Update of the like-sign dimuon charge asymmetry from the DØ experiment

Peter H. Garbincius
Fermilab
for the DØ Collaboration
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The \textbf{DØ} Detector for Run II

- \textit{pp} symmetry
- excellent \(\mu\)-id flip magnets
- \(\sqrt{s} = 1.96\) TeV

\text{DØ} like-sign dimuon charge asymmetry - Garbincius - DPF - Santa Cruz - August 2013
Mystery & Motivation

• DØ previously published 3 measurements of the like-sign dimuon charge asymmetry at 1 fb\(^{-1}\), 6.1 fb\(^{-1}\), & 9 fb\(^{-1}\), each observing \(A_{cp} \neq \text{SM}\) prediction at \(\sim 1.7 - 3.9 \sigma\) significance

• This is one of only a few inconsistencies with SM

• *Repeating* with full 10.4 fb\(^{-1}\) Run II data sample, improved background subtraction, methodology

• *Is this observation real?*

• *Is our understanding of SM complete?*

• *Is there something else going on besides the SM?*
**CP violation in mixing**

\[ B^0 \leftrightarrow \bar{B}^0 \text{ and } B_s^0 \leftrightarrow \bar{B}_s^0 \]

\[ pp \rightarrow \bar{b}b \ldots \text{etc.} \]

some examples

\[ b \rightarrow B^- \rightarrow \mu^- X \quad \text{“right-sign } \mu \text{”} \]
\[ \bar{b} \rightarrow \bar{B}^0 \rightarrow \bar{B}^0 \rightarrow \mu^- X \quad \text{“wrong-sign } \mu \text{”} \]

or

\[ \bar{b} \rightarrow \bar{B}^+ \rightarrow \mu^+ X \quad \text{“right-sign } \mu \text{”} \]
\[ b \rightarrow B^0 \rightarrow \bar{B}^0 \rightarrow \mu^+ X \quad \text{“wrong-sign } \mu \text{”} \]

also sequential decays, such as

\[ b \rightarrow c \rightarrow \mu^+ \quad \text{are another source of} \]

\[ \text{“wrong-sign } \mu \text{”} \]

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**generic % of b \rightarrow \mu**

*Pythia simulation*

- \[ b \rightarrow \mu^- 73\% \]
- \[ b \rightarrow \bar{b} \rightarrow \mu^+ 11\% \]
- \[ b \rightarrow c \rightarrow \mu^+ 16\% \]
SM Assumption

- (prior) only source of charge asymmetry for like-sign dimuons is CP violation in mixing for All IP1,IP2: $A_{CP}^{mix}(SM) = (-0.008 \pm 0.001)\%$

- however, (recently) G. Borissov & B. Hoeneisen Phys. Rev. D 87, 074020 (2013) added CP violation in interference between mixed and non-mixed final states, such as $b \rightarrow B^0 \rightarrow D^- D^+ (\rightarrow \mu^+ "wrong sign")$

This interference doesn’t contribute to $\alpha_{CP}$ for single muons since $D^+ \rightarrow \mu^+$ and $D^- \rightarrow \mu^-$ balance
• for scale, for All(IP1,IP2) bin:

\[ A_{\text{CP}}^{\text{interference}}(\text{SM}) = (-0.035 \pm 0.008)\% \sim 4 \times A_{\text{CP}}^{\text{mixing}}(\text{SM}) \]

\[ A_{\text{CP}}^{\text{mixing}}(\text{SM}) = (-0.008 \pm 0.001)\% \]

\[ A_{\text{CP}}(\text{SM}) = A_{\text{CP}}^{\text{mixing}}(\text{SM}) + A_{\text{CP}}^{\text{interference}}(\text{SM}) = (-0.043 \pm 0.010)\% \]

\[ A_{\text{CP}}(\text{DØ measured with } 9 \text{ fb}^{-1}) = (-0.276 \pm 0.092)\% \]

combined stat + syst uncertainty

• \( A_{\text{CP}}^{\text{interference}} \) is linearly depended on \( \Delta \Gamma_d/\Gamma_d \)
so this gives possibility of measuring \( \Delta \Gamma_d/\Gamma_d \)

