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Measurement of the τ Lepton Mass at the KEDR Detector¶

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A precise τ lepton mass measurement performed at the VEPP-4M collider with the KEDR detector is reported. The mass value is evaluated from the $\tau^+\tau^-$ cross section behavior around the production threshold. The result based on 6.7 pb^{-1} of data is $m_\tau = 1776.81^{+0.25}_{-0.23} \pm 0.15$ MeV. Using 0.8 pb^{-1} of data collected at the ψ' peak, we have also determined that $\Gamma_{ee}B_{\tau\tau}(\psi') = 9.0 \pm 2.6$ eV.

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INTRODUCTION

The τ lepton mass, m_τ, is one of the fundamental characteristics of the Standard Model. Together with the lifetime and the decay probability to $e\bar{\nu}_e\nu_\tau$, this value can be used to test the lepton universality, which is one of the postulates of the modern Electroweak theory. The world average value $m_\tau = 1776.99^{+0.29}_{-0.26}$ [1] is dominated by the result of the BES collaboration [2], whose statistical analysis and uncertainty estimations were recently discussed in [3, 4]. Thus, additional measurements are desirable to improve the mass accuracy and ensure future progress in the lepton universality tests.

The direct method of the τ mass determination is a study of the threshold behavior of the $\tau^+\tau^-$ production cross section in e^+e^- collisions as was done in experiments [5] and then [2]. The key question of such experiments is the precision of the beam energy determination. The important feature of the present work is the application of two independent methods of the beam energy measurement, while the previous experiments relied on the extrapolation based on the J/ψ and ψ' mesons as reference points. It should also be noted that the beam energy in our experiment is monitored with an accuracy better than 5×10^{-5}, and the absolute energy calibration is performed with a precision of 1×10^{-5}.

The experiment is still in progress. Here, we report the intermediate result on m_τ, the accuracy of which reached that of the world average value.

VEPP-4M collider and KEDR detector. The layout of the VEPP-4M/VEPP-3 accelerator complex is presented in Fig. 1.

The VEPP-4M collider [6] has a circumference of 366 m and operates in a 2 × 2 bunches mode. The beam energy can vary in the range of 1–6 GeV, and the peak luminosity at the τ-production threshold $E_{beam} \approx 1.78$ GeV is about 2×10^{30} cm^{-2} s^{-1}.

The beams, optionally polarized, are injected from the VEPP-3 booster at energy up to 1.9 GeV. This

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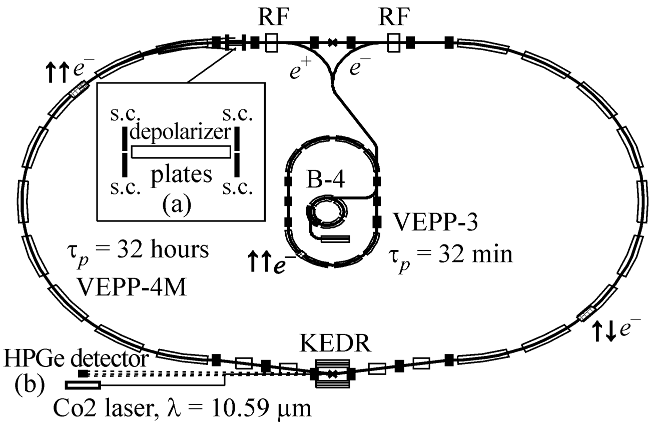

Fig. 1. VEPP-4M/VEPP-3 accelerator complex in the energy calibration mode: (a) Touschek polarimeter; (b) Compton backscattering monitor; the spin polarization time τ_p is for 1.85 GeV.

