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Additional Evidence for B^0-$\bar{B}^0$ Mixing*

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ABSTRACT

The rate of like-charge dimuons has been measured with the MAC detector in hadronic events produced in e^+e^- annihilation at $\sqrt{s} = 29$ GeV. If the observed excess is attributed to B^0-$\bar{B}^0$ mixing, the corresponding value of the mixing parameter $\chi = \Gamma(B \to \mu^- X)/\Gamma(B \to \mu^\pm X)$ is $\chi = 0.21^{+0.29}_{-0.15}$ and $\chi > 0.02$ at 90% C.L.

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Immediately after the discovery of the beauty quark bound state, upsilon,[1] speculation began that significant mixing might occur between the B^0 and $\bar{B}^0$ mesons.[2,3] UA1 data provided the first indication of such mixing[4] and the ARGUS collaboration recently reported a measurement which shows a large amount of B^0_d-$\bar{B}^0_d$ mixing.[5] The MAC collaboration has performed a measurement of B^0-$\bar{B}^0$ mixing using data collected at the PEP storage ring of the Stanford Linear Accelerator Center.

To measure B^0-$\bar{B}^0$ mixing we use hadronic events with two identified muons. The muons provide flavor enrichment and also provide charge tagging to discriminate between the decays $b \rightarrow \mu^- \bar{\nu}_\mu c$ and $\bar{b} \rightarrow \mu^+ \nu_\mu \bar{c}$. Prompt dimuons in $e^+e^- \rightarrow b\bar{b}$ events have opposite charges if there is no mixing; with mixing like-charge prompt dimuons can also be produced. Like-charge backgrounds arise from events in which one of the muons is produced from the cascade decay $b \rightarrow c \rightarrow \mu$ and from events in which a hadron is misidentified as a muon.

The MAC detector is described in detail elsewhere.[6] A brief description of the components most important for this measurement is given here. The central detector is a ten-layer drift chamber in an axial magnetic field of 5.7 kG, with six layers at angles of $\pm 3°$ to the beam axis, and with the first and last layers at radii of 12 and 45 cm, respectively. The vertex chamber inside the central detector has six layers of thin-walled axial drift tubes. Calorimeters covering 98% of the solid angle surround the central detector. The barrel calorimeter has an electromagnetic shower detector of lead interspersed with proportional wire chambers, comprising a total of 14 radiation lengths. The hadronic barrel and end-cap calorimeters are constructed of alternating layers of steel and proportional wire chambers. Penetrating particles traverse an average of ~6.5 nuclear interaction lengths in the calorimeters. The small inner diameter of the calorimeters minimizes the path length available for decays of pions and kaons into muons. The steel of the hadronic calorimeter is toroidally magnetized to 17 kG. The entire calorimetric detector is surrounded by an outer drift chamber system consisting of four to six layers that measures the exit polar angles of muons traversing the steel, and consequently muon momenta to ~25%.

Muons are identified over 95% of the solid angle by requiring: (1) consistent measurements of the muon momentum vector from independent reconstruction in the inner and outer drift chambers; (2) energy deposition in the hadron calorimeter consistent with the passage of a minimum ionizing particle; (3) $2 < p < 10$ GeV/c, where p is the weighted average of the two independent momentum measurements; and (4) $p_\perp/p > 0.1$, where $p_\perp$ is the transverse momentum relative to the thrust axis, to remove the fake muon background in the core of the jet and reduce background from charm decays. The thrust axis[7] is determined from energy deposition in the calorimeters with muon-associated calorimeter energy augmented to correspond to the measured muon momentum. To have greater assurance of the reliability of the thrust axis reconstruction, events are rejected if the thrust is less than 0.72 or if the thrust axis is within 30° of the beam axis.

