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Measurement of hadronic cross sections at CMD-3

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The CMD-3 experiment at the VEPP-2000 collider in Novosibirsk carries out a comprehensive study of the exclusive cross-sections of $e^+e^- \to hadrons$ in the center-of-mass energy range from the threshold to $\sqrt{s} < 2$ GeV. The CMD-3 results provide an important input for calculation of the hadronic contribution to the muon anomalous magnetic moment. Currently there are world-wide efforts to improve the accuracy of this calculation to match the expected precision of the new experiment at Fermilab to measure muon (g-2), now taking data. The best precision is still achieved by integrating the measured total cross-section of $e^+e^- \to hadrons$. The calculation is strongly dominated by low-energy data, in particular, by data at $\sqrt{s} < 2$ GeV. Other interesting topics of the CMD-3 physics program include a study of hadron cross-sections at the nucleon-antinucleon threshold and a search for two-photon production of C-even resonances.

The energy scan of the whole energy range was performed in 2011-2013 and, after detector and collider upgrade and increase in luminosity by factor 2-3, in 2017-2019. The total luminosity integral collected so far is 250 pb^{-1}. Here we present the current status of experiment and the survey of results of data analysis.

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1. VEPP-2000 and CMD-3

The electron-positron collider VEPP-2000[1] started operation at Budker Institute of Nuclear Physics (Novosibirsk, Russia) in 2010. The machine covers the c.m. energy range from $\sqrt{s} = 0.32$ GeV to 2.0 GeV and employs the novel technique of round beams to reach a design luminosity up to 10^{32} cm^{-2}s^{-1} at 2 GeV. Detectors CMD-3[2] and SND[3] are installed at the two interaction regions of VEPP-2000.

CMD-3 (Cryogenic Magnetic Detector) is a general-purpose detector, composed of the drift chamber, Z-chamber, the electromagnetic calorimeter, the time-of-flight system and the muon counters. The thin $0.13X_0$ superconducting solenoid generates 13 kGs magnetic field inside the drift chamber for measurement of particles momenta.

The primary goal of experiments at VEPP-2000 is to study the exclusive channels of hadron production in e^+e^- annihilation in the whole energy range available at VEPP-2000.

The total cross section of $e^+e^- \to hadrons$ is closely related to the problem of the muon anomalous magnetic moment, a_μ. A high-precision measurement of a_μ provides a powerful test of the Standard Model (SM). The most recent measurement of a_μ, done at BNL with 0.54 ppm precision [4], is $2.2 \div 2.5$ ppm, or ~ 3.5 standard deviations above the Standard Model expectation $a_\mu(\mathrm{SM})$ [5]. In order to reach better precision for $\Delta a_\mu = a_\mu(\mathrm{exp}) - a_\mu(\mathrm{SM})$, the precision of both the experimental value and Standard model expectation should be improved. The new experiment [6] aimed at measuring a_μ to 0.14 ppm is currently taking data at FNAL. The accuracy of $a_\mu(SM)$ evaluation is determined by the knowledge of the hadronic (QCD) contribution $a_\mu(\mathrm{had})$, which, in the lowest order, is calculated using dispersion relations by integrating $\sigma(e^+e^- \to hadrons)$. The dominant contribution to the integral, more than 90%, comes from the energy range $\sqrt{s} < 2$ GeV, covered by VEPP-2000.

2. Collected data

The first scan of the whole energy range was performed in 2011-2013. In 2011 and 2012 seasons the data were collected at energies above the φ meson — in the c.m. energy range from 1.0 GeV to 2.0 GeV, with 25 MeV steps in 2011 and slightly coarser steps in 2012. About 30 pb^{-1} were collected, with about 10 pb^{-1} above the $p\overline{p}$ threshold. The 2013 season was dedicated to a c.m. energy scan below 1.0 GeV, down to 0.32 GeV, in 20 MeV steps, except for the $\omega(782)$ region, where finer steps up to 2 MeV were used. About 20 pb^{-1} were collected, with about 8 pb^{-1} near the $\omega(782)$ peak. At the beginning of each experimental season data were taken near the φ peak to calibrate the systems and the energy scale.

During the 2012 season the beam energy monitoring system[7], which utilizes Compton backscattering of laser photons from the electron beam, has been installed and commissioned. With the system the beam energy in continuously monitored during the data taking with relative precision of $< 10^{-4}$.

