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Search for the $\Phi(1860)$ Pentaquark at COMPASS

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Abstract. Narrow $\Xi^-\pi^\pm$ and $\bar{\Xi}^+\pi^\pm$ resonances produced by quasi-real photons have been searched for by the COMPASS experiment at CERN. The study was stimulated by the recent observation of an exotic baryonic state decaying into $\Xi^-\pi^-$, at a mass of 1862 MeV, interpreted as a pentaquark. While the ordinary hyperon states $\Xi(1530)^0$ and $\bar{\Xi}(1530)^0$ are clearly seen, no exotic baryon is observed in the data taken in 2002 and 2003.

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1 Introduction

Since many years hadron spectroscopy is concerned with the search for new hadrons and their subsequent spectroscopy. Particularly interesting are systems with a flavour content different from the usual baryonic qqq and $\bar{q}\bar{q}\bar{q}$ or the mesonic $q\bar{q}$ structure. In the last two years evidence has been reported on new states interpreted as pentaquarks with a quark content of $qqqq\bar{q}$. The observation of a state at about 1540 MeV named Θ^+ [1,2] has been reported by a large number of experiments but has also been refuted by others, where the positive observations stem mostly from photoproduction (virtual or real).

Another candidate for an exotic pentaquark state named $\Phi(1860)$ (originally called Ξ (1860)) has only been reported by a single experiment (NA49) using a high-energy proton beam [3]. Subsequent Φ searches performed with different beams and reactions, however, were to no avail [4–12]. Searches for the $\Phi(1860)$ in photoproduction experiments at a photon virtuality $Q^2 > 1$ GeV^2 were performed by the ZEUS [12] and HERMES Collaborations [10]. The statistics in these experiments—judged by the number of observed Ξ^- events—was however similar or even below the one of the NA49 experiment. A high-statistics search using high-energy real photons ($E_\gamma \geq 50$ GeV) was conducted by the FOCUS Collaboration [8].

The COMPASS experiment at CERN, set up to study the nucleon structure using high-energy muon scattering, has also collected a large sample of doubly strange Ξ^- baryons in the final state from quasi-real photoproduction. This paper describes the search for the doubly strange pentaquark system (and its antiparticle), produced inclusively in muon-nucleon interactions and decaying according to $\Phi(1860)^{--} \to \Xi^-\pi^- \to \Lambda\pi^-\pi^- \to p\pi^-\pi^-\pi^-$. The data are dominated by quasi-real photoproduction, $Q^2 \ll 1$ GeV^2. We compare the results to the observation of the well-known state $\Xi(1530)^0$ which has the same decay chain except for the charge of the pion in the first decay, $\Xi(1530)^0 \to \Xi^-\pi^+$.

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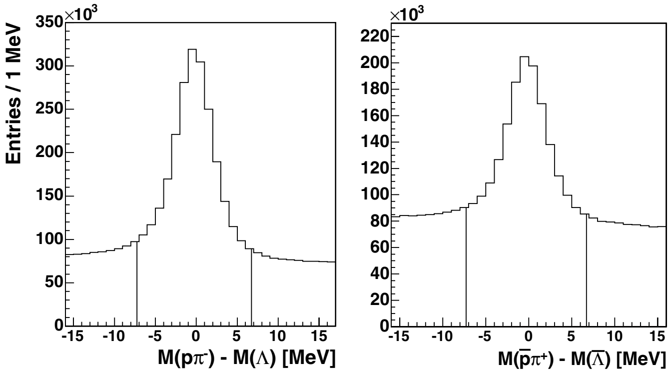

Fig. 1. The $p\pi^-$ $(\overline{p}\pi^+)$ invariant mass spectra with respect to the nominal Λ mass. The vertical lines show the mass cut ($\pm3\sigma$) selecting events for further analysis (cf. Sect. 3.2)

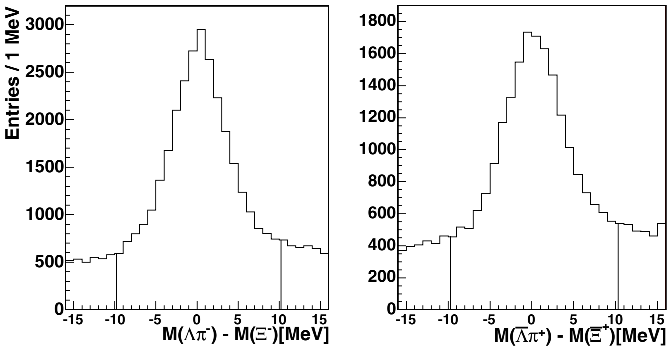

Fig. 2. The $\Lambda\pi^-$ $(\overline{\Lambda}\pi^+)$ invariant mass spectra relative to the nominal Ξ^- mass. The vertical lines show the mass cut ($\pm3\sigma$) selecting events for further analysis

2 The experimental setup

COMPASS is a fixed-target experiment at the CERN Super Proton Synchrotron (SPS) using high-energy muon and hadron beams. The apparatus is described in detail in [13, 14]. The data for this analysis have been taken in the years 2002 and 2003 with a 160 GeV polarised muon beam hitting a solid-state ^{6}LiD target, polarised longitudinally (80% of the beam time) and transversely (20%) with respect to the beam direction. The direction of polarisation was flipped regularly, such that any possible polarisation dependence was averaged out in this analysis.

