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SEARCH FOR B^0-$\bar{B}^0$ OSCILLATIONS AT THE CERN PROTON-ANTIPROTON COLLIDER

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We report on a search for $B^0 \leftrightarrow \bar{B}^0$ oscillations (mixing) using events with two identified muons from data collected at the CERN $\bar{p}p$ collider. In the absence of $B^0 \leftrightarrow \bar{B}^0$ oscillations, dimuons coming directly from decays of beauty–antibeauty pairs must have *opposite* signs. Like-sign dimuons are expected from events where one muon arises from beauty decay and the other from the charm decay of the associated beauty–charm cascade. Taking these processes into account, together with the contribution from charm production, the predicted ratio of like-sign to unlike-sign muon pairs is 0.26 ± 0.03. Experimentally we measure $0.42 \pm 0.07 \pm 0.03$. A natural explanation for the excess of like-sign events is the existence of a significant amount of $B^0 \leftrightarrow \bar{B}^0$ transitions. The fraction of beauty particles that produce first-generation decay muons with the opposite electric charge from that expected without mixing is deduced to be $\chi = 0.121 \pm 0.047$. Combined with the null result from searches for $B^0 \leftrightarrow \bar{B}^0$ oscillations at e^+e^- colliders, our results are consistent with transitions in the B^0_s system, as favoured theoretically.

1. Introduction. The decays of neutral kaons have so far been the unique tool for studying second-order weak interactions. Since weak interactions need not conserve flavour quantum numbers, transitions between $K^0 = (\bar{s}d)$ and $\bar{K}^0 = (\bar{d}s)$ are permitted. As is well known, the mass eigenstates are not K^0 and $\bar{K}^0$, but their linear combinations K^0_S and K^0_L. The mass difference between these states, ΔM, result in a time-dependent phase difference between the K^0_S and K^0_L wave functions and a consequent periodic variation of the K^0 and $\bar{K}^0$ components. Thus $K^0 \leftrightarrow \bar{K}^0$ oscillations are observed, with a period given by $2\pi/\Delta M$. An excellent review of the physics of the K^0 system can be found in ref. [1] [‡1].

Since the discovery of the new quark flavours, charm and beauty, it has become natural to consider the possibility of oscillations in the case of neutral D or B mesons [3]. Mixing is observable in the K^0 system only because the lifetime is comparable to the oscillation period. The decay of D^0 mesons is Cabibbo favoured, resulting in a short lifetime. It is therefore not surprising that no mixing has been observed in the D^0–$\bar{D}^0$ system [4].

The recent observation that beauty particles have relatively long lifetimes [5] suggests that oscillations may be observable in the B^0–$\bar{B}^0$ system. The degree of mixing (r) can be expressed as the probability that a B^0 oscillates into a $\bar{B}^0$ relative to the probability that it remains a B^0:

$$r = \mathrm{Prob}(B^0 \to \bar{B}^0)/\mathrm{Prob}(B^0 \to B^0)$$

$$\simeq (\Delta M/\Gamma)^2/[2 + (\Delta M/\Gamma)^2] ,$$

[‡1] A more recent review of *CP* violation phenomena is given in ref. [2].

assuming $\Delta\Gamma \ll \Delta M$, $\Delta\Gamma$ is the difference between the decay widths of the B^0_H and B^0_L states, $B^0_{B\,L} = (B^0 \pm \bar{B}^0)/\sqrt{2}$ and *CP* violation is neglected. Oscillations may occur for the two neutral meson states $B^0_d = (\bar{b}d)$ and $B^0_s(\bar{b}s)$. The B^0_H–B^0_L mass difference can be calculated according to box diagrams using the experimentally determined values of elements in the Kobayashi–Maskawa matrix [6] [‡2], which describes weak couplings between quarks of different flavours. Following Wolfenstein's parametrisation [8] [‡3]

