Measurement of CP observables in semileptonic decays at LHCb

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Neutral B meson mixing

• Oscillation and decay description:

\[ \frac{d}{dt} \left( \begin{array}{c} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{array} \right) = \left( \begin{array}{cc} M_{11} - i \frac{\Gamma_{11}}{2} & M_{12} - i \frac{\Gamma_{12}}{2} \\ M_{12}^* - i \frac{\Gamma_{12}^*}{2} & M_{22} - i \frac{\Gamma_{22}}{2} \end{array} \right) \left( \begin{array}{c} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{array} \right) \]

• Mass eigenstates are superpositions of flavor eigenstates:

\[ |B_L\rangle = p|B_q\rangle + q|\bar{B}_q\rangle \]
\[ |B_H\rangle = p|B_q\rangle - q|\bar{B}_q\rangle \]

• Mixing observables

\[ \Delta m = m_H - m_L \]
\[ \Delta \Gamma = \Gamma_L - \Gamma_H \]
CP violation in B meson mixing

• Oscillation and decay description

\[ i \frac{d}{dt} \begin{pmatrix} |B_q(t)\rangle \\ \overline{B_q}(t) \end{pmatrix} = \begin{pmatrix} M_{11} - i \frac{\Gamma_{11}}{2} & M_{12} - i \frac{\Gamma_{12}}{2} \\ M^{*}_{12} - i \frac{\Gamma^{*}_{12}}{2} & M_{22} - i \frac{\Gamma^{*}_{22}}{2} \end{pmatrix} \begin{pmatrix} |B_q(t)\rangle \\ \overline{B_q}(t) \end{pmatrix} \]

• Mass eigenstates are superpositions of flavor eigenstates

\[ |B_L\rangle = p|B_q\rangle + q|\overline{B_q}\rangle \]
\[ |B_H\rangle = p|B_q\rangle - q|\overline{B_q}\rangle \]

• Mixing observables

\[ \Delta m = m_H - m_L \]
\[ \Delta \Gamma = \Gamma_L - \Gamma_H \]

\[ a = 1 - \left| \frac{q}{p} \right| \]

Measures CP violation in mixing

\[ \mathcal{P}(\overline{B} \to B) \neq \mathcal{P}(B \to \overline{B}) \]

sensitive probe of New Physics
Semileptonic CP asymmetries

- Using semileptonic flavor specific B decays:

\[ a_{sl} = a = \frac{N(\bar{B} \to B \to f) - N(B \to \bar{B} \to \bar{f})}{N(\bar{B} \to B \to f) + N(B \to \bar{B} \to \bar{f})} \]

- SM predictions:

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

- Experimental status:

... 2013: ”Study of CP-violating charge asymmetries of single muons and like-sign dimuons in \( p\bar{p} \) collisions”, DØ, Phys. Rev. D 89, 012002.

\(~3\sigma\) tension with the SM

SM ? …or DØ di-muon analysis like?

- In this talk:

reminder of \( a_{sl}^s \) measurement from LHCb using 1 fb\(^{-1}\) of data

\( a_{sl}^d \) measurement from LHCb using 3 fb\(^{-1}\) of data
LHCb

Single-arm forward spectrometer at LHC collider

- ~25 kHz $b\bar{b}$ pairs, ~500 kHz $c\bar{c}$ pairs produced in the forward region

Large samples of semileptonic $B$ decays

- Analysis based on tracking and muon system + RICH detectors to identify charged hadrons

- Magnet polarity is reversed frequently (useful to understand first order left-right detection asymmetries)

- $pp$ collisions: $B$ mesons production asymmetry

$$A_P = \frac{\sigma(\bar{B}) - \sigma(B)}{\sigma(\bar{B}) + \sigma(B)}$$
**Measurement**

$$B_s^0 \rightarrow D_s \mu \nu \mu X$$

- Untagged, time integrated semileptonic asymmetry:
  
  $$A_{\text{meas}} = \frac{\Gamma(D_s^- \mu^+) - \Gamma(D_s^+ \mu^-)}{\Gamma(D_s^- \mu^+) + \Gamma(D_s^+ \mu^-)} = \frac{a_{s1}^s}{2} + A_D \left( A_P + \frac{a_{s1}^s}{2} \right) \frac{\int e^{\Gamma s t} \cos(\Delta m_s t) \epsilon(t) dt}{\int e^{\Gamma s t} \cosh(\Delta \Gamma_s t / 2) \epsilon(t) dt}$$
  
