Measurements of $\beta$ and $\beta_s$

Beauty - Isola d’Elba - 7th May 2018

@GreigCowan (Edinburgh), on behalf of the LHCb collaboration
CPV in $B_{(s)}^0$ mixing and decay

\[ \phi_d = 2\beta \]
\[ \phi_s = -2\beta_s \]

Measurable phases

Precise predictions
\[ 2\beta_{SM} = (47.48^{+2.26}_{-1.96})^\circ \]
\[ 2\beta_s^{SM} = (2.122 \pm 0.037)^\circ \]

[CKMfitter]
CPV in $B_{(s)}^0$ mixing and decay

$B^0_{H(L)} = pB^0 \pm q\overline{B}^0$

$\lambda_{fCP} = \frac{q \overline{A}_{fCP}}{p A_{fCP}}$

Measurable phases

$\phi_d = 2\beta + \Delta\phi^{pen} + \Delta\phi^{NP}$

$\phi_s = -2\beta_s + \Delta\phi_s^{pen} + \Delta\phi_s^{NP}$

+ smaller weak exchange (E) and penguin annihilation (PA) diagrams

Precise predictions

$2\beta^{SM} = (47.48^{+2.26}_{-1.96})^\circ$

$2\beta_s^{SM} = (2.122 \pm 0.037)^\circ$ [CKMfitter]
Measuring $\phi_q$

Study time-dependent CP asymmetry

\[
\frac{\Gamma_{B^0(s)} \to f(t) - \Gamma_{B^0(s)} \to f(t)}{\Gamma_{B^0(s)} \to f(t) + \Gamma_{B^0(s)} \to f(t)} = \frac{S_f \sin(\Delta m(s)t) - C_f \cos(\Delta m(s)t)}{\cosh(\frac{\Delta \Gamma(s)}{2}) + A_f \cosh(\frac{\Delta \Gamma(s)}{2})}
\]

\[
A_f = -\frac{2 \Re(\lambda_f)}{1 + |\lambda_f|^2}, \quad C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}, \quad S_f = \frac{2 \Im(\lambda_f)}{1 + |\lambda_f|^2}
\]

Mixing parameters

\[
\Delta m \equiv (m_H - m_L) \quad \text{Mixing frequency}
\]
\[
\Gamma \equiv (\Gamma_L + \Gamma_H)/2 \quad \text{Average width}
\]
\[
\Delta \Gamma \equiv \Gamma_L - \Gamma_H \quad \text{Width difference}
\]

Experimental requirements:
- Excellent decay-time resolution (~45 fs)
- Modelling decay-time efficiency (due to lifetime/IP cuts)
- Production + detection asymmetries (~1%)
- Tagging of meson flavour @ production
Flavour physics at the LHC

nPVs $\sim 2$

nTracks $\sim 200$

$p_T(B) \sim 5$ GeV

$p_T(\text{child}) \sim 1$ GeV

$\sigma_{bb}(7 \text{ TeV}) = 72.0 \pm 0.3 \pm 6.8 \mu b$

$\sigma_{bb}(13 \text{ TeV}) = 154.3 \pm 1.5 \pm 14.3 \mu b$

[B decays with lifetime of $\sim 1.5$ ps]

[PRD 87 (2013) 112010]

[PRL 118 (2017) 052002]
Flavour tagging

Use information in the event (e.g., charge of kaon associated with b-quark hadronisation) to tag flavour of B meson at production

Precision on $A_{CP}$ scales with tagging power

Calibrate tagging algorithm response using modes with known flavour (e.g., $B^+ \rightarrow J/\psi K^+, B_s^0 \rightarrow D_s \pi\ldots$)

$$\epsilon_{\text{tag}} = \frac{N_{\text{tagged}}}{N_{\text{tagged}} + N_{\text{untagged}}}$$

$$\omega = \frac{N_{\text{wrong}}}{N_{\text{right}} + N_{\text{wrong}}}$$

$$\epsilon_{\text{eff}} = \epsilon_{\text{tag}} D^2 = \epsilon_{\text{tag}} \langle (1 - 2\omega)^2 \rangle$$

$$\sigma_{\text{stat}}(A_{CP}) \propto 1/\sqrt{\epsilon_{\text{eff}} N}$$
Measuring $\phi_d$

Golden mode: $B^0 \rightarrow J/\psi K_S$

With Run I, LHCb has a similar precision to Belle/BaBar

$$S_f = \sin 2\beta = 0.691 \pm 0.017 \quad [HFLAV]$$

$$\sin 2\beta^{SM} = 0.740^{+0.020}_{-0.025} \quad [CKM\text{Fitter}]$$

Dominant systematics:

LHCb background tagging asymmetry $\rightarrow$ expect to scale with more data

Belle vertex reconstruction and time resolution

$\Delta \Gamma_d \neq 0 \ ?$

$$s \times \Delta \Gamma_d / \Gamma_d = (-2 \pm 10. ) \times 10^{-3} \quad [HFLAV]$$

$$\text{SM} \ \Delta \Gamma_d / \Gamma_d = (-3.97 \pm 0.90) \times 10^{-3} \quad [\text{Artuso et al}]$$
Measuring $\phi_d$

**Golden mode:** $B^0 \to J/\psi K_S$

With Run I, LHCb has a similar precision to Belle/BaBar:

$$S_f = \sin 2\beta = 0.691 \pm 0.017 \quad \text{[HFLAV]}$$

$$\sin 2\beta^{SM} = 0.740^{+0.020}_{-0.025} \quad \text{[CKMfit]}$$

Electron and other $[c\bar{c}]$ modes provide additional $\sim 15\%$ on the overall precision → improved electro reconstruction in LHCb upgrade-II would help

$LHCb @ 300/fb \to \sigma(S) \sim 0.003$

$$\frac{\Gamma_{B^0(s)\to f(t)} - \Gamma_{B^0(s)\to f(t)}}{\Gamma_{B^0(s)\to f(t)} + \Gamma_{B^0(s)\to f(t)}} = \frac{S_f \sin(\Delta m_{(s)} t) - C_f \cos(\Delta m_{(s)} t)}{\cosh(\frac{\Delta \Gamma_{(s)} t}{2}) + A_f^\Delta \Gamma_{(s)} \sinh(\frac{\Delta \Gamma_{(s)} t}{2})}$$

$$S(B^0 \to \psi(2S)(\mu^+\mu^-)K_s^0) = 0.760 \pm 0.034$$

$$C(B^0 \to \psi(2S)(\mu^+\mu^-)K_s^0) = -0.017 \pm 0.029$$

[JHEP 11 (2017) 170]
**Measuring $\phi_s$**

**Golden mode:** $B^0_s \rightarrow J/\psi \phi$, but need angular analysis to separate CP-odd/even components as we have two vectors in final state and small $K^+K^-$ S-wave

**Bonus feature:** measure $\phi_s$, $\Delta \Gamma_s$, $\Gamma_s$, $\Delta m_s$

New physics is not large $\rightarrow$ stat-limited so need **increased precision** and to control size of penguin contributions

\[
\frac{\Gamma_{B^0_{(s)} \rightarrow f}(t) - \Gamma_{B^0_{(s)} \rightarrow f}(t)}{\Gamma_{B^0_{(s)} \rightarrow f}(t) + \Gamma_{B^0_{(s)} \rightarrow f}(t)} = \frac{S_f \sin(\Delta m_{(s)} t) - C_f \cos(\Delta m_{(s)} t)}{\cosh(\frac{\Delta \Gamma_{(s)} t}{2})} + A_f \Delta \Gamma_{(s)} \sinh(\frac{\Delta \Gamma_{(s)} t}{2})
\]

CP $|J/\psi \phi\rangle_\ell = (-1)^\ell |J/\psi \phi\rangle_\ell$
Measuring $\phi_s$

**Golden mode:** $B^0_s \rightarrow J/\psi \phi$, but need angular analysis to separate CP-odd/even components as we have two vectors in final state and small $K^+K^-$.

