REVIEW OF RECENT RESULTS FROM CMD-2 DETECTOR AT VEPP-2M

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The Cryogenic Magnetic Detector (CMD-2) is shortly described. Preliminary results for the cross sections of e^+e^- annihilation into hadrons are presented in the c.m. energy range from 0.37 to 1.39 GeV. The total integrated luminosity of about 31 pb^{-1} has been collected. The new results for the ρ and ω meson parameters were abtained. The major decay modes of the ϕ meson as well as its rare decays have been studied. The tagged η mesons in ϕ meson decays were used to look for some decay modes of K_S^0 and η mesons. The multihadrons cross sections in a broad energy range are presented.

Introduction

Despite thirty years of experimental studies e^+e^- annihilation into hadrons at low energies is still rather far from the complete understanding. More precise measurements are needed to determine ρ, ω and ϕ meson parameters as well as continuum properties providing the unique information about interactions of light quarks.

Exact data on the pion form factor is necessary for the precise determination of the ratio R = $\sigma(e^+e^- \to \text{hadrons})/\ \sigma(e^+e^- \to \mu^+\mu^-)$, which in the VEPP-2M energy range is dominated by the $e^+e^- \to \pi^+\pi^-$ channel. Knowledge of R with high accuracy is required to evaluate the hadronic contribution to the (g-2) of muon and to the running electromagnetic constant $\alpha(M_Z^2)$. In case of the muon (g-2) the energy range of VEPP-2M gives the major contribution both to the hadronic contribution itself and to its uncertainty.

The precise measurement of the hadronic cross section was one of the main goal CMD-2 detector running at the VEPP-2M e^+e^- collider in Novosibirsk since 1992. A short description of the most interesting results is presented in this paper.

1. CMD-2 detector

The CMD-2 is a general purpose detector. The two cross sections of the detector are shown in Fig. 1 in outline.

The drift chamber of the detector (DC) [3] has 80 jet type drift cells. The resolution in the plane transverse to the beam axis is about of 250 μ. The double layer multiwire proportional chamber (ZC) [4] is installed just after DC. ZC has an accurate resolution ($\sim$0.5 mm) of the z-coordinate of particle track along the beam direction. The time resolution of ZC is near 5 ns. The beam cicle time at VEPP-2M is 60 ns. Both chambers are inside a thin (0.38 X_0) superconducting solenoid with a field of 1 T.

The barrel calorimeter is placed outside of the solenoid and consists of 892 CsI crystals [5] of $6 \times 6 \times 15\ cm^3$ size. The crystals are arranged in eight octants. The light readout is performed by PMTs. The energy resolution is about of 8% for photons with the energy more than 100 MeV. The both azimuthal and polar angle resolution is about of 0.02 radian.

The endcap calorimeter [6] consists of 680 BGO crystals of $2.5\times2.5\times15\ cm^3$ size. The light readout is performed by vacuum phototriodes placed on the crystals. The energy and angular resolution were found to be $\sigma_E/E = 4.6\%/\sqrt{E(GeV)}$ and $\sigma_{\phi,\theta} = 2\cdot10^{-2}/\sqrt{E(GeV)}$ radians respectively. The solid angle covered by both parts of the calorimeter is about of 96% of 4π.

The muon range system consists of two double layers of the streamer tubes operating in a self-quenching mode and is aimed to separate pions and muons. The inner and outer parts of this system are arranged in 8 modules each and cover 55% and 48% of the solid angle respectively. More details on the detector can be found elsewhere [2].

