Physics potential of the decays $B_{s,d} \rightarrow J/\psi \eta$ and $B_s \rightarrow J/\psi \phi$ in the ATLAS experiment at the LHC

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The CP asymmetry predicted by the Standard Model in the decay modes $B_s \rightarrow J/\psi + \eta$ and $B_s \rightarrow J/\psi + \phi$ is very small, and the observation of a sizeable effect would be a clear indication of new physics beyond the Standard Model. Contrary to the final state $J/\psi \phi$, the former final state is a CP eigenstate, and therefore complex angular distribution analyses are not necessary for the asymmetry measurement. In this paper, the approaches for the study of these two decay channels are presented.

1 Introduction

The decay mode $B_s \rightarrow J/\psi \eta$ is analogous to the mode $B_s \rightarrow J/\psi \phi$, which has been studied extensively in view of CP violation measurements. In these two decay modes, the CP asymmetry predicted by the Standard Model is very small, and the observation of a sizeable effect would be a clear signal of physics beyond the Standard Model.

The decay channel $B_s \rightarrow J/\psi \eta$ can be used to measure various parameters in the $B_s$-meson system. In the ATLAS experiment, assuming an integrated luminosity of 30 fb$^{-1}$, roughly 10,000 decays can be reconstructed with a signal-to-background ratio of about 1:1, as will be shown later in this paper. It can be thus foreseen that the measurement of the branching fraction of this mode, the measurement of the $B_s$ lifetime, as well as other measurements will be feasible, which constitutes an important cross-check of other measurements performed using other decay channels.

Moreover, the decay mode $B_s \rightarrow J/\psi \eta$, when combined with its U-spin symmetric channel, $B_d \rightarrow J/\psi \eta$, provides a new strategy for the extraction of the $\gamma$ angle of the Unitarity Triangle [1]. Indeed, while the phase $\exp(i \gamma)$ is CKM suppressed for the decay mode $B_s \rightarrow J/\psi \eta$, this is not the case for the decay mode $B_d \rightarrow J/\psi \eta$. CP violation effects could thus potentially be more easily accessible through the latter mode by measuring the time-dependent asymmetry of $B_d$. The overall normalization can be fixed by measuring CP averaged rates of $B_d \rightarrow J/\psi \eta$ and $B_s \rightarrow J/\psi \eta$, which assumes the validity of the U-spin symmetry (the approximate symmetry of $u$, $d$ and $s$ quarks). The measurements seem to be, however, out of reach due to the small expected branching ratio of $B_d \rightarrow J/\psi \eta$, and the overlapping mass peaks of the $B_d$ and $B_s$ [2].

The $B_s - \bar{B}_s$ system is characterized by two eigenstates with different masses and decay rates. The experimental determination of the mass difference $\Delta m_s$ and the rate difference $\Delta \Gamma_s$ will be valuable input for flavour dynamics in both the Standard Model and its possible extensions. While the measurement of $\Delta m_s$ has been proven to be accessible through the decays $B_s \rightarrow D_s \pi$ and $B_s \rightarrow D_s a_1$, $\Delta \Gamma_s$ is expected to be precisely measured in ATLAS through the decay channel $B_s \rightarrow J/\psi \phi$.

2 The $B_{s,d} \rightarrow J/\psi \eta$ decay channel

Signal samples of $B_{s,d} \rightarrow J/\psi \eta$ were generated using the Monte Carlo program PYTHIA 5.7 [3]. The $J/\psi$ meson was forced to decay into $\mu^+ \mu^-$, and only events passing the ATLAS level-1 trigger requirements for B hadrons [3] (a muon with a $p_T > 6$ GeV and $| \eta | < 2.4$)\footnote{Throughout this paper, the symbol $p_T$ is used for the transverse momentum with respect to the beam direction, and $\eta$ for the pseudorapidity.} and the $\eta$ meson decaying into $\gamma \gamma$ were retained. The branching ratio for the decay $\eta \rightarrow \gamma \gamma$ is $(39.33 \pm 0.25)\%$ [5]. Events were further selected to satisfy the ATLAS second level trigger: the presence of a second muon with $p_T > 3$ GeV and $| \eta | < 2.5$. The resulting signal samples were consisting of about 17,000 $B_s$ events and 15,000 $B_d$ events.

A full GEANT-based simulation was used to simulate the response of the ATLAS inner detector and the electromagnetic calorimeter. The muon chambers were not included in the simulation, but only real muons were included in the analysis. The muon identification efficiencies were assumed to be 85% for the first muon (the muon with $p_T > 6$ GeV) and 78% for the second muon (the muon with $p_T > 3$ GeV). The 85% efficiency for the muon with the higher transverse momentum includes both reconstruction and level-1 trigger efficiencies.

