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A REANALYSIS OF $B^0 - \overline{B}^0$ MIXING IN e^+e^-ANNIHILATION AT 29 GeV

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ABSTRACT

Data taken by the Mark II detector at the PEP storage ring was used to measure the rate of dilepton production in multihadronic events produced by e^+e^- annihilation at $\sqrt{s} = 29$ GeV. We determine the probability that a hadron initially containing a b-($\bar{b}$)-quark decays to a positive (negative) lepton to be $0.17^{+0.15}_{-0.08}$, with 90% confidence level limits of 0.06 and 0.38.

INTRODUCTION

Measurements of $B^0 - \overline{B}^0$ mixing have been made in several experiments.[1] These all rely on the observation of two leptons in the final state, and the correlation between the lepton charge and the parent quark charge for prompt, semileptonic B-hadron decays. Mixing is signaled by an excess of like-sign dilepton production.

We have previously published an upper limit on $B^0 - \overline{B}^0$-mixing based on a smaller data sample.[2] In this Letter we present the results of a new analysis[3] of multihadronic events containing leptons produced in e^+e^-annihilation at $\sqrt{s} = 29$ GeV. By performing a fit to events containing one and two leptons, we obtained estimates for the absolute numbers of all possible dilepton combinations, including background sources. Using a new method to separate events in which both leptons come from prompt, semileptonic decays of B hadrons from all others, we find an excess of signal events in which both leptons have the same charge. This excess is interpreted as evidence for mixing in the $B^0 - \overline{B}^0$ system. This result supercedes our previously published limit.

DETECTOR DESCRIPTION

The data were taken by the Mark II detector in two configurations at the PEP e^+e^- storage ring at Stanford Linear Accelerator Center. The detectors have been described in detail elsewhere.[4] In the original PEP5 detector, charged particles were tracked in a 16-layer cylindrical drift chamber and a 7-layer precision vertex drift chamber in a 2.3 kG solenoidal magnetic field. Charged-particle momenta p (GeV/c) were measured with a resolution of $\delta p/p = [(0.010p)^2 + (0.025)^2]^{1/2}$. In the upgraded detector, the PEP5 drift chambers were replaced by a 72-layer central drift chamber and a 6-layer high precision vertex chamber [5] in a 4.5 kG field giving a combined momentum resolution of $\delta p/p = [(0.003p)^2 + (0.014)^2]^{1/2}$. In both configurations, electrons were identified by their energy deposition in a lead-liquid argon calorimeter, which covers 64% of the 4π solid angle. Muons were identified over 45% of the 4π solid angle in a planar, 4-layer, iron/proportional tube system.

The total accumulated luminosity used in this analysis was 209 pb^{-1} in the PEP5 configuration, and 15 pb^{-1} in the upgrade configuration.

EVENT SELECTION

Hadronic events were selected by requiring at least five reconstructed charged tracks which formed a vertex less than 4 cm radially, and within ± 6 cm axially from the expected e^+e^- annihilation point. None of these tracks was allowed to be from identified photon conversions. The scalar sum of the momenta of all charged tracks was required to be at least 3.0 GeV, and the sum of the visible charged and neutral energy was required to be at least 7.5 GeV.

Charged-particle clusters (jets) were found using our standard cluster finding procedure, described in a previous publication. [6] Only the charged tracks, excluding the candidate leptons, were used by the cluster finding algorithm. We required all events to have at least one reconstructed cluster. In order for the event to be well contained in the detector, we required that the absolute value of the cosine of the angle between the beamline and the event thrust axis be smaller than 0.7. A total of 81,744 events passed these cuts, 76,738 being from the PEP5 data and 5006 from the upgrade data.

Lepton identification using the Mark II detector has been discussed in detail in a previous publication.[7] In this analysis, electrons were required to have momenta greater than 1 GeV/c and muons were required to have momenta greater than 1.8 GeV/c. Muons were identified using a relatively loose, three standard deviation road about the direction of the track, extrapolated from the drift chamber. We defined the transverse momentum (p_{tc}) of a track to be the component of the track's momentum perpendicular to the closest charged-particle cluster in the event. This definition avoided possible transverse momentum correlations between the two leptons, which would have been present had the transverse momentum (often referred to as p_t) been calculated with respect to the event thrust axis.

