Discovery of the Doubly Charmed Baryon Ξ_{cc}^{++} at LHCb

AO XU AND ZHENWEI YANG
CENTER FOR HIGH ENERGY PHYSICS, TSINGHUA UNIVERSITY, CHINA

ABSTRACT

Using proton-proton collision data collected by the LHCb experiment in 2016, a new baryon is observed in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum, with the Λ_c^+ baryon reconstructed in the $pK^- \pi^+$ decay mode. The new particle, which decays via weak interactions, is identified as the doubly charmed baryon Ξ_{cc}^{++}, the mass of which is measured to be $3621.40 \pm 0.72(\text{stat}) \pm 0.27(\text{syst}) \pm 0.14(\Lambda_c^+)$ MeV/c^2. The last uncertainty is due to the limited knowledge of the Λ_c^+ mass. The center-of-mass energy of the data sample used in this measurement is $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 1.7 fb^{-1}. The observation is confirmed in a separate sample collected by LHCb at 8 TeV in 2012, corresponding to an integrated luminosity of 2.0 fb^{-1}. The results from the two samples are consistent, and strongly disfavor the SELEX reported structure interpreted as the Ξ_{cc}^+ baryon.

INTRODUCTION

The quark model proposed by M. Gell-Mann and G. Zweig in 1960s revolutionized our understanding of matter [1,2]. It classifies hadrons in terms of their quark and antiquark content. When the lightest four quarks (u,d,s,c) are included, the quark model predicts hadron states that form $SU(4)$ multiplets [3], among which all expected ground states with charm quantum number $C=0$ or $C=1$ have been discovered [4]. The states with $C=2$ are baryons with two charm quarks, dubbed doubly charmed baryons. Three doubly charmed baryons that decay via weak interactions are expected: Ξ_{cc}^{++}, Ξ_{cc}^+ and Ω_{cc}^+. Each of these three states are predicted to have spin-parity quantum numbers $J^P=1/2^+$. The former two form an isospin doublet, and the last one is an isospin singlet.

Many efforts have been devoted to the study of doubly charmed baryons since four decades ago. Calculations of most theoretical models give the mass of the Ξ_{cc} states in the range 3500 to 3700 MeV/c^2 [5-18]. Due to the approximate isospin symmetry the mass difference between the Ξ_{cc}^+ and Ξ_{cc}^{++} states is expected to be only a few MeV/c^2 [19-21]. On the other hand, the lifetimes are expected to be significantly different, 50 to 250 fs for the Ξ_{cc}^+ baryon and 200 to 700 fs for the Ξ_{cc}^{++} baryon [7,14,18,22-25].

In 2002 and 2005 the SELEX experiment claimed the observations of the Ξ_{cc}^+ baryon at a mass of 3519 ± 2 MeV/c^2 [26,27]. They reported signal yields of 15.9 (5.62) events over 6.1 ± 0.5 (1.38 ± 0.13) background in the $\Lambda_c^+ K^- \pi^+$ (pD^+K^-) final state. These results have resulted in a long standing puzzle, since they provided a number of significantly unexpected features, e.g., a very short lifetime (<33 fs) and a very large production rate (20%) relative to that of the Λ_c^+ baryon. The FOCUS [28], BaBar [29], and Belle [30] experiments made searches for the SELEX reported state, but failed to find any evidence. The LHCb experiment also failed to find any signal using pp collision data at a centre-of-mass energy $\sqrt{s} = 7$ TeV collected in 2011, corresponding to an integrated of 0.65 fb^{-1} [31].

