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Observation of Structures in the $J/\psi\phi$ Mass Spectrum at CMS

E. Asli Yetkin [1]

Physics Department, Mimar Sinan Fine Arts University, TURKEY

E-mail: eaa@cern.ch

Abstract. Observation of charmonium like new states since 2003, which do not fit into conventional quark model renewed the interest in exotic states. Many models like meson molecule, tetraquark, and quark-gluon hybrid are proposed to explain the observed charmonium spectroscopy. The observation of Y(3940)[1] near the $J/\psi\omega$ threshold motivated the searches for similar structures near $J/\psi\phi$ threshold. In this proceeding, we summarize the recent developments on the observation of a peaking structure in the $J/\psi\phi$ mass spectrum from $B^{\pm} \to J/\psi\phi K^{\pm}$ decay.

1. Introduction

In 2009, the CDF collaboration has reported an evidence for a narrow structure near the $J/\psi\phi$ threshold in the exclusive $B^{\pm} \to J/\psi\phi K^{\pm}$ decay and called it Y(4140)[2]. In 2011, they updated their results with a larger data set and observed Y(4140) with a significance greater than 5σ[3]. They also observed a second structure in the same mass spectrum, Y(4274), with a significance above 3σ. Y(4140) could be a good candidate for the exotic mesons since it contains both a $s\bar{s}$ and a $c\bar{c}$ pairs, has mass well beyond open charm pair and its width is relatively narrow. Potential explanations for the observed structures include a $D_s^{*+}D_s^{*-}$ molecule, an exotic charmonium hybrid, and a tetraquark state.

After LHC became operational the LHCb collaboration also searched for the Y(4140) structure in $B^{\pm} \to J/\psi\phi K^{\pm}$ decays using the LHC data and reported a result in conflict with CDF result[4]. In order to solve this puzzle, CMS performed an analysis using $5.2 fb^{-1}$ pp collision data collected at LHC at 7 TeV center of mass energy[6]. The $B^{\pm}$ candidates are reconstructed in the decay channel $B^{\pm} \to J/\psi\phi K^{\pm}$, where $J/\psi \to \mu^{+}\mu^{-}$ and $\phi \to K^{+}K^{-}$. Recently similar search is also reported by D0 collaboration[7]. In this proceeding, details of CMS analysis will be summarized and the results will be compared to the CDF, LHCb, and D0 measurements.

2. Reconstruction of B Signal

In CMS, reconstruction of the B signal starts at data collection level where the data sample is selected on the basis of the dimuon decay mode of J/ψ. The events containing J/ψ candidates are selected by the HLT dimuon trigger and the J/ψ candidates are used in the B reconstruction if the reconstructed dimuon invariant mass is within the 150 MeV of the J/ψ mass[5]. The

[1] On behalf of the CMS Collaboration

$B^{\pm} \to J/\psi\phi K^{\pm}$ candidates are reconstructed by combining additional three charged tracks (total charge of ±1) to the J/ψ vertex. Kaon mass is assigned to the three charged tracks. There are two K^+K^- combinations from the three charged kaon tracks, and the one with a lower invariant mass which satisfy $1.008 < m(K^+K^-) < 1.035$ is accepted as the ϕ candidate. The study of MC simulations of the $B^{\pm}$ decay and data show that the ϕ signal from the other combination is negligible.

The invariant-mass spectrum of the selected $J/\psi\phi K^{\pm}$ candidates is shown in the left plot of Fig.1 for a mass difference $\Delta m < 1.568$GeV where Δm defined as $m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$. This selection is applied to eliminate the $B_s^0 \to \psi(2S)\phi \to J/\psi\pi^+\pi^-\phi$ background at higher values of Δm.

The invariant-mass spectrum is fit with a Gaussian signal function and a second-degree polynomial background function. The returned mass of 5.2796 ± 0.0006 (stat.) GeV is consistent with the nominal value[5] and the extracted width value of 9.6 ± 0.7 (stat.) MeV agrees with MC prediction. With 2480 ± 160 (stat.) B yield the selected data set is the world's largest $B^{\pm} \to J/\psi\phi K^{\pm}$ sample up to date.

