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Precision measurement of the branching fraction for the decay $\psi(2S) \to \tau^+\tau^- at BESIII$

Jianyong Zhang,[a,*] **Bingxin Zhang,**[a] **Xiaohu Mo,**[a] **Ping Wang**[a] **and Isabella Garzia**[b]

[a] *Institute of high energy physics, Chinese academy of sciences*
Yuquan road 19B, Shijingshan District, Beijing, China
[b] *University of Ferrara-INFN Ferara*

E-mail: jyzhang@ihep.ac.cn

Abstract

Using $(2259.3 \pm 11.1) \times 10^6 \psi(2S)$ events acquired with the BESIII detector, the branching fraction of $\psi(2S) \to \tau^+\tau^-$ is measured with improved precision to be $Br(\psi(2S) \to \tau^+\tau^-) = (3.240 \pm 0.023 \pm 0.081) \times 10^{-3}$, where the first and second uncertainties are statistical and systematic, respectively, which is consistent with the world average value within one standard deviation. This value, along with those for the branching fractions of the $\psi(2S)$ decaying into e^+e^- and $\mu^+\mu^-$, is in good agreement with the relation predicted by the sequential lepton hypothesis.

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*Speaker

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1. INTRODUCTION

In recent years, experimental studies of B meson decays have hinted toward deviations from the Standard Model (SM) expectations of Lepton Flavor Universality (LFU) in semileptonic decays. Many experiments have provided evidence suggesting that it may be better to probe LFU by searching for deviations of the ratios

$$R(D^{(*)}) = \frac{\Gamma(B \to D^{(*)}\tau^+\nu_\tau)}{\Gamma(B \to D^{(*)}l^+\nu_l)}, (l = e, \mu) \tag{1}$$

from their expected values. The combined results of BaBar [1], Belle [2] and LHCb [3] show a deviation from the SM prediction by 3.1 σ [4]. Meanwhile, this process also affords a unique platform to compare the three generations of the leptonic weak interaction by studying the leptonic decays of $\psi(2S) \to e^+e^-, \mu^+\mu^-$, and $\tau^+\tau^-$. The sequential lepton hypothesis leads to a relationship between the branching fractions of these decays, $B_{e^+e^-}$, $B_{\mu^+\mu^-}$, and $B_{\tau^+\tau^-}$, given by

$$\frac{B_{e^+e^-}}{\nu_e(\frac{3}{2} - \frac{1}{2}\nu_e^2)} = \frac{B_{\mu^+\mu^-}}{\nu_\mu(\frac{3}{2} - \frac{1}{2}\nu_\mu^2)} = \frac{B_{\tau^+\tau^-}}{\nu_\tau(\frac{3}{2} - \frac{1}{2}\nu_\tau^2)}, \tag{2}$$

with $\nu_l = \sqrt{1 - (4m_l^2/M_{\psi(2S)}^2}$ and l = e, μ, τ . Substituting the nominal masses of the leptons and $\psi(2S)$, we obtain

$$B_{e^+e^-} \approx B_{\mu^+\mu^-} \approx \frac{B_{\tau^+\tau^-}}{0.3890} \equiv B_{l^+l^-} \tag{3}$$

The BESIII Collaboration collected about 2259 million $\psi(2S)$ events in 2021 [5], such a large data sample allows for a more precise study.

2. DETECTOR AND DATA SAMPLES

The BESIII detector [6] records symmetric e^+e^- collisions provided by the BEPCII storage ring [7] in a center of mass energy range from 1.84 to 4.95 GeV, with a peak luminosity of 1.1 $\times 10^{33} cm^{-2}s^{-1}$ achieved at $\sqrt{s}$ = 3.773 GeV. The cylindrical core of the BESIII detector covers 93 % of the full solid angle and consists of a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), which are all enclosed in a superconducting solenoidal magnet providing a magnetic field of about 1.0 T. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identification modules interleaved with steel. The property of the can be found in Ref. [6]

