Measurements of $\phi_s$ at the LHCb experiment

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These proceedings present the current status of measurements of the $CP$-violating phase $\phi_s$ by the LHCb collaboration, reviewing the measurements in channels such as $B_s^0 \rightarrow J/\psi \phi$, $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ and $B_s^0 \rightarrow \psi(2S)\phi$. The observation of the $B_s^0 \rightarrow \eta_c \phi$ decay mode is presented for the first time, which can be used to measure $\phi_s$ with larger data samples that will be collected over the coming years by the LHCb experiment. Finally, the expected increase in precision from LHCb measurements of $\phi_s$ over the next decade is presented.

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1. Introduction and motivation

A key observable to be measured in the $B^0_s$ meson system is the $CP$-violating phase, $\phi_s$, which arises due to the interference between $B^0_s$ meson mixing and decay processes. It is defined as $\phi_s \equiv -\arg(\bar{\lambda}_f) \equiv -\arg\left(\frac{2A_f}{p_{\lambda / \rho}}\right)$, where $q, p$ are complex eigenvalues related to $B^0_s$ mixing and $A_f$ ($\bar{A}_f$) are the complex amplitudes for $B^0_s$ ($\bar{B}^0_s$) meson decay to final state $f$. Global fits to experimental data give a precise prediction for $\phi_s$ in the Standard Model of $-0.0376 \pm 0.0008 \text{rad}$ [1]. Any deviation from this prediction would be a clear sign for non-Standard Model physics, strongly motivating the need for precise experimental measurements of this quantity. In this article I will review the measurements of this observable from the LHCb collaboration and discuss new measurements of $B^0_s$ meson decay channels that can be used to measure $\phi_s$ in the future. All measurements shown here use 3 fb$^{-1}$ of data collected by the LHCb experiment [2] in $pp$ collisions at the LHC during 2011 and 2012.

2. State-of-the-art of $\phi_s$ measurements

2.1 $\phi_s$ from $B^0_s \to J/\psi \phi$ and $B^0_s \to J/\psi \pi^+\pi^-$

The so-called “golden mode” for measuring $\phi_s$ is using a flavour-tagged time-dependent angular analysis of the $B^0_s \to J/\psi \phi$ decay, where $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$. This $b \to c\bar{c}s$ mediated decay has a high branching fraction and the presence of two muons in the final state leads to a high trigger efficiency. The angular analysis is necessary to disentangle the interfering $CP$-odd and $CP$-even components in the final state, which arise due to the relative angular momentum between the two vector resonances. In addition, there is a small ($\sim 2\%$) $CP$-odd $K^+K^- S$-wave contribution that must be accounted for. The LHCb detector has excellent time resolution ($\sim 45$ fs [3]) and tagging power ($\sim 4\%$ [4]), both of which are crucial to the measurement. In Run 1, the LHCb collaboration used a sample of $\sim 96000$ $B^0_s \to J/\psi \phi$ decays to measure $\phi_s$, the width difference between the light and heavy $B^0_s$ mass eigensates ($\Delta \Gamma_s$), the average decay time ($\Gamma_s$), mixing frequency ($\Delta m_s$) and direct $CP$ violation parameter ($|\lambda|$). Figure 1 shows the results of this analysis, which gave $\phi_s = -0.058 \pm 0.049 \pm 0.006$ rad, $\Delta \Gamma_s = 0.0805 \pm 0.0091 \pm 0.0032$ ps$^{-1}$ and $\Gamma_s = 0.6603 \pm 0.0027 \pm 0.0015$ ps$^{-1}$ [5]. These are the most precise determinations of these parameters to date and are consistent with SM predictions [1, 6]. The dominant systematic uncertainties in these measurement arise from knowledge about the decay time and angular efficiencies.
It is possible that due to unknown hadronic effects or beyond the SM physics, the values of $\phi_s$ and $|\lambda|$ could be different for each of the four polarisation states [7,8]. For the first time, the LHCb collaboration relaxed this assumption in the analysis, finding that no polarisation dependence was visible within the available statistical precision.

