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Muon g-2 and hadronic vacuum polarization: Recent developments

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We discuss various experiments on e^+e^- annihilation into hadrons relevant to the problem of the muon anomalous magnetic moment. They include a status of the ISR measurements of the $e^+e^- \to \pi^+\pi^-$ as well as studies of numerous hadronic final states in experiments with the CMD-3 and SND detectors at the VEPP-2000 e^+e^- collider.

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1. Introduction

Muon anomalous magnetic moment is one of the most precisely known physical quantities. In 2006 the BNL E821 Collaboration published the final results of their measurement of the muon $a_\mu \equiv (g_\mu - 2)/2$ [1]. Various calculations show that the Standard Model (SM) prediction is about 3.5 standard deviations below the experimental value [2, 3]. At the moment two new measurements of a_μ, each aimed at 4-fold increase of accuracy, are planned at Fermilab and J-PARC. If the central value of the experimental result is confirmed, the deviation between experiment and theory will reach 8-10 standard deviations unambiguously pointing to effects of New Physics. The theoretical prediction accuracy is currently limited by the uncertainties of the hadronic vacuum polarization extracted from the cross sections of e^+e^- annihilation into hadrons measured by a scan method at CMD-2 and SND detectors at the VEPP-2M (Fig. 1(left)) and initial-state radiation (ISR) at BaBar (Fig. 1(right)), see the review of e^+e^- experiments in Ref. [4].

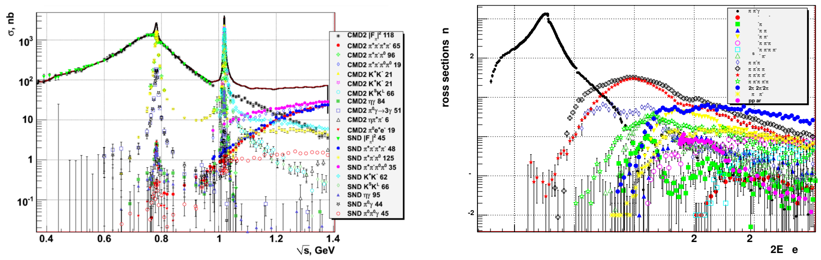

Figure 1: Current status of exclusive measurements [4]: (left) CMD-2 and SND, (right) BaBar

It is therefore absolutely necessary to improve the experimental accuracy and experiments on e^+e^- annihilation into hadrons are currently in progress in various centers.

2. ISR measurements of $e^+e^- \to \pi^+\pi^-$

The process $e^+e^- \to \pi^+\pi^-$ is known to give the largest contribution to the leading-order hadronic term $a_\mu^{\mathrm{LO,had}}$, about 73%. Recent ISR measurements of this process substantially improved the accuracy of its cross section. The BaBar Collaboration used a data sample collected at the peak of the $\Upsilon(4S)$ resonance to achieve the record precision of about 0.5% near the ρ meson peak [5, 6], see Fig. 2.

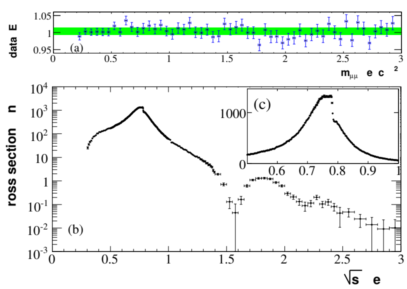

Figure 2: $e^+e^- \to \pi^+\pi^-(\gamma)$ at BaBar

KLOE was using ISR running at the ϕ meson peak and gradually increased the precision of their measurements to 0.7%, see Fig. 3 [7, 8, 9]. However, the results of KLOE and BaBar differ, the discrepancy reaching 5% in some energy regions, far beyond the declared precision.

