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e^+e^- ANNIHILATION *versus* τ DECAYS AND MUON ANOMALOUS MAGNETIC MOMENT*

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New results on the low energy e^+e^- annihilation into hadrons from Novosibirsk and Beijing are described. The validity of the CVC relation between e^+e^- and τ decays is considered. Implications of the new measurements for the evaluation of the hadronic contribution to the muon anomalous magnetic moment are discussed.

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1. Introduction

The recently reported measurement of the muon anomalous magnetic moment $a_\mu = (g_\mu - 2)/2$ by the E821 collaboration at BNL [1] and a possible deviation of its result from the predictions of the Standard Model (SM) [2] has generated numerous speculations about possible new physics (for a review and discussion see [3]).

a_μ known today to 0.7 ppm is one of the best measured quantities in physics. Although the electron anomalous magnetic moment a_e is known to even higher accuracy than a_μ, measurements of the latter are better suited for a search for new physics since in most of the cases new effects are proportional to the lepton mass squared and we immediately obtain a gain of $(m_\mu/m_e)^2 \sim 4 \times 10^4$.

Within the SM, the uncertainty of the theoretical value of the leading order a_μ is dominated by the uncertainty of the hadronic contribution. Although it cannot be determined from the first principles, $a_\mu^{\rm had,LO}$ can be calculated via the dispersion integral (see *e.g.* [4] and references therein)

$$a_\mu^{\rm had,LO} = \left(\frac{\alpha\, m_\mu}{3\pi}\right)^2 \int\limits_{4m_\pi^2}^{\infty} \frac{R(s)\hat{K}(s)}{s^2}\, ds\,, \tag{1}$$

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where the QED kernel $\hat{K}(s)$ is a smooth function of energy varying from 0.63 at $s = 4m_\pi^2$ to 1 at $s \to \infty$ and $R(s)$ is the following dimensionless quantity characterizing the total cross section of $e^+e^- \to$ hadrons:

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}\,. \tag{2}$$

The precision of the $a_\mu^{\text{had,LO}}$ calculation depends on the approach used and varies from 1.34 ppm based on e^+e^- data only [5] to 0.53 ppm if in addition τ-lepton decay data as well as perturbative QCD and QCD sum rules are extensively used [2]. As it is clear from Eq. (1), the major contribution to its uncertainty comes from the systematic error of the $R(s)$ measurement at low energies ($s < 2$ GeV^2), which is, in its turn, dominated by the systematic error of the measured cross section $e^+e^- \to \pi^+\pi^-$ or pion form factor F_π directly related to it.

Assuming conservation of the vector current (CVC) and isospin symmetry, the spectral function of the $\tau^- \to \pi^-\pi^0\nu_\tau$ decay can be related to the isovector part of the pion form factor measured in e^+e^- annihilation [6]. The detailed measurement of the spectral functions was provided by ALEPH [7], OPAL [8] and CLEO-II [9]. The comparison of the pion form factor measured at e^+e^- colliders with the spectral function of the $\tau^- \to \pi^-\pi^0\nu_\tau$ decay provides a test of CVC. If CVC holds with high accuracy, τ-lepton decay data can be also used to improve the accuracy of the calculations mentioned above [10, 11].

Thus, new high precision measurements of the cross section of the process $e^+e^- \to$ hadrons and particularly of the pion form factor as well as precise determinations of the hadronic mass spectra in τ lepton decays become extremely important.

2. New results from e^+e^- colliders

2.1. Experiments at VEPP-2M

Since 1974 the e^+e^- collider VEPP-2M has been successfully running in the Budker Institute of Nuclear Physics in Novosibirsk in the c.m. energy range from the threshold of hadron production to 1400 MeV, its maximum luminosity being $\sim 3 \times 10^{30}$ cm^{-2}s^{-1} at the ϕ meson energy [12]. In the last series of experiments two detectors (CMD-2 and SND) installed at VEPP-2M collected about 30 pb^{-1} each.

