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Measurement of the τ lepton mass at 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 behaviour 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 $\Gamma_{ee} \cdot B_{\tau\tau}(\psi') = 9.0 \pm 2.6$ 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] which statistical analysis and uncertainty estimations were recently discussed in Refs. [3] and [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 behaviour of the $\tau^+\tau^-$ production cross section in e^+e^- collisions as it was done in the 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 an 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 be also noted that the beam energy in our experiment is monitored with the accuracy better than $5 \cdot 10^{-5}$ and the absolute energy calibration is done with the precision of $1 \cdot 10^{-5}$.

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.

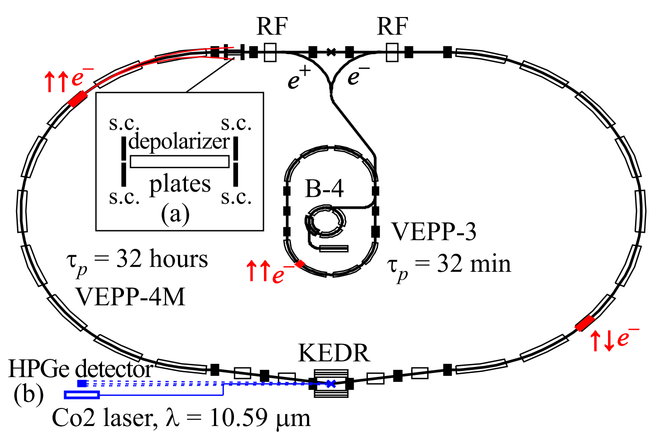

Fig.1. VEPP-4M/VEPP-3 accelerator complex in the energy calibration mode: (a) Touschek polarimeter, (b) Compton backscattering monitor; spin polarization time τ_p is for 1.85 GeV

The VEPP-4M collider [6] has a circumference of 366 m and operates in a 2×2 bunches mode. The beam

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energy can vary in the range of 1÷6 GeV, the peak luminosity at the τ – production threshold $E_{\rm beam} \approx 1.78$ GeV is about $2 \cdot 10^{30}\,{\rm cm}^{-2} \cdot {\rm s}^{-1}$.

The beams, optionally polarized, are injected from the VEPP-3 booster at the energy up to 1.9 GeV. This allows to apply the resonant depolarization method (RDM) [7] for the precise energy calibration. The Touschek (intra-beam scattering) polarimeter of 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 infra-red laser light (Fig.1b) by the method developed at the synchrotron light source BESSY-I [8]. The statistical accuracy of a single measurement is about 100 keV, 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 the 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 KEDR operates at the magnetic field of 6 kGs.

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

Experiment scenario. A cross section of the process $e^+e^- \to \tau^+\tau^-$ measured at certain center-of-mass energy W is expressed as

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

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

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

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 τ lepton velocity.

Due to Coulomb interaction of the produced τ^+ and τ^- the cross section (2) energy dependence 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

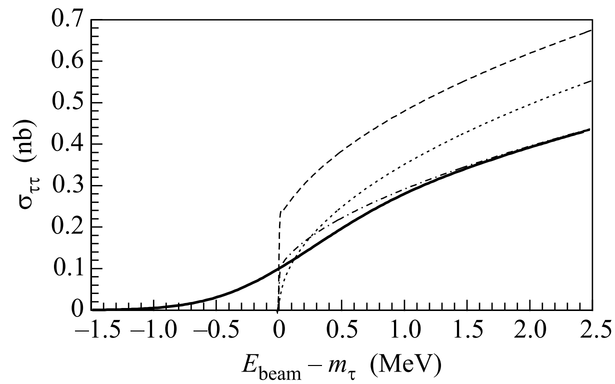

Fig.2. $e^+e^- \to \tau^+\tau^-$ cross section near threshold as function of the beam energy (dotted line – Born approximation; dashed line – plus the Coulomb interaction, the final state radiation and the vacuum polarization; dash-dotted line – plus initial state radiation; solid line – plus the beam energy spread)

reason the following scan scenario was chosen: 70% of the integrated luminosity $\mathcal{L}$ are taken at three points $E_{\rm beam} = m_\tau - 0.5$, 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 remaining 15% – well above the threshold to determine the effective detection efficiency ε. The interval of ± 0.5 MeV covers 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 is a calculation based on the measured magnet currents. It provides the relative accuracy that seems to be not better than $3 \cdot 10^{-4}$. The uncontrollable energy variations are of the same order of magnitude. Thus the precise beam energy calibration is required for the τ mass determination and, at least, the reliable energy stability tests are necessary for an accurate uncertainty estimate.