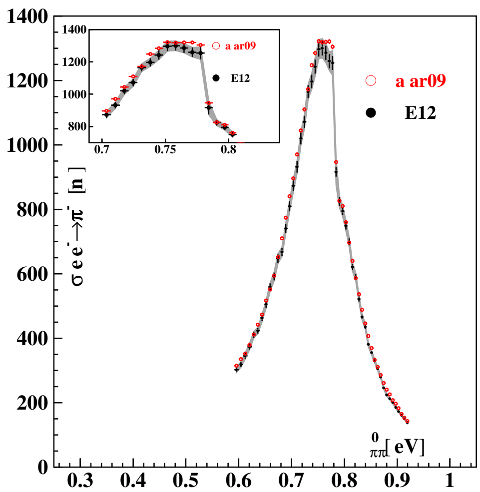

Figure 3: $e^+e^- \to \pi^+\pi^-(\gamma)$ at KLOE

A very recent precise measurement has been performed by the BES Collaboration running at the $\psi(3770)$ peak [10]. Their ISR measurement reaches precision of about 0.9%, see the cross section in Fig. 4 (left). Although superficially data of different groups are not in real conflict, their

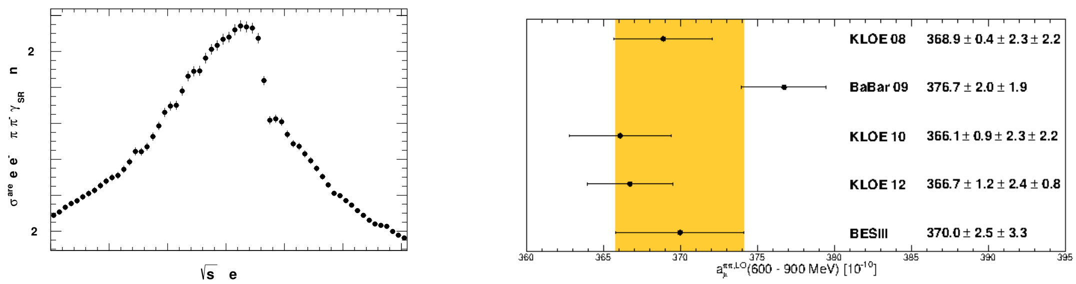

Figure 4: $e^+e^- \to \pi^+\pi^-(\gamma)$ at BESIII (left), comparison of BESIII results on a_μ (right).

integration reveals local problems illustrated in Fig. 4 (right) in terms of the hadronic contribution to muon anomaly. Here the yellow band corresponding to the uncertainty of the BESIII result is consistent within uncertainties with both BaBar and KLOE. The BESIII central value lies between those of BaBar and KLOE being somewhat closer to the latter. To understand this effect better, we show in Fig. 5 comparison between the results of BESIII and those from other groups: SND [11] and CMD-2 [12] (left), BaBar (middle) and KLOE (right). While the scan data from SND and CMD-2 are not contradicting to the ISR data, local discrepancies mentioned above are obvious between the data of BaBar, KLOE and BES. Obviously, new measurements with comparable or even better precision are needed.

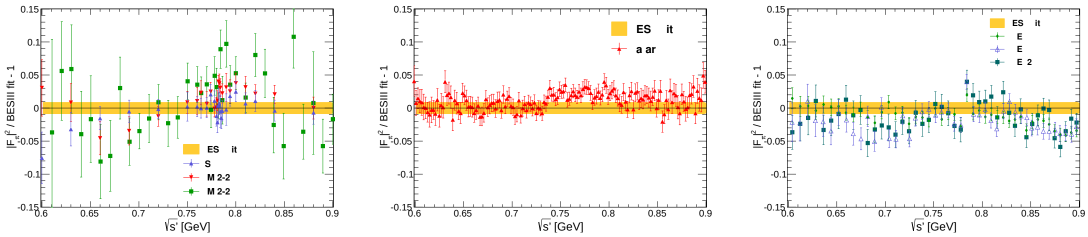

Figure 5: Comparison of results from CMD-2, SND, BaBar and KLOE

3. Experiments at VEPP-2000

Two detectors, CMD-3 and SND, are running at the new low-energy VEPP-2000 e^+e^- collider in Novosibirsk [13]. An integrated luminosity of ~ 60 fb^{-1} was collected by each in 2011 - 2013 in the center-of-mass (c.m.) energy range 320 - 2000 MeV. Lately analysis has been mainly focused on the c.m. energies above the ϕ meson. In particular, both groups made an attempt to improve the precision of various cross sections important for the muon anomaly problem [14].

