EPJ Web of Conferences **81**, 01022 (2014)
DOI: 10.1051/epjconf/20148101022
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# Heavy Meson Production and Spectroscopy at CMS

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**Abstract.**
This proceeding summarizes the search for new physics via a rare heavy meson decays– $B_s \to \mu^+\mu^-$, the observation of an unexpected structure in the $J/\psi\phi$ spectrum through exclusive $B^+ \to J/\psi\phi K^+$ decays, as well as the measurement of $X(3872)$ production cross section using the pp collision data collected at the CMS experiment.

## 1 Introduction

Large and high quality proton-proton collision data have been collected by both ATLAS and CMS experiments at the world's highest center-of-mass energy. The CMS collaboration collected an integrated luminosity of 6 fb$^{-1}$ at $\sqrt{s}$ = 7 GeV and 24 fb$^{-1}$ at $\sqrt{s}$ = 8 GeV of pp collision data at the LHC. Using these datasets the ATLAS and CMS collaborations have discovered the Higgs boson which completes the standard model of particle physics. The data also provide a great opportunity to perform other measurements and search for physics beyond the standard model. This report summarizes a search for new physics via the rare process $B_s \to \mu^+\mu^-$, the observation of an unexpected structure in the $J/\psi\phi$ invariant mass spectrum through exclusive $B^+ \to J/\psi\phi K^+$ decays, as well as the measurement of $X(3872)$ production cross section.

## 2 Measurement of $B_s \to \mu^+\mu^-$

The standard model predicts very small branching fractions for the $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays because they are mediated by effective flavor-changing neutral currents and are helicity suppressed. In this report, we present the search for these decays based on the pp collision data collected by the CMS experiment during 2011 ($\sqrt{s}$ =7 TeV) and 2012 ($\sqrt{s}$ = 8 TeV) at the LHC. Compared to the previous CMS publication [1], the result from this analysis is enhanced by improved muon identification, improved and expanded selection variables, as well as the use of Multi-Variate Analysis (MVA) technique. The invariant mass of the dimuon pair in the range of 5.2 < m < 5.45 GeV was kept blind until the final event selections were determined. The details of this analysis can be found in Ref. [2].

The signal candidates are characterized by opposite sign dimuon pairs originating from a well-reconstructed secondary B vertex. A boosted decision tree (BDT) constructed within the TMVA

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Article available at http://www.epj-conferences.org or http://dx.doi.org/10.1051/epjconf/20148101022

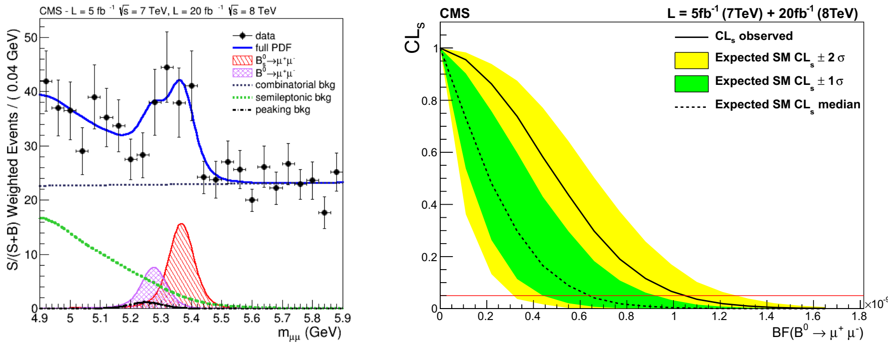


**Figure 1.** (Left) The weighted dimuon mass from all categorized BDT bins. The events in each category are weighted with S/(S + B), where S (B) is the number of signal (background) candidates determined at the $B_s^0$ peak position in each bin. (Right) Expected and observed $\mathrm{CL_S}$ for $\mathcal{B}(\mathrm{B}^0 \to \mu^+\mu^-)$ as a function of the assumed branching fraction [2].

