Updated Measurement of the Anomalous Like-sign Dimuon Asymmetry at D0

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The Tevatron (you are here!)

Collides protons and antiprotons at centre-of-mass energy 1.96 TeV;

Accelerator performance better than ever in 2011 – learning from the past;

In final push before collisions stop at the end of September 2011.
Experimental Strengths

D0 Experiment

Central tracking detector (silicon, scintillating fibers): impact parameter (IP) resolution $\sim 35 \mu m$;

Wide acceptance in three-layered muon system ($|\eta| < 2.2$);

Thick shielding before muon system – hadronic punch-though suppressed.

Regular reversal of toroid (muon-system) and solenoid (tracker) magnet polarities – cancels many detector asymmetries.
Neutral $B^0_{(q=d,s)}$ mesons mix into their antiparticles via box diagrams:

Process **not CP symmetric** – $R(B^0_q \rightarrow \bar{B}^0_q) \neq R(\bar{B}^0_q \rightarrow B^0_q)$ – due to complex phase $\phi_{(d,s)}$ in quark mixing matrix, but…

…SM prediction of resulting asymmetry is **tiny**, much smaller than experimental precision. **New particles** entering loops can enhance this asymmetry significantly.

Measure CPV through asymmetry of decay products.

Flavor-specific semileptonic asymmetries defined for both $B^0_s$ and $B^0_d$:

$$\alpha^q_{sl} = \frac{\Gamma(\bar{B}^0_q \rightarrow B^0_q \rightarrow \mu^+X) - \Gamma(B^0_q \rightarrow \bar{B}^0_q \rightarrow \mu^-X)}{\Gamma(\bar{B}^0_q \rightarrow B^0_q \rightarrow \mu^+X) + \Gamma(B^0_q \rightarrow \bar{B}^0_q \rightarrow \mu^-X)}$$

$$= \frac{\Delta \Gamma_q}{\Delta M_q} \tan \phi_q$$

Physical parameters characterizing $B^0_q$ system
Measuring CPV in Mixing

D0 experiment measures an inclusive asymmetry, with contributions from both $B^0_d$ and $B^0_s$:

$$a^b_{sl} = \frac{N(\bar{B}^0 \rightarrow \mu^+X) - N(B^0 \rightarrow \mu^-X)}{N(\bar{B}^0 \rightarrow \mu^+X) + N(B^0 \rightarrow \mu^-X)} = C_d a^d_{sl} + C_s a^s_{sl}$$

More $B^0_d$ produced, but most decay before mixing: $C_d \approx C_s \approx 0.5$

Challenge: separate signal (semileptonic mixed decays of B mesons) from the many other muon-producing backgrounds.

To suppress such backgrounds, require second muon of the same charge:

$$A^b_{sl} = \frac{N(b\bar{b} \rightarrow \mu^+\mu^+)}{N(b\bar{b} \rightarrow \mu^+\mu^+)} - \frac{N(b\bar{b} \rightarrow \mu^-\mu^-)}{N(b\bar{b} \rightarrow \mu^-\mu^-)} = a^b_{sl} = (0.028 \pm 0.006)\% in S.M.$$ 

We therefore have two ways to extract $a^b_{sl}$, and take advantage of the correlated backgrounds by combining the two measurements.
Analysis Strategy

1) Measure ‘raw’ asymmetries by counting single muons ($n^{\pm}$) and dimuon events ($N^{\pm\pm}$);

2) Express in terms of $a^b_{sl}$:

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-} = \sum_{i=0}^{5} f_{\mu}^i \left( f_s^i (c_b a^b_{sl} + \delta_i) + f_{k}^i a_k^i + f_{\pi}^i a_{\pi}^i + f_{p}^i a_p^i \right)$$

- **Raw asymmetry (event counting)**
- **Weighted average over bins of muon $p_T$**
- **Asymmetry from heavy-flavor decays**
- **Asymmetries from backgrounds and detector effects**
Analysis Strategy

