

Recent results from $e^+e^- \rightarrow$ hadrons

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New results on the low energy e^+e^- annihilation into hadrons from Novosibirsk and Beijing are described. Implications of the new measurements for the evaluation of the hadronic contribution to the muon anomalous magnetic moment are discussed.

1. Introduction

e^+e^- annihilation into hadrons is one of the most important suppliers of experimental information on the quark interactions. At high energy it serves as a test of perturbative QCD whereas at low energies it provides insight into nonperturbative effects in QCD as well as valuable input to various phenomenological models describing strongly interacting particles.

It became conventional to use the dimensionless quantity $R(s)$ to characterize the total cross section of $e^+e^- \rightarrow$ hadrons:

$$R = \sigma(e^+e^- \rightarrow \text{hadrons}) / \sigma(e^+e^- \rightarrow \mu^+\mu^-). \quad (1)$$

$R(s)$ is widely used for various calculations. Particularly, knowledge of $R(s)$ with high accuracy is required for the evaluation of $a_\mu^{had,LO}$, the leading order hadronic contribution to the anomalous magnetic moment of the muon $a_\mu = (g_\mu - 2)/2$ (see [1] and references therein) or the value of the fine structure constant at the Z boson mass [2].

a_μ known today to better than 1.0 ppm is one of the best measured quantities in physics. The recently reported measurement of a_μ by the E821 collaboration at BNL [3] and a possible deviation of its result from the predictions of Standard Model (SM) [4–6] has generated numerous speculations (for a review and discussion see [7]).

Within SM, the uncertainty of the theoretical value of the leading order a_μ is dominated by the uncertainty of the hadronic contribution that can

be calculated via the dispersion integrals.

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

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 $s \rightarrow \infty$.

The precision of the $a_\mu^{had,LO}$ calculation depends on the approach used and varies from 1.34 ppm based on e^+e^- data only [2] to 0.53 ppm if in addition τ -lepton decay data as well as perturbative QCD and QCD sum rules are extensively used [4]. As it is clear from Eq. 2, the major contribution to its uncertainty comes from the systematic error of the $R(s)$ measurement at low energies ($s < 2 \text{ GeV}^2$), which, in turn, is dominated by the systematic error of the measured cross section $e^+e^- \rightarrow \pi^+\pi^-$ 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 $\tau^- \rightarrow X^- \nu_\tau$ decay, where X^- is a vector hadronic state with $I=1$ can be related to the corresponding isovector state X^0 produced in e^+e^- annihilation [8]. (Here X can be $2\pi, 4\pi, \omega\pi, \dots$). The detailed measurement of the spectral functions was provided by ALEPH [9], OPAL [10] and CLEO-II [11]. Comparison of the hadronic cross sections measured at e^+e^- colliders with the spectral functions of the corresponding τ^- decays provides a test of CVC. If CVC holds with high accuracy, τ -lepton decay data can be also used to substantially improve the accuracy of the calculations mentioned above [12].

Recent indications that the accuracy of CVC relations is not as good as believed for many years necessitates a careful reanalysis of such estimations [13,5]. Thus, new high precision measurements of the cross section of $e^+e^- \rightarrow \text{hadrons}$ 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 [14]. Its maximum luminosity reached $\sim 3 \cdot 10^{30} \text{ cm}^{-2}\text{s}^{-1}$ at the ϕ meson energy. 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 [15] is a general purpose detector. Inside a superconducting solenoid with a field of 1 T there are a drift chamber and proportional Z-chamber, both also used for the trigger, 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 exclusive cross sections of various hadronic channels of e^+e^- annihilation and detailed studies of the low lying vector mesons - ρ , ω and ϕ .

SND described in detail elsewhere [16] is a nonmagnetic detector with drift chambers for tracking and a three layer NaI electromagnetic calorimeter. Outside it there are a muon streamer tube chamber 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 [17] 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 ($\omega \rightarrow \pi^+\pi^-\pi^0, \pi^0\gamma$; $\eta \rightarrow 2\gamma, \pi^+\pi^-\pi^0, 3\pi^0, \pi^+\pi^-\gamma$)
- 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 per detector can be used for that purpose.

New results are available on most of the hadronic channels.