To estimate the composition of the dilepton events we performed an inclusive lepton analysis on two distinct event samples: those which contained only one lepton, and those which contained two leptons separated by more than 90°. To avoid backgrounds from two-photon processes and tau pairs, events which contained one or more leptons with $p > 7.5$ GeV/c and $p_{tc} > 3.5$ GeV/c were rejected. Also, in the one-lepton sample the lepton was required to have a charged-particle cluster found within 90°, to have $p < 9$ GeV/c, and $p_{tc} < 3.5$ GeV/c. Background electrons from Dalitz π^0 decays and photon conversions were removed by a pair finding algorithm.[8] After all cuts there were 6108 candidate electrons and 1568 candidate muons in the single-lepton sample; and 191 electron-electron, 117 electron-muon and 23 muon-muon pairs in the two-lepton sample. We estimate that less than 1.4% of the one-lepton events and less than 1.2% of the two-lepton events come from tau-pair and two-photon backgrounds.

ANALYSIS PROCEDURE

The leptons in the one-lepton sample were separated into a two-dimensional array of bins of momentum (p) and transverse momentum (p_{tc}) with widths of 0.5 GeV/c. For each lepton pair in the two-lepton sample we calculated two variables which were used to statistically separate the signal from the background. The first variable was the magnitude of the vector cross product of the lepton momenta. This variable, which we refer to as the *momentum cross product*, is large for high momentum lepton pairs which are relatively acollinear. The second variable was the smaller of the two lepton transverse momenta. This variable, which we refer to as the *minimum* p_{tc}, is large when *both* leptons have high momenta and are isolated from jets. The two-lepton events were separated into a two-dimensional array of bins of *momentum cross product* and *minimum* p_{tc} which had widths of 1.5 $(\text{GeV/c})^2$ and 0.5 GeV/c, respectively.

We performed a binned maximum-likelihood fit to the observed one- and two-lepton distributions. The five distinct distributions (one-muon, one-electron, electron-electron, muon-muon and electron-muon) were fit simultaneously to distributions generated by a Monte Carlo simulation. We used the Lund 6.3 code[9] with the second-order QCD matrix element and the Peterson fragmentation function[10] to simulate e^+e^- annihilation in our detector. Included in this simulation were leptons from:

1. background from misidentification of hadrons;
2. background from decays of charged pions and kaons to muons, and unidentified photon conversions and Dalitz π^0decays to electrons;
3. primary bottom-quark decay;
4. primary charm-quark decay; and
5. decay of charm-quarks in $b\bar{b}$ events (secondary-b decay).

The background lepton distributions were obtained from parametrizations of the pēr-track misidentification and decay probabilities as described in our previous publication.[7] The eight variables in the fit were the average semileptonic branching ratios for B- and C-hadron decays to electrons and muons, and multiplicative scale factors for the electron and muon misidentification and decay backgrounds. Because the kinematics of each lepton were independent of the sign of its charge, no information about the lepton charge was used in the fit.

The shapes of the two-lepton distributions were obtained by selectively generating large samples of each of the possible two-lepton combinations. The absolute normalization for each of these distributions was obtained by the following procedure: The probability for a given produced quark flavor, q, to decay to a given type of detected lepton, $P(q \rightarrow \ell_1)$, was estimated from the fit to the one-lepton data and was, therefore, a function of the eight fit variables. The probability for *both* produced quarks in the event to decay to a given two-lepton combination was then the product of the two probabilities for either quark to decay to either lepton, multiplied by a correction factor, C. This factor accounted for possible acceptance correlations, the different cuts applied to the one- and two-lepton samples, and combinatoric factors. The normalization for the given two-lepton combination, $N_{\ell_1\ell_2}$, was then the product of this two-lepton probability and the estimated number of events, $N_{q\bar{q}}$, of flavor q in the hadronic data sample:

$$N_{\ell_1\ell_2} = N_{q\bar{q}}\ C\ P(q \to \ell_1)\ P(q \to \ell_2) \quad .$$

We show the *momentum cross product vs. minimum* p_{tc} distributions for four dilepton combinations in Fig. 1. These Monte Carlo distributions contain the expected numbers of events present in the hadronic data sample. For large values of the *momentum cross product* and *minimum* p_{tc}, the B-primary dileptons are essentially background free.

