CLEO CONF 97-17
EPS97 398

# Evidence of a New State Decaying into $\Xi_c^{*0}\pi^+$

CLEO Collaboration

(July 24, 1997)

## Abstract

Using data recorded by the CLEO-II detector at CESR, we report preliminary evidence of a new charmed baryon that decays into $\Xi_c^+\pi^+\pi^-$ via an intermediate $\Xi_c^{*0}$. We measure the mass difference $M(\Xi_c^+\pi^-\pi^+) - M(\Xi_c^+)$ to be $349.4 \pm 0.7 \pm 1.0$ MeV. We interpret this new particle as the $J^P = \frac{3}{2}^-$ $\Xi_{c1}^+$, the charmed-strange analogue of the $\Lambda_{c1}^+(2625)$.

G. Brandenburg,[1] R. A. Briere,[1] A. Ershov,[1] Y. S. Gao,[1] D. Y.-J. Kim,[1] R. Wilson,[1] H. Yamamoto,[1] T. E. Browder,[2] Y. Li,[2] J. L. Rodriguez,[2] T. Bergfeld,[3] B. I. Eisenstein,[3] J. Ernst,[3] G. E. Gladding,[3] G. D. Gollin,[3] R. M. Hans,[3] E. Johnson,[3] I. Karliner,[3] M. A. Marsh,[3] M. Palmer,[3] M. Selen,[3] J. J. Thaler,[3] K. W. Edwards,[4] A. Bellerive,[5] R. Janicek,[5] D. B. MacFarlane,[5] P. M. Patel,[5] A. J. Sadoff,[6] R. Ammar,[7] P. Baringer,[7] A. Bean,[7] D. Besson,[7] D. Coppage,[7] C. Darling,[7] R. Davis,[7] N. Hancock,[7] S. Kotov,[7] I. Kravchenko,[7] N. Kwak,[7] S. Anderson,[8] Y. Kubota,[8] S. J. Lee,[8] J. J. O'Neill,[8] S. Patton,[8] R. Poling,[8] T. Riehle,[8] V. Savinov,[8] A. Smith,[8] M. S. Alam,[9] S. B. Athar,[9] Z. Ling,[9] A. H. Mahmood,[9] H. Severini,[9] S. Timm,[9] F. Wappler,[9] A. Anastassov,[10] J. E. Duboscq,[10] D. Fujino,[10,*] K. K. Gan,[10] T. Hart,[10] K. Honscheid,[10] H. Kagan,[10] R. Kass,[10] J. Lee,[10] M. B. Spencer,[10] M. Sung,[10] A. Undrus,[10,†] R. Wanke,[10] A. Wolf,[10] M. M. Zoeller,[10] B. Nemati,[11] S. J. Richichi,[11] W. R. Ross,[11] P. Skubic,[11] M. Bishai,[12] J. Fast,[12] J. W. Hinson,[12] N. Menon,[12] D. H. Miller,[12] E. I. Shibata,[12] I. P. J. Shipsey,[12] M. Yurko,[12] S. Glenn,[13] S. D. Johnson,[13] Y. Kwon,[13,‡] S. Roberts,[13] E. H. Thorndike,[13] C. P. Jessop,[14] K. Lingel,[14] H. Marsiske,[14] M. L. Perl,[14] D. Ugolini,[14] R. Wang,[14] X. Zhou,[14] T. E. Coan,[15] V. Fadeyev,[15] I. Korolkov,[15] Y. Maravin,[15] I. Narsky,[15] V. Shelkov,[15] J. Staeck,[15] R. Stroynowski,[15] I. Volobouev,[15] J. Ye,[15] M. Artuso,[16] A. Efimov,[16] M. Goldberg,[16] D. He,[16] S. Kopp,[16] G. C. Moneti,[16] R. Mountain,[16] S. Schuh,[16] T. Skwarnicki,[16] S. Stone,[16] G. Viehhauser,[16] X. Xing,[16] J. Bartelt,[17] S. E. Csorna,[17] V. Jain,[17,§] K. W. McLean,[17] S. Marka,[17] R. Godang,[18] K. Kinoshita,[18] I. C. Lai,[18] P. Pomianowski,[18] S. Schrenk,[18] G. Bonvicini,[19] D. Cinabro,[19] R. Greene,[19] L. P. Perera,[19] G. J. Zhou,[19] B. Barish,[20] M. Chadha,[20] S. Chan,[20] G. Eigen,[20] J. S. Miller,[20] C. O'Grady,[20] M. Schmidtler,[20] J. Urheim,[20] A. J. Weinstein,[20] F. Würthwein,[20] D. W. Bliss,[21] G. Masek,[21] H. P. Paar,[21] S. Prell,[21] M. Sivertz,[21] V. Sharma,[21] D. M. Asner,[22] J. Gronberg,[22] T. S. Hill,[22] D. J. Lange,[22] S. Menary,[22] R. J. Morrison,[22] H. N. Nelson,[22] T. K. Nelson,[22] C. Qiao,[22] J. D. Richman,[22] D. Roberts,[22] A. Ryd,[22] M. S. Witherell,[22] R. Balest,[23] B. H. Behrens,[23] W. T. Ford,[23] H. Park,[23] J. Roy,[23] J. G. Smith,[23] J. P. Alexander,[24] C. Bebek,[24] B. E. Berger,[24] K. Berkelman,[24] K. Bloom,[24] D. G. Cassel,[24] H. A. Cho,[24] D. S. Crowcroft,[24] M. Dickson,[24] P. S. Drell,[24] K. M. Ecklund,[24] R. Ehrlich,[24] A. D. Foland,[24] P. Gaidarev,[24] R. S. Galik,[24] L. Gibbons,[24] B. Gittelman,[24] S. W. Gray,[24] D. L. Hartill,[24] B. K. Heltsley,[24] P. I. Hopman,[24] J. Kandaswamy,[24] P. C. Kim,[24] D. L. Kreinick,[24] T. Lee,[24] Y. Liu,[24] G. S. Ludwig,[24] N. B. Mistry,[24] C. R. Ng,[24] E. Nordberg,[24] M. Ogg,[24,**] J. R. Patterson,[24] D. Peterson,[24] D. Riley,[24] A. Soffer,[24] B. Valant-Spaight,[24] C. Ward,[24] M. Athanas,[25] P. Avery,[25] C. D. Jones,[25] M. Lohner,[25] C. Prescott,[25] J. Yelton,[25] and J. Zheng[25]

