PROCEEDINGS OF SCIENCE

CP violation in $\mathrm{B_s}$ mixing

Alessandro Cerri[a], **Mario Galanti**[b] **and Stefania Vecchi**[*c]
[a]*LBNL (USA) – Sussex University (UK)*
[b]*Dipartimento di Fisica "G. Galilei", Università degli Studi di Padova (Italy) – CERN*
[c]*INFN - Sezione di Ferrara (Italy)*
E-mail: `alessandro.cerri@cern.ch`, `mario.galanti@cern.ch`,
`vecchi@fe.infn.it`

This note reports about the measurements of CP violation in the $\mathrm{B_s}$ system by the ATLAS, CMS, and LHCb experiments at LHC. The main experimental challenges and techniques are briefly summarized. The results published so far by the three experiments are shown, stressing in particular those on the weak phase ϕ_s, which is measured in $\mathrm{B_s} \to \mathrm{J}/\psi\phi$ events by ATLAS and LHCb to be $\phi_s = 0.12 \pm 0.23 \pm 0.11$ rad and $\phi_s = 0.07 \pm 0.09 \pm 0.01$ rad respectively. The efforts done by the three experiments to obtain a more precise determination of ϕ_s and of the other observables are described, giving some prospects on the potential improvements that can be achieved with the Run II of LHC.

VI Italian workshop on p-p physics at the LHC,
8-10 May 2013
Acquario di Genova, Ponte Spinola, Area Porto Antico, Genova, Italy

---

[*] Speaker.

PoS(LHCPP2013)034

1. Introduction

The CP violation in the mixing of $\mathrm{B_s}$ mesons constitutes a powerful check of the Standard Model (SM) and an indirect probe for new physics (NP). In general a $\mathrm{B_s}$ meson can mix into a $\overline{\mathrm{B}}_\mathrm{s}$, and viceversa, via higher-order box diagrams. If we consider a final state which is not a CP eigenstate, like i.e. $\mathrm{B_s}(\overline{\mathrm{B}}_\mathrm{s}) \to \mathrm{J}/\psi\phi$, there is interference between direct and mixing-mediated decays, characterized in the case of $\mathrm{B_s} \to \mathrm{J}/\psi\phi$ by a weak phase ϕ_s, which is predicted by the Standard Model to be $\phi_\mathrm{s} = (-0.0364 \pm 0.0016)$ rad [1]. This value is close to zero and is predicted with a very good accuracy by the SM; moreover, it depends strongly on the interference pattern, so any deviation from the SM prediction can be a hint of mixing loops going through NP particles. The current experimental uncertainty on ϕ_s is still dominated by the statistical error; for this reason, providing more precise measurements has become one of the physics goals also at the LHC.

2. ϕ_s measurement at the LHC

2.1 General description and requisites

Three of the main LHC experiments, ATLAS, CMS, and LHCb, have included the measurement of ϕ_s in their physics program. The main decay channel used is $\mathrm{B_s} \to \mathrm{J}/\psi\phi$, with $\mathrm{J}/\psi \to \mu^+\mu^-$ and $\phi \to \mathrm{K^+K^-}$. For its high yield and the presence of two muons that can be easily triggered, it is the "golden" channel for the measurement of ϕ_s. Other complementary channels include $\mathrm{B_s} \to \mathrm{J}/\psi\pi^+\pi^-$, $\mathrm{B_s} \to \mathrm{J}/\psi\eta$, $\mathrm{B_s} \to \mathrm{J}/\psi\eta'$, $\mathrm{B_s} \to \mathrm{D_s}^+\mathrm{D_s}^-$, where the ones lacking a J/ψ, due to the purely hadronic final state, can be effectively exploited only by LHCb. In general, the uncertainties on ϕ_s are still dominated by statistics. The inclusion of additional decay modes as well as the optimization of trigger and selection efficiencies are crucial ingredients.