Inspired by the work of F.-S. Yu et al [32], which predicts that the branching fraction of the $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ decay could be as high as 10%, the LHCb experiment performed a search using this mode and made an observation of the Ξ_{cc}^{++} baryon, recently submitted to Phys. Rev. Lett. [33]. Figure 1 shows an example Feynman dia-

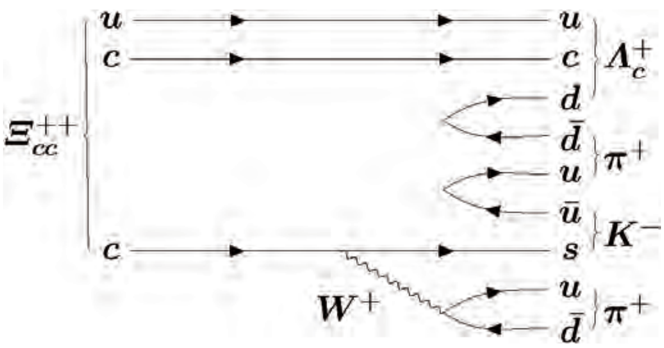

Fig. 1: Example Feynman diagram that contributes to the decay $\Xi_{cc}^{++}\rightarrow\Lambda_c^+ K^- \pi^+\pi^+$.

gram that contributes to this decay. In the analysis the Λ_c^+ baryon is reconstructed in the final state $pK^- \pi^+$. The data sample used is collected by the LHCb experiment with pp collisions at $\sqrt{s}$ =13 TeV provided by the Large Hadron Collider(LHC) at CERN in 2016. The corresponding integrated luminosity is 1.7 fb^{-1}. Inclusion of charge-conjugate processes is implied throughout.

DETECTOR

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2<\eta<5$, designed to study particles containing b or c quarks, and is described in detail in Refs.[34, 35]. The detector elements most relevant to this analysis are a silicon-strip vertex detector surrounding the pp interaction region, a tracking system that provides a measurement of the momentum of charged particles, and two ring-imaging Cherenkov detectors [36] that are able to discriminate between different species of charged hadrons. The online event selection is performed by a trigger that consists of a hardware stage, which is based on information from the calorimeter and muon systems, followed by a software stage, which fully reconstructs the event [37]. The online reconstruction incorporates near-real-time alignment and calibration of the detector [38], which in turn allows the reconstruction of the Ξ_{cc}^{++} decay to be performed entirely in the trigger software.

ANALYSIS STRATEGY

The production cross-section of the Ξ_{cc}^{++} baryon is expected to be small [39], while the background level in pp collisions at the LHC is expected to be high. Therefore, the principle of the event selection is to keep high signal efficiency as well as high background rejection rate. To avoid fake signal peaks due to bias, the search region for the signal in the data was kept blinded to the analysts until all selection criteria had been finalized.

To reconstruct the $\Xi_{cc}^{++}\rightarrow\Lambda_c^+ K^- \pi^+ \pi^+$ candidate, all six charged particles in the final state are required to have good track quality, to have proper hadron-identification information, and to have transverse momentum p_T greater than 500 MeV/c. Possible duplicate tracks are minimized by requiring a minimal angle between each pair of the same-charge final-state particles. The first step is to reconstruct the Λ_c^+ candidate from three charged particles that from a good-quality vertex. Since the Λ_c^+ baryon has a finite decay length, the three particles should not originate from any pp collision primary vertex (PV), and the Λ_c^+ decay vertex is required to be away from its associated PV. The associated PV of a particle is defined to be the PV with respect to which the particle has the smallest impact parameter significance, which is the difference in the PV fit x^2 with and without the particle in question. Three additional charged particles, which should form a good-quality vertex with the Λ_c^+ candidate, are then included to reconstruct a $\Xi_{cc}^{++}\rightarrow\Lambda_c^+ K^- \pi^+ \pi^+$ candidate. Since The Ξ_{cc}^{++} baryon is also expected to have a finite decay length, its vertex should be away from its associated PV, and should be upstream of the Λ_c^+ decay vertex. The Ξ_{cc}^{++} candidate is required to have p_T greater than 4 GeV/c.