[*]Permanent address: Lawrence Livermore National Laboratory, Livermore, CA 94551.
[†]Permanent address: BINP, RU-630090 Novosibirsk, Russia.
[‡]Permanent address: Yonsei University, Seoul 120-749, Korea.
[§]Permanent address: Brookhaven National Laboratory, Upton, NY 11973.
[**]Permanent address: University of Texas, Austin TX 78712

[1]Harvard University, Cambridge, Massachusetts 02138
[2]University of Hawaii at Manoa, Honolulu, Hawaii 96822
[3]University of Illinois, Champaign-Urbana, Illinois 61801
[4]Carleton University, Ottawa, Ontario, Canada K1S 5B6
and the Institute of Particle Physics, Canada
[5]McGill University, Montréal, Québec, Canada H3A 2T8
and the Institute of Particle Physics, Canada
[6]Ithaca College, Ithaca, New York 14850
[7]University of Kansas, Lawrence, Kansas 66045
[8]University of Minnesota, Minneapolis, Minnesota 55455
[9]State University of New York at Albany, Albany, New York 12222
[10]Ohio State University, Columbus, Ohio 43210
[11]University of Oklahoma, Norman, Oklahoma 73019
[12]Purdue University, West Lafayette, Indiana 47907
[13]University of Rochester, Rochester, New York 14627
[14]Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309
[15]Southern Methodist University, Dallas, Texas 75275
[16]Syracuse University, Syracuse, New York 13244
[17]Vanderbilt University, Nashville, Tennessee 37235
[18]Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
[19]Wayne State University, Detroit, Michigan 48202
[20]California Institute of Technology, Pasadena, California 91125
[21]University of California, San Diego, La Jolla, California 92093
[22]University of California, Santa Barbara, California 93106
[23]University of Colorado, Boulder, Colorado 80309-0390
[24]Cornell University, Ithaca, New York 14853
[25]University of Florida, Gainesville, Florida 32611

