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Measurement of $\chi_{c1}(3872)$ production in proton-proton collisions at $\sqrt{s} = 8$ and 13 TeV



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ABSTRACT: The production cross-section of the $\chi_{c1}(3872)$ state relative to the $\psi(2S)$ meson is measured using proton-proton collision data collected with the LHCb experiment at centre-of-mass energies of $\sqrt{s} = 8$ and 13 TeV, corresponding to integrated luminosities of 2.0 and 5.4 fb⁻¹, respectively. The two mesons are reconstructed in the $J/\psi\pi^+\pi^-$ final state. The ratios of the prompt and nonprompt $\chi_{c1}(3872)$ to $\psi(2S)$ production cross-sections are measured as a function of transverse momentum, p_T , and rapidity, y , of the $\chi_{c1}(3872)$ and $\psi(2S)$ states, in the kinematic range $4 < p_T < 20$ GeV/ c and $2.0 < y < 4.5$. The prompt ratio is found to increase with p_T , independently of y . For the prompt component, the double ratio of the $\chi_{c1}(3872)$ and $\psi(2S)$ production cross-sections between 13 and 8 TeV is observed to be consistent with unity, independent of p_T and centre-of-mass energy.

KEYWORDS: Hadron-Hadron Scattering

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1 Introduction

The $\chi_{c1}(3872)$ state was observed in the $J/\psi\pi^+\pi^-$ invariant-mass spectrum by the Belle collaboration in 2003 [1], and was subsequently confirmed by the BaBar, CDF and D0 collaborations [2–4]. Its quantum numbers have been determined to be $J^{PC} = 1^{++}$ by the LHCb collaboration [5]. Nevertheless, despite intense experimental and theoretical studies, the nature of the state is still unclear. The mass is close to the $D^0\bar{D}^{*0}$ threshold, which led to models where the $\chi_{c1}(3872)$ state is a $D^0\bar{D}^{*0}$ molecule with a very small binding energy [6, 7]. The LHCb collaboration indeed measured that the mass is slightly below that threshold [8, 9]. However, the differential production cross-section measured by the CMS collaboration [10] is lower than that predicted by non-relativistic QCD (NRQCD) [11] for the $D^0\bar{D}^{*0}$ molecule hypothesis. If the $\chi_{c1}(3872)$ state were a weakly bound molecule state, it could also be produced by the creation of a $D^*\bar{D}^*$ pair at short distance followed by a rescattering into the $\chi_{c1}(3872)\pi$ final state [12, 13]. However the production of the $\chi_{c1}(3872)$ accompanied by a pion has not been observed so far [14]. Alternatively, the $\chi_{c1}(3872)$ state can be interpreted as an admixture of $\chi_{c1}(2P)$ and $D^0\bar{D}^{*0}$ molecule states, produced through its $\chi_{c1}(2P)$ component [15]. Under this hypothesis, a next-to-leading-order (NLO) NRQCD calculation [16] tuned to the results obtained by the CMS collaboration, agrees well with measurements performed by the ATLAS collaboration in a much wider range of the $\chi_{c1}(3872)$ transverse momentum [17]. Recently, the ratio of

prompt-production cross-sections between $\chi_{c1}(3872)$ and $\psi(2S)$ states produced directly from proton-proton (pp) collisions, as a function of multiplicity of the charged particles in an event, has been measured by the LHCb collaboration using 8 TeV pp collision data [18]. This ratio is found to decrease with multiplicity. The interpretation of this observation is still unclear [19, 20]. Recent measurements of the $B_s^0 \rightarrow \chi_{c1}(3872)\phi$ branching fraction [21, 22] would support the interpretation of the $\chi_{c1}(3872)$ state as a tetraquark [23].

In this paper, the double-differential production cross-section of the $\chi_{c1}(3872)$ state relative to that of the $\psi(2S)$ meson, where both decay to $J/\psi\pi^+\pi^-$ with J/ψ decaying to $\mu^+\mu^-$ final state, is measured using pp collision data collected by the LHCb detector at centre-of-mass energies of $\sqrt{s} = 8$ and 13 TeV. The cross-section is determined in intervals of the $J/\psi\pi^+\pi^-$ transverse momentum, p_T , and rapidity, y , within the ranges $4 < p_T < 20$ GeV/ c and $2.0 < y < 4.5$. The cross-section ratio $\sigma_{\chi_{c1}(3872)}/\sigma_{\psi(2S)}$ is measured separately for prompt and nonprompt production of the $\chi_{c1}(3872)$ and $\psi(2S)$ mesons, the latter occurring via b -hadron decays. In this ratio, the systematic uncertainties largely cancel. The production cross-section of the $\chi_{c1}(3872)$ state at a centre-of-mass energy of $\sqrt{s} = 7$ TeV has been previously measured with 35 pb $^{-1}$ of pp collision data [24]. Using the data recorded during the 2012 and 2016–2018 data-taking periods, corresponding to integrated luminosities of 2.0 and 5.4 fb $^{-1}$, the signal yields increase by about a factor of 400, allowing a measurement of the double-differential cross-section to be performed for the first time.

2 Detector and simulation

The LHCb detector [25, 26] 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 [27], 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 [28, 29] 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 minimum distance of a track to a primary pp -collision vertex (PV), the impact parameter (IP), is measured with a resolution of $(15 + 29/p_T)$ μm , with p_T , in GeV/ c . Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov (RICH) detectors [30]. The online event selection is performed by a trigger system [31], which consists of a hardware stage, based on information from the muon system, followed by a software stage, which is applied to perform a full event reconstruction. To avoid domination of the trigger CPU time by a few events with high occupancy, a set of global event requirements [31] is applied on the hit multiplicity of each sub-detector used by the pattern recognition algorithms. These requirements reject high-multiplicity events with a large number of pp interactions.

Simulated samples are used to develop the event selection and to estimate the detector acceptance and the efficiency of the imposed selection requirements. Simulated pp collisions are generated using PYTHIA [32, 33] with a specific LHCb configuration [34]. Decays of

unstable particles are described by EVTGEN [35], in which final-state radiation is generated using PHOTOS [36]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [37, 38] as described in ref. [39].

3 Event selection

In the online event selection, signal candidates are required to pass dedicated J/ψ trigger algorithms. These algorithms require at least one muon to have high transverse momentum at the hardware stage, and a pair of oppositely-charged muon candidates to originate from a common vertex and to have an invariant mass in a wide window around the J/ψ mass at the software stage.

The $\chi_{c1}(3872)$ and $\psi(2S)$ candidates are both reconstructed in the $J/\psi\pi^+\pi^-$ final state, with the J/ψ meson decaying into a pair of oppositely charged muons. At least one reconstructed primary vertex is required per event. Muon candidates are required to be well identified, and have $p_T > 650 \text{ MeV}/c$ and $p > 10 \text{ GeV}/c$. Only reconstructed muon tracks of good quality are selected. The $\mu^+\mu^-$ pair is required to have a combined $p_T > 3 \text{ GeV}/c$ and an invariant mass in the range $3010\text{--}3170 \text{ MeV}/c^2$. The χ^2/ndf of the dimuon vertex fit is required to be less than 20, where ndf is the number of degrees of freedom.

