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OBSERVATION OF THE CHARMED BARYON Λ_c IN e^+e^- ANNIHILATION AT 10 GeV

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The ARGUS Collaboration

H.Albrecht, P.Böckmann, R.Gläser, G.Harder,
A.Krüger, A.Nippe, M.Schäfer, W.Schmidt-Parzefall, H.Schröder,
H.D.Schulz, F.Sefkow, J.Spengler, R.Wurth, A.Yagil[1]
DESY, Hamburg, Germany

R.D.Appuhn, A.Drescher, D.Kamp, H.Kolanoski, U.Matthiesen,
H.Scheck, G.Schweda, B.Spaan, A.Walther, D.Wegener
Institut für Physik[2], Universität Dortmund, Germany

J.C.Gabriel, T.Ruf, K.R.Schubert, J.Stiewe, K.Strahl, R.Waldi, S.Werner
Institut für Hochenergiephysik[3], Universität Heidelberg, Germany

K.W.Edwards[4], W.R.Frisken[5], D.J.Gilkinson[6] D.M.Gingrich[6], H.Kapitza[4],
P.C.H.Kim[6], R.Kutschke[6], D.B.MacFarlane[7], J.A.McKenna[6], K.W.McLean[7],
A.W.Nilsson[7], R.S.Orr[6], P.Padley[6], J.A.Parsons[6], P.M.Patel[7], J.D.Prentice[6],
H.C.J.Seywerd[6], J.D.Swain[6], G.Tsipolitis[7], T.-S.Yoon[6], J.C.Yun[4]
Institute of Particle Physics[8], Canada

R.Ammar, S.Ball, D.Coppage, R.Davis, S.Kanekal, N.Kwak
University of Kansas[9], Lawrence, KS, USA

B.Boštjančič, G.Kernel, P.Križan, M.Pleško
Institut J. Stefan and Oddelek za fiziko[10], Univerza v Ljubljani, Ljubljana, Yugoslavia

L.Jönsson
Institute of Physics[11], University of Lund, Sweden

A.Babaev, M.Danilov, B.Fominykh, A.Golutvin, I.Gorelov,
V.Lubimov, V.Matveev, A.Semenov, S.Semenov, V.Shevchenko,
V.Soloshenko, V.Tchistilin, I.Tichomirov, Yu.Zaitsev
Institute of Theoretical and Experimental Physics, Moscow, USSR

R.Childers, C.W.Darden, R.C.Fernholz, Y.Oku
University of South Carolina[12], Columbia, S.C., USA

[1] Weizmann Institute of Science, Rehovot, Israel. Supported by the Minerva Stiftung.
[2] Supported by the German Bundesministerium für Forschung und Technologie, under the contract number 054DO51P.
[3] Supported by the German Bundesministerium für Forschung und Technologie, under the contract number 054HD24P.
[4] Carleton University, Ottawa, Ontario, Canada.
[5] York University, Downsview, Ontario, Canada.
[6] University of Toronto, Toronto, Ontario, Canada.
[7] McGill University, Montreal, Quebec, Canada.
[8] Supported by the Natural Sciences and Engineering Research Council, Canada.
[9] Supported by the U.S. National Science Foundation.
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Abstract. Using the ARGUS detector at DORIS II, we have studied the production of the charmed baryon Λ_c in e^+e^- annihilation at centre-of-mass energies near 10 GeV. The Λ_c^+ was seen in the three decay modes $pK^-\pi^+$, $\Lambda\pi^+\pi^-\pi^+$ and $\overline{K}^0p$, with products of normalized cross-section times branching ratio $[R \cdot Br]$ of $(10.8 \pm 1.4 \pm 1.2) \times 10^{-3}$, $(6.6 \pm 1.5 \pm 0.9) \times 10^{-3}$ and $(6.7 \pm 1.4 \pm 0.8) \times 10^{-3}$ respectively. The measured mass for the Λ_c was $(2283.1 \pm 1.7 \pm 2.0)$ MeV/c^2. A limit on the decay rates to $\Lambda\pi^+$ is reported. The fragmentation function of the Λ_c was measured.