In recent years there has been great progress in charmed baryon spectroscopy. States with no orbital angular momentum, but with all three quark spins aligned, have spin/parity $J^P = \frac{3}{2}^+$. These states have now been reported both in the $\Sigma$ sector [1], and the $\Xi_c$ sector [2,3]. Three experiments [4] have now seen a doublet of particles decaying into $\Lambda_c^+\pi^+\pi^-$, and the consensus is that these states are the lowest lying orbitally excited states of the $\Lambda_c^+$. The quark model picture of these excited $\Lambda_c^+$ baryons is that they consist of a light diquark which has one unit of orbital angular momentum with respect to the heavy (charmed) quark, leading to a $J^P = \frac{1}{2}^-, \frac{3}{2}^-$ doublet. They are now commonly referred to as the $\Lambda_{c1}^+$ particles [5], where the numerical subscript refers to the total angular momentum of the light degrees of freedom. Clearly similar orbital excitations must exist in the $\Xi_c^+$ sector. Using data from the CLEO II detector, we present preliminary evidence for a new state decaying into $\Xi_c^{*0}\pi^+$, with the subsequent decay $\Xi_c^{*0} \to \Xi_c^+\pi^-$. We believe that this signal is due to the $J^P = \frac{3}{2}^-$ $\Xi_{c1}^+$, which is a $cus$ quark combination in which the $u$ and $s$ spins are antiparallel and the $us$ has orbital angular momentum L=1 with respect to the charmed quark.

The data presented here were taken by the CLEO II detector [6] operating at the Cornell Electron Storage Ring. The sample used in this analysis corresponds to an integrated luminosity of 4.8 $fb^{-1}$ from data taken on the $\Upsilon(4S)$ resonance and in the continuum at energies just above and below the $\Upsilon(4S)$. We detected charged tracks with a cylindrical drift chamber system inside a solenoidal magnet. Photons were detected using an electromagnetic calorimeter consisting of 7800 cesium iodide crystals.

Reconstruction of $\Xi_c^+$ candidates follows closely the procedure outlined in our previous publication concerning the $\Xi_c^{*0}$ [2]. This analysis uses an augmented data sample and improved treatment of secondary and tertiary vertices, and uses only the two decay modes $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ and $\Xi_c^+ \to \Xi^0\pi^+\pi^0$.

Candidates for $\Lambda$ decays are reconstructed from $p\pi^-$ combinations, that intersect at a point greater than 2 mm from the primary event vertex. The $\Lambda$ candidates are required to have a measured invariant mass within 5.0 MeV/c$^2$ (about three standard deviations) of the known $\Lambda$ mass.

The $\Xi^-$ candidates are formed by combining each $\Lambda$ candidate with each remaining negatively charged track[1]. A vertex is formed from the intersection of the $\Lambda$ track and the negatively charged track. The momentum components of the charged track are recalculated at the candidate $\Xi^-$ vertex. We require that the measured flight path of the reconstructed $\Xi^-$ be greater than 2 mm, that the reconstructed $\Xi^-$ be consistent with coming from the main event vertex, and the measured distance between the event vertex and the $\Xi^-$ decay point be less than the distance between the event vertex and the $\Lambda$ vertex. Combinations with a measured invariant mass within 5 MeV/c$^2$ (about three standard deviations) of the known $\Xi^-$ mass are kinematically fit to this mass and used to reconstruct $\Xi_c^+$ candidates.

Candidates for $\Xi^0$ baryons are formed by combining each $\Lambda$ candidate with each $\pi^0$ candidate. These $\pi^0$ candidates are formed from a pair of photons detected in the CsI calorimeter. As a first approximation they are assumed to come from the event vertex and only a loose cut is applied on the $\gamma\gamma$ invariant mass. The $\Lambda$ candidates used for $\Xi^0$

[1] Charge conjugate states are implied throughout.

reconstruction are required to have a measured flight path of greater than 1.5 cm and not to point back to the event vertex. The $\Xi^0$ is assumed to be created at the event vertex, and to have a momentum equal to the sum of the momenta of the $\Lambda$ and $\pi^0$ candidates. The decay point of the $\Xi^0$ is taken to be the point of intersection between the $\Xi^0$ candidate and the $\Lambda$ candidate. This decay point is required to be at least 3 mm from the event vertex. The 4-momentum of the $\pi^0$ candidate was recalculated using the $\Xi^0$ decay point as the point of origin of the photons, and its mass is required to be consistent ($< 3.5\sigma$) with the known $\pi^0$ mass. The $\Lambda\pi^0$ invariant mass is then recalculated using this improved estimate of the $\pi^0$ momentum, and those combinations within 8 MeV/c$^2$ ($\approx 3\sigma$) of the known $\Xi^0$ mass are kinematically fit to this mass and used to reconstruct $\Xi_c^+$ baryons.

