Evidence for an Anomalous Like-Sign Dimuon Charge Asymmetry

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We measure the charge asymmetry $A \equiv (N^{++} - N^{--})/(N^{++} + N^{--})$ of like-sign dimuon events in 6.1 fb^{-1} of $p\bar{p}$ collisions recorded with the D0 detector at a center-of-mass energy $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron collider. From A we extract the like-sign dimuon charge asymmetry in semileptonic b-hadron decays: $A^b_{\rm sl} = -0.009\,57 \pm 0.002\,51(\text{stat}) \pm 0.001\,46(\text{sys})$. It differs by 3.2 standard deviations from the standard model prediction $A^b_{\rm sl}(\text{SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$, and provides first evidence of anomalous CP violation in the mixing of neutral B mesons.

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Studies of particle production and decay under the reversal of discrete symmetries [charge conjugation (C), parity (P) and time reversal] have yielded considerable insight into the structure of theories that describe high energy phenomena. The violation of these discrete symmetries has only been observed in the weak interaction. Of particular interest is the observation of CP violation [1], a phenomenon well established in the K^0 and B^0_d systems, but not in the B^0_s system where the effects of CP violation are expected to be small in the standard model (SM) [2]. A review of the experimental results and of the theoretical framework for describing CP violation in the mixing of $B^0_q \leftrightarrow \bar{B}^0_q$ ($q = d, s$) mesons [3] can be found in Ref. [4]. At the Fermilab Tevatron collider, b quarks are produced mainly in $b\bar{b}$ pairs. In like-sign dimuon events, one muon can arise from direct semileptonic decay, e.g., $b \to \mu^- X$, of a $\bar{B}^0_q$ or B^- meson, and the other from a $B^0_q \leftrightarrow \bar{B}^0_q$ oscillation followed, in this example, by a semileptonic decay of the $\bar{B}^0_q$ meson, $B^0_q \to \bar{B}^0_q \to \mu^- X$. Extensions of the SM containing additional contributions to the Feynman "box" diagrams responsible for B^0_q mixing may enhance CP violation in mixing [5–9]. The violation of CP symmetry is a necessary condition for baryogenesis, the process thought to be responsible for the matter-antimatter asymmetry of the Universe [10]. However, the observed level of CP violation in the K^0 and B^0_d systems is not sufficient to accommodate this asymmetry, suggesting the presence of additional sources of CP violation beyond the SM [11].

This Letter and a more detailed article [12] present a measurement of the charge asymmetry for like-sign muon pairs. The data, corresponding to an integrated luminosity of 6.1 fb^{-1}, were recorded with the D0 detector [13] at the Fermilab Tevatron proton-antiproton ($p\bar{p}$) collider, operating at a center-of-mass energy of 1.96 TeV. The D0 experiment is well suited to the investigation of the small effects of CP violation because the periodic reversal of the D0 solenoid and toroid magnetic field polarities results in a cancellation of most detector-related charge asymmetries. In addition, the $p\bar{p}$ initial state is CP invariant, and the high center-of-mass energy provides access to mass states beyond the reach of the B factories running at $\sqrt{s} = M[\Upsilon(4S)] < 2M(B_s)$.

The like-sign dimuon charge asymmetry A is defined as

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}, \quad (1)$$

where N^{++} and N^{--} represent the number of events in which the two muons with the highest p_T, defined as the momentum component transverse to the beam axis, satisfying the kinematic selections described below, have the same positive or negative charges. After removing contributions from background and from remaining detector effects, any residual asymmetry is assumed to arise solely from the mixing of B_q^0 ($q = d, s$) mesons (via $B_q^0 \leftrightarrow \bar{B}_q^0$ oscillations) that later decay semileptonically. This corrected asymmetry $A_{\rm sl}^b$ is defined as

$$A_{\rm sl}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}, \quad (2)$$

where N_b^{++} and N_b^{--} represent the number of events containing two b-quark hadrons decaying semileptonically into two positive or two negative muons, respectively. Assuming CPT invariance, each neutral B_q^0 meson contributes a term to this asymmetry

$$A_{\rm sl}^b = \beta_d a_{\rm sl}^d + \beta_s a_{\rm sl}^s, \quad (3)$$

with

$$a_{\rm sl}^q = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q, \quad (4)$$

where ϕ_q is the CP-violating phase, and ΔM_q and $\Delta\Gamma_q$ are the mass and width differences between the eigenstates of the propagation matrices of the neutral B_q^0 mesons. The values of $\beta_d = 0.506 \pm 0.043$ and $\beta_s = 0.494 \pm 0.043$ are taken from previous measurements [4]. The SM predicts [2,12]:

$$A_{\rm sl}^b({\rm SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}, \quad (5)$$

and an experimental result significantly different from this expectation would therefore be indicative of the presence of physics beyond the SM.

