Measurement of the ratio of the lepton widths $\Gamma_{ee}/\Gamma_{\mu\mu}$ for the $J/\psi$ meson

V.M. Aulchenko$^{a,b}$, E.M. Baldin$^{a,b,*}$, A.K. Barladyan$^a$, A.Yu. Barnyakov$^a$, M.Yu. Barnyakov$^a$, S.E. Baru$^a$, I.Yu. Basok$^a$, A.M. Batrakov$^a$, A.E. Blinov$^{a,c}$, V.E. Blinov$^{a,c}$, A.V. Bobrov$^{a,b}$, V.S. Bobrovnikova$^a$, A.V. Bogomyagkova$^a$, A. Bondar$^{a,b}$, A.R. Buzykaev$^a$, S.I. Eidelman$^{a,b}$, D.N. Grigoriev$^{a,b,c}$, V.R. Groshev$^a$, Yu.M. Glukhovchenko$^a$, V.V. Gulevich$^a$, D.V. Gusev$^a$, S.E. Karnaev$^a$, G.V. Karpov$^a$, S.V. Karpov$^a$, T.A. Kharlamova$^a$, V.A. Kiselev$^a$, V.V. Kolmogorov$^a$, S.A. Kononov$^{a,b}$, K.Yu. Kotov$^a$, E.A. Kravchenko$^{a,b}$, V.N. Kudryavtsev$^a$, V.F. Kulikov$^{a,b}$, G.Ya. Kurkin$^{a,c}$, E.A. Kuper$^{b,1}$, I.A. Kuyanova$^a$, E.B. Levichev$^{a,c}$, D.A. Maksimov$^{a,b}$, V.M. Malyshev$^a$, A.L. Maslennikov$^a$, O.I. Meshkova, I.I. Morozov$^{a,b}$, N.Yu. Muchnoi$^{a,b}$, V.V. Neufeld$^a$, S.A. Nikitin$^a$, I.B. Nikolaev$^{a,b}$, I.N. Okunev$^a$, A.P. Onuchin$^{a,c}$, S.B. Oreshkin$^a$, I.O. Orlov$^{a,b}$, A.A. Osipov$^a$, I.V. Ovtin$^{a,c}$, S.V. Peleganchuk$^a$, S.G. Pivovarov$^{a,c}$, P.A. Piminov$^a$, V.V. Petrov$^a$, A.O. Poluektov$^a$, V.G. Prisekin$^a$, O.L. Rezanova$^{a,b}$, A.A. Ruban$^a$, V.K. Sandryev$^a$, G.A. Savinov$^a$, A.G. Shamov$^a$, D.N. Shatalov$^a$, B.A. Shwartz$^{a,b}$, E.A. Simonov$^a$, S.V. Sinyatkin$^a$, A.N. Skrinsky$^a$, A.V. Sokolov$^{a,b}$, A.M. Sukharev$^a$, E.V. Starostina$^{a,b}$, A.A. Talyshev$^{a,b}$, V.A. Tayursky$^a$, V.I. Telnov$^{a,b}$, Yu.A. Tikhonov$^{a,b}$, K.Yu. Todyshev$^{a,b}$, G.M. Tumaikin$^a$, Yu.V. Usov$^a$, A.I. Vorobiov$^a$, V.N. Zhilich$^a$, V.V. Zhulanov$^{a,b}$, A.N. Zhuravlev$^{a,b}$

$^a$ Budker Institute of Nuclear Physics, 11, Akademika Lavrentieva Prospect, Novosibirsk, 630090, Russia
$^b$ Novosibirsk State University, 2, Pirogova Street, Novosibirsk, 630090, Russia
$^c$ Novosibirsk State Technical University, 20, Karl Marx Prospect, Novosibirsk, 630092, Russia

Abstract

The ratio of the electron and muon widths of the $J/\psi$ meson has been measured using direct $J/\psi$ decays in the KEDR experiment at the VEPP-4M electron–positron collider. The result

$$\Gamma_{ee}/\Gamma_{\mu\mu} = 1.0022 \pm 0.0044 \pm 0.0048 (0.65\%)$$

is in good agreement with the lepton universality. The experience collected during this analysis will be used for $J/\psi$ lepton width determination with up to 1% accuracy.

© 2014 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/3.0/). Funded by SCOAP3.

