HIGH ACCURATE MEASUREMENT OF τ MASS AT BESIII

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on behalf of BESIII Collaboration

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The new experiment at BESIII aims at the uncertainty less than 0.1 MeV, or 5.6×10^{-5} for the relative error. To make full use of machine time, the optimization study is performed to acquire the best strategy of data taking. The results of m_τ based on the test scan sample at BESIII are presented.

Keywords: τ mass; scan optimization; uncertainty.

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1. Introduction

Improvement of accuracy of τ mass (m_τ) is needed in its own right. Listed as follows are the measured mass values of three leptons according to PDG2012:¹

$$\begin{aligned} m_e &= 0.510998910 \pm 0.000000013 \text{ MeV} \quad (\delta m_e/m_e \approx 2.554 \times 10^{-8}), \\ m_\mu &= 105.658367 \pm 0.000004 \text{ MeV} \quad (\delta m_\mu/m_\mu \approx 3.786 \times 10^{-8}), \\ m_\tau &= 1776.82 \pm 0.16 \text{ MeV} \quad (\delta m_\tau/m_\tau \approx 9.568 \times 10^{-5}). \end{aligned} \quad (1)$$

As one of three elementary leptons in nature, the accuracy of m_τ is almost 4 orders of magnitude lower than the other two leptons, that is electron and muon, whose accuracy is already at the level of 10^{-8} .

One well-known motivation for getting accurate m_τ consists in the lepton universality test. By the light of the following formula

$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \left(\frac{m_\mu}{m_\tau}\right)^5 \frac{\tau_\mu}{\tau_\tau} \frac{B_{\tau \rightarrow e\nu\bar{\nu}}}{B_{\mu \rightarrow e\nu\bar{\nu}}} (1 + \Delta_e), \quad (2)$$

where g_τ and g_μ are τ - and μ -related coupling constants; τ_τ and τ_μ , $B_{\tau \rightarrow e\nu\bar{\nu}}$ and $B_{\mu \rightarrow e\nu\bar{\nu}}$ are the corresponding life times and decay branching ratios, respectively;

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Δ_e is the correct factor (which in fact includes the contributions from phase factor, radiative correction factor of QED, correct factor of propagator of W-meson etc.), the universality test is sensitive to m_τ because of 5 power dependence.

Another test also depends only on the accuracy of m_τ . Here is an interesting formula of masses of three leptons discovered in 1981:²

$$m_e + m_\mu + m_\tau = \frac{2}{3}(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2. \quad (3)$$

According to the error propagation formula (f_m indicates the difference between the right and left sides of Eq. (3))

$$\delta f_m = \sqrt{\sum_{k=e,\mu,\tau} \left[m_k - \frac{2}{3} \left(\sum_{i=e,\mu,\tau} \sqrt{m_k m_i} \right) \right]^2} \cdot \left(\frac{\delta m_k}{m_k} \right)^2 \approx \frac{1}{3} \delta m_\tau, \quad (4)$$

which indicates that the test of Eq. (3) depends almost merely on the accuracy of m_τ .

Table 1. Measurement results of m_τ from different experiment groups.

Measured m_τ (value+statistic+systematic)	Year	Exp. Group	Data sample	Method
$1776.68 \pm 0.12 \pm 0.41$	2009	Babar ¹⁰	423 fb ⁻¹	Pseudo-mass
$1776.81^{+0.25}_{-0.23} \pm 0.15$	2007	KEDR ⁹	6.7 fb ⁻¹	Threshold-scan
$1776.61 \pm 0.13 \pm 0.35$	2007	Belle ⁸	414 fb ⁻¹	Pseudo-mass
$1776.96^{+0.18+0.25}_{-0.21-0.17}$	1996	BES ⁵	5.1 fb ⁻¹	Threshold-scan

As a matter of fact, since the discovery of τ lepton, many experiments have been performed to measure m_τ .³⁻¹⁰ However, the value of m_τ in PDG2012 is based mostly on the four results as summarized in Table 1, where two results were acquired using the method of pseudo-mass while the others using the method of threshold scan. The latter method was and will be adopted by BES collaboration. The great improvement for the new experiment at BESIII is the establishment of the high accurate beam energy measurement system (BEMS)¹¹ that decreases the systematic uncertainty due to beam energy to the level of 10^{-5} . With this system and the expectable large data sample, it is time for BES to perform τ mass scan to get a good results.