framework [3] is trained to separate the real muons from the charged hadrons. The background components are estimated from the data sidebands (the combinatorial background) and from simulated events (other B decays that appear in the signal region). To separate signal events from background events, the output discriminant $b$ from BDT is used in two ways: (1) 1D-BDT method is used for the determination of the upper limit on $\mathcal{B}(B^0 \to \mu^+\mu^-)$; (2) categorized-BDT method is used to extract $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$. In the categorized-BDT method, the discriminant $b$ is used to define 12 event categories with different signal-to-background ratios and the dimuon invariant mass distributions from 12 categories are fitted simultaneously to extract the final result. The S/(S+B) weighted dimuon mass from all categorized BDT bins is shown in Fig. 1 (left), where S and B is the number of signal and background events determined at the $B_s^0$ peak position in each bin.

The $B_s^0(B^0) \to \mu^+\mu^-$ branching fraction is measured as

$$\mathcal{B}(B_s^0(B^0) \to \mu^+\mu^-) = \frac{N_s}{N_{obs}^{B^+}} \frac{f_u}{f_s} \frac{\epsilon_{tot}^{B^+}}{\epsilon_{tot}} \mathcal{B}(B^+) \tag{1}$$

where $N_s$ is the number of reconstructed $B_s^0(B^0) \to \mu^+\mu^-$ decays, $N_{obs}^{B^+}$ is the number of the reconstructed $B^+ \to J/\psi K^+$ decays, $\frac{\epsilon_{tot}^{B^+}}{\epsilon_{tot}}$ is total $B^+$ efficiency divided by the total signal efficiency, $\mathcal{B}(B^+) = (6.0 \pm 0.2) \times 10^{-5}$ is the branching fraction for $B^+ \to J/\psi K^+ \to \mu^+\mu^- K^+$ [4], and $\frac{f_u}{f_s} = 0.256 \pm 0.020$ (needed for $\mathcal{B}(B_s^0)$ only) is the ratio of the $B^+$ and $B_s^0$ fragmentation fractions measured by the LHCb experiment [5].

An excess of $B_s^0 \to \mu^+\mu^-$ decays is observed above the background expectation with a significance above 4.2 standard deviations. The measured decay-time integrated branching fraction is $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$. The uncertainty includes both statistical and systematical components. No significant excess is observed for $B^0 \to \mu^+\mu^-$ and an upper limit $\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.1 \times 10^{-9}$ at 95% confidence level is determined with the $\mathrm{CL}_s$ approach. The right plot in Fig. 1 shows the observed and expected $\mathrm{CL}_s$ versus the assumed $\mathcal{B}(B^0 \to \mu^+\mu^-)$.

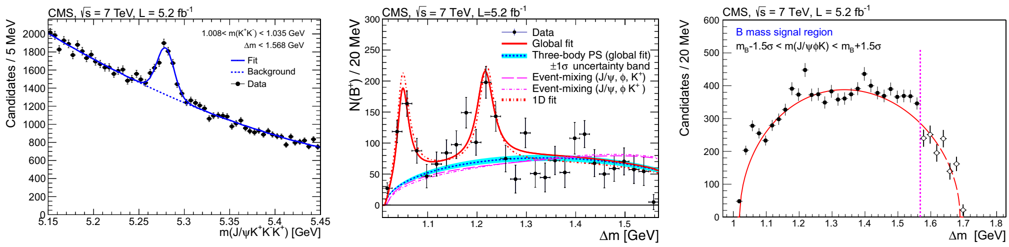


**Figure 2.** The $J/\psi\phi K^{\pm}$ mass distribution with the standard event selection (left). The number of $J/\psi\phi K^{\pm}$ candidates as a function of $\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$(middle). The $\Delta m$ spectrum, including non-B candidates after subtracting $B_s^0$ contribution, within $\pm 1.5\sigma$ of the B nominal mass. The dashed vertical line indicates the boundary of the region eliminated from the analysis (right region). The data in the left region are represented by black markers. The entries in the right region are subtracted of the $B_s^0$ background component and are represented by open circles. The red curve is a three-body phase-space distribution, normalized in the left region (solid) after subtracting the yields from the corresponding two structures, and extrapolated to the right region (dashed line)[9].

