MEASUREMENT OF CP VIOLATION PHASE IN B_s^0 MIXING FROM (PSEUDO)SCALAR–VECTOR DECAYS IN LHCb EXPERIMENT. EXPECTED RESULTS FROM MONTE CARLO STUDY*

Katarzyna Senderowska

Faculty of Physics and Applied Computer Science
AGH University of Science and Technology
al. Mickiewicza 30, 30-059 Cracow, Poland

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CP symmetry violation in B_s^0–$\overline{B_s^0}$ mixing can be measured in B_s^0 decays to vector–(pseudo)scalar final state. Example of such decay is the $B_s^0 \to \chi_{c0}\phi$ which has never been observed so far. The CP symmetry breaking phase of B_s^0–$\overline{B_s^0}$ mixing, β_s, can be directly extracted from the CP asymmetry observable since the final state is the CP eigenstate. This measurement can complement the one coming from the analysis of the $B_s^0 \to J/\psi\phi$ decay. $B_s^0 \to J/\psi\phi$ decay is expected to provide the best sensitivity for the β_s but the angular distribution analysis is needed to disentangle the admixture of different CP eigenstates of the vector–vector final state. In this paper the CP violation in B_s^0 mesons decays is briefly introduced, the status of current state of β_s measurement is presented and finally the analysis of the $B_s^0 \to \chi_{c0}\phi$, as a case study of B_s^0 decay to vector–(pseudo)scalar decay in LHCb experiment, is described.

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1. CP violation in B_s^0 meson decays

1.1. Introduction

In the Standard Model, CP violation is described in terms of the Cabibbo–Kobayashi–Maskawa (CKM) matrix which elements are related to the probabilities of the transitions between three quark families. Among several ways to parametrize CKM matrix, the most widespread is Volfenstein parametrization, where matrix parameters depend on three real mixing

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angles and one complex phase. This complex phase is the only source of CP violation in the Standard Model (SM). The CKM is a 3×3 unitary matrix what implies six orthogonality conditions that can be represented as triangles in the complex plane. Within the SM framework, the CP violating phase in the $B_s^0 \to \chi_{c0}\phi$ decay, as well as other B_s^0 decays to CP eigenstates, is expected to be $\phi_s \approx -2\beta_s$, where $\beta_s = \arg(\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*})$ being the smallest angle of the triangle which corresponds to the unitarity condition $V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$.

CP violation in B_s^0 decays to the vector–(pseudo)scalar emerges due to interference between amplitudes of the two B_s^0 decay processes: a direct decay and the oscillation B_s^0–$\overline{B_s^0}$ followed by the decay into the same final state. All these decays proceed via $\bar{b} \to \bar{c}c\bar{s}$ quark-level transitions. The quark diagram for the $B_s^0 \to \chi_{c0}\phi$ is shown in Fig. 1. With a very good approximation the decay amplitude depends on a single CKM amplitude ($V_{cs}V_{cb}^*$), which is known with small theoretical uncertainty. The decay amplitude is a sum of tree level and QCD penguin amplitudes. The penguin contribution is suppressed and therefore can be neglected.

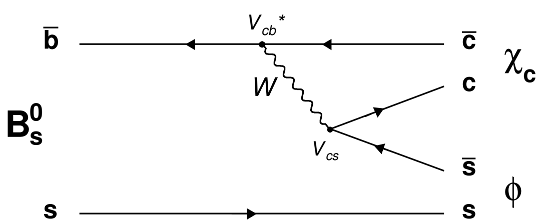

Fig. 1. Feynmann diagram for $B_s^0 \to \chi_{c0}\phi$ decay.

The ϕ_s phase can be accessed from CP asymmetry measurement according to the formula below

$$\begin{aligned} A_{\mathrm{CP}}(t) &= \frac{\Gamma\left(B_s^0(t) \to f\right) - \Gamma\left(\overline{B_s^0}(t) \to f\right)}{\Gamma\left(B_s^0(t) \to f\right) + \Gamma\left(\overline{B_s^0}(t) \to f\right)} \\ &= \frac{-\sin(\phi_s)\sin(\Delta m_s t)}{\cosh(\frac{\Delta\Gamma_s t}{2}) - \cos(\phi_s)\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)} \,. \end{aligned} \tag{1}$$

The best sensitivity to ϕ_s measurement is expected to come from the $B_s^0 \to J/\psi\phi$ decay [1]. Its final state is a mixture of CP eigenstates and therefore an angular analysis is needed to separate different CP contributions.

