Observation of $B^0 - \overline{B^0}$ Mixing

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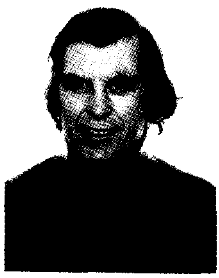

ABSTRACT

Using the ARGUS detector at the DORIS II, e^+e^- storage ring we have studied 88,000 $\Upsilon(4s)$ decays. We have observed $B^0 - \overline{B^0}$ mixing by three methods: we have fully reconstructed a $\Upsilon(4s) \to B^0 B^0$ event, observed a 3 standard deviation signal of 4.1 events containing one reconstructed $B^0(\overline{B^0})$ together with an additional fast $l^+(l^-)$, and measured a 4 standard deviation excess of 24.8 like-sign fast lepton pairs. We have measured the mixing parameter r = 0.21 ± 0.08.

INTRODUCTION

In the continuing exploration of the Standard Model an understanding of quark masses and mixings has become a touchstone not only for consolidation of the model but also, perhaps, for its demise. Without an understanding of the mechanism that gives the quarks and leptons mass, the model is at best incomplete; but the discovery of a fourth family or of a principle that clearly limits their number to three could well herald the new physics which is so ubiquitously and avidly sought.

Our present knowledge of quark and lepton masses is almost entirely experimental but the hope abides that more data will reveal the patterns that will indicate a theoretical solution to these problems.

Equally elusive as a theory of fermion mass generation, is a theoretical understanding of the mixing of the physical quarks in the weak eigen states, which is quantified in the Cabibbo-Kobayashi-Maskawa matrix. With no reliable theoretical prediction and some of the elements bounded only by unitarity constraints, new experimental input is urgently needed.

As soon as the neutral charmed meson (D^0) was discovered the possibility of $D^0 - \overline{D^0}$ mixing, analogous to the $K^0 - \overline{K^0}$ mixing was discussed [2] and now, several years after the observation of B mesons a number of searches have been made for mixing both in the $B^0 - \overline{B^0}$ system and in $B_s - \overline{B}_s$ [3-5]. There are strong indications that measurements of mixing in the neutral mesons containing one heavy quark will aid in determining the CKM matrix elements, point the way to possible elucidation of CP violation in weak decays and possibly provide sign posts to new physics beyond the standard model. Until the t-quark is experimentally observed $B^0 - \overline{B^0}$ mixing may also provide useful limits on its mass.

EXPERIMENTAL RESULTS

We report here a measurement of $B^0 - \overline{B^0}$ mixing using data collected with ARGUS at the DORIS II, e^+e^- storage ring. A sample of B^0 and $\overline{B^0}$ mesons from 88,000 $\Upsilon(4s)$ decays was collected in runs with an integrated luminosity of 103 pb^{-1}. The ARGUS detector, with cylindrical vertex and main drift chambers, a 0.8 Tesla solenoidal magnetic field, time-of-flight counters, shower counters and muon detectors is briefly described in reference [6]. The particle identification capabilities of the time-of-flight system and of the $\frac{dE}{dx}$ measurements in the main drift chamber are described in reference [7].

$B^0\overline{B^0}$ mixing is detected in our experiment by observing evidence of the decay products of a B^0B^0 pair[1] from the same event. This was accomplished in three ways:

- by fully reconstructing a single event comprising two B^0 decays
- by finding events with an identifiable B^0 and a fast lepton l^+ indicating that the companion B had also decayed as a B^0
- by measuring the excess of fast l^+l^+ pairs in $\Upsilon(4s)$ decays over that measured or expected from the known background processes.

The large branching ratio for $B \to D^*X$ and the clean D^* signal present in the $\Upsilon(4s)$ events that also contain a lepton of momentum greater than 1.0 GeV/c, shown in Figure 1, demonstrate the value of using the D^* in finding B^0 decays. We have reconstructed [9]:

$$\begin{aligned} B^0 &\to D^{*-}\pi^+ \\ &\to D^{*-}\pi^+\pi^0 \\ &\to D^{*-}\pi^+\pi^+\pi^- \end{aligned}$$

[1] Reference in this paper, to a particular charge state implies the charge conjugate state as well.