A multivariate filter based on the multilayer perceptron algorithm [40] is used to further suppress the background level. The filter is trained with signal events from simulation and background events from a control sample of the data, the wrong-sign (WS) $\Lambda_c^+ K^- \pi^+ \pi^-$ combination. The signal events used in the training are produced with the standard LHCb simulation software [41-46]. The Ξ_{cc}^{++} baryon is generated by a dedicated generator GENXICC [47], with the mass and lifetime assumed to be 3.6 GeV/c^2 and 333 fs. The selection described above is applied to both signal and background samples used in the training, and candidates in both samples are required to lie in a mass region, defined as $2270<m_{\text{cand}}(\Lambda_c^+)<2306$ MeV/c^2 and $3300<m_{\text{cand}}(\Xi_{cc}^{++})<3800$ MeV/c^2, with $m_{\text{cand}}(\Lambda_c^+)$ the reconstructed Λ_c^+ mass and $m_{\text{cand}}(\Xi_{cc}^{++})$ the reconstructed mass of the $\Lambda_c^+ K^- \pi^+ \pi^+$ combination, defined as $m(\Lambda_c^+ K^- \pi^+ \pi^+)-m_{\text{cand}}(\Lambda_c^+)+m_{\text{PDG}}(\Lambda_c^+)$. The value $m_{\text{PDG}}(\Lambda_c^+)=2286.46 \pm 0.14$ MeV/c^2 is the known Λ_c^+ mass [4]. Ten kinematic and topological variables that are suitable to discriminate the signal from the background are used in the multivariate filter [33]. The optimal criterion to be applied to the multivariate filter output is chosen to maximize the expected value of a figure of merit [49]. After the

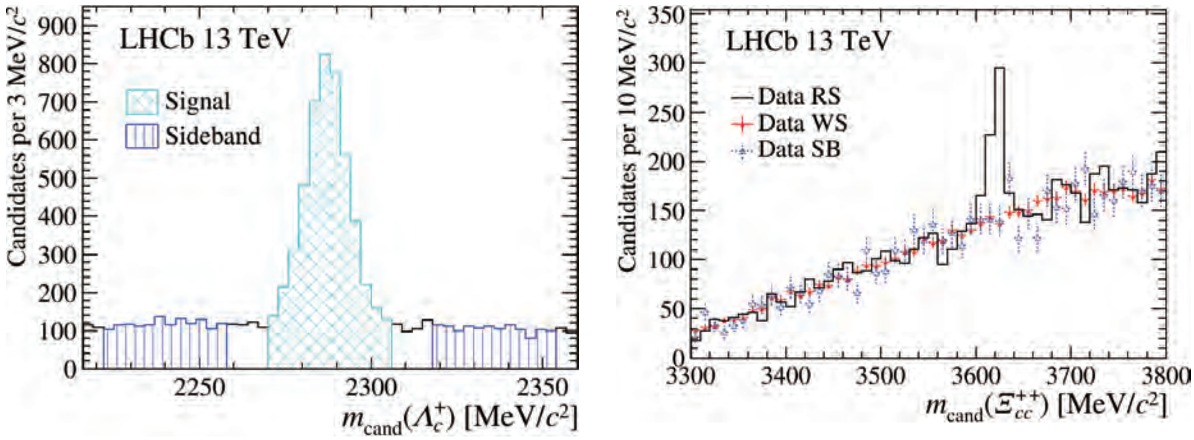

Fig. 2: Invariant mass spectra of (left) Λ_c^+ and (right) Ξ_{cc}^{++} candidates in the final selected data sample. In the upper plot candidates outside the Λ_c^+ signal region are also displayed. The lower plot shows the right-sign (RS) signal sample $\Xi_{cc}^{++}\to\Lambda_c^+ K^- \pi^+ \pi^+$ along with two control samples (normalized): candidates $\Lambda_c^+ K^- \pi^+ \pi^+$ in the Λ_c^+ sideband (SB) and wrong-sign (WS) $\Lambda_c^+ K^- \pi^+ \pi^-$ candidates.

multivariate filter is applied, a small fraction of events still have more than one candidates. For candidates that are reconstructed with the same six final-state charged particles but two of them (with the same charge and the same particle type) interchanged, e.g., the π^+ from the Λ_c^+ decay and one π^+ from the Ξ_{cc}^{++} decay, a peaking structure will appear in the background. For such candidates, only one of them is retained at random.

