Experimental overview of CPV parameter $\phi_s$

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on behalf of the LHCb collaboration

Flavour Physics & CP Violation 2017, Prague
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Introduction to $\phi_s$

- $\beta_s$ in $B^0_s$ system analogous to $\beta$ in $B^0_d$ system
  (see talk by Justin Albert, Tue 14:30)

- Access in interference between $B^0_s$ mixing and decay

- Cleanest measurement in $B \to c\bar{c}s$ transitions, e.g.
  $B^0_s \to J/\psi \phi$

- Assuming only a SM tree contribution

$$\phi_s = -\arg(\lambda_f) = \phi^S_M - 2\phi_D = -2 \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}}\right) \equiv -2\beta_s$$

$$\phi^S_M = 2 \arg(V_{ts}V_{tb}^*)$$

$$\phi_D = \arg(V_{cs}V_{cb}^*)$$

$$\phi_s^{SM} = -37.6 \pm 0.8 \text{ mrad}$$

no penguins [CKMFitter]
Introduction to $\phi_s$

- $\beta_s$ in $B_s^0$ system analogous to $\beta$ in $B_d^0$ system (see talk by Justin Albert, Tue 14:30)

- Access in interference between $B_s^0$ mixing and decay

- Cleanest measurement in $B \rightarrow c\bar{c}s$ transitions, e.g. $B_s^0 \rightarrow J/\psi\phi$

- Sensitive to NP in the mixing even at high energy scales

$$\phi_s = -\arg(\lambda_f) = \phi_M - 2\phi_D = -2\beta_s + \Delta\phi_{NP}$$

$$\phi_D = \arg(V_{cs}V_{cb}^*)$$
Outline

1 $\phi_s$ measurement
   - $\phi_s$ measurement in $b \rightarrow c\bar{c}s$ transitions
   - Controlling penguin pollution
   - $\phi_s$ measurement in $b \rightarrow sq\bar{q}$ transitions

2 Future potential in $\phi_s$ measurements
Outline

1. $\phi_s$ measurement
   - $\phi_s$ measurement in $b \to c\bar{c}s$ transitions
     Controlling penguin pollution
   - $\phi_s$ measurement in $b \to s q \bar{q}$ transitions

2. Future potential in $\phi_s$ measurements
**Golden mode**

- $B_s^0 \rightarrow J/\psi [\mu^- \mu^+] K^+ K^-$ is the “golden mode” for $\phi_s$
  - Precise SM prediction, high sensitivity to NP
  - Relatively large BF, $\mathcal{O}(10^{-3})$

- Also measurement of $\Gamma_s = \frac{\Gamma_H + \Gamma_L}{2}$, $\Delta \Gamma_s = \Gamma_L - \Gamma_H$, $\Delta m_s = m_H - m_L$

- First measured by CDF and D0
- Measurements by ATLAS, CMS and LHCb during Run I of the LHC

### LHC Run I $B_s^0 \rightarrow J/\psi KK$ measurements

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\sqrt{s}$</th>
<th>Int. luminosity</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>7 – 8 TeV</td>
<td>19.2 fb$^{-1}$</td>
<td>[JHEP 08 (2016) 147], [PRD 90, 052007 (2014)]</td>
</tr>
<tr>
<td>CMS</td>
<td>8 TeV</td>
<td>19.7 fb$^{-1}$</td>
<td>[PLB 757, 97 (2016)]</td>
</tr>
<tr>
<td>LHCb</td>
<td>7 – 8 TeV</td>
<td>3 fb$^{-1}$</td>
<td>[PRL 114, 041801 (2015)], [PRL 108, 101803 (2012)]</td>
</tr>
</tbody>
</table>
Measurement of $\phi_s$

$\phi_s$ accessed in $B_s^0$ decay time distribution

$$a_{CP}(t) \equiv \frac{\Gamma(B_s^0 \rightarrow f) - \Gamma(B_s^0 \rightarrow \bar{f})}{\Gamma(B_s^0 \rightarrow f) + \Gamma(B_s^0 \rightarrow \bar{f})} = \eta_f \sin(\phi_s) \sin(\Delta m_s t)$$

$$a_{CP}(t) \approx e^{-\frac{1}{2} \Delta m_s^2 \sigma_t^2} (1 - 2\omega) \eta_f \sin(\phi_s) \sin(\Delta m_s t)$$