The success of the muon identification criteria may be judged by the probability of misidentifying a hadron as a prompt muon. Hadrons which either penetrate the calorimeters or decay into secondary muons may fake prompt muons. We use taus which decay into three charged particles as a clean source of hadrons. With all of the cuts listed above except the $p_\perp/p$ cut, the misidentification probability is found to be $(0.37 \pm 0.09)\%$ for tau data and $(0.40 \pm 0.04)\%$ for tau Monte Carlo events. The agreement indicates that the muon identification is modeled well by the Monte Carlo. For hadronic events with the $p_\perp/p$ cut the Monte Carlo predicts $(0.46 \pm 0.01)\%$ misidentification. A predicted $(58 \pm 3)\%$ of the misidentifications are penetrating hadrons and the balance are decays $\pi \to \mu$ and $K \to \mu$.

The full MAC data sample of 310 pb^{-1} is used for this analysis. The muon selection criteria yield 2813 single muon events with 2790 ± 53 predicted by the Monte Carlo. There are 47 dimuon events with 51 ± 5.6 predicted. The data are modeled with the Lund Monte Carlo,[8] and EGS and HETC[9] are used to simulate the passage of every particle through the detector. Monte Carlo predictions are largely based on a 2800 pb^{-1} sample of generated beauty and charm dimuon events. However, the background due to misidentification is determined from a 307 pb^{-1} sample of generated hadronic events with a natural mixture of flavors and decay modes. Agreement between the data and Monte Carlo is illustrated by the p and $p_\perp$ spectra in Fig. 1.

Dividing $p_\perp$ into "low" (< 1 GeV/c) and "high" (≥ 1 GeV/c) regions, the data are partitioned into three bins: $p_\perp < 1$ for both muons (L-L), $p_\perp \geq 1$ for only one muon (L-H), and $p_\perp \geq 1$ for both muons (H-H). Since high $p_\perp$ is characteristic of prompt muons from b decays,[10] the H-H bin has the greatest purity of $b\bar{b}$ events (almost 100%). Events are divided into two jets by a plane perpendicular to the thrust axis and are classified as "same-jet" or "opposite-jet" depending on the directions of the two muon tracks. Table 1 shows numbers of dimuon events and Monte Carlo predictions according to this classification. The data agree well with the predictions.

The significant quantities in measuring mixing are the relative numbers of like-charge and unlike-charge dimuons in opposite jets. Same-jet dimuons contain no information about mixing but are a good check on the modeling of backgrounds. Table 2 shows the data and the Monte Carlo predictions without mixing. The same-jet data agree very well with the predictions, however, the opposite-jet data deviate from the prediction in the H-H bin where, due to the high $b\bar{b}$ purity, mixing would most increase the number of like-charge dimuons. The probability that the deviation in the H-H bin is a statistical fluctuation is ~8%.

The fraction F = (number of like-charge dimuons)/(total dimuons) is plotted in Fig. 2(a). We see reasonable agreement between data and Monte Carlo predictions without mixing for same-jet dimuons and for the first two bins of opposite-jet dimuons, but a discrepancy of $\sim 2\sigma$ in the opposite-jet H-H bin. Fig. 2(b) shows the sensitivity to mixing defined by $S = (U_B - L_B)/N$ where U_B and L_B are the predicted numbers of unlike-charge and like-charge beauty flavored dimuon events without mixing and N is the total number of predicted events of all flavors. A maximum value of $S = 1$ would be obtained if all identified muons were from prompt decays of hadrons containing b quarks. The large value of S for the H-H bin (0.64 ± 0.14) suggests mixing as a natural explanation for the excess of like-charge dimuons in the data.

To describe the amount of mixing we use the parameter f defined by

$$f = 2\chi(1 - \chi)$$

$$\text{where} \qquad \chi = \frac{\Gamma(B \to \mu^- X)}{\Gamma(B \to \mu^\pm X)} = \frac{\Gamma(\bar{B} \to \mu^+ X)}{\Gamma(\bar{B} \to \mu^\pm X)}$$

that is, χ is the fraction of "wrong" sign B decays, where B represents an average over the beauty particles in the sample ($B_u^\pm$, B_d^0, B_s^0, Λ_b, *etc*). The parameters F, S, and f are related by

$$F(f) = F_0 + fS \tag{1}$$

where F_0 is the Monte Carlo prediction with zero mixing. If we attribute the deviation in the H-H bin to mixing, we can use Eq. 1 to calculate the amount of mixing

