Compton Backscattering for Energy Calibration

Nickolai Muchnoi,
Budker INP, Novosibirsk

2019 Joint Workshop on Future charm-tau Factory

C. M. S. energy determination in the τ-lepton threshold scan experiment

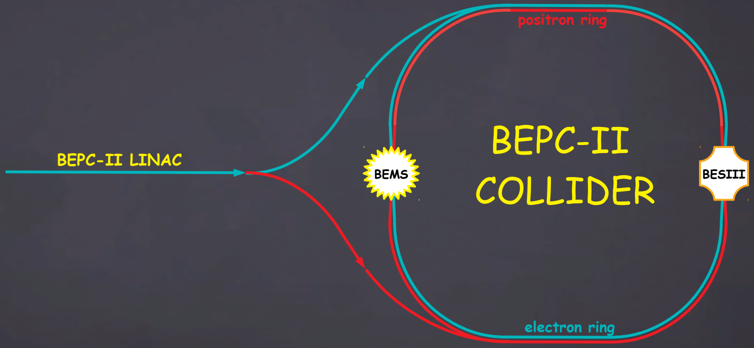
Nickolai Muchnoi (Budker INP)
on behalf of the BEMS group

September 21, 2019

Intro

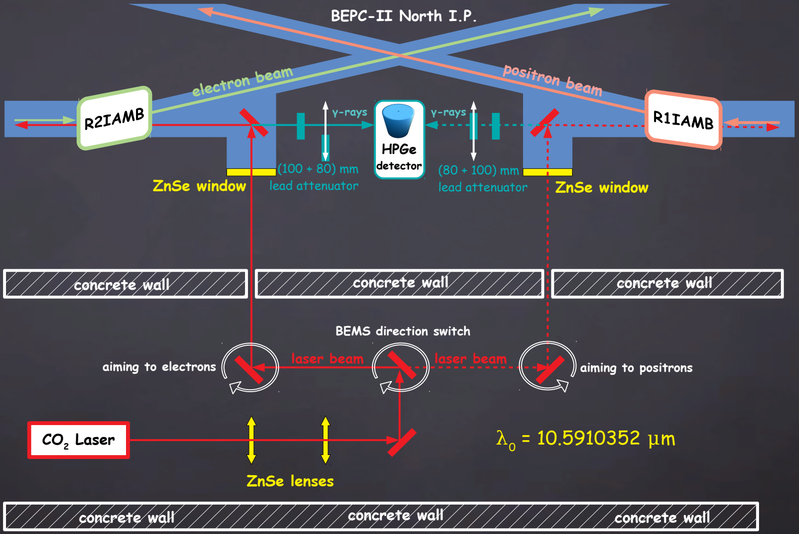
- BEPC-II collider has the Beam Energy Measurement System (BEMS) since 2010.
- In April 2018 the τ threshold scan experiment was performed in order to improve the accuracy of τ-lepton mass knowledge.
- BEMS allows to measure the average $e^{\pm}$ collision energy and beam energy spread while BES-III detector measures the cross sections.

BEPC-II Collider

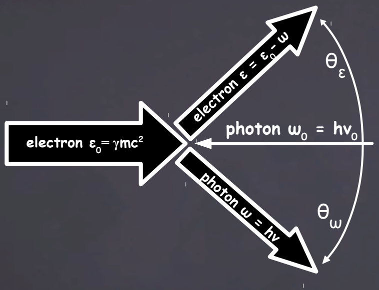


- SR losses: $E_{\text{ip}} = E_{\text{BEMS}} + 4.75 \cdot 10^{-6} \left(E_{\text{BEMS}}\right)^4$ [GeV]
- IP angle: $E_{\text{cm}} = 2\cos(0.011)\sqrt{E_{\text{ip}}^{e^+} \; E_{\text{ip}}^{e^-}}$