$e^{-\frac{1}{2} \Delta m_s^2 \sigma_t^2}$ Decay time with finite resolution $\sigma_t$

$\eta_f$ $CP$ eigenvalue

$(1 - 2\omega)$ Flavour tagging with mistag probability $\omega$

Two types of tagging

→ Same-side tagging:
  $B_s^0$ flavour from charge of kaon originating from primary vertex

→ Opposite-side tagging:
  $B_s^0$ flavour from charge of kaon, muon or electron originating from a secondary vertex
\( \phi_s \) from \( B_s^0 \rightarrow J/\psi KK \)

\( \eta_f \) CP eigenvalue

\( B_s^0 \rightarrow J/\psi KK \) is an admixture of \( CP \)-even \( (\eta_f = 1) \) and \( CP \)-odd \( (\eta_f = -1) \) eigenstates

\[
\rightarrow \phi[KK], \ CP\text{-even}(A_0 + A_{\parallel}) + CP\text{-odd}(A_{\perp})
\]

\[
\rightarrow KK \text{ S-wave, } \ CP\text{-odd} (A_S)
\]

Use angular distribution to disentangle \( CP \)-even and \( CP \)-odd components

\[
d^4 \Gamma(B_s^0 \rightarrow J/\psi \phi) \propto \sum_{i=1}^{10} h_k(t) f_k(\Omega)
\]

\[
h_k(t) = N_k e^{-\Gamma_s t} \left[ a_k \cosh \left( \frac{1}{2} \Delta \Gamma_s t \right) + b_k \sinh \left( \frac{1}{2} \Delta \Gamma_s t \right) + c_k \cos \left( \frac{1}{2} \Delta m_s t \right) + d_k \sin \left( \frac{1}{2} \Delta m_s t \right) \right]
\]
**ϕ_s from B^0_S → J/ψ KK**

**General strategy**

- Peaking backgrounds
  \[ B^0_d → J/ψ Kπ \text{ and } Λ_b → J/ψ pK^- \]
- Fit to \( M(J/ψ KK) \), three helicity angles and time distribution
- Taking into account angular and time acceptance effects, time resolution

- Determine \( ϕ_s, ΔΓ_s \) and \( Γ_s \), as well as \( ϕ \) polarization and \( S \)-wave \( (f_0(975)) \) fractions
- ATLAS and CMS assume no direct CPV, \( |λ| = 1 \left( λ ≡ η \frac{g A_i}{P A_i} \right) \)
- \( |λ| \) free in LHCb fit

<table>
<thead>
<tr>
<th>Tagging power ( ε_{tag}(1 − 2ω)^2 )</th>
<th>Tagging category</th>
<th>Time res.</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS  1.49 ± 0.02%</td>
<td>OS (µ, e, b-jet)</td>
<td>97 fs</td>
<td>[PLB 757, 97 (2016)]</td>
</tr>
<tr>
<td>CMS    1.307 ± 0.032%</td>
<td>OS (µ, e)</td>
<td>78 fs</td>
<td>[JHEP 08, 147 (2016)]</td>
</tr>
<tr>
<td>LHCb   3.73 ± 0.15%</td>
<td>OS (µ, e, K) + SS (K)</td>
<td>46 fs</td>
<td>[PRL 114, 041801 (2015)]</td>
</tr>
</tbody>
</table>
Latest result with $14.4\,\text{fb}^{-1}$ at 8 TeV \cite{JHEP 08 (2016) 147} 
previous with $4.9\,\text{fb}^{-1}$ at 7 TeV \cite{PRD 90, 052007 (2014)}

$N_{\text{sig}} \approx 75 \times 10^3$
Main sources of systematic uncertainty

- Flavour tagging: $\pm 25$ mrad
- $B_d^0$ background due to interference between $B_d^0 \to J/\psi K^*$ and $B_d^0 \to \psi K\pi$: $\pm 23$ mrad
- Choice of $p_T$ bins for angular acceptance model: $\pm 20$ mrad
$\phi_s$ measurement

