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Prospects for β_s measurement

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The CP violating phase Φ_s in the $B_s^0 \to J/\psi\phi$ decay is predicted in Standard Model to be $\Phi_s = -2\beta_s$ where β_s is related to the Cabibbo-Kobayashi-Maskawa matrix elements as $\beta_s = \arg\left(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*\right)$. In the Standard model Φ_s is very small but New Physics contribution can enhance it quite significantly. The LHC experiments are in a very good position to measure the β_s angle thanks to the large beauty production cross-section and the high luminosity of the machine. In the present document the status of the trigger and offline analysis of the golden mode $B_s^0 \to J/\psi\phi$ in ATLAS, CMS and LHCb are discussed with a prospects of the achievable sensitivity.

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1. Introduction

The source of Charge-Parity (CP) violation in the Standard Model (SM) is the Cabibbo-Kobayashi-Maskawa (CKM) matrix. It is a 3x3 complex unitary matrix which relates the electroweak eigenstates to the mass eigenstates of down-type quarks. The unitary constraint allows 6 orthogonality relations between the CKM elements to be derived which can be represented as triangles in a complex plane. The relations $V_{\mathrm{us}}V^*_{\mathrm{ub}} + V_{\mathrm{cs}}V^*_{\mathrm{cb}} + V_{\mathrm{ts}}V^*_{\mathrm{tb}} = 0$ is particularly useful to describe the CP observables in the $\mathrm{B}^0_{\mathrm{s}}$ decays. The corresponding triangle is squashed since the magnitude of one side of the triangle is suppressed with respect to the others by a factor $O(\lambda^2)$, where λ is the sine of the Cabibbo angle. The smaller angle of the "bs unitary triangle" is defined as β_{s} ($\beta_{\mathrm{s}} = \arg(-V_{\mathrm{ts}}V^*_{\mathrm{tb}}/V_{\mathrm{cs}}V^*_{\mathrm{cb}})$) and its value is predicted quite precisely in the SM: $2\beta_{\mathrm{s}} = (3.68 \pm 0.17) \cdot 10^{-2}$.

Such an angle can be measured using the interference between decays with and without mixing of the $\mathrm{B}^0_{\mathrm{s}}$ with the $\mathrm{b} \rightarrow \mathrm{c}\bar{\mathrm{c}}\mathrm{s}$ quark transition. If the final state is a CP eigenstate, the CP asymmetry:

$$A_{CP}(t) = \frac{\Gamma(\overline{\mathrm{B}}^0_{\mathrm{s}}(t) \rightarrow f) - \Gamma(\mathrm{B}^0_{\mathrm{s}}(t) \rightarrow f)}{\Gamma(\overline{\mathrm{B}}^0_{\mathrm{s}}(t) \rightarrow f) + \Gamma(\mathrm{B}^0_{\mathrm{s}}(t) \rightarrow f)} = \frac{\eta_f sin(\Phi_s) sin(\Delta m_s)}{cosh(\Delta\Gamma_s t/2) - \eta_f cos(\Phi_s) sinh(\Delta\Gamma_s t/2)} \tag{1.1}$$

where $\Phi_s = -2\beta_{\mathrm{s}}$ in the SM, Δm_s is the $\mathrm{B}^0_{\mathrm{s}}$ oscillation frequency, $\Delta\Gamma_s = \Gamma_H - \Gamma_L$ is the difference between the decay widths of the heavy and light mass eigenstates, and η_f is the CP eigenvalue of the final state. The small predicted value of Φ_s in the SM and its small theoretical uncertainty makes its measurement an excellent test of the SM and search for New Physics (NP).

Recently the CDF and D0 experiments published their first measurements of Φ_{s} which are 2.2σ away from the SM prediction [1]. It is expected that LHC experiments have the necessary sensitivity to unambiguously confirm or reject possible NP contributions to this observable.