Beam Energy Measurement System



Inverse Compton Scattering



If $\gamma \gg 1$: $\varepsilon_0, \varepsilon, \omega \gg \omega_0$

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

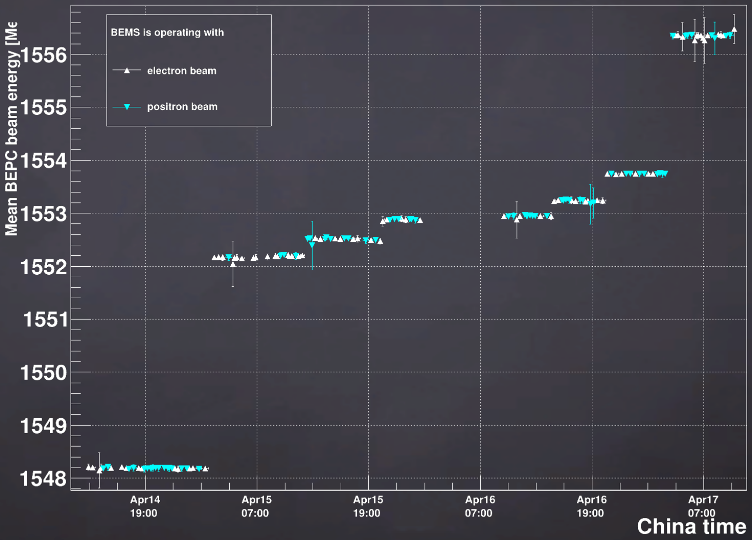
$$u \in [0, \kappa] \text{, where } \kappa = \frac{4\omega_0\varepsilon_0}{(mc^2)^2}$$

If $\omega_0 = 1$ eV & $\varepsilon_0 = 1$ GeV:

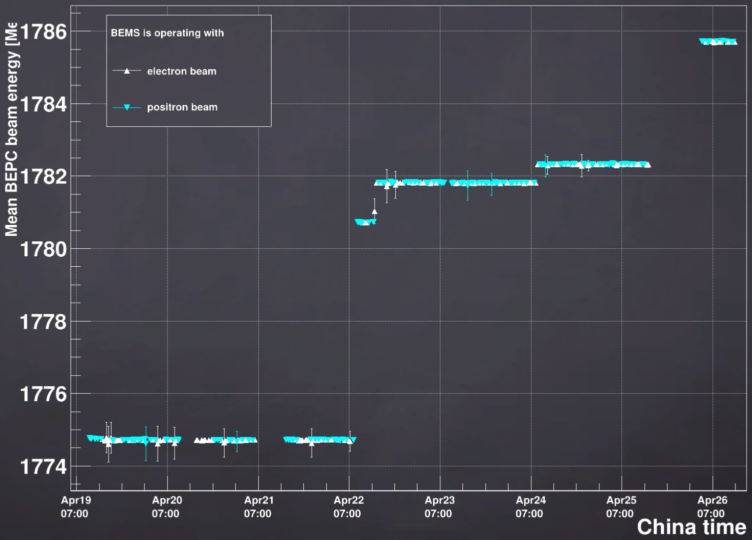
$$\kappa \simeq 0.0153$$

$$\omega_{max} = \frac{\varepsilon_0 \kappa}{1+\kappa}, \text{ hence } \varepsilon_0 = \frac{\omega_{max}}{2}\left[1 + \sqrt{1 + \frac{(mc^2)^2}{\omega_0 \omega_{max}}}\right]$$

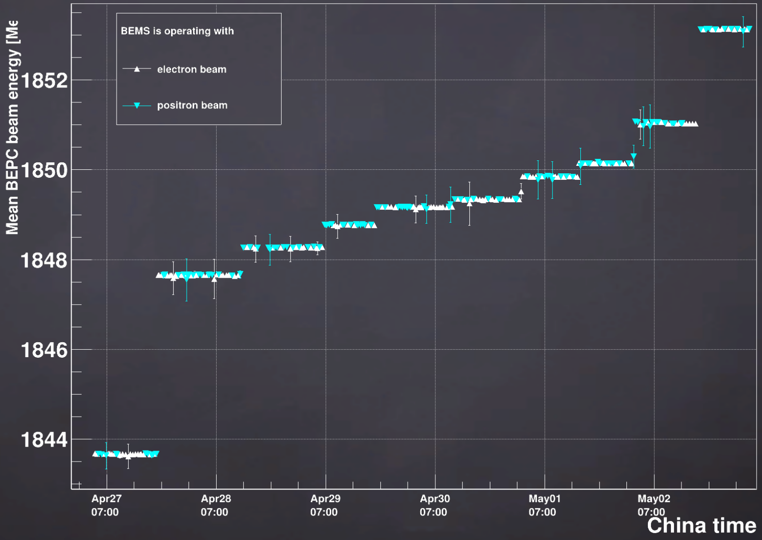
Scan of J/ψ (2018)



