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Observation of an excess of di-charmonium events in the four-muon final state with the ATLAS detector

The ATLAS Collaboration

A search is made for potential $cc\bar{c}\bar{c}$ tetraquarks decaying into a pair of charmonium states in the four muon final state using proton–proton collision data at $\sqrt{s}$ = 13 TeV, corresponding to an integrated luminosity of 140 fb^{-1} recorded by the ATLAS experiment at LHC. Two decay channels, $J/\psi + J/\psi \rightarrow 4\mu$ and $J/\psi + \psi(2S) \rightarrow 4\mu$, are studied. Backgrounds are estimated based on a hybrid approach involving Monte Carlo simulations and data-driven methods. Statistically significant excesses with respect to backgrounds dominated by the single parton scattering are seen in the di-J/ψ channel consistent with a narrow resonance at 6.9 GeV and a broader structure at lower mass. A statistically significant excess is also seen in the J/ψ+ψ(2S) channel. The fitted masses and decay widths of the structures are reported.

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Beyond the conventional mesons ($q\bar{q}$) and baryons (qqq or $\bar{q}\bar{q}\bar{q}$), exotic hadrons composed of four ($qq\bar{q}\bar{q}$) or five quarks ($qqqq\bar{q}$) are also allowed under color confinement. The $X(3872)$ particle discovered by Belle in 2003 was the first tetraquark (TQ) candidate [1], and was followed by a series of further candidates designated as X, Y, and Z states [2]. In 2020, LHCb observed a narrow $X(6900)$ structure in the di-J/ψ channel [3]. The structure could be interpreted as a tetraquark with four charm quarks, $T_{cc\bar{c}\bar{c}}$ [4–11]. An additional enhancement closer to the di-J/ψ mass threshold was also observed in the LHCb data. Since the 6.9 GeV LHCb resonance is above the J/ψ+ψ(2S) mass threshold, a structure in the J/ψ+ψ(2S) channel is also possible. Both channels are investigated by ATLAS in a quite different phase space region from LHCb, and the new channel of J/ψ+ψ(2S) provides more information for di-charmonium excesses. For example in some predictions, the two channels are coupled via Pomeron exchange between the two charmonia, and $X(6900)$ is dynamically produced [12].

A search in the 4μ final state produced through the di-J/ψ and J/ψ+ψ(2S) channels is carried out, using 140 fb^{-1} of LHC proton–proton (pp) data collected by the ATLAS experiment at a center-of-mass energy of $\sqrt{s}$ = 13 TeV between the years 2015 and 2018. Only the data where all detector systems are functional and recording high-quality data are used. The ATLAS detector [13] covers nearly the entire solid angle around the collision point[1] with layered tracking detectors, calorimeters and muon chambers. The muon and tracking systems are of particular importance in the reconstruction of charmonia. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector and a transition radiation tracker. The muon spectrometer (MS) surrounds the calorimeters and consists of three large superconducting air-core toroids with eight coils each, a system of tracking chambers, and detectors for triggering. Muons are reconstructed using information from the ID and MS systems.

Background processes are estimated partly by Monte Carlo (MC) simulations and partly from data. The main backgrounds are di-charmonium production via single parton scattering (SPS) [14–20], and double parton scattering (DPS) [21–27], non-prompt J/ψ production from b-hadron decays, prompt single J/ψ production and non-resonant di-muon production. Pythia 8.244 [28] is used to generate SPS, DPS and non-prompt di-charmonium events. Both the color-singlet and color-octet intermediate states are included for J/ψ and ψ(2S). The A14 [29] set of parameter values and the `NNPDF23LO` [30] parton distribution functions (PDF) [31] are used. PHOTOS 3.61 [32] is applied to simulate final state radiation in particle decays. The remaining backgrounds which contain a single or no charmonium are modeled using the data.