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 Ref. [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) done since 2003 have allowed to operate at $E_{\rm beam} \approx 1772$ MeV, where the polarization lifetime is

$\lesssim$ 1000 sec 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 $1700 \div 1830$ MeV forced, to employ a complicated machine operation scenario shown in Fig.3. After staying

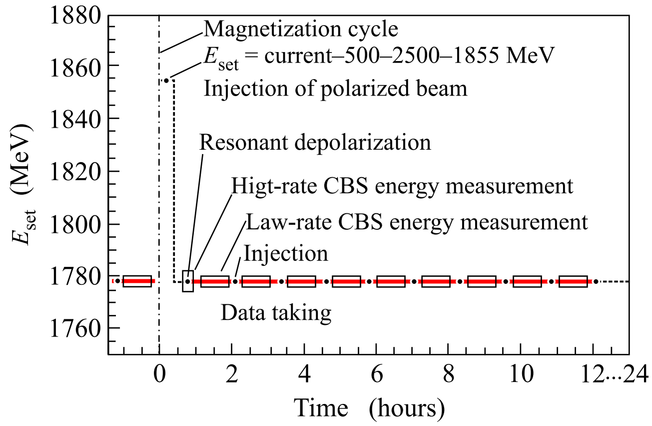

Fig.3. The VEPP-4M operation scenario in 2005-2006 (in 2004-2005 only high-rate Compton backscattering measurements were used, incompatible with the data taking)

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 the accuracy better than 20 keV. The results of the typical resonant depolarization run is shown in Fig.4. Between the depolarizations the energy was directly measured using the CBS monitor (Fig.3) with the 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 errors quoted above. The magnetization cycles allowus to reproduce the machine energy with the accuracy $\sim 1 \cdot 10^{-4}$, 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 c.m. energy spread σ_W must be known with high accuracy. The VEPP-4M settings related to the beam energy spread were optimized for the τ mass experiment and kept unchanged since 2004.

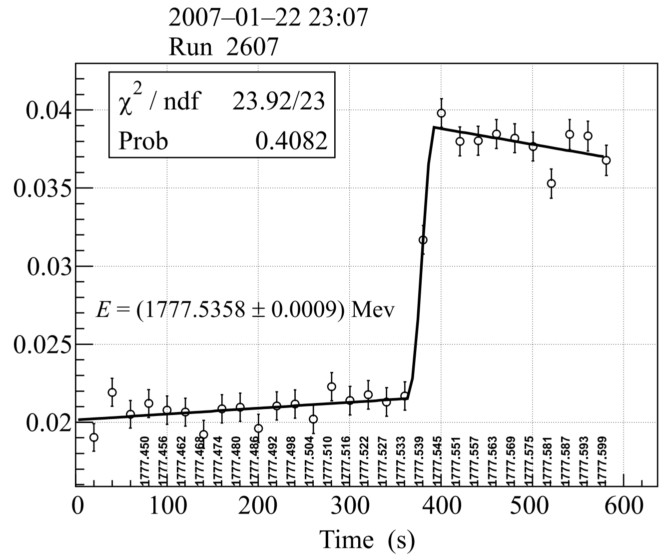

Fig.4. A typical resonant depolarization run: the ratio of the intrabeam scattering rates from the unpolarized and polarized bunches minus one

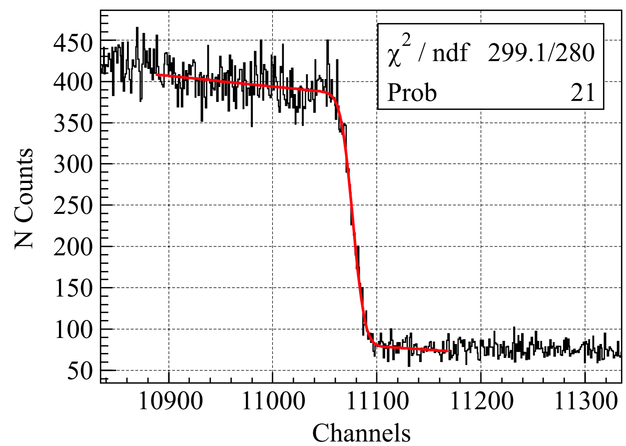

Fig.5. A typical fit of the Compton backscattering spectrum edge (5.78 MeV) accounting for the background and the detection efficiency variations

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 $W - M_{\psi'}$ we obtained