Charged pion candidates are selected using particle identification (PID) information from the RICH detectors. The (transverse) momentum of the pions is required to be greater than (500) $3000 \text{ MeV}/c$, while the pion track χ^2/ndf to be less than 4.

The $\chi_{c1}(3872)$ and $\psi(2S)$ candidates are reconstructed by combining each J/ψ candidate with a pair of oppositely charged pions. In order to improve the $J/\psi\pi^+\pi^-$ invariant-mass resolution, a vertex fit constraining the $\mu^+\mu^-$ invariant mass to the known J/ψ mass [40], $m_{J/\psi} = 3096.9 \text{ MeV}/c^2$, is performed. The vertex fit χ^2/ndf is required to be less than 5. The decay energy release, $Q \equiv M_{J/\psi\pi^+\pi^-} - m_{J/\psi} - M_{\pi^+\pi^-}$, with $M_{J/\psi\pi^+\pi^-}$ and $M_{\pi^+\pi^-}$ being the invariant masses of, respectively, $J/\psi\pi^+\pi^-$ and $\pi^+\pi^-$ systems, is required to be less than $300 \text{ MeV}/c^2$.

A pseudo-decay-time of the $\chi_{c1}(3872)$ and $\psi(2S)$ candidates is constructed as

$$t_z = \frac{(z - z_{PV}) \times m}{p_z}, \quad (3.1)$$

where z and z_{PV} are the candidate decay vertex and best-reconstructed PV positions along the beam (z) axis, p_z is the z component of the $\chi_{c1}(3872)$ or $\psi(2S)$ momenta, and m represents the known masses of these states [40]. Only candidates with $|t_z| < 10 \text{ ps}$ are kept for further analysis. The pseudo-decay-time of promptly produced $\chi_{c1}(3872)$ and $\psi(2S)$ mesons is zero, whereas that of mesons originating from b -hadron decays follows an exponential distribution. This variable is used to statistically discriminate between promptly and nonpromptly produced candidates.

4 Cross-section determination

The differential production cross-section of $\chi_{c1}(3872)$ relative to $\psi(2S)$ mesons times their ratio of branching fractions ($\mathcal{B}$) to the $J/\psi\pi^+\pi^-$ final state measured in (p_T, y) intervals is

defined as

$$R \equiv \frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \times \frac{\mathcal{B}(\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-)}{\mathcal{B}(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)} = \frac{N_{\chi_{c1}(3872)}}{N_{\psi(2S)}} \times \frac{\epsilon_{\psi(2S)}}{\epsilon_{\chi_{c1}(3872)}}, \quad (4.1)$$

where $N_{\chi_{c1}(3872)}$ and $N_{\psi(2S)}$ are the observed signal yields of $\chi_{c1}(3872)$ and $\psi(2S)$ mesons, and $\epsilon_{\chi_{c1}(3872)}$ and $\epsilon_{\psi(2S)}$ are the total efficiencies, respectively. The yields of prompt $\chi_{c1}(3872)$ and $\psi(2S)$ mesons and those from b -hadron decays are determined in each (p_T, y) interval from a two-dimensional extended binned maximum-likelihood fit to the $J/\psi \pi^+ \pi^-$ invariant-mass spectrum and the pseudo-decay-time distribution. As the trigger thresholds varied for different periods of data taking, the signal yields and efficiencies are determined separately for each year.

For the invariant-mass model, the sum of two double-sided Crystal Ball (F_{DSCB}) functions [41] is used to describe the $\psi(2S)$ signal. The two F_{DSCB} functions share a common mean (μ) and have different width parameters $\sigma_1^{\psi(2S)}$ and $\sigma_2^{\psi(2S)}$. The relative fraction (f) of the F_{DSCB} functions is determined from simulation. The radiative-tail parameters of the F_{DSCB} functions (α_l, α_r, n) are parameterised as a function of the mass resolution, which is obtained using simulated samples. The combinatorial background in the $\psi(2S)$ signal window, defined by $M_{J/\psi \pi^+ \pi^-}$ within the 3650–3720 MeV/ c^2 interval, is described by an exponential function (F_{Exp}) with the slope parameter (c_0) freely varied. The invariant-mass model for the selected $\psi(2S)$ candidates can be written as

$$\begin{aligned} F_{\psi(2S)}(m) = & N_{\psi(2S)} \left(f \cdot F_{\text{DSCB}}(m|\mu, \sigma_1^{\psi(2S)}, \alpha_l, \alpha_r, n) \right. \\ & \left. + (1 - f) \cdot F_{\text{DSCB}}(m|\mu, \sigma_2^{\psi(2S)}, \alpha_l, \alpha_r, n) \right) \\ & + N_{\text{bkg}}^{\psi(2S)} F_{\text{Exp}}(m|c_0), \end{aligned} \quad (4.2)$$

where $N_{\psi(2S)}$ is the signal yield of the $\psi(2S)$ meson, and $N_{\text{bkg}}^{\psi(2S)}$ is the number of background events.

The fit function for the $\chi_{c1}(3872)$ signal is defined with a non-relativistic Breit-Wigner shape (F_{BW}) convolved with an invariant-mass resolution function, which has the same parameterisation as the $\psi(2S)$ signal. The worse signal-to-background ratio in the $\chi_{c1}(3872)$ mass region is mainly due to the fact that the production rate of $\chi_{c1}(3872)$ state is much smaller than that of the $\psi(2S)$ charmonium. The $\chi_{c1}(3872)$ mass (M) is fixed to the known $\psi(2S)$ mass [40], $m_{\psi(2S)} = 3686.10 \text{ MeV}/c^2$, shifted by $185.49 \text{ MeV}/c^2$ [9], and its width (Γ) is Gaussian constrained to $1.19 \pm 0.19 \text{ MeV}$, which is the average value of two previous LHCb measurements [8, 9]. The ratios of the mass resolutions between the $\chi_{c1}(3872)$ and $\psi(2S)$ signals are determined from simulated samples. An exponential function is used to describe the combinatorial background in the $\chi_{c1}(3872)$ mass window, with $M_{J/\psi \pi^+ \pi^-}$ between 3830 and 3910 MeV/ c^2 . The invariant-mass model for the selected $\chi_{c1}(3872)$ candidates can be written as

$$\begin{aligned} F_{\chi_{c1}(3872)}(m) = & N_{\chi_{c1}(3872)} \left(f \cdot F_{\text{BW}}(m|M, \Gamma) \otimes F_{\text{DSCB}}(m|\mu, \sigma_1^{\chi_{c1}(3872)}, \alpha_l, \alpha_r, n) \right. \\ & \left. + (1 - f) \cdot F_{\text{BW}}(m|M, \Gamma) \otimes F_{\text{DSCB}}(m|\mu, \sigma_2^{\chi_{c1}(3872)}, \alpha_l, \alpha_r, n) \right) \\ & + N_{\text{bkg}} F_{\text{Exp}}(m|c_0), \end{aligned} \quad (4.3)$$

where $N_{\chi_{c1}(3872)}$ is the signal yield of the $\chi_{c1}(3872)$ state, and N_{bkg} is the number of background events.

