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Measurements of ϕ_s at the LHCb experiment

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These proceedings present the current status of measurements of the *CP*-violating phase ϕ_s by the LHCb collaboration, reviewing the measurements in channels such as $B_s^0 \to J/\psi\phi$, $B_s^0 \to J/\psi\pi^+\pi^-$ and $B_s^0 \to \psi(2S)\phi$. The observation of the $B_s^0 \to \eta_c\phi$ decay mode is presented for the first time, which can be used to measure ϕ_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 ϕ_s over the next decade is presented.

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[†] On behalf of the LHCb collaboration

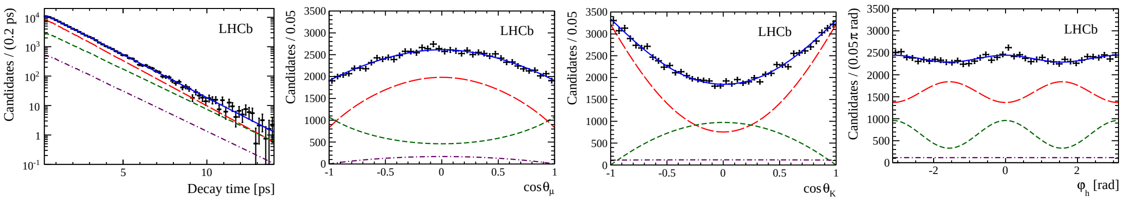

Figure 1: Projections of $B_s^0 \to J/\psi\,\phi$ data onto the decay time and three helicity angles. The projection of the total fit model is shown (blue) along with the individual *CP*-odd (green), *CP*-even (red) and S-wave (purple) contributions.

1. Introduction and motivation

A key observable to be measured in the B_s^0 meson system is the *CP*-violating phase, ϕ_s, which arises due to the interference between B_s^0 meson mixing and decay processes. It is defined as $\phi_s \equiv -\arg(\lambda_f) \equiv -\arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right)$, where q, p are complex eigenvalues related to B_s^0 mixing and A_f ($\bar{A}_f$) are the complex amplitudes for B_s^0 ($\bar{B}_s^0$) meson decay to final state f. Global fits to experimental data give a precise prediction for ϕ_s in the Standard Model of -0.0376 ± 0.0008 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_s^0 meson decay channels that can be used to measure ϕ_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 ϕ_s measurements

2.1 ϕ_s from $B_s^0 \to J/\psi\,\phi$ and $B_s^0 \to J/\psi\,\pi^+\pi^-$

The so-called “golden mode" for measuring ϕ_s is using a flavour-tagged time-dependent angular analysis of the $B_s^0 \to J/\psi\,\phi$ 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 (~ 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 ~ 96000 $B_s^0 \to J/\psi\,\phi$ decays to measure ϕ_s, the width difference between the light and heavy B_s^0 mass eigensates ($\Delta\Gamma_s$), the average decay time (Γ_s), mixing frequency (Δm_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, $\Delta\Gamma_s = 0.0805 \pm 0.0091 \pm 0.0032\ \text{ps}^{-1}$ and $\Gamma_s = 0.6603 \pm 0.0027 \pm 0.0015\ \text{ps}^{-1}$ [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.