The results of the fit, shown in Table 1, agreed well with our previously published values[7] for the B- and C-hadron semileptonic branching ratios, as did the estimates for the misidentification and decay backgrounds. The observed and predicted distributions for the one- and two-lepton samples are shown in Figs. 2 and 3.

To check the results of the fit, the one- and two-lepton samples were fit separately. Again, there was agreement within the statistical errors of the two fits. The total numbers of two-lepton events predicted from the statistically independent one-lepton fit were in very good agreement with those observed, as shown in Table 2.

To extract information about B-mixing, we define the probability, χ, that a hadron, initially containing a b- ($\bar{b}$)-quark, decays to a positive (negative) lepton to be:

$$\chi \equiv \frac{\Gamma(\overline{B} \to \ell^+ X)}{\Gamma(\overline{B} \to \ell^\pm X)} = \frac{\Gamma(B \to \ell^- X)}{\Gamma(B \to \ell^\pm X)} \quad ,$$

where Γ is the total time-integrated rate. The fraction of like-sign events in which both leptons come from primary b-decay is then $2\chi(1-\chi)$, where we have assumed that the two B-hadrons are produced in an uncorrelated way, and that they undergo mixing without interference. This definition of χ includes all produced B mesons and baryons, not just the neutral mesons, and neglects possible CP violations in the $B^0 - \overline{B}^0$ system.

We assumed that all dilepton events containing a misidentified hadron or background decay lepton have equal like- and unlike-sign probabilities.[11] Like-sign dileptons can also arise from events containing b-secondary decays ($b \rightarrow c \rightarrow \ell^+$). These events are also sensitive to mixing since the lepton from the charm decay is still correlated with the parent b-quark charge.[12] We further assumed that D-mixing was negligible, and therefore that dileptons from C-primary decays have opposite charges.

Given all the possible dilepton distributions, we estimated the expected total number of like- and unlike-sign dileptons in each bin, as a function of χ. We then calculated the log-likelihood for the observed numbers of like- and unlike-sign events, summed over all bins in the distribution, for electron-electron, electron-muon, and muon-muon events. These three log-likelihoods (functions of χ) were then added together to form the overall log-likelihood function. The most likely value was 0.17 with 90% confidence level upper and lower limits of 0.29 and 0.08, respectively. Table 3 shows the observed and predicted numbers of like- and unlike-sign dileptons in the kinematic region most sensitive to mixing.

SYSTEMATIC ERRORS

To check that our method was sensitive to B-mixing, two samples of Monte Carlo events with generated values $\chi = 0.0$ and $\chi = 0.25$ were analysed. These samples had an integrated luminosity equivalent to that of the data. The measured values of χ obtained using our likelihood procedure agreed well with these generated values. Possible systematic biases introduced by the fit procedure were checked by performing the fit to the observed like- and unlike-sign dilepton distributions only. All eight parameters were free to vary within two standard deviations above and below their values from the previous fit. The value of χ which maximised the likelihood was found to be $0.17^{+0.12}_{-0.08}$. The correlation coefficients between χ and the other parameters were all smaller than 0.15.