3. Observation of Peaks in the $J/\psi\phi$ Mass Spectrum

To search for possible structures in the $J/\psi\phi$ mass spectrum, the dataset is separated in to the 20 MeV-wide Δm intervals from 1.008 to 1.568 GeV and the $J/\psi\phi K^{\pm}$ mass distributions for each bin are fit to extract the B signal yield in that Δm interval. A double Gaussian function is used for the signal and a 2^{nd} degree polynomial for the combinatorial background. The mean values of the two Gaussian signals are fixed to the nominal B mass, the with of the Gaussians and the relative fractions are fixed to the values obtained from the signal simulation for each Δm bin. The obtained Δm spectrum is after correcting for relative efficiency is shown by black dot marker in Fig.2.

The mass and the widths values of the observed two structures are extracted by fitting the $J/\psi\phi K^{\pm}$ invariant-mass distribution in each Δm interval with a global unbinned maximum-likelihood (UML) fit. In each fit interval, the $B^{\pm}$ mass is fixed to its nominal value and the mass resolution is fixed to the value calculated from simulation. The combinatorial background in each fit is modeled as a second-degree polynomial. In the global fit, the $B^{\pm}$ yield is expressed

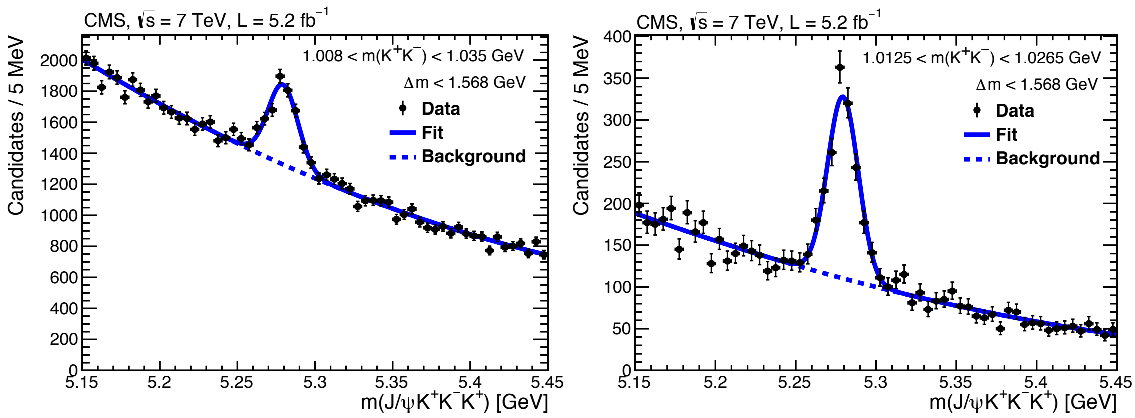

Figure 1. The $J/\psi\phi K^{\pm}$ mass distribution with the standard event selection (left) and the tighter requirements (right). The solid curves show the result of fitting these distributions to a Gaussian signal and a second-degree polynomial background while the dashed curves show the background contribution[6].

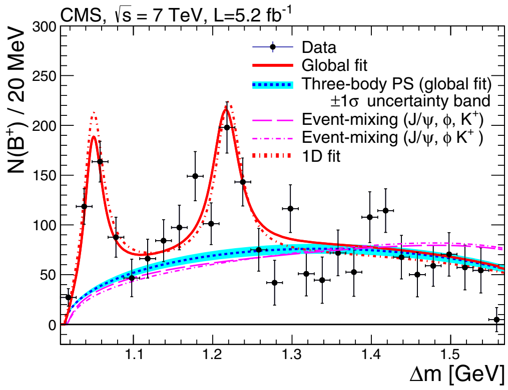

Figure 2. The number of $J/\psi\phi K^{\pm}$ candidates as a function of $\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$. The solid curve is the global unbinned maximum-likelihood fit of the data, and the dotted curve is the background contribution assuming three-body PS. The band is the $\pm1\sigma$ uncertainty range for the background obtained from the global fit. The dashed and dash-dotted curves are background curves obtained from two different event-mixing procedures, as described in the text, and normalized to the number of three-body PS background events. The short dashed curve is the 1D fit to the data[6].