**Bonus feature:** measure $\phi_s$, $\Delta \Gamma_s$, $\Gamma_s$, $\Delta m_s$

New physics is not large $\rightarrow$ stat-limited so need **increased precision** and to control size of penguin contributions

\[ \text{CP}|J/\psi \phi\rangle_{\ell} = (-1)^{\ell}|J/\psi \phi\rangle_{\ell} \]

\[ \phi_s = -21 \pm 31 \text{ mrad} \]
\[ \Delta \Gamma_s = 0.090 \pm 0.005 \text{ ps}^{-1} \]

[CKMfitter]: $\phi_s^{\text{SM}} = -37.6^{+0.7}_{-0.8} \text{ mrad}$

[HFLAV] $\phi_s = -21 \pm 31 \text{ mrad} \quad \Delta \Gamma_s = 0.090 \pm 0.005 \text{ ps}^{-1}$

**LHCb:**
- $J/\psi \phi$ [PRL114, 041801 (2015)]
- $J/\psi K^+K^−$ [arXiv:1704.08217 (2017)]
- $D_s^+D_s^−$ [PRL113, 211801 (2014)]

**CMS:**

**ATLAS:**
- $J/\psi \phi$ [JHEP 08 (2016) 147]
Beyond $B_s^0 \rightarrow J/\psi \phi$

Previous studies focussed on low-mass region where $\phi(1020)$ dominates over a small KK S-wave

Use time-dependent amplitude analysis to increase sensitivity to $\phi_s$ using high $m(KK)$ region

[Stone, Zhang, PLB 719 (2013) 383]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_s \text{ [ ps}^{-1}]$</td>
<td>0.650 ± 0.006 ± 0.004</td>
</tr>
<tr>
<td>$\Delta \Gamma_s \text{ [ ps}^{-1}]$</td>
<td>0.066 ± 0.018 ± 0.010</td>
</tr>
<tr>
<td>$\phi_s \text{ [ mrad]}$</td>
<td>119 ± 107 ± 34</td>
</tr>
<tr>
<td>$</td>
<td>\lambda</td>
</tr>
</tbody>
</table>

$\sim 2x$ larger uncertainty than the $B^0_s \rightarrow J/\psi \phi$ analysis

Systematics from resonance line-shapes
Scaling of current precision using current detector and expected running conditions

$B^0_s \to J/\psi KK$ and $B^0_s \to J/\psi \pi \pi$ will remain the dominant modes

Currently stat dominated, but must be able to control systematics (efficiencies and resolutions)

Hadronic trigger improvements in upgrade will help $B_s \to D_s D_s$ and if we can use timing to improve photon reconstruction in LHCb upgrade-II then $B_s^0 \to J/\psi \eta$ becomes interesting (no angular analysis needed for both channels)

[PLB 762C (2016) 484] [PRL 113 (2014) 211801] [PLB 762C (2016) 484]
U-spin or SU(3) *flavour symmetry* (+ dynamically assumptions) to constrain size of penguin with $b \rightarrow c \bar{c}d$ or compute them with OPE, QCD- factorisation

$B_s^0 \rightarrow J/\psi K_S$ and $B^0 \rightarrow J/\psi K_S$ are U-spin partners $\rightarrow$ control penguins in $\phi_d$, but limited precision with Run 1 data

Improved $K_S$ reconstruction in LHCb upgrade will help

Improved $K_S$ reconstruction in LHCb upgrade will help

$\phi_d = 2\beta + \Delta \phi_d^{pen} + \Delta \phi_d^{NP}$

<table>
<thead>
<tr>
<th>Param</th>
<th>Fitted value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{\Delta \Gamma}$</td>
<td>$0.49^{+0.77}_{-0.65} \pm 0.06$</td>
</tr>
<tr>
<td>$C_{dir}$</td>
<td>$-0.28 \pm 0.41 \pm 0.08$</td>
</tr>
<tr>
<td>$S_{mix}$</td>
<td>$-0.08 \pm 0.40 \pm 0.08$</td>
</tr>
</tbody>
</table>

[De Bruyn, Fleischer, JHEP 03 (2015) 145]

no penguin suppression

$\epsilon \sim 5\%$
Penguin pollution roadmap: $\phi_d$

Limited precision from $B_s \to J/\psi K_S$ limited but can place constraints on penguin size from direct/mixing CP asymmetries ($A_{CP}$) and ratios of BRs ($H$) of $B \to J/\psi X$ decays, e.g.,

$$A_{CP}(B^+ \to J/\psi K^+) = (0.09 \pm 0.27 \pm 0.07) \times 10^{-2}$$
$$A_{CP}^{\prime}(B^+ \to J/\psi \pi^+) = (1.91 \pm 0.89 \pm 0.16) \times 10^{-2}$$

Mostly $K\pi$ detector asymmetry

E + PA amplitudes must be neglected in $B_0 \to J/\psi \pi^0$ as they have no counterpart in $B_0 \to J/\psi K_S$. These effects are should be tiny and can be probed through $B_0(s) \to J/\psi \pi^0$ and $B_0 \to J/\psi \rho^0$ in the future

Small penguin shift but experimental precision is $\sigma(\phi_d) \sim 1.6^\circ$ so must continue to improve

$$S(J/\psi \pi^0) \sigma = 0.027 \text{ (stat)} \pm 0.027 \text{ (syst)}$$
$$A(J/\psi \pi^0) \sigma = 0.035 \text{ (stat)} \pm 0.017 \text{ (syst)}$$

[Belle-II projections @ 50 ab$^{-1}$ from A. Gaz, P. Urquijo, L Li Gioi]
Penguin pollution roadmap: $\phi_s$

Relax assumption that $\lambda_f \equiv \eta_f(q/p)(\bar{A}_f/A_f)$ is same for all $(J/\psi K^+K^-)_f$ polarisations $\rightarrow$ measure $\lambda_f = |\lambda_f| \exp(-i\phi_s)$, but this shows no sign of polarisation dependence

$SU(3)_f$: $B_s^0 \to J/\psi K^*$ and $B^0 \to J/\psi \rho^0$ are $b \to c\bar{c}d$ transitions (related by $s$-$d$ spectator exchange). $B^0 \to J/\psi \rho^0$ contains $E + PA$ diagrams that are not present in $B_s^0 \to J/\psi K^*$

Measure penguin phase shift for each polarisation state, $f \in (0, \perp, \parallel, S)$

$$\Delta\phi_{s,0}^{J/\psi \phi} = 0.000_{-0.011}^{+0.009} \text{ (stat)} \pm 0.004 \text{ (syst) rad}$$
$$\Delta\phi_{s,\parallel}^{J/\psi \phi} = 0.001_{-0.014}^{+0.010} \text{ (stat) } \pm 0.008 \text{ (syst) rad}$$
$$\Delta\phi_{s,\perp}^{J/\psi \phi} = 0.003_{-0.014}^{+0.010} \text{ (stat) } \pm 0.008 \text{ (syst) rad}$$

