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χ_{c1} and χ_{c2} resonance parameters with the decays $\chi_{c1,c2} \to J/\psi\,\mu^+\mu^-$

LHCb collaboration[†]

Abstract

The decays $\chi_{c1} \to J/\psi\,\mu^+\mu^-$ and $\chi_{c2} \to J/\psi\,\mu^+\mu^-$ are observed and used to study the resonance parameters of the χ_{c1} and χ_{c2} mesons. The masses of these states are measured to be

$$m(\chi_{c1}) = 3510.71 \pm 0.04\,(\text{stat}) \pm 0.09\,(\text{syst})\,\text{MeV}\,,$$
$$m(\chi_{c2}) = 3556.10 \pm 0.06\,(\text{stat}) \pm 0.11\,(\text{syst})\,\text{MeV}\,,$$

where the knowledge of the momentum scale for charged particles dominates the systematic uncertainty. The momentum-scale uncertainties largely cancel in the mass difference

$$m(\chi_{c2}) - m(\chi_{c1}) = 45.39 \pm 0.07\,(\text{stat}) \pm 0.03\,(\text{syst})\,\text{MeV}\,.$$

The natural width of the χ_{c2} meson is measured to be

$$\Gamma(\chi_{c2}) = 2.10 \pm 0.20\,(\text{stat}) \pm 0.02\,(\text{syst})\,\text{MeV}\,.$$

These results are in good agreement with and have comparable precision to the current world averages.

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Studies of the properties and production of quarkonia at hadron colliders provide an important testing ground for Quantum Chromodynamics [1]. Measurements of the spectra test potential models [2] whilst the production rate can be calculated pertubatively in nonrelativistic effective field theories such as NRQCD [3]. Most studies of χ_{c1} and χ_{c2} mesons at hadron colliders have exploited the radiative decays $\chi_{c1,c2} \to J/\psi\,\gamma$ with the subsequent decay $J/\psi \to \mu^+\mu^-$ [4–8]. The branching fractions for these processes are large, allowing a signal to be observed despite high background.

Recently, the BESIII collaboration [9] reported the first observation of the electromagnetic Dalitz decays [10] of χ_{c0}, χ_{c1} and χ_{c2} mesons into the $J/\psi\,e^+e^-$ final state. This Letter reports the first observation of the $\chi_{c1} \to J/\psi\,\mu^+\mu^-$ and $\chi_{c2} \to J/\psi\,\mu^+\mu^-$ decay modes, using $J/\psi \to \mu^+\mu^-$ decays. These decays are used to measure the χ_{c1} and χ_{c2} masses together with the χ_{c2} natural width. The event topology with four muons in the final state provides a clean signature that is ideal for studies in hadron collisions.

This analysis uses the LHCb data set collected in pp collisions up to the end of 2016. The data collected at centre-of-mass energies of 7 and 8 TeV corresponds to integrated liminosities of 1 and $2\,\mathrm{fb}^{-1}$ and is collectively referred to as Run 1, while data collected at centre-of-mass energy of 13 TeV corresponds to $1.9\,\mathrm{fb}^{-1}$ and is referred to as Run 2.

The LHCb detector is a single-arm spectrometer covering the pseudorapidity range $2 < \eta < 5$, described in detail in Refs. [11, 12]. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector [13], 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 [14] placed downstream of the magnet. The tracking system measures the momentum of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV (natural units with $c = \hbar = 1$ are used throughout this Letter). The momentum scale is calibrated using samples of $J/\psi \to \mu^+\mu^-$ and $B^+ \to J/\psi\,K^+$ decays collected concurrently with the data sample used for this analysis [15–17]. The use of the large J/ψ data sample allows to correct for variations of the momentum scale at the level of $10^{?4}$ or less that occur over time whilst the use of the $B^+ \to J/\psi\,K^+$ decay allows the momentum scale to be determined as a function of the K^+ kinematics. The procedure is validated using samples of $K^0_{\mathrm{S}} \to \pi^+\pi^-$, $\psi(2S) \to J/\psi\,\pi^+\pi^-$, $\psi(2S) \to \mu^+\mu^-$, other fully reconstructed b-hadron and $\Upsilon(nS), n = 1, 2, 3$ decays. Based upon these studies the accuracy of the procedure is evaluated to be 3×10^{-4}. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers [18]. The online event selection is performed by a trigger [19], 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. The events used in this analysis are selected by a hardware trigger that requires one or two muons with transverse momentum, p_{T}, larger than 1.5 GeV. At the software trigger stage, a pair of oppositely charged muons with an invariant mass consistent with the known J/ψ mass [20] is required. In Run 1 the full event information for selected events was stored. To keep the rate within the available bandwidth it was necessary to require $p_{\mathrm{T}}(J/\psi) > 3\,\mathrm{GeV}$. For Run 2, a new data taking scheme was introduced [21] allowing real-time alignment to be performed in the trigger [22] that, together with an increase in the online computing resources, made possible the full track reconstruction in the online system [23, 24]. Consequently, lower-level information could be discarded, reducing the event size and allowing all events selected at the hardware stage that contain a J/ψ candidate to be stored without any p_{T} requirement.