For the pseudo-decay-time model, a delta function is used to describe the t_z distribution of the prompt $\chi_{c1}(3872)$ and $\psi(2S)$ signals, while an exponential function is used for that from b -hadron decays. Both are convolved with a resolution function ($F_{\text{resolution}}$) chosen to be the sum of three Gaussian functions. The average pseudodecay-time of the nonprompt $\psi(2S)$ signal, referred to hereafter as pseudo-lifetime (τ'_b), is allowed to vary freely in the fit and found to be around 1.5 ps with a mild dependence on the $\psi(2S)$ kinematics. Due to the high level of background in the $\chi_{c1}(3872)$ candidate sample, the pseudo-lifetime of nonprompt $\chi_{c1}(3872)$ candidates is fixed to 1.5 ps. It is possible that the reconstructed $\chi_{c1}(3872)$ or $\psi(2S)$ candidate is associated to a wrong PV, which would result in a long tail in the t_z distribution and would weakly contribute to the signal peak in the mass distribution. A nonparametric model is defined for this component by combining each signal candidate with the closest PV in a different event of the selected sample and taking the resulting t_z distribution as a template in the fit. The dominant background component is combinatorial, in which the J/ψ candidate is combined with a random pion pair uncorrelated with the signal candidate. The pseudo-decay-time model of the $\chi_{c1}(3872)$ and $\psi(2S)$ states can be written as

$$F_{t_z}(t_z) = \left(N_{\text{prompt}}\delta(t_z) + \frac{N_{\text{nonprompt}}}{\tau'_b}e^{-t_z/\tau'_b} \right) \otimes F_{\text{resolution}}(t_z) + N_{\text{tail}}F_{\text{tail}}(t_z) + N_{\text{bkg}}F_{\text{background}}(t_z), \quad (4.4)$$

where N_{prompt} , $N_{\text{nonprompt}}$, N_{tail} and N_{bkg} are the number of prompt $\chi_{c1}(3872)$ ($\psi(2S)$) states, $\chi_{c1}(3872)$ ($\psi(2S)$) from b -hadron decay, the wrong-PV candidates and background event yields, respectively.

The t_z distribution of the background in each (p_T, y) interval is obtained using the *sPlot* technique [42] with the $J/\psi\pi^+\pi^-$ invariant mass as a discriminating observable. The resulting model is fixed in the combined invariant mass and pseudo-decay-time fit. The fit is performed separately for each data-taking year. As an example, figure 1 shows the $M_{J/\psi\pi^+\pi^-}$ and t_z distributions along with the fit projections for the 2016 data sample in the kinematic interval $12 < p_T < 14 \text{ GeV}/c$ and $2 < y < 3$.

The total efficiency in each kinematic interval is determined as the product of detector geometrical acceptance, particle reconstruction, event selection including trigger requirements, and particle identification efficiencies. The geometrical acceptance is calculated separately from $\chi_{c1}(3872)$ and $\psi(2S)$ simulated events. The track reconstruction and the particle-identification efficiencies are evaluated using simulated samples calibrated with data. The efficiencies for prompt and nonprompt $\chi_{c1}(3872)$ and $\psi(2S)$ signals are found to be slightly different, which is mainly caused by events containing b -hadron decays having larger occupancies and thus smaller tracking efficiencies. This effect does not affect the ratio of $\psi(2S)$ and $\chi_{c1}(3872)$ efficiencies, which is present in the cross-section ratio in eq. (4.1). The ratio of the total efficiencies of $\psi(2S)$ to $\chi_{c1}(3872)$ mesons is shown in figure 2 for the 2012 and 2016 data taking periods. The smaller efficiency at low p_T of the $\psi(2S)$ meson is due to its smaller mass.

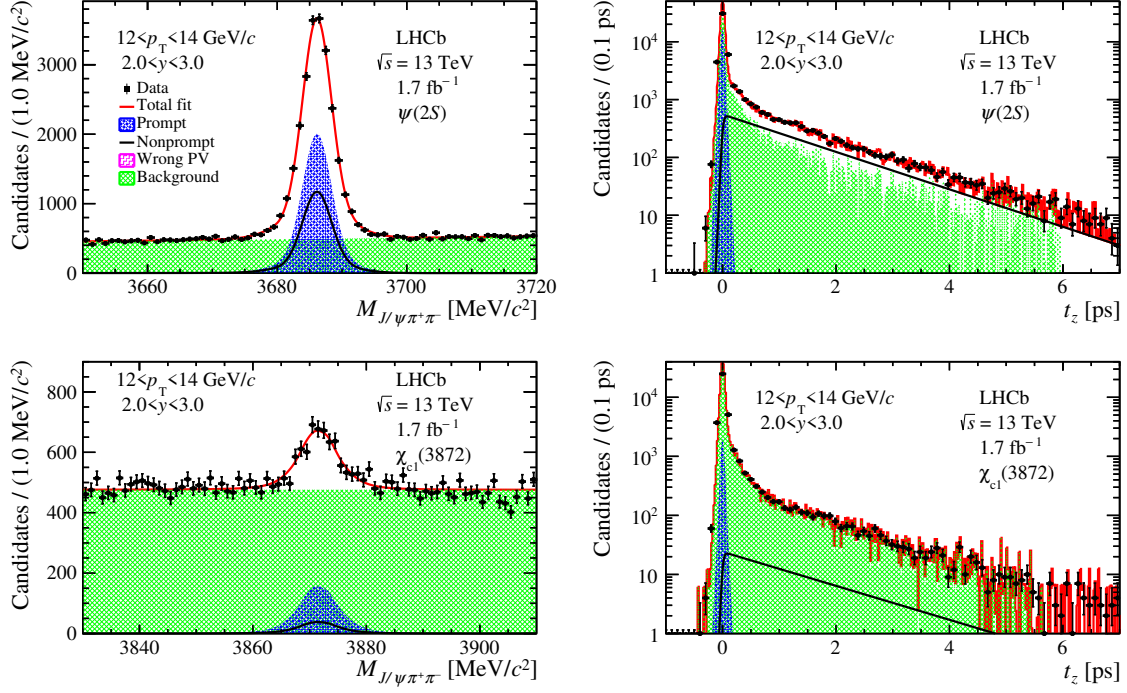


Figure 1. Distributions of (left) invariant mass and (right) pseudo-decay-time for (top) $\psi(2S)$ and (bottom) $\chi_{c1}(3872)$ candidates in the kinematic interval $12 < p_T < 14 \text{ GeV}/c$ and $2.0 < y < 3.0$ for the 2016 data sample. Fit projections are overlaid. The solid red curve represents the total fit projection and the shaded green area corresponds to the background component. The prompt contribution of $\chi_{c1}(3872)$ and $\psi(2S)$ mesons is shown as the cross-hatched blue area, whereas the corresponding nonprompt component from b -hadron decays is illustrated as a solid black line. The wrong PV contribution is consistent with zero.