Small penguin shift ($\sim 0.06^\circ$) to be compared with current experimental precision is $\sigma(\phi_s) \sim 0.03$ rad

*[JHEP 11 (2015) 082]*
$\phi_s q\bar{q}$ from loop-dominated $B_s^0$ decays

Measure CPV phase from mixing + decay in $B_s^0 \rightarrow (K^+\pi^-)(K^-\pi^+)$ and $B_s^0 \rightarrow \phi\phi \rightarrow (K^+K^-)(K^+K^-)$. Compare to $B_s^0 \rightarrow J/\psi\phi$

$|\phi_s s\bar{s}|_{SM} < 0.02$ rad

[Bartsch et al., arXiv:0810.0249]
[Beneke et al., NPB 774 (2007) 64]
[Cheng et al., PRD 80 (2009) 114026]
$\phi_s^{d\bar{d}}$ from $B_s^0 \rightarrow (K^+\pi^-)(K^-\pi^+)$

Flavour-tagged ($\varepsilon_{\text{tag}} \sim 5\%$), decay-time dependent amplitude analysis of the 4-body final state (6D to analyse)

Rich structure of interfering scalar/vector/tensor $K\pi$ resonances in $B_s^0 \rightarrow (K^+\pi^-)(K^-\pi^+)$, including $K_0^*(1430)^0$, $K^*(892)^0$, $K_2^*(1430)^0$

Excellent hadron-PID for bkg suppression

9 Q2B channels $\rightarrow$ 19 amplitudes
$\phi_s^{d\bar{d}}$ from $B_s^0 \rightarrow (K^+\pi^-)(K^-\pi^+)$

First CPV results
Small longitudinal VV fraction

Systematic uncertainty dominated by modelling the angular efficiency from simulation

+ 2 dimensions not shown
$\phi_{s}^{s\bar{s}}$ from $B_{s}^{0} \rightarrow \phi \phi \rightarrow (K^{+}K^{-})(K^{+}K^{-})$

**2011-2016 dataset**

\[ N_{\text{sig}} \sim 8000 \]

$\phi_{s}^{s\bar{s}} = -0.07 \pm 0.13 \pm 0.03 \text{ rad}$

$|\lambda| = +1.02 \pm 0.05 \pm 0.03$

Dominant uncertainty from knowledge mass shape and angular/time efficiency from simulation/control samples

\[ A_{U} = 0.000 \pm 0.012 \text{ (stat)} \pm 0.004 \text{ (syst)} \]

\[ A_{V} = -0.003 \pm 0.012 \text{ (stat)} \pm 0.004 \text{ (syst)} \]

**TPAs**

CP-even

CP-odd

Single and double S-wave
Tagged, decay time dependent $B_s^0 \rightarrow D^{\pm} h^\pm$ are sensitive to $\gamma \pm 2{\beta}_s$ without penguin pollution. Taking ${\beta}_s$ from $b \rightarrow c \bar{c} s$ transitions we can measure $\gamma$. $r(D\pi) \sim 0.02$, $r(D_s K) \sim 0.4$

Data-driven time efficiency, tagging and resolution calibration. **Yields increase by ~4** after Run 2 (hadronic trigger eff and $\sigma_{bb} 8 \rightarrow 13$ TeV)

<table>
<thead>
<tr>
<th>$B^0 \rightarrow D^{\pm} \pi^{\pm}$</th>
<th>$S_f [%]$</th>
<th>$S_f' [%]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle [11]</td>
<td>6.8 ± 2.9 ± 1.2</td>
<td>3.1 ± 3.0 ± 1.2</td>
</tr>
<tr>
<td>Babar [10]</td>
<td>−2.3 ± 4.8 ± 1.4</td>
<td>4.3 ± 4.8 ± 1.4</td>
</tr>
<tr>
<td>This analysis</td>
<td>5.8 ± 2.0 ± 1.1</td>
<td>3.8 ± 2.0 ± 0.7</td>
</tr>
</tbody>
</table>

**Ultimate precision:**

@300/fb expect $\sigma(\gamma) \sim 1^\circ \rightarrow$ use $\gamma$ as input and measure $\beta_s$

Need improved $\Delta m_s$, currently statistics limited $\rightarrow$ require better understanding of LHCb length/momentum scales ($\sim 0.03\%$), more simulation (LHCb k-factor correction), vertex resolution (Belle-II) and fit biases (LHCb+Belle-II)
Most precise, **statistically dominated**, measurements of $\phi_{d,s}$ from $b\to c\bar{c}s$ transitions $\to$ look forward to Run-2 updates (and LHCb-upgrade)

- $B_s^0 \to J/\psi K K$, $B_s^0 \to J/\psi \pi\pi$, ... and $B^0 \to J/\psi K_s + \text{higher } [c\bar{c}] \text{ modes}$

Roadmap to control **penguin contributions** defined ($U$-spin, $SU(3)_f$)

LHCb measuring $\phi_s$ using penguin-dominated modes $\to$ promising precision

- $B_s^0 \to \phi\phi$ and $B_s^0 \to (K\pi)(K\pi)$

**Future:**

- need improved measurements of **B-mixing parameters/lifetimes**
- penguin-free $b\to c\bar{u}d$ transitions (e.g., $B_s^0 \to D^0 K_S$, $B^0 \to D^0\pi^+\pi^-$) will become interesting
Penguin pollution roadmap: $\phi_s$

$\phi(1020)$ is mixture of SU(3)$_f$ octet and singlet $\rightarrow$ how to handle this in SU(3) analysis of $B^0 \rightarrow J/\psi \phi$? 

**Option:** use $b \rightarrow c \bar{c} d$ modes such as $B^0_s \rightarrow J/\psi K^*$ and $B^0 \rightarrow J/\psi \omega$

What about $B^0_s \rightarrow J/\psi \omega$ with predicted BR $\sim 6 \times 10^{-6}$? $\rightarrow$ will require good mass resolution, which is $\sim 3$ times worse than $B^0 \rightarrow J/\psi \pi \pi$

With $300$/fb, we could look at $\omega \rightarrow \mu \mu$, giving better resolution and low background

Search for $B^0 \rightarrow J/\psi \phi$, with predicted BR $\sim 2 \times 10^{-7}$, which proceeds only via E + PA diagrams, which can tell us about comparisons between $B^0_s \rightarrow J/\psi \phi$ and $B^0 \rightarrow J/\psi K^*$

$$\mathcal{B}(\bar{B}^0 \rightarrow J/\psi \phi) < 1.9 \times 10^{-7}$$
Penguin-free modes

Time evolution of e.g., $B^0 \to D^{(*)} h^0$ decays governed by $\beta$ with no penguin contribution → provides SM reference
**$\phi_d$ from $b \to c\bar{u}d$ transitions**

\[
B^0 \to D_{CP}^0 h^0 \quad \sin 2\beta = 0.66 \pm 0.10 \pm 0.06, \quad C = -0.02 \pm 0.07 \pm 0.03 \\
B^0 \to D^0 h^0, D \to K_S\pi\pi \quad \sin 2\beta = 0.80 \pm 0.14 \pm 0.06 \pm 0.03; \quad \cos 2\beta = 0.91 \pm 0.22 \pm 0.09 \pm 0.07
\]