1. Introduction

The lepton width of a hadronic resonance $\Gamma_\ell$ describes fundamental properties of the strong interaction potential [1]. Comparison of the electron and muon widths $\Gamma_{ee}/\Gamma_{\mu\mu}$ allows one to test the lepton universality and provides information on the models predicting new forces differentiating between lepton species [2].

Currently the two most precise values of the ratio of the $J/\psi$ meson lepton widths come from the CLEO results obtained in 2005 [3] and the recent BESIII measurement [4]. For that analysis both experiments used the $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$, $J/\psi \rightarrow \ell^+ \ell^-$ decay chain ($\ell = e, \mu$).

Our analysis is based on direct $J/\psi$ decays. Its scheme and the sources of systematic uncertainties are completely different from...
those in the CLEO and BESIII measurements. This analysis continues
the work on the lepton width determination [5] but uses an
independent statistical sample. In the future we anticipate precise
measurement of the J/ψ lepton width at the 1% level.

A large resonance cross section provides high statistics of J/ψ
decays even with a relatively low collider luminosity. The inte-
gerated luminosity collected off resonance gives information about
the QED continuum background. In addition to subtracting the
QED background for calculating the numbers of the J/ψ → ℓ⁺ℓ⁻
decays, one has to suppress cosmic ray events. J/ψ hadronic de-
cays and take into account the interference between the resonance
J/ψ → ℓ⁺ℓ⁻ process and QED background. The QED backg-
rounds for the J/ψ → ℓ⁺ℓ⁻ and J/ψ → μ⁺μ⁻ processes are funda-
mentally different due to Bhabha scattering.

2. Experiment

The experiment was performed with the KEDR detector [6]
at the VEPP-4M e⁺e⁻ collider [7]. An integrated luminosity of
2.1 pb⁻¹ corresponding to production of about 6.5 × 10⁶ J/ψ
mesons was collected in the J/ψ resonance energy range from
3086 to 3107 MeV. The experimental data sample was divided
into two parts (Fig. 1 and Fig. 2 for e⁺e⁻ and μ⁺μ⁻ events, re-
spectively): “on-resonance”, with |W - M_J/ψ| < 1.3 MeV (∼ 80% of
statistics), and “off-resonance”, with |W - M_J/ψ| > 8.9 MeV,
where W is the center-of-mass energy. The energy spread σ_w was
about 0.7 MeV.

KEDR is a general-purpose detector with solenoidal magnetic
field. It consists of a vertex detector, a drift chamber, scintillation
time-of-flight counters, aerogel Cherenkov counters, a barrel liquid
krypton calorimeter, an endcap CsI calorimeter, and a muon system
built in the yoke of a superconducting coil generating a field of
0.65 T. The detector also includes a tagging system to detect scattered
electrons for a study of two-photon processes. The on-line
luminosity is measured by two independent single bremsstrahlung
monitors.

The VEPP-4M collider can operate in the wide range of beam
energy from 1 to 6 GeV. The peak luminosity in the J/ψ energy
region is about 2 × 10³⁰ cm⁻² s⁻¹. One of the main features of the
VEPP-4M is its capability to precisely measure the beam energy us-
ing two techniques [8]: resonant depolarization and infrared light
Compton backscattering.

3. Theory

In the soft photon approximation, analytical expressions for the
e⁺e⁻ → ℓ⁺ℓ⁻ cross sections near a narrow resonance including
radiative corrections are presented in Eqs. (1) and (2) below:

\[
\left( \frac{d\sigma}{d\Omega} \right)_{ee → ee}^{\text{th.}} = \frac{1}{M^2} (1 + \delta_{\text{QED}}) \left[ \frac{9}{4} \frac{\Gamma_{ee}}{\Gamma_{ee}} \right] (1 + \cos^2 \theta) \Im \mathcal{F}
\]

\[
- \frac{3\alpha \Gamma_{ee}}{2M} \left[ (1 + \cos^2 \theta) - \frac{(1 + \cos^2 \theta)^2}{(1 - \cos \theta)} \right] \Re \mathcal{F}
\]

\[
+ \left( \frac{d\sigma}{d\Omega} \right)_{QED}^{ee}
\]

\[
(1)
\]

