Direct Measurement of the $\phi(1020)$ Leptonic Branching Ratio

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(Received 30 August 2000)

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

DOI: 10.1103/PhysRevLett.86.1698 PACS numbers: 13.20.–v, 14.40.Cs, 29.85.+c

Truly neutral vector mesons play an important role in hadron physics due to their direct coupling to photons. This phenomenon is the basis of the phenomenological vector meson dominance model which successfully describes electromagnetic interactions of hadrons. The key parameters of this model are V-γ coupling constants. They can be extracted from the vector meson leptonic widths under the 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-γ coupling constant is just one number per vector meson. Could these numbers tell us something nontrivial about the underlying QCD dynamics? Shortly after the 1974 "charm revolution," Yennie noticed that independently of the vector meson flavor content the following relation holds [2,3]:

$$\Gamma(V \to e^+e^-)/\langle e_q \rangle^2 \approx 12\ \text{keV}, \qquad (1)$$

where $\langle e_q \rangle$ is the mean electric charge of the valence quarks inside the vector meson V in the units of an electron charge. For ρ, ω, and ϕ mesons this gives the famous rule: $\Gamma(\rho \to e^+e^-):\Gamma(\omega \to e^+e^-):\Gamma(\phi \to e^+e^-) =$ 9:1:2, which can be considered as an SU(3) symmetry prediction. The surprising fact here is a relatively high ($\sim$10%) precision of the 9:1:2 rule 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 $\Gamma(\Upsilon \to e^+e^-) = 1.2$ keV [4] and was closer to reality than any other author [3]. The current experimental situation with leptonic widths [5] is shown in Table I.

In the nonrelativistic potential model [6] the leptonic decay width is given by the Van Royen–Weisskopf formula [7]: $\Gamma(V \to e^+e^-) = 16\pi\alpha^2\langle e_q \rangle^2 |\Psi(r=0)|^2/M_V^2$.

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 the linear potential gives $|\Psi(r=0)|^2 \sim M_V$. So the leptonic widths tell us that the 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 ρ, ω, and ϕ relativistic corrections are essential. There are also strong interaction corrections governed by the scale dependent α_s. It was argued [8] that these corrections modify the Van Royen–Weisskopf formula in the following way:

$$\Gamma(V \to e^+e^-) \approx 16\pi\alpha^2\langle e_q \rangle^2 |\Psi(r = 1/m_q)|^2 \times [1 - 0.36\alpha_s(M_V)]/M_V^2 . \qquad (2)$$

Intuitively, appearance of the constituent quark Compton wavelength $1/m_q$ in (2) looks natural, because in relativistic theory a particle cannot be localized within a region smaller than its Compton wavelength [9]. Thus we can expect the quark-antiquark pair to annihilate when approaching each other's relativistic extents [8]. But this intuitive clarity of (2) does not make an explanation of the remarkable regularity of (1) simpler, because (2) shows

TABLE I. The leptonic widths of vector mesons.

	Γ_{exp}, keV	$\langle e_q \rangle^2$	$\frac{\Gamma_{\text{exp}}}{\langle e_q \rangle^2}$, keV
ρ	6.77 ± 0.32	1/2	13.5 ± 0.6
ω	0.60 ± 0.02	1/18	10.8 ± 0.4
ϕ	1.30 ± 0.03	1/9	11.7 ± 0.3
J/ψ	5.26 ± 0.37	4/9	11.8 ± 0.8
Υ	1.32 ± 0.05	1/9	11.9 ± 0.5

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that leptonic widths are sensitive to both the 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 the leptonic branching ratio of the $\phi(1020)$ meson. There are two leptonic decays: $\phi \to e^+e^-$ and $\phi \to \mu^+\mu^-$. The μ-e universality implies for these decays that $B(\phi \to \mu^+\mu^-) = B(\phi \to e^+e^-) \times 0.9993$. Presently only the $\phi \to \mu^+\mu^-$ decay was measured directly ([11–17]). There are two Particle Data Group (PDG) values for this decay branching ratio [5]. One of them, $B(\phi \to \mu^+\mu^-) = (2.5 \pm 0.4) \times 10^{-4}$, is based on the experiments on photoproduction of ϕ meson [11,12]. Another value of the branching ratio $B(\phi \to \mu^+\mu^-) = (3.7 \pm 0.5) \times 10^{-4}$ is obtained from e^+e^- experiments [13,14,17]. In addition the NOVOSIBIRSK-CMD-2 experiment at VEPP-2M [15,16] has some preliminary results on this decay. One can see that the difference between two PDG values for the decay $\phi \to \mu^+\mu^-$ is about 2 standard deviations and the accuracy of these results is relatively low. Current branching ratio $B(\phi \to e^+e^-) = (2.91 \pm 0.07) \times 10^{-4}$ [5] is based on measurements of the ϕ-meson total production cross section in e^+e^- collisions. It was obtained by summation of all ϕ-meson decay modes: $\phi \to K^+K^-$, K_SK_L, 3π, 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 ϕ 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 a wave-like interference pattern in the energy dependence of the $e^+e^- \to \mu^+\mu^-$ cross section in the region close to the ϕ-meson peak. The amplitude of the interference wave is proportional to $B(\phi \to l^+l^-) \equiv \sqrt{B(\phi \to e^+e^-)B(\phi \to \mu^+\mu^-)}$. 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 [21] leads to 0.8% systematic error in the interference amplitude. Large statistics collected by the SND detector in the vicinity of the ϕ 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 $B(\phi \to e^+e^-)$.