The quantity relevant for the experiments is the time-dependent asymmetry $\mathscr{A}(t)$, defined as:

$$\mathscr{A}(t) = \frac{\Gamma(\mathrm{B_s}(t) \to f) - \Gamma(\overline{\mathrm{B}}_\mathrm{s}(t) \to f)}{\Gamma(\mathrm{B_s}(t) \to f) + \Gamma(\overline{\mathrm{B}}_\mathrm{s}(t) \to f)} \sim \sin(\phi_\mathrm{s}) \cdot \sin(\Delta m_\mathrm{s} t). \tag{2.1}$$

To properly measure $\mathscr{A}(t)$, it is mandatory to keep under control the background contamination, to have a good proper time resolution, with additional precision obtained by determining the flavor of the B hadron at production.

Background reduction requires cuts on the invariant mass of the decay products and a good determination of the decay vertex. Both selections rely on high momentum and vertex resolutions of the inner tracking system. CMS and LHCb cut on the impact parameter of the $\mathrm{B_s}$ to remove the prompt background, while ATLAS does not, in order to exploit the full statistical power of the sample. In addition, LHCb uses particle identification techniques to select the correct hadrons in the final state.

Vertex resolution is important also in terms of per-event proper-time resolution, which is a crucial ingredient in the signal likelihood sensitivity to ϕ_s.

Flavor-tagging techniques employed are broadly categorized in same-side (SS) and opposide-side (OS) taggers. The SS taggers usually rely on the identification of hadrons produced in the fragmentation of the b quark that originates the B meson under study or in the decay of excited B hadrons originating the signal B, and at LHC are so far exploited only by the LHCb experiment.

The OS taggers, on the contrary, are also used by CMS and ATLAS, and tag the flavor of the second B hadron produced in the event. OS tagging can be achieved for instance by looking at semileptonic decays to e and μ, to decay chains of the type $\mathrm{b} \to \mathrm{c} \to \mathrm{s}$ giving kaons in the final state, or by an inclusive reconstruction of the b-jet. The figure of merit to estimate the *tagging power* of the algorithms is $\varepsilon_{\mathrm{tag}}\mathscr{D}^2$, where $\varepsilon_{\mathrm{tag}}$ is the tagging efficiency and $\mathscr{D}^2$ is the *dilution factor*, expressed in terms of the tagging purity ω as $\mathscr{D}^2 = (1-2\omega)^2$. This quantity measures the effective attenuation of the measured asymmetry due to the performance of the tagging algorithm. The values achieved by ATLAS and LHCb for the tagging power are respectively $\varepsilon_{\mathrm{tag}}\mathscr{D}^2 = (1.45 \pm 0.05)\%$ ($\varepsilon_{\mathrm{tag}} = 32.1\%$) [2] and $\varepsilon_{\mathrm{tag}}\mathscr{D}^2 = (3.13 \pm 0.12 \pm 0.20)\%$ ($\varepsilon_{\mathrm{tag}} = 39.4\%$) [3].

2.2 Analysis of $\mathrm{B_s} \to \mathrm{J}/\psi\phi$ decays

The analysis of $\mathrm{B_s} \to \mathrm{J}/\psi\phi$ decays is being carried on by all the three experiments. ATLAS [2] and LHCb [3] have already measured the $\mathrm{B_s}$ mixing phase ϕ_{s}, the $\mathrm{B_s}$ average lifetime Γ_{s}, and the lifetime difference $\Delta\Gamma_{\mathrm{s}}$, while CMS [4] has only measured Γ_{s} and $\Delta\Gamma_{\mathrm{s}}$ so far, and is still working on ϕ_{s}. The approaches to this measurement are similar, although with a few differences that will be summarized below.

The final state consists of the two muons from the J/ψ decay and the two kaons from the ϕ. The resonant and non-resonant backgrounds are separated from the signal through the analysis of the angular distributions, which, due to kinematic constraints, can be fully described by only three degrees of freedom. ATLAS and CMS express them in the *transversity basis*, while LHCb uses the *helicity basis* instead.

Both ATLAS and LHCb already have a flavor-tagged measurement, while it is still under development for CMS. The signal contribution to the measured $\mu^+\mu^-\mathrm{K}^+\mathrm{K}^-$ sample is found with template fits to the distributions of invariant mass, angles, and proper decay time variables. The exact choice of variables changes from an experiment to another, and also the fit technique is different. LHCb uses the *sPlot* technique [5], performing first a fit on the invariant mass, to determine the signal *sWeights* and then an *sFit* [6] on the other variables; on the contrary, ATLAS and CMS do a single fit to all the distributions.

