Charge Asymmetries in Semileptonic B Decays

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for the D0 Collaboration

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Anomalous like-sign dimuon asymmetry

\[ Y \]

\[ \mu^+ \]

\[ B^0 \]

\[ \overline{B}^0 \]

\[ B^0 \]

\[ \mu^+ \]

\[ X \]

\[ A^b_{sl} \equiv \frac{N^{++}_b - N^{--}_b}{N^{++}_b + N^{--}_b} \]

\[ = C_d a^{d}_{sl} + C_s a^{s}_{sl} \]

where \( a^q_{sl} = \frac{\Delta \Gamma_q}{\Delta M_q} \tan \phi_q \)

arxiv.org:1106.6308 PRD 84 052007 (2011)

\[ C_d(s) \] is the fraction of \( B_d(B_s) \) events in the data sample.
D0 - Dimuon Charge Asymmetry

\[ A_{sl}^b = (-0.787 \pm 0.172 \text{(stat)} \pm 0.093 \text{(syst)}) \% \]

- Anomalous Dimuon - 3.9\( \sigma \) deviation from SM expectations
- Split the data (blue band, grey band):
  \[ a_{sl}^d = (-0.12 \pm 0.52) \% , \]
  \[ a_{sl}^s = (-1.81 \pm 1.06) \% . \]

- Need to investigate in as many different ways as possible.

**SM Prediction**

\[ a_{sl}^d = (-4.1 \pm 0.6) \times 10^{-4} , \]
\[ a_{sl}^s = (1.9 \pm 0.3) \times 10^{-5} . \]

(arXiv:1102.4274)

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Semi-leptonic Charge asymmetries

\[ a_{sl}^q = \frac{\Gamma (\bar{B}_q^0 \to B_q^0 \to \ell^+ \nu X) - \Gamma (B_q^0 \to \bar{B}_q^0 \to \ell^- \bar{\nu} \bar{X})}{\Gamma (\bar{B}_q^0 \to B_q^0 \to \ell^+ \nu X) + \Gamma (B_q^0 \to \bar{B}_q^0 \to \ell^- \bar{\nu} \bar{X})}, \]

\[ a_{sl}^q = \frac{A - A_{bg}}{F_{osc}^{B_q^0}} \]

\[ A = \frac{N(\mu^+ D_q^{(*)-}) - N(\mu^- D_q^{(*)+})}{N(\mu^+ D_q^{(*)-}) + N(\mu^- D_q^{(*)+})} \]

- Use lepton charge to identify the B-meson flavour
- Correct for detector and physics background asymmetries
- Scale by the fraction of mixed events (using MC simulations)
- Assume no production asymmetry, no direct CP violation in charged D-mesons or B-meson semileptonic decay, only CP violation in mixing for B mesons.
Kaon Corrections

- $K^+$ and $K^-$ have very different interaction cross sections

- Use the decay $K^* \rightarrow K\pi$ to measure the asymmetry as a function of momentum and $\eta$

![Graph showing $a_K$ as a function of $p(K)$ for different $|\eta(K)|$ ranges.]

$D_0$ 10.4 fb$^{-1}$, Preliminary
Residual Muon and Track Asymmetries

- The residual muon $p_T$ dependent reconstruction asymmetry between +ve and -ve tracks is measured using $J/\psi \rightarrow \mu\mu$ in a tag and probe analysis.

