PROCEEDINGS OF SCIENCE

Measurement of the ratio of the leptonic widths $\Gamma_{ee}/\Gamma_{\mu\mu}$ for the J/ψ

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,b], I. Yu. Basok[a], A. M. Batrakov[a], O. L. Beloborodova[a,b], A. E. Blinov[a], V. E. Blinov[a,c], A. V. Bobrov[a], V. S. Bobrovnikov[a], A. V. Bogomyagkov[a,b], A. E. 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[a,b], E. B. Levichev[a,c], D. A. Maksimov[a,b], V. M. Malyshev[a], A. L. Maslennikov[a], O. I. Meshkov[a,b], S. I. Mishnev[a], 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], 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], A. A. Ruban[a], V. K. Sandyrev[a], G. A. Savinov[a], A. G. Shamov[a], D. N. Shatilov[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], A. N. Yushkov[a], V. N. Zhilich[a], V. V. Zhulanov[a,b] and A. N. Zhuravlev[a,b]

[a]*Budker Institute of Nuclear Physics, Novosibirsk, Russia*
[b]*Novosibirsk State University, Novosibirsk, Russia*
[c]*Novosibirsk State Technical University, Novosibirsk, Russia*
E-mail: E.M.Baldin@inp.nsk.su

Using direct J/ψ decays the ratio of the electron and muon widths of the J/ψ meson was measured with the KEDR experiment at the VEPP-4M electron-positron collider. The result

$$\Gamma_{e^+e^-}(J/\psi)/\Gamma_{\mu^+\mu^-}(J/\psi) = 1.0022 \pm 0.0044 \pm 0.0048 \ (0.65\%).$$

is in good agreement with lepton universality. Experience collected during this analysis will be used for J/ψ lepton width determination with 1% accuracy.

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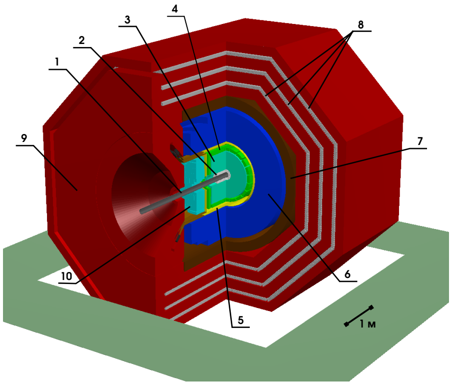

Figure 1: (1) Vacuum chamber, (2) Vertex detector, (3) Drift chamber, (4) Threshold aerogel counters, (5) ToF counters, (6) Liquid krypton calorimeter, (7) Superconducting coil, (8) Magnet yoke, (9) Muon tubes, (10) CsI-calorimeter

1. Introduction

Currently the world average value [1] of the J/ψ meson lepton width is completely dominated by the CLEO results obtained in 2005 [2]. Recently the BESIII collaboration announced the most precise measurement of the ratio of the electron and meson widths [3]. For that analysis both experiments used the $\psi(2S) \to J/\psi\pi^+\pi^-$, $J/\psi \to \ell^+\ell^-$ decay chain ($\ell = e,\mu$).

Our analysis is based on direct J/ψ decays and continues work on lepton width determination [4] anticipating a precise J/ψ lepton width measurement at the 1% level.

2. Experiment

The experiment was performed with the KEDR detector [5] at the VEPP-4M e^+e^- collider [6]. The integrated luminosity of 2.1 pb^{-1} corresponding to production of about $6.5\cdot 10^6$ J/ψ mesons was collected in the J/ψ energy range. The experimental data sample was divided into two parts (Fig. 3): “resonance” with $|W - M_{J/\psi}| < 1.3\,\mathrm{MeV}$ ($\approx 80\%$ of statistics) and “continuum” with $|W - M_{J/\psi}| > 8.9\,\mathrm{MeV}$. The energy spread σ_W was about 0.7 MeV.

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 $2\times 10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. One of the main features of the VEPP-4M is its capability to measure the beam energy precisely using two techniques [7]: resonant depolarization and infrared light Compton backscattering.

The KEDR detector is a general-purpose detector with solenoidal magnetic field. The structure of the detector is presented in Fig. 1.

