NEW RESULTS FROM SELEX

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1. Introduction

The SELEX experiment (E781) at Fermilab is a fixed target experiment aimed at studying charm baryon production in the forward hemisphere and charm baryon spectroscopy. However**,** the versatility of the apparatus also allowed for the study of such reactions as elastic scattering of electrons on Σ^- hyperons (in inverse kinematics), Primakoff scattering of π^- mesons, and some others. The data were taken in 1996–1997. Results on charm-anticharm production asymmetries, Λ_c^+ production x_F-dependence in different beams, the Λ_c^+ lifetime, the total cross section for interaction of π^-, Σ^- and protons with nucleons at ~600 GeV, the charge radius of the Σ^- hyperon, and some other results have already been reported [1]. Since then, new results from the SELEX data have been obtained. The polarizations of the Σ^+ hyperons produced by 800 GeV/c protons on Be and Cu targets have been determined [2]. An upper limit on the width of the radiative decay of $\Sigma(1385)^-$ to $\Sigma^-\gamma$ has been set, and the cross section for the reaction $\gamma\Sigma^- \to \Lambda\pi^-$ at $\sqrt{s} \approx 1.4$ GeV has been evaluated [3]. In this report, the most interesting recent SELEX results on observation of the doubly charmed baryon Ξ_{cc}^+ [4, 5] and of a narrow charm–strange meson D_{sJ}^+ (2632) [6] are presented and discussed.

2. Experimental setup

The SELEX experiment used the Fermilab charged Hyperon beam which is composed of 50% Σ^- and 50% π^- with the energy of about 600 GeV for negative polarity and 92% p and 8% π^+ with the energy of 540 GeV for positive polarity. The beam was run at the forward production angle ($\Theta = 0°$). Beam particles were identified by beam Transition Radiation Detectors (TRD). The experiment was designed to have high acceptance and resolution in x_F region $0.1 < x_F < 1$. The spectrometer schematic layout is shown in Fig. 1.

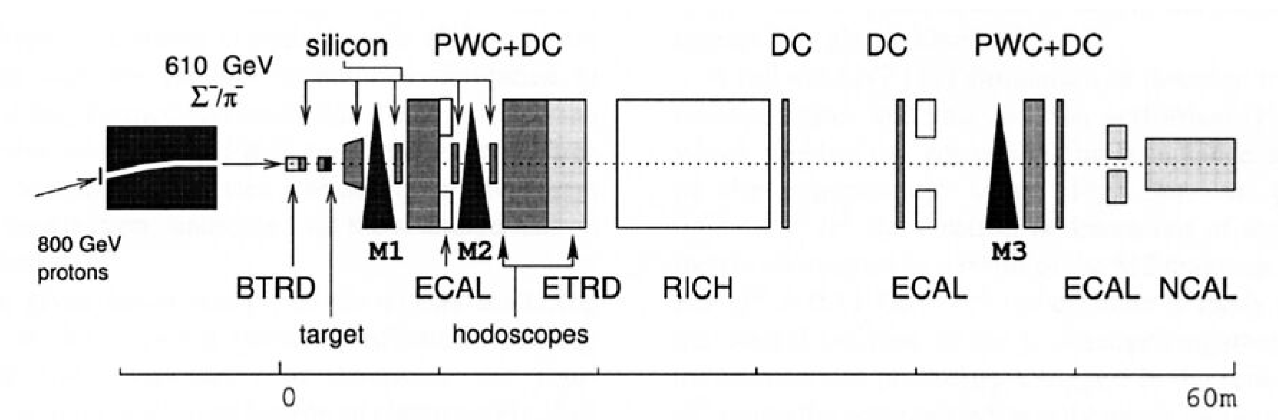

Fig. 1. Schematic view of the experimental setup. BTRD – beam transition radiation detector, ETRD – electron transition radiation detector, ECAL – electromagnetic calorimeter, PWC – proportional wire chambers, DC – drift chambers, RICH – ring image Cherenkov detector, NCAL – neutron calorimeter, M1, M2, and M3 – analyzing magnets

Interactions occurred in a target stack of 5 foils: 2 made of copper and 3 made of carbon. The total interaction length of all targets was about 5% for protons. Each foil was spaced by 1.5 cm from its neighbors. An additional Pb target was also employed in some runs. Trigger requirements (for charm physics) were: ≥ 4 charged tracks in the forward 150 mrad cone and ≥ 2 hits in a counter hodoscope located behind the second analyzing magnet. Triggering took place for about 30% of inelastic interactions.

