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# Flavour Tagging and Systematics for $B_s^0 \to J/\psi\phi$ Measurement in ATLAS

**Tatjana Agatonović Jovin**[*†]
*Vinča Institute of Nuclear Sciences, University of Belgrade*
*12-14 Mihaila Petrovića Alasa, Belgrade, Serbia*
*E-mail:* Tatjana.Jovin@cern.ch

The ATLAS experiment presents an updated measurement of *CP* violation in the $B_s$-meson system by studying the asymmetry of $B_s^0 \to J/\psi\phi$ decays into *CP* eigenstates using a *flavour-tagged* time-dependent analysis. Tagging the flavour of the initial-state $B_s$-meson is of particular importance in removing an ambiguity in the measurement of the weak mixing phase $\phi_s^{J/\psi\phi}$ present in the previous untagged measurement [1].

In this article, the principles and performance of flavour-tagging methods and modelling of systematic effects for $B_s^0 \to J/\psi\phi$ measurement are presented. The analysis presented here uses LHC proton-proton data at $\sqrt{s} = 7$ TeV collected by the ATLAS detector in 2011.

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[*] Speaker.
[†] On behalf of the ATLAS collaboration.

 

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## 1. Introduction

In the Standard Model, *CP* violation occurs through complex phases in the CKM matrix [2]. While the matrix elements, in which large phase occur ($V_{ub}$ , $V_{td}$) generate large *CP* violation in the $B_d^0$ system, they do not appear in leading order diagrams contributing to either $B_s^0 \leftrightarrow \overline{B_s^0}$ mixing or to the decay $B_s^0 \to J/\psi\phi$. For this reason, the Standard Model expectation of *CP* violation in $B_s^0 \to J/\psi\phi$ is small (sub-leading penguin contributions are neglected). Experimentally, *CP* violation in $B_s^0 \to J/\psi\phi$ decay occurs *in the interference between mixing and decay*, when the $B_s^0$ mass eigenstates arising from $B_s^0 \leftrightarrow \overline{B_s^0}$ oscillations, decay into polarization states of the final $J/\psi\phi$ system with different *CP* eigenvalues. It is proportional to the weak mixing phase $\phi_s \sim \phi_M$ that is related to CKM matrix elements using the relation $\phi_s \cong -2\beta_s$ where $\beta_s = arg(-V_{ts}V_{tb}^* / V_{cs}V_{cb}^*)$. The small Standard Model value of $2\beta_s = (0.036 \pm 0.002)$ rad [3] yields a tiny value of *CP* violation. Many *new physics* models predict large $\phi_s$ values whilst satisfying all existing constraints. Consequently, processes such as $B_s^0 \leftrightarrow \overline{B_s^0}$ mixing play a prominent role in the search for new physics in $b \to s$ *flavour-changing neutral currents* (FCNC's).

In this article, the calibration and performance of the *flavour tagging* algorithms used for the updated measurement of time-dependent asymmetries in $B_s^0 \to J/\psi\phi$ decay in the ATLAS experiment are presented. Furthermore, the modelling of systematic effects for the $B_s^0 \to J/\psi\phi$ measurement is also described.

### 1.1 Phenomenology of the $B_s^0 \to J/\psi\phi$ decay

The $B_s^0 \leftrightarrow \overline{B_s^0}$ system is characterized by two eigenstates with different masses and decay rates. The states with definite mass and lifetime are physical eigenstates of the whole Hamiltonian $\mathcal{H}$ and they can be written as $B_s^L$ (the lighter) and $B_s^H$ (the heavier) that are linear combinations of the $B_s^0$ flavour eigenstates, $|B_s^L\rangle = p|B_s^0\rangle + q|\overline{B_s^0}\rangle$ and $|B_s^H\rangle = p|B_s^0\rangle - q|\overline{B_s^0}\rangle$. The *CP*-violating phase is defined as the weak phase difference between the $B_s^0 \leftrightarrow \overline{B_s^0}$ mixing amplitude and the $b \to c\bar{c}s$ decay amplitude. In the absence of *CP* violation, the $B_s^H$ state would correspond exactly to the *CP*-odd state and the $B_s^L$ to the *CP*-even state. The mass and width difference between $B_s^H$ and $B_s^L$ are defined as: $\Delta M_s = M_s^H - M_s^L$, $\Delta\Gamma_s = \Gamma_s^L - \Gamma_s^H$, with a mean decay width of $\Gamma_s = (\Gamma_s^H + \Gamma_s^L)/2$, where $M_s^{H,L}$ and $\Gamma_s^{H,L}$ denote the masses and decay widths of the $B_s^H$ and $B_s^L$ flavour eigenstates.

