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LEPTONIC DECAYS OF VECTOR MESONS : THE BRANCHING RATIO OF THE ELECTRON-POSITRON DECAY MODE OF THE PHI MESON

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Abstract: An experiment designed to measure the branching ratio of phi meson to e^+e^- was performed at DESY. The experiment was done by measuring the phi production and phi decay to e^+e^- with the same apparatus. The results of this experiment, based on 10^4 $\phi^\circ \rightarrow K^+K^-$ events and 40 $\phi^\circ \rightarrow e^+e^-$ events on carbon, yield a branching ratio of $(2.70 \pm 0.80) * 10^{-4}$ or a partial width of (0.92 ± 0.33) keV. Comparison of this result with various theoretical models will be made.

At the DESY 7.5 GeV electron synchrotron, experiments are in progress to investigate the leptonic decays of vector mesons[(1)]. We report here a measurement of the branching ratio

$$BR = \frac{\Gamma(\phi \rightarrow e^+e^-)}{\Gamma(\phi \rightarrow all)} \qquad (1)$$

from which the coupling constant γ_ϕ^2 may be obtained directly. To obtain (1) the rates of the two reactions

$$\gamma + C \longrightarrow C + \phi \hookrightarrow e^+ + e^- \qquad (2)$$

and

$$\gamma + C \longrightarrow C + \phi \hookrightarrow K^+ + K^- \qquad (3)$$

were measured under similar kinematic conditions using the same apparatus, a symmetric double-arm magnetic spectrometer which has been described previously [2]. The measurement of (3) is the subject of the preceding letter [3], which is referred to as (A) in what follows.

To first order, both the Bethe-Heitler (BH) and Compton diagrams contribute to the reaction

$$\gamma + C \longrightarrow C + e^+ + e^- \qquad (4).$$

For the case that the lepton pair e^+e^- has an invariant mass $M \leq 600$ MeV/c^2 the Compton term has been estimated and measured [4] to contribute less than a few per cent to (4) for pair production angles $\Theta \leq 7°$. Therefore, for $M \leq 600$ MeV/c^2 the reaction (4) can be used as a sensitive test of quantum electro-dynamics at small distances [2]. As first suggested by Berman and Drell [5] however, the Compton contribution will be greatly enhanced if M is equal to the mass of a vector meson (ρ, ω, ϕ); hence (4) can also be used to study the leptonic decays of vector mesons.

For a measurement of the branching ratio (1) to be meaningful, three major error sources must be reduced or avoided:

a) Bethe-Heitler (BH) background must be kept small, as its subtraction contributes to (1) a statistical uncertainty as well as an uncertainty caused by lack of precise knowledge of inelastic carbon form factors. At symmetry, for a given pair invariant mass $M \simeq 2\,p\Theta$ (p is the momentum of the electron and positron, Θ the angle of each with respect to the beam) the BH counting rate varies roughly as Θ^{-6}, whereas the $\phi \longrightarrow e^+e^-$ pair rate varies as Θ^{-3}.

Therefore,
$$\frac{\phi \rightarrow e^+e^-}{BH} \sim \theta^{3} \qquad (5)$$
and the relative BH background can be reduced by observing e^+e^- at large angles.

b) The process $\rho \longrightarrow e^+e^-$ contributes to the measured e^+e^- rate at the ϕ mass. The systematic errors in this contribution can be reduced if ρ-production and the decay $\rho \rightarrow e^+e^-$ are measured in the same apparatus.

c) To obtain an accurate value of the branching ratio (1) both the ϕ production-cross section and the ϕ polarization must be known over the kinematic region for which e^+e^- pairs are accepted. For this experiment, systematic errors caused by the ϕ cross section measurement were reduced by measuring both (2) and (3) with the same apparatus. Also, the ϕ polarization was determined directly in (A); the conclusion was that ϕ production at forward angles proceeds via diffraction and that the ϕ is completely transversely polarized. The decay angular distribution $W(\Theta^*)$ in the ϕ rest system is determined to be

for K-pairs:
$$W_{KK}(\theta^*) = \frac{3}{8\pi} \sin^2\theta^* \qquad (7)$$
from which one obtains readily that for electron pairs:
$$W_{ee}(\theta^*) = \frac{3}{16\pi}\left(1 + \cos^2\theta^*\right) \qquad (8)$$

(Θ^* is the angle in the ϕ rest system between the decay products and the recoil target particle direction).

