PROCEEDINGS OF SCIENCE

Discovery of the doubly charmed baryon Ξ_{cc}^{++} at LHCb

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The LHCb collaboration announced the first observation of the doubly charmed baryon Ξ_{cc}^{++}, which was discovered decaying to a $\Lambda_c^+ K^- \pi^+ \pi^+$ final state. A highly significant structure is found in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum in proton-proton collision data collected by the LHCb experiment at center-of-mass energies of 13 TeV and 8 TeV. The peak contains 313 ± 33 decays in the 13 TeV sample and 113 ± 21 decays in the 8 TeV, with local significances in excess of 12σ and 7σ respectively. The narrow structure has a width that is consistent with experimental resolution, and its properties are consistent with those of a weakly decaying state and inconsistent with those of a strongly decaying state. The difference between the masses of the structure, identified as Ξ_{cc}^{++}, and the Λ_c^+ baryon is $1334.94 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.})\,\text{MeV}/c^2$, and the mass of the Ξ_{cc}^{++} baryon is $3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)\,\text{MeV}/c^2$.

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1. Introduction

The LHCb collaboration announced its discovery of the Ξ_{cc}^{++} baryon at the 2017 European Physical Society Conference on High Energy Physics. The findings were concurrently submitted for publication and have recently been published [1]. These Proceedings summarize the published work with an emphasis on the supporting studies that are detailed in the supplemental material available from the publisher[1] and in the supplementary material released with the preprint of the publication on the CERN Document Server (CDS).[2]

The constituent quark model of hadrons predicts the existence of three weakly decaying ground state $J^P = \frac{1}{2}^+$ baryons with two charmed valence quarks: Ξ_{cc}^+ (ccd) and Ξ_{cc}^{++} (ccu), which form an isospin doublet, and Ω_{cc}^+ (ccs). Several QCD computational formalisms have been used to predict their masses, lifetimes, relative production rates, and the spectroscopy of their excited states. (Please refer to the bibliography of Ref. [1] for a snapshot of the extensive literature.) However, there has been a relative paucity of experimental evidence for doubly charmed baryons. The only previously published evidence of their existence are the observations of the Ξ_{cc}^+ baryon claimed by the SELEX collaboration [2]. They observed narrow peaking structures at a mean mass of $3518.7 \pm 1.7\,\mathrm{MeV}/c^2$ in the mass spectra of $\Lambda_c^+ K^- \pi^+$ (15.9 signal events over 6.1 ± 0.5 background events, 6.3σ significance) and pD^+K^- (5.62 signal events over 1.38 ± 0.13 background events, 4.8σ significance). The lifetime of the state was unexpectedly short (less than 33 fs at the 90% confidence level) and had a production rate several orders of magnitude larger than theoretical predictions for their hyperon-beam-on-fixed-target collisions [3]—identification of the state as the Ξ_{cc}^+ baryon implied that 20% of all Λ_c^+ baryons observed by the SELEX experiment were produced in decays of Ξ_{cc}^+ baryons [2]. The FOCUS collaboration searched for evidence of doubly charmed baryon production in photon-on-fixed-target collisions [4] and the BaBar [5] and Belle [6] collaborations searched in e^+e^- collisions, but none found evidence for the state observed by SELEX nor for any other state identifiable as a doubly charmed baryon.

With a detector designed for flavor physics that is collecting the world's largest data sets of charmed hadrons, the LHCb experiment is an ideal laboratory for the further study of doubly charmed baryons [7]. Although LHCb's first search for Ξ_{cc}^+ in decays to $\Lambda_c^+ K^- \pi^+$ [8] produced in pp collisions at 7 TeV failed to find evidence for doubly charmed baryons, the sensitivity of that study was limited by design choices in the trigger and selection. The trigger and selections for doubly charmed baryons were subsequently refined to improve the sensitivity of the analysis methods, and the present observation of the Ξ_{cc}^{++} baryon is a direct consequence of those improvements.

2. Observation

We find a prominent and narrow structure in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum of pp collision data produced by the Large Hadron Collider and collected by the LHCb experiment. The structure

[1]The supplemental material available from the publisher of the study includes details of the confirming analysis with an independent data set.

[2]The supplementary material available on CDS contains additional plots that are included or described in this article and background-subtracted plots of the invariant masses of various combinations of the $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ decay products.