The LHCb collaboration has also used a similar analysis of $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ decays to measure $\phi_s$ [9]. Here, the full $\pi^+ \pi^-$ mass spectrum is used in the measurement, which has previously been studied and found to be $>97.7\%$ completely $CP$-odd [10], dominated by the $f_0(980)$ component. With this time-dependent amplitude analysis, $\phi_s$ was measured to be $0.070 \pm 0.068 \pm 0.008$ rad, the dominant systematic uncertainty coming from knowledge about the composition of resonances in the $\pi^+ \pi^-$ spectrum. Since the final state is almost all $CP$-odd, a simplified tagged fit to only the $B_s^0$ decay time distribution yields compatible results. Combining the $B_s^0 \rightarrow J/\psi \phi$ and $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ results gives $\phi_s = -0.010 \pm 0.039$ rad.

### 2.2 $\phi_s$ from $B_s^0 \rightarrow \psi(2S)\phi$

Other $B_s^0$ decay modes with $b \rightarrow c \bar{c} s$ transitions can be used to measure $\phi_s$. In Ref. [11], LHCb studied the $B_s^0 \rightarrow \psi(2S)\phi$ (with $\psi(2S) \rightarrow \mu^+ \mu^-$) decays for the first time using the same analysis techniques as Ref. [5]. Figure 2 shows $\sim 4500$ signal decays in Run 1 data, selected using a boosted decision tree that has been trained using simulated signal events and a background sample from the high-mass sideband. Figure 2 also shows the projections of the data and fit onto the decay time and helicity angles, demonstrating a good fit to the data. In addition to $\Delta \Gamma_s$ and $\Gamma_s$, $\phi_s$ was measured to be $0.23^{+0.29}_{-0.28} \pm 0.02$ rad. For the first time the magnitude of the transversity amplitudes and their phases were measured for this decay, which are different to those in $B_s^0 \rightarrow J/\psi \phi$ as expected [12].

### 2.3 Global combination

The global combination of $\phi_s$ and $\Delta \Gamma_s$ measurements from the Heavy Flavour Averaging Group [13] is shown in Figure 3, using measurements from the LHCb collaboration discussed here along with those from the CDF [14], D0 [15], ATLAS [16] and CMS [17] collaborations. They
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Figure 3: HFAG combination [13] of $\phi_s$ and $\Delta \Gamma_s$ from several experiments.

find $\Delta \Gamma_s = 0.085 \pm 0.006 \text{ps}^{-1}$ and $\phi_s = -0.030 \pm 0.033 \text{rad}$. The results are dominated by those from the LHCb collaboration and are consistent with the SM predictions. There remains space for new physics contributions at the $\sim 20\%$ level, however, as the experimental precision improves, it is essential that there is good control over hadronic effects (so-called "penguin pollution") that could mimic the effect from beyond-the-SM physics.

2.4 $\phi_s^{s\bar{s}}$ from $B_0^s \rightarrow \phi \phi$

A related $CP$-violating phase, $\phi_s^{s\bar{s}}$, can be measured by applying similar methods as above to $B_0^s$ meson decays that go via a $b \rightarrow s\bar{s}t$ transition. The LHCb collaboration has performed such an analysis using $B_0^s \rightarrow \phi \phi$ [18], measuring $\phi_s = -0.17 \pm 0.15 \pm 0.03 \text{rad}$, which is consistent with the Standard Model predictions, all of which are very close to zero [19–21]. An upcoming study of $B_0^s \rightarrow K^+ \pi^- K^+ \pi^-$ decays will provide another avenue for measuring this quantity [22].

3. Future prospects for measuring $\phi_s$

The measurement of $\phi_s$ using $B_0^s \rightarrow J/\psi \phi$ decays has so far restricted to using the region of $K^+ K^-$ phase space near the $\phi(1020)$ resonance. A full amplitude analysis of the $B_0^s \rightarrow J/\psi K^+ K^-$ system was performed in Ref. [23], indicating a significant contribution from other $K^+ K^-$ resonances such as the $f_2^0(1525)$ that can be used when measuring $\phi_s$ to increase the statistical precision. This approach will require the application of the same analysis formalism as in Ref [9]. Similarly, the recently observed $B_0^s \rightarrow \phi \pi^+ \pi^-$ decay [23] could be used with future data samples from Run 2 and beyond to measure $\phi_s^{s\bar{s}}$, again with a flavour-tagged, decay-time dependent amplitude analysis, including all appropriate $\pi^+ \pi^-$ resonances.