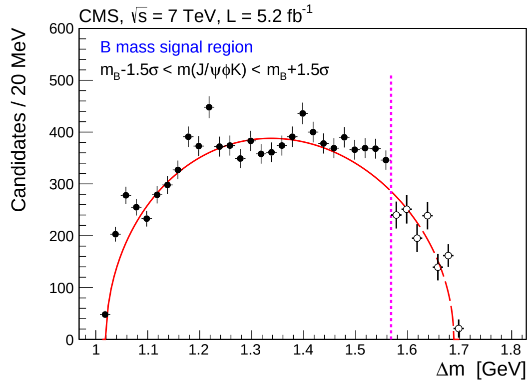

Figure 3. The Δm spectrum, including non-B candidates after subtracting B_s^0 contribution, within $\pm1.5\sigma$ of the B nominal mass. The dashed vertical line indicates the boundary of the region eliminated from the analysis (right region). The data in the left region are represented by black point markers. The entries in the right region are subtracted of the B_s^0 background component and are represented by open point markers. 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)[6].

as the product of the relative efficiency times the number of signal events from the two BWs and the nonresonant continuum events. The invariant $J/\psi\phi K^{\pm}$ mass distribution is fit for each Δm bin simultaneously by projecting the above product into each bin. The returned signal yields from the UML fit for each mass structures are 310 $\pm$ 70 (stat.) and 418 $\pm$ 170 (stat.). The mass and the width values of the first structure are Δm_1 = 1051.3 $\pm$ 2.4 (stat.) MeV, Γ_1 = 28^{+15}_{-11} (stat.) MeV and for the second structure are Δm_2= 1217.1 $\pm$ 5.3 (stat.) MeV, Γ_2 = 38^{+30}_{-11} (stat.) MeV. The projection of the UML fit assuming two structures onto the $J/\psi\phi$ mass spectrum is represented as the solid line in Fig.2. To check the robustness of the fitting procedure an alternative one-dimensional (1D) binned χ^2 fit is applied to the Δm spectrum. The signal and the background functions are not changed in the 1D fit. The result of the 1D fit, assuming two structures, is shown as the dashed line in Fig.2. The extracted mass, widths, and signal yields from the 1D fit are consistent with the values obtained from the global fit.

The Δm background shape is also investigated with event-mixing technique where Δm spectrum is reconstructed from data (a) by combining J/ψ, ϕ, and $K^{\pm}$ coming from different events (b) by combining J/ψ from one event and ϕ,$K^{\pm}$ from another event. The resulting Δm distribution with two-signal-hypothesis fit is shown in Fig.2, as shown the three-body phase space background which is used as the default background model for this analysis lies above the event-mixing background in all Δm bins in the range of interest.

CMS performed various test to examine the robustness of the observed two structures. Each event selection criteria is individually varied and no bias in the selection procedure is observed. The relative efficiency used to correct the extracted spectrum is varied and the fit is

Table 1. Systematic uncertainties in the measured masses and widths of the two peaking structures.

	$m_1(MeV)$	$\Gamma_1(MeV)$	$m_2(MeV)$	$\Gamma_2(MeV)$
$B^{\pm}$ Background PDF	0.8	7.4	2.6	9.9
$B^{\pm}$ Signal PDF	0.2	3.6	2.7	0.2
Relative efficiency	4.8	6.0	0.9	10.0
Δm binning	3.7	1.5	2.7	0.2
Δm structure PDF	0.8	9.3	0.6	4.9
Δm mass resolution	0.8	6.4	0.6	4.6
Δm background shape	0.2	7.0	0.3	0.2
Selection requirements	0.8	7.8	5.5	1.8
Total	6.3	19	7.3	16

repeated. The result confirm the robustness of the significance of the first structure. The Δm spectrum obtained through a different background subtraction technique (sPlot formalism) is compared to the Δm spectrum shown in Fig.2. No indication of bias is found. The analysis is repeated by requiring a tighter B selection to reduce the combinatorial background. Tighter event selection reduce the background by a factor of ten and keep the 40% of the B signal as shown in Fig.1(right). The extracted Δm spectrum for these events looks similar to Fig.2, where the fitted mass and width values of the two peaking structures are consistent with the results obtained from the nominal data sample.