3. Theory

The analytical expressions for the $e^+e^- \to \ell^+\ell^-$ cross sections near the narrow resonance with radiative corrections in the soft photon approximation are presented below (3.1)–(3.2):

$$\begin{aligned}\left(\frac{d\sigma}{d\Omega}\right)^{ee\to ee} = & \frac{1}{M^2}\left(1+\delta_{\mathrm{rc}}\right)\left\{\frac{9}{4}\frac{\Gamma^2_{e^+e^-}}{\Gamma M}\left(1+\cos^2\theta\right)\mathrm{Im}\,\mathscr{F} - \right.\\ & \left. -\frac{3\alpha}{2}\frac{\Gamma_{e^+e^-}}{M}\left[\left(1+\cos^2\theta\right)-\frac{(1+\cos\theta)^2}{(1-\cos\theta)}\right]\mathrm{Re}\,\mathscr{F}\right\}+\left(\frac{d\sigma}{d\Omega}\right)^{ee\to ee}_{\mathrm{QED}},\end{aligned} \tag{3.1}$$

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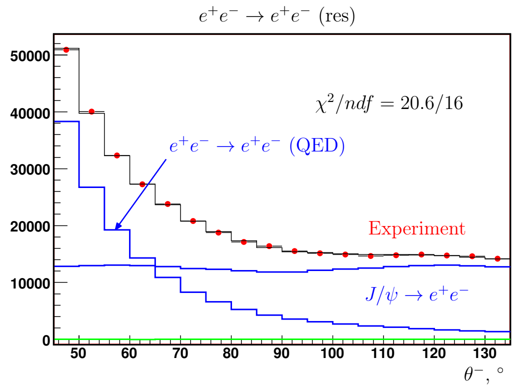

Figure 2: Distribution of selected $e^+e^- \to e^+e^-$ events for the resonance data part with respect to the electron scattering angle

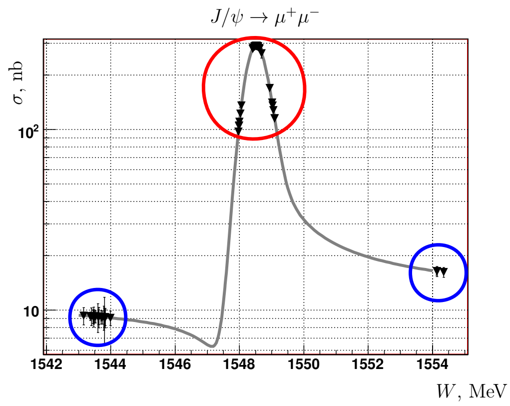

Figure 3: The theoretical dimuon cross section in the experimental energy ranges. The red circle corresponds to the "resonance" data, the blue circles are the "continuum" data.

$$\left(\frac{d\sigma}{d\Omega}\right)^{ee\to\mu\mu} = \frac{1}{M^2}(1+\delta_{\rm rc})\left\{\frac{9}{4}\frac{\Gamma_{e^+e^-}\Gamma_{\mu^+\mu^-}}{\Gamma M}\operatorname{Im}\mathscr{F} - \frac{3\alpha}{2}\frac{\sqrt{\Gamma_{e^+e^-}\Gamma_{\mu^+\mu^-}}}{M}\operatorname{Re}\mathscr{F}\right\}(1+\cos^2\theta) + \left(\frac{d\sigma}{d\Omega}\right)^{ee\to\mu\mu}_{\rm QED}, \tag{3.2}$$

$$\mathscr{F} = \left(\frac{\frac{M}{2}}{-W+M-\frac{i\Gamma}{2}}\right)^{1-\beta}, \quad \beta = \frac{4\alpha}{\pi}\left(\ln\frac{W}{m_e}-\frac{1}{2}\right) \simeq 0.077,$$
$$\delta_{\rm rc} = 1+\frac{3}{4}\beta+\frac{\alpha}{\pi}\left(\frac{\pi^2}{3}-\frac{1}{2}\right)+\beta^2\left(\frac{37}{96}-\frac{\pi^2}{12}-\frac{L}{72}\right),$$

where $L = \ln(W^2/m_e^2)$. Corrections to the vacuum polarization are omitted in the interference terms.