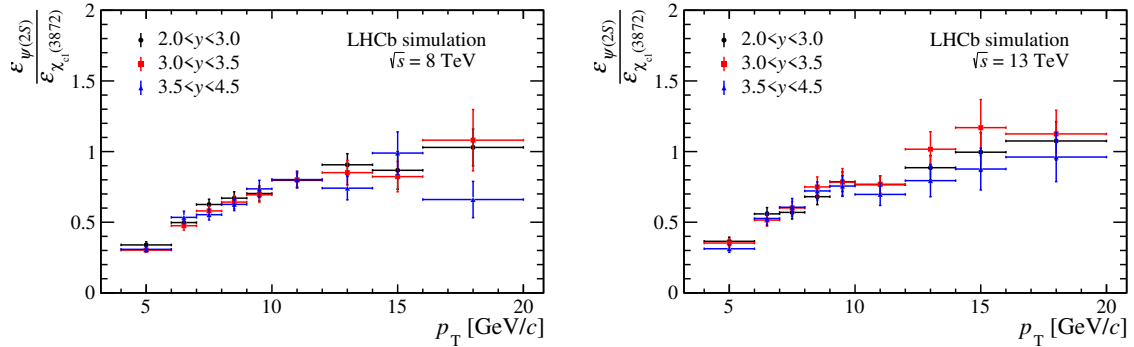


Figure 2. Efficiency ratio of $\psi(2S)$ to $\chi_{c1}(3872)$ mesons as a function of p_T in three rapidity intervals.

5 Systematic uncertainties

A variety of systematic uncertainty sources is studied and summarised in table 1. The uncertainties arise from the $J/\psi\pi^+\pi^-$ invariant mass and pseudo-decay-time fit models, and the computation of efficiencies. Some uncertainties depend on kinematics, with the largest values always appearing in the intervals with smaller sample sizes.

The signal lineshape chosen in the invariant-mass model can affect the measured signal yields. Such effects are evaluated using pseudoexperiments in which the signal description is taken from the simulated sample, and the background is generated with the shape and fraction determined from the fits to the data. The same fit model as used for the data is applied to these samples. The difference between the fitted value of the $N_{\chi_{c1}(3872)}/N_{\psi(2S)}$ ratio and the input value is taken as systematic uncertainty. In the default fit, the parameters of the fit model, such as the fraction of two F_{DSCB} functions, the resolution ratios $\sigma_2^{\psi(2S)}/\sigma_1^{\psi(2S)}$ and $\sigma_i^{\chi_{c1}(3872)}/\sigma_i^{\psi(2S)}$ ($i = 1, 2$) are fixed in the fit to the data. These parameters are varied within their statistical uncertainties, and the average shift of the $N_{\chi_{c1}(3872)}/N_{\psi(2S)}$ ratio is assigned as uncertainty. The contributions to the systematic uncertainty due to the background mass shape are estimated by replacing the exponential function by a second-order polynomial function, and evaluating the difference of $N_{\chi_{c1}(3872)}/N_{\psi(2S)}$ between the alternative and the default fits.

There are several analysis choices that could affect the nonprompt fit fraction, $F_b = N_{\text{nonprompt}}/(N_{\text{nonprompt}} + N_{\text{prompt}})$, and they are studied separately for each data-taking year. The first is the t_z resolution model. A sum of three Gaussian functions is used to describe the t_z resolution of the $\psi(2S)$ and $\chi_{c1}(3872)$ signal. As an alternative, a sum of two Gaussian functions is used, and the relative differences of the fitted F_b ratio for the $\chi_{c1}(3872)$ and $\psi(2S)$ signal, $F_b^{\chi_{c1}(3872)}/F_b^{\psi(2S)}$, are assigned as systematic uncertainty. The mean value of the t_z resolution function is fixed to zero in the reference fit. However, the reconstructed t_z distribution could be biased, for example due to tracks from b -hadron decays being included in the PV reconstruction. The mean value of the resolution function is left to vary freely and the difference of the $F_b^{\chi_{c1}(3872)}/F_b^{\psi(2S)}$ ratio is assigned as systematic uncertainty. The long tail of the t_z distribution is due to misassociated primary vertices that can affect the fit result. Instead of using the different-event method, the tail is described with a bifurcated exponential with equal slope parameters on the positive and negative sides. The relative difference of $F_b^{\chi_{c1}(3872)}/F_b^{\psi(2S)}$ values between the two fits is used to assign the corresponding uncertainty. The t_z distribution for the background is obtained using the *sPlot* technique. The possible correlation between $M_{J/\psi\pi^+\pi^-}$ and t_z is checked by comparing the signal yields obtained with fits to $M_{J/\psi\pi^+\pi^-}$ distribution in each t_z bin to those obtained using the *sPlot* technique, and is found to be small. The effects on $F_b^{\chi_{c1}(3872)}/F_b^{\psi(2S)}$ is evaluated by fitting the t_z distribution obtained with fits to $M_{J/\psi\pi^+\pi^-}$ distribution in each t_z bin, and the resulting 2.4% difference from the nominal one is taken as a systematic uncertainty. The pseudo-lifetime of nonprompt $\chi_{c1}(3872)$ candidates is fixed to 1.5 ps in the reference fit, which could affect the fitted F_b fraction. As an alternative, the $\chi_{c1}(3872)$ pseudo-lifetime is fixed to that of the $\psi(2S)$ meson in each kinematic bin. The difference of $F_b^{\chi_{c1}(3872)}/F_b^{\psi(2S)}$ ratios between the reference and the alternative fits for each year is assigned as systematic uncertainty.

Sources		Systematic uncertainty (%)			
		8 TeV	13 TeV		
		2012	2016	2017	2018
Mass fit	Signal lineshape	0.6	2.3		
	Fraction of two F_{DSCB}	0.0–3.6	0.0–5.6		
	$\sigma_2^{\psi(2S)} / \sigma_1^{\psi(2S)}$	0.0–2.7	0.0–6.8		
	$\sigma_1^{\chi_{c1}(3872)} / \sigma_1^{\psi(2S)}$	0.2–3.6	0.2–5.1		
	$\sigma_2^{\chi_{c1}(3872)} / \sigma_2^{\psi(2S)}$	0.2–5.6	0.2–6.2		
	Background lineshape	0.0–1.5	0.0–3.7		
t_z fit	t_z resolution function	0.0–1.4	0.0–3.0	0.0–1.6	0.0–1.0
	Fixed mean of t_z resolution	0.0–0.4	0.0–1.0	0.0–0.8	0.0–0.6
	Wrong PV	0.0–2.8	0.0–4.1	0.0–3.6	0.0–1.8
	Background shape	2.4	2.4		
	Fixed pseudo-lifetime	0.1–10.9	1.0–12.1	1.3–8.0	1.3–7.8
Tracking		0.1–0.7	0.1–0.2	0.1–1.4	0.1–1.0
Muon identification		0.0–6.1	0.0–1.8	0.0–1.8	0.0–1.5
Pion identification		0.1–6.7	0.0–0.4	0.0–0.9	0.0–0.3
Trigger thresholds		—	0.0–15.1	0.3–6.4	0.3–7.3
Simulation weighting		4.5–9.3	3.6–7.4	3.2–8.9	3.2–6.1
Global event requirements		0.5	1.9		
$M_{\pi^+\pi^-}$ spectrum		2.0	2.0		
Trigger efficiency		1.0	1.0		
Total systematic uncertainty		6.7–14.8	7.1–17.9	6.0–15.3	6.0–13.1
Total statistical uncertainty: prompt		7–17	5–19	6–31	5–13
Total statistical uncertainty: nonprompt		13–26	11–23	10–32	9–19

Table 1. Systematic uncertainties of the production cross-section of $\chi_{c1}(3872)$ relative to $\psi(2S)$ mesons in the kinematic region $4 < p_T < 20$ GeV/ c and $2.0 < y < 4.5$. Ranges are due to the variation across the (p_T, y) intervals. When only a range is given for the 13 TeV data it is shared between different data-taking years. The large ranges in some cases are due to statistical fluctuations of the signal or control samples used to evaluate the uncertainties. The systematic uncertainties due to the $M_{J/\psi\pi^+\pi^-}$ and t_z fit are considered to be 100 % correlated, and the statistical and systematic uncertainties due to PID and tracking are considered to be uncorrelated.

