Measurement of the decay $\phi \to \mu^+\mu^-$. 

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Abstract

The process $e^+e^- \to \mu^+\mu^-$ has been studied with SND detector at VEPP-2M $e^+e^-$ collider in the vicinity of $\phi(1020)$ resonance. The product of branching ratios of $\phi$ meson into leptons

$$\sqrt{B(\phi \to \mu^+\mu^-) \cdot B(\phi \to e^+e^-)} = (3.14 \pm 0.22 \pm 0.14) \cdot 10^{-4}$$

was measured from the interference in the cross section of the process $e^+e^- \to \mu^+\mu^-$. The branching ratio $B(\phi \to \mu^+\mu^-) = (3.30 \pm 0.45 \pm 0.32) \cdot 10^{-4}$ was obtained.

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1 Introduction

The \( \phi \rightarrow \mu^+\mu^- \) decay reveals itself as an interference pattern in the energy dependence of the cross section of process \( e^+e^- \rightarrow \mu^+\mu^- \) in the region around \( \phi \)-resonance peak. The interference amplitude is determined by the branching ratio of the decay \( \phi \rightarrow \mu^+\mu^- \). The table value of the branching ratio \( B(\phi \rightarrow \mu^+\mu^-) = (2.5 \pm 0.4) \times 10^{-4} \) is based on the experiments on photoproduction of \( \phi \) meson \[4\]. The study of the interference pattern in the energy dependence of the cross sections over all decay channels \[4\]. The study of the interference \( e^+e^- \rightarrow \phi \rightarrow \mu^+\mu^- \) gives the independent evaluation of the \( \phi \)-meson leptonic width. First measurement of the decay \( \phi \rightarrow \mu^+\mu^- \) on \( e^+e^- \) collider was performed in Orsay in 1972 \[5\]. In this experiment the value of branching ratio of \( \phi \)-meson leptonic decay \( \sqrt{B(\phi \rightarrow \mu^+\mu^-) \cdot B(\phi \rightarrow e^+e^-)} = (2.93 \pm 0.96 \pm 0.32) \times 10^{-4} \) was obtained. Later similar measurements were performed in Novosibirsk \[8\].

2 Experiment

The experiment was carried out with SND detector (Fig. 1) at VEPP-2M in 1996–1997. SND is a general purpose non-magnetic detector \[8\]. The main part of the SND is a spherical electromagnetic calorimeter, consisting of 1630 NaI(Tl) crystals. The solid angle of the calorimeter is \( \sim 90\% \) of \( 4\pi \) steradian. The angles of charged particles are measured by two cylindrical drift chambers covering \( 95\% \) of \( 4\pi \) steradian solid angle. The important part of the detector for the process under study is a muon system, consisting of streamer tubes and plastic scintillation counters, with 1 cm iron plates between blocks of tubes and counters. The simultaneous hits in the streamer tubes and scintillation counters produce a signal of muon system. The time difference between the hit and the beam collision is measured by inner \[11\] and outer scintillation counters \[11\].

The experiment was carried out in the energy range \( 2E_h = 984-1040 \) MeV and consisted of 6 data taking runs \[2\], \[3\]:

PHI\_9601 – PHI\_9606. Five runs were used for analysis, corresponding to the total integrated luminosity \( \Delta L = 2.61 \text{ pb}^{-1} \).

![Figure 1: Detector SND — view across the beam; 1 — beam pipe, 2 — drift chambers, 3 — inner scintillation counters, 4 — NaI(Tl) counters, 5 — vacuum phototriodes, 6 — iron absorber, 7 — streamer tubes, 8 — outer scintillation counters](image)

About \( 4.6 \times 10^6 \) of \( \phi \) mesons were produced. The integrated luminosity was measured with the accuracy of about \( 3\% \) using \( e^+e^- \rightarrow e^+e^- \) and \( e^+e^- \rightarrow \gamma\gamma \) events.