Offline, J/ψ candidates are combined with a pair of oppositely charged muons to form $\chi_{c1,c2} \to J/\psi\,\mu^+\mu^-$ candidates. Several criteria are applied to reduce the background and maximize the sensitivity for the mass measurement. Selected muon candidates are required to be within the range $2 < \eta < 4.9$. Misreconstructed tracks are suppressed by the use of a neural network trained to discriminate between these and real particles. Muon candidates are selected with a neural network trained using simulated samples to discriminate muons from hadrons and electrons. Finally, to improve the mass resolution, a kinematic fit is performed [25]. In this fit the mass of the J/ψ candidate is constrained to the known mass of the J/ψ meson [20] and the position of the $\chi_{c1,c2}$ candidate decay vertex is constrained to be the same as that of the primary vertex. The χ^2 per degree of freedom of this fit is required to be less than four, which substantially reduces the background while retaining almost all the signal events.

In the simulation, pp collisions are generated using Pythia [26] with a specific LHCb configuration [27]. For this study, signal decays are generated using EvtGen [28] with decay amplitudes that depend on the invariant dimuon mass, $m(\mu^+\mu^-)$, using the model described in Ref. [29]. This model assumes that the decay proceeds via the emission of a virtual photon from a pointlike meson and is known to provide a good description of the corresponding dielectron mode [9]. Final-state radiation is accounted for using Photos [30]. The interaction of the generated particles with the detector, and its response, are implemented using the Geant4 toolkit [31] as described in Ref. [32].

The signal yields and parameters of the $\chi_{c1,c2}$ resonances are determined with an extended unbinned maximum likelihood fit performed to the $J/\psi\,\mu^+\mu^-$ invariant mass distribution. In this fit, the χ_{c1} and χ_{c2} signals are modelled by relativistic Breit-Wigner functions with Blatt-Weisskopf form factors [33] with a meson radius parameter of $3\,\mathrm{GeV}^{-1}$. Jackson form factors [34] are considered as an alternative to estimate the uncertainty associated with this choice. The orbital angular momentum between the J/ψ meson and the $\mu^+\mu^-$ pair is assumed to be $0\,(1)$ for the $\chi_{c1}\,(\chi_{c2})$ cases.

The relativistic Breit-Wigner functions are convolved with the detector resolution. Three resolution models are found to describe the simulated data well: a double-Gaussian function, a double-sided Crystal Ball function [35, 36] and a symmetric variant of the Apollonios function [37]. The double-Gaussian function is used by the default model and the other functions are considered to estimate the systematic uncertainty. The parameters of the resolution model are determined by a simultaneous fit to the χ_{c1} and χ_{c2} simulated samples. All the parameters apart from the core resolution parameter, σ, are common between the two decay modes. For all the models in the simulation it is found that $\alpha \equiv \sigma^{\chi_{c2}}/\sigma^{\chi_{c1}} = 1.13 \pm 0.01$. This is close to the value expected, $\alpha = 1.11$, from the assumption that the resolution scales with the square root of the energy release.

