

Near-threshold $D\bar{D}$ spectroscopy and observation of a new charmonium state



The LHCb collaboration

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ABSTRACT: Using proton-proton collision data, corresponding to an integrated luminosity of 9 fb^{-1} , collected with the LHCb detector between 2011 and 2018, a new narrow charmonium state, the X(3842) resonance, is observed in the decay modes $X(3842) \rightarrow D^0\bar{D}^0$ and $X(3842) \rightarrow D^+D^-$. The mass and the natural width of this state are measured to be

$$\begin{aligned} m_{X(3842)} &= 3842.71 \pm 0.16 \pm 0.12 \text{ MeV}/c^2, \\ \Gamma_{X(3842)} &= 2.79 \pm 0.51 \pm 0.35 \text{ MeV}, \end{aligned}$$

where the first uncertainty is statistical and the second is systematic. The observed mass and narrow natural width suggest the interpretation of the new state as the unobserved spin-3 $\psi_3(1^3D_3)$ charmonium state.

In addition, prompt hadroproduction of the $\psi(3770)$ and $\chi_2(3930)$ states is observed for the first time, and the parameters of these states are measured to be

$$\begin{aligned} m_{\psi(3770)} &= 3778.1 \pm 0.7 \pm 0.6 \text{ MeV}/c^2, \\ m_{\chi_2(3930)} &= 3921.9 \pm 0.6 \pm 0.2 \text{ MeV}/c^2, \\ \Gamma_{\chi_2(3930)} &= 36.6 \pm 1.9 \pm 0.9 \text{ MeV}, \end{aligned}$$

where the first uncertainty is statistical and the second is systematic.

KEYWORDS: Charm physics, Hadron-Hadron scattering (experiments), Heavy quark production, Quarkonium

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1 Introduction

Since the discovery of the J/ψ resonance in 1974 [1, 2], the spectrum of hidden charm mesons has been mapped out experimentally with high precision. Theoretically, the spectra and properties of these states are well described by potential models [3]. In recent years, there has been a revival of interest in charmonium spectroscopy initially triggered by the discovery of the $\chi_{c1}(3872)$ meson¹ by the Belle experiment [4] and the subsequent observation of other states that do not fit into the conventional hidden-charm spectrum. To be confident that the new states are exotic in nature, all predicted $c\bar{c}$ states need to be accounted for.

Amongst the expected charmonia close to $D\bar{D}$ threshold, the states $\eta_{c2}(1^1D_2)$ and $\psi_3(1^3D_3)$ remain undiscovered [5, 6]. Though the latter state lies above the open charm threshold, the decay to the $D\bar{D}$ final state is suppressed due to the F-wave centrifugal barrier factor. Consequently, the $\psi_3(1^3D_3)$ state is expected to be narrow with a natural width of 1–2 MeV [7, 8]. Predictions for the mass of this state lie in the range 3815–3863 MeV/ c^2 [6, 9–15]. Since it has negative C parity, it cannot be produced in either $\gamma\gamma$ annihilation or $g\bar{g}$ fusion. In ref. [8] it is suggested that a possible production mechanism for this state is via electric-dipole radiative transitions from the $\chi_{c2}(2^3P_2)$ tensor state. In this paper, the observation of a new $c\bar{c}$ meson decaying to both the D^+D^- and $D^0\bar{D}^0$ final states is reported. The data sample used for this analysis corresponds to an integrated

¹Also known as the X(3872) state.

luminosity of 9 fb^{-1} recorded with the LHCb detector in pp collisions at centre-of-mass energies of 7, 8 and 13 TeV, during the years 2011–2018. The mass and width of the new state are quite similar to those expected for the missing $\psi_3(1^3D_3)$ state with $J^{PC} = 3^{--}$. In addition, the production of both $\psi(3770)$ and $\chi_{c2}(3930)$ mesons is observed. The first state is well known through measurements at e^+e^- colliders, but so far it has only been observed in a hadronic environment in the $\mu^+\mu^-$ mass spectrum of $B^+ \rightarrow K^+\mu^+\mu^-$ decays² [16]. The latter state has only been previously observed in the $\gamma\gamma \rightarrow D\bar{D}$ process by the Belle and BaBar experiments [17, 18]. Both analyses prefer a spin assignment of 2 for this state based upon one-dimensional angular distributions.

2 The LHCb detector and simulation

The LHCb detector [19, 20] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the pp interaction region [21], a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes [22, 23] placed downstream of the magnet. The tracking system provides a measurement of the momentum, p , of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/ c . The momentum scale is calibrated using samples of $J/\psi \rightarrow \mu^+\mu^-$ and $B^+ \rightarrow J/\psi K^+$ decays collected concurrently with the data sample used for this analysis [24, 25]. The relative accuracy of this procedure is estimated to be 3×10^{-4} using samples of other fully reconstructed b hadrons, Υ and K_S^0 mesons. The minimum distance of a track to a primary vertex (PV), the impact parameter (IP), is measured with a resolution of $(15 + 29/p_T) \mu\text{m}$, where p_T is the component of the momentum transverse to the beam, in GeV/ c . Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors (RICH) [26]. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers [27].

The online event selection is performed by a trigger [28], which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. At the hardware trigger stage, events are required to have a muon with high p_T or a hadron, photon or electron with high transverse energy in the calorimeters. The software trigger requires a two-, three- or four-track secondary vertex with a significant displacement from any primary pp interaction vertex. At least one charged particle must have transverse momentum $p_T > 1.6 \text{ GeV}/c$ and be inconsistent with originating from a PV.

The analysis procedure is validated using a simulation in which pp collisions are generated using PYTHIA [29, 30] with a specific LHCb configuration [31]. Decays of unstable particles are described by EVTGEN [32], in which final-state radiation is generated using

²The inclusion of charge-conjugate processes is implied throughout the paper.

