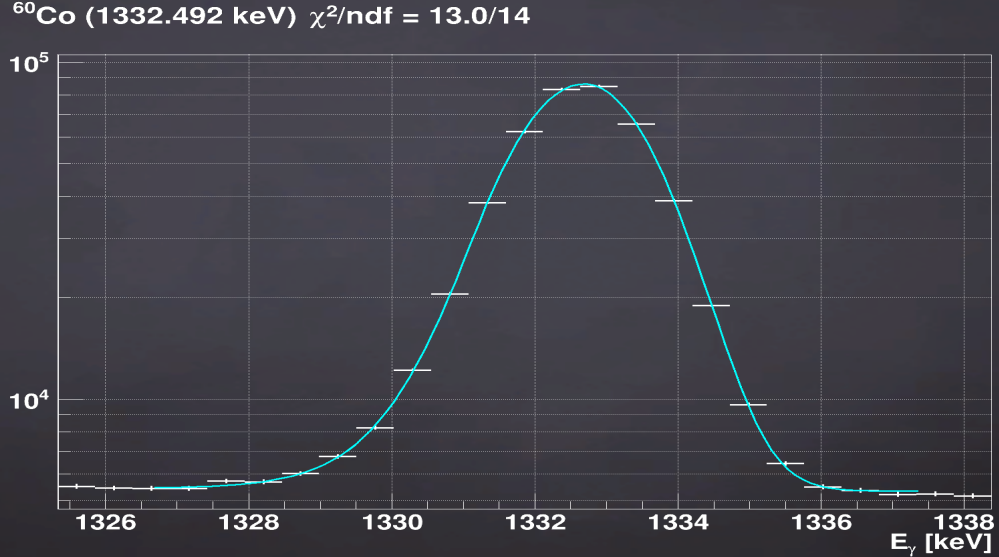
Photopeak Model

$$f(x) = B + \frac{C}{2}\mathrm{erfc}\left(\frac{x}{\sqrt{2}\sigma_R}\right) + \frac{N}{N_1}\begin{cases} \exp\left(-\dfrac{x^2}{2\sigma_R^2}\right) & \text{if } x > 0; \\ \exp\left(-\dfrac{x^2}{2\sigma_L^2}\right) & \text{if } -\kappa\sigma_L < x \leq 0; \\ \exp\left(\dfrac{\kappa x}{\sigma_L} + \dfrac{\kappa^2}{2}\right) & \text{if } x \leq -\kappa\sigma_L \end{cases}$$

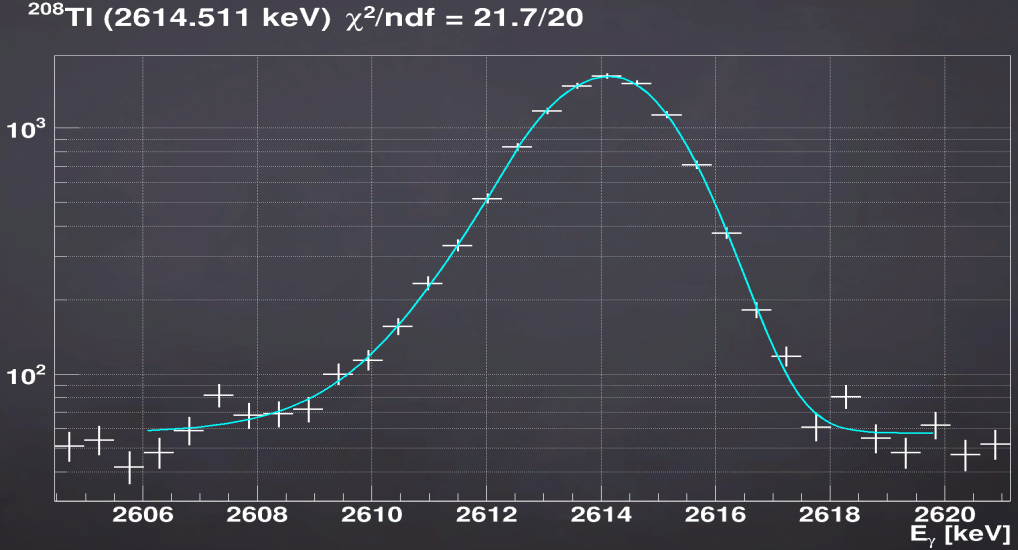
Here $x = (E - E_{\mathsf{max}})$ is the difference between the energy deposition in the detector and its most probable value, B is the background level, N is the number of counts in the photopeak while N_1 is the normalization constant:

$$N_1 = \sqrt{\frac{\pi}{2}}\sigma_R + \left\{\frac{1}{\kappa}\exp\left(-\frac{\kappa^2}{2}\right) + \sqrt{\frac{\pi}{2}}\mathrm{erf}\left(\frac{\kappa}{\sqrt{2}}\right)\right\}\sigma_L$$