\[
\left( \frac{d\sigma}{d\Omega} \right)_{ee → \mu\mu}^{\text{th.}} = \frac{1}{M^2} (1 + \delta_{\text{QED}}) \left[ \frac{9}{4} \frac{\Gamma_{ee} - \Gamma_{\mu e}^{\mu\mu}}{\Gamma_{ee}} \right] \Im \mathcal{F}
\]

\[
- \frac{3\alpha \sqrt{\Gamma_{ee} - \Gamma_{\mu e}^{\mu\mu}}}{2M} \Re \mathcal{F} \right] (1 + \cos^2 \theta)
\]

\[
+ \left( \frac{d\sigma}{d\Omega} \right)_{QED}^{\mu\mu}
\]

\[
(2)
\]

\[ \mathcal{F} = \frac{\pi \beta}{\sin(\pi \beta)} \left( \frac{M}{W + M - \beta^2} \right)^{1-\beta} \]

\[ \beta = \frac{4\alpha}{\pi} \left( \frac{W}{m_e} - \frac{1}{2} \right) \simeq 0.077, \]

\[ \delta_{\text{QED}} = \frac{3}{4} \beta + \frac{\alpha}{\pi} \left( \frac{\pi^2}{3} - \frac{1}{2} \right) + \beta^2 \left( \frac{37}{12} - \frac{\pi^2}{36} \right) \ln(W/m_e) \]

where W is the center-of-mass energy, and θ is the lepton scatter-
ing angle with respect to the electron beam direction. Corrections
to the vacuum polarization in the interference terms have been
omitted.

The formulae used in this analysis are based on the analytical
expression for the radiative correction integral in the soft photon
approximation (SPA), first obtained in [9]. The accuracy was
improved using [10] as described in [11].

To compare experimental data with the theoretical cross sec-
tions, it is necessary to perform their convolution with a distribu-
tion of the total beam energy, which is assumed to be Gaussian:
Particle of high mass of muons, a more precise expression for the angular selection term. For suppression of the edges of the muon system. To suppress the background of cos- 

\[ \sigma_{\ell\ell}(W) = \int \frac{1}{\sqrt{2\pi}\sigma_W} \exp\left(-\frac{(W-W')^2}{2\sigma_W^2}\right) \sigma_{\ell\ell}^{\text{th}}(W')\,dW'. \quad (3) \]

The beam energy spread \( \sigma_W \) is much larger than the \( J/\psi \) full width \( \Gamma \).

4. Event selection

The following selection requirements were imposed on both \( e^+e^- \) and \( \mu^+\mu^- \) events (the `+` and `−` superscripts correspond to a positive particle and negative one, respectively):

1. Two charged tracks with opposite signs from a common vertex in the interaction region,
2. The total energy deposition in the calorimeter (outside the two energy clusters belonging to the selected particles) is less than 0.15 GeV,
3. Polar \( \theta \) and azimuthal \( \phi \) acollinearity <10\(^\circ\),
4. The momentum \( p^+ > 0.5 \) GeV.

Only for the \( e^+e^- \) selection: the energy deposition for each particle \( E^\pm > 0.7 \) GeV; \( \theta^- \in (41–139)^\circ \) and \( \theta^+ \in (38–142)^\circ \). The fiducial polar angle \( \theta \) is restricted by the physical edges of the liquid krypton calorimeter (37–143)^\circ.

Only for the \( \mu^+\mu^- \) selection: 0.06 GeV < \( E^\pm < 0.7 \) GeV; \( \theta^- \in (49–131)^\circ \) and \( \theta^+ \in (46–134)^\circ \). The polar angle \( \theta \) is restricted by the edges of the muon system. To suppress the background of cosmic events we employed the time-of-flight system. For suppression of the background from \( J/\psi \) hadronic decays, a hit in the muon system is required for a \( \mu^- \) track.

The \( \theta^- \) angle distributions of the selected events are shown in Fig. 3 and Fig. 4 for \( e^+e^- \) and \( \mu^+\mu^- \), respectively.

5. Simulation

The contributions of the \( e^+e^- \) and \( \mu^+\mu^- \) resonance and interference events were simulated according to the theoretical angular distributions (1) and (2), respectively. The final state radiation was taken into account using the PHOTOS [12] package.