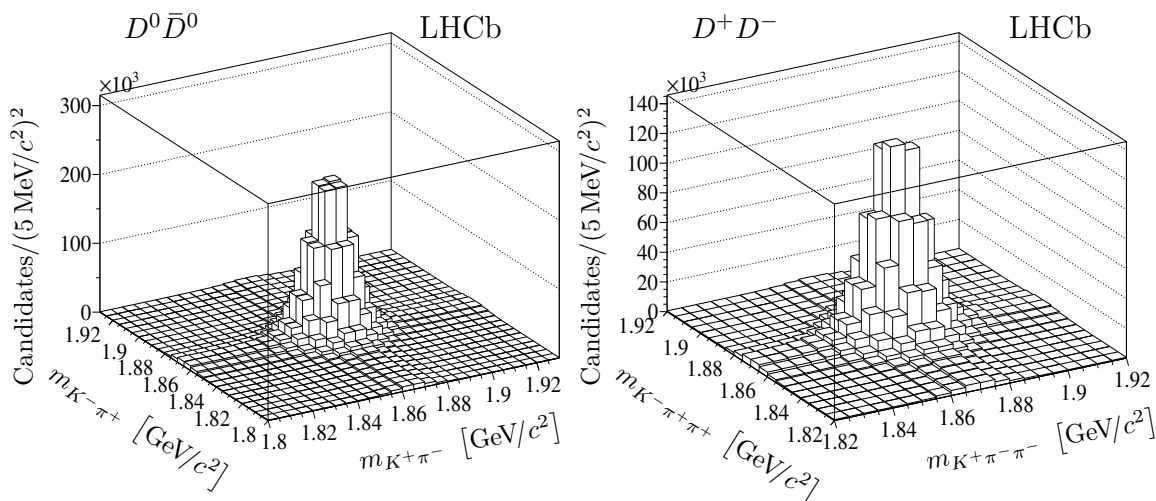


Figure 1. Distributions of (left) $m_{K^- \pi^+}$ versus $m_{K^+ \pi^-}$ and (right) $m_{K^- \pi^+ \pi^+}$ versus $m_{K^+ \pi^- \pi^-}$ for selected $D\bar{D}$ candidates.

PHOTOS [33]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [34, 35] as described in ref. [36].

3 Selection

The criteria used to select D^0 and D^+ candidates are similar to those described in refs. [37–39]. The selection starts from good-quality charged tracks with $p_T > 250 \text{ MeV}/c$ that are inconsistent with being produced in a pp interaction vertex. Selected tracks are required to be identified as either kaons or pions using information from the RICH detectors, and are then used to build D^0 and D^+ candidates reconstructed in the $D^0 \rightarrow K^- \pi^+$ and $D^+ \rightarrow K^- \pi^+ \pi^+$ decay modes. The tracks forming D^0 and D^+ candidates are required to originate from a common vertex. To reduce combinatorial background, the decay time of D^0 and D^+ candidates is required to exceed $100 \mu\text{m}/c$ and the momentum direction to be consistent with the vector from the primary to the secondary vertex. The latter requirement also reduces the contribution from charm hadrons produced in the weak decays of long-lived beauty hadrons. Selected D^0 and D^+ candidates, generically referred to as D candidates hereafter, with $p_T > 1 \text{ GeV}/c$ are combined to form $D^0 \bar{D}^0$ and $D^+ D^-$ candidates. A fit is performed for each $D\bar{D}$ candidate [40], such that both D mesons are required to originate from a common vertex that is consistent with the PV location. A requirement on the fit χ^2 reduces, to a negligible level, the background from D and \bar{D} candidates produced in two independent pp interactions, and further suppresses the contribution from beauty hadrons.

The two-dimensional distributions for the D and \bar{D} masses are shown in figure 1. Only D candidates with mass within $\pm 20 \text{ MeV}/c^2$ (approximately $\pm 3\sigma$) of the known D -meson masses [41] are kept for subsequent analysis. The purity of the selected samples is 88% and 83% for the $D^0 \bar{D}^0$ and $D^+ D^-$ modes, respectively.

4 $D\bar{D}$ mass spectra

To improve the $D\bar{D}$ mass resolution, a new fit [40] is performed with the masses of both D candidates constrained to the known values [41]. After this fit, the $D\bar{D}$ mass spectra for selected $D^0\bar{D}^0$ and D^+D^- pairs close to the $D\bar{D}$ threshold with $m_{D\bar{D}} < 4.2 \text{ GeV}/c^2$ are shown in figure 2. Four peaking structures are seen:

- A narrow peak in the $D^0\bar{D}^0$ spectrum just above the threshold, interpreted as the $\chi_{c1}(3872) \rightarrow D^{*0}\bar{D}^0$ decay, followed by $D^{*0} \rightarrow D^0\pi^0$ or $D^{*0} \rightarrow D^0\gamma$ — due to the small energy release in this decay, the mass of the $D\bar{D}$ pair gives a narrow peak in the $D^0\bar{D}^0$ mass spectrum at the $D^0\bar{D}^0$ threshold;
- A broad peak close to $3780 \text{ MeV}/c^2$, visible both in $D^0\bar{D}^0$ and D^+D^- mass spectra and associated with the contribution from $\psi(3770) \rightarrow D\bar{D}$ decays;
- A very narrow peak at $m_{D\bar{D}} \approx 3840 \text{ MeV}/c^2$, referred to hereafter as X(3842);
- A wide structure in the D^+D^- mass spectrum at $m_{D^+D^-} \approx 3920 \text{ MeV}/c^2$ also visible in the $D^0\bar{D}^0$ mass spectrum and interpreted to be due to $\chi_{c2}(3930) \rightarrow D\bar{D}$ decays.