To accommodate uncertainties in the b-quark fragmentation function, the fragmentation ϵ parameter was varied between the values 0.001 and 0.010. (This range of values was obtained from our previous inclusive lepton analysis.[7]) The resulting values for χ were $0.18^{+0.14}_{-0.06}$ and $0.16^{+0.12}_{-0.06}$ for $\epsilon_b = 0.001$ and $\epsilon_b = 0.010$, respectively. Variations in the semileptonic branching ratios for B- and C-hadrons within the errors of the fit had a negligible effect on the likelihood function. Fixing these branching ratios at the world average values also did not affect the likelihood function. To check our background estimates at high values of p, p_{tc} we restricted the single-leptons to $p > 4$ GeV/c, $p_{tc} > 1.5$ GeV/c, and the dileptons to *momentum cross product* > 6.0 (GeV/c)^2, *minimum* $p_{tc} > 1.5$ GeV/c in the fit. With this reduced data sample the most likely value for χ was $0.18^{+0.12}_{-0.07}$. Also, using this sample we increased the levels of the misidentification and decay backgrounds by 50% while keeping all other fit parameters fixed. The value for χ in this case was $0.18^{+0.12}_{-0.08}$. These results indicate that our measured value of χ is relatively insensitive to the background estimates.

Combining all sources of systematic error including possible tracking biases and detector acceptance correlations we arrive at the result $\chi = 0.17^{+0.15}_{-0.08}$, with 90% confidence level limits of 0.06 and 0.38.

B_d^0- AND B_s^0-MIXING

To extract information about the B_d^0- and B_s^0-mixing parameters r_d and r_s, defined by[13]

$$r_d \equiv \frac{\Gamma(\mathrm{B_d^0} \rightarrow \ell^+ X)}{\Gamma(\mathrm{B_d^0} \rightarrow \ell^- X)} \quad , \qquad r_s \equiv \frac{\Gamma(\mathrm{B_s^0} \rightarrow \ell^+ X)}{\Gamma(\mathrm{B_s^0} \rightarrow \ell^- X)} \quad ,$$

we assumed that all B-hadrons have equal semileptonic branching ratios. The measured value of χ was then given by

$$\chi = f_d \left(\frac{r_d}{1 + r_d} \right) + f_s \left(\frac{r_s}{1 + r_s} \right) \quad ,$$

where f_s and f_d are the fraction of B_d^0 and B_s^0 present in the data. To accommodate uncertainties in the composition of the B-hadron sample we chose two possible cases: $f(B_u) = 0.375$, $f(B_d) = 0.375$, $f(B_s) = 0.15$, $f(B_{other}) = 0.10$; and $f(B_u) = 0.40$, $f(B_d) = 0.40$, $f(B_s) = 0.20$, $f(B_{other}) = 0.0$. Given these assumptions, we obtained the contours shown in Fig. 4(a) and 4(b). Our result favors maximal B_s^0-mixing, although it cannot rule out zero B_s^0-mixing at the 90% confidence level.

CONCLUSION

In a new analysis of 224 pb^{-1} of e^+e^- annihilation data at 29 GeV we find evidence for B-mixing, and determine the probability that a hadron initially containing a b-($\bar{b}$)-quark decays to a positive (negative) lepton to be $0.17^{+0.15}_{-0.08}$, with 90% confidence level limits of 0.06 and 0.38. This result is consistent with full B_s^0-mixing, although it cannot rule out zero B_s^0-mixing at the 90% confidence level.

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following parameters were used: $\Lambda_{\overline{MS}} = 0.5$ GeV, $y_{min} = 0.015, A = 0.9, B = 0.7, \epsilon_c = 0.05, \epsilon_b = 0.005, \sigma_q = 0.265$ GeV/c, $P_s = 0.35, P_{qq} = 0.10$.

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11. There is a slight correlation between the original quark charge and the background lepton charge which was determined by looking at opposite-jet, hadron-lepton pairs in the single-lepton sample. The ratio of unlike- to like-sign events was determined to be 1.066 ± 0.028. This result was confirmed using the Monte Carlo one-lepton sample, and was essentially independent of the original quark flavor. This effect was included in the calculation of the likelihood functions.

12. There is a small probability for a b-quark jet to contain more than one charm hadron. The leptons produced by semileptonic decays of these charm hadrons will not necessarily be charge-correlated with the original b-quark charge. Using the Monte Carlo we estimated that $14\% \pm 5\%$ of all B-secondary decays have the opposite charge to that expected. This effect was included in the calculation of the likelihood functions.

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Table 1. Results of the one- and two-lepton fit. The errors are the statistical and systematic errors, respectively.