Downstream of the target region, charged reaction products were measured in 20 vertex silicon planes having the position resolution of 4 μm for high momentum tracks. Beam tracks were measured in 8 planes of 2 μm pitch beam silicon. The downstream tracking system included 18 silicon planes for precise measurement of high momentum (100–600 GeV) tracks. In total, the SELEX silicon system had 74,000 strips with analog and digital information.

Another distinct feature of SELEX was an extensive particle identification system, which included 3,000 phototubes Ring Imaging Cherenkov detector (RICH) with K/π separation up to 165 GeV, beam TRD for beam tagging (Σ^-/π^-, p/π^+), downstream electron TRD to identify secondary $e^{\pm}$, 3 lead-glass photon calorimeters covering the forward hemisphere. The downstream tracking system had 3 analyzing magnets, 26 Proportional Wire Chamber (PWC) planes with position resolution ~0.8 mm, and 3 vector drift chamber (DC) stations with 24 ~100 μm resolution planes each.

PNPI has made a significant contribution to the apparatus of the SELEX experiment, providing good particle identification (Beam and Electron Transition Radiation Detectors, BTRD and ETRD) and tracking capabilities (Proportional Wire Chambers). The readout electronics (CROS) for these detectors and also for other detectors (RICH, NCAL) – 11,000 channels in total – was fabricated at PNPI as well. Another important contribution of PNPI was the design and commissioning of 60,000 FASTBUS readout channels for the Si vertex detector. PNPI has also provided SELEX with the front-end electronics for the drift chambers, as well as with the electronics for BTRD.

3. First observation of the doubly charmed baryon Ξ_{cc}^{+}

In the SELEX experiment, a signal was observed [4] which was interpreted as due to the doubly charmed baryon Ξ_{cc}^{+} in the charged decay mode $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$. The experiment selected charm candidate events using an online secondary vertex algorithm. A scintillator trigger demanded an inelastic collision with at least four charged tracks in the interaction scintillators and at least two hits in a positive particle hodoscope after the second analyzing magnet. Event selection in the online filter required full track reconstruction for the measured fast tracks ($p \geq 15$ GeV/c). These tracks were extrapolated back into the vertex silicon planes and linked to silicon hits. The beam track was measured in upstream silicon detectors. A full three-dimensional vertex fit was then performed. In the course of the experiment, data from 15.2×10^9 inelastic interactions were recorded and 1×10^9 events were written to tape using both positive and negative beams. 67% of events were induced by Σ^-, 13% by π^-, and 18% by protons.

The Ξ_{cc}^{+} analysis began with a sample of Λ_c^+ single-charm baryons decaying to $pK^-\pi^+$ [1]. Candidates were selected with a topological identification of three-prong positively-charged secondary vertices, requiring a momentum measurement for each track. The RICH identification of the proton and kaon was required. Charged tracks with reconstructed momenta which traversed the RICH ($p \geq 22$ GeV/c) were identified as protons or kaons if those hypotheses were more likely than the pion hypothesis. The other positive track was identified as a pion when possible; otherwise, it was assumed to be a pion. The primary vertex was refit using all other found tracks.

A Cabibbo-allowed decay of a doubly charmed baryon must have a net positive charge and contain a charmed quark, a strange quark, and a baryon. In the discussed work, a search for decay modes such as $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$ with an intermediate $K^-\pi^+$ secondary vertex between the primary vertex and the Λ_c^+ vertex was performed.

Events were analyzed for evidence of a secondary vertex composed of an opposite-signed pair between the primary and the Λ_c^+ decay point. All tracks not assigned to the Λ_c^+ candidate were used in the search.

A new primary vertex was formed from the beam track and tracks assigned to neither the Λ_c^+ nor the $K^-\pi^+$ vertices. The new secondary vertex had to have an acceptable fit χ^2 and a separation of at least 1σ from the new primary one. The $\Lambda_c^+ K^-\pi^+$ transverse momentum with respect to the incident beam direction was required to be in the range $0.2 < p_t$ [GeV/c] < 2.0.