The data sample was collected with triggers requiring either two muons with invariant mass compatible with J/ψ or ψ(2S) mesons (mass in the range of $[2.5, 4.3]$ GeV), or three muons containing at least one such di-muon pair [33, 34]. Combinations of triggers with different prescales [35] depending on the run period are used to give the largest acceptance. The trigger efficiency for the $X(6900)$ relative to the offline selection is about 72%. Dedicated ATLAS offline software is used to reconstruct the charmonium and 4μ candidates in each event recorded by the triggers. In each event containing at least four muons with two opposite-charge pairs, the ID tracks are fit to a common vertex. Afterwards, each vertex of the two pairs is refit with a J/ψ or ψ(2S) mass constraint [36]. The resolution of the TQ mass with these mass constraints ($m_{4\mu}$) is about 0.33% for $X(6900)$.

The *loose* identification selection criteria [37] are required for all muon candidates. Depending on the muon trigger thresholds and muon identification requirements, different muon momenta on the four muons are required. Several requirements are imposed on the following variables to further suppress the background:

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) and the z-axis along the beam pipe. The x-axis points from the IP to the center of the LHC ring, and the y-axis points upwards.

the vertex fit quality based on χ^2 per degrees of freedom N, the signed distances between the primary[2] and reconstructed 4μ vertices ($L_{xy}^{4\mu}$), and between the former vertices and the di-muon mass-constrained sub-vertices ($L_{xy}^{\text{di-}\mu}$). Events with $\Delta R < 0.25$[3] between the two reconstructed charmonia are used to study the signal, whereas events with $\Delta R \geq 0.25$ are used to validate the shape of the 4μ mass distribution for the SPS background and constrain its normalization. The shape of the signal 4μ mass distribution is not much affected by ΔR as well as muon p_{T} requirements. A summary of the kinematic requirements for the analysis regions is listed in Table 1.

Table 1: Summary of event selection requirements for different regions.

Signal region	Control region	Non-prompt region
Di-muon or tri-muon triggers, oppositely charged muons from each charmonium, *loose* muons, $p_{\text{T}}^{1,2,3,4} > 4, 4, 3, 3$ GeV and $\lvert\eta_{1,2,3,4}\rvert < 2.5$ for the four muons, $m_{J/\psi} \in [2.94, 3.25]$ GeV, or $m_{\psi(2S)} \in [3.56, 3.80]$ GeV, Loose vertex requirements $\chi^2_{4\mu}/N < 40$ ($N = 5$) and $\chi^2_{\text{di-}\mu}/N < 100$ ($N = 2$),		
Vertex $\chi^2_{4\mu}/N < 3$, $L_{xy}^{4\mu} < 0.2$ mm, $\lvert L_{xy}^{\text{di-}\mu}\rvert < 0.3$ mm, $m_{4\mu} < 11$ GeV,		Vertex $\chi^2_{4\mu}/N > 6$,
$\Delta R < 0.25$ between charmonia	$\Delta R \geq 0.25$ between charmonia	or $\lvert L_{xy}^{\text{di-}\mu}\rvert > 0.4$ mm

The SPS and DPS backgrounds contain two prompt charmonia and are modeled by MC simulations. Because the event generator does not reproduce the data distributions well, kinematic corrections are derived from two dedicated control regions. Since SPS (DPS) events are characterized by two charmonia which are nearby (distant) in $\eta - \phi$ space, the control region is defined with a 4μ mass sideband within [7.5, 12] GeV ([14, 24.5] GeV) without the ΔR requirement. The corrections are implemented by assigning event weights to MC simulations such that distributions of kinematic variables such as di-J/ψ p_{T}, $\Delta\phi$ and $\Delta\eta$ between charmonia, and the lowest muon p_{T} match the data in the control regions. The corrections are then applied to all mass regions and the SPS modelling is validated in the $\Delta R > 0.25$ control region.

The non-prompt background also contains two charmonia, albeit originating from b-hadron decays. These typically contain a decay vertex that is displaced from the primary pp interaction. This background is also modeled using MC simulation, but normalized and validated by dedicated control regions obtained by reversing the vertex quality requirements as shown in Table 1. Events from prompt single charmonium production and non-resonant di-muon production are collectively called "Others", and have at least one charmonium candidate containing random combinations of mostly fake muons. Fake muons are tracks, typically charged hadrons, that are misidentified as muons. A data-driven method is used because MC simulations do not accurately estimate this kind of background. A fake muon control region from data is used to model the Others background, which is defined by requiring that one charmonium candidate contains a track that is not reconstructed as a muon candidate, with all the other requirements kept unchanged. Events in the charmonium mass sidebands are used for both the normalization and shape corrections for Others.