\( \Delta \Gamma_d/\Gamma_d \): World Avg. = \( (1.5 \pm 1.8)\% \) \quad SM = \( (0.42 \pm 0.08)\% \)

anticipate DØ can measure \( \Delta \Gamma_d/\Gamma_d \) to \( \approx \pm 1\% \)

• similar contribution of \( \Delta \Gamma_s/\Gamma_s \) is much smaller
and is already determined well (see HFAG-2012)
Measurement Method

Use both:

**single inclusive muons** (denoted by lower case)
and **like-sign dimuons** (upper case)

Do **not** expect to see charge asymmetries for single inclusive muons

=> serves as closure or consistency check that we are **not generating false asymmetries**
**Charge Asymmetries**

RAW observed asymmetries (in each data bin):

\[
a \equiv \frac{n^+ - n^-}{n^+ + n^-} \quad A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}
\]

Residual (background subtracted) asymmetries

\[
a_{CP} \equiv a - a_{bkg} \quad A_{CP} \equiv A - A_{bkg}
\]

\[a_{CP} \text{ and } A_{CP} \text{ are normalized to all muons}\]

sample: \(2.2 \times 10^9 \mu^\pm; 2.2 \times 10^7 \mu^+\mu^-; 6.2 \times 10^6 \mu^\pm\mu^\pm\)
\[ a_{CP} = a - a_{bkg} \]
\[ a_{bkg} = a_\mu + f_K a_K + f_\pi a_\pi + f_p a_p \]

**dominant** \[ f_K a_K \approx +0.625\%, \ a_\mu \approx -0.288\% \]

\[ f_K = \text{fraction of charged } K \text{ in } \mu \text{ sample, measured from } \]
\[ K^{*0} \rightarrow \pi^- K^+ (\rightarrow \mu^+) \text{ and } K^{*+} \rightarrow \pi^+ K_s^0 (\rightarrow \pi^+ \pi^-) \]

\[ \text{and convert } f_{K^{*0}} + f_{K^{*+}} \rightarrow f_K \pm \text{ by isospin invariance} \]

\[ a_K \text{ asymmetry due to } \sigma_{\text{inelastic}}(K^-) > \sigma_{\text{inelastic}}(K^+) \text{ is measured with } \]
\[ K^{*0} \rightarrow \pi^- K^+ (\rightarrow \mu^+ \nu) \text{ & c.c. and } \phi \rightarrow K^+ K^- (\text{with } K^\pm \rightarrow \mu^\pm \nu) \]

\[ a_\mu = \text{muon detector charge asymmetry measured} \]
\[ \text{with } J/\psi \rightarrow \mu^+ \mu^- \text{ central tracking only, no } \mu \text{ trigger} \]

**new check**: \[ f_K \text{ and } f_\pi \text{ are cross-checked using tracks } \]
\[ \text{measured in both central and local muon trackers, differences are included in systematic uncertainties} \]
evolution of this DØ measurement

This new full 10.4 fb\(^{-1}\) analysis is still in collaboration review and is not ready for public release yet

So I can only give a status report, view of checks with single inclusive muons, and indication of expected sensitivities!