CMD-2 described in detail elsewhere [13] is a general purpose detector. Inside a superconducting solenoid with a field of 1 T there are a drift chamber, a proportional Z-chamber and an endcap BGO electromagnetic calorimeter. Outside there is a barrel CsI electromagnetic calorimeter and muon streamer tube chambers. The main goal of CMD-2 is to perform a high precision measurement of the cross sections of exclusive hadronic channels and detailed studies of the low lying vector mesons — ρ, ω and ϕ.

SND described in detail elsewhere [14] is a nonmagnetic detector with drift chambers for tracking and a three layer NaI electromagnetic calorimeter. Outside it there are muon streamer tube chambers and plastic scintillators. The main goal of SND is to study ρ, ω and ϕ decays as well as main hadronic channels.

Both experiments possess some special features making high precision measurements feasible:

- large data samples due to the high integrated luminosity and large acceptance,
- multiple scans of the same energy ranges to avoid possible systematic effects; the step was 10 MeV in the c.m. energy for the continuum region and 1–2 MeV near the ω and ϕ peaks,
- the absolute calibration of the beam energy using the resonance depolarization method [15] reduces to a negligible level a systematic error caused by an uncertainty in the energy measurement which can be significant for cross sections with strong energy dependence,
- good space and energy resolution lead to small background,
- redundancy — unstable particles are independently detected via different decay modes ($\omega \to \pi^+\pi^-\pi^0, \pi^0\gamma$; $\eta \to 2\gamma, \pi^+\pi^-\pi^0, 3\pi^0, \pi^+\pi^-\gamma$),
- detection efficiencies and calorimeter response are studied by using "pure" experimental data samples rather than Monte Carlo events; *e.g.* more than 20 million ϕ meson decays can be used for that purpose.

New results are available on most of the hadronic channels. We will briefly mention those with the largest cross section, relevant to the evaluation of $a_\mu^{\mathrm{had,LO}}$.

There are new results on the process $e^+e^- \to \pi^+\pi^-$. This reaction has been extensively studied before [16–19]. The most precise pion form factor data were obtained in late 70s, early 80s by CMD and OLYA detectors [18]. Their accuracy was limited by systematic errors of the experiments, varying from 2% to 15% over the VEPP-2M energy range. In the new measurement CMD-2 collected more than 2 million events of the process $e^+e^- \to \pi^+\pi^-$ from 370 to 1380 MeV. Below 600 MeV separation of Bhabha and $\pi^+\pi^-$ events is performed by measuring their momentum. Above this energy the energy deposition of the final particles in the calorimeter has been used.

The number of events of the reaction $e^+e^- \to \mu^+\mu^-$ was evaluated from QED which validity at these energies had been verified before.

The systematic uncertainty of less than 0.6% was achieved in the final analysis of the data set of about 114 000 events collected in the energy range 610 to 960 MeV in 1994–1995 [20]. Table I lists dominant sources of the systematic error. Analysis is in progress for the rest of events and the expected systematic error ranges from 1% to 3% [21]. Fig. 1 shows results of the pion form factor measurement coming from CMD-2.

TABLE I

Systematic errors in the pion form factor measurement at CMD-2.

Source	Contribution [%]
Event separation	0.2
Radiative corrections	0.4
Detection efficiency	0.2
Fiducial volume	0.2
Correction for pion losses	0.2
Beam energy determination	0.1
Total	0.6

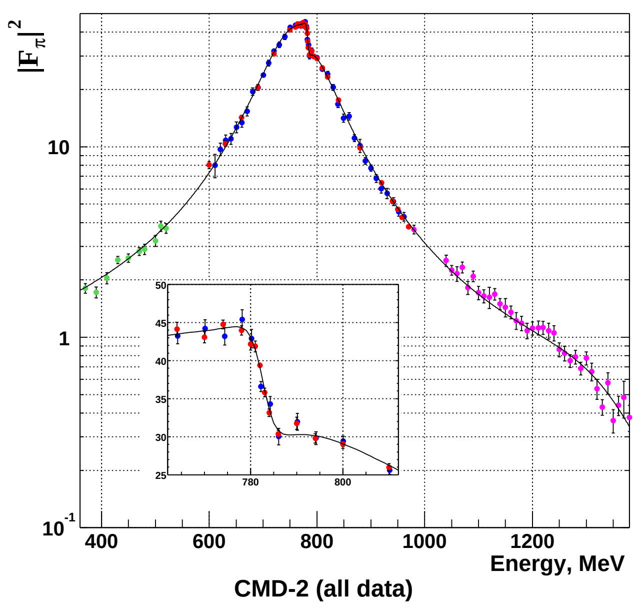

Fig. 1. New data on the pion form factor from CMD-2.