Dominant systematic from **vertex reconstruction, peaking backgrounds (and $D \to K\pi\pi$ Dalitz model)**

$B^0 \to D^{(*)} h^0$ is difficult at LHCb due to $\gamma$’s in $h^0$ decay so target for upgrade-I, -II is time-dependent Dalitz analysis of $B^0 \to D^0\pi^+\pi^-$ and $B^0_s \to D^0 K^+K^-$, which measures $\cos 2\beta$ and $\sin 2\beta$ when $D \to CP$ eigenstate

**Ultimate precision @ 50 (300) fb^{-1}:**

$\sigma(\sin 2\beta) \sim 0.018 (0.007)$ and $\sigma(\cos 2\beta) \sim 0.030 (0.017)$. Need to model $\pi\pi$ S-wave

Model-independent $D \to K_{S}\pi\pi$ can give $\sigma(\beta) < 1^\circ$

- [Belle+BaBar, PRL 115 (2015) 121604]
- [Belle+BaBar arXiv:1804.06152]
- [Bondar et al., PLB 624 (2005) 1]
- [PRD 92 (2015) 032002]
- [Bondar et al., JHEP 03 (2018) 195]
$B_s^0 \rightarrow D^0 K_S$: no possibility of penguin pollution ($r \sim 0.02$), but typically requires knowledge of $\gamma$, so expect some biases. Theoretically cleaner by $\times 10^3$.

\[ B(B_s^0 \rightarrow \bar{D}^0 \bar{K}^0) = [4.3 \pm 0.5 \text{(stat)} \pm 0.3 \text{(syst)} \pm 0.3 \text{(frag)} \pm 0.6 \text{(norm)}] \times 10^{-4} \]
\[ B(B_s^0 \rightarrow \bar{D}^{*0} \bar{K}^0) = [2.8 \pm 1.0 \text{(stat)} \pm 0.3 \text{(syst)} \pm 0.2 \text{(frag)} \pm 0.4 \text{(norm)}] \times 10^{-4} \]

(fs/fd and BR($B^0 \rightarrow D^0 K_S$))

**Future:**

- improved $K_S$ reconstruction
- Inclusion of more $D$ decay modes, including multibody $D$ decays, either model dependent or independent.
$b \rightarrow c\bar{u}d(s)$ and $b \rightarrow u\bar{c}d(s)$

$B_{(s)}^0 \rightarrow D_{(s)}^\mp h^\pm$ are sensitive to $\gamma \pm 2\beta_{(s)}$ without penguin pollution. Taking $\beta_{(s)}$ from $b \rightarrow c\bar{c}s$ transitions we can measure $\gamma$. $r(D_{\pi}) \sim 0.02$, $r(D_{s}K) \sim 0.4$

Data-driven decay time efficiency, tagging and resolution calibration. **Yields increase by factor ~4** after Run 2 (hadronic trigger efficiency and $\sigma_{bb} 8 \rightarrow 13$ TeV)

<table>
<thead>
<tr>
<th></th>
<th>$S_f$ (%)</th>
<th>$S_f$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle  [11]</td>
<td>6.8 ± 2.9 ± 1.2</td>
<td>3.1 ± 3.0 ± 1.2</td>
</tr>
<tr>
<td>Babar  [10]</td>
<td>−2.3 ± 4.8 ± 1.4</td>
<td>4.3 ± 4.8 ± 1.4</td>
</tr>
<tr>
<td>This analysis</td>
<td>5.8 ± 2.0 ± 1.1</td>
<td>3.8 ± 2.0 ± 0.7</td>
</tr>
</tbody>
</table>

**Ultimate precision:**

@300/fb expect $\sigma(\gamma) \sim 0.4^\circ$ → use $\gamma$ as input and measure $\beta_{(s)}$

Need improved $\Delta m_{(s)}$, currently statistics limited → require better understanding of LHCb length/momentum scales ($\sim 0.03\%$), more simulation (LHCb k-factor correction), vertex resolution (Belle-II) and fit biases (LHCb+Belle-II)
$\phi_d$ from $b \to c\bar{c}d$ transitions

4$\sigma$ evidence for CPV in $B^0 \to D^+D^-$

Use $\phi_d$ from $b \to c\bar{c}s$ as input to compute the penguin phase shift

$S = \sin(2\beta + \Delta\phi)$

$\Delta\phi = -0.16^{+0.19}_{-0.21}$ rad

Consistent with no penguin pollution

[SU(3) relation to $B_s \to D_sD_s$, control penguins]

[Belle, PRD 86 (2012) 071103]
[Fleischer, EPJC 51 (2007) 849]
[Jung, Schacht, PRD 91 (2015) 034027]
[Bel et al., JHEP 07 (2015) 108]
Production asymmetries

![Graph showing production asymmetries](image)

<table>
<thead>
<tr>
<th>Source</th>
<th>$A_{P}(B^{+})$</th>
<th>$A_{P}(B^{0})$</th>
<th>$A_{P}(B^{0}_{s})$</th>
<th>$A_{P}(A_{s}^{0})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal mass shape</td>
<td>0.0016</td>
<td>0.0005</td>
<td>0.0036</td>
<td>0.0024</td>
</tr>
<tr>
<td>Decay-time bias</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0008</td>
<td>0.0004</td>
</tr>
<tr>
<td>$\Delta m_{d}$, $\Delta m_{s}$</td>
<td>0.0000</td>
<td>0.0001</td>
<td>0.0014</td>
<td>0.0007</td>
</tr>
<tr>
<td>Decay-time resolution</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0026</td>
<td>0.0014</td>
</tr>
<tr>
<td>Final-state radiation</td>
<td>0.0000</td>
<td>0.0001</td>
<td>0.0000</td>
<td>0.0001</td>
</tr>
<tr>
<td>Decay-time reconstruction efficiency</td>
<td>0.0000</td>
<td>0.0001</td>
<td>0.0000</td>
<td>0.0001</td>
</tr>
<tr>
<td>Combinatorial background mass shape</td>
<td>0.0003</td>
<td>0.0000</td>
<td>0.0004</td>
<td>0.0003</td>
</tr>
<tr>
<td>Partially reconstructed background mass shape</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0029</td>
<td>0.0015</td>
</tr>
<tr>
<td>$\Delta \Gamma_{s}$</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>$A_{D}(K^{+})$</td>
<td>0.0018</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0013</td>
</tr>
<tr>
<td>$</td>
<td>q/p</td>
<td><em>{p</em>{T}}$, $</td>
<td>q/p</td>
<td><em>{p</em>{T}}$</td>
</tr>
<tr>
<td>Uncertainties from fragmentation fractions</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0058</td>
</tr>
<tr>
<td>Difference between $\omega_{i}$ or $\omega_{i}^{data}$</td>
<td>0.0003</td>
<td>0.0003</td>
<td>0.0003</td>
<td>0.0003</td>
</tr>
<tr>
<td>Neglecting term with $A_{P}(\Xi_{b})$ in $E_{Q}$, 3</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0071</td>
</tr>
<tr>
<td>Validity of $N_{p} = N_{p}$ in each bin</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0032</td>
</tr>
<tr>
<td>$A_{CP}(B^{+} \rightarrow J/\psi K^{+})$</td>
<td>0.0028</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0028</td>
</tr>
<tr>
<td>$A_{D}(K^{0})$</td>
<td>0.0001</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0002</td>
</tr>
</tbody>
</table>