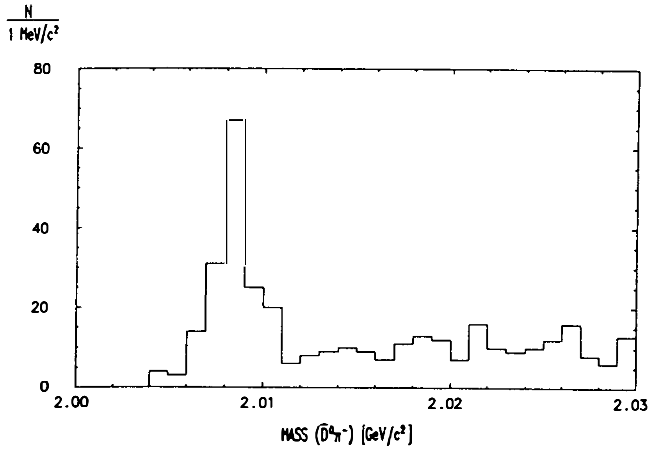

Figure 1: Mass spectrum of $M(\overline{D^0}\pi^-)$ for events with a lepton with momentum $P_l > 1.0$ GeV/c and $P(\overline{D^0}\pi^-) < 2.45$ GeV/c.

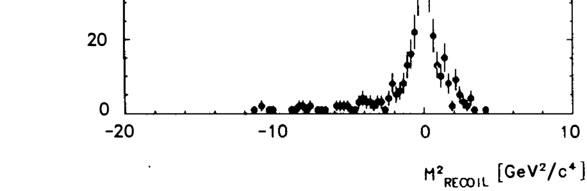

Figure 2: M^2_{recoil} spectrum for $B^0 \to D^{*-}l^+(\nu_l)$.

with $D^{*-} \to \overline{D^0}\pi^-$ and

$$\begin{aligned} \overline{D^0} &\to K^+\pi^- \\ &\to K^+\pi^-\pi^0 \\ &\to K^+\pi^-\pi^+\pi^- \\ &\to K^0_s\pi^+\pi^- \end{aligned}$$

We also used the channel $B^0 \to D^{*-}l^+(\nu_l)$ where l^+ is a muon or positron. This partial reconstruction is possible because the B^o mesons are produced almost at rest. Selecting D^{*-} with momentum less than 2.45 GeV/c, the kinematic limit for D^*s from B decay, and a lepton with momentum greater than 1.0 GeV/c, one can calculate an appropriate M^2_{recoil} for the unseen neutrino

$$M^2_{recoil} = (E_{beam} - (E_{D^{*-}} + E_{l^+}))^2 - \left(\vec{P_{D^{*-}}} + \vec{P_{l^+}}\right)^2$$

The spectrum of M^2_{recoil}, shown in Figure 2 has a peak at zero, as expected, on a low background. That this peak corresponds to the decay of B^0 mesons is confirmed by the agreement with a Monte Carlo simulation of $\Upsilon(4s) \to B^0\overline{B^0}$ followed by $B^0 \to D^{*-}l^+\nu_l$.

Events in which a B^0 meson was reconstructed as above were examined for evidence of a second B^0 decay using a larger set of possible final states. One event was found with two B^o decays reconstructed as follows:

$$\begin{aligned} B^0_1 &\to D^{*-}_1\mu^+_1(\nu_1) \\ D^{*-}_1 &\to \pi^-_{1_s}\overline{D^0} \\ \overline{D^0} &\to K^+_1\pi^-_1 \end{aligned}$$

and

$$\begin{aligned} B^0_2 &\to D^{*-}_2\mu^+_(\nu_2) \\ D^{*-}_2 &\to \pi^0 D^- \\ D^- &\to K^+_2\pi^-_2\pi^-_2 \end{aligned}$$

The computer reconstruction of the tracks from this event, in ARGUS, is shown in Figure 3 and the kinematic information is summarized in Table 1. The reconstructed D^{*-}, $\overline{D^0}$ and D^- masses agree well with those of reference [8].