CMD-2 measured with high accuracy the main parameters of the ω and ϕ mesons using their decays to $\pi^+\pi^-\pi^0$ [22,23], and also studied the ϕ meson by its $K_{\rm S}K_{\rm L}$ decay mode [24]. SND performed a high precision measurement of three main decay modes of the ϕ meson in one experiment [25]. These studies allow a significant improvement in the accuracy of the leptonic widths of the ω and ϕ mesons.

SND also studied production of three pions above the ϕ and showed that the energy dependence of the cross section is consistent with the existence of at least one additional isoscalar resonance [26]. These conclusions are confirmed by preliminary results from CMD-2.

Both detectors observed production of four pions. CMD-2 showed that in the energy range above the ϕ the $a_1(1260)^{\pm}\pi^{\mp}$ intermediate mechanism dominates in the $\pi^+\pi^-\pi^+\pi^-$ channel whereas both $a_1(1260)^{\pm}\pi^{\mp}$ and $\omega\pi$ contribute to the $\pi^+\pi^-\pi^0\pi^0$ final state [27]. The contribution of other possible intermediate states is small. The collected data sample includes about 60 000 events and the systematic uncertainty of the total cross sections is less than 15%. Below 1 GeV CMD-2 reliably selected about 200 events of the reaction $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ and measured the cross sections as low as about 50 pb near the ρ peak [28]. The measurement of the SND detector for which the data sample above the ϕ was about 80 000 events and the systematic uncertainty ranged from 8% to 20%, confirmed the CMD-2 results on the production mechanisms [29].

However, in both 4π channels the SND cross sections are higher than those of CMD-2. The systematic uncertainties are still high and their further analysis is needed to clarify the picture.

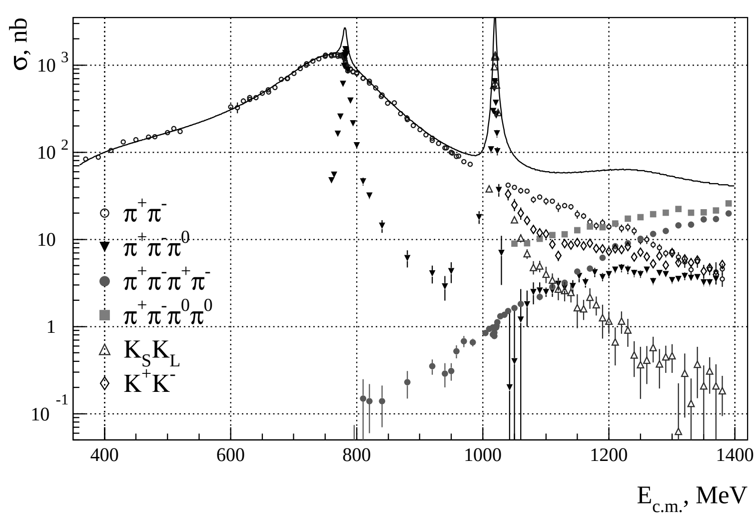

Fig. 2. Hadronic cross sections from CMD-2.

Both detectors measured the cross section of the reaction $e^+e^- \to \omega\pi^0$ in the $\omega \to \pi^0\gamma$ channel collecting several thousand events each with the systematic error of 5% for SND [30] and 6.6% for CMD-2 [31]. The results of both groups are consistent within systematic errors.

Thus, in the new experiments at the VEPP-2M collider in Novosibirsk in the c.m. energy range from 0.37 to 1.38 GeV most of the hadronic reactions contributing to R have been measured with much better accuracy than before. The overall picture of the energy dependence of various hadronic cross sections measured by CMD-2 is shown in Fig. 2.

