TESTS OF STANDARD MODEL IN LEPTONIC SECTOR AND R^*

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We describe the current status of a few tests of the Standard Model using high-precision measurements in the leptonic sector. In particular, lepton universality after recent measurements of the τ lepton mass as well as muon anomalous magnetic moment are discussed. Also reported are recent measurements of the R value in the charmonium and bottomonium energy ranges.

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1. Introduction

Experiments with colliding beams have become the major source of results in high energy physics. e^+e^- colliders provide particularly clean conditions for various tests of the Standard Model (SM). In this report we will discuss a few important applications of recent high-precision experiments performed at low energy e^+e^- colliders.

2. τ lepton mass and lepton universality

Lepton universality is an important intrinsic feature of the SM. Basically, it means that four-fermion couplings are flavor-independent. For example, we can compare the value of the Fermi constant in $\tau^- \to e^-\nu_\tau\bar{\nu}_e$ and $\mu^- \to e^-\nu_\mu\bar{\nu}_e$ decays. If lepton universality holds, the quantity r depending on lepton parameters ($F_{\rm cor} \approx 1$)

$$r = \left(\frac{G_{\tau\to e\nu_\tau\bar{\nu}_e}}{G_{\mu\to e\nu_\mu\bar{\nu}_e}}\right)^2 = \left(\frac{m_\mu}{m_\tau}\right)^5 \left(\frac{t_\mu}{t_\tau}\right) \mathcal{B}\left(\tau \to e\nu_\tau\bar{\nu}_e\right) \frac{F_{\rm cor}(m_\mu, m_e)}{F_{\rm cor}(m_\tau, m_e)}\,, \qquad (1)$$

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should equal one. Note that τ lepton mass enters the relation in the fifth power and thus its value and accuracy are crucial for a sensitive SM test. In 1992 the value of r was 0.9405 ± 0.0249 or by -2.4σ off unity [1]. The situation changed dramatically after the BES group made a precise mass measurement near threshold [2]. Their mass value of $1776.96^{+0.31}_{-0.27}$ MeV was 7.14 MeV smaller than the previous world average with an order of magnitude higher precision. Taking also into account some improvement of the τ lepton lifetime and leptonic branching fraction, one obtained $r = 0.9999 \pm 0.0069$ in excellent agreement with lepton universality. It is worth noting here that the majority of the measurements prior to or after the BES experiment gave a higher m_τ value, therefore necessitating its independent determination.

Two new high-precision measurements of the τ lepton mass appeared recently — at KEDR [3] and at Belle [4]. The experiment KEDR at the Novosibirsk collider VEPP-4M used the same technique as BES, *i.e.* measured the energy dependence of the cross section of τ pair production near threshold. An important advantage of the Novosibirsk experiment is the ability to determine the absolute value of the beam energy with unprecedental accuracy. It is based on the resonance depolarizaton method, which allowed a recent remeasurement of the J/ψ and $\psi(2S)$ masses with very high precision [5]. In the τ lepton mass measurement a relatively slow resonance depolarization was complemented by monitoring beam energy with backscattered laser photons. The energy dependence of the cross section measured by KEDR is shown in Fig. 1.

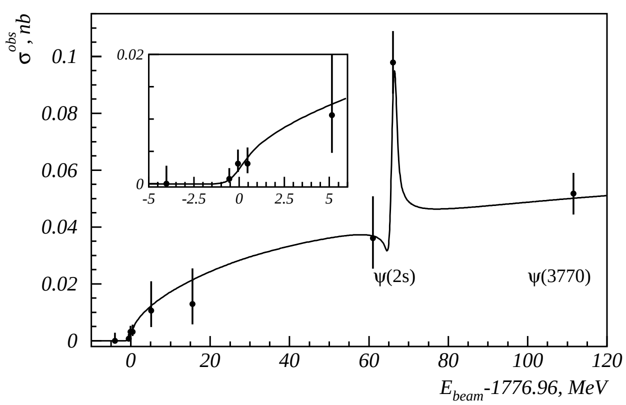

Fig. 1. Cross section of $e^+e^- \to \tau^+\tau^-$ at KEDR.

