ANOMALOUS DIMUON CHARGE ASYMMETRY IN $p\bar{p}$ COLLISIONS

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We present an overview of the measurements of the like-sign dimuon charge asymmetry by the DØ Collaboration at the Fermilab Tevatron $p\bar{p}$ Collider. The results differ from the Standard Model prediction of CP violation in mixing and interference of B^0 and B_s^0 by 3.6 standard deviations.

1 Introduction

The DØ Collaboration has measured the inclusive muon charge asymmetry and the like-sign dimuon charge asymmetry in $p\bar{p}$ collisions at a center of mass energy $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron Collider [1, 2, 3, 4]. The measured inclusive muon charge asymmetry is consistent with zero, while the like-sign dimuon charge asymmetry is significantly negative. The result differs from the Standard Model prediction of CP violation in mixing, and CP violation in interference of decay amplitudes with and without mixing, of B^0 and B_s^0 by 3.6 standard deviations [4]. In this note we present an overview of these measurements and their current status. The DØ detector is shown in Figure 1.

The original motivation for this measurement was CP violation in mixing [5]. Most like-sign dimuons at DØ (after removing background muons from kaon and pion decay) are from events with a $b\bar{b}$ pair. One of the b's decays to a "right sign" muon, i.e. to a muon of the same charge sign as the parent b quark, while the other b in the event hadronizes to a B^0 or B_s^0 meson that oscillates before decaying to a "wrong sign" muon. CP violation is expected to be negligible for "right sign" muons, while it is expected to be non-negligible for "wrong sign" muons due to CP violation in mixing [5] and, as was recently realized [6], also due to CP violation in interference of decay amplitudes with and without mixing, of B^0 and B_s^0. The charge asymmetry of inclusive muons is predicted to be very small compared to the present experimental uncertainty [4] because most muons of events with a $b\bar{b}$ or a $c\bar{c}$ are "right sign" muons, and because CP violation in interference does not contribute. Therefore, the inclusive muon charge asymmetry provides a null-test that validates the measurements of the detector and background charge asymmetries. Like-sign dimuons have one "right sign" muon which tags the other muon to be of the "wrong sign".

2 Definitions

Most $p\bar{p}$ collisions produce no muons, a few produce one recorded muon, very few produce two recorded muons, and fewer still produce two *like-sign* recorded muons, i.e. 4×10^{14} (mostly not recorded), 2.2×10^9, 2.8×10^7 and 6.2×10^6 respectively in the final data set of 10.4 fb^{-1}. We obtain the *raw* inclusive muon and like-sign dimuon charge asymmetries by counting inclusive

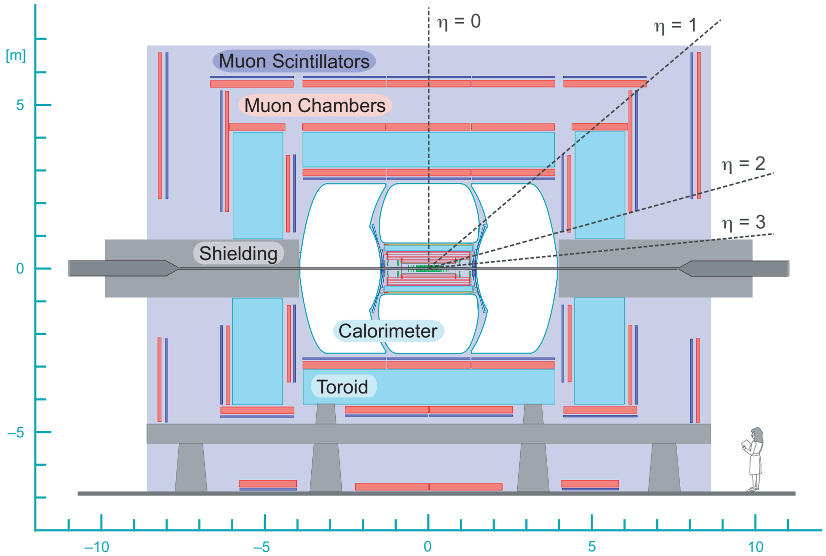

Figure 1 – The DØ detector.