  $$\sim 10^{-4}$$

- Fast $B_s^0$ oscillation dilutes second term below precision of this measurement
- Signal yields for each charge extracted from KKπ invariant mass distributions
- Correct raw asymmetry for detection and background asymmetries
- See Basem Khanji’s talk tomorrow
Result

\[ L = 1 \text{ fb}^{-1} \]

\[ a_{s1}^s = (-0.06 \pm 0.50^{\text{stat}} \pm 0.36^{\text{syst}})\% \]

**SM!**


3 fb\(^{-1}\) Measurement Coming Soon...
Measurement: analysis strategy

• Untagged, time dependent, charge asymmetry of the final state particles:

\[ A_{\text{meas}}(t) = \frac{\Gamma(f, t) - \Gamma(f', t)}{\Gamma(f, t) + \Gamma(f', t)} = \frac{a_{s1}^d}{2} + (A_D) - \left( A_P + \frac{a_{s1}^d}{2} \right) \frac{\cos(\Delta m dt)}{\cosh(\Delta \Gamma dt/2)} \]

• Time-dependent fit to disentangle the \( CP \) violating asymmetry from the \( B^0 \) production asymmetry

• Independent determination of the detection asymmetries with control samples
Detection asymmetries

- Data samples: \( B^0 \rightarrow D^{\pm} \mu^{\mp} \nu_\mu \) and \( B^0 \rightarrow D^{\ast \pm} \mu^{\mp} \nu_\mu \) decays collected in 2011 and 2012.

Detection asymmetry of the final state:

\[
A_D = \frac{\epsilon(\mu^+ K^+ \pi^- \pi^-) - \epsilon(\mu^- K^- \pi^+ \pi^+)}{\epsilon(\mu^+ K^+ \pi^- \pi^-) + \epsilon(\mu^- K^- \pi^+ \pi^+)}
\]

\[
A_D = A_{\mu \pi} + A_{K \pi}
\]

\( N_{\text{signal}} = 1.8 \text{M} \)

\( N_{\text{signal}} = 0.34 \text{M} \)
μπ detection asymmetry

- Transverse momentum dependence of the tracking efficiencies
  
  re-weight the data sample to obtain a good overlapping kinematic phase space between μ and π. Residual asymmetry (0.00 +/- 0.02)%

- Muon-ID and trigger asymmetries: A tag-and-probe method is applied to $J/\psi \rightarrow \mu\mu$ decays

Few per-mille corrections, depending on run period, magnet polarity. **Overall uncertainty 0.04%**
**Kπ detection asymmetry**

- Using prompt D+ decays into Kππ and K_Sπ

\[ A_{K\pi} \equiv \frac{\epsilon(K^+\pi^-) - \epsilon(K^-\pi^+)}{\epsilon(K^+\pi^-) + \epsilon(K^-\pi^+)} \]

\[ = A(D \rightarrow K\pi\pi) - A(D \rightarrow K_S\pi) - A(K_S) \]

- Re-weighting needed to map: the Kπ pair of the control sample to match the signal, the D kinematics to cancel the D production asymmetry, the pion in the two control samples.

- Neutral kaon asymmetry: \( A(K_S) = (0.054 \pm 0.011)\% \)

\[ A_{K\pi} = (1.15 \pm 0.08(\text{stat}) \pm 0.07(\text{syst}))\% \]

 Reweighted (for the D+ mode)

- Main contribution: nuclear kaon interaction, the method accounts for all possible sources of detection asymmetry
Time dependent fit: B decay time and Resolutions

- The momentum of the B meson cannot be measured precisely due to the partial reconstruction of the decay.
- The B decay time is corrected using the factor:
  \[ k = \frac{p_{\text{reco}}}{p_{\text{true}}} \]
- The k-factors are also used to model the decay time resolution:

\[ t = \frac{L \cdot M_{PDG}}{|\vec{p}|} \cdot k_{av}(M) \]

- Similar method used for \( \Delta m_{d,s} \) measurement using semileptonic B decay

\[ \mathcal{P}_{\text{sig}} = (T(t) \otimes_t R(t) \otimes_k F(k)) \cdot A(t) \]
Time dependent fit: the full picture