The response of the BESIII detector is reproduced using a GEANT4-based [8] MC simulation software package, which includes the geometric and material description of the BESIII detector, the detector response and digitization models. Simulated MC samples of signal and background processes are produced to optimize the event selection criteria, determine the detection efficiency and estimate the background contamination. In the inclusive MC sample, the production of the $\psi(2S)$ resonance is simulated by the KKMC generator The signal MC sample for the process $\psi(2S) \to \tau^+\tau^-$ are generated using ConExc generator In order to take into account the initial state radiation (ISR) effect and continuum background process on detection efficiency, the lineshape of

the Born cross section for these processes obtained by calculating multiple energy points from 3.670 GeV to 3.700 GeV in the vicinity of $\psi(2S)$ considering beam energy spread effect is used as input into the ConExc generator to simulate the signal process.

3. EVENT SELECTION AND BACKGROUND ANALYSIS

Candidate events of $\psi(2S) \to \tau^+\tau^-$ are identified by their pure leptonic decay modes with one τ decaying into an electron and the other into a muon final state. We select candidate events with a total number of charged tracks equal to 2 and net charge equals to zero. For each track, the point of closest approach to the interaction point (IP) must be within 1 cm in the plane perpendicular to the beam direction and within 10 cm along the beam direction. Moreover a polar angle is required to be in the range $|\cos\theta|$ <0.93. Furthermore, a track should pass the vertex fit, and its momentum is required to be less than 1.2 GeV/c based on signal MC studies. The number of photons in the EMC is required to be zero due to no photon in the final state of our signal.

The two charged tracks are required to be identified as an electron and a muon, respectively. An electron is identified if it satisfies the following requirements: the ratio of deposited energy in the EMC to its momentum ($E/P(e)$) falls between 0.8 and 1.2, the $\chi^2_{dE/dx}(e)$ of the fitted track in the MDC is less than 4, and the difference between the expected flight time and the measured time in the TOF $|\Delta tof|(e)$ is less than 0.3 ns. The other charged track is identified as a muon if $E/P(\mu) < 0.7$, $\chi^2_{dE/dx}(\mu) < 4$ and $|\Delta tof|(\mu) < 0.3$ ns. To distinguish between the μ and π particles, an additional requirement on the incident depth of track in the MUC and momentum should be greater than $a \times (p - b)$ cm, where the parameters a = 81 cm and b = 0.65 GeV/c.

In order to distinguish the signal and background events, the following variables are used:

$$P4_{\rm mis} = P4_{\psi(2S)} - P4_{e\mu}, \tag{4}$$

$$\cos\theta_{\rm mis} = \frac{-(p_e + p_\mu)_z}{|p_e + p_\mu|}, \tag{5}$$

$$U_{\rm mis} = E_{mis} - P_{mis}, \tag{6}$$

where $P4_{\rm mis}$, $P4_{\psi(2S)}$, and $P4_{e\mu}$ are the four momenta of the missing particles, the $\psi(2S)$ resonance and the leptonic pairs (electron-muon pairs), respectively. The missing mass $M_{\rm mis}$, obtained by calculation of the missing four momentum ($P4_{\rm mis}$), is required to be less than 3.05 GeV/c^2 after optimization, effectively eliminating a lot of $\pi^+\pi^- J/\psi$ backgrounds. The polar angle of missing particles $\theta_{\rm mis}$ in Eq. 5 is required to be $|\cos\theta_{\rm mis}| < 0.8$ to reject the two-photon backgrounds. After above selection, 280412 candidate events are survived.

The potential backgrounds are estimated using inclusive MC sample of $\psi(2S)$ events.The dominant backgrounds are from the decay of $\psi(2S) \to \tau^+\tau^- \to e^+\nu_e\bar{\nu_\tau}\pi^-\bar{\nu_\tau}$ and $\pi^+\bar{\nu_\tau}e^-\bar{\nu_e}\nu_\tau$. The number of background events from inclusive MC sample and two-photon processes are estimated to be 11531 and 308, respectively, while the effect of QED backgrounds (Bhabha, di-μ and di-γ) is negligible. The total number of background events is estimated to be 11839, with a background fraction of approximately 4.3%.

