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Measurement of $B^0\bar{B}^0$ Mixing at the Fermilab Tevatron Collider

The CDF Collaboration

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Abstract

The $B^0\overline{B}^0$ average mixing parameter χ has been extracted from $e\mu$ and ee events produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. In a sample of 900 $e\mu$ events, the like-sign to opposite-sign charge ratio R is measured to be 0.556 ± 0.048 (stat) $^{+0.035}_{-0.042}$ (sys). In the absence of mixing, the expected value of R would be 0.23 ± 0.06. The corresponding number for 212 ee events is 0.573 ± 0.116 (stat)

± 0.047 (sys) with an expected non-mixing value of 0.24 ± 0.07. The observed excess in R leads to a combined determination of $\chi = 0.176 \pm 0.031$ (stat+sys) $\pm\ 0.032$ (model), where the last uncertainty is due to Monte Carlo modeling.

The phenomenon of mixing, in which a neutral meson transforms into its antiparticle via flavor-changing weak interactions, can provide constraints on the elements of the Cabbibo-Kobayashi-Maskawa matrix. Early evidence of $B^0\overline{B}^0$ mixing was observed at the CERN $p\bar{p}$ collider [1] and at e^+e^- colliders.[2,3] We report a measurement of $B^0\overline{B}^0$ mixing obtained by the CDF collaboration at the Fermilab Tevatron Collider.

Neutral B mesons, $B^0_d(\bar{b}d)$ and $B^0_s(\bar{b}s)$, may be produced in the reaction $p\bar{p} \rightarrow b\bar{b} \rightarrow B\overline{B} + X$, where B ($\overline{B}$) refers to all $\bar{b}$ (b) flavored hadrons. In the absence of mixing, the direct semi-leptonic decay of a $B\overline{B}$ pair results in a pair of leptons with opposite charges. The B^0 or $\overline{B}^0$ meson may undergo mixing, $B^0 \rightarrow \overline{B}^0$ or vice versa, and subsequently decay semi-leptonically, resulting in a like-sign pair. The magnitude of mixing is determined from the relative rate of like-sign di-lepton pairs

$$R = \frac{N(\ell^+\ell^+) + N(\ell^-\ell^-)}{N(\ell^+\ell^-)} \quad ,$$

where ℓ can be an e, μ or τ lepton. The results in this report are based on $e\mu$ and ee events. The probability of $B^0\overline{B}^0$ mixing can be expressed as

$$\chi = \frac{prob(b \rightarrow \overline{B}^0 \rightarrow B^0 \rightarrow \ell^+)}{prob(b \rightarrow \ell^\pm)} \quad ,$$

where the leptons can come from both direct and sequential B decays and the denominator includes all possible hadrons formed with the b quark. We determine χ using our measured value of R and a Monte Carlo calculation of the contribution from other processes.

The CDF detector has been described in detail elsewhere.[4,5] The $e\mu$ sample was collected primarily with an electron-muon trigger, and the ee sample was collected with a di-electron trigger. The integrated luminosity for the $e\mu$ (ee) trigger is 2.7 pb^{-1} (3.7 pb^{-1}). In the data analysis, both electrons in ee events are required to have $E_T \geq 5$ GeV. In $e\mu$ events, the electrons are required to have $E_T \geq 5$ GeV, and the muons are required to have $P_T \geq 3$ GeV/c. Lepton selection criteria are applied to both the $e\mu$ and ee candidate events in order to reject hadrons. These criteria are described in detail in reference [5].

After the lepton selections, there remain sources of di-leptons unrelated to $B^0\overline{B}^0$ mixing. Some of these can be removed by imposing requirements on the di-lepton invariant mass, $M_{\ell\ell}$. Since charmed mesons do not have sizable mixing behavior, the decays of a single B hadron via the chain b $\rightarrow c\ell\nu$ followed by c $\rightarrow s\ell\nu$ always result in opposite-sign di-leptons, kinematically restricted to a low invariant mass. To remove this background, we exclude events in the region $M_{\ell\ell} < 5.0$ GeV/c^2, where $\ell\ell$ refers to ee or $e\mu$ for both same-sign and opposite-sign events. In addition, the decays $J/\psi \rightarrow e^+e^-$ and $\Upsilon \rightarrow e^+e^-$ form a background that would affect the measurement of mixing in the ee channel. The invariant mass cut below 5.0 GeV/c^2 removes the former, and excluding the region $8.0 < M_{ee} < 10.8$ GeV/c^2 removes the latter. After these cuts, there are 346 like-sign and 554 opposite-sign $e\mu$ events, composed of 181 $e^+\mu^+$, 165 $e^-\mu^-$, 290 $e^-\mu^+$, and 264 $e^+\mu^-$ events, and 78 like-sign and 134 opposite-sign ee events.