Combinatorial background is modelled by a second-order polynomial function. The total fit function consists of the sum of the background and the χ_{c1} and χ_{c2} signals. The free parameters are the yields of the two signal components, the yield of the background component, the two background shape parameters, the χ_{c1} and χ_{c2} masses, $\sigma^{\chi_{c1}}$ and the natural width of the χ_{c2} resonance, $\Gamma(\chi_{c2})$. The other resolution parameters are fixed to the simulation values. Since the natural width of the χ_{c1} state $\Gamma(\chi_{c1}) = 0.84 \pm 0.04\,\mathrm{MeV}$ [20] is less than the detector resolution ($\sigma^{\chi_{c1}} = 1.41 \pm 0.01\,\mathrm{MeV}$), this study has limited sensitivity to its value. By applying Gaussian constraints on the natural width of the χ_{c1} state (to the value from Ref. [20]) and α (to the value found in the simulation) the χ_{c2} width is determined in a data-driven way using the observed resolution for the χ_{c1} state.

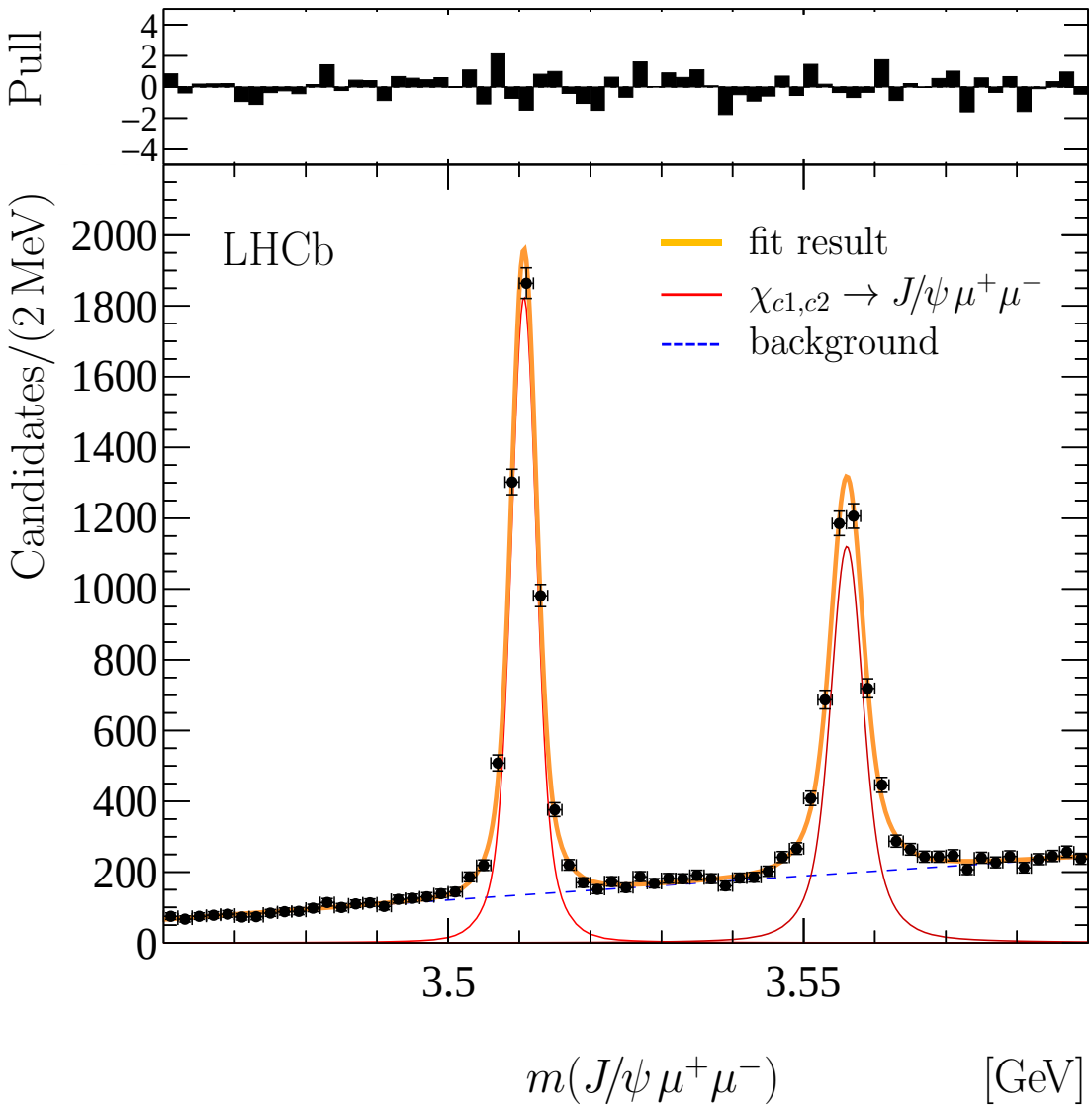

Figure 1: Mass distribution for selected $J/\psi\,\mu^+\mu^-$ candidates. The fit is shown in thick orange, the χ_{c1} and χ_{c2} signal components are shown by the thin red solid curve and the background component by the dashed blue curve.