[2] The primary interaction vertex is the collision vertex reconstructed excluding the 4μ candidate tracks and with the smallest distance of closest approach in z from the 4μ vertex.

[3] The angular distance is defined as $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$, with η and ϕ being the pseudorapidity and azimuthal angle of a particle, respectively.

In the di-J/ψ channel, events from resonances in the J/ψ+$\psi(2S)$ channel via $\psi(2S)\to J/\psi + X$, $\psi(2S)\to \gamma\chi_{cJ}$, and $\chi_{cJ} \to \gamma J/\psi$, where particles other than di-J/ψ are ignored, are included as the feed-down background. The feed-down events normalization in di-J/ψ ($N_{\rm fd}$) and the fitted signal yield in J/ψ+$\psi(2S)$ (N) are related by

$$N_{\rm fd} = \frac{\mathcal{B}'\epsilon'}{\mathcal{B}\left(\psi(2S)\to\mu\mu\right)\epsilon}N, \tag{1}$$

where ϵ (ϵ') is the signal (feed-down) efficiency in J/ψ+$\psi(2S)$ (di-J/ψ), and the branching fraction $\mathcal{B}' = \left[\mathcal{B}\left(\psi(2S)\to J/\psi + X\right) + \mathcal{B}\left(\psi(2S)\to\gamma\chi_{cJ}\right)\mathcal{B}(\chi_{cJ}\to\gamma J/\psi)\right]\mathcal{B}(J/\psi\to\mu\mu)$, where $X = \pi^+\pi^-, \pi^0\pi^0, \eta, \pi^0$. The systematic uncertainty on $N_{\rm fd}$ is dominated by the uncertainty on N.

Unbinned maximum likelihood fits are performed to extract the signal information from data in the 4μ mass spectra. The likelihood used for the fit is

$$\mathcal{L} = \mathcal{L}_{SR}\left(\vec{\theta},\vec{\lambda}\right)\cdot\mathcal{L}_{CR}\left(\vec{\theta}\right)\cdot\prod_{j=1}^{K}G\left(\theta'_j;\theta_j,\sigma_j\right), \tag{2}$$

where $\mathcal{L}_{SR}$ ($\mathcal{L}_{CR}$) is the likelihood in the signal (control) region, $\vec{\lambda}$ are the parameters of interest, θ_j are nuisance parameters (NP) which account for systematic uncertainties shared between the two regions. Each NP has a Gaussian distribution constraint with a subsidiary measurement θ'_j, a mean θ_j and a width set to $\sigma_j = 1$ by construction. Only the background yields in the control regions are used in simultaneous fits with the signal regions. Background yields in the two regions are related by a transfer factor obtained from MC predictions and data-driven estimations, with systematic variations for both components.

In the di-J/ψ channel, the feed-down normalized by Eq. 1 is included as an additional background, and two fit models are considered. In model A, the signal probability density function in $\mathcal{L}_{SR}$ consists of three interfering S-wave Breit–Wigner (BW) resonances multiplied with a phase space factor and convolved with a mass resolution function, which gives

$$f_s(x) = \left|\sum_{i=0}^{2}\frac{z_i}{m_i^2 - x^2 - im_i\Gamma_i(x)}\right|^2\sqrt{1-\frac{4m_{J/\psi}^2}{x^2}}\otimes R(\theta), \tag{3}$$

where m_i ($\Gamma_i(x)$) are the masses (widths) of resonances, z_i are complex numbers representing the relative magnitudes and phases (z_1 is fixed to unity with zero phase for this purpose), $\Gamma_i(x) = \Gamma_i\frac{m_i}{x}\frac{q}{q_i}$, where q (q_i) is the momentum of one charmonium in the rest frame of the di-charmonium system at the invariant mass equal to x (m_i) [38], and R is the mass resolution function. The m_i terms are ordered by the subscripts. In model B, two resonances are considered. The first one interferes with the SPS background, while the second is standalone. The signal+SPS probability distribution function gives

