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# DIRECT MEASUREMENT OF THE $\phi(1020)$ LEPTONIC BRANCHING RATIO

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**Abstract**

The process $e^+e^- \to \mu^+\mu^-$ was studied by SND detector at VEPP-2M $e^+e^-$ collider in the $\phi(1020)$-resonance energy region. The effective $\phi$ meson leptonic branching ratio was measured: $B(\phi \to l^+l^-) \equiv \sqrt{B(\phi \to e^+e^-) \cdot B(\phi \to \mu^+\mu^-)} = (2.89 \pm 0.10 \pm 0.06) \cdot 10^{-4}$, which agrees well with the PDG value $B(\phi \to e^+e^-) = (2.91 \pm 0.07) \cdot 10^{-4}$ confirming $\mu$–$e$ universality. Without additional assumption of $\mu$–$e$ universality the branching ratio $B(\phi \to \mu^+\mu^-) = (2.87 \pm 0.20 \pm 0.14) \cdot 10^{-4}$ was obtained.

# Introduction

Vector mesons play an important role in hadron physics due to their direct coupling to photons. This phenomenon is a base of the phenomenological Vector Meson Dominance model which successfully describes electromagnetic interactions of hadrons. The key parameters of this model are $V-\gamma$ coupling constants. They can be extracted from the vector meson leptonic widths under assumption that leptonic decay proceeds via one-photon annihilation of the quark-antiquark pair constituting the meson. Leptonic widths also determine the total production cross sections of vector mesons in $e^+e^-$ annihilation and are important for calculation of the hadronic contribution to the photon vacuum polarization [1].

The $V-\gamma$ coupling constant is just one number per vector meson. Could these numbers tell us something non-trivial about an underlying QCD dynamics? Shortly after 1974 "charm revolution", Yennie noticed that independently of the vector meson flavor content the following relation holds [2, 3]

$$\frac{\Gamma(V \to e^+e^-)}{< e_q >^2} \approx 12 \text{ keV}, \tag{1}$$

where $< e_q >$ is the mean electric charge of the valence quarks inside the vector meson $V$ in the units of an electron charge. For $\rho$, $\omega$ and $\phi$ mesons this gives the famous 9:1:2 rule

$$\Gamma(\rho \to e^+e^-) : \Gamma(\omega \to e^+e^-) : \Gamma(\phi \to e^+e^-) = 9 : 1 : 2, \tag{2}$$

which can be considered as an SU(3) symmetry prediction. The surprising fact here is a relatively high ($\sim 10\%$) precision of (2) despite SU(3)-flavor symmetry breaking. Inclusion of charm gives even more badly broken SU(4) symmetry, but Yennie's relation remains valid with the same precision, which means that SU(4) symmetry still persists for the leptonic widths ratios! Inspired by this strange fact, Gounaris predicted $\Gamma(\Upsilon \to e^+e^-) = 1.2\,\mathrm{keV}$ [4] and was closer to reality than any other author [3]. Current experimental situation with leptonic widths is shown in Table 1.

Table 1: The leptonic widths of vector mesons [5].

| | $\Gamma_{exp}$, keV | $< e_q >^2$ | $\frac{\Gamma_{exp}}{<e_q>^2}$, keV |
|---|---|---|---|
| $\rho$ | $6.77 \pm 0.32$ | 1/2 | $13.5 \pm 0.6$ |
| $\omega$ | $0.60 \pm 0.02$ | 1/18 | $10.8 \pm 0.4$ |
| $\phi$ | $1.30 \pm 0.03$ | 1/9 | $11.7 \pm 0.3$ |
| $J/\psi$ | $5.26 \pm 0.37$ | 4/9 | $11.8 \pm 0.8$ |
| $\Upsilon$ | $1.32 \pm 0.05$ | 1/9 | $11.9 \pm 0.5$ |

