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Experimental Measurement of the Mass of the τ Lepton at the Beijing Electron Positron Collider (BEPC)

BES Collaboration

The τ lepton mass was measured with the data taken by the Beijing spectrometer (BES) at the BEPC at the Institute of High Energy Physics in Beijing. Approximately 5000 nb^{-1} integrated luminosity was accumulated. Pairs of τ lepton produced near the threshold have been studied in eμ final states. The maximum likelihood method was used for both of predicting a sequence of experimental energies to approach the threshold and data fitting. The measurement yields the τ mass of $1776.9^{+0.4}_{-0.5} \pm 0.2$ MeV.

1. INTRODUCTION

Since the heavy lepton-τ was found at SPEAR in 1975, the mass of τ has been measured by four experimental groups: DASP, DELCO, SPEC, and MARKII, with DELCO giving the most accurate results. DELCO did a scan at 17 energy points with center-of-mass energy ranging from 3.1 to 7.4 GeV, counted the number of τ pair events tagged by e^+e^- eX (X is an charged particle except to electron) process, and measured the R value, where $R = \sigma(e^+e^- \to \tau^+\tau^-)/\sigma(e^+e^- \to \mu^-\mu^-)$ for each energy point. A fitting of the above-measured R value to the theoretical formula of production cross section yielded the mass of the τ lepton $M_\tau = 1783^{+3}_{-4}$ MeV. The results of the other three groups were consistent with DELCO but contained greater errors. The world average value given by averaging over the results of the four groups was $1784^{+2.7}_{-3.6}$ MeV [1].

In recent years, greater interest has paid to τ mass measurement because the e-μ-τ universality faced a new challenge. Under the theory of standard model, if e, μ, τ are sequential leptons, which have the same couplings to the weak current; i.e., $G_\tau = G_\mu = G_e$, the following relationship would exist between M_τ, the τ lifetime τ_τ, and the leptonic decay branching ratio $Br(\tau \to e\nu_\tau\nu_e)$:

$$Br(\tau \to e\nu_\tau\nu_e) = \frac{G_F^2 m_\tau^5}{192\pi^3}\tau_\tau. \tag{1}$$

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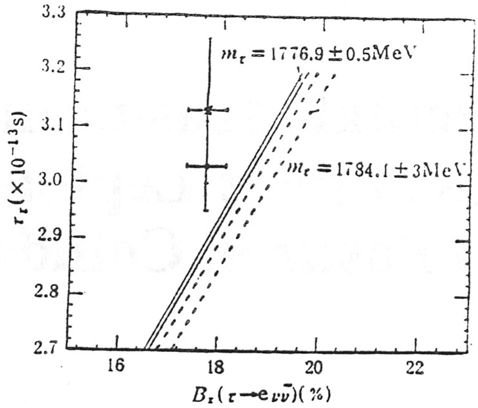

Fig. 1
The relationship between the mass, the leptonic branching ratio and the life time of τ lepton.

• PDG90; × LEP91.

Substitution of the experimental data m_τ and Br = (17.7 ± 0.4)% [2] into the above equation yielded the theoretical value of τ lifetime 2.83×10^{-13} s, which was not close to the 1990 experimental value (world average) of $(3.03 \pm 0.08) \times 10^{-13}$ s. The discrepancy to the 1991 measured data $(3.13 \pm 0.13) \times 10^{-13}$ s is even greater. The new data is obtained by averaging over the results of three groups, *L3*, Delphi, and Opal (see Fig. 1). In short, in order to test the lepton universality and verify the experimental values of Br and τ_τ, more accurate measurement on m_τ is necessary. This is the motivation behind the m_τ measurement on the Beijing spectrometer (BES) at the Beijing electron positron collider (BEPC).

The BEPC can work in a center-of-mass energy of 3-5 GeV, with high luminosity, stable beam energy, and good adjustment function. The detector BES has run stably and reliably with strong ability to identify particles, ensuring the accuracy of the m_τ measurement.