$$f(x) = \left(\left|\frac{z_0}{m_0^2 - x^2 - im_0\Gamma_0(x)} + A(x)e^{i\phi}\right|^2 + \left|\frac{z_2}{m_2^2 - x^2 - im_2\Gamma_2(x)}\right|^2\right)\sqrt{1-\frac{4m_{J/\psi}^2}{x^2}}\otimes R(\theta), \tag{4}$$

where $A(x)$ and ϕ are the SPS background amplitude and phase relative to the resonance at m_0 ($|A(x)|^2$ reproduces the non-interfering SPS background from the MC prediction). In this model, the control region becomes irrelevant and is excluded from the likelihood given in Eq. 2.

Models A and B are analogous to models I and II of the LHCb study [3], respectively. However, interferences between the signal resonances are introduced in model A, which is not done in the analysis by

LHCb. The number of resonances in model A starts from one and increases to three with the fit quality gradually improving. A 4th resonance is added only for systematics, as the fit quality does not improve appreciably. For comparison, a two-resonance model with interference, and a three-resonance model without interferences, are also tried. It is found that when compared with model A, these models are excluded with a confidence level of more than 95% based on toy MC studies.

In the J/ψ+ψ(2S) channel, two fit models are also considered. Model α assumes that the same interfering resonances observed in the di-J/ψ channel also decay into J/ψ+ψ(2S), in addition to a standalone fourth resonance in this channel. The signal probability distribution function gives

$$f_s(x) = \left(\left| \sum_{i=0}^{2} \frac{z_i}{m_i^2 - x^2 - i m_i \Gamma_i(x)} \right|^2 + \left| \frac{z_3}{m_3^2 - x^2 - i m_3 \Gamma_3(x)} \right|^2 \right) \sqrt{1 - \left(\frac{m_{J/\psi} + m_{\psi(2S)}}{x} \right)^2} \otimes R(\theta), \quad (5)$$

where the parameters of the first three resonances, whose contribution appears as a structure just above the $m_{J/\psi} + m_{\psi(2S)}$ mass threshold, are fixed to the values from the fit to the di-J/ψ channel. In contrast, model β assumes a single resonance in this channel (i.e., without the $z_{0,1,2}$ terms in Eq. 5).

The systematic uncertainties are classified into those affecting exclusively normalizations, and those affecting the mass spectrum shape as well. Only the latter are relevant, since the signal and background normalizations are freely floating parameters. The systematic uncertainties in $m_{4\mu}$, with and without the muon momentum calibration corrections, are treated as resolution uncertainties. Because the resolution of the $m_{4\mu}$ is mass dependent and a constant mass is used in the nominal fit, resolutions in different mass ranges are treated as systematic uncertainties. A shape uncertainty is assigned to account for bin-to-bin fluctuations from the limited MC sample size for backgrounds. In the SPS background, a Pythia model parameter uncertainty from `pT0timesMPI` [28], which controls the suppression of the soft double charmonia production, is assigned, and its nominal value is tuned to data in the SPS control region. A shape uncertainty in the background due to residual di-charmonium p_{T} mismodeling is applied. Based on toy MC studies, biases from the fit in the resonance parameters are also considered as systematic uncertainties. The P and D-wave BW functions are substituted for the S-wave for resonances away from the threshold to estimate systematic uncertainties due to different orbital angular momentum assumptions[4]. Systematic shape variations in the $X(6900)$ in the di-J/ψ channel, and in the second resonance for the J/ψ+ψ(2S) channel due to the ΔR and muon p_{T} requirements are considered as well. In the di-J/ψ channel, a 4th resonance around 7.2 GeV (hinted by the LHCb analysis) is added to the fit, and the feed-down background normalizations are varied according to the uncertainties in J/ψ+ψ(2S). The transfer factor uncertainty is dominated by the SPS model parameter, so it is not treated as a separate NP. In the J/ψ+ψ(2S) channel, the uncertainty in a transfer factor between the signal and control regions, and a shape uncertainty derived from the non-prompt region due to Others (shape inconsistency), are included. Interference between the 4th resonance and the other ones are included in systematic uncertainties. In model α, systematic uncertainties on the lower resonance shape from the di-J/ψ channel model A fit are also included. Other systematic uncertainties such as the parton PDF and Pythia parameters affect signal and background normalizations only, and are not incorporated in the fits.