<table>
<thead>
<tr>
<th>(\int L dt)</th>
<th>asymmetry (A_{CP})</th>
<th>(\text{(DØ), Phys.Rev. D})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 fb(^{-1})</td>
<td>((-0.28 \pm 0.13 \pm 0.09))%</td>
<td>1.7(\sigma)* 74, 092001 (2006)</td>
</tr>
<tr>
<td>6.1 fb(^{-1})</td>
<td>((-0.252 \pm 0.088 \pm 0.092))%</td>
<td>3.2(\sigma)* 82, 032001 (2010)</td>
</tr>
<tr>
<td>9.0 fb(^{-1})</td>
<td>((-0.276 \pm 0.067 \pm 0.063))%</td>
<td>3.9(\sigma)* 84, 052007 (2011)</td>
</tr>
<tr>
<td>10.4 fb(^{-1})</td>
<td>((? \pm 0.064 \pm 0.055))%</td>
<td>?(\sigma) &amp; # (2013)</td>
</tr>
</tbody>
</table>

Analysis has changed significantly over this evolution

* Discrepancy with \(A_{CP}^{\text{mix}}(\text{SM})\) only.
& Discrepancy with \(A_{CP}^{\text{mix}}(\text{SM})\) and \(A_{CP}^{\text{int}}(\text{SM})\).

improved systematic uncertainties
Muon Requirements

• Standard DØ single and multi-muon triggers
• Slightly tighter DØ tracking & quality requirements
• Require $p_T > 4.2 \text{ GeV or } |p_z| > 5.2 \text{ GeV}$
  to ensure track penetrates through muon toroids
• $p_T \geq 1.5 \text{ GeV and } p_T \leq 25 \text{ GeV}$ to suppress $\mu$ from $W^\pm \& Z^0$
• $M_{\mu\mu} > 2.8 \text{ GeV}$ to avoid 2 $\mu$ from same $b \rightarrow \mu^- \nu \, c (\rightarrow \mu^+)$
• 9 Bins for each muon:
  0 $\leq |\eta| \leq 0.7$, $p_T < 5.6$, 5.7-7, 7-25 GeV
  0.7 $\leq |\eta| \leq 1.2$, $p_T < 5.6$, 5.6-25 GeV
  1.2 $\leq |\eta| \leq 2.2$, $p_T < 3.5$, 3.5-4.2, 4.2-5.6, 5.6-25 GeV
• 3 (transverse) I.P. bins: 0-50, 50-120, 120-3000 $\mu$m
  $\mu$ from $b$ decays are predominantly at large I.P.
  $\mu$ from K and $\pi$ decays are predominantly at small I.P.
**closure test for single muons**

**expect** \( a - a_{bkg} = 0 \)

\[ a_{bkg} \approx a_K f_K \]

bkg mostly \( K \to \mu \)

**All IP**

\[ |\eta| < 0.7 \]

\[ 0.7 < |\eta| < 2.2 \]

**IP < 50 \mu m**

\[ 0 < |\eta| < 0.7 \]

\[ 0.7 < |\eta| < 2.2 \]
**closure test for single muons**

expect \( a - a_{bkg} = 0 \)

\[ a_{bkg} = a_K f_K + a_\mu \approx 0 \]

**50 < IP < 120 \( \mu \)m**

![Graph 1](image1)

**120 < IP < 3000 \( \mu \)m**

![Graph 2](image2)
These asymmetries are a linear combo of semi-leptonic decay asymmetries & $\Delta \Gamma_d/\Gamma_d$

$$a_{CP}^b(bins) = c_d(bins) \ a_{sl}^d + c_s(bins) \ a_{sl}^s$$

$$A_{CP}^b(bins) = C_d(bins) \ a_{sl}^d + C_s(bins) \ a_{sl}^s + C_\delta(bins) \ \Delta \Gamma_d/\Gamma_d$$

$D\emptyset$ also measured these semi-leptonic asymmetries

- $a_{sl}^d$ in $B^0 \to D^- \mu^+ X$ and $B^0 \to D^{*-} \mu^+ X$ & c.c. decays
  - also measured by b-factories

- $a_{sl}^s$ in $B_s^0 \to D_s^- \mu^+ X$ & c.c. decays

see Avdhesh Chandra’s DPF presentation #235 - yesterday
With full & improved 10.4 fb⁻¹ analysis with 3 IP bins 0-50 µm, 50-120 µm, 120-3000 µm it is expected that the area of these uncertainty ellipses will decrease to ~56% of this prior area.
indicating prior DØ measurement of

\[ a_{sl}^d = (0.68 \pm 0.47)\% \quad \text{and} \quad a_{sl}^s = (-1.12 \pm 0.76)\% \]
World Combo

DØ (prior 9 fb$^{-1}$) plus LHCb plus B-Factories

2.26 $\sigma$ deviation from SM

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Remaining Questions:

• Is it possible that the entire like-sign dimuon charge asymmetry is due to large $\Delta \Gamma_d / \Gamma_d$?