The main background for these measurements arises from events with at least one muon from kaon or pion decay or from the sequential decay of b quarks, $\bar{b} \to \bar{c} \to \mu^- X$. The most important background asymmetry arises from the fact that K^+ and K^- mesons interact differently with the material of the detector, and thus their decay rates into positive and negative muons are not identical.

The asymmetry $A_{\rm sl}^b$ can also be obtained from the measurement of the charge asymmetry $a_{\rm sl}^b$ in semileptonic decays of b quarks to muons of "wrong" charge, i.e., a muon of charge opposite to the sign of the charge of the original b quark, induced through $B_q^0 \leftrightarrow \bar{B}_q^0$ oscillations [3]:

$$a_{\rm sl}^b \equiv \frac{\Gamma(\bar{B} \to B \to \mu^+ X) - \Gamma(B \to \bar{B} \to \mu^- X)}{\Gamma(\bar{B} \to B \to \mu^+ X) + \Gamma(B \to \bar{B} \to \mu^- X)} = A_{\rm sl}^b. \quad (6)$$

The asymmetry $a_{\rm sl}^b$ can be measured from the inclusive muon charge asymmetry

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-}, \quad (7)$$

where n^+ and n^- correspond to the number of positive and negative muons satisfying the kinematic selections. For the asymmetry a, the signal comes from B_q^0 mixing, followed by the semileptonic decay. In addition to the background already considered for A, the direct production of c quark pairs followed by their semileptonic decays constitutes an additional source of muons contributing to a.

We define all muons from weak decays of b and c quarks as signal, and use the branching fractions and momentum spectra of particles in the decay chains that produce such muons to determine the dilution of the $A_{\rm sl}^b$ asymmetry in the observed asymmetry of the signal component. The dilutions, defined as the coefficients which relate the signal asymmetries to $A_{\rm sl}^b$, are 0.070 ± 0.006 and 0.486 ± 0.032 for the inclusive muon and for the like-sign dimuon signal asymmetries, respectively. The difference in the dilution coefficients arises because the presence of the second muon with the same charge preferentially selects those events that contain a B_s^0 or B_d^0 that has oscillated. Therefore, the asymmetry A is far more sensitive to $A_{\rm sl}^b$ than a.

We measure the asymmetries A and a in the like-sign dimuon and inclusive muon data, respectively. These have different contributions from background processes and from detector asymmetries, which are measured directly in data as a function of the muon transverse momenta, and are used to correct the measured asymmetries. After applying all corrections, the only expected source of residual asymmetry in both the inclusive muon and dimuon samples is the asymmetry $A_{\rm sl}^b$. Given the difference in sensitivity between A and a and the fact that the asymmetry a is dominated by detector effects, we do not take a weighted average of the two determinations of $A_{\rm sl}^b$. Instead, we use the measurement of a to constrain the background contributions to A, thereby achieving a further reduction of the total uncertainty on $A_{\rm sl}^b$. This is possible because the detector effects and their related systematic uncertainties largely cancel in an appropriately-chosen linear combination of A and a.

The inclusive muon and like-sign dimuon samples are obtained from data collected with single and dimuon triggers, respectively. Charged particles with transverse momentum in the range $1.5 < p_T < 25$ GeV and with pseudorapidity $|\eta| < 2.2$ [14] are considered as muon candidates. The upper limit on p_T is applied to suppress the contribution of muons from W and Z boson decays. To ensure that the muon candidate passes through the detector, including all three layers of the muon system, we require either $p_T > 4.2$ GeV or a longitudinal momentum component $|p_z| > 6.4$ GeV. Muon candidates are selected by matching central tracks with a segment reconstructed in the muon system and by applying tight quality requirements aimed at reducing false matching and background from cosmic rays and beam halo. The transverse impact parameter of the muon track relative to the reconstructed $p\bar{p}$ interaction vertex must be smaller than 0.3 cm, with the longitudinal distance from the point of closest approach to this vertex smaller than 0.5 cm. Strict quality requirements are also applied to the tracks and to the reconstructed $p\bar{p}$ interaction vertex. The inclusive muon sample contains all muons passing the selection requirements. The two muons in the like-sign dimuon sample are required to have an invariant mass greater than 2.8 GeV to minimize the number of events in which both muon candidates originate from the same b quark.

