PROCEEDINGS OF SCIENCE

Search for exotic resonances with the CMS experiment

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A search for exotic resonances using proton-proton collisions at $\sqrt{s} = 13$ TeV recorded by the CMS experiment at the LHC is presented. In particular, the search is targeting resonance structures in $J/\psi J/\psi$ mass spectrum near the threshold. The data sample being used corresponds to an integrated luminosity of $135\,\mathrm{fb}^{-1}$.

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1. Introduction

The "quark model" has provided a successful description of the properties of mesons and baryons. However, many experimentally observed states do not fit the quarks model description: e.g. "tetraquarks" (four-quark bound states), "pentaquarks" (five-quark bound states), "glueballs" (all-gluon bound states) or more generally "exotic hadrons". After the $X(3872)$ discovery [1], many exotic states have been observed [2], but their interpretation remains contested. The main issue is how to model their quark structure, although some theorists provide alternative explanations to the bound state interpretation [3].

In 2020 the LHCb Collaboration observed a peak at about 6.9 GeV ($X(6900)$) in the $J/\psi J/\psi$ mass spectrum [4] exceeding 5 standard deviations (σ). The measured $X(6900)$ mass was found to be compatible with an all-charm tetraquark state. Although the $X(6900)$ observation is convincing, the interpretation of the $J/\psi J/\psi$ mass spectrum remains uncertain.

2. Analysis samples and selection strategy

Data collected during the 2016-2018 period has been used for the analysis. Events of interest are selected using a two-tiered trigger system. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detector. The second level, known as the high-level trigger (HLT), consists of a farm of processors running the event reconstruction software. For 2016 data (36.3 fb^{-1}) at least three muon candidates were required at L1. The HLT required muon $|\eta| < 2.5$ and a pair of oppositely charged muons having: a relative distance of closest approach < 0.5 cm, χ^2 fit probability into a common vertex $> 0.5\%$ and an invariant mass between 2.95 and 3.25 GeV. For 2017-2018 data (98.6 fb^{-1}) the L1 required at least three muons, with two of them having opposite charge and an invariant mass smaller than 9 GeV. For the (sub-)leading muon in the oppositely-charged pair it was required $p_T > (3)\,5$ GeV. The HLT requirementw for 2017-2018 data were identical to 2016 one, in addition, all muons must have hits in at least two muon stations, and each muon forming a trigger J/ψ candidate must have $p_T > 3.5$ GeV.

Signal and background shapes modeling has been studied using simulated samples. Signal samples for a resonance X decaying into a $J/\psi J/\psi$ pair where produced using the JHUGen 7.40 [5] and PYTHIA 8.0 [6]. Background samples were produced using PYTHIA, HELAC-Onia [7] and CASCADE [8] generators. The particle interaction within the CMS detector is simulated using GEANT4 [9] software.

The analysis selection targets $J/\psi J/\psi$ pair decaying into four muons. Muons are required to pass *Soft ID* [10], $p_T > 2.0$ GeV, and $|\eta| < 2.4$ GeV. The opposite-sign muon pair forming the J/ψ candidate must have a mass $m(\mu^+\mu^-)$ between 2.95 and 3.25 GeV, $p_T > 3.5$ GeV and a vertex fit probability $> 0.5\%$. The four muons must fit to a common vertex with a fit probability $> 0.5\%$. When the oppositely-charged muon pair is fit into a J/ψ candidate and its invariant mass is constrained to the known J/ψ mass $m_{J/\psi}$ [11], the fit probability must be $> 0.1\%$. Then the two constrained J/ψ candidates are fit into a common vertex and the vertex fit probability is required to be $> 0.1\%$. If multiple double-J/ψ candidates are present, the pairing with the smallest mass uncertainty-weighted distance in the two-dimensional $m(\mu^+\mu^-)$-$m_{J/\psi}$ plane is considered.