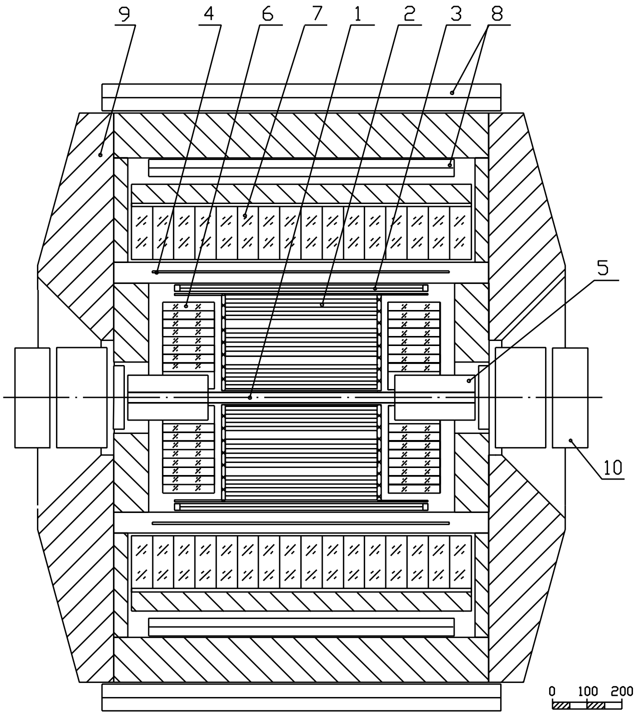

Figure 1: Cross-sections of the CMD-2 detector. 1 – vacuum chamber; 2 – drift chamber; 3 – Z-chamber; 4 – main solinoid; 5 – compensating solinoid; 6 – BGO endcap calorimeter; 7 – CsI barrel calorimeter; 8 – muon range system; 9 – magnet yoke; 10 – collider lenses.

2. Measurement of the ρ- and ω-meson parameters

A large data sample of about 2 million $e^+e^- \to \pi^+\pi^-$ events was collected by CMD-2 detector in the whole energy range available at VEPP-2M . Analysis of the data is completed for 10% of the statistic only. The beam energy was measured by the resonance depolarization technique at almost all energy points. The special kinematic cuts were applied to events in order to separate the collinear ones. The likelihood function was written with the following global fit parameters: $(N_{ee} + N_{\mu\mu})$, $N_{\pi\pi}/(N_{ee}+N_{\mu\mu})$, N_{cosmic}. The ratio $N_{\mu\mu}/N_{ee}$ was fixed according to QED calculation. The number of cosmic events was determined before the fit and was fixed during the fit. The radiative corrections (RC) for these channels were calculated according to works [7]. The estimated systematic error for RC is better than 0.3%. The emission of the second photon inside a narrow cone along the electron and positron (initial and final) was taken into account. The lepton and hadron contributions to vacuum polarization were included in the RC for $e^+e^- \to e^+e^-$, $\mu^+\mu^-$, but they were excluded for the channel $e^+e^- \to \pi^+\pi^-$.

The pion form factor presented in Fig. 2 is based on the data sample at 53 energy points in the energy range from 0.37 to 0.96 GeV. The obtained ρ meson parameters based on Gounaris-Sakurai parameterization were found to be: $\boldsymbol{M_\rho} = \mathbf{775.8 \pm 0.7}$ MeV, $\boldsymbol{\Gamma_\rho} = \mathbf{146.2 \pm 1.4}$ MeV,
$\boldsymbol{\Gamma_{\rho\to e^+e^-}}$ =$\mathbf{6.89 \pm 0.12}$ keV, $\boldsymbol{Br(\omega \to \pi^+\pi^-)}$=$\mathbf{(1.26 \pm 0.24)\%}$.
Here and below the first errors are statistical and the second are systematic.

The energy range around the ω meson was scanned with a total integrated luminosity of about 6.5 pb^{-1}, but the detail analyses is done for 2% of the data corresponds to $\sim 7 \times 10^4$ ω meson decays. The high precision measurements of the ω meson parameters were performed using the dominant decay mode: $\omega \to \pi^+\pi^-\pi^0$. Events with two tracks originating from the same vertex, each with a polar angle $0.85 < \theta < \pi - 0.85$ within fiducial volume of the detector were selected only.

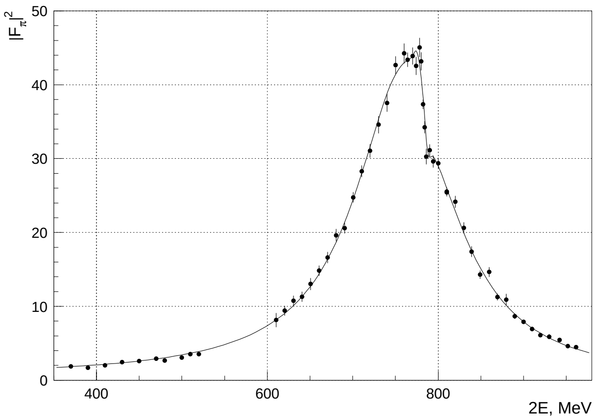

Figure 2: The pion form factor vs c.m.energy and the fit with Gounaris-Sakurai parameterization.