The beam tracks were reconstructed in a beam telescope consisting of silicon microstrip and scintillating fibre detectors. The interaction products are observed in a forward magnetic spectrometer, with two stages for low and high momenta, respectively, each equipped with high-resolution tracking detectors and electromagnetic and hadronic calorimetry. Information from the RICH detector installed in the first stage of the spectrometer was not used in this analysis. Muons were identified downstream of iron and concrete walls.

3 Analysis

Data reduction and analysis is described in detail in [15]. The initial data set consists of $1.8{\cdot}10^9$ raw events. The tracks and momenta of charged particles were reconstructed in both spectrometer stages. Using the tracks of the incoming and scattered muon together with other outgoing charged particle tracks, the primary interaction point was determined and was required to be located within the target volume. Events without a reconstructed primary interaction point were discarded. Long-living strange particles were detected by their decay, appearing as a secondary vertex downstream of the primary interaction point.

3.1 The Λ and $\overline{\Lambda}$ selection

The Λ decay into p and π^-appears as a secondary vertex with two outgoing particles of opposite charge. From their four-momenta the invariant mass of the Λ candidate was reconstructed. In order to reduce the background under the signal, the Λ decay point was required to be located downstream of the target volume. Secondary vertices caused by photon conversion, $\gamma \to e^+e^-$, were removed by requiring $|\cos\theta^*| < 0.9$, with θ^* being the c.m.s. emission-angle of the negative particle with respect to the flight direction of the Λ. For the reconstruction of $\overline{\Lambda}$, the mass assignment of the two charged particles was inverted. The resulting $p\pi^-$ $(\overline{p}\pi^+)$ invariant mass spectra are presented in Fig. 1. They were fitted by the sum of a Gaussian for the Λ signal and a polynomial parametrising the background. The total numbers of Λ $(\overline{\Lambda})$ particles are given in Table 1.

3.2 The Ξ^- and $\overline{\Xi}^+$ selection

The Λ candidates in the mass range marked in Fig. 1 were selected for the further analysis with the nominal Λ mass assigned to all candidates. The closest distance of approach (CDA) of the Λ line of flight to all other tracks, corresponding to negatively charged particles and not connected to the primary vertex, was calculated. For the CDA smaller than 0.8 cm, a possible Ξ^- decay point was reconstructed, and only combinations with this decay point downstream of the primary interaction point and upstream of the Λ decay point were retained. These cuts have been tuned to minimise the background without reducing the Ξ^- signal. In Fig. 2 the $\Lambda\pi^-$ $(\overline{\Lambda}\pi^+)$ invariant mass spectra with respect to the Ξ^- $(\overline{\Xi}^+)$ nominal mass are shown. The total numbers of Ξ^- and $\overline{\Xi}^+$ particles obtained by the fit procedure described for the $\Lambda(\overline{\Lambda})$ signals are given in Table 1.

3.3 The $\Xi\pi$ mass spectra

The $\Xi(1530)^0$ and $\overline{\Xi}(1530)^0$ resonances are so short-living that their decay point coincides with the primary interac-

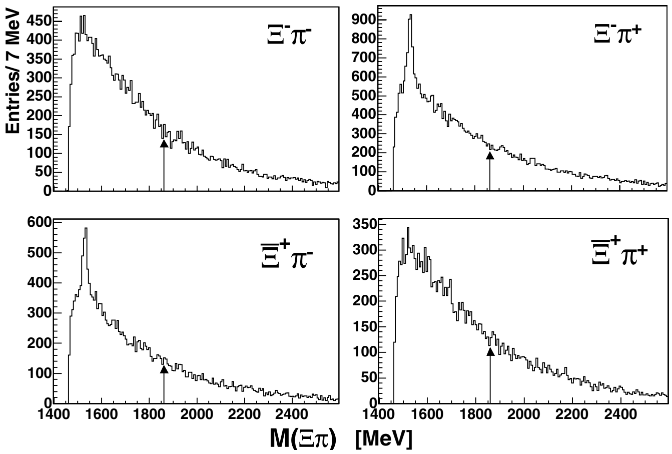

Fig. 3. $\Xi\pi$ invariant mass spectra of the four possible charge combinations. Arrows indicate the position of the $\Phi(1860)$ signal [3]