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 pb^{-1} [17]. 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 [18] allowing us to increase the average luminosity by a factor of 2. Higher luminosity led to relative reduction of the cosmic ray background. The total integrated luminosity $\Delta L = 8.6$ pb^{-1} collected in 1998 corresponds to 13.2×10^6 produced ϕ mesons.

The SND experimental setup is described in detail in Ref. [19]. The main part of the SND is a spherical electromagnetic calorimeter. The angles of charged particles are measured by two cylindrical drift chambers (DC). 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 systematic uncertainty of the luminosity measurement is 2%, but its contribution to the systematic error of the interference amplitude estimated using the process $e^+e^- \to \gamma\gamma$ is only 0.8%.

The primary selection criteria for $\mu^+\mu^-$ events were similar to those of our previous work [17]: (i) total energy deposition in the calorimeter is more than 270 MeV; (ii) there are two collinear charged tracks in an event with acollinearity angles in azimuth and polar directions: $|\Delta\varphi| < 10°$, $|\Delta\theta| < 25°$ and with the polar angles within $45° < \theta < 135°$; (iii) event is not tagged as $e^+e^- \to e^+e^-$ by e/π separation procedure [20]. To suppress the background from the processes $e^+e^- \to \pi^+\pi^-$, $\pi^+\pi^-\pi^0$, K_SK_L, K^+K^- the outer muon system was used: a requirement for both charged particles to produce hits in the muon system renders contribution from this background negligible. For example, the contribution from the process $e^+e^- \to \pi^+\pi^-$ is about 0.2% in the ϕ-meson peak.

The cosmic ray background was suppressed by restriction of the time τ measured by outer scintillation counters with respect to the beam collision moment [17]: $|\tau| < 10$ ns. About 30% of events selected by the cuts described above are still cosmic ray background. To determine the

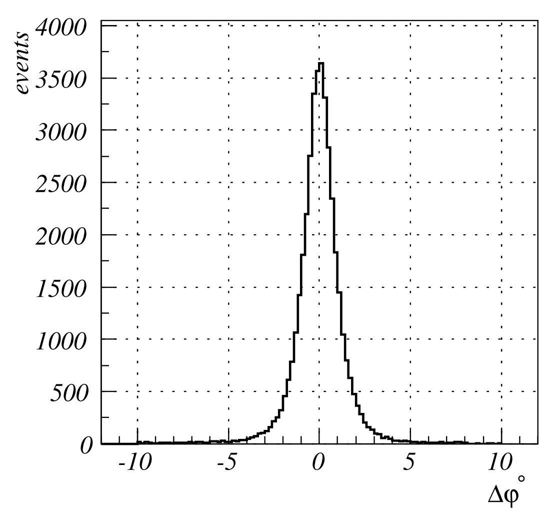

FIG. 1. The $\Delta\varphi$ distribution in $e^+e^- \to \mu^+\mu^-$ events.

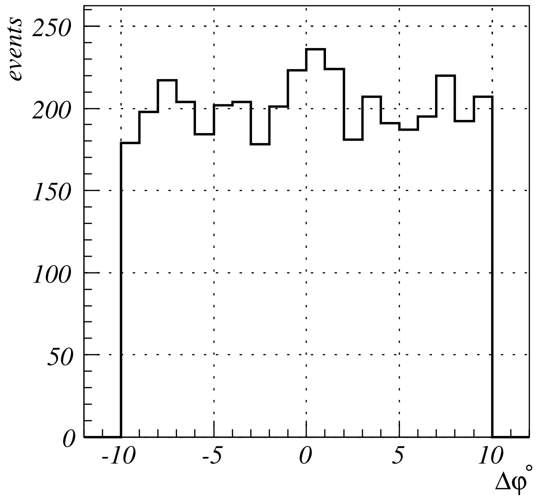

FIG. 2. The $\Delta\varphi$ distribution for cosmic ray events.

contribution of cosmic background more accurately the selected events were divided into two classes: (i) $|\Delta\varphi| < 5°$; (ii) $|\Delta\varphi| > 5°$. 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 after 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 $k_{cs} = N_1^{cs}/N_2^{cs} = 1.028 \pm 0.033$.