Total systematic uncertainty | 0.0037 | 0.0011 | 0.0059 | 0.0108 |

$A_{P}(B^{0})_{\sqrt{s}=7\text{ TeV}} = 0.0044 \pm 0.0088$ (stat) $\pm 0.0011$ (syst)

$A_{P}(B^{0})_{\sqrt{s}=8\text{ TeV}} = -0.0140 \pm 0.0055$ (stat) $\pm 0.0010$ (syst)

$A_{P}(B^{0}_{s})_{\sqrt{s}=7\text{ TeV}} = -0.0065 \pm 0.0288$ (stat) $\pm 0.0059$ (syst)

$A_{P}(B^{0}_{s})_{\sqrt{s}=8\text{ TeV}} = 0.0198 \pm 0.0190$ (stat) $\pm 0.0059$ (syst)
\[ \Delta \Gamma_d \neq 0 ? \]

Measurements of \( S_f = \sin 2\beta \) assume \( \Delta \Gamma_d = 0 \)

Measure \( \Delta \Gamma_d \) by comparing decay time distributions of \( B^0 \to J/\psi K^* + B^0 \to J/\psi K_S \) \[\text{[Gershon, JPG 38 (2011) 015007]}\]

\( \Delta \Gamma_d \neq 0 \) could explain the D0 dimuon asymmetry

\[
A_{CP} = C_d A_{SL}^d + C_s A_{SL}^s + C_{\Delta \Gamma_d} \frac{\Delta \Gamma_d}{\Gamma_d}
\]

[Borissov, Hoeneisen PRD 87 (2013) 074020] [D0, PRD 89 (2014) 012002]

\[
\int L \, dt = 20.3 \, \text{fb}^{-1}
\]

\[
\Delta \Gamma_d \approx \left( -0.1 \pm 1.1 \pm 0.9 \right) \times 10^{-2}
\]

[also LHCb with only 2011 data, JHEP 04 (2014) 114]
Polarisation-dependent $\phi_s$

Penguin pollution and/or CP violation could be different for each polarisation state, $f \in (0, \perp, \parallel, S)$

Relax assumption that $\lambda_f = \eta_f (q/p)(\bar{A}_f/A_f)$ is same for all $(J/\psi K^+ K^-)_f$ polarisations $\rightarrow$ measure $\lambda_f = |\lambda_f| \exp(-i\phi_f)$

No sign of polarisation dependence $\rightarrow$ penguins are small

Ultimate precision: Need to monitor stat + syst correlations between these parameters and others (e.g., $\Delta \Gamma_s$, $|A_f|^2$) from $B_s^0 \rightarrow J/\psi K^+ K^-$ angular fit

<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>$\phi^0_s$ [rad]</td>
<td>$-0.045 \pm 0.053 \pm 0.007$</td>
</tr>
<tr>
<td>$\phi^\parallel - \phi^0_s$ [rad]</td>
<td>$-0.018 \pm 0.043 \pm 0.009$</td>
</tr>
<tr>
<td>$\phi^\perp - \phi^0_s$ [rad]</td>
<td>$-0.014 \pm 0.035 \pm 0.006$</td>
</tr>
<tr>
<td>$\phi^S - \phi^0_s$ [rad]</td>
<td>$0.015 \pm 0.061 \pm 0.021$</td>
</tr>
</tbody>
</table>
$$B_s^0 \rightarrow J/\psi \phi$$ systematic uncertainties

| Source                        | $\Gamma_s$ [ps$^{-1}$] | $\Delta \Gamma_s$ [ps$^{-1}$] | $|A_\perp|^2$ | $|A_0|^2$ | $\delta_\parallel$ [rad] | $\delta_\perp$ [rad] | $\phi_s$ | $|\lambda|$ | $\Delta m_s$ [ps$^{-1}$] |
|-------------------------------|-------------------------|--------------------------------|--------------|-----------|--------------------------|----------------------|----------|-------------|--------------------------|
| Total stat. uncertainty       | 0.0027                  | 0.0091                         | 0.0049       | 0.0034    | $+0.10_{-0.17}$          | $+0.14_{-0.15}$      | 0.049    | 0.019       | $+0.055_{-0.057}$         |
| Mass factorisation            | –                       | 0.0007                         | 0.0031       | 0.0064    | 0.05                      | 0.05                | 0.002    | 0.001       | 0.004                     |
| Signal weights (stat.)        | 0.0001                  | 0.0001                         | –            | –         | –                        | –                   | –        | –           | –                        |
| $b$-hadron background         | 0.0001                  | 0.0004                         | 0.0004       | 0.0002    | 0.02                      | 0.02                | 0.002    | 0.003       | 0.001                     |
| $B^+_c$ feed-down              | 0.0005                  | –                               | –            | –         | –                        | –                   | –        | –           | –                        |
| Angular resolution bias       | –                       | –                               | 0.0006       | 0.0001    | $+0.02$                  | $-0.03$             | 0.01     | –           | –                        |
| Ang. efficiency (rewooting)   | 0.0001                  | –                               | 0.0011       | 0.0020    | 0.01                      | –                   | –        | 0.001       | 0.005                     |
| Ang. efficiency (stat.)       | 0.0001                  | 0.0002                         | 0.0011       | 0.0004    | 0.02                      | 0.01                | –        | 0.004       | 0.002                     |
| Decay-time resolution         | –                       | –                               | –            | –         | –                        | –                   | 0.01     | 0.002       | 0.001                     |
| Trigger efficiency (stat.)    | 0.0011                  | 0.0009                         | –            | –         | –                        | –                   | –        | –           | –                        |
| Track reconstruction (simul.) | 0.0007                  | 0.0029                         | 0.0005       | 0.0006    | $+0.01$                  | $-0.02$             | 0.002    | 0.001       | 0.001                     |
| Track reconstruction (stat.)  | 0.0005                  | 0.0002                         | –            | –         | –                        | –                   | –        | –           | 0.001                     |
| Length and momentum scales    | 0.0002                  | –                               | –            | –         | –                        | –                   | –        | –           | 0.005                     |
| S-P coupling factors          | –                       | –                               | –            | –         | 0.01                      | 0.01                | –        | 0.001       | 0.002                     |
| Fit bias                      | –                       | –                               | 0.0005       | –         | $+0.06_{-0.07}$           | 0.06                | 0.006    | 0.007       | 0.011                     |

**Next $B^0_s \rightarrow J/\psi \phi$ update will fix mass factorisation (new model). Backgrounds should scale**

**Angular efficiencies** will continue to dominate → large MC and data control channels (e.g., $B^0 \rightarrow J/\psi K^*$)

**Lifetime efficiency** → next slide
Systematic uncertainties: lifetimes

Major systematic will continue to be understanding decay time efficiency ⇒ need large MC samples and data control channels

Need **improved measurement of** $B^0, B^+$ **lifetimes**, which requires excellent control of absolute efficiency (LHCb) and vertex resolution (Belle-II)

$$\tau(B^0) = 1.518 \pm 0.004 \text{ ps} \ [HFLAV]$$
$$\tau(B^+) = 1.638 \pm 0.004 \text{ ps}$$