The preliminary results of the three experiments are shown in Table 1. CMS fixes ϕ_{s} at 0 for the determination of $\Delta\Gamma_{\mathrm{s}}$ and Γ_{s}. In all cases, the results are in agreement with the SM predictions, and the main uncertainties come from the limited sample statistics. Systematic uncertainties are different for the various experiments and for the quantity measured. Common sources are the background model and the background subtraction. Other important sources include, for example, flavor tagging (ATLAS), time resolution (CMS), angular acceptance (LHCb), and time acceptance (CMS, LHCb).

2.3 Other measurements

In order to have a better picture of CP violation in the $\mathrm{B_s}$ system, other measurements are being done or are planned at LHC.

First, there are some channels for which the mixing-decay interference proceeds in the same way as for $\mathrm{B_s} \to \mathrm{J}/\psi\phi$. These can therefore be used to reduce the statistical uncertainties on ϕ_{s}. An example is the $\mathrm{B_s} \to \mathrm{J}/\psi\pi^+\pi^-$ decay: an analysis of this channel has been published by LHCb [7], which finds $\phi_\mathrm{s} = -0.14^{+0.17}_{-0.16} \pm 0.01$ rad with an error dominated by the statistics, due to the low yield. ATLAS and CMS are also working on this decay mode, and will release their results in the future.

The decay $\mathrm{B_s} \to \phi\phi$ is interesting because it only proceeds through penguin diagrams. For this reason, the interference with the mixing produces a different phase, predicted by the SM to be $|\phi_\mathrm{s}^{\phi\phi}| < 0.02$ rad. LHCb recently published the results of a complete CP analysis of this mode, yielding $\phi_\mathrm{s}^{\phi\phi} = [-2.46, -0.76]$ rad @68% CL [8]. ATLAS and CMS cannot effectively contribute to this measurement because of the purely-hadronic final state.

Further constraints to ϕ_s and $\Delta\Gamma_\mathrm{s}$ can be obtained by the measurement of the effective $\mathrm{B_s}$ lifetime in a pair of pure CP-even and CP-odd final states [9]. This analysis is simpler than a direct ϕ_s measurement, since it does not need flavor tagging. Public results have recently been released by LHCb, which considered the CP-even decay $\mathrm{B_s} \to \mathrm{K^+K^-}$ ($\tau_\mathrm{KK} = 1.455 \pm 0.046 \pm 0.006$ ps) [10], and the two CP-odd decays $\mathrm{B_s} \to \mathrm{J}/\psi \mathrm{f_0}(980)$ (giving $\tau_{\mathrm{J}/\psi \mathrm{f_0}(980)} = 1.700 \pm 0.040 \pm 0.026$ ps) [10] and $\mathrm{B_s} \to \mathrm{J}/\psi\pi^+\pi^-$ ($\tau_{\mathrm{J}/\psi\pi^+\pi^-} = 1.652 \pm 0.024 \pm 0.024$ ps) [7]. ATLAS is planning to produce results on this measurement as well.

Another probe to the CP violation in the $\mathrm{B_s}$ mixing comes from the measurement of the *charge asymmetry* a^b_{sl} in events with two same-sign muons or electrons coming from semi-leptonic B decays. The SM predicts $a^\mathrm{d}_{sl} = (1.9 \pm 0.3) \times 10^{-5}$ and $a^\mathrm{s}_{sl} = (4.1 \pm 0.6) \times 10^{-4}$ respectively, for the $\mathrm{B_d}$ and $\mathrm{B_s}$ contributions to the total asymmetry [11]. This makes the measurement experimentally challenging, requiring a high control over the production and reconstruction asymmetries and over the background contamination. The current experimental picture is not clear. Measurements of a^d_{sl} at the B factories find it in agreement with the SM [12, 13], while the D0 experiment at Tevatron probed a^b_{sl}, finding a 3.9 σ discrepancy with respect to theory [14] (later reduced to $< 3\ \sigma$ [15]). At LHC, LHCb has measured a^s_{sl} (using the decay $\mathrm{B_s} \to \mathrm{D_s}^-\mu^+X$) to be in agreement with the SM, though with a large uncertainty ($a^\mathrm{s}_{sl} = -0.24 \pm 0.54 \pm 0.33\%$) [16], while CMS is currently working on measuring a^b_{sl}.