In the case of decays such as the $B_s^0 \to \chi_{c0}\phi$, where the final state consists of one vector and one (pseudo)scalar with well defined CP eigenvalues the measurement can be directly performed. There are other decays which can be analysed in the similar manner: the $B_s^0 \to J/\psi\eta$ [2], the $B_s^0 \to J/\psi\eta'$ [3], the $B_s^0 \to J/\psi f^0$ [4], and the $B_s^0 \to \eta_c\phi$ [5]. The ϕ_s measurements performed in all these channels could be a valuable cross-check of the basic one coming from $B_s^0 \to J/\psi\phi$ analysis. Also, all these results could be combined together to improve the overall sensitivity.

The ϕ_s phase is believed to be a sensitive probe of New Physics. Its value is not only very small within the SM, but also determined with a relatively small theoretical uncertainty ($\phi_s = 0.0360^{+0.0020}_{-0.0016}$ rad). The new postulated particles could contribute to the $B_s^0 - \overline{B_s^0}$ box diagram and significantly modify the SM prediction.

1.2. Current state of ϕ_s measurement and LHCb prospects

CP violation in neutral B_s^0 mesons sector has not yet been measured with a sufficient precision. The results from Tevatron experiments reported during 2010 summer conferences (ICHEP 2010, FPCP2010) suggest huge values of ϕ_s phase, however the statistical significance is at the level of 1σ only.

The expected statistical uncertainty on ϕ_s measurement coming from the analysis of the $B_s^0 \to J/\psi\phi$ decay at LHCb was estimated using Toy Monte Carlo experiments under the assumption of centre-of mass energy of 7 TeV and $b - \bar{b}$ cross-section of 292 μb. With $1\,\mathrm{fb}^{-1}$ of the collected data the statistical uncertainty on ϕ_s measurement is expected to be 0.07.

2. The $B_s^0 \to \chi_{c0}\phi$ event selection in LHCb experiment

2.1. The $B_s^0 \to \chi_{c0}\phi$ decay reconstruction

The topology of the $B_s^0 \to \chi_{c0}\phi$ decay is illustrated in Fig. 2. Due to short lifetimes of ϕ and χ_{c0} particles, all final products of the decay form a common secondary vertex (SV). Each χ_{c0} candidate is combined using four charged pions, while ϕ candidate is reconstructed via K^+K^- mode.

The $B_s^0 \to \chi_{c0}\phi$ branching fraction has not been measured yet. The estimation can be made using similar decay of the $B_d^0 \to \chi_{c0}K^{*0}$. Taking into account corrections for $s \to d$ quark replacement, the BR($B_s^0 \to \chi_{c0}\phi$) is expected to be 1.19×10^{-4}. Thus, the visible branching fraction of the full decay chain amounts to 1.85×10^{-6} and the total number of the $B_s^0 \to \chi_{c0}\phi$ events produced after one nominal year of data taking ($2\,\mathrm{fb}^{-1}$ of integrated luminosity) is expected to be about 336.8 thousand.

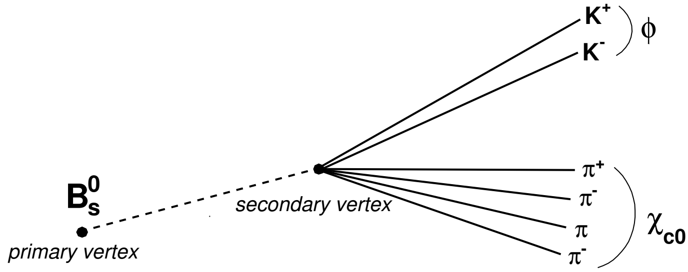

Fig. 2. The $B_s^0 \to \chi_{c0}\phi$ decay topology.

The study has been based on the data samples produced by the standard LHCb simulation and reconstruction software. The signal sample corresponding to the $B_s^0 \to \chi_{c0}\phi$ events and the background sample containing pure b–$\bar{b}$ inclusive events have been used to tune the selection criteria.