2. PRINCIPLE OF THE MEASUREMENT

In the process of e^+e^- collision, when the center-of-mass energy W equals or exceeds $2m_\tau$, the τ pair is produced. Because of its short lifetime, τ decays to other particles immediately, for instance,

$$e^+e^- \to \tau^\pm\tau^\mp, \quad \tau \to \mu^\mp\nu_\mu\nu_\tau, \quad \tau \to e^\pm\nu_e\nu_\tau \tag{2}$$

The CM energy W_s, which equals $2m_\tau$, is called the threshold energy of τ production. The τ mass measurement in e^+e^- collision is equivalent to the search of threshold energy $W_s(2m_\tau)$ in the process $e^+e^- \to \tau^+\tau^-$, in which the $\tau^+\tau^-$ can be found by their decay products. The $e\mu$ final state (and the undetectable partner neutrinos) decayed from τ pairs is the most reliable mode for tagging the τ lepton. To determine the threshold of process (2), the production cross section of $e^-e^- \to \tau^-\tau^-$ in the vicinity of the threshold must be measured accurately.

In summary, there are two key points in the experiment of the τ mass measurement: (1) theoretically, the study on the behavior of the τ production cross section near the threshold; (2) experimentally, choose a sequence of experiment energy points to approach the threshold.

2.1 The Production Cross Section of $\tau^+\tau^-$ Near the Threshold

Besides the radiative corrections of final state, the Coulomb interaction between τ^- and τ^- should also be considered in the calculation of the production cross section at or just above W_s because of the low momentum of the τ pairs produced [3]. In this case, the formula of the cross section can be written as:

$$\sigma_1(e^+e^- \longrightarrow \tau^+\tau^-) = \sigma_0 F_c F_r. \tag{3}$$

where σ_0 is the bare cross section for producing a fermion pair in e^+e^- annihilation process without any corrections,

$$\sigma_0 = \frac{4\pi\alpha^2}{3S}\frac{\beta(3-\beta)}{2}; \tag{4}$$

F_c is the Coulomb interaction factor [4],

$$F_c = \frac{\pi\dfrac{\alpha}{\beta}}{1-\exp\left(-\pi\dfrac{\alpha}{\beta}\right)}; \tag{5}$$

and F_r is the final state radiative correction and spin correction factor,

$$F_r = 1 + \left(\frac{\alpha}{\pi\beta}\right)\left\{(1+\beta^2)\left[\ln\left(\frac{1+\beta}{2}\right)\ln\left(\frac{1+\beta}{1-\beta}\right) + 2l\left(\frac{1-\beta}{1+\beta}\right) - \frac{\pi^2}{3}\right.\right.$$
$$\left. + 2l\left(\frac{1+\beta}{2}\right) - 2l\left(\frac{1-\beta}{2}\right) - 4l(\beta) + l(\beta^2)\right] + \left[\frac{11}{8}(1+\beta^2) - 3\beta\right.$$
$$\left.\left. + \frac{\beta^4}{2(3-\beta)}\right]\ln\left(\frac{1+\beta}{1-\beta}\right) + 6\beta\ln\left(\frac{1+\beta}{2}\right) - 4\beta\ln\beta + \frac{3}{4}\beta\frac{5-3\beta^2}{3-\beta^2}\right\}. \tag{6}$$

In Eqs. (4)–(6), α, β, S are the fine structure constant, the velocity of τ, and the squared center-of-mass energy, respectively, and

$$l(x) = -\int_0^x \ln(1-\lambda)\frac{d\lambda}{\lambda}.$$

When initial state radiative correction and vacuum polarization $\Pi(S)$ are included, the formula becomes [5]:

$$\sigma_2 = \int_0^{1-\frac{4m_\tau^2}{S}} dx F(x,S)\sigma_1(S(1-x))|1-\Pi(S)|^{-2} \tag{7}$$

where

$$F(x,S) = tx^{t-1}\left[1 + \frac{3}{4}t + \frac{\alpha}{\pi}\left(\frac{\pi^2}{3} - \frac{1}{2}\right) - \frac{t^2}{24}\left(\frac{1}{3}\ln\frac{S}{m_e^2} + 2\pi^2 - \frac{37}{4}\right)\right]$$
$$- t\left(1 - \frac{1}{2}x\right) + \frac{1}{8}t^2\left[4(2-x)\ln\frac{1}{x} - \frac{1+3(1-x)^2}{x}\ln(1-x) - 6 + x\right],$$