Most tracks from the $K^-\pi^+$ vertex have insufficient momentum to reach the RICH. Masses were assigned according to topology. For the signal channel, negative tracks were assigned the kaon mass and positive tracks the pion mass. A candidate event from the $\Lambda_c^+ K^-\pi^+$ sample is shown in Fig. 2.

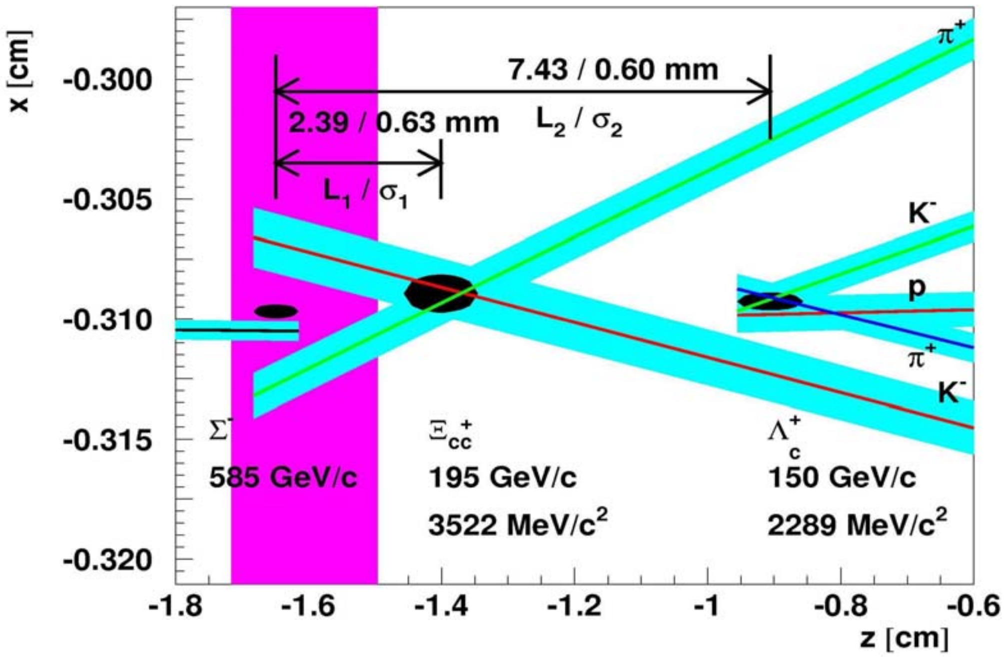

Fig. 2. A candidate event with the production target, 1σ track error corridors, and vertex error ellipses. This is a plan view of three-dimensional tracks and vertices. Three additional found tracks which form the primary vertex with the beam track are not shown

Figure 3a shows the invariant mass of the $\Lambda_c^+ K^-\pi^+$ system, the Λ_c^+ mass being fixed at 2284.9 MeV/c^2. The data, plotted in 5 MeV/c^2 bins, exhibit a large, narrow excess at 3520 MeV/c^2. This excess is stable for different bin widths and bin centers. Figure 3b shows the wrong-sign invariant mass distribution of the $\Lambda_c^+ K^+\pi^-$ system with the same binning as in Fig. 3a. There is no significant excess.

In Fig. 3c the shaded region from Fig. 3a is replotted in 2.5 MeV/c^2 bins and fit with a maximum likelihood technique to a Gaussian plus linear background. The fit has χ^2/d.o.f. = 0.45, indicating that the background is linear in this region.

The combinatorial background under the signal peak was determined under an assumption of the linearity of the background, which is justified by the fit. Two symmetric regions of the mass plot are defined in Fig. 3c: (i) the signal region 3520$\pm$5 MeV/c^2 with 22 events and (ii) 115 MeV/c^2 sideband regions above and below the signal region, containing 162 – 22 = 140 events. The estimated number of expected background events in the signal region from the sidebands is 140 × 5/(115) = 6.1 ± 0.5 events. This determination has a (Gaussian) statistical uncertainty, solely from counting statistics. The single-bin significance of this signal is the excess in the signal region divided by the total uncertainty in the background estimate: $15.9/\sqrt{6.1+0.5^2} = 6.3\sigma$. The Poisson probability of observing at least this excess, including the Gaussian uncertainty in the background, is 1.0×10^{-6}.

