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Evidence for an anomalous like-sign dimuon charge asymmetry

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The DØ Collaboration has recently measured the charge asymmetry of same-sign dimuon events in 6.1 fb^{-1} of data collected in $p\bar{p}$ collisions at the Fermilab Tevatron collider. This allows the extraction of the same-sign dimuon charge asymmetry in semileptonic b-hadron decays, which is predicted to be extremely small in the standard model. The result is found to differ by 3.2 standard deviations from the standard model value, providing the first evidence for anomalous CP-violation in the mixing of neutral B mesons. The analysis, and the method used to extract the result are described in detail.

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1. Introduction

At the Fermilab Tevatron collider, the overwhelming majority of b quarks are produced in $b\bar{b}$ pairs. Most b ($\bar{b}$) quarks hadronize into $\bar{B}$ (B) mesons, of which a small fraction decays semileptonically to $\mu^- + X$ ($\mu^+ + X$). However, in case of neutral $\bar{B}$ (B) mesons, the meson's oscillation can lead to a "wrong charge" decay, e.g. $\bar{B} \to B \to \mu^+ + X$. The CP-asymmetry in "wrong charge" muons from decays of oscillated B mesons can then be defined [1]:

$$a^b_{sl} = \frac{\Gamma(\bar{B} \to \mu^+ X) - \Gamma(B \to \mu^- X)}{\Gamma(B \to \mu^+ X) + \Gamma(B \to \mu^- X)} = A^b_{sl}, \tag{1.1}$$

where

$$A^b_{sl} = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}. \tag{1.2}$$

Here N_b^{++} (N_b^{--}) is the number of dimuon events with two positive (negative) muons produced from semileptonic b-hadron decays.

This asymmetry can be extracted in multiple ways. A direct method is to measure the asymmetry in time-dependent, tagged, exclusive B-meson decays, as was recently done for B_s mesons by the DØ collaboration [2] for example. Another, less direct method consists in measuring the charge asymmetry in single muon or same-sign dimuon events. This allows the use of much larger statistics, at the cost of having to determine the contribution of other sources of muons to the asymmetry. The recent DØ measurement [3, 4] using this method is described in this talk.

The Fermilab Tevatron Collider is in a unique position to study this asymmetry: it benefits from a CP-invariant initial state ($p\bar{p}$), and a substantial contribution from B_s mesons. Indeed, using the previously measured production fractions for the different types of B mesons, together with their mixing properties ($\Delta m_q, \Delta\Gamma_q$ with $q = d, s$) we have:

$$A^b_{sl} = (0.506 \pm 0.043) a^d_{sl} + (0.494 \pm 0.043) a^s_{sl}, \tag{1.3}$$

where a^d_{sl} and a^s_{sl} are the flavor-specific asymmetries for B_d and B_s mesons respectively. In terms of the CP-violating mixing phase these can be expressed as

$$a^q_{sl} = \frac{|\Gamma^{12}_q|}{|M^{12}_q|} \sin\phi_q = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q. \tag{1.4}$$

In the standard model (SM), A^b_{sl} is predicted to be very small [5]:

$$A^b_{sl}(SM) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}. \tag{1.5}$$

2. Measurement Strategy and Dataset

The measurement strategy is composed of four main steps:

1. Measure both raw single and same-sign dimuon asymmetries:

$$a = \frac{n^+ - n^-}{n^+ - n^-}, \text{and } A = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}, \tag{2.1}$$

where n^+ and N^{++} (n^- and N^{--}) are the number of events with one and two positive (negative) muons, respectively. Both of these have contributions from $a^b_{sl} (= A^b_{sl})$, other processes with prompt muons[1], and detector-related backgrounds.

2. The (non-prompt) detector and reconstruction-related backgrounds are determined. This is done with very little input from simulation.

3. The fraction of prompt single- and same-sign dimuons originating from mixed B-meson decays is determined.

4. The different signal and (heavily correlated) background contents of the single and same-sign dimuon samples is exploited to minimize the uncertainty on A^b_{sl}.

The data sample was collected with the DØ detector at the Fermilab Tevatron collider. DØ is a modern multipurpose collider detector [6], whose design offers one major advantage for this measurement: it has both a central solenoid and a toroidal magnet system in the muon system, and (roughly) bi-weekly polarity changes ensure that approximately equal datasets are collected in each possible polarity combination. This leads to a first-order cancellation of most detector-related asymmetries.