To better parameterise the background, fits to the $D\bar{D}$ mass spectra are performed separately in three different overlapping mass regions: a narrow region $3.80 < m_{D\bar{D}} < 3.88 \text{ GeV}/c^2$ around the X(3842) peak; the high-mass region $3.8 < m_{D\bar{D}} < 4.2 \text{ GeV}/c^2$ and the near-threshold region $m_{D\bar{D}} < 3.88 \text{ GeV}/c^2$.

4.1 Mass region $3.80 < m_{D\bar{D}} < 3.88 \text{ GeV}/c^2$

The narrow natural width and the mass of the X(3842) state suggest the interpretation of the X(3842) state as the $\psi_3(1^3D_3)$ charmonium state with $J^{PC} = 3^{--}$ [8]. The X(3842) signal is modelled by a relativistic Breit-Wigner function with Blatt-Weisskopf form factors [42]. The orbital angular momentum between the D and \bar{D} mesons is assumed to be $L = 3$. Alternative hypotheses for the spin assignment are discussed in section 5. The relativistic Breit-Wigner function is convolved with the detector resolution, described by a sum of two Gaussian functions with common mean and parameters fixed from simulation. The effective resolution depends on $m_{D^+D^-}$ and increases from $0.9 \text{ MeV}/c^2$ for $\psi(3770) \rightarrow D^+D^-$ to $1.9 \text{ MeV}/c^2$ for $\chi_{c2}(3930) \rightarrow D^+D^-$ signals and is approximately 10% larger for the $D^0\bar{D}^0$ final state. The background in this region is found to be well described by a second-order polynomial function.

An extended unbinned maximum-likelihood fit is performed simultaneously to the $D^0\bar{D}^0$ and D^+D^- mass spectra. The mass and the natural width of the X(3842) signals in the $D^0\bar{D}^0$ and D^+D^- final state are considered as common parameters in this fit whilst all other parameters are allowed to vary independently. All parameters related to the detector resolution are fixed to values found using simulation. The result of the fit to the data is shown in figure 3 and the resulting parameters of interest are summarised in table 1. The statistical significance of the X(3842) signal is evaluated using Wilks' theorem [43] to be above 7σ for the $D^0\bar{D}^0$ decay mode and above 21σ for the D^+D^- decay mode.

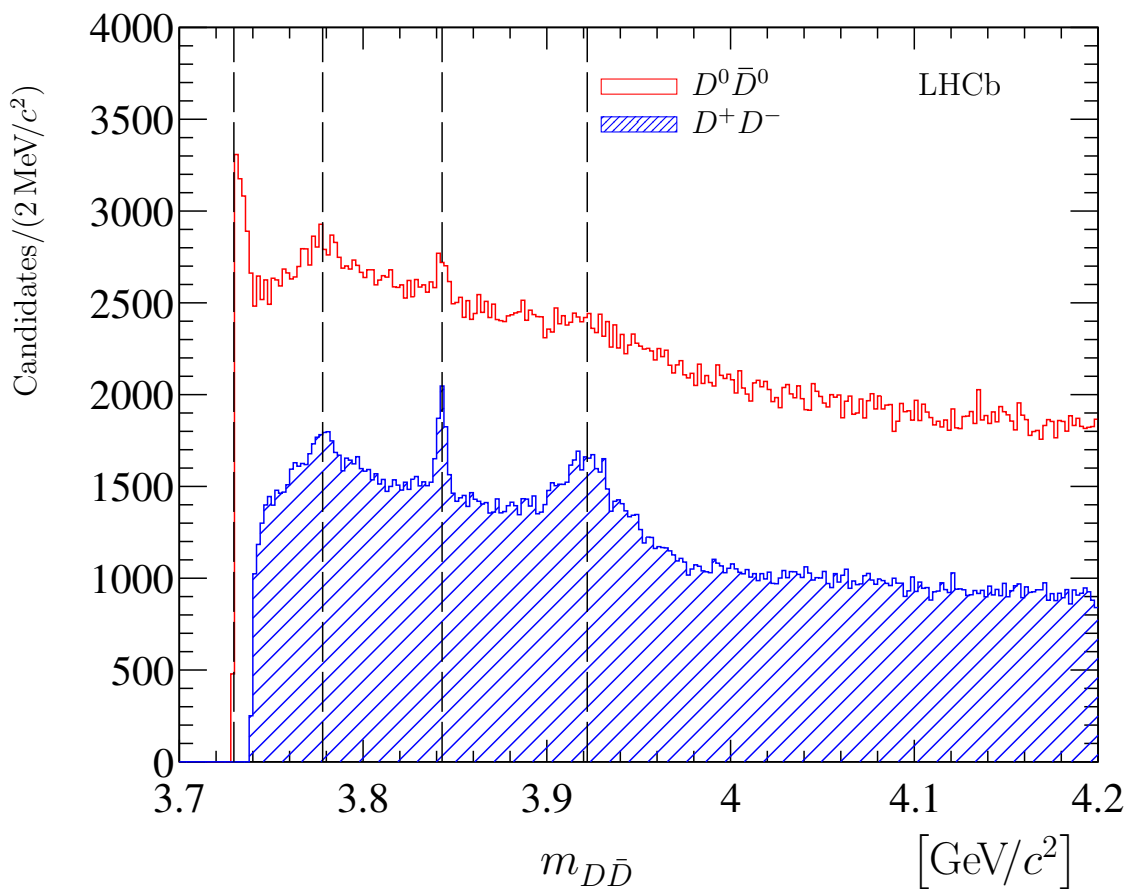


Figure 2. The mass spectra for selected $D\bar{D}$ combinations. The open red histogram corresponds to $D^0\bar{D}^0$ pairs, while the hatched blue histogram corresponds to D^+D^- pairs. Vertical black dashed lines help to identify the peaks from (left to right) $\chi_{c1}(3872) \rightarrow D^{*0}\bar{D}^0$, $\psi(3770) \rightarrow D\bar{D}$, $X(3842) \rightarrow D\bar{D}$ and $\chi_{c2}(3930) \rightarrow D\bar{D}$ decays.