The fit of this model to the full data sample is shown in Fig. 1 and the resulting parameters of interest are summarized in Table 1. The fitted value of $\sigma^{\chi_{c1}}$ is 1.51 ± 0.04 MeV, which agrees at the level of 5% with the value found in the simulation. Figure 2 shows the $m(\mu^+\mu^-)$ mass distribution for selected candidates where the background has been subtracted using the *sPlot* technique [38]. The data agree well with the model described in Ref. [29].

The dominant source of systematic uncertainty on the mass measurements comes from the knowledge of the momentum scale. This is evaluated by adjusting the momentum scale by the 3×10^{-4} uncertainty on the calibration procedure and rerunning the mass fit. Uncertainties of 88 keV and 102 keV are assigned to the χ_{c1} and χ_{c2} mass measurements, respectively. A further uncertainty arises from the knowledge of the correction for energy loss in the spectrometer, which is known with 10 % accuracy [12]. Based on the studies in

Table 1: Signal yields and resonance parameters from the nominal fit. No correction for final-state radiation is applied to the mass measurements at this stage.

Fit parameter		Fitted value
$N(\chi_{c1})$		4755 ± 81
$N(\chi_{c2})$		3969 ± 96
$m(\chi_{c1})$	[MeV]	3510.66 ± 0.04
$m(\chi_{c2})$	[MeV]	3556.07 ± 0.06
$\Gamma(\chi_{c2})$	[MeV]	2.10 ± 0.20