The remaining backgrounds to our determination of R must be removed by performing a background subtraction. The sources of such events include μ candidates from decays-in-flight of pions and kaons, electron candidates from photon conversion or Dalitz decays, and charged hadrons which mimic leptons. For ee candidates, there is an additional background due to Drell-Yan production. The methods used to remove these backgrounds are different for $e\mu$ and ee, and are discussed below separately.

To determine the background fraction for the $e\mu$ events, we use the fact that the $e\mu$ events are a subset of an inclusive electron sample. Even after all selection cuts, such an inclusive sample would still contain both real and fake electrons. Each track in this sample, excluding the electron, may be associated with a real muon or may mimic a muon. Together with the electron candidate, these tracks can lead to real or fake $e\mu$ events. With our detector, we expect events with a fake muon to be the dominant background in the $e\mu$ event candidates. The amount of real-e fake-μ and fake-e fake-μ backgrounds is given by the product of the number of tracks in the inclusive electron events and the fake-μ per track rate, F_μ. The remaining background is fake-e real-μ events, which is a subset of the fake electron events. The number of tracks in the fake electron events times the real-μ per track rate, R_μ, is the fake-e real-μ background.

In the analysis, we determine the probability f_μ that a track is called a muon, which is $F_\mu + R_\mu$. The product of f_μ and the number of tracks in an inclusive electron sample contains all of the backgrounds above together with an extra term, which arises from R_μ times the number of tracks in the real electron events. This extra term contributes to an over-estimate of the background, and will be discussed later. The quantity f_μ is obtained from a sample of 278,000 events collected with a minimum-bias trigger. Fake electron events arising from a low E_T^e inclusive electron trigger are expected to have a similar rate of heavy quark production as events from the minimum-bias trigger. Thus the probability of real muon production is similar in events from these two types of triggers. We define m-tracks as those tracks which satisfy the tracking requirements for a muon and point to the muon chambers. In the minimum-bias sample, there are 2959 m-tracks. Eight of these m-tracks satisfy all muon criteria including the muon chamber requirements.[5] This leads to a rate of muon candidates per m-track $f_\mu = 0.27\%$.

Since we do not have an inclusive electron sample collected with $E_T^e \geq 5$ GeV, we determine the $e\mu$ background fraction from two inclusive electron samples collected with trigger E_T^e thresholds of 7 GeV and 12 GeV. The 7 GeV trigger was pre-scaled. The event overlap is less than 5% between the two electron samples with different thresholds. From these two inclusive electron samples, which comprise both signal and background events, there are respectively 1324 and 2897 m-tracks, excluding tracks associated with the electron candidates. Applying the measured value of f_μ gives the expected number of fake $e\mu$ events, shown in column 3 of Table I. These represent an upper limit on the number of events in which one or both leptons is mis-identified. Dividing this number by the total number of $e\mu$ events observed in each sample, the fractional background (Table I, column 5) is seen to be independent of the electron E_T threshold. Based on this, we take the background fraction in the $e\mu$ sample to be 19 $\pm$ 9%, which includes statistical and systematic uncertainties. The systematic uncertainties are described below.

Table I Background Estimation Using Inclusive Electron Samples

$E_T^e(GeV)$	N(tracks)	N(fake $e\mu$ expected)	N($e\mu$ observed)	background
≥ 7	1324	3.6 ± 1.6	19	$19 \pm 9\%$
≥ 12	2897	7.8 ± 3.5	44	$18 \pm 8\%$

The above method for determining the background fraction requires the properties of m-tracks in minimum-bias events to be similar to those in electron candidate events. If the K/π ratio in the minimum-bias sample were different from that in the inclusive electron samples, the rate of muons per track could change. This is therefore a source of systematic uncertainty. We determine the effect of this using Monte Carlo simulation studies of fake muons. The value of f_μ changes by less than 15% when the K/π ratio is varied in the range from 0.12 to 0.36 measured in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV for track $P_T \geq 3$ GeV/c.[6] In similar Monte Carlo studies, f_μ changes by 20% due to different track P_T over the range 3 GeV/c $\leq P_T \leq$ 12 GeV/c. These variations are included in our systematic uncertainty. In addition, a comparison of qualities of muon candidates in minimum-bias events and in a J/ψ sample shows that a large fraction of the muons in the minimum-bias sample is background. Thus the over-estimate of the background, due to real muons per m-track rate times the number of tracks in real electron events, is small compared to the 47% uncertainty on the background fraction.