$$t = \frac{2\alpha}{\pi}\left(\ln\frac{S}{m_e^2} - 1\right).$$

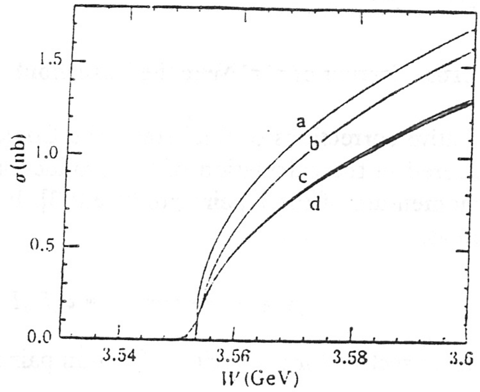

Fig. 2
Cross section curves of τ pair production from the process $e^+e^- \rightarrow \tau^+\tau^-$ near the threshold.

a. The cross section σ_1 which is σ_0 plus the consideration of Coulomb interaction: b. The bare cross section σ_0 without corrections; c. The cross section σ_τ, being σ_2 and includes the effect of beam energy spread; d. The cross section σ_2 which is σ_1 plus the correction of initial state radiation.

Figure 2 shows four curves which are for the bare cross section, the cross section with initial state radiative correction, the cross section including only Coulomb interaction, and the cross section with the energy spread.

2.2 Maximum Likelihood Function Method [6,8,9]

Our study indicated that the most sensitive region to measure the m_τ is at the vicinity of the threshold, even though it has the smallest cross section and produces the lowest rate of $\tau^+\tau^-$ pair; on the contrary, the region far from the threshold, which has a larger cross section and a higher rate, is not sensitive. The best experimental region given by Monte Carlo simulation is in the range of (m_τ - 0.3 MeV) to (m_τ + 3 MeV) for the sake of sensitivity. On the τ mass measurement, two aspects are of key importance: the choice of a sequence of scan energy points approaching the threshold, and the calculation of m_τ by means of the number of $\tau^+\tau^-$ events observed at various energies. The maximum likelihood function (MLF) method can solve these problems.

If the cross section $\sigma(W, m_\tau)$, the CM energy W_i of e^+e^- collision and the beam energy spread Δ_i at W_i are known, the expected events number of $\tau^+\tau^-$ for the integrated luminosity l_i is:

$$\mu_i(m_\tau) = \int_0^\infty A l_i \sigma_2(W_i, m_\tau) \frac{1}{\sqrt{2\pi}\,\Delta_i} e^{-\frac{(W-W_i)^2}{2\Delta_i^2}} dW, \tag{8}$$

where A is the detection efficiency, $\frac{1}{\sqrt{2\pi}\,\Delta_i} e^{-\frac{(W-W_i)^2}{2\Delta_i^2}}$ is the energy distribution of the collision beams.

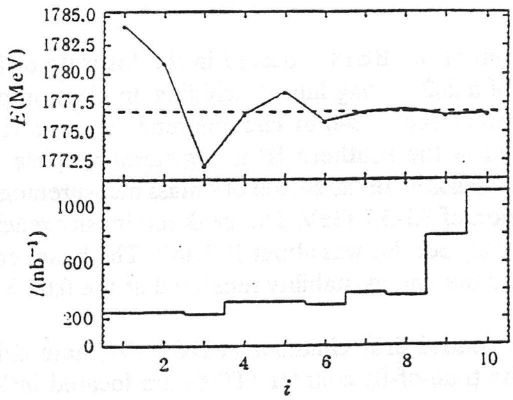

Fig. 3
The beam energy and the integrated luminosity of the experiment points.

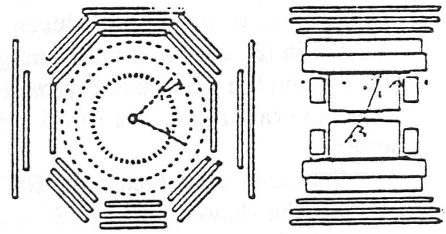

Fig. 4
A typical $e\mu$ event.

The probability for observing N_i $\tau^+\tau^-$ events is a Poisson distribution around the average μ_i as the following:

$$P_i(m_\tau) = \frac{\mu_i^{N_i}(m_\tau)}{N_i!} e^{-\mu_i(m_\tau)}. \tag{9}$$

Note that the values of μ_i and N_i are small when W_i is near the threshold. According to the maximum likelihood principle, the probability P_i takes its maximum value if m_τ in Eq. (9) stands for the real mass of τ lepton and N_i is the observed number of $\tau^+\tau^-$ events.