The two K^+ tracks are uniquely identified by time-of-flight and $\frac{dE}{dx}$ measurement in the drift chamber. The highest momentum tracks in the event are the muons with $p(\mu_1) = 2.186$ GeV/c and $p(\mu_2) = 1.579$ GeV/c. Their $\frac{dE}{dx}$ and shower counter signals are consistent with muon identification and the first (μ_1) is clearly identified in the muon chambers. The second muon track points at a gap between the muon chambers and it is not detected outside the shower counters but a special kinematic feature of this event allows us to reconstruct it completely even with two missing neutrinos. The momenta of D^*_1 and μ_1 restrict the momentum of B_1 onto a narrow cone around the direction of the $D^{*-}_1\mu^+_1$ system and therefore similarly restrict the equal and opposite momentum of B_2. This allows a calculation of the missing mass in the B_2 decay and it is only consistent with zero or with a π^o. Since no additional gamma rays are seen in the shower counters the identification of the missing neutral in B_2 decay as a neutrino confirms the identification of μ_2. For the measured mixing strength of 0.2 (see below) we expect to reconstruct 0.3 events with both $B^{\bullet}$ mesons decaying to $D^*l\nu_l$. To estimate the

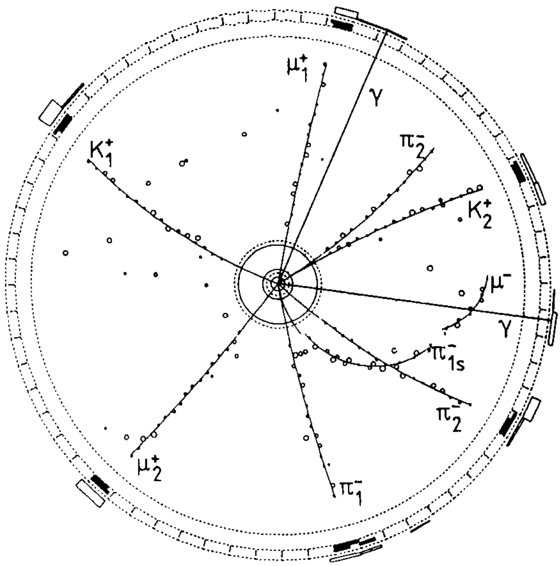

Figure 3: Computer reconstruction of the decay tracks from an $\Upsilon(4s) \to B^0\overline{B^0} \to B^0B^0$ event.

Decay	Mass(GeV/c²)	P(GeV/c)	M^2_{Recoil}(GeV²/c⁴)
$B_1^0 \to D_1^{*-}\mu_1^+(\nu_1)$	$4.393 \pm 0.088^*$	$1.090 \pm 0.108^*$	-0.609
$D_1^{*-} \to \pi_1^-\overline{D}^0$	2.008 ± 0.001	1.196 ± 0.013	
$\overline{D}^0 \to K_1^+\pi_1^-$	1.873 ± 0.021	1.091 ± 0.012	
$B_2^0 \to D_2^{*-}\mu_2^+(\nu_2)$	$3.969 \pm 0.032^*$	$1.244 \pm 0.015^*$	-0.275
$D_2^{*-} \to \pi^0 D^-$	2.008 ± 0.005	1.611 ± 0.017	
$\pi^0 \to 2\gamma$	0.180 ± 0.028	0.136 ± 0.019	
$D^- \to K_2^+\pi_2^-\pi_2^-$	1.886 ± 0.015	1.478 ± 0.007	

Table 1: Kinematical quantities of the observed $\Upsilon(4s) \to B_1^0 B_2^0$ event. (*) mass and momentum without neutrino.

background 22,000 $\Upsilon(4s) \to B^0\overline{B^0}$ Monte Carlo events in which B_1^0 would be reconstructed in the observed channel and in which the remaining particles had the same charged and neutral multiplicity, were examined. In none of these could a fake, second B^0 be reconstructed. This single event provides strong evidence for the existence of $B^0 - \overline{B^0}$ oscillations.

To measure the magnitude of the $B^0 - \overline{B^0}$ mixing we make use of both the reconstructed B^0 decays and fast leptons with $p_l > 1.4$ GeV/c which, in $\Upsilon(4s)$ decays are almost all the products of semi-leptonic B decays. A small fraction of these leptons results from semi-leptonic decays of charmed mesons that are themselves the product of B decays. These are particularly troublesome in a mixing search since a positively charged lepton from the decay of the c quark in a $b \to c \to s$ cascade of a $\overline{B^0}$ decay can be mistaken for an l^+ from primary semi-leptonic B^0 decay; together with a reconstructed B^0 decay or another fast l^+ from the decay of the accompanying B^0 it can be mistaken for evidence of $B^0\overline{B^0} \to B^0B^0$. In Figure 4 is shown the Monte Carlo spectrum of leptons from both primary B^0 decays (a), and the cascade $\overline{D}$ decays (b). It shows that a selection of $p_l > 1.4$ GeV/c excludes most of the cascade leptons; the remaining background can be estimated by the Monte Carlo and subtracted from the data.