3 Event selection

The energy behavior of the cross section of the process

\[ e^+e^- \rightarrow \mu^+\mu^- (\gamma) \] (1)

was studied in the vicinity of \( \phi \) meson. Events with two collinear charged particles were selected for analysis. The selection of the events of the process (1) was performed with the following cuts on angles of acollinearity of the charged particles in azimuth and polar directions: \( |\Delta \phi | < 10^\circ \), \( |\Delta \theta | < 25^\circ \). Additional photon emitted by either initial or final particles was permitted. To avoid possible losses of events due to beam background or knock-on electrons in the drift chambers, one additional charged particle was also permitted. To suppress the beam background the production point of charged particles was required to be within 0.5 cm from the interaction point in the azimuth plane and \( \pm 7.5 \) cm along the beam direction (the longitudinal size of the interaction region \( \sigma_z \) is about 2 cm). The polar angles of the charged particles were limited to the range \( 45^\circ < \theta < 135^\circ \), corresponding to the acceptance angle of the muon system.

The main sources of background are the cosmic muons and the processes

\[ e^+e^- \rightarrow e^+e^- \] (2)

\[ e^+e^- \rightarrow \pi^+\pi^- (\gamma) \] (3)
To suppress the background from the process (2) a procedure of $e/\pi(\mu)$ separation was used. The algorithm is similar to that, developed for the ND detector [14]. It utilizes the difference in total energy depositions and the longitudinal energy deposition profiles for electrons, pions and muons. As a result of this procedure the background from the process (2) was suppressed down to 4% of the events of the process (1). To suppress the contribution of the process (3) a procedure of $\pi/\mu$ separation by the muon system has been used. In the energy range under study the probability to hit the muon system for a muon varies from 80 to 93% and is as low as 1.5% for pions of the process (3). A requirement of a hit in the muon system also reduced the background from the process (2) by two order of magnitude, making its contribution negligible.

After these cuts 80% of selected events are still cosmic background. The rejection of the events with the hit in two top segments of the muon system (about 45° in azimuth direction) (Fig. 1) suppressed the cosmic events by two times. Further suppression of the cosmic background was performed using the following parameters:

1. the time difference between the hit of the muon system and the beam collision – $\tau$;
2. the time difference between the hits in upper and lower halves of the muon system – $\text{TOF}$;
3. the sum of the distances from the tracks to the production point – $R$;
4. the likelihood function – $P_\mu$, which is built on the basis of the energy depositions in the calorimeter layers for the muon:

$$P_\mu = P_{\mu 1}(E_1) \cdot P_{\mu 2}(E_2) \cdot P_{\mu 3}(E_3), \quad (4)$$

where $P_{\mu i}(E_i)$ is the value of the probability density function for the energy depositions $E_i$ in $i$-th calorimeter layer. These functions were obtained from the data sample, where muons were selected by muon system using strict cuts ($|\tau| < 5$ ns, $\text{TOF} < 0$ ns, see explanation below).

The distribution of the parameter $\tau$ is shown in Fig. 3. The scale for parameter $\tau$ was adjusted to have a peak at 0 for $e^+e^- \rightarrow \mu^+\mu^-$ events. The events with $|\tau| < 5$ ns were selected for further analysis. In about 75% of the selected events there is a hit in the lower half of the muon system. For these events Fig. 3 shows the distribution of the time of flight $\tau$.
and cosmic background respectively.

To subtract the cosmic background the combination of the independent parameters $R$ and $P$, was used:

$$RP = \ln(P) - 16 \cdot R(cm) + 25. \quad (5)$$

The factor before $R$ has been chosen to provide maximum separation between cosmic events and the events of the process $[1]$. Additive constant equal to 25 fixes the scale of the parameter $RP$. Fig. 4 shows the $RP$ distribution for the events with $TOF > 5$ ns (mainly cosmic events) and for the events with $TOF < 0$ ns (mainly events of the process $[3]$). Most of the events of the process $[3]$ are in the region $RP > 0$. At each energy point the number of events of the process $[3]$ was estimated by the following formula:

$$N_{\mu} = N_{RP>0} - C \cdot N_{RP<0}. \quad (6)$$

Here $C = \frac{N_{RP>20}}{N_{RP<0}}$; $N_{RP>0}$ and $N_{RP<0}$ were determined from the sample of the events with $TOF > 5$ ns; $N_{RP>0}$, $N_{RP<0}$ — from the sample of the events with $TOF < 5$ ns.