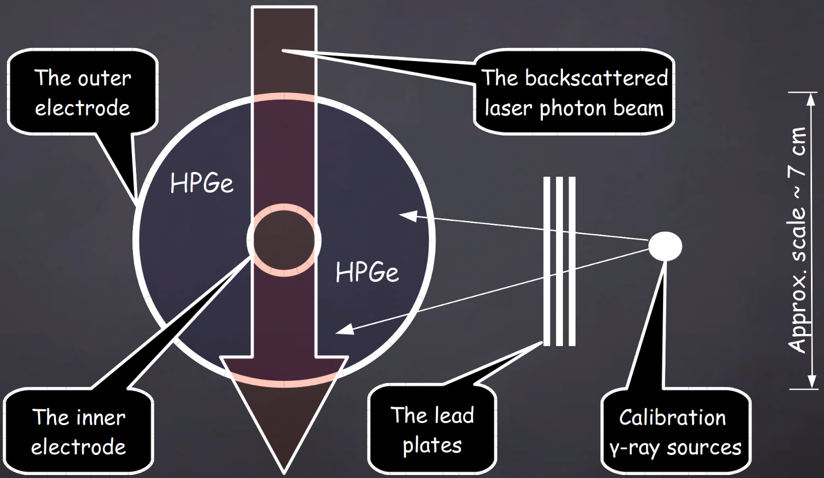
Scan of τ-threshold (2018)



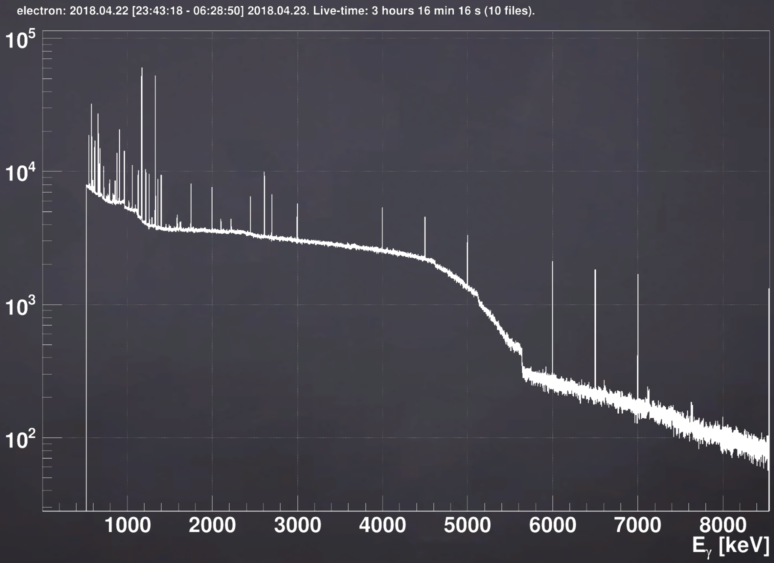
Scan of $\psi(2S)$ (2018)