Most of the background comes from the processes with the hard photon emission: $e^+e^- \to e^+e^-\gamma$, $\pi^+\pi^-\gamma$, $\mu^+\mu^-\gamma$. These processes have the same signature as the reaction $e^+e^- \to \pi^+\pi^-\pi^0$, except for the very different distribution on acollinearity angle $\triangle\phi$ between two charged particles which peacked near $\triangle\phi = 0$. Thus, the rejection of events with a small $\triangle\phi$ drastically reduces the background.

The charged trigger efficiency was determined by "TEST" events with the neutral trigger, geometry efficiency — by simulation.

The resonant depolarization method was used for the precise calibration of the beam energy at each point. The production cross section was calculated according to the expression:

$$\sigma(e^+e^- \to \pi^+\pi^-\pi^0) = N_{3\pi}/L \cdot \epsilon_{trig} \cdot \epsilon_{MC} \cdot \epsilon_{M^2_{miss}} \cdot (1 + \delta_{rad}),$$

where $N_{3\pi}$ is the number of events; L is the integrated luminosity determined from large angle Bhabha events; δ_{rad} is the radiative correction calculated according to [8] with an accuracy better than 0.5%. The following parameters have been obtained from the fit:

$\boldsymbol{M_\omega} = \mathbf{782.71 \pm 0.07 \pm 0.04}$ MeV; $\boldsymbol{\sigma_0} = \mathbf{1457 \pm 23 \pm 19}$ nb,;
$\boldsymbol{\Gamma_\omega} = \mathbf{8.68 \pm 0.23 \pm 0.10}$ MeV; $\boldsymbol{\Gamma_{e^+e^-}} = \mathbf{0.595 \pm 0.014 \pm 0.009}$ keV.

These results are more precise than those from previous experiments. The mass value differs (930 keV) more than seven standard deviations in CMD87 ([9]). Due to the present more thorough study of systematic errors, our mass measurement supersedes that of [9]. The common excitation curve for the ω and ϕ meson is presented in Fig. 3.

3. Measurements of ϕ meson parameters

The ϕ-meson parameters were measured using data on the four major decay modes of $\phi \to K_S K_L$, K^+K^-, 3π, $\eta\gamma$. The first results based on a relatively small integrated luminosity of about 300 nb^{-1} were published in [10]. The new more precise results were obtained for the channel $\phi \to K^0_L K^0_S$ when K^0_S decays into a $\pi^+\pi^-$. The data sample was collected in four scans of the energy range from 984 to 1040 MeV with the integrated luminosity of 2.37 pb^{-1} and contains 2.97×10^5 of selected $K^0_L K^0_S$. The following parameters have been obtained from the fit:

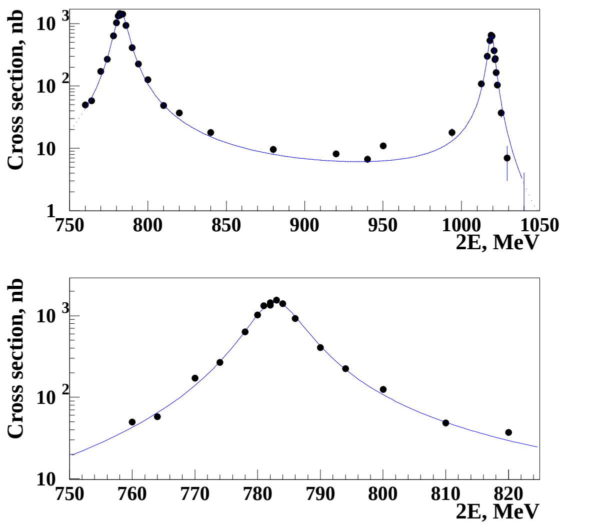

Figure 3: The upper figure — cross section vs c.m.energy and common fit for the ω, ϕ mesons. The lower figure — cross section in the energy range around ω-meson.

