Measurements of $CP$-violating phases in B decays at LHCb

Laurence Carson, University of Edinburgh

on behalf of the LHCb Collaboration

Rencontres de Blois 2015
Menu of Results

- Latest LHCb $\gamma$ Combination (*LHCb-CONF-2014-004*)
- Constraints on $\gamma$ using $^{(†)} B^\pm \rightarrow D^0 (\rightarrow hh\pi^0)h^\pm$ decays
  (*arXiv: 1504.05442 [hep-ex]*)
- Constraints on $\gamma$ using $B^\pm \rightarrow D^0 (\rightarrow hh)h^\pm\pi\pi$ decays
- Measurement of $\sin(2\beta)$ using $B^0 \rightarrow J/\psi K_S$
- Measurement of $\varphi_s$ using $B_s \rightarrow J/\psi K^+K^-$

$^{(†)}$ “$h$” refers to a charged kaon or pion
\(\gamma\) in Tree-Level \(B\) Decays

- \(\gamma\) is the least well-known angle of the CKM triangle.
- Direct measurements from the B-Factories give:
  \[\gamma = (69^{+17}_{-16})^\circ\]  \((\text{Babar, PRD 87 (2013) 052015})\)
  \[\gamma = (68^{+15}_{-14})^\circ\]  \((\text{Belle, arXiv: 1301.2033 [hep-ex]})\)

- Measurements of \(\gamma\) from \(B\) decays mediated only by tree-level transitions provide a “standard candle” for the Standard Model.
- This can be compared with \(\gamma\) values from \(B\) decays involving loop-level transitions
  - For example, \(B^0(s) \rightarrow hh'\) decays.
- A significant difference between these would indicate a New Physics contribution to the loop process.
Time-Integrated $\gamma$ Methods

- Sensitivity to $\gamma$ in $B^\pm \to Dh^\pm$ decays comes from interference between $b \to c$ and $b \to u$ transitions at tree level, where the $D$ final state is accessible to both $D^0$ and $\bar{D}^0$.

- Aside from $\gamma$, have hadronic unknowns $r_{B(D)}$, $\delta_{B(D)}$, where ratio of suppressed to favoured $B(D)$ decay amplitudes is $r_B e^{i(\delta_B - \gamma)} (r_D e^{i\delta_D})$.

- Method to extract these hadronic unknowns (and $\gamma$) depends on the $D$ final state.

- Three main classes of method:
  - **GLW**: $D \to$ CP-eigenstate, e.g. $\pi\pi$, KK ($\text{Phys. Lett. B 253} (1991) 483$, $\text{Phys. Lett. B 265} (1991)$ 172), also quasi-GLW e.g. $\pi\pi\pi^0$, KK$\pi^0$ ($\text{Phys. Lett. B 740} (2015)$ 1)
  - **ADS**: $D \to$ quasi-flavour-specific state, e.g. $K\pi$, $K\pi\pi\pi$, $K\pi\pi^0$, $K_S K\pi$ ($\text{Phys. Rev. Lett. 78} (1997)$ 257, $\text{Phys. Rev. D 63} (2001)$ 036005)
The LHCb Experiment

- Forward arm spectrometer, optimised for study of $B$ and $D$ decays.
- Collected $1/fb$ of data at $E_{CM} = 7$ TeV in 2011 and $2/fb$ at 8 TeV in 2012.
- Data-taking at $E_{CM} = 13$ TeV to begin in the coming weeks!

**Key capabilities:**
- High trigger efficiency, including on purely hadronic final states.
- Excellent Impact Parameter (IP) and Mass Resolution
- Hadronic PID over wide momentum range

**VELO:**
- Primary vertex impact parameter displaced vertex

**RICH:**
- PID: primarily $K, \pi$ separation

**Muon System**

**Interaction region**

**Tracking Station:**
- $p$ for lower energy tracks and long lived $V^0$ reconstruction

**Tracking Stations:**
- $p$ of charged particles that traverse the magnet

**Calorimeters:**
- $h, e, \gamma, \pi^0$
Gamma Combination

- The most recent LHCb combination (for CKM 2014) uses:
  - $B^\pm \rightarrow D(\rightarrow K\pi, KK \text{ or } \pi\pi)h^\pm$ using 1/fb,
  - $B^\pm \rightarrow D(\rightarrow K\pi\pi\pi)h^\pm$ using 1/fb,
  - $B^\pm \rightarrow D(\rightarrow K_SKK \text{ or } K_S\pi\pi )K^\pm$ using 3/fb,
  - $B^\pm \rightarrow D(\rightarrow K_SK\pi)K^\pm$ using 3/fb,
  - $B^0 \rightarrow D(\rightarrow K\pi, KK \text{ or } \pi\pi)K^*0$ using 3/fb,
  - $B_s \rightarrow D_s^\mp K^\pm$ (time-dependent) using 1/fb