4. Cross section calculation on $e^+e^- \to \tau^+\tau^-$

Experimentally, the measured total τ-pair production cross section has the form [9]:

$$\begin{aligned}\sigma_{\rm exp}(s, m_\tau, \Delta) = \int_0^\infty d\sqrt{s'} G(\sqrt{s'}, \sqrt{s}) \\ \times \int_0^{1-\frac{4m_\tau^2}{s'}} dx F(x, s') \frac{\bar{\sigma}_t(s'(1-x), m_\tau)}{|1 - \Pi(s'(1-x))|^2} \,.\end{aligned} \tag{7}$$

Here, $F(x, s)$ is the initial state radiation factor [9], parameterized as

$$\begin{aligned}F(x,s) = \beta x^{\beta-1}[1 + \frac{3}{4}\beta + \frac{\alpha}{\pi}\frac{\pi^2}{2} - \frac{1}{2} + \beta^2\frac{9}{32} \\ - \frac{1}{12}\pi^2] - \beta(1 - \frac{1}{2}x) + \frac{1}{8}\beta^2[4(2-x) \\ \ln\frac{1}{x} - \frac{1+3(1-x^2)}{x}\ln(1-x) - 6 + x],\end{aligned} \tag{8}$$

with

$$\beta = \frac{2\alpha}{\pi}\left(\ln\frac{s}{m_e^2} - 1\right).$$

Π is the vacuum polarization factor, and $G(\sqrt{s'}, \sqrt{s})$, is usually treated as a Gaussian distribution

$$G(\sqrt{s'}, \sqrt{s}) = \frac{1}{2\pi\Delta} e^{\frac{-(\sqrt{s}-\sqrt{s'})^2}{2\Delta}} \,,$$

where Δ depicts the energy spread of the e^+e^- collider. We explicitly indicate the dependence of the cross section on s and m_τ in Eq. (7).

The total cross section $\bar{\sigma}_{\rm tot}$ consists of three parts,

$$\bar{\sigma}_{\rm tot}(s) = F_s(s) \cdot (\sigma_{\rm con}(s) + \sigma_{\rm int}(s) + \sigma_{\rm res}(s))/\sigma_{\rm con}(s) \,, \tag{9}$$

where $\sigma_{\rm con}(s)$, $\sigma_{\rm res}(s)$, and $\sigma_{\rm int}(s)$ stand for the cross sections of continuum, resonance, and interference parts, respectively, defined as

$$\begin{aligned}\sigma_{\rm con}(s) &= \frac{4\pi\alpha^2}{3s} \,, \\ \sigma_{\rm res}(s) &= \frac{12\pi\Gamma_e^2}{(s-M_R^2)^2 + M_R^2\Gamma_\tau^2} \,, \\ \sigma_{\rm int}(s) &= \frac{8\alpha\Gamma_e}{\pi\sqrt{s}} \frac{s - M_R^2}{(s-M_R^2)^2 + M_R^2\Gamma_\tau^2} \,,\end{aligned} \tag{10}$$

and

$$F_s(s) = \sigma_{\rm con}(s) \cdot \frac{\pi(3-v^2)}{1 - \exp(-\pi\alpha/v)} \tag{11}$$

with

$$v^2 \equiv 1 - \frac{4m_\tau^2}{s}. \tag{12}$$

Notice that v is function of s and m_τ. Here s, m_τ, Γ_e, Γ_τ and M_R are the c.m. energy, mass of τ, width of electron, width of τ lepton and the mass of $\psi(2S)$ resonance, respectively. Finally, we obtain all kinds of cross section distribution according to above formula. The continuum plus interference cross section at the center of mass energy 3686.10 MeV with energy spread of 1.3 MeV, is calculated to be σ_{Q+I} = 2.125 nb.

