Observation of Two Narrow States Decaying Into $\Xi_c^+\gamma$ and $\Xi_c^0\gamma$

CLEO Collaboration

(March 25, 2022)

Abstract

We report the first observation of two narrow charmed strange baryons decaying to $\Xi_c^+\gamma$ and $\Xi_c^0\gamma$, respectively, using data from the CLEO II detector at CESR. We interpret the observed signals as the $\Xi_c^{+}\prime(c\{su\})$ and $\Xi_c^{0}\prime(c\{sd\})$, the symmetric partners of the well-established antisymmetric $\Xi_c^+(c[su])$ and $\Xi_c^0(c[sd])$. The mass differences $M(\Xi_c^{+}\prime) - M(\Xi_c^+)$ and $M(\Xi_c^{0}\prime) - M(\Xi_c^0)$ are measured to be $107.8 \pm 1.7 \pm 2.5$ and $107.0 \pm 1.4 \pm 2.5$ MeV/$c^2$, respectively.
C. P. Jessop, K. Lingel, H. Marsiske, M. L. Perl, V. Savinov, D. Ugolini, X. Zhou, T. E. Coan, V. Fadeyev, I. Korolkov, Y. Maravin, I. Narzsky, R. Stroynowski, J. Ye, T. Wlodek, M. Artuso, E. Dambasuren, S. Kopf, G. C. Moneti, R. Mountain, S. Schuh, T. Skwarnicki, S. Stone, A. Titov, G. Viehhauser, J. C. Wang, E. Csorna, K. W. McLean, S. Marka, Z. Xu, R. Godang, K. Kinoshita, I. C. Lai, P. Pomianowski, S. Schrenk, G. Bonvicini, D. Cinabro, R. Greene, L. P. Perera, G. J. Zhou, S. Chan, G. Eigen, E. Lipelies, J. S. Miller, M. Schmidtler, A. Shapiro, W. M. Sun, J. Urheim, A. J. Weinstein, F. Würthwein, D. E. Jaffe, G. Masek, H. P. Paar, E. M. Potter, S. Prell, V. Sharma, D. M. Asner, A. Eppich, J. Gronberg, T. S. Hill, D. J. Lange, R. J. Morrison, H. N. Nelson, T. K. Nelson, D. Roberts, B. H. Behrens, W. T. Ford, A. Gritsan, H. Krag, J. Roy, J. G. Smith, J. P. Alexander, R. Baker, C. Bebek, B. E. Berger, K. Berkelman, V. Boisvert, D. G. Cassel, D. S. Crowcroft, M. Dickson, S. von Dombrowski, P. S. Drell, K. M. Ecklund, R. Ehrlich, A. D. Fland, P. Gaidarov, L. Gibbons, B. Gittelman, S. W. Gray, D. L. Hartill, B. K. Heltsley, P. I. Hopman, J. Kandaswamy, D. L. Kreinick, T. Lee, Y. Liu, N. B. Mistry, C. R. Ng, E. Nordberg, M. Ogg, J. R. Patterson, D. Peterson, D. Riley, A. Soffer, B. Valant-Spaight, A. Warburton, C. Ward, M. Athanas, P. Avery, C. D. Jones, M. Lohner, Prescot, A. I. Rubiera, J. Yelton, J. Zheng, G. Brandenburg, R. A. Briere, A. Ershov, Y. S. Gao, D. Y. -J. Kim, R. Wilson, T. E. Browder, Y. Li, J. L. Rodríguez, H. Yamamoto, T. Bergfeld, B. I. Eisenstein, J. Ernst, G. E. Gladding, G. D. Gollin, R. M. Hans, E. Johnson, I. Karliner, M. A. Marsh, M. Palmer, M. Selen, J. J. Thaler, K. W. Edwards, A. Bellerive, R. Janicek, P. M. Patel, A. J. Sadoff, R. Ammar, P. Baringer, A. Bean, D. Besson, D. Copp, R. Davis, S. Kotov, I. Kravchenko, N. Kwak, L. Zhou, S. Anderson, Y. Kubota, S. J. Lee, R. Mahapatra, J. J. O’Neill, R. Poling, T. Riehle, A. Smith, M. S. Alam, S. B. Athar, Z. Ling, A. H. Mahmood, S. Timm, F. Wappler, A. Anastassov, J. E. Dubossy, K. K. Gan, C. Gwon, T. Hart, K. Honscheid, H. Kagan, R. Kass, J. Lee, J. Lorenc, H. Schwarhoff, A. Wolf, M. M. Zoller, S. J. Richichi, H. Severini, P. Skubic, A. Undrus, M. Bishai, S. Chen, J. Fast, J. W. Hinson, N. Menon, D. H. Miller, E. I. Shibata, I. P. J. Shipsey, S. Glenn, Y. Kwon, A. L. Lyon, S. Roberts, and E. H. Thorndike.

1Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309
2Southern Methodist University, Dallas, Texas 75275
3Syracuse University, Syracuse, New York 13244
4Vanderbilt University, Nashville, Tennessee 37235

*Permanent address: University of Cincinnati, Cincinnati OH 45221
†Permanent address: University of Texas, Austin TX 78712.
¶Permanent address: Yonsei University, Seoul 120-749, Korea.
5Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
6Wayne State University, Detroit, Michigan 48202
7California Institute of Technology, Pasadena, California 91125
8University of California, San Diego, La Jolla, California 92093
9University of California, Santa Barbara, California 93106
10University of Colorado, Boulder, Colorado 80309-0390
11Cornell University, Ithaca, New York 14853
12University of Florida, Gainesville, Florida 32611
13Harvard University, Cambridge, Massachusetts 02138
14University of Hawaii at Manoa, Honolulu, Hawaii 96822
15University of Illinois, Urbana-Champaign, Illinois 61801
16Carleton University, Ottawa, Ontario, Canada K1S 5B6
and the Institute of Particle Physics, Canada
17McGill University, Montréal, Québec, Canada H3A 2T8
and the Institute of Particle Physics, Canada
18Ithaca College, Ithaca, New York 14850
19University of Kansas, Lawrence, Kansas 66045
20University of Minnesota, Minneapolis, Minnesota 55455
21State University of New York at Albany, Albany, New York 12222
22Ohio State University, Columbus, Ohio 43210
23University of Oklahoma, Norman, Oklahoma 73019
24Purdue University, West Lafayette, Indiana 47907
25University of Rochester, Rochester, New York 14627
CLEO \cite{1,2} and other experimental groups \cite{3,4} have previously reported the observation of the $J^P = (\frac{3}{2})^+$ ground states $\Xi_c^0 \,(c[sd])$ and $\Xi_c^{+} \,(c[su])$ baryons, where [su] and [sd] denote the antisymmetric nature of their wave functions with respect to interchange of the light quarks. The partners of the above charmed strange baryons are the $\Xi_c^0 \,(c[sd])$ and $\Xi_c^{-} \,(c[su])$, where \{sd\} and \{su\} specify that the wave functions are symmetric with respect to interchange of the light quarks. In this report we present the first observation of the $\Xi_c^{-}$. The mass splitting $M(\Xi_c^0) - M(\Xi_c^{-})$ \cite{10,17} is expected to be in the range of $100 - 114$ MeV/$c^2$. With such a mass difference, the transition $\Xi_c^{-} \to \Xi_c^0 \pi$ is kinematically forbidden, allowing only the decay $\Xi_c^{-} \to \Xi_c \gamma$. The above theoretical models also predict the mass difference $M(\Xi_c^0) - M(\Xi_c^{-})$ to be about 60-70 MeV/$c^2$.

The data used in this analysis was collected with the CLEO II detector \cite{18} operating at CESR, and corresponds to an integrated luminosity of 4.96 fb$^{-1}$ from the $\Upsilon(4S)$ resonance and continuum region at energies just below it. The charmed strange baryon $\Xi_c^0$ was reconstructed in the decay modes $\Xi_c^{-} \pi^+ , \Xi_c^{-} \pi^+ \pi^0 , \Xi_c^{-} \pi^+ \pi^0 \pi^0$ and $\Omega^- K^+$, and $\Xi_c^{+}$ in the decay modes $\Xi_c^{+} \pi^- + \pi^+$ and $\Xi_c^{+} \pi^- + \pi^0$ \cite{3,4,13}. In all cases, the signal area above the combinatorial background is found by fitting to the sum of one or more Gaussian functions with widths fixed at Monte Carlo predicted values, and a low-order Chebychev polynomial. Where particle identification is used, a joint probability for the pion, kaon, or proton hypothesis is defined using measurements of specific ionization ($dE/dx$) in the wire drift chambers and time-of-flight in the scintillation counters. A charged track is defined to be consistent with a particular mass hypothesis if the corresponding probability is greater than 0.1%.

