Anomalous like-sign dimuon charge asymmetry

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Last year result

- DØ Collaboration reported last year the evidence of anomalous like-sign dimuon charge asymmetry using 6.1 fb\(^{-1}\) of data

\[
A_{s}^{b} = \frac{N_{b}^{++} - N_{b}^{--}}{N_{b}^{++} + N_{b}^{--}}
\]

- \(N_{b}^{++}, N_{b}^{--}\) – number of events with two \(b\) hadrons decaying semileptonically and producing two muons of the same charge

\[
A_{s}^{b} = (-0.957 \pm 0.251 \text{ (stat)} \pm 0.146 \text{ (syst)})\%
\]

\[
A_{s}^{b}(SM) = (-0.023^{+0.005}_{-0.006})\%
\]

- Differs from SM prediction by 3.2\(\sigma\)

- Result can also be presented in terms of semileptonic charge asymmetries of \(B^0\) and \(B^0_s\) mesons: \(a_{s}^{d}\) and \(a_{s}^{s}\)
Main features of measurement

- Measure raw like-sign dimuon charge asymmetry $A$ and raw inclusive muon charge asymmetry $a$:
  \[
  A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}} \quad \text{and} \quad a \equiv \frac{n^+ - n^-}{n^+ + n^-}
  \]
  - $N^{++}, N^{--}$ – the number of events with two like-sign dimuons
  - $n^+, n^-$ – the number of muons with given charge

- Background (i.e., non-CP violating charge asymmetry, mainly produced by $\pi \to \mu$ and $K \to \mu$ decays) is measured directly in data

- Raw asymmetry $a$ is determined mainly by the background contribution and is used to constraint the background and reduce systematic uncertainties

- Raw asymmetry $A$ contains both the background and possible signal contribution and is used to measure $A_{sl}^b$
In this updated measurement:

- Increased statistics 6.1 fb\(^{-1}\) → 9.0 fb\(^{-1}\)
- Improved muon selection
  - 13% increase of statistics for the same integrated luminosity
  - 20% reduction of background from K → \(\mu, \pi \rightarrow \mu\) decays
- Improved analysis technique
- Study dependence of asymmetry on muon impact parameter

Cut on muon \(|p_z|\) changed from 6.4 to 5.4 GeV (shown as a dashed line). Smallest muon momentum required for detection by the muon system (solid line).
New result

• We get for 9.0 fb⁻¹:

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

• Consistent with our previous measurement with 6.1 fb⁻¹
• Deviates from the SM prediction by 3.9 \( \sigma \)
\( \alpha_{sl}^d \) and \( \alpha_{sl}^s \) contributions

- Asymmetry \( A_{sl}^b \) is a linear combination of \( \alpha_{sl}^d \) and \( \alpha_{sl}^s \) — semileptonic charge asymmetries of \( B^0 \) and \( B^0_s \)

\[
A_{sl}^b = C_d \alpha_{sl}^d + C_s \alpha_{sl}^s
\]

- Coefficients \( C_d \) and \( C_s \) depend on mean mixing probability and the production fractions of \( B^0 \) and \( B^0_s \) mesons, respectively

- We use the values of \( B^0 \) and \( B^0_s \) fractions measured at LEP and averaged by HFAG
  - Measurements of production fractions at LEP are consistent with the values obtained at LHCb

\[
C_d = 0.594 \pm 0.022 \\
C_s = 0.406 \pm 0.022
\]
\(a_{sl}^d\) and \(a_{sl}^s\) contributions

- New constraint in \(a_{sl}^d\) versus \(a_{sl}^s\) plane
- Result is consistent with other measurements of \(a_{sl}^d\) and \(a_{sl}^s\)
Closure test

- The raw inclusive muon charge asymmetry $a$ is mainly determined by the background asymmetry $a_{bkg}$.
- The contribution of $A^b_{sl}$ in $a$ is suppressed by factor $k = 0.031 \pm 0.003$.
- We measure $a_{bkg}$ in data, and we can verify how does it describe the observed raw asymmetry $a$.
- We compare $a$ and $a_{bkg}$ as a function of muon $p_T$.
- We get $\chi^2$/dof = 0.8/6 for the difference between these two distributions.

