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Mixing and CP violation in the decay of $B_s \to J/\psi\phi$ in ATLAS

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The $B_s \to J/\psi\phi$ decay is characterized by the average decay width Γ_s of the heavy and the light mass eigenstates, the decay width difference $\Delta\Gamma_s$ and by the CP violating phase ϕ_s. The final state is a mixture of CP even and CP odd components that are disentangled via an angular analysis. The measurement of the decay channel provides the possibility to test the predictions of the Standard Model. In particular the measurement of the CP violating phase ϕ_s has the capability to unveil New Physics induced enhancement of the small Standard Model value. In this document the analyses of the $B_s \to J/\psi\phi$ decay with the ATLAS detector at the LHC is presented.

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1. Introduction

New phenomena beyond the predictions of the Standard Model (SM) may alter *CP* violation in *B*-decays. A channel that is expected to be sensitive to new physics contributions is the decay $B_s \to J/\psi\phi$. *CP* violation in the $B_s \to J/\psi\phi$ decay occurs due to interference between direct decays and decays occurring through $B_s - \overline{B_s}$ mixing. The oscillation frequency of B_s meson mixing is characterized by the mass difference Δm_s of the heavy (B_H) and light (B_L) mass eigenstates. The *CP*-violating phase ϕ_s is defined as the weak phase difference between the $B_s - \overline{B_s}$ mixing amplitude and the $b \to c\bar{c}s$ decay amplitude. In the absence of *CP* violation, the B_H state would correspond exactly to the *CP*-odd state and the B_L to the *CP*-even state. In the SM the phase ϕ_s is small and can be related to CKM quark mixing matrix elements via the relation $\phi_s \simeq -2\beta_s$, with $\beta_s = \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$; a value of $\phi_s \simeq -2\beta_s = -0.0368 \pm 0.0018$ rad [1] is predicted in the SM. Many new physics models predict large ϕ_s values whilst satisfying all existing constraints, including the precisely measured value of Δm_s [2, 3].

Another physical quantity involved in $B_s - \overline{B_s}$ mixing is the width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H$ of B_L and B_H which is predicted to be $\Delta\Gamma_s = 0.087 \pm 0.021$ ps^{-1}[4]. Physics beyond the SM is not expected to affect $\Delta\Gamma_s$ as significantly as ϕ_s [5]. Extracting $\Delta\Gamma_s$ from data is nevertheless useful as it allows theoretical predictions to be tested [5].

The decay of the pseudoscalar B_s to the vector-vector final-state $J/\psi\phi$ results in an admixture of *CP*-odd and *CP*-even states, with orbital angular momentum $L = 0$, 1 or 2. The final states with orbital angular momentum $L = 0$ or 2 are *CP*-even while the state with $L = 1$ is *CP*-odd. Flavour tagging is used to distinguish between the initial B_s and $\overline{B_s}$ states. The *CP* states are separated statistically through the time-dependence of the decay and angular correlations amongst the final-state particles.

2. Reconstruction and candidate selection

The $B_s \to J/\psi\phi$ analysis uses measurements provided by the inner tracking detectors and the muon spectrometers[6]. The analysis is based on a data sample from an integrated luminosity 4.9fb^{-1} collected in 2011 by the ATLAS detector in pp collisions at $\sqrt{s} = 7$TeV with di-muon triggers selecting $J/\psi \to \mu^+\mu^-$ candidates. The momentum thresholds for muons with pseudorapidity $|\eta| < 2.5$ were set to 4GeV$/c$ for both muons or to 4GeV$/c$ and 2GeV$/c$ correspondingly. The two oppositely charged muons in the J/ψ candidate must come from a common decay vertex and have an invariant mass in a region around the world average J/ψ mass [7].