The charmed baryon Λ_c was first observed in e^+e^- annihilation by Mark II [1] at SPEAR and more recently by CLEO [2] at CESR; here we report a study with the ARGUS detector at the e^+e^- storage ring DORIS II at DESY. The Λ_c^+, produced at centre-of-mass energies around 10 GeV, was observed in the decay modes $pK^-\pi^+$, $\Lambda\pi^+\pi^-\pi^+$ and $\overline{K}^0p$ †. The $pK^-\pi^+$ channel was used to study the fragmentation of charm quarks into charmed baryons, to allow comparison with previous measurements [3] of hadronization into charmed mesons. Limits on the rates of Λ_c production in direct $\Upsilon(1S)$ and $\Upsilon(2S)$ decays are reported, which provide information on charm production in gluon jets.

The data for this study correspond to an integrated luminosity of 219 pb^{-1}, obtained on the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(4S)$ resonances, and in the nearby continuum. The ARGUS detector is a solenoidal magnetic spectrometer with good momentum resolution and particle identification capabilities. The main components of the detector are a vertex detector, a main drift chamber which measures both the spatial position of tracks and their specific ionization, time-of-flight counters, a lead-scintillator electromagnetic calorimeter, and a muon detection system using the magnet coil and yoke as a hadron filter. A more detailed description of the ARGUS detector is given in reference 4. This analysis relied mostly on information from the vertex and main drift chambers and the time-of-flight system.

Multihadron events were selected by requiring events to have at least 3 tracks, either originating from a common vertex, or accompanied by an energy deposition of at least 1.7 GeV in the shower counters. Only those tracks with a polar angle, θ, such that $|\cos\theta| < 0.91$, and with a momentum transverse to the beam direction of greater than 60

† In this paper references to a specific charged state should be taken to imply the charge-conjugate state also.

MeV/c were chosen. Charged particle identification was made on the basis of measurements of specific ionization in the drift chamber, and of time-of-flight. For this analysis, only those particle hypotheses were accepted for which the likelihood ratio constructed from this information exceeded 5% for pions, and 15% for kaons or protons [3].

A search was made for the Λ_c^+ in the invariant $pK^-\pi^+$ mass distribution (Figure 1) with the requirement that the scaled momentum, x_p, of the $pK^-\pi^+$ system exceeds 0.5, where $x_p = P(pK\pi)/P_{max}$ and $P_{max} = \sqrt{E_{beam}^2 - M^2(pK\pi)}$. As will be shown below, the charm fragmentation process results in a rather hard momentum distribution for the Λ_c, quite analogous to that for charmed mesons. Hence, the requirement on x_p is a good means of suppressing combinatorial background. Such a cut also removes possible contributions to the production rate from B-meson decays, since a sizeable fraction of the data was obtained on the $\Upsilon(4S)$.

A fit to the resulting mass distribution was made using a Gaussian for the signal with a fixed RMS width of 14.0MeV/c^2, determined from Monte Carlo studies, and a third order polynomial for the background. The value obtained for the Λ_c mass was $(2279.9 \pm 2.4 \pm 2.0)$ MeV/c^2, with 450 ± 59 events in the peak. The systematic error reflects the uncertainty in the calibration of the magnetic field. The momentum scale has been adjusted by requiring the mass of reconstructed K_S^0 mesons to coincide with the nominal value [5], leaving a residual scale error of $\pm 0.2\%$.

Previously reported values for the mass of the Λ_c have fallen into two regions. Most recent experiments [1, 2, 6] have found a mass near 2280 MeV/c^2, while earlier results [7, 8] were closer to 2260 MeV/c^2. An exception to this trend was a measurement reported by the BIS-2 collaboration [9] of (2268 ± 6) MeV/c^2, reviving somewhat the controversy surrounding the Λ_c mass. Our result supports the higher value.

In studies of charmed hadrons, signal contamination by kinematical reflections, due to the fact that particle identification is not always unique, has often proven to be a problem. Of particular concern for the Λ_c is the decay $D^+ \to \pi^+K^-\pi^+$, which can simulate $\Lambda_c^+ \to pK^-\pi^+$ if a π^+ from the D^+ is misidentified as a proton. To determine the size of this reflection component in the signal, we have studied the invariant $pK^-\pi^+$ mass spectrum for $\pi^+K^-\pi^+$ combinations lying in the D^+ mass band, where the identification of the π^+ was ambiguous. This procedure was found to be consistent with results obtained

using Monte Carlo generated D^+ mesons. In both cases the reflection contamination was found to be less than 5%.