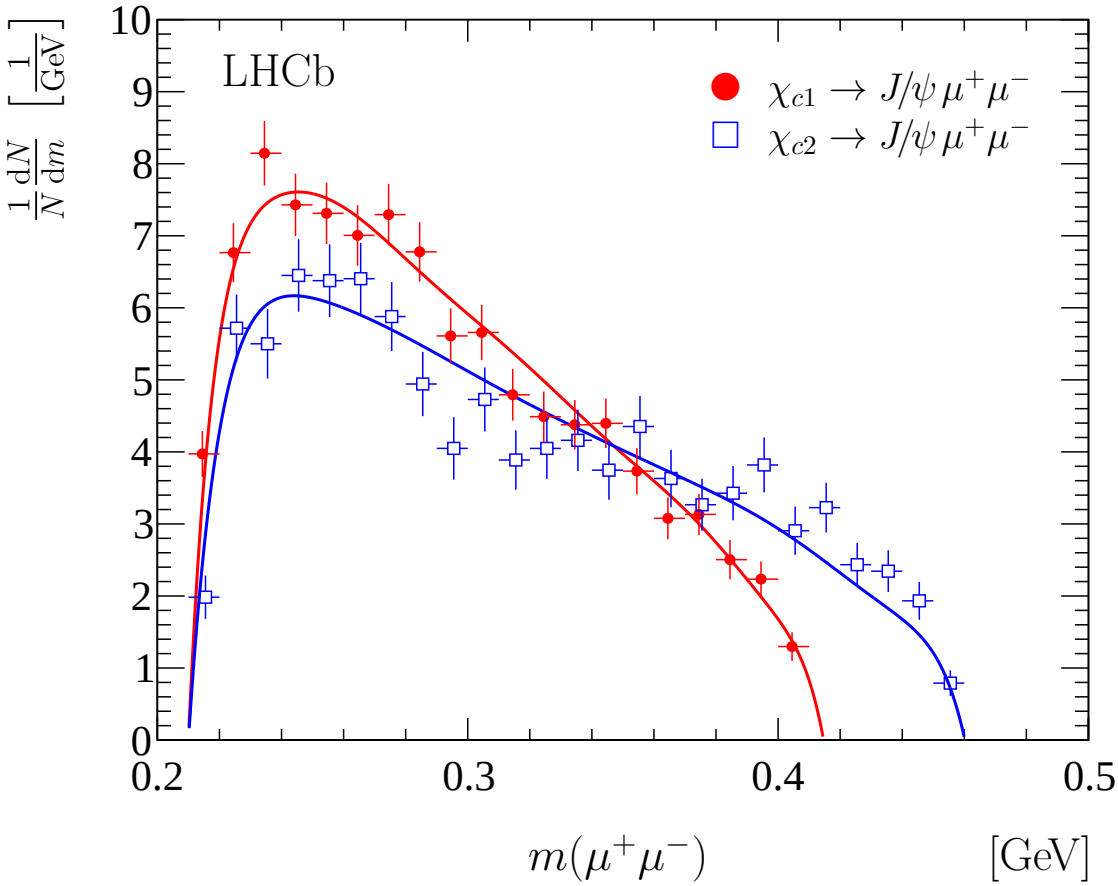

Figure 2: Background-subtracted $m(\mu^+\mu^-)$ distribution for $\chi_{c1} \to J/\psi\,\mu^+\mu^-$ (solid red circles) and $\chi_{c2} \to J/\psi\,\mu^+\mu^-$ (open blue squares) decays. The distributions are normalized to unit area. The curves show the expected distribution from the simulation, which uses the model described in Ref. [29].

Ref. [17] a 20 keV uncertainty is assigned.

The distortion of the lineshape due to final-state radiation introduces a bias on the mass. This bias is evaluated using the simulation to be 47 ± 7 keV (29 ± 10 keV) for the χ_{c1} (χ_{c2}) where the uncertainty is statistical. The central values of the mass measurements are corrected accordingly and the uncertainties are propagated.

Other uncertainties arise from the fit modelling and are studied using a simplified simulation. Several variations of the relativistic Breit-Wigner distribution are considered.

Table 2: Systematic uncertainties on the mass and mass difference measurements.

Source of uncertainty	$m(\chi_{c1})$ [keV]	$m(\chi_{c2})$ [keV]	$m(\chi_{c2}) - m(\chi_{c1})$ [keV]
Momentum scale	88	102	18
Energy loss correction	20	20	—
Final-state radiation	7	10	12
Resonance shape	15	24	25
Background model	< 2	< 2	< 2
Resolution model	7	2	6
Sum in quadrature	92	107	34

Using Jackson form factors, modifying the meson radius parameter and varying the orbital angular momentum, the observed χ_{c1} (χ_{c2}) mass changes by at most 15 (24) keV, which is assigned as a systematic uncertainty. Similarly, fitting with a double-sided Crystal Ball or Apollonios model, variations of 7 keV and 2 keV are seen for the χ_{c1} and χ_{c2} masses and assigned as systematic uncertainties. Finally, varying the order of the polynomial background function results in a further uncertainty of 2 keV. The uncertainties due to the momentum scale and energy loss correction largely cancel in the mass difference. The assigned systematic uncertainties on the mass measurements are summarized in Table 2.

The main uncertainty on the determination of the natural width of the χ_{c2} is due to the knowledge of the detector resolution. This is accounted for in the statistical uncertainty since the resolution scale is determined using the χ_{c1} signal in data. Similarly, the uncertainty on the knowledge of the χ_{c1} width is propagated via the Gaussian constraint in the mass fit. By running fits with and without the constraint the latter is evaluated to be 40 keV. Further uncertainties of 10 keV and 20 keV arise from the assumed Breit-Wigner parameters and resolution model, respectively. Other systematic uncertainties, *e.g.* due to the background model, are negligible. The stability of the results is studied by dividing the data into different running periods and also into kinematic bins and repeating the fit. None of these tests shows evidence of a systematic bias.