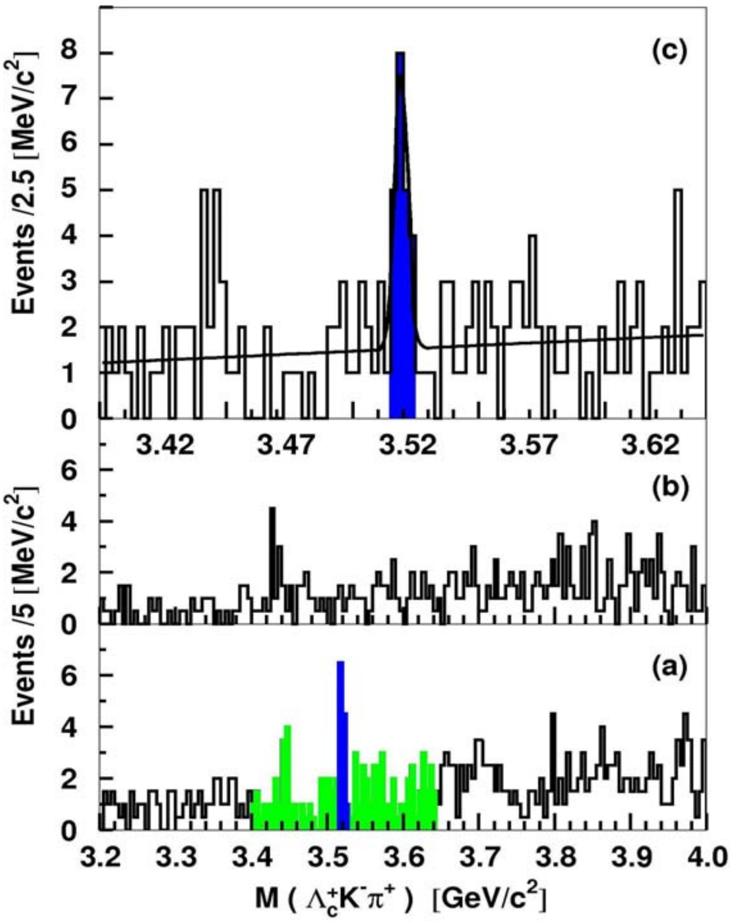

Fig. 3. (a) The mass distribution $\Lambda_c^+ K^- \pi^+$ in 5 MeV/c^2 bins. The shaded region 3.40–3.64 GeV/c^2 contains the signal peak and is shown in more detail in (c). (b) The wrong-sign combination $\Lambda_c^+ K^+ \pi^-$ mass distribution in 5 MeV/c^2 bins. (c) The signal (shaded) region (22 events) and sideband mass regions with 162 total events in 2.5 MeV/c^2 bins. The fit is a Gaussian plus linear background

The reconstruction mass window is 3.2 –4.3 GeV/c^2 with 110 bins of width 10 MeV/c^2 in this interval. The overall probability of observing an excess at least as large as the one which is seen anywhere in the search interval is 1.1×10^{-4}. The width of the observed state is consistent with the experimental resolution, less than 5 MeV/c^2. An analysis of the flight path from the primary vertex to the Ξ_{cc}^+ decay point indicates that the lifetime of Ξ_{cc}^+ is very short, smaller than 33 fs (at 90% confidence level).

Thus, the narrow state seen in this experiment at 3520 MeV/c^2 is interpreted as the doubly charmed baryon Ξ_{cc}^+ which decays into $\Lambda_c^+ K^- \pi^+$. This is the first observation of doubly charmed baryons. In order to confirm the interpretation of this state as a doubly charmed baryon, it is essential to observe the same state in some other way, in particular in a different decay mode. The further analysis of the SELEX data has allowed to see Ξ_{cc}^+ in the channel $\Xi_{cc}^+ \to pD^+K^-$ [5]. This study was begun with the SELEX $D^\pm$ sample that was previously used in lifetime and hadro-production studies [1]. Intermediate vertices were looked for using all charge zero pairs of tracks from the set of reconstructed tracks not assigned to the *D*-meson candidate. The additional positive track in this final state had to be RICH-identified as a proton if it traversed the RICH. The negative track in the new vertex was assigned the kaon mass. The Ξ_{cc}^+ signal search was based on a 10 MeV/c^2 window centered on the Ξ_{cc}^+ mass 3519 MeV/c^2 from Ref. [4]. The expected mass resolution for the decay $\Xi_{cc}^+ \to pD^+K^-$ was 4 MeV/c^2. The right-sign mass combinations in Fig. 4a show an excess of 5.4 events over a background of 1.6 events. The wrong-sign mass combinations ($\bar{c}$ quark in the decay) for the $pD^-\pi^+$ final state are also plotted in Fig. 4b, scaled by 0.6 for the D^+/D^- ratio. The wrong-sign background shows no evidence for a significant narrow structure near 3519 MeV/c^2. The average wrong-sign occupancy is 0.4 events/bin, exactly the background seen in the right-sign channel. This confirms the combinatoric; character of the background population in the right-sign signal. All possible permutations of particle assignments were investigated. The only significant structure observed is in the channel $\Xi_{cc}^{+} \to pD^{+}K^{-}$, the place where the decay of a doubly charmed baryon can occur.