2.2. R measurement at BES

Until recently the energy range above 1.4 GeV was studied much worse. Despite numerous measurements of exclusive cross sections and R by various groups in Frascati, Orsay, DESY and SLAC, the existing data have big scatter and large systematic uncertainties ranging from 10% to 25%.

A real breakthrough occurred after recent experiments with the BES detector at Beijing [32] in which the total cross section and R were thoroughly measured in the energy range from 2 to 5 GeV. High statistics collected in this experiment combined with the better acceptance than before and careful analysis of the systematic uncertainties provided a basis for the significant improvement of the accuracy of $R(s)$. Table II illustrates the progress by comparing some characteristics of the BES experiment with the R measurement by the $\gamma\gamma2$ group at Frascati [33].

TABLE II

Comparison of $\gamma\gamma2$ and BES measurements.

Detector	$\gamma\gamma2$	BES
$\sqrt{s}$, GeV	2.0–3.1	2.0–3.0
Acceptance, %	19–23	50–68
Syst. error, %	21	5.2–8.2
$\int L dt, \mathrm{nb}^{-1}$	130	990
$\mathrm{N}_{\mathrm{had}}$	920	18 500

In Fig. 3 we depict $R(s)$ for the whole energy range up to 10 GeV. The data are in good agreement with the prediction of perturbative QCD shown by the curve.

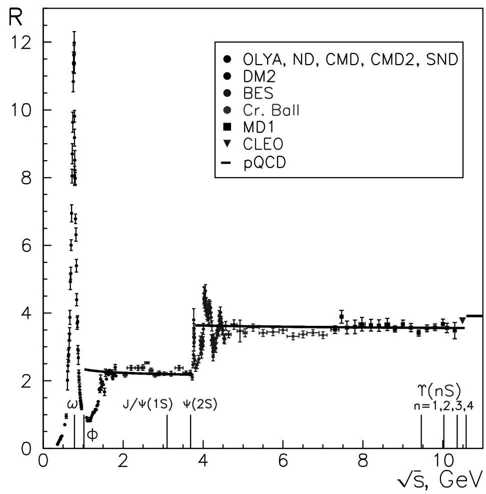

Fig. 3. $R(s)$ below 10 GeV.

3. Comparison to τ lepton decays

For the Cabibbo allowed vector part of the weak hadronic current the distribution over the mass of produced hadrons is given by

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2|V_{ud}|^2 S_{EW}}{32\pi^2\alpha^2 m_\tau^3} \times \left(m_\tau^2 - q^2\right)^2 \left(m_\tau^2 + 2q^2\right) v_1(q^2)\,, \tag{3}$$

where G_F is the Fermi constant, $|V_{ud}|$ is the corresponding element of the CKM matrix, S_{EW} is a factor taking into account electroweak radiative corrections approximately equal to 1.02 [34] and $v_1(q^2)$ is a spectral function

$$v_1(q^2) = \frac{q^2\sigma_{e^+e^-}^{I=1}(q^2)}{4\pi\alpha^2}\,. \tag{4}$$

Numerous tests of these relations based on the e^+e^- and τ data showed their validity within the experimental accuracy [35]. However, recent e^+e^- results as well as a new high statistics measurement of ALEPH [36] revealed problems in both 2π and 4π modes [37]. In the 2π channel the spectral functions measured by CLEO [9], ALEPH [7,36] and OPAL [8] are consistent with each other and in general well reproduce the picture observed in e^+e^- annihilation: the $\rho(770)$ meson peak followed by the $\rho(1450)$ and possibly $\rho(1700)$. This is illustrated by Fig. 4. However, a more elaborate comparison of the spectral functions expressed as a ratio of e^+e^- to τ shows that the e^+e^- data are significantly lower by 2–3% below the ρ peak, the discrepancy increasing to 10% at 0.9–1.0 GeV, see Fig. 5. Note that all τ data are corrected for various effects of isospin breaking according to Refs. [38,39].