1) Measure ‘raw’ asymmetries by counting single muons \((n^\pm)\) and dimuon events \((N^{\pm\pm})\);

2) Express in terms of \(a_{\text{sl}}^b\):

\[
a \equiv \frac{n^+ - n^-}{n^+ + n^-} = \sum_{i=0}^{5} f^i \mu \left\{ f^i_s (c_b a_{\text{sl}}^b + \delta_i) + f^i_k a^i_k + f^i_\pi a^i_\pi + f^i_p a^i_p \right\}
\]

Asymmetries from backgrounds and detector effects

Residual muon reconstruction asymmetries (almost entirely cancelled by magnet polarity reversal)

Fraction

Charge asymmetry

Kaon DIF and punch-through

Pion DIF and punch-through

...proton punch-through
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- Asymmetry from heavy-flavor decays
- Remaining fraction of muons after kaon, pion, proton components taken into account:
  i.e. “Heavy Flavor Fraction”
- Dilution factor (muons from charge symmetric HF processes)
- What we want to extract

Similar expression for dimuon case. Many BG quantities are the same, or highly correlated, e.g. presence of second muon doesn’t change kaon asymmetry $a_k^i$. 
3) Measure all quantities $f_{k,\pi,p}\,^i,\, a_{k,\pi,p}\,^i,\, \delta_i$ in data, with limited input from simulation;

$\sim 15\%$ muons from kaons

$= +0.776 \pm 0.021 \%$

asymmetry from kaons
3) Measure all quantities $f_{k, \pi, p}^i$, $a_{k, \pi, p}^i$, $\delta_i$ in data, with limited input from simulation;

\[
\begin{align*}
\text{~15\% muons from kaons} & \quad D\bar{O}, 9.0 \text{ fb}^{-1} \\
\text{~30\% muons from pions} & \quad D\bar{O}, 9.0 \text{ fb}^{-1}
\end{align*}
\]
3) Measure all quantities $f_{k,\pi,p}^i$, $a_{k,\pi,p}^i$, $\delta_i$ in data, with limited input from simulation;

- $\sim 15\%$ muons from kaons
- $\sim 30\%$ muons from pions
- $\sim 0.4\%$ `muons' from protons

$= +0.776 \pm 0.021 \%$ asymmetry from kaons
$= +0.007 \pm 0.027 \%$ asymmetry from pions
$= -0.014 \pm 0.022 \%$ asymmetry from protons
Analysis Strategy

3) Measure all quantities \( f^i_{k,\pi,\rho}, a^i_{k,\pi,\rho}, \delta_i \) in data, with limited input from simulation;

Contribution from residual muon reconstruction asymmetry:

\[
\sum_i (1 - f^i_k - f^i_\pi - f^i_\rho) \delta_i = -0.047 \pm 0.012 \%
\]

<table>
<thead>
<tr>
<th>Source</th>
<th>inclusive muon</th>
<th>like-sign dimuon</th>
</tr>
</thead>
<tbody>
<tr>
<td>((f_K a_K \text{ or } F_K A_K) \times 10^2)</td>
<td>(+0.776 \pm 0.021)</td>
<td>(+0.633 \pm 0.031)</td>
</tr>
<tr>
<td>((f_\pi a_\pi \text{ or } F_\pi A_\pi) \times 10^2)</td>
<td>(+0.007 \pm 0.027)</td>
<td>(-0.002 \pm 0.023)</td>
</tr>
<tr>
<td>((f_p a_p \text{ or } F_p A_p) \times 10^2)</td>
<td>(-0.014 \pm 0.022)</td>
<td>(-0.016 \pm 0.019)</td>
</tr>
<tr>
<td>([(1 - f_{\text{bkg}}) \delta \text{ or } (2 - F_{\text{bkg}}) \Delta] \times 10^2)</td>
<td>(-0.047 \pm 0.012)</td>
<td>(-0.212 \pm 0.030)</td>
</tr>
<tr>
<td>((a_{\text{bkg}} \text{ or } A_{\text{bkg}}) \times 10^2)</td>
<td>(+0.722 \pm 0.042)</td>
<td>(+0.402 \pm 0.053)</td>
</tr>
<tr>
<td>((a \text{ or } A) \times 10^2)</td>
<td>(+0.688 \pm 0.002)</td>
<td>(+0.126 \pm 0.041)</td>
</tr>
<tr>
<td>([(a - a_{\text{bkg}}) \text{ or } (A - A_{\text{bkg}})] \times 10^2)</td>
<td>(-0.034 \pm 0.042)</td>
<td>(-0.276 \pm 0.067)</td>
</tr>
</tbody>
</table>