muons or like-sign dimuon events:

$$a = \frac{n(\mu^+) - n(\mu^-)}{n(\mu^+) + n(\mu^-)}, \qquad A = \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)}. \tag{1}$$

We obtain the *residual* charge asymmetries by subtracting the asymmetry of the detector and backgrounds ("muons" from charged kaon and pion decay, and hadrons that punch-through to the outer muon detectors):

$$a_{CP} = a - a_{\rm bkg}, \qquad A_{CP} = A - A_{\rm bkg}. \tag{2}$$

These CP-violating residual charge asymmetries a_{CP} and A_{CP} are normalized to all muons or like-sign dimuons, including background "muons". The corresponding charge asymmetries that exclude events with background "muons" from the normalization are a_S and A_S. To cancel first order detector asymmetries we collect equal numbers of events for each of the four solenoid and toroid polarity combinations [1]. The residual detector asymmetry and the background asymmetries are *measured* by reconstructing exclusive decays in the *same* data sets [2, 3, 4].

3 History

The history of the measurements of the like-sign dimuon charge asymmetry at DØ is summarized in Table 1. Note that the results have not changed significantly with a factor 10 increase of the data set, and many improvements of the analysis methods, over the years. The decrease of $|A_{CP}|$ in the last measurement is due to a finer binning of the measurements in transverse momentum p_T and pseudo-rapidity η. The studies, measurements and cross-checks are already 22 years old.

4 Measurement with the full data set of 10.4 fb^{-1}

All measurements are done in 9 bins of $(p_T, |\eta|)$ [4]. The results for inclusive muons are presented in Figure 2. Note that the measured background charge asymmetry $a_{\rm bkg}$ is consistent with the raw asymmetry a obtained by counting events in all bins. We obtain a weighted average $a_{CP} = (-0.032 \pm 0.042({\rm stat}) \pm 0.061({\rm syst}))\%$, which is consistent with zero as expected (the Standard Model prediction is $a_{CP} = (-0.0007 \pm 0.0002)\%$). Figure 2 demonstrates that we understand the detector and background asymmetries within the quoted uncertainties.

Table 1: Measurements of the like-sign dimuon charge asymmetry at DØ. ϵ is the discrepancy between the measurement and the Standard Model prediction for CP violation in mixing (* and interference) of B^0 and B_s^0.

$\int Ldt$	Asymmetry A_{CP}	ϵ	DØ , Phys.Rev. D
1.0 fb^{-1}	$(-0.28 \pm 0.13 \pm 0.09)\%$	1.7σ	**74**, 092001 (2006)
6.1 fb^{-1}	$(-0.252 \pm 0.088 \pm 0.092)\%$	3.2σ	**82**, 032001 (2010)
9.0 fb^{-1}	$(-0.276 \pm 0.067 \pm 0.063)\%$	3.9σ	**84**, 052007 (2011)
10.4 fb^{-1}	$(-0.235 \pm 0.064 \pm 0.055)\%$	3.6σ *	**89**, 012002 (2014)