- Tracking asymmetry studied with $K_s \rightarrow \pi\pi$, $K^* \rightarrow K_s\pi$, plus other resonances showing no measurable correction

- See $<$0.05% effects in MC for pions - apply as a systematic
\[ a_{s1} \text{ in } B_s^0 \rightarrow \mu^+ D_s^- \]

- Select Data Sample from 10.4 fb^{-1}
- Extract raw asymmetry by fitting \( D_s \) resonance in the invariant mass spectrum:

\[
A = \frac{N_{\mu^+ D_s^-} - N_{\mu^- D_s^+}}{N_{\mu^+ D_s^-} + N_{\mu^- D_s^+}},
\]

- Correct for residual muon and tracking reconstruction asymmetries.
- Correct for dilution.
- Unblind after corrections are finalised

\[
a_{s1} = \frac{A - A_\mu - A_{\text{track}}}{F_{B_s^0 \text{osc}}},
\]

No need for kaon correction
The raw asymmetry $A$

- Non-lifetime biasing cuts + Log Likelihood ratio cut
- Blinded sensitivity tests performed
- Sum and difference fitted simultaneously

$F(\text{sum}) = F_s(D_s) + F_s(D) + F_b$

$F(\text{diff}) = AF_s(D_s) + A_DF_s(D) + A_bF_b$

$$A = [-0.40 \pm 0.33 \text{ (stat.)} \pm 0.05 \text{ (syst.)}] \%.$$  

- Apply corrections of

$$A_{bg} = [0.11 \pm 0.06 \text{ (syst.)}] \%.$$
Dilution - \((B_{s/d})\)

- Model \(\mu D_q\) events with Pythia, EvtGen, & Geant
- Weight events to match
  - \(B\) meson lifetimes and mixing parameters
  - \(B_s\) fraction that have mixed is essentially 50%.
  - In \(B_s\) analysis contamination from oscillated \(B_d\)'s is 0.5% (assuming a 1% asymmetry in \(B_d\) implies a 0.005% effect)

\[
P(B_s^0 \rightarrow \bar{B}_s^0) = \frac{1}{2} \left[ 1 - \frac{\cos(\Delta M_s \cdot t)}{\cosh(\Delta \Gamma_s \cdot t)} \right], \quad P(B_d^0 \rightarrow \bar{B}_d^0) = \frac{1}{2} \left[ 1 - \frac{\cos(\Delta M_d \cdot t)}{\cosh(\Delta \Gamma_d \cdot t)} \right]
\]

\[
F^{OSC}_{B_s^0} = 0.465 \pm 0.017
\]
\[ a_{s1}^s = \left[ -1.08 \pm 0.72 \text{ (stat)} \pm 0.17 \text{ (syst)} \right] \% , \]

- World’s best measurement
- Consistent with like-sign dimuon result
- Submitted to PRL and will appear on arXiv on Sunday night

http://www-d0.fnal.gov/Run2Physics/WWW/results/final/B/B12D/
Comparison with LHCb

- New preliminary LHCb result released today
  \[ a_{s_{l}}^{s}(\text{LHCb}) = (-0.24 \pm 0.63) \% \]

- All results are consistent
  - \( \chi^2 = 0.77/1 \) dof for \( a_{s_{l}}^{s} \) combination

- Average of \( B_{s}^0 \rightarrow \mu^{+}D_{s}^{-} \)
  \[ a_{s_{l}}^{s}(B_{s}^0 \rightarrow \mu D_{s}) = (-0.60 \pm 0.48) \% \]
$a^{d_{sl}}$ in $B_d^0 \rightarrow \mu^+ D^{(*)-}$

- Measure $a^{d_{sl}}$ in two channels in a binned lifetime analysis.

$B_d^0 \rightarrow \mu^+ \nu D^- X$

$B_d^0 \rightarrow \mu^+ \nu D^{*--} X$

- Lifetime Bins

<table>
<thead>
<tr>
<th>Bin Range</th>
<th>B0 Lifetime (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.10 - 0.00</td>
<td></td>
</tr>
<tr>
<td>0.00 - 0.02</td>
<td></td>
</tr>
<tr>
<td>0.02 - 0.05</td>
<td></td>
</tr>
<tr>
<td>0.05 - 0.10</td>
<td></td>
</tr>
<tr>
<td>0.10 - 0.20</td>
<td></td>
</tr>
<tr>
<td>0.20 - 0.60</td>
<td></td>
</tr>
</tbody>
</table>
\( a^d_{s1} \) in \( B_d^0 \rightarrow \mu^+ D^{(*)-} \)