## 3 Observation of the structures in the $J/\psi\phi$ mass spectrum

In 2009, the CDF collaboration has reported the evidence for a narrow structure near the $J/\psi\phi$ threshold in the exclusive $B^{\pm} \to J/\psi\phi K^{\pm}$ decay [6, 7]. In 2011, the LHCb collaboration performed a similar search using the LHC data but did not confirm the CDF result [8]. In 2012, CMS performed an independent study using 5.2 fb$^{-1}$ of pp collision data collected at 7 TeV [9]. The $B^{\pm}$ candidates were reconstructed in the decay channel $B^{\pm} \to J/\psi\phi K^{\pm}$, where $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$. The $J/\psi$ candidates were reconstructed by combining two opposite sign muons which were selected by the HLT dimuon trigger. The $B$ signal was reconstructed by combining the selected muon candidates with three charged tracks consistent with originating from the displaced $J/\psi$ vertex. The total charge of the three tracks was required to be $\pm 1$ and they were assigned with the kaon mass. Each $\mu^+\mu^-K^+K^-K^{\pm}$ combination was refitted imposing the five tracks from a common vertex and constraining the $\mu^+\mu^-$ invariant mass to the nominal $J/\psi$ mass. There are two $K^+K^-$ combination out of three charged kaons and only the one with lower mass was considered as a $\phi$ candidate. The reconstructed mass of the $K^+K^-$ pair was required to satisfy 1.008 <m($K^+K^-$)< 1.035 GeV. These selection requirements were designed to maximize the signal yield and decided before $J/\psi\phi$ mass spectrum was examined. The obtained $J/\psi K^+K^-K^{\pm}$ mass spectrum for the selected $B$ candidates for a mass difference $\Delta m < 1.568$ GeV, where $\Delta m$ is defined as $m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$, is shown in Fig. 2 (left). The $\Delta m$ requirement is applied to eliminate the $B_s^0 \to \psi(2S)\phi \to J/\psi\pi^+\pi^-\phi$ background at higher values of $\Delta m$. The CMS experiment reconstructed 2480±160(stat) B$^+$ candidates in this channel, which is the world's largest sample to date.

To search for possible structures in the $J/\psi\phi$ mass spectrum, the dataset was separated into 20 MeV $\Delta m$ bins from 1.008 to 1.568 GeV and the $J/\psi\phi K^{\pm}$ mass distributions were fitted to extract the $B$ signal for each $\Delta m$ bin. A double Gaussian function was used for the signal and a $2^{nd}$ order Chebychev polynomial was used for the background. The mean values of the two Gaussian signals were fixed to the nominal $B$ mass, the width of the Gaussian and the relative fractions were fixed to the values obtained from the signal simulation. The obtained $\Delta m$ spectrum is shown in Fig. 2 (middle).

The mass and the widths values of the observed two structures were extracted by fitting the $J/\psi\phi K^{\pm}$ invariant-mass distribution in each $\Delta m$ interval with a global unbinned maximum-likelihood (UML) fit. In each fit interval, the $B^{\pm}$ mass was fixed to its nominal value and the mass resolution was fixed to the value obtained from simulation. The combinatorial background in each fit was modeled as a second-degree polynomial. The signal yields for the two structures are 310 ± 70 (stat) and 418 ± 170 (stat). The mass and the width values of the two structures are $\Delta m_1$ = 1051.3 ± 2.4 (stat) MeV and $\Gamma_1 = 28^{+15}_{-11}$ (stat) MeV; and $\Delta m_2$= 1217.1 ± 5.3 (stat) MeV and $\Gamma_2 = 38^{+30}_{-11}$ (stat) MeV. The projection of the UML fit assuming two structures onto the $J/\psi\phi$ mass spectrum is represented by the solid line in Fig.2 (middle).