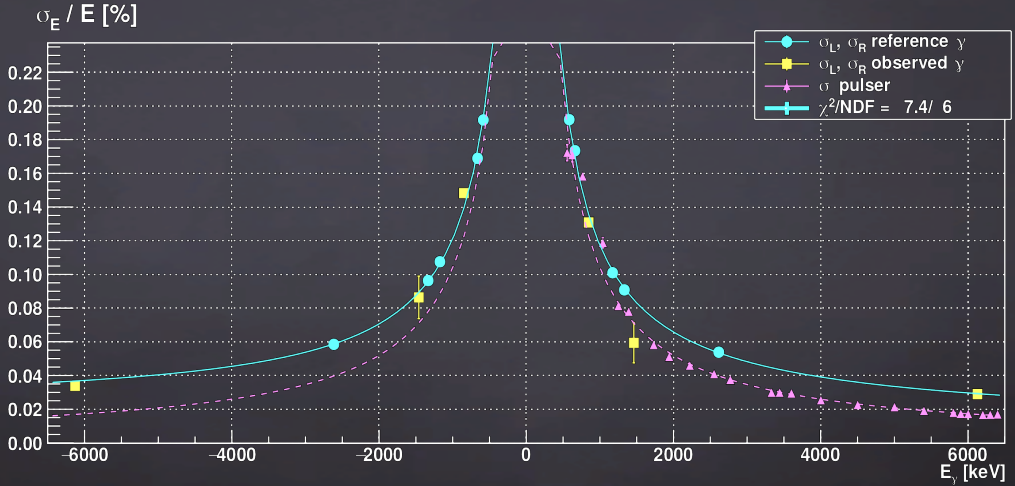
Photopeak Fit Example



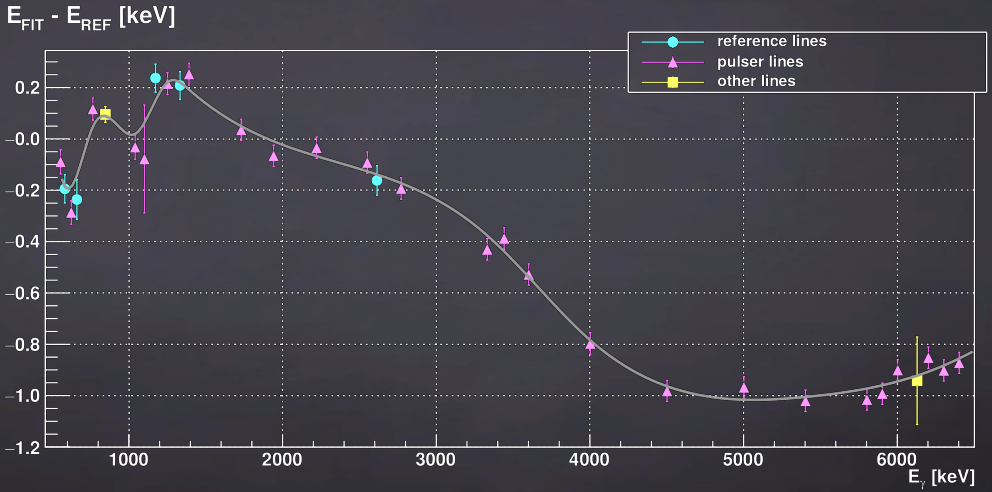
Photopeak Fit Example



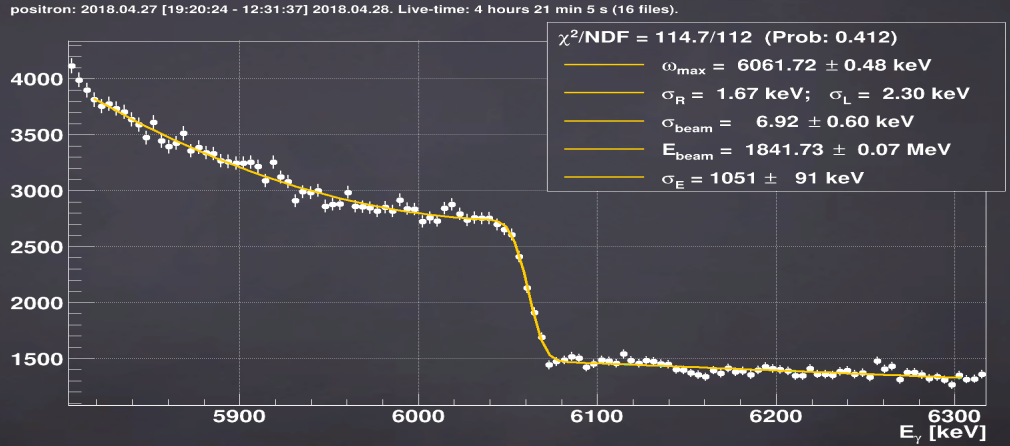
Energy Resolution



Absolute Energy Scale

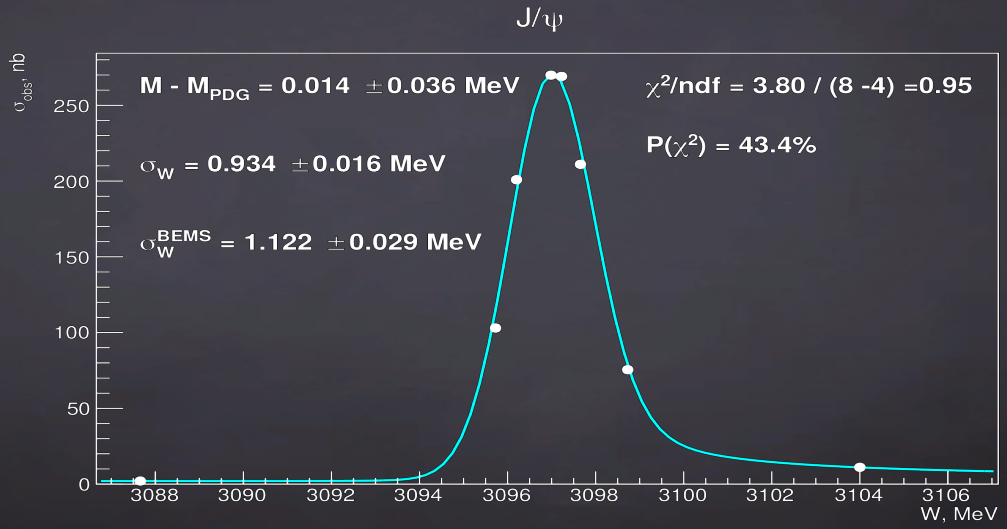