$$F_{\text{data}} = F_0 + fS \Longrightarrow f = 0.37^{+0.13}_{-0.21}.$$

To fit all three bins we maximize the likelihood function $\mathcal{L}(f)$ given by

$$\ln \mathcal{L}(f) = \sum_i L_i \ln\,(F_{0_i} + fS_i) + U_i \ln\,[1 - (F_{0_i} + fS_i)]$$

where L_i and U_i are the numbers of like- and unlike-charge dimuon events in bin i of the data. The log likelihood is plotted in Fig. 3 with Monte Carlo uncertainties folded in and from it we determine the result

$$f = 0.34^{+0.16}_{-0.22} \qquad f > 0.04 \text{ at } 90\% \text{ C.L.}$$

$$\text{or equivalently} \qquad \chi = 0.21^{+0.29}_{-0.15} \qquad \chi > 0.02 \text{ at } 90\% \text{ C.L.}$$

The lower limit from this experiment is compatible with the results of other B^0-$\bar{B}^0$ mixing experiments shown in Table 3. However, we note some important distinctions. First, unlike e^+e^- collisions at the Υ(4s) resonance, e^+e^- collisions at the energy of PEP are above the threshold for production of B_s^0 mesons. B_s^0

mixing is expected to be much greater than B_d^0 mixing.[15] Second, the MAC measurement relies exclusively on dimuon events which, unlike dielectron events, are not contaminated by 2-photon backgrounds. Third, in contrast with $p\bar{p}$ collisions, the $e^+e^- \rightarrow b\bar{b}$ differential cross section is well-known, the events are quite clean, and cross checks on misidentification background are available.

In summary, the present measurement from MAC utilizes a data sample which is well-understood and is sensitive to mixing of both B_s^0 and B_d^0 mesons. The data favor non-zero mixing and put a lower limit on the value of the mixing parameter χ.

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TABLE CAPTIONS

1. Numbers of dimuon events (Monte Carlo predictions in parentheses). Errors are due to finite Monte Carlo statistics. Errors due to uncertainties in Monte Carlo parameters make a negligible contribution.

2. Like and unlike charge dimuons (Monte Carlo predictions in parentheses). Errors are as in Table 1.

3. Results of B^0-$\bar{B}^0$ mixing experiments. The parameter r_d [16] is related to χ by $r_d = \chi_d/(1-\chi_d)$ and $\chi = p_s\chi_s + p_d\chi_d$ where p_i = proportion of B_i^0 in the sample and where equal semileptonic branching ratios are assumed for all beauty hadrons.

Table 1.

$p_\perp$ bin	Same Jet	Opposite Jet	Total
L-L	1 (1.5 ± 1.0)	11 (10.2 ± 1.9)	12 (11.7 ± 2.1)
L-H	4 (4.9 ± 1.5)	11 (16.3 ± 2.7)	15 (21.2 ± 3.1)
H-H	8 (7.6 ± 2.1)	12 (10.5 ± 1.4)	20 (18.1 ± 2.5)
Total	13 (14 ± 2.8)	34 (37 ± 3.6)	47 (51 ± 4.6)

Table 2.

$p_\perp$ bin	Same Jet		Opposite Jet	
	Like Charge	Unlike Charge	Like Charge	Unlike Charge
L-L	0 $(0.5^{+.7}_{-.5})$	1 (1.0 ± 0.7)	1 (2.7 ± 1.3)	10 (7.5 ± 1.5)
L-H	1 (1.0 ± 1.0)	3 (3.9 ± 1.1)	4 (5.0 ± 1.8)	7 (11.3 ± 2.0)
H-H	1 (2.0 ± 1.4)	7 (5.6 ± 1.5)	5 (1.9 ± 0.8)	7 (8.6 ± 1.2)
Total	2 (3.5 ± 1.9)	11 (10.5 ± 2.0)	10 (9.6 ± 2.4)	24 (27.4 ± 2.8)

Table 3.

