Application of the amplitude analysis method to the study of mass and angular spectra of heavy tetraquarks in di-J/ψ and J/ψ-$\psi(2S)$ decay channels

Применение метода амплитудного анализа к изучению массовых и угловых спектров тяжелых тетракварков в каналах распада на пары J/ψ-J/ψ и J/ψ-$\psi(2S)$.

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Экспериментальное открытие резонансного рождения пар J/ψ мезонов и J/ψ-$\psi(2S)$ мезонов в pp-столкновениях вблизи порога может быть объяснено существованием полностью очарованных тетракварков (широкая структура на 6600 МэВ и узкие структуры на 6900 и 7200 МэВ). Многочисленные теоретические модели, последовавшие за экспериментальным открытием, описывают наблюдаемые данные, исходя из разных предположений о физике новых состояний, и дают предсказания для новых наблюдений. Дальнейшие исследования требуют прецизионных экспериментальных измерений. В данной работе метод амплитудного анализа применен для описания массовых и угловых спектров наблюдаемых сигналов в данных установки ATLAS одновременно в каналах распада на J/ψ-J/ψ и J/ψ-$\psi(2S)$. Измерены массы и ширины наблюдаемых резонансов с учетом интерференции сигналов и фона.

The experimental discovery of resonant-like states in the di-J/ψ mass spectra in pp-collisions near the production threshold suggests the existence of fully-charmed tetraquarks (broad structure at 6600 MeV and narrow structures at 6900 and 7200 MeV). Numerous theoretical models following this discovery provide descriptions of the observed data, propose mechanisms underlying formation of this new states, and predict additional phenomena. Further investigations require precision experimental measurements. In this work, the amplitude analysis method is applied to describe mass and angular spectra of the observed signals in ATLAS experimental data simultaneously in J/ψ-J/ψ and J/ψ-$\psi(2S)$ decay channels. Mass and width of the resonances are measured accounting for interference effects between signals and background.

PACS: 13.25.Ft; 14.40.Rt

Introduction

The narrow resonant-like structures were discovered by three main LHC experiments (LHCb [1], ATLAS [2] and CMS [3]) in the di-J/ψ, J/ψ-$\psi(2S)$ invariant mass spectra suggesting existence of the fully-heavy tetraquarks $T_{cc\bar{c}\bar{c}}$.

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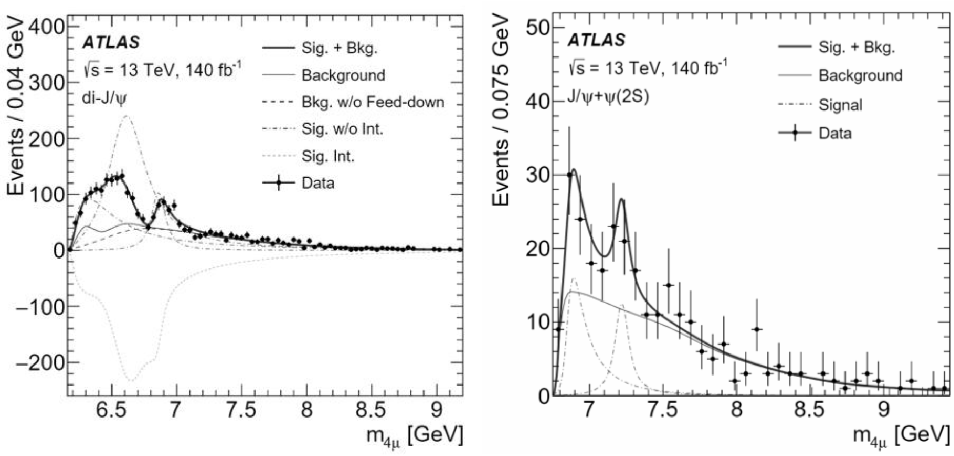


(a) (b)

Fig. 1: The fit to the mass spectra in the signal regions in the di-J/ψ(a) and J/ψ-$\psi(2S)$(b) channels. The dash-dotted lines depict individual resonance components, while the short-dashed lines represent interference effects among them [2].

In particular, in the latest studies of di-J/ψ and J/ψ-$\psi(2S)$ channels with 4-muon final states, the ATLAS Collaboration reports [2] four resonant states (broad structures at 6600 MeV and narrow structures at 6900 and 7200 MeV). The best model for J/ψ-J/ψ mass spectrum (see Figure 1a) includes three resonant states and considers interference between all of them. And the best model of J/ψ-$\psi(2S)$ (see Figure 1b) includes one additional state at 7.2 GeV. Also it seems that the low mass threshold effects in di-charmonia production need further investigation in a more precise analyses.