The process $e^+e^- \rightarrow \pi^+\pi^-$ is particularly important for various applications because of its large cross section at low energies. This reaction has been extensively studied before [18–20]. The most precise pion form factor data were obtained in late 70s – early 80s by CMD and OLYA detectors [19]. 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 with the CMD-2 detector more than 2 million events of the process $e^+e^- \rightarrow \pi^+\pi^-$ were detected 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 $e^+e^- \rightarrow \mu^+\mu^-$ 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

Table 1
Main sources of systematic errors.

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

of about 114000 events collected in the energy range 610 to 960 MeV in 1994-1995 [21]. Table 1 lists the 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% [22]. Fig. 1 shows results of the pion form factor measurement coming from CMD-2.

There are still some weak points in this analysis:

- it is important to determine directly the number of muons checking thereby the correctness of the procedure of particle identification as well as the normalization. To this end muon chambers can be used;
- the knowledge of the radiative corrections now dominates among possible sources of systematic uncertainties. It is necessary to check them using experimental events;
- a correction for the radiation of a photon by final pions was applied based on theoretical formulae that assumed pointlike pions. One could try to test this assumption using experimental events with the radiation of a hard photon.

CMD-2 measured with high accuracy the main parameters of the ω and ϕ mesons using their decays to $\pi^+\pi^-\pi^0$ [23,24], they also studied the ϕ meson in its $K_S K_L$ decay mode [25]. SND performed a high precision measurement of three main decay modes of the ϕ meson in one exper-

iment [26]. 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 [27]. These conclusions are confirmed by preliminary results from CMD-2. The exact position of the resonance peak may be significantly lower than that of the $\omega(1420)$.

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 [28]. The contribution of other possible intermediate states is small. The collected data sample includes about 60000 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 $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$ and measured the cross sections as low as about 50 pb near the ρ peak [29]. The measurement of the SND detector for which the data sample above the ϕ was about 80000 events and the systematic uncertainty ranged from 8 to 20%, confirmed the CMD-2 results on the production mechanisms [30].

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. The corresponding cross sections are shown in Fig. 2 and Fig. 3 together with the results of the previous measurements at VEPP-2M, DCI and ADONE (for the references see [28]).

Both detectors measured the cross section of the reaction $e^+e^- \rightarrow \omega\pi^0$ in the $\omega \rightarrow \pi^0\gamma$ channel collecting several thousand events each with the systematic error of 5% for SND [31] and 8.5% for CMD-2 [32]. Results of both groups are consistent within systematic errors.

CMD-2 reliably observed multihadronic processes $e^+e^- \rightarrow \eta\pi^+\pi^-$ and $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^0$ with the systematic accuracy of 15% [33].

CMD-2 has already published the results of the

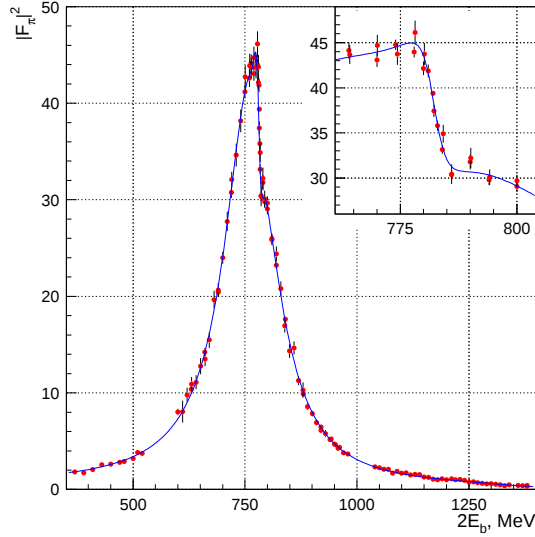


Figure 1. New data on the pion form factor.

measurement of the cross section for the process $e^+e^- \rightarrow K_S^0 K_L^0$ [34] with (5–10)% systematic uncertainty, which are consistent with the preliminary measurements by SND [35]. Analysis is in progress by CMD-2 for the K^+K^- final state produced at the ϕ meson and above it.

Both groups measured radiative decays of the ω and ϕ mesons [36,37].

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.