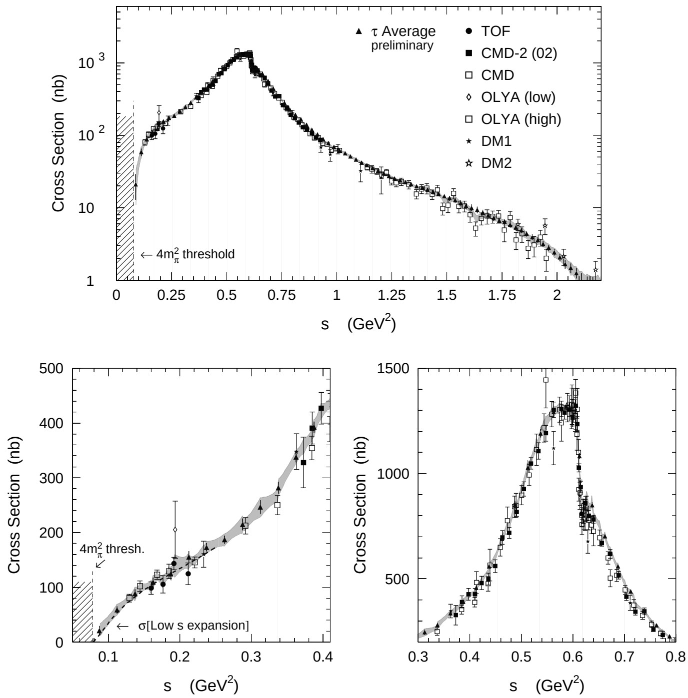

Fig. 4. Comparison of the $\pi^+\pi^-$ spectral functions from e^+e^- and isospin-breaking corrected τ data, expressed as e^+e^- cross sections. The band indicates the combined e^+e^- and τ result within 1σ errors.

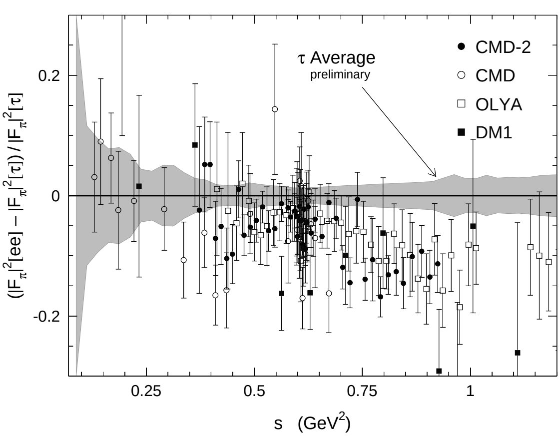

Fig. 5. Relative comparison of the $\pi^+\pi^-$ spectral functions from e^+e^- and isospin-breaking corrected τ data, expressed as a ratio to the τ spectral function. The band shows the uncertainty on the latter.

Let us discuss now the 4π channels. Qualitatively, the behavior of the e^+e^- and τ spectral functions is similar, see comparison of the $2\pi^+2\pi^-$ and $\pi^+\pi^-2\pi^0$ spectral functions from e^+e^- and τ in Fig. 6. Moreover, the CMD-2 analysis of intermediate mechanisms in the 4π production is consistent with the conclusions of CLEO [40]. The model used by CMD-2 to account for their results has been successfully applied [41] to describe various two pion and three pion distributions for both CLEO and ALEPH. It also provided a good input for updating the TAUOLA code for Monte Carlo simulation of τ decays [42]. While spectral functions are consistent in the $2\pi^+2\pi^-$ case, there is an obvious problem for the $\pi^+\pi^-2\pi^0$ final state, where the τ spectral function is on the average slightly higher in the energy range below 1.4 GeV and significantly higher above that energy.