The $J/\psi$ was reconstructed by fitting pairs of opposite-charge muons passing the level-2 selection ($\mu 6 (\mu 3)$)\footnote{In the following, the notation $\mu 6 (\mu 3)$ is used to indicate a muon with a $p_T > 6$ (3) GeV.} to a common vertex and by calculating their invariant mass. The $\chi^2$/d.o.f. of the vertex fit was required to be less than 6.0, and the decay vertex of the $J/\psi$ was required to be detached from the primary vertex by at least 250 $\mu$m in the transverse plane. The $J/\psi$ mass resolution was found to be...
The momentum. All charged particles with $p_T > 0.5$ GeV, 39 MeV. The resolution of the $J/\psi$ decay vertex in the transverse plane was 64 $\mu$m. The efficiency of the reconstruction within a three-standard-deviation mass window was 79%. If a $J/\psi$ was found, the analysis proceeded with $\eta$-reconstruction in the electromagnetic calorimeter. The $\eta$ reconstruction is described in more detail in Ref. [17]. The mass distribution, Fig. 1, was fitted with two Gaussians, and the obtained mass resolution was $\sigma = 70$ MeV. The total reconstruction efficiency was 2.3% within two standard deviations from the nominal mass.

The $J/\psi$ and $\eta$ candidates were combined to reconstruct both the $B_s$ and $B_d$. A mass resolution of around 67 MeV was found for both channels, with an overall signal efficiency of $\sim 1\%$ within three standard deviations from the nominal mass.

The background considered was a sample of $B \rightarrow J/\psi X$ decays, processed and selected in the same way as the signal events. The resulting efficiency was less than 0.009%. The table below summarizes the event rates for both signals and background.

| $|\eta| < 2.5$ around the reconstructed $B$-meson were included in the jet, if the distance between the particle and the B-meson, $\Delta R = \sqrt{\eta^2 + \phi^2}$, was less than 0.8. Particles not originating from near the primary vertex were excluded by requiring that the transverse impact parameter $d_0$ was less than 1 cm and the $z$-coordinate of the particle at the point of closest approach was within 5 cm of the $z$ of the primary vertex. The particles from the B-meson decay itself were excluded as well. In the analysis, the reconstructed B-meson was defined as $B_s$ ($\bar{B}_s$) if the jet-charge had $Q_{jet} > +c$ ($Q_{jet} < -c$), where $c$ is a tunable cut.

The exponent $k$ was optimized to maximize the tagging quality factor $Q = D_{tag}^2 \cdot \epsilon_{tag}$, where $D_{tag}$ is the tagging dilution factor, originating from wrong-sign tags ($D_{tag} = 1 - 2W$, where $W$ is the fraction of wrong-sign tags), and $\epsilon_{tag}$ is the tagging efficiency. The optimum parameters were found to be $k = 0.2$, $c = 0.2$, resulting in a quality factor of 3.85% with $D_{tag} = 0.26$, $\epsilon_{tag} = 0.57$.

The table below summarizes the event rates for both signal and background events for an integrated luminosity of 30 $fb^{-1}$. $\theta_p$ is the $\eta - \eta'$ mixing angle (see Ref. [8]).

![Figure 1](image1.png)  
**Figure 1.** Invariant mass distribution of $\eta$-mesons in signal events after all the cuts.

![Figure 2](image2.png)  
**Figure 2.** Invariant mass distribution of the reconstructed $B_s$ signal (white) and the background (dashed).

| $\theta_p = -10^0$ | $\theta_p = -20^0$ |
|-------------------|-------------------|
| $\text{Br}(B_s \rightarrow J/\psi \eta)$ | $8.3 \cdot 10^{-4}$ | $9.5 \cdot 10^{-4}$ |
| $N_{\text{obs}}$ | 8 400 | 9 600 |

| $\text{Br}(B_d \rightarrow J/\psi \eta)$ | $4.1 \cdot 10^{-6}$ | $1.6 \cdot 10^{-6}$ |
| $N_{\text{obs}}$ | 200 | 80 |
| $N_{\text{obs}}$ | 10 800 | 10 800 |

| $|\eta| < 2.5$ |
|-------------------|
| $\text{Number of Events}$ | $\text{Number of Events}$ |
| $0$ | $1000$ |
| $0.1$ | $2000$ |
| $0.2$ | $3000$ |
| $0.3$ | $4000$ |
| $0.4$ | $5000$ |
| $0.5$ | $6000$ |
| $0.6$ | $7000$ |
| $0.7$ | $8000$ |
| $0.8$ | $9000$ |
| $0.9$ | $10 000$ |
| $1$ | $11 000$ |

| $\text{Number of Events}$ |
|--------------------------|
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| $0.5$ | $6000$ |
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| $0.7$ | $8000$ |
| $0.8$ | $9000$ |
| $0.9$ | $10 000$ |
| $1$ | $11 000$ |
The observable asymmetry is:

\[ a_{\text{obs}}(t) = D a_{CP}(t) = D \sin \phi_M \sin \Delta m_s t, \]

where \( D = D_{\text{tag}} D_{\text{back}} \) combines the experimental dilution factors due to mistagging and background. \( D_{\text{back}} = N_{\text{obs}}^S / (N_{\text{obs}}^S + N_{\text{obs}}^B) \) is the ratio of the number of observed signal events to the total number of observed events.

