Pentaquark Searches at CDF

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Abstract

Experimental results of a search for the $\Xi^{3/2}/2(1860)$ cascade pentaquark state in data collected with the CDF 2 Detector in Run II at the Tevatron are presented. No evidence for these states in the neutral $\Xi^{-} \pi^{+}$ and doubly charged $\Xi^{-} \pi^{-}$ modes has been found. Preliminary upper limits on yields at 1862 MeV/c² relative to the well established resonance $\Xi^{*}(1530)^{0}$ are presented.

1 Introduction

Evidence for an exotic pentaquark state $\Theta^{+}(1540)$ with strangeness $S = +1$ has been claimed by a number of experimental groups. Enhancements with a significance of 4.4 to 7.0 standard deviations have been observed in the invariant mass of $K^{+}N$ in photoproduction [1] and in $pK_{0}^{0}$ [2]. The signals seen have been assigned to a $\Theta^{+}(1540)$ state. These results have inspired a search for other exotic baryon states. The NA49 Collaboration has reported [3] the observation of a strangeness $S = -2$, isospin $I = 3/2$ state $\Xi_{3/2}^{-} \rightarrow \Xi^{-} \pi^{-}$. An indication of a neutral mode in $M(\Xi^{-} \pi^{+})$ has been demonstrated [3] as well. Recently the H1 Collaboration at HERA has published [4] an observation of a narrow anti-charmed baryon state in the mode $D^{*+}\bar{p}$ at $\sim 3099$ MeV/c² and interpreted this as a heavy pentaquark $\Theta_{c}^{0}$.

The pentaquark state $\Theta^{+}$, according to the chiral soliton model [5], is considered as a bound state of five quarks. Experimental evidence for pentaquark $\Theta^{+}$ suggested the existence of other pentaquark partners classified within the antidecuplet $10$ representation [5] or the $10_f \oplus 8_f$ multiplet as predicted by the constituent quark model approach in [5].

The experimental status of pentaquark baryons includes some controversy. The signal of $\Theta^{+}$ claimed by [1, 2] is not confirmed by [7]. The cascade pentaquark claimed by [3] has not been seen by [8]. Negative results on both $\Theta^{+}$ and $\Xi_{3/2}^{3/2}$ have been reported by large statistics experiments [9]. These experiments exploit their excellent mass resolution and large data samples to calibrate the mass spectra of interest by well established states like $\Lambda(1520) \rightarrow pK^{-}$ and $\Lambda_{c}^{+} \rightarrow pK_{s}^{0}$ (for $\Theta^{+}$ searches) and $\Xi^{*}(1530)^{0} \rightarrow \Xi^{-} \pi^{+}$ (for $\Xi_{3/2}^{3/2}$ searches).

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Recently the CDF Collaboration undertook a comprehensive search for several pentaquark states using its Run II 220 pb$^{-1}$ of data taken with the upgraded CDF 2 Detector. We present here the particular search for the cascade pentaquark $\Xi_{3/2}^-$ through its modes $\Xi_{3/2}^0 \rightarrow \Xi^- \pi^+$ and $\Xi_{3/2}^- \rightarrow \Xi^- \pi^-$, both of which involve the doubly strange cascade baryon $\Xi^-$ in the final state. The analysis is based on two data samples. The first one was collected by a trigger selecting events with at least two tracks of opposite charge each, having a momentum above 2.0 GeV/c and an impact parameter measured by the CDF silicon detector to be larger than 100 $\mu$m. The total momentum of both tracks was required to be larger than 5.5 GeV/c. This “two displaced track trigger” sample is enriched by events with heavy quarks decaying via hadronic modes. A complementary dataset was taken with a trigger requiring an inclusive jet of transverse energy $E_T > 20$ GeV.

**2 Cascades in the CDF 2 Detector**

The final state cascade baryon $\Xi^- \rightarrow \Lambda^0 \pi^-$ decays almost 100% of time into $\Lambda^0 \pi^-$, with a subsequent decay of the $\Lambda^0$. Since the days of bubble chamber experiments this spectacular mode has been identified and reconstructed as a single track vertex (we call it here VERTEX_1) formed by a kinked track, presumably the $\pi^-$, followed in the fiducial volume by another, $V^0$ vertex (VERTEX_2), presumably the $\Lambda^0$ decaying to $p\pi^-$, as sketched at Fig.1. In our analysis VERTEX_2 was subjected to a 3-dimensional fit. Then the three tracks $p\pi^-$ and $\pi^+$, $\pi^-$ were fitted to a common 3-dimensional vertex with the constraint that $M(p\pi^-) = M_{\Lambda^0}^{PDG}$ and that VERTEX_2 points back to VERTEX_1, see also Fig.1.

![Figure 1: Sketch of the cascade decay topology.](image1)

The resulting invariant mass spectrum of cascade candidates $M(\Xi^- \rightarrow \Lambda^0 \pi^-)$ is shown on Fig.2. The clear signal at the $\Xi^-$ mass is seen on top of a large combinatorial background.

![Figure 2: The invariant mass spectrum of $M(\Lambda^0 \pi^-)$ after vertex fits described above. The cascade signal is present with a large combinatorial background.](image2)

The long lifetime of $\Xi^-$ hyperons ($c\tau=4.91$ cm) permits reconstruction of their tracks from hits in the CDF silicon tracker (SVX II). A novel technique developed by CDF uses the vertex position and momentum of $\Xi^-\pi^-$ pairs to reconstruct $\Xi^-$ tracks.