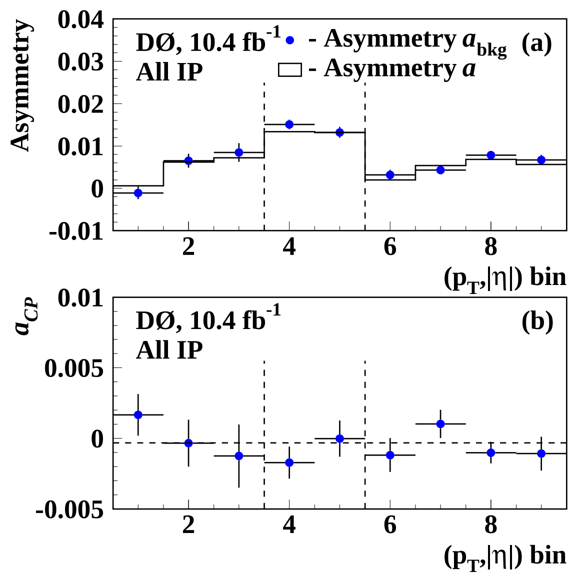

Figure 2 – Raw inclusive muon charge asymmetry a obtained by counting muons, measured detector and background charge asymmetries a_{bkg}, and their difference $a_{CP} = a - a_{\text{bkg}}$ in 9 bins of $(p_T, |\eta|)$. The horizontal line shows the weighted average which is consistent with zero.

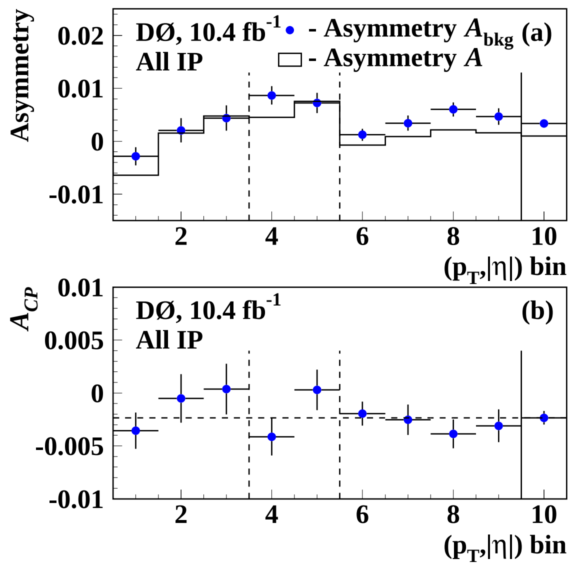

Figure 3 – Raw like-sign dimuon charge asymmetry A obtained by counting like-sign dimuons, measured detector and background asymmetries A_{bkg}, and their difference $A_{CP} = A - A_{\text{bkg}}$ in 9 bins of $(p_T, |\eta|)$. The histogram has two entries per event. The 10th bin and the horizontal line present the weighted average which is significantly negative.

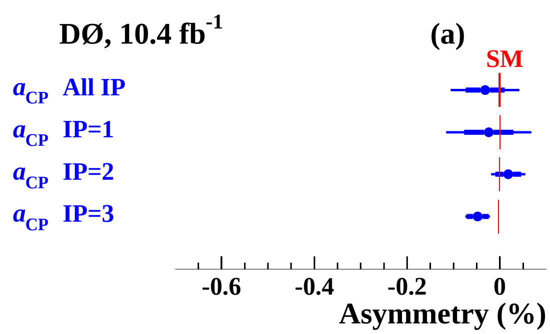

Figure 4 – Inclusive muon charge asymmetry a_{CP} for all muons, and for muons with transverse impact parameter less than 50 μm (IP=1), in the range 50 μm to 120 μm (IP=2), and in the range 120 μm to 3000 μm (IP=3).

The results for like-sign dimuons are presented in Figure 3. Note that the measured background charge asymmetry A_{bkg} follows the raw asymmetry A obtained by counting events, but there is an offset: $A_{CP} = A - A_{\text{bkg}}$ is significantly negative, and is negative (with limited significance) for the central muon detector (bins 1, 2 and 3), forward muon detector (bins 6 to 9), and for their overlap region (bins 4 and 5). We mention that the central and forward muon detectors have different technologies and their reconstruction softwares are independent. A_{CP} does not depend significantly on the $(p_T, |\eta|)$ bin. The weighted average is $A_{CP} = (-0.235 \pm 0.064(\text{stat}) \pm 0.055(\text{syst}))\%$, while the Standard Model prediction is $A_{CP} = (-0.043 \pm 0.010)\%$.