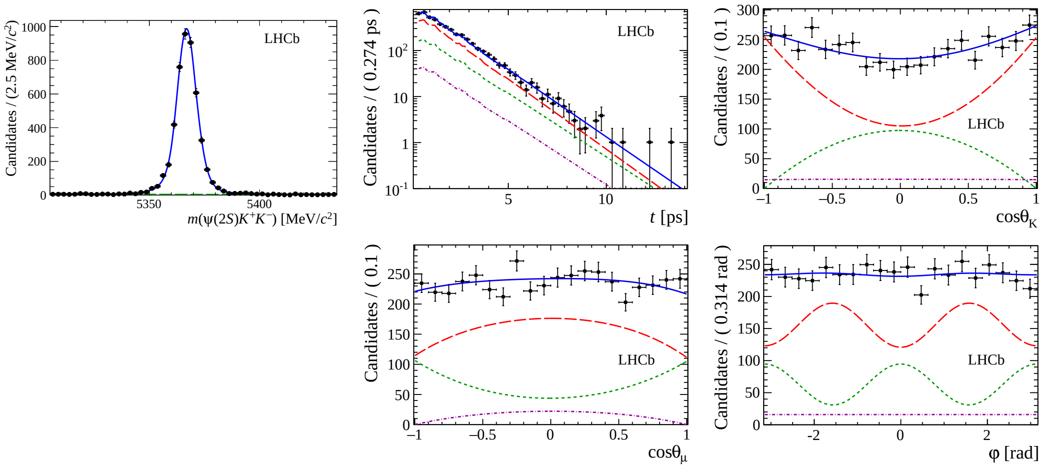

Figure 2: Distribution of $\psi(2S)\phi$ invariant mass of selected $B_s^0 \to \psi(2S)\phi$ candidates and projections of $B_s^0 \to \psi(2S)\phi$ data and fit model (see Figure 1 for legend).

It is possible that due to unknown hadronic effects or beyond the SM physics, the values of ϕ_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 $B_s^0 \to J/\psi\pi^+\pi^-$ decays to measure ϕ_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, ϕ_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 $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi\pi^+\pi^-$ results gives $\phi_s = -0.010 \pm 0.039$ rad.

2.2 ϕ_s from $B_s^0 \to \psi(2S)\phi$

Other B_s^0 decay modes with $b \to c\bar{c}s$ transitions can be used to measure ϕ_s. In Ref. [11], LHCb studied the $B_s^0 \to \psi(2S)\phi$ (with $\psi(2S) \to \mu^+\mu^-$) decays for the first time using the same analysis techniques as Ref. [5]. Figure 2 shows ~ 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 Γ_s, ϕ_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 $B_s^0 \to J/\psi\phi$ as expected [12].

2.3 Global combination

The global combination of ϕ_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

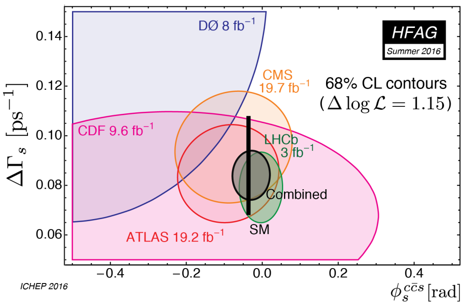

Figure 3: HFAG combination [13] of ϕ_s and $\Delta\Gamma_s$ from several experiments.

find $\Delta\Gamma_s = 0.085 \pm 0.006\,\mathrm{ps}^{-1}$ and $\phi_s = -0.030 \pm 0.033$ 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 $\phi_s^{s\bar{s}s}$ from $B_s^0 \to \phi\phi$

A related *CP*-violating phase, $\phi_s^{s\bar{s}s}$, can be measured by applying similar methods as above to B_s^0 meson decays that go via a $b \to s\bar{s}s$ transition. The LHCb collaboration has performed such an analysis using $B_s^0 \to \phi\phi$ [18], measuring $\phi_s = -0.17 \pm 0.15 \pm 0.03$ rad, which is consistent with the Standard Model predictions, all of which are very close to zero [19–21]. An upcoming study of $B_s^0 \to K^+\pi^-K^+\pi^-$ decays will provide another avenue for measuring this quantity [22].

3. Future prospects for measuring ϕ_s

The measurement of ϕ_s using $B_s^0 \to J/\psi\,\phi$ 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 $B_s^0 \to J/\psi\,K^+K^-$ system was performed in Ref. [23], indicating a significant contribution from other K^+K^- resonances such as the $f_2'(1525)$ that can be used when measuring ϕ_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 $B_s^0 \to \phi\pi^+\pi^-$ decay [23] could be used with future data samples from Run 2 and beyond to measure $\phi_s^{s\bar{s}s}$, again with a flavour-tagged, decay-time dependent amplitude analysis, including all appropriate $\pi^+\pi^-$ resonances.