From 81 selected events the mass value is $m_\tau = 1776.81^{+0.25}_{-0.23} \pm 0.15$ MeV. KEDR continues running to increase a data sample and decrease systematics, which is now dominated by the 100 keV uncertainty due to the detector efficiency.

The Belle collaboration used a different way of measuring m_τ — a so called pseudomass method [4]. In this method the invariant mass of all detected τ decay products is calculated. Since a neutrino always escapes detection, this invariant mass (referred to as pseudomass) is always smaller than the τ mass, however, in the kinematic limit of very small neutrino energies it tends to m_τ. Therefore, a fit determining the end-point of the pseudomass spectrum gives the m_τ value. In reality, this spectrum is smeared by resolution effects as well as by radiative corrections, but comparison with the Monte Carlo simulation allows to extract the τ mass. In Fig. 2 we show the pseudomass distribution obtained from a data sample of 414 fb^{-1} or 370×10^6 $\tau^+\tau^-$ pairs and selecting three-pion decays of the τ lepton.

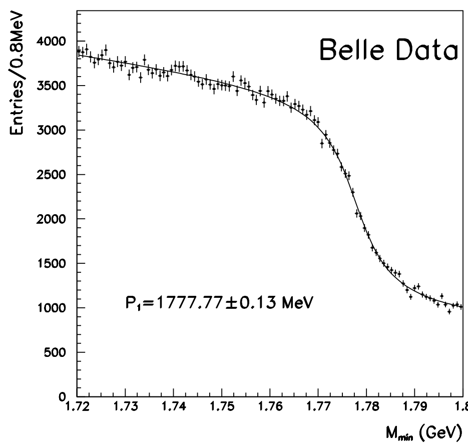

Fig. 2. Pseudomass distribution at Belle.

Two main sources of systematic uncertainties are beam energy and tracking (0.26 MeV) and spectrum parameterization (0.18 MeV). The final result is

$$m_\tau = 1776.61 \pm 0.13 \pm 0.35 \text{ MeV}\,. \tag{2}$$

Since this method allows separate consideration of the τ leptons of different charge, one can obtain m_{τ^+} and m_{τ^-} independently and test CPT by comparing them. The result is

$$\Delta m = m_{\tau^+} - m_{\tau^-} = 0.05 \pm 0.23 \pm 0.14 \text{ MeV}\,, \tag{3}$$

or

$$\frac{|\Delta m|}{m_\tau} < 2.8 \times 10^{-4} \text{ at } 90\%\text{CL} \tag{4}$$

improving the existing limit from OPAL [6] by one order of magnitude.

Both results agree with each other as well as with the BES measurement and confirm a lower mass value. The result of KEDR currently has accuracy close to the world average. If we average the results of KEDR and Belle with the previously obtained mass values, we obtain $m_\tau = 1776.83 \pm 0.18\,\mathrm{MeV}$. Together with the world average values of the lifetime and leptonic branching it gives $r = 1.0039 \pm 0.0040$ consistent with leptonic universality. Note also the increased test sensitivity (0.0040 compared to 0.0249 in 1992).

3. Anomalous magnetic moment

The muon anomalous magnetic moment, a_μ, is one of the most accurately known physical quantities, which has been recently measured by the E821 group [7] to be $a_\mu = (11659208.0 \pm 6.3) \times 10^{-10}$. Its comparison to the theoretical prediction in the SM provides its stringent test. Any significant difference of a_μ^{exp} from a_μ^{th} indicates new physics beyond the SM. It is conventional to write a_μ as $a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{had}}$.

For the QED part terms up to α^3 are known analytically [8]. Taking into account a recent more accurate numerical calculation of the α^4 terms and the leading log α^5 terms [9–11] and taking $\alpha^{-1} = 137.035999710(96)$ from the latest result for a_e [12, 13], one obtains [14]:

$$a_\mu^{\mathrm{QED}} \; = \; (116584718.09 \pm 0.14 \pm 0.08) \times 10^{-11}\,, \tag{5}$$

where the errors are due to the uncertainties of the $\mathcal{O}(\alpha^5)$ term and α.