For a serial observed values W_i, $N_i (i = 1, 2, 3, \cdots, n)$ a likelihood function can be defined as

$$L(m_\tau) = \prod_{i=1}^{n} P_i(m_\tau). \tag{10}$$

Similarly, the likelihood function L takes its maximum value only if the parameter of m_τ is the real mass of the τ lepton.

It is easy to see that the MLF method can not only determine the mass of the τ lepton by use of whole set of experimental data, but can also predict the next energy point where the measurement will be carried out in the process of sequential scan for approaching the threshold. For example, the beam energy of the $(j + 1)$-th point can be selected as

$$E_{j+1} = m_{\tau j} - 0.3\mathrm{MeV}, \tag{11}$$

where $m_{\tau j}$ is the value of maximizing the likelihood function $L_j(m_\tau)$ in the former j measurements at energy points $(W_1, W_2, \cdots, W_j)$:

$$L(m_\tau) = \prod_{i=1}^{j} P_i(m_\tau) \tag{12}$$

Formulas (8)-(10) show that the likelihood function depends on the cross section σ_T, the observed numbers of $\tau^-\tau^-$ events at different energies, the experiment energies W_i, luminosities l_i, beam energy spread values, and detection A, all of which must be measured as precisely as possible.

3. THE EXPERIMENTAL MEASUREMENT

The m_τ measurement was carried out at the BEPC, located in the Institute of High Energy Physics (CAS). The BEPC is composed of a 202-m long linac (including an electron preinjector, a positron generator, and a main accelerator) and a 240-m circumference storage ring with two interaction points (IP). The BES situated at the southern IP is a general-purpose detector for investigating the particles produced in e^+e^- collision. In the period of τ mass measurement, the BEPC was run in the center-of-mass energy region of 3.1-3.7 GeV. The peak luminosity reached 4×10^{30} $cm^{-2}s^{-1}$, and the average integrated luminosity per day was about 100 nb^{-1}. The beam energy tuning resolution (accuracy) was ~0.25 MeV, and the energy stability remained at the 0.02 MeV level or better.

The four subdetectors of BES, the central drift chamber (CDC), the main drift chamber (MDC), the shower counter (SC), and the time-of-fly counter (TOF) are located inside the 0.4T magnetic field, outside of which there is a three-layer double tube muon identifier. The BES can measure the momentum of charged particles and the energy of electromagnetic shower with momentum resolution of $0.02\sqrt{1 + p^2}$ (p in GeV/c) and energy resolution of $0.22/\sqrt{E}$ (E in GeV). Particle identification can be done with the help of TOF by measuring the flying time with a 330-ps time resolution and MDC by measuring the dE/dx value with a resolution of 8.5%. The luminosity monitor placed around the beam pipe measures the luminosity by detecting the small angle (1.8°-6°) Bhabha scattering. In order to monitor the various parameters of the collider and the detector, such as the experimental energies, beam current, the magnetic field, the environment temperatures, etc., the online system records them onto the data tapes every 5 min. See [7] for details.

3.1 Experimental Procedure

The procedure for the τ mass measurement comprises three parts.

a) Determination of the absolute energy scale and beam energy spread for BEPC.

This determination was made by interpolating the results of repeated scans of the J/ψ and ψ' resonances. This type of scan was performed many times before, after, or during the threshold-approaching process and yielded information on beam energy stability and its uncertainty.

b) Measurement of the number of $\tau^+\tau^-$ events in the vicinity of the threshold.