3.1 Observation of $B_s^0 \to \eta_c\phi$

At this conference the LHCb collaboration announced a preliminary observation of the $B_s^0 \to \eta_c\phi$ decay mode, with $\eta_c \to K^+K^-\pi^+\pi^-, \pi^+\pi^-\pi^+\pi^-, K^+K^-K^+K^-, p\bar{p}$ [24]. This decay is another $b \to c\bar{c}s$ transition that could be used to measure ϕ_s. Figure 4 shows the invariant mass of the B_s^0 system in the $p\bar{p}$ mode along with the $p\bar{p}$ spectrum, with the η_c and J/ψ 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/ψ channel and found to be $\mathscr{B}(B_s^0 \to \eta_c\phi) = (5.01 \pm 0.53(\mathrm{stat}) \pm 0.27(\mathrm{syst}) \pm 0.63(\mathscr{B})) \times 10^{-4}$. First evidence of the $B_s^0 \to \eta_c\pi^+\pi^-$ decay was also presented.

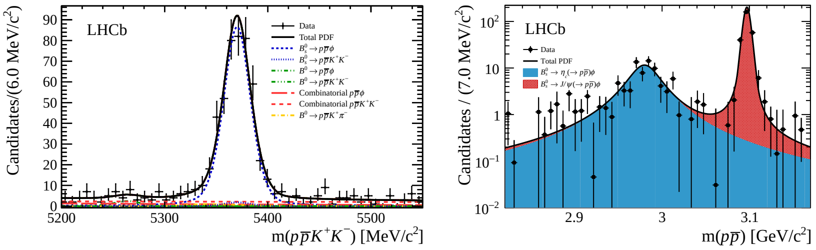

Figure 4: Invariant mass distributions for selected $K^+K^-p\overline{p}$ (left) and $p\overline{p}$ (right) candidates.

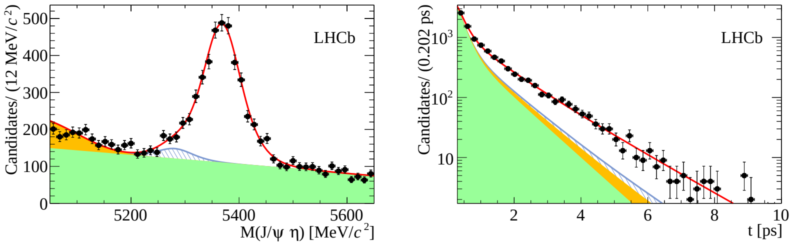

Figure 5: Distributions of $J/\psi\,\eta$ invariant mass and decay time for selected $B_s^0 \to J/\psi\,\eta$ decays. Combinatorial background (green), partially reconstructed background (orange) and background from $B^0 \to J/\psi\,\eta$ decays (blue) are shown.

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 Γ_L. The final state is challenging, containing only two charged tracks and the invariant mass resolution is $\sim 48\,\mathrm{MeV}/c^2$ (see Figure 5), compared to $\sim 8\,\mathrm{MeV}/c^2$ for $B_s^0 \to J/\psi\,\phi$ decays. Using ~ 3000 signal candidates, the lifetime was measured to be $\tau = 1.479 \pm 0.034 \pm 0.011\,\mathrm{ps}$, 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 ϕ_s from a flavour-tagged fit to the decay time distribution.

An update of the HFAG averages of $\Delta\Gamma_s$ and Γ_s was presented, showing good consistency between all measurements and the SM predicitions [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 ϕ_s and B_s^0 meson lifetimes using Run-1 data. So far all measurements are consistent with predictions from the Standard Model. New $b \to c\bar{c}s$ 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 ϕ_s and $\phi_s^{s\bar{s}\bar{s}}$ will reduce as a function of time for key decay channels discussed in these proceedings. The precision is expected to reach $\sim 0.01\,\mathrm{rad}$ 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].

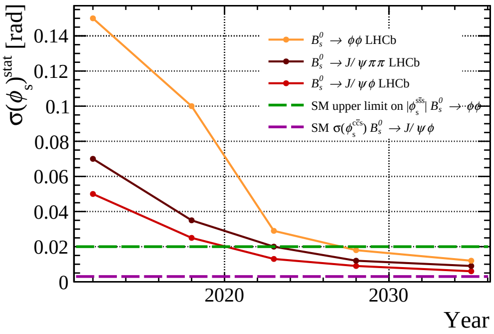

Figure 6: Projection of how precision on ϕ_s from LHCb measurements will scale as a function of time for different decay modes. Information taken from Ref. [28].

5. Acknowledgements

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