$\boldsymbol{\sigma_0(\phi \to K_L^0 K_S^0) = 1376 \pm 7 \pm 33}$ nb,
$\boldsymbol{M_\phi = 1019.483 \pm 0.011 \pm 0.025}$ MeV, $\boldsymbol{\Gamma_\phi = 4.280 \pm 0.033 \pm 0.025}$ MeV,
$\boldsymbol{Br\phi \to ee \cdot Br(\phi \to K_L^0 K_S^0) = (0.975 \pm 0.004 \pm 0.017) \times 10^{-4}}$.

4. Study of the process $e^+e^- \to \eta\gamma$ in c.m. energy range from 600 to 1380 MeV

Radiative magnetic dipole transitions of ρ, ω and ϕ mesons to $\eta\gamma$ have traditionally been a good laboratory for various tests of theoretical concepts from the quark model and SU(3) symmetry to Vector Dominance Model (VDM).
Large integrated luminosity collected by CMD-2 in recent experiments allows qualitatively new analysis of the $\eta\gamma$ final state produced in e^+e^- annihilation. The analysis is based on the data sample corresponding to 26.3 pb^{-1}.

To study the process $e^+e^- \to \eta\gamma$ the decay mode $\eta \to 3\pi^0$ was chosen when there are seven photons in final state. At the first stage of analysis events were selected which have no tracks in the DC, the number of photons from 6 to 8, the total energy deposition in calorimeters more than 1.5 E_{beam}, the total momentum $P_{tot} < 0.4 \cdot E_{beam}$. Among of these photons there is one monochromatic with the energy 362 MeV. Other photons have been pairing to form π^0 by combinatorial way and the combinations with the best χ^2 were chosen. After kinematic reconstruction requiring energy-momentum conservation events were remained which had good reconstruction quality. The detection efficiency for this process was determined by simulation and was found to be (10.8±0.1)%.

The maximum likelihood method was applied to fit the experimental data. Two different models were considered for the fit: the first one is VDM with the ρ, ω, ϕ mesons and in the second one an additional ρ' meson was included. Results of the fits are shown in Fig. 4.

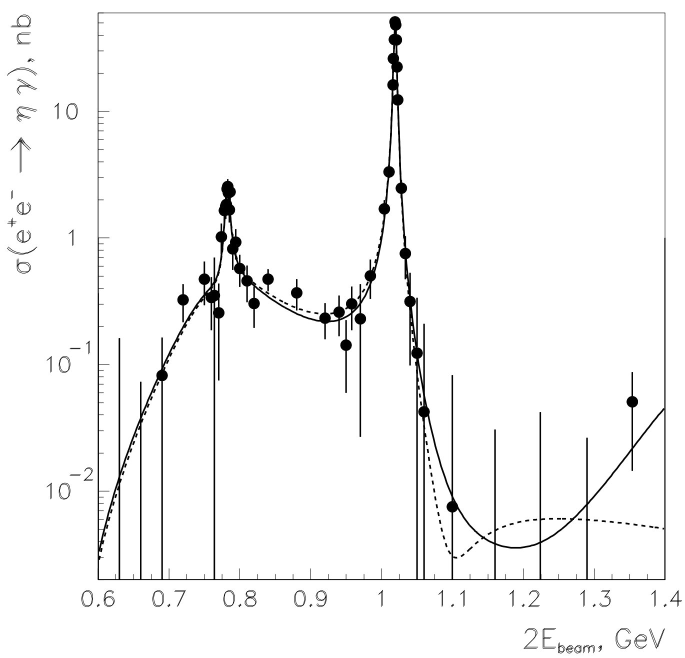

Figure 4: Cross-section of the $e^+e^- \to \eta\gamma$ process in the optimal fits: the solid curve is VDM, the dashed one is VDM + ρ'.

