CP-violation in $B$ decays

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on behalf of the LHCb Collaboration

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The CKM matrix in the Wolfenstein parameterization is

$$\begin{pmatrix}
  1 - \lambda^2/2 & \lambda & A\lambda^3 (\bar{\rho} - i\bar{\eta}) \\
  -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
 A\lambda^3 (1 - \bar{\rho} - i\bar{\eta}) & -A\lambda^2 & 1
\end{pmatrix} + \mathcal{O}(\lambda^4)$$

Two $CP$-violating parameters of interest are

$$\beta = \arg\left[ -\frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*} \right], \quad \beta_s = \arg\left[ -\frac{V_{cs} V_{cb}^*}{V_{ts} V_{tb}^*} \right]$$
SM Unitarity

\[ (\bar{\rho}, \bar{\eta}) \]

\[ \sim \chi^2(-\bar{\rho}, -\bar{\eta}) \]

\[ \left| \frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right| \]

\[ \left| \frac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*} \right| \]

\[ (0, 0) \rightarrow (1, 0) \]

\[ \beta = 25.2^\circ \]

\[ \beta_s = -1.05^\circ \]
How do you measure this?

\[
\begin{align*}
B & \xrightarrow{V_{cd} V_{cb}^*} f_{CP} \\
& \xrightarrow{(V_{td} V_{tb}^*)^2} \bar{B} \\
& \xrightarrow{(V_{cd} V_{cb}^*)^*} \Rightarrow \phi = 2\beta
\end{align*}
\]

and equivalently for \(B \to B_s\), \(d \to s\), \(\beta \to \beta_s\) [1]

- \textit{CP}-violation in interference for \(b \to c\bar{c}s\) decays
- Experimentally/theoretically convenient “golden modes”
  \[\beta: \ B^0 \to J/\psi K^0_S\]
  \[\beta_s: \ B_s \to J/\psi \phi\]
What do you actually measure?

- Penguins add different phase at $O(\lambda^2)$
- U-spin symmetric processes can constrain $\Delta \phi(s)$
- New physics could introduce new phases in mixing or decay
LHCb Detector
What asymmetry is actually measured?

- The measured $CP$-asymmetry in events at decay time $t$ is diluted by time resolution and mistagging:

$$A_{\text{raw}}(t) = A_{\text{CP}}(t) \times D_{\text{resolution}} \times D_{\text{tagging}} \sim \frac{S \sin \Delta m t - C \cos \Delta m t}{\cosh \frac{\Delta \Gamma t}{2} + A \Delta \Gamma \sinh \frac{\Delta \Gamma t}{2}} \exp \left(-\frac{1}{2} \Delta m^2 \sigma_t^2 \right)$$

- Modified by production/reconstruction asymmetries
- Likelihood function also must account for
  - Lifetime distributions
  - Lifetime acceptance functions
Incorrectly tagged events dilute asymmetry and hurt precision

Effective reduction in statistical power $\epsilon_{\text{eff}}$

Currently at $\sim 3\%$ for $B^0$ and $3\%–5\%$ for $B_s$
$B^0 \to J/\psi K_S^0$ analysis

- $CP$-odd final state
- $A_{CP}(t) = S \sin \Delta mt - C \cos \Delta mt$, where
  
  $$S = \frac{2 |\lambda_{CP}| \sin \phi}{1 + |\lambda_{CP}|^2}, \quad C = \frac{1 - |\lambda_{CP}|^2}{1 + |\lambda_{CP}|^2}$$

- In the SM, $|\lambda_{CP}| \approx 1$ and so $S = \sin \phi \approx \sin 2\beta$ and $C = 0$
- Knowledge from $B$ factories (via HFAG):

<table>
<thead>
<tr>
<th></th>
<th>$S$</th>
<th>$C$</th>
<th>$\beta$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFAG</td>
<td>0.665 ± 0.024</td>
<td>−0.004 ± 0.015</td>
<td>20.8 ± 0.9</td>
</tr>
<tr>
<td>SM (CKMFitter)</td>
<td>0.771 ± 0.029</td>
<td>0</td>
<td>25.2 ± 1.3</td>
</tr>
</tbody>
</table>
$B^0 \to J/\psi K_S^0$ fit