The golden mode for this measurement is $\mathrm{B}^0_{\mathrm{s}} \rightarrow \mathrm{J}/\psi(\mu\mu)\phi(\mathrm{KK})$ which has a large BR ($3 \cdot 10^{-5}$) and a clean dimuon signature very useful for triggering and offline analysis. The drawback of this mode is the fact that the final state is not a CP eigenstate since the transition is from a pseudoscalar meson to two vectors, so three values of angular momentum are allowed in final state. To decouple the even and odd CP eigenstates an angular analysis is required.

2. LHC experiments

The Large Hadron Collider at CERN is a proton proton collider which will operate at a center of mass energy of 14 TeV with a maximum luminosity of $10^{34} cm^{-2} s^{-1}$ [2]. The high $\mathrm{b}\bar{\mathrm{b}}$ cross section (500 μb) combined with the the high luminosity makes the collider very suitable for B physics. In fact one of the LHC experiment (LHCb) is dedicated to the B physics while the two general purpose experiments (ATLAS and CMS) will reserve an important part of their physics programs for B physics.

In pp collision the b and $\bar{\mathrm{b}}$ are produced almost collinearly with the beam line, and both in the same forward or backward direction. LHCb has exploited this kinematics, adopting a single arm forward spectrometer covering the η range 1.8-5 while ATLAS/CMS general purpose detectors cover the $|\eta| < 2.5$ region. The $\mathrm{b}\bar{\mathrm{b}}$ cross section in the acceptance of the experiments is 230 μb for LHCb and 100 μb for ATLAS/CMS. The pp cross section at the LHC is more than 2 orders of magnitude greater than the b$\overline{\text{b}}$ cross section. To reduce the huge background in pp collisions LHCb chooses to work at lower luminosity ($2 \cdot 10^{32} cm^{-2}s^{-1}$) so to maximize the number of events with one pp interaction. ATLAS and CMS plan to perform their B physics program mainly in the first years when the collider is expected to run with a luminosity of $10^{33} cm^{-2}s^{-1}$. In the following a brief description of the trigger and detector relevant for the β_s measurement is presented.

The LHCb spectrometer is composed of a silicon strip vertex detector, 2 Cherenkov detectors, a tracking system , a magnet with 4 Tm bending power, a calorimeter system and a muon detector. From full Monte Carlo simulation the momentum resolution is estimated to be 0.4%, while the μ identification is greater than 90% for a π contamination of 1%. The RICH detectors give a K identification efficiency of 88% for a π contamination of 3%.

The ATLAS detector is composed of an inner detector with a 3 pixel layers, 8 layers of microstrips and several planes of straw tubes detector in a 2T solenoidal magnetic field. Outside the tracking system there is a calorimeter and a muon detector. The momentum resolution is estimated to be in the range 1-2%, while the muon identification performance is similar to LHCb.

The CMS detector includes 3 layers of pixels and 10 layers of silicon strips. A solenoid produces a magnetic field of 4 T. Outside the magnet there are the calorimeter and the muon system. The tracking system allows to get a momentum resolution of 1-2%. The muon system provides identification capability similar to ATLAS and LHCb.

The experiments have a trigger composed of 2 (CMS and LHCb) or 3 (ATLAS) levels. The first is hardware while the rest are software triggers. The first level reduces the accelerator 40 MHz input rate to 75 kHz, 100 kHz, 1 MHz respectively for ATLAS, CMS and LHCb. The interesting events are triggered on the basis of high transverse momentum (Pt) muon or dimuon. The Pt threshold is high in ATLAS (6 GeV/c) and CMS (7 GeV/c for single and 3 GeV/c for dimuon) while it is medium in LHCb (1-1.3 GeV/c).

The LHCb software trigger level reduces the rate to 2 kHz. It confirms the triggering muons using the tracking system and searches for additional muons in single muon triggered events. The event is accepted if the dimuon mass is greater than 2.5 GeV/c^2, no cut on Impact Parameter (IP) is applied to not bias the proper time acceptance of the offline analysis. The bandwidth dedicated to this inclusive selection is about 600 Hz.