PoS(EPS-HEP2017)408

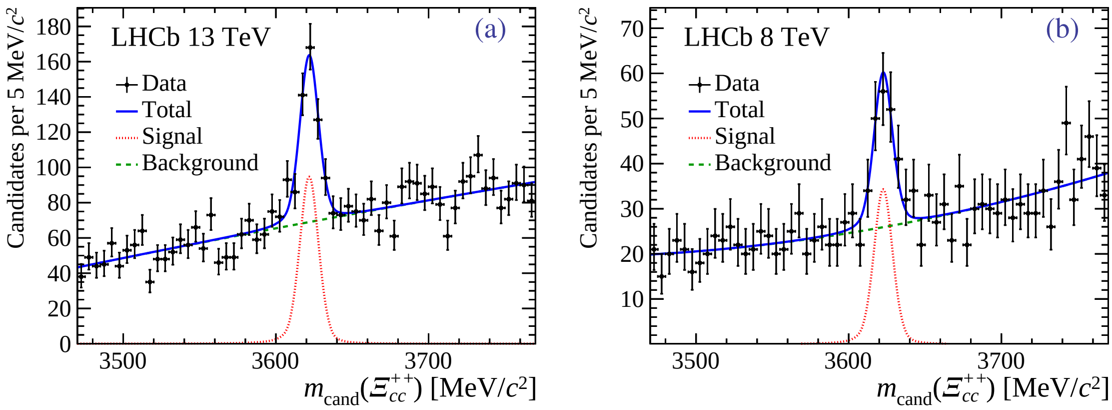

Figure 1: Invariant mass distributions of $\Lambda_c^+ K^- \pi^+ \pi^+$ candidates with fit projections overlaid for (a) 13 TeV and (b) 8 TeV data sets.

is consistent with the observation of the doubly charmed baryon Ξ_{cc}^{++} decaying to a $\Lambda_c^+ K^- \pi^+ \pi^+$ final state. The data sets for the discovery consist of pp collisions at a center-of-mass (CoM) energy of 13 TeV corresponding to an integrated luminosity of 1.7 fb^{-1} and at a CoM energy of 8 TeV corresponding to an integrated luminosity of 2.0 fb^{-1}. The two data sets are analyzed separately, and each yields a statistically independent observation of Ξ_{cc}^{++}. Because of the greater yield and statistical significance in the 13 TeV sample, the analysis of that data set is the primary result described in our Letter, while the analysis of the 8 TeV data set is a confirmation that is described more fully in the supplemental material of the publication [1].

In both data sets, Ξ_{cc}^{++} candidates are reconstructed in the decay chain $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$, $\Lambda_c^+ \to p K^- \pi^+$.[3] The candidates are coarsely filtered with cuts on various quantities that include reconstruction quality metrics, particle identification scores, and topological and dynamic variables, A multivariate discriminant that is based on quality, topological, and dynamic variables and that is trained to discriminate simulated $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ decays from backgrounds represented by wrong-sign (WS) $\Lambda_c^+ K^- \pi^+ \pi^-$ combinations in data selects the final analysis sample.

2.1 Primary analysis at 13 TeV

The Ξ_{cc}^{++} candidates in 13 TeV data are produced by LHCb's Turbo processing in which the decay chain is fully reconstructed and loosely selected in the software trigger [9]. Because there is no subsequent event reconstruction, we reduce the storage required to retain Turbo events for analysis, which has proven invaluable for measurements such as this one that involve examining very large data sets, e.g. the sample of $\Lambda_c^+ \to p K^- \pi^+$ decays detected by LHCb, for relatively rare processes, e.g. production of Λ_c^+ baryons in $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ decays. After the final selection is applied to the candidates, the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum in the range 3300-3800 MeV$/c^2$ has a single prominent narrow peak at approximately 3600 MeV$/c^2$. No structures are observed in the corresponding

[3] Similarly, the charge-conjugate decay chain is also reconstructed, and the analysis is based on the combined set of candidates from the charge-conjugate modes. No attempt to separately analyze the conjugate decays are presented, and charge conjugation is implied throughout this article.

PoS(EPS-HEP2017)408

region of the WS $\Lambda_c^+ K^- \pi^+ \pi^-$ mass spectrum nor in the spectrum of $[pK^-\pi^+]_{\text{SB}} K^-\pi^+\pi^+$ candidates where $[pK^-\pi^+]_{\text{SB}}$ combinations are taken from sidebands of the Λ_c^+ mass distribution.

