Study of rare B-decays with the CMS experiment

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1 Introduction

Heavy flavor physics is the study of high energy hadronic interactions among quark flavors. The production of heavy flavor plays an important role in testing Quantum Chromodynamics (QCD) calculations. Here we discuss the production and decay of B-mesons containing b quarks. The physics properties show up through different experimental observables. This enables us to search for physics phenomena beyond Standard Model (SM) by comparing the experimental result with theory prediction. Any significant deviation of the measured observable from the SM prediction would hint the presence of New Physics (NP). In this paper, the results from CMS [1] experiment using the data collected at 7/8/13 TeV center-of-mass energy are presented.

2 Dimuon spectrum with 13 TeV data

After long shut down of the LHC accelerator, the pp collisions started again around middle of 2015. The center-of-mass energy was 13 TeV. The CMS, ATLAS and LHCb experiments already produced many results using these 13 TeV data. CMS could reproduce the dimuon mass spectrum, which was seen earlier 7 TeV and 8 TeV data samples. Figure 1 shows the dimuon invariant mass with 13.1 fb$^{-1}$ of data collected at 13 TeV center-of-mass energy. The colors correspond to dedicated dimuon triggers with low $p_T$ thresholds, in specific mass windows, while the light gray continuous distribution represents events collected with a dimuon trigger with high $p_T$ threshold. One can clearly see different resonances, such as $\phi$, $J/\psi$, $\psi'$, $\omega$ in the distribution.

3 $B^+$ production cross section with 13 TeV data

The measurements of b-hadron production cross sections provide essential information to understand QCD. Such studies have been carried out by several collider experiments. The recent studies of b-hadron production at the higher energies provided by the Run 2 of the LHC provide a new important test of theoretical calculations. Here we discuss the
Figure 1: The dimuon mass distribution collected with various dimuon triggers, during the first 13 TeV data taking in 2015. Different resonances are clearly visible in the distribution.

Figure 2: The plots show (left) the invariant mass distribution of the $B^+ \rightarrow J/\psi K^+$ candidates, integrated in the phase space region $10 < p_T^B < 17$ GeV with $|y^B| < 1.45$ and $17 < p_T^B < 100$ GeV with $|y^B| < 2.1$, (middle) in the region $17 < p_T^B < 24$ GeV with $|y^B| < 2.1$, and (right) $10 < p_T^B < 100$ GeV with $0.4 < |y^B| < 0.6$.

measurement of the $B^+$ differential cross section in pp collisions at 13 TeV, as function of transverse momentum ($p_T^B$) and rapidity ($y^B$). This result is based on a data sample collected by the CMS experiment, corresponding to an integrated luminosity of 49.4 pb$^{-1}$,
and uses the channel \( pp \rightarrow B^+ X \rightarrow J/\psi K^+ X \), selecting events where the \( J/\psi \) decays into a pair of muons. The muons are required to have at least one reconstructed segment in the muon stations that matches the extrapolated position of a track reconstructed in the silicon tracker, to satisfy \( p_T > 4.2 \text{ GeV} \) and \(|\eta| < 2.1\), and to have good quality in the fit to a track. The \( J/\psi \) candidates have an invariant mass within \( \pm 150 \text{ MeV} \) of the nominal \( J/\psi \) mass. Each \( J/\psi \) candidate must have \( p_T > 8 \text{ GeV} \) and the \( \chi^2 \) probability of the dimuon vertex fit is required to be larger than 10\%. Both muons must be either within \(|\eta| < 1.6\) or one of the muons must have \( p_T > 11 \text{ GeV} \). Candidate \( B^+ \) mesons are reconstructed by combining a \( J/\psi \) candidate with a charged track of \( p_T > 1 \text{ GeV} \). The track is assumed to be a kaon and the track-fit \( \chi^2 \) must be less than five times the number of degrees of freedom. To reduce the peaking and non-peaking backgrounds, many kinematic and topological cuts have been applied. Finally, the signal yield is extracted with an extended unbinned maximum likelihood fit to the invariant mass distribution of the \( B^+ \) candidates, in each of the \( p_T^B \) and \(|y^B|\) bins. Figure 2 shows the invariant mass distribution of all the \( B^+ \) candidates included in the analysis together with the corresponding fit result \([2]\).