- Time-dependent binned maximum likelihood fit to:

- The analysis is performed independently on magnet polarity and year datasets

- Main background: $B^+ \rightarrow D^{(*)-} \mu^+ X^+$ external input for the detection asymmetries and the $B^+$ production asymmetry
Backgrounds

- **Main background:** \[ B^+ \rightarrow D^{(*)-} \mu^+ X^+ \]
  
  Branching fractions and shapes are taken from simulation and measured Branching Fractions.

  \[
  f_{B^+}(D^{*-} \mu^+ X^+) = (8.8 \pm 2.2)\% \quad f_{B^+}(D^- \mu^+ X^+) = (12.7 \pm 2.2)\% 
  \]

  B+ production asymmetry from LHCb measurement using \( B^+ \rightarrow J/\psi K^+ \) decays \( \text{arXiv:1408.0978} \) corrected by the CP asymmetry \( \text{(PDG 2014)} \)

  \[
  A_P(B^+) = (-0.6 \pm 0.6)\% 
  \]

- **Other backgrounds:** \[ \Lambda_b^0 \rightarrow D^{(*)-} \mu^+ X_n \]

  \[
  f_{\Lambda_b^0} \sim 2\% 
  \]

  from production ratio, \( \text{Phys. Rev.D85 (2012) 032008} \)

  efficiency ratio

  branching ratio of \( \Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \) and \( \Lambda_b^0 \rightarrow D^0 p \pi^- \)
  \( \text{Phys. Rev.D89 (2014) 032001} \)

  \[
  A_P(\Lambda_b^0) \sim (-0.9 \pm 1.5)\% 
  \]

  raw asymmetry in \( \Lambda_b^0 \rightarrow J/\psi p K^+ \)
  subtracting kaon and proton detection asymmetries \( \text{JHEP 07(2014) 103} \)
Systematic uncertainties

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$a^d_{sl}$</th>
<th>$A_P(7,\text{TeV})$</th>
<th>$A_P(8,\text{TeV})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection asymmetry</td>
<td>0.26</td>
<td>0.20</td>
<td>0.14</td>
</tr>
<tr>
<td>$B^+$ background</td>
<td>0.13</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>$\Lambda_b^0$ background</td>
<td>0.07</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>$B_s^0$ background</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Combinatorial $D$ background</td>
<td>0.03</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$k$-factor distribution</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Decay time acceptance</td>
<td>0.03</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>Knowledge on $\Delta m_d$</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Quadratic sum</td>
<td>0.30</td>
<td>0.22</td>
<td>0.17</td>
</tr>
</tbody>
</table>

- Leading contribution: uncertainty on the measurement of the detection asymmetries
- $B^+$ background second largest contribution. Different strategy foreseen for the future
- In general the systematics related to the fit model are small.

<table>
<thead>
<tr>
<th>Source</th>
<th>Statistical</th>
<th>Systematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{K\pi}$</td>
<td>0.18%</td>
<td>0.13%</td>
</tr>
<tr>
<td>$A_{\mu}^{trg,PTD}$</td>
<td>0.06%</td>
<td>0.06%</td>
</tr>
<tr>
<td>$A_{\pi}^{nucl}$</td>
<td></td>
<td>0.07%</td>
</tr>
<tr>
<td>$A_{\mu\pi}^{trk\ residual}$</td>
<td>0.04%</td>
<td></td>
</tr>
</tbody>
</table>

Example (for $D^+$ mode)
Results (I)

$\alpha_{s1}^d = (-0.02 \pm 0.19({\text{stat}}) \pm 0.30({\text{syst}}))\%$

$\alpha_{s1}^s = (-0.06 \pm 0.50({\text{stat}}) \pm 0.36({\text{syst}}))\%$

NEW preliminary

MOST PRECISE VALUE FROM A SINGLE MEASUREMENT

SM!!
Results (II)

\[ A_P(7 \text{ TeV}) = (-0.66 \pm 0.26(\text{stat}) \pm 0.22(\text{syst}))\% \]
\[ A_P(8 \text{ TeV}) = (-0.48 \pm 0.15(\text{stat}) \pm 0.17(\text{syst}))\% \]