RESULTS

Figure 2 shows the invariant mass distributions of the Λ_c^+ and Ξ_{cc}^{++} candidates. In the right plot of Fig. 2 a clear structure is observed in the signal mode at a mass around 3620 MeV/c^2; on the contrary, no significant structure is visible in the WS events or in the Λ_c^+ mass sideband events used as control samples. An unbinned extended maximum likelihood fit to the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass distribution is performed to measure the properties of the peaking structure, as shown in Fig. 3. The fit is restricted to the mass window 3620 ± 150 MeV/c^2 to simplify the description of the background shape, i.e. a second-order polynomial with parameters free to float. The peaking structure is empirically described by the sum of a Gaussian function and a modified Gaussian function with power-law tails on both sides, with peak parameters fixed to values in simulation apart from the peak position, yield and an overall resolution parameter. The signal yield from the fit is 313 ± 33, and the resolution parameter is 6.6 ± 0.8 MeV/c^2, which is consistent with the detector resolution. The local statistical significance evaluated with a likelihood ratio test is above twelve standard deviations (σ). The mass of the Ξ_{cc}^{++} baryon is measured to be $3621.40\pm0.72(\mathrm{stat})\pm0.27(\mathrm{syst})\pm0.14(\Lambda_c^+)$MeV/c^2, where the last uncertainty is due to the limited knowledge of the Λ_c^+ mass [4]. In this result corrections have been made to account for biases due to the selections and the final-state photon radiation, and systematic uncertainties due to the momentum-scale calibration [49,50], the event selection, the unknown Ξ_{cc}^{++} lifetime, and the mass fit model are taken into account.

To make sure that the observation is robust, many cross-checks have been performed. The signal significance under all the following checks remains above 12σ, including fixing the resolution parameter to the simulated value in the fit to the invariant mass distribution, varying the selection criterion for the multivariate filter, using an alternative selection without any multivariate classifier. No fake peaking structure is observed in the control samples, when various intermediate resonances are required to be present. The contributions of misidentified $D^+\to K^- \pi^+ \pi^+$ and $D_s^+\to K^+ K^- \pi^+$ are found to be negligible.

The decay time properties of the signal are investigated by requiring that the proper decay time of the Ξ_{cc}^{++} candidate exceeds five times its resolution. As shown in Fig. 4 the peaking structure remains significant. The local statistical significance is still above 12σ according to a likelihood ratio test. Therefore, the observed peaking structure is demonstrated to originate from a weak decay. Taking into account the fact that the mass of the peaking structure is around 3621 MeV/c^2, it must be a state containing two charm quarks, i.e., the doubly charged doubly charmed baryon Ξ_{cc}^{++}.

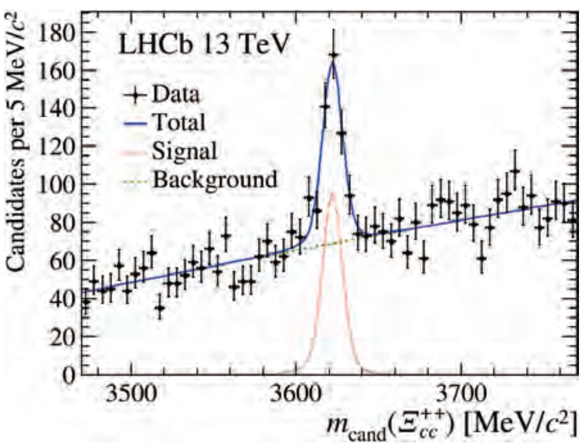

Fig. 3: Invariant mass distribution of $\Lambda_c^+ K^- \pi^+ \pi^+$ candidates for the 13 TeV data sample with fit projects overlaid.