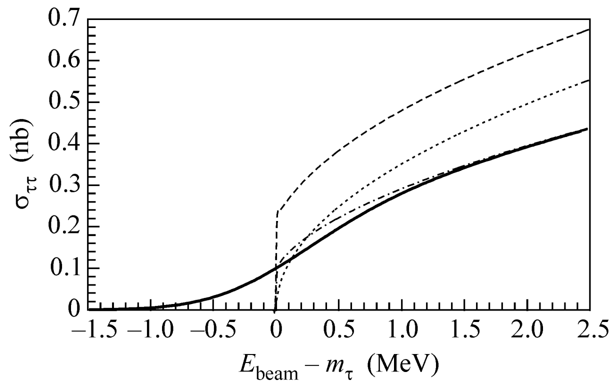

Fig. 2. $e^+e^- \longrightarrow \tau^+\tau^-$ cross section near the threshold vs. the beam energy (the dotted line is the Born approximation; the dashed line includes the Coulomb interaction, final state radiation, and vacuum polarization; the dash–dotted line additionally includes the initial state radiation; and the solid line additionally includes the beam energy spread).

allows one to apply the resonant depolarization method (RDM) [7] for the precise energy calibration. The Touschek (intrabeam scattering) polarimeter of the VEPP-4M (Fig. 1a) requires special runs for the calibration. During data taking, the beam energy can be monitored using the Compton backscattering (CBS) of the infrared laser light (Fig. 1b) by the method developed at the BESSY-I synchrotron light source [8]. The statistical accuracy of a single measurement is about 100 keV, and the systematic uncertainty of the method verified by the resonant depolarization is close to 60 keV.

The KEDR detector [9] consists of the vertex detector, the drift chamber, the time-of-flight system of scintillation counters, the particle identification system based on aerogel Cherenkov counters, the calorimeter with longitudinal segmentation (liquid krypton in the barrel part and CsI crystals in the end caps), and the muon tube system inside the magnet yoke. Currently, the KEDR operates at a magnetic field of 6 kGs.

The longitudinal segmentation of the calorimeter provides good e/π identification, which is used to select $\tau^+\tau^-$ events.

Experiment scenario. The cross section for the process $e^+e^- \longrightarrow \tau^+\tau^-$ measured at a certain c.m. energy W is expressed as

$$\sigma(W) = \frac{1}{\sqrt{2\pi}\sigma_W}\int dW'\exp\left\{-\frac{(W-W')^2}{2\sigma_W^2}\right\} \times \int dx F(x, W')\sigma_{fs}(W'\sqrt{1-x}), \quad (1)$$

where the first integral takes into account the c.m. energy spread σ_W, and the second one accounts for the energy loss due to the initial state radiation [10], while

$$\sigma_{fs}(W) = \frac{4\pi\alpha^2}{3W^2}\frac{\beta(3-\beta^2)}{2}\frac{F_c(\beta)F_r(\beta)}{|1-\Pi(W)|^2} \quad (2)$$

includes the Coulomb interaction correction $F_c(\beta) = (\pi\alpha/\beta)/(1 - \exp(-\pi\alpha/\beta))$, the final state radiative correction $F_r(\beta)$ [11], and the vacuum polarization effect $|1 - \Pi(W)|^2$. The quantity $\beta = (1 - (2m_\tau/W)^2)^{1/2}$ is the t lepton velocity.

Due to the Coulomb interaction of the produced τ^+ and τ^-, the energy dependence of cross section (2) has a step at $W = 2m_\tau$ (Fig. 2).

The narrow region of a few MeV around the threshold is the most sensitive to the mass value. For this reason, the following scan scenario was chosen: 70% of the integrated luminosity $\mathcal{L}$ is taken at three points $E_{\text{beam}} = m_\tau - 0.5$, m_τ, $m_\tau + 0.5$ MeV with the world average value of m_τ; 15% of the data are collected well below the threshold to fix the background level σ_B; and the remaining 15% are collected well above the threshold to determine the effective detection efficiency ε. The interval of ±0.5 MeV covers the possible uncertainty of the mass; a few additional points above the threshold were foreseen to increase the robustness of the three-parameter data fit.

Beam energy determination. A conventional way of the beam energy determination consists of a calculation based on the measured magnet currents. It provides a relative accuracy that seems to be not better than 3×10^{-4}. The uncontrollable energy variations are of the same order of magnitude. Thus, the precise beam energy calibration is required for the r mass determination, and at least the reliable energy stability tests are necessary for an accurate uncertainty estimate.