2.2. Event selection

The event selection explores the properties of B_s^0 mesons and its decay products. The relatively long lifetime results in a detectable flight distance of the order of a centimetre and the significant impact parameter of decay products[1]. The high mass results in larger transverse momentum of the B_s^0 decay products compared to the average for the tracks coming from the pp interactions. These properties are suitable to remove large amount of combinatorial background of particles originating from light quark production. Moreover, there are powerful topological properties allowing background suppression. Making use of the quality of the SV fit expressed in terms of χ^2 value per degree of freedom (NDF) and compatibility of the B_s^0 momentum vector with respect to a vector pointing from PV to SV one can further reject background events. One should not forget about the strength of particle identification of the LHCb apparatus.

The idea of the selection is to use a two step procedure. In a first step a cut based selection is applied to enrich the background in a signal like events. In the second step the multivariate analysis method based on Fisher discriminant is used to optimize signal-to-background ratio.

Cut based selection was performed using the standard LHCb analysis software. For the optimization of the selection criteria, the TMVA [6] toolkit based on ROOT [7] framework was used.

[1] Impact parameter is defined as closest distance of the particle trajectory to the primary vertex (PV).

2.2.1. Cut-based selection

The selection starts with the choice of the final B_s^0 decay products: kaons and pions. The quality of each track is assured by demanding the χ^2/NDF of a Kalman fit of a track to be less than 6. A minimum transverse momentum (p_T) of pions and kaons of 350 MeV/c is required to cut out tracks with large uncertainty of its impact parameter. In order to provide a particle identification, the cuts on difference of the logarithm of likelihoods (DLL), estimated using the system of RICH detectors, between the kaon, pion and proton hypotheses were applied. Many tracks arising from the primary vertex can be eliminated by a cut on impact parameter significance with respect to the primary vertex. Kaons and pions passing the above criteria are used to reconstruct ϕ and χ_{c0} candidates.

The ϕ mesons are formed of two charged tracks of opposite signs identified as kaons. Kaons should originate from a common space point thus a vertex fit is applied and a maximum value of χ^2_SV/NDF is required to be less than 25. p_T of ϕ candidate has to exceed 800 MeV/c and the invariant mass of the kaon pair is required to be in a mass window of ± 50 MeV/c^2 around the nominal ϕ mass.

The χ_{c0} candidate is combined from charged pion tracks. In order to reduce the large number of all possible combinations of four pions in the event, the two intermediate dummy ρ^0 resonances (consisting of $\pi^+\pi^-$) are formed. Next, the two are used to create a χ_{c0}. Four pion tracks are required to fit a common vertex with a χ^2 smaller than 16. p_T of χ_{c0} candidate should be greater than 1000 MeV/c. The invariant mass should be within 100 MeV/c^2 around the nominal χ_{c0} mass.

Finally, a B_s^0 candidate is reconstructed. The secondary vertex consisting of all final tracks is formed and its χ^2_SV/NDF is checked to be less than 16. Two pointing cuts are applied: χ^2_IP cut and direction angle cut. The χ^2_IP of B_s^0 has to be less than 9. The cut on the cosine of the angle between the B_s^0 momentum vector and a vector pointing from PV to SV is applied and set to $\cos(\theta_\mathrm{pointing}) > 0.99982$. The invariant mass of B_s^0 candidate is demanded to be ± 500 MeV/c^2 around the nominal B_s^0 mass and its p_T to exceed 1500 MeV/c.

The overall signal efficiency is 20.19% while the background retention for b–$\bar{b}$ inclusive events is 0.02%.

2.2.2. Optimization of the selection criteria with multivariate analysis

The set of eight variables with the highest discriminating power and small relative correlation coefficients are used to construct a Fisher discriminant:

— $\mathrm{DLL}_{K\pi}$ of K^- from ϕ ,

— χ^2_{IP} of ϕ ,

— χ^2_{IP} of χ_{c0} ,

— p_{T} of B^0_s ,

— $\chi^2_{\mathrm{SV}}/\mathrm{NDF}$ of B^0_s ,

— $\cos(\theta_{\mathrm{pointing}})$ of B^0_s ,

— χ^2_{FD} of B^0_s .

The signal and background events that passed the cut based selection were split randomly into two samples for training and testing of the multivariate selection. The multivariate algorithm explores the multidimensional cut space — corresponding to the chosen variables — in order to optimize the significance $\frac{\mathrm{S}}{\sqrt{\mathrm{S+B}}}$, where S and B are signal and background yields respectively. The distribution of Fisher discriminant for the signal and background events is shown in Fig. 3.

