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Study of the $B_s^0 \rightarrow J/\psi\phi \rightarrow \mu^+\mu^-K^+K^-$ channel with CMS

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Abstract

The prospects for the study of the $B_s^0 \rightarrow J/\psi\phi \rightarrow \mu^+\mu^-K^+K^-$ decay channel with the CMS detector at LHC are presented. Emphasis is given to the strategies of the High Level Trigger and offline selection of signal events. Selection efficiencies and signal event yields are estimated.

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1 The $B_s^0 \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$ decay channel

The $B_s^0 \rightarrow J/\psi \phi$ decay channel followed by $J/\psi \rightarrow \mu^+ \mu^-$ and $\phi \rightarrow K^+ K^-$ decays is an example of the B_s^0 decay to CP eigenstates. This channel is usually referred to as a *gold-plated* transition, because it allows the measurement of the Wolfenstein parameter η , fixing the height of the unitarity triangle. The measurements of the widths of the B_s^0 heavy and light mass eigenstates Γ_s^H and Γ_s^L as well as of the difference of their widths Δm_s , which is responsible for the $B_s^0 - \bar{B}_s^0$ oscillation is also possible with this channel.

1.1 Measurement of physical observables

The experimental ways of measuring the physical observables can be subdivided in two groups, depending whether the flavour tag of the decayed B_s^0 meson is available. The widths of the heavy and light mass eigenstates Γ_s^H and Γ_s^L as well as the Wolfenstein parameter η can be measured from the angular distributions of the final state components [1], using both tagged or untagged data samples. The extraction of observables can be performed using the Likelihood fit or the method of angular moments [2].

The measurement of the mass difference Δm_s is only possible with the tagged data sample. This observable can be extracted from the angular distributions of the final state components.

1.2 Angular analysis

The final state of the $B_s^0 \rightarrow J/\psi \phi$ decay is an admixture of the CP eigenstates. Since J/ψ and ϕ are massive vector mesons ($J^{PC} = 1^{--}$) with the same (even) CP parity, their zero-angular-momentum spectrum consists of states with orbital angular momenta $L = 0, 1, 2$ (even, odd and even respectively). The angular dependencies of CP-odd and CP-even components are different and can be separated through their angular distributions.

The angular distributions of the final state components can be described with only three physical angles. Typically the angular analysis is performed in the helicity frame shown in Figure 1 [3]. In the rest frame of the B_s^0 the direction of flight of the ϕ meson defines the z axis. The x -axis is defined as any arbitrary fixed direction in the plane normal to the z -axis. The y -axis is then fixed uniquely via $y = z \times x$. The right-handed coordinate system is assumed.

The angles $(\Theta_{l^+}, \chi_{l^+})$ describe the direction of the μ^+ in the rest frame of the J/ψ . The angles $(\Theta_{K^+}, \chi_{K^+})$ give the direction of K^+ in the ϕ rest frame. The third physical angle χ is defined as $\chi = \chi_{l^+} - \chi_{K^+}$.

Figure 1: Definition of the physical angles describing the kinematics of the final state in the $B_s^0 \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$ decay.

In general, the angular distributions of the final state components have the following form:

$$\frac{d^4 \Gamma}{d \cos \Theta_{l^+} d \cos \Theta_{K^+} d \chi dt} \sim \sum_{i=1}^6 b_i(t) g_i(\Theta_{l^+}, \Theta_{K^+}, \chi), \quad (1)$$

where $g_i(\Theta_{l+}, \Theta_{K+}, \chi)$ are the angular distributions, depending on the kinematics of the final state and $b_i(t)$ are the time evolutions of physical observables. The quantities $b_i(t)$ are the bilinear combination of transversity amplitudes corresponding to the linear polarizations of the final state $A_0(t)$, $A_{\parallel}(t)$ and $A_{\perp}(t)$ [1]:

$$\begin{aligned} & |A_0(t)|^2 \quad |A_{\parallel}(t)|^2 \quad |A_{\perp}(t)|^2 \\ \Im(A_0^*(t)A_{\perp}(t)) \quad \Re(A_0^*(t)A_{\parallel}(t)) \quad \Im(A_{\parallel}^*(t)A_{\perp}(t)) \end{aligned}$$

These bilinear combinations (treated hereafter as physical observables) are functions of Γ_s^H , Γ_s^L , Δm , strong phases and the Wolfenstein parameter η . The extraction of these parameters from the angular distributions of the final state components can be performed by the means of Likelihood fit, or using the method of angular moments [1].