The inclusive muon charge asymmetry a_{CP} is also measured in 27 bins: 9 bins of $(p_T, |\eta|) \times$ 3 bins of transverse impact parameter (IP). The like-sign dimuon charge asymmetry A_{CP} is also measured in 54 bins: 9 bins of $(p_T, |\eta|) \times$ 6 bins of $(\text{IP}_1, \text{IP}_2)$. In all cases the asymmetry does not vary significantly with $(p_T, |\eta|)$. See [4] for full details. Averaging over the 9 bins of $(p_T, |\eta|)$ we obtain the results summarized in Figures 4 and 5.

The measurements of a_{CP} and A_{CP} in bins of IP are correlated. These measurements are in

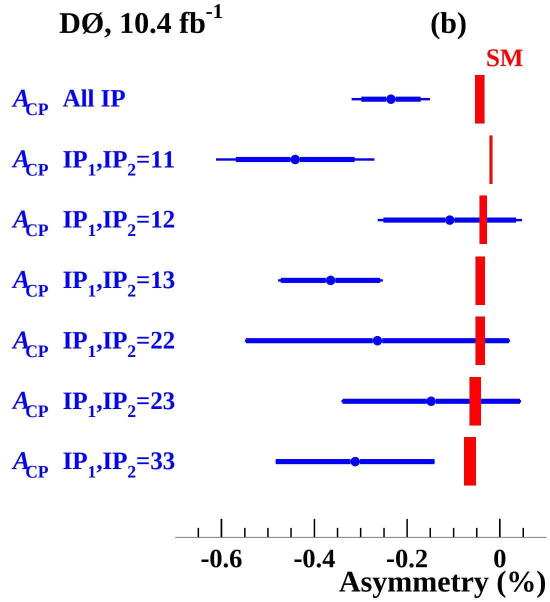

Figure 5 – Like-sign dimuon charge asymmetry A_{CP} for all muons, and for dimuons in six bins of (IP_1, IP_2).

disagreement with the Standard Model prediction for CP violation in mixing and interference of B^0 and B_s^0 by 3.6 standard deviations. At the present time we do not understand the origin of this discrepancy. It could be due to missing Standard Model contributions, inaccurate predictions of $\Delta\Gamma_d$ or a_{sl}^d (i.e. the real and imaginary parts of the matrix element Γ_{12}^d) due to low energy non-perturbative effects, an experimental issue that has evaded all cross-checks to date, or New Physics. $\Delta\Gamma_d$ is the decay rate difference of the eigenstates of the $(B^0, \bar{B}^0)$ system, and a_{sl}^d is the semi-leptonic charge asymmetry of decays of B^0 and $\bar{B}^0$ to "wrong sign" muons.

If we assume that the only sources of charge asymmetry are CP violation in mixing and interference of B^0 and B_s^0, we obtain 3-dimensional likelihood contours in the space of a_{sl}^d, a_{sl}^s and $\Delta\Gamma_d$. A slice is shown in Figure 6 at the best fit value of $\Delta\Gamma_d$ [4, 7, 8].

5 Conclusions

We obtain a 3.6 standard deviation discrepancy between the measurements and the Standard Model prediction of CP violation in mixing and interference of B^0 and B_s^0. At the present time we do not understand the origin of this discrepancy, which has not yet been confirmed nor ruled out by other experiments, see Table 2. At DØ we are currently measuring the like-sign dimuon charge asymmetry of sub-samples of the data set with the hope of solving this puzzle.

1. V.M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D **74**, 092001 (2006).
2. V.M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D **82**, 032001 (2010). V.M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **105**, 081801 (2010).
3. V.M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D **84**, 052007 (2011).
4. V.M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D **89** 012002 (2014).
5. G.C. Branco, L. Lavoura, and J.P. Silva, "CP Violation", Oxford Science Publications (1999).
6. G. Borissov and B. Hoeneisen, Phys. Rev. D **87**, 074020 (2013).
7. V.M. Abazov et al. (D0 Collaboration), Phys. Rev. D86, 072009 (2012).
8. V.M. Abazov et al. (D0 Collaboration), Phys. Rev. Lett. 110, 011801 (2013).
9. J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012) and 2013 partial update for the 2014 edition.