After correcting for acceptance, the product of cross-section times branching ratio for this decay channel is found to be $(9.0 \pm 1.2 \pm 1.0)$ pb. We have assumed charm production from the resonances to be negligible (see below) and have included resonance electro-magnetic decay corrections for the luminosity contributed by the $\Upsilon(1S)$ and $\Upsilon(2S)$ subsamples. Normalizing to the muon-pair cross-section at the average centre-of-mass energy of 10.2 GeV, this is equivalent to $R \cdot Br(\Lambda_c^+ \to pK^-\pi^+) = (10.8 \pm 1.4 \pm 1.2) \times 10^{-3}$. The systematic error includes contributions from the uncertainty of the luminosity measurement, the extrapolation to small x_p, and the predicted width of the Λ_c peak. Acceptances were calculated using a detector Monte Carlo. Events were generated for the annihilation process $e^+e^- \to c\bar{c}$, with the charm quarks fragmenting into baryons by combining quarks with diquarks, according to the Feynman-Field model [10]. They were then processed through a detector simulation and reconstructed using the standard analysis program. The form of the Λ_c momentum distribution from the Monte Carlo was adjusted to match the Peterson [11] fit to the observed spectrum, as discussed below.

Charm quark fragmentation into charmed baryons was examined by observing the signal for $\Lambda_c^+ \to pK^-\pi^+$ in seven intervals in x_p. In order to reduce combinatorial background, only pions with momenta greater than 600 MeV/c were used. Data collected on the $\Upsilon(4S)$ were excluded from this analysis. The number of Λ_c's in each interval was determined by fitting the data using a Gaussian with a fixed mass and an RMS width determined by the Monte Carlo, plus a polynomial background. Acceptance corrections were applied separately for each bin.

The resulting momentum spectrum is shown in Figure 2, along with a fit using the expression by Peterson *et al.* [11] for the fragmentation function:

$$s\frac{d\sigma}{dx_p} \sim \frac{1}{x_p(1 - \frac{1}{x_p} - \frac{\epsilon}{1 - x_p})^2}.$$

The parameter ϵ is interpreted, for mesons, as the square of the ratio of the spectator to charm quark mass, $(M_q/M_c)^2$. If baryon production is due to the creation of diquark anti-diquark pairs from the vacuum, the same form remains valid. However, in this case the diquark is the spectator system, so that ϵ should be equal to $(M_{(qq)}/M_c)^2$. From a fit to the observed x_p distribution, a value of $0.236^{+0.068}_{-0.048}$ for ϵ was obtained, with a χ^2 of 2.6 for five degrees of freedom (errors are statistical only).

It is interesting to note that the shape of the Λ_c momentum distribution is very similar to that measured for charmed mesons [3]. The reported value from a fit of the Peterson form to the observed x_p distribution for D^* mesons was $\epsilon = 0.19 \pm 0.03$. Presumably, QCD and QED radiative corrections are similar for the D^* and the Λ_c. Therefore, if this simple model of baryon production is correct, the diquark must have a mass near that of the u quark in the D^*.

Previous observations of baryon production in e^+e^- annihilations have shown an enhancement of the hyperon yield in direct $\Upsilon(1S)$ decays over the yield from the continuum [12]. For comparison, the Λ_c production rates in direct resonance decays were determined. This was accomplished by measuring the rates in the $\Upsilon(1S)$ and $\Upsilon(2S)$ data samples, and subtracting the continuum contribution by scaling the observed rate in our continuum sample. Since the momentum spectrum of charmed hadrons from gluon jets would be quite soft, no x_p cut can be made. Instead we required the pion momentum to be greater than 600 MeV/c, which leads to a constant acceptance, even at low momentum. The Λ_c yield per multi-hadron event from direct $\Upsilon(1S)$ and $\Upsilon(2S)$ decays was found to be less than 15% and 20% (90% CL) of the corresponding continuum rate respectively. If one assumes that charm quarks are produced in 40% of the continuum hadronic events, and that the probability of producing a Λ_c^+ from a charm quark is comparable for Υ and for continuum events, then one finds that charm is produced in less than 6% of $\Upsilon(1S)$ decays. The predicted rate [13] is 3%, based on $c\bar{c}$ production from one of the three gluon jets.