The electroweak term is $a_\mu^{\mathrm{EW}} = (15.4 \pm 0.1 \pm 0.2) \times 10^{-10}$, where the first uncertainty is due to hadronic loops while the second one is caused by the errors of M_H, M_t and 3-loop effects [15].

The hadronic contribution is $a_\mu^{\mathrm{had}} = a_\mu^{\mathrm{had,LO}} + a_\mu^{\mathrm{had,HO}} + a_\mu^{\mathrm{had,LBL}}$, where the dominant contribution comes from the leading-order term

$$a_\mu^{\mathrm{had,LO}} = \Big(\frac{\alpha m_\mu}{3\pi}\Big)^2 \int\limits_{4m_\pi^2}^{\infty} ds\, \frac{R(s)\,\hat{K}(s)}{s^2}\,, \tag{6}$$

with $R(s) = \sigma(e^+e^- \to \mathrm{hadrons})/\sigma(\mathrm{e^+e^-} \to \mu^+\mu^-)$, and the kernel $\hat{K}(s)$ growing from 0.63 at $s = 4m_\pi^2$ to 1 at $s \to \infty$, $1/s^2$ emphasizing the role of low energies. Particularly important is the reaction $e^+e^- \to \pi^+\pi^-$ with a large cross section below $1\,\mathrm{GeV}$.

Our new estimate takes into account the recent progress in the low energy e^+e^-annihilation and includes the data not yet available previously [16–18]. In addition to the previously published ρ meson data [19], CMD-2 reported their final results on the pion form factor F_π from 370 to 1380 MeV [20–22]. The new ρ meson sample has an order of magnitude larger statistics and a systematic error of 0.8%. SND measured F_π from 390 to 970 MeV with a systematic error of 1.3% [23]. KLOE studied F_π using the method of radiative return or ISR [24–26] at $590 < \sqrt{s} < 970\,\mathrm{MeV}$ with a sample of 1.5×10^6 events and systematic error of 1.3% [27]. BaBar also used ISR and achieved impressive results on various final states with more than two hadrons [28–30].

In Fig. 3 we show the pion form factor data from CMD-2, KLOE and SND. The $|F_\pi|$ values from CMD-2 and SND are in good agreement. The KLOE data are consistent with them near the ρ meson peak, but exhibit a somewhat different energy dependence. However, the contributions to a_μ from all three experiments are consistent.

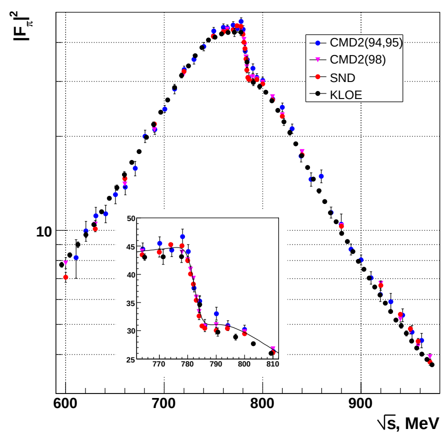

Fig. 3. $|F_\pi|$ from CMD-2, KLOE and SND.

Using the new data below 1.8 GeV discussed above in addition to the whole data set of [16, 17] for old experiments, and assuming that for the hadronic continuum above 1.8 GeV one can already use the predictions of perturbative QCD, we can reevaluate the leading-order hadronic contribution and obtain $a_\mu^{\mathrm{had,LO}} = (690.9 \pm 3.9_{\mathrm{exp}} \pm 2.0_{\mathrm{th}}) \times 10^{-10}$ [31], where the theoretical error is due to uncertainties of radiative corrections in old measurements and mentioned above use of pertubative QCD. It can be seen that due to a higher accuracy of e^+e^- data the uncertainty of $a_\mu^{\mathrm{had,LO}}$ is now 4.4 (0.63%) compared to 15.3 of Ref. [16] and 7.2 of Ref. [18] in units of 10^{-10}. The most recent estimate of the higher-order hadronic contribution performed in [32] gives $(-9.8 \pm 0.1) \times 10^{-10}$ and has a negligible error compared to that of the leading-order one.