The $B_s^0 \to J/\psi\phi$ decay proceeds via three final state helicity configurations. Their linear combinations are *CP* eigenstates with different *CP* eigenvalues [4]. The two vector mesons $J/\psi$ and $\phi$ can have their spins transversely polarized with respect to their momentum and be either parallel or perpendicular to each other. Alternatively, they can both be longitudinally polarized. These polarization states are denoted by $|\mathcal{P}_{||}\rangle$, $|\mathcal{P}_{\perp}\rangle$ and $|\mathcal{P}_0\rangle$, where final states with orbital angular momentum L = 0 or 2 are *CP*-even, respectively $|\mathcal{P}_0\rangle$ and $|\mathcal{P}_{||}\rangle$, while the state with L = 1 is *CP*-odd, $|\mathcal{P}_{\perp}\rangle$. Flavour tagging is used to distinguish between the initial $B_s^0$ and $\overline{B_s^0}$ states. For the extraction of *CP*-violating parameters, the amplitudes describing the decay to *CP*-eigenstates need to be separated statistically through the time-dependence of the decay and angular corellations among the final-state particles [5].

## 2. Flavour Tagging for $B_s^0 \to J/\psi\phi$ Measurement in ATLAS

To tag the *initial flavour* of neutral *B*-mesons, *opposite-side flavour tagging* (*OST*) algorithms are used [6], where the information from the other *B*-meson (tagging *B*) is exploited that is typically produced from the non-signal *b* quark in the event.

To study and calibrate the *OST* methods, the true dilution is extracted from the self-tagged control channel $B^{\pm} \to J/\psi K^{\pm}$. The flavour of the candidate meson is tagged by the charge of the daughter particle kaon, which predominantly decays into a muon of the same charge [7]. This gives a truth value to compare with the tagging decision, allowing the true dilution to be measured in the sample.

In this analysis, the events satisfy the same data quality, trigger and reconstruction selection criteria as those described in Ref. [8]. Tha data sample corresponds to approximately $\mathcal{L}$ = 4.5 fb$^{-1}$ of integrated luminosity collected by the ATLAS detector from *pp* collisions in 2011.

The two inclusive methods are performed to infer the flavour of the *B*-meson:

- *opposite-side soft-lepton tagging* - by identifying the *muon cone charge* defined as a sum of charges of momentum weighted tracks in the cone around the highest $p_T$ muon on the opposite side of the signal *B* decays.
- *opposite b-jet-charge tagging* - by identifying the charge of the opposite-side *b*-jet.

The discriminating variable *Q* is the muon cone charge or the jet charge defined as:

$$Q_{\mu;\,jet} = \frac{\sum_i^{N\,tracks} q^i \cdot \left(p_T^i\right)^{\kappa}}{\sum_i^{N\,tracks} \left(p_T^i\right)^{\kappa}}$$

where $q^i$ and $p_T^i$ are charge and transverse momentum of the track and κ is a scale parameter that is optimized yielding κ = 1.1. After reconstructing *Q* using the flavour-tagging calibration samples, the probability $P(B|Q)$ that the signal contains a $\bar{b}$ quark at production is calculated for each of the $B^+$ and $B^-$, defining $P(Q|B^+)$ and $P(Q|B^-)$, respectively.

The methodology is to search first for high-momentum muons and select all charged tracks with $p_T^i > 0.5$ GeV and $|\eta| < 2.5$ within a cone with radius $\Delta R < 0.5$ around the muon direction. In the absence of a muon, a *b*-flavour tagged jet [9] is required in the event with tracks associated to the same primary interaction vertex as the signal decay, excluding those from the signal candidate. The jet is reconstructed using the anti-$k_t$ algorithm within a cone size $\Delta R = 0.6$. In the case of multiple jets, the jet with a highest value of the *b*-tag weight reference is used. The sum is over all track associated with the jet, using the method described in [6]. Figure 1 shows the distribution of charges for jet-charge and muon cone charge from $B^{\pm}$ signal-side candidates.