The beam energy of the first point was chosen as 1784 MeV, which was the recent world average of m_τ(PDG90). At this point, the $\tau^+\tau^-$ (actually $e\mu$) events were found, and the beam energy was decreased to 1781 MeV as the second point at which $\tau^+\tau^-$ event was observed again. Therefore the beam energy was chosen even as low as 1772 MeV for the third point, and no any $\tau^+\tau^-$ event was found. Putting these three energies and corresponding numbers of $\tau^+\tau^-$ events into Eq. (12), the calculation of the MLF method gave the estimated value of m_τ. The value of (m_τ - 0.3 MeV) was used for the beam energy of the fourth point. Continuing under the same strategy, the beam energy of the i-th point ($i \geq 4$) was predicted by MLF of (i - 1) preceding points and was gradually closer to the threshold. In this measurement, a total of ten beam energy points were taken, most of which had the integrated luminosity of 250-400 nb^{-1}. When the MLF calculation predicted the beam energy E_{j+1} as the next point based on preceding j measurements, E_{j+1} was taken as the next measurement point only if the difference between E_{j+1} and E_j was bigger than 0.25 MeV, the minimum tuning step of the beam energy of BEPC. Otherwise, the experiment continued at the E_j point. Figure 3 shows the measurement process described by the experiment point sequential number (horizontal axis), beam energy (top half in vertical axis), and integrated luminosity (bottom half in vertical axis) for each points.

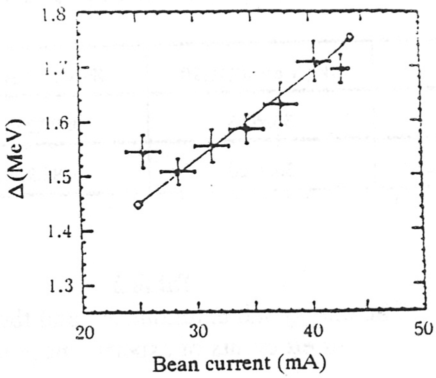

Fig. 5
The relationship between the beam energy spread and beam current obtained in ψ' scan.

c) Measurement of the number of $\tau^+\tau^-$ events in higher energies (1790 and 1800 MeV).

The two extra points which were not required by the MLF method and were dozens of MeV from the threshold, contributed only slightly to the result of m_τ measurement but improved the acceptance efficiency determination in two-parameter fit because more $\tau^+\tau^-$ events observed at these two points, due to their large cross section.

3.2 The Selection of $\tau^+\tau^-$ Events [10]

In order to select $\tau^+\tau^-$ events from the large number of backgrounds composed by multihadron, QED process, beam-gas interaction, and other kind of events, double tagging $e\mu$ events were used because they are background-free theoretically and experimentally. Preliminary study shows they also have lower rate of background events. The branching fraction of $e\mu$ channel in $\tau^+\tau^-$ events is

$$|x_0| < 1.5\text{cm}, \quad |y_0| < 1.5\text{cm}, \quad |z_0| < 15\text{cm}.$$

The criteria to select $e\mu$ events are:

a) the accepted $e\mu$ events must have two charged tracks with total charge equal to zero;

b) each track should have momentum in range of $(p_{\min}, p_{\max})$. The $p_{\min} = 0.35$ GeV/c and the $p_{\max}$ was calculated from the process of $\tau \to e\nu_\tau\nu_e$, in which $E_\tau = E_{\text{beam}}$, the neutrinos were flying parallel each other in opposite direction of the electron and p_e was along the direction of p_τ, $p_{\max} = |p_e|$;

c) $|x_0| < 1.5$ cm, $|y_0| < 1.5$ cm, $|z_0| < 15$ cm should be satisfied by both tracks, the x_0, y_0, z_0 are the coordinates of the point with the distance of closest approach to the beam spot of each track;

d) $2.5° < A_{\text{col}} < 177.5°$, $A_{\text{cop}} > 10°$, $(A_{\text{col}} + A_{\text{cop}}) > 50°$, where A_{col}, A_{cop} are the acolinearity and acoplanarity of two tracks, respectively;

e) the number of isolated photons must be zero. The isolated photon was defined by the following conditions:

— $E_{SC} \geq 60$ MeV for a neutral track. If there are more than one neutral track and the angle between them is less than 8°, take them as one track only;

— one of the azimuthal angles and the polar angle between the neutral and any charged tracks are bigger than 15°;

Table 1
The results of BEPC energy scan for J/ψ, ψ' and their standard values.

	W_c(MeV)PDG90	W(MeV) BEPC	Δ(MeV)BEPC
J/ψ	3096.93	3097.2±0.2	1.1
ψ'	3686.00	3686.9±0.2	1.4

Table 2
The energy value, luminosity and the number of $e\mu$ events of experiment points.