Figure: Distribution of (a) the reconstructed mass and (b) logarithmic distribution of the decay time of tagged $B^0 \to J/\psi K_S^0$ candidates.
$B^0 \rightarrow J/\psi K^0_S$ results


Figure:
Projections of the fit and $s$Weight-ed data to $\bar{B} - B$ asymmetry

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$S$</th>
<th>$C$</th>
<th>$\rho(S, C)$</th>
<th>$\beta (^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb</td>
<td>$0.731 \pm 0.040$</td>
<td>$-0.038 \pm 0.032$</td>
<td>0.483</td>
<td>$24.7 \pm 1.8$</td>
</tr>
<tr>
<td>SM (CKMFitter)</td>
<td>$0.771 \pm 0.029$</td>
<td>—</td>
<td>—</td>
<td>$25.2 \pm 1.3$</td>
</tr>
</tbody>
</table>
$B_s \to J/\psi K^+ K^-$ analysis

- $K^+ K^-$ comes from $P$-wave $\phi + S$-wave (e.g. $f_0(980)$)
  - $J/\psi$ and $\phi$ have relative orbital angular momentum
  - $CP |\ell\rangle \propto (-1)^{\ell} \Rightarrow CP$-even/odd angular modes
  - Must unfold $3 + 1$ amplitudes $\Rightarrow 10$ angular modes

- Analyzed in bins of $m(K^+ K^-)$
  - Relative phase between $P$-/$S$-waves depends on $m(K^+ K^-)$
  - Trend can resolve $\Delta \Gamma \leftrightarrow -\Delta \Gamma$, $\phi_s \leftrightarrow \pi - \phi_s$ ambiguity
  - Previous study confirmed $\Delta \Gamma > 0$ and $\phi_s \sim 0$
Angular modes

where $S = \frac{2|\lambda_{CP}| \sin \phi_s}{1+|\lambda_{CP}|^2}$, $C = \frac{1-|\lambda_{CP}|^2}{1+|\lambda_{CP}|^2}$, and $A_{\Delta \Gamma} = -\frac{2|\lambda_{CP}| \cos \phi_s}{1+|\lambda_{CP}|^2}$
Angular acceptance

- Necessary to understand angular acceptance
- Relevant angles are in CM frames:

\[ \cos \theta_K, \cos \theta_\mu, \phi_h \]

![Diagram showing angular acceptance](image)

**LHCb simulation**

- **Muon \( p_T \) cuts**

\[ \theta_K, \theta_\mu, \phi_h \text{ [rad]} \]
$B_s \rightarrow J/\psi K^+ K^-$ fit and results

Figure: $CP$-even, $CP$-odd, and $S$-wave

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$\phi_s$ (mrad)</th>
<th>$\beta_s$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb [3]</td>
<td>$-58 \pm 49$</td>
<td>$-1.7 \pm 1.4$</td>
</tr>
<tr>
<td>SM (CKMFitter)</td>
<td>$-36.6 \pm 1.2$</td>
<td>$-1.05 \pm 0.04$</td>
</tr>
</tbody>
</table>
$B_s \rightarrow J/\psi \pi^+ \pi^-$ analysis

- Dominated by $CP$-odd scalar $f_0 \rightarrow \pi^+ \pi^-$ resonances
  - Small ($\sim 1\%$) $D$-wave $f_2(1270), f'_2(1525)$ components
  - Possible $P$-wave $\rho$ contribution $< 1.5\%$ at 95\% C.L.

- Updated measurement does angular analysis
  - As in $P$- vs. $S$-wave $K^+ K^-$, relative phase in interference
  - $m(\pi^+ \pi^-)$ modeled for Dalitz-plot formalism [4]

![Graphs showing decay time and angular distributions for $B_s \rightarrow J/\psi \pi^+ \pi^-$](image).
$B_s \rightarrow D^+_s D^-_s$ analysis

- $CP$-even final state
- $D_s$ is reconstructed in $KK\pi$, $K\pi\pi$, and $\pi\pi\pi$ channels
- BDT used to improve signal-to-background ratio

![Graphs showing $M(D^+_s D^-_s)$ distribution and decay time]

[6, arXiv:1409.4619 (hep-ex)]
HFAG has combined LHCb measurements with CDF, D0, CMS, and ATLAS results:

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<th>$\beta_s$ ($^\circ$)</th>
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<tr>
<td>LHCb $J/\psi K^+ K^-$ [3]</td>
<td>$-58 \pm 49$</td>
<td>$-1.7 \pm 1.4$</td>
</tr>
<tr>
<td>LHCb $J/\psi \pi^+ \pi^-$ [5]</td>
<td>$70 \pm 68$</td>
<td>$2.0 \pm 1.9$</td>
</tr>
<tr>
<td>LHCb $D_s^+ D_s^-$ [6]</td>
<td>$20 \pm 170$</td>
<td>$0.6 \pm 4.9$</td>
</tr>
<tr>
<td>HFAG</td>
<td>$-15 \pm 35$</td>
<td>$-0.6 \pm 1.1$</td>
</tr>
<tr>
<td>SM</td>
<td>$-36.6$</td>
<td>$-1.05$</td>
</tr>
</tbody>
</table>
$\phi_s$ Analyses

$B_s \rightarrow \phi\phi$ analysis

$\phi_s$ from $b \rightarrow c\bar{c}s$ and $b \rightarrow s\bar{s}s$ - is this the same angle?

- In SM, same (to $\mathcal{O}(\lambda^2)$) as tree-level $b \rightarrow c\bar{c}s$ transitions

- Penguin-dominated $b \rightarrow s\bar{s}s$ process is more sensitive to NP

- Rather than combining measurements . . .

- . . . better to keep separate and look for evidence of NP
$B_s \rightarrow \phi \phi$ fit and results

$B_s \rightarrow \phi \phi$ fit and results

**Table:**

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\phi_s$ (mrad)</th>
<th>$\beta_s$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s \rightarrow \phi \phi$ [7]</td>
<td>$-170 \pm 153$</td>
<td>$4.9 \pm 4.4$</td>
</tr>
<tr>
<td>$b \rightarrow c \bar{c}s$ average (HFAG)</td>
<td>$-15 \pm 35$</td>
<td>$0.6 \pm 1.1$</td>
</tr>
</tbody>
</table>

**Figure:** $CP$-even, $CP$-odd, and $S$-wave
Updated LHCb measurement of sin 2\(\beta\) with full 3 fb\(^{-1}\) is consistent with \(B\)-factory measurement and with the SM

New and updated measurements of \(\phi_s\) in the \(B_s \to J/\psi\phi, J/\psi\pi\pi\), and \(D_sD_s\) channels improve precision, remain compatible with the SM

Updated measurement of \(\phi_s\) in penguin-dominated \(B_s \to \phi\phi\) channel shows no deviation
Backup slides
Where do phases come from?

\[ e^{i\beta(s)} = -\frac{V_{cd(s)} V_{cb}^*}{V_{td(s)} V_{tb}^*} \]

\[ b \rightarrow c\bar{c}s \quad b \rightarrow c\bar{d} - \text{difficult} \]

\[ b \rightarrow c\bar{c}s \times K^0/\bar{K}^0 \text{ mixing} \]

\[ B(s)/\bar{B}(s) \text{ mixing} \]
Constraining penguin contributions

- Strong force invariant under “U-spin symmetry” $s \leftrightarrow d$
- Exchange spectator $s \leftrightarrow d$ and $b \rightarrow c\bar{c}s \leftrightarrow b \rightarrow c\bar{c}d$
  \[
  \beta: \quad B \rightarrow J/\psi K_S^0 \leftrightarrow B_s \rightarrow J/\psi K_S^0 \\
  \beta_s: \quad B_s \rightarrow J/\psi \pi\pi \leftrightarrow B_d \rightarrow J/\psi \pi\pi
  \]
- Originally envisioned as a way to measure $\gamma$ [8, 9]
- Instead, inputing $\gamma$ sets a constraint on $\Delta\phi_x$:
  - $B_s \rightarrow J/\psi K_S^0$ has too high systematics to constrain $\Delta\phi_d$ [10]
  - $B^0 \rightarrow J/\psi \pi^+\pi^-$ constrains $\Delta\phi_s$ to $[-1.05^\circ, +1.18^\circ]$ [11]
Flavor tagging overview