Absolute lifetime predictions suffer from uncertainties ~ $m_b^5$; lifetime ratios under better control

$$\frac{\tau(B_s)}{\tau(B^0)} = 1.00050 \pm 0.00108 - 0.0225 \delta \quad [Jubb \ et \ al, \ arXiv:1603.07770]$$
$$\frac{\tau(B_s)}{\tau(B^0)} = 0.990 \pm 0.004 \ [HFLAV]$$

**Next LHCb $B_s^0 \to J/\psi K^+K^-$ update will measure** $\sigma(\Gamma_s / \Gamma_d) \sim 0.005$
Impact on new physics

$$M_{12}^{NP, s} = M_{12}^{SM, s} \Delta_s$$

$$\Delta_s = |\Delta_s| e^{i\phi_s}$$

$$\Delta_s^{SM} = 1$$

Even given the constraints that show consistency with the SM, NP still allowed at the 10% level
Penguin contributions

Penguin contribution could lead to non-zero CPV in decay for $b \rightarrow c \bar{c} s$ transitions. Currently $C_f$ values in $B^0_{(s)}$ decays are consistent with zero at few %

Most precise constraint from $A_{CP}(B^+ \rightarrow J/\psi K^+)$ but possible suppression from small strong phase difference → more information required

$$A_{CP}(B^+ \rightarrow J/\psi K^+) = (0.09 \pm 0.27 \pm 0.07) \times 10^{-2}$$
$$A^{CP}(B^+ \rightarrow J/\psi \pi^+) = (1.91 \pm 0.89 \pm 0.16) \times 10^{-2}$$

Dominant syst from $K\pi$ detector asymmetry determination

Same argument for $b \rightarrow c \bar{c} d$ transitions

$$(B^+ \rightarrow J/\psi \pi^+, B^- \rightarrow D^- D^0)$$

B-factories have precision of $\sim10\%$ on $D^-$ mode

$$A^{CP}(B^- \rightarrow D^- D^0) = (-0.4 \pm 0.5 \pm 0.5)\%$$
$$A^{CP}(B^- \rightarrow D^- D^0) = (2.3 \pm 2.7 \pm 0.4)\%$$
$B^0 \rightarrow J/\psi \pi^0$ and $DD$

$J/\psi \pi^0$ $S_{CP}$ vs $C_{CP}$

$\sigma(S) = 0.027$ (stat) ± 0.027 (syst)
$\sigma(A) = 0.035$ (stat) ± 0.017 (syst)

[Belle-II projections @ 50 ab$^{-1}$ from A. Gaz, P. Urquijo, L Li Gioi]

[Belle, PRD 86 (2012) 071103]
Penguin pollution roadmap: $\phi_s$

Similar story for $\phi_s$ from $B_S \rightarrow D_s D_s$ decays

Use direct/mixing CP asymmetries and ratios of BRs of $B^0 \rightarrow D^+ D^-$ decays to constrain size of penguins

$H$ observable is not theoretically clean due to possible sizeable E+PA contributions

**penguin shift may be larger here...**

Enhanced E + PA topologies, indications for significant penguin contributions $\rightarrow$ ultimately control penguins for $\phi_s$ in $B_s \rightarrow D_s D_s$ decays

**Future:** $B_s^0 \rightarrow D_s^* D_s^*$ and $B^0 \rightarrow D^* D^*$, need TD angular analysis
**$B_s^0$ effective lifetimes**

Effective lifetimes of CP-even/odd final states constrain $\Gamma_{L,H}$ and give information on $\phi_s$ (ignores sub-leading penguins...)

$$\tau_{\text{eff}} \Gamma_s = 1 + A_f^{\Delta \Gamma_s} y_s + \left[ 2 - (A_f^{\Delta \Gamma_s})^2 \right] y_s^2 + \ldots$$

$$y_s = \frac{\Delta \Gamma_s}{2 \Gamma_s}$$

(Tagged $B_s^0 \to J/\psi \phi$ will always dominate the precision for mixing and lifetime quantities, but useful to measure $\tau_{\text{eff}}$ as cross-check)

**Run 2 and beyond:** time-dependent flavour-tagged analyses become possible for some channels (e.g., with 300/fb, we could have 4% $\times$ 300k $\sim$ 12k tagged $B_s^0 \to J/\psi \eta$, $\eta \to \gamma \gamma$ candidates)
LHCb run 1 and 2

LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2017

- 2 fb⁻¹
- 3 fb⁻¹

Year


Integrated Recorded Luminosity (1/fb)

2017 (6.5 TeV): 0.30 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb

LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger: 1 MHz readout, high E_T/PT signatures

450 kHz h²
400 kHz μ/μμ
150 kHz e/γ

Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz Rate to storage
Flavour tagging

**Upgrade challenge:** increase in track multiplicity and pile-up (~6 for upgrade-I and ~55 for upgrade-II) that have negative effect on $\omega$ and $\varepsilon(\text{tag})$

FT performance directly linked to the ability to associate PV $\leftrightarrow$ track. To improve/maintain tagging performance need:

**Hardware:** timing information (upgrade-II workshops)

**Software:** deep neural networks to learn correlations between all tracks and the signal B meson

Should be able to regain Run-2 performance in Run-3 by retuning algorithms and use of deep learning inclusive tagger

\[ \varepsilon_{\text{tag}} = \frac{N_{\text{tagged}}}{N_{\text{tagged}} + N_{\text{untagged}}} \]

\[ \omega = \frac{N_{\text{wrong}}}{N_{\text{right}} + N_{\text{wrong}}} \]

\[ \varepsilon_{\text{eff}} = \varepsilon_{\text{tag}} D^2 = \varepsilon_{\text{tag}} (1 - 2\omega)^2 \]

\[ \sigma_{\text{stat}}(A_{CP}) \propto 1 / \sqrt{\varepsilon_{\text{eff}}N} \]
“In view of this situation it is safe to say that SU(3)\textsubscript{F}-based estimates of the penguin pollution in $B_s^0 \rightarrow J/\psi \phi$ rest on \textit{shaky ground}”

\[ \phi_s^{d\bar{d}} \text{ from } B_s^0 \rightarrow (K^+\pi^-)(K^-\pi^+) \]