The track detection efficiencies are determined from a simulated sample in each (p_T, y) interval, and are corrected using control data. The statistical uncertainty due to the limited size of the control data sample is propagated using a large number of pseudoexperiments. For each pseudoexperiment, a new efficiency-correction ratio as a function of the (p_T, y) interval is generated according to a Gaussian distribution where the original efficiency ratio and its uncertainty are used as the Gaussian mean and standard deviation, respectively.

The systematic uncertainty due to particle identification is studied considering the following contributions. The first is the statistical uncertainty due to the limited size of the calibration sample, which is estimated using pseudoexperiments and found to be negligible compared to other systematic uncertainties. The second is due to the binning scheme of the calibration sample. This contribution is studied by varying the binning in momentum, pseudorapidity and track multiplicity. The maximum differences among these contributions on the efficiency ratios are taken as systematic uncertainty.

The hardware-trigger thresholds on muon and hadron p_T varied throughout data taking, however only one value is used in the simulation. Differences in the trigger efficiencies observed when varying the thresholds in the simulation are taken as a source of systematic uncertainty. The p_T and y distributions of the simulated $\chi_{c1}(3872)$ and $\psi(2S)$ samples are corrected to match those in the data. The uncertainty on the simulation weighting is studied by propagating the statistical uncertainty on the correction using the bootstrap method [43]. The bootstrap method is used to generate 100 pseudoexperiments according to the data sample. The simulation weightings are performed with the generated pseudoexperiments. The efficiencies are calculated for each weighting, and the root-mean-square of the resulting efficiency distribution is taken as systematic uncertainty. The effects of the global event requirements are estimated through the difference of the $\epsilon_{\psi(2S)}/\epsilon_{\chi_{c1}(3872)}$ ratio between the data and the simulation. The $M_{\pi^+\pi^-}$ distributions in the data and the simulation are slightly different, especially in the high $M_{\pi^+\pi^-}$ region. This difference affects the $\epsilon_{\psi(2S)}/\epsilon_{\chi_{c1}(3872)}$ ratio and is taken as systematic uncertainty. The systematic uncertainty on the trigger efficiency is taken from J/ψ pair production measurement [44].

6 Results

The double-differential cross-section of the $\chi_{c1}(3872)$ state relative to that of the $\psi(2S)$ meson is measured as a function of p_T and y using pp collision data taken at centre-of-mass energies of $\sqrt{s} = 8$ and 13 TeV. The analysis assumes unpolarised production (a study on the impact of polarisation is described in appendix A). For the per-year measurements at 13 TeV, the combination of the cross-section ratios is performed using the Best Linear Unbiased Estimate (BLUE) method [45–47]. The weighted average of these measurements is calculated by minimising the total uncertainty of the result and accounting for correlations between per-year measurements. The cross-section ratios for promptly and nonpromptly produced mesons measured with the 8 and 13 TeV data samples as a function of p_T and y are shown in figures 3 and 4, respectively. The cross-section times branching ratios of the $\chi_{c1}(3872)$ over $\psi(2S)$, integrated over the kinematic region $4 < p_T < 20$ GeV/ c and

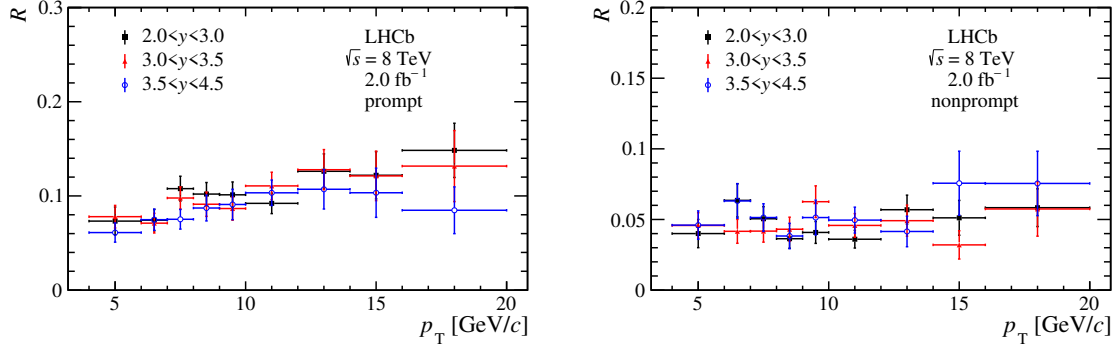


Figure 3. Ratios of differential cross-section times the branching ratio to the $J/\psi\pi^+\pi^-$ final state between $\chi_{c1}(3872)$ and $\psi(2S)$ mesons from (left) prompt production and (right) nonprompt from b -hadron decays, for the $\sqrt{s} = 8$ TeV sample as a function of p_T in intervals of rapidity. In all panels, the error bars represent the sum in quadrature of the statistical and systematic uncertainties.

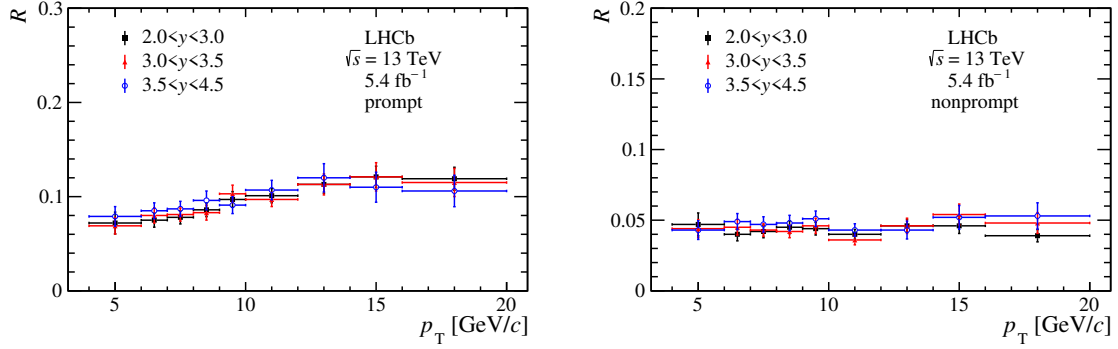


Figure 4. Ratios of differential cross-section times the branching ratio to the $J/\psi\pi^+\pi^-$ final state between $\chi_{c1}(3872)$ and $\psi(2S)$ mesons from (left) prompt production and (right) nonprompt from b -hadron decays, for the $\sqrt{s} = 13$ TeV sample as a function of p_T in intervals of rapidity. In all panels, the error bars represent the sum in quadrature of the statistical and systematic uncertainties.