	$N_{X(3842)}$	$m_{X(3842)}$ [MeV/ c^2]	$\Gamma_{X(3842)}$ [MeV]
$D^0\bar{D}^0$	930 ± 170	3842.71 ± 0.16	2.79 ± 0.51
D^+D^-	2070 ± 190		

Table 1. Yields, mass and width of the X(3842) state from the fit to $D\bar{D}$ mass spectra in the narrow $3.80 < m_{D\bar{D}} < 3.88$ GeV/ c^2 region. Uncertainties are statistical only.

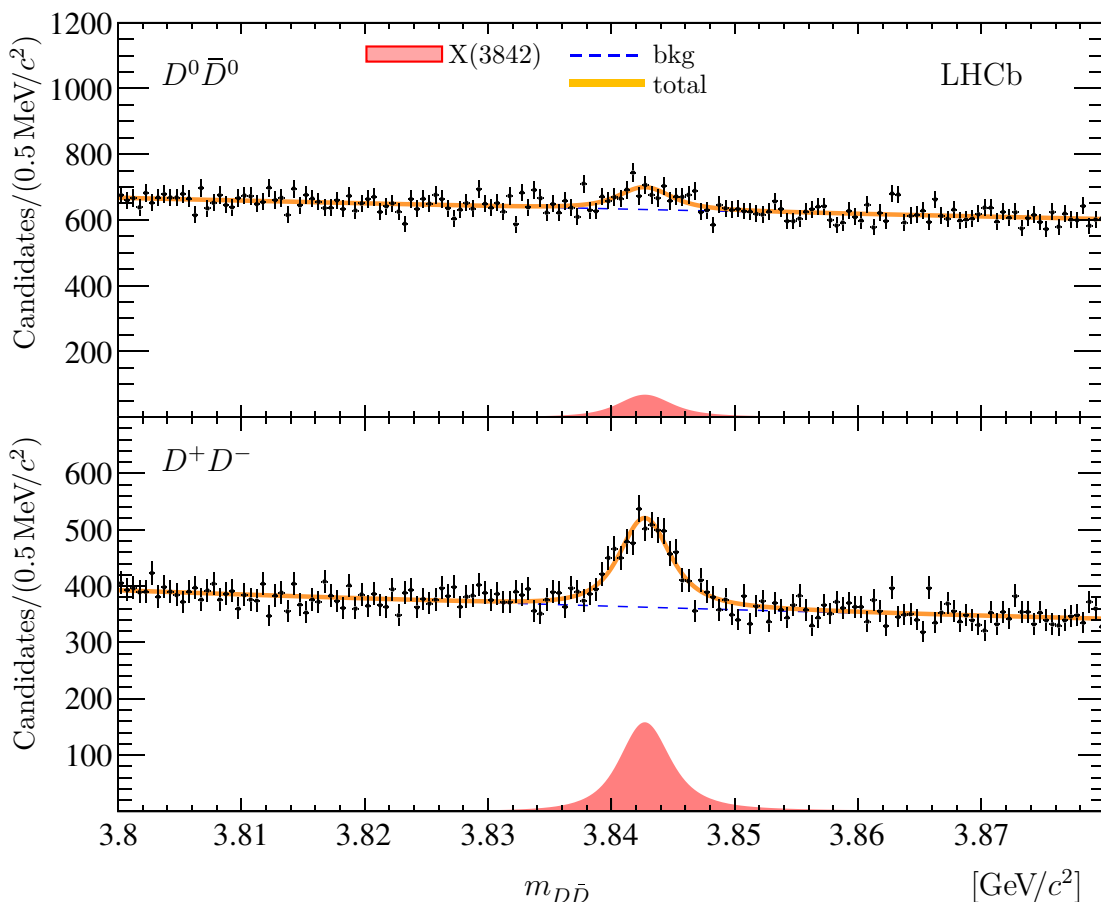


Figure 3. Mass spectra of (top) $D^0\bar{D}^0$ and (bottom) D^+D^- candidates in the narrow $3.80 < m_{D\bar{D}} < 3.88 \text{ GeV}/c^2$ region. The result of the simultaneous fit described in the text is superimposed.

4.2 Mass region $3.80 < m_{D\bar{D}} < 4.20 \text{ GeV}/c^2$

Two signal components are used to describe the $3.80 < m_{D\bar{D}} < 4.20 \text{ GeV}/c^2$ region: the X(3842) component, described earlier, and a component for the $\chi_{c2}(3930)$ decay, modelled by the convolution of a relativistic D-wave Breit-Wigner function with the resolution model described above. The background in this mass region is modelled by an exponential function multiplied by a second-order polynomial function. The total fit consists of the sum of the background and the X(3842) and $\chi_{c2}(3930)$ signals. A simultaneous extended binned maximum-likelihood fit to the $D^0\bar{D}^0$ and D^+D^- mass spectra is performed with the mass and natural width of the X(3842) state fixed to the results of the fit in the narrow $3.80 < m_{D\bar{D}} < 3.88 \text{ GeV}/c^2$ region. The mass and the natural width of the $\chi_{c2}(3930)$ signals in the $D^0\bar{D}^0$ and D^+D^- final states and the slope of the background exponential function are common parameters and all other parameters are allowed to vary independently. The result of the fit of this model to the data is shown in figure 4 and the resulting parameters of interest are summarised in table 2. If the wide peak in figure 4