The 4μ mass spectra fit to data in the two channels are shown in Figure 1. The fitted masses and widths of resonances are given in Table 2. Both the significance of all resonances, and the one for

[4] The first resonance at the threshold is always assumed to be S-wave, as the data has no constraining power for its width when $L = 1, 2$.

$X(6900)$ alone, far exceed 5σ[5]. The mass of the third resonance, m_2, is consistent with the LHCb mass. Although both the models A and B describe the data well, the broad structure at the lower mass could result from other physical effects, such as the feed-down from higher di-charmonium resonances, e.g., $T_{cc\bar{c}\bar{c}} \to \chi_{cJ}\chi_{cJ'} \to J/\psi J/\psi\gamma\gamma$ where the soft photons are not reconstructed. In the J/ψ+ψ(2S) channel, the signal significance with signal shape parameters of model α (β) fixed to their best-fit values is 4.7σ (4.3σ). In the fit with model α, the significance of the second resonance alone is found to be 3.0σ.

Table 2: The fitted masses and natural widths (in GeV), and relative uncertainties of signal yields ($\Delta s/s$) in the di-J/ψ and J/ψ+ψ(2S) channels. The results of both the models are given in each channel. The first uncertainties are statistical while the second ones are systematic.

di-J/ψ	model A	model B
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$	$6.65 \pm 0.02^{+0.03}_{-0.02}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$	$0.44 \pm 0.05^{+0.06}_{-0.05}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$	—
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$	
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$	—
J/ψ+ψ(2S)	model α	model β
m_3	$7.22 \pm 0.03^{+0.01}_{-0.04}$	$6.96 \pm 0.05 \pm 0.03$
Γ_3	$0.09 \pm 0.06^{+0.06}_{-0.05}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 21\%^{+25\%}_{-15\%}$	$\pm 20\% \pm 12\%$

[5] The asymptotic formula based on the profile likelihood ratio, $Z = \sqrt{2\ln\frac{L(\hat{s},\hat{\theta})}{L(0,\hat{\hat{\theta}})}}$, is used to calculate the overall significance, where s is the signal yield and θ are NPs [39]. Similarly for $X(6900)$ alone, $Z = \sqrt{2\ln\frac{L(\hat{z}_3,\hat{\theta})}{L(0,\hat{\hat{\theta}})}}$ is used. In the calculations, the signal shape parameters are all fixed to their best-fit values.