USEFUL INPUT FOR OTHER CP ASYMMETRY MEASUREMENTS AT LHCb
Conclusions

• Measurements of the semileptonic CP asymmetry in the $B_s$ and $B_d$ sectors from LHCb have been shown today:

$$a_{s1}^s = (-0.06 \pm 0.50\,(\text{stat}) \pm 0.36\,(\text{syst}))\%$$
$$a_{s1}^d = (-0.02 \pm 0.19\,(\text{stat}) \pm 0.30\,(\text{syst}))\%$$

• Both measurements are in good agreement with the Standard Model

• The update of $a_{s1}^s$ using the full 3 fb$^{-1}$ of data is coming soon!

• Still room for improvement! (studies to improve the detection asymmetries determination on going, plan to include more decay modes....)
Backup slides
# Experimental status

<table>
<thead>
<tr>
<th>Exp. &amp; Ref.</th>
<th>Method</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO 1</td>
<td>Dileptons + partial hadronic</td>
<td>$a_{sl}^d = (1.4 \pm 4.1 \pm 0.6)%$</td>
</tr>
<tr>
<td>Belle 2</td>
<td>Dileptons</td>
<td>$a_{sl}^d = (-0.11 \pm 0.79 \pm 0.85)%$</td>
</tr>
<tr>
<td>BaBar 3</td>
<td>Full hadronic rec.</td>
<td>$a_{sl}^d = (-5.8 \pm 2.6 \pm 2.2)%$</td>
</tr>
<tr>
<td>BaBar 4</td>
<td>Dileptons</td>
<td>$a_{sl}^d = (0.16 \pm 0.54 \pm 0.38)%$</td>
</tr>
<tr>
<td>BaBar 5</td>
<td>Partial semilept.</td>
<td>$a_{sl}^d = (0.06 \pm 0.17^{+0.38}_{-0.32})%$</td>
</tr>
<tr>
<td>Average of $B$ factories above 6</td>
<td></td>
<td>$a_{sl}^d = (0.02 \pm 0.32)%$</td>
</tr>
<tr>
<td>D0 7</td>
<td>Partial semilept.</td>
<td>$a_{sl}^d = (0.68 \pm 0.45 \pm 0.14)%$</td>
</tr>
<tr>
<td>D0 8</td>
<td>Dimuon</td>
<td>$a_{sl}^d = (-0.62 \pm 0.42)%$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$a_{sl}^s = (-0.86 \pm 0.74)%$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\rho = -0.79$</td>
</tr>
<tr>
<td>D0 9</td>
<td>Partial semilept.</td>
<td>$a_{sl}^s = (-1.12 \pm 0.74 \pm 0.17)%$</td>
</tr>
<tr>
<td>LHCb 10</td>
<td>Partial semilept.</td>
<td>$a_{sl}^s = (-0.06 \pm 0.50 \pm 0.36)%$</td>
</tr>
<tr>
<td>Average of all measurements above 6</td>
<td></td>
<td>$a_{sl}^d = (-0.09 \pm 0.21)%$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$a_{sl}^s = (-0.77 \pm 0.42)%$</td>
</tr>
</tbody>
</table>

Stability checks

- The analysis is performed independently in (Up,Down)*(2011,2012)*(D+*D*)

- The detection asymmetries are statistically highly correlated in the two modes.

- More crosschecks documented in the analysis note

- For the final result: arithmetic average of the magnet polarities, weighted average of the years and decay modes)
Time dependent fit

- Time-dependent binned maximum likelihood fit to:

\[ P_{\text{sig}}(t, q) = N e^{-\Gamma_d t} \left( 1 \pm A_D \pm \frac{a_{sl}^d}{2} \pm \left( A_P + \frac{a_{sl}^d}{2} \right) \cos(\Delta m_d t) \right) \]

\[ P_{B+}(t, q) = N e^{-\Gamma_{u+t}} \left( 1 \pm A_{D,B+} \pm A_{P,B+} \right) \]

\[ P_{SB}(t, q) = N e^{-\Gamma_{SB}} \left( 1 \pm A_{D,SB} \pm A_{P,SB} \cos(\Delta m_{SB} t) \right) \]

+ Need to account for all resolution and acceptances

- External input for the detection asymmetries and the B+ production asymmetry