Although the fits quality (χ^2) are good for both models, but it is clear seen that at high energies the measured cross section is not described by one VDM. This fact is a hint for possible additional contributions coming from the higher resonance. Another words we consider our observation as evidence for the existence for $\rho' \to \eta\gamma$ decay. The following results were obtained from the fit:

$\boldsymbol{Br_{\rho\to e^+e^-}\cdot Br_{\rho\to\eta\gamma}=(1.46\pm 0.17\pm 0.10)\cdot 10^{-7}}$,
$\boldsymbol{Br_{\omega\to e^+e^-}\cdot Br_{\omega\to\eta\gamma}=(3.60\pm 0.51\pm 0.22)\cdot 10^{-7}}$,
$\boldsymbol{Br_{\phi\to e^+e^-}\cdot Br_{\phi\to\eta\gamma}=(3.849\pm 0.040\pm 0.158)\cdot 10^{-6}}$,
$\boldsymbol{Br_{\rho'\to e^+e^-}\cdot Br_{\rho'\to\eta\gamma}=(9.4\pm 2.0)\cdot 10^{-9}}$,
$\boldsymbol{m_\phi=1019.40\pm 0.04\pm 0.05}$ MeV,
$\boldsymbol{m_{\rho'}=1497\pm 14}$ MeV, $\boldsymbol{\Gamma_{\rho'}=226\pm 44}$ MeV.

5. Study of the $\phi\to\eta'\gamma$ decay

The discovery of the rare decay $\phi\to\eta'\gamma$ by CMD-2 has brought the last piece into the otherwise complete mosaic of radiative dipole magnetic transitions between light vector and pseuduscalar mesons. A search of this rare radiative decay was performed with the integrated luminosity of about 14.5 pb^{-1} at 14 energy points around the ϕ meson when η' decays into $\pi^+\pi^-\eta$. The analysis of events has been performed using three different decay modes of η: a. $\eta\to\gamma\gamma$, b. $\eta\to\pi^+\pi^-\gamma$ and c. $\eta\to\pi^+\pi^-\pi^0$.

For the first case (a), there are two charged pions and three photons in the final state. The monochromatic recoil photon has a fixed energy of 60 MeV. The invariant mass of two other (more hard) photons should equal M_η. The main source of the background comes from the decay $\phi\to\eta\gamma$ when η decay into $\pi^+\pi^-\pi^0$. In this case the final state has the same particles but their kinematics is drastically different. The hardest photon is monochromatic with the energy 362 MeV and the invariant mass of two others is M_{π^0}. The decay $\phi\to\eta\gamma$ is two orders of magnitude more probable and it is a source of the main background. The branching ratio of $Br(\phi\to\eta'\gamma)$ was calculated relative to $Br(\phi\to\eta\gamma)$. This ratio is not sensitive to systematic uncertainties coming from luminosity, detector inefficiency, resolution and so on. Using the values of the all needed branching ratios from PDG the following result has been obtained: $\boldsymbol{Br(\phi\to\eta'\gamma)=(0.82^{+0.21}_{-0.19}\pm 0.11)\times 10^{-4}}$.

For the second(b) and third(c) decay modes of η the specific signature are four charged particles and two or three photons in the final state. The softest photon is monochromatic with the energy of 60 MeV. One of the combinations of two particles with opposite charges has to form a missing mass to M_{π^0} or zero. The kinematic constrained fit with additional angular cuts was applied to select events with the best χ^2. The main source of the background comes from decays: $\phi\to K^0_SK^0_L$ when $K^0_S\to\pi^+\pi^-$ and $K_L\to\pi^+\pi^-\pi^0$. The number of these background events was subtracted according to the simulation results. The following result has been obtained:
$\boldsymbol{Br(\phi\to\eta'\gamma)=(4.9\pm 1.8\pm 0.6)\times 10^{-5}}$.

6. Study of the conversion decays

Conversion decays, when a virtual photon is converted into a lepton pair, are closely related to corresponding radiative decays. The branching ratios for conversion decays $\phi\to\eta e^+e^-$, $\phi\to\pi^0e^+e^-$ as well as Dalitz decay $\eta\to e^+e^-\gamma$ were determined using a data sample with the integrated luminosity of $15.5pb^{-1}$.

The decay $\phi\to\eta e^+e^-$ was detected via the mode $\eta\to\gamma\gamma$ and the $\eta\to 3\pi^0$, the decay $\phi\to\pi^0e^+e^-$ – via the $\pi^0\to\gamma\gamma$ and the decay $\eta\to e^+e^-\gamma$ – via the mode $\phi\to\eta\gamma$. The process $\phi\to\eta\gamma,\ \eta\to\pi^+\pi^-\gamma$ was used to determine the number of ϕ-mesons.