The number of cosmic ray background events in class (i) was calculated for each energy point E_i by the following formula: $N_1^{cs}(E_i) = k_{cs}T(E_i)dN_2/dT$. Here $T(E_i)$ is a data acquisition time for an energy point E_i, dN_2/dT is the cosmic event rate in class (ii) 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: $N^\mu(E_i) = N_1(E_i) - N_1^{cs}(E_i)$. The errors of the numbers $N^\mu(E_i)$ include the errors of $N_1(E_i)$ and $N_1^{cs}(E_i)$.

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

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

where α is the fine structure constant; $\beta(E) = (1 - 4m_\mu^2/E^2)^{1/2}$; m_ϕ, Γ_ϕ, $\Delta_\phi(E) = m_\phi^2 - E^2 - iE\Gamma(E)$ are the ϕ-meson mass, width, and inverse propagator, respectively; $\sigma_0(E)$ is the Born cross section of the process $e^+e^- \to \mu^+\mu^-$; $Z_\mu \equiv Q_\mu e^{i\psi_\mu}$ is the interference parameter. The modulus of the interference parameter is related to the leptonic branching ratio: $Q_\mu = B(\phi \to l^+l^-) \cdot 3/\alpha$. The factor $R(E)$ takes into account the detection efficiency and radiative corrections:

$$R(E) = \varepsilon_\mu \frac{\sigma_{\mu\mu}(E)}{\sigma_0(E)\,|1 - Z\frac{m_\phi\Gamma_\phi}{\Delta_\phi(E)}|^2}. \tag{4}$$

Here $\sigma_{\mu\mu}$ is the result of Monte Carlo integration of the differential cross section of the process $e^+e^- \to \mu^+\mu^-(\gamma)$ [21] 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_μ. The parameter ε_μ represents the energy independent factor in the detection efficiency. It is determined mainly by the cut on total energy deposition in the calorimeter. The value of $\varepsilon_\mu = 0.84 \pm 0.01$ was obtained using Monte Carlo simulation of the process $e^+e^- \to \mu^+\mu^-(\gamma)$ in the SND detector [22], but in the fitting procedure ε_μ was left free. In the calculation of radiative corrections the interference parameter was assumed purely real and equal to $Z = B(\phi \to e^+e^-) \cdot 3/\alpha = 0.120$ with the PDG table value for $B(\phi \to e^+e^-)$.

The fitting was performed for two experimental runs independently. Fits with a free ψ_μ yield the interference phase, which is in good agreement with the expected zero value: (i) $\psi_\mu = (1.0 \pm 2.8)°$; (ii) $\psi_\mu = (0.1 \pm 2.8)°$. Therefore the interference phase was fixed to $\psi_\mu = 0$. The fit results presented in Table II show statistical agreement between two experimental runs. Therefore combined fit was performed to obtain the final results which are listed in the third column of Table II. The values of ε_μ obtained in the fit and from Monte Carlo simulation agree well. The energy dependence of the measured cross section and the fitting curve are shown in Fig. 3. The systematic error of Q_μ includes 1.7% from the uncertainty in the energy

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

Parameter	PHI_9801	PHI_9802	Combined
χ^2/NDF	19.4/15	11.3/15	33.8/30
Q_μ, 10^{-2}	12.1 ± 0.6	11.0 ± 0.6	11.9 ± 0.4
ε_μ, 10^{-2}	83.1 ± 0.3	82.5 ± 0.3	83.1(82.8) ± 0.3
$B(\phi \to l^+l^-)$, 10^{-4}	2.99 ± 0.15	2.74 ± 0.14	2.89 ± 0.10

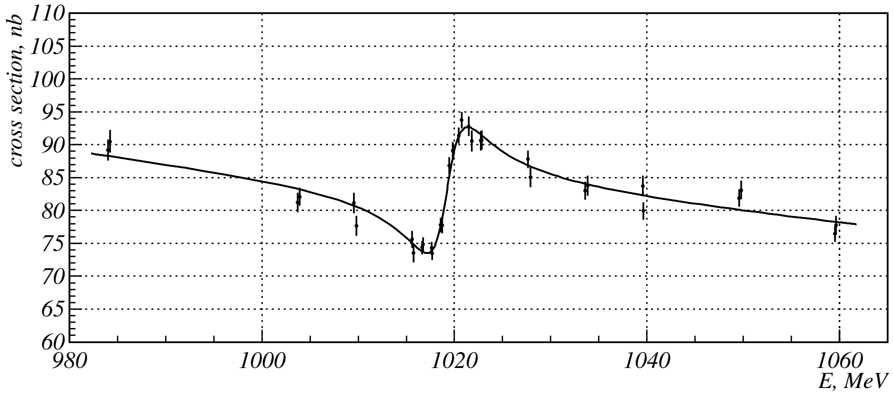

FIG. 3. The measured cross section of the process $e^+e^- \to \mu^+\mu^-$.

dependence of the probability for muons to hit the outer system, 0.8% from the luminosity measurements, and 0.8% from the calculation of the radiative corrections. The resulting systematic error is 2%.