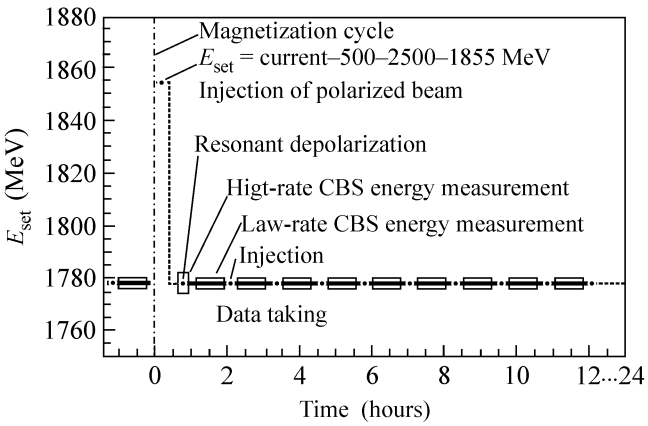

Fig. 3. VEPP-4M operation scenario in 2005–2006 (in 2004–2005 only high-rate Compton backscattering measurements were used, which were incompatible with the data taking).

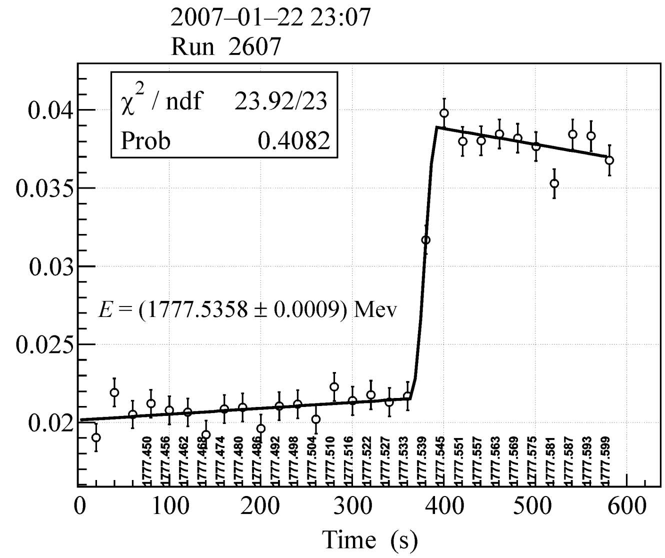

Fig. 4. Typical resonant depolarization run: the ratio of the intrabeam scattering rates from the unpolarized and polarized bunches minus one.

In the previous KEDR experiments on the high precision J/ψ and ψ' meson mass measurements [12], various sources of the systematic uncertainties in the beam energy determination were thoroughly studied to achieve a 10 keV accuracy.

In this experiment, basic energy calibrations were performed by the resonant depolarization with the smoothing interpolation of the RDM results between the calibrations as described in [12] (the guiding field measurements and the ring and the tunnel temperature measurements are employed for the interpolation).

The improvements of the Touschek polarimeter (Fig. 1a) accomplished since 2003 have allowed operation at $E_{beam} \approx 1772$ MeV, where the polarization lifetime is $\lesssim$1000 s because of the closeness of the integer spin resonance $\nu = 4$ (1762.59 MeV). However, the absence of polarization in VEPP-3 in the energy range of 1700–1830 MeV forced employment of the complicated machine operation scenario shown in Fig. 3. After staying in the threshold region, the magnetization cycle must be performed in VEPP-4M to inject the polarized beam above the region quoted. This and also some forced changes in the accelerator cooling system reduced the accuracy of the energy interpolation between the calibrations from 8 keV obtained in [12] to 30 keV.

The resonant depolarizations were performed normally once a day with accuracy better than 20 keV. The results of a typical resonant depolarization run is shown in Fig. 4. Between the depolarizations, the energy was directly measured using a CBS monitor (Fig. 3) with a statistical accuracy of about 100 keV. The multiparameter fit of the Compton spectrum edge is shown in Fig. 5. It accounts for the nonuniform background and the detection efficiency variations.

An example of VEPP-4M energy behavior during three successive runs is presented in Fig. 6. The RDM measurements were performed at the start of each run. During the run, the energy values were measured by CBS and evaluated using interpolation. The values obtained by these two methods agree within the errors quoted above. The magnetization cycles allow us to reproduce the machine energy with an accuracy of $\sim 1 \times 10^{-4}$; however, it is not a limiting factor for the mass measurement accuracy.