The detection efficiency $\varepsilon_{\mu}$ for the process $[3]$ was determined from the Monte Carlo simulation. The events generator was based on the formulae from the work $[1]$. The passage of the particles through the detector was simulated by the program UNIMOD2 $[4]$. The energy dependence of the detection efficiency is especially important for the process under study. This dependence is determined mainly by the probability for a muon to reach the muon system.

The detection efficiency determined from the Monte Carlo was corrected in order to take into account the effects, which were not included into simulation. First is the efficiency of a software 3-rd level trigger, which selected the events during the data taking. This efficiency equals to 97–98% for all runs, except the run PH29601, where it was 93%. Second effect not included into the simulation is the inefficiency of the muon system. It was determined from the experimental data for each energy point and was also used as a correction for overall efficiency. This correction is about 9% and was determined mainly by the dead time of the time channels.

4 Data analysis

The energy dependence of the detection cross section was fitted with the following formula:

$$\sigma_{vis} = \varepsilon_{\mu}(E)\sigma_{\mu\mu(\gamma)}(E) + \varepsilon_{\pi}\sigma_{\pi\pi}(E), \quad (7)$$

where $E = 2E_{0}; \varepsilon_{\mu}(E)$ and $\varepsilon_{\pi} \approx 0.017$ — the detection efficiencies of the processes $[1]$ and $[3]$; $\sigma_{\mu\mu(\gamma)}$ and $\sigma_{\pi\pi}$ — the cross sections of these processes. The energy dependence of the efficiency obtained from the simulation was approximated by a smooth function.

To perform a combined fit of the detection cross sections for all experimental runs the scale factors $\varepsilon_{sf}$ for each run were introduced into the detection efficiencies as free fit parameters. They are asymptotic detection efficiencies at energies higher than 520 MeV, because the probability for a muon with such energy to hit the muon system is almost constant. This method provides an evaluation of efficiencies independent from simulation.

The cross section $\sigma_{\pi\pi}$ was calculated according to formulae from the work $[3]$ and taking into account the experimental data on the pion form factor $[7]$ and the decay $\phi \rightarrow 2\pi$ $[1]$. The cross section $\sigma_{\mu\mu(\gamma)}(E)$ was taken in the following form:

$$\sigma_{\mu\mu(\gamma)}(E) = \sigma_{\mu\mu}(E) \cdot \beta(E), \quad (8)$$

$$\sigma_{\mu\mu}(E) = 83.50(nb)\frac{m^2_{\phi}}{E^2} |Z|^2, \quad (9)$$

$$Z = 1 - Q \cdot e^{i\psi_{\mu} - i\psi_{\phi} - \frac{m_{\phi}^2}{m_{\phi}^2 - E^2 - i\Gamma_{\phi}(E)},}$$

where $\sigma_{\mu\mu}(E)$ is the Born cross section of the process $e^+e^- \rightarrow \mu^+\mu^-$; $m_{\phi}, \Gamma_{\phi}$ — mass and width of $\phi$ meson; $Q, \psi_{\mu}$ — module and phase of the interference amplitude; $\beta(E)$ — factor taking into account the radiative corrections. This factor was obtained as a ratio of the cross
section of process (1) to the Born cross section for the same acceptance angles and with the $\phi$-meson contribution. The cross section of the process (1) was calculated by the Monte Carlo method using the formulae from the work [15] with appropriate cuts on the angles and momenta of the final muons.

The luminosity measurement was performed taking into account the interference term in the cross section of the process (3). The interference amplitude is about 0.5% and the phase differs by 180 degrees from the phase in the process (1).