$2.0 < y < 4.5$, are obtained to be

$$\begin{aligned}
 R_{\text{prompt}}^{8 \text{ TeV}} &= (7.6 \pm 0.5 \pm 0.9) \times 10^{-2}, \\
 R_{\text{nonprompt}}^{8 \text{ TeV}} &= (4.6 \pm 0.4 \pm 0.5) \times 10^{-2}, \\
 R_{\text{prompt}}^{13 \text{ TeV}} &= (7.6 \pm 0.3 \pm 0.6) \times 10^{-2}, \\
 R_{\text{nonprompt}}^{13 \text{ TeV}} &= (4.4 \pm 0.2 \pm 0.4) \times 10^{-2},
 \end{aligned}$$

where the first uncertainties are statistical and the second systematic.

The double ratio of the prompt $\chi_{c1}(3872)$ and $\psi(2S)$ production cross-sections between 13 and 8 TeV is also calculated using the measured cross-section ratio for 8 TeV and the combined ratio for 13 TeV. Figure 5 shows the double ratio of production cross-sections as a function of p_T integrated over the kinematic region $2.0 < y < 4.5$. A first-order polynomial of the form $R^{13 \text{ TeV}}/R^{8 \text{ TeV}} = a_0 + a_1 p_T$ is used to fit the double ratio, yielding $a_0 = 0.99 \pm 0.23$ and a slope of $a_1 = (4 \pm 23) \times 10^{-3} (\text{GeV}/c)^{-1}$, consistent with zero.

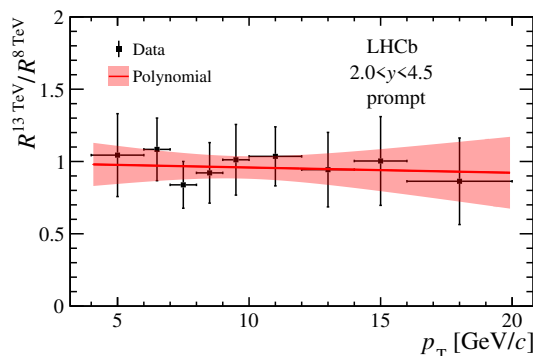


Figure 5. Double ratio of the prompt $\chi_{c1}(3872)$ production cross-section relative to that of $\psi(2S)$ mesons between 13 and 8 TeV as a function of p_T integrated over $2.0 < y < 4.5$. The red line with the solid band represent the fit result to a first-order polynomial and its uncertainty.

7 Conclusion

In summary, the production cross-section of the $\chi_{c1}(3872)$ state relative to the $\psi(2S)$ meson is measured using pp data collected at centre-of-mass energies of 8 and 13 TeV. The double-differential cross-section ratio times their ratio of branching fractions to the $J/\psi\pi^+\pi^-$ final state, as a function of p_T and y in the ranges $4 < p_T < 20$ GeV/ c and $2.0 < y < 4.5$, are determined for prompt and nonprompt production of $\chi_{c1}(3872)$ states relative to $\psi(2S)$ mesons. The prompt ratio increases as a function of p_T , showing that the $\chi_{c1}(3872)$ production is less suppressed relative to the one of prompt $\psi(2S)$ mesons in the higher p_T region. This behaviour is similar to the case of prompt production of $\psi(2S)$ relative to J/ψ mesons as measured by the CMS [48] and LHCb experiments [49], and is consistent with theoretical predictions [50]. Using the production cross-section of the $\psi(2S)$ meson measured by the LHCb experiment at 13 TeV [51], the absolute production cross-section of the $\chi_{c1}(3872)$ meson at 13 TeV multiplied by its branching fraction to the $J/\psi\pi^+\pi^-$ final state is determined as a function of p_T , as detailed in appendix B. The result is found to agree in the $p_T > 10$ GeV/ c region with NLO NRQCD predictions [16], which model the $\chi_{c1}(3872)$ state as a mixture of $\chi_{c1}(2P)$ and $D^0\bar{D}^{*0}$ molecule states, produced through its $\chi_{c1}(2P)$ component. The prompt cross-section ratios at 13 and 8 TeV are also compared, and no significant dependence on the centre-of-mass energy is found. The nonprompt ratios of cross-sections at 13 and 8 TeV are consistent with a flat distribution, determined by the b -decay branching ratios.

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A Polarisation of $\psi(2S)$ and $\chi_{c1}(3872)$ mesons

The polarisation of the J/ψ meson is directly inherited from the $\psi(2S)$ parent, since the dipion system is produced in an S -wave state relative to the J/ψ meson. For the $\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-$ decay, the determination of the $\chi_{c1}(3872)$ polarisation can be obtained by measuring the dimuon angular decay distribution in the rest frame of the J/ψ daughter, as discussed in refs. [52, 53]. The angular dependence of the $J/\psi \rightarrow \mu^+ \mu^-$ decay for $\chi_{c1}(3872)$ and $\psi(2S)$ mesons is

$$\frac{d^2 N}{d \cos \theta d \phi} \propto 1 + \lambda_\theta \cos^2 \theta + \lambda_\phi \sin^2 \theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos \phi, \quad (\text{A.1})$$

where λ_i are the polarisation parameters and $\theta(\phi)$ are the polar (azimuthal) angles between the positively charged muon in the $J/\psi \rightarrow \mu^+ \mu^-$ rest frame and the direction of the $\psi(2S)$ meson in the laboratory frame. Various polarisation hypotheses are considered:

- Unpolarised, with an isotropic distribution that is independent of the polarisation parameters, $\lambda_\theta = \lambda_\phi = \lambda_{\theta\phi} = 0$. This is used as the central hypothesis.
- Transversely polarised with $\lambda_\theta = +1, \lambda_\phi = \lambda_{\theta\phi} = 0$, labelled as T_{+0} .
- Transversely polarised with $\lambda_\theta = +1, \lambda_\phi = +1, \lambda_{\theta\phi} = 0$, labelled as T_{++} .
- Transversely polarised with $\lambda_\theta = +1, \lambda_\phi = -1, \lambda_{\theta\phi} = 0$, labelled as T_{+-} .
- Longitudinally polarised, with the parameters $\lambda_\theta = -1, \lambda_\phi = \lambda_{\theta\phi} = 0$, labelled as L .
- Off-Plane Positive, with the polarisation parameters $\lambda_\theta = 0, \lambda_\phi = 0, \lambda_{\theta\phi} = +0.5$, labelled as $OP+$.
- Off-Plane Negative, with the polarisation parameters $\lambda_\theta = 0, \lambda_\phi = 0, \lambda_{\theta\phi} = -0.5$, labelled as $OP-$.