The estimated single significance is 4.8σ. The Poisson probability of observing at least this much excess, including the Gaussian uncertainty in the background, is 6.4×10^{-4}.

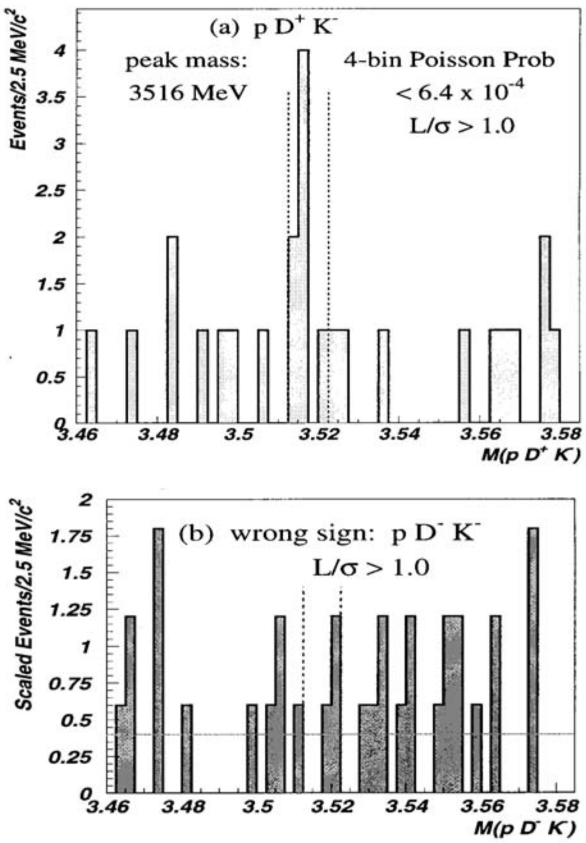

Fig. 4. (a) $\Xi_{cc}^{+} \to pD^{+}K^{-}$ mass distribution for right-sign mass combinations. Vertical dashed lines indicate the region of smallest fluctuation probability as described in the text. (b) Wrong-sign events with a $pD^{-}K^{+}$, scaled by 0.6 as described in the text. The horizontal line shows a maximum likelihood fit to the occupancy

In order to estimate the mass of the $\Xi_{cc}^{+} \to pD^{+}K^{-}$ state in light of the sparse statistics in Fig. 4a, the width of the Gaussian was fixed to 4 MeV/c^2 and the data distribution was fit around the signal peak. The fit mass was 3518 ± 3 MeV/c^2. This result agrees with the measurement of 3519 ± 2 MeV/c^2 from the original doubly charmed baryon report [4]. The weighted average mass is 3518.7 ± 1.7 MeV/c^2. The observation of the Ξ_{cc}^{+} decay into the $pD^{-}K^{+}$ final state is an independent confirmation of the doubly charmed baryon Ξ_{cc}^{+} previously seen [4] in the $\Xi_{cc}^{+} \to \Lambda_c^{+}K^{-}\pi^{+}$ decay mode.