Charmed baryons can be produced from either secondary decays of $B$ mesons or directly from $e^+e^-$ annihilations to $c\bar{c}$ jets. We define $x_p$ and $x_p'$ as the scaled momentum of the $\Xi_c$ and $\Xi_c'$, respectively. Here $x_p = p/p_{\text{max}}$; $p$ is the momentum of the charmed baryon, $p_{\text{max}} = \sqrt{E_b^2 - M^2}$, $E_b$ is the beam energy and $M$ is the mass of the charmed baryon being considered. Charmed baryons produced from $B$ decays are kinematically limited to $x_p < 0.4$, while $(60 - 70)\%$ of those produced from the continuum have $x_p > 0.4$. To reduce random combinatorial background, we apply a mode-dependent cut of $x_p > 0.5 - 0.6$, thus excluding charm baryons produced in $B$ decays.

We begin by reconstructing $\Lambda \to p\pi^-, \Xi^0 \to \Lambda \pi^0, \Xi^- \to \Lambda \pi^-, \text{and} \Omega^- \to \Lambda K^-$. We select hyperons by requiring the distance between the reconstructed secondary decay vertex and the beam interaction point as measured in the plane perpendicular to the beam line, to be at least 2 mm for $\Lambda$ and $\Xi^-$, and 3 mm for $\Xi^0$, respectively. No such cut is applied for $\Omega^-$.

Candidates for $\Lambda \to p\pi^-$ decays are reconstructed from pairs of oppositely charged tracks, assuming the higher momentum one to be a proton and requiring it to be consistent with the proton hypothesis. The invariant mass of the combination is calculated using a three-dimensional vertex-constrained fit at the point of intersection. All $p\pi^-$ combinations within 5 MeV/$c^2$ ($\approx 3$ standard deviations ($\sigma$)) of the nominal mass are accepted as $\Lambda$ candidates.

A $\Xi^-$ candidate vertex is reconstructed by finding the intersection between a $\Lambda$ candidate and $\pi^-$ track, and requiring the $\Xi^-$ direction to be consistent with coming from the event vertex. A fit to the resultant distribution of $\Lambda\pi^-$ invariant mass combinations yields a total
of $11578 \pm 125$ reconstructed $\Xi^-$ candidates. All such combinations within $5 \text{ MeV}/c^2$ ($\approx 3\sigma$) of the nominal mass are accepted as $\Xi^-$ candidates.

For $\Omega^-$ reconstruction, we combine each $\Lambda$ candidate with any negatively charged track that is consistent with the kaon hypothesis. The $\Omega^-$ vertex is found using a procedure very similar to that used for finding $\Xi^-$. A fit to the distribution of $\Lambda K^-$ invariant mass combinations yields a signal of $373 \pm 32$ events, and combinations within $5 \text{ MeV}/c^2$ of the nominal mass are selected as $\Omega^-$ candidates.

The $\Xi^0$ candidates are reconstructed from $\Lambda$ and $\pi^0$ pairs. Candidates for $\pi^0$ are formed from pairs of photons detected in the CsI calorimeter, with at least one photon coming from the barrel ($|\cos \theta| < 0.7$) rather than the endcap regions, where $\theta$ is the polar angle with respect to the $e^+$ direction. Only photons with energy greater than 50 MeV and distinctly separated from charged tracks are used. As a first approximation, the $\pi^0$ mass is calculated assuming the event vertex to be its point of origin. A $\Xi^0$ vertex is then found from the intersection of the $\Lambda$ and $\pi^0$ directions. The mass and four-momentum of the $\pi^0$ is recalculated assuming the $\Xi^0$ vertex to be its origin. A new vertex is calculated using the new $\pi^0$ and $\Lambda$ directions. A fit to the $\Lambda \pi^0$ mass distribution yields $7568 \pm 227$ signal events, and all $\Lambda \pi^0$ combinations within $8 \text{ MeV}/c^2$ of the nominal mass are defined as $\Xi^0$ candidates.