For the study of Λ_c^+ decays into $\Lambda\pi^+$, $\Lambda\pi^+\pi^-\pi^+$, and $\overline{K}^0p$ the Λ and K_s^0, because of their long lifetime, permit the use of vertex information as a means of reducing backgrounds. Λ and K_s^0 candidates were selected from $p\pi^+$ and $\pi^+\pi^-$ combinations forming secondary vertices. Furthermore, a requirement was made that the momentum vector of the Λ or K_s^0 coincide with the vector connecting the primary and secondary vertices ($\chi^2 < 30$). Each combination within ± 9 MeV/c^2(± 18 MeV/c^2) of the nominal $\Lambda(K_s^0)$ mass and with a $\chi^2 < 25$ for a fit to the appropriate mass hypothesis was accepted as a $\Lambda(K_s^0)$ candidate. A mass constraint fit was then applied to improve the momentum

resolution.

The search for the $\Lambda_c^+ \to \Lambda\pi^+\pi^-\pi^+$ and $\Lambda\pi^+$ decay channels was made by combining Λ candidates with pions from the primary vertex. The requirement was made that x_p of the $\Lambda\pi^+\pi^-\pi^+$ or $\Lambda\pi^+$ system exceeds 0.5, as was used for the $pK^-\pi^+$ channel. The resulting invariant mass distribution for $\Lambda\pi^+\pi^-\pi^+$ is shown in Figure 3a. A fit with a Gaussian of RMS width fixed to 11.2 MeV/c^2 and a third order polynomial background finds a signal of 105 ± 24 events at a mass of $(2285.5 \pm 3.5 \pm 2.0)$ MeV/c^2. Taking into account detector acceptance and the known branching ratio for $\Lambda \to p\pi^-$ (62.4%), we find $R \cdot Br(\Lambda_c^+ \to \Lambda\pi^+\pi^-\pi^+)$ to be $(6.6 \pm 1.5 \pm 0.9) \times 10^{-3}$. The ratio $Br(\Lambda_c^+ \to \Lambda\pi^+\pi^-\pi^+)/Br(pK^-\pi^+)$, for which many common sources of systematic error cancel, is $0.61 \pm 0.16 \pm 0.04$. The value for the product of cross-section times branching ratio is consistent with the measurement by CLEO [2].

No signal was seen in the $\Lambda\pi^+$ mass distribution (Figure 3b). A fit, using a Gaussian with mass equal to the mean Λ_c^+ value reported here and fixed RMS width, yielded an upper limit of 43 events (90% CL) in this channel. This corresponds to an upper limit on $R \cdot Br(\Lambda_c^+ \to \Lambda\pi^+)$ of 1.9×10^{-3} or $Br(\Lambda_c^+ \to \Lambda\pi^+)/Br(\Lambda_c^+ \to pK^-\pi^+) < 0.16$, both at the 90% confidence level.

The $\Lambda_c^+ \to \overline{K}^0p$ decay channel was studied by combining K_s^0 candidates with identified protons from the primary vertex. In addition to requiring $x_p > 0.5$, the cosine of the decay angle of the K_s^0 with respect to the K_s^0p boost direction in the K_s^0 rest frame was required to be greater than -0.8. This cut eliminates K_s^0's from the second charm jet in the event, which tend to be travelling backwards in this frame. The mass distribution of K_s^0p, shown in Figure 4, exhibits a distinct peak, which, when fitted using a Gaussian with an RMS width of 14.8 MeV/c^2, was found to contain 73 ± 15 events centered at a mass of $(2287.4 \pm 3.4 \pm 1.5)$ MeV/c^2. After corrections for detector acceptance and unseen decay modes of the K_s^0, we find $R \cdot Br(\Lambda_c^+ \to \overline{K}^0p)$ to be $(6.7 \pm 1.4 \pm 0.8) \times 10^{-3}$ or $Br(\Lambda_c^+ \to \overline{K}^0p)/Br(pK^-\pi^+) = 0.62 \pm 0.15 \pm 0.03$. The ratio of branching ratios is in good agreement with the MARK II measurement [1]. There have been several determinations of $Br(\Lambda_c^+ \to \Lambda\pi^+)/Br(\Lambda_c^+ \to \overline{K}^0p)$ in charm production by neutrino interactions [8,14], which yielded an average value of 0.57 ± 0.35 for this ratio. Our upper limit of 0.26 (90% CL) suggests a ratio at the low end of this allowed range.