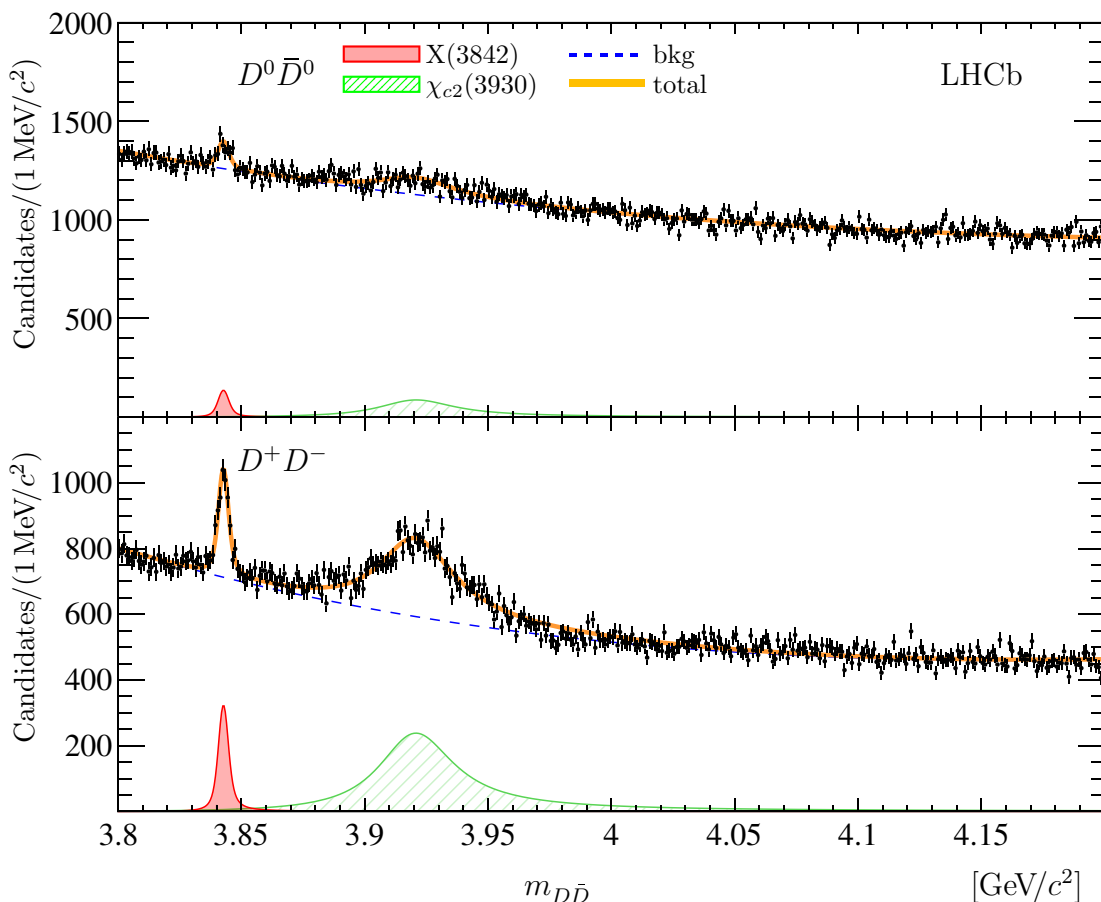


Figure 4. Mass spectra of (top) $D^0\bar{D}^0$ and (bottom) D^+D^- candidates in the high-mass $3.80 < m_{D\bar{D}} < 4.20 \text{ GeV}/c^2$ region. The result of the simultaneous fit described in the text is superimposed.

	$N_{\chi_{c2}(3930)} [10^3]$	$m_{\chi_{c2}(3930)} [\text{MeV}/c^2]$	$\Gamma_{\chi_{c2}(3930)} [\text{MeV}]$
$D^0\bar{D}^0$	4.7 ± 0.5	3921.90 ± 0.55	36.64 ± 1.88
D^+D^-	13.0 ± 0.6		

Table 2. Yields, mass and width of the $\chi_{c2}(3920)$ state from the fit to $D\bar{D}$ mass spectra in the high-mass $3.88 < m_{D\bar{D}} < 4.20 \text{ GeV}/c^2$ region. Uncertainties are statistical only.

is instead assumed to be spin-0 then the mass decreases by $0.12 \text{ MeV}/c^2$ while variations in the width and the uncertainties in the mass and width are negligible.

4.3 Mass region $m_{D\bar{D}} < 3.88 \text{ GeV}/c^2$

To fit the $D\bar{D}$ mass spectra in the near-threshold region, $m_{D\bar{D}} < 3.88 \text{ GeV}/c^2$, components for the $X(3842)$ and $\psi(3770)$ decays to $D\bar{D}$ signals and the background are included. In the case of the $D^0\bar{D}^0$ mass spectrum, an additional contribu-

	$N_{\psi(3770)} [10^3]$	$m_{\psi(3770)} [\text{MeV}/c^2]$
$D^0\bar{D}^0$	5.1 ± 0.5	3778.13 ± 0.70
D^+D^-	5.7 ± 0.4	

Table 3. Yields and mass of the $\psi(3770)$ state from the fit to $D\bar{D}$ mass spectra in the near-threshold $m_{D\bar{D}} < 3.88 \text{ GeV}/c^2$ region. Uncertainties are statistical only.

tion from $\chi_{c1}(3872) \rightarrow D^{*0}\bar{D}^0$ decays followed by $D^{*0} \rightarrow D^0\pi^0$ or $D^{*0} \rightarrow D^0\gamma$ is required. The $\psi(3770) \rightarrow D\bar{D}$ component is modelled as a relativistic multi-channel P-wave Breit-Wigner function [44, 45], accounting for decays into $D^0\bar{D}^0$, D^+D^- and non- $D\bar{D}$ final states [41], convolved with a double-Gaussian resolution model. The background is modelled as a product of a scaled two-body phase-space function and a second-order polynomial function. The shape of the feed-down contribution from $\chi_{c1}(3872)$ decays is described using simulated two-body $\chi_{c1}(3872) \rightarrow D^{*0}\bar{D}^0$ and three-body $\chi_{c1}(3872) \rightarrow D^0\bar{D}^0\pi^0$ decays. The latter corresponds to off-shell decays of the intermediate D^{*0} mesons [46, 47]. The simulation of $\chi_{c1}(3872) \rightarrow D^{*0}\bar{D}^0$ decays assumes that the D^{*0} mesons are unpolarised and the three-body decay dynamics are not included. The contributions from the two-body and three-body decays of the $\chi_{c1}(3872)$ state are allowed to vary independently in the fit.