We first discuss the reconstruction of $\Xi^+_c$ candidates in the decay modes $\Xi^-\pi^+\pi^+$ and $\Xi^0\pi^+\pi^0$. As presented earlier, $\Xi^-$ and $\Xi^0$ candidates are combined with charged or neutral pions which are consistent with originating from the event vertex. In the case of the first decay mode, only charged tracks with momentum greater than 100 MeV/c are used. For the second decay mode, which has more combinatorial background because of the $\pi^0$, both the charged and neutral pions are required to have momenta greater than 250 MeV/c. We form invariant mass distributions of $\Xi^-\pi^+\pi^+$ combinations with $x_p > 0.5$ and $\Xi^0\pi^+\pi^0$ combinations with $x_p > 0.6$. Fitting these distributions with Monte Carlo predicted widths of 8.5 and 15 MeV/$c^2$, respectively, we obtain yields of $(155 \pm 15)$ and $(70 \pm 14)$ signal events in these two decay modes or a combined yield of $(225 \pm 21)$. Combinations within $2\sigma$ of the fitted peak masses in each decay mode are then selected as $\Xi^+_c$ candidates. The invariant mass distribution for the summed combinations in both $\Xi^+_c$ decay modes is shown in Fig. 1(a).

We reconstruct $\Xi^0_c$ in the four decay modes $\Xi^-\pi^+, \Xi^-\pi^+\pi^0, \Omega^-K^+$, and $\Xi^0\pi^+\pi^-$. We start with the hyperon candidates, which are defined according to procedures discussed previously, and add charged tracks which are consistent with coming from the event vertex. For the decay mode $\Xi^-\pi^+\pi^0$, we assume the photons used for reconstructing $\pi^0 \rightarrow \gamma\gamma$ are coming from the event vertex. Only $\gamma\gamma$ combinations having invariant mass within $12.5 \text{ MeV}/c^2$ ($2.5\sigma$) of the nominal mass are used as $\pi^0$ candidates. In the case of $\Omega^-K^+$, we use only primary charged tracks consistent with the kaon hypothesis. Only combinations with $x_p > 0.5$ are used in the case of the first three decay modes; for the last decay mode, since the combinatorial background is higher, a cut of $x_p > 0.6$ is used. Fitting the invariant mass distributions corresponding to the decay modes $\Xi^-\pi^+, \Xi^-\pi^+\pi^0, \Omega^-K^+$, and $\Xi^0\pi^+\pi^-$ with Monte Carlo predicted widths of 8, 10, 7 and 12 MeV/$c^2$, we obtain yields of $(133 \pm 41)$, $(86 \pm 13)$, $(24 \pm 5)$ and $(46 \pm 10)$ signal events, respectively. This gives a combined $\Xi^0_c$ yield of $(289 \pm 44)$ events. The sum of the four $\Xi^0_c$ invariant mass distributions is shown in Fig. 1(b).

To search for $\Xi^{t'}_c$ and $\Xi^{0'}_c$, we start with the $\Xi^+_c$ and $\Xi^0_c$ candidates reconstructed according
to the procedure described in the earlier sections. We then form $\Xi_c^+\gamma$ and $\Xi_c^0\gamma$ combinations using photons with energy greater than 100 MeV. Only showers detected in the barrel CsI crystal calorimeter $(|\cos \theta| < 0.7)$, with clear isolation from nearby charged tracks and shower fragments are used as photon candidates. The lateral shower profile of the candidate is required to be consistent with that of a photon. A photon is also rejected if it is part of a good $\pi^0$ candidate, as defined in the section on $\Xi_c^0$ reconstruction. About $(30-50)\%$ of photons from $\Xi_c'$ are lost due to this veto. Instead of plotting the $\Xi_c\gamma$ invariant mass combinations, we plot the mass difference $\Delta M = M(\Xi_c\gamma) - M(\Xi_c)$, which has better mass resolution as the errors from $\Xi_c$ reconstruction are common to both terms and therefore cancel. In plotting the $\Delta M$ distributions, the $x_p$ cut on $\Xi_c$ reconstruction is removed and instead we place a cut on $x_p'$, the $x_p$ of the $\Xi_c \gamma$ combination. Final states including $\Xi_0$ have larger combinatorial backgrounds. We therefore require $x_p' > 0.6$ for these states and $x_p' > 0.5$ for all other final states.