Events were selected with two charged particles in DC and photons in the calorimeter. These events were subject to the kinematic fit with energy-momentum conservation. The conversion decays have a peculiar feature of their kinematics: the angle between e^+ and e^- is as a rule close to zero.

The significant background for these events comes from the γ-quantum conversion in the detector material. The detection efficiencies for these processes were determined by simulation. The decay $\phi\to\pi^0e^+e^-$ has background from $\phi\to\pi^+\pi^-\pi^0$ via the same final state. This background

was suppressed by using the information about energy deposition by electrons and pions in the calorimeter. As a result the following branching ratios were obtained:
$\boldsymbol{Br(\phi \to \eta e^+e^-) = (1.13 \pm 0.14 \pm 0.07) \times 10^{-4}}$ when $\eta \to \gamma\gamma$,
$\boldsymbol{Br(\phi \to \eta e^+e^-) = (1.21 \pm 0.14 \pm 0.09) \times 10^{-4}}$ when $\eta \to \pi^0\pi^0\pi^0$,
$\boldsymbol{Br(\phi \to \pi^0 e^+e^-) = (1.22 \pm 0.34 \pm 0.21) \times 10^{-5}}$,
$\boldsymbol{Br(\eta \to e^+e^-\gamma) = (7.10 \pm 0.64 \pm 0.46) \times 10^{-3}}$.
The obtained results are in agreement with the theoretical predictions and have better statistical accuracy than previous measurements quoted by PDG.

The conversional decay of ω meson to $\pi^0 e^+e^-$ is closely related to radiative decay $\omega \to \pi^0\gamma$. The interest to all conversional decays is growing up with experiments on quark-gluon plasma. Due to difference in leptoproduction at these experiments one have to know more precision values of conversional decay branchings.

The conversional decay of ω meson to $\pi^0 e^+e^-$ was firstly observed in the ND experiment (Novosibirsk) [12]. This preliminary results based on statistic in 1 pb^{-1}. It is a part of statistic (about 20%) collected by CMD-2 detector during run at low energies range between 0.76 – 0.81 GeV in the center of mass.

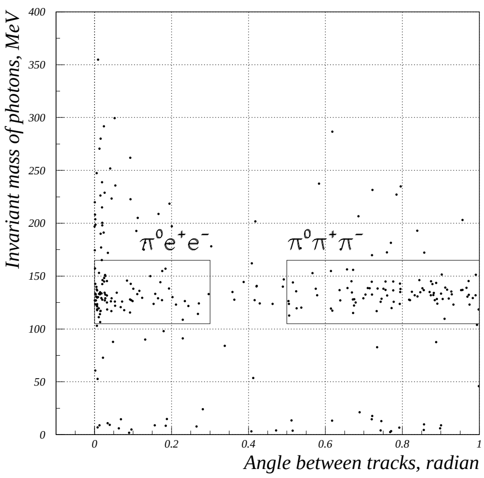

Figure 5: Events in two-dimensional plot invariant mass versus angle between tracks. The region of selected events shown as a rectangle in the left side. Correspondantly, at the right side we can see the events from decay into $\pi^0\pi^+\pi^-$.

The simple topology of events, 2 tracks in DC and 2 photons in calorimeters determines the main background this process. It is the major mode of ω meson decay into $\pi^0\pi^+\pi^-$. The criteria that suppress main background are the angle between tracks and the ratio of cluster energy that belongs to track to its momentum. Another significant background to this decay comes from the γ-quantum convertions in detector material, mainly in the vacuum tube, of decay $\omega \to \pi^0\gamma$. We found 72 events that satisfied selection criteria (Fig. 5).

The background coming from electromagnetic processes has not resonance character and was subtracted from selected events using experimental data out of ω meson energy range. The registration efficiencies for the effect events and background were obtained from MC simulation. As a result of fit the value for branching ratio ω meson conversional decay into $\pi^0 e^+e^-$ was found to be: $(3.9 \pm 1.4) \cdot 10^{-4}$.