A simultaneous binned extended maximum-likelihood fit to the $D^0\bar{D}^0$ and D^+D^- mass spectra is performed. In this fit, the mass and width of the X(3842) signal are fixed from the results of the unbinned fit in the narrow $3.80 < m(D\bar{D}) < 3.88 \text{ GeV}/c^2$ region, the mass of the $\psi(3770)$ state is allowed to vary, while the natural width of the $\psi(3770)$ state is Gaussian-constrained to the known value of $\Gamma_{\psi(3770)} = 27.2 \pm 1.0 \text{ MeV}$ [41]. The mass of the $\psi(3770)$ state and the scale factor for the background two-body phase space function are common parameters and all other parameters are allowed to vary independently. The result of the fit to the $D^0\bar{D}^0$ and D^+D^- mass spectra is shown in figure 5 and the resulting parameters of interest are summarised in table 3. The fit quality in the region $m_{D^0\bar{D}^0} < 3.74 \text{ GeV}/c^2$ is poor, possibly due to large effects of the neglected dynamics in $\chi_{c1}(3872) \rightarrow D^0\bar{D}^0X$ decays. However, it is found that the exact description of the $\chi_{c1}(3872)$ contribution does not affect the measurement of the mass of the $\psi(3770)$ state.

5 Systematic uncertainties

In the proximity of the $D\bar{D}$ mass threshold most potential systematic uncertainties for the mass and natural width measurements become negligible when D mass constraints are applied. The main systematic uncertainties for the measured X(3842), $\chi_{c2}(3930)$ and $\psi(3770)$ resonance parameters are related to the signal and background parameterisation, the momentum-scale calibration and the uncertainty in the known D^0 and D^+ masses [41]. These are described below and summarised in table 4.

To evaluate the systematic uncertainty related to the parameterisation of the signal shape, the parameters of the relativistic Breit-Wigner functions are varied. In particular, the meson radius, entering the Blatt-Weisskopf centrifugal factor with the default value

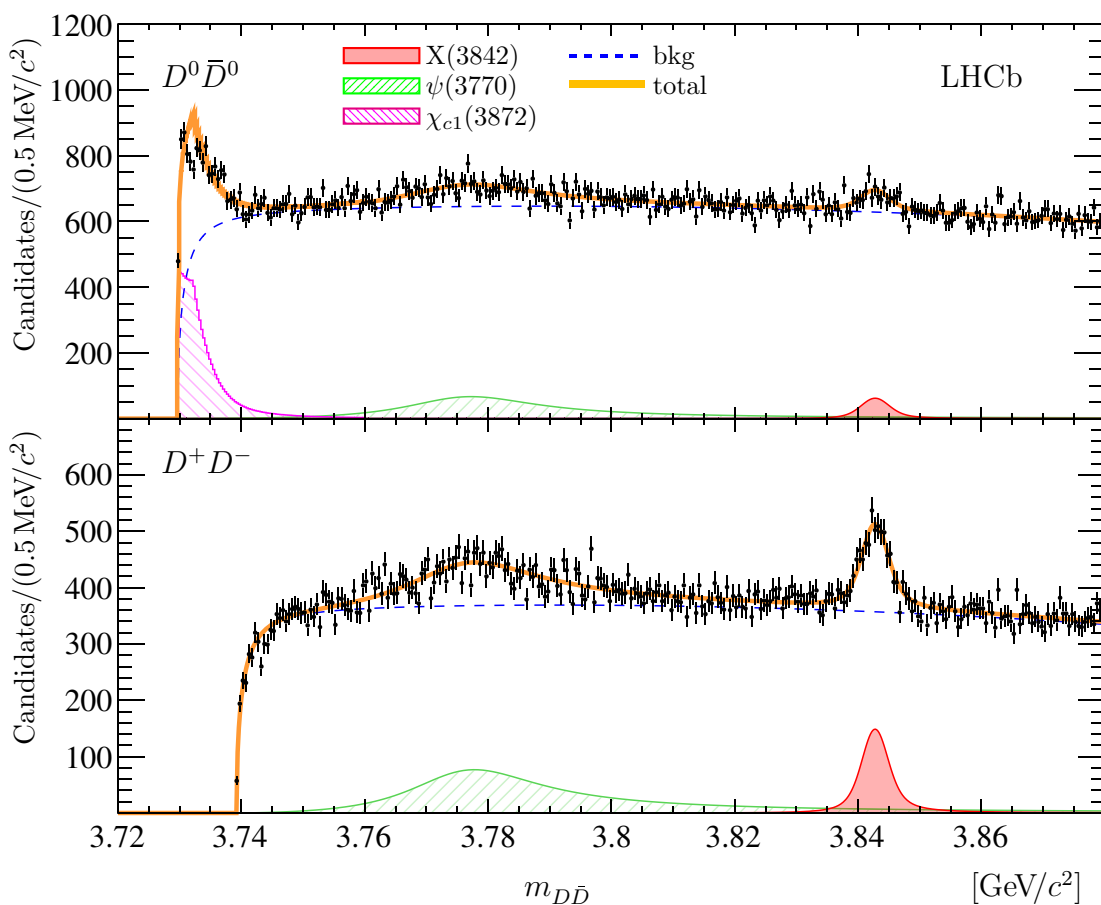


Figure 5. Mass spectra of (top) $D^0\bar{D}^0$ and (bottom) D^+D^- candidates in the near-threshold $m_{D\bar{D}} < 3.88 \text{ GeV}/c^2$ region. The result of the simultaneous fit described in the text is superimposed.