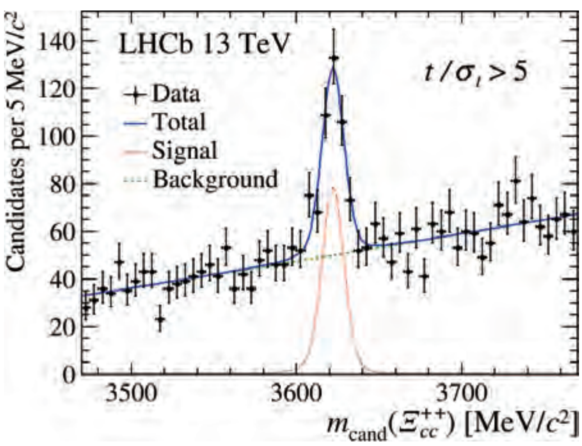

Fig. 4: Invariant mass distribution of the $\Lambda_c^+ K^- \pi^+ \pi^+$ candidates for the 13 TeV data sample with an additional requirement that the proper decay time divided its resolution is larger than 5. The fit projections are overlaid.

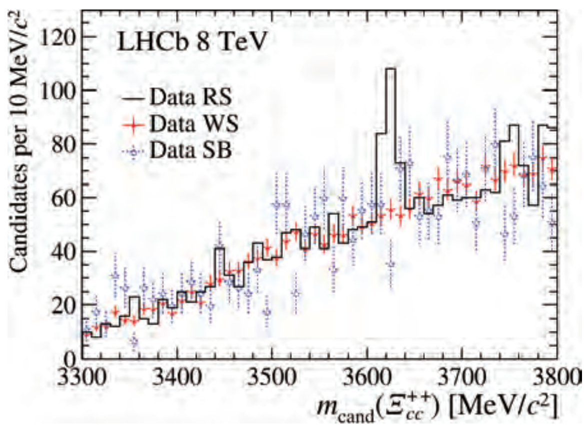

Fig. 5: Invariant mass spectrum of Ξ_{cc}^{++} candidates in the final selected data sample at 8 TeV. The right-sign (RS) signal sample $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ is shown together with two control samples (normalized): candidates $\Lambda_c^+ K^- \pi^+ \pi^+$ in the Λ_c^+ sideband (SB) and wrong-sign (WS) $\Lambda_c^+ K^- \pi^+ \pi^-$ candidates.

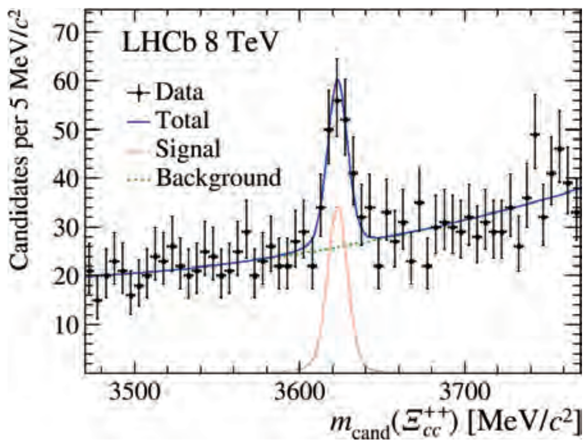

Fig. 6: Invariant mass distribution of $\Lambda_c^+ K^- \pi+\pi+$ candidates for the 8 TeV data sample with fit projects overlaid.