Compton Edge in γ-spectrum

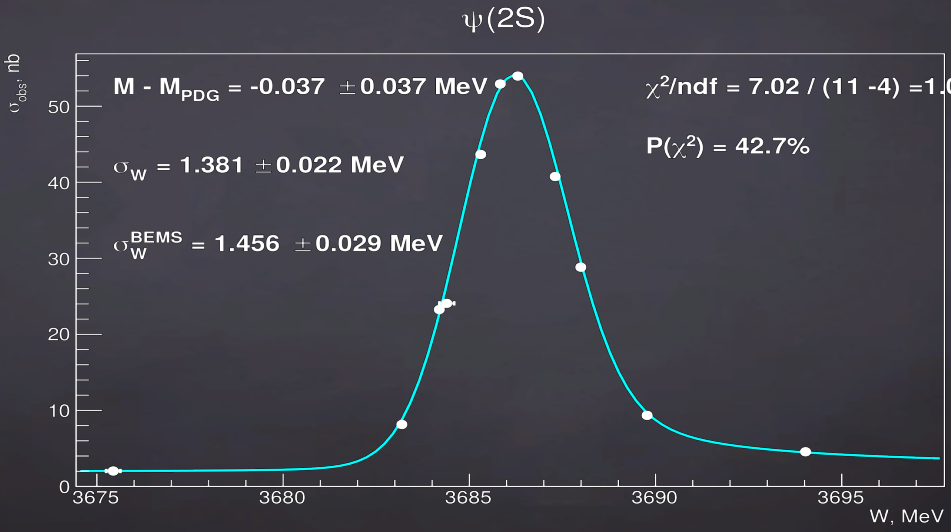


$$E_{\rm beam} = \frac{\omega_{\rm max}}{2}\left(1+\sqrt{1+\frac{m^2}{\omega_0\omega_{\rm max}}}\right), \qquad \omega_0 = 0.11706523\ \text{eV}.$$