In summary, we have observed the Λ_c^+ in the $pK^-\pi^+$, $\Lambda\pi^+\pi^-\pi^+$ and $\overline{K}^0p$ decay channels. The weighted mean mass for the Λ_c from the three decay modes was $(2283.1 \pm 1.7 \pm 2.0)$ MeV/c^2. The branching fractions of the $\Lambda\pi^+\pi^-\pi^+$ and $\overline{K}^0p$ channels relative to $\Lambda_c^+ \to pK^-\pi^+$ were determined to be $0.61 \pm 0.16 \pm 0.04$ and $0.62 \pm 0.15 \pm 0.03$ respectively. The charm quark fragmentation was found to produce a hard Λ_c momentum spectrum, in fact, similar in shape to that for charmed mesons (D^*). The spectrum was well fitted by the Peterson form of the fragmentation function. No significant Λ_c production from the $\Upsilon(1S)$ or $\Upsilon(2S)$ resonances was observed.

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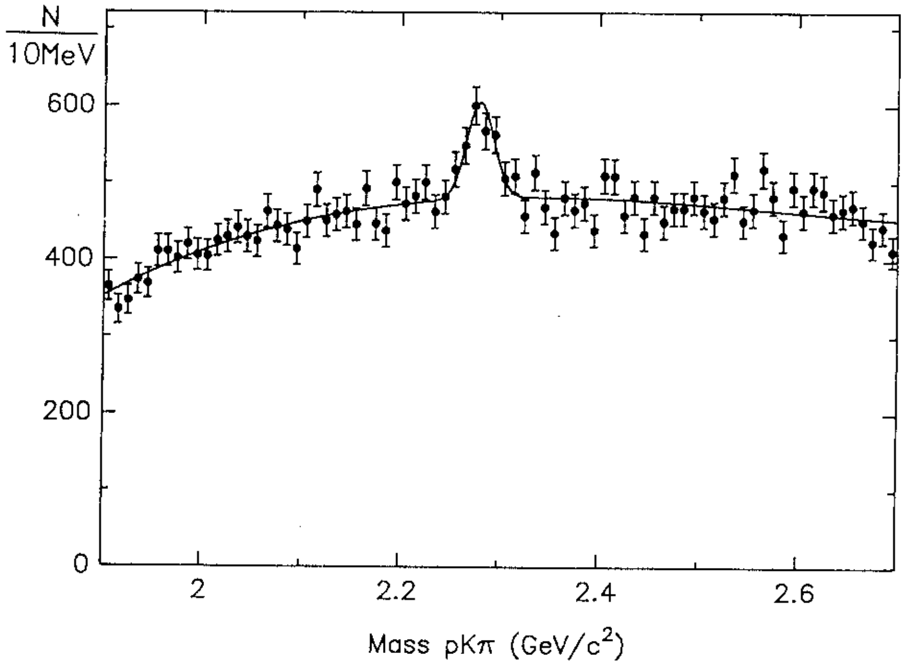
Figure captions

Figure 1: Invariant mass distribution of $pK^-\pi^+$ combinations with $x_p > 0.5$. The solid line is the best fit using a Gaussian for the Λ_c^+ and a polynomial background.

Figure 2: Acceptance corrected Λ_c fragmentation function with Peterson fit superimposed.

Figure 3: Invariant mass distribution, with $x_p > 0.5$, for (a) $\Lambda\pi^+\pi^-\pi^+$ and (b) $\Lambda\pi^+$ combinations. The solid line is the best fit using a Gaussian for the Λ_c^+ and a polynomial background.

Figure 4: Invariant mass distribution for $\overline{K}^0p$ combinations with $x_p > 0.5$ and $\cos\alpha > -0.8$. The solid line is the best fit using a Gaussian for the Λ_c^+ and a polynomial background.