For the purpose of illustrating the good statistics and signal to noise ratio of the $\Xi_c^+$ signals, and to reduce the combinatorial background, we have placed a cut $x_p > 0.6$, where $x_p = p/p_{max}$, $p$ is the momentum of the charmed baryon, $p_{max} = \sqrt{E_{beam}^2 - M^2}$, and $E_{beam}$ is the beam energy. We fitted the invariant mass distributions for these modes to a sum of a Gaussian signal and a second order polynomial background and obtain signals of $138 \pm 14$ and $82 \pm 14$ respectively. The $x_p$ cut used for Figure 1 was not used in the final analysis, as we prefer to apply an $x_p$ cut only on the $\Xi_c^+\pi^-\pi^+$ combinations. However, the value of 0.6 for the $x_p$ cut on the $\Xi_c^+$ results in a similar $\Xi_c^+$ sample as used in the final analysis.

The $\Xi_c^+$ candidates defined above were then combined with each remaining charged track in the event and the mass difference $M(\Xi_c^+\pi^-) - M(\Xi_c^+)$ was calculated. Once again for the purpose of illustrating the signal, we have placed a cut on $x_p$, in this case $x_p > 0.65$, on the $\Xi_c^+\pi^-$ combinations. The fit shown in Figure 2 uses a Chebychev polynomial with threshold suppression to characterize the background, and a Breit-Wigner of fixed width (2.6 MeV), convoluted with a Gaussian resolution function ($\sigma = 1.6$ MeV/c$^2$, calculated using CLEO's detector simulation program). This width is the central value found for the width of the $\Xi_c^{*0}$ obtained in our previous paper [2]. The fit yields $30.1 \pm 6.6$ $\Xi_c^{*0}$ candidates. We define $\Xi_c^{*0}$ candidates as those within 8 MeV of the $\Xi_c^{*0}$ mass.

We then combine these $\Xi_c^{*0}$ candidates with one more of the remaining charged tracks in the event and plot $M(\Xi_c^+\pi^-\pi^+) - M(\Xi_c^+)$ (Figure 3). We place a cut of $x_p > 0.7$ on the final combination. Because charmed particles produced in $e^+e^-$ annihilation are known to have a hard momentum spectrum, whereas background combinations lie mostly at low momentum, this cut eliminates a large fraction of the background while retaining a good fraction of signal. The value of 0.7 for this cut was chosen to match that used in our previous analysis of the $\Lambda_{c1}^+$ baryons [4]. Figure 3 shows a very clean signal of 11 events, where the background estimate using a linear background shape is 0.3 events. The mass difference found from this plot is $349.4 \pm 0.7 \pm 1.0$ MeV. The systematic error quoted is an estimate of the uncertainties due to the overall momentum scale and the corrections for energy lost by a charged pion when passing through the detector. The fit shown uses a signal function of a Gaussian of fixed width of 2.5 MeV, obtained from Monte Carlo simulation. Using a Gaussian signal of floating width, gives a measured width of $2.1 \pm 0.6$ MeV which is consistent with the detector resolution of 2.5 MeV. We obtain an upper limit on the width of the new particle of 2.4 MeV at the 90% confidence level. We prefer to present the data as a dipion mass difference rather than $M(\Xi_c^{*0}\pi^+) - M(\Xi_c^{*0})$ because the latter measurement is complicated by the intrinsic width of the $\Xi_c^{*0}$, which is not well known.

We also present the data as a scatter plot (Figure 4). On the y-axis we plot $M(\Xi_c^+\pi^-) - M(\Xi_c^+)$, and on the x-axis $M(\Xi_c^+\pi^-\pi^+) - M(\Xi_c^+)$. The cluster of events in the bottom left of the plot is the signal. If the decay proceeded via $\Xi_c^+\pi^-\pi^+$ without resonating through the $\Xi_c^{*0}$, then we would expect a vertical band of points rather than a tight cluster. From the absence of decays outside the $\Xi_c^{*0}$ region we can calculate that the fraction of the $\Xi_c^+\pi^-\pi^+$ decays of the new state that proceed via an intermediate $\Xi_c^{*0}$ is greater than 76% at the 90% confidence level.