Our first measurement of the $B^0\overline{B^0}$ mixing is made by finding events in which a fitted $B^0 \to D^{*-}l^+(\nu_l)$ is accompanied by a fast $l^\pm(p_l > 1.4GeV/c)$ and forming the ratio of numbers of events

$$r = \frac{N(B^0l^+) + N(\overline{B^0}l^-)}{N(B^0l^-) + N(\overline{B^0}l^+)} = \frac{\text{“}mixed\ events\text{”}}{\text{“}unmixed\ events\text{”}}$$

As shown in reference [10], for neutral pseudo-scalar meson anti-meson pairs produced exclusively by e^+e^- single photon annihilation this is also equal to the ratio of the decay widths

$$r_1 = \frac{\Gamma(B^0 \to \overline{B^0} \to X')}{\Gamma(B^0 \to X)}$$

The M^2_{recoil} spectrum for the $B^0 \to D^{*-}l^+(\nu_l)$ events in which a second lepton with $p_{l^\pm} >$ 1.4 GeV/c is shown in Figure 5. The events in the peak of this spectrum together with two events in which a B^0 decaying to hadrons is fully reconstructed and which also contain a fast lepton give 23 candidates for unmixed events and 5 for mixed events. The method of subtracting background that is used for the fast dilepton events described below, predicts 0.4 events due to hadron misidentification as leptons and 0.5 events due to secondary leptons. With a resulting total background of 0.9 ± 0.3 events and a corresponding background for the unmixed events of 2.2 ± 1.1 events we obtain a value of

$$r = \frac{N(B^0l^+) + N(\overline{B^0}l^-)}{N(B^0l^-) + N(\overline{B^0}l^+)} = 0.20 \pm 0.12$$

The probability that the background would fluctuate from .9 to 5 events corresponds to a signal significance of 3σ.

Finally, we also used the traditional method of measuring same sign and opposite sign fast dileptons which produces a data sample with a larger background but nevertheless a more accurate measurement of r.

Backgrounds in the fast lepton pair sample arise from misidentification of hadrons as leptons and from various sources of lepton pairs other than semi-leptonic decays of B mesons. Where possible, these background events are eliminated by the cuts. The remainder is subtracted by actually measuring the contribution from our experimental data or by Monte Carlo simulation of the events.

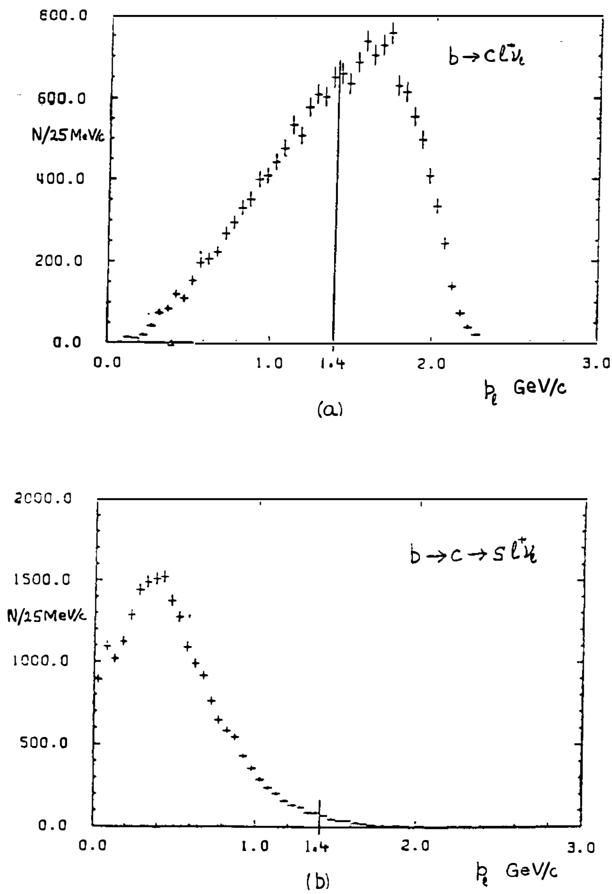

Figure 4: Monte Carlo spectra of lepton momentum spectrum from (a) semi-leptonic B^0 decay, (b) semi-leptonic decay of secondary D muon.