For the inclusive electron sample (after the 5 GeV/c^2 mass cut), the ratio of the number of electrons paired with an m-track of the same sign to the number of opposite-sign pairs is 0.95 ± 0.06, consistent with no sign correlation. The background fraction of $19 \pm 9\%$ therefore corresponds to 86 like-sign and 86 opposite-sign $e\mu$ pairs in the 900 total events, resulting in a final background-subtracted $e\mu$ sample of 260 like-sign and 468 opposite-sign events. From this we obtain

$$R(e\mu) = 0.556 \pm 0.048 \text{ (stat) } ^{+0.035}_{-0.042} \text{ (sys)},$$

where the systematic uncertainty is calculated by varying simultaneously the numbers of like-sign and opposite-sign background events by one standard deviation.

For the ee events, the background after the electron selection and the di-lepton invariant mass cuts are due to mis-identified hadrons, photon conversions and Dalitz pairs, and Drell-Yan production. We determine the background due to mis-identified hadrons by comparing the behavior of the hadronic to electromagnetic energy ratio in our data to two other samples; one of pure electrons, and one of hadrons which satisfy nearly all electron criteria. The first sample is obtained from J/ψ decay, and the second consists of electron candidates which display large mismatches between electromagnetic shower position and the location of the track extrapolated to the calorimeter. Such a mismatch is typical of the spatial proximity of charged and neutral pions. The contribution of early showering pions to the mis-identified hadron background is minimal due to our electron selection criteria. The total number of events containing a mis-identified hadron is 27.1 ± 9.2; there is no sign correlation between the real and fake electrons in these events.

To reject electrons produced in photon conversions and Dalitz decays, we pair each electron with tracks of the opposite charge within a polar angle $\Delta\theta < 5^o$ and calculate the separation between the tracks at the point at which they are parallel. If this point is within the radius at which photons are likely to convert and the separation is less than 0.5 cm then the event is rejected. Dalitz pairs are also rejected by this criterion. We do not reconstruct tracks with $P_T \lesssim 0.4$ GeV/c [7], therefore conversion pairs in which one electron has low P_T are not rejected by this method. Based on a Monte Carlo calculation of the efficiency of the rejection, the total number of conversion electrons remaining in our sample is 19 ± 14 events. The fraction of like-sign pairs in events identified as containing a conversion electron is $0.41 \pm .09$, consistent with no sign correlation.

Drell-Yan events in our sample are distinguished by an opposite-sign electron pair with a lack of energy deposition in the region nearby each electron. This contrasts with electrons associated with B decay which have nearby jet activity. We define a variable E_T isolation (E_T^{iso}) as the transverse energy deposited in the annulus between $r = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ and $r = 0.7$ around the electron.[5] This variable is independent of the electron P_T. The amount of background from the Drell-Yan processes in the ee sample is determined by fitting the E_T^{iso} distribution of all opposite-sign pairs to a weighted sum of the E_T^{iso} behavior of Drell-Yan di-electrons and that of our like-sign pairs, which are free of any Drell-Yan contribution. A sample of $Z^0 \to e^+e^-$ [8] is used to measure the E_T^{iso} dependence of Drell-Yan di-electrons. After rejecting events in which both electrons do not have at least 2.4 GeV E_T deposited in the annulus, we determine the remaining Drell-Yan background in our opposite-sign ee sample to be 15.4 ± 4.6 events.

After removing these backgrounds, there are 55 like-sign and 96 opposite-sign ee events, from which we obtain

$$R(ee) = 0.573 \pm 0.116 \text{ (stat) } \pm 0.047 \text{ (sys)}.$$

The observed values of R from both the $e\mu$ and ee events have been used to extract the average $B^0\overline{B}^0$ mixing parameter χ, as described below.