Parameter	Result (%)
$\mathrm{Br}(B \to e)$	$13.7 \pm 0.8 \pm 1.3$
$\mathrm{Br}(B \to \mu)$	$13.7 \pm 1.1 \pm 1.1$
$\mathrm{Br}(C \to e)$	$11.0 \pm 0.8 \pm 1.7$
$\mathrm{Br}(C \to \mu)$	$7.9 \pm 1.1 \pm 1.1$

Table 2. Predicted numbers of dileptons based on the fit to the one-lepton data only.

Dilepton type	Observed	Predicted
$e \cdot e$	191	199.4
$e \cdot \mu$	117	117.5
$\mu \cdot \mu$	23	25.2

Table 3

Results for the region most sensitive to mixing

mom. cross product > 7.5 $(GeV/c)^2$,
min. p_{tc} > 1.0 GeV/c

	opposite sign			*same sign*			*both signs*	
$e \cdot e$	9	(8.0)	[6.3]	2	(1.4)	[3.1]	11	(9.3)
$e \cdot \mu$	5	(9.4)	[7.4]	3	(1.7)	[3.8]	8	(11.1)
$\mu \cdot \mu$	1	(2.7)	[2.1]	1	(0.4)	[1.0]	2	(3.1)
total	15	(20.1)	[15.8]	6	(3.5)	[7.9]	21	(23.5)

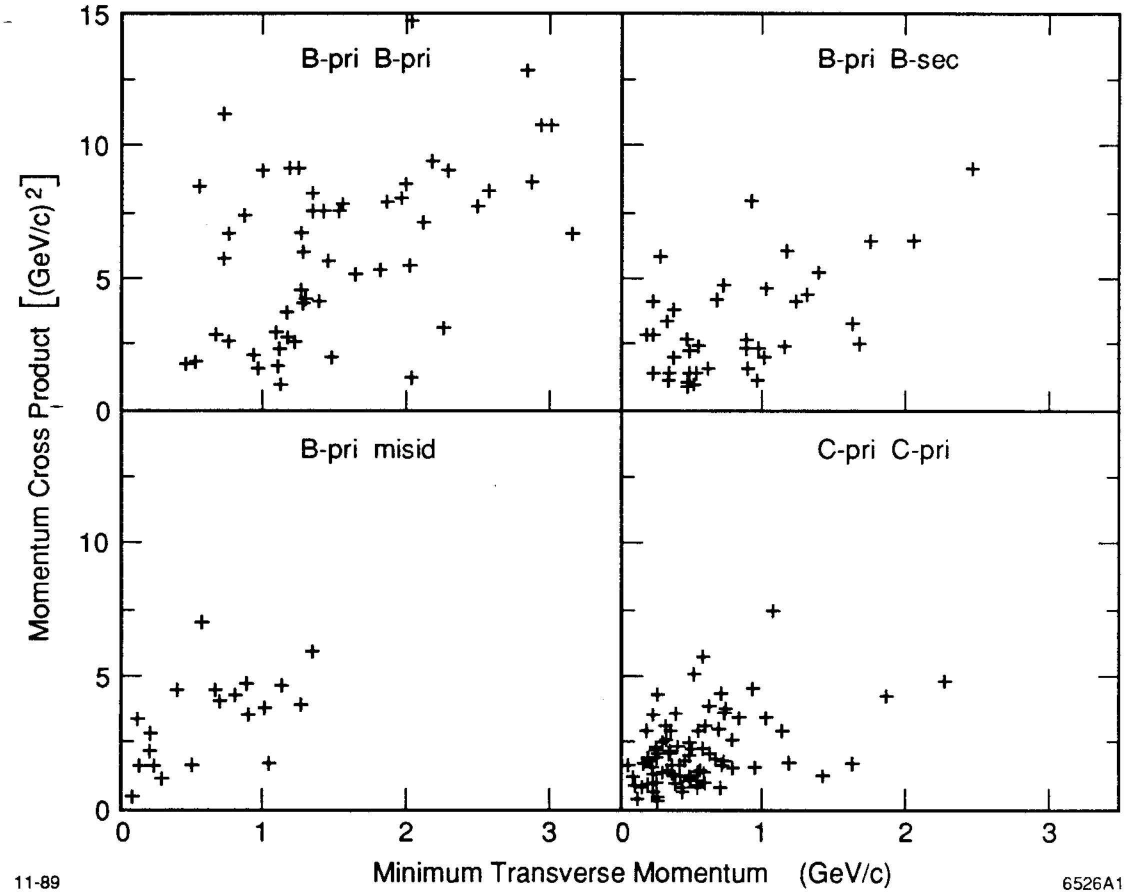
mom. cross product > 12.0 $(GeV/c)^2$,
min. p_{tc} > 1.5 GeV/c