N/10MeV
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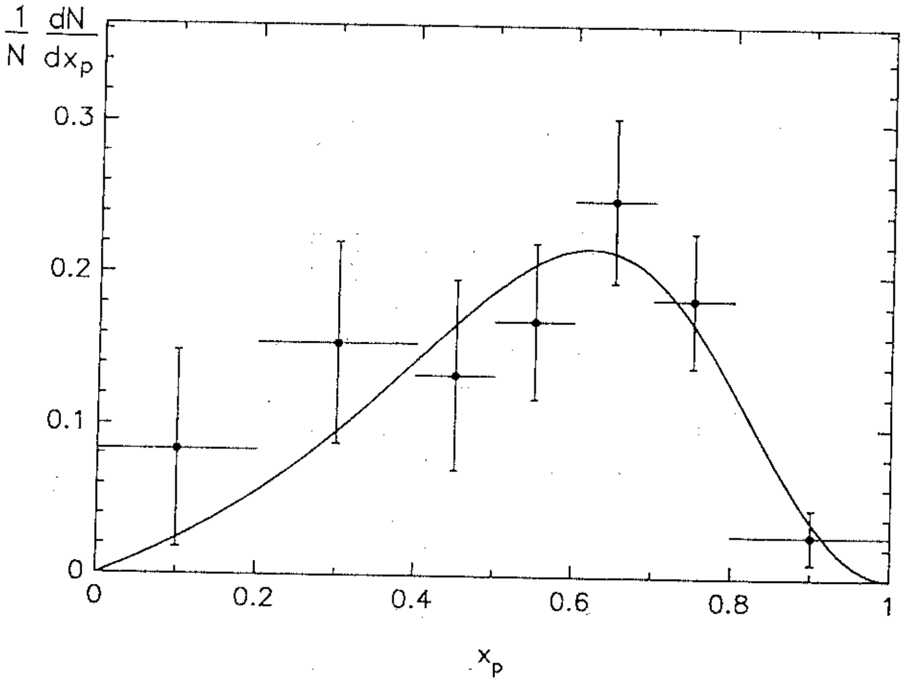
400
200
0
2
2.2
2.4
2.6
Mass pKπ (GeV/c²)

Fig.1



1/N dN/dx_p
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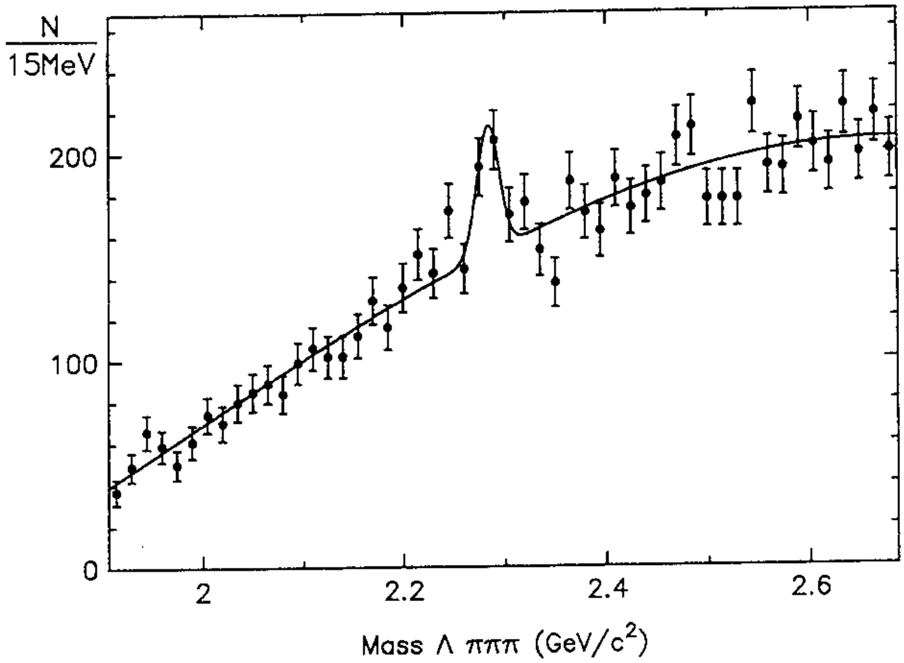
0.1
0
0
0.2
0.4
0.6
0.8
1
x_p