Theoretical predictions for $T_{cc\overline{c}\overline{c}}$

In pp-collisions, J/ψ-meson pairs can be produced via either double-parton scattering (DPS) or single-parton scattering (SPS). These different production mechanisms predict different p_T spectra of the di-J/ψ and J/ψ-$\psi(2S)$ system [4], which implies that accurate measurements of the tetraquark candidates p_T spectra may shed light on its production mechanism.

New states in di-J/ψ and J/ψ-$\psi(2S)$ spectra can be described as bound states in $cc\overline{c}\overline{c}$ system [6, 7]. Theoretical models of such bound states include compact tetraquarks, diquark-antidiquark structures, as well as new mechanisms in di-charmonium interactions. These different models predict different spin-parity options of new resonances, existence of higher-mass resonances and different possible decay channels [6–8]. Further investigations require precision experimental measurements.

Amplitude analysis of the $T_{cc\overline{c}\overline{c}}$ decay to 4-muon final states

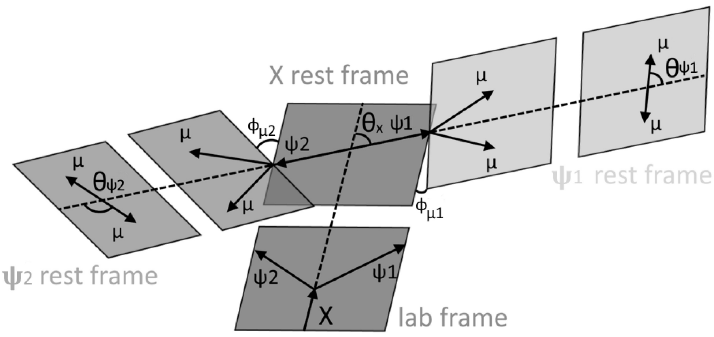


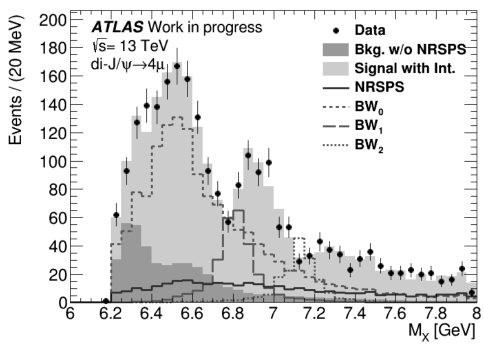
Fig. 2: The decay kinematics is determined by definitions of angular variables in two-particle decay.

Existing experimental studies provide measurements of mass and width of the new resonances, however, their spin-parity properties have not been investigated yet [9]. The helicity amplitude formalism enables a more precise analysis of the properties of $X(6900)$ and other signal states. This method is commonly employed to describe angular distributions in decay chains and determine initial particles in relativistic scattering and decay processes. The amplitudes provide information about the kinematics of resonance decays. It gains sensitivity for spin-parity, accounts for interference effects between different amplitudes and takes into account resolution detector effects in the ATLAS experiment. Variables that define decay kinematics are mass of the resonance and angular characteristics (see Figure 2): θ_X, the angle between one of the ψ mesons and the X-resonance in the rest frame of latter; ϕ_{μ_1} and ϕ_{μ_2}, which are angles between X-resonance decay plain and the ψ-meson decay plains; θ_{ψ_1} and θ_{ψ_2}, the two angles between muon in the psi-meson decay and the corresponding ψ-meson in the rest frames of latter.

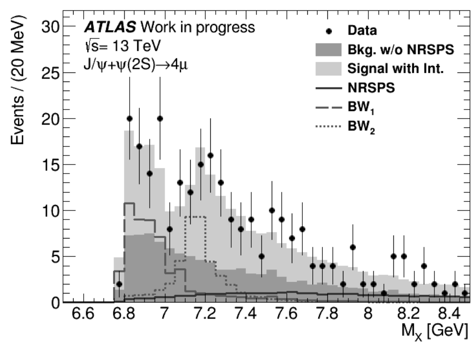
The mass and angular spectra are obtained from the phase space of the $X \to \psi_1\psi_2 \to 4\mu$ decay weighted by the analytic matrix element $\mathcal{M}_{total}$:

$$\mathcal{M}_{total} = \sum_{\lambda_X} |\sum_{i} \sum_{\substack{\lambda_{\psi_1},\lambda_{\psi_2},\\ \Delta\lambda_{\mu_1},\Delta\lambda_{\mu_2}}} A_{X_i \to \psi_1\psi_2 \to 4\mu}|^2. \tag{1}$$