To reduce the contribution of continuum lepton pairs the following selections were made: (1) the second Fox-Wolfram moment [11] less than 0.6; (2) charged multiplicity $n_{ch} \geq 5$ and total multiplicity, $n_{ch} + \frac{1}{2}n_\gamma \geq 7$. All tracks were required to have $\cos\theta_{lab} < 0.9$ in order to ensure that they are well reconstructed in the drift chambers and well identified. Leptons are identified using a combined likelihood calculated from all the relevant information in the detector [12]. This included time-of-flight, $\frac{dE}{dx}$ measurement in the drift chamber, the energy deposited and its topology in the shower counters and, in the case of muons, a required hit in an outer muon chamber together with its correlation with the extrapolated track position. Events with exactly two well identified leptons with $p > 1.4$ GeV/c were selected.

Known sources of lepton pairs were eliminated where possible. Lepton pairs from B decay to J/ψ or ψ' were excluded by rejecting e^+e^- or $\mu^+\mu^-$ pairs with a mass within ±150 MeV/c^2 of the J/ψ or ψ' masses. Electrons produced by photon conversion were suppressed by rejecting electron tracks accompanied by a positron candidate of any momentum within a 32° cone around the electron direction.

The opening angle θ_l between lepton tracks coming from separate B meson decays should be isotropic whereas two leptons from a B decay cascade or a fast pair from the continuum tend to be back to back. This distribution is shown in Figure 6 and it can be seen that rejecting pairs for which $\cos\theta_{ll} <$ -0.85 further reduces the background.

The numbers of events passing this selection are shown in Table 2 for both the $\Upsilon(4s)$ energy and for the continuum slightly below it.

The $\Upsilon(4s)$ contribution of dileptons is found by subtracting the continuum numbers scaled by 2.5, the ratio of the luminosities and then correcting the e^+e^- and $\mu^+\mu^-$ numbers for the loss of acceptance due to the J/ψ and ψ' cuts. Further backgrounds, however, still remain resulting from hadrons faking leptons, from gamma conversions and $J/\psi(\psi')$ decays in which one of the lepton tracks from the pair is missed and from the remaining secondary, cascade charm decay leptons.

The number of hadrons misidentified as leptons is measured as a function of momentum and then folded with the momentum spectrum of hadrons accompanying fast leptons in order to measure the numbers of fake fast dilepton pairs in each category.

Clean samples of well identified high energy pions and kaons for this study were obtained from $\tau^- \rightarrow \nu_\tau\pi^+\pi^-\pi^-(n\pi^o)$ $(n = 0, l)$ and from

$$D^{*-} \rightarrow D^0\pi^+$$
$$D^0 \rightarrow K^-\pi^+$$

The fractions of π and K tracks which were accepted as leptons due to decay in flight and punch through in the case of muons or interaction in the shower counters in the case of electrons, were measured as a function of momentum. The π/e and K/e misidentification rates were both $(0.5\pm0.1)\%$. The π/μ misidentification rate was $(2.2\pm0.2)\%$ and that for the K/μ was $(1.9\pm0.5)\%$ obtained by applying the measured momentum dependent fake rate to the observed lepton hadron pairs. The resulting momentum distribution of fake lepton tracks are shown in Figure 7 for misidentifications resulting in fake like sign (a), and unlike sign (b), lepton pairs. Since the rates for pions and kaons are so similar, in fact equal within errors, it is not necessary to know the relative numbers of K and π tracks in the B^0 decay events.

A Monte Carlo simulation of B decay events was used to correct for the remaining backgrounds from cascade charm decay leptons and gamma conversion or J/ψ (ψ') decay lepton pairs in which one track was missed in the detector. A spectator model for the b quark decay [13] and the Lund string breaking fragmentation model [14] for the final state hadron fragmentation were used in the Monte Carlo. As the acceptances for electrons and muons were

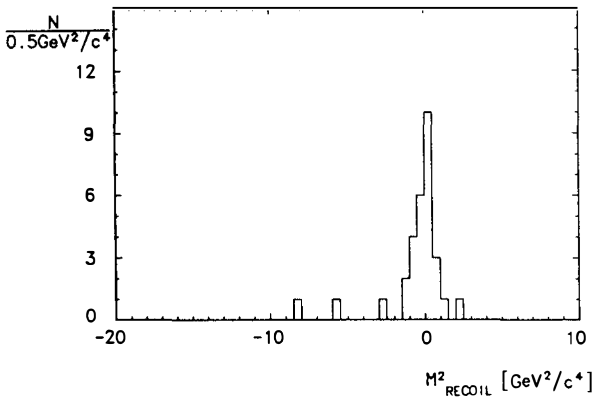

Figure 5: M^2_{recoil} spectrum for events shown in Figure 2 that also contain an extra fast lepton.