3. Discussion and future prospects

A more accurate measurement of ϕ_s and of the other related observables is among the goals of all the three experiments for the restart of the data taking after the first long shutdown (LS1) of LHC. During the Run 2 of LHC, it is foreseen that all the experiments will collect a much larger statistical sample than the one analyzed so far, coming from the 2011 data taking and respectively

	ATLAS	CMS	LHCb
Signal [K ev.]	22.7	14.4	27.6
ϕ_s [rad]	$0.12 \pm 0.23 \pm 0.11$	0 (fixed)	$0.07 \pm 0.09 \pm 0.01$
Γ_s [ps^{-1}]	$0.677 \pm 0.007 \pm 0.003$	$0.655 \pm 0.008 \pm 0.003$	$0.663 \pm 0.005 \pm 0.006$
$\Delta\Gamma_\mathrm{s}$ [ps^{-1}]	$0.053 \pm 0.021 \pm 0.009$	$0.048 \pm 0.024 \pm 0.003$	$0.100 \pm 0.016 \pm 0.003$

Table 1: Summary of the measurements of ϕ_s, Γ_s, and $\Delta\Gamma_\mathrm{s}$ done by ATLAS [2], CMS [4], and LHCb [3] in the $\mathrm{B_s} \to \mathrm{J}/\psi\phi$ channel.

of ~ 5 fb^{-1} for ATLAS and CMS and ~ 1 fb^{-1} for LHCb. ATLAS and CMS will have a clear advantage, integrating a luminosity of O(100 fb^{-1}) versus $\sim 5-7$ fb^{-1} for LHCb. The higher center-of-mass energy of the pp collisions (13 TeV) will also increase by a factor $\sim$2 the total $\sigma_{\mathrm{b}\bar{\mathrm{b}}}$ with respect to the 2011 data taking. Together with these advantages, the increased luminosity and energy will also pose new challenges to the experiments. In order to deal with them, the work is mainly focused on improving the analysis performance and the trigger efficiency.

The LHCb experiment can clearly exploit the optimal heavy-flavor performance of its detector and is expected to provide the most precise determination of ϕ_{s}, with the implementation of several different flavor taggers (SS and OS), a solid particle identification, and the possibility to study also purely hadronic final states. For all the experiments, the most important areas of work are the performance of the tagging algorithms, with possible improvements to the tagging power $\varepsilon\mathscr{D}^2$, and the complementary analyses. In this respect, the measurement of the effective lifetime is interesting, because it does not require flavor tagging and does not depend critically on the proper lifetime resolution: thus, in this channel it is foreseeable that ATLAS and CMS will achieve uncertainties comparable to those of LHCb.

Given the dramatic increase in the instantaneous luminosity in the Run 2 of LHC, the trigger will be the single most critical point for ATLAS and CMS, while for LHCb this will not be an issue because of the luminosity leveling. The main challenge will be to keep the rates of the first level di-muon triggers under control without raising excessively the thresholds. The strategies to achieve this range from the usage of a *topological trigger* allowing to select on the angle of the two muons (ATLAS), to an upgrade of the trigger farm to be performed in several steps (ATLAS, CMS). Nevertheless, a decrease of the trigger efficiency with respect to the current analyses is foreseeable.

Taking into account the effects mentioned above, one can roughly estimate that the statistical uncertainty on ϕ_{s} will be reduced by a factor 4-5 with respect to the current measurements. If also the systematics will be kept under control, this will be enough to have a precise test of the SM prediction and some sensitivity to NP scenarios.

References

[1] J. Charles et al., *Predictions of selected flavour observables within the Standard Model*, *Phys. Rev.* **D** 84 (2011) 033005 [`arXiv:1106.4041`], with updated results and plots available at `http://ckmfitter.in2p3.fr`.