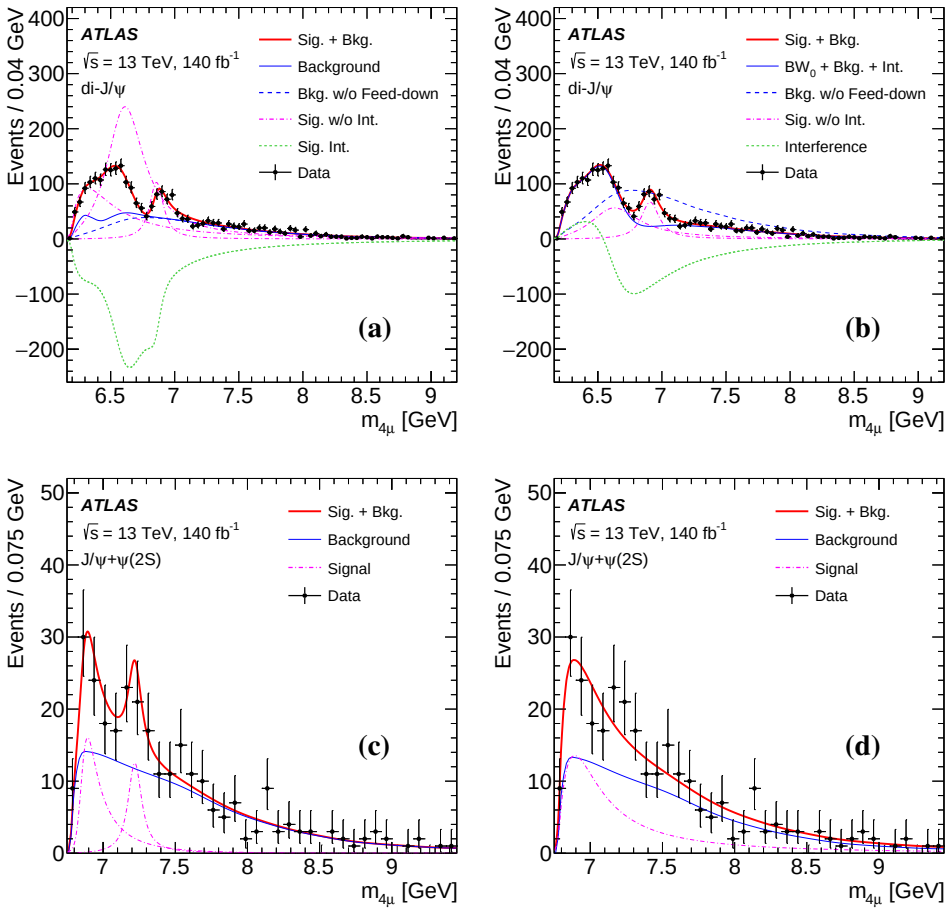

Figure 1: The fit to the mass spectra in the signal regions in the di-J/ψ (a,b) and J/ψ+ψ(2S) (c,d) channels. Fit results for models A (a), B (b), α (c) and β (d) are shown. The purple dash-dotted lines represent the components of individual resonances, and the green short dashed ones represent the interferences among them.

In conclusion, the results of a search for potential $cc\bar{c}\bar{c}$ tetraquarks decaying into a pair of J/ψ charmonium states, or into a J/ψ and ψ(2S), in the 4μ final state are presented based on pp collisions data collected by the ATLAS experiment at $\sqrt{s}$ = 13 TeV corresponding to an integrated luminosity of 140 fb^{-1}. A significant excess of events (far exceeding 5σ) in data above the expected background is observed in the di-J/ψ channel. Analogous to LHCb observations, a broad structure at lower mass and a resonance around 6.9 GeV are observed. A three-resonance model with interferences, or a model with the lower broad structure interfering with the SPS background, describes the excess better than models with fewer interfering resonances or with no interferences. In the J/ψ+ψ(2S) channel, a 4.7σ excess of events is observed when considering a model involving two resonances, one of which is near the 6.9 GeV threshold. In both channels, details of the lower-mass structure cannot be discerned directly from the data, and other interpretations (e.g. multiple non-interfering resonances, reflection effects and threshold enhancements) cannot be excluded. More data are required to better characterize the excesses observed in both channels.

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Appendix

Signal events are simulated with the event generator JHU [41] and CTEQ6L1 PDF [42], or with PYTHIA and the NNPDF23LO PDF. Feed-down backgrounds from the J/ψ+ψ(2S) channel to di-J/ψ are included. A natural width of 100 MeV is assumed for all the resonances with no interference between them. An extensive software suite [43] is used in data simulation [44], in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment. The MC simulated events are weighted to reproduce the same number of pp interactions per bunch crossing (pileup) and trigger conditions as occur in data.

The J/ψ and 4μ mass distributions of data and predictions in the signal regions of the two channels before the fits are shown in Figure 2(a,b,c). Similar structures were also observed by CMS [45]. Similar 4μ mass distributions in the control regions are shown in Figure 3. Distributions in the SPS and DPS control regions without the ΔR requirement between the charmonia are shown in Figure 4-5. The systematic uncertainties in the fitted masses and widths of the highest resonances in models A and α of the two channels are summarized in Table 3.