	opposite sign			*same sign*			*both signs*	
$e \cdot e$	2	(1.3)	[1.1]	0	(0.33)	[0.56]	2	(1.7)
$e \cdot \mu$	2	(2.4)	[1.8]	2	(0.23)	[0.82]	4	(2.7)
$\mu \cdot \mu$	0	(0.61)	[0.44]	1	(0.02)	[0.19]	1	(0.63)
total	4	(4.3)	[3.3]	3	(0.58)	[1.57]	7	(5.0)

numbers in parentheses are the predictions with $\chi = 0$
numbers in brackets are the predictions with $\chi = 0.17$

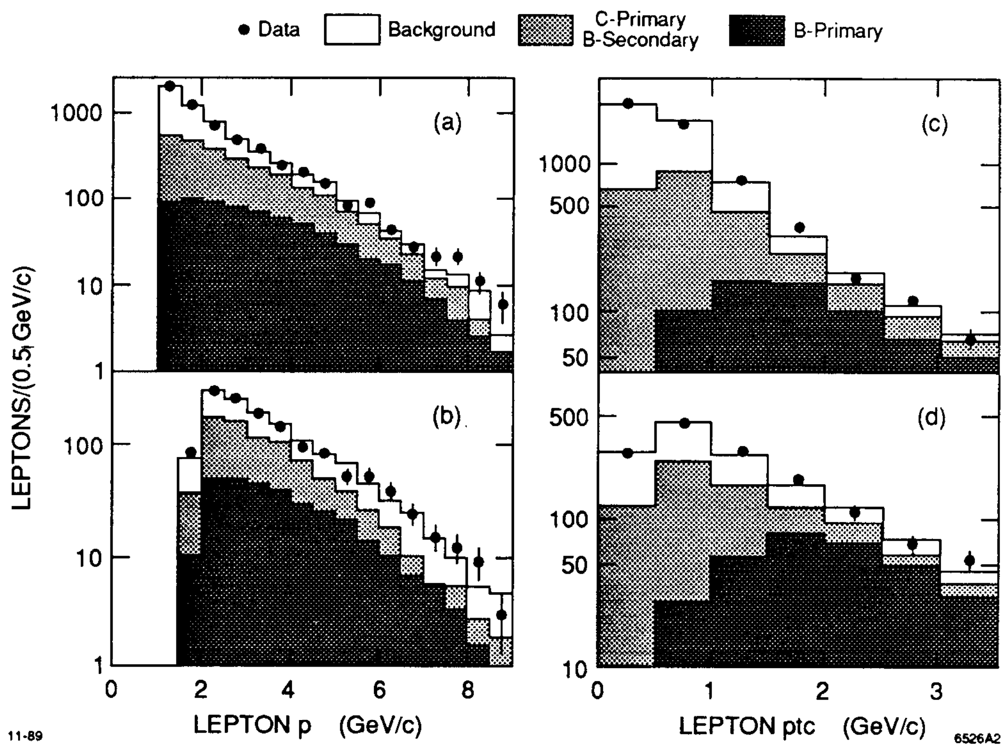
FIGURE CAPTIONS

1. Four dilepton distributions normalised to the size of the hadronic data sample.
2. (a) Electron momentum for one-lepton sample. (b) Muon momentum for one-lepton sample. (c) Electron transverse momentum for one-lepton sample. (d) Muon transverse momentum for one-lepton sample.
3. (a) Dilepton momentum cross-product. (b) Dilepton minimum transverse momentum.
4. (a) We have assumed $fd = 0.375$, $fs = 0.15$. (b) We have assumed $fd = 0.400$, $fs = 0.20$. The shading represents the regions allowed by ARGUS and CLEO which are excluded by this measurement. Light shaded region is excluded at the 1σ level, dark shaded region is excluded at the 90% confidence level.