2.2. R Measurement at BES

Until recently the energy range above 1.4 GeV was studied much worse (see e.g. Figs. 2,3 where cross sections of the four pion production, the dominant process above 1 GeV, are shown below the c.m.energy of 2 GeV). 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%

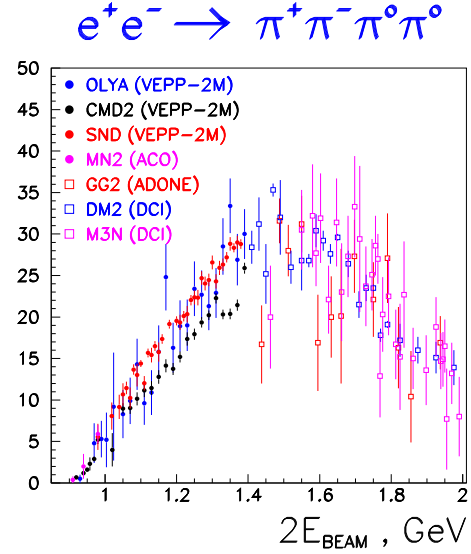
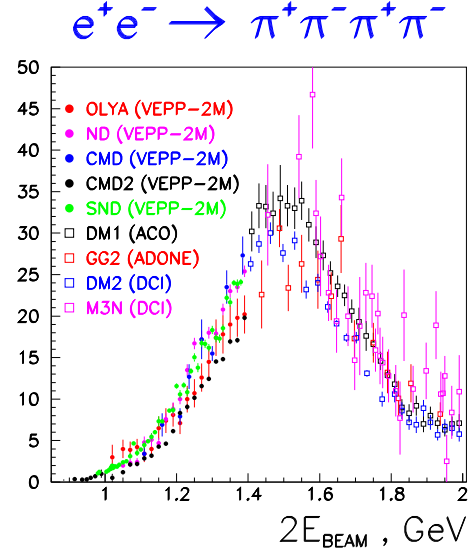

 Figure 2. Cross section of the process $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$.

 Figure 3. Cross section of the process $e^+e^- \rightarrow 2\pi^+2\pi^-$.

Table 2

 Comparison of $\gamma\gamma 2$ and BES measurements.

Detector	$\gamma\gamma 2$	BES
$\sqrt{s}$, GeV	2.0 – 3.1	2.0 – 3.0
Acceptance, %	19–23	50–68
Syst.error, %	21	5.2–8.2
$\int Ldt, \text{nb}^{-1}$	130	990
N_{had}	920	18500

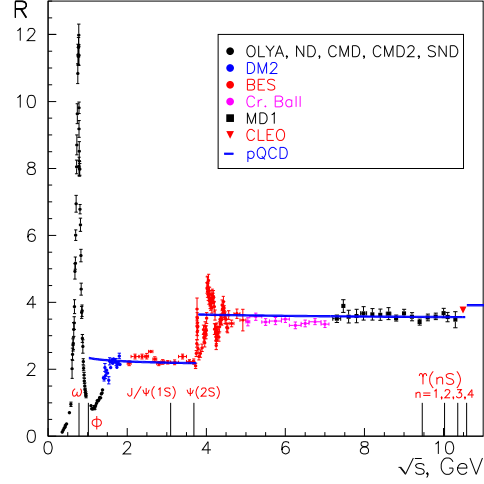
to 25% [5].

A real breakthrough occurred after recent experiments with the BES detector at Beijing [38] 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 2 illustrates the progress by comparing some characteristics of the BES experiment with the R measurement by the $\gamma\gamma 2$ group at Frascati [39] in the energy range from 2.0 to 3.0 GeV.

In Fig. 4 we show the experimentally measured value of R as a function of energy below 10 GeV. Thresholds of $s\bar{s}$ and $c\bar{c}$ creation are obviously observed. The solid line showing the prediction of pQCD is in good agreement with the experimental observations. One can summarize that below 10 GeV (with the exception of the c.m.energy range from 1.4 to 2 GeV) the quantity R is known with good accuracy.