The most difficult situation is with the light-by-light hadronic contribution, which is estimated only theoretically. Even the correct sign of this term was established quite recently [33]. The older predictions based on the chiral model and vector dominance [34,35] were compatible and much lower than that using short-distance QCD constraints [36] (see also [37]). Their approximate averaging in [38] gives $(120 \pm 35) \times 10^{-11}$. Even higher uncertainty is listed in Ref. [39] who added some terms not taken into account in Ref. [36] to obtain $(110 \pm 40) \times 10^{-11}$.

The total hadronic contribution is $a_\mu^{\text{had}} = (693.1 \pm 5.6) \times 10^{-10}$. This result agrees with other recent estimations [18, 32, 40–42] and has better accuracy due to the new e^+e^-data. All separate contributions are collected in Table I. The improved precision of the leading-order hadronic contribution

TABLE I

Experiment *versus* theory.

Contribution	$a_\mu \times 10^{-10}$
Experiment	11659208.0 ± 6.3
QED	11658471.94 ± 0.14
Electroweak	$15.4 \pm 0.1 \pm 0.2$
Hadronic	693.1 ± 5.6
Theory	11659180.5 ± 5.6
Experiment–Theory	27.5 ± 8.4 (3.3σ)

allows to confirm previously observed excess of the experimental value over the SM prediction with a higher than before significance of more than three standard deviations. For the first time during last years the accuracy of the SM prediction is slightly better than the experimental one.

What is the future of this SM test? From the experimental side there are suggestions to improve the accuracy by a factor of 2.5 at E969 (BNL) or even by an order of magnitude at JPARC. It is clear that it will be extremely difficult to improve the accuracy of the SM prediction significantly. One can optimistically expect that by 2008 new high-statistics ISR measurements at KLOE, BaBar and Belle together with the more precise R below 4.3 GeV from CLEO-c will decrease the error of $a_\mu^{\text{had,LO}}$ from 4.4 to 2.8×10^{-10}. Experiments are planned at the new machine VEPP-2000 now commissioning, which is a VEPP-4M upgrade with two detectors (CMD-3 and SND) up to $\sqrt{s} = 2\,\text{GeV}$ with $L_{\max} = 10^{32}$ cm^{-2}s^{-1}. A similar machine (DAΦNE-II) is discussed in Frascati. New R measurements below 5 GeV will be done at the $\tau - c$ factory now under construction in Beijing. We can estimate that by 2010 the accuracy of $a_\mu^{\text{had,LO}}$ will be improved from 2.8 to 2.2×10^{-10} and the total error of 4.1×10^{-10} will be limited by the LBL term (3.5×10^{-10}) and still higher than the expected 2.5×10^{-10} in E969.

There is still no explanation for the observed discrepancy between the predictions based on τ lepton and e^+e^-data [18]. For this reason we are not using τ data in this update. One expected that more light on the problem would be shed by the high-statistics measurement of the two-pion spectral function by Belle which preliminary results indicated to better agreement with e^+e^-data than before [43]. However, it turns out that while in a relatively small range of masses from 0.8 to 1.2 GeV the $\pi\pi$ spectral function measured at Belle is below the ALEPH one, this effect is compensated by the spectral function behavior at low and high masses, so that the resulting contribution to the hadronic part of the muon anomaly is about the same as before.

Let us hope that progress of theory will allow a calculation of $a_\mu^{\rm had}$ from first principles (QCD, Lattice). One can mention here a new approach in the QCD instanton model [44] or calculations on the lattice [45, 46].

4. *R* measurement

Until recently the situation with R in the charmonium region was determined by more than 25-year-old data. For example, parameters of the ψ family in PDG were based on the measurements of DASP [47] and MARK I [48]. In Ref. [49] an attempt was made to use more precise data from Crystal Ball [50] and BES [51] and it was shown that the above parameters can change strongly. Finally, the BES group published the analysis of their data [52]. In their parameterization R is described by a smooth u, d, s background plus a coherent sum of the four ψ states, each an incoherent sum of two-body D_1D_2 states. Their results are shown in Fig. 4. Preliminary results for the precise R determination in the charmonium region were also reported by CLEO [53].