The data taking was suspended from the second half of 2013 through 2016 for major upgrade of the VEPP-2000 collider, which among other things included switching to a ten times more powerful positron source and increase of maximum energy of the booster ring to 1 GeV. During the

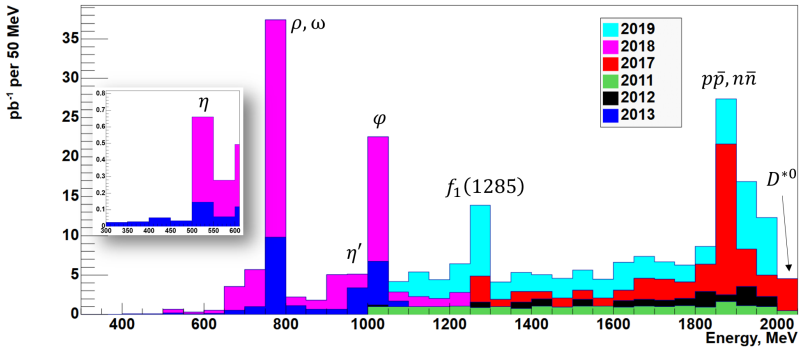

Figure 1: Distribution of the luminosity integral collected by CMD-3 detector up to date over the available VEPP-2000 energy range.

break the CMD-3 detector was upgraded as well, most notably, the new time of flight system was installed.

The data taking was resumed in 2017. In 2017 and 2019 seasons additional data was collected above the φ meson, while in 2018 the scan of energies below the φ meson was performed. Thanks to the increased performance of the collider after upgrade, total amount of data collected in 2017-2019 about three times larger than the integral collected in 2011-2013. The overall distribution of the collected luminosity integral over the VEPP-2000 energy range is shown in Fig. 1.

3. Overview of the results

The analysis of data is in process and a number of results on exclusive cross sections were published (mainly based on 2011-2013 data). All major hadronic channels are under analysis including channels with up to 7 pions or 2 kaons and 2 pions in the final state. Thanks to high statistics available, the analysis of the intermediate dynamics for multihadron states is performed together with the measurement of production cross section.

3.1 Exclusive cross sections of $e^+e^- \to hadrons$

The CMD-3 collaboration published several results with a few charged particles in the final state: $e^+e^- \to K_S K_L$ [8], $e^+e^- \to K^+K^-$ [9] and $e^+e^- \to 2(\pi^+\pi^-)$ [10] around the φ-meson; $e^+e^- \to 3(\pi^+\pi^-)$ [11], $e^+e^- \to K^+K^-\pi^+\pi^-$ [12], $e^+e^- \to \pi^+\pi^-\pi^0\eta$ [13] and, recently, $e^+e^- \to 3(\pi^+\pi^-)\pi^0$ [14], $e^+e^- \to \pi^+\pi^-\eta$ [15] and $e^+e^- \to K^+K^-\eta$ [16] in the wide energy range above 1 GeV; and $e^+e^- \to p\bar{p}$ [17] from the production threshold up to 2 GeV.

The data analysis is in progress for many more final states (about 20 total).

3.2 Cross section of $e^+e^- \to \pi^+\pi^-$

The dominant hadronic cross section below 1 GeV is $e^+e^- \to \pi^+\pi^-$ and it has to be measured to high precision, well below 1%, to improve accuracy of the calculation of the hadronic contribution to a_μ. Several high precision measurements are available: direct scan from CMD-2 and SND at VEPP-2M collider, predecessor of VEPP-2000, and ISR-based from KLOE and BaBar. There is tension between existing results, most striking between KLOE and BaBar, beyond claimed errors.

In 2013 and 2018 the CMD-3 collected the world-largest sample of $e^+e^- \to \pi^+\pi^-$ data. The data analysis for this channel is in progress.

3.3 $N\bar{N}$ threshold

In 2017 the dedicated scan of energy range around $p\bar{p}$ and $n\bar{n}$ production thresholds was performed with small energy steps. A very fast rise of $p\bar{p}$ cross section was observed [18] with width $\sim$1 MeV, consistent with the beam energy spread. A sharp drop at the same energies was observed for $e^+e^- \to 3(\pi^+\pi^-)$ and $e^+e^- \to K^+K^-\pi^+\pi^-$ cross sections. Surprisingly, no narrow structure at $N\bar{N}$ threshold was observed for $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ cross section. We plan to collect more data at $N\bar{N}$ threshold.

4. Conclusion

CMD-3 has collected about 250 pb^{-1} of $e^+e^- \to hadrons$ data in $0.32 < \sqrt{s} < 2.0$ GeV energy range with the plan to collect total of 0.5–1.0 fb^{-1} over the next few years. The data analysis is in progress. Results on cross section and dynamics for several exclusive modes of hadron production have been published. Results of experiments at VEPP-2000 are especially important for the quest of reaching better precision of calculation of hadronic contribution to muon (g-2).

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