- The experimental likelihoods are combined as:
  $$\mathcal{L}(\vec{\alpha}) = \prod_i f_i(\bar{A}_i^{\text{obs}} | \bar{A}_i(\vec{\alpha}_i))$$
  where $A$ are the experimental observables ($R_{CP}$, $x_+$, etc) and $\alpha$ the physics parameters ($\gamma$, $r_B$, etc).

- The effects of $D^0\bar{D}^0$ mixing, and possible CPV in the $D$ decays, are taken into account.

- Combination using DK only gives $\gamma = (73^{+9}_{-10})^\circ$ and $r_B = 0.091^{+0.008}_{-0.009}$
\[ \gamma \text{ from } B^{\pm} \rightarrow D^0(\rightarrow hh\pi^0)h^{\pm} \]

- Analysing the three-body ADS final state $K\pi\pi^0$ requires knowledge of how the average interference amplitude ($\kappa_{K\pi\pi^0}$) and strong phase difference ($\delta_{K\pi\pi^0}$) vary across the $D$ Dalitz plot
  - This is taken from a CLEO-c measurement, Phys. Lett. B 731 (2014) 197
  - CLEO-c can make such measurements due to quantum-correlated $D^0-\overline{D}^0$ production from the $\psi(3770)$ resonance
  - The large measured value $\kappa_{K\pi\pi^0} = 0.82 \pm 0.07$ implies small dilution of $\gamma$ sensitivity.
- For the quasi-GLW (qGLW) final states $\pi\pi\pi^0$ and $KK\pi^0$, the relevant parameter is the fractional $CP$-even content, $F_+^{hh\pi^0}$
  - This has also been measured by CLEO-c, Phys. Lett. B 740 (2015) 1
  - The large measured values $F_+^{\pi\pi\pi^0} = 0.968 \pm 0.018$ and $F_+^{KK\pi^0} = 0.731 \pm 0.062$ imply that these decays are close to being $CP$-even eigenstates.
- The observables for $K\pi\pi^0$ are the yield ratios $R_{ADS(h)}$ between the favoured and suppressed $D$ states, and the charge asymmetries $A_{ADS(h)}$ in the suppressed state.
- The observables for $\pi\pi\pi^0$ and $KK\pi^0$ are the ratios $R_{qGLW}$ between $DK$ and $D\pi$ states, and the charge asymmetries $A_{qGLW(h)}$.  

7
\( \gamma \) from \( B^{\pm} \rightarrow D^{0}(\rightarrow hh\pi^{0})h^{\pm} \)

- These observables are related to the physics parameters via:

\[
R_{\text{ADS}(K)}^{K\pi\pi^{0}} \approx (r_B)^2 + (r_D^{K\pi\pi^{0}})^2 + 2\kappa_{D}^{K\pi\pi^{0}} r_{B} r_{D}^{K\pi\pi^{0}} \cos(\delta_{B} + \delta_{D}^{K\pi\pi^{0}}) \cos \gamma \\
A_{\text{ADS}(K)}^{K\pi^{0}} \approx [2\kappa_{D}^{K\pi^{0}} r_{B} r_{D}^{K\pi^{0}} \sin(\delta_{B} + \delta_{D}^{K\pi^{0}}) \sin \gamma] / R_{\text{ADS}(K)}^{K\pi^{0}} \\
R_{q\text{GLW}}^{h'h'\pi^{0}} = 1 + (r_B)^2 + (2F_{+}^{h'h'\pi^{0}} - 1)2r_B \cos \delta_B \cos \gamma \\
A_{q\text{GLW}(K)}^{h'h^{0}} = (2F_{+}^{h'h^{0}} - 1)2r_B \sin \delta_B \sin \gamma / R_{q\text{GLW}}^{h'h^{0}}
\]