Fitting the mass difference $\Delta M^+ = M(\Xi_c^+\gamma) - M(\Xi_c^+) \simeq 0$ distributions corresponding to the two $\Xi_c^+$ decay modes used in the analysis, we obtain $(16.1 \pm 5.1)$ and $(7.5 \pm 3.6)$ signal events, respectively. Similarly, fits to the mass difference $\Delta M^0 = M(\Xi_c^0\gamma) - M(\Xi_c^0)$ distributions corresponding to the four $\Xi_c^0$ decay modes separately yield signal areas of $(7.0 \pm 4.0)$, $(11.6 \pm 4.4)$, $(3.8 \pm 2.0)$, and $(6.0 \pm 3.3)$ events, respectively. It may be noted that there is at least one mode in each case with an enhancement of $3\sigma$ statistical significance and corroborating enhancements in the other decay modes in the mass difference region around 108 MeV/$c^2$.

Fig. 2 (a) and (b) show the combined mass difference distributions for the $\Xi_c^+\gamma$ and $\Xi_c^0\gamma$ combinations, respectively, where the contributions from the different decay modes have been summed. The distributions are fitted with widths fixed at the Monte Carlo values of 5 MeV/$c^2$ in both cases. In Fig. 2 (a), the narrow resonance corresponds to a signal area of $(25.5 \pm 6.5)$ events at mass difference $\Delta M^+ = (107.8 \pm 1.7)$ MeV/$c^2$ with a statistical significance of $3.9\sigma$. Similarly, a fit to Fig. 2 (b) yields a signal area of $(28.0 \pm 7.1)$ events at mass difference $\Delta M^0 = (107.0 \pm 1.4)$ MeV/$c^2$ with statistical significance of $3.9\sigma$. We associate these resonances with the isospin doublet $\Xi_c^{'+}$ and $\Xi_c^0$. To rule out the possibility that the signal is due to random background under the $\Xi_c$ signal, we reconstruct $\Xi_c\gamma$ combinations using fake $\Xi_c$ candidates from the side-band of the $\Xi_c$ nominal mass region. The corresponding mass difference distributions ($\Delta M$) show no evidence of peaking in the region of interest.

In order to probe the systematic stability of the measured mass differences, we studied the effect of different background shapes, alternate selection criteria, and the calibration of the calorimeter absolute energy scale. The major contributor to systematic shifts was found to be the removal of the $\pi^0$ veto. This has the effect of increasing the efficiency by 30% and 60% for $\Xi_c^{'+}$ and $\Xi_c^0$, respectively, but also doubling the background, dominantly from $\Xi_c^\prime \rightarrow \Xi_c \pi^0$ in which one of the photons from $\pi^0$ decay is ignored in the reconstruction. Based on all these studies we assign a systematic error to the mass differences of $\pm 2.5$ MeV/$c^2$.

To measure the $x_p'$ spectrum for $\Xi_c^0$ production, we assume that at the level of statistics available in our data, the fragmentation functions for $\Xi_c^{'+}$ and $\Xi_c^0$ are the same, so that we can combine the data for the two resonances together. The yield is then obtained as a function of $x_p'$ for all the decay modes of both the resonances from $0.5 < x_p' < 1.0$ and corrected for $x_p'$-dependent reconstruction efficiencies. The normalized distribution is shown in Fig. 3. A fit to the Peterson fragmentation function yields the fragmentation parameter $\epsilon_q =
0.20^{+0.23}_{-0.09} \pm 0.07, which is similar to the previously published result of $\epsilon_q = 0.23^{+0.06}_{-0.05} \pm 0.03$ for $\Xi_c^+$ production [19].

We measure that $(37 \pm 11 \pm 7)$% of all $\Xi_c^+$ produced from the continuum are from $\Xi_c^+$ decays, while $(35 \pm 9 \pm 7)$% of all $\Xi_0^c$ are from $\Xi_0^c$ decays. The comparable fraction of $\Xi_c^+$'s from $\Xi_0^c$ decays is $(27 \pm 6 \pm 6)$% [8]. The fraction of $\Xi_c$ from $\Xi_0^c$ is predicted by Adamov and Goldstein [21] to be 1.7 times that from $\Xi_c^+$.