Mode of Production	Experiment	Result
e^+e^- at $\sqrt{s} = 29$ GeV	MAC	$\chi = 0.21^{+0.29}_{-0.15}$
		$\chi > 0.02$ at 90% C.L.
e^+e^- at $\sqrt{s} = 29$ GeV	Mark II[12]	$\chi < 0.12$ at 90% C.L.
e^+e^- at $\sqrt{s} = 34.6$ GeV	JADE[14]	$\chi < 0.13$ at 90% C.L.
e^+e^- at $\Upsilon(4s)$	ARGUS[5]	$r_d = 0.21 \pm 0.08$
e^+e^- at $\Upsilon(4s)$	CLEO[13]	$r_d < 0.24$ at 90% C.L.
$p\bar{p}$	UA1[4]	$\chi = 0.121 \pm 0.047$

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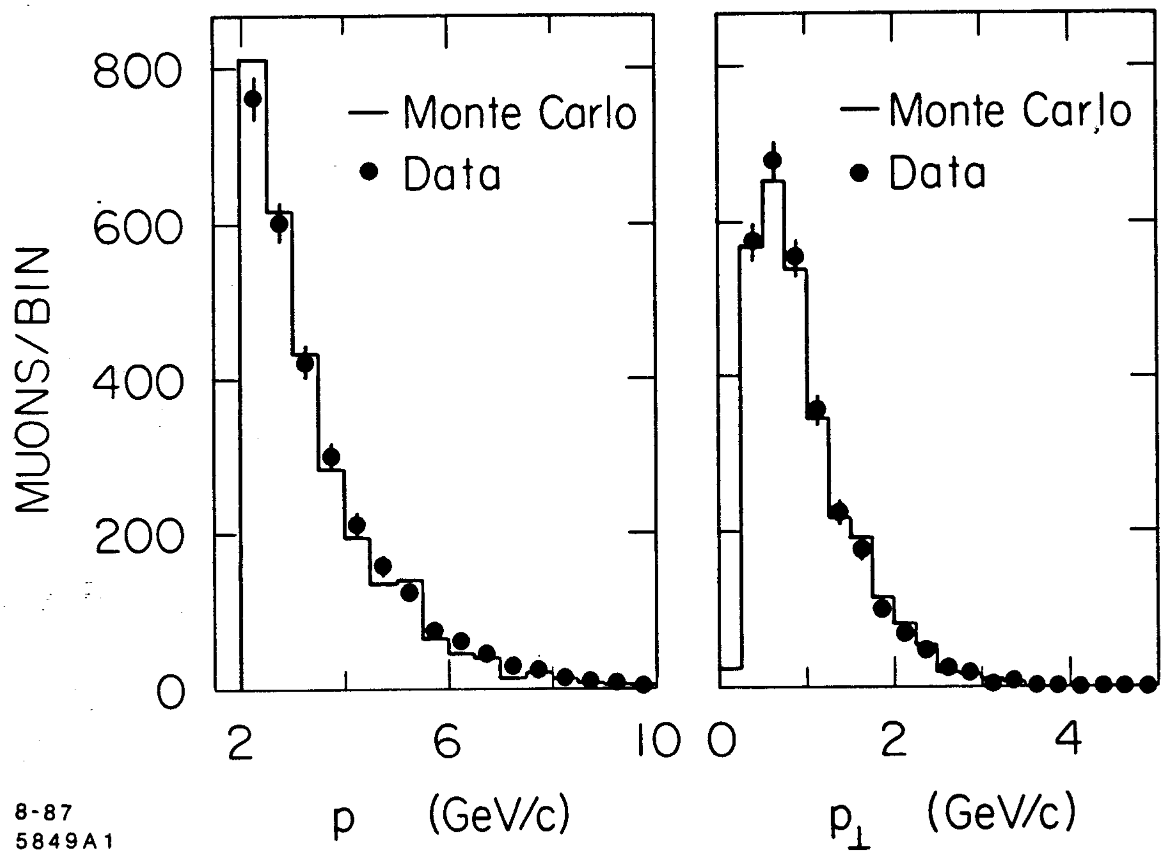
FIGURE CAPTIONS