**LHCb simulation**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common parameters</td>
<td></td>
</tr>
<tr>
<td>( \phi_s^{d\bar{d}} [\text{rad}] )</td>
<td>(-0.10 \pm 0.13 \pm 0.14)</td>
</tr>
<tr>
<td>(</td>
<td>\lambda</td>
</tr>
<tr>
<td>Vector/Vector (VV)</td>
<td></td>
</tr>
<tr>
<td>( f_{VV} )</td>
<td>(0.067 \pm 0.004 \pm 0.024)</td>
</tr>
<tr>
<td>( f_{V}\bar{V} )</td>
<td>(0.208 \pm 0.032 \pm 0.046)</td>
</tr>
<tr>
<td>( f_{T\bar{T}} )</td>
<td>(0.297 \pm 0.029 \pm 0.042)</td>
</tr>
<tr>
<td>( \delta_{VV}^{[\text{rad}]} )</td>
<td>(2.40 \pm 0.11 \pm 0.33)</td>
</tr>
<tr>
<td>( \delta_{V\bar{T}}^{[\text{rad}]} )</td>
<td>(2.62 \pm 0.26 \pm 0.64)</td>
</tr>
<tr>
<td>Scalar/Vector (SV and VS)</td>
<td></td>
</tr>
<tr>
<td>( f_{SV} )</td>
<td>(0.329 \pm 0.015 \pm 0.071)</td>
</tr>
<tr>
<td>( f_{VS} )</td>
<td>(0.133 \pm 0.013 \pm 0.065)</td>
</tr>
<tr>
<td>( \delta_{SV}^{[\text{rad}]} )</td>
<td>(-1.31 \pm 0.10 \pm 0.35)</td>
</tr>
<tr>
<td>( \delta_{VS}^{[\text{rad}]} )</td>
<td>(1.86 \pm 0.11 \pm 0.41)</td>
</tr>
<tr>
<td>Scalar/Scalar (SS)</td>
<td></td>
</tr>
<tr>
<td>( f_{SS} )</td>
<td>(0.225 \pm 0.010 \pm 0.069)</td>
</tr>
<tr>
<td>( \delta_{SS}^{[\text{rad}]} )</td>
<td>(1.07 \pm 0.10 \pm 0.40)</td>
</tr>
<tr>
<td>Scalar/Tensor (ST and TS)</td>
<td></td>
</tr>
<tr>
<td>( f_{ST} )</td>
<td>(0.014 \pm 0.006 \pm 0.031)</td>
</tr>
<tr>
<td>( f_{TS} )</td>
<td>(0.025 \pm 0.007 \pm 0.033)</td>
</tr>
<tr>
<td>( \delta_{ST}^{[\text{rad}]} )</td>
<td>(-2.3 \pm 0.4 \pm 1.7)</td>
</tr>
<tr>
<td>( \delta_{TS}^{[\text{rad}]} )</td>
<td>(-0.10 \pm 0.26 \pm 0.82)</td>
</tr>
<tr>
<td>Vector/Tensor (VT and TV)</td>
<td></td>
</tr>
<tr>
<td>( f_V^{[\text{rad}]} )</td>
<td>(0.160 \pm 0.016 \pm 0.049)</td>
</tr>
<tr>
<td>( f_T^{[\text{rad}]} )</td>
<td>(0.911 \pm 0.020 \pm 0.165)</td>
</tr>
<tr>
<td>( f_{VV}^{[\text{rad}]} )</td>
<td>(0.012 \pm 0.008 \pm 0.053)</td>
</tr>
<tr>
<td>( f_{V\bar{T}}^{[\text{rad}]} )</td>
<td>(0.036 \pm 0.014 \pm 0.048)</td>
</tr>
<tr>
<td>( f_{TV}^{[\text{rad}]} )</td>
<td>(0.62 \pm 0.16 \pm 0.25)</td>
</tr>
<tr>
<td>( f_{TV}^{[\text{rad}]} )</td>
<td>(0.24 \pm 0.10 \pm 0.14)</td>
</tr>
<tr>
<td>( \delta_{VT}^{[\text{rad}]} )</td>
<td>(-2.06 \pm 0.19 \pm 1.17)</td>
</tr>
<tr>
<td>( \delta_{VT}^{[\text{rad}]} )</td>
<td>(-1.8 \pm 0.4 \pm 1.0)</td>
</tr>
<tr>
<td>( \delta_{VT}^{[\text{rad}]} )</td>
<td>(-3.2 \pm 0.3 \pm 1.2)</td>
</tr>
<tr>
<td>( \delta_{VT}^{[\text{rad}]} )</td>
<td>(-1.0 \pm 0.1 \pm 0.1)</td>
</tr>
<tr>
<td>( \delta_{VT}^{[\text{rad}]} )</td>
<td>(-0.2 \pm 0.3 \pm 0.2)</td>
</tr>
<tr>
<td>( \delta_{VT}^{[\text{rad}]} )</td>
<td>(-1.3 \pm 0.4 \pm 1.1)</td>
</tr>
<tr>
<td>Tensor/Tensor (TT)</td>
<td></td>
</tr>
<tr>
<td>( f_{TT}^{[\text{rad}]} )</td>
<td>(0.011 \pm 0.003 \pm 0.007)</td>
</tr>
<tr>
<td>( f_{TT}^{[\text{rad}]} )</td>
<td>(0.25 \pm 0.14 \pm 0.18)</td>
</tr>
<tr>
<td>( f_{TT}^{[\text{rad}]} )</td>
<td>(0.17 \pm 0.11 \pm 0.14)</td>
</tr>
<tr>
<td>( f_{TT}^{[\text{rad}]} )</td>
<td>(0.30 \pm 0.18 \pm 0.21)</td>
</tr>
<tr>
<td>( f_{TT}^{[\text{rad}]} )</td>
<td>(0.015 \pm 0.033 \pm 0.107)</td>
</tr>
<tr>
<td>( \delta_{TT}^{[\text{rad}]} )</td>
<td>(1.3 \pm 0.5 \pm 1.8)</td>
</tr>
<tr>
<td>( \delta_{TT}^{[\text{rad}]} )</td>
<td>(3.00 \pm 0.29 \pm 0.57)</td>
</tr>
<tr>
<td>( \delta_{TT}^{[\text{rad}]} )</td>
<td>(2.6 \pm 0.4 \pm 1.5)</td>
</tr>
<tr>
<td>( \delta_{TT}^{[\text{rad}]} )</td>
<td>(2.3 \pm 0.8 \pm 1.7)</td>
</tr>
<tr>
<td>( \delta_{TT}^{[\text{rad}]} )</td>
<td>(0.7 \pm 0.6 \pm 1.3)</td>
</tr>
</tbody>
</table>
\[ \phi_s d \bar{d} \text{ from } B_s^0 \rightarrow (K^+\pi^-)(K^-\pi^+) \]

Table 4: Summary of the systematic uncertainties on the two CP parameters, the CP-averaged fractions and the strong phase differences (in radians) for each of the components listed in Table 1.

| Parameter                                      | \( \phi_s^{\text{dir}} \) [rad] | |f| | f_{SV} | f_{ST} | f_{SV} | \delta_{SV} | \delta_{ST} | f_{SV} | f_{SV} | \delta_{SV} | \delta_{ST} | f_{SV} | f_{SV} | \delta_{SV} | \delta_{ST} |
|------------------------------------------------|----------------------|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Yield and shape of mass model                  | 0.012                | 0.001 | 0.001 | 0.004 | 0.004 | 0.011 | 0.020 | 0.002 | 0.003 | 0.233 | 0.023 | 0.004 | 0.012 |
| Signal weights of mass model                   | 0.012                | 0.007 | 0.002 | 0.006 | 0.002 | 0.024 | 0.112 | 0.001 | 0.005 | 0.049 | 0.022 | 0.005 | 0.047 |
| Decay-time-dependent fit procedure             | 0.006                | 0.002 | 0.001 | 0.006 | 0.002 | 0.007 | 0.017 | 0.003 | 0.002 | 0.007 | 0.027 | 0.001 | 0.009 |
| Decay-time-dependent fit parameterisation      | 0.049                | 0.013 | 0.021 | 0.025 | 0.026 | 0.187 | 0.202 | 0.042 | 0.029 | 0.159 | 0.234 | 0.064 | 0.227 |
| Acceptance weights (simulated sample size)    | 0.106                | 0.078 | 0.004 | 0.031 | 0.029 | 0.236 | 0.564 | 0.037 | 0.030 | 0.250 | 0.290 | 0.015 | 0.256 |
| Other acceptance and resolution effects        | 0.063                | 0.008 | 0.005 | 0.018 | 0.005 | 0.136 | 0.149 | 0.006 | 0.004 | 0.167 | 0.124 | 0.017 | 0.194 |
| Production asymmetry                           | 0.002                | 0.002 | 0.000 | 0.000 | 0.000 | 0.001 | 0.017 | 0.002 | 0.002 | 0.002 | 0.008 | 0.000 | 0.002 |
| Total                                          | 0.141                | 0.089 | 0.024 | 0.046 | 0.042 | 0.333 | 0.641 | 0.071 | 0.065 | 0.346 | 0.405 | 0.069 | 0.399 |