The Δm distribution for the events that are eliminated to remove the effect of B_s^0 background is also studied. This study is performed to make sure the eliminated events do not cause reflections in the low Δm region. The study show that, after subtraction of the B_s^0 background the Δm distribution of events with $\Delta m >$1.568 GeV is consistent with the prediction based on the three-body phase-space hypothesis for the non-resonant background. The Δm spectrum, including non-B candidates after subtracting B_s^0 contribution is shown in Fig.3.

The estimation of the systematic uncertainties in the mass and the width measurements of the observed two structures are determined by performing several studies on the data and also on the MC simulation. The uncertainties related to the probability density functions (PDFs) for signal and background are studied by using different PDFs such as first, second, and third order polynomials, exponential functions, single and double Gaussian functions. The uncertainty due to the relative efficiency is studied by varying the relative efficiency in various bins and comparing with the 2D efficiencies. Estimating contribution due to the binning of the Δm spectrum is studied by using 10 MeV bins instead of 20 MeV bins. To estimate the uncertainty from the signal fitting function, the fit to the Δm distribution is repeated using either a nonrelativistic BW or a P-wave relativistic BW function for each structure. By varying mass resolution obtained from simulation the uncertainty due to the Δm mass resolution is studied. The overall systematic uncertainties in the measurement of the masses and widths of the two structures are found by adding in quadrature the individual items which are summarized in Table1.

4. Summary

CMS observed a peaking structure in the $J/\psi\phi$ mass spectrum from $B^{\pm} \to J/\psi\phi K^{\pm}$ decays by analyzing the data collected at $\sqrt{s} = 7$ TeV pp collisions at the LHC. A statistical significance of greater than 5σ is found assuming an S-wave relativistic BW lineshape for this structure above a

Table 2. Summary of the mass and width measurements of the two structures observed in the $J/\psi\phi$ mass spectrum.

Experiment	$m_1(MeV)$	$\Gamma_1(MeV)$	$m_2(MeV)$	$\Gamma_2(MeV)$
CDF	$4143.0^{+2.9}_{-3.0} \pm 0.6$	$15.3^{+10.4}_{-6.1} \pm 2.5$	$4274.4^{+8.4}_{-6.7} \pm 1.9$	32.3+21.9±7.6
CMS	4148.0±2.4±6.3	28^{+15}_{-11}±19	4313.8±5.3±7.3	38^{+30}_{-11}±16
D0	4159.0±4.3±6.6	19.9±12.6$^{+1.0}_{-8.0}$	4328.5±12.0	30(constrained)
LHCb	no observation		no observation	

three-body PS shape for the non-resonant background. Adding the J/ψ mass [5] to the extracted Δm values, the mass and width are measured to be $m_1 = 4148.0 \pm 2.4(stat.) \pm 6.3(syst.)$ MeV and $\Gamma_1 = 28^{+15}_{-11}$(stat.)±19(syst.) MeV. The measured mass and width are consistent with the Y(4140) values reported by CDF experiment[2]. The recent measurement performed by D0 can also accommodate the first structure[7].

In addition, evidence for a second peaking structure is found in the same mass spectrum, with measured mass and width values of $m_2 = 4313.8 \pm 5.3(stat.) \pm 7.3(syst.)$ MeV and $\Gamma_2 = 38^{+30}_{-11}$(stat.)±16(syst.) MeV. The significance of the second structure could not able to reliably determined due to possible reflections of two body decays. A summary of the mass and the width measurements of CMS and other experiments are summarized in Table2. The two structures are well above the threshold of open charm (DD) decays and have relatively narrow widths. Conventional charmonium mesons with these masses would be expected to have larger widths and to decay predominantly into open charm pairs with small branching fractions into $J/\psi\phi$. Angular analysis of the final state particles for $B^{\pm} \to J/\psi\phi K^{\pm}$ decay and determination of their J^{PC} can clarify the nature of these structures.

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