Point number	E_i(MeV)	ΔE(MeV)	l(nb^{-1})	$N_{e\mu}$
1	1784.19	0.087	245.8	2
2	1780.99	0.028	248.9	1
3	1772.09	0.076	232.8	0
4	1776.57	0.032	323.0	0
5	1778.49	0.029	322.5	2
6	1775.95	0.034	296.9	0
7	1776.75	0.019	384.0	0
8	1776.98	0.056	360.8	1
9	1776.45	0.059	794.1	0
10	1776.62	0.054	1109.1	1
11	1799.51	0.070	499.7	5
12	1789.55	0.066	250.0	2

f) one and only one track has the signature of muon. The muon signature is defined by at least one double hits on one layer (mostly the first layer) of muon counter for a track. The muon track must have a measured shower energy less than 0.5 GeV;

g) another track must have the signature of electron. There are three parallel definitions for the electron signature:

(1) when $p_e \leq 0.6$ GeV$/c$, the identification is made by dE/dx and the velocity ß. The requirement for ß is $0.9 < ß < 1.5$. The requirement for dE/dx is $XSE > 0$; or $XSE < -1$ and $|XSE| < XSPI$ where XSE and $XSPI$ are the number of σ (the standard deviation) deviating from the average dE/dx values of electron and pion, respectively;

(2) when $p_e \geq 0.7$ GeV$/c$, the identification would be made by the shower energy E_{SC} of the track. The E_{SC} must not less than 0.6 GeV;

(3) when 0.6 GeV$/c < p_e <$ 0.7 GeV$/c$, and a) if the muon track has double hits on more than two layers, the second track is identified as an electron if either condition of (1) or (2) can be satisfied; b) otherwise, both of the conditions of (1) and $E_{SC} > 0.55$ GeV must be satisfied.

The event selection criteria were established based on the studies to a sample of Monte Carlo τ lepton pairs, a data sample of 200 nb^{-1} of ψ' taken in early 1990, and a data sample of 5 million of J/ψ. The selection efficiency obtained from Monte Carlo method was 14.3%, while the background rejection rate is 1.4×10^{-6}. Figure 4 is an event display of the typical $e\mu$ event which satisfied above criteria.

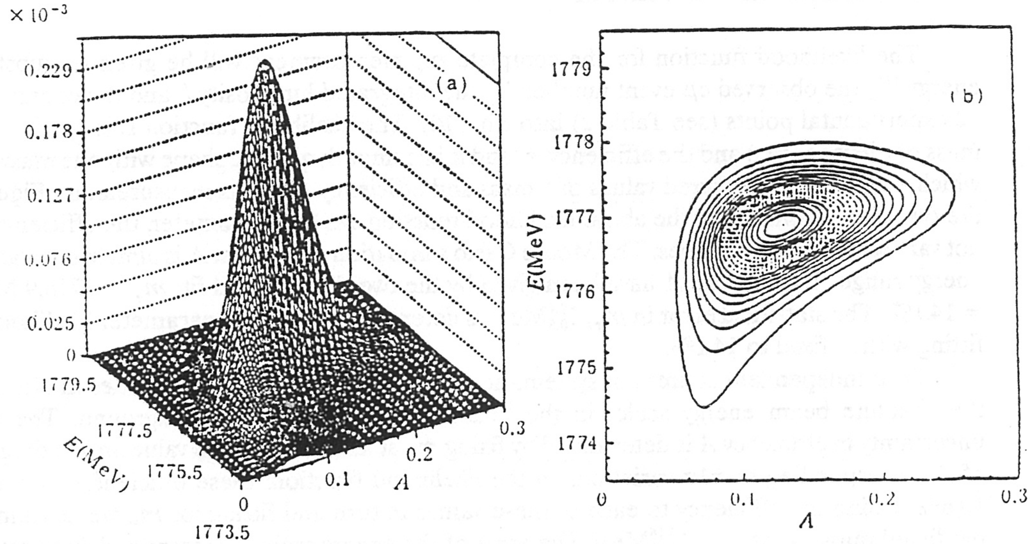

Fig. 6
The two-dimensional fitting camber of maximum likelihood function (a) and its project on the m_τ-efficiency plane (b).

