Amplitude analysis of di-charmonium resonances in three decay channels

Амплитудный анализ дичармониевых резонансов в трех каналах распада

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Две узкие резонансные структуры на 6.9 и 7.2 ГэВ и широкая структура вблизи порога рождения di-J/ψ недавно наблюдались коллаборациями LHCb [1], ATLAS [2] и CMS [3] в спектрах инвариантных масс di-J/ψ и J/ψ+$\psi(2S)$ с четырмя мюонами в конечном состоянии. Это указывает на существование полностью тяжёлых кандидатов в тетракварки с конфигурацией кварков $cc\bar{c}\bar{c}$: $X(6900)$, $X(7200)$ и $X(6500)$. Однако их квантовые свойства пока не подтверждены [4].

В данной работе представлен амплитудный анализ вдля di-J/ψ и J/ψ+$\psi(2S)$ каналов распада с 4μ и 4μ+2π в конечных состояниях для изучения свойств этих экзотических резонансов. С помощью одновременной подгонки массовых и угловых распределений определены массы и ширины наблюдаемых структур в рамках гипотезы о двух интерферирующих состояниях с $J^P = 0^+$ для каждого. В работе также приводится сравнение моделей с другими спин-четностями для $X(6900)$.

Two narrow resonant structures at 6.9 and 7.2 GeV, as well as a broad structure near the di-J/ψ production threshold, have recently been observed by the LHCb [1], ATLAS [2], and CMS [3] collaborations in the di-J/ψ and J/ψ+$\psi(2S)$ invariant-mass spectra with four muons in the final state. This suggests the existence of fully heavy tetraquark candidates with a $cc\bar{c}\bar{c}$ quark configuration: $X(6900)$, $X(7200)$ and $X(6500)$. However, their quantum properties have not yet been confirmed [4].

This report presents an amplitude analysis for the di-J/ψ and J/ψ+$\psi(2S)$ channels with 4μ and $4\mu + 2\pi$ in final states, aimed at studying the properties of these exotic resonances. By performing a simultaneous fit to the mass and angular distributions, the masses and widths of the observed structures are determined under the hypothesis of two interfering states with $J^P = 0^+$ for both. The comparisons with other spin—parity hypotheses for $X(6900)$ are also presented.

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Introduction

The LHCb [1], ATLAS [2], and CMS [3] experiments have observed resonant-like structures in the signal and measured their natural masses and widths, taking into account interference effects in their best-fit models. For the first time, all three structures were established with a significance well above five standard deviations by CMS in the Run 2 + Run 3 analysis [5],

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and confirming the signal structure in the previous Run 2 analysis. In the J/ψ+$\psi(2S)$ channel with four muons in final state, CMS also observed two resonance states, in particular $X(7200)$, with a significance of about 4σ [6]. Although it was an independent analysis, the extracted parameters are consistent with those obtained in the first channel.

The most interesting questions, which remain open, concern the production mechanism [7], internal structure and quantum properties of the signal. Numerous theoretical models predict mass spectra that depend on the spin–parity assignment and consider different possible natures of the observed structures [8–12]. For example, compact models usually views the spectrum of states as radial or orbital excitations of the X particle with the same J^P quantum numbers [8].

The latest CMS paper provides estimations of the possible quantum numbers of the resonances [13]. The spectrum of states is interpreted as radial excitations of particle X, which implies the same spin—parity for all three states. Applying the Matrix Element Likelihood Approach (MELA) [14] to Run 2 data in the di-J/ψ channel, CMS found that the $J^P = 2^+$ assignment is favored, while 0^- is excluded at 95% confidence level.

Methodology

The measurement of natural properties and quantum numbers is based on the amplitude analysis approach within the helicity formalism, which allows one to simultaneously describe the dependence of the signal on the invariant-mass distributions and on the angular correlations among the decay products. The helicity formalism naturally accounts for spin and parity hypotheses: by comparing the predicted angular distributions for different J^P assignments with the data, one can test which hypotheses are compatible with the observations.