Source	X(3842)		$\chi_{c2}(3930)$		$\psi(3770)$
	σ_m [MeV/ c^2]	σ_Γ [MeV]	σ_m [MeV/ c^2]	σ_Γ [MeV]	σ_m [MeV/ c^2]
Signal model	0.02	0.02	0.01	0.15	0.62
Resolution		0.31		0.20	
Background model		0.13	0.15	0.81	0.03
Momentum scale	0.07	—	0.05	—	
D -meson masses	0.10	—	0.10	—	0.10
Sum in quadrature	0.12	0.35	0.19	0.85	0.63

Table 4. Summary of systematic uncertainties for the measured masses (σ_m) and width (σ_Γ) of the X(3842), $\chi_{c2}(3930)$ and $\psi(3770)$ states. Uncertainties for the mass (width) smaller than $10 \text{ keV}/c^2$ (10 keV) are not shown.

of 3.5 GeV^{-1} , is varied between 1.5 GeV^{-1} and 5 GeV^{-1} . In the case of the X(3842) state, where the quantum numbers are unknown, the orbital momentum is varied between zero and four. For the X(3842) and $\chi_{c2}(3930)$ states, alternative signal descriptions with multi-channel relativistic Breit-Wigner functions with $D^0\bar{D}^0$ and D^+D^- and radiative non- $D\bar{D}$ decays are used. For the $\psi(3770)$ signal, the parameters of the multi-channel relativistic P-wave Breit-Wigner function, namely the ratio of branching fractions to $D^0\bar{D}^0$ and D^+D^- final states, and the branching fraction for non- $D\bar{D}$, are varied within their known uncertainties [41].

The determination of the natural width of the X(3842) and $\chi_{c2}(3930)$ states relies on accurate modelling of the detector resolution. Comparing data and simulation for decay modes with low energy release such as the $\chi_{c1} \rightarrow J/\psi \mu^+ \mu^-$ decay, agreement at the 10% level is found [48]. Even better agreement is found for b -hadron decays to pairs of open charm hadrons such as $B^0 \rightarrow D_s^+ D^-$, $A_b^0 \rightarrow A_c^+ D_s^-$ and $A_b^0 \rightarrow A_c^+ D^-$ [49], where the energy release is larger. Hence, to estimate the corresponding uncertainty the resolution scale is varied by 10% and the fit is repeated. Alternative resolution models, such as a symmetric double-sided Crystal Ball function [50, 51] and a symmetric variant of the Apollonios function [52] are used to estimate the uncertainty associated with this choice.

The uncertainty in the knowledge of the width of the $\psi(3770)$ resonance [41] is propagated by applying a Gaussian constraint in the fit, and it is therefore a part of the statistical uncertainty for the measured mass of the $\psi(3770)$ state. The effect of fixing the parameters of the X(3842) state in the fits in the $m_{D\bar{D}} < 3.88 \text{ GeV}/c^2$ and $m_{D\bar{D}} > 3.8 \text{ GeV}/c^2$ regions on the parameters of the $\chi_{c2}(3930)$ and $\psi(3770)$ states is found to be negligible. The effect of the poorly known shape for the $\chi_{c1}(3872) \rightarrow D^0\bar{D}^0 X$ component has no visible effect on the determination of the mass of the $\psi(3770)$ state.

The impact of the choice of the background model is estimated by changing the order of the polynomial functions from second to fourth order and, for fits in the $3.80 < m_{D\bar{D}} < 3.88 \text{ GeV}/c^2$ and $m_{D\bar{D}} < 3.88 \text{ GeV}/c^2$ regions, by including an exponential factor to the background model. For the fit in the $3.80 < m_{D\bar{D}} < 3.88 \text{ GeV}/c^2$ region, the contributions from the long tails of the wide $\psi(3770)$ and $\chi_{c2}(3930)$ resonances are accounted for.

The Particle Data Group (PDG) [41] reports various heavy or exotic charmonium candidates that decay to $D\bar{D}$, $D^*\bar{D}$ and $D^*\bar{D}^*$ final states. Typically, these states are relatively broad and consequently they will only be visible as a distortion of the background shape. To study the impact of these charmonium states on the measurements made here, the decays $Z_c(3900) \rightarrow D^0 D^{*-}$, $X(4020) \rightarrow D^* \bar{D}^*$, $\chi_{c0}(3860) \rightarrow D\bar{D}$, and decays of $\psi(4040)$, $\psi(4160)$, $\psi(4415)$ to $D\bar{D}$, $D^*\bar{D}$ and $D^*\bar{D}^*$ final states [41] are simulated and individually added as fit components in turn. For these studies, the measurements of the relative direct ($D\bar{D}$) and feed-down ($D^*\bar{D}$ and $D^*\bar{D}^*$) contributions [41] provide important constraints. Fits including decays of the $\chi_{c0}(3860)$, $\psi(4040)$ or $\psi(4160)$ states are found to modify the background component and cause a maximum of $0.15 \text{ MeV}/c^2$ bias on the mass and a maximum of 0.5 MeV bias on the natural width of the $\chi_{c2}(3930)$ state. These are accounted for as uncertainties due to the background description. Contributions from other charmonium or charmonium-like states have no effect in the determination of the parameters of the X(3842), $\chi_{c2}(3930)$ and $\psi(3770)$ states.

An important experimental uncertainty for the mass measurements is the knowledge of the momentum scale. This is minimised by the application of the D -mass constraints. The residual uncertainty from this source is evaluated by adjusting the momentum scale by the 3×10^{-4} uncertainty on the calibration procedure and repeating the mass fit. A further uncertainty of $0.1 \text{ MeV}/c^2$ arises from the knowledge of the D^0 and D^+ masses [41].