γ-rays detection



γ-rays spectrum example

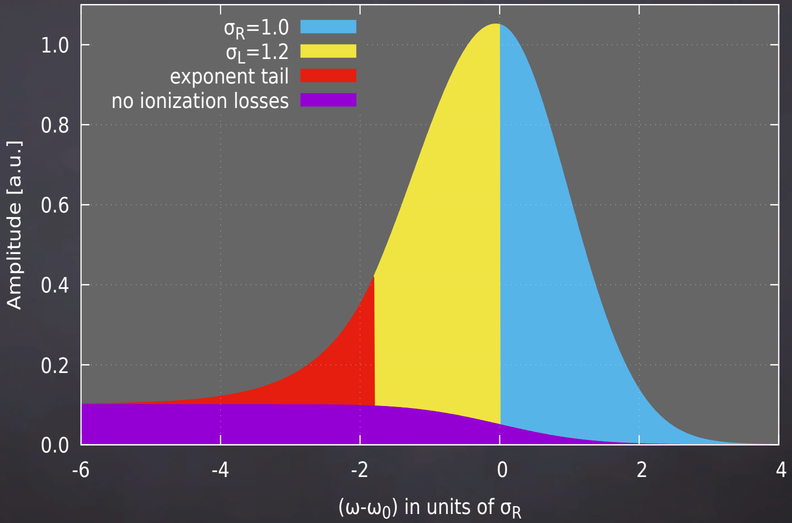


HPGe Scale Calibration

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

HPGe Photopeak Model



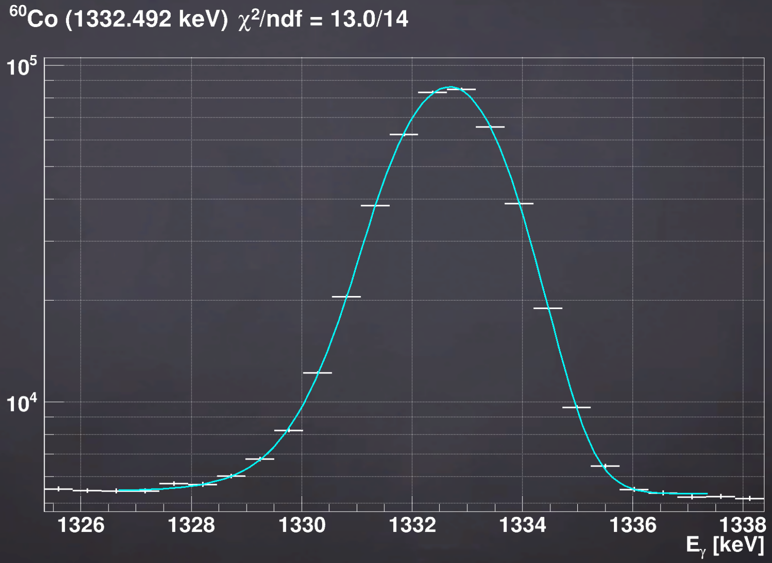
HPGe Photopeak Model (new)

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

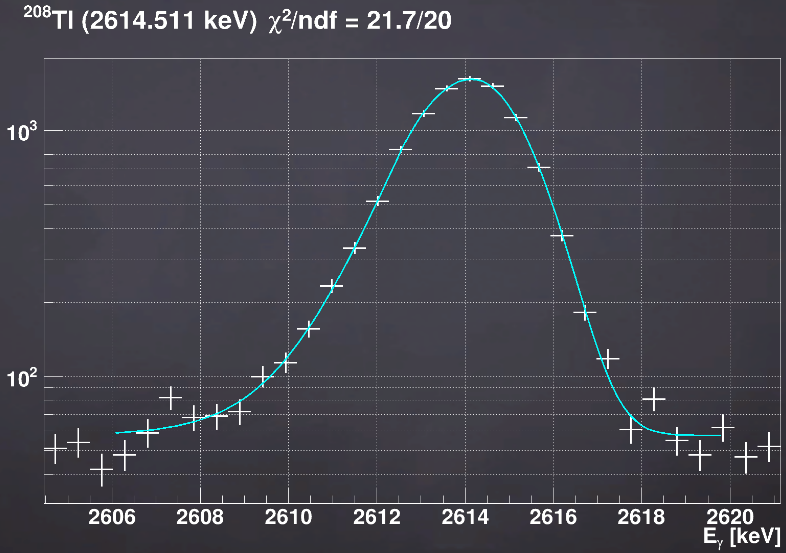
Here $x = (E - E_{\text{max}})$ is the difference between the energy deposition in the detector and its most probable value, B is the background level, N is the number of counts in the photopeak while N_1 is the normalization constant:

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

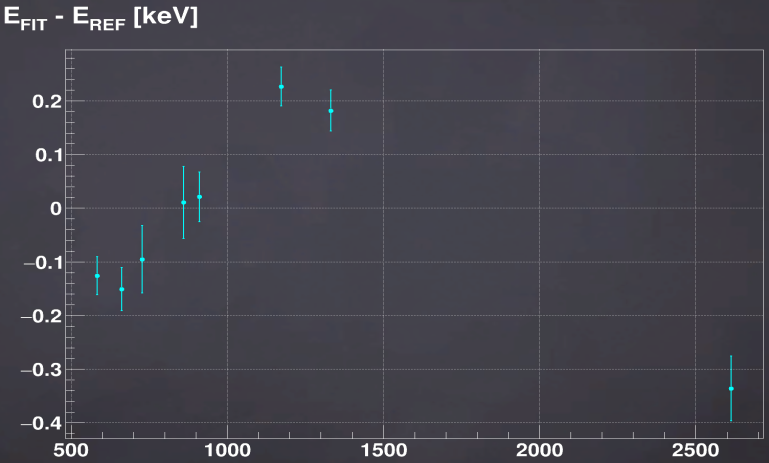
HPGe Photopeak Fit



HPGe Photopeak Fit



Absolute Energy Scale: γ-lines



Syst. error is: $\frac{|\Delta E_\gamma|}{E_\gamma} \simeq \frac{1\ \text{keV}}{6000\ \text{keV}} \simeq 200\ \text{ppm}$