- Significance for suppressed \([\pi K\pi^{0}]_{D}K\) signal is 2.8\( \sigma \).
- First evidence (4.5\( \sigma \)) is obtained for the \([KK\pi^{0}]_{D}K\) signal.
\[ \gamma \text{ from } B^\pm \to D^0(\to hh\pi^0)h^\pm \]

- The suppressed \([\pi K\pi^0]_D\pi\) signal is observed (5.3\(\sigma\)) for the first time.

\[
\begin{align*}
A_{K\pi^0}^{K\pi^0} &= -0.20 \pm 0.27 \pm 0.04 \\
A_{\pi K\pi^0}^{\pi K\pi^0} &= 0.438 \pm 0.190 \pm 0.011 \\
A_{qGLW}^{K\pi^0} &= 0.30 \pm 0.20 \pm 0.02 \\
A_{qGLW}^{\pi K\pi^0} &= 0.054 \pm 0.091 \pm 0.011 \\
A_{qGLW}^{\pi\pi^0} &= -0.030 \pm 0.040 \pm 0.005 \\
A_{qGLW}^{\pi\pi^0} &= -0.016 \pm 0.020 \pm 0.004 \\
A_K^{K\pi^0} &= 0.010 \pm 0.026 \pm 0.005 \\
\end{align*}
\]

- Using only the DK observables, LHCb measures \(r_B = 0.11 \pm 0.03\).
- No significant constraints are placed on \(\gamma\) with the current dataset.
\( \gamma \) from \( B^\pm \rightarrow D^0(\rightarrow hh)h^\pm\pi\pi \)

- LHCb has performed ADS and GLW analyses of \( B^\pm \rightarrow D^0\pi^\pm\pi^+\pi^- \) and \( B^\pm \rightarrow D^0K^\pm\pi^+\pi^- \) decays, where \( D \rightarrow K\pi, KK \) or \( \pi\pi \).

- The sensitivity to \( \gamma \) depends on the coherence factor \( \kappa \) of the \( X_d (=\pi^+\pi^+\pi^-) \) or \( X_s (=K^\pm\pi^+\pi^-) \) system. The \( \kappa \) value can be determined from data.

- For the ADS modes, the ratios of the suppressed to favoured \( D \rightarrow K\pi \) final states are measured:
  \[
  R_{X^\pm} = \frac{\Gamma(B^\pm \rightarrow [K^\mp\pi^\pm]_D X^\pm)}{\Gamma(B^\pm \rightarrow [K^\pm\pi^\mp]_D X^\pm)} = \frac{r_B^2 + r_D^2 + 2\kappa r_B r_D \cos(\delta_B + \delta_D \pm \gamma)}{1 + r_B^2 + 2\kappa r_B r_D \cos(\delta_B - \delta_D \pm \gamma)}
  \]

- For the GLW modes, the ratios to the favoured \( K\pi \) final state are measured, along with the charge asymmetries:
  \[
  R_{CP+}^{h^+h^-} \equiv 2\frac{\Gamma(B^- \rightarrow [h^+h^-]_D X_s^-) + \Gamma(B^+ \rightarrow [h^+h^-]_D X_s^+)}{\Gamma(B^- \rightarrow [K^-\pi^+]_D X_s^-) + \Gamma(B^+ \rightarrow [K^+\pi^-]_D X_s^+)} = 1 + r_B^2 + 2\kappa r_B \cos \delta_B \cos \gamma.
  \]
  \[
  A_{X^\pm}^f \equiv \frac{\Gamma(B^- \rightarrow f_D X^-) - \Gamma(B^+ \rightarrow \bar{f}_D X^+)}{\Gamma(B^- \rightarrow f_D X^-) + \Gamma(B^+ \rightarrow \bar{f}_D X^+)} = 2\kappa r_B \sin \delta_B \sin \gamma / R_{CP+}
  \]
$\gamma$ from $B^\pm \rightarrow D^0(\rightarrow hh)h^\pm\pi\pi$

- First evidence (3.6$\sigma$) obtained for the suppressed ADS decay $[\pi K]_D K\pi\pi$.