The differential cross sections as a function of \( p_T^B \), integrated within \(|y^B| < 1.45\) or for \(|y^B| < 2.1\), and as a function of \( y^B \), with \( p_T^B > 10 \text{ GeV} \) or \( p_T^B > 17 \text{ GeV} \), are shown in Fig. 3 (left and right panels, respectively), where they are compared to FONLL (shaded boxes) and PYTHIA (dashed lines) calculations. The 7 TeV measurements are also displayed, for completeness. The bottom panels display the ratios of measured cross sections to those predicted by FONLL; the PYTHIA/FONLL ratios are also shown, as dashed lines. The measured values show a reasonable agreement, both in terms of shape and of normalization, with FONNL calculations and with the results obtained with PYTHIA event generator.

Figure 3: The differential cross section for \( \frac{d\sigma}{dp_T^B} \) (left) and \( \frac{d\sigma}{dy^B} \) (right). See the text for details.
4 Study of $B^0_s \rightarrow \mu^+\mu^-$

In the standard model (SM) of particle physics, tree-level diagrams do not contribute to flavor-changing neutral-current (FCNC) decays. However, FCNC decays may proceed through higher-order loop diagrams, and this opens up the possibility for contributions from non-SM particles. In the SM, the rare FCNC decays $B_d \rightarrow \mu^+\mu^-$ have small branching fractions of $\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$, corresponding to the decay-time integrated branching fraction, and $\mathcal{B}(B_d \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$. Charge conjugation is implied throughout this Letter. Several extensions of the SM, such as supersymmetric models with non-universal Higgs boson masses, specific models containing leptoquarks, and the minimal supersymmetric standard model with large $\tan\beta$, predict enhancements to the branching fractions for these rare decays. The decay rates can also be suppressed for specific choices of model parameters. Over the past 30 years, significant progress in sensitivity has been made, with exclusion limits on the branching fractions improving by five orders of magnitude.

The search for the $B \rightarrow \mu^+\mu^-$ signal, where $B$ denotes $B^0_s$ or $B^0$, is performed by CMS in the dimuon invariant mass regions around the $B^0_s$ and $B^0$ masses. To avoid possible biases, the signal region $5.20 < m_{\mu\mu} < 5.45$ GeV was kept blind until all selection criteria were established. The $B \rightarrow \mu^+\mu^-$ candidates are constructed from two oppositely charged muons with $p_T > 4$ GeV and be consistent in direction and $p_T$ with the muons that triggered the event. A boosted decision tree (BDT) constructed within the TMVA framework is trained to further separate genuine muons from those arising from misidentified charged hadrons. The variables used in the BDT can be divided into four classes: basic kinematic quantities, silicon-tracker fit information, combined silicon and muon track fit information, and muon detector information. The BDT is trained on MC simulation samples of $B$-meson decays to kaons and muons. Compared to the “tight” muons, the BDT working point used to select muons for this analysis reduces the hadron-to-muon mis-identification probability by 50% while retaining 90% of true muons. The probability to misidentify a charged hadron as a muon because of decay in flight or detector punch-through is measured in data from samples of well-identified pions, kaons, and protons. This probability ranges from $(0.5–1.3) \times 10^{-3}$, $(0.8–2.2) \times 10^{-3}$, and $(0.4–1.5) \times 10^{-3}$, for pions, kaons, and protons, respectively, depending on whether the particle is in the barrel or end cap, the running period, and the momentum. Each of these probabilities is ascribed an uncertainty of 50%, based on differences between data and MC simulation.