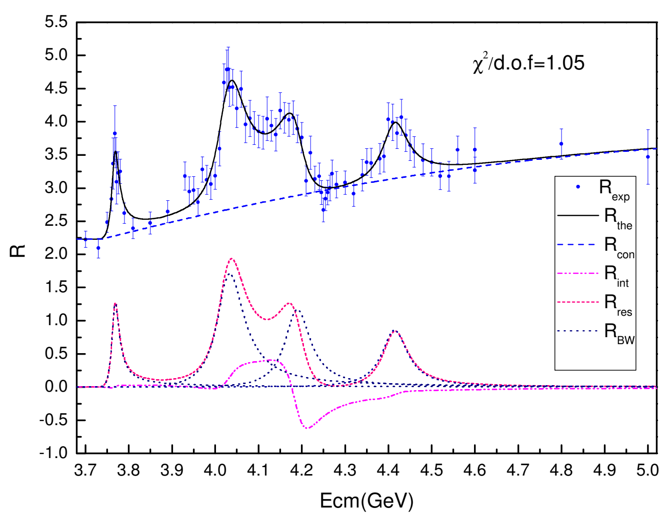

Fig. 4. Higher charmonia at BES.

Probably most promising would be the R determination from exclusive measurements of different final states with charmed meson pairs. First results of this type were recently obtained in initial-state-radiation analyses at B factories in which the cross sections of the reactions $e^+e^- \to D^+D^-$ and $e^+e^- \to D^{(*)+}D^{*-}$ were measured by BaBar [54] and Belle [55], respectively. Taken together, both cross sections reasonably well reproduce the pattern of R observed by BES. Both groups see a minimum in the $Y(4260)$ region, which may be due to $D_s^*D_s^*(DD^{**})$ thresholds or interference effects. A new feature is a broad signal at 3900 MeV observed by BaBar.

Finally, one should mention a high energy R measurement at CLEO [56] in which R values were obtained at seven c.m. energy points between 6.964 and 10.538 GeV with a very high accuracy — the total uncertainty was 2% only, see Fig. 5. Their results well agree with the pQCD predictions supporting the old measurement of Crystal Ball between 5 and 7 GeV [57] and disfavoring that of Mark I [58]. Altogether, the new results on R will provide improved determinations of various QCD parameters.

In conclusion, recent precise measurements in the leptonic sector have been performed. Lepton universality has been confirmed after the new τ lepton mass measurements. Significant progress of e^+e^- experiments at low energy (BaBar, BES, CMD-2, KLOE and SND) substantially improved our knowledge of $a_\mu^{\rm had,LO}$. Future experiments as well as development of theory should clarify whether the observed 3.3σ difference between $a_\mu^{\rm exp}$ and

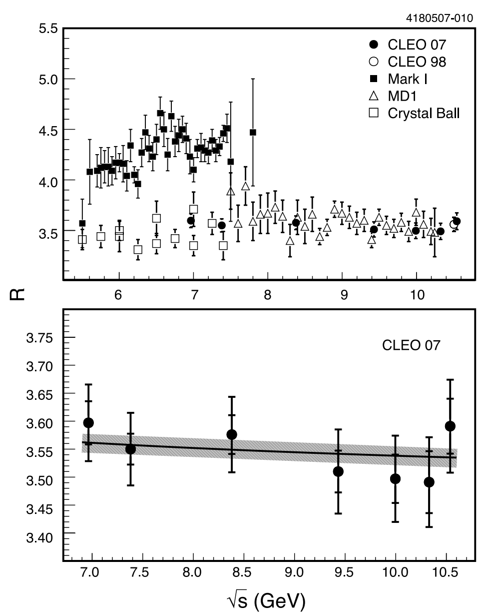

Fig. 5. R measurement at CLEO.

$a_\mu^{\rm th}$ is real and what consequences for the Standard Model it implies. New measurements of R between 3 and 10 GeV (BaBar, Belle, BES and CLEO) allow an improved determination of the running α [59], α_s and other QCD parameters [60].

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