- Clear signals (first observations) seen for the GLW decays $[KK]_D K\pi\pi$ and $[\pi\pi]_D K\pi\pi$. 
\( \gamma \) from \( B^\pm \rightarrow D^0(\rightarrow hh)h^\pm\pi\pi \)

- Clear signal is also seen for the suppressed ADS decay \([\pi K]_D\pi\pi\pi\).

\[
\begin{align*}
R_{X_d^+} & = (42.8 \pm 5.3 \pm 2.1) \times 10^{-4}, \\
R_{X_d^-} & = (42.5 \pm 5.3 \pm 2.1) \times 10^{-4}, \\
A_{X_s}^{K+K^-} & = -0.045 \pm 0.064 \pm 0.011, \\
A_{X_s}^{\pi^+\pi^-} & = -0.054 \pm 0.101 \pm 0.011, \\
A_{X_d}^{K^-\pi^+} & = 0.013 \pm 0.019 \pm 0.013, \\
A_{X_d}^{K+K^-} & = -0.019 \pm 0.011 \pm 0.010, \\
A_{X_d}^{\pi^+\pi^-} & = -0.013 \pm 0.016 \pm 0.010, \\
A_{X_d}^{K^-\pi^+} & = -0.002 \pm 0.003 \pm 0.011,
\end{align*}
\]

\[
\begin{align*}
R_{\text{ADS}} & \equiv (R_{X_s^-} + R_{X_s^+})/2 = (\frac{.82}{.30}) \times 10^{-4}, \\
A_{\text{ADS}} & \equiv \frac{R_{X_s^-} - R_{X_s^+}}{R_{X_s^-} + R_{X_s^+}} = (-0.32_{-0.34}^{+0.27})
\end{align*}
\]

\[
R_{CP^+} = 1.040 \pm 0.064
\]

- Confidence levels for \( \gamma \) are extracted using \( DX_s \) decays only, and using both \( DX_s \) and \( DX_d \) decays.
$B^0_{(S)}$ Mixing Phases

- Final states common to $B^0_0$ can show CPV in interference between mixing and decay: $\varphi_{s,d} = \varphi_M - 2\varphi_D$.
- Measuring $\varphi_{s,d}$ requires time-dependent analysis, as well as tagging of the B flavour at production.
- For $\varphi_d$, measure $B^0 \rightarrow J/\psi K_S$ asymmetry:

$$\frac{\Gamma(B^0(t) \rightarrow J/\psi K^0_S) - \Gamma(B^0(t) \rightarrow J/\psi K^0_S)}{\Gamma(B^0(t) \rightarrow J/\psi K^0_S) + \Gamma(B^0(t) \rightarrow J/\psi K^0_S)}$$

$$= \frac{S \sin(\Delta m t) - C \cos(\Delta m t)}{\cosh(\frac{\Delta \Gamma t}{2}) + A_{\Delta \Gamma} \sinh(\frac{\Delta \Gamma t}{2})}$$

$$= S \sin(\Delta m t) - C \cos(\Delta m t) \text{ (since } \Delta \Gamma_d \approx 0)$$
- In the SM, $S \approx \sin(2\beta)$ and $C \approx 0$.
- In the SM, and ignoring penguin effects, the $\varphi_s$ in $B_s \rightarrow J/\psi \phi$ is $-2\beta_s$, where

$$\beta_s = \arg \left(-\frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*}\right)$$

For $B_s \rightarrow J/\psi \phi$, vector-vector final state necessitates angular analysis.
\[ \sin(2\beta) \text{ with } B^0 \rightarrow J/\psi K_S \]

- \( K_S \) reco challenging at LHCb, due to large boost causing very large flight distance
  - \( K_S \) may decay inside or outside vertex detector.

- Effective tagging efficiency is \( \varepsilon_{\text{eff}} \equiv \varepsilon_{\text{tag}}(1-2\omega)^2 \approx 3.0\% \) (\( \varepsilon_{\text{tag}} \approx 36\%, \ \omega \approx 35\% \)).
  - Significantly increased w.r.t. previous analysis (\( \approx 2.4\% \)), due to use of the SS\( \pi \) tagger.

- Perform multi-dim. fit to mass, decay time, decay-time error, tag decision and per-event mistag probability.

- The precision is competitive with that of the B-Factories (total error on \( S \) of \( \approx 0.03 \)).

\[ S = 0.731 \pm 0.035 \text{ (stat)} \pm 0.020 \text{ (syst)} \]
\[ C = -0.038 \pm 0.032 \text{ (stat)} \pm 0.005 \text{ (syst)} \]
An alternative fit is also performed that allows for different CPV in the different polarisation states; no significant differences are seen.