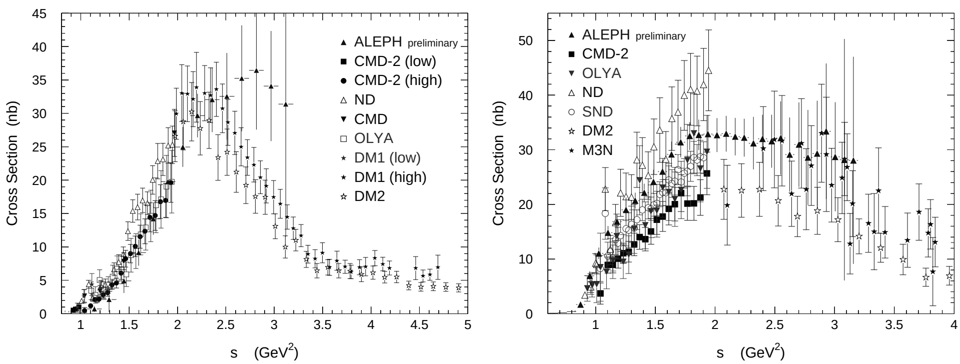

Fig. 6. Comparison of the $2\pi^+2\pi^-$ (left) and $\pi^+\pi^-2\pi^0$ (right) spectral functions from e^+e^- and isospin-breaking corrected τ data, expressed as e^+e^- cross sections.

We summarize the comparison in Table III showing the expected branching ratios for the τ decays discussed above obtained with the relevant e^+e^- spectral functions. To obtain the branching ratios, we integrated Eq. (3). Assuming lepton unversality in the charge weak current, one has from the recent ALEPH data $B(\tau^- \to e^-\bar{\nu}_e\nu_\tau) = (17.810 \pm 0.039)\%$ [36] which is used in Table III.

TABLE III

Branching ratios of τ decays into 2 and 4 pions [%].

Mode	τ data	e^+e^- via CVC	$\Delta(\tau - e^+e^-)$
$\pi^-\pi^0\nu_\tau$	25.46 ± 0.12	23.98 ± 0.30	$+1.48 \pm 0.32$
$\pi^-3\pi^0\nu_\tau$	1.01 ± 0.08	1.09 ± 0.08	-0.08 ± 0.11
$2\pi^-\pi^+\pi^0\nu_\tau$	4.54 ± 0.13	3.63 ± 0.21	$+0.91 \pm 0.25$

As expected, a large discrepancy is observed for the 2 pion final state, which is as large as 4.6σ. The situation with the 4π channels is different. Agreement is observed for the $\pi^- 3\pi^0$ mode, whereas for the $2\pi^-\pi^+\pi^0$ mode the relative difference is $(22 \pm 6)\%$, too high to be ascribed to any reasonable level of isospin symmetry breaking. It rather points to experimental problems that have to be investigated.

4. Implications of the new data for a_μ

Let us estimate the implications of the new results in the e^+e^- and τ sectors for the hadronic contribution to $(g_\mu - 2)/2$. We will start from the conservative estimate using e^+e^- data only. Below 5 GeV we perform direct integration of the e^+e^- data in Eq. (1) and above this energy rely on the predictions of perturbative QCD. Below 2 GeV to determine R we use the sum of exclusive channels and from 2 to 5 GeV the direct R measurements. Results of the calculation are summarized in Table IV. It can be seen that the contribution of the energy range above 5 GeV is 1.5% only, so that the uncertainty from using QCD is negligible. The total leading order hadronic contribution appears to be $(684.7 \pm 7.0) \times 10^{-10}$ and the uncertainty is much smaller than before.

TABLE IV

Contributions to $a_\mu^{\mathrm{had,LO}}$.

$\sqrt{s}$ [GeV]	$\Delta a_\mu^{\mathrm{had,LO}}$ [$\times 10^{-10}$]	$\Delta a_\mu^{\mathrm{had,LO}}$ [%]
$2\pi, < 2$	498.8 ± 5.6	72.8
ω	36.9 ± 1.2	5.4
ϕ	34.8 ± 1.1	5.1
0.6–2.0	62.9 ± 2.4	9.2
2.0–5.0	33.9 ± 1.7	5.0
$J/\psi, \psi'$	7.4 ± 0.4	1.1
5.0–12.0	8.1 ± 0.1	1.2
> 12.0	1.8	0.3
Total	684.7 ± 7.0	100.0

In an attempt to improve the accuracy, let us try to use independent τ data for the major 2π and 4π contributions responsible for 73% and 4.5% of the total, respectively. The remainder is taken as before from e^+e^- data and QCD.