The fit of the experimental data gives the interference phase $\psi_\mu = (4.5 \pm 3.4) ^\circ$, which is consistent with the theoretical expectation of $0^\circ$. Therefore the final fit was made with the fixed phase $\psi_\mu = 0^\circ$. As a result the value of the interference amplitude

$$Q = 0.129 \pm 0.009$$

and the detection efficiencies $\varepsilon^{i}\phi_{f}$ for five runs were obtained (table 1).

Table 1: The detection efficiencies $\varepsilon^{i}\phi_{f}$ for the process (1), obtained from the simulation and the experiment.

| No      | $\varepsilon^{i}\phi_{f}, MC$ | $\varepsilon^{i}\phi_{f}, exp$ |
|---------|-------------------------------|-------------------------------|
| PHI_9601 | 0.270\pm0.003                 | 0.254\pm0.005                |
| PHI_9602 | 0.282\pm0.004                 | 0.277\pm0.004                |
| PHI_9604 | 0.287\pm0.003                 | 0.292\pm0.003                |
| PHI_9605 | 0.289\pm0.003                 | 0.290\pm0.003                |
| PHI_9606 | 0.287\pm0.003                 | 0.260\pm0.003                |

The systematic error of the amplitude of the interference is determined by the errors of the luminosity estimation and the calculation of the radiative corrections. The measurement of the luminosity using the events of the process $e^+e^- \rightarrow \gamma\gamma$ gives the estimation of the systematic error $\delta_{\text{lum}} = 2.1%$. Additional systematic error can be due to imprecise evaluation of the background from the process (3). The estimation of this contribution is $\delta_{\text{bkg}} = 0.6%$. The contribution of the error in the calculation of the radiative corrections to the systematic errors of the interference amplitude is $\delta_{\phi} = 4%$. The resulting systematic error is $\delta = 4.6%$.

The interference amplitude is related to the branching ratio of the decay $\phi \rightarrow \mu^+\mu^-$ by the following formula:

$$Q = \frac{3\sqrt{B(\phi \rightarrow e^+e^-)}B(\phi \rightarrow \mu^+\mu^-)}{\alpha},$$

where $\alpha$ is the fine structure constant. From this relation the product $\sqrt{B(\phi \rightarrow e^+e^-)}B(\phi \rightarrow \mu^+\mu^-) = (3.14\pm0.22\pm0.14) \times 10^{-4}$. Using the table value $B(\phi \rightarrow e^+e^-) = (2.99\pm0.08) \times 10^{-4}$ [14], we obtain $B(\phi \rightarrow \mu^+\mu^-) = (3.30\pm0.45\pm0.32) \times 10^{-4}$.

5 Conclusion

In this work the energy dependence of the cross section of the process $e^+e^- \rightarrow \mu^+\mu^-$ in the vicinity of the $\phi$ resonance was studied. The interference pattern determined by the decay $\phi \rightarrow \mu^+\mu^-$ was measured, giving the product of the leptonic branching ratios of $\phi$ meson $\sqrt{B(\phi \rightarrow e^+e^-)}B(\phi \rightarrow \mu^+\mu^-) = (3.14\pm0.22\pm0.14) \times 10^{-4}$. Assuming $\mu-e$-universality one can compare this value with the table branching ratio $B(\phi \rightarrow e^+e^-) = (2.99\pm0.08) \times 10^{-4}$ [14] They are in good agreement. Not using $\mu-e$-universality the branching ratio $B(\phi \rightarrow \mu^+\mu^-) = (3.30\pm0.45\pm0.32) \times 10^{-4}$ was obtained. It is close to one standard deviation from the table value $B(\phi \rightarrow \mu^+\mu^-) = (2.5\pm0.4) \times 10^{-4}$ [14].

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Figure 5: The energy dependence of Born cross section of the process $e^+e^- \rightarrow \mu^+\mu^-$ with $\phi$-meson contribution.

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