The sensitivity for measuring the *CP* asymmetry depends on the *tagging power* $\varepsilon_{eff} = \varepsilon\mathcal{D}^2 = \sum_i \varepsilon_i (2P_i(B|Q) - 1)^2$, where $\varepsilon_i$ is the *efficiency* of an individual tagger and $P_i(B|Q)$ is the probability that a specific event has a signal decay containing a $\bar{b}$ defined as $P_i(B|Q) = P_i(Q|B^+)/(P_i(Q|B^+) + P_i(Q|B^-))$ and $P_i(\overline{B}|Q) = 1 - P_i(B|Q)$, where the sum is taken over the bins of the probability distribution as a function of the charge variable.

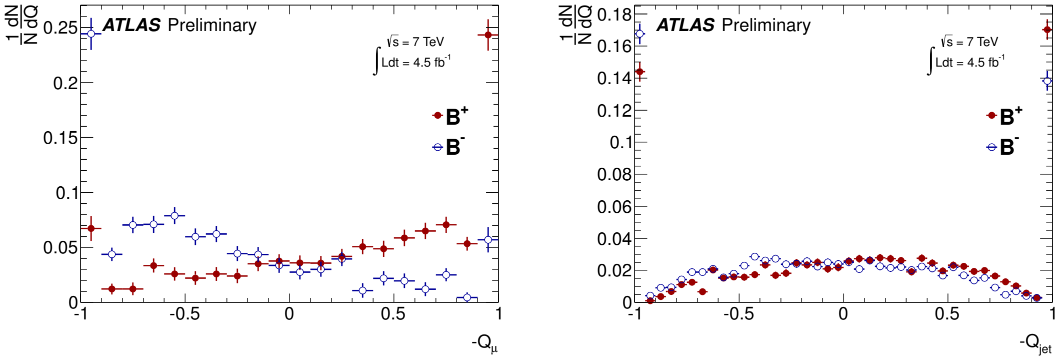


*Figure 1: Muon cone charge distribution for* $B^{\pm}$ *signal candidates for combined muons (left) and jet-charge distribution for* $B^{\pm}$ *signal candidates (right)* [8]

The efficiency, $\varepsilon = R + W/(R + W + U)$, represents the fraction of tagged events to the entire sample, where $R$, $W$ and $U$ are the number of correctly tagged, incorrectly tagged and untagged events, respectively. The *effective dilution*, $\mathcal{D} = \sqrt{\sum_i \varepsilon_i (2P_i(B|Q)-1)^2 / \sum_i \varepsilon_i}$, is calculated for more than one tag and indicates how well the $B$ meson is tagged correctly or incorrectly.

The combination of the tagging methods is applied according to the hierarchy of performance. A single best performing tagging measurement is taken, according to the order: muon, jet.

## 3. Systematic Uncertainties for $B_s^0 \to J/\psi\phi$

Systematic uncertainties are assigned by considering several effects that are not accounted for in the likelihood fit. These include:

- *Inner Detector Alignment* - the impact of the residual misalignment of the ID effecting the impact parameter (IP) distribution with respect to the primary vertex is estimated using simulated events with and without distorted geometry.
- *Angular acceptance method* - the systematic uncertainty introduced from the choice of binning; different acceptance functions are calculated using different bin width and central values.
- *Trigger efficiency* - to correct for the trigger lifetime bias, the events are re-weighted using the correction parameter $\varepsilon$, and the uncertainty of $\varepsilon$ is used to estimate the systematic uncertainty due to the time efficiency correction.
- *Default fit model* - using the bias of the pull-distributions of 1500 pseudo-experiments multiplied by the statistical uncertainty of each parameter, the systematic uncertainty is calculated.
- *Signal and background mass model, resolution model, background lifetime and background angles model* - in order to estimate the size of the systematic uncertainty caused by the assumptions made in the fit, variations of the fit model are tested in pseudo-experiments.
- $B_d$ *contribution* - systematic effects arising from the precision of the $B_d$ fraction estimates are obtained by fitting the data with $B_d$ fractions increased and decreased by $1\sigma$.
- *Tagging* - this is estimated by comparing the default fit with the fits using the alternate tag-probability.