Figure 1a shows the mass distribution around the observed peak. The mass variable that is plotted, $m_{\text{cand}}(\Xi_{cc}^{++})$, is the mass difference between the reconstructed combination mass, $m(\Lambda_c^+ K^-\pi^+\pi^+)$, and the reconstructed Λ_c^+ mass, $m_{\text{cand}}(\Lambda_c^+)$, corrected by the world-average Λ_c^+ mass of $m_{\text{PDG}}(\Lambda_c^+) = 2286.46 \pm 0.14$ M

$$m_{\text{cand}}(\Xi_{cc}^{++}) \equiv m(\Lambda_c^+ K^-\pi^+\pi^+) - m_{\text{cand}}(\Lambda_c^+) + m_{\text{PDG}}(\Lambda_c^+).$$

The line overlaid onto Fig. 1a is the result of a fit to the distribution to determine the yield. We observe 313 ± 33 Ξ_{cc}^{++} signal decays in the 13 TeV data set, which corresponds to a local significance in excess of 12σ when evaluated with a likelihood ratio test. The width of the peak is consistent with the expected detector resolution. When corrected for known detector and reconstruction effects, the mass difference between the Ξ_{cc}^{++} state and the Λ_c^+ baryon is $1334.94 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.})\,\text{MeV}/c^2$, and the mass of the state is $3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)\,\text{MeV}/c^2$ where the final uncertainty is from the world-average of the Λ_c^+ mass. The main contributions to the systematic uncertainty of the mass difference are the uncertainty of the momentum scale correction of the reconstruction and the uncertainty of the correction to account for correlations between the reconstructed mass of the candidates and the selection variables.

PoS(EPS-HEP2017)408

2.2 Supporting observation at 8 TeV

The analysis of the 8 TeV data set is described in detail in the supplemental material released with the publication of the primary analysis [1]. Collected in 2012, the 8 TeV data set was the result of a different processing model than the 13 TeV data set, which was collected in 2016. Events for the analysis were chosen by a $\Lambda_c^+ \to pK^-\pi^+$ selection in the software trigger [11]. Rather than directly analyzing the Λ_c^+ candidates reconstructed in the trigger, we apply a second more precise reconstruction to the full event, reconstitute the trigger Λ_c^+ candidates within the new reconstruction, and then use the reconstituted Λ_c^+ candidates to create $\Lambda_c^+ K^-\pi^+\pi^+$ and WS $\Lambda_c^+ K^-\pi^+\pi^-$ combinations. The selection variables, including the output of the multivariate discriminant, are largely the same as those used in the 13 TeV analysis, but the thresholds for the cuts have differences due to the trigger, reconstruction, and optimal working point for the expected Ξ_{cc}^{++} production kinematics in 8 TeV pp collisions.

As in the 13 TeV data set, a single narrow peak is observed in the $\Lambda_c^+ K^-\pi^+\pi^+$ mass spectrum and no structure is seen in the mass spectra of either the WS $\Lambda_c^+ K^-\pi^+\pi^-$ candidates or the $[pK^-\pi^+]_{\text{SB}} K^-\pi^+\pi^+$ candidates from the Λ_c^+ mass sideband. Figure 1b shows the $m_{\text{cand}}(\Xi_{cc}^{++})$ distribution around the peak overlaid with a fit to determine the peak position and yield. The peak is in the same place in the two samples, differing by only $0.8 \pm 1.4\,\text{MeV}/c^2$ (the uncertainty includes only the statistical uncertainties from the fits). Its width is consistent with the expected detector resolution. We observe 113 ± 21 Ξ_{cc}^{++} signal decays in the 8 TeV data set, which corresponds to a local significance in excess of 7σ when evaluated with a likelihood ratio test. When combined with the 13 TeV sample, the total yield consists of 426 ± 39 $\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$ decays. The observation of a large corroborating signal in an independent data set with substantial differences in the data processing gives us confidence in the robustness of our discovery.