The phase space of the signal is modeled through the $X \to \psi_1\psi_2$ decay, weighted by the analytical matrix-element expression originally derived in our previous work [15]. The signal extraction is based on a simultaneous binned χ^2 fit performed in the three X decay channels. The fit uses the invariant-mass spectra and the angle between one of the ψ mesons and the X-resonance in the rest frame of latter,as well as the distributions of the two final-state particles, as input observables. The data are compared to the signal-plus-background model. The goodness-of-fit is evaluated using χ^2/ndf and by comparing the fitted distributions of the observables to the data.

Results

The amplitude analysis method has been applied to describe the mass and angular spectra of the signals in the di-J/ψ and J/ψ+$\psi(2S)$ decay channels observed with LHC. Figures 1a–1c show the best-fit result of the amplitude analysis with the model containing two interfering states in the

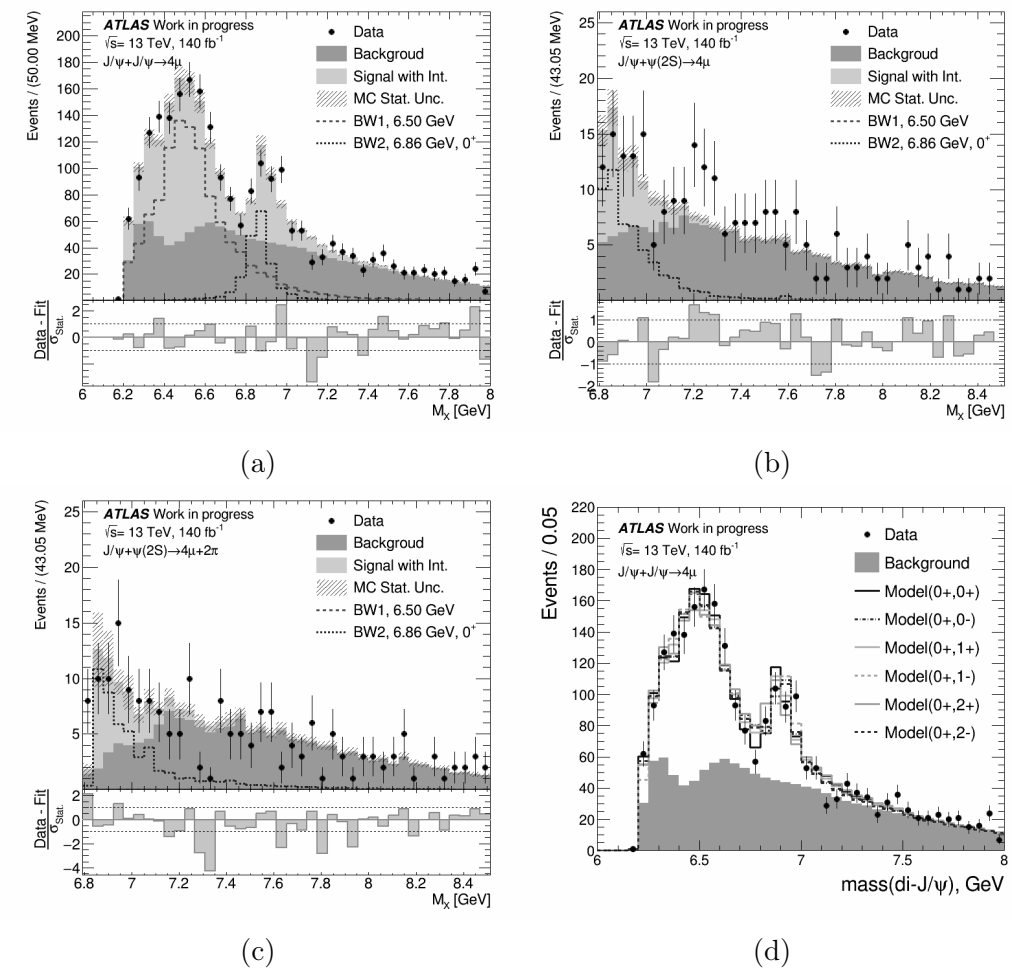


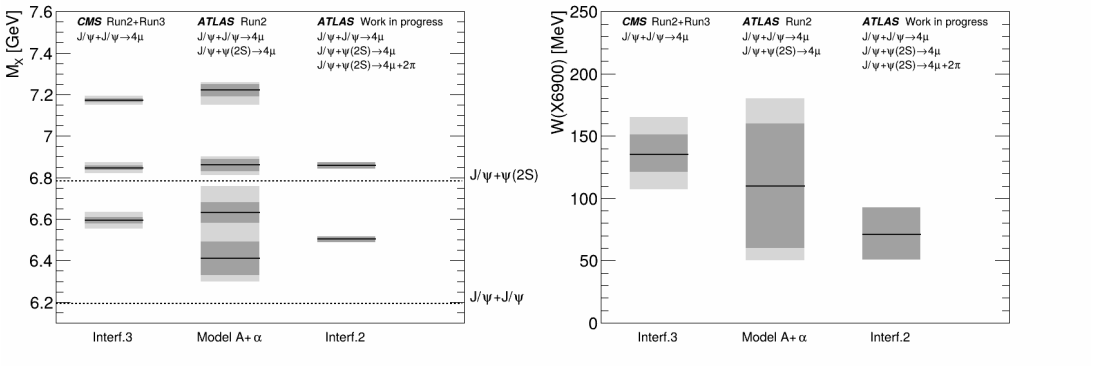
Fig. 1: The fit to the mass spectra in the signal regions in the di-J/ψ (a), J/ψ+$\psi(2S)$ with 4-μ in final state (b) and J/ψ+$\psi(2S)$ decay channel with 4-μ+2π in final state (c). The dashed lines on the first three plots depict individual resonance components, while the light-gray filled component represent interference effects among them. The fourth plot (d) shows the comparison of models with different J^P for $X(6900)$ for the di-J/ψ mass distribution.

$X \to$ di-$J/\psi \to 4\mu$, $X \to J/\psi$-$\psi(2S) \to 4\mu$, and $X \to J/\psi$-$\psi(2S) \to 4\mu+2\pi$ decay channels.