The data used in this analysis were collected between April 2002 and August 2009, corresponding to 6.1 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. From this data, two samples were selected:

- **Single muon sample:** A "good" muon candidate, for which the track segments reconstructed in the central tracker and muon system match well, is required, with pseudorapidity $|\eta| < 2.2$ and transverse[2] momentum $1.5 < p^\mu_T < 25$ GeV (where the upper cut is used to suppress contributions from weak boson decays). If $p_T < 4.2$ GeV, $p_z > 6.4$ GeV is imposed to ensure the muon has sufficient momentum to go through the toroidal magnets. Finally, the muon's transverse impact parameter relative to the closest primary vertex must be < 0.3 cm, and the longitudinal distance from the point of closest approach to this vertex must be < 0.5 cm.

- **Dimuon sample:** Two muons satisfying all the single muon selection criteria must be present in the event. These must match the same primary vertex, and, to suppress muons originating from sequential decays from the same B-meson, their invariant mass must satisfy $m_{\mu\mu} > 2.8$ GeV.

3. Raw Asymmetries

The raw asymmetries are:

$$a = \frac{n^+ - n^-}{n^+ - n^-} = (+0.955 \pm 0.003)\%, \tag{3.1}$$

[1]Here "prompt" denotes any muon produced in decays of particles with lifetimes short enough that the vast majority of the decays happen inside the beampipe.

[2]Transverse denotes the direction perpendicular to the beam axis, which is the z axis in the DØ coordinate system.

from 1.5×10^9 single muon events, and

$$A = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = (+0.564 \pm 0.053)\%, \tag{3.2}$$

from 3.7×10^6 same-sign dimuon events. These can be expressed as

$$a = kA^b_{sl} + a_{bkg}, \text{ and } A = KA^b_{sl} + A_{bkg}, \tag{3.3}$$

with a_{bkg} and A_{bkg} representing the contributions from detector and reconstruction-related ("non-prompt") backgrounds to the single and dimuon asymmetries respectively, and k and K the dilution factors due to other sources of prompt muons in both samples.

4. Detector and Reconstruction-Related Backgrounds

Various sources contribute to the detector and reconstruction-related backgrounds, so that these can be written as:

$$a_{bkg} = f_K a_K + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta, \; A_{bkg} = F_K A_K + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta, \tag{4.1}$$

where f_K, f_π, f_p and F_K, F_π, F_p are the contributions from kaons, pions and protons[3] identified as muons in the single and dimuon samples, respectively. a_K, a_π, a_p and A_K, A_π, A_p are the corresponding reconstructed charge asymmetries, $f_{bkg} = f_K + f_\pi + f_p$, $F_{bkg} = F_K + F_\pi + F_p$, and δ and Δ are the prompt muon charge reconstruction asymmetries in the single and dimuon samples. In the dimuon part of Eq.4.1, only terms linear in the asymmetries were kept.

4.1 Kaon Contribution

The dominant contributions to the background terms arise from the kaon terms. This is due to the fact that the detector is made of matter, and the interaction cross-sections of K^+ and K^- with matter are very different. The underlying reason is that for K^+ there is no equivalent to the hyperon-producing reaction $K^- N \to Y\pi$. This leads to a significant positive asymmetry from kaon decaying in flight or punching through the calorimeter. To eliminate uncertainties from material modeling in the simulation, this asymmetry is measured directly in data in multiple bins of muon candidate (i.e. kaon) p_T.

Kaons are tagged in the single muon sample by reconstructing $\phi(1020) \to K^+K^-$ and $K^{*0} \to K^+\pi^-$ decays from the combination of the muon candidate with another track. The yield for K^- is then subtracted from that for K^+, and since the results agree for the ϕ and K^{*0} channels, they are combined. Figure 1 shows both the sum (top) and (difference) of positive and negative kaons from ϕ decays misidentified as muons for the bin $4.2 < p^\mu_T < 7$ GeV, and Fig. 2 shows the kaon asymmetry a_K for the different muon p_T bins.

The number of kaons contributing to the asymmetry is also determined using $K^{*0} \to K^+\pi^-$ decays. From $f_{K^{*0}}$ and $F_{K^{*0}}$, the contributions of kaons from the decays of K^{*0}-mesons to the single and dimuon samples, the overall contribution from kaons can be extracted using

$$f_K = \frac{N(K_S)}{N(K^{*+} \to K_S\pi^+)} f_{K^{*0}}, \text{ and } F_K = \frac{N(K_S)}{N(K^{*+} \to K_S\pi^+)} F_{K^{*0}}. \tag{4.2}$$

[3] The proton category also includes fake tracks.