On the basis of considerations a, b, c above, the experimental arrangement was chosen to minimize systematic errors as follows:

First, the largest central pair opening angles compatible with a reasonable counting rate were chosen, namely 22-30°. The uncertainty in inelastic form factors [6] then introduces an error $\simeq$ 5% in the BH subtraction.

Second, the $\rho \to e^+e^-$ contribution was estimated by several independent methods: a) Both the pion pair yield at the ϕ mass and the $\rho \to e^+e^-$ branching ratio were measured with the same apparatus [1] and hence the contribution of ρ under the ϕ peak calculated. b) With the knowledge of the branching ratio of $\rho \to e^+e^-$ and with the best fit values of mass and width to the measured $\rho \to e^+e^-$ spectrum, various assumptions of the Breit-Wigner mass distribution were used to extrapolate the ρ spectrum under the ϕ peak. The (ρ, ϕ) interference contribution was calculated assuming the production amplitude at resonance to be imaginary for both ρ and ϕ [7], it gives a 2.5% contribution when integrated over the acceptance. The various methods yield results (5-15%) consistent with each other and an average value of 10% was removed from the ϕ peak as the most likely ρ plus (ρ, ϕ) interference contamination.

Third, as described in (A), the normalization uncertainty in the production was reduced to $\pm$ 8% by a systematic study of the production mechanism of reaction (3).

Finally, to ensure that our result is not biased by interference between BH and Compton ($\phi \rightarrow e^+e^-$) terms, and at the same time to be able to measure this interference effect (as described in a letter to be published (8)), half of the data was taken at each spectrometer polarity.

To measure the counting rate of reaction (2) the invariant-mass distribution of e^+e^- was measured for $900 < M_{ee} < 1150$ MeV/c^2, a total of 100 events being accumulated at 3 settings of the spectrometer: $\theta = 11.1°, 11.6°$, $p = 2500$ MeV/c; $\theta = 15°$, $p =$ 1950 MeV/c. For each setting, the counting rate was corrected for dead time, accidentals, and beam loss in the target. The events were grouped in 40-MeV-wide mass bins using the hodoscope information. Before the events from different settings were combined to form a mass distribution, the expected BH-yield was subtracted for each setting. The BH yield was calculated by Monte Carlo method, in which the laboratory vector momenta of e^+e^- were generated at random in the target. The trajectory of each particle was then followed through the spectrometer, and the accepted events were weighted with the BH cross section. The effects of multiple scattering and bremsstrahlung were included in this computation. Analytic formulae for elastic and quasi-elastic carbon form factors were used (6). The mass distribution was then formed by combining the yields of the 3 spectrometer settings. In the mass region $950 \leq M \leq 1070$ MeV/c^2, a total of 84 events were observed; whereas the expected BH yield is 43 events.

The mass spectrum is shown in Fig. 1. The BH background has been subtracted, and all corrections have been applied. The spectrum is in agreement with the expected e^-e^+ mass distribution from the Monte Carlo program. The solid curve is the ϕ mass distribution produced via the program which generated ϕ mesons ($m_\phi = 1019.5$, $\Gamma_\phi = 3.4$ MeV) at the target. The events were weighted by the ϕ production mechanism and the e^-e^+ pairs were then passed through the spectrometer allowing for multiple scattering and bremsstrahlung loss until they reached a particular hodoscope combination. The effects of the bremsstrahlung loss are two: It increases the width of the observed peak to $\simeq 40$ MeV/c^2 and it shifts the location of the peak to a lower position. The good agreement between the Monte Carlo yield and actual data shows that almost all the events are ϕ and the subtraction of ρ contamination is a realistic one.