3. New e^+e^- Data and $a_\mu^{had,LO}$

Let us estimate the implications of the new results on e^+e^- cross sections discussed above for $a_\mu^{had,LO}$. We'll start from the contribution from the annihilation into two pions, which dominates the hadronic contribution to $(g_\mu - 2)/2$. To this end we compare its value in the energy range 610 to 960 MeV calculated from CMD-2 data only to that based on the previous e^+e^- measurements [18,19]. Table 3 presents results of the $a_\mu^{\pi\pi}$ calculations performed using Eq. (2) and the direct in-


 Figure 4. Total e^+e^- cross section in terms of R

tegration of the experimental data. The method is straightforward and has been described elsewhere [2]. The first line of the Table 3 (Old data) gives the result based on the data of OLYA, CMD and DM1 while the second one (New data) is obtained from the CMD-2 data only. The third line (Old + New) presents the weighted average of these two estimates based on completely independent old and new datasets. For convenience, we list separately statistical and systematic uncertainties in the second column while the third one gives the total error obtained by adding them in quadrature. One can see that the estimate based on the CMD-2 data is in good agreement with that coming from the old data. It is worth noting that the statistical error of the new measurement is slightly larger than the systematic uncertainty. However, when the whole data sample on two pion production collected by CMD-2 (more than one million events) is analyzed, one expects to significantly decrease the statistical error above. Because of the small systematic error of the new data, the uncertainty of the new result for $a_\mu^{\pi\pi}$ is almost three times better than the previous one.

Table 3
Contributions of the $\pi\pi$ channel to $(g-2)/2$

Data	$a_\mu^{\pi\pi}, 10^{-10}$	Error, 10^{-10}
Old	$374.8 \pm 4.1 \pm 8.5$	9.4
New	$368.1 \pm 2.6 \pm 2.2$	3.4
Old+New	$368.9 \pm 2.2 \pm 2.3$	3.2

As a result, the combined value based on both old and new data is completely dominated by the CMD-2 measurement.

One can now go further and estimate the full $a_\mu^{had,LO}$ by taking into account all previously available e^+e^- experimental data as well as the new data from Novosibirsk and Beijing described above [5]. Similarly to Ref. [2], only experimental data will be used below 5 GeV whereas above that energy the predictions of pQCD will be used. This approach is pretty safe since the energy range above 5 GeV contributes only 1.5% to $a_\mu^{had,LO}$ and the contribution to its uncertainty is negligible. The resulting value is $(684.7 \pm 6.0 \pm 3.6) \cdot 10^{-10}$, where the first error is the total experimental error (including both statistical and systematic uncertainties) whereas the second one arises because of the corrections for vacuum polarization and final state radiation. The achieved accuracy of $7 \cdot 10^{-10}$ is by a factor of more than 2 better than the previous one based on the e^+e^- data only [2]. This result is in good agreement with the recent evaluation of $a_\mu^{had,LO}$ in Ref. [6] based on about the same e^+e^- data set, but using somewhat different method of combining data of different experiments.

Since E821 Collaboration plans to improve the accuracy, it is clear that further progress is also needed from the theoretical side. At the present time the analysis of the $\pi\pi$ data as well as other hadronic final states in the whole energy range accessible to CMD-2 is in progress. Independent information is also expected in close future from other experiments studying low energy e^+e^- annihilation [40]. When all the above mentioned data are taken into account, one can expect further improvement of the overall error of $a_\mu^{had,LO}$

compared to the current one.

It is very tempting to use an independent set of the τ lepton data to improve the existing evaluations of the hadronic effects. However, as we learned from the talk of A. Höcker at this Workshop [41], recent analysis revealed the apparent incompatibility of e^+e^- and τ lepton spectral functions [5]. As a result, the τ lepton based evaluation and the e^+e^- based one are hardly consistent, so that their averaging doesn't improve the accuracy. More work is needed to clarify the reasons of this effect.

4. 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 allowing significant improvement of the uncertainty of $a_\mu^{had,LO}$.

Precise tests of the relation between the e^+e^- cross sections and τ branching ratios will require better understanding of the isospin symmetry breaking effects and radiative corrections. Together with the more detailed analysis of systematic effects in both e^+e^- and τ lepton sectors, it should allow to perform new precise evaluations of the hadronic corrections.

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 [40].

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