In conclusion, we obtain the following ϕ meson parameters from the measured Q_μ value: $B(\phi \to l^+l^-) = (2.89 \pm 0.10 \pm 0.06) \times 10^{-4}$; $B(\phi \to e^+e^-) \cdot B(\phi \to \mu^+\mu^-) = (8.36 \pm 0.59 \pm 0.37) \times 10^{-8}$. This result is in good agreement with our previous one $B(\phi \to l^+l^-) = (3.14 \pm 0.22 \pm 0.14) \times 10^{-4}$ [17]. Using the PDG value of $B(\phi \to e^+e^-) = (2.91 \pm 0.07) \times 10^{-4}$ we obtain $B(\phi \to \mu^+\mu^-) = (2.87 \pm 0.20 \pm 0.14) \times 10^{-4}$. The good agreement of $B(\phi \to \mu^+\mu^-)$ and $B(\phi \to e^+e^-)$ confirms the μ-e universality.

This work is supported in part by Russian Foundation for Basic Research, Grants No. 99-02-16815 and No. 99-02-17155. We thank G. V. Fedotovich for useful discussions.

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[1] S. Eidelman and F. Jegerlehner, Z. Phys. C **67**, 585 (1995).
[2] D. R. Yennie, Phys. Rev. Lett. **34**, 239 (1975).
[3] J. J. Sakurai, Physica (Amsterdam) **96A**, 300 (1976).
[4] G. J. Gounaris, Phys. Lett. **72B**, 91 (1977).
[5] Particle Data Group, D. E. Groom *et al.,* Euro. Phys. J. C **15**, 1 (2000).
[6] C. Quigg and J. L. Rosner, Phys. Rep. **56**, 167 (1979); H. Grosse and A. Martin, Phys. Rep. **60**, 341 (1980).
[7] R. Van Royen and V. F. Weisskopf, Nuovo Cimento A **50**, 617 (1967); **51**, 583 (1967).
[8] E. C. Poggio and H. J. Schnitzer, Phys. Rev. D **20**, 1175 (1979); **21**, 2034 (1980); H. Krasemann, Phys. Lett. **96B**, 397 (1980).
[9] T. D. Newton and E. P. Wigner, Rev. Mod. Phys. **21**, 400 (1949).
[10] See, for example, W. Jaus, Phys. Rev. D **44**, 2851 (1991); B. Margolis and R. R. Mendel, Phys. Rev. D **28**, 468 (1983); N. Barik, P. C. Dash, and A. R. Panda, Phys. Rev. D **47**, 1001 (1993); **53**, 4110 (1996); P. Maris and P. C. Tandy, Phys. Rev. C **60**, 055214 (1999); B. D. Jones and R. M. Woloshyn, Phys. Rev. D **60**, 014502 (1999); B. C. Metsch and H. R. Petry, Acta Phys. Pol. B **27**, 3307 (1996).
[11] D. R. Earles *et al.,* Phys. Rev. Lett. **25**, 1312 (1970).
[12] S. Hayes *et al.,* Phys. Rev. D **4**, 899 (1971).
[13] J. E. Augustin *et al.,* Phys. Rev. Lett. **30**, 462 (1973).
[14] I. B. Vasserman *et al.,* Phys. Lett. **99B**, 62 (1981).
[15] R. R. Akhmetshin *et al.,* Budker Institute Report No. BINP 99-11, 1999.
[16] R. R. Akhmetshin *et al.,* Nucl. Phys. **A675**, 424c (2000).
[17] M. N. Achasov *et al.,* Phys. Lett. B **456**, 304 (1999).
[18] V. V. Anashin *et al.,* Budker Institute Report No. BINP 84-123, 1984.
[19] M. N. Achasov *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **449**, 125 (2000).
[20] M. N. Achasov *et al.,* Phys. Lett. B **474**, 188 (2000).
[21] A. B. Arbuzov *et al.,* J. High Energy Phys. **9710**, 001 (1997).
[22] A. D. Bukin *et al.,* Budker Institute Report No. BINP 90-93, 1990.