In summary, the decays $\chi_{c1} \to J/\psi\,\mu^+\mu^-$ and $\chi_{c2} \to J/\psi\,\mu^+\mu^-$ are observed and the mass of the χ_{c1} meson together with the mass and natural width of the χ_{c2} are measured. The results for the mass measurements are

$$\begin{aligned} m(\chi_{c1}) &= 3510.71 \pm 0.04 \pm 0.09\,\text{MeV}, \\ m(\chi_{c2}) &= 3556.10 \pm 0.06 \pm 0.11\,\text{MeV}, \\ m(\chi_{c2}) - m(\chi_{c1}) &= \quad 45.39 \pm 0.07 \pm 0.03\,\text{MeV}, \end{aligned}$$

where the first uncertainty is statistical and the second is systematic. The dominant systematic uncertainty is due to the knowledge of the momentum scale and largely cancels in the mass difference. It can be seen in Table 3 that the measurements are in good agreement with and have comparable precision to the best previous ones, made using $p\overline{p}$ annihilation at threshold by the E760 [39] and E835 experiments [40] at Fermilab. They are considerably more precise than the best measurement based on the final-state reconstruction [41]. It should be noted that the world average for the χ_{c1} mass has a scale factor of 1.5 to account for the poor agreement between the results [20]. The result for

Table 3: LHCb measurements compared to both previous measurements from Ref. [39] and the current world averages from Ref. [20]. The quoted uncertainties includes statistical and systematic uncertainties.

Quantity [MeV]	LHCb measurement	Best previous measurement	World average
$m(\chi_{c1})$	3510.71 ± 0.10	3510.72 ± 0.05	3510.66 ± 0.07
$m(\chi_{c2})$	3556.10 ± 0.13	3556.16 ± 0.12	3556.20 ± 0.09
$\Gamma(\chi_{c2})$	2.10 ± 0.20	1.92 ± 0.19	1.93 ± 0.11

the χ_{c2} natural width is

$$\Gamma(\chi_{c2}) = 2.10 \pm 0.20\,(\text{stat}) \pm 0.02\,(\text{syst})\,\text{MeV}\,.$$

It has similar precision to and is in good agreement with previous measurements [20].

The observations presented here open up a new avenue for hadron spectroscopy at the LHC. These decay modes can be used to measure the production of χ_{c1} and χ_{c2} states with a similar precision to the converted photon study presented in Ref. [6]. Importantly, it will be possible to extend measurements down to very low $p_{\mathrm{T}}(\chi_{c1,c2})$ probing further QCD predictions [42–44]. In addition, measurements of the transition form factors [45] will provide inputs on the interaction between charmonium states and the electromagnetic field. With larger data samples, studies of the Dalitz decays of other heavy-flavour states will become possible. For example, measurement of the transition form factor of the $X(3872)$ via its Dalitz decay may help elucidate the nature of this enigmatic state [9].

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References

[1] N. Brambilla *et al.*, *Heavy quarkonium: Progress, puzzles, and opportunities*, Eur. Phys. J. **C71** (2011) 1534, `arXiv:1010.5827`.

[2] E. Eichten *et al.*, *Charmonium: The model*, Phys. Rev. **D17** (1978) 3090, Erratum ibid. **B21** (1980) 313.

[3] N. Brambilla, A. Pineda, J. Soto, and A. Vairo, *Effective field theories for heavy quarkonium*, Rev. Mod. Phys. **77** (2005) 1423, `arXiv:hep-ph/0410047`.

[4] CDF collaboration, A. Abulencia *et al.*, *Measurement of* $\sigma_{\chi_{c2}}\mathcal{B}(\chi_{c2} \to J/\psi\gamma)/\sigma_{\chi_{c1}}\mathcal{B}(\chi_{c1} \to J/\psi\gamma)$ *in* $p\bar{p}$ *collisions at* $\sqrt{s} = 1.96$ *TeV*, Phys. Rev. Lett. **98** (2007) 232001, `arXiv:hep-ex/0703028`.

[5] LHCb collaboration, R. Aaij *et al.*, *Measurement of the cross-section ratio* $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ *for prompt* χ_c *production at* $\sqrt{s} = 7$ *TeV*, Phys. Lett. **B714** (2012) 215, `arXiv:1202.1080`.