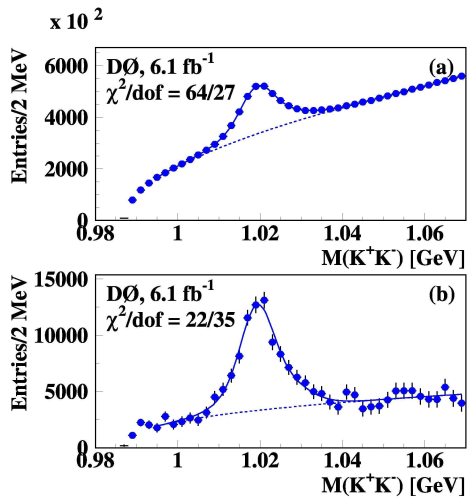

Figure 1: Reconstructed $\phi(1020) \to K^+K^-$ decays where one of the kaons is misidentified as a muon for $4.2 < p_T^\mu < 7$ GeV: both the sum (top) and difference (bottom) of positive and negative misidentified kaons are shown.

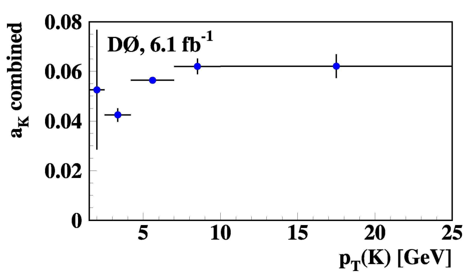

Figure 2: Charge asymmetry for kaons misidentified as muons in five muon p_T bins as determined from $\phi(1020) \to K^+K^-$ and $K^{*0} \to K^+\pi^-$ decays.

Here $N(K_S)$ is the number of reconstructed K_S mesons and $N(K^{*+} \to K_S\pi^+)$ the number of these reconstructed to originate from K^{*+}-meson decays. Equation 4.2 relies on isospin invariance, and simulation is used to confirm that the pion reconstruction efficiency is the same for K^{*+} and K^{*0}-meson decays once the K_S or K^+-meson has been reconstructed.

The uncertainty on the number of kaons contributing to the single and dimuon samples is the dominant systematic uncertainty in this measurement. The uncertainties on the number of K^* mesons as extracted from the fit, and the validity of the assumption of isospin invariance are correlated between the single and dimuon samples, whereas additional uncertainties on F_K-only come from the background parameterizations in the single and dimuon samples, and a potential difference in the fraction of kaons from K^{*0} between the two samples.

4.2 Background Asymmetries

The pion and proton reconstruction asymmetries a_π, a_p are measured in data using $K_S \to \pi\pi$ and $\Lambda \to p\pi$ decays, and, as for the kaon asymmetry, are measured in muon p_T bins. The asym-

$1-f_{bkg}$	f_K	f_π	f_p
$(58.1\pm1.4)\%$	$(15.5\pm0.2)\%$	$(25.9\pm1.4)\%$	$(0.7\pm0.2)\%$
	$a_K f_K$	$a_\pi f_\pi$	$a_p f_p$
	$(+0.854\pm0.018)\%$	$(+0.095\pm0.027)\%$	$(+0.012\pm0.022)\%$
	$A_K F_K$	$A_\pi F_\pi$	$A_p F_p$
	$(+0.828\pm0.035)\%$	$(+0.095\pm0.025)\%$	$(+0.000\pm0.021)\%$

Table 1: Summary of the background contributions to the asymmetries. Only statistical uncertainties are given.

metries in the single muon sample, integrated over muon p_T are: $a_K = +0.0551\pm0.0011$, $a_\pi = +0.0025\pm0.0010$, and $a_p = +0.023\pm0.028$.

The values of $f_\pi, f_p, F_\pi,$ and F_p are derived from f_K and F_K together with n_π/n_K and n_p/n_K, where n_f denotes the number of particles of type f per event, using simulation. The corresponding uncertainties are evaluated from past measurements and a check on n_K in data. These numbers are adjusted for the different probabilities for pions, kaons and protons to be reconstructed as a muon, as determined from ϕ, K_S, and Λ decays.