Conclusion

For the first time the pion form factor is measured with the systematic error 0.6%. This accuracy is adequate to the requirements of (g-2) experiments at BNL.

For the first time the rare $\phi \to \eta'\gamma$ decay was measured in three different channels. These measurements complete a list of the magnetic dipole transitions between vector and pseudoscalar mesons and it is a milestone for the theory of radiative decays.

Our results on the electric dipole transitions confirm earlier observations of the decay modes $\phi \to \pi^0\pi^0\gamma$, $\eta\pi^0\gamma$ by SND while the $\phi \to \pi^+\pi^-\gamma$ decay was observed for the first time.
New results, not mentioned in this paper, were obtained using the tagged kaons and η mesons. Some of them are outlined in the Table.

Table — some recent results from CMD-2 experiments

	CMD-2 Data	PDG'98
$Br(\phi \to \mu^+\mu^-\gamma)$	$(1.43 \pm 0.45 \pm 0.14) \cdot 10^{-5}$	$(2.3 \pm 1.0) \cdot 10^{-5}$
$Br(\phi \to \rho\gamma)$	$< 1.2 \cdot 10^{-5}$	$< 7 \cdot 10^{-4}$
$Br(\phi \to \rho\gamma\gamma)$	$< 5 \cdot 10^{-4}$	no data
$Br(\phi \to \eta\pi^+\pi^-)$	$< 1.8 \cdot 10^{-5}$	no data
$Br(\phi \to \pi^+\pi^-\pi^+\pi^-)$	$(3.9 \pm 1.7 \pm 2.1) \cdot 10^{-6}$	$< 8.7 \cdot 10^{-4}$
$Br(\phi \to \pi^+\pi^-\pi^+\pi^-\pi^0)$	$< 4.6 \cdot 10^{-6}$	no data
$Br(\rho \to e^+e^-)$	$(4.67 \pm 0.15) \cdot 10^{-5}$	$(4.49 \pm 0.22) \cdot 10^{-5}$
$Br(\rho \to \pi^+\pi^-\pi^+\pi^-)$	$(1.8 \pm 0.9 \pm 0.3) \cdot 10^{-5}$	$< 2 \cdot 10^{-4}$
$Br(K^+ \to \pi^+\pi^0)$	$(21.69 \pm 0.48 \pm 1.03)\%$	$(21.16 \pm 0.14)\%$
$Br(K^+ \to \pi^0e^+\nu)$	$(4.89 \pm 0.17 \pm 0.17)\%$	$(4.82 \pm 0.06)\%$
$Br(\eta \to \pi^+\pi^-e^+e^-)$	$(3.5 \pm 2.0) \cdot 10^{-4}$	$(13^{+12}_{-8}) \cdot 10^{-4}$
$Br(\eta \to \pi^+\pi^-)$	$< 3.3 \cdot 10^{-4}$	$< 9 \cdot 10^{-4}$
$Br(\eta \to \pi^0\pi^0)$	$< 5 \cdot 10^{-4}$	no data

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References

[1] *S.I.Dolinsky et al.* Soviet Journal of Nuclear Physics, 48 (1988) 277.

[2] G.A.Aksenov et al., Preprint BINP 85-118, Novosibiresk, 1985.

[3] F.V.Ignatov et al., Preprint BINP 99-64, Novosibirsk, 1999.

[4] E.V.Anashkin et al., Nucl. Instr. and Meth., A323 (1992) 178.

[5] V.M.Aulchenko et al., Nucl. Instr. and Meth., A336 (1993) 53.

[6] D.N.Grigoriev et al., IEEE Trans. Nuc. Sci., 42, N4 (1995) 505.

[7] A.B.Arbuzov et al., JHEP 10 (1997) 006, A.B.Arbuzov et al., JHEP 10 (1997) 001.

[8] E.A.Kuraev and V.S.Fadin, Sov. J. Nucl. Phys., 41 (1985) 466.

[9] L.M.Barkov et al., JETP Lett., 46 (1987) 164.

[10] R.R.Akhmetshin et al., Phys.Lett., B364 (1995) 199.

[11] Review of Particle Physics, The European Physical Journal, C3 (1998).

[12] *S.I.Dolinsky et al.* Sov. J. Nucl. Phys., 48 (1988) 277.