- Incorrectly tagged events dilute asymmetry and hurt precision
  - $A$ diluted by a factor $\langle D_{\text{tagging}} \rangle$, where $D_{\text{tagging}} = p(R) - p(W)$
  - Statistical power reduced by $\langle D_{\text{tagging}}^2 \rangle$
- Fraction of events tagged $\epsilon$ also reduces statistical power
- Effective tagging efficiency:
  $$\epsilon_{\text{eff}} = \epsilon \langle D^2 \rangle$$
Flavor tagging overview (cont’d)

- Import FT figures of merit:
  - The tagging efficiency (or rate) $\epsilon = \frac{N_{\text{tagged}}}{N_{\text{signal}}}$
  - The ev. by ev. mistag probability $\eta$
  - The ev. by ev. dilution $D_{\text{tagging}} = 1 - 2\eta$
  - The tagging power (or effective tagging efficiency) $\epsilon_{\text{eff}} = \epsilon \langle D^2 \rangle$

- Taggers are tuned (trained, optimized) to maximize $\epsilon_{\text{eff}}$

- Taggers are calibrated to ensure that

  $$\omega(\eta) = \frac{N_{\text{wrong},\eta}}{N_{\text{tagged},\eta}} = \eta$$
Evolution of $\sin 2\beta$ sensitivity ($J/\psi K^0_S$)

<table>
<thead>
<tr>
<th></th>
<th>Nov '12</th>
<th>Mar. '15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>1.0 fb$^{-1}$</td>
<td>3.0 fb$^{-1}$</td>
</tr>
<tr>
<td>Tagging Power</td>
<td>2.38%</td>
<td>3.02%</td>
</tr>
<tr>
<td>Total</td>
<td>1.0x</td>
<td>3.8x</td>
</tr>
<tr>
<td>Error</td>
<td>0.07</td>
<td>0.035</td>
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</table>
Evolution of $\phi_s$ sensitivity ($J/\psi\phi$)

<table>
<thead>
<tr>
<th></th>
<th>Mar. '12</th>
<th>June '13</th>
<th>Jan. '15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>0.37 fb$^{-1}$</td>
<td>1.0 fb$^{-1}$</td>
<td>3.0 fb$^{-1}$</td>
</tr>
<tr>
<td>Tagging Power</td>
<td>1.91%</td>
<td>3.13%</td>
<td>3.73%</td>
</tr>
<tr>
<td>Total</td>
<td>1.0x</td>
<td>4.4x</td>
<td>15.8x</td>
</tr>
<tr>
<td>Error</td>
<td>0.18</td>
<td>0.09</td>
<td>0.049</td>
</tr>
</tbody>
</table>
Evolution of $\phi_s$ sensitivity ($J/\psi \pi^+ \pi^-$)

<table>
<thead>
<tr>
<th></th>
<th>Apr. '12</th>
<th>June '13</th>
<th>May '14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>1.0 fb$^{-1}$</td>
<td>1.0 fb$^{-1}$</td>
<td>3.0 fb$^{-1}$</td>
</tr>
<tr>
<td>Tagging Power</td>
<td>2.43%</td>
<td>3.37%</td>
<td>3.89%</td>
</tr>
<tr>
<td>Total</td>
<td>1.0x</td>
<td>1.4x</td>
<td>4.8x</td>
</tr>
<tr>
<td>Error</td>
<td>0.175</td>
<td>0.165</td>
<td>0.068</td>
</tr>
</tbody>
</table>
Lifetime acceptance example ($B_s \rightarrow J/\psi\phi$)

- Lifetime acceptance of biased trigger determined with data
- Orthogonal sample selected via an independent trigger
$B_s \rightarrow J/\psi \pi \pi$ mass spectra

- Figure (a): Combination/ (20 MeV) vs $m(\pi^+\pi^-)$ [GeV] for LHCb.
- Figure (b): Combination/ (5 MeV) vs $m(J/\psi \pi^+\pi^-)$ [MeV] for LHCb.
$B_s \to \phi\phi$ analysis

- Most easily measured in $(K^+K^-)(K^+K^-)$ final state
  - Either $K^+K^-$ can also come from S-wave resonance
  - $PP + PS + SS \Rightarrow 3 + 1 + 1$ amplitudes $\Rightarrow 15$ angular modes
- Binning in $m(K^+K^-)$ employed again
- BDT used to improve signal-to-background ratio
  - Uses kaon isolation information
  - Peaking backgrounds to contend with
References I