$$V = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

$$= \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

$$+ O(\lambda^3) ,$$

where $\lambda = \sin\Theta_c = 0.23$ and Θ_c is the Cabibbo angle. Currently, $A = 1.0 \pm 0.2$ and $\rho^2 + \eta^2 < 0.65$ [8,9]. The terms V_{us} and V_{ud} determine the transition rate for $K^0 \leftrightarrow \bar{K}^0$ or equivalently the mass difference $\Delta M_s \approx |V^*_{ud} V_{us}|^2 \sim \lambda^2$. Since the term $V_{ts} \sim \lambda^2$ in the Kobayashi–Maskawa matrix is large compared to $V_{td} \sim \lambda^3$, $B^0_s \leftrightarrow \bar{B}^0_s$ oscillations are likely to be more prominent than $B^0_d \leftrightarrow \bar{B}^0_d$ oscillations. A recent calculation [10] gives $\Delta M/\Gamma(B^0_d) \leqslant 0.1$ and $\Delta M/\Gamma(B^0_s)$ in the range 1–4. The corresponding values for the degree of oscillations are $r_d \leqslant 0.005$ and r_s in the range 0.33–0.89. Hence, no significant oscillations are expected for B^0_d and substantial oscillations are predicted for B^0_s.

Experiments at e^+e^- colliders have recently placed limits on $B^0 \leftrightarrow \bar{B}^0$ oscillations. CLEO [‡4] and ARGUS [‡5] have excluded substantial oscillations in the $B^0_d \leftrightarrow \bar{B}^0_d$ system by measuring the rate of like-sign dileptons from samples of $\bar{B}B$ events on the $\Upsilon(4S)$ resonance. However, they have no sensitivity to oscillations in the $B^0_s \leftrightarrow \bar{B}^0_s$ system since the $\Upsilon(4S)$ is below the threshold for producing $\bar{B}^0_s B^0_s$ pairs. The MARK II Collaboration [14] has examined dilepton events produced in e^+e^- collisions at $\sqrt{s} = 29$ GeV. While they are in principle sensitive to $B^0_s \leftrightarrow \bar{B}^0_s$ mixing, they so far have too few events to place a significant limit on this channel.

The technique used to search for $B^0 \leftrightarrow \bar{B}^0$ oscillations in the present paper is similar to the one already applied in the e^+e^- experiments [11–14], namely it consists of looking for an excess of like-sign dimuon events. In first generation decays, $\bar{p}p \to \bar{b}b + X$ followed by $b \to \mu^-\bar{\nu} + X$ and $\bar{b} \to \mu^+\nu + X$, only unlike-sign dimuon events are produced. If oscillations occur, the $\bar{b}$ antiquark in the B^0 meson may, for example, be transformed into a b quark in the $\bar{B}^0$, resulting in a $\mu^-\mu^-$ event. Likewise, $\bar{B}^0$ mesons converting into B^0 mesons can give rise to $\mu^+\mu^+$ events. In addition, like-sign dimuon events are produced in a mix of first-and second-generation decays, for instance, $\bar{p}p \to \bar{b}b + X$ followed by $b \to \mu^-\bar{\nu}X$ and $\bar{b} \to \bar{c}X$ with $\bar{c} \to \mu^-\bar{\nu} + X$. The signature for $B^0 \leftrightarrow \bar{B}^0$ oscillations is a yield of like-sign dimuon events in excess of that expected for second-generation decays. No significant contribution to mixing is expected from the D^0–$\bar{D}^0$ system where stringent limits have already been set [4].

2. *Data sample and background calculation.*

Because of the large cross section for beauty production at the CERN $\bar{p}p$ collider [15], semi-leptonic decays of beauty particles are the dominant source of pairs of high-p_T muons ($p^{\mu}_T > 3$ GeV/*c*), where we define p_T as the component of the muon momentum transverse to the *beam direction*. We can therefore study a relatively large sample of muon pairs from beauty decays, with little $\bar{c}c$ contamination. Data were recorded during three collider runs at $\sqrt{s} = 546$ and 630 GeV with a total integrated luminosity of 692 nb^{-1}. The dimuon event selection procedure and background calculation are described in ref. [15], and only a brief summary is given here. We select a sample of 512 dimuon events with $m_{\mu\mu} > 6$ GeV/c^2 and with $p_T > 3$ GeV/*c* for each muon, excluding $Z^0 \to \mu^+\mu^-$ decays. The isolation of the muons (i.e., the absence of hadronic activity around each muon) is used to separate Drell–Yan and Υ events from

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[‡2] Ref. [6] certains a generalisation of the work of Cabibbo [7].

[‡3] For a recent review see ref. [9].

[‡4] The CLEO Collaboration reports a 90% confidence level upper limit of $r_d < 0.30$ [11]. They have recently improved this limit to $r_d < 0.18$ [12].