6 Production mechanism

The selection criteria used in this analysis significantly suppress a potential contribution from weak decays of long-lived beauty hadrons. To probe the residual contribution from b -hadron decays, the sample of $D\bar{D}$ pairs is split into two subsamples according to the value of the t_z variable [53]

$$t_z \equiv \frac{z_{D\bar{D}} - z_{\text{PV}}}{p_z} m_{D\bar{D}},$$

where $z_{D\bar{D}}$ and z_{PV} are the positions along the z -axis (the beam direction) of the reconstructed $D\bar{D}$ vertex and of the primary vertex, and p_z is the measured $D\bar{D}$ momentum in the z direction. Promptly produced charmonia are characterised by a nearly symmetric and narrow distribution around $t_z = 0$, whilst almost all $D\bar{D}$ pairs being produced in the weak decays of long-lived beauty hadrons have $t_z > 0$. Comparison of the observed yields of the X(3842), $\chi_{c2}(3930)$ and $\psi(3770)$ signals for $t_z < 0$ and $t_z > 0$ subsamples shows no sizeable contributions from decays of b hadrons to the X(3842) and $\chi_{c2}(3930)$ signals, while a contribution of $\sim 35\%$ to the observed yield of the $\psi(3770) \rightarrow D\bar{D}$ decays is found.

Reference [8] suggests the decay $\chi_{c2}(2^3P_2) \rightarrow \psi_3(1^3D_3)\gamma$ as a possible production mechanism for the $\psi_3(1^3D_3)$ state. The hypothesis is tested as follows. Identifying the $\chi_{c2}(3930)$ as $\chi_{c2}(2^3P_2)$ and X(3842) as $\psi_3(1^3D_3)$ and taking $\Gamma(\chi_{c2}(2^3P_2) \rightarrow \psi_3(1^3D_3)\gamma)$ to be 100 keV [8], from the present measurement of the $\chi_{c2}(3930)$ state width and the observed yields of $\chi_{c2}(3930) \rightarrow D\bar{D}$ decays, at most 5% of the observed X(3842) $\rightarrow D\bar{D}$ decays can originate from the decays of the $\chi_{c2}(3930)$ state. This suggests, assuming the $\psi_3(1^3D_3)$ assignment is correct, that either $\Gamma(\chi_{c2}(2^3P_2) \rightarrow \psi_3(1^3D_3)\gamma)$ is significantly larger than expected or that a large fraction of the X(3842) signal is produced via a different production mechanism.

7 Results and discussion

Using the LHCb dataset collected between 2011 and 2018, near-threshold $D\bar{D}$ mass spectra are studied and a new narrow charmonium state, the X(3842), is observed in the decay modes $X(3842) \rightarrow D^0\bar{D}^0$ and $X(3842) \rightarrow D^+D^-$ with very high statistical significance. The mass and the natural width of this state are measured to be

$$\begin{aligned} m_{X(3842)} &= 3842.71 \pm 0.16 \pm 0.12 \text{ MeV}/c^2, \\ \Gamma_{X(3842)} &= 2.79 \pm 0.51 \pm 0.35 \text{ MeV}, \end{aligned}$$

where the first uncertainty is statistical and the second is systematic. The narrow natural width and measured value of the mass suggests the interpretation of the X(3842) state as the $\psi_3(1^3D_3)$ charmonium state with $J^{PC} = 3^{--}$.

		$m_{\chi_{c2}(3930)}$ [MeV/ c^2]	$\Gamma_{\chi_{c2}(3930)}$ [MeV]
Belle	[17]	$3929 \pm 5 \pm 2$	$29 \pm 10 \pm 2$
BaBar	[18]	$3926.7 \pm 2.7 \pm 1.1$	$21.3 \pm 6.8 \pm 3.6$
This analysis		$3921.9 \pm 0.6 \pm 0.2$	$36.6 \pm 1.9 \pm 0.9$

Table 5. Summary of mass and width measurements for the $\chi_{c2}(3930)$ state.

In addition, prompt hadroproduction of the $\chi_{c2}(3930)$ state is observed for the first time, and the parameters of this state are measured to be

$$m_{\chi_{c2}(3930)} = 3921.9 \pm 0.6 \pm 0.2 \text{ MeV}/c^2,$$

$$\Gamma_{\chi_{c2}(3930)} = 36.6 \pm 1.9 \pm 0.9 \text{ MeV}.$$

These values are considerably more precise than previous measurements made at e^+e^- machines, as can be seen from table 5. The mass measured in this analysis is 2σ lower than the current world average whilst the natural width is 2σ higher. It is interesting to note that the measured value of the mass is roughly midway between the masses quoted in ref. [41] for this state and for the X(3915) meson, which is only known to decay to the $J/\psi\omega$ final state [54–58]. Further studies are needed to understand if there are two distinct charmonium states in this region or only one as suggested in ref. [59].

Finally, prompt hadroproduction of the $\psi(3770)$ state is observed for the first time, and the mass of this state is measured to be

$$m_{\psi(3770)} = 3778.1 \pm 0.7 \pm 0.6 \text{ MeV}/c^2.$$

The measured mass agrees well with the value determined by Shamov and Todyshev [60] from available e^+e^- cross-section data. It also agrees well with and has a better precision than the current world average [41], referred as PDG average in table 6, which is dominated by the value measured by the KEDR collaboration [44]. Reference [41] also quotes a value, referred as PDG fit, resulting from a fit that includes precision measurements of the mass difference between the $\psi(3770)$ and $\psi(2S)$ states made by the BES collaboration [45, 61, 62]. Both the measurement made here and the PDG average are in disagreement with the PDG fit value.

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		$m_{\psi(3770)}$ [MeV/ c^2]
Shamov and Todyshev	[60]	3779.8 ± 0.6
PDG average	[41]	3778.1 ± 1.2
PDG fit	[41]	3773.13 ± 0.35
This analysis		$3778.1 \pm 0.7 \pm 0.6$

Table 6. Summary of mass measurements for the $\psi(3770)$ state.

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The LHCb collaboration

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