In the nonrelativistic potential model [6] the leptonic decay width is given by the Van Royen–Weisskopf formula [7]

$$\Gamma(V \to e^+e^-) = \frac{16\pi\alpha^2 < e_q >^2}{M_V^2}\, |\Psi(r=0)|^2. \tag{3}$$

Equation (1) implies then that quarkonium wave function at the origin $\Psi(r=0)$ is proportional to the meson mass $M_V$. Note that for Coulomb potential $|\Psi(r=0)|^2 \sim M_V^3$, while linear potential gives $|\Psi(r=0)|^2 \sim M_V$. So the leptonic widths tell us that actual potential appears to be something in between. But even if we postulate such a potential, the relation (1) still has no simple explanation. For light quark systems like $\rho$, $\omega$, and $\phi$ relativistic corrections are essential. There are also strong interaction corrections governed by the scale dependent $\alpha_s$. It was argued [8] that these corrections modify the Van Royen - Weisskopf formula in the following way:

$$\Gamma(V \to e^+e^-) \approx \frac{16\pi\alpha^2 < e_q >^2}{M_V^2} \left|\Psi\left(r=\frac{1}{m_q}\right)\right|^2 (1 - 0.36\ \alpha_s(M_V)). \tag{4}$$

Intuitively, appearance of the constituent quark Compton wavelength $1/m_q$ in (4) looks natural, because in relativistic theory a particle cannot be localized within a region smaller than its Compton wavelength

[9]. Thus we can expect quark-antiquark pair to annihilate once approaching each other's relativistic extents [8]. But this intuitive clarity of (4) doesn't make an explanation of the remarkable regularity of (1) simpler, because (4) shows that leptonic widths are sensitive to the both nonperturbative and perturbative aspects of QCD. Thus it is not surprising that the leptonic widths become a traditional touchstone for various quark models [6, 10].

This paper is devoted to the measurement of leptonic branching ratio of the $\phi(1020)$ meson. There are two leptonic decays: $\phi \to e^+e^-$ and $\phi \to \mu^+\mu^-$. The $\mu$–$e$ universality implies for these decays that their branching ratios are equal with the accuracy of 0.01%. Presently only the $\phi \to \mu^+\mu^-$ decay was measured directly ([11]–[15]). Current branching ratio $B(\phi \to e^+e^-) = (2.91 \pm 0.07) \cdot 10^{-4}$ [5] is based on measurements of the $\phi$-meson total production cross section in $e^+e^-$ collisions. It was obtained by summation of all $\phi$-meson decay modes: $\phi \to K^+K^-$, $K_SK_L$, $3\pi$, etc.. Up to now the accuracy of $B(\phi \to e^+e^-)$ was much higher than that of $B(\phi \to \mu^+\mu^-)$. But there is a serious factor limiting the precision of $B(\phi \to e^+e^-)$ obtained in such an indirect way. It is the interference between $\phi$ meson and other vector states, which description is model dependent. Direct measurement of the $\phi \to e^+e^-$ decay in the $e^+e^- \to \phi \to e^+e^-$ reaction is difficult due to its small probability and huge background from the $e^+e^- \to e^+e^-$ Bhabha scattering.

The decay $\phi \to \mu^+\mu^-$ reveals itself as an interference pattern in the energy dependence of the $e^+e^- \to \mu^+\mu^-$ cross section in the region close to the $\phi$-meson peak. The interference amplitude is proportional to $B(\phi \to l^+l^-) = \sqrt{B(\phi \to e^+e^-) \cdot B(\phi \to \mu^+\mu^-)}$. The accuracy of the $B(\phi \to l^+l^-)$ measurement in this case is limited only by uncertainty in the calculation of the pure QED part of the $e^+e^- \to \mu^+\mu^-$ cross section. The 0.2% accuracy claimed in [16] leads to 0.8% systematic error in the interference amplitude. Large statistics collected by SND detector in the vicinity of the $\phi$ resonance allowed us to make direct measurement of the leptonic branching ratio $B(\phi \to l^+l^-)$ with the accuracy comparable with that of previous indirect measurements of $B(\phi \to e^+e^-)$.