Events containing like-sign di-leptons from b and c quark decays can arise from processes other than mixing. The dominant process is the semi-leptonic decay of one b and the sequential decay $b \to c \to \ell$ of the other. The ratio of sequential decays (N_s) to first-generation decays (N_f) for both di-lepton samples is $N_s/N_f = 0.25 \pm 0.06$ as determined using the Monte Carlo program ISAJET [9] together with a full detector simulation. High order processes such as gluon splitting are included, but their contributions are significantly reduced by our kinematic cuts. After the cuts, distributions for variables sensitive to higher order processes, such as $P_T(e\mu)$, are well reproduced by the Monte Carlo model. The uncertainties on N_s/N_f in the model are due to b and c quark semi-leptonic branching ratios obtained from reference [10] (15%), b fragmentation (10%), and $b\bar{b}$ correlations due to higher order processes (10%). A smaller source of opposite-sign di-leptons is the semi-leptonic decay of $c\bar{c}$ pairs. The fraction of these events is $N_c/N_f = 0.07 \pm 0.07$ ($e\mu$) and 0.02 ± 0.02 (ee), where the difference is mainly due to P_T thresholds. We assign a 100% error to the ratio of $c\bar{c}$ and $b\bar{b}$ production cross-sections from ISAJET, which gives a 100% error on the fraction N_c/N_f .

The average $B^0\overline{B}^0$ mixing parameter χ is related to R by:

$$R = \frac{2\chi(1-\chi) + [(1-\chi)^2 + \chi^2]\frac{N_s}{N_f}}{[(1-\chi)^2 + \chi^2] + 2\chi(1-\chi)\frac{N_s}{N_f} + \frac{N_c}{N_f}} \quad .$$

In the absence of mixing, the expected values would be $R(e\mu) = 0.23 \pm 0.06$ and $R(ee) = 0.24 \pm 0.07$, both of which are inconsistent with the observed values. From the observed values of R for the $e\mu$ and ee events, we obtain $\chi(e\mu)$=0.179 $\pm$ 0.027 (stat) $\pm$ 0.022 (sys) $\pm$ 0.032 (model), $\chi(ee)$=0.172 $\pm$ 0.060 (stat) $\pm$ 0.024 (sys) $\pm$ 0.026 (model), and the combined value of

$$\chi = 0.176 \pm 0.031 \text{ (stat+sys)} \pm 0.032 \text{ (model)},$$

where the uncorrelated statistical and systematic uncertainties have been combined, and the Monte Carlo model uncertainty treated as common. The asymmetry of the systematic uncertainty in $R(e\mu)$ leads to negligible asymmetry in $\chi(e\mu)$. The muon P_T spectra for the data, and for Monte Carlo with the determined mixing and background are shown in Figure 1 for like-sign and opposite-sign $e\mu$ events separately. Similar results are obtained for the ee events.

The value of χ determined above is averaged over all B mesons and baryons that may be produced in an event. These include neutral mesons such as B_d^0 and B_s^0 which transform into their own antiparticles via mixing and charged B mesons and baryons which do not undergo mixing. To separate the mixing parameters for B_d^0 and B_s^0 in the expression

$$\chi = P_d \chi_d + P_s \chi_s \quad ,$$

where

$$\chi_{d(s)} \equiv \frac{Prob(B^0_{d(s)} \to \overline{B}^0_{d(s)})}{Prob(B^0_{d(s)} \to B^0_{d(s)}) + Prob(B^0_{d(s)} \to \overline{B}^0_{d(s)})}$$

and

$$P_{d(s)} = Prob(b \to B^0_{d(s)}) \frac{BR(B^0_{d(s)} \to \ell^+ X)}{BR(b \to B \to \ell^\pm X)}$$

requires a measurement of the fractions P_d and P_s.[1] By assuming the same branching ratio for semi-leptonic decays of all B mesons, assuming B_u, B_d and B_s are produced in the ratio 0.375 : 0.375 : 0.15,[12] we obtain constraints on the χ_d - χ_s plane shown in Figure 2. The ARGUS and CLEO combined results for χ_d and the Standard Model predictions [11] are also shown. Our results are consistent with recent measurements of $B^0\overline{B}^0$ mixing by other experiments.[12]