Excellent agreement between the expected and observed values of $a$, including a $p_T$ dependence.
Dependence on muon impact parameter

- Muons from $\pi \to \mu$ and $K \to \mu$ have small impact parameter (IP)
  - When the decay is outside the tracking volume
  - Hadrons mainly come from primary interaction
- Muons from B decays have large impact parameter
- To test the origin of dimuon charge asymmetry we perform two complimentary measurements requiring
  - IP > 120 $\mu$m for both muons
  - IP < 120 $\mu$m for both muons
$a_{sl}^d$ and $a_{sl}^s$ contributions

• The contributions of $a_{sl}^d$ and $a_{sl}^s$ in $A_{sl}^b$ changes significantly when we select muons with IP above or below given threshold:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP &gt; 120 μm</td>
<td>$A_{sl}^b = (0.728 \pm 0.018)a_{sl}^d + (0.272 \pm 0.018)a_{sl}^s$</td>
</tr>
<tr>
<td>IP &lt; 120 μm</td>
<td>$A_{sl}^b = (0.397 \pm 0.022)a_{sl}^d + (0.603 \pm 0.022)a_{sl}^s$</td>
</tr>
</tbody>
</table>

• These contributions are determined by the mean mixing probability of $B^0$ and $B^0_s$ in the selected sample.
\( a_{sl}^d \) and \( a_{sl}^s \) contributions

- Mean mixing probability of \( B^0 \) increases in the subsample of events with IP > 120 \( \mu m \)
  - Period of \( B^0 \) oscillation \( 2\pi/\Delta M_d \) is much larger than its lifetime, therefore muons with small impact parameter (IP < 120 \( \mu m \)) are dominantly produced by non-oscillating decays of \( B^0 \)
  - Selecting events with IP>120 \( \mu m \) we increase the fraction of oscillating \( B^0 \)
  - Fraction of oscillating \( B^0_s \) mesons does not change for IP>120 \( \mu m \) because of small period of \( B^0_s \) oscillation

![Normalized IP distribution for muons produced in oscillating decays of \( B^0 \) and \( B^0_s \)]
Results with IP cuts

- We obtain:

\[
\begin{align*}
&\text{for IP > 120 }\mu\text{m} \quad A_{sl}^b = (-0.579 \pm 0.210 \pm 0.094)\% \\
&\text{for IP < 120 }\mu\text{m} \quad A_{sl}^b = (-1.14 \pm 0.37 \pm 0.32)\% 
\end{align*}
\]

- From these results we get the separate values of \( a_{sl}^d \) and \( a_{sl}^s \):

\[
\begin{align*}
a_{sl}^d &= (-0.12 \pm 0.52)\% \\
a_{sl}^s &= (-1.81 \pm 1.06)\%
\end{align*}
\]
Conclusions

• New measurement of dimuon charge asymmetry is performed

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

• This result deviates from the SM prediction by 3.9\sigma

• Dependence of charge asymmetry on muon impact parameter tested

\[
\begin{align*}
\text{for IP} & > 120 \ \mu\text{m} & \quad A_{sl}^b &= (-0.579 \pm 0.210 \pm 0.094)\% \\
\text{for IP} & < 120 \ \mu\text{m} & \quad A_{sl}^b &= (-1.14 \pm 0.37 \pm 0.32)\%
\end{align*}
\]

• From IP study we obtain the measurement of \( a_{sl}^d \) and \( a_{sl}^s \):

\[
\begin{align*}
\alpha_{sl}^d &= (-0.12 \pm 0.52)\% \\
\alpha_{sl}^s &= (-1.81 \pm 1.06)\%
\end{align*}
\]

• Result is consistent with the hypothesis that the dimuon charge asymmetry is produced in semileptonic B decays
Improved analysis technique

- Main background comes from $K \rightarrow \mu$ decays
- The most important quantity is $R_K = F_K / f_K$ – ratio of the fractions of $K \rightarrow \mu$ in the like-sign dimuon and inclusive muon samples
- Previously determined by measuring production of $K^{*0} \rightarrow K^+ \pi^-$ decays with $K \rightarrow \mu$ in the like-sign dimuon and inclusive muon samples
- Perform a complementary measurement using the production of $K_S \rightarrow \pi^+ \pi^-$ with $\pi \rightarrow \mu$
- Results in both channels are consistent
  \[ \Delta R_K = 0.01 \pm 0.05 \]
- Important confirmation of the validity of $F_K / f_K$ measurement

\[ \text{Difference between } R_K \text{ values measured using } K^{*0} \text{ and } K_S \text{ events} \]
Consistency checks

- Repeat closure test in bins of $|\eta|$ 
  - $\chi^2$/dof = 2.8/4

- Dependence of the dimuon asymmetry on the dimuon mass
  - Good consistency of predicted and observed asymmetry for measured $A_{#text{sl}}^b$
  - Significant disagreement for $A_{#text{sl}}^b = A_{#text{sl}}^b (\text{SM})$