Combining with $\phi_s$ measured by LHCb in $B_s \to J/\psi \pi \pi$ (Phys. Lett. B 736 (2014) 186) yields: $\phi_s = -0.010 \pm 0.039 \text{ rad}$, which is the most precise measurement to date, and is in good agreement with the SM prediction of $\phi_s (\text{no peng}) = -0.0365 \pm 0.0012 \text{ rad}$. 

---

**Parameter** | **Value**
--- | ---
$\Gamma_s [\text{ps}^{-1}]$ | $0.6603 \pm 0.0027 \pm 0.0015$
$\Delta \Gamma_s [\text{ps}^{-1}]$ | $0.0805 \pm 0.0091 \pm 0.0032$
$\phi_s [\text{rad}]$ | $-0.058 \pm 0.049 \pm 0.006$
$|\lambda|$ | $0.964 \pm 0.019 \pm 0.007$
Summary & Prospects

• Latest LHCb $\gamma$ combination with $B^+ \rightarrow D^0K^+$ decays, using various methods (ADS, GLW, GGSZ) gives
  \[
  \gamma = (73^{+9}_{-10})^\circ
  \]
  – More precise than the B-factory measurements

• Always looking to add new $B$ decays, and new $D$ final states
  – First constraints on $\gamma$ with $B^+ \rightarrow D^0(\rightarrow hh\pi^0)h^+$, and with $B^+ \rightarrow D^0(\rightarrow hh)h^+\pi\pi$, now available

• Measurement of time-dependent CPV in $B^0 \rightarrow J/\psi K_S$ decays now competitive with B-Factories, $S = 0.731 \pm 0.040$

• Precise measurement of $\phi_s = -0.010 \pm 0.039$ rad using $B_s \rightarrow J/\psi hh$

• Stay tuned for more results in the future!
  – More measurements with Run I dataset are on the way
  – Run II data-taking at $E_{CM} = 13$TeV (increased $\sigma_{bb}$) about to begin
  – Expect to record $\approx 6/fb$ of data in Run II
Backup
CKM Matrix

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{1}{2} \lambda^2 & \lambda & A \lambda^3 (\rho - i \eta) \\ -\lambda & 1 - \frac{1}{2} \lambda^2 & A \lambda^2 \\ A \lambda^3 (1 - \rho - i \eta) & -A \lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Unitarity: $$V_{CKM} V_{CKM}^+ = 1$$, e.g. $$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$
Gamma Combination

CLEO-c result on $D \rightarrow K\pi\pi\pi$

Other parameters measured:

CLEO-c result on $D \rightarrow K_sK\pi$
$B^{\pm} \rightarrow D^0(\rightarrow hh\pi^0)\pi^{\pm}$
B$^\pm \rightarrow$D$^0(\rightarrow hh)h^\pm\pi\pi$

Three-body masses:

Figure 3: Signal distributions of the (left) $X_d^-$ invariant mass in $B^- \rightarrow DX_d^-$ decays and (right) $X_s^-$ invariant mass, in $B^- \rightarrow DX_s^-$ decays, for $D \rightarrow K^-\pi^+$. The distributions are obtained using the $s$Plot method. In both cases, all selections, except the $M(X^-) < 2\text{ GeV}/c^2$ and the $K^{*0}$ mass selection, are applied. The dip at $1.97\text{ GeV}/c^2$ is due to the $D_s^+$ meson veto.

Sum of $B^+$ and $B^-$

$B^\pm \rightarrow [K^\mp\pi^\pm], K^\mp\pi^\pm$
Calibration of SSπ mistag probability using $B^0 \to J/\psi K_S^*$

Table A1: Systematic uncertainties $\sigma_S$ and $\sigma_C$ on $S$ and $C$. Entries marked with a dash represent studies where no significant effect is observed.

