B physics at CMS

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Abstract. The Compact Muon Solenoid (CMS) is a multi-purpose detector which will be operated at the Large Hadron Collider (LHC) at CERN. Several benchmark processes representative of exclusive B physics analyses have been studied to assess the capability of CMS to identify, select and reconstruct the decay of the b-flavoured hadrons. These present a significant challenge due to their relatively low momentum and high background.

1. Introduction
CMS is one of the two general purpose experiments which will be operated at the LHC to explore the full range of physics that can be accessed at LHC energies and it is well suited to conduct B physics studies. B physics studies will be experimentally easiest at the initial low luminosity, where pile-up effects are small and vertex detectors very close to the beam pipe are expected to survive for several years. Much of the B physics program will therefore be performed during the first few years of LHC operation, although searches for rare decays can probably also be performed at higher luminosities.

2. The trigger
The CMS experiment has a two-level trigger architecture. The Level-1 trigger is a hardware-based trigger with custom-designed electronics [1], and the High Level trigger (HLT) [2] is a software trigger implemented in standard commercial computers using similar reconstruction algorithms as the offline reconstruction. Most of the B physics program will be based on the Level-1 dimuon trigger, with some use of the single muon trigger. The dimuon trigger requires two muons above threshold, and a requirement that these muons have opposite charge can be used. At low luminosity it is foreseen that it will be possible to use an identical threshold of 3 GeV/c on the transverse momentum of each muon. In the HLT, b candidates are identified by doing a partial reconstruction of the decay products in the tracker in restricted regions of interest and imposing invariant mass and vertex requirements. An invariant mass requirement can be used to identify J/ψ decays and the decay length can be used to distinguish prompt J/ψ from those originating from the decay of a b hadron.

3. The decay B_{s}^{0} \rightarrow J/ψ φ
The decay B_{s} \rightarrow J/ψ φ \rightarrow μ^{+}μ^{-}K^{+}K^{-} [3] is of particular interest, since it allows to study many properties of the B_{s}^{0} system, in particular the difference between the widths and the masses of the two weak eigenstates, B_{s}^{H} and B_{s}^{L}.
The $B^0_s$ decay chain is selected at Level-1 by the dimuon trigger. In the present study, the HLT selection has been separated in two steps. In the first, $J/\psi$ candidates with a displaced vertex are identified. Tracks are reconstructed in the tracking regions defined by the Level-1 muon candidates, and all track pairs of opposite charge for which the invariant mass is within 150 MeV/$c^2$ of the world-average $J/\psi$ mass are retained. The resolution on the invariant mass of the $J/\psi$ is 51 MeV/$c^2$. To remove the prompt $J/\psi$ background, the two muon candidates are then fitted to a common decay vertex and the significance of the transverse decay length is required to be above 3. With this selection, the accept rate is reduced to approximately 15 Hz, with 80% of the $J/\psi$ originating in the decay of $b$ hadrons. In the second step, a further reduction is achieved by searching for the decay of a $\phi$ meson to achieve a full reconstruction of the $B^0_s$ decay. The resolution on the invariant mass of the $B^0_s$ meson is then found to be 65 MeV/$c^2$. By fitting the 4 tracks to a common decay vertex and requiring the significance of the transverse decay length to be above 3, the total rate is well below 0.1 Hz, and a yield of approximately 456,000 signal events can be expected within 30 fb$^{-1}$ of data.

In the offline selection, candidates are reconstructed by combining two muons of opposite charge with two further tracks of opposite charge. As CMS does not possess a particle identification system suitable for this measurement, all measured tracks have to be considered as possible kaon candidates, which adds a substantial combinatorial background. A kinematic fit is then made, where the four tracks are constrained to come from a common vertex and the invariant mass of the two muons is constrained to be equal to the mass of the $J/\psi$. With this fit, the resolution of the invariant mass of the $B^0_s$ is of 14 MeV/$c^2$. The invariant mass of the two kaons is required to be within 8 MeV/$c^2$ of the world-average mass of the $\phi$ meson. With this selection, a yield of approximately 327,000 signal events can be expected within 30 fb$^{-1}$ of data, with a background of 39,000 events. These do not include a requirement on the four-track invariant mass of the candidates, since the sidebands could be used later in the analysis. However, by choosing a window of $\pm$36 MeV/$c^2$ around the $B^0_s$ mass, the number of background events is reduced by a further 59%, while reducing the number of signal candidates by 2.9%.

To measure the width difference $\Delta \Gamma_s$, an unbinned maximum likelihood fit on the observed time evolution of the angular distribution is performed [4], taking into account the distortion of the distribution by the detector acceptance, trigger efficiency and the different selection criteria. A sample of 1.3 fb$^{-1}$ is considered here, which allows to have a realistic ratio of misidentified $B^0 \to J/\psi K^{*0}$ and signal events. The results of the fit is given in Table 1, where both the statistical and expected systematic uncertainties are quoted. A first measurement of the difference of the width of the weak eigenstates could thus be made with an uncertainty of 20%. On a larger sample of 10 fb$^{-1}$, the statistical uncertainty would be reduced to 0.011.