Check of electronics

Multichannel Analyzer:
preamp & ADC
ORTEC® DSPEC Pro™:

integral nonlinearity:
±250 ppm

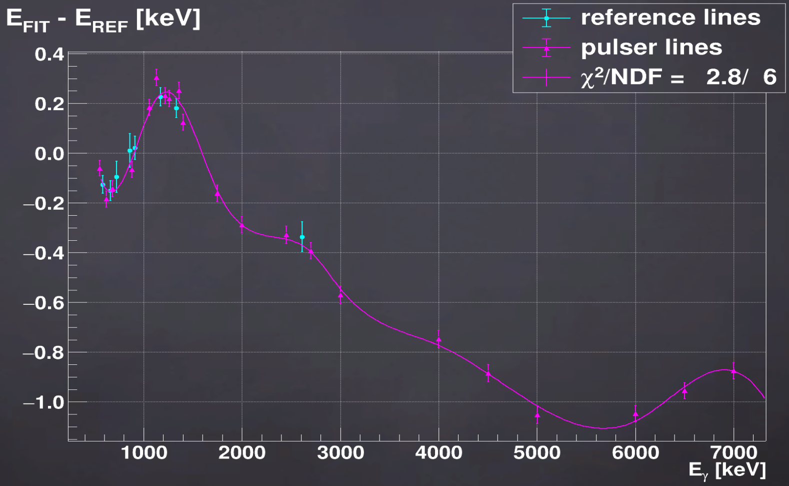
(www.ortec-online.com)

Precision Pulse
Generator (PPG)
Berkeley Nucleonics
Corp PB-5

amplitude nonlinearity
±15 ppm

(www.berkeleynucleonics.com)

Curved Ruler Approach



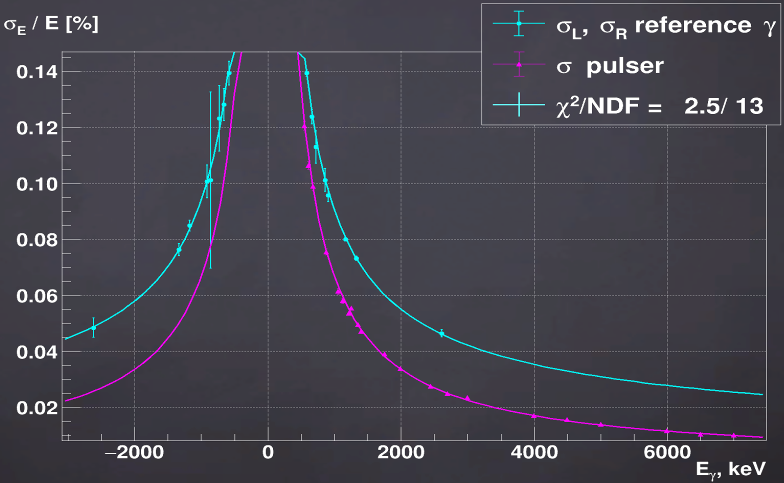
HPGe Energy Resolution

Combined fit for σ_R and σ_L dependence on E_γ:

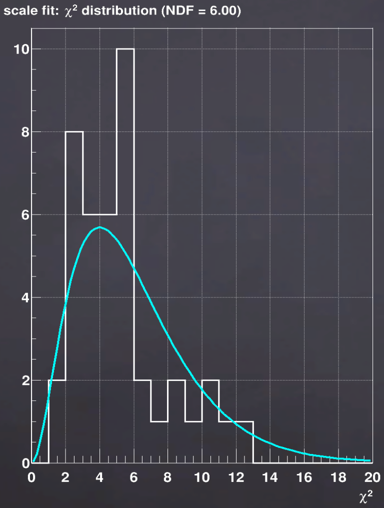
$$\sigma_R = \sqrt{p_0^2 + \epsilon f_R E_\gamma}$$
$$\sigma_L = \sqrt{p_0^2 + \epsilon f_L E_\gamma}$$