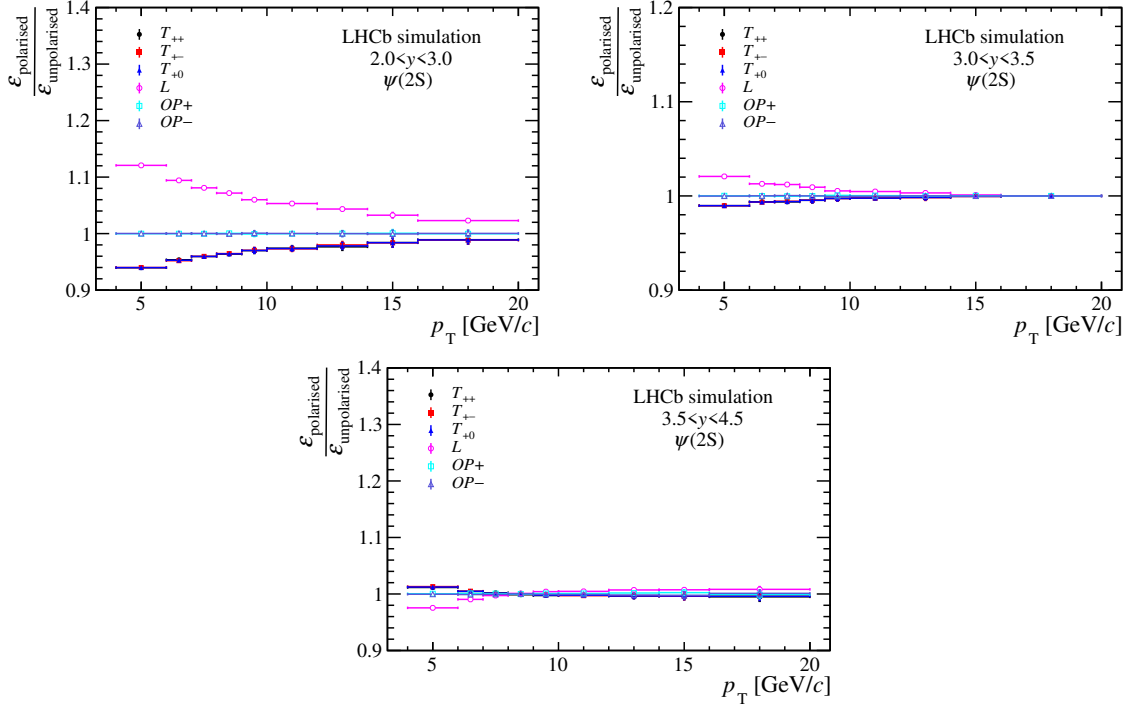


Figure 6. Ratio of acceptance efficiencies for $\psi(2S)$ mesons for various polarisation hypotheses with respect to the unpolarised case.

p_T [GeV/c]	T_{+0}	T_{++}	T_{+-}	L	$OP+$	$OP-$
4-6	0.940	0.940	0.940	1.121	1.000	1.000
6-7	0.953	0.954	0.952	1.094	1.000	1.000
7-8	0.960	0.959	0.960	1.081	1.000	1.000
8-9	0.964	0.964	0.965	1.072	1.000	1.000
9-10	0.970	0.970	0.970	1.060	0.999	1.001
10-12	0.974	0.974	0.973	1.053	1.000	1.000
12-14	0.978	0.977	0.980	1.043	1.000	1.000
14-16	0.984	0.984	0.984	1.033	1.001	0.999
16-20	0.989	0.989	0.988	1.023	1.000	1.000

Table 2. Ratio of acceptance efficiencies for $\psi(2S)$ mesons for various polarisation hypotheses with respect to the unpolarised case, in the interval $2.0 < y < 3.0$.

The acceptance weights are calculated for each of these scenarios in each (p_T, y) interval. The ratios of the acceptance efficiencies for each polarisation scenario to those of the unpolarised case are shown in figure 6 for $\psi(2S)$ mesons and figure 7 for the $\chi_{c1}(3872)$ state, and the values are listed in tables 2, 3, and 4 for the former, and tables 5, 6, and 7 for the latter.

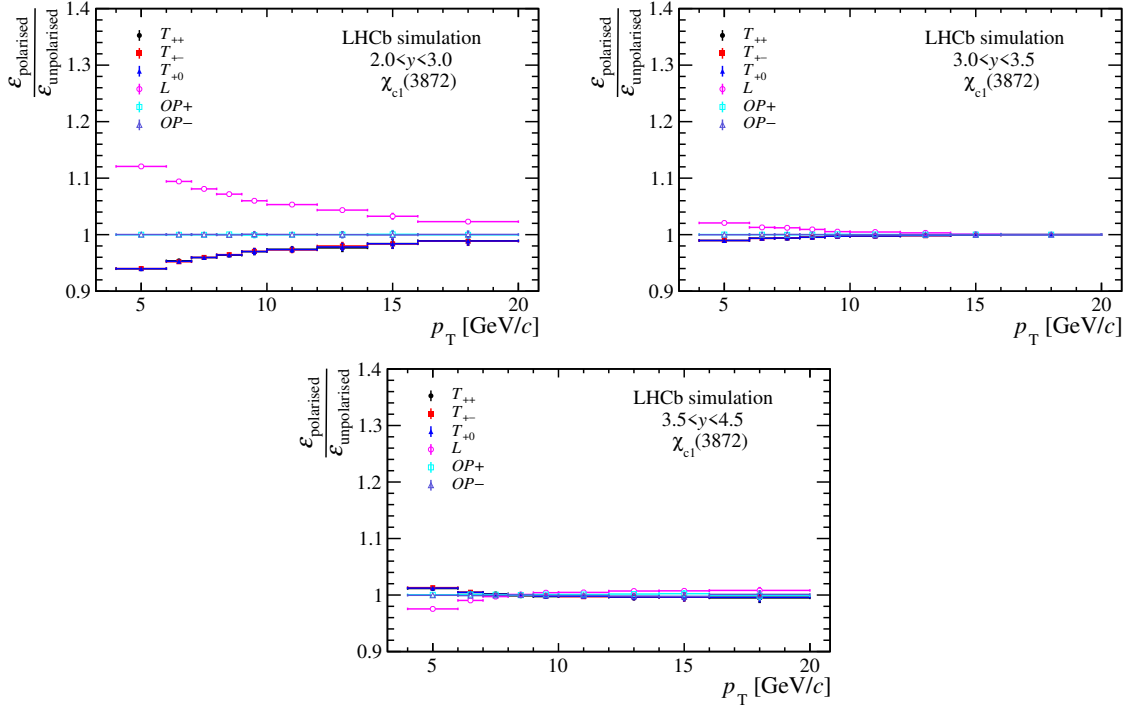


Figure 7. Ratio of acceptance efficiencies for $\chi_{c1}(3872)$ mesons for various polarisation hypotheses with respect to the unpolarised case.

p_T [GeV/ c]	T_{+0}	T_{++}	T_{+-}	L	$OP+$	$OP-$
4-6	0.990	0.990	0.990	1.021	1.000	1.000
6-7	0.994	0.994	0.993	1.013	1.000	1.000
7-8	0.994	0.994	0.994	1.012	1.000	1.000
8-9	0.995	0.995	0.996	1.009	1.000	1.000
9-10	0.997	0.997	0.997	1.005	1.001	0.999
10-12	0.998	0.998	0.998	1.005	1.000	1.000
12-14	0.998	0.999	0.998	1.003	1.000	1.000
14-16	1.000	1.000	0.999	1.001	1.000	1.000
16-20	1.000	1.000	1.000	1.000	1.000	1.000

Table 3. Ratio of acceptance efficiencies for $\psi(2S)$ mesons for various polarisation hypotheses with respect to the unpolarised case, in the interval $3.0 < y < 3.5$.