- Measure \( a^d_{s1} \) in two channels in a binned lifetime analysis.

\[
B_d^0 \rightarrow \mu^+ \nu D^- X \quad \quad \quad \quad \quad \quad \quad B_d^0 \rightarrow \mu^+ \nu D^{*-} X
\]

- Use the first two lifetime bins as a control region to test corrections as expect no mixing.
Mass Distributions - 0.10 - 0.20 cm

$B_d^0 \rightarrow \mu^+ \nu D^- X$

$B_d^0 \rightarrow \mu^+ \nu D^*- X$

D0 10.4 fb$^{-1}$, Preliminary

$N(\mu D^0) / 4$ MeV/c$^2$

$N(\mu^+ D^-) / 0.5$ MeV/c$^2$

$\Delta M = M(K_{\pi\pi}D) - M(K_{\pi\pi})$ (GeV/c$^2$)

D0 10.4 fb$^{-1}$, Preliminary

$N(\mu^+ D^0) / 4$ MeV/c$^2$

$N(\mu^+ D^*) / 0.5$ MeV/c$^2$

$\Delta M = M(K_{\pi\pi}D^*) - M(K_{\pi\pi})$ (GeV/c$^2$)
Extract $a_{s1}^d$ 

$B_d^0 \rightarrow \mu^+ \nu D^- X$

$B_d^0 \rightarrow \mu^+ \nu D^{*-} X$

$A - A_{BG}$

$F_{B-osc} \times a_{s1}^d$

Asymmetry ($\%$)  

$0$  

$0.1$  

$0.2$  

$0.3$  

$0.4$  

$0.5$  

$0.6$

VPDL$(B^0)$ (cm)

$-0.1$  

$0$  

$0.1$  

$0.2$  

$0.3$  

$0.4$  

$0.5$  

$0.6$

D0 10.4 fb$^{-1}$, Preliminary

$A_{s1}^d (\mu D) = [0.53 \pm 0.63 \text{ (stat.)} \pm 0.16 \text{ (syst.)}] \%$

$A_{s1}^d (\mu D^*) = [1.32 \pm 0.62 \text{ (stat.)} \pm 0.16 \text{ (syst.)}] \%$

Weighted Average

$A_{s1}^d = [0.93 \pm 0.45 \text{ (stat.)} \pm 0.14 \text{ (syst.)}] \%$
Combination of D0 Results

- Combine all three D0 measurements (including correlations)

\[
\begin{align*}
\alpha_{s1}^s &= (-1.81 \pm 0.56) \% \\
\alpha_{s1}^d &= (0.22 \pm 0.30) \% \\
\rho &= -0.50
\end{align*}
\]

- p-value(SM) = 0.29\% 3.0 standard deviations

\[
\chi^2 = 4.66/2 \text{ dof}
\]

- \(a_{s1}^s\) is 3.2 standard deviations from zero
Including B-Factory $a_{sl}^d$

- Average new D0 result with HFAG PDG 2012 average of B-Factory results: $a_{sl}^d = (-0.05 \pm 0.56)\%$ \text{arXiv:1207.1158}

- Combination of two values of $a_{sl}^d$ has $\chi^2 = 1.79$ so we scale up the uncertainty

- Combine with D0 dimuon and $a_{sl}^s$

  \[
  a_{sl}^s = (−1.63 \pm 0.56)\%
  \]
  \[
  a_{sl}^d = (0.02 \pm 0.30)\%
  \]
  \[
  \rho = −0.51
  \]

- $p$-value(SM) = 0.26\%, $\chi^2 = 2.06/2$ dof 2.90 standard deviations from SM

\[
\begin{align*}
  a_{sl}^d & = (−0.12 \pm 0.52)\%, \\
  a_{sl}^s & = (−1.81 \pm 1.06)\%.
\end{align*}
\]
• Presented new measurements of $a_{s_{1}}^{d}$ and $a_{s_{1}}^{s}$ in exclusive final states.