	$e^\pm e^\pm$	$\mu^\pm \mu^\pm$	$e^\pm \mu^\pm$
Dilepton candidates			
$\Upsilon(4S)$ + Continuum	8	16	26
Continuum	0	0	0
$\Upsilon(4S)$ direct	8.0 ± 3.9	16.0 ± 4.8	26.0 ± 5.8
Background			
Fakes	0.7	5.7	4.9
Conversion	0.5	-	0.5
Secondary decays	2.3	2.9	4.6
J/ψ decays	0.7	0.9	1.5
Signal	3.8 ± 3.9 ± 0.9	6.5 ± 4.8 ± 1.3	14.5 ± 5.8 ± 1.8
Sum: 50 dilepton candidates **Background:** 25.2 ± 5.0 ± 3.8 events **Signal:** 24.8 ± 7.6 ± 3.8 like-sign lepton pairs			
	$e^+ e^-$	$\mu^+ \mu^-$	$e^\pm \mu^\mp$
Dilepton candidates			
$\Upsilon(4S)$ + Continuum	60	92	149
Continuum	3	1	2
$\Upsilon(4S)$ direct	52.6	89.5	144.1
Corrected for J/ψ cut	58.5 ± 9.8 ± 1.6	99.6 ± 11.3 ± 2.5	144.1 ± 12.4
Background			
Fakes	1.4	12.1	10.2
Conversion	0.5	-	0.5
Secondary decays	0.7	1.5	1.6
J/ψ decays	1.0	0.9	1.5
Signal	54.9 ± 9.8 ± 1.6	85.1 ± 11.3 ± 3.1	130.3 ± 12.4 ± 1.8
Signal: 270.3 ± 19.4 ± 5.0 unlike-sign lepton pairs			
Mixing parameter r	0.17 ± 0.19 ± 0.04	0.19 ± 0.16 ± 0.04	0.28 ± 0.14 ± 0.04
Combined mixing parameter r=0.22 ± 0.09 ± 0.04			

Table 2: Dilepton rates.

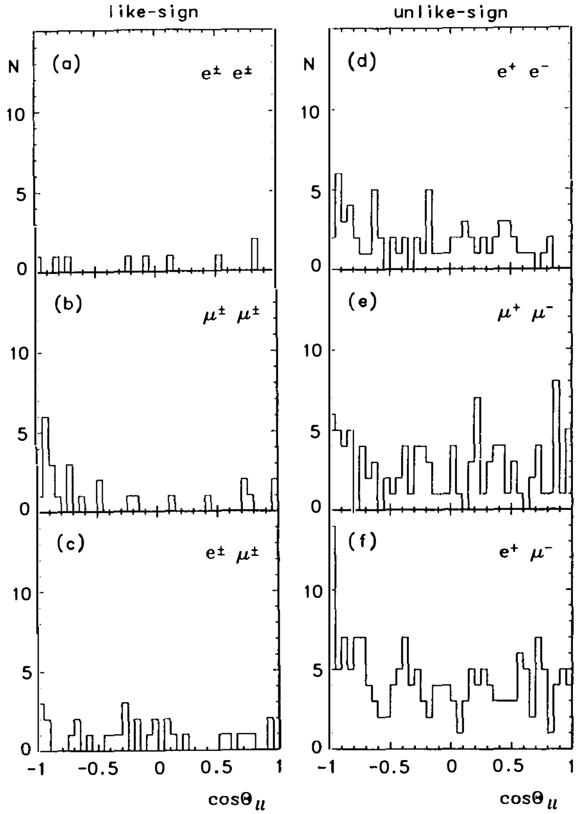

Figure 6: Lepton pair opening angle distributions for like-sign and unlike-sign pairs.