The formulas used in this analysis are based on the analytical expression for the radiative correction integral in the soft photon approximation (SPA) first obtained in [8]. The accuracy was improved using [9] as described in [10].

4. $J/\psi \to \ell^+\ell^-$ event counting

We begin our analysis by determining independently the number of e^+e^- and $\mu^+\mu^-$ events produced in direct J/ψ decay.

In Fig. 2 we show the distribution of the electron scattering angle for selected $e^+e^- \to e^+e^-$ events in the resonance data part. The displayed points represent the experimental values, while the histograms correspond to the simulation. The Bhabha angle distribution differs from $J/\psi \to e^+e^-$ decays. At small angles Bhabha scattering prevails, while at large angles events of resonance decay dominate. So these processes can be separated by using only a data sample collected at the "resonance". The "continuum" events are not required.

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A "resonance" data sample was collected in the vicinity of the resonance peak. Thus we need to take into account the interference effects (the green line in Fig. 2). However, the interference effects are a small correction only.

The number of observed experimental events could be compared with simulation:

$$\frac{dN_{ee}^{\rm obs}}{d\theta} = aN_0^{\rm sim}\left(\mathrm{Res}(\theta) + \frac{2\alpha}{3\mathscr{B}_{ee}}\langle F_{\rm res}(E)\rangle\,\mathrm{Int}(\theta)\right) + L_{\rm res}\left(\frac{d\sigma}{d\theta}\right)_{\rm QED} \tag{4.1}$$

where a and L are the fit parameters. The fit parameter L corresponds to the absolute luminosity calibration. $\mathrm{Res}(\theta)$ and $\mathrm{Int}(\theta)$ are the angular distributions from simulation for resonance and interference, respectively, $\mathscr{B}_{ee}$ is a branching fraction for $J/\psi \to e^+e^-$, $N_0^{\rm sim}$ is the total number of $J/\psi \to e^+e^-$ decays events in simulation. Thus from the detection efficiency $\varepsilon_{J/\psi\to ee}$ we can calculate the number of J/ψ decays during experiment: $N_{J/\psi\to ee} = aN_0^{\rm sim}/\varepsilon_{J/\psi\to ee}$. This efficiency was determined by Monte Carlo and corrected using data. The statistical error for the number of e^+e^- decays is 0.33%.

The $\langle F\rangle$ coefficient that reflects the energy variation in the data set is calculated from theory and corresponds to the interference magnitude.

The same procedure was performed for continuum statistics. In our "continuum" data the resonant contribution and interference effects are also not completely negligible. The number of Bhabha events in continuum is necessary for $J/\psi \to \mu^+\mu^-$ decay calculation.

For calculating the number of $\mu^+\mu^-$ decays (Fig. 3) we need to take into account interference, subtract QED background and divide by the detection efficiency:

$$N_{J/\psi\to\mu\mu} = \frac{\left\{N_{\rm res}^{\rm exp} - N_{\rm int}^{\rm th} - \frac{L_{\rm res}}{L_{\rm cont}} \times \left(N_{\rm cont}^{\rm exp} - N_{\rm int}^{\rm th}\right)\right\}}{\varepsilon_{J/\psi\to\mu\mu}}. \tag{4.2}$$

As in the e^+e^- case, the efficiency was determined by Monte Carlo and corrected using data. The statistical error for the number of $J/\psi \to \mu^+\mu^-$ decays is 0.29%.

5. Event selection

The following selection requirements were imposed for both e^+e^- and $\mu^+\mu^-$ events ($+$ and $-$ signs correspond to the positive and negative particle, respectively):

1. 2 charged tracks with opposite signs from a common vertex in the interaction region,
2. $E_{\rm all} - (E_+ + E_-) < 0.15\,\mathrm{GeV}$,
3. θ and φ acollinearity $< 10^\circ$,
4. $p_\pm > 0.5\,\mathrm{GeV}$.

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

Only for $\mu^+\mu^-$ selection: $0.06\,\mathrm{GeV} < E^\pm < 0.7\,\mathrm{GeV}$, $\theta^- \in (49 \div 131)$ and $\theta^+ \in (46 \div 134)$. The polar angle θ is restricted by the edges of the muon system. To suppress background of cosmic events the time-of-flight system was employed. To suppress background from J/ψ hadrons decays, the continuation in the muon system is required for μ^- .