In Table V we compare the independent evaluations in e^+e^- and τ sectors. It is clear from the table that the discussed above discrepancies now result in a smaller estimate from e^+e^- data compared to that from the τ data. The total discrepancy of $(-24.3 \pm 7.9) \times 10^{-10}$ amounts to 3.1 standard deviations and precludes from a straightforward combination of the two evaluations.

TABLE V

Comparison of the e^+e^- and τ based evaluations of $a_\mu^{\mathrm{had,LO}}$ $[10^{-10}]$.

Mode	e^+e^-	τ	$\Delta(e^+e^- - \tau)$
$\pi^+\pi^- < 0.5$ GeV	58.0 ± 2.0	56.0 ± 1.6	$+2.0 \pm 2.6$
$\pi^+\pi^-$, 0.5 GeV–m_τ	440.8 ± 4.9	464.0 ± 4.0	-23.2 ± 6.3
$\pi^+\pi^- 2\pi^0$	16.7 ± 1.3	21.4 ± 1.5	-4.7 ± 1.8
$2\pi^+ 2\pi^-$	13.9 ± 0.9	12.3 ± 1.0	$+1.6 \pm 2.0$
Total	529.4 ± 6.1	553.7 ± 5.3	-24.3 ± 7.9

Adding the QED, higher-order hadronic, light-by-light scattering and weak contributions, the following results for a_μ are obtained:

$$a_\mu^{\mathrm{SM}} = (11659169.3 \pm 7.8) \times 10^{-10} \quad e^+e^- \text{ based}, \tag{5}$$

$$a_\mu^{\mathrm{SM}} = (11659193.6 \pm 6.9) \times 10^{-10} \quad \tau \text{ based}. \tag{6}$$

Comparing then to the present experimental average from Ref. [1] and adding experimental and theoretical errors in quadrature, one obtains

$$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (33.7 \pm 11.2) \times 10^{-10} \quad e^+e^- \text{ based}, \tag{7}$$

$$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (9.4 \pm 10.5) \times 10^{-10} \quad \tau \text{ based}, \tag{8}$$

corresponding to 3.0 and 0.9 standard deviations, respectively. A graphical comparison is shown in Fig. 7 together with our previous estimates [2, 5] obtained before the CMD-2 and new τ data were available, as well as the recent evaluation of Ref. [43].

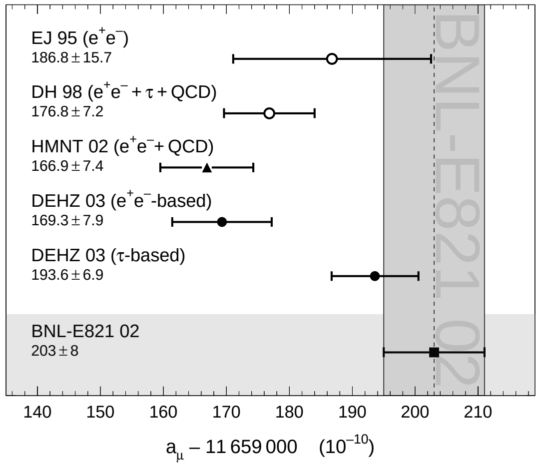

Fig. 7. Comparison with the BNL measurement.

5. Conclusions

Thus, new experiments in Novosibirsk and Beijing considerably improved the accuracy of $R(s)$ in the energy ranges below 1.38 GeV and between 2 and 5 GeV. This in its turn results in the significant improvement of the uncertainty of $a_\mu^{\rm had}$.

Further improvement could come from the τ spectral functions. However, precise tests of the CVC based relation between the e^+e^- cross sections and τ spectral functions show unexpected discrepancies. To resolve the problem, further experimental progress together with better understanding of the effects of isospin symmetry breaking and radiative corrections is needed [44].

Further significant progress will become possible after new experiments planned at Beijing, Cornell and Novosibirsk. Also promising looks a possibility to study low energy e^+e^- annihilation by the radiative return from the $\Upsilon(4S)$ or ϕ mesons [45].

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