[6] LHCb collaboration, R. Aaij *et al.*, *Measurement of the relative rate of prompt* χ_{c0}, χ_{c1} *and* χ_{c2} *production at* $\sqrt{s} = 7$ *TeV*, JHEP **10** (2013) 115, `arXiv:1307.4285`.

[7] CMS collaboration, S. Chatrchyan *et al.*, *Measurement of the relative prompt production rate of* χ_{c1} *and* χ_{c2} *in pp collisions at* $\sqrt{s} = 7$ *TeV*, Eur. Phys. J. **C72** (2012) 2251, `arXiv:1210.0875`.

[8] ATLAS collaboration, G. Aad *et al.*, *Measurement of* χ_{c1} *and* χ_{c2} *production with* $\sqrt{s} = 7$ *TeV pp collisions at ATLAS*, JHEP **07** (2014) 154, `arXiv:1404.7035`.

[9] BESIII collaboration, M. Ablikim *et al.*, *Observation of* $\psi(3686) \to e^+e^-\chi_{cJ}$ *and* $\chi_{cJ} \to e^+e^-J/\psi$, Phys. Rev. Lett. **118** (2017) 221802, `arXiv:1701.05404`.

[10] R. H. Dalitz, *On an alternative decay process for the neutral* π *meson, Letters to the Editor*, Proc. Phys. Soc. **A64** (1951) 667.

[11] LHCb collaboration, A. A. Alves Jr. *et al.*, *The LHCb detector at the LHC*, JINST **3** (2008) S08005.

[12] LHCb collaboration, R. Aaij *et al.*, *LHCb detector performance*, Int. J. Mod. Phys. **A30** (2015) 1530022, `arXiv:1412.6352`.

[13] R. Aaij *et al.*, *Performance of the LHCb Vertex Locator*, JINST **9** (2014) P09007, `arXiv:1405.7808`.

[14] R. Arink *et al.*, *Performance of the LHCb Outer Tracker*, JINST **9** (2014) P01002, `arXiv:1311.3893`.

[15] LHCb collaboration, R. Aaij *et al.*, *Measurement of b-hadron masses*, Phys. Lett. **B708** (2012) 241, `arXiv:1112.4896`.

[16] LHCb collaboration, R. Aaij *et al.*, *Measurements of the* Λ_b^0, Ξ_b^-, *and* Ω_b^- *baryon masses*, Phys. Rev. Lett. **110** (2013) 182001, `arXiv:1302.1072`.

[17] LHCb collaboration, R. Aaij *et al.*, *Precision measurement of D meson mass differences*, JHEP **06** (2013) 065, `arXiv:1304.6865`.

[18] A. A. Alves Jr. *et al.*, *Performance of the LHCb muon system*, JINST **8** (2013) P02022, `arXiv:1211.1346`.

[19] R. Aaij *et al.*, *The LHCb trigger and its performance in 2011*, JINST **8** (2013) P04022, `arXiv:1211.3055`.

[20] Particle Data Group, C. Patrignani *et al.*, *Review of particle physics*, Chin. Phys. **C40** (2016) 100001, and 2017 update.

[21] B. Sciascia, *LHCb Run 2 trigger performance*, PoS **BEAUTY 2016** (2016) 029.

[22] G. Dujany and B. Storaci, *Real-time alignment and calibration of the LHCb Detector in Run II*, J. Phys. Conf. Ser. **664** (2015) 082010.

[23] R. Aaij *et al.*, *Tesla: An application for real-time data analysis in High Energy Physics*, Comput. Phys. Commun. **208** (2016) 35, `arXiv:1604.05596`.

[24] A. Dziurda, *Full offline reconstruction in real time with the LHCb detector*, EPJ Web Conf. **127** (2016) 00007.

[25] W. D. Hulsbergen, *Decay chain fitting with a Kalman filter*, Nucl. Instrum. Meth. **A552** (2005) 566, `arXiv:physics/0503191`.

[26] T. Sjöstrand, S. Mrenna, and P. Skands, *A brief introduction to PYTHIA 8.1*, Comput. Phys. Commun. **178** (2008) 852, `arXiv:0710.3820`.