2. Mass measurement through scan

For m_τ scan experiment, several points (say N_{pt} points) need to be taken in the vicinity of τ -pair threshold. The following likelihood function is constructed:⁵

$$LF = \prod_i^{N_{pt}} \frac{\mu_i^{N_i} e^{-\mu_i}}{N_i!}, \quad (5)$$

where N_i is the observed number of $\tau^+\tau^-$ events obtained by $e\mu$ -tagged final state^a at i -th scan point. Here N_i is assumed obeying Poisson distribution, whose expectation μ_i is given by

$$\mu_i(m_\tau) = [\epsilon \cdot B_{e\mu} \cdot \sigma_{obs}(m_\tau, E_{cm}^i) + \sigma_{BG}] \cdot \mathcal{L}_i \quad . \quad (6)$$

In above equation, $\mathcal{L}_i$ is the integrated luminosity at the point i ; ϵ is the overall efficiency of $e\mu$ final state for identifying $\tau^+\tau^-$ events, which includes trigger efficiency and event selection efficiency; $B_{e\mu}$ is the combined branching ratio for decays $\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$ and $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$, or the corresponding charge conjugate mode; σ_{obs} (with m_τ as a parameter), which can be calculated by the improved Voloshin's formulas,¹² is the observed cross section measured at point i with energy E_{cm}^i ; and σ_{BG} is the total cross section of background channels after $\tau^+\tau^-$ selection. If m_τ is set as a free parameter, the minimization of LF in Eq. (5) yields the best estimation for m_τ .

The aim of the study of statistical optimization is to find out the scheme that can provide the highest precision on m_τ for a specified period of data taking time or equivalently for a given integrated luminosity. The main conclusions for the optimization study are summarized as follows:¹³⁻¹⁶

- (1) For N free parameters, N scan points are enough;
- (2) The optimal position can be obtained by single parameter scan;
- (3) Luminosity allocation can be determined analytically or by simulation method;
- (4) The uncertainty of m_τ is proportional to the inverse of square root of luminosity.

By virtue of these conclusions, the optimal scan strategy is made: firstly, J/ψ scan (points 1-7), then scan in vicinity of τ -pair threshold (points 8-12), last ψ' scan (points 13-19). After that, repeat (in τ -region, the data are taken only at points 9 and 10). The two-circle process is designed to understand the stability of accelerator and detector. The key issue here is to acquire 100 pb^{-1} data in τ -region to guarantee the uncertainty of m_τ less than 0.1 MeV . The scan plan and part of offline results are summarized in Table 2.

3. Data analysis

At BEPCII, the electron's and positron's beams collide with an angle 22 mrad . Therefore, the center-of-mass energy (E_{cm}) must be calculated with care. Notice $\alpha = 22 \text{ mrad}$ is a small quantity, with conditions $E_{+,-} \gg m_e$ and $E_{+,-} \simeq E_{beam}$ ($E_{+,-}$ denote the beam energy E_{beam} for positron E_+ or electron E_-), it ready to obtain the formula

^aFor briefness, the $e\mu$ channel means $\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau, \tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$, or $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau, \tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$.

Table 2. Scan plan and offline results. Superscript “*exp*” indicates the expected value of scan plan; while “*offline*” denotes the measured value from offline analysis. E_{beam} and $\mathcal{L}$ represent the beam energy and integrated luminosity respectively. (†: the expected values are listed in last two columns; ‡: the measured values are little different from the expected ones due to the fluctuation of accelerator.)

Energy Region	order	E_{beam}^{exp} (MeV)	$\mathcal{L}^{exp}$ (pb^{-1})	$E_{beam}^{offline}$ (MeV)	$\mathcal{L}^{offline}$ (pb^{-1})	order	E_{beam}^{exp} (MeV) J/ψ	ψ'
J/ψ	1-7	†	9	‡	1.51	1/13	1544.0	1838.0
τ	8	1771.0	14	1771.2	4.25	2/14	1547.8	1841.9
	9	1776.6	14+25	1776.9	5.57	3/15	1548.2	1842.5
	10	1777.0	14+12			4/16	1548.6	1843.1
	11	1780.4	7	1780.6	3.89	5/17	1549.0	1843.8
	12	1792.0	14	1800.1	9.55	6/18	1549.4	1844.5
ψ'	13-19	†	10	‡	7.53	7/19	1552.0	1847.0

$$E_{cm} \simeq 2E_{beam}(1 - \frac{\alpha^2}{8}). \quad (7)$$

The effect due to the colliding angle is around 0.11 MeV, a very small quantity but can not be neglected for our accuracy requirement.