[‡5] The ARGUS Collaboration reports a 90% confidence level upper limit of $r_d < 0.12$ [13].

heavy flavour decays. We define $S=[\sum E_T(\mu_1)]^2+[\sum E_T(\mu_2)]^2$ where $\sum E_T(\mu)$ is the scalar sum of the transverse energy measured in calorimeter cells in a cone of $\Delta R=(\Delta\varphi^2+\Delta\eta^2)^{1/2}<0.7$ around the muon, η is the pseudo-rapidity and φ is the azimuthal angle measured in radians. We classify dimuons to be isolated when $S<9$ GeV^2. There are 98 unlike-sign and 15 like-sign events which satisfy this criterion. In the non-isolated sample there are 257 unlike-sign and 142 like-sign events. The charges of all the muons in the sample are well determined. The total background to the dimuon sample is estimated to be 132 ± 21 events, divided into 8 unlike-sign plus 8 like-sign for the isolated dimuons, and 58 unlike-sign plus 58 like-sign for the nonisolated dimuons [15].

3. *The evidence for $B^0\leftrightarrow\bar{B}^0$ oscillations.* We have determined the background subtracted ratio of the number of like-sign to unlike-sign dimuons $R=N[\pm\pm]/N[+-]$ by two methods: (i) using only the non-isolated events for which the contribution from Drell–Yan and $\Upsilon\to\mu^+\mu^-$ decays are negligible, and (ii) using all the events and subtracting the measured contribution from $\Upsilon\to\mu^+\mu^-$ [15] and the calculated number of Drell–Yan events [16]. With method (i) we obtain $R=0.42\pm0.07\pm0.03$ and with method (ii) $R=0.45\pm0.07\pm0.05$. The second error is the systematic error reflecting the uncertainty in the background subtraction.

We proceed now to an estimate of the expected value of R in the absence of flavour mixing. The rate of like-sign dimuon events from second generation decays relative to first-generation decays can be reliably calculated since it depends mainly on weak decays and measured branching ratios. We have recently made a detailed comparison between the predictions of QCD Monte Carlo programs [17] [‡6] and the measured beauty and charm decay properties [23]. The Monte Carlo's reproduce the measured properties of B meson decays: the inclusive lepton spectrum, the inclusive D and D* spectra, and the total charged particle multiplicity. For all beauty states (B) we assume the same branching ratio $\mathrm{BR}(B\to\mu^++X)=12\%$. Dimouns from $\bar{c}c$ production are also included in the Monte Carlo calculations and our measurement of the relative transverse momentum between the muons and their accompanying jets (p_T^{rel}) described in ref. [15] is consistent with the prediction that they account for about 10% of dimuons from heavy flavour decays. Also included in the Monte Carlo program are (i) decays of beauty particles into J/ψ, and (ii) higher order processes, including double $\bar{c}c$ production via gluon splitting ($g\to\bar{c}c$ or $\bar{b}b$). Double parton scattering is not included in the Monte Carlo, but it has been estimated to be insignificant provided that there are no strong correlations at the parton level.

The predicted [17–22] ratio of numbers of like-sign and unlike-sign dimuons from $\bar{b}b$ and $\bar{c}c$ production, without oscillations, is $R=N[\pm\pm]/N[+-]=0.26\pm0.03$. The predicted value for R may be written

$$R=N_s/(N_f+N)\ ,$$

where N_f is the predicted number of dimuon events passing our cuts due to two first-generation decays from $\bar{b}b$, N_s is the number due to one first plus one second-generation decay from $\bar{b}b$, and N_c is the number due to $\bar{c}c$ decays. Monte Carlo calculations show that we can neglect the small contributions due to two second-generation beauty decays and to double $\bar{c}c$ or $\bar{b}b$ production. Note that R depends only on the ratios N_s/N_f and N_c/N_f. The uncertainty on the prediction for R with no oscillations (±0.03) has been estimated by propagating the errors on the average beauty and charm muonic branching ratios [‡7] and by varying the $\bar{c}c$ contribution, N_c, by ±50% to account for the uncertainty in the parametrisation of the charm fragmentation function. The ISAJET value of $R=0.26\pm0.03$ can be compared with independent calculations [17,20] [‡8], summarized in table 1, which

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[‡6] Proton structure functions are taken from ref. [18]. Branching ratios for charm and beauty states are taken from the latest experimental measurements [19]. For nonleptonic decays of beauty states, which are mostly unmeasured, branching ratios were taken from the Eurojet program [20,21]. For both programs we have made a detailed comparison of the results with measured beauty and charm decay properties. Calculations were done using a modified version of the ISAJET Monte Carlo (version 5.21) in which the spectator particle parameters have been adjusted to be consistent with UA1 data. See ref. [22].