An unbinned maximum-likelihood fit to the $m_{\mu\mu}$ distribution is used to extract the signal and background yields. Events in the signal window can result from genuine signal, combinatorial background, background from semileptonic b-hadron decays, and the peaking background. The probability density functions (PDFs) for the signal, semileptonic, and peaking backgrounds are obtained from fits to MC simulation. The dimuon mass distributions for the four channels (barrel and endcap in 7 and 8 TeV data) are fitted simultaneously. No significant excess is observed for $B_d \rightarrow \mu^+\mu^-$ and an upper limit of $\mathcal{B}(B_d \rightarrow \mu^+\mu^-) < 1.1 \times 10^{-9}$ is established at 95% CL. For $B^0_s \rightarrow \mu^+\mu^-$, an
excess of events with a significance of 4.3 standard deviations is observed, and a branching fraction of \( B(B_s^0 \rightarrow \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9} \) is determined, in agreement with the standard model expectations [3]. The CMS and LHCb reported the combined result for \( B \rightarrow \mu^+\mu^- \) to exploit fully the statistical power of the data and to account for the main correlations between them [4]. The results are shown in Figure 4. The ATLAS experiment performed similar search for \( B_s^0 \rightarrow \mu^+\mu^- \) and \( B_d \rightarrow \mu^+\mu^- \) decays using pp collision data corresponding to an integrated luminosity of 25 fb\(^{-1}\), collected at 7 and 8 TeV in the full LHC Run 1 data-taking period. This analysis supersedes the previous result based on 2011 data and exploits improved analysis techniques in addition to the larger dataset. For \( B^0 \) an upper limit \( B(B_d \rightarrow \mu^+\mu^-) < 4.2 \times 10^{-10} \) is placed at the 95% confidence level, based on the CL\(_{s}\) method. The limit is compatible with the predictions based on the SM and with the combined result of the CMS and LHCb experiments. For \( B_s^0 \) the result is \( B(B_s^0 \rightarrow \mu^+\mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9} \), where the errors include both the statistical and systematic uncertainties [5]. An upper limit \( B(B_s^0 \rightarrow \mu^+\mu^-) < 3.0 \times 10^{-9} \) at 95% CL is placed, lower than the SM prediction, and in better agreement with the measurement of CMS and LHCb.

5 Angular analysis of the decay \( B^0 \rightarrow K^{*0}\mu^+\mu^- \)

The FCNC decay, \( B^0 \rightarrow K^{*0}\mu^+\mu^- \), provides many opportunities to search for new phenomena beyond SM. In addition to the branching fraction, other properties of the decay...
can be measured, including the forward-backward asymmetry of the muons, $A_{FB}$, and the longitudinal polarization fraction of the $K^{*0}$, $F_L$. To better understand this decay, these quantities can be measured as a function of the dimuon invariant mass squared ($q^2$). The offline reconstruction requires two muons of opposite charge and two oppositely charged hadrons. The muons are required to match those that triggered the event readout, and also to pass general muon identification requirements. The hadron tracks are required to fail the muon identification criteria, have $p_T > 0.8$ GeV, and have an extrapolated distance of closest approach to the beamspot in the transverse plane greater than twice the sum in quadrature of the distance uncertainty and the beamspot transverse size. The two hadrons with invariant mass within 90 MeV of the nominal $K^{*0}$ mass are selected for further consideration. The $B^0$ candidates are obtained by fitting the four charged tracks to a common vertex, and applying a vertex constraint to improve the resolution of the track parameters. Other offline selection requirement are also applied to select the $B^0$ signal candidates from data. For each $q^2$ bin, the observables of interest are extracted from an unbinned extended maximum-likelihood fit to three variables: the $B^0$ invariant mass and the two angular variables $\theta_K$ and $\theta_l$. The results are consistent with standard model predictions and previous measurements [6]. They are shown in Figure 5.

![Figure 5](image-url)

Figure 5: Measured values of $F_L$ and $A_{FB}$ versus $q^2$ for $B^0 \to K^{*0} \mu^+ \mu^-$. The statistical uncertainty is shown by the inner vertical bars, while the outer vertical bars give the total uncertainty. The horizontal bars show the bin widths. The vertical shaded regions correspond to the $J/\psi$ and $\psi'$ resonances. The other shaded regions show the two SM predictions after rate averaging across the $q^2$ bins to provide a direct comparison to the data. Controlled theoretical predictions are not available near the $J/\psi$ and $\psi'$ resonances.

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