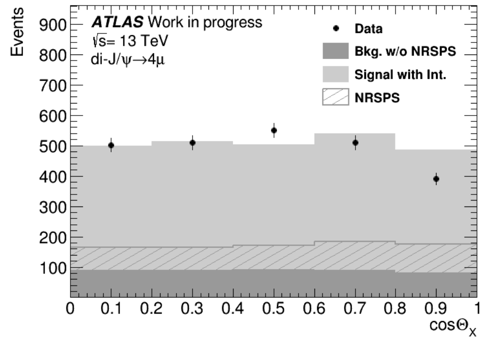
Index i enumerates resonances and is omitted below for simplifying. $A_{X\to\psi_1\psi_2\to 4\mu}$ in an equation (1) is an amplitude of X resonant state, which is averaged over the helicities λ_X of the initial particle X, while helicities λ_{ψ_1}, λ_{ψ_2}, $\Delta\lambda_{\mu_1}$, and $\Delta\lambda_{\mu_2}$ of intermediate and final particles are summed coherently. The amplitude $A_{X\to\psi_1\psi_2\to 4\mu}$ is described by helical amplitude $H^{X\to\psi_1\psi_2}_{\lambda_{\psi_1}\lambda_{\psi_2}}$ (which contains fit parameters), Breit-Wigner function BW with the resonance pole mass M_0^X and width Γ_0^X, Blatt-Weisskopf factor B'_L (responsible for suppression of amplitude components with higher orbital momenta L), and Wigner D-matrices of X, ψ_1 and ψ_2:



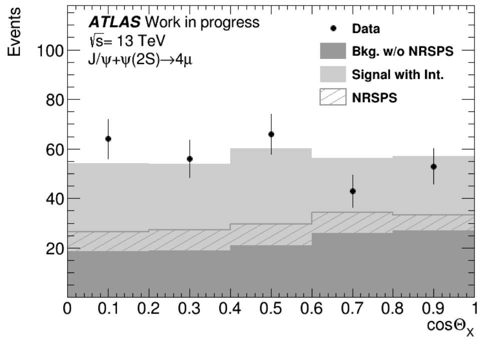
(a)



(b)



(c)



(d)

Fig. 3: represents the resulting combined signal and background distributions of (a) di-J/ψ invariant mass, (b) J/ψ-$\psi(2S)$ invariant mass, (c) distribution of $\cos\theta_X$ in di-J/ψ, and (d) $\cos\theta_X$ in J/ψ-$\psi(2S)$ channel. The data are represented by the points. Dashed lines represent resonant amplitudes before their coherent summation, black line is non-resonant contribution to the spectrum, dark-gray is the sum of other backgrounds. The light-gray histogram represents the resulting signal+background distribution.

$$A_{X\to\psi_1\psi_2\to 4\mu} = \mathcal{H}^{X\to\psi_1\psi_2}_{\lambda_{\psi_1}\lambda_{\psi_2}} BW(m_{\psi_1\psi_2}|M_0^X,\Gamma_0^X) B'_L(q,q_0,d)\left(\frac{q}{M_0^X}\right)^L$$
$$D^{J_X}_{\lambda_X,\lambda_{\psi_1}-\lambda_{\psi_2}}(0,\theta_X,0)^* D^1_{\lambda_{\psi_1},\Delta\lambda_\mu}(\phi_{\psi_1},\theta_{\psi_1},0)^* D^1_{\lambda_{\psi_2},\Delta\lambda_\mu}(\phi_{\psi_2},\theta_{\psi_2},0)^*. \quad (2)$$

In our notations of B'_L arguments, q is ψ momentum in the X reference frame, q_0 is the same momentum at $m_{\psi_1\psi_2} = M_0^X$, and d is a scale parameter of $T_{cc\bar{c}\bar{c}}$.

Results

The amplitude analysis method has been applied to describe mass and angular spectra of the observed signals in J/ψ-J/ψ and J/ψ-$\psi(2S)$ decay channels observed in ATLAS experimental data. Figure 3 demonstrates the result of the amplitude analysis of di-J/ψ and J/ψ-$\psi(2S)$ resonant production. All resonances are assumed to have 0^+ spin-parity. Their masses are

6.54, 6.81 and 7.14 GeV, and widths are 1.11, 0.12, and 0.09 GeV, respectively. These parameters were extracted from a simultaneous fit to the J/ψ-J/ψ and J/ψ-$\psi(2S)$ channels. The analysis accounts for interference effects, which play a crucial role in describing mass and angular distributions.

Conclusion

Future plans include testing different spin-parity options for the signal amplitudes. Future investigations of invariant mass, transverse momentum, and angular distributions are essential for understanding the key quantum characteristics of the observed states in di-J/ψ and J/ψ-$\psi(2S)$ spectra. It will also help to shed light on the mechanisms of charmonia interactions responsible for existence of such resonances and thus better determine theoretical grounds predicting their spectra and quantum numbers.

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