For the resonance contribution of \( \mu^+\mu^- \) due to the relatively high mass of muons, a more precise expression for the angular distribution \( \frac{d^2\sigma}{d\Omega} \propto \beta \times (1 + \cos^2\theta + (1 - \beta^2) \times \sin^2\theta) \) was taken. The contribution of the \( \sin^2\theta \) term to this analysis is about 0.2%.

The uncertainty in the Bhabha process simulation was evaluated via comparison of our result with two independent event generators: BHWIDE [13] and MCGPJ [14]. For the \( e^+e^- \rightarrow \gamma\gamma \) process, the BAYAKA generator [15] was employed. For estimating the \( J/\psi \) background, the BES generator [16] was used.

To take the coincidence of the signal and background into account, we added the random events recorded every 2 \( \cdot 10^{-6} \) beam crossing to the simulated events.

6. \( J/\psi \rightarrow e^+e^- \) event counting

We begin our analysis by determining independently the number of \( e^+e^- \) and \( \mu^+\mu^- \) events produced in \( J/\psi \) decays.

A summary of observed events, principal backgrounds, signals and their efficiency is presented in Table 1.

Table 1

| Event number       | \( N_{\text{ee}} \) | \( N_{\text{mm}} \) |
|--------------------|---------------------|--------------------|
| \( \text{on-resonance} \) | 425 786 ± 658 | 162 515 ± 406 |
| QED (bck)          | 190 345 ± 770 | 5750 ± 181       |
| \( J/\psi \rightarrow \text{hadr. (bck)} \) | 373 | 215 |
| \( J/\psi \rightarrow \ell\ell \) decays | 235 298 ± 774 | 156 550 ± 447 |
| Efficiency          | \( \varepsilon_{ee}, \% \) | \( \varepsilon_{mm}, \% \) |
| \( \varepsilon_{\text{ToF}} \) | 77.78          |
| \( \varepsilon \)   | 60.14          |
| \( N(J/\psi \rightarrow \ell\ell)/\varepsilon \) | 391 281 ± 1287 | 390 412 ± 1113 |

The \( \text{on-resonance} \) data sample was collected in the vicinity of the resonance peak. Thus we have to take into account the
interference effects between $J/\psi$ decays and QED background (the histogram close to zero in Fig. 3). However, the interference effects are an \(~\sim\)1% correction only.

For separating $J/\psi \to e^+e^-$ events from the Bhabha QED background, the number of observed experimental events was fitted to the expected contributions:

$$dN_{ee}^{\text{obs}}(\theta)/d\theta = n \times \text{Res}(\theta) + \{C(E)\} \times \text{Int}(\theta) + L \times \text{QED}(\theta),$$

where $n$ and $L$ are the fit parameters which correspond to the number of observed $J/\psi \to e^+e^-$ events and to the absolute luminosity calibration, respectively. Res$(\theta)$, Int$(\theta)$ and QED$(\theta)$ are the angular distributions from the simulation for the resonance, interference and Bhabha QED background, respectively (Section 5).

The same histograms as presented in Fig. 3 with one degree bin width were used in the fitting procedure. Thus from the detection efficiency $\epsilon_{J/\psi \to e^+e^-}$ we can calculate the number of $J/\psi$ decays during the experiment: $N_{J/\psi \to ee} = n \epsilon_{J/\psi \to e^+e^-}$. The Res$(\theta)$, Int$(\theta)$ and QED$(\theta)$ angular distributions and this efficiency were determined from the simulation and corrected using information about performance of various detector subsystems. The statistical uncertainty of the number of $e^+e^-$ decays is 0.33%.

The $\{C(E)\}$ coefficient, which reflects the energy variation in the data set, is calculated from theory, see Eq. (1), and is determined by the interference magnitude.

The same procedure was performed for the continuum statistics, since in our “off-resonance” data, the resonant contribution and interference effects are also not completely negligible. The number of Bhabha events in continuum is necessary to calculate the number of $J/\psi \to \mu^+\mu^-$ decays.

For calculating the number of $\mu^+\mu^-$ decays (Fig. 2) we have to take the interference into account, subtract the QED background and divide that by the detection efficiency:

$$N_{J/\psi \to \mu^+\mu^-} = \frac{\left[N_{\text{exp}}^{\mu^+\mu^-} - N_{\text{int}}^{\mu^+\mu^-} \times (N_{\text{cont}}^{\mu^+\mu^-} - N_{\text{int}}^{\mu^+\mu^-})\right]}{\epsilon_{J/\psi \to \mu^+\mu^-}}.
$$

As in the $e^+e^-$ case, the efficiency was determined from the simulation and corrected using information about performance of various detector subsystems. The statistical error of the number of $J/\psi \to \mu^+\mu^-$ decays is 0.29%.