3.3 The Determination of Beam Energy Scale and Spread

Table 1 lists the values of J/ψ, ψ' resonance energy, the uncertainties, and the energy spread, all of which were measured at BEPC, and the masses of J/ψ, ψ' in PDG90. Assuming the relation between the measured CM energy and the corrected one is

$$W_c = aW + 2b. \tag{13}$$

Substituting values of Table 1 into Eq. (13) the coefficients a, b can be obtained: a = 0.9989, b = 1.467 MeV. The energy of each experiment point in the τ mass measurement has been corrected by Eq. (13), and shown in Table 2.

It has been learned from Eq. (8) that the beam energy spread Δ_i is a important parameter which could affect the value of μ_i, then m_τ. The energy spreads at the various energy points during the τ mass measurement which can be obtained from the interpolation between the widths of J/ψ, ψ' resonances, are proportional to the squared beam energies and to the current intensities of the beam. Figure 5 shows the energy spread Δ as the function of beam current. The energy spread of every experiment point has been determined by the average current intensity and the energy of that point.

3.4 The Measurement of Luminosity

The small-angle luminosity monitor of the BES provided the integrated luminosity of each experiment point. The high event rate of small-angle Bhabha scattering made the statistical error of luminosity small. In order to determine the systematic error, comparison of luminosity analysis between off-line and on-line, between wide angle and small angle of Bhabha events has been made. The results of the different methods are consistent each other and give the estimation value of systematic error.

4. THE EXPERIMENTAL RESULT

The likelihood function for the complete m_τ measurement will be given by substituting the energy W_i, the observed eμ event number N_i, the integrated luminosity l_i and the energy spread $_i$ of 12 experimental points (see Table 2) into Eq. (10). The likelihood function L is the function of the mass of τ lepton (m_τ) and the efficiency A, and it has smooth quadric shape with one maximum value which will give the measured values of τ mass and efficiency A in this measurement. Figure 6 shows the two-dimensional fit of the above likelihood function. As a fit parameter, the efficiency A should not vary when energy changes. The Monte Carlo simulation shows that A is almost constant in a wide energy range. The m_τ and A have been given by the two-dimensional fit: m_τ = 1776.9 MeV and A = 14.1%. The statistical error in m_τ, $^{+0.4}_{-0.5}$MeV, is determined from one-parameter likelihood function fitting with A fixed to 14.1%.

Four independent sources of systematic error are considered: uncertainties in efficiency A, in the absolute beam energy scale, in the beam spread, and in the background. The systematic uncertainty in efficiency A is determined by fixing m_τ at its best-estimate value and finding the values of A corresponding to $\pm 1\sigma$ variations in the likelihood function; these efficiencies are 18.3% and 10.6%. Fixing the efficiency to each of these values in turn and fitting for m_τ yields changes in the predicted mass of $\Delta m_\tau = {}^{+0.16}_{-0.20}$MeV. The error of the energy scale is determined from several scans of the J/ψ and ψ' (see Sec. 3.3). The reproducibility of the fits to these scans, together with the other uncertainties, yields a systematic uncertainty of $\Delta m_\tau = \pm 0.09$ MeV. The uncertainty in center-of-mass energy spread is $\pm$0.08 MeV, yielding a systematic error $\Delta m_\tau = \pm 0.02$ MeV. Finally, the systematic error due to uncertainty in background is estimated from the 1σ Poisson errors on the J/ψ background events and from the uncertainty in the hadronic cross section at $\tau^+\tau^-$ threshold. The resultant uncertainty is $\Delta m_\tau = \pm 0.01$ MeV. These independent systematic errors are added in quadrature to yield a total systematic error of $\Delta m_\tau = {}^{+0.18}_{-0.22}$ MeV.

In conclusion, using a maximum likelihood fit to $\tau^+\tau^-$ cross section data near threshold, the mass of the τ lepton has been measured as m_τ = 1776.9 ± 0.2 MeV, where the first error is statistical and the second systematic. This result is 7.2 MeV below the PDG average and has significantly smaller errors. Inserting this new value for calculating $Br\ (\tau \to e\nu_e\nu_\tau)$ and τ_τ, the differences between their theoretical expectations and experimental results become smaller, and the e-μ-τ universality could be more favored than before. It should be also noted that, this new result for m_τ yields a reduction in the upper limit on τ neutrino mass $m\nu_\tau$.

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