Muon candidates from decays of charged kaons and pions and from incomplete absorption of hadrons that penetrate the calorimeter and reach the muon detectors (“punch-through”), as well as false matches of central tracks to segments reconstructed in the outer muon detector, are considered as detector backgrounds. We use data to measure the fraction of each source of background in both the dimuon and inclusive muon samples, and the corresponding asymmetries. Data are also used to determine the intrinsic charge-detection asymmetry of the D0 detector. Since the interaction length of the K^+ meson is greater than that of the K^- meson [4], kaons provide a positive contribution to the asymmetries A and a. The asymmetries for other background sources (pions, protons, and falsely reconstructed tracks) are at least a factor of 10 smaller.

The asymmetry for kaon tracks that are eventually misidentified as muons ($K \to \mu$ tracks) is measured in data using $K^{*0} \to K^+\pi^-$, $\bar{K}^{*0} \to K^-\pi^+$, and $\phi \to K^+K^-$ decays. For both channels we select muon candidates from the entire inclusive muon sample and examine mass distributions separately for events with $K^+ \to \mu^+$ and $K^- \to \mu^-$ tracks, extracting the sum and the difference in the number of K^{*0} or ϕ meson decays containing positive or negative $K \to \mu$ tracks. The distribution of this difference as a function of the invariant mass of the K^{*0} candidates is shown in Fig. 1. The resulting asymmetry is corrected using simulations [12] for the fraction of kaons ($\approx 6\%$) that decay prior to being reconstructed. Similarly, the asymmetries for pion or proton tracks misidentified as muons are measured using samples of $K_S \to \pi^+\pi^-$ and $\Lambda \to p\pi^-$ decays, respectively.

The fraction of muons from kaons is also determined from the $K^{*0} \to K^+\pi^-$ sample. The fraction of all kaons arising from K^{*0} decay is taken from the observed $K^{*\pm} \to K_S\pi^\pm$ decays using the assumption of isospin invariance, which is validated in data [4]. The probability of identifying the associated $\pi^\pm$ in the K^{*0} decay is taken to be the same as in $K^{*\pm}$, as is confirmed by simulation. The fractions of pions and protons associated with identified muons, relative to the fraction of muons from kaons, are estimated using the decays $K_S \to \pi^+\pi^-$, $\phi \to K^+K^-$, and $\Lambda \to p\pi^-$, and the spectra and multiplicities of pions, kaons, and protons from simulation.

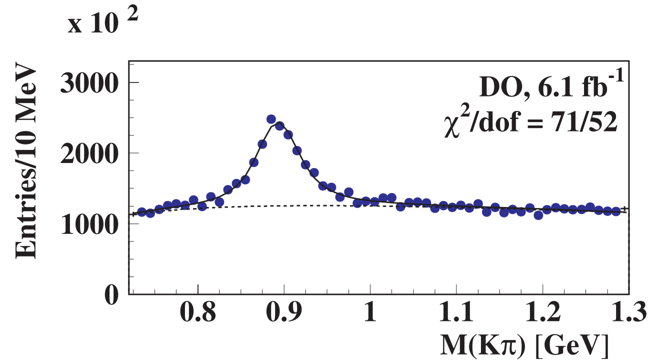

FIG. 1 (color online). The difference in the number of events for the $K^+\pi^-$ and $K^-\pi^+$ mass distributions of K^{*0} candidates in the inclusive muon sample. The solid line represents the result of the fit, while the dashed line shows the background contribution.

After subtracting the muons originating from kaons, pions, and protons, we find the fraction of muons in the inclusive muon sample from prompt sources constituting the signal sample (heavy flavor) to be $0.581 \pm 0.014(\text{stat}) \pm 0.039(\text{syst})$. The signal fraction arising from prompt sources for the like-sign dimuon sample, after subtracting the contribution from events where one or both muons are background, is $0.665 \pm 0.016(\text{stat}) \pm 0.033(\text{syst})$.