Although the statistics are very limited, they are sufficient to do a rough investigation of the momentum spectrum with which the new particle is produced. We relax the $x_p$ cut from 0.7 to 0.5, and fit the dipion mass difference plot (Figure 3) in bins of $x_p$. The fit uses a fixed width derived from the Monte-Carlo study, with the mass fixed at the value found for $x_p > 0.7$. The yields in each bin of $x_p$ were corrected for the detector efficiency, and the resulting $x_p$ distribution shown in Figure 5. The fit to this spectrum is of the functional form due to Peterson *et al* [9]. The fitted parameter $\epsilon_r$ is measured to be $\epsilon_r = 0.058^{+.037}_{-.024}$. This value is very similar to that found for the $\Lambda_{c1}^+$ spectrum [4], and harder than those found for charmed baryons with no orbital angular momentum.

There has been little theoretical work in recent years on the spectroscopy of orbitally excited $\Xi_c$ states. However, the models [7] that do exist predict that the excitation energy of the first orbitally excited doublet should be similar to the analogous value in the $\Lambda_c^+$ case (308 and 342 MeV for the two states). Furthermore the decay patterns of the $\Xi_{c1}$ states should be closely analogous to those of the $\Lambda_{c1}^+$. The preferred decay of the $J^P = \frac{3}{2}^-$ $\Xi_{c1}$ should be to $\Xi_c{}^*\pi$ because the spin-parity of the baryons allows this decay to proceed via an S-wave decay. Decays to $\Xi_c'$ would have to proceed via a D-wave and would therefore be suppressed. In the case of the $J^P = \frac{1}{2}^-$ $\Xi_{c1}$ the situation is reversed. It is natural therefore to expect a particle found by its decay to $\Xi_c^*\pi$ to have $J^P = \frac{3}{2}^-$. When the total spin and parity of the baryon is considered, decays directly to the ground state, not allowed for the $\Lambda_{c1}^+$ because of isospin conservation, are allowed for the $\Xi_{c1}$ via a D-wave. Taking into account the large phase space available, such decays might be expected to be large. However, in the Heavy Quark Effective Theory model [8], where the angular momentum and parity of the light quark degrees of freedom must be considered separately from the heavy quark, such decays are forbidden. Thus in the HQET picture, we would expect that the dominant decay of a $J^P = \frac{3}{2}^-$ $\Xi_{c1}^+$ would be to $\Xi_c^{*0}\pi^+$, consistent with our observation.

In conclusion, we present evidence for the production of a new state decaying into $\Xi_c^{*0}\pi^+$. The measured mass of the new state is given by $M(\Xi_c^+\pi^-\pi^+) - M(\Xi_c^+) = 349.4 \pm 0.7 \pm 1.0$ MeV, and its width is $\Gamma < 2.4$ MeV at the 90% confidence level. Although we do not measure the spin or parity of this state, the decay mode, mass, and momentum distribution are all consistent with the new state being the $J^P = \frac{3}{2}^-$ $\Xi_{c1}^+$ state, the charmed-strange analogue of the $\Lambda_{c1}^+(2625)$.

## ACKNOWLEDGEMENTS

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. J.P.A., J.R.P., and I.P.J.S. thank the NYI program of the NSF, M.S. thanks the PFF program of the NSF, G.E. thanks the Heisenberg Foundation, K.K.G., M.S., H.N.N., T.S., and H.Y. thank the OJI program of DOE, J.R.P., K.H., M.S. and V.S. thank the A.P. Sloan Foundation, R.W. thanks the Alexander von Humboldt