Measurements of an integrated luminosity at CMD-3 use two processes, $e^+e^- \to e^+e^-$ and $e^+e^- \to \gamma\gamma$, allowing a precision of $\sim 1\%$ [15]. At SND, events of large-angle Bhabha scattering are used to determine an integrated luminosity with a systematic accuracy of 2% [16].

CMD-3 declares an aggressive goal of reaching 0.35% accuracy in the measurement of the pion form factor, see their prelimiary results in Fig. 6 [17]. Up to to the c.m. energy of 700 MeV

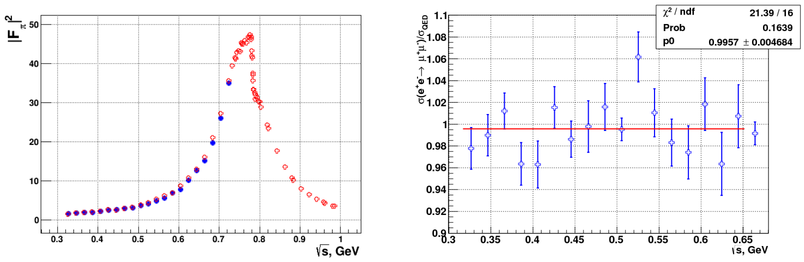

Figure 6: CMD-3 results on the pion form factor

they can separate pions from muons by two independent methods - from the information from the drift chamber and from the electromagnetic calorimeters, the latter being used in the whole energy range.

Both detectors continued analysis of the collected data samples and reported measurements of cross sections for various processes with pions and η mesons. SND published their final results on $e^+e^- \to \pi^+\pi^-\pi^0$ [18], Fig. 7 (left). and $e^+e^- \to \pi^+\pi^-\eta$ [16], Fig. 7 (right).

CMD-3 and SND studied all three possible charge combinations of the six-pion production, see the cross sections in Fig. 8. The left plot of Fig. 8 shows the case when all pions are charged with the obvious dip around the $N\bar{N}$ threshold [19]. Such behavior of the cross section has been observed before at BaBar [20] and even in much earlier e^+e^- and photoproduction measurements and is probably a threshold effect due to the opening of the $N\bar{N}$ channel [21]. The behavior of the cross section for the $2\pi^+2\pi^-2\pi^0$ final state (the middle plot in Fig. 8) is also not regular near the

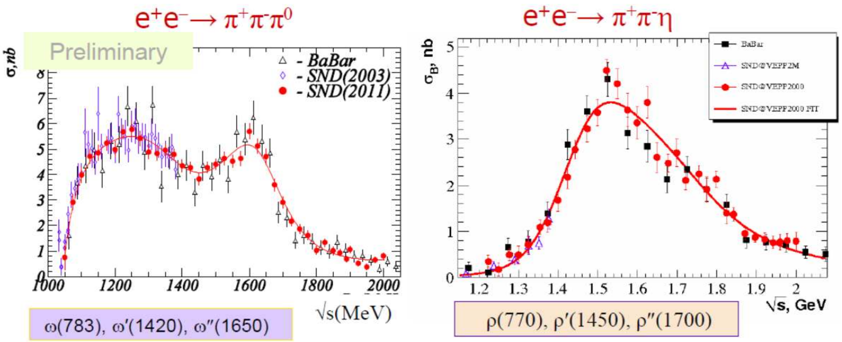

Figure 7: Recent results on hadronic cross sections from SND: (left) $e^+e^- \to \pi^+\pi^-\pi^0$ [18], (right) $e^+e^- \to \pi^+\pi^-\eta$ [16]