Two additional oppositely charged hadron tracks with $p_{\mathrm{T}}(h) > 0.5$GeV$/c$ and $|\eta(h)| < 2.5$ are combined to form $\phi \to K^+K^-$ candidates with an invariant mass lying in a small window of 10 MeV around the world average ϕ mass [7]

The B_s candidates are constructed from all combinations of J/ψ and ϕ candidates in each event. The four tracks of every $B_s \to J/\psi\phi$ candidate are fitted to a common vertex with the invariant mass $m(\mu^+\mu^-)$ set to J/ψ world average value [7]. Each B_s candidate enters the fit with measurements of mass and decay time including corresponding uncertainties and three transversity angles. No cut on the proper B_s decay time is applied resulting in about 130000 B_s candidates in the mass range of 5.15 GeV < m(B_s^0) < 5.65 GeV.

3. Tagged Analysis

ATLAS has updated its untagged analysis[8] of the B_s decay published in 2012 with the application of initial state flavor tagging [9]. The differential decay rate describing the signal decay includes terms for the S-wave decays $B_s \to J/\psi f_0$ and non-resonant $B_s \to J/\psi K^+K^-$. The S-wave component is a pure CP odd state parameterized by an additional amplitude $|A_S(0)|$ and a related strong phase δ_s. The four amplitudes are normalized to one: $|A_0(0)|^2 + |A_\perp(0)|^2 + |A_{||}(0)|^2 + |A_S(0)|^2 = 1$. The normalized tagged differential decay rate [9] constitutes the time and angular dependent part of the signal component of the likelihood function. To take the detector resolution into account it is convoluted with a Gaussian resolution function making use of the event-by-event decay time uncertainty. The sculpting of the angular distributions by the detector is accounted for applying a four-dimensional binned acceptance method that provides an efficiency depending on the transversity angles and the p_T of the B_s candidates. A single Gaussian function smeared with an event-by-event mass resolution models the signal mass. The background mass is modelled by a linear function and the proper decay time of the background is described by the sum of a Gaussian, two positive exponentials and a negative exponential for events with poor decay time resolution. The background angular model is described by functions that were empirically determined from sideband data. The likelihood function includes additional terms for the contamination of the data sample with peaking background from B_d reflections. The decays $B_d \to J/\psi K^*$ and non-resonant $B_s \to J/\psi K\pi$ can be identified as B_s candidates if the final state pion is mis-reconstructed as a kaon. Their contribution to the data sample and their mass, decay time and angular shapes are determined using MC simulation and the corresponding parameters are kept fix in the fit. In total the fit features 25 free parameters including the physics parameters of interest ϕ_s, $\Delta\Gamma_s$ and Γ_s. The parameter Δm_s is fixed at $17.77\hbar$ ps^{-1} [2].

Table 1: Summary of tagging performance for the different tagging methods. Uncertainties shown are statistical only. The efficiency and tagging power are each determined by summing over the individual bins of the charge distribution. The effective dilution is obtained from the measured efficiency and tagging power, as shown in the table. For the efficiency, dilution, and tagging power, the corresponding uncertainty is each determined by combining the appropriate uncertainties on the individual bins of each charge distribution.

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	1.45 ± 0.05

Flavour tagging enters the fit in form of a probability that the B_s candidate is a particle or antiparticle. ATLAS uses two methods for opposite side flavour tagging which are both studied and calibrated using the $B^\pm \to J/\psi K^\pm$ decay in data. The first flavour tagging method is the muon cone charge tagger using muons from semi-leptonic B decay on the opposite side. The events are searched for an additional muon originating near the primary interaction. If there is more than one additional muon, the one with the highest p_T is chosen. A muon cone charge variable is calculated from tracks (excluding the signal tracks) found in the inner tracking detectors that are in a cone of $\Delta R < 0.5$ around the momentum axis of the muon. The muon cone charge is constructed as sum of the charge of the tracks weighted with their transverse momentum and a tag probability is derived from that.