Both states have $J^P = 0^+$. Their masses are 6.502 and 6.857 GeV, and their widths are 0.365 and 0.068 GeV, respectively (see Table 1). The $X(6900)$ properties are consistent with the previous ATLAS [2] and CMS [5] measurements (see Figure 2). The state at 6.5 GeV makes a negligible contribution to the $X \to J/\psi$+$\psi(2S)$ channels (see Figures 1b–1c). The branching fractions of the state at 6.9 GeV into the $X \to J/\psi$+$\psi(2S)$ channels are approximately equal, as expected. The alternative hypotheses with different J^P assignments for $X(6900)$ provide a similar fit quality and cannot be excluded based on the Run 2 data (see Figure 1d).

	$\mathrm{BW}_1(\mathrm{J^P}=0^+)$	$\mathrm{BW}_2(\mathrm{J^P}=0^+)$
M, GeV	$6.502^{+0.014}_{-0.015}$	$6.857^{+0.015}_{-0.014}$
Γ, GeV	$0.365^{+0.046}_{-0.041}$	$0.068^{+0.022}_{-0.020}$

Table 1: The measured masses and widths in best model with two states with $J^P = 0^+$. Only statistical uncertainties are presented.



(a) (b)

Fig. 2: The mass spectra (a) and natural width of $X(6900)$ (b) comparison of the amplitude analysis of 3 channels with 2-state model (Interf.2) and the previous CMS (Interf.3) [5] and ATLAS (Model A+α) [2] results. The dark-gray bands around the curves show the statistical uncertainty, while the light-gray correspond to the overall uncertainty.

The minimal two-state model provides a good description of the Run 2 ATLAS data in all three channels and agrees with previous experimental measurements of the masses and widths. The available statistics are not sufficient to exclude the tested spin—parity quantum number hypotheses within the two-state model. Future plans include testing models with identical J^P assignments for the two- and three-state hypotheses using the Run 2 and Run 3 data in the three decay channels.

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