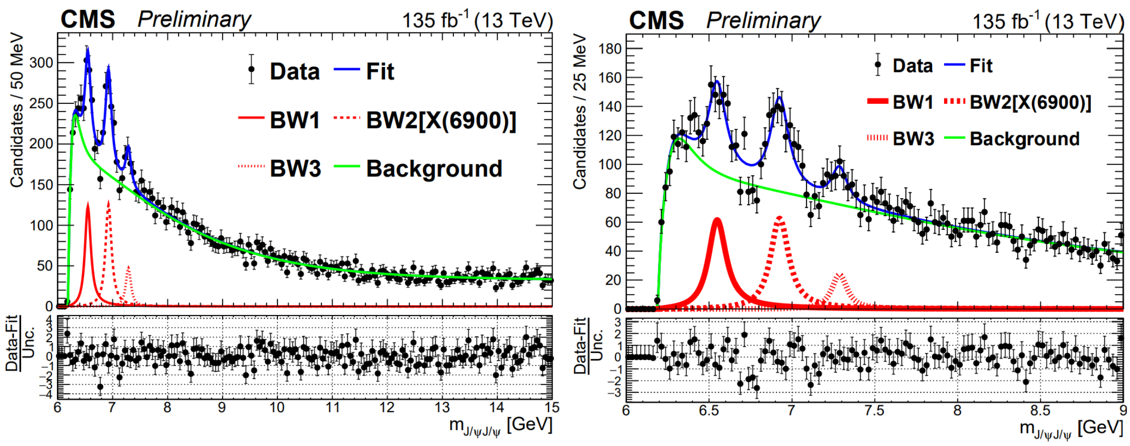

Figure 1: The $J/\psi J/\psi$ invariant mass fit over the full mass range (left) and its projection in the mass range below 9 GeV (right), while lower panels show the deviation of data points from the fit [12].

3. Fit strategy

The $J/\psi J/\psi$ invariant mass spectrum and the fit result are shown in Fig. 1. The fit model is build by performing a sequence of fits, starting from the background only hypothesis, peaking feature are added if their local significance exceeds 3σ.

The non-resonant single (NRSPS) and double parton scattering (NRDPS) background shapes, f_{NRSPS} and f_{NRDPS}, are parameterizations by means of simulations:

$$f_{\mathrm{NRSPS}}(x, x_0, \alpha, p_1, p_2, p_3) = (x - x_0)^{\alpha} \left(1 - \left(\frac{1}{(15 - x_0)^2}\right)(15 - x)^2\right) \exp\left(-\frac{(x - x_0)^{p_3}}{2p_2^{p_3}}\right), \quad (1)$$

$$f_{\mathrm{NRDPS}}(x, a, p_0', p_1', p_2') = \sqrt{x_t}\, \exp -a x_t (p_0' + p_1' x_t + p_2' x_t^2)\,, \quad (2)$$

where $x_0 = 2m_{J/\psi}$ and $x_t = x - x_0$. The background modeling function is the sum of f_{NRSPS}, f_{NRDPS} and a BW function describing the threshold enhancement observed at low masses. Peaking features are modeled using relativistic Breit-Wigner (BW) functions. The signal and background parameter are extracted performing an extended unbinned maximum likelihood fit of the data.

4. Results

As a result of the sequential fit procedure, three peaks (BW1, BW2 and BW3) were found at about 6650, 6900 and 7300 MeV, having a local significance of 6.5, 9.4 and 4.1 σ. The 6.9 GeV peak is compatible with LHCb results. The mass, width and yield for the three signal peaks are summarized in Tab. 1. Systematic uncertainties are determined for the masses and widths by varying aspects or inputs to the fit, the most relevant are: signal shape modeling, NRSPS parametrization and shape variations when including feeddown components.

When the fit is evaluated in the full mass range, it provides a good description of the data: the χ^2 fit probability is 79%. However, when only data below 7.5 GeV are taken into account the fit probability drops to 1%. The fit model does not describe the dips around 6750 and 7150 MeV, resulting in a poor fit when restricting the χ^2 evaluation range below 7.5 GeV. Further studies

	BW1	BW2	BW3
Mass	6552 ± 10 ± 12	6927 ± 9 ± 5	7287 ± 19 ± 5
Width	124 ± 29 ± 34	122 ± 22 ± 19	95 ± 46 ± 20
Yield	474 ± 113	492 ± 75	156 ± 56

Table 1: Mass, width and yield of the tree peaking structures after the signal+babkground fit. The first uncertainty is statistical, while the second is systematic [12].

with more complex models are needed, e.g. models incorporating interference or non-interference including multiple overlapping resonances with narrow widths to describe an individual peak.

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