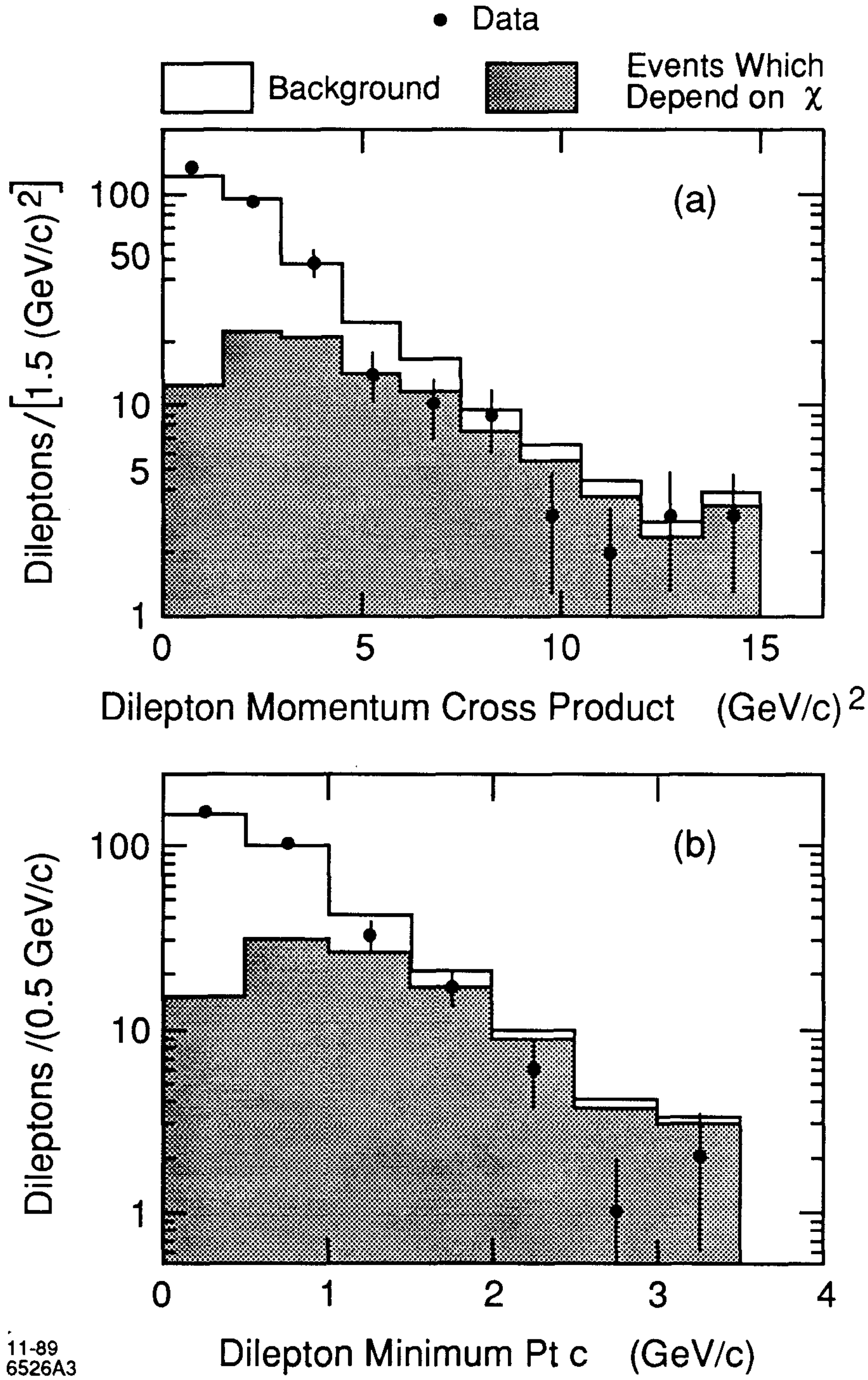
B-pri B-pri
B-pri B-sec
B-pri misid
C-pri C-pri
Momentum Cross Product [(GeV/c)^2]
Minimum Transverse Momentum (GeV/c)
0
5
10
15
1
2
3
11-89
6526A1