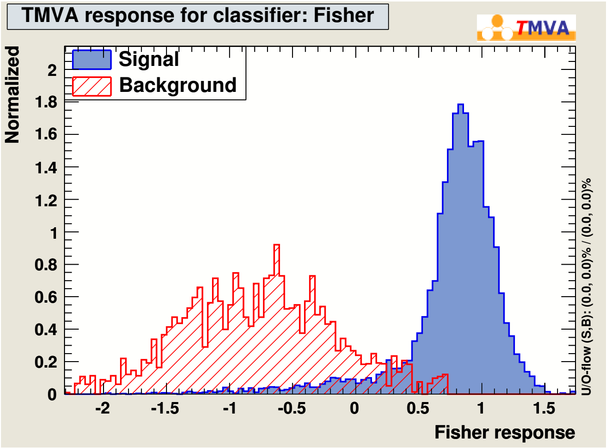

Fig. 3. The distributions of Fisher discriminant for training samples.

After TMVA optimization, the mass windows were tightened to the intervals listed below:

— ϕ mass window: 1019.5 MeV$/c^2$ ± 20 MeV$/c^2$,

— χ_{c0} mass window: 3415 MeV$/c^2$ ± 70 MeV$/c^2$,

— B^0_s mass window: 5366.3 MeV$/c^2$ ± 50 MeV$/c^2$.

As a result all background events from the b–$\bar{b}$ inclusive sample were rejected.

2.2.3. Selection efficiency and expected event yield

The total signal efficiency can be defined as a number of reconstructed, selected and triggered signal events, divided by the total number of generated signal events. It can be decomposed into factors related to geometrical acceptance, trigger efficiency and selection cuts. The detailed results are presented in Table I.

TABLE I

Different contributions to the selection efficiency for the $B_s^0 \to \chi_{c0}\phi$ decay.

$\epsilon_{\mathrm{geometrical}}$	$\epsilon_{\mathrm{selection/geometrical}}$	$\epsilon_{\mathrm{trigger/selection}}$	$\epsilon_{\mathrm{total}}$
33.11%	16.10%	19.68%	1.05%

The total efficiency for the $B_s^0 \to \chi_{c0}\phi$ is 1.05%. The corresponding retention of b–$\bar{b}$ inclusive events is less than 4.41×10^{-8} at 90% C.L. Only the upper limit can be determined since no background events were selected. The expected number of the $B_s^0 \to \chi_{c0}\phi$ decays observed by LHCb experiment in one year of data taking at the nominal LHCb luminosity is equal to 3538, while the corresponding signal to background ratio after selection and before any triggers is $\frac{S}{B} > 1.5$ at 90% C.L.

2.3. The properties of selected signal

- Invariant mass resolutions

  The invariant mass distributions for the reconstructed χ_{c0}, ϕ and B_s^0 mesons in a wide B_s^0 mass window are illustrated in Fig. 4. All the spectra are fitted with a double Gaussian. The approximated mean values of the mass distributions and mass resolutions, taken from core Gaussian parameters, are as follows:

  — ϕ mass distribution: $\mu_\phi = 1019$ MeV$/c^2$, $\sigma_\phi = 2.31$ MeV$/c^2$,
  — χ_{c0} mass distribution: $\mu_{\chi_{c0}} = 3414$ MeV$/c^2$, $\sigma_{\chi_{c0}} = 12.07$ MeV$/c^2$,
  — B_s^0 mass distribution: $\mu_{B_s^0} = 5366$ MeV$/c^2$, $\sigma_{B_s^0} = 11.88$ MeV$/c^2$.

  The average values are compatible with the generated particle masses.

- Vertex resolution

  The B decay vertex resolutions are determined using the residual distributions of the generated and reconstructed vertex coordinates. The results for x, y and z coordinate respectively are presented in Fig. 5. Each histogram is fitted with a double Gaussian. The core resolutions denoted as σ_1 in Fig. 5 are dominant.