BEMS check at J/ψ - 2018

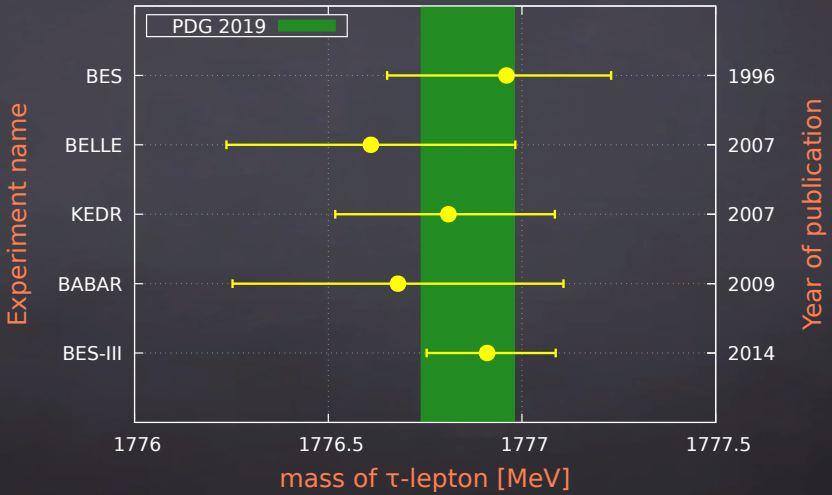


BEMS check at $\psi(2S)$ - 2018

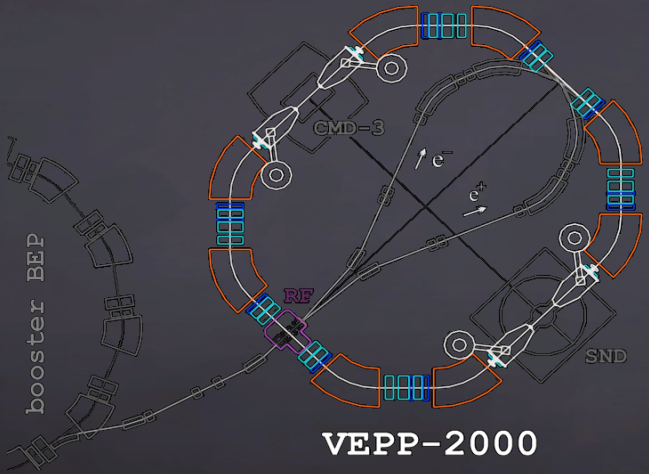


Phys. Rev. D 90, 012001 (2014)

"Precision measurement of the mass of the τ lepton"



VEPP-2000 e^+e^- collider



Circumference:

$$P = 24.4 \text{ m}$$

C. m. s. energy:

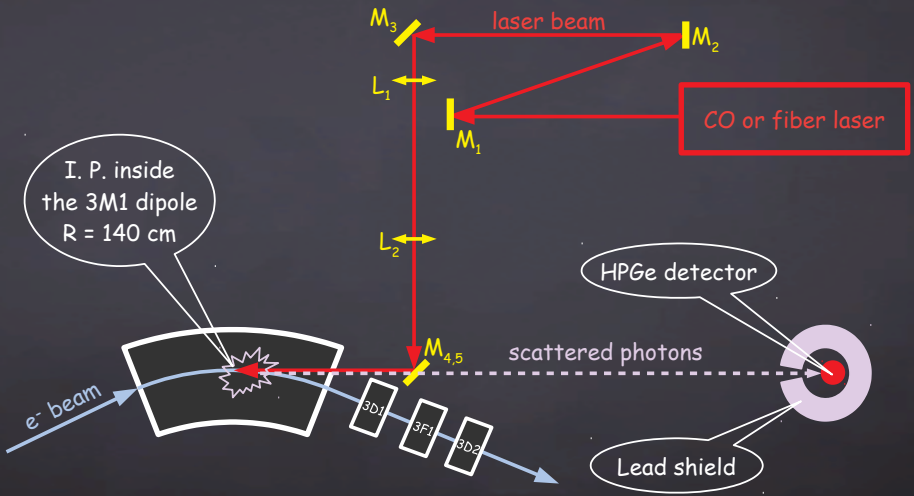
$$E = 200 - 2000 \text{ MeV}$$

Luminosity / i.p.:

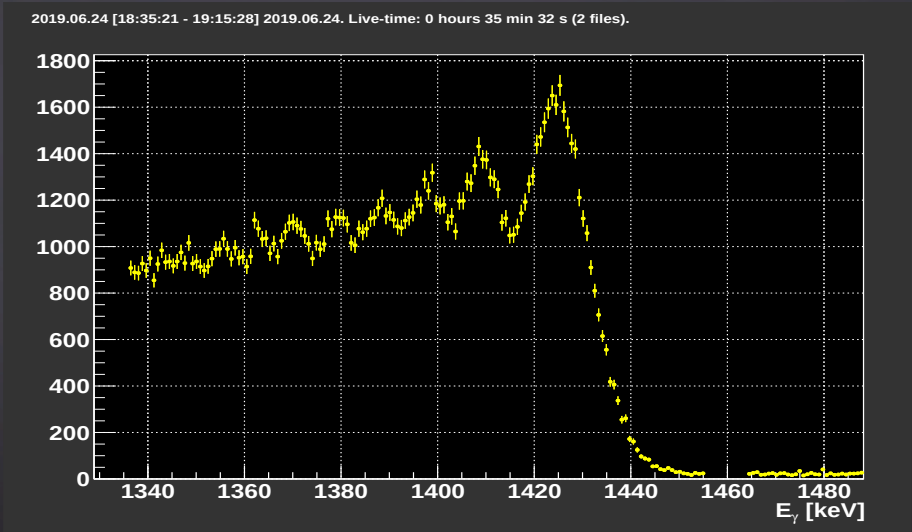
$$L = 10^{32} \text{ cm}^{-2}\text{s}^{-1}$$

Could not find a free straight section for laser i.p.!

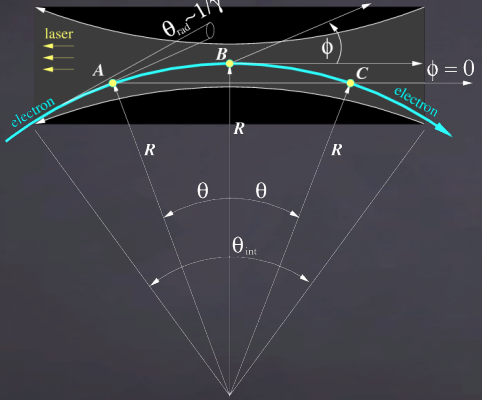
VEPP-2000 BEMS



Spectrum $\varepsilon_0 = 640$ MeV, $\lambda_0 = 5.426463$ um



Interference



$\theta_{int} \gg \theta_{rad}$: take only $\phi = 0$

Time for electron $A \to B \to C$: $t_e = \dfrac{2R\theta}{\beta c}$

Time for photon $A \to C$: $t_\gamma = \dfrac{2R\sin\theta}{c}\cos\psi$

Phase advance: $\Delta\Phi = 2\pi c\left[\dfrac{t_e}{\lambda} - \dfrac{t_\gamma}{\lambda} - \dfrac{2t_e}{\lambda_0}\right]$

λ_0 – laser wavelength. Since $\theta, \psi, 1/\gamma \ll 1$

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

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

Energy spectrum

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

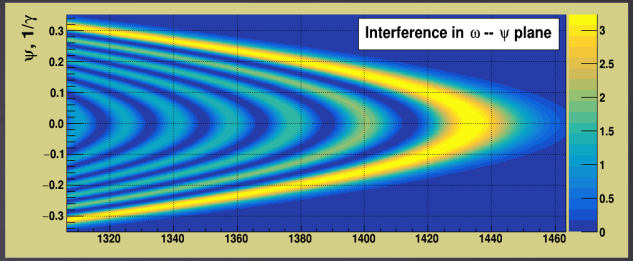
$$x = \left[\frac{\omega R}{2\hbar c}\right]^{2/3}\left[\frac{1}{\gamma^2} - \frac{4\omega_0}{\omega} + \psi^2\right].$$