CROSSCHECKS IN 8 TEV DATA

The observation of the doubly charmed baryon Ξ_{cc}^{++} is confirmed by a similar study on a separate data sample collected by the LHCb experiment in 2012. The center-of-mass energy of the *pp* collisions is 8 TeV, and the integrated luminosity is 2.0 fb^{-1}. The preselection prior to the multivariate filter was chosen to be as similar as that for the 13 TeV sample. The multivariate filter trained with the 13 TeV sample was directly applied to the 8 TeV sample, however, the selection criterion of the filter output was reoptimized with simulated and control samples at 8 TeV.

Figure 5 shows the Ξ_{cc}^{++} mass spectrum in the 8 TeV sample after the final selection. A peaking structure around 3620 MeV/c^2 is again observed in the RS sample, while no significant structure is visible in the WS and SB control samples. To check if the properties of this peaking structure is consistent with the one observed in the 13 TeV data sample, the same fit procedure described in the previous section is applied to the 8 TeV right-sign sample. The results of the fits are shown in Fig. 6. The signal yield from the fit is 113 ± 21, and the resolution parameter is 6.6 ± 1.4 MeV/c^2, which is consistent with the detector resolution and the value obtained in the 13 TeV data sample. The local statistical significance evaluated with a likelihood ratio test is above seven standard deviations overlaid. The Ξ_{cc}^{++} mass difference between the two data samples is 0.8 ± 1.4(stat) MeV/c^2. Therefore, the properties of the two peaking structures observed in the two data samples are consistent. The combined signal yield in the two samples is 426 ± 39.

CONCLUSION

A highly significant peaking structure is observed in the $\Lambda_c^+ K^- \pi^+ \pi^+$ final state in pp collision data collected by the LHCb experiment at a center-of-mass energy $\sqrt{s} = 13$ TeV with an integrated luminosity of 1.7 fb^{-1}. The signal yield is 313 ± 33 and the local statistical significance is above twelve standard deviations. The mass of this structure is measured to be $3621.40 \pm 0.72(\mathrm{stat}) \pm 0.27(\mathrm{syst}) \pm 0.14(\Lambda_c^+)$ MeV/c^2 with the last uncertainty originating from the limited knowledge of the Λ_c^+ mass. The width of the structure is consistent with the detector resolution, and the signal candidates are seen to decay to the $\Lambda_c^+ K^- \pi^+ \pi^+$ final state via weak interactions. Therefore, this is a state consistent with the properties of the Ξ_{cc}^{++} baryon that decays weakly. The robustness is assured by a variety of crosschecks, and is confirmed by the observation of the same peak structure in a separate data sample collected by the LHCb experiment at $\sqrt{s} = 8$ TeV.

The mass difference between the Ξ_{cc}^{++} state observed by LHCb and the the Ξ_{cc}^{++} state reported by SELEX [26,27] is 103 ± 2 MeV/c^2, two orders of magnitude larger than the expectation from the small isospin symmetry breaking [19-21]. Therefore, the structure observed by SELEX is unlikely to be the Ξ_{cc}^{+} state if the structure observed here is the Ξ_{cc}^{++} state, contributing to solve the longstanding puzzle created by the SELEX result.