[‡7] The average semi-leptonic branching ratios for beauty and charm particle decays were taken from the measurements in ref. [23]: $\mathrm{BR}(B\to e)=(12\pm0.7)\%$, $\mathrm{BR}(D\to e)=(13\pm1.3)\%$.

[‡8] $R=0.25$ for no mixing, $R=0.36$ for full B_s^0 mixing and $f_s=0.2$ [24]. $R=0.25$ for no mixing $R=0.41$ for full B_s^0 mixing and $f_s=0.20$ [25]. $R=0.21$ for no mixing, $R=0.36$ for full B_s^0 mixing and $f_s=0.20$ [20].

Table 1

Predictions for R without oscillations (column 1), with oscillations for different values of f_s (columns 2,3,4) assuming full mixing in B_s^0 states only ($\chi_d = 0$, $\chi_s = 1/2$). The last column contains the predicted fraction of dimuon events due to $\bar{c}c$ decays.

Reference	No mixing $N_s(N_f+N_c)$	Maximum B_s^0 mixing			Charm fraction $N_c/(N_f+N_s+N_c)$
		$f_s = 0.10$	$f_s = 0.20$	$f_s = 0.30$	
Barger et al. [24]	0.25	0.31	0.36	0.42	0.23
Halzen et al. [25]	0.25	0.33	0.41	0.48	0.11
ISAJET [17]	0.26	0.34	0.42	0.50	0.10
EUROJET [20]	0.21	0.28	0.36	0.43	0.15

predict values for R in the range 0.21–0.25.

The possible effect of $\bar{t}t$ production has also been taken into consideration, for a top mass of 25 GeV/c^2, which is near the lowest value allowed by e^+e^- experiments [26], we would expect a $\bar{t}t$ production cross section of 13 nb corresponding to 11 like-sign and 25 unlike-sign events passing the selection criteria. If one includes these additional events, the prediction for R increases to only 0.27. The effect is even smaller for higher masses of the top quark.

Our measured value of $R(0.42 \pm 0.07 \pm 0.03)$ is larger than that expected for the case of no mixing (0.26 ± 0.03). On the other hand, predictions for full B_s^0 mixing give R in the range 0.28–0.50 depending mainly on the fraction of dimuon events due to B_s^0 decays and the contribution from $\bar{c}c$ as shown in table 1.

An experimentally accessible quantity that measures the degree of osciallations is the fraction of beauty hadrons that decay into muons of the opposite charge to that expected from first-order weak decay. This fraction is

$$\chi = \mathrm{BR}(b \to \bar{B}^0 \to B^0 \to \mu^+ + X)/\mathrm{BR}(b \to B \to \mu^\pm + X).$$

Note that the denominator includes all beauty hadrons (mesons and baryons) and is the average semimuonic branching ratio weighted by the relative probabilities to produce the different states in b quark fragmentation. We refer to χ as the fraction of "wrong-sign" decays in the sample of all beauty hadrons (mesons and baryons) where only first generation decays are considered. Given the predictions for N_f, N_s and N_c, χ is related to our measured value of R as follows.

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

For $\chi = 0$ we recover the no-mixing expression, $R = N_s/(N_f+N_c)$. Using the measurement of R, the Monte Carlo predictions for the ratio N_s/N_f and for the charm fraction $N_c/(N_f+N_s+N_c)$, we obtain a measurement of the mixing parameter χ. The dependence of χ on R and N_c is shown in fig. 1, using the predicted ratio $N_s/N_f = 0.30$. For $N_c/(N_f+N_s+N_c) = 0.10$ we find $\chi = 0.10 \pm 0.05$.