In the latter method the observables $b_i(t)$ can be extracted from the angular distribution (1), using a set of weight functions $w_i(\Theta_{l+}, \Theta_{K+}, \chi)$, such that:

$$\begin{aligned} & \int d \cos \Theta_{l+} d \cos \Theta_{K+} d \chi w_i(\Theta_{l+}, \Theta_{K+}, \chi) \\ & \cdot g_j(\Theta_{l+}, \Theta_{K+}, \chi) \sim \delta_{ij}. \end{aligned}$$

Each of the physical observables $b_i(t)$ can be then extracted from (1):

$$\begin{aligned} b_i(t) = & \int d \cos \Theta_{l+} d \cos \Theta_{K+} d \chi \\ & \frac{d^4 \Gamma}{d \cos \Theta_{l+} d \cos \Theta_{K+} d \chi dt} w_i(\Theta_{l+}, \Theta_{K+}, \chi) \end{aligned} \quad (2)$$

2 The CMS experiment at LHC

The LHC is a proton-proton collider with a center-of-mass energy of $\sqrt{s} = 14$ TeV and a bunch crossing time of 25 ns. At this energy the cross section of the $b\bar{b}$ pairs production is expected to be around $500 \mu\text{b}$. The total $B_s^0 \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$ cross section is estimated to be around $97 \cdot 10^3$ fb. For the first three years, an initial phase with an instantaneous luminosity in the order of $2 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ is foreseen. The production of approximately 10^{13} $b\bar{b}$ events per year is expected.

The CMS is one of two general purpose detectors which will be operated at the LHC. The tracker [4] is located, together with the electromagnetic and hadronic calorimeters, inside a solenoid magnet generating a 4 T field. The tracker is composed of a pixel detector followed by a Silicon Strip Tracker (SST). The muons system is located in the return yoke, and the first muon chamber is located immediately after the solenoid to extend the lever arm of muon tracks to improve the p_t measurement.

The CMS has a two-step trigger and data acquisition system, designed to inspect the detector output at full bunch crossing frequency and to store the selected events at the maximal allowed storage rate of 100 Hz. The first level trigger (L1) is a hardware trigger designed to reduce the rate of accepted events to less than 100 kHz. It is based on the identification of muons, electrons, photons, jets and missing transverse energy. The second level trigger or HLT (High Level Trigger) is a software trigger, running on a dedicated farm of commercial processors and designed to reduce the maximum L1 output rate to the final output rate of 100 Hz. The bandwidth of 100 Hz should then be shared between all the channels of interest.

3 Event triggering

The High Level Trigger selection of $B_s^0 \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$ events is based on the L1 hardware dimuon trigger. This trigger reconstructs up to four muon candidates with a threshold on the transverse momentum of $p_t^\mu > 3$ GeV. It uses the Resistive Plate Chambers, Drift Tubes and Cathode Strip Chambers of the muon detector to identify and measure muon tracks with a pattern comparator logic. The transverse momentum, pseudorapidity and azimuthal angle of trajectories are assigned via look-up tables. From the list of candidates provided by L1, the muon pairs with opposite charge are selected for further analysis.

In the next step, tracks, corresponding to L1 muon candidates, are reconstructed in the tracker and J/ψ -meson candidates are selected. The procedure starts with the reconstruction of the primary interaction vertex candidates (PV) of the current event.

The search for the primary vertex is based on the information provided by the Pixel detector. Only the longitudinal (z) coordinate (estimated with resolution of approximately $70 \mu\text{m}$) is reconstructed. The transverse coordinates of the primary vertex are constrained by the size of the beam spot to be around $15 \mu\text{m}$ in both x and y directions.

The three most probable PV candidates are retained for further analysis. These candidates are then used to define the center of the tracking regions for the reconstruction of muon trajectories, and the directions of the regions are defined by the momentum of L1 muon candidates.

The same track reconstruction algorithm used in the full offline reconstruction, the Combinatorial Kalman Filter [5], is used in the HLT, by stopping reconstruction once enough information is available (partial reconstruction). Indeed, the resolutions on the track parameters reach an asymptotic value after using only the first five to six hits starting at the pixel detector. The muon mass is assigned to the candidate tracks and an invariant mass of the muon pairs with opposite charge is then reconstructed (Figure 2(left)). Only muon pairs for which the invariant mass is

Figure 2: Distributions of residuals of the reconstructed mass of the J/ψ (left), ϕ (middle) and B_s^0 (right) mesons.

within 100 MeV of the mean of the expected mass distribution of reconstructed J/ψ and for which $p_t(\mu) > 2 \text{ GeV}$ are retained for further analysis.

In order to suppress the combinatorial background, the decay vertices of these candidates are reconstructed with a Kalman filter. Candidates with the total χ^2 of the fit less than 10 and significance of the transverse decay length above 3 are retained.