Various tests to check the robustness of the observed structures were performed and no indication of possible bias was found. The event selection, $\Delta m$ binning, the background and signal models, the relative efficiency used to correct the $\Delta m$ spectrum were varied. A different background subtraction method (sPlot technique) was used. Tighter $B$ selection was imposed to reduce the combinatorial background where the background is reduced by a factor of ten while keeping the 40% of the $B$ signal. The $\Delta m$ distribution for the events that were eliminated ($\Delta m > 1.568$ GeV) to remove the effect of $B_s^0$ background was also studied. This study was performed to make sure the eliminated events do not cause reflections in the low $\Delta m$ region. The study shows that, the $\Delta m$ distribution of events with $\Delta m >$1.568 GeV is consistent with the prediction from the three-body phase-space hypothesis for the non-resonant background after subtraction of the $B_s^0$ component. The $\Delta m$ spectrum, including non-B candidates after subtracting $B_s^0$ contribution, is shown in Fig.2 (right).

Adding the $J/\psi$ mass [10] to the extracted $\Delta m$ values, the mass and width of the $Y(4140)$ are measured to be $m_1 = 4148.0 \pm 2.4(\text{stat}) \pm 6.3(\text{syst})$ MeV and $\Gamma_1 = 28^{+15}_{-11}(\text{stat}) \pm 19(\text{syst})$ MeV. The measured mass and width values are consistent with the Y(4140) values reported by the CDF experiment [6]. The recent measurement performed by D0 confirms the $Y(4140)$ with a significance of $3.1\sigma$ [11]. In 2014, the Babar experiment reported a search of $Y(4140)$ from the exclusive B decays, no significant signal was found. The upper limit is consistent with the branching fraction of $Y(4140)$ reported by the CDF experiment [12].

## 4 Production of X(3872)

The spectroscopy of exotic mesons program performed at the CMS experiment includes the measurement of X(3872) production via decays to $J/\psi\pi^+\pi^-$. Using 4.8 fb$^{-1}$ data collected in 2011 at $\sqrt{s}$ = 7 TeV, the CMS collaboration studied the production of X(3872) by measuring its cross sections times branching fraction, its prompt and non-prompt fraction, as well as the invariant mass spectrum of $\pi^+\pi^-$ from X(3872) [13].

The ratio of the cross section times the $J/\psi\pi^+\pi^-$ branching fraction is measured from the X(3872) and $\psi(2S)$ signal events correcting for the acceptance and the efficiency, which are estimated from simulation:

$$R = \frac{\sigma(pp \to X(3872) + \text{anyt.}) \cdot \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\sigma(pp \to \psi(2S) + \text{anyt.}) \cdot \mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} = \frac{N_{X(3872)} \cdot A_{\psi(2S)} \cdot \epsilon_{\psi(2S)}}{N_{\psi(2S)} \cdot A_{X(3872)} \cdot \epsilon_{X(3872)}} \tag{2}$$

The signal events for X(3872) and $\psi(2S)$ are separately extracted from the unbinned maximum-likelihood fits to the $J/\psi\pi^+\pi^-$ invariant mass spectrum. The signal for the $\psi(2S)$ resonance is modeled with two Gaussian functions with a common mean, and with a single Gaussian function for the X(3872). The non-resonant background is modeled as a second-order Chebyshev polynomial. Acceptance and efficiencies are estimated from simulation, assuming that both X(3872) and $\psi(2S)$ are unpolarized and $J^{PC}$ of X(3872) is $1^{++}$ as measured by the LHCb experiment [14]. The cross section times branching fraction ratio as a function of transverse momentum of the $J/\psi\pi^+\pi^-$ systems is shown in Fig. 3 (left) for the acceptance-corrected R. No significance dependence on the transverse momentum is observed.