Since the muons from second generation decays have a softer p_T spectrum than those from first generation decays, we have also determined χ with a likelihood fit in which the differences in the p_T distributions for like- and unlike-sign dimuon events are taken into account. The two-dimensional p_T distributions for first- and second-generation decays of pairs of beauty particles, and decays of pairs of charm particles were determined using the ISAJET Monte Carlo program [17]. The fraction of events from $\bar{c}c$

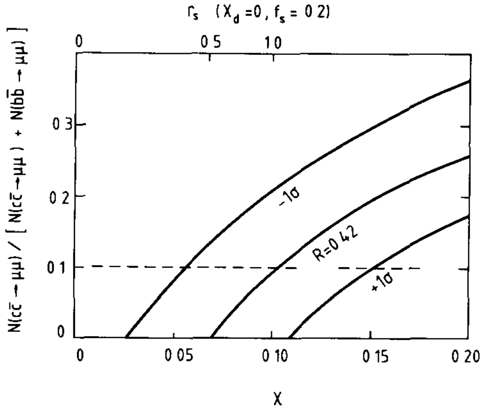

Fig. 1. Variation of χ, the fraction of wrong-sign beauty decays, as a function of the fraction of $\bar{c}c$ decays in the data sample. The curves correspond to the experimental measurement of the ratio of numbers of like-sign to unlike-sign dimuons.

was also taken from the Monte Carlo with a ±50% error based on the uncertainty in the parametrisation of the charm framentation function. The uncertainties on the measured beauty and charm muonic branching ratios [‡7] were propagated to determine the errors on the fraction of events from first- and second-generation beauty decays. The calculated background distributions were used, with an 18% error on the normalization. The likelihood curve is shown in fig. 2, giving $\chi=0.121\pm0.047$. The alternative of no mixing ($\chi=0$) is disfavoured relative to the best fit for χ with a likelihood ratio of 1.73 or 2.9 standard deviations.

The mixing parameter χ measured in this analysis is an average over all beauty states as in ref. [14]. Oscillations can only occur for the neutral meson states B_d^0 and B_s^0 and we define mixing parameters χ_d and χ_s for these mesons to be

$$\chi_{d(s)}=\mathrm{Prob}(B^0_{d(s)}\to\bar{B}^0_{d(s)})$$

$$=\frac{\mathrm{BR}(B^0_{d(s)}\to\mu^-+X)}{\mathrm{BR}(B^0_{d(s)}\to\mu^\pm+X)}$$

They are related to χ by

$$\chi=\frac{(\mathrm{BR})_d f_d\chi_d}{\langle\mathrm{BR}\rangle}+\frac{(\mathrm{BR})_s f_s\chi_s}{\langle\mathrm{BR}\rangle},$$

where $(\mathrm{BR})_{d,s}$ are the muonic branching ratios for B_d^0 and B_s^0 decays, $\langle\mathrm{BR}\rangle=\sum f_i\mathrm{BR}_i$ is the muonic branching ratio for all beauty states, i, and $f_{d(s)}$ are the fractions of beauty quarks hadronizing into $B^0_{d(s)}$ mesons. Most of these quantities are unknown. Based on measurements of the K^+/π^+ ratio at large p_T at the ISR [27], reflecting the probability that a scattered u quark picks up an $\bar{s}$ or $\bar{d}$ in the fragmentation process, we assume that $f_d=0.40$ and $f_s=0.20$. Thus, for example, taking $\chi_d=0.0$ and $\chi_s=0.5$ (maximal B_s^0 mixing) and equal semi-leptonic branching ratios for the different beauty particles, we get $\chi=0.10$, consistent with the measured value.

Our result is consistent with experiments at e^+e^- colliders, which exclude substantial mixing in the $B_d^0\leftrightarrow\bar{B}_d^0$ channel, if we assume that mixing occurs mainly in the $B_s^0\leftrightarrow\bar{B}_s^0$ system. We express all results in terms of the mixing parameters

$$r_{d(s)}=\frac{\mathrm{BR}[B^0_{d(s)}\to\mu^-+X]}{\mathrm{BR}[B^0_{d(s)}\to\mu^+X]}=\frac{\chi_{d(s)}}{[1-\chi_{d(s)}]}$$

In fig. 3 we show the 90% confidence level limits for r_d and r_s coming from ARGUS [13] and MARK II [14] as well as from our own measurement, calculated for $f_d=0.40$ and $f_s=0.20$ and equal semi-leptonic branching ratios for all beauty particles. The allowed region overlaps with the theoretical predictions $r_d\simeq0$ and $r_s=0.33$–0.89 [10].