Background dominated

Significantly different from zero
4) Account for dilution from charge-symmetric processes (i.e. determine coefficients $c_b$, $C_b$):

<table>
<thead>
<tr>
<th>Process</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1$ $b \rightarrow \mu^- X$</td>
<td>$w_1 = 1$</td>
</tr>
<tr>
<td>$T_{1a}$ $b \rightarrow \mu^- X$ (nos)</td>
<td>$w_{1a} = (1 - \chi_0)w_1$</td>
</tr>
<tr>
<td>$T_{1b}$ $\bar{b} \rightarrow b \rightarrow \mu^- X$ (osc)</td>
<td>$w_{1b} = \chi_0 w_1$</td>
</tr>
<tr>
<td>$T_2$ $b \rightarrow c \rightarrow \mu^+ X$</td>
<td>$w_2 = 0.096 \pm 0.012$</td>
</tr>
<tr>
<td>$T_{2a}$ $b \rightarrow c \rightarrow \mu^+ X$ (nos)</td>
<td>$w_{2a} = (1 - \chi_0)w_2$</td>
</tr>
<tr>
<td>$T_{2b}$ $b \rightarrow \bar{b} \rightarrow c \rightarrow \mu^+ X$ (osc)</td>
<td>$w_{2b} = \chi_0 w_2$</td>
</tr>
<tr>
<td>$T_3$ $b \rightarrow c \bar{c} q$ with $c \rightarrow \mu^+ X$ or $\bar{c} \rightarrow \mu^- X$</td>
<td>$w_3 = 0.064 \pm 0.006$</td>
</tr>
<tr>
<td>$T_4$ $\eta, \omega, \rho^0, \phi(1020), J/\psi, \psi' \rightarrow \mu^+ \mu^-$</td>
<td>$w_4 = 0.021 \pm 0.002$</td>
</tr>
<tr>
<td>$T_5$ $b \bar{b} c \bar{c}$ with $c \rightarrow \mu^+ X$ or $\bar{c} \rightarrow \mu^- X$</td>
<td>$w_5 = 0.013 \pm 0.002$</td>
</tr>
<tr>
<td>$T_6$ $c \bar{c}$ with $c \rightarrow \mu^+ X$ or $\bar{c} \rightarrow \mu^- X$</td>
<td>$w_6 = 0.675 \pm 0.101$</td>
</tr>
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Weights measured using simulation
This analysis uses LEP value for $\chi_0$, following recent CDF update.

Results:
- $c_b = 0.061 \pm 0.007$
- $C_b = 0.474 \pm 0.032$

Inclusive muon sample dominated by charge-symmetric backgrounds (94%)
Dimuon sample has a large contribution (47%) from mixed B mesons (remember: around 50% each of $B^0_d$ and $B^0_s$)
Results with 9fb$^{-1}$

Final asymmetry from both samples:

From inclusive muon sample: \[ A^b_{sl} = [ -1.04 \pm 1.30 \text{ (stat.)} \pm 2.31 \text{ (syst.) } ] \% \]
(2.041 x 10$^9$ muons)

From like-sign dimuon sample: \[ A^b_{sl} = [ -0.808 \pm 0.202 \text{ (stat.)} \pm 0.222 \text{ (syst.) } ] \% \]
(6.019 x 10$^6$ muons)