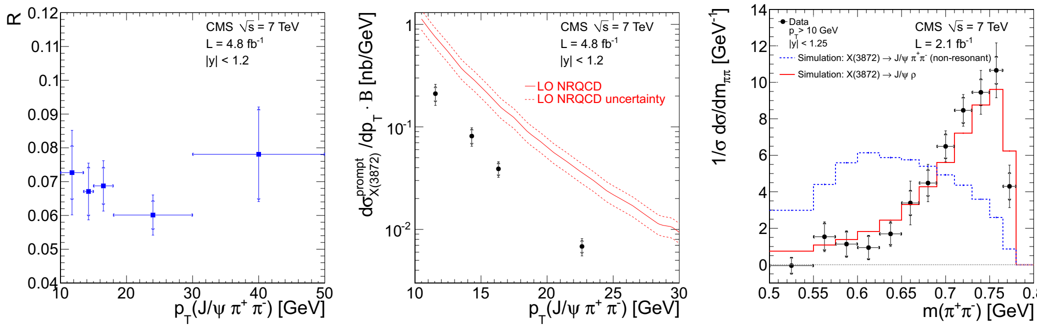


**Figure 3.** Ratios of the X(3872) and $\psi$(2S) cross sections times branching fractions with acceptance corrections for the muon and pion pairs, as a function of $p_T$ (Left). Prompt X(3872) production times branching fraction $\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$ as a function of $p_T$. The inner error bars indicate the statistical uncertainty and the outer error bars indicate the total uncertainty (Middle). The acceptance and efficiency corrected dipion invariant mass spectrum for X(3872) $\to J/\psi\pi^+\pi^-$ (Right). The distribution is normalized dividing by the total cross section for 0.5 <m($\pi^+\pi^-$)< 0.78 GeV [13].

The cross section times branching fraction for prompt X(3872) production is determined using the cross section ratio R, the non-prompt fraction, and CMS measurement of the prompt $\psi(2S)$ production [15]. The measurement is performed differentially, as a function of transverse momentum up to 30 GeV within the rapidity range |y|< 1.2. It is compared with predictions based on NRQCD factorization [16]. The predictions given in Ref. [16] are adapted to the phase space used in the CMS measurement. The comparison shows that although predictions describe the shape reasonably well, the predicted cross section is much larger than that in data. The CMS experiment measures the integrated prompt X(3872) cross section times branching fraction in the kinematical region 10<$p_T$<30 GeV and |y|< 1.2 as 1.06 ± 0.11(stat) ± 0.15(syst) nb. The NRQCD prediction for prompt X(3872) production is 4.01 ± 0.88 nb [16] which is well above the CMS measurement. This CMS measurement is further discussed in various theoretical articles [17–20].

The invariant mass distribution of $\pi^+\pi^-$ pair from X(3872) $\to J/\psi\pi^+\pi^-$ for the kinematical range 10<$p_T$<50 GeV and |y|< 1.25 (Fig. 3 right) is measured to further investigate the decay properties of the X(3872). The data are compared to signal simulations with and without intermediate $\rho^0$ in the $J/\psi\pi^+\pi^-$ decay. The study shows that the intermediate $\rho^0$ decay (X(3872) $\to J/\psi\rho^0 \to \mu^+\mu^-\pi^+\pi^-$) gives better description of the data.

Besides the results described above, the CMS experiment has also performed other studies of heavy meson production and spectroscopy. For instance, search for possible new bottomonium states decaying into $\Upsilon\pi^+\pi^-$ decays [21], the measurement of the $\chi_{b2}$ over $\chi_{b1}$ cross section ratio [22], the branching fraction of $B_c \to J/\psi\pi^+$ and $B_c \to J/\psi\pi^+\pi^+\pi^-$ decays [23] and the double $J/\psi$ production cross section [24]. The results are discussed in Ref. [25].

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