Future potential in $\phi_s$ measurements

$\phi_s$ from $B_s^0 \rightarrow J/\psi KK$: CMS [PLB 757, 97 (2016)]

- Result with 19.7 fb$^{-1}$ at 8 TeV

$N_{\text{sig}} \approx 49 \times 10^3$
$\phi_s$ from $B_S^0 \to J/\psi KK$: CMS [PLB 757, 97 (2016)]

$\phi_s = -75 \pm 97(\text{stat}) \pm 31(\text{syst})\text{mrad}$

Main sources of systematic uncertainty

- Angular efficiency, varying MC model parameters: ±16 mrad
- Model bias: ±15 mrad
- $|\lambda|$ free par.: ±15 mrad
- Kaon $p_T$ reweighting to match data-MC discrepancy: ±14 mrad
**\( \phi_s \) from \( B_s^0 \rightarrow J/\psi KK \): LHCb [PRL 114, 041801 (2015)]**

- LHCb measurement with 3 fb\(^{-1} \), previous with 1 fb\(^{-1} \) at 7 TeV [PRL 108, 101803 (2012)]
- Fit to \( M(J/\psi KK) \) used to subtract background, followed by a fit to three helicity angles and decay time in six \( M(KK) \) bins
- \(|\lambda|\) consistent with 1
- **Main systematic uncertainty**
  Angular acceptance (MC size): \( \pm 4 \text{ mrad} \)

\[
N_{\text{sig}} \approx 96 \times 10^3
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>( \Gamma_s ) [ps(^{-1} )]</td>
<td>0.6603 ± 0.0027 ± 0.0015</td>
</tr>
<tr>
<td>( \Delta \Gamma_s ) [ps(^{-1} )]</td>
<td>0.0805 ± 0.0091 ± 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 (^{+0.10}<em>{-0.17} +0.06^{+0.06}</em>{-0.07})</td>
</tr>
<tr>
<td>(\delta_\perp) [rad]</td>
<td>3.08 (^{+0.14}_{-0.15} \pm 0.06)</td>
</tr>
<tr>
<td>(\phi_s) [rad]</td>
<td>-0.058 ± 0.049 ± 0.006</td>
</tr>
<tr>
<td>(</td>
<td>\lambda</td>
</tr>
<tr>
<td>(\Delta m_s) [ps(^{-1} )]</td>
<td>17.711 (^{+0.055}_{-0.057} \pm 0.011)</td>
</tr>
</tbody>
</table>
\( \phi_s \) from \( B_s^0 \to J/\psi KK: \) LHCb [PRL 114, 041801 (2015)]

- Compare results with assigning different \( \phi_s^i \) for \( i = 0, \perp, \|, S \)
  - Measure \( \lambda^i = |\lambda^i|e^{-i\phi_s^i} \)
- Result consistent with original fit

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

\[ CP \text{ even} \]
\[ CP \text{ odd} \]
\[ S \text{ wave} \]
\( \phi_s \) in \( b \rightarrow c\bar{c}s: \, B_s^0 \rightarrow J/\psi KK \) in the high \( M(KK) \) region \([\text{arXiv:1704.08217}]\)

- LHCb Run I (3 fb\(^{-1}\)) \( B_s^0 \rightarrow J/\psi KK \) \( \phi_s \) from \( M(KK) > 1.05 \text{ GeV} \) (above \( \phi(1020) \))

\[
N_{\text{sig}} \approx 31 \times 10^3 \quad M(KK) > 1.05 \text{ GeV}
\]

- Determine resonant structure and \( \phi_s \), \( \Gamma_s \) and \( \Delta \Gamma_s \)
  
  \( \rightarrow \) Also fit \( M(KK) \)
  
  \( \rightarrow \approx 10\% \ f_2'(1525) \) and \( S \)-wave each

- **Main systematic uncertainty**
  
  Resonance modelling: \( \pm 23.6 \text{ rad} \)