Now use linear combination of inclusive and dimuon asymmetries, \( A' = A - \alpha a \) with \( \alpha = 0.89 \) chosen to minimise total uncertainty on \( A^b_{sl} \):

\[ A^b_{sl} = [ -0.787 \pm 0.172 \text{ (stat.)} \pm 0.093 \text{ (syst.) } ] \% \]

This result differs from the SM prediction by 3.9\( \sigma \)

Systematic uncertainty reduces significantly due to extra information in (background dominated) inclusive muon sample
Use *sample composition* and *mixing probability* to express as constraint in \((a^d_{sl}, a^s_{sl})\) plane.

Results consistent with previous measurements of flavor-specific asymmetries.
Comparison with Previous Result

Previous D0 measurement
PRD 82, 032001 (2010) (6.1fb⁻¹)

First 6.1fb⁻¹, new technique:

Final 2.9fb⁻¹, new technique:

So what’s new?

- Event selection optimized:
  - Looser minimum $|p_z|$ cut (6.4→5.4 GeV) based on new study of detector thickness;
  - Tighter match required between muon track and central track – reduces BG contribution from D.I.F.;
- New method to extract ratio of kaon fractions in two samples $R_k = F_k/f_k$: eliminates dependence on mass resolution, and better quantifies correlations.
- Second, independent channel used to measure $R_k$: consistent results found.
Cross-Checks

Measured inclusive muon asymmetry $a$ is dominated by background: should match $a_{\text{bkg}}$:

Dimuon asymmetry versus $M(\mu\mu)$ – inconsistent with SM, but consistent with measured $A_{\text{sl}}^b$.

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Measurement also repeated with many different requirements to enhance/suppress backgrounds. Final $A_{\text{sl}}^b$ consistent in all samples (Total $\chi^2 = 16$ for 18 different tests)
Dependence on Impact Parameter

Muon impact parameter strongly influences:

**Heavy flavor fraction**

- Data (points) vs MC (line)
- Non-HF fraction

**Fraction of `oscillated' $B^0_q$ mesons**

By dividing into two samples corresponding to $\text{IP}(\mu) < 120\mu m$ and $\text{IP}(\mu) > 120\mu m$, we can:

1) Confirm stable measurement in background enhanced and suppressed samples;
2) Test for larger asymmetry from $B^0_d$ or $B^0_s$ mesons:

For $\text{IP}(\mu) < 120\mu m$:

$$A^{b}_{sl} = (0.397 \pm 0.053)a^{d}_{sl} + (0.603 \pm 0.053)a^{s}_{sl}$$

For $\text{IP}(\mu) > 120\mu m$:

$$A^{b}_{sl} = (0.728 \pm 0.030)a^{d}_{sl} + (0.272 \pm 0.030)a^{s}_{sl}$$

**DØ, 9.0 fb$^{-1}$**
## Dependence on Impact Parameter

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- Kaon and pion fractions much lower in $IP_{>120}\mu m$ sample
- HF fraction increases from $\sim$50% $\rightarrow$ $\sim$90%
- Even inclusive muon asymmetry significantly different from BG expectation for $IP_{>120}\mu m$
Dependence on Impact Parameter

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- Kaon and pion fractions much lower in IP>120µm sample
- HF fraction increases from ~50% → ~90%
- Even inclusive muon asymmetry significantly different from BG expectation for IP>120µm

Measured asymmetry larger in $B^0_d$ suppressed sample, but too early to make strong conclusions.
Conclusions

• Dimuon asymmetry offers a tantalizing possibility for BSM physics in B meson mixing:
  o Current measurement inconsistent with SM at the ~4σ level
  o D0 already planning next update with more use of IP information
  o Need independent confirmation from other experiments.

• Further studies ongoing in exclusive decay modes to extract flavor-specific asymmetries in B^0 and B^0_s systems.

• We thank the community for their interest and ideas.

[arXiv:1106.6308 [hep-ex] (accepted by PRD one week ago, 23rd August 2011)]