The branching ratio (1) is now easily obtained by normalizing the number (40) of observed $\phi \longrightarrow e^+e^-$ events to the total number of ϕ produced. The latter was calculated using the production cross section on carbon (based on 10^4 events) measured in the same apparatus. Taking the production mechanism (eq. (2) of (A)) and polarization factors given in eqs. (7) and (8) into account, we obtain the result:

$$\frac{\Gamma(\phi \rightarrow e^+e^-)}{\Gamma(\phi \rightarrow K^+K^-)} = (5.7 \pm 1.7) \times 10^{-4}$$

Using the currently accepted value of $\dfrac{\Gamma(\phi \rightarrow K^+K^-)}{\Gamma(\phi \rightarrow all)} = 0.473$ (9)

we obtain the branching ratio

$$BR = \frac{\Gamma(\phi \rightarrow e^+e^-)}{\Gamma(\phi \rightarrow all)} = (2.70 \pm 0.80) \times 10^{-4}$$

Using $\Gamma_\phi = 3.4$ MeV/c^2, we obtain a corresponding partial width $\Gamma(\phi \rightarrow e^+e^-) = (0.92 \pm 0.33)$ keV. (The error in Γ_ϕ of $\pm$ 20% is included in this calculation).

Following the suggestion of Sakurai [10], the predictions of the current mixing models together with Weinberg's first sum rule are shown as solid lines and circles in Fig.2. The radii of the circles $= \sqrt{\frac{1}{3} m_\rho \Gamma(\rho \to ee)}$ are determined from our previous measurement [1]. The vertical lines represent our measurement of $\Gamma(\phi \to ee)$ and together with the circles they define an "allowed region" for this model. The predictions of Oakes and Sakurai [10] with $\Theta = 28.2^\circ \left(\tan\Theta = \sqrt{\frac{m_\omega \Gamma(\omega \to ee)}{m_\phi \Gamma(\phi \to ee)}}\right)$ and of Das, Mathur, and Okubo [11] with $\Theta = 39^\circ$ are shown as solid lines.

The predictions of the quark model of Dar and Weisskopf [12], and the models of Lee, Kroll, and Zumino [13] (mass mixing models with $\Theta_Y = \Theta_N = 32^\circ, 39^\circ$ and current mixing model with $\Theta_Y = 33^\circ$, $\Theta_N = 21^\circ$, but without Weinberg's sum rule) are shown as points.

The data are two standard deviations away from the mass mixing model with $\Theta_Y = \Theta_N = 32^\circ$ and three standard deviations away from the current mixing model without Weinberg's sum rule. The data agree best with the quark model prediction. However, detailed comparison with various theories cannot be made until better knowledge of the width of the ρ and the branching ratio of $\omega \to e^+e^-$ is available.