4. Observation of a narrow charm-strange meson D_{sJ}^{+} (2632)

In 2003, the BABAR Collaboration reported the first observation of a massive, narrow charm-strange meson D_{sJ}^{+}(2317) below the *DK* threshold. Confirmations quickly followed from CLEO and BELLE. The CLEO Collaboration showed that a higher-lying state, suggested by BABAR, existed and was a partner to D_{sJ}^{+}(2317). A number of theory papers suggested different explanations for the unexpectedly low mass of the state which had been thought to lie above the *DK* threshold. It was predicted that the pattern of paritydoubled states is expected to continue to higher excitations with similar splittings. In the SELEX experiment, a search for D_{sJ}^{+} with higher masses was undertaken [6]. This search was begun with the SELEX $D_s^{\pm} \to K^+K^-\pi^{\pm}$ sample used in lifetime and hadro-production studies [1]. The D_s meson momentum vector had to point back to the primary vertex with $\chi^2 < 8$, and its decay point must have a vertex separation significance of at least eight from the primary. Tracks that traversed RICH ($p \geq 22$ GeV/c) were identified as kaons if this hypothesis was most likely. The pion was required to be RICH-identified if it went into its acceptance.

Because of high-multiplicity, the photon detection in an open charm-trigger is challenging. SELEX has three lead glass calorimeters covering much of the forward solid angle. The energy scale for the detector was set first by using electron beam scans. Then π^0 decays were reconstructed from exclusive trigger data, which selected low-multiplicity radiative final states: $\eta \to \gamma\gamma$ and $\pi^+\pi^-\pi^0$, $\omega \to \pi^+\pi^-\pi^0$ as well as η' and $f(1285)$ mesons. The final energy scale corrections were developed using π^0 decays from the high multiplicity charm-trigger data. Further checks in the charm data set were made using single photon decays, *e.g.* $\Sigma^0 \to \Lambda\gamma$. The uncertainty in the photon energy scale was less than 2 %. Candidates for $\eta \to \gamma\gamma$ were selected in the $\gamma\gamma$ mass range 400–800 MeV/c^2. Each photon of the pair had $E_\gamma > 2$ GeV. The photon pair had $E_\gamma > 15$ GeV. The $\gamma\gamma$ mass distribution from 10^6 charm-trigger events (0.1% of the data) is shown in Fig. 5 where the η signal over a large combinatorial background is seen. A fit to a Gaussian plus an exponentially falling background yields an η mass of 544.8 ± 2.9 MeV/c^2 consistent with the PDG value. The observed resolution of 28 ± 4 MeV/c^2 is consistent with the SELEX simulation result, 30 MeV/c^2.

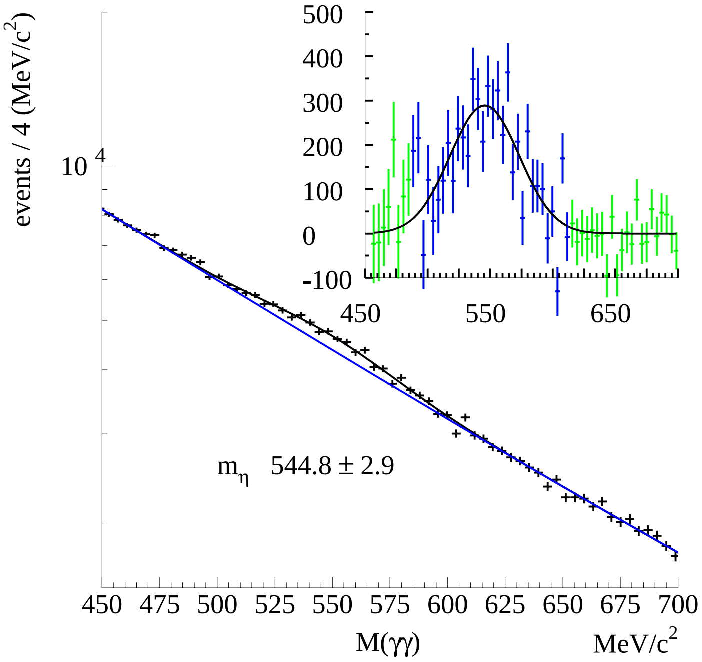

Fig. 5. $M(\gamma\gamma)$ distribution for photon pairs in the η mass region from 0.1% of the data sample. The inset shows the background subtracted η signal. The dark points indicate the η signal region

High-mass charm-strange decays that followed the pattern D_s plus pseudoscalar meson were searched. The event selection used included the η selection discussed above and the D_s selection described previously. The η signal region is shown in Fig. 5. The results of the D_{sJ} search are shown in the $M(KK\pi^{\pm}\eta) - M(KK\pi^{\pm})$ mass-difference distribution in Fig. 6. The η four vector was defined in this plot with the measured η momentum and the PDG η mass. A clear peak is seen in Fig. 6 at a mass difference of 666.9±3.3 MeV/c^2.