<table>
<thead>
<tr>
<th>Origin</th>
<th>$\sigma_S$</th>
<th>$\sigma_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background tagging asymmetry</td>
<td>0.0179 (2.5%)</td>
<td>0.0015 (4.5%)</td>
</tr>
<tr>
<td>Tagging calibration</td>
<td>0.0062 (0.9%)</td>
<td>0.0024 (7.2%)</td>
</tr>
<tr>
<td>$\Delta \Gamma$</td>
<td>0.0047 (0.6%)</td>
<td></td>
</tr>
<tr>
<td>Fraction of wrong PV component</td>
<td>0.0021 (0.3%)</td>
<td>0.0011 (3.3%)</td>
</tr>
<tr>
<td>$z$-scale</td>
<td>0.0012 (0.2%)</td>
<td>0.0023 (7.0%)</td>
</tr>
<tr>
<td>$\Delta m$</td>
<td></td>
<td>0.0034 (10.3%)</td>
</tr>
<tr>
<td>Upper decay time acceptance</td>
<td></td>
<td>0.0012 (3.6%)</td>
</tr>
<tr>
<td>Correlation between mass and decay time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decay time resolution calibration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decay time resolution offset</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low decay time acceptance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production asymmetry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td>0.020 (2.7%)</td>
<td>0.005 (15.2%)</td>
</tr>
</tbody>
</table>
$\mathbf{B}_s \rightarrow \mathbf{J}/\psi \phi$

**Polarisation-independent:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_s$ [(\text{ps}^{-1})]</td>
<td>$0.6603 \pm 0.0027 \pm 0.0015$</td>
</tr>
<tr>
<td>$\Delta \Gamma_s$ [(\text{ps}^{-1})]</td>
<td>$0.0805 \pm 0.0091 \pm 0.0032$</td>
</tr>
<tr>
<td>$</td>
<td>A_\perp</td>
</tr>
<tr>
<td>$</td>
<td>A_0</td>
</tr>
<tr>
<td>$\delta_\parallel$ [rad]</td>
<td>$3.26 \pm^{0.10}<em>{-0.17} \pm^{0.06}</em>{-0.07}$</td>
</tr>
<tr>
<td>$\delta_\perp$ [rad]</td>
<td>$3.08 \pm^{0.14}_{-0.15} \pm 0.06$</td>
</tr>
<tr>
<td>$\phi_s$ [rad]</td>
<td>$-0.058 \pm 0.049 \pm 0.006$</td>
</tr>
<tr>
<td>$</td>
<td>\lambda</td>
</tr>
<tr>
<td>$\Delta m_s$ [(\text{ps}^{-1})]</td>
<td>$17.711 \pm^{0.055}_{-0.057} \pm 0.011$</td>
</tr>
</tbody>
</table>

**Polarisation-dependent:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\lambda^0</td>
</tr>
<tr>
<td>$</td>
<td>\lambda^\parallel/\lambda^0</td>
</tr>
<tr>
<td>$</td>
<td>\lambda^\perp/\lambda^0</td>
</tr>
<tr>
<td>$</td>
<td>\lambda^S/\lambda^0</td>
</tr>
<tr>
<td>$\phi_s^0$ [rad]</td>
<td>$-0.045 \pm 0.053 \pm 0.007$</td>
</tr>
<tr>
<td>$\phi_s^\parallel - \phi_s^0$ [rad]</td>
<td>$-0.018 \pm 0.043 \pm 0.009$</td>
</tr>
<tr>
<td>$\phi_s^\perp - \phi_s^0$ [rad]</td>
<td>$-0.014 \pm 0.035 \pm 0.006$</td>
</tr>
<tr>
<td>$\phi_s^S - \phi_s^0$ [rad]</td>
<td>$0.015 \pm 0.061 \pm 0.021$</td>
</tr>
</tbody>
</table>

**Source**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_s$ [(\text{ps}^{-1})]</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta \Gamma_s$ [(\text{ps}^{-1})]</td>
<td>-</td>
</tr>
<tr>
<td>$</td>
<td>A_\perp</td>
</tr>
<tr>
<td>$</td>
<td>A_0</td>
</tr>
<tr>
<td>$\delta_\parallel$ [rad]</td>
<td>-</td>
</tr>
<tr>
<td>$\delta_\perp$ [rad]</td>
<td>-</td>
</tr>
<tr>
<td>$\phi_s$ [rad]</td>
<td>-</td>
</tr>
<tr>
<td>$</td>
<td>\lambda</td>
</tr>
<tr>
<td>$\Delta m_s$ [(\text{ps}^{-1})]</td>
<td>-</td>
</tr>
</tbody>
</table>