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Source	Err, %
Interference	
Relative luminosity	0.01
Energy measurement	0.02
Radiation corrections	0.10
Background	
$J/\psi \to$ hadrons	0.10
Cosmic	0.07
Simulation	
Bhabha	0.11
PHOTOS	0.02

to be continued ↗

Source	Err, %
Trigger	
1st level	0.20
2nd level	0.11
Event selection	
tracking system	0.10
calorimeter	0.10
muon system	0.04
θ angle cuts	0.10
θ angle determination	0.14
Selection asymmetry	0.14
ToF inefficiency	0.26
Total	*0.48*

Table 1: Systematic uncertainties

6. Simulation

The contributions of the e^+e^- and $\mu^+\mu^-$ resonance and interference events were simulated according to the theoretical angular distributions (3.1)–(3.2). The final state radiation was accounted for by using the PHOTOS [11] package.

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

The uncertainty in the Bhabha process simulation was evaluated by comparing our result with two independent event generators: BHWIDE [12] and MCGPJ [13]. For the $e^+e^- \to \gamma\gamma$ process the BABAYAGA generator [14] was employed. For estimating J/ψ background the BES generator [15] was used.

To account for a coincidence of the signal and background the experimental data sample recorded with "random trigger" was added to simulated events.

7. Systematic uncertainty

A list of main systematic uncertainties is presented in Table 1. Relative luminosity, energy measurement and theoretical radiation correction are important mainly for the interference effects which are small corrections only.

The hadron contribution was estimated by using Monte Carlo and the scale of uncertainty was estimated by using nuclear interaction simulation packages FLUKA [16] and GHEISHA [17] (as implemented in GEANT 3.21 [18]).

The corrections to detector and trigger efficiency were obtained by using data. Event selection uncertainties were estimated by varying cuts. The uncertainty of θ angle determination was evaluated by comparing results obtained by using for angle measurements the tracking system and liquid krypton calorimeter.

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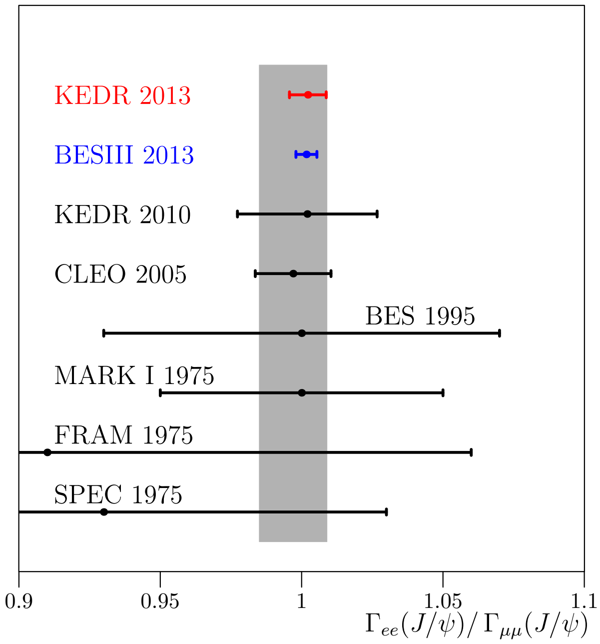

Figure 4: $\Gamma_{ee}/\Gamma_{\mu\mu}$ comparison. The position and width of the bar corresponds to the PDG2012 fit [1].

The event selection was asymmetrical with respect to a particle sign. The same procedures were performed with opposite sign. The final result is half-sum and estimated error is half-difference.

The main error comes from the ToF inefficiency. It's a very large correction in comparison with others. The correction was obtained by using $\mu^+\mu^-$ data and uncertainty was estimated by using e^+e^- data where the cosmic background is negligible.

8. Result

Our final result is:

$$\Gamma_{e^+e^-}(J/\psi)/\Gamma_{\mu^+\mu^-}(J/\psi) = 1.0022 \pm 0.0044 \pm 0.0048 \ (0.65\%).$$

This result is in good agreement with lepton universality. Comparison with other measurements is presented in Fig. 4.

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