The second tagging method is the jet charge tagger. In the absence of a muon, a b-tagged jet reconstructed using the "anti-kT " algorithm is required in the event. The jet tracks are associated to the same primary vertex as the signal decay, excluding those from the signal candidate. Jets and tracks which are close to the signal momentum axis are not taken into account. The tag probability is derived from the jet charge which is a sum of the charge of the tracks in the jet weighted with their transverse momentum. The performance of the flavour tagging algorithms is shown in table 1. The following values have been obtained for the physics parameters in the ATLAS analysis [9]:

$$\begin{aligned}
\phi_s &= 0.12 \pm 0.25\ (\text{stat.}) \pm 0.11\ (\text{syst.})\ \text{rad} \\
\Delta\Gamma_s &= 0.053 \pm 0.021\ (\text{stat.}) \pm 0.009\ (\text{syst.})\ \text{ps}^{-1} \\
\Gamma_s &= 0.677 \pm 0.007\ (\text{stat.}) \pm 0.003\ (\text{syst.})\ \text{ps}^{-1} \\
|A_0(0)|^2 &= 0.529 \pm 0.006\ (\text{stat.}) \pm 0.011\ (\text{syst.}) \\
|A_\parallel(0)|^2 &= 0.220 \pm 0.008\ (\text{stat.}) \pm 0.009\ (\text{syst.}) \\
\delta_\perp &= 3.89 \pm 0.46\ (\text{stat.}) \pm 0.13\ (\text{syst.})\ \text{rad}
\end{aligned}$$

The dominant systematic uncertainty for ϕ_s is the error of the tag probability and for all other parameters the modelling of the background angles constitutes the largest uncertainty. Compared to the untagged fit[8], the statistical uncertainty of ϕ_s, which was measured with $\phi_s = 0.21 \pm 0.41\ (\text{stat.}) \pm 0.10\ (\text{stat.})$ rad has decreased by $\sim 40\%$. The obtained values and uncertainties of the parameters are consistent with the untagged analysis and ϕ_s and $\Delta\Gamma_s$ are in agreement with the Standard Model. The likelihood contour plot in the ϕ_s- $\Delta\Gamma_s$ plane for the tagged analysis is shown in figure 1

4. Summary

ATLAS has performed analyses of the decay $B_s \to J/\psi\phi$ measuring ϕ_s and $\Delta\Gamma_s$. All results are in agreement with previous measurements and with the Standard Model. Since the statistical uncertainties still dominate for the essential parameters, future updates of the analyses including the usage of data collected in 2012 and enhancements of the analysis methods, have the capability to improve the precision of the results.

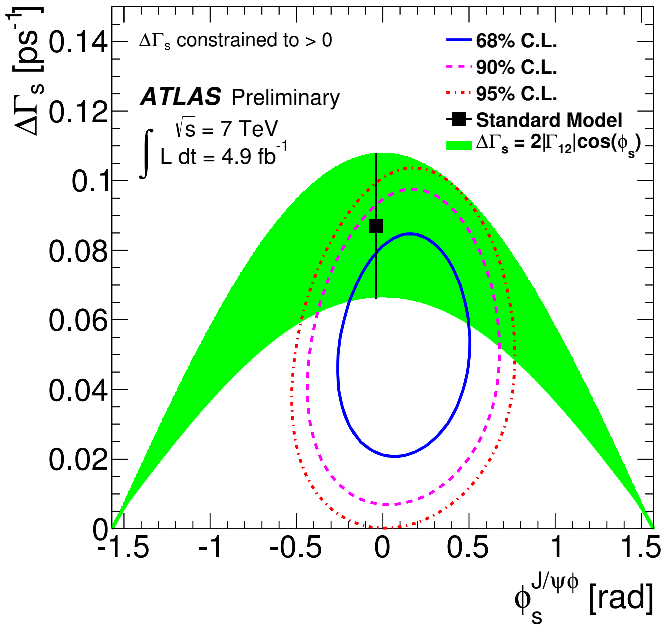

Figure 1: Likelihood contours in ϕ_s - $\Delta\Gamma_s$ plane. The blue and red contours show the 68% and 95% likelihood contours, respectively (statistical errors only). The green band is the theoretical prediction of mixing- induced CP violation.

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