p_T [GeV/ c]	T_{+0}	T_{++}	T_{+-}	L	$OP+$	$OP-$
4-6	1.012	1.012	1.013	0.975	1.000	1.000
6-7	1.005	1.005	1.005	0.990	1.001	0.999
7-8	1.001	1.002	1.001	0.997	1.001	0.999
8-9	0.999	0.999	1.000	1.001	1.000	1.000
9-10	0.998	0.997	0.999	1.004	1.001	0.999
10-12	0.998	0.998	0.997	1.005	1.001	0.999
12-14	0.996	0.996	0.997	1.007	1.002	0.998
14-16	0.996	0.997	0.996	1.007	1.002	0.998
16-20	0.996	0.995	0.997	1.008	0.999	1.001

Table 4. Ratio of acceptance efficiencies for $\psi(2S)$ mesons for various polarisation hypotheses with respect to the unpolarised case, in the interval $3.5 < y < 4.5$.

p_T [GeV/ c]	T_{+0}	T_{++}	T_{+-}	L	$OP+$	$OP-$
4-6	0.941	0.941	0.941	1.118	1.000	1.000
6-7	0.952	0.952	0.952	1.096	1.000	1.000
7-8	0.958	0.958	0.958	1.084	1.000	1.000
8-9	0.964	0.963	0.965	1.071	1.000	1.000
9-10	0.968	0.968	0.968	1.063	0.999	1.001
10-12	0.973	0.972	0.973	1.055	1.000	1.000
12-14	0.977	0.978	0.975	1.047	1.000	1.000
14-16	0.985	0.984	0.986	1.030	1.000	1.000
16-20	0.986	0.987	0.986	1.027	1.001	0.999

Table 5. Ratio of acceptance efficiencies for $\chi_{c1}(3872)$ mesons for various polarisation hypotheses with respect to the unpolarised case, in the interval $2.0 < y < 3.0$.

p_T [GeV/ c]	T_{+0}	T_{++}	T_{+-}	L	$OP+$	$OP-$
4-6	0.990	0.990	0.990	1.021	1.000	1.000
6-7	0.992	0.992	0.993	1.015	1.000	1.000
7-8	0.994	0.994	0.995	1.012	1.000	1.000
8-9	0.995	0.995	0.996	1.009	1.000	1.000
9-10	0.997	0.998	0.997	1.005	0.999	1.001
10-12	0.997	0.997	0.998	1.005	1.000	1.000
12-14	0.999	0.999	0.999	1.002	1.000	1.000
14-16	0.998	0.998	0.998	1.003	1.000	1.000
16-20	0.999	0.999	0.999	1.002	1.001	0.999

Table 6. Ratio of acceptance efficiencies for $\chi_{c1}(3872)$ mesons for various polarisation hypotheses with respect to the unpolarised case, in the interval $3.0 < y < 3.5$.

p_T [GeV/ c]	T_{+0}	T_{++}	T_{+-}	L	$OP+$	$OP-$
4-6	1.014	1.014	1.013	0.972	1.000	1.000
6-7	1.006	1.006	1.006	0.988	1.001	0.999
7-8	1.003	1.003	1.003	0.995	1.001	0.999
8-9	0.999	0.998	1.000	1.002	1.000	1.000
9-10	0.999	0.999	0.999	1.002	1.001	0.999
10-12	0.996	0.997	0.996	1.007	1.001	0.999
12-14	0.996	0.996	0.995	1.008	1.001	0.999
14-16	0.997	0.996	0.997	1.006	0.999	1.001
16-20	0.998	0.998	0.998	1.004	1.000	1.000

Table 7. Ratio of acceptance efficiencies for $\chi_{c1}(3872)$ mesons for various polarisation hypotheses with respect to the unpolarised case, in the interval $3.5 < y < 4.5$.

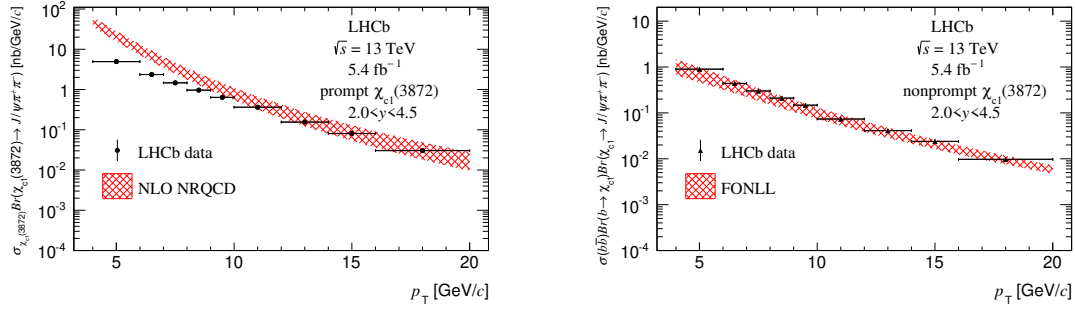


Figure 8. Measured production cross-section times branching fractions as a function of p_T for (left) prompt $\chi_{c1}(3872)$ mesons compared to NLO NRQCD predictions [16] and (right) from b decays compared to FONLL predictions [54, 55].

B Absolute cross-section of $\chi_{c1}(3872)$

As defined in eq. (4.1), the absolute production cross-section of the $\chi_{c1}(3872)$ state times the branching fraction can be calculated using the measured cross-section ratio times $\sigma_{\psi(2S)}\mathcal{B}(\psi(2S) \rightarrow J/\psi\pi^+\pi^-)$. The value of $\sigma_{\psi(2S)}$ is taken from the $\psi(2S) \rightarrow \mu^+\mu^-$ analysis [51]. The world average for the $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ branching fraction is $\mathcal{B}(\psi(2S) \rightarrow J/\psi\pi^+\pi^-) = (34.68 \pm 0.30) \times 10^{-2}$ [40]. Figure 8 shows the measured cross-section times branching fractions as a function of p_T for prompt $\chi_{c1}(3872)$ mesons compared to NLO NRQCD predictions [16] and from b decays compared to FONLL predictions [54, 55]. The prompt $\chi_{c1}(3872)$ production in NLO NRQCD can be expressed as

$$d\sigma(pp \rightarrow \chi_{c1}(3872)) = d\sigma(pp \rightarrow \chi_{c1}(2P)) \cdot k, \quad (\text{B.1})$$

where $k = Z_{c\bar{c}} \cdot \mathcal{B}(\chi_{c1}(3872) \rightarrow J/\psi\pi^+\pi^-)$, and $Z_{c\bar{c}}$ is the probability of the $\chi_{c1}(2P)$ component in the $\chi_{c1}(3872)$. A fit was performed to the CMS data [10] using eq. (B.1), and a value of $k = 0.014 \pm 0.006$ is obtained [16]. The prompt production is consistent with NLO NRQCD in the $p_T > 10 \text{ GeV}/c$ region. The same settings of FONLL as for $\psi(2S)$ mesons are used, except that $\mathcal{B}(b \rightarrow \chi_{c1}(3872))\mathcal{B}(\chi_{c1}(3872) \rightarrow J/\psi\pi^+\pi^-) = (4.3 \pm 0.5) \times 10^{-5}$ is taken from this analysis. The FONLL calculation is also consistent with the measurement. The absolute production cross-section can be derived from this result by using the recently measured $\mathcal{B}(\chi_{c1}(3872) \rightarrow J/\psi\pi^+\pi^-) = (4.1 \pm 1.3)\%$ [56] but the precision is insufficient to further improve the comparison with the various predictions.

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