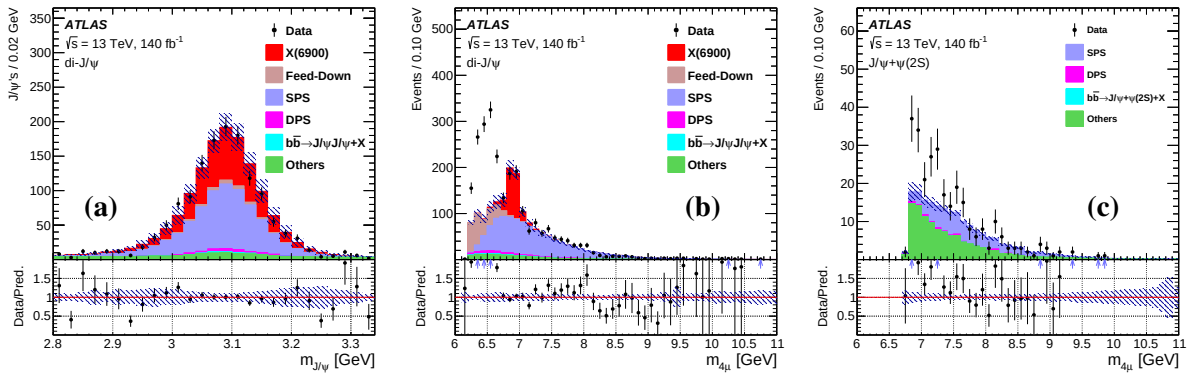

Figure 2: The J/ψ mass spectrum with 6.7 GeV < $m_{4\mu}$ <7.1 GeV (a) and the 4μ mass spectrum (b) in the signal region in the di-J/ψ channel, and the similar mass spectrum in the J/ψ+ψ(2S) channel (c). The signal from the $X(6900)$ is scaled to match data around 6.9 GeV. The bars and shaded areas represent uncertainties of data and predictions in each bin, respectively. The arrows in the lower panel indicate that the ratio of data to prediction is out of range in that bin.

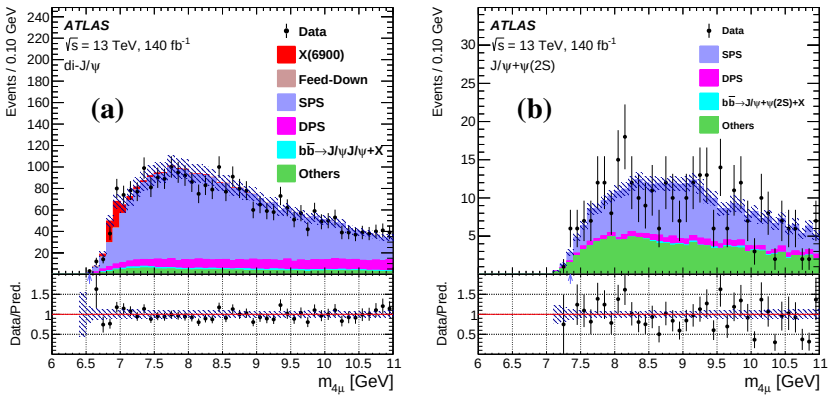

Figure 3: The 4μ mass spectra in the control regions with $\Delta R \geq 0.25$ in the di-J/ψ (a) and J/ψ+ψ(2S) (b) channels. The bars and shaded areas represent uncertainties of data and predictions in each bin, respectively. The arrows in the lower panel indicate that the ratio of data to prediction is out of range in that bin.