# Experiment

Our previous study of the $e^+e^- \to \mu^+\mu^-$ cross section was done using the 1996 data sample with the total integrated luminosity of 2.6 $\mathrm{pb}^{-1}$ [15]. In 1998 two experimental runs were carried out in the center of mass energy range $E = 984 - 1060$ MeV in 16 energy points. The collider operated with superconducting wiggler [17] allowing to increase the average luminosity by a factor of two. Higher luminosity led to relative reduction of the cosmic ray background. The total integrated luminosity $\Delta L = 8.6$ $\mathrm{pb}^{-1}$ collected in 1998 corresponds to $13.2 \cdot 10^6$ produced $\phi$ mesons.

The SND experimental setup is described in detail elsewhere in ref. [18]. The main part of the SND is a spherical electromagnetic calorimeter. The angles of charged particles are measured by two cylindrical drift chambers. An outer muon system, consisting of streamer tubes and plastic scintillation counters, covers the detector. The integrated luminosity was measured using $e^+e^- \to e^+e^-$ events selected in the same acceptance angle as the events of the process under study $e^+e^- \to \mu^+\mu^-$. The uncertainty of the luminosity measurement was estimated to be 2%, but its contribution in the systematic error of the interference amplitude is only 0.8%.

# Event selection

The primary selection criteria for $\mu^+\mu^-$ events were similar to those of our previous work [15]:

- total energy deposition in the calorimeter is more than 270 MeV;
- there are two collinear charged tracks in an event with acollinearity angles in azimuth and polar directions: $\mid \Delta\varphi \mid < 10^\circ$, $\mid \Delta\theta \mid < 25^\circ$ and with the polar angles within $45^\circ < \theta < 135^\circ$ ;
- event is not tagged as $e^+e^- \to e^+e^-$ by $e/\pi$ separation procedure [19].

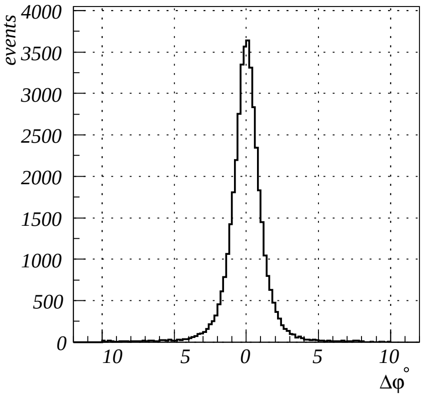


Figure 1: The $\Delta\varphi$ distribution in $e^+e^- \to \mu^+\mu^-$ events.

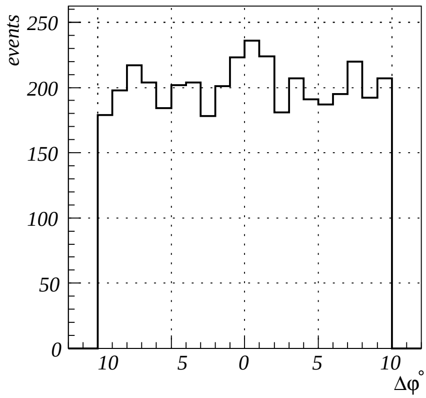


Figure 2: The $\Delta\varphi$ distribution for cosmic ray events.

To suppress the background from the processes $e^+e^- \to \pi^+\pi^-$, $\pi^+\pi^-\pi^0$, $K_SK_L$ the outer muon system was used: a requirement for both charged particles to produce hits in muon system renders contribution from this background negligible.

The cosmic ray background was suppressed by restriction of the time $\tau$ measured by outer scintillation counters with respect to the beam collision moment [15]: $|\ \tau\ | < 10$ ns. About 30% of events selected by the cuts described above are still cosmic ray background. To determine it more accurately the selected events were divided into two classes:

1. $|\ \Delta\varphi\ | < 5°$;

2. $|\ \Delta\varphi\ | > 5°$.