The CMS software level has an output rate of 150 Hz. The B physics bandwidth is around 5 Hz. The trigger performs an exclusive selection. A partial track reconstruction is used: first the muon and J/ψ is detected with an IP cut, then the kaons tracks are searched for around the J/ψ cone, finally the ϕ and the B_s^0 are reconstructed.

ATLAS has two software levels with output rates of 1-2 kHz and 100 Hz. About 10% of final output rate is dedicated to B physics. The first software level confirms the muons using the inner detector, searches for additional muons and applies an invariant mass cut. In the last level more sophisticated track and vertex reconstruction algorithms are performed and an IP cut is applied to reject prompt J/ψ.

3. Offline selection and expected sensitivity

The offline events selection of $\text{B}_s^0 \rightarrow \text{J}/\psi\phi$ decays are based on Pt and PID of final state particles, invariant mass and vertex quality and Pt of the intermediate and final states, and in addition

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	ATLAS	CMS	LHCb
L (fb^{-1})	10	10	2
Signal yield (k)	90	109	114
B/S	0.18	0.25	2.0
$\sigma(M_{B_s^0})(MeV/c^2)$	16.5	14	17
$\sigma(\tau)(fs)$	83	77	39
ε_{tag} (%)	4.6	N.A.	6.2

Table 1: Event yield in one nominal year, B/S, resolutions and the tagging power for the three experiments

a cut on the B_s^0 pointing to the primary vertex is applied. In ATLAS and CMS a cut on B_s^0 decay length is used while LHCb chooses to not use such a cut to avoid bias in the proper time. More details can be found in [3, 4, 5]. The invariant mass spectra for the B_s^0 are reported in Fig 1.

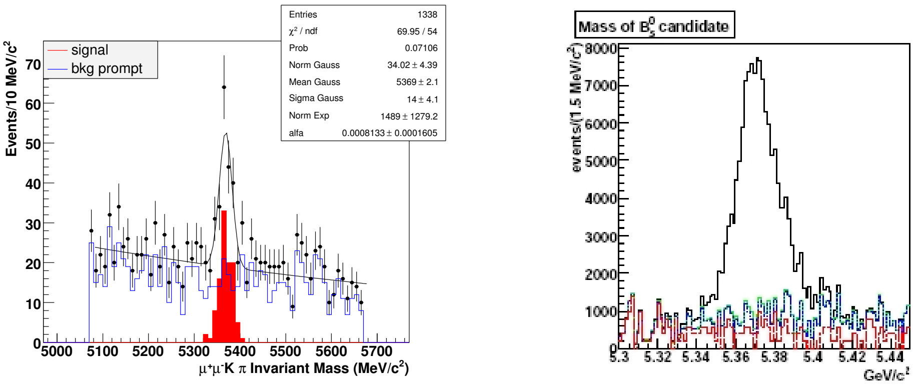

Figure 1: Invariant mass of B_s^0 candidates. Left is the LHCb result with signal (red), background from prompt J/ψ (blue), signal plus total background (black). Right is the CMS result: background is from inclusive $b \rightarrow J/\psi X$ (red), from $B^0 \rightarrow J/\psi K^{*0}$ (blue) and from combinatorial in signal events (green).

The expected yield for signal and background level, the resolution on the reconstructed B_s^0 mass and proper time are reported in Table 1. The expected numbers of reconstructed signal events per year are similar among the three experiments. For ATLAS and CMS the background is dominated by long-lived beauty decays, while for the LHCb it is dominated by prompt J/ψ events (B/S=1.8 for prompt and 0.2 for long-lived) due to the absence of a decay length cut. The resolution on invariant mass is similar among the experiments. The proper time resolution is a factor two better in LHCb than in ATLAS and CMS due to the better momentum resolution and to the vertex detector being closer to beam line ($\sim$ 1 cm in LHCb, $\sim$ 5 cm in ATLAS and CMS). Since the Φ_s measurement requires to resolve the fast B_s^0 oscillation the proper time resolution is an important parameter to achieve good sensitivity: the Φ_s sensitivity depends approximately on $\exp(-0.5 * \sigma(\tau)^2/\Delta m_s^2)$. The three angles used to decopuple the even and odd CP eigenstates are measured with a resolution of about 10 mrad in ATLAS, 15 mrad in CMS and 30 mrad in LHCb. It has been shown by LHCb that its contribution to the β_s sensitivity is negligible.