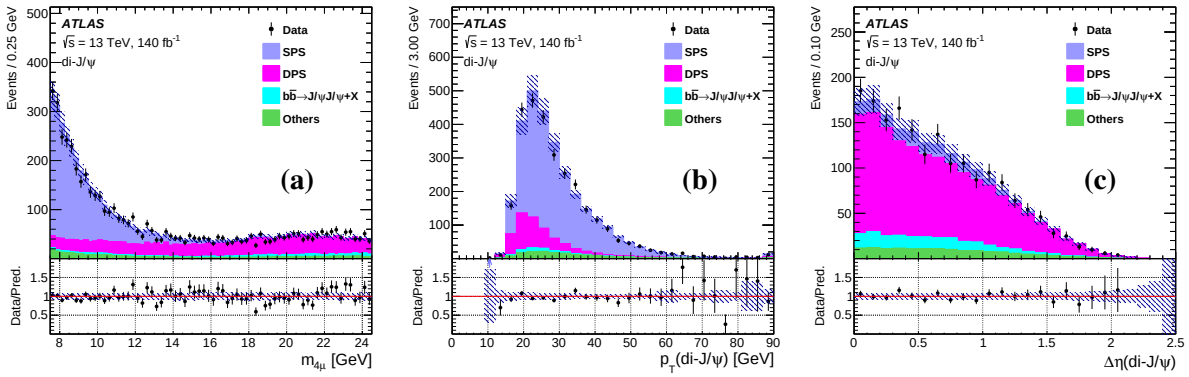

Figure 4: The 4μ mass spectrum within $[7.5,\ 24.5]$ GeV and without the ΔR requirement (a), p_{T} of the di-charmonium in the SPS control region with 7.5 GeV $< m_{4\mu} <$ 12.0 GeV (b), and $\Delta\eta$ between the charmonia in the DPS control region with 14.0 GeV $< m_{4\mu} <$ 24.5 GeV (c), in the di-J/ψ channel.

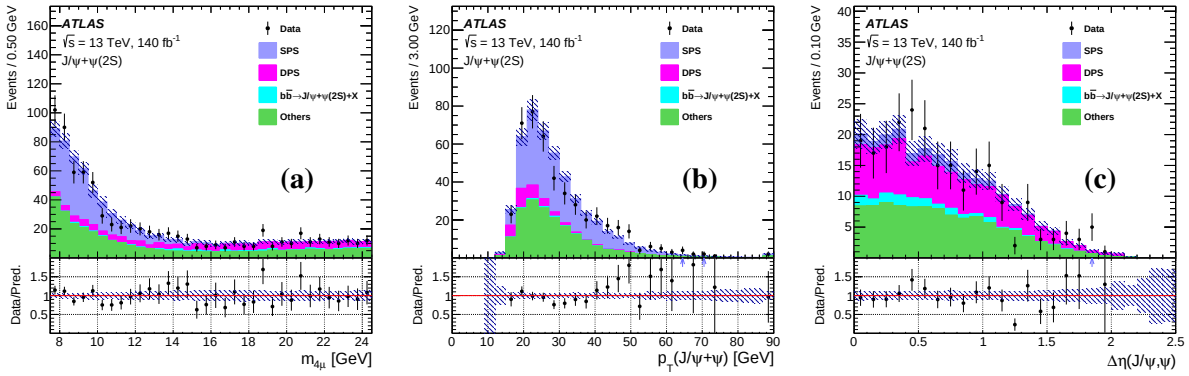

Figure 5: The 4μ mass spectrum within $[7.5,\ 24.5]$ GeV and without the ΔR requirement (a), p_{T} of the di-charmonium in the SPS control region with 7.5 GeV $< m_{4\mu} <$ 12.0 GeV (b), and $\Delta\eta$ between the charmonia in the DPS control region with 14.0 GeV $< m_{4\mu} <$ 24.5 GeV (c), in the J/ψ+ψ(2S) channel.

Table 3: Different sources of systematic uncertainty in the mass and natural width (in MeV) of the third (second) resonance in model A (α) of the di-J/ψ (J/ψ+ψ(2S)) channel.

Systematic	di-J/ψ		J/ψ+ψ(2S)	
Uncertainties (MeV)	m_2	Γ_2	m_3	Γ_3
Muon calibration	±6	±7	<1	±1
SPS model parameter	±7	±7	<1	
SPS di-charmonium p_{T}	±7	±8	<1	
Background MC sample size	±7	±8	±1	<1
Mass resolution	±4	-3	-1	$^{+2}_{-4}$
Fit bias	-13	$+10$	$^{+9}_{-10}$	$^{+50}_{-16}$
Shape inconsistency	<1		±4	±6
Transfer factor	—		±5	±23
Presence of 4th resonance	<1		—	
Feed-down	$^{+4}_{-1}$	$^{+6}_{-2}$	—	
Interference of 4th resonance	—		-32	-11
P and D-wave BW	$+9$	$+19$	<1	±1
ΔR and muon p_{T} requirements	$^{+3}_{-2}$	$^{+6}_{-4}$	$^{+1}_{-2}$	-2
Lower resonance shape	—		$^{+3}_{-7}$	$^{+31}_{-34}$

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