The resolution in $\Delta\varphi$ is about 1°. The $\Delta\varphi$ distribution for $e^+e^- \to \mu^+\mu^-$ events (Fig. 1) was obtained from the experimental data with the strong cuts on a difference between time measurements by the muon system for both tracks. Almost all $\mu^+\mu^-$ events belong to the first class. The second class contains only 1.7% of $\mu^+\mu^-$ events. The $\Delta\varphi$ distribution for pure cosmic ray events collected in a special run without beams is shown in Fig. 2. The uniformity of this distribution is an artifact of our DC track reconstruction algorithm in which the origin of a charged track in the $X$-$Y$ plane is fixed to the beam collision point. From Fig. 2 the ratio between numbers of cosmic ray events in the two classes was found

$$k_{cs} = \frac{N_1^{cs}}{N_2^{cs}} = 1.028 \pm 0.033.$$

The number of cosmic ray background events in the first class was calculated for each energy point $E_i$ by the following formula:

$$N_1^{cs}(E_i) = \dot{N}_2 \cdot k_{cs} \cdot T(E_i).$$

Here $T(E_i)$ is a data acquisition time for an energy point $E_i$, $\dot{N}_2$ is the class two cosmic event rate averaged over both 1998 experimental runs. The net number of $\mu^+\mu^-$ events for each energy point was obtained by subtraction of the cosmic ray background:

$$N^\mu(E_i) = N_1(E_i) - N_1^{cs}(E_i).$$

# Fitting

Energy dependence of the detection cross section was fitted according to the following formula:

$$\begin{aligned} \sigma_{\mu\mu}^{vis}(E) &= \sigma_0(E) \cdot R(E) \left| 1 - Z_\mu \frac{m_\phi \Gamma_\phi}{\Delta_\phi(E)} \right|^2, \\ \sigma_0(E) &= \frac{2\pi\alpha^2 \beta(E)(1 - \beta^2(E)/3)}{E^2}, \end{aligned} \tag{5}$$

where $\alpha$ is the fine structure constant; $\beta(E) = (1 - 4 \cdot m_\mu^2/E^2)^{1/2}$; $m_\phi$, $\Gamma_\phi$, $\Delta_\phi(E) = m_\phi^2 - E^2 - iE\Gamma(E)$ are the $\phi$-meson mass, width and inverse propagator respectively; $\sigma_0(E)$ is Born cross section of the process $e^+e^- \to \mu^+\mu^-$; $Z_\mu \equiv Q_\mu e^{i\psi_\mu}$ — interference amplitude. The module of the interference amplitude is related to the leptonic branching ratios:

$$Q_\mu = 3 \cdot \frac{\sqrt{B(\phi \to e^+e^-)B(\phi \to \mu^+\mu^-)}}{\alpha}. \tag{6}$$

The factor $R(E)$ takes into account the detection efficiency and radiative corrections:

$$R(E) = \varepsilon_\mu \frac{\sigma_{\mu\mu}(E)}{\sigma_0(E)\left|1 - Z\frac{m_\phi \Gamma_\phi}{\Delta_\phi(E)}\right|^2}. \tag{7}$$

Here $\sigma_{\mu\mu}$ is the result of Monte Carlo integration of the differential cross section of the process $e^+e^- \to \mu^+\mu^-(\gamma)$ [16] for our geometric cuts with the energy dependent probability for muons to hit outer scintillation counters taken into account. The uncertainty in the energy dependence of this probability adds 1.7% to the systematic error of $Q_\mu$. The total systematic error of the interference amplitude which includes all contributions described above is 2%. The parameter $\varepsilon_\mu$ represents energy independent contributions into detection efficiency. It is determined mainly by the cut on total energy deposition in the calorimeter. In the calculation of radiative corrections the interference amplitude was assumed purely real and equal to

$$Z = \frac{3B(\phi \to e^+e^-)}{\alpha} = 0.120$$

with the PDG table value for $B(\phi \to e^+e^-)$.