Energy spread determination. To calculate the $\tau^+\tau^-$ cross section from Eq. 1, the cm energy spread law

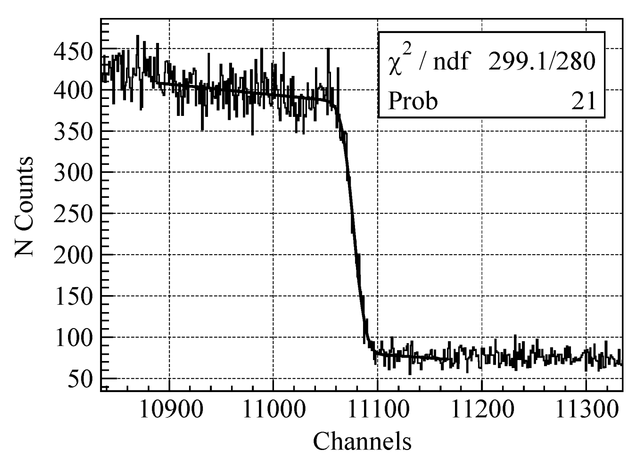

Fig. 5. Typical fit of the Compton backscattering spectrum edge (5.78 MeV) accounting for the background and the detection efficiency variations.

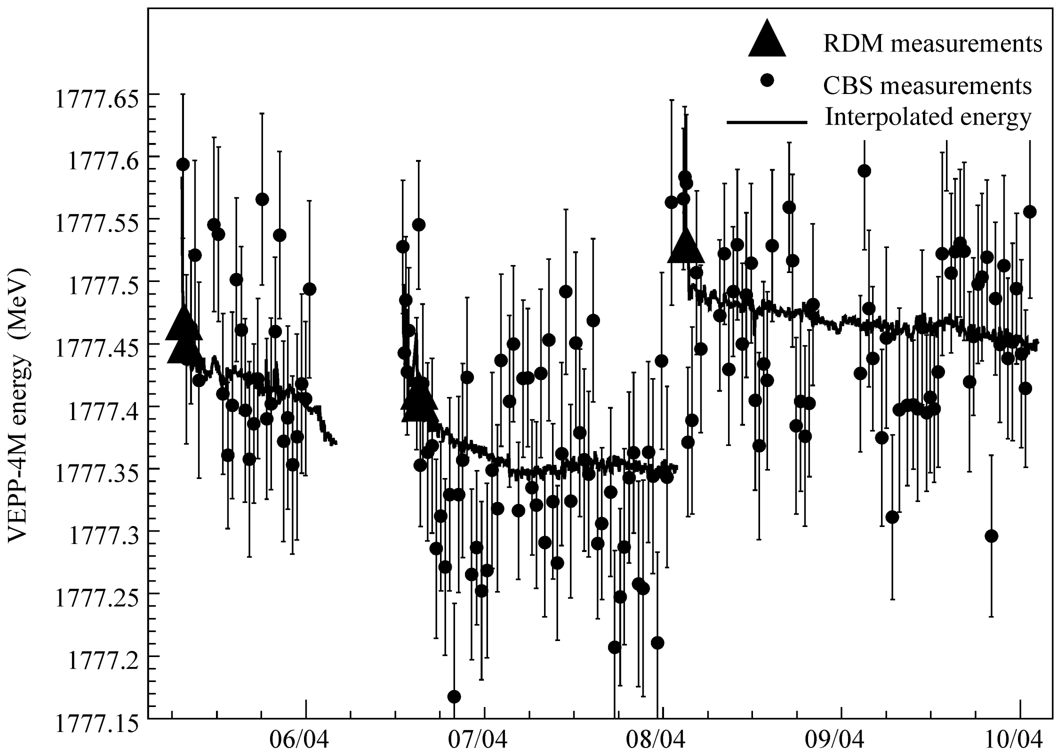

Fig. 6. Example of VEPP-4M energy behavior, April 2006.

must be known with high accuracy. The VEPP-4M settings related to the beam energy spread were optimized for the τ mass experiment and have been kept unchanged since 2004.

Three scans of ψ' and one scan of J/ψ performed in 2004–2006 to determine σ_W in the vicinity of the τ threshold resulted in

$$\sigma_W(\psi') = 1.15 \pm 0.02 \pm 0.03 \text{ MeV},$$
$$\sigma_W(J/\psi) = 0.72 \pm 0.01 \pm 0.02 \text{ MeV}.$$

At the J/ψ peak, an 11% deviation from the expected value of $\sigma_W(\psi') \times (M_{J/\psi}/M_{\psi'})^2$ exists. A similar deviation took place during the J/ψ and of ψ' mass measurements [12] with different spread-related settings.