In conclusion, we have observed two narrow resonances decaying to $\Xi_c^+\gamma$ and $\Xi_0^c\gamma$. The mass differences $M(\Xi_c^+\gamma) - M(\Xi_c^+)$ and $M(\Xi_0^c\gamma) - M(\Xi_0^c)$ are measured to be $(107.8 \pm 1.7 \pm 2.5)$ and $(107.0 \pm 1.4 \pm 2.5)$ MeV/$c^2$, respectively; the second error in each case is systematic. This is in good agreement with theoretical expectations for these mass differences, assuming the resonances to be $\Xi_c^{*+}$ and $\Xi_c^{*0}$, respectively. This is also in good agreement with the models which predict the mass difference $M(\Xi_c^*) - M(\Xi_c')$ to be about 60-70 MeV/$c^2$. Since the $J^P = (1/2)^+$ charmed strange baryons $\Xi_c^{*+}$ and $\Xi_c^{*0}$ have already been observed, the most likely interpretation of the observed resonances would be as the $J^P = (1/2)^+$ charmed strange baryons $\Xi_c^{*+}$ and $\Xi_c^{*0}$, respectively.

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. This work was supported by the National Science Foundation, the U.S. Department of Energy, Research Corporation, the Natural Sciences and Engineering Research Council of Canada, the A.P. Sloan Foundation, the Swiss National Science Foundation, and the Alexander von Humboldt Stiftung.
REFERENCES

[1] CLEO Collaboration, M. S. Alam et al., Phys. Lett. B 226, 401 (1989).
[2] CLEO Collaboration, P. Avery et al., Phys. Rev. Lett. 62, 863 (1989).
[3] WA62 Collaboration, S. Biagi et al., Phys. Lett. B 150, 230 (1985)
   S. Biagi et al., Z. Phys. C 28, 175, (1985).
[4] E687 Collaboration, P. Coteus et al., Phys. Rev. Lett. 59, 1530 (1987).
[5] ACCMOR Collaboration, S. Barlag et al., Phys. Lett. B 236, 495 (1990).
[6] ARGUS Collaboration, H. Albrecht et al., Phys. Lett. B 247, 121 (1990).
[7] For the sake of brevity, we use $\Xi_c$, $\Xi'_c$, and $\Xi^*_c$ to imply either the charged or neutral
   member of the isospin multiplet. Charge conjugates are implied throughout the paper.
[8] CLEO Collaboration, P. Avery et al., Phys. Rev. Lett. 75, 4364 (1995).
[9] CLEO Collaboration, L. Gibbons et al., Phys. Rev. Lett. 77, 810 (1996).
[10] J. Franklin, Phys Rev. D 53, 564 (1996).
[11] C. Glenn Boyd, M. Lu, and M. J. Savage, Phys Rev. D 55, 5474 (1997).
[12] K. Maltman and N. Isgur, Phys. Rev. D 22, 1701 (1980).
[13] J. G. Körner, M. Krämer and D. Pirjol, Prog. Part. Nucl. Physics 33, 787 (1994).
[14] R. Roncaglia, D. B. Lichtenberg, and E. Predazzi, Phys. Rev. D 52, 1722 (1995).
[15] M. J. Savage, Phys. Lett. B 359, 189, (1995).
[16] A. Falk, Phys. Rev. Lett 77, 223 (1996).
[17] E. Jenkins, Phys. Rev. D 54, 4515 (1996), E. Jenkins, Phys. Rev. D 55, 10 (1997).
[18] CLEO Collaboration, Y. Kubota et al., Nucl. Instrum. Methods Phys. Res. Sec. A 320, 66 (1992).
[19] CLEO Collaboration, K. Edwards et al., Phys. Lett. B 373, 362 (1996).
[20] C. Peterson et al., Phys Rev. D 27, 105 (1993).
[21] A. Adamov and G. Goldstein, hep-ph/9612443, Tufts University, Medford, MA 02155, 20 Dec. 1996.
FIG. 1. (a) Summed invariant mass distributions for $\Xi^-$ and $\Xi^0\pi^+\pi^0$ combinations with $x_p > 0.5$ and 0.6, respectively, and (b) for $\Xi^-$, $\Xi^-\pi^+\pi^0$, $\Omega^-K^+$, and $\Xi^0\pi^+\pi^-$ combinations with $x_p > 0.5$, 0.5, 0.5 and 0.6, respectively.
FIG. 2. Invariant mass difference $\Delta M(\Xi_c\gamma - \Xi_c)$ distributions for $\Xi_c^+\gamma$ and $\Xi_c^0\gamma$, where contributions from the different $\Xi_c$ decay modes have been summed in each case.
FIG. 3. Fragmentation function for $\Xi_c'$ (weighted average of $\Xi_c^{+}$ and $\Xi_c^{0}$ momentum distributions).