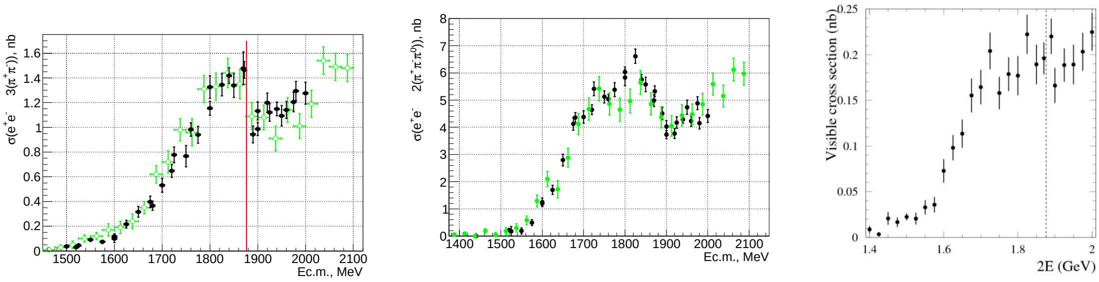

Figure 8: Cross sections of six-pion annihilation at CMD-3: (left) $e^+e^- \to 3\pi^+3\pi^-$ at CMD-3, (middle) $e^+e^- \to 2\pi^+2\pi^-2\pi^0$ at CMD-3, (right) $e^+e^- \to \pi^+\pi^-4\pi^0$ at SND

$N\bar{N}$ threshold, but somewhat differs from that in the $3\pi^+3\pi^-$ case [22]. Finally, SND measured for the first time ever the cross section of $e^+e^- \to \pi^+\pi^-4\pi^0$, where the size of the data sample does not allow any conclusions about the $N\bar{N}$ threshold, Fig. 8 (right). These final states have interesting and rich dynamics which analysis should be performed simultaneously for all three final states.

CMD-3 continued studies of various processes with kaons in the final state using good K/π separation based on measuring dE/dx in the drift chamber. In Fig. 9 we show the cross section of the process $e^+e^- \to K^+K^-$ near the ϕ meson at CMD-3 (left) and in the whole energy range at SND (right) [23].

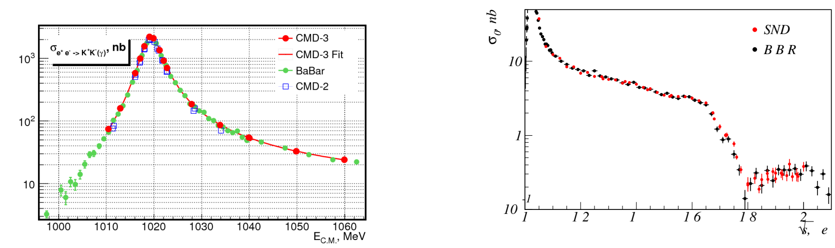

Figure 9: Cross section of $e^+e^- \to K^+K^-$: (left) near the ϕ meson at CMD-3, (right) from 1 to 2 GeV at SND

They also reported results on the cross section and dynamics of the $K^+K^-\pi^+\pi^-$, $K^+K^-\eta$ and $K^+K^-\pi^0$ final states.

SND has already published their measurements of the processes with only neutral particles in the final state – $e^+e^- \to \pi^0\pi^0\gamma$ [24] and $e^+e^- \to \eta\gamma$ [25], see Fig. 10.

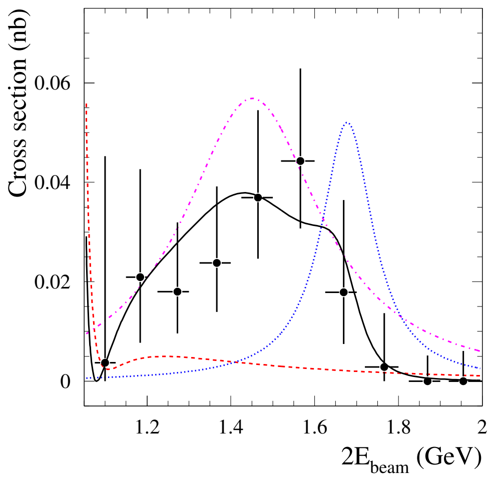

Figure 10: Cross section of $e^+e^- \to \eta\gamma$ at SND [25].