To estimate the combinatoric background, each D_s candidate was matched with η candidates from other sample events to form an event-mixed sample representing the combinatoric background of true single charm production and real η candidates. As can be seen in Fig. 6, the event-mixed background models the background shape very well, but does not produce any signal peak.

To estimate the signal yield, the combinatoric background (light shaded area) was subtracted from the signal data. The resulting difference histogram is plotted in the inset in Fig. 5 in the mass-difference range appropriate to the D_{sJ} search (D^+_{sJ} masses up to 2900 MeV/c^2). Outside the peak region the data scatter about 0. The difference histogram was fit with only a Gaussian with no residual back-ground terms. The Gaussian width was fixed at the simulation value of 10.9 MeV/c^2. The fit yield is 43.4 ± 9.1 events at a mass of 2635.4 ± 3.3 MeV/c^2.

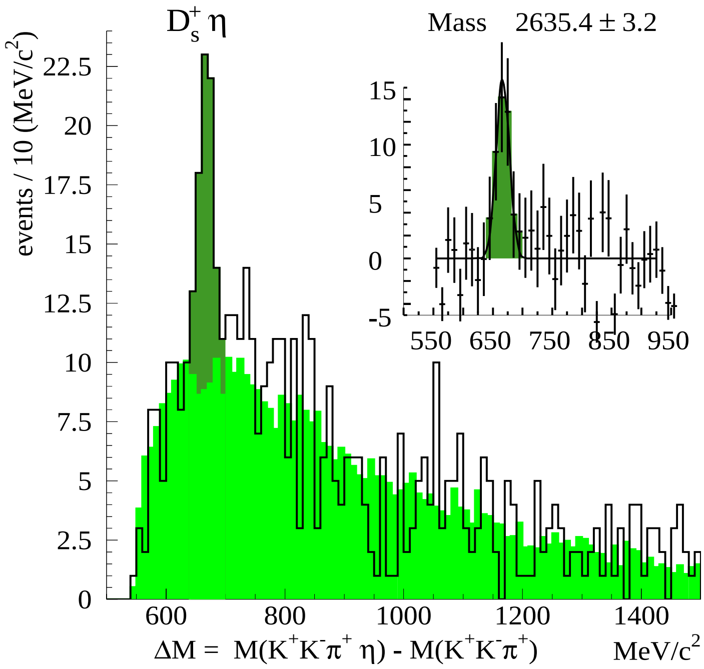

Fig. 6. $M(KK\pi^\pm\eta)$ - $M(KK\pi^\pm)$ mass-difference distribution. Charged conjugates are included. The darker shaded region is the events excess used in the estimation of signal significance. The lighter shaded region is the event mixed combinatoric background described in the text. The inset shows the difference of the two with a Gaussian fit to the signal

The Poisson fluctuation probability for this excess is 3×10^{-7} including the uncertainty in the background. A conservative estimate of the fluctuation probability anywhere in the search region (up to 2900 MeV/c^2) is 6×10^{-6}.

The decay $D^+_{sJ}(2632) \to D^0 K^+$ is kinematically allowed. After the $D^+_{sJ}(2632) \to D^+_s$ the η signal had been found, this second decay mode was searched for as confirmation. The D^0 sample was the Σ^-- induced $D^0 \to K^-\pi^+$ subset of the sample used in the SELEX measurement of the D^0 lifetime [1].