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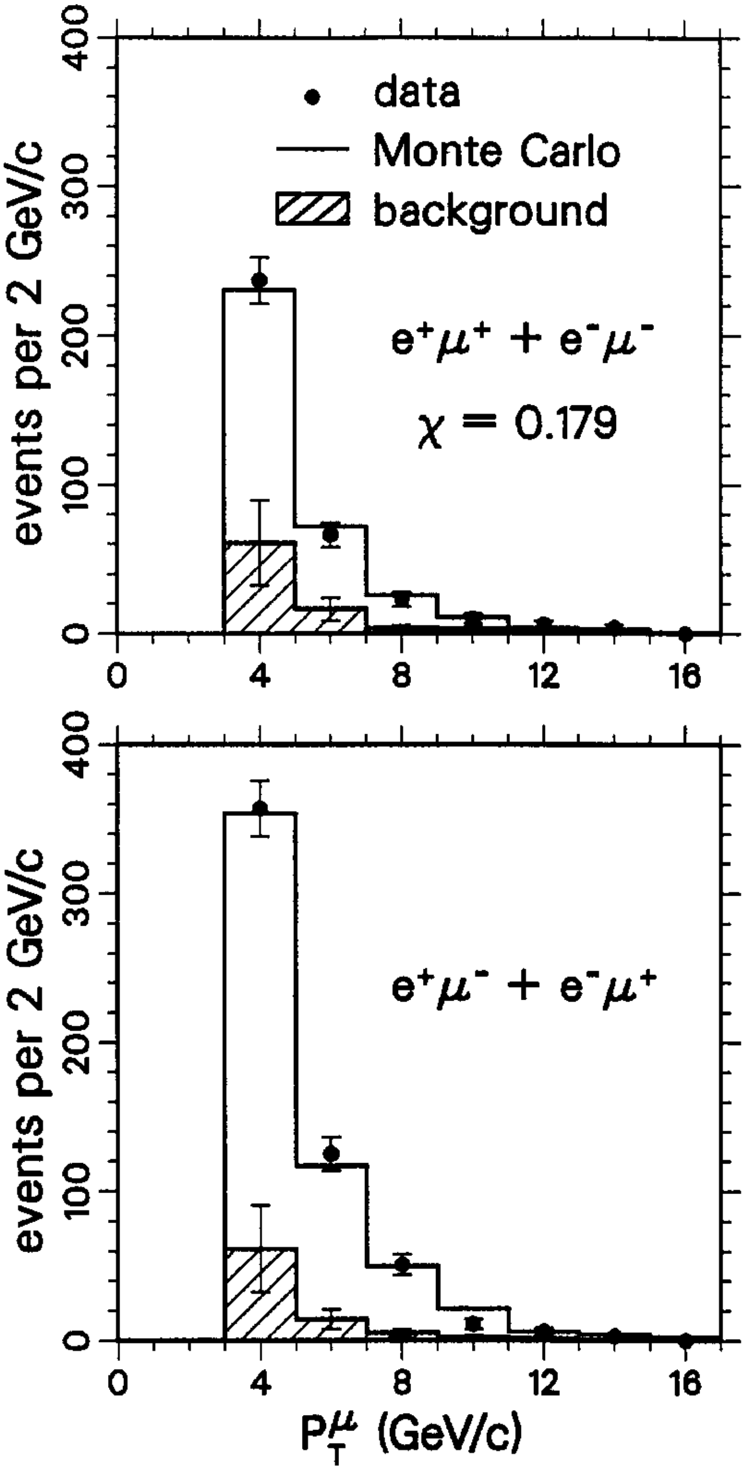
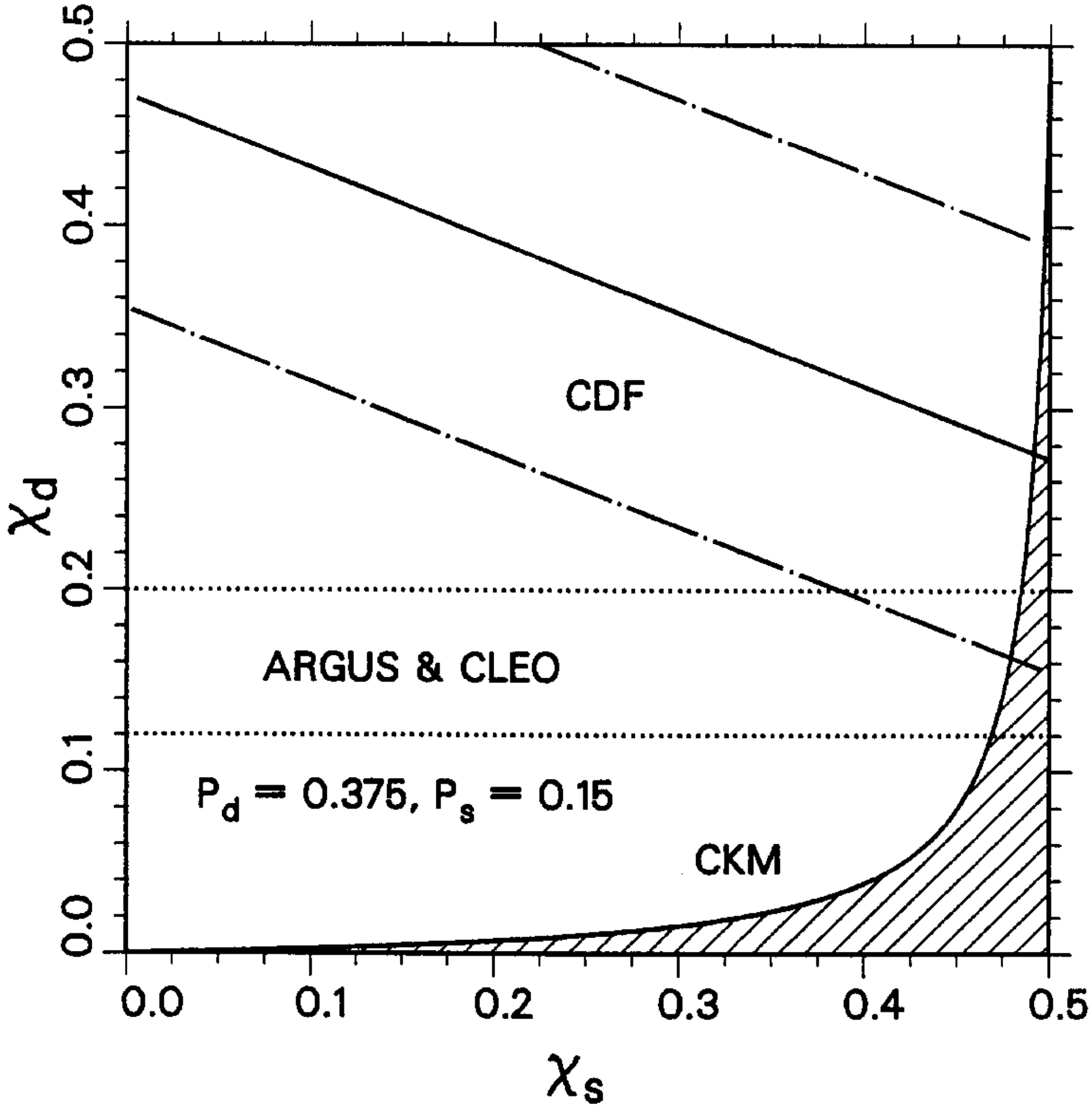
Figure Captions

Figure 1: Muon P_T spectra for the data, Monte Carlo with the observed mixing, and background in like-sign and opposite-sign $e\mu$ events. The uncertainties for the data are statistical only, while those for the background are 47% as described in the text. Both the data and the Monte Carlo include the background.

Figure 2: The mixing probability of B_d^0 versus that of B_s^0, assuming B_u, B_d and B_s are produced in the ratio 0.375 : 0.375 : 0.15. The χ_d range is the ARGUS and CLEO combined result of 0.16 ± 0.04. The shaded region is allowed by the Standard Model. The bands represent $\pm 1\sigma$ uncertainty.



events per 2 GeV/c
data
Monte Carlo
background
$e^+\mu^+ + e^-\mu^-$
$\chi = 0.179$
$e^+\mu^- + e^-\mu^+$
P_T^{μ} (GeV/c)
0
100
200
300
400
4
8
12
16



CDF
ARGUS & CLEO
P_d = 0.375, P_s = 0.15
CKM
χ_d
χ_s
0.0
0.1
0.2
0.3
0.4
0.5