<table>
<thead>
<tr>
<th>Parameter</th>
<th>f_{TT}</th>
<th>f_{TS}</th>
<th>\delta_{ST}</th>
<th>\delta_{SS}</th>
<th>f_{TT}</th>
<th>f_{TT}</th>
<th>f_{TT}</th>
<th>f_{ST}</th>
<th>f_{ST}</th>
<th>f_{ST}</th>
<th>\delta_{ST}</th>
<th>\delta_{ST}</th>
<th>f_{TT}</th>
<th>f_{TT}</th>
<th>f_{TT}</th>
<th>f_{ST}</th>
<th>f_{ST}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield and shape of mass model</td>
<td>0.002</td>
<td>0.004</td>
<td>0.111</td>
<td>0.023</td>
<td>0.001</td>
<td>0.003</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.003</td>
<td>0.025</td>
<td>0.023</td>
<td>0.055</td>
<td>0.110</td>
<td>0.053</td>
<td>0.018</td>
</tr>
<tr>
<td>Signal weights of mass model</td>
<td>0.004</td>
<td>0.006</td>
<td>0.151</td>
<td>0.105</td>
<td>0.002</td>
<td>0.003</td>
<td>0.003</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.003</td>
<td>0.029</td>
<td>0.025</td>
<td>0.131</td>
<td>0.126</td>
<td>0.080</td>
<td>0.073</td>
</tr>
<tr>
<td>Decay-time-dependent fit procedure</td>
<td>0.001</td>
<td>0.002</td>
<td>0.248</td>
<td>0.017</td>
<td>0.002</td>
<td>0.004</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td>0.008</td>
<td>0.005</td>
<td>0.012</td>
<td>0.069</td>
<td>0.025</td>
<td>0.062</td>
<td>0.017</td>
</tr>
<tr>
<td>Decay-time-dependent fit parameterisation</td>
<td>0.006</td>
<td>0.017</td>
<td>0.736</td>
<td>0.247</td>
<td>0.011</td>
<td>0.053</td>
<td>0.019</td>
<td>0.008</td>
<td>0.008</td>
<td>0.008</td>
<td>0.080</td>
<td>0.048</td>
<td>0.286</td>
<td>0.308</td>
<td>0.260</td>
<td>0.260</td>
<td>0.228</td>
</tr>
<tr>
<td>Acceptance weights (simulated sample size)</td>
<td>0.014</td>
<td>0.015</td>
<td>1.463</td>
<td>0.719</td>
<td>0.026</td>
<td>0.145</td>
<td>0.054</td>
<td>0.027</td>
<td>0.199</td>
<td>0.102</td>
<td>1.117</td>
<td>1.080</td>
<td>0.888</td>
<td>0.712</td>
<td>0.417</td>
<td>0.947</td>
<td></td>
</tr>
<tr>
<td>Other acceptance and resolution effects</td>
<td>0.002</td>
<td>0.003</td>
<td>0.184</td>
<td>0.226</td>
<td>0.015</td>
<td>0.024</td>
<td>0.004</td>
<td>0.005</td>
<td>0.045</td>
<td>0.017</td>
<td>0.163</td>
<td>0.164</td>
<td>0.191</td>
<td>0.022</td>
<td>0.246</td>
<td>0.171</td>
<td></td>
</tr>
<tr>
<td>Production asymmetry</td>
<td>0.001</td>
<td>0.001</td>
<td>0.037</td>
<td>0.026</td>
<td>0.001</td>
<td>0.003</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
<td>0.002</td>
<td>0.006</td>
<td>0.015</td>
<td>0.003</td>
<td>0.018</td>
<td>0.003</td>
<td>0.007</td>
<td>0.041</td>
</tr>
<tr>
<td>Total</td>
<td>0.031</td>
<td>0.033</td>
<td>1.688</td>
<td>0.817</td>
<td>0.049</td>
<td>0.165</td>
<td>0.063</td>
<td>0.048</td>
<td>0.252</td>
<td>0.143</td>
<td>1.171</td>
<td>1.159</td>
<td>0.970</td>
<td>0.802</td>
<td>0.546</td>
<td>1.076</td>
<td></td>
</tr>
</tbody>
</table>

**K\pi** S-wave and higher **K*** resonances
$\phi s^{\bar{s}}$ from $B_s^0 \rightarrow \phi \phi \rightarrow (K^+K^-)(K^+K^-)$

2011-2016 dataset

Parameter | Result
--- | ---
$\phi s^{\bar{s}}$ ( rad ) | $-0.07 \pm 0.13$
$|\lambda|$ | $1.02 \pm 0.05$
$|A_\perp|^2$ | $0.287 \pm 0.008$
$|A_0|^2$ | $0.382 \pm 0.008$
$\delta_\perp$ ( rad ) | $2.81 \pm 0.21$
$\delta_\parallel$ ( rad ) | $2.52 \pm 0.05$

| Parameter | Mass model | AA | TA | TR | Fit bias | Total |
--- | --- | --- | --- | --- | --- | --- |
$|A_0|^2$ | $0.0035$ | $0.0098$ | $0.0008$ | $0.0001$ | $0.0018$ | $0.0106$ |
$|A_\perp|^2$ | $0.0021$ | $0.0046$ | $0.0007$ | $0.0002$ | $0.0012$ | $0.0052$ |
$\delta_\parallel$ (rad) | $0.0128$ | $0.0653$ | $0.0049$ | $0.0031$ | $0.0179$ | $0.0692$ |
$\delta_\perp$ (rad) | $0.0640$ | $0.0100$ | $0.0085$ | $0.0064$ | $0.0701$ | $0.0960$ |
$\phi s^{\bar{s}}$ (rad) | $0.0119$ | $0.0072$ | $0.0077$ | $0.0035$ | $0.0126$ | $0.0206$ |
$|\lambda|$ | $0.0063$ | $0.0217$ | $0.0023$ | $0.0053$ | $0.0097$ | $0.0253$ |

Efficiency from $B_s^0 \rightarrow D_s\pi$ control
Triple product asymmetries from $B_s^0 \rightarrow \phi \phi$

$$\sin \Phi = (\hat{n}_{V_1} \times \hat{n}_{V_2}) \cdot \hat{p}_{V_1},$$
$$\sin 2\Phi = 2(\hat{n}_{V_1} \cdot \hat{n}_{V_2})(\hat{n}_{V_1} \times \hat{n}_{V_2}) \cdot \hat{p}_{V_1}$$

$U \equiv \sin \Phi \cos \Phi$ \quad $V \equiv \sin (\pm \Phi)$

$$A_U \equiv \frac{\Gamma(U > 0) - \Gamma(U < 0)}{\Gamma(U > 0) + \Gamma(U < 0)}$$

$$A_V \equiv \frac{\Gamma(V > 0) - \Gamma(V < 0)}{\Gamma(V > 0) + \Gamma(V < 0)}$$