The results are shown in Fig. 7a, where both the known $D^+_{sJ}(2573)$ state and another peak above the $D^+_{sJ}(2573)$ are clearly seen. Each peak was fit with a Breit-Wigner convoluted with a fixed width Gaussian plus a constant background term (as suggested from the wrong-sign data discussed below). The Gaussian resolution was set to the simulation value of 4.9 MeV/c^2. The mass difference and width of the $D^+_{sJ}(2573)$ returned by the fit, $\Delta M = 705.4 \pm 4.3$ MeV/c^2 and $\Gamma = 14^{+9}_{-6}$ MeV/c^2, respectively, agree well with the PDG values of $\Delta M = 707.9 \pm 1.5$ MeV/c^2 and $\Gamma = 15^{+5}_{-4}$ MeV/c^2. The fitted mass difference of the second Breit-Wigner is 767.0 ± 2.0 MeV/c^2, leading to a mass for the new peak of 2631.5 ± 2.0 MeV/c^2. The fitted yield is 13.2 ± 4.9 events. The signal spread is consistent with the Gaussian resolution, even when plotted in 2.5 MeV/c^2 bins, limiting the possible natural width. For the Breit-Wigner fit, a limit for the width of < 17 MeV/c^2 at 90% confidence level was found. This signal has a significance of 5.3σ in a ± 15 MeV/c^2 interval. The mass difference between this signal and the one seen in the $D^+_s\,\eta$ mode is 3.9 ± 3.8 MeV/c^2, statistically consistent with being the same mass. The combined measurement of the mass of this state in the studied decay modes is 2632.5 ± 1.7 MeV/c^2. Unlike the D_s case, the D^0K^+ decay contributes a small fraction to the SELEX D^0 sample.

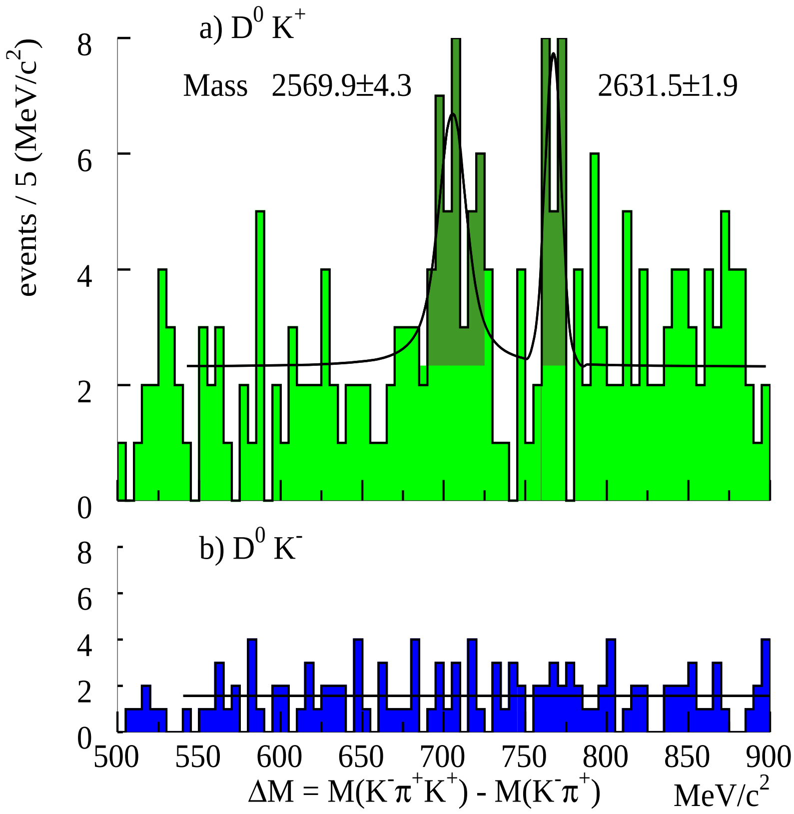

Fig. 7. (a) $D_s(2632)\to D^0K^+$ mass-difference distribution. Charged conjugates are included. The shaded regions are the events excesses used in the estimation of signal significances. (b) Wrong-sign background D^0K^- events, as described in the text

The combinatorial background will be equally likely to produce a D^0K^- combination (wrong-sign kaon) as a D^0K^+. The wrong-sign combinations are shown in Fig. 7b. There is no structure in these data which fit well to a constant background. Therefore, it may be concluded that the peak at 2631.5 MeV/c^2 is real and confirms the observation in the $D_s^+\eta$ mode.

The relative branching ratio $\Gamma(D^0K^+)/\Gamma(D_s^+\eta)$ was estimated to be 0.14 ± 0.06. The observed $D_{sJ}(2632)$ state is very narrow, consistent with a width due only to the resolution in the D^0K^+ decay mode. The mechanism that keeps this state narrow is unclear. The D^0K^+ channel is well above the hreshold, with a Q value ~275 MeV. The branching ratios for this state are also unusual. The $D_s^+\eta$ decay rate dominates the D^0K^+ rate by a factor of ~7 despite having half the phase space.

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