Assuming a linear growth of the deviation with $\Omega - M_{\psi'}$, we obtained

$$\sigma_W(2m_\tau) = 1.07 \pm 0.02 \pm 0.04 \text{ MeV}.$$

No essential dependence of the energy spread on the beam current was observed at the ψ' region in the resonance scans or by means of the beam diagnostics [13].

Selection of τ events. To diminish the systematic uncertainties, the event selection criteria were chosen as loose as possible, while the background was considered to be negligible. The two-prong events due to

$$e^+e^- \longrightarrow (\tau \longrightarrow e\nu_\tau\bar{\nu}_e, \mu\nu_\tau\bar{\nu}_\mu, \pi\nu_\tau, K\nu_\tau, \rho\nu_\tau)$$
$$(\tau \longrightarrow e\nu_\tau\bar{\nu}_e)^*$$
$$+ \text{c.c.}$$

were selected. At least one track must be identified as an electron using the signal in the calorimeter and the momentum measurements. The $\mu/\pi/K$ identification was not applied; it does not reduce the systematic uncertainty of the mass. No photons with $E_\gamma > 30$ MeV were allowed. The other cuts were $E < 2200$ MeV, $p_T > 200$ MeV, and $p_T/(W - E) > 0.06$, where p_T is the total transverse momentum, E is the total energy of the detected particles, and $W = 2E_{\text{beam}}$.

With such cuts, the residual background (mainly two-photon) is expected to be uniform in the energy region of the experiment.

Simulation (MC) of the experiment was performed with the code based on the GEANT 3.21 package [14].

The detection efficiency at the τ threshold was calculated using the event generator KORAL-B [15]; it is about 2.5% with a relative reduction by 10% at $W = 3777$ MeV.

The distributions of some parameters of interest for the real data and the simulation are presented in Fig. 7.

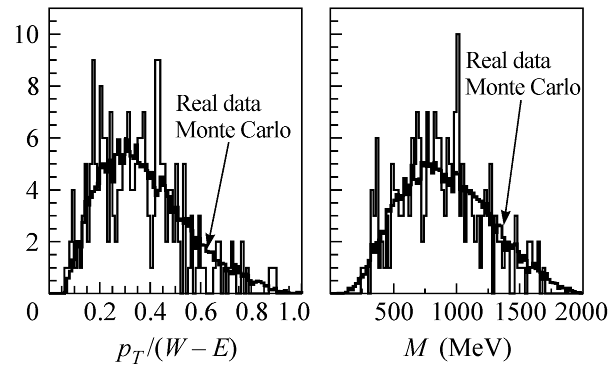

Fig. 7. Distributions (left) in the p_T over the missing energy $(W-E)$ and (right) in the invariant mass of the detected system; the real data (small statistics) and the simulation (high statistics).

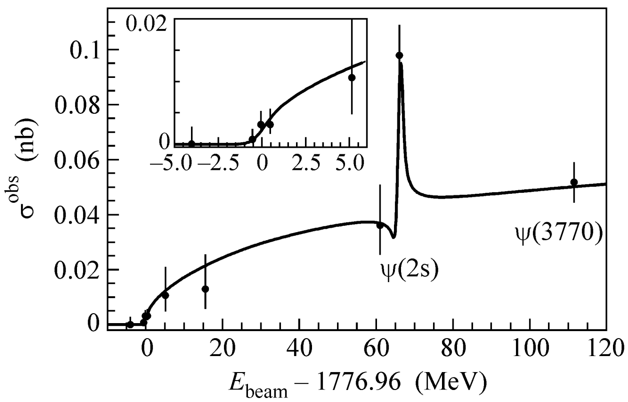

Fig. 8. Observed $\tau^+\tau^-$ cross section versus the beam energy.

RESULTS

The results of the $\tau^+\tau^-$ threshold scan are collected in Table 1 and presented in Fig. 8. The energy $\langle E\rangle$ assigned to the point is the average of all the measured values. The corresponding standard deviation δ_E is related to the machine energy instability and is much less than the beam energy spread $\sigma_E \approx \sigma_W/\sqrt{2}$.