Fig.2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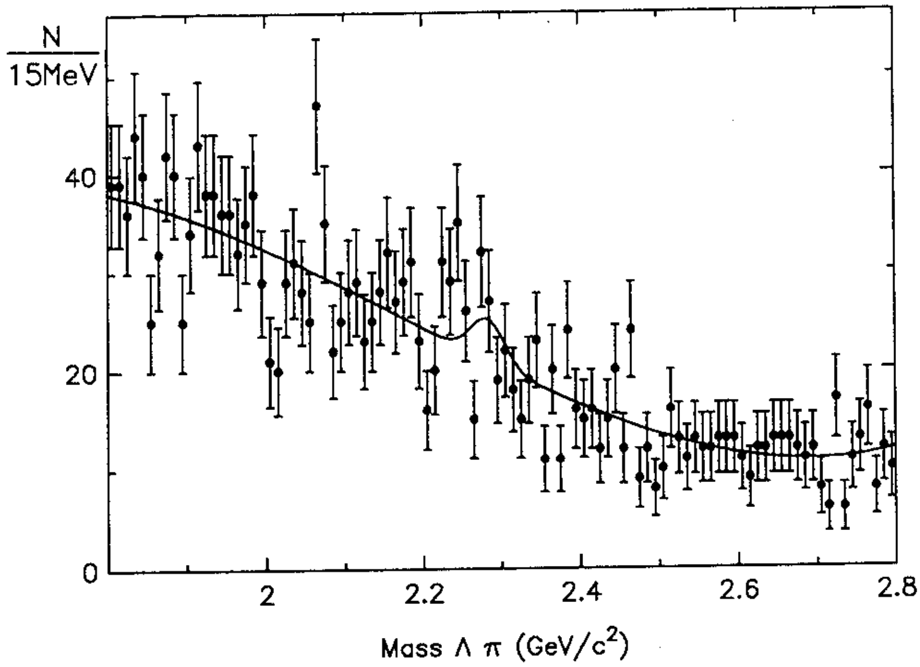
100
0
2
2.2
2.4
2.6
Mass Λ πππ (GeV/c²)

Fig.3a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20
0
2
2.2
2.4
2.6
2.8
Mass Λ π (GeV/c²)

Fig.3b

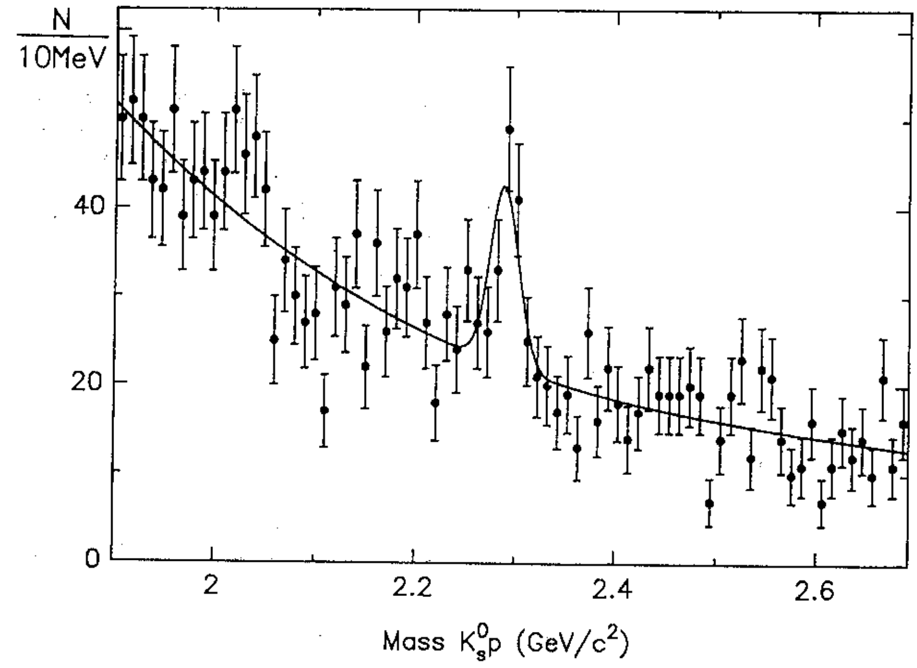

Fig.4