• Are there still missing SM contributions to $A_{CP}$?

• Is the DØ observation that $A_{CP} \neq$ SM prediction real? Need checking by other experiments.

Thank you,

Peter

and many thanks to:

Guennadi Borissov, Lancaster University
Bruce Hoeneisen, Univ. San Francisco de Quito
Back-up Slides
Why study this asymmetry at DØ?

• **Charge Symmetric** \( pp \) initial state
  \( @ \sqrt{s} = 1.96 \) TeV

• **Excellent \( \mu \) id** — massive U-LAr calorimeter and magnetized iron muon toroid spectrometer
  — minimize hadronic punch through
  — remeasure & verify muon trajectory

• **Flip polarities** of solenoid and toroid magnets
  — cancels many acceptance systematic effects
Charge Asymmetries

**RAW** observed asymmetries (in each data bin):

\[ a \equiv \frac{n^+ - n^-}{n^+ + n^-} \quad A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}} \]

**Residual** (background subtracted) asymmetries

\[ a_{\text{CP}} \equiv a - a_{\text{bkg}} \quad A_{\text{CP}} \equiv A - A_{\text{bkg}} \]

\( a_{\text{CP}} \) and \( A_{\text{CP}} \) are normalized to all muons

prompt \( b \to \mu \) & \( c \to \mu \), which are included in \( a_{\text{CP}} \) and \( A_{\text{CP}} \)

are considered “short” decays (within the beam pipe).

\( K \to \mu \) and \( \pi \to \mu \) decays within the central tracking volume

are also treated as “short” decays since they have not had

an appreciable chance to interact in matter before decaying

and therefore are not a source of instrumental \( a_{\text{bkg}} \) charge asymmetry due to \( \sigma_{\text{inelastic}}(h^-) > \sigma_{\text{inelastic}}(h^+) \). The \( K \to \mu \) and \( \pi \to \mu \) decays have small I.P. \( b \to \mu \) and \( c \to \mu \) have larger I.P.
regularly flip polarities of toroid magnet & solenoid magnet to reduce detector asymmetries
FIG. 1: Definition of the \((p_T, |\eta|)\) bins. Global kinematic selections are 1.5 < \(p_T\) < 25 GeV, \((p_T > 4.2\text{ GeV or } |p_z| > 5.4\text{ GeV})\), and \(|\eta| < 2.2\).

IP of other muon when one muon is in IP=1 bin, IP=2 bin, and IP=3 bin. Common normalization at lowest IP.
analysis improvements

• Use only “good” runs
• Increased track quality requirements #hits SMT ≥2 → ≥3
• New Monte Carlo simulation for \( \bar{b}b \rightarrow \mu^+\mu^- X \) (without prior \( E_{\text{tot}} > 20 \) GeV cut) to calculate fraction of oscillated \( B^0 \) and \( B_{s}^0 = C_b \) change by \((+11\pm12)\%
• Calculate \( K^{*0} \) reconstruction efficiency individually for each IP and \( (p_T, |\eta|) \) bins
• Alternative cross-check of background fraction using locally measured track parameters in \( \mu \) detector for All IP agrees to within \((-10\pm4)\% \rightarrow \text{incl. in syst. uncert.} \)
$\mathcal{A}_K = \frac{\varepsilon(K^+) - \varepsilon(K^-)}{\varepsilon(K^+) + \varepsilon(K^-)} = (1.05 \pm 0.04\text{(syst)})\%$