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

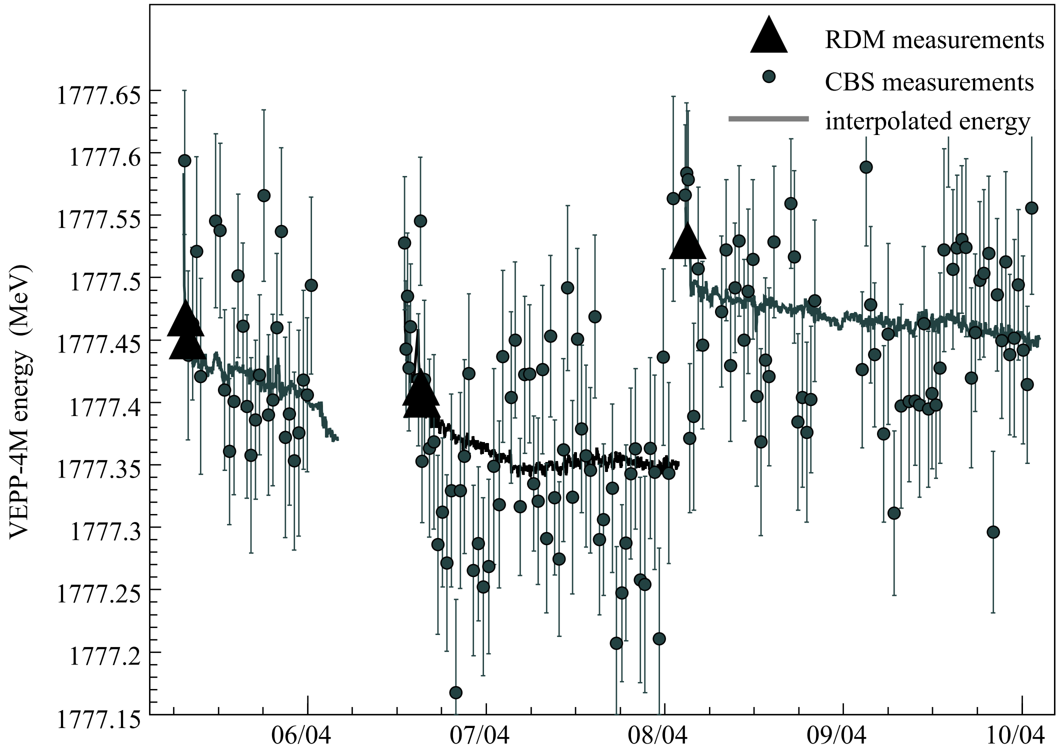

Fig.6. An example of VEPP-4M energy behavior, April 2006

No essential dependence of the energy spread on the beam current was observed at the ψ' region neither in the resonance scans nor by means of the beam diagnostic [13].

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

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

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 $E_\gamma > 30\,\text{MeV}$ were allowed. The other cuts were $E < 2200$ MeV, $p_T > 200\,\text{MeV}$, $p_T/(W-E) > 0.06$, where p_T is the total transverse momentum, E is 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 package GEANT 3.21 [14]. The detection efficiency at the τ threshold was calculated using the event generator KORAL − B [15], it is about 2.5% with the relative reduction by 10% at $W = 3777\,\text{MeV}$.

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

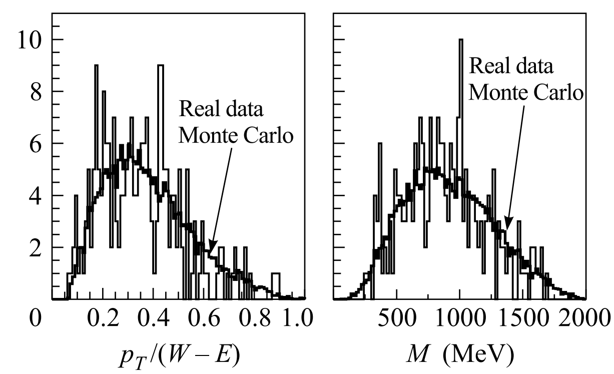

Fig.7. The distributions in the p_T over the missing energy $(W-E)$ (left) and in the invariant mass of the detected system (right); the real data (small statistics) and the simulation (high statistics)

Results. The results of the $\tau^+\tau^-$ threshold scan are collected in Table 1 and presented in Fig.8. The energy

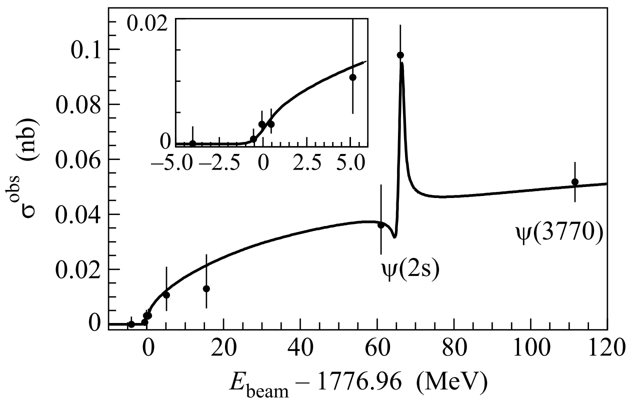

Fig.8. The observed $\tau^+\tau^-$ cross section versus the beam energy

$\langle E\rangle$ assigned to the point is the average of all 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 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 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 ψ' production and decay; it contains $\Gamma_{ee}\cdot B_{\tau\tau}(\psi')$ as an additional free parameter. Radiative corrections to ψ' production and interference were accounted according to [16] using the world average value of ψ' total width $\Gamma = 337 \pm 13\,\text{keV}$ [1].

The fit yielded

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

the background is consistent with zero.

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

Conclusion. A new precise measurement of the τ lepton mass gives

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

in good agreement with the world average

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

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

Tabl 1

The summary of the $\tau^+\tau^-$ threshold scan data: $\langle E\rangle$, δ_E – the time average of the beam energy and the corresponding standard deviation, $\mathcal{L}$ – the integrated luminosity, $N_{\tau\tau}$ – the number of events, $\sigma^{obs}_{\tau\tau}$ – 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	

Tabl 2

The 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

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

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

The product of the world average values [1] is

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

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

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