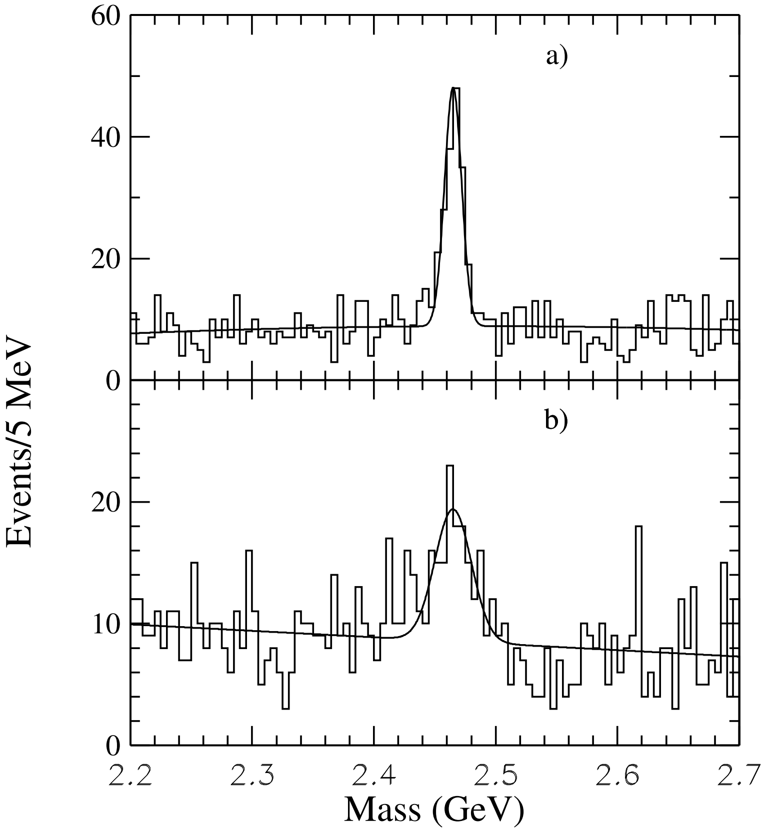


FIG. 1. Mass spectra for (a) $\Xi^-\pi^+\pi^+$ combinations, and (b) $\Xi^0\pi^+\pi^0$ combinations. There is an $x_p$ cut of 0.6 applied.

Stiftung, and M.S. thanks Research Corporation for support. This work was supported by the National Science Foundation, the U.S. Department of Energy, and the Natural Sciences and Engineering Research Council of Canada.

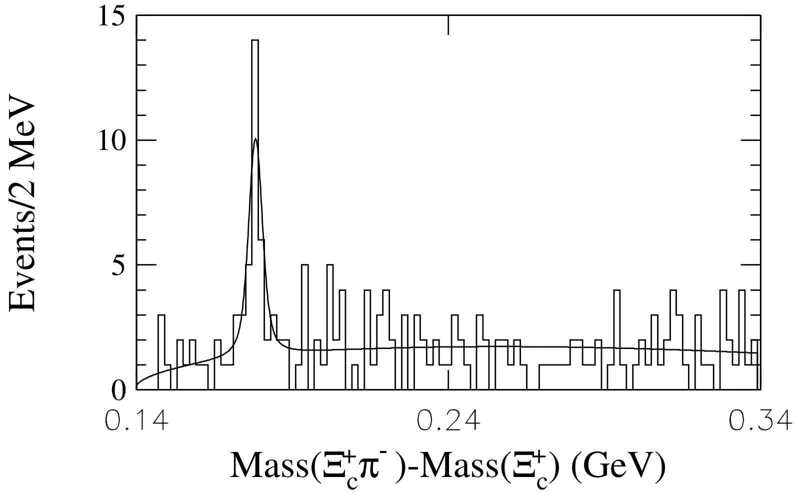


FIG. 2. The mass difference $M(\Xi_c^+\pi^-) - M(\Xi_c^+)$ showing a clear $\Xi_c^{*0}$ signal. There is an $x_p > 0.65$ cut applied on the $\Xi_c^+\pi^-$ combination.

## REFERENCES


[1] G. Brandenberg et al., PRL **78**, 2304 (1997).

[2] P. Avery et al., PRL **75**, 4364 (1995).

[3] L. Gibbons et al., PRL **77**, 811 (1996).

[4] P. Avery et al., PRL **74**, 3331 (1995), H. Albrecht et al., Phys. Lett. **B317**, 227 (1993), P. Frabetti et al., Phys. Lett. **B46** 1 (1996), H. Albrecht et al., DESY-97-008.

[5] For example, P. Cho, Phys. Rev. **D50** 3295 (1994), D. Pirjol and T-M. Yan, CLNS 97/1457.

[6] Y. Kubota et al., Nucl. Instr. and Meth. **A320**, 66.

[7] N. Isgur and K. Maltman, Phys. Rev. D22, 1701 (1980), L Glozman and D.O.Riska, hep-ph/9509269 v2. This latter paper is corrected from the earlier published version, Nucl. Phys. A 603, 326 (1996).

[8] N. Isgur and M. Wise. PRL **66** 1130 (1991).