To determine the value of the τ lepton mass, the log-likelihood fit of the observed number of events at nine points was performed. The expected number of events at the point was parameterized as

$$n_i = (\varepsilon r_i \sigma(2\langle E\rangle_i, m_\tau) + \sigma_B)\mathcal{L}_i,$$

where ε, m_τ, and σ_B are the free parameters of the fit defined in the description of the beam energy determination, and r_i is the relative efficiency variation obtained with the Monte Carlo simulation. The cross section $\sigma(W, m_\tau)$ was calculated according to Eq. 1 with the additional term describing the ψ' production and decay; it contains $\Gamma_{ee}B_{\tau\tau}(\psi')$ as an additional free parameter. The radiative corrections to the ψ' production and interference were accounted for according to [16] using the world average value of the ψ' total width $\Gamma = 337 \pm 13$ keV [1].

The fit yielded

$$m_\tau = 1776.81^{+0.25}_{-0.23}\ \text{MeV}, \quad \varepsilon = 2.25 \pm 0.28\%,$$
$$\sigma_B = 0^{+0.58}\ \text{pb}, \quad \Gamma_{ee}B_{\tau\tau}(\psi') = 9.0 \pm 2.6\ \text{eV},$$

Table 1. Summary of the $\tau^+\tau^-$ threshold scan data: $\langle E\rangle$, δ_E is the time average of the beam energy and the corresponding standard deviation, $\mathcal{L}$ is the integrated luminosity, $N_{\tau\tau}$ is the number of events, $\sigma^{obs}_{\tau\tau}$ is the observed cross section

Scan point	$\langle E\rangle$, MeV	δ_E, MeV	$\mathcal{L}$, nb^{-1}	$N_{\tau\tau}$	$\sigma^{obs}_{\tau\tau}$, pb
1	1771.945	0.160	668	0	$0.0^{+2.8}$
2	1776.408	0.086	1382	1	$0.7^{+1.7}_{-0.6}$
3	1776.896	0.045	1605	6	$3.7^{+2.2}_{-1.5}$
4	1777.419	0.061	1288	4	$3.1^{+2.5}_{-1.5}$
5	1782.103	0.060	283	4	$14.1^{+11.3}_{-6.8}$
6	1792.457	0.102	233	3	$12.9^{+12.5}_{-7.1}$
7	1837.994	0.092	305	14	$45.8^{+16.0}_{-12.2}$
8(ψ')	1843.040	0.065	807	79	$97.9^{+11.0}_{-11.0}$
9	1888.521	0.228	967	49	$50.7^{+7.2}_{-7.2}$
Total (excluding ψ')			6731	81	

Table 2. Estimates of the systematic uncertainties in the τ lepton mass (keV)

Beam energy determination	40
Detection efficiency variations	100
Energy spread determination accuracy	25
Energy dependence of the background	20
Luminosity measurement instability	90
Beam energy spread variation	15
Cross section calculation (r.c., interference)	30
Sum in quadrature	150

and the background is consistent with zero.

The conservative estimates of the systematic uncertainties in m_τ are summarized in Table 2.

CONCLUSIONS

A new precise measurement of the τ lepton mass gives

$$m_\tau = 1776.81^{+0.25}_{-0.23} \pm 0.15 \text{ MeV}$$

which is in good agreement with the world average

$$m_\tau = 1776.99^{+0.29}_{-0.26} \text{ MeV}$$

[1] and has approximately the same accuracy. It is also consistent with a recent measurement with the Belle detector [17].

Using 0.8 pb^{-1} at the ψ' peak, the following result was obtained for the $\psi' \longrightarrow \tau\tau$ decay probability:

$$\Gamma_{ee}B_{\tau\tau}(\psi') = 9.0 \pm 2.6 \text{ eV}.$$

The product of the world average values [1] is

$$\langle\Gamma_{ee}\rangle\langle B_{\tau\tau}\rangle(\psi') = 6.9 \pm 1.7 \text{ eV}.$$

Data taking for this experiment is being continued with the goal of achieving a 0.15 MeV accuracy in the τ mass. The accuracy of the $\psi' \longrightarrow \tau\tau$ decay probability will also be well improved.

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