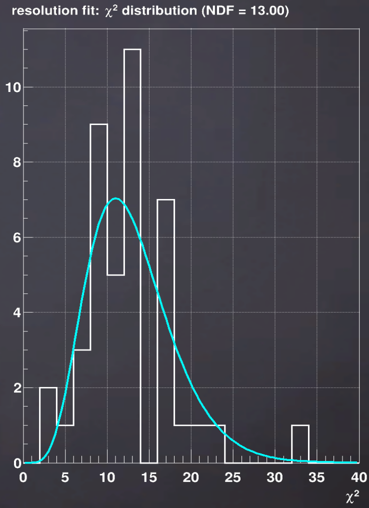
- σ_R and σ_L are in [keV],
- p_0 is the noise impact to the resolution,
- $\epsilon =$2.96 eV is the e-hole pair creation energy in Ge,
- f_R, f_L - dimensionless parameters (Fano factor).

HPGe energy resolution

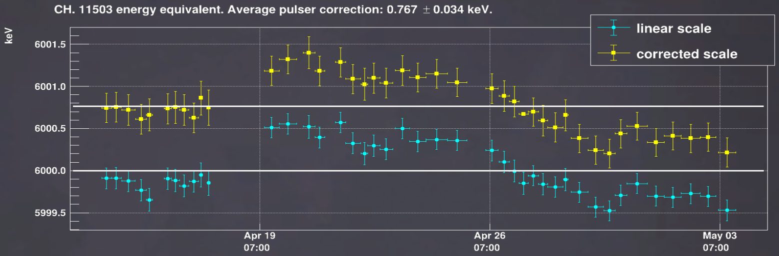


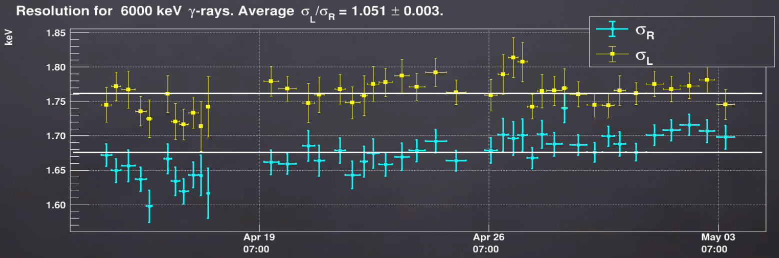
Scale & resolution: 42 energy points



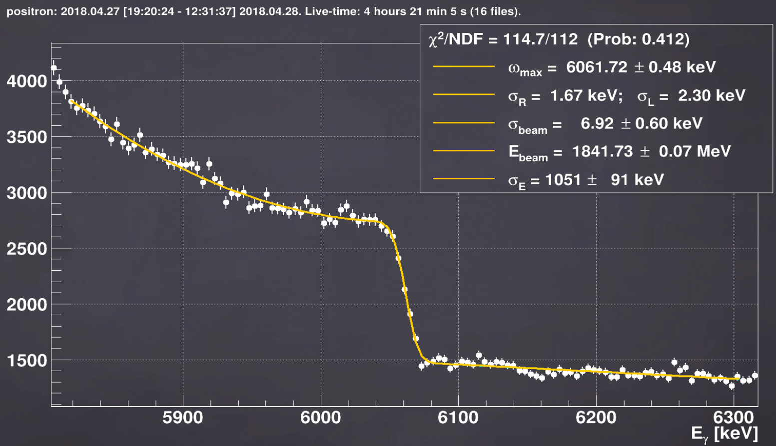


Scale & resolution: 42 energy points





Compton Edge in γ-spectrum



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

Beam spread & HPGe resolution

Beam energy spread (gaussian) blurs the edge:

$$\omega_{max} = E\frac{\kappa}{1+\kappa} \quad \Longrightarrow \quad \sigma_\omega(\omega_{max}) = \frac{(2+\kappa)\kappa}{(1+\kappa)^2}\sigma_E.$$

The joint effect of beam spread σ_ω and HPGe σ_R, σ_L:

$$S(x) = \frac{\exp\left(\frac{-x^2/2}{\sigma_R^2+\sigma_\omega^2}\right)\operatorname{erfc}\left(\frac{-x\sigma_R/\sigma_\omega}{\sqrt{2(\sigma_R^2+\sigma_\omega^2)}}\right)}{(1+\sigma_L/\sigma_R)\sqrt{2\pi(\sigma_R^2+\sigma_\omega^2)}} +$$

$$+\frac{\exp\left(\frac{-x^2/2}{\sigma_L^2+\sigma_\omega^2}\right)\operatorname{erfc}\left(\frac{x\sigma_L/\sigma_\omega}{\sqrt{2(\sigma_L^2+\sigma_\omega^2)}}\right)}{(1+\sigma_R/\sigma_L)\sqrt{2\pi(\sigma_L^2+\sigma_\omega^2)}},$$

where $x = E_\gamma - \omega_{max}(E_0)$ and E_0 is the mean electron energy.