Fig. 1



Data
Background
C-Primary
B-Secondary
B-Primary
(a)
(b)
(c)
(d)
LEPTONS/(0.5 GeV/c)
LEPTON p (GeV/c)
LEPTON ptc (GeV/c)
11-89
6526A2

Fig. 2



Data
Background
Events Which Depend on χ
Dileptons/[1.5 (GeV/c)²]
(a)
Dilepton Momentum Cross Product (GeV/c)²
Dileptons /(0.5 GeV/c)
(b)
Dilepton Minimum Pt c (GeV/c)
11-89
6526A3

Fig. 3

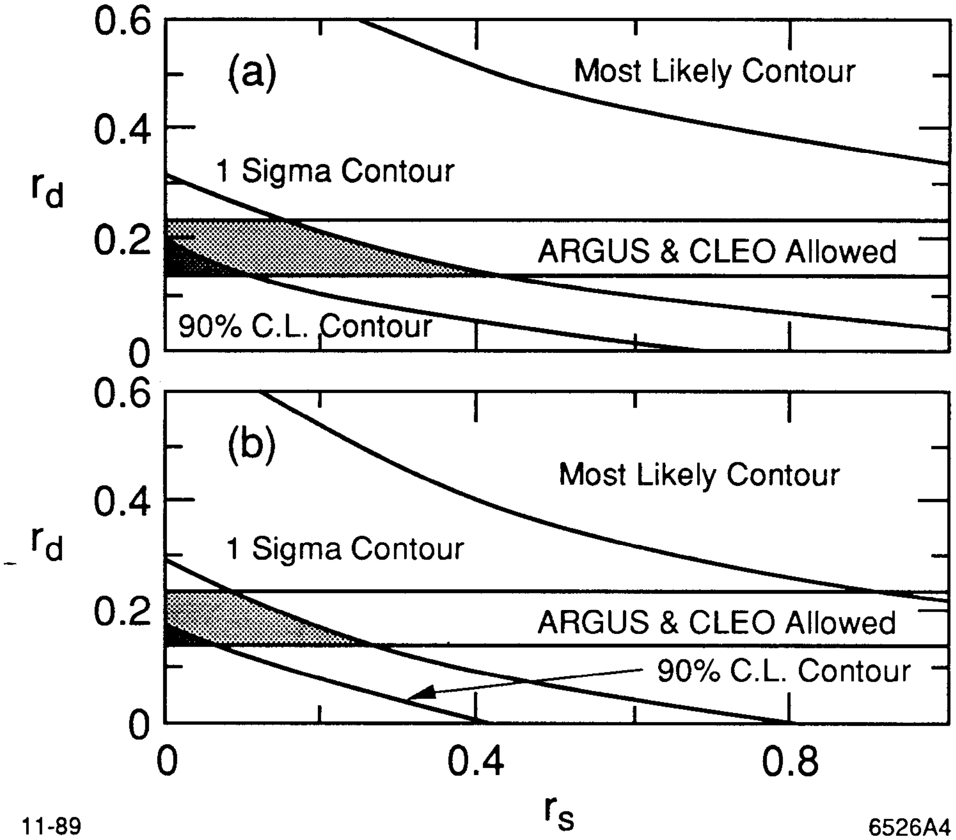

(a)
Most Likely Contour
1 Sigma Contour
ARGUS & CLEO Allowed
90% C.L. Contour
(b)
Most Likely Contour
1 Sigma Contour
ARGUS & CLEO Allowed
90% C.L. Contour
r_d
r_s
0.6
0.4
0.2
0
0
0.4
0.8
11-89
6526A4

Fig. 4