- Combination with \( B \rightarrow J/\psi \phi \) improves precision by over 7%

\[
\begin{align*}
\phi_s &= 119 \pm 107 \pm 34 \text{ mrad} \\
|\lambda| &= 0.994 \pm 0.018 \pm 0.006 \\
\Gamma_s &= 0.650 \pm 0.006 \pm 0.004 \text{ ps}^{-1} \\
\Delta \Gamma_s &= 0.066 \pm 0.018 \pm 0.010 \text{ ps}^{-1}
\end{align*}
\]

\[
\begin{align*}
\phi_s &= -25 \pm 45 \pm 8 \text{ mrad} \\
|\lambda| &= 0.978 \pm 0.013 \pm 0.003 \\
\Gamma_s &= 0.6588 \pm 0.0022 \pm 0.0015 \text{ ps}^{-1} \\
\Delta \Gamma_s &= 0.0813 \pm 0.0073 \pm 0.0036 \text{ ps}^{-1}
\end{align*}
\]
**φ_s in b → c¯c s: Combination**

LHCb measurements also in $B_s^0 \rightarrow J/\psi \pi \pi$, $B_s^0 \rightarrow \psi(2S)\phi$ and $B_s^0 \rightarrow D_s D_s$

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Mode</th>
<th>Lumi</th>
<th>$\phi_s$ [rad]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb</td>
<td>$J/\psi$ KK</td>
<td>3 fb$^{-1}$</td>
<td>$-0.058 \pm 0.049 \pm 0.006$</td>
<td>[PRL 114, 041801 (2015)]</td>
</tr>
<tr>
<td></td>
<td>$J/\psi$ KK HM</td>
<td>3 fb$^{-1}$</td>
<td>$+0.119 \pm 0.107 \pm 0.034$</td>
<td>[arXiv:1704.08217]</td>
</tr>
<tr>
<td></td>
<td>$J/\psi$ $\pi\pi$</td>
<td>3 fb$^{-1}$</td>
<td>$-0.070 \pm 0.068 \pm 0.008$</td>
<td>[PLB 736 (2014) 186]</td>
</tr>
<tr>
<td></td>
<td>$\psi(2S)\phi$</td>
<td>3 fb$^{-1}$</td>
<td>$+0.23^{+0.29}_{-0.28} \pm 0.02$</td>
<td>[PLB 762 (2016) 253]</td>
</tr>
<tr>
<td></td>
<td>$D_s^+ D_s^-$</td>
<td>3 fb$^{-1}$</td>
<td>$+0.02 \pm 0.17 \pm 0.02$</td>
<td>[PRL 113, 211801 (2014)]</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$J/\psi \phi$</td>
<td>19.2 fb$^{-1}$</td>
<td>$-0.098 \pm 0.084 \pm 0.040$</td>
<td>[JHEP 1608 (2016) 147]</td>
</tr>
<tr>
<td>CMS</td>
<td>$J/\psi \phi$</td>
<td>19.7 fb$^{-1}$</td>
<td>$-0.075 \pm 0.097 \pm 0.031$</td>
<td>[PLB 757 (2016) 97]</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>$-0.021 \pm 0.031$</td>
<td>[HFLAV]</td>
</tr>
<tr>
<td>Theory</td>
<td>-</td>
<td>-</td>
<td>$-0.0376 \pm 0.0008$</td>
<td>[CKMFit]</td>
</tr>
</tbody>
</table>

- $B_s^0 \rightarrow J/\psi$ KK gives the lowest uncertainties
- LHCb dominates world average
- Results consistent with SM prediction but still a lot of room for NP
Outline

1. $\phi_s$ measurement
   - $\phi_s$ measurement in $b \rightarrow c\bar{c}s$ transitions
   - Controlling penguin pollution
   - $\phi_s$ measurement in $b \rightarrow s\bar{q}\bar{q}$ transitions

2. Future potential in $\phi_s$ measurements
\( \phi_s \) in \( B_s^0 \rightarrow J/\psi \) KK: Penguin pollution \( \Delta \phi_s^{\text{peng}} \)

- Measured \( \phi_s \) in \( B_s^0 \rightarrow J/\psi \phi \) contains penguin pollution!

\[
\phi_s^{\text{exp}} = -2\beta_s + \Delta \phi_s^{\text{peng}} + \Delta \phi_s^{\text{NP}}
\]

Crucial to control \( \Delta \phi_s^{\text{peng}} \) to claim NP!