The Edge

The pure edge without blurs:

$$F(x) = A(1 + A'x + A''x^2)\int_x^{\infty}\delta(y)\,dy + B(1 + B'x),$$

The fit function is obtained by the convolution:

$$N(x) = F(x) * S(x)$$

J/ψ

ENERGY POINT No	t [s]	dt [s]	E [MeV]	dE stat [MeV]	dE cal [MeV]	W [MeV]	dW [MeV]
1 (1548.200 MeV)	1523696074	11176	3087.356	0.178	0.021	1.204	0.165
1 (1548.200 MeV)	1523719423	12139	3087.659	0.094	0.021	1.312	0.090
2 (1552.169 MeV)	1523751209	17528	3095.726	0.077	0.018	1.058	0.075
3 (1552.509 MeV)	1523784134	14521	3096.203	0.069	0.021	1.132	0.068
4 (1552.847 MeV)	1523806307	7620	3096.986	0.083	0.023	1.009	0.107
5 (1552.948 MeV)	1523854993	9368	3097.226	0.099	0.021	1.270	0.094
6 (1553.231 MeV)	1523875207	10187	3097.654	0.082	0.023	1.047	0.074
7 (1553.741 MeV)	1523897336	11604	3098.728	0.078	0.022	1.183	0.080
8 (1556.346 MeV)	1523922760	12486	3104.000	0.082	0.019	1.010	0.080

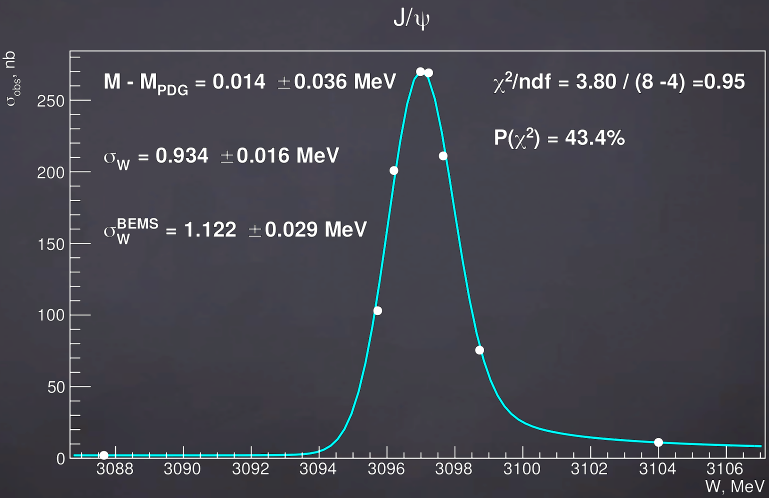
τ threshold

ENERGY POINT No	t [s]	dt [s]	E [MeV]	dE stat [MeV]	dE cal [MeV]	W [MeV]	dW [MeV]
9 (1774.760 MeV)	1524127512	19464	3538.988	0.215	0.026	1.123	0.202
9 (1774.760 MeV)	1524170172	23174	3538.763	0.094	0.025	1.307	0.088
10 (1774.705 MeV)	1524225406	15384	3538.421	0.142	0.028	1.437	0.133
10 (1774.705 MeV)	1524253662	12867	3538.664	0.108	0.026	1.271	0.116
11 (1774.712 MeV)	1524308179	13376	3539.420	0.291	0.025	1.573	0.259
11 (1774.712 MeV)	1524341140	19579	3539.356	0.114	0.025	1.673	0.120
12 (1780.724 MeV)	1524371452	8548	3550.828	0.164	0.028	1.142	0.188
13 (1781.819 MeV)	1524395909	15723	3552.769	0.129	0.026	1.384	0.134
13 (1781.819 MeV)	1524428709	17073	3552.929	0.117	0.026	1.355	0.131
14 (1781.791 MeV)	1524471188	18801	3552.717	0.119	0.026	1.742	0.113
14 (1781.791 MeV)	1524511367	21374	3552.823	0.127	0.025	1.706	0.137
15 (1782.328 MeV)	1524561024	27764	3553.893	0.092	0.025	1.452	0.089
15 (1782.328 MeV)	1524614438	25644	3553.901	0.115	0.025	1.476	0.126
16 (1785.711 MeV)	1524706348	16120	3560.285	0.150	0.026	1.287	0.152