### Table 1. Results of the maximum likelihood fit for an integrated luminosity of 1.3 fb$^{-1}$.

| Parameter | Input value | Result | Stat. error | Sys. error | Total error | Rel. error |
|-----------|-------------|--------|-------------|------------|-------------|------------|
| $|A_0(0)|^2$ | 0.57 | 0.5823 | 0.0061 | 0.0152 | 0.0163 | 2.8% |
| $|A_{||}(0)|^2$ | 0.217 | 0.2130 | 0.0077 | 0.0063 | 0.0099 | 4.6% |
| $|A_{\perp}(0)|^2$ | 0.213 | 0.2047 | 0.0065 | 0.0099 | 0.0118 | 5.8% |
| $\bar{\Gamma}_s$ | 0.712 ps$^{-1}$ | 0.7060 ps$^{-1}$ | 0.0080 ps$^{-1}$ | 0.0227 ps$^{-1}$ | 0.0240 ps$^{-1}$ | 3.4% |
| $\Delta \Gamma_s$ | 0.142 ps$^{-1}$ | 0.1437 ps$^{-1}$ | 0.0255 ps$^{-1}$ | 0.0113 ps$^{-1}$ | 0.0279 ps$^{-1}$ | 19% |
| $\Delta \Gamma/\Gamma$ | 0.2 | 0.2036 | 0.0374 | 0.0173 | 0.0412 | 20% |
4. Searches for the decay $B_s^0 \to \mu^+\mu^-$

In the Standard Model of electroweak interactions, the decay $B_s^0 \to \mu^+\mu^-$ is forbidden for tree level processes and can proceed at low rate through higher order flavor-changing neutral current processes, with a branching fraction predicted to be $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.42 \pm 0.54) \times 10^{-9}$[5]. Higher branching fractions would indicate contributions from physics beyond the Standard Model, and several models predict large increases of the decay rate.

The HLT selection is similar to the first step of the $B_s^0 \to J/\psi \phi$ HLT. Tracks are reconstructed in the tracking regions defined by the Level-1 muon candidates, and invariant mass and transverse decay length requirements are imposed. With this selection, 150 $B_s^0 \to \mu^+\mu^-$ events can be expected in a dataset of 10 fb$^{-1}$, with an accept rate for the background below 1.7 Hz.

For the offline selection, all muon candidates are reconstructed in the tracker, and track pairs of opposite charge for which the invariant mass is within 100 MeV/$c^2$ of the world-average $B_s^0$ mass are retained. Furthermore, the angular separation between the two tracks $(\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2})$ is required to be between 0.3 and 1.2. When fitting the distribution of the mass of the reconstructed $B_s^0$ candidate with two Gaussians, the core has a standard deviation of 32 GeV/$c^2$ and the tails a standard deviation of 60 GeV/$c^2$. The isolation of the $B_s^0$ candidate, defined as $I = p_T(B_s)/[p_T(B_s) + \sum p_T]$, is required to be greater than 0.85. The sum is the scalar sum of the transverse momenta of all the tracks, except the two muons, within a cone of $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} \leq 1$ around the momentum vector of the $B_s^0$ candidate. The two muon candidates are then fitted to a common decay vertex and the transverse decay length significance is required to be above 18. Finally, the cosine of the angle between the momentum vector of the $B_s^0$ candidate and its flightpath is required to be larger than 0.995.

Given the low branching fraction expected for the signal, the study is necessarily limited by the sizes of the samples of the expected backgrounds. The backgrounds studied are muon pairs from independent semi-leptonic $B$ decays, misidentified hadrons from either non-resonant QCD background or hadronic $B$ decays, and other non-resonant rare $B$ decays. Since no background events remain after applying all the cuts, the isolation and vertex quality cuts are factorized to estimate the efficiency of the selection on the background. In a dataset of 10 fb$^{-1}$, $6.1 \pm 0.6$ (stat) $\pm 1.5$ (syst) signal events and $14.1^{+22.3}_{-14.1}$ background events are expected to be selected, and the 90% C.L. upper limit on the branching fraction, including the statistical and systematic uncertainties, would be $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.4 \times 10^{-8}$.

5. Study of the $B_c$ meson

Finally, the $B_c$ meson can be studied in its decay $B_c \to J/\psi \pi$. With similar selection requirements as for the $B_s^0 \to J/\psi \phi$ analysis, a sample of 120 $B_c$ candidates can be expected in a dataset of 10 fb$^{-1}$. This would allow to measure the mass of the $B_c$ meson with a statistical uncertainty of 2 MeV/$c^2$ and a systematic uncertainty of 14.9 MeV/$c^2$ and the lifetime with a statistical uncertainty of 13.1 $\mu$m and a systematic uncertainty of 3.0 $\mu$m.

6. Conclusion

The CMS experiment is well suited for $B$ physics, due to the large $b$ production cross section and high luminosity. It has a powerful muon system which is invaluable in the Level-1 Trigger and a robust and versatile tracker and track reconstruction algorithms, with sufficient redundancy to operate in a very challenging environment. These have also show a good performance in the High Level Trigger already. This will allow to collect a large number of $b$-flavoured hadrons, which can be reconstructed with high precision.

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