Table 2: The results of the fit with $\psi_\mu = 0$ for two experimental runs. Only statistical errors are shown.

| Parameter | PHI_9801 | PHI_9802 | Combined |
|---|---|---|---|
| $\chi^2/NDF$ | 19.4/15 | 11.3/15 | 33.8/30 |
| $Q_\mu,\ 10^{-2}$ | $12.1 \pm 0.6$ | $11.0 \pm 0.6$ | $11.9 \pm 0.4$ |
| $\varepsilon_\mu,\ \%$ | $83.1 \pm 0.3$ | $82.5 \pm 0.3$ | $83.1 \pm 0.3/82.8 \pm 0.3$ |
| $B(\phi \to l^+l^-),\ 10^{-4}$ | $2.99 \pm 0.15$ | $2.74 \pm 0.14$ | $2.89 \pm 0.10$ |

The fitting was performed for two experimental runs independently. Fits with a free $\psi_\mu$ yield the interference phase, which is in good agreement with the expected zero value: 1) $\psi_\mu = (1.0 \pm 2.8)^\circ$, 2) $\psi_\mu = (0.1 \pm 2.8)^\circ$. Therefore the interference phase was fixed to $\psi_\mu = 0$. The $Q_\mu$ and $\varepsilon_\mu$ were free fit parameters. The fit results presented in Table 2 show statistical agreement between two experimental

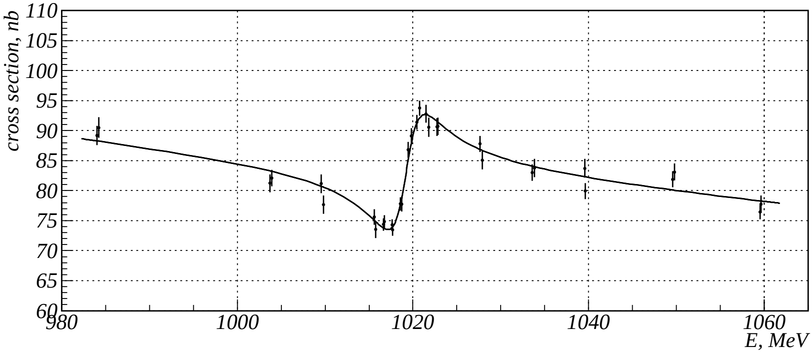


Figure 3: The measured cross section of the process $e^+e^- \to \mu^+\mu^-$.

runs. Therefore combined fit was performed to obtain the final results which are listed in the third column of the Table 2. The energy dependence of the measured cross section and the fitting curve are shown in Fig. 3.

# Results

The following $\phi$ meson parameters can be obtained from the measured $Q_\mu$ value:

$$B(\phi \to l^+l^-) \equiv \sqrt{B(\phi \to e^+e^-)B(\phi \to \mu^+\mu^-)} = (2.89 \pm 0.10 \pm 0.06) \cdot 10^{-4},$$

$$B(\phi \to e^+e^-) \cdot B(\phi \to \mu^+\mu^-) = (8.36 \pm 0.59 \pm 0.37) \cdot 10^{-8}.$$

The total error in $B(\phi \to l^+l^-)$ equals 4% which is comparable with the PDG error of $B(\phi \to e^+e^-) = (2.91 \pm 0.07) \cdot 10^{-4}$. The good agreement of the experimental values $B(\phi \to l^+l^-)$ and $B(\phi \to e^+e^-)$ confirms the $\mu$–$e$ universality.

Using PDG value of $B(\phi \to e^+e^-)$ and equation (6) we obtain:

$$B(\phi \to \mu^+\mu^-) = (2.87 \pm 0.20 \pm 0.14) \cdot 10^{-4}.$$

The precision of this result is 1.6 times better than in PDG tables: $B(\phi \to \mu^+\mu^-) = (3.7 \pm 0.5) \cdot 10^{-4}$.

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