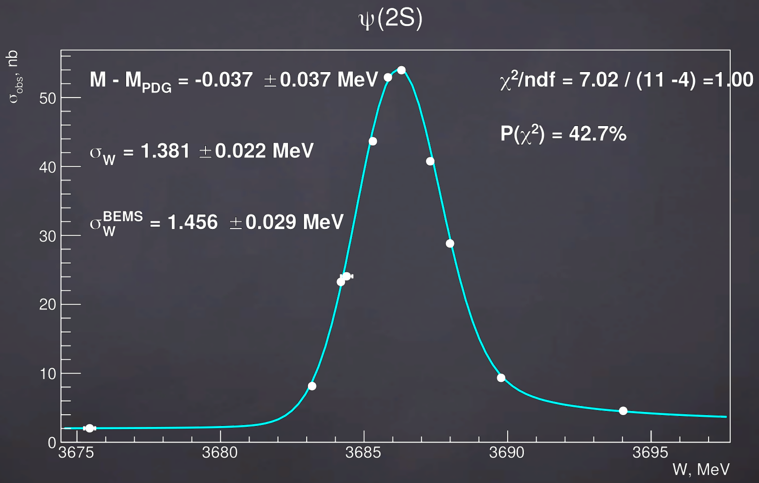
$\psi(2S)$

ENERGY POINT No	t [s]	dt [s]	E [MeV]	dE stat [MeV]	dE cal [MeV]	W [MeV]	dW [MeV]
17 (1805.470 MeV)	1524738149	13656	3599.575	0.176	0.027	1.725	0.176
17 (1805.470 MeV)	1524764871	12837	3599.473	0.143	0.027	1.372	0.150
18 (1843.674 MeV)	1524789411	11570	3675.268	0.162	0.028	1.471	0.173
18 (1843.674 MeV)	1524814425	13413	3675.651	0.178	0.026	1.609	0.173
19 (1847.650 MeV)	1524840424	12552	3683.295	0.161	0.028	1.487	0.173
19 (1847.650 MeV)	1524873344	20152	3683.137	0.120	0.027	1.542	0.109
20 (1848.261 MeV)	1524900284	6598	3684.393	0.201	0.029	1.742	0.202
21 (1848.260 MeV)	1524936436	21726	3684.193	0.115	0.026	1.410	0.111
22 (1848.774 MeV)	1524979166	20405	3685.306	0.115	0.026	1.199	0.102
23 (1849.157 MeV)	1525015037	15006	3685.809	0.131	0.026	1.441	0.127
23 (1849.157 MeV)	1525045335	15161	3685.860	0.139	0.027	1.430	0.132
24 (1849.341 MeV)	1525087690	26962	3686.302	0.096	0.026	1.477	0.091
25 (1849.846 MeV)	1525137105	22384	3687.305	0.096	0.026	1.465	0.094
26 (1850.151 MeV)	1525181580	22059	3687.993	0.096	0.026	1.369	0.090
27 (1851.070 MeV)	1525228563	24702	3689.773	0.098	0.026	1.575	0.090
28 (1853.122 MeV)	1525274805	20073	3694.027	0.098	0.026	1.367	0.099
29 (1806.125 MeV)	1525323570	22772	3601.385	0.110	0.026	1.479	0.110

BEMS check at J/ψ



BEMS check at $\psi(2S)$



Summary

- Reanalysis of BEMS data has been done for the 2018 τ-threshold scan.
- The BEMS accuracy for the average C.M.S. energy were checked by comparison of J/ψ and $\psi(2S)$ masses with their PDG values.
- The BEMS impact to τ-mass determination accuracy is estimated as 20 keV.
- The σ_W^{BEMS} is $\simeq$10% higher than the value obtained from resonances widths. Most likely beam energy distribution averaged over luminosity (BES-III) is not equal to that averaged over time (BEMS).

Future use of Lessons Learned

- Use separate systems for each ring.
- Keep HPGe away from RF system, collimators, positron source, etc.
- Laser backscattering should occure in short straight sections or even in dipoles.