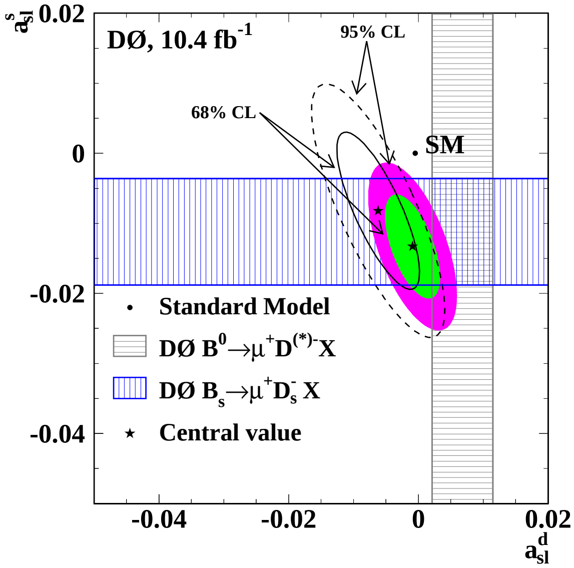

Figure 6 – The 68% and 95% confidence level contours from fit with $\Delta\Gamma_d/\Gamma_d = 0.0050$ (corresponding to the best fit value), and combination of all DØ measurements (filled areas).

Table 2: Contributions to A_S allowed by experiments (with $\pm 1\sigma$ confidence). Compare with the measured $A_S = (-0.319 \pm 0.132)\%$. This is an update of Table II of [6] using the world averages of [9]. *From the Standard Model prediction and the constraint from $B_s^0 \to J/\psi\phi$ we expect this contribution to be negligible. **These tree level decays are expected to contribute negligibly to A_S. ***This contribution to A_S is proportional to $\Delta\Gamma_d$ and assumes the Standard Model prediction $\Delta\Gamma_d = (0.42 \pm 0.08)\%$. If $\Delta\Gamma_d$ turns out to be larger than the prediction due to low energy non-perturbative effects, then this ΔA_S could be sizable.

CP violation in	ΔA_S allowed by exp.	Comments
mixing $B^0 \leftrightarrow \bar{B}^0$	$(+0.021 \pm 0.083)\%$	from exp. $a_{\rm sl}^d$
mixing $B_s^0 \leftrightarrow \bar{B}_s^0$	$(-0.374 \pm 0.124)\%$	from exp. $a_{\rm sl}^s$ *
interference $B^0 \to (\bar{B}^0) \to c\bar{c}d\bar{d}$	$(-0.050 \pm 0.012)\%$	from SM $\Delta\Gamma_d$ ***
interference $B_s^0 \to (\bar{B}_s^0) \to c\bar{c}s\bar{s}$	$(-0.0009 \pm 0.0003)\%$	from exp. $\Delta\Gamma_s$
direct decays $b \to c\bar{c}\bar{d}$	$(+0.003 \pm 0.013)\%$	from exp. Br & CPV
direct decays $b \to c\bar{c}\bar{s}$	$(+0.000 \pm 0.043)\%$	from exp. Br
direct decays $b \to \mu X$	$(-0.17 \pm 0.39)\%$	from a_{CP} **
direct decays $c \to \mu X$	$(-0.07 \pm 0.17)\%$	from a_{CP} **
production $p\bar{p} \to b\bar{c}X$	$(-0.15 \pm 0.35)\%$	from a_{CP}
neutrinoless double β decay	$(-0.12 \pm 0.29)\%$	from a_{CP}
direct decay to "right sign" μ	$(-0.13 \pm 0.30)\%$	from a_{CP}
direct decay to "wrong sign" μ	$(-0.46 \pm 1.07)\%$	from a_{CP}