$1$Unless otherwise stated all references to the specific charge combination imply the charge conjugate combination as well.
a cascade hyperon fitted in the CDF outer tracker to seed the hyperon tracking in SVX II. This procedure results in a substantial background reduction and improved vertex and impact parameter resolution of the $\Xi^-$, see Fig. 3. The overall relative efficiency of the hyperon reconstruction with SVX II hits is $\sim 40\%$. The yields of cascades in the CDF 2 Detector are larger by a factor of $\sim 20$ than the ones found by the NA49 experiment [3].

![Figure 3: The invariant mass spectrum of $\Xi^-$ hyperons which have tracks successfully reconstructed in the silicon tracker. A cut on impact parameter $d_0(\Xi) < 150 \, \mu m$ was applied, selecting hyperons produced promptly in the primary vertex region. The very clean signal based on the data sample of integrated $L$=220 pb$^{-1}$ taken by the two displaced track trigger contains $\sim$36000 events. The analogous signal (not shown here) for the inclusive jet $E_T>$20.0 GeV dataset of the same $L$ contains $\sim$4870 events.](image)

3 Pentaquarks in the $\Xi^-\pi^+$ and $\Xi^-\pi^-$ Decay Modes

The hyperon tracks reconstructed in SVX II with mass $M(\Xi) \in M_{PDG} \pm 10$ MeV/c$^2$ (see Fig. 3) were combined with all remaining tracks with $P_T > 400$ MeV/c and 3 or more hits in the SVX II tracker. Then the track pairs $\Xi^-\pi^+$-$\pi^-$ were subjected to a vertex fit constrained by the requirement for the secondary vertex to point to the primary one. The invariant mass spectra $M(\Xi^-\pi^+\pi^-)$ are shown in Fig. 4 and 5.

![Figure 4: The invariant mass spectrum for $\Xi^-\pi^+$ whose hyperons have tracks successfully reconstructed in the silicon tracker. The two displaced track trigger data sample of $L$=220 pb$^{-1}$ is used. The fit to a Breit-Wigner convoluted with a Gaussian finds 2182$\pm$92 events in the peak for $\Xi^*(1530)^0 \rightarrow \Xi^-\pi^+$. The peak is used as a gauge signal for pentaquark searches. The similar spectrum (not shown here) for the inclusive jet $E_T>$20 GeV sample yields 387$\pm$34 events for $\Xi^*(1530)^0$. The pentaquark signal region at 1862 MeV/c$^2$ is fitted with a Gaussian of a fixed width $\sigma$=8 MeV/c$^2$ predicted by Monte-Carlo simulation.](image)

![Figure 5: The invariant mass spectrum for $\Xi^-\pi^-$ whose hyperons have tracks successfully reconstructed in the silicon tracker. The two displaced track trigger data sample of $L$=220 pb$^{-1}$ is used. The spectrum is fitted by a polynomial background shaped by a square-root threshold function. The NA49 signal region at $M(\Xi^-\pi^-)$ = 1862 MeV/c$^2$ is fitted with a Gaussian of fixed width $\sigma$=8 MeV/c$^2$. A similar spectrum (not shown here) is observed for the inclusive jet $E_T>$20 GeV sample.](image)
The spectra $M(\Xi^-\pi^+)$ (Fig. 4) and $M(\Xi^-\pi^-)$ (Fig. 5) corresponding to neutral and doubly charged cascade pentaquark modes do not reveal any enhancement around $M=1862$ MeV/c$^2$. Similar results have been obtained with the inclusive jet $E_T>20$ GeV sample. We have set upper limits on the production of pentaquarks decaying via both modes. These are shown in a Table 1 below.

| Mode | $\sigma\cdot Br(\Xi^-\pi^+)/\sigma\cdot Br(\Xi^*(1530)^0)$ | $\sigma\cdot Br(\Xi^-\pi^-)/\sigma\cdot Br(\Xi^*(1530)^0)$ | combined statistics |
|------|---------------------------------|---------------------------------|-------------------|
| Two Displaced Track Trigger Sample | 0.06 | 0.07 | 0.07 |
| | 0.03 | 0.04 | 0.08 |
| Inclusive Jet $E_T>20$ GeV Sample | 0.06 | 0.08 | 0.07 |
| | 0.07 | 0.09 | 0.11 |
| combined statistics | 0.07 | 0.08 | 0.09 |

Table 1: Upper limits set for a $\Xi_{3/2}^0$ and $\Xi_{3/2}^-$ pentaquark states. The yields were calculated relative to the calibrating signal of $\Xi^*(1530)^0$ seen in both data samples.

4 Summary

The CDF Collaboration conducted a search for doubly strange $S=-2$ pentaquark states in the $\Xi^-\pi^+$ and $\Xi^-\pi^-$ decay modes. The signals of the basic hyperon $\Xi^-$ state comprised $\sim 36000$ events in the two displaced trigger dataset and $\sim 4900$ events in the inclusive jet $E_T>20$ GeV dataset. The well established resonance $\Xi^*(1530)^0 \rightarrow \Xi^-\pi^+$ was used as a calibrating signal and yielded $2182\pm 92$ events from the two displaced trigger sample and $387\pm 34$ events from the inclusive jet $E_T>20$ GeV sample. No evidence of exotic baryon states produced in CDF Detector at Tevatron has been found. Upper limits on production of states in the mass range of $\sim 1862$ MeV/c$^2$ have been set. CDF Collaboration is pursuing a vigorous program of searches for possible pentaquark production at the Tevatron.

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