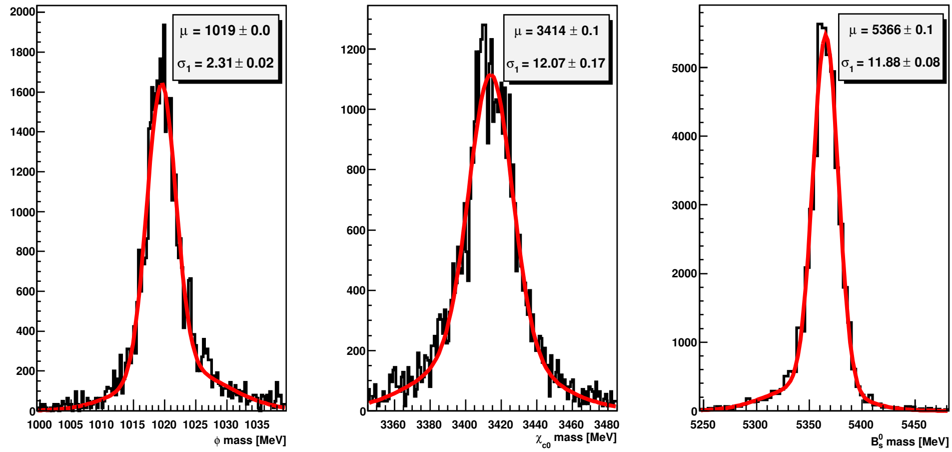

Fig. 4. Invariant mass distributions for selected ϕ , χ_{c0} and B_s^0 mesons.

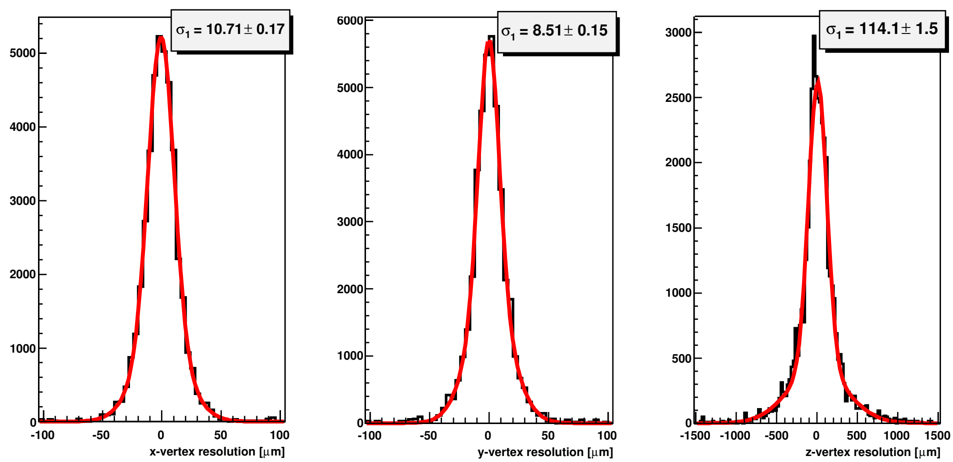

Fig. 5. B_s^0 decay vertex resolution in x, y and z coordinated for the selected events.

- Proper time resolution

  The distributions of the proper time and the resolution (difference between measured and generated values) are shown in Fig. 6. Good proper time precision of about 29 ps is predicted.

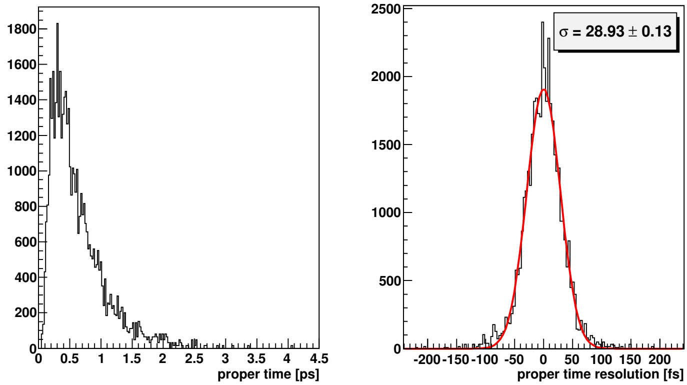

Fig. 6. B_s^0 proper time distribution and proper time resolution for the selected events.

3. Summary

The decays of B_s^0 into the vector–(pseudo)scalar system may complement the flagship measurement of CP breaking phase of B_s^0–$\overline{B_s^0}$ oscillations for the B_s^0 decays into $J/\psi\phi$. A Monte Carlo based study of one example of such decays, the $B_s^0 \to \chi_{c0}\phi$, has been presented. The number of observed decays in LHCb data collected in one year ($2\,\mathrm{fb}^{-1}$ of integrated luminosity) is expected to be about 3.5 thousand at the S/B ratio better than 1.5 at 90% C.L.

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