3.1 Observation of $B_0^s \rightarrow \eta_c \phi$

At this conference the LHCb collaboration announced a preliminary observation of the $B_0^s \rightarrow \eta_c \phi$ decay mode, with $\eta_c \rightarrow K^+ K^- \pi^+ \pi^- \pi^+ \pi^- \pi^+ \pi^-$, $K^+ K^- K^+ K^- p\bar{p}$ [24]. This decay is another $b \rightarrow c\bar{s}s$ transition that could be used to measure $\phi_s$. Figure 4 shows the invariant mass of the $B_0^s$ system in the $p\bar{p}$ mode along with the $p\bar{p}$ spectrum, with the $\eta_c$ and $J/\psi$ charmonium resonances clearly visible. A simultaneous amplitude fit is performed using all modes and including contributions from interfering non-resonant components. The branching fraction is extracted relative to the $J/\psi$ channel and found to be $\mathcal{B}(B_0^s \rightarrow \eta_c \phi) = (5.01 \pm 0.53(\text{stat}) \pm 0.27(\text{syst}) \pm 0.63(\mathcal{B})) \times 10^{-4}$. First evidence of the $B_0^s \rightarrow \eta_c \pi^+ \pi^-$ decay was also presented.
shows how the precision on $\Delta \Gamma$ non-Standard Model physics [30].

improves it will be essential to control hadronic effects that can hide small contributions from non-Standard Model physics [30].

3.2 $B_s^0 \to J/\psi \eta$ effective lifetime

The LHCb collaboration has recently observed the $B_s^0 \to J/\psi \eta(\to \gamma \gamma)$ decay [25] and used it to measure the $B_s^0$ effective lifetime. As this mode is a CP-even eigenstate the effective lifetime gives a measurement of $\Gamma_L$. The final state is challenging, containing only two charged tracks and the invariant mass resolution is $\sim 48$ MeV/$c^2$ (see Figure 5), compared to $\sim 8$ MeV/$c^2$ for $B^0 \to J/\psi \phi$ decays. Using $\sim 3000$ signal candidates, the lifetime was measured to be $\tau = 1.479 \pm 0.034 \pm 0.011$ ps, consistent with other measurements of the CP-even lifetime [26, 27]. In the future the $B_s^0 \to J/\psi \eta$ mode can be used to measure $\phi_s$ from a flavour-tagged fit to the decay time distribution.

An update of the HFAG averages of $\Delta \Gamma_s$ and $\Gamma_s$ was presented, showing good consistency between all measurements and the SM predictions [6]. The $\Delta \Gamma_s$ prediction has an uncertainty more than three times larger than the experimental average.

4. Summary

The LHCb collaboration has made leading measurements of the CP-violating phase $\phi_s$ and $B_s^0$ meson lifetimes using Run-1 data. So far all measurements are consistent with predictions from the Standard Model. New $b \to c \eta s$ decay modes have been investigated and measurements performed to either measure CP violating effects or make preparations for such measurements in the future. Figure 6 shows how the precision on $\phi_s$ and $\phi_{s\tau}$ will reduce as a function of time for key decay channels discussed in these proceedings. The precision is expected to reach $\sim 0.01$ rad at end of Run 3 [28] (the LHCb upgrade era) which is further discussed in Ref. [29]. As the precision improves it will be essential to control hadronic effects that can hide small contributions from non-Standard Model physics [30].
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Year

2020
2030

[rad]

stat

$\sigma$

0
0.02
0.04
0.06
0.08
0.1
0.12
0.14

Figure 6: Projection of how precision on $\phi_s$ from LHCb measurements will scale as a function of time for different decay modes. Information taken from Ref. [28].

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