Determine \( \Delta \phi_s^{\text{peng}} \) from SU(3)-related modes, where penguin unsuppressed [arXiv:0810.4248]

- \( B^0 \rightarrow J/\psi \rho \) (BF, direct and mixing-induced \textit{CP} asymmetry) [LHCb, PLB742(2015)38-49]
- \( B_s^0 \rightarrow J/\psi K^* \) (BF, direct \textit{CP} asymmetry) [LHCb, JHEP11(2015)082]

However, \( B_s^0 \rightarrow J/\psi K^* \) has no PA and E (neglected because small)
**φ_s** in $B_s^0 \rightarrow J/\psi KK$: Penguin pollution $\Delta \phi_s^{peng}$

1. $b \rightarrow c\bar{c}s$ amplitude ($i = 0, \|\perp\)$:
   
   $$A_i'(B_s^0 \rightarrow J/\psi \phi) = \left(1 - \frac{\lambda^2}{2}\right) A_i' \left[1 + \epsilon a_i' e^{i\theta'} e^{i\gamma}\right]$$

2. $b \rightarrow c\bar{c}d$ amplitude, e.g. $B_s^0 \rightarrow J/\psi \rho$:
   
   $$A_i(B_s^0 \rightarrow J/\psi \rho) = -\lambda A_i \left[1 + a_i e^{i\theta} e^{i\gamma}\right]$$

3. SU(3): $a_i' = a_i$, $\theta_i' = \theta_i$; extract $\Delta \phi_s^{peng}(a_i, \theta_i)$ from fit to CP parameters and BF

$$\lambda \equiv |V_{us}| \approx 0.225, \epsilon \equiv \frac{\lambda^2}{1 - \lambda^2} \approx 0.054, \gamma$$ unitarity triangle angle

**SU(3): $a_i' = a_i, \theta_i' = \theta_i$; extract $\Delta \phi_s^{peng}(a_i, \theta_i)$ from fit to CP parameters and BF

\[\phi_s\] penguin pollution of $J/\psi \phi$

LHCb with $3 \text{ fb}^{-1}$ ($J/\psi K^* + J/\psi \rho$)


Consistent with zero

\[\begin{align*}
\Delta \phi_s^0 &= 0.000^{+0.011}_{-0.009} \text{(stat)} +^{0.009}_{-0.004} \text{(syst)} \\
\Delta \phi_s^\parallel &= 0.001^{+0.010}_{-0.014} \text{(stat)} \pm 0.008 \text{(syst)} \\
\Delta \phi_s^\perp &= 0.003^{+0.010}_{-0.014} \text{(stat)} \pm 0.008 \text{(syst)}
\end{align*}\]
Outline

1. \(\phi_s\) measurement
   - \(\phi_s\) measurement in \(b \to c\bar{c}s\) transitions
   - Controlling penguin pollution
   - \(\phi_s\) measurement in \(b \to s\bar{q}\bar{q}\) transitions

2. Future potential in \(\phi_s\) measurements
\(\phi_s\) measurement in \(b \rightarrow s q \bar{q}\) transitions

\[\begin{align*}
\bar{b} &\rightarrow W^+ \rightarrow s \bar{s} \phi_s \\
\bar{s} &\rightarrow \phi_s \phi_s \\
\end{align*}\]

- \(\phi_s^{s\bar{s}}\) and \(\phi_s^{s\bar{d}}\) measured in loop-dominated \(B_s^0\) decays, sensitive to NP
- NP could enter as an unknown heavy particle in the loop

LHCb measurement of \(B_s^0 \rightarrow \phi [KK] \phi [KK]\), 3 fb\(^{-1}\) [PRD 90 (2014) 052011]

- SM: \(|\phi_s^{s\bar{s}}| < 0.02\) [arXiv:8010.0249], [NP B774 (2007)64], [PRD 80 (2009) 114026]