1. Momentum and transverse momentum spectra of single muons.

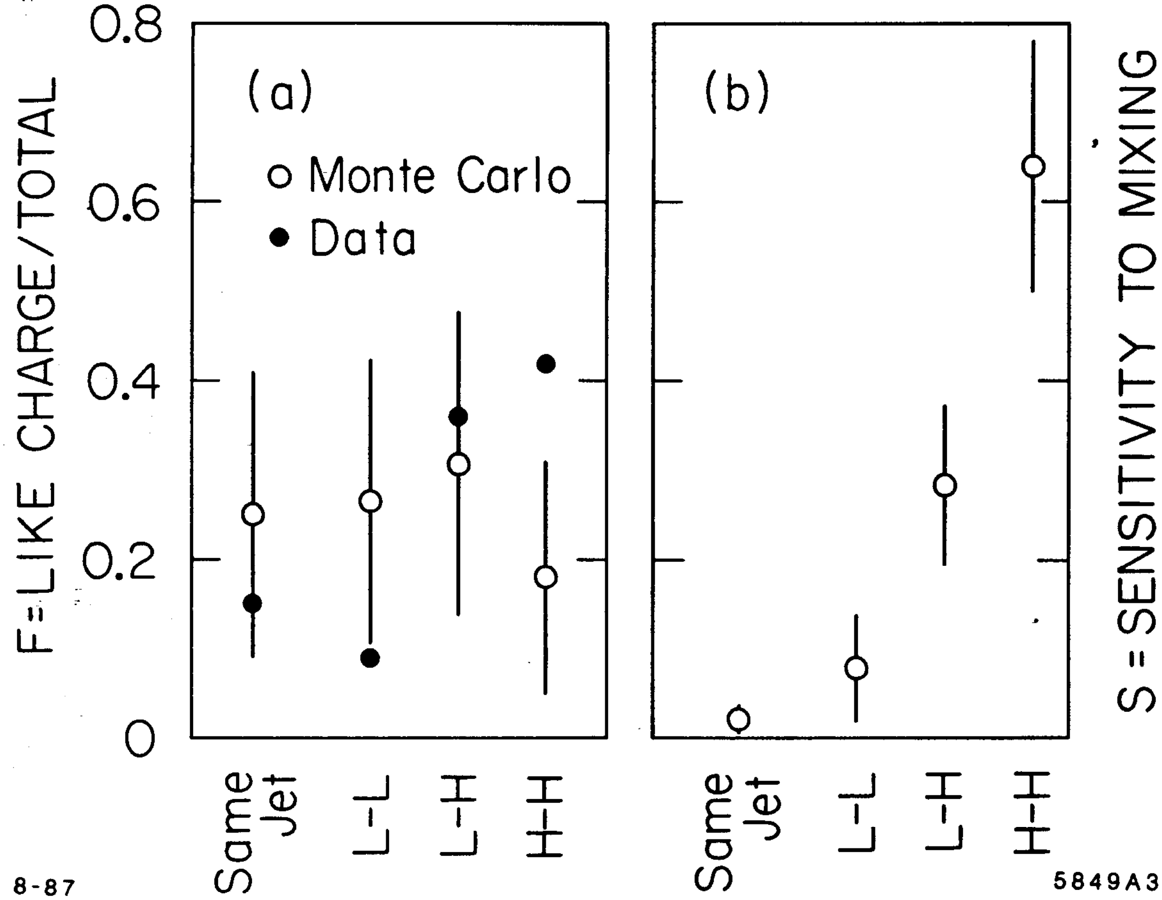
2. Fraction of like-charge dimuon events and sensitivity to mixing for same-jet events (the three $p_\perp$ bins combined) and for opposite-jet events in $p_\perp$ bins L-L, L-H, and H-H. The error bars in (a) roughly indicate the expected fluctuation from the prediction for comparison with the observed signal shown by the points.[11]

3. Log likelihood of the mixing parameter f.



MUONS/BIN
800
600
400
200
0
— Monte Carlo
• Data
2
6
10
p (GeV/c)
— Monte Carlo
• Data
0
2
4
$p_\perp$ (GeV/c)
8-87
5849A1