The reversal of both solenoid and toroid magnet polarities suppresses many detector effects, reducing thereby any charge asymmetry introduced by track reconstruction and muon identification considerably [15]. The small residual reconstruction asymmetry is measured using a sample of $J/\psi \to \mu^+\mu^-$ decays reconstructed from two central detector tracks, with at least one matching a track segment in the muon detector. This measurement is performed as a function of the muon p_T and indicates a residual detector asymmetry of order 10^{-3}.

The uncorrected asymmetries a and A are obtained by counting the number of events of each charge in the inclusive muon and like-sign dimuon samples, respectively. There are 1.495×10^9 muons in the inclusive muon sample and 3.731×10^6 events in the like-sign dimuon sample. The uncorrected asymmetries are

$$a = +0.009\,55 \pm 0.000\,03(\text{stat}), \tag{8}$$

$$A = +0.005\,64 \pm 0.000\,53(\text{stat}). \tag{9}$$

In comparison, the dominant contribution to A from background is due to kaon decay and has the value $0.008\,28 \pm 0.000\,35(\text{stat})$. After correcting for background and for the dilutions of the A^b_{sl} asymmetry in the observed asymmetries of the signal component, we obtain

TABLE I. Sources of uncertainty on A_{sl}^b in Eqs. (10), (11), and (13). The first eight rows correspond to statistical uncertainties and the next three rows to systematic uncertainties.

Source	$\delta(A_{sl}^b)$ (10)	$\delta(A_{sl}^b)$ (11)	$\delta(A_{sl}^b)$ (13)
A or a (stat)	0.000 66	0.001 59	0.001 79
K fraction (stat)	0.002 22	0.001 23	0.001 40
π fraction	0.002 34	0.000 38	0.000 10
p fraction	0.003 01	0.000 44	0.000 11
K asymmetry	0.004 10	0.000 76	0.000 61
π asymmetry	0.006 99	0.000 86	0.000 35
p asymmetry	0.004 78	0.000 54	0.000 01
Detector asymmetry	0.004 05	0.001 05	0.000 77
K fraction (syst)	0.021 37	0.003 00	0.001 28
π, K, p multiplicity	0.000 98	0.000 25	0.000 18
A_{sl}^b dilution	0.000 80	0.000 46	0.000 68
Total statistical	0.011 18	0.002 66	0.002 51
Total systematic	0.021 40	0.003 05	0.001 46
Total	0.024 15	0.004 05	0.002 90

$$A_{sl}^b = +0.0094 \pm 0.0112(\text{stat}) \pm 0.0214(\text{syst}) \quad (10)$$

from the inclusive muon sample and

$$A_{sl}^b = -0.007\,36 \pm 0.002\,66(\text{stat}) \pm 0.003\,05(\text{syst}) \quad (11)$$

from the like-sign dimuon sample. Since the same background processes contribute to the uncorrected asymmetries a and A, their uncertainties are strongly correlated. We take advantage of this correlation to obtain a single optimized value of A_{sl}^b with higher precision, by using a linear combination of the uncorrected asymmetries

$$A' \equiv A - \alpha a. \quad (12)$$

We scan the coefficient α in order to minimize the total uncertainty on the value of A_{sl}^b, which occurs when $\alpha = 0.959$. The corresponding final result for the asymmetry A_{sl}^b is

$$A_{sl}^b = -0.009\,57 \pm 0.002\,51(\text{stat}) \pm 0.001\,46(\text{syst}). \quad (13)$$

It differs by 3.2 standard deviations from the SM prediction for A_{sl}^b of Eq. (5). The contributions to the total uncertainty of A_{sl}^b in Eqs. (10), (11), and (13) are listed in Table I, and the result in Eq. (13) is dominated by statistical uncertainties.

Several consistency checks are performed by dividing the data into smaller samples using additional selections based on data taking periods, muon and track quality requirements, and changing the requirements on impact parameter, transverse momentum, polar angle, and rapidity of the muons. The resulting variations of A_{sl}^b are statistically consistent with the result of Eq. (13), even if the individual values of the uncorrected asymmetries A and a vary widely between the different samples due to changes in the background contributions. Both the size and the dependence on the muon momentum of the asymmetry a, which is dominated by background, are reproduced correctly through measurements of the background fractions and asymmetries. Similarly, the dependence of the like-sign dimuon asymmetry on the dimuon invariant mass observed in data, as shown in Fig. 2, is reproduced by expectations when A_{sl}^b is fixed to its measured value, while there are significant discrepancies if $A_{sl}^b = 0$ is assumed.