[9] C. Peterson et al., Phys. Rev. **D27**, 105 (1983)

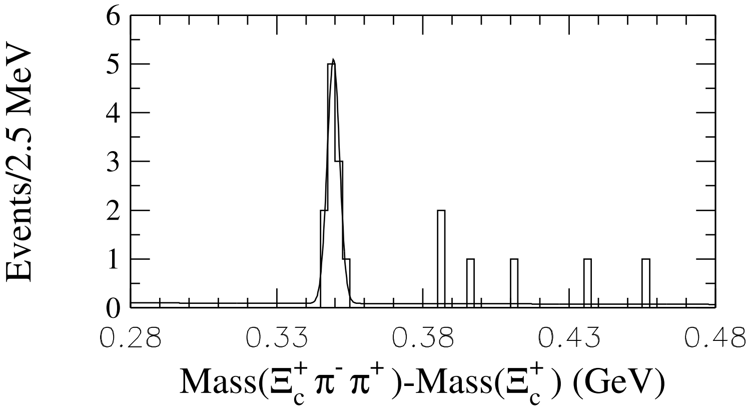


FIG. 3. The mass difference $M(\Xi_c^+\pi^+\pi^-) - M(\Xi_c^+)$ for combinations that lie in the $\Xi_c^{*0}$ band. combinations, an $x_p$ cut of 0.7 applied.

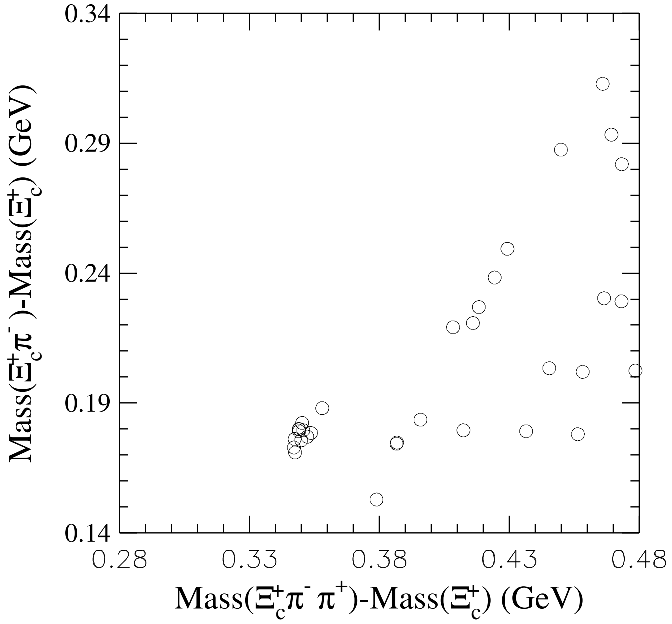


FIG. 4. Scatter plot of $M(\Xi_c^+\pi^- - M(\Xi_c^+)$ versus $M(\Xi_c^+\pi^-\pi^+) - M(\Xi_c^+)$. The signal is the small cluster in the bottom left hand corner.

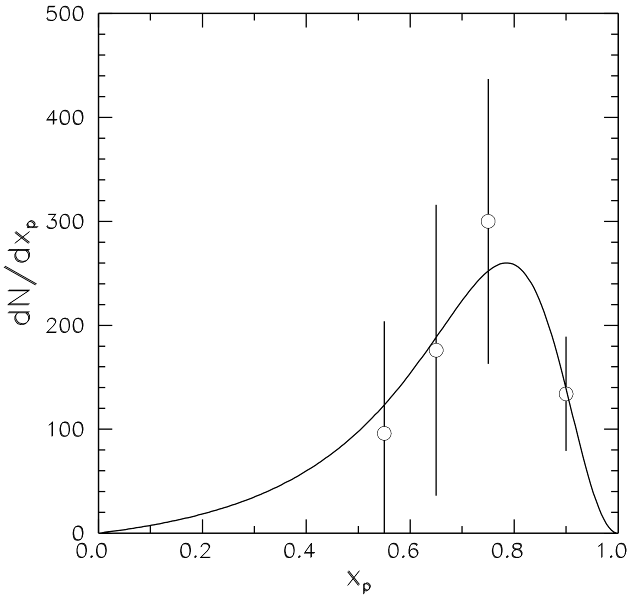


FIG. 5. Scaled momentum distribution of the new particle. The fit is of the form of the Peterson function.