## 4. Results and Discussion

The tagging performance obtained for different taggers is given in Table 1. The errors are statistical only. The OST method shows comparable results to those of similar measurements, despite the limited number of taggers and relatively simple algorithm for their combination.

*Table1: Summary of tagging performance for the different tagging methods* [8]

| *Tagger* | *Efficiency* [%] | *Dilution* [%] | *Tagging Power* [%] |
|---|---|---|---|
| Segment Tagged muon | 1.08 ± 0.02 | 36.7 ± 0.7 | 0.15 ± 0.02 |
| Combined muon | 3.37 ± 0.04 | 50.6 ± 0.5 | 0.86 ± 0.04 |
| Jet charge | 27.7 ± 0.1 | 12.68 ± 0.06 | 0.45 ± 0.03 |
| Total | 32.1 ± 0.1 | 21.3 ± 0.08 | 1.46 ± 0.05 |

For each event, characterized by a value of discriminating variable $Q$, one can define the probability $P(Q|B^-)$ ($P(Q|B^+)$) that the decision, that on the opposite signal side $b$ (or $\bar{b}$) quark is produced, is correct. This probability is further used in the likelihood fit, to extract the parameters of interest in $B_s^0 \to J/\psi\phi$ measurement, where each $B_s$ candidate receives a per candidate probability and its statistical uncertainty.

The systematic treatment of the $B_s^0 \to J/\psi\phi$ fit results due to uncertainties in tagging is performed by varying the tag probabilities by the statistical uncertainty in each bin of the distribution, as well as varying the models of parametrizing the probability distributions, as described in Ref. [8].

## 5. Conclusion

Using data recorded in the 2011 run, the flavour-tagging technique and the treatment of systematic errors in an updated *CP* violation measurement in $B_s^0 \to J/\psi\phi$ decays, have been presented. The use of the opposite-charge muon and the b-jet-charge as the OST methods eliminates the ambiguity in the extraction of the *CP*-violating weak mixing phase $\phi_s$ and reduces its overall uncertainty, giving the measured value of $\phi_s = 0.12 \pm 0.25(\text{stat}) \pm 0.11(\text{syst})$ rad. This result is consistent with theoretical expectation lying within 1σ of the expected value in the Standard Model.

## References

[1] ATLAS Collaboration, G. Aad et al., *Time-dependent angular analysis of the decay* $B_s^0 \to J/\psi\phi$ *and extraction of* $\Delta\Gamma_s$ *and the CP-violating weak phase* $\phi_s$ *by ATLAS*, *JHEP* **1212** (2012) 072 [arXiv:1208.0572] [hep-ex].

[2] M. Kobayashi and T. Maskawa, *CP-Violation in the Renormalizable Theory of Weak Interaction*, *Prog. Theor. Phys.* **49** (1973) 652.

[3] UTfit Collaboration, M. Bona et al., *Constraints on new physics from the quark mixing unitarity triangle*, *Phys. Rev. Lett.* **97** (2006) 151803, [arXiv:hep-ph/0605213].

[4] A. S. Dighe et al., *Angular distributions and lifetime differences in* $B_s^0 \to J/\psi\phi$ *decays*, *Phys. Lett.* **B 369** (1996) 144 [arXiv:hep-ph/9511363].



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[5] I. Dunietz et al., *How to extract CP-violating asymmetries from angular correlations*, *Phys. Rev.* **D 43** (1991) 2193-2208.

[6] ATLAS Collaboration, G. Aad et al., *Expected Performance of the ATLAS Experiment - Detector, Trigger and Physics*, arXiv:0901.0512 [hep-ex].

[7] PDG Collaboration, K. Nakamura et al., *Review of particle physics, J.Phys.G.* **G37** (2010) 075021, and 2011 partical update for the 2012 edition.

[8] ATLAS Collaboration, G. Aad et al., *Flavour tagged time dependent angular analysis of the $B_s^0 \to J/\psi\phi$ decay and extraction of $\Delta\Gamma_s$ and the weak phase $\phi_s$ in ATLAS*, ATLAS-CONF-2013-039, http://cds.cern.ch/record/1541823.

[9] ATLAS Collaboration, G. Aad et al., *Commissioning of the ATLAS high-performance b-tagging algorithms in the 7 TeV collision data*, ATLAS-CONF-2011-102, http://cds.cern.ch/record/1369219.