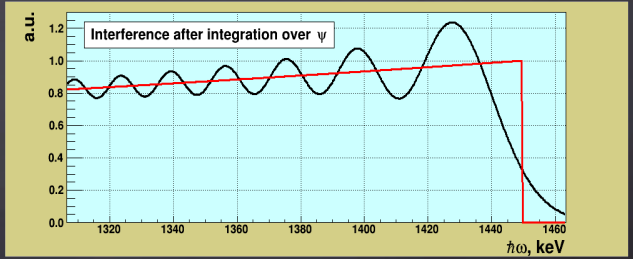
$$\frac{d\sigma}{d\omega} = \frac{d\sigma_{KN}}{d\omega}\int_z^\infty \mathrm{Ai}(x)\,dx,\ \text{where}$$

$$z = (u/\chi)^{2/3}(1-\kappa/u),\ \text{where}$$

$$\chi = \gamma\frac{B}{B_c},\ u = \frac{\omega}{\varepsilon_0 - \omega},\ \kappa = 4\frac{\varepsilon_0\omega_0}{m^2c^4}$$

$$B_c = \frac{m^2c^2}{\hbar e} = 4.414\cdot 10^9\ \text{[T]}$$

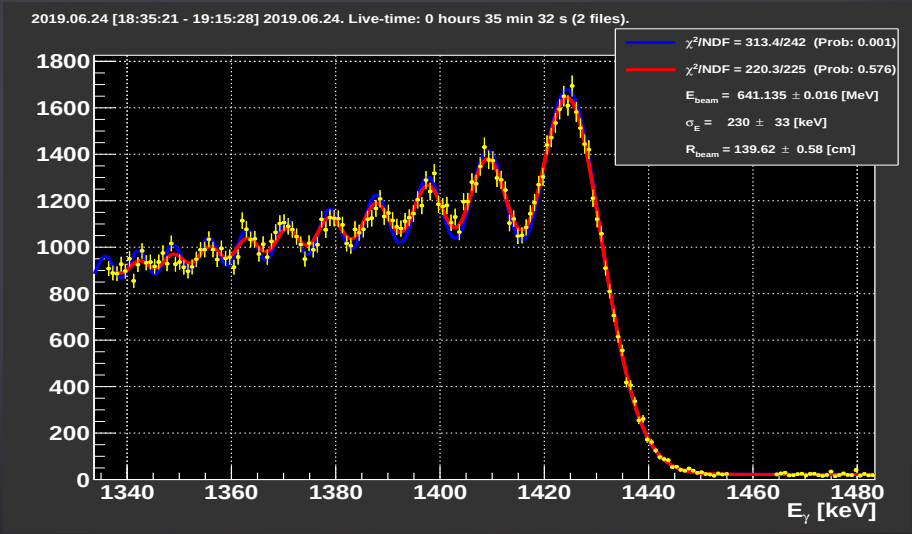




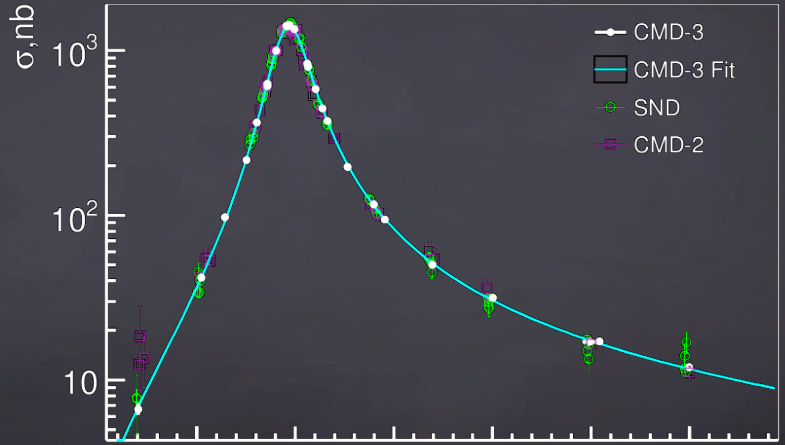
$\omega_0 = 0.117$ eV; $\varepsilon_0 = 900$ MeV; $R = 140$ cm

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

The Fit Result



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



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

Summary

- Laser back-scattering is applied for c. m. s. energy calibration on two lepton colliders – BEPC-II and VEPP-2000.
- Center-of-mass energy was calibrated with accuracy $\gtrsim$ 30 keV in the energy range from 360 MeV to 3700 MeV.
- The new τ-lepton mass measurement was performed in 2018 by BES-III detector. The new result is expected to arrive this year.

Thank You!