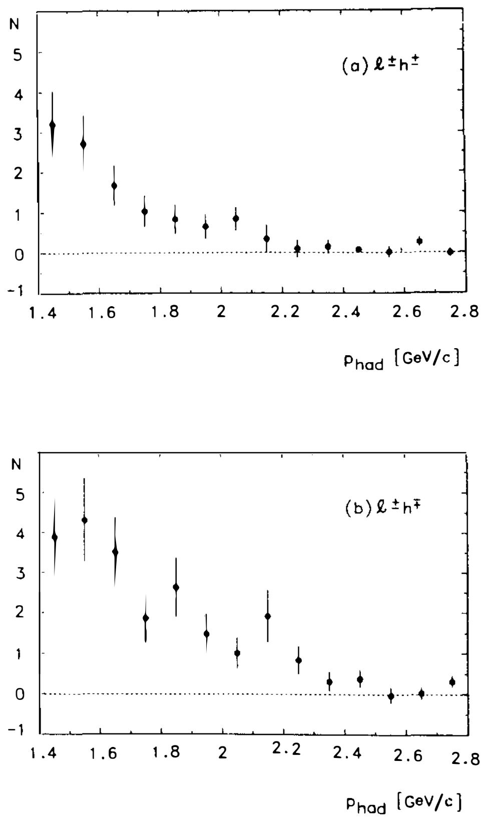

Figure 7: Misidentified hadron rates for faking like sign (a) and unlike sign (b) lepton pairs.

different, the corrections for each of the three lepton pair combinations were made separately and a separate mixing parameter was calculated for each, as shown in Table 2. The 50 like-sign dilepton candidates include a calculated and measured background of $25.2 \pm 5.0 \pm 3.8$ events; the probability that the 50 events are a statistical fluctuation is equivalent to 4.0 standard deviations. The resulting signal of $24.8 \pm 7.6 \pm 3.8$ is our third evidence for $B^0 - \overline{B^0}$ mixing.

Since the charged B mesons also contribute to the like-sign dileptons, the mixing parameter, in this case, is given by

$$r = \frac{[N(l^+l^+) + N(l^-l^-)](1+\lambda)}{N(l^+l^-) - [N(l^+l^+) + N(l^-l^-)]\lambda}$$

To account for the differences of the branching ratios of the $\Upsilon(4s)$ to charged and neutral B pairs and of the charged and neutral B mesons to leptons, we introduce the factor

$$\lambda = \frac{f^+}{f^0}\left(\frac{Br^+_{sl}}{Br^\bullet_{sl}}\right)^2$$

where f^+ and Br^+_{sl} are the branching ratios of the $\Upsilon(4s)$ into charged B pairs and of the charged Bs into leptons, respectively. We assume $\lambda = 1.2$ and thus obtain

$$r = 0.22 \pm 0.09 \pm 0.04$$

Taking into account the fact that the dilepton sample contains two like-sign and elevent unlike-sign events from the previous sample we can combine our two measurements of the mixing parameter to give

$$r = 0.21 \pm 0.08m$$

The dependence on λ is weak; r varies only from 0.17 to 0.24 as λ increases from 0.7 to 1.7. Some experiments have chosen to express their results as the ratio of mixed events to the total number of decays. For that parameter, $\chi = r/(1-r)$ we deduce $\chi = 0.17 \pm 0.05$.

In the framework of the Standard Model, with three families of quarks [15], the mixing is expected to be dominated by the contribution of the t quark to the second order weak box diagram [16]. The $B^0 - \overline{B^0}$ is probably governed by

$$x = \frac{\Delta M}{\Gamma} = 32\pi \frac{B f_B^2 m_t^2 m_b}{m_\mu^5} \frac{\tau_b}{\tau_\mu} \mid V_{td} \mid^2 \eta_{QCD}$$

related to experiment by

$$r = \frac{x^2}{x^2+2}$$

and for which we obtain the value $x = 0.73 \pm 0.28$.

Prior to this measurement, predicted values of x for this process were very much smaller -- for example $x = 0.12$ for $m_t = 60GeV/c^2$ [17]. Already, however, a steady flow of preprints is appearing which show that our new experimental result can readily be incorporated into the Standard Model without pushing the other parameters into regions of any great controversy (for example [18]). The abundant flexibility of the Standard Model is thus demonstrated once again.

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