The asymmetries in the dimuon sample are then calculated taking into account the slightly different muon p_T distributions through

$$F_K A_K = \sum_{i=0}^{4} F_\mu^i F_K^i a_K^i, \tag{4.3}$$

where the sum runs over the five muon p_T bins. Equivalent equations are used for the asymmetries A_π and A_p. The background contributions to the asymmetries are summarized in Table 1. Results from simulation, which are not used in the analysis itself, are very similar.

4.3 Muon Charge Reconstruction Asymmetry

The regular reversal of magnet polarities suppresses the asymmetry in prompt muon charge reconstruction substantially. The residual asymmetry is measured in data using $J/\psi \to \mu\mu$ candidates in dimuon and muon-plus-track events. An example is given in Fig. 3. The results are $\delta = (-0.076\pm0.028)\%$ and $\Delta = (-0.068\pm0.023)\%$.

5. Dilution Factors

Equation 3.3 can be rewritten as

$$a - a_{bkg} = kA_{sl}^b, \text{ and } A - A_{bkg} = KA_{sl}^b. \tag{5.1}$$

The dilution factors k and K are due to multiple processes contributing to the single- and same-sign dimuon samples after background subtraction. These include not only direct $b \to \mu^- X$ decays (with or without B-meson oscillation), but also sequential $b \to c \to \mu^+ X$ decays and a few other processes. The dilution factors are determined from simulation of heavy flavor decays, with uncertainties arising from our knowledge of these decays. The results are

$$k = 0.041\pm0.003, \text{ and } K = 0.342\pm0.023. \tag{5.2}$$

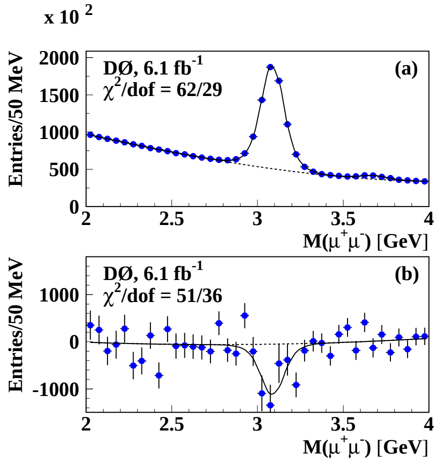

Figure 3: Example of data samples used to determine the muon charge reconstruction asymmetry: dimuon mass for $[(\mu^+ + \text{track}) + (\mu^- + \text{track})]$ (top) and $[(\mu^+ + \text{track}) - (\mu^- + \text{track})]$ (bottom) candidates in the bin 4.2 GeV $< p_T^\mu <$ 7 GeV.

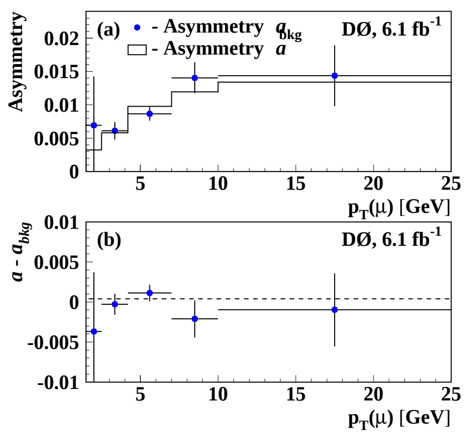

Figure 4: Observed and expected asymmetries (top) and their difference (bottom) in the single muon sample in bins of muon p_T. In the top plot, the histogram, wth negligible uncertainties, represents the observation, and the points the expectation from the background evaluation.

6. Results

The same-sign dimuon sample, where the dimuon requirement acts as a simple initial-flavor tag, is much more sensitive to A_{sl}^b ($K \gg k$), whereas the single muon sample, with its limited sensitivity, can be used to test the background determination. The result of this test is shown in Fig. 4 in bins of muon p_T, and shows excellent agreement between the expectation from the background evaluation and the data. This is an important, non-trivial validation of the background determination procedure.