[2] ATLAS Collaboration, *Flavour tagged time dependent angular analysis of the* $\mathrm{B_s} \to \mathrm{J}/\psi\phi$ *decay and extraction of* $\Delta\Gamma$ *and the weak phase* ϕ_{s} *in ATLAS*, ATLAS-CONF-2013-039.

[3] LHCb Collaboration, *Measurement of CP violation and the* $\mathrm{B_s}^0$ *meson decay width difference with* $\mathrm{B_s}^0 \to \mathrm{J}/\psi\mathrm{K}^+\mathrm{K}^-$ *and* $\mathrm{B_s}^0 \to \mathrm{J}/\psi\pi^+\pi^-$ *decays*, *Phys. Rev.* **D** 87 (2013) 112010, LHCb-PAPER-2013-002, CERN-PH-EP-2013-055 [`arXiv:1304.2600`].

[4] CMS Collaboration, *Measurement of the* $\mathrm{B_s}$ *lifetime difference*, CMS-PAS-BPH-11-006.

[5] M. Pivk and F. R. Le Diberder, *sPlot: a statistical tool to unfold data distributions*, *Nucl. Instrum. Meth.* **A** 555 (2005) 356 [`arXiv:physics/0402083`].

[6] Y. Xie, *sFit: a method for background subtraction in maximum likelihood* [`arXiv:0905.0724`].

[7] LHCb Collaboration, *Measurement of the CP-violating phase* ϕ_s *in* $\overline{B}_s^0 \to J/\psi\pi^+\pi^-$ *decays*, *Phys. Lett.* **B** 713 (2012) 378-386, LHCb-PAPER-2012-006, CERN-PH-EP-2012-107 [`arXiv:1204.5675`].

[8] LHCb Collaboration, *First measurement of the CP-violating phase in* $B_s^0 \to \phi\phi$ *decays*, *Phys. Rev. Lett.* 110 (2013) 241802, LHCB-PAPER-2013-007, CERN-PH-EP-2013-046 [`arXiv:1303.7125`].

[9] R. Fleischer and R. Knegjens, *Effective Lifetimes of* B_s *Decays and their Constraints on the* B_s^0-$\overline{B}_s^0$ *Mixing Parameters*, *Eur. Phys. J.* **C** 71 (2011) 1789 [`arXiv:1109.5115`].

[10] LHCb Collaboration, *Measurement of the* $\overline{B}_s^0$ *effective lifetime in the* $J/\psi f_0(980)$ *final state*, *Phys. Rev. Lett.* 109 (2012) 152002, LHCb-PAPER-2012-017, CERN-PH-EP-2012-180 [`arXiv:1207.0878`].

[11] A. Lenz and U. Nierste, *Numerical updates of lifetimes and mixing parameters of B mesons*, TTP11-03, TUM-HEP-792/11 [`arXiv:1102.4274`].

[12] BABAR Collaboration, *Search For T, CP, and CPT Violation in* $B^0 - \overline{B}^0$ *Mixing with Inclusive Dilepton Events*, *Phys. Rev. Lett.* 96 (2006) 251802 [`arXiv:hep-ex/0603053`].

[13] BELLE Collaboration, *Charge asymmetry of same-sign dileptons in* $B^0 - \overline{B}^0$ *mixing*, *Phys. Rev.* **D** 73 (2006) 112002 [`arXiv:hep-ex/0505017`].

[14] D0 Collaboration, *Measurement of the anomalous like-sign dimuon charge asymmetry with 9 fb*$^{-1}$ *of* $p\overline{p}$ *collisions*, *Phys. Rev.* **D** 84 (2011) 052007 [`arXiv:1106.6308`].

[15] D0 Collaboration, *Measurement of the semileptonic charge asymmetry in* B^0 *meson mixing with the D0 detector*, *Phys. Rev.* **D** 86 (2012) 072009 [`arXiv:1208.5813`].

[16] LHCb Collaboration, *Measurement of the flavour-specific CP violating asymmetry* a_{sl}^s *in* B_s *decays*, CERN-LHCb-CONF-2012-022.