Assuming that the decay time resolution is \( \Delta \tau = 0.073 \) ps, the error on the CP asymmetry was estimated to be:

\[ \delta (\sin \phi_M) = 0.27, \ x_s = \Delta m_s / \Gamma_s = 19, \]
\[ \delta (\sin \phi_M) = 0.31, \ x_s = 30, \]

where

\[ \phi_M = -2 \lambda^2 \eta = -2 \lambda \sin \gamma |V_{ub}| / |V_{cb}|, \]

where \( \lambda = \sin \theta_C, \ \theta_C \) is the Cabibbo angle, \( \eta \) is the height of the Unitarity Triangle and \( \gamma \) is one of the angles of the Unitarity Triangle.

### 3 The Bs → J/ψφ decay channel

The Bs → J/ψφ mode has a clean experimental signature. For its reconstruction, the same approach as for the Bs→J/ψη was used. Details are given in [6].

The Bs → J/ψφ leads to three final state helicity configurations and their linear combinations are CP eigenstates with different CP parities [9]. For the extraction of the CP-violating weak mixing phase \( \phi_s = \arg(V^*_{cs} V_{cb} / V^*_{cs} V_{cb}) \) the helicity amplitudes need to be separated. Experimentally, one can measure three independent angles and the Bs proper decay time. The initial Bs flavour can be tagged in part of the events. The ATLAS precision for these measurements was determined by detector response simulations and was used as input to angular analyses based on a maximum likelihood fit in repeated Monte Carlo experiments. The likelihood function \( L \) is defined as:

\[ L = \prod_{i=1}^{N} \frac{\int_{0}^{t_{\text{max}}} W(t_i, \Omega) \cdot \text{Res}(t, t_i) dt'}{\int_{0}^{t_{\text{max}}} W(t, \Omega) \cdot \text{Res}(t, t) dt'} \]

with:

\[ W(t, \Omega) = \epsilon_1 \omega^+(t, \Omega) + \epsilon_2 \omega^-(t, \Omega) + b e^{-\Gamma_0 t} \]

where \( \epsilon_1 = \epsilon_2 = 0.5 \) for untagged events, \( \epsilon_1 = 1-r, \ \epsilon_2 = r \) if the Bs is tagged as a particle and \( \epsilon_1 = r, \ \epsilon_2 = 1-r \) if the Bs tagged as an anti-particle, \( r \) is the wrong tag fraction, \( b \) is the level of background and \( \Gamma_0 \) is the average decay rate of the background. The probability density \( \omega^\pm \) is defined by:

\[ \omega^{\pm}(\theta_1, \theta_2, \phi) = \frac{1}{(4\pi)^2} \sum_{i=1}^{6} f(t_i)^{\pm} F_i(\theta_1, \theta_2, \phi) \]

in which \( f(t_i)^{\pm} \) are expressed in terms of four parameters of Bs weak decay and oscillations: \( \Delta \Gamma_s, \ \Gamma_s, \ x_s = \Delta m_s / \Gamma_s, \ \xi_s \), and four independent parameters of helicity amplitudes: \( |A_0(t = 0)|, |A_{\pm}(t = 0)| \), and the two strong phases \( \delta_1 \) and \( \delta_2 \). The angular functions \( F_i \) are given in [10][11], where more details about the analysis are also given. In the maximum likelihood fit of the \( \Delta \Gamma_s \), the \( \Gamma_s \) and the weak phase \( \phi_s \) were simultaneously determined along with two helicity amplitude values and their strong phases. The mixing parameter \( x_s \) was assumed to have been measured in the Bs → D_s π and Bs → D_s K and was fixed.

While all the eight parameters are independent in the theoretical models, the experimental resolution causes some of them become correlated, particularly the two strong phases, which prevented their simultaneous determination. Thus in the final analysis these two parameters were fixed. For an integral luminosity of 30 fb\(^{-1}\), \( \Delta \Gamma_s \) can be determined with a relative error of 12%, while the precision of \( \phi_s \) depends on the value of \( x_s \) and on the proper time resolution, as shown in Fig. 3, where the discovery lines for ATLAS and LHCb are displayed in the \( (x_s, -\phi_s) \) plane, together with regions allowed by the Standard Model and by one
example of new physics known as the Left-Right symmetric model [12].

4 Conclusions

ATLAS is expected to measure several parameters in the Bs meson system, which will be valuable input for the flavour dynamics in the Standard Model and its possible extensions.

A clear signal of the decay mode $B_s \rightarrow J/\psi \eta$ is expected to be reconstructed with the ATLAS detector, and several measurements are possible such as the measurement of the branching fraction and the $B_s$ meson lifetime. The experimental resolution of the CP asymmetry measured shows some sensitivity to very large asymmetries as predicted by some models beyond the Standard Model. The measurement of the $\gamma$ angle seems, however to be compromised because the $B_d \rightarrow J/\psi \eta$ is not observable. After 3 years at luminosity $10^{33}$ cm$^{-2}$s$^{-1}$ ATLAS is expected to determine $\Delta \Gamma_s$ with the relative errors of 12%. The ATLAS discovery line (Fig. 3) shows that the precision is high enough to be sensitive to new physics.

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