A study of the nucleon form factors near threshold was continued. SND significantly improved the precision of $\sigma(e^+e^- \to n\bar{n})$ [26] compared to the previous results from FENICE [27], see Fig. 11. CMD-3 measured the cross section of the process $e^+e^- \to p\bar{p}$ and made an attempt to extract the ratio of the electric and magnetic form factors based on the angular distribution of the final nucleons [28], see Fig. 12.

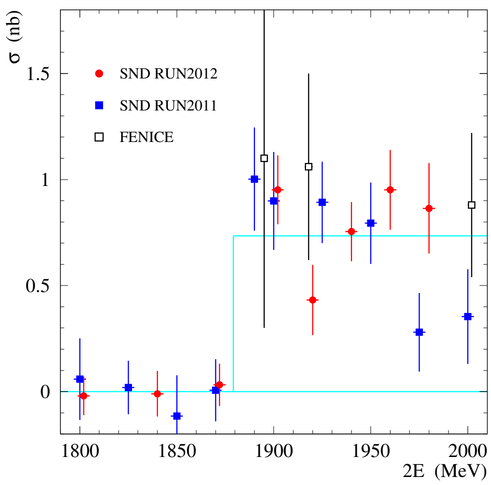

Figure 11: Cross section of the process $e^+e^- \to n\bar{n}$ at SND [26]

Both detectors used an original method of Ref. [29] to measure the partial width of a strongly suppressed $\eta' \to e^+e^-$ decay using the inverse process. CMD-3 reported an upper limit of $\Gamma(\eta' \to e^+e^-) < 0.0024$ eV at 90% CL based on 2.69 pb^{-1} and one mode of η' decay [30]. SND used 2.9 pb^{-1} and five modes of η' decay to improve it to < 0.0020 eV. Finally, they combine the data

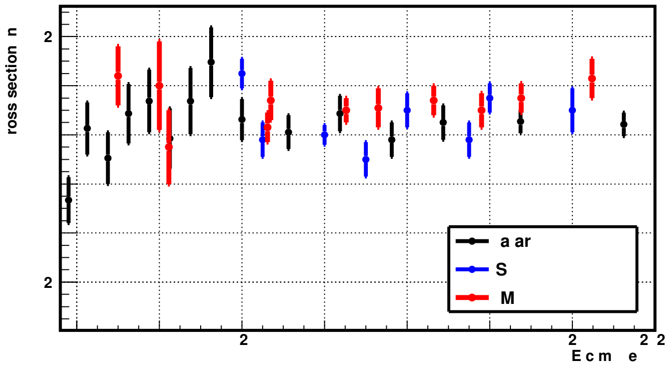

Figure 12: Cross section of the process $e^+e^- \to p\bar{p}$ at CMD-3 [28].

samples of CMD-3 and SND to find $\Gamma(\eta' \to e^+e^-) < 0.0011$ eV at 90% CL [31] which is still about two orders of magnitude below the unitary bound. SND has also performed a feasibility study for a search for $\eta \to e^+e^-$ via $e^+e^- \to \eta$ and concluded that the only promising decay mode for that is $\eta \to 3\pi^0$. A dedicated two-week run with the luminosity expected at the c.m.energy around the η meson mass will allow to improve the existing limit [32].

After the upgrade of the VEPP-2000 collider and commissioning the new injection complex the luminosity of the complex is expected to increase by an order of magnitude. Both detectors will run for another five years with a goal of collecting 1-2 fb^{-1} and increasing significantly the accuracy of all hadronic channels.

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