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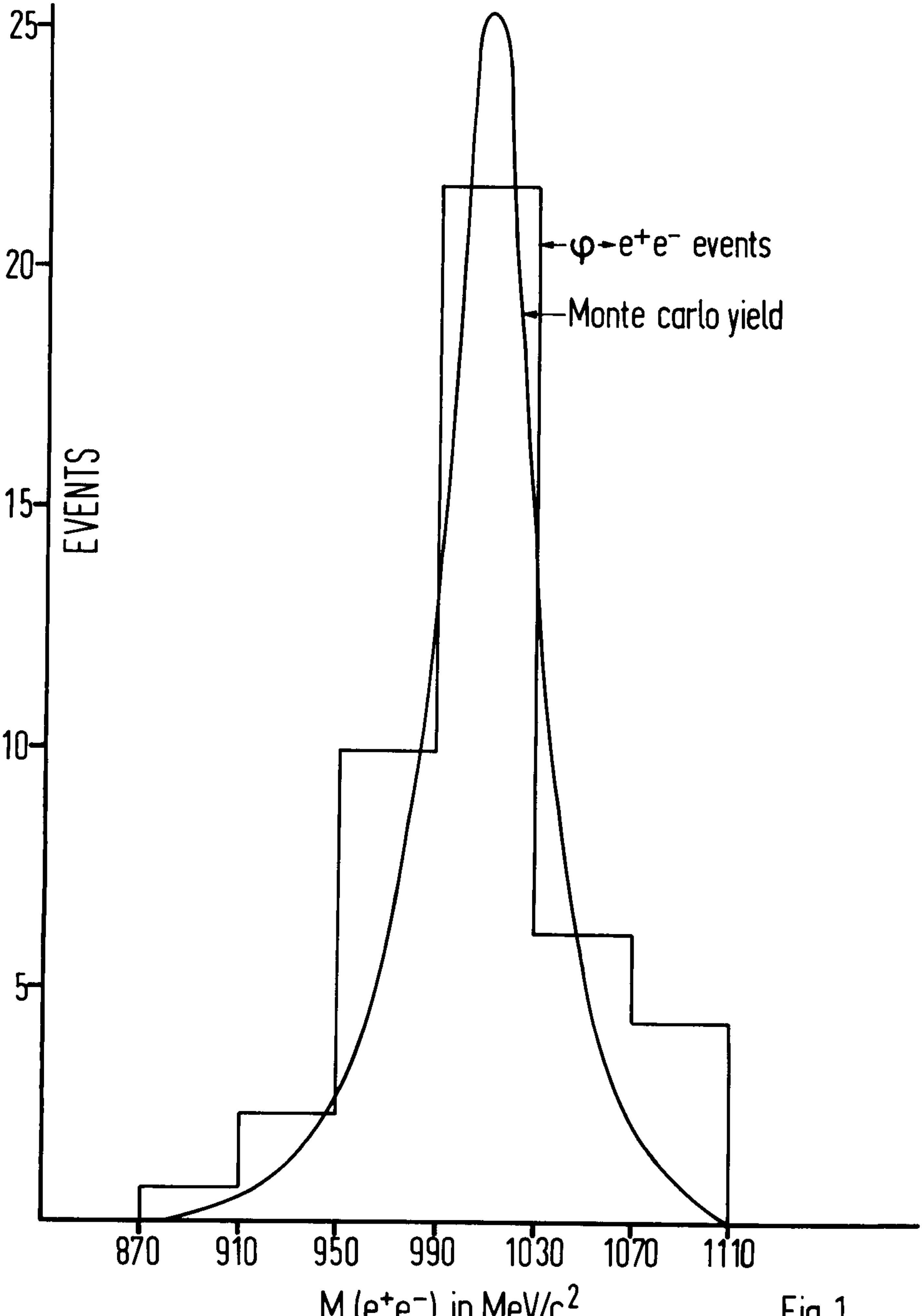
Figure caption:

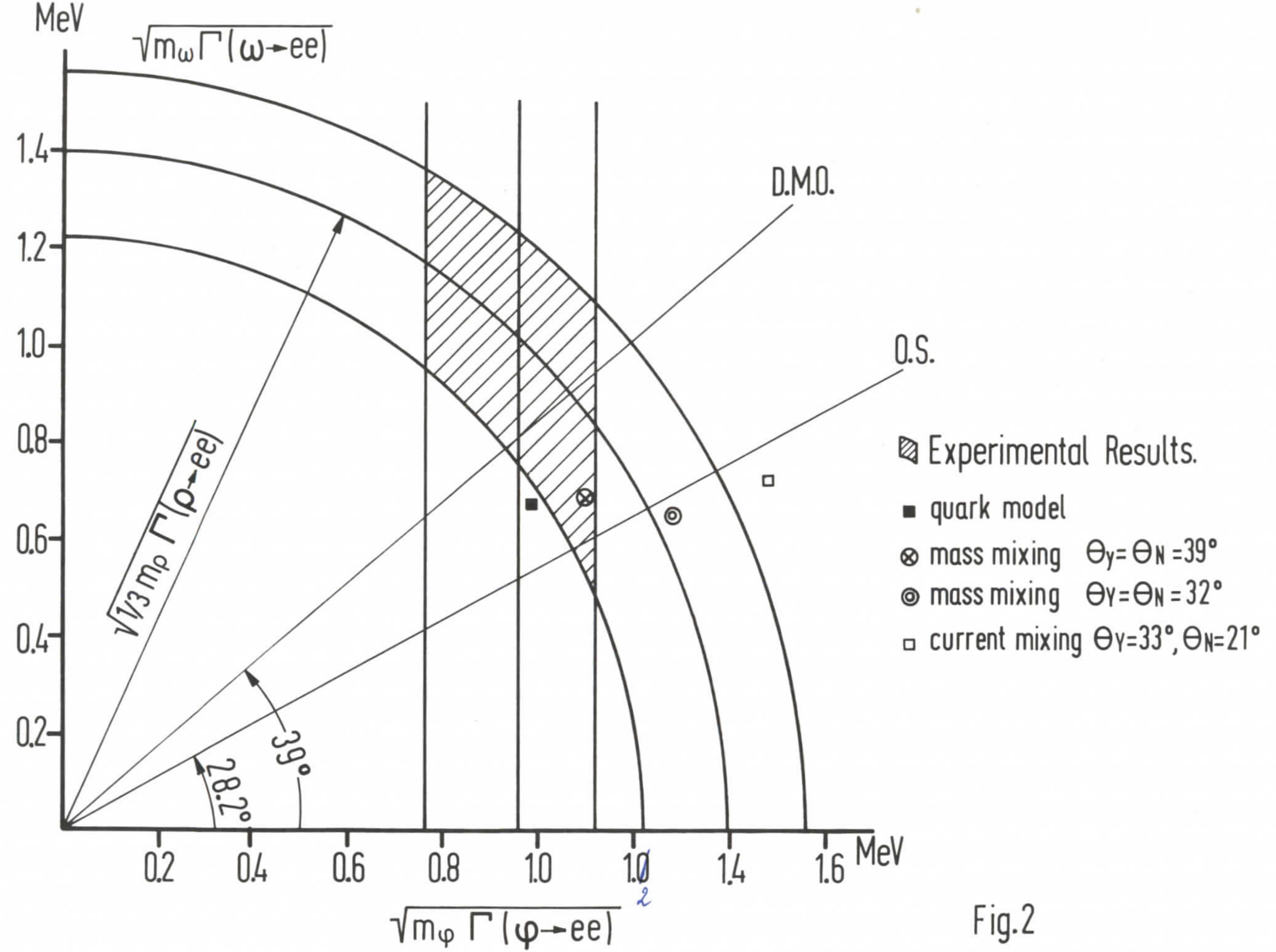
Fig. 1 - The measured $\phi \rightarrow e^+e^-$ spectrum, Bethe-Heitler background has been subtracted and all corrections made. The spectrum is in agreement with the expected e^+e^- mass distribution from the Monte Carlo program (solid curve). See text for detail.

Fig. 2 - Comparison of the result of this experiment with predictions of various models.



25
20
15
10
5
EVENTS
φ→e+e− events
Monte carlo yield
870
910
950
990
1030
1070
1110
M (e+e−) in MeV/c2

Fig. 1



MeV
$\sqrt{m_\omega \Gamma(\omega \to ee)}$
1.4
1.2
1.0
0.8
0.6
0.4
0.2
D.M.O.
O.S.
$\sqrt{1/3\, m_\rho \Gamma(\rho \to ee)}$
39°
28.2°
Experimental Results.
quark model
mass mixing $\Theta_Y = \Theta_N = 39°$
mass mixing $\Theta_Y = \Theta_N = 32°$
current mixing $\Theta_Y = 33°, \Theta_N = 21°$
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
MeV
$\sqrt{m_\varphi \Gamma(\varphi \to ee)}$

Fig.2