[27] I. Belyaev *et al.*, *Handling of the generation of primary events in Gauss, the LHCb simulation framework*, J. Phys. Conf. Ser. **331** (2011) 032047.

[28] D. J. Lange, *The EvtGen particle decay simulation package*, Nucl. Instrum. Meth. **A462** (2001) 152.

[29] A. Faessler, C. Fuchs, and M. I. Krivoruchenko, *Dilepton spectra from decays of light unflavored mesons*, Phys. Rev. **C61** (2000) 035206, `arXiv:nucl-th/9904024`.

[30] P. Golonka and Z. Was, *PHOTOS Monte Carlo: A precision tool for QED corrections in Z and W decays*, Eur. Phys. J. **C45** (2006) 97, `arXiv:hep-ph/0506026`.

[31] Geant4 collaboration, J. Allison *et al.*, *Geant4 developments and applications*, IEEE Trans. Nucl. Sci. **53** (2006) 270; Geant4 collaboration, S. Agostinelli *et al.*, *Geant4: A simulation toolkit*, Nucl. Instrum. Meth. **A506** (2003) 250.

[32] M. Clemencic *et al.*, *The LHCb simulation application, Gauss: Design, evolution and experience*, J. Phys. Conf. Ser. **331** (2011) 032023.

[33] J. M. Blatt and V. F. Weisskopf, *Theoretical nuclear physics*, Springer, New York, 1952. doi: 10.1007/978-1-4612-9959-2.

[34] J. D. Jackson, *Remarks on the phenomenological analysis of resonances*, Nuovo Cim. **34** (1964) 1644.

[35] T. Skwarnicki, *A study of the radiative cascade transitions between the Upsilon-prime and Upsilon resonances*, PhD thesis, Institute of Nuclear Physics, Krakow, 1986, DESY-F31-86-02.

[36] LHCb collaboration, R. Aaij *et al.*, *Observation of J/ψ-pair production in pp collisions at $\sqrt{s} = 7\ TeV$*, Phys. Lett. **B707** (2012) 52, `arXiv:1109.0963`.

[37] D. Martínez Santos and F. Dupertuis, *Mass distributions marginalized over per-event errors*, Nucl. Instrum. Meth. **A764** (2014) 150, `arXiv:1312.5000`.

[38] M. Pivk and F. R. Le Diberder, *sPlot: A statistical tool to unfold data distributions*, Nucl. Instrum. Meth. **A555** (2005) 356, `arXiv:physics/0402083`.

[39] E760 collaboration, T. A. Armstrong *et al.*, *Study of the χ_{c1} and χ_{c2} charmonium states formed in $\overline{p}p$ annihilations*, Nucl. Phys. **B373** (1992) 35.

[40] E865 collaboration, M. Andreotti *et al.*, *Measurement of the resonance parameters of the $\chi_1(1^3P_1)$ and $\chi_2(1^3P_2)$ states of charmonium formed in $p\bar{p}$ annihilations*, Nucl. Phys. **B717** (2005) 34, `arXiv:hep-ex/0503022`.

[41] BES collaboration, M. Ablikim *et al.*, *Precise measurement of spin-averaged $\chi_{cJ}(1P)$ mass using photon conversions in $\psi(2S) \to \gamma\chi_{cJ}$*, Phys. Rev. **D71** (2005) 092002, `arXiv:hep-ex/0502031`.

[42] Y.-Q. Ma, K. Wang, and K.-T. Chao, *QCD radiative corrections to χ_{cJ} production at hadron colliders*, Phys. Rev. **D83** (2011) 111503, `arXiv:1002.3987`.

[43] A. K. Likhoded, A. V. Luchinsky, and S. V. Poslavsky, *Production of heavy quarkonia in hadronic experiments*, Phys. Atom. Nucl. **78** (2015) 1056, [Yad. Fiz. **78** (2015) 1119].

[44] D. Boer and C. Pisano, *Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER*, Phys. Rev. **D86** (2012) 094007, `arXiv:1208.3642`.

[45] L. G. Landsberg, *Electromagnetic decays of light mesons*, Phys. Rept. **128** (1985) 301.

LHCb collaboration

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