• Both are the world’s most precise single experiment measurements.

\[ a_{s_{1}}^{s} = [-1.08 \pm 0.72 \text{ (stat)} \pm 0.17 \text{ (syst)}] \% , \]

\[ a_{s_{1}}^{d} = [0.93 \pm 0.45 \text{ (stat.)} \pm 0.14 \text{ (syst.)}] \% \]

• Both measurements are consistent with the anomalous like-sign dimuon charge asymmetry

• Combined value of $a_{s_{1}}^{s}$ is significantly different from the SM (-1.63 \pm 0.56)\% : 2.91 standard deviations from zero.

• Final update on anomalous like-sign dimuon asymmetry this summer (effectively doubling statistics for IP measurement).
• Combine with D0 and B-Factory average $a_{sI}^d$.

\[ a_{sI}^s = (-1.02 \pm 0.42) \% \]
\[ a_{sI}^d = (-0.15 \pm 0.29) \% \]
\[ \rho = -0.40 \]

• $p$-value(SM) = 1.3%
2.5 standard deviations

\[ \chi^2 = 4.00/2 \text{ dof} \]

• $a_{sI}^s$ is 2.5 standard deviations from zero
Backup
Combination Details

- Page 15: Only using D0 Results
  
  - Make full use of the correlations between uncertainties of the IP dependence of the like sign dimuon anomalous like-sign dimuon charge asymmetry.
  
  - The $a_{s1}^{d}$ and $a_{s1}^{s}$ measurements are assumed to be independent as they are dominated by the statistical uncertainty (There is correlation in some of the systematic uncertainties).

\[
a_{s1}^{q} = \frac{|p/q|_{d(s)}^{2} - |q/p|_{d(s)}^{2}}{|p/q|_{d(s)}^{2} + |q/p|_{d(s)}^{2}}
\]
• Page 16: D0 Anomalous Dimuon Asymmetry, D0 $a_{d_{sl}}$ and $a_{s_{sl}}$ and B-factory combination of $a_{d_{sl}}$.

• We combine the D0 and B-Factory values of $a_{d_{sl}}$ before carrying out the 2-D combination.

• Combination of two values of $a_{d_{sl}}$ has $\chi^2 = 1.79$ so we scale up the uncertainty by $\sqrt{(1.79)}$ as is used in the PFG. I.e. $\sqrt{(1.79)} \times 0.36\% = 0.48\%$

• The combined D0 and B-Factory values of $a_{d_{sl}}$ is:

$$ a_{s_{sl}}^d = (0.52 \pm 0.48)\% $$
Combination Details

- Page 16: D0 Anomalous Dimuon Asymmetry, D0 $a_{\text{sl}}^d$ and $a_{\text{sl}}^s$ and B-factory combination of $a_{\text{sl}}^d$.

- Current HFAG average has uncertainties of $a_{\text{sl}}^d$: 0.33% and $a_{\text{sl}}^s$: 0.64% including previous D0 measurements.

- Our combination

$$a_{\text{sl}}^s = (-1.63 \pm 0.56)\%$$
$$a_{\text{sl}}^d = (0.02 \pm 0.30)\%$$
$$\rho = -0.51$$

$$|q/p|_s = 1.0082 \pm 0.0028$$
$$|q/p|_d = 0.9999 \pm 0.0015$$
• HFAG PDG 2012 average of B-Factory results:
  \( a_{sl}^d = (-0.05 \pm 0.56)\% \)

\[
\begin{align*}
  a_{sl}^s &= (-0.88 \pm 0.42)\% \\
  a_{sl}^d &= (-0.37 \pm 0.30)\% \\
  \rho &= -0.42
\end{align*}
\]

• p-value(SM) = 0.69% 2.7 standard deviations
  \( \chi^2 = 1.57/2 \text{ dof} \)

• \( a_{sl}^s \) is 2.1 standard deviations from zero