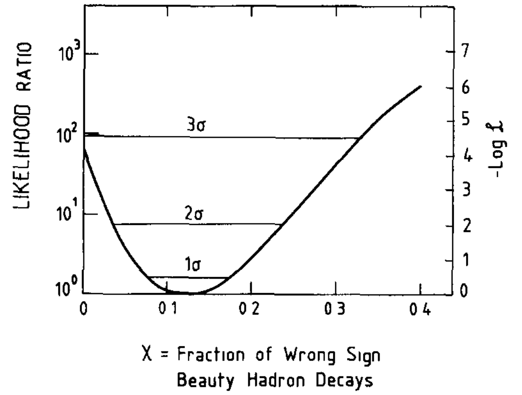

Fig. 2. Likelihood ratio as a function of χ, resulting from a fit to the p_T distributions of first- and second-generation $b\bar{b}$ decays, $c\bar{c}$ decays, and dimuon background. The righthand scale shows the logarithm of the likelihood ratio. The likelihood ratio values corresponding to 1,2 and 3 standard deviations are represented as horizontal lines.

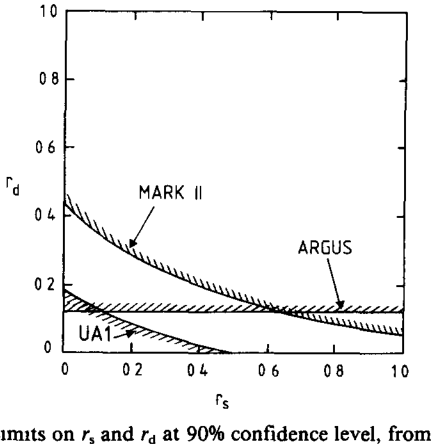

Fig. 3. Limits on r_s and r_d at 90% confidence level, from Argus, Mark II and UA1. The mixing parameters r_s and r_d are the ratios of wrong-sign to right-sign B_s^0 and B_d^0 decays, respectively. The curves for Mark II and UA1 are for $f_d=0.40$ and $f_s=0.20$, where f_d and f_s are the fractions of beauty quarks hadronizing into B_d^0 and B_s^0 mesons, respectively. We assume equal semi-leptonic branching ratios in the muon channel (12%) for all beauty states.

Finally, we can give a very rough estimate of the B_H–B_L mass difference Taking $\Gamma = 1/\tau_B$, where $\tau_B = (1\ 12 \pm 0\ 16) \times 10^{-12}$ s is the measured beauty lifetime [5], the limit $r_s > 0\ 12$ from fig 3 corresponds to a mass difference $\Delta M(B_s^0) > 3 \times 10^{-4}$ eV, to be compared with $\Delta M(K^0) = (3\ 521 \pm 0\ 014) \approx 10^{-6}$ eV

4 Conclusions We have examined the charge composition of the UA1 dimuon event sample described in ref [15] to search for $B^0 \leftrightarrow \bar{B}^0$ oscillations We determine $R = N[\pm\pm]/N[+-]$ by two methods which give $R = 0\ 42 \pm 0\ 07 \pm 0\ 03$ and $R = 0\ 45 \pm 0\ 07 \pm 0\ 05$ We find an excess of like-sign dimuon events compared to expectations for production and cascade decays of beauty particles with no oscillations Predictions without oscillations give R between 0 21 and 0 26 A natural explanation for the large fraction of like-sign dimuon events is a significant amount of $B^0 \leftrightarrow \bar{B}^0$ oscillations The fraction of wrong-sign b-quark decays (averaged over all b-hadron states) is $\chi = 0\ 121 \pm 0\ 047$ The alternative of no mixing ($\chi = 0$) is disfavoured with a likelihood ratio of 1 73 or 2 9 standard deviations. The parameter χ is averaged over the unknown beauty particle composition of jets at the collider

Our result is compatible with existing limits on $B^0 \leftrightarrow \bar{B}^0$ oscillations coming from experiments at e^-e^- colliders provided the oscillations occur mainly in the B_s^0 system, as favoured theoretically The limit on the ratio of wrong-sign to right-sign decays for B_s^0, $r_s > 0\ 12$, corresponds to a mass difference, $\Delta M(B_s^0) > 3 \times 10^{-4}$ eV

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