Since there is significant correlation between the systematic uncertainties on the background

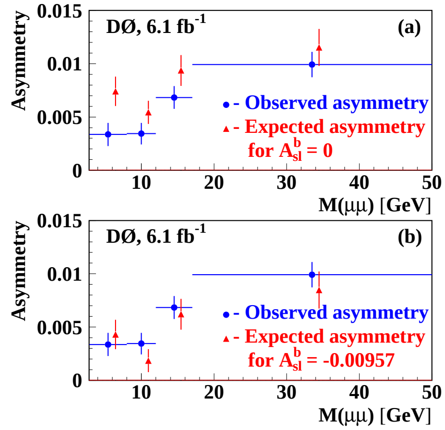

Figure 5: Observed and expected asymmetries for $A_{sl}^b = 0$ (top) and $A_{sl}^b = -0.957\%$ in the same-sign dimuon sample in bins of dimuon mass.

evaluation in the single- and dimuon channels, and the single muon channel is background dominated, it can be used to reduce the background asymmetry uncertainty in the dimuon channel. To that effect, a new asymmetry is defined:

$$A' = A - \alpha a = (K - \alpha k)A_{sl}^b + (A_{bkg} - \alpha a_{bkg}). \tag{6.1}$$

The factor α can be chosen to minimize the uncertainty on the extracted value of A_{sl}^b. Since the backgrounds are highly correlated, its optimal value is expected to be close to one, and indeed it is found to be $\alpha = 0.959$. The final result is then

$$A_{sl}^b = -0.00957 \pm 0.00251(stat) \pm 0.00146(syst). \tag{6.2}$$

This deviates by 3.2 standard deviations from the SM prediction given in Eq. 1.5.

7. Cross-Checks

Since no tagging is applied, the observed asymmetry need not originate from CP-violation in B-meson mixing. However, the dependence of the asymmetry on the dimuon mass, shown in Fig. 5, suggests that it is due to a process with similar production and decay properties.

A series of sixteen stability tests were performed in which the sample selection criteria were varied, leading to large variations (up to a factor two) in the value of the raw asymmetry A. In all cases, the value of A_{sl}^b remained well within the uncertainties of the main measurement. This demonstrates the robustness of the result against significant changes in acceptance and background content.

Using Eq. 1.3, this result can be compared with existing measurements of a_{sl}^d [7] and a_{sl}^s [2]. Figure 6 shows the compatibility between these measurements in the (a_{sl}^d, a_{sl}^s) plane. It is also possible, taking the value of a_{sl}^d from the B-factories [7], to extract $a_{sl}^s = (-1.46 \pm 0.75)\%$. Thanks to Eq. 1.4, the result can then be juxtaposed to the measurements of $\Delta\Gamma_s$ and ϕ_s made in $B_s \to J/\psi\phi$

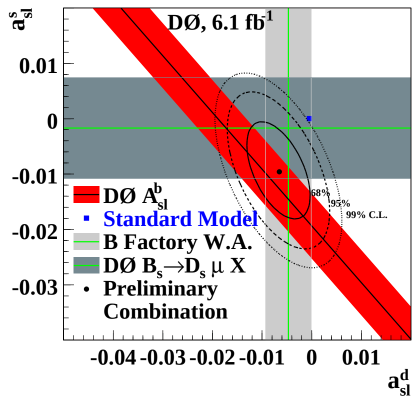

Figure 6: Comparison of this result (diagonal red band) with direct measurements of a^d_{sl} (vertical light grey band) and a^s_{sl} (horizontal dark grey band). The ellipses show DØ's combination of the three measurements.

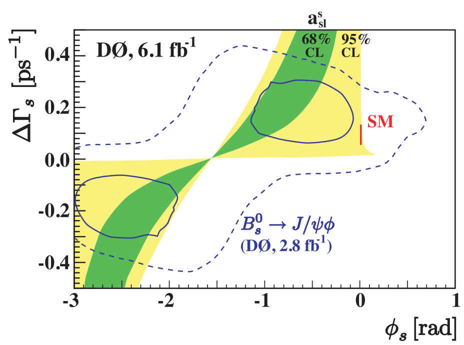

Figure 7: Comparison of this result with the measurements of $\Delta\Gamma_s$ and ϕ_s made in $B_s \to J/\psi\phi$ decays.

decays [8]. This is shown in Fig. 7. The result, although significantly differing from the SM prediction, is seen to be compatible with all other measurements of CP-violating parameters in *B*-meson mixing.

8. Conclusions

Using very little input from simulation, a new measurement of the charge asymmetry in like-sign dimuon events was performed. Under the assumption that the asymmetry originates in *B*-meson mixing, the result is

$$A^b_{sl} = -0.00957 \pm 0.00251(stat) \pm 0.00146(syst). \tag{8.1}$$

This result is consistent with all other measurements of CP-violation in *B*-meson mixing but inconsistent with the SM prediction at 99.8% C.L., or 3.2 standard deviations. All stability tests show excellent robustness against variations in muon selection and acceptance.

References

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