- \(B_s^0 \rightarrow \phi \phi\) is a \(P \rightarrow VV\) decay but due to proximity of \(f_0(975)\) resonance also \(P \rightarrow SV\) and \(P \rightarrow SS\) contributions
- Three \(CP\)-even \((A_{||}, A_0, A_{SS})\) and two \(CP\)-odd \((A_{\perp}, A_S)\) amplitudes
  Disentangled in an angular analysis
- \(\sigma(t) \approx 43\) fs
- \(\epsilon(1 - 2\omega)^2 = 3.04 \pm 0.24\%\)

\[\phi_s = -0.17 \pm 0.15 \pm 0.03 \text{ rad}\]

\[\lambda = 1.04 \pm 0.07 \pm 0.03\]
Outline

1. $\phi_s$ measurement
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2. Future potential in $\phi_s$ measurements
Future potential in $\phi_s$ measurements

More details in LHCb prospects talk by Diego Martínez Santos, Fri 11:30

- LHC Run I 2011-2012 – most analyses (about to be) published
- Currently in Run II – expect soon first updates on $\phi_s$!
- Run II: Higher production cross-section due to $\sqrt{s}$ increase

ATLAS
- Significant $\phi_s$ sensitivity improvement expected during Run II
- Time resolution improved by a factor 1.5 (60 fs) thanks to new pixel detector
- In 2015+2016 already collected twice the Run I integrated luminosity
- However, tighter trigger requirements and prescaling

LHCb
- Expected to record 5 fb$^{-1}$ during Run II (vs 3 fb$^{-1}$ in Run I)
- Run II luminosity stays the same as in Run I
- Add new modes with more data
Future potential in $\phi_s$ measurements in $b \to c\bar{c}s$ transitions

Ongoing at LHCb: $B_s^0 \to J/\psi [e^+e^-]KK$

Two recent LHCb $3 \text{ fb}^{-1}$ results on decays sensitive to $\phi_s (b \to c\bar{c}s)$

- Pro: Both decays are $B_s^0 \to VP$ ($CP$ even), so no angular analysis needed
- Con: Much less events
- Measure $\phi_s$ with more data

$B_s^0 \to J/\psi \eta [\gamma \gamma]$ [PLB762 (2016) 484-492]

Measurement of $\tau_{eff} \propto \Gamma_L^{-1}$ ($N_{sig} \approx 3 \times 10^3$)

$\tau_{eff} = [1.479 \pm 0.034(\text{stat}) \pm 0.011(\text{syst})] \text{ ps}$

$B_s^0 \to \eta_c \phi$ first observation [arXiv:1702.08048]

$\mathcal{B}(B_s^0 \to \eta_c \phi) = [5.01 \pm 0.53(\text{stat}) \pm 0.27(\text{syst}) \pm 0.64(J/\psi \phi)] \times 10^{-4}$

- $\eta_c \to 2K$, $2K2\pi$, $4\pi$, $p\bar{p}$; $\phi \to KK$ ($N_{sig} \approx 1.7 \times 10^3$)
- Also evidence for non-resonant mode $B_s^0 \to \eta_c [p\bar{p}] \pi^+\pi^-$

$\mathcal{B}(B_s^0 \to \eta_c \pi^+\pi^-) = [1.76 \pm 0.59(\text{stat}) \pm 0.12(\text{syst}) \pm 0.29(J/\psi \pi\pi)] \times 10^{-4}$
Future potential in $\phi_s$ measurements in $b \to sq\bar{q}$ transitions

$B_s^0 \to \phi\pi^+\pi^-$ first observation by LHCb with $3 \text{fb}^{-1}$ [PRD 95, 012006 (2017)]

$\mathcal{B}(B_s^0 \to \phi\pi^+\pi^-) = [3.48 \pm 0.23(\text{stat}) \pm 0.17(\text{syst}) \pm 0.35(\phi\phi)] \times 10^{-6} \ (N_{\text{sig}} \approx 700)$

Measure $\phi_{ss}^{s\bar{s}}$ when more data available

Ongoing at LHCb: $\phi_{s}^{s\bar{d}}$ in $B_s^0 \to K^*K^*$ with $3 \text{fb}^{-1}$
Summary

- $\phi_s$ sensitive to new physics, which could enter in the $B_s^0 - \bar{B}_s^0$ mixing

- Measurements in good agreement with SM predictions in $b \to c\bar{c}s$ transitions but still a lot of room for new physics effects
  → With increasing precision important to control penguin contributions