To extract Φ_s with good sensitivity a tagged analysis must be performed. ATLAS and LHCb have developed a tagging procedure. In ATLAS tagging based on the jet-charge and lepton charge from the other b of the event has been implemented. In LHCb several tagging algorithms are

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combined to get the best tagging power: lepton and kaon charge from the opposite b decay, charge of the kaon produced during the $\mathrm{B_s^0}$ fragmentation and charge of the vertex of the opposite b decay. The effective tagging power ($\varepsilon * (1-2w)^2$), where ε is the tagging efficiency while w is the wrong tag fraction) is reported in Table 1.

A sensitivity study has been performed by ATLAS and LHCb using "toy" Monte Carlo. Event samples are generated according to the theoretical distribution and an unbinned maximum likelihood fit is performed. Whenever possible the characteristics of the generated samples (resolution, efficiency, purity, acceptance) are taken from the studies with fully-simulated events. ATLAS used 100 toys, in addition to β_s the fitted parameters were the average width Γ_s, the width difference $\Delta\Gamma_s$, plus some parameters of three helicity amplitudes of the decay. The strong phase of the helicity amplitudes and the wrong tagging fraction have been treated as fixed parameters. The resolution $\sigma(2\beta_\mathrm{s})$ with $10fb^{-1}$ of integrated luminosity is 0.08. LHCb used 250 toys and in addition to the ATLAS fitted parameters also the strong phase of the helicity amplitudes and the wrong tagging fraction were allowed to vary in the fit. The $\sigma(2\beta_\mathrm{s})$ with $2fb^{-1}$ of integrated luminosity is 0.03. A study of the systematic uncertainties was done in LHCb showing that $\sigma(2\beta_\mathrm{s})$ was very weakly influenced by the prompt and long-lived background fraction while it is influenced significantly by the wrong tag fraction and proper time resolution. LHCb is developing a procedure to control the resolution, acceptance and wrong tag fraction from the data itself. The proper time and angular acceptances can be controlled using the $\mathrm{B^0 \rightarrow J/\psi K^{*0}}$ sample for which a common selection with the signal sample has been developed: the expected number of reconstructed events is 650,000 in $2fb^{-1}$. The opposite side wrong tag fraction can be controlled via the sample of $\mathrm{B^0 \rightarrow J/\psi K^{*0}}$ and $\mathrm{B^+ \rightarrow J/\psi K^+}$ while the same side wrong tag fraction can be extracted using the $\mathrm{B_s^0 \rightarrow D_s^- \pi^+}$.

In addition to the golden mode LHCb studied the β_s sensitivity achievable using other decay modes ($\mathrm{J/\psi\eta}$, $\mathrm{J/\psi\eta'}$, $\eta_c\phi$ and D_sD_s). The expected yield of these modes are a factor 10-20 smaller that the yield of $\mathrm{B_s^0 \rightarrow J/\psi(\mu\mu)\phi(KK)}$ but they are CP eigenstates so no angular analysis is required. The expected sensitivity from all these CP-eigenstates modes on $\sigma(2\beta_\mathrm{s})$ was found to be 0.046 with $2fb^{-1}$ of integrated luminosity.

4. Conclusions

The Monte Carlo studies by ATLAS, CMS and LHCb have shown good potential for a precise measurement of the $\mathrm{B_s^0 \rightarrow J/\psi\phi}$ CP violating phase. The number of reconstructed events is about 100,000 in one year for each experiment, while the sensitivity to the phase is about 0.03 in LHCb and 0.08 in ATLAS.

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