For the selected events, the ϕ and the B_s^0 candidates are reconstructed. Since no particle identification is available, all tracks with $p_t > 0.5 \text{ GeV}$ are partially reconstructed in a narrow cone around the J/ψ . A kaon mass is assigned to all reconstructed trajectories and the invariant mass of the opposite charge pairs is calculated (Figure. 2 (middle)). Only candidates for which the invariant mass is within 10 MeV of the mean of the expected mass distribution of the ϕ are retained.

Finally the invariant mass of the four-track ($\mu^+\mu^-K^+K^-$) candidates is reconstructed (Figure 2(right)). While calculating the invariant mass of the B_s^0 , the invariant mass of the muon pair is assumed to be the J/ψ mass. Only candidates for which the invariant mass is within 60 MeV of the mean of the expected mass distribution of B_s^0 are retained.

The combinatorial background is suppressed applying the above χ^2 and transverse decay length requirements on the four-track $\mu^+\mu^-K^+K^-$ vertex. The overall signal efficiency of the High Level Trigger is about 8.7%¹⁾. A yield of some 252'000 signal events is expected with 30 fb^{-1} . This corresponds to two to three years run in the low luminosity mode ($2 \cdot 10^{33} \text{ cm}^{-1}\text{s}^{-1}$).

4 Offline selection

The offline selection strategy is based on the muon reconstruction using the information from the tracker and muon chambers. The reconstruction of muon trajectories can be performed using two different algorithms. The first one, called *L3 Muon Reconstructor*, uses the Level-1 muon information and combines it with the tracker. This algorithm reconstructs muon pairs with the transverse momentum above 3 GeV. The second algorithm, is called

¹⁾ All the selection efficiencies quoted hereafter are calculated with respect to the generator level cuts: $p_t(\mu^\pm) > 2 \text{ GeV}$, $p_t(\text{hadrons}) > 0.5 \text{ GeV}$, $\eta(\mu, K) < 2.5$, where η is the pseudorapidity of the particle.

Global Muon Reconstructor. It uses hit multiplets in muon chambers to reconstruct trajectory candidates and combines them with the output of the tracker. The latter algorithm has a more flexible p_t threshold than the former.

Muon candidates reconstructed with both strategies are added together and the resulting set is cleaned of mutually-exclusive trajectories, using 50% of shared hits as a rejection criterion. The muon mass is assigned to all candidate tracks and an invariant mass of the muon pairs with opposite charge is then reconstructed (Figure 3(left)). Candidates, for which the invariant mass is within 120 MeV of the mean of the expected mass distribution of the

Figure 3: Distributions of the reconstructed mass of the J/ψ (left) and B_s^0 (right) candidates.

J/ψ and $p_t(\mu) > 2$ GeV are retained.

Next, all tracks in a narrow cone around the direction of the J/ψ candidates are reconstructed. These tracks are assigned a kaon mass and the invariant mass of the opposite charge combinations is calculated. Only candidates for which the invariant mass is within 12 MeV of the mean of the expected mass distribution of the ϕ and $p_t > 0.5$ GeV are retained.

Finally, B_s^0 candidates are reconstructed by fitting the four-track ($\mu^+\mu^-K^+K^-$) combinations to their common vertex. The invariant mass of the muon pairs is constrained to be equal to the mass of the J/ψ and the following requirement on the probability of the χ^2 of the fit is applied: $\text{Pr}(\chi^2) > 5 \cdot 10^{-4}$. The distribution of the invariant mass of the B_s^0 candidates thus reconstructed is presented in Figure 3 (right). Only candidates, for which the invariant mass is within 67 MeV of the mean of the expected mass distribution of the B_s^0 are retained for further analysis.

The combined efficiency of the High Level Trigger and offline selection for signal events is expected to be around 5%. A yield of some 145'000 signal events is expected with 30 fb^{-1} . The background level is expected to be less than 10%, dominated by $B_d^0 \rightarrow J/\psi K^*$ and $b \rightarrow J/\psi X$ decays.

5 Conclusion

Due to the expected large number of the signal events and relatively low background, the CMS experiment provides an excellent opportunity to improve the present knowledge of the B_s^0 system. The expectations for the relative error on $\Delta\Gamma$ made with the likelihood fit of time dependent angular distributions of the final state particles are presented in Figure 4. For the 30 fb^{-1} of accumulated data, a relative uncertainty on $\Delta\Gamma$ is expected to be approximately 16% for $\Delta\Gamma/\Gamma = 0.15$.

References

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Figure 4: Expected relative error on $\Delta\Gamma$ as a function accumulated statistics (left) and as a function of relative error on the proper lifetime (right).

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