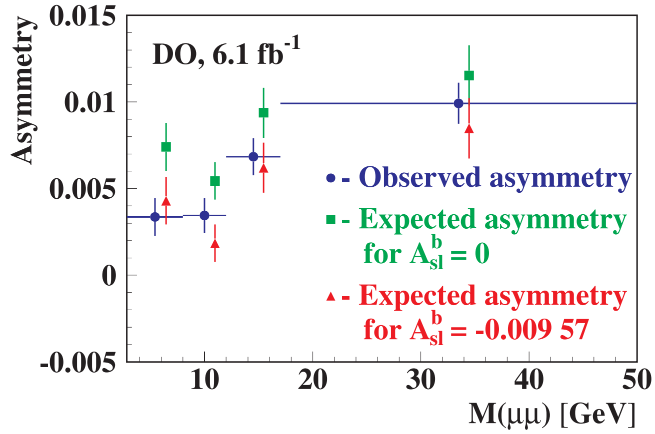

FIG. 2 (color online). The observed and expected like-sign dimuon charge asymmetry A as a function of dimuon invariant mass. The expected asymmetry is shown for $A_{sl}^b = 0$ and $A_{sl}^b = -0.009\,57$.

The measured value of A_{sl}^b places a constraint on the charge asymmetries in semileptonic decays of B_d^0 and B_s^0 mesons and on the CP-violating phases of the B_d^0 and B_s^0 mixing matrices, as given by Eqs. (3) and (4). Figure 3 presents our measurement of A_{sl}^b in the a_{sl}^d-a_{sl}^s plane, together with direct measurements of a_{sl}^d from the B-factories [16–18] and of our independent measurement of a_{sl}^s in

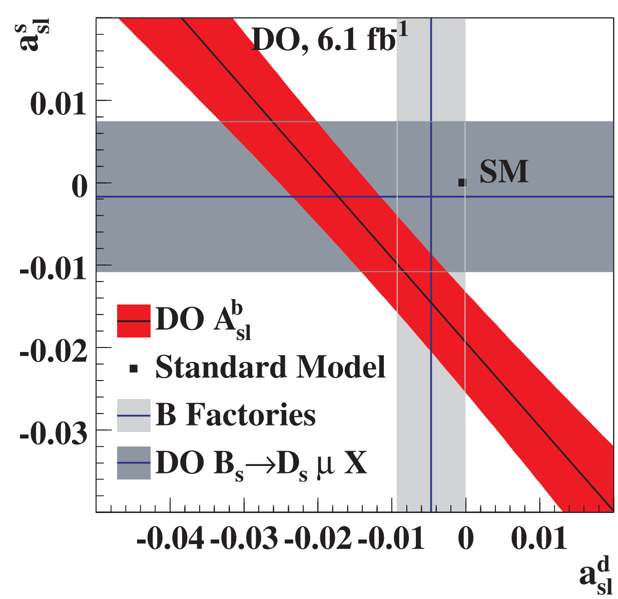

FIG. 3 (color online). Comparison of A_{sl}^b in data with the SM prediction for a_{sl}^d and a_{sl}^s. Also shown are other measurements of $a_{sl}^d = -0.0047 \pm 0.0046$ [16–18] and $a_{sl}^s = -0.0017 \pm 0.0091$ [19]. The bands represent the ± 1 standard deviation uncertainties on each measurement.

$B_s^0 \to D_s \mu X$ decays [19]. Additional comparisons and combinations of these results with previous measurements sensitive to the same physics effect are given in Ref. [12].

In conclusion, we have measured the like-sign dimuon charge asymmetry $A_{\rm sl}^b$ of semileptonic b-hadron decays:

$$A_{\rm sl}^b = -0.009\,57 \pm 0.002\,51(\text{stat}) \pm 0.001\,46(\text{syst}). \quad (14)$$

This result is consistent with our previous measurement [15] obtained with 1 fb^{-1} and supersedes it. The asymmetry disagrees with the prediction of the SM by 3.2 standard deviations. This is the first evidence for anomalous *CP* violation in the mixing of neutral *B* mesons.

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