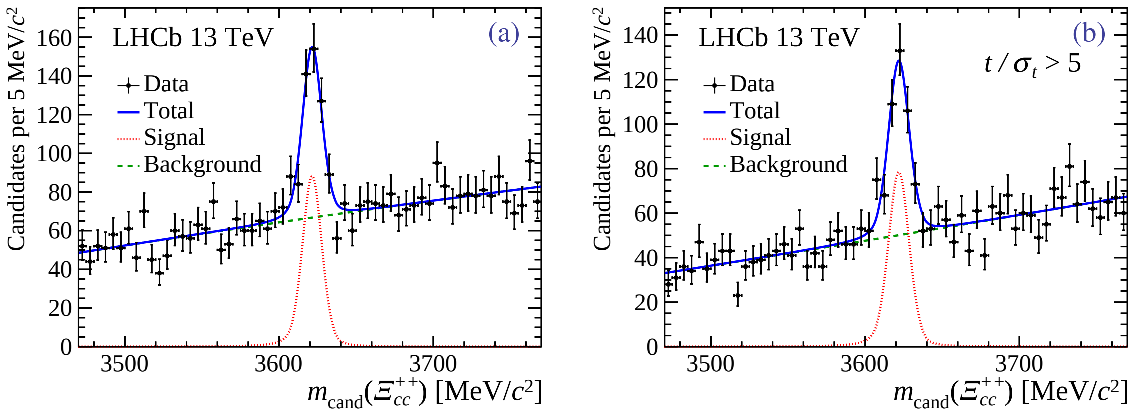

Figure 2: Invariant mass distributions of $\Lambda_c^+ K^- \pi^+ \pi^+$ candidates with fit projection overlaid for the 13 TeV data set (a) for a selection based only on rectangular cuts and (b) for the subset of candidates of Fig. 1a for which the significance of the proper decay time exceeds five standard deviations.

2.3 Properties of the state

The absence of a corresponding feature in the WS $\Lambda_c^+ K^- \pi^+ \pi^-$ mass spectrum demonstrates that the Ξ_{cc}^{++} peak is not an artifact of the multivariate discriminant. However, the peak can also be clearly observed without the multivariate discriminant. Figure 2a shows the $m_{\rm cand}(\Xi_{cc}^{++})$ spectrum for candidates of the 13 TeV data set that are selected with simple rectangular cuts on quality, topological, dynamic, and particle identification variables. The local statistical significance of the peak remains greater than 12σ when applying this alternate selection.

A lifetime measurement of the observed Ξ_{cc}^{++} state is underway, but we obtain preliminary indications that the state is relatively long-lived by examining the subset of candidates for which the reconstructed lifetime exceeds five times its estimated uncertainty. Figure 2b plots the $m_{\rm cand}(\Xi_{cc}^{++})$ distribution for this subset of the 13 TeV data set. A corresponding plot for the 8 TeV data set can be found in the supplementary material for the preprint of the publication on CDS [1]. The 13 TeV peak still exceeds 12σ significance and the 8 TeV peak exceeds 7σ significance. From the prevalence of the signal at such displacements from the primary pp interaction point, we can confidently conclude that the Ξ_{cc}^{++} baryon has a non-negligible lifetime that is easily resolvable by the LHCb detector.

In summary, we observe 426 ± 39 decays of a Ξ_{cc}^{++} state that has a mass of $3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)\,\text{MeV}/c^2$ and a width that is much smaller than experimental resolution and that is consistent with a particle that flies a significant distance before decaying.

3. Discussion

This is the first published observation of the Ξ_{cc}^{++} baryon. The published SELEX Ξ_{cc}^{+} state has a mass that is $103 \pm 2\,\text{MeV}/c^2$ smaller than that of our Ξ_{cc}^{++} state [2], so the two observations are inconsistent with being isospin partners. A consistent interpretation of the two observations may prove challenging.

PoS(EPS-HEP2017)408

The FOCUS [4] and BaBar [5] searches for doubly charmed baryons included examinations of the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum (and other doubly charged decay modes) but found no evidence for Ξ_{cc}^{++} just as they found no evidence for its isospin partner Ξ_{cc}^{+}. In preliminary unpublished work shown at conferences [12], the SELEX collaboration has also examined the $\Lambda_c^+ K^- \pi^+ \pi^+$ distribution. Although there are hints of peaks at masses more than $100\,\text{MeV}/c^2$ above and below our measured mass of $3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)\,\text{MeV}/c^2$, which are not present in our mass spectrum, there are no claims for evidence of a peak near our measured mass.

The discovery of the Ξ_{cc}^{++} baryon represents the first result from an active and growing effort at LHCb to study the physics of doubly charmed baryons. Measurements of the lifetime and production rate of the newly discovered state are in progress, as are searches for Ξ_{cc}^{++} decaying to additional decay modes. Searches for the Ξ_{cc}^{+} and Ω_{cc}^{+} baryons and measurements of their properties have a high priority. We have launched into an exciting new line of research with an experiment that is ideally suited to its exploration.

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PoS(EPS-HEP2017)408

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PoS(EPS-HEP2017)408