7. Systematic uncertainties

A list of main systematic uncertainties in the ratio of $\Gamma_{ee}/\Gamma_{\mu^+\mu^-}$ is presented in Table 2.

| Source                  | Correct., % | Err., % |
|------------------------|-------------|---------|
| Interference           | 0.01        |         |
| Luminosity             | 0.02        |         |
| Energy measurement     | 0.10        |         |
| Radiation corrections  |             |         |
| Background             |             |         |
| $J/\psi \to \text{hadrons}$ | 0.10        |         |
| $e^+e^- \to \gamma\gamma$ | 0.07        |         |
| Cosmic                 |             |         |
| Simulation             |             |         |
| Bhabha                 | 0.11        |         |
| PHOTOS                 | 0.02        |         |
| Trigger                |             |         |
| 1st level              | 0.20        |         |
| 2nd level              | 0.11        |         |
| Event selection        |             |         |
| Tracking system        | 0.10        |         |
| Calorimeter            | 0.10        |         |
| Muon system            | 0.04        |         |
| $\theta$ angle cuts    | 0.10        |         |
| $\theta$ angle det     | 0.14        |         |
| Selection asymmetry    | 0.14        |         |
| ToF inefficiency       | 0.26        |         |
| Total systematic       | 0.48        |         |

The corrections to the detector efficiency were obtained using experimental data. Event selection uncertainties were estimated via variations of the cuts. The uncertainty of the $\theta$ angle determination was evaluated via comparison of the angular measurements performed in the tracking system and the liquid krypton calorimeter.

The event selection was asymmetrical with respect to the particle sign. The same procedures were performed with the opposite sign. The final result is the half-sum and the estimated uncertainty is the half-difference of the results of these two procedures.

The main error comes from the ToF time measurement inefficiency due to a dead time in the time expander. It is a rather large correction as compared with the others. The time distribution for $\mu^-$ is presented in Fig. 5. The cosmic background is flat and could be easily measured. Thus it is possible to estimate the efficiency for the $\mu^+$ with $\mu^-$ time cuts applied and vice versa. The net time-of-flight efficiency is a product of these values:

$$\epsilon_{\text{ToF}} = \epsilon_{\mu^+}(\mu^-) \times \epsilon_{\mu^-}(\mu^+) = (77.78 \pm 0.12 \pm 0.03)\%$$

provided that there are no correlations. This assumption was checked with an electron data sample ($\epsilon_{\text{ToF}}^{ee} = 76.35\%$ as compared with $\epsilon_{\text{ToF}}^{ee} = 76.41\%$). The absolute difference

$$\delta \epsilon_{\text{ToF}}/\epsilon_{\text{ToF}} = (\epsilon_{\text{ToF}}^{\text{real}} - \epsilon_{\text{ToF}}^{\text{calc}})/\epsilon_{\text{ToF}}^{\text{calc}} = 0.21\%$$

estimates the possible correlation magnitude. Adding the statistical uncertainty (\sim0.12%) and uncertainty from the cosmic background (\sim0.03%) estimation in quadrature, we obtain a total systematic uncertainty of 0.26%.
Fig. 5. The ToF time distribution for $\mu^-$. The arrows represent the ToF cuts $\pm 3\sigma_t$, where $\sigma_t = 0.36$ ns is a ToF time resolution.

Fig. 6. Comparison of the current and earlier measurements of the ratio $\Gamma_{ee}/\Gamma_{\mu\mu}$. The vertical grey band marks the average value and uncertainty of the 2012 PDG compilation [20].

8. Result

To conclude, a measurement of the ratio of the lepton widths $\Gamma_{ee}$ and $\Gamma_{\mu\mu}$ has been performed at the VEPP-4M collider using the KEDR detector. Our final result is as follows:

$$\Gamma_{e^+e^-}(J/\psi)/\Gamma_{\mu^+\mu^-}(J/\psi) = 1.0022 \pm 0.0044 \pm 0.0048.$$