- $\phi_s$ from loop-dominated $b \to s q\bar{q}$ decays so far also in agreement with SM

- Run II data from the LHC will allow the inclusion of more modes and improved uncertainties on the ones already measured: STAY TUNED

Thanks for your attention!
Future potential in $\phi_s$ measurements.
Future potential in $\phi_s$ measurements

\[
\frac{d^4\Gamma(B^0_s \rightarrow J/\psi\phi)}{dt \, d\Omega} \propto \sum_{i=1}^{10} h_k(t) f_k(\Omega),
\]

\[
h_k(t) = N_k e^{-\Gamma_s t} \left[ a_k \cosh(\frac{1}{2} \Delta \Gamma_s t) + b_k \sinh(\frac{1}{2} \Delta \Gamma_s t) \pm c_k \cos(\frac{1}{2} \Delta m_s t) \pm d_k \sin(\frac{1}{2} \Delta m_s t) \right]
\]

$B^0_s$ flavour dependent
**φ_s from B_{s}^{0} \rightarrow J/\psi KK: ATLAS [JHEP 08, 147 (2016)]**

\[
\phi_s = -110 \pm 82(\text{stat}) \pm 42(\text{syst}) \text{ mrad}
\]

**Main sources of systematic uncertainty**

- Flavour tagging: ±25 mrad
- B_{d}^{0} background: ±23 mrad
- Choice of \( p_T \) bins: ±20 mrad Angular acceptance modelled in bins of \( p_T \)
\( \phi_s \) from \( B_s^0 \rightarrow J/\psi KK: \) CMS [PLB 757, 97 (2016)]

- Result with 19.7 fb\(^{-1}\) at 8 TeV

\[ N_{\text{sig}} \approx 49 \times 10^3 \]
$\phi_s$ from $B_s^0 \rightarrow J/\psi KK$: LHCb [PRL 114, 041801 (2015)]
Future potential in $\phi_s$ measurements in $b \to c\bar{c}s$ transitions [PLB762 (2016) 484-492]

$B_s^0 \to J/\psi \eta [\gamma \gamma]$, LHCb 3 fb$^{-1}$

- $b \to c\bar{c}s$ transition
- First measure $\tau_{\text{eff}} \propto \Gamma_L^{-1}$: improves $\tau_L$ precision, testing consistency between $\Delta \Gamma_s = \Gamma_L - \Gamma_H$ from $B_s^0 \to J/\psi \phi$ and direct $\Gamma_L, \Gamma_H$ measurement

$$\tau_{\text{eff}} = [1.479 \pm 0.034(\text{stat}) \pm 0.011(\text{syst})] \text{ps}$$

- Add $\phi_s$ with more data
- Cons: Much less events and worse mass resolution
- Pro: $B_s^0 \to VP$ ($CP$ even), so no angular analysis needed

$N_{\text{sig}} \approx 3 \times 10^3$
Future potential in $\phi_s$ measurements in $b \rightarrow c\bar{c}s$ transitions [arXiv:1702.08048]

$B_s^0 \rightarrow \eta_c \phi$ first observation with Run I data (3 fb$^{-1}$)

$$\mathcal{B}(B_s^0 \rightarrow \eta_c \phi) = [5.01 \pm 0.53{\text{(stat)}} \pm 0.27{\text{(syst)}} \pm 0.64(\psi/\phi)] \times 10^{-4}$$

- $b \rightarrow c\bar{c}s$ transition, $B \rightarrow PV$ (CP-even), no angular analysis needed
- $\eta_c \rightarrow 2K, 2K2\pi, 4\pi, p\bar{p}; \phi \rightarrow KK$

| $N_{sig}$ | $\approx 1.7 \times 10^3$ |

- Account for interference between $\eta_c$ and NR mode
- Add $\phi_s$ with more data

- Also evidence for non-resonant mode $B_s^0 \rightarrow \eta_c [p\bar{p}] \pi^+ \pi^-$

$$\mathcal{B}(B_s^0 \rightarrow \eta_c \pi^+ \pi^-) = [1.76 \pm 0.59{\text{(stat)}} \pm 0.12{\text{(syst)}} \pm 0.29(\psi/\pi \pi)] \times 10^{-4}$$