References

[1] M. Gell-Mann, Phys. Lett. 8, 214 (1964).
[2] G. Zweig, Report No. CERN-TH-401 (1964); Report No. CERN-TH-412 (1964).
[3] A. De Rújula et al, Phys. Rev. D12 (1975) 147.
[4] Particle Data Group, C. Patrignani et al, Chin. Phys. C40 (2016) 100001, and 2017 update.
[5] S. S. Gershtein et al, Phys. Atom. Nucl. 63 (2000) 274; Mod. Phys. Lett. A14 (1999) 135; Phys. Rev. D62 (2000) 054021.
[6] C. Itoh et al, Phys. Rev. D61 (2000) 057502.
[7] K. Anikeev et al, arXiv:hep-ph/0103169.
[8] D. Ebert et al, Phys. Rev. D66 (2002) 014008.
[9] D.-H et al, Phys. Rev. D70 (2004) 094004.
[10] W. Roberts et al, Int. J. Mod. Phys. A23 (2008) 2817.
[11] A. Vacarce et al, Eur. Phys. J. A37 (2008) 217.
[12] J.-R. Zhang et al, Phys. Rev. D78 (2008) 094007.
[13] Z.-G. Wang, Eur. Phys. J. A45 (2010) 267.
[14] M. Karliner et al, Phys. Rev. D90 (2014) 094007.
[15] K.-W. Wei et al, Phys. Rev. D92 (2015) 076008.
[16] Z.-F. Sun et al, Phys. Rev. D93 (2016) 094002.
[17] C. Alexandrou et al, arXiv:1704.02647.
[18] S. Fleck et al, Pro. Theor. Phys. 82 (1989) 760.
[19] C.-W. Hwang et al, Phys. Rev. D78 (2008) 073013.
[20] S. J. Brodsky et al, Phys. Lett. B698 (2011) 251.
[21] M. Karliner et al, arXiv:1706.06961.
[22] B. Guberina et al, Eur. Phys. J. C9 (1999) 213.
[23] V. V. Kiselev et al, Phys. Rev. D60 (1999) 014007.
[24] C.-H. Chang et al, Comm. Theor. Phys. 49 (2008) 993.
[25] A. V. Berezhnoy et al, Phys. Atom. Nucl. 79 (2016) 260.
[26] SELEX, Phys. Rev. Lett. 89 (2002) 112001.
[27] SELEX, Phys. Lett. B628 (2005) 18.
[28] S. P. Ratti, Nucl. Phys. Proc. Suppl. 115 (2003) 33.
[29] BaBar, Phys. Rev. D74 (2006) 011103.
[30] Belle, Phys. Rev. Lett. 97 (2006) 162001.
[31] LHCb, JHEP 12 (2013) 090.
[32] F.-S. Yu et al, arXiv:1703.09086.
[33] LHCb, arXiv:1707.01621, submitted to PRL.
[34] LHCb, JINST 3 (2008) S08005.
[35] LHCb, Int. J. Mod. Phys. A30 (2015) 1530022.
[36] M. Adinolfi et al, Eur. Phys. J. C73 (2013) 2431.
[37] R. Aaij et al, JINST 8 (2013) P04022.
[38] G. Dujany et al, J. Phys. Conf. Ser. 664 (2015) 082010.
[39] C.-H. Chang et al, Phys. Rev. D73 (2006) 094022.
[40] A. Hoecker et al, PoS ACAT (2007) 040.
[41] T. Sjöstrand et al, Comp. Phys. Comm. 178 (2008) 852; JHEP 05, 026 (2006).
[42] I. Belyaev et al, J. Phys. Conf. Ser. 331, 032047 (2011).
[43] D. J. Lange, Nucl. Instrum. Meth. A462, 152 (2001).
[44] P. Golonka and Z. Was, Eur. Phys. J. C45, 97 (2006).
[45] Geant4 collaboration, Nucl. Instrum. Meth. A506 (2003) 250; IEEE Trans. Nucl. Sci. 53 (2006) 270.
[46] M. Clemencic et al, J. Phys. Conf. Ser. 331 (2011) 032023.
[47] C.-H. Chang et al, Comp. Phys. Comm. 177 (2007) 467; Comp. Phys. Comm. 181 (2010) 1144.
[48] G. Punzi, arXiv:physics/0308063.
[49] LHCb, Phys. Lett. B708 (2012) 241.
[50] LHCb, JHEP 06 (2013) 065

Zhenwei Yang received his PhD from the Department of Physics, Tsinghua University, China. He is an associate professor at the Department of Engineering Physics and Center for High Energy Physics, Tsinghua University in China.

Ao Xu received his bachelor degree from the Department of Engineering Physics, Tsinghua University, China, and is now a PhD student at the Department of Engineering Physics and Center for High Energy Physics, Tsinghua University in China.