Since BESIII detector located at the south interaction point while BEMS located at the north crossing point, the data taking of two systems is independent on some extend, the matching of two kinds of information is fairly important, especially when the running status of accelerator or detector is not very stable. A great effects have been made to fix the values of E_{cm} for resonance scans of J/ψ and ψ' .

Di-gamma and Bhabha events are adopted to calculate the luminosity, together with the number of selected hadron events, the cross section of resonance can be evaluated. Then, the fit of resonance parameters, especially resonance mass and energy spread, are performed. The corresponding results are used for the uncertainty estimation of energy calibration and energy spread determination.

For τ -pair event selection, optimization for each criterion selection is performed. Totally thirteen channels are analyzed, that is ee , $e\mu$, $e\pi$, eK , $\mu\mu$, $\mu\pi$, μK , $\pi\pi$, πK , KK , $e\rho$, $\mu\rho$, and $\pi\rho$. Due to cut and energy difference, the efficiencies vary from 10% to 40%. The comparison between data and Monte Carlo simulation reveals the good consistency.

The optimized fitting curve is shown in Fig. 1. The consistency between measured points and theoretical curve is up go the state of the art. Many systematic uncertainties have been studied, include the accuracy of theoretical formula, errors due to energy scale and energy spread, effect of efficiency and luminosity, and so on (refer to the table in Fig. 1 for the special values). The synthetic error is around 120 keV, which is at the same level of the statistic error, and the total error is around 0.171 MeV (or the relative error at the level of 9.6×10^{-5}). The final result is as follows:

$$m_\tau = 1776.82 \pm 0.12(\text{stat.}) \pm 0.12(\text{sys.}) \text{ MeV}. \quad (8)$$

Fig. 1. τ mass fit considering the effects due to the initial state radiation and the energy spread of accelerator.

Systematic errors	
Source	keV
Theo.	10
E_{Spread}	12
E_{Scale}	90
Evt.selection	50
Eff.	48
Bg.shape	40
Lum.	6
Sum	122

4. Summary

Using around 20 pb^{-1} τ data, BESIII collaboration has measured the mass of τ lepton, whose central value is similar to that of PDG, while the uncertainty is comparable with that of PDG; Lepton universality is tested at the level of 5 per mille, and the mass equality of three leptons is established within the error of 57 keV; Experience is acquired from the present data analysis, more detailed plan is made for the finer m_τ scan in the future.

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References

1. J. Beringer *et al.* (Particle Data Group), Phys. Rev. D **86**, 010001 (2012).
2. Y. Koide, Phys. Rev. D **28**, 252 (1983); Mod. Phys. Lett. A **5**, 2319 (1990).
3. W. Bacino *et al.*, Phys. Rev. Lett. **41**, 13 (1978).
4. ARGUS Collab. (H. Albrecht *et al.*), Phys. Lett. B **292**, 221 (1992).
5. BES Collab. (J.Z. Bai *et al.*), Phys. Rev. Lett. **69**, 3021 (1992); Phys. Rev. D **53**, 20 (1996).
6. CLEO Collab. (A. Anastassov *et al.*), Phys. Rev. D **55**, 2559 (1997).
7. OPAL Collab. (G. Abbiendi *et al.*), Phys. Lett. B **492**, 23 (2000).
8. Belle Collab. (K. Belous *et al.*), Phys. Rev. Lett. **99**, 011801 (2007).
9. KEDR Collab. (V.V. Anashin *et al.*), J. Exp. The. Phys. Lett. **85**, 347 (2007).
10. Babar Collab. (B. Aubert *et al.*), Phys. Rev. D **80**, 092005 (2009).
11. X.H. MO *et al.*, China Phys. C **32**, 995 (2008);
X.H. MO *et al.*, China Phys. C **34**, 912 (2010);
E.V. Abakumova *et al.*, Nucl. Instrum. Methods A **659**, 21 (2011).
12. M.B. Voloshin, Phys. Lett. B **556**, 153 (2003).

13. Y.K. WANG *et al.*, Nucl. Instrum. Methods A **583**, 479 (2007).
14. Y.K. WANG *et al.*, China Phys. C **33**, 501 (2009).
15. M.N. Achasov *et al.*, China Phys. C **36**, 573 (2012).
16. B.Q. Wang and X.H. Mo, China Phys. C **37**, 026202 (2013).