Fig. 1



0.8
0.6
0.4
0.2
0
F=LIKE CHARGE/TOTAL
(a)
Monte Carlo
Data
(b)
S=SENSITIVITY TO MIXING
Same Jet
L-L
L-H
H-H
8-87
5849A3

Fig. 2

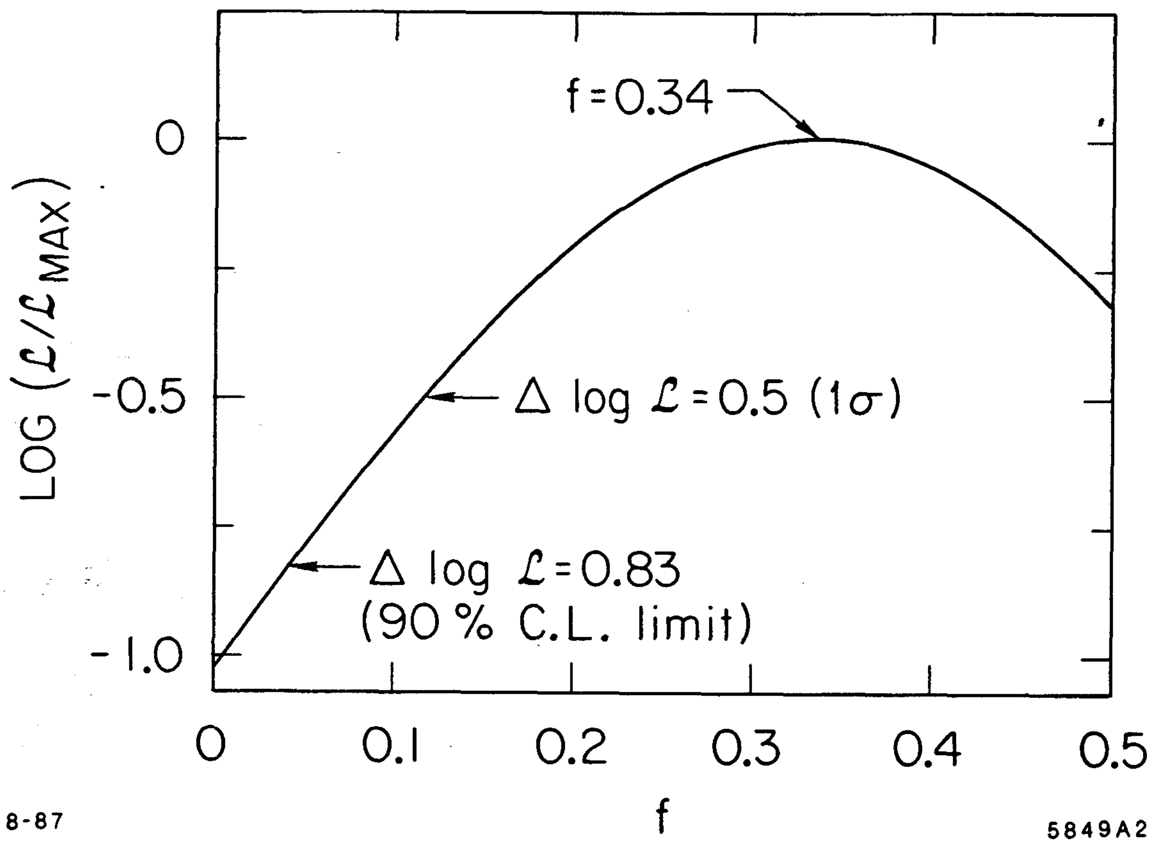

f=0.34
0
-0.5
-1.0
LOG ($\mathcal{L}/\mathcal{L}_{MAX}$)
Δ log $\mathcal{L}$=0.5 (1σ)
Δ log $\mathcal{L}$=0.83
(90 % C.L. limit)
0
0.1
0.2
0.3
0.4
0.5
f
8-87
5849A2

Fig. 3