5. Systematic Uncertainty

Systematic uncertainties in the branching fraction measurement come from the luminosity measurement, total number $\psi(2S)$ events, tracking efficiency, particle identification (PID) efficiency, μ and π separation, number of photon requirement, missing mass ($M_{\rm mis}$) and cos$\theta_{\rm mis}$ requirement, QED cross section calculation, branching fraction of τ decays, and background estimation.

Table 1: Relative systematic uncertainties in the measurement of the branching fraction of the $\psi(2S) \to \tau^+\tau^-$.

Source	Uncertainty (%)
Luminosity	1.1
$N_{\psi(2S)}$	0.5
Track efficiency	1.0
PID	1.2
μ and π separation	1.0
N_γ requirement	0.2
$M_{\rm mis}$ requirement	0.8
$\theta_{\rm mis}$ requirement	0.1
Background	0.3
Cross section calculation	0.4
Quoted branching fraction	0.3
MC statistics	0.1
Total	2.5

All the systematic certainties are summarized in Table 1. Combining all the contributions of individual items, a total systemic uncertainty of 2.5% on the $Br(\psi(2S) \to \tau^+\tau^-)$ is estimated.

6. The branching fraction measurement and summary

Eq. 13 is used to calculate the branching fraction of $\psi(2S) \to \tau^+\tau^-$

$$\mathcal{B}_{\tau^+\tau^-} = \frac{\frac{N_{\rm sig}-N_{\rm bkg}}{\mathcal{B}_{e\mu}\cdot\epsilon} - \sigma_{Q+I}\mathcal{L}}{N_{\psi(2S)}}, \tag{13}$$

where $N_{\rm sig}$ is the number of observed signal events, $N_{\rm bkg}$ is the number of background events estimated with the inclusive MC sample and two-photon processes, ϵ is the detection efficiency estimated from signal MC sample. $\mathcal{B}_{e\mu}$ is the product of the branching fractions of $\tau^+ \to e^+\nu_e\bar{\nu_\tau}$ and $\tau^+ \to \mu^+\nu_\mu\bar{\nu_\tau}$. $N_{\psi(2S)}$ is the total number of $\psi(2S)$ events [5], and $\mathcal{L}$ is the luminosity of the data sample [5]. The obtained results are summarized in Table 2. The branching fraction of $\psi(2S)$ $\to \tau^+\tau^-$ is calculated to be

$$\mathcal{B}_{\tau^+\tau^-} = (3.240 \pm 0.023 \pm 0.081) \times 10^{-3}, \tag{14}$$

where the first and second uncertainties are statistical and systematic, respectively.

Table 2: Number used in calculating the branching fraction of $\psi(2S) \to \tau^+\tau^-$.

$N_{\rm obs}$	$N_{\rm bkg}$	$\mathcal{L}$ (pb^{-1})	ϵ	$N_{\psi(2S)}(10^6)$	σ_{Q+I} (nb)	$\mathcal{B}_{\tau^+\tau^-}(10^{-3})$
280412 ± 530	11839 ± 109	3208.5	0.3065	2259.3	2.125	3.240 ± 0.023 ± 0.081

In summary, we have measured the branching fraction of $\psi(2S) \to \tau^+\tau^-$ with improved precision. Together with the world average value of $\mathcal{B}_{e^+e^-}$ and $\mathcal{B}_{\mu^+\mu^-}$ from PDG [10], a perfect agreement is shown in Table 3. Assuming lepton universality, the average value $\mathcal{B}_{l^+l^-}$ is determined to be $(8.06 \pm 0.14) \times 10^{-3}$.

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Table 3: Leptonic branching fractions of the $\psi(2S)$ in 10^{-3}

$\mathcal{B}_{e^+e^-}$ [10]	$\mathcal{B}_{\mu^+\mu^-}$ [10]	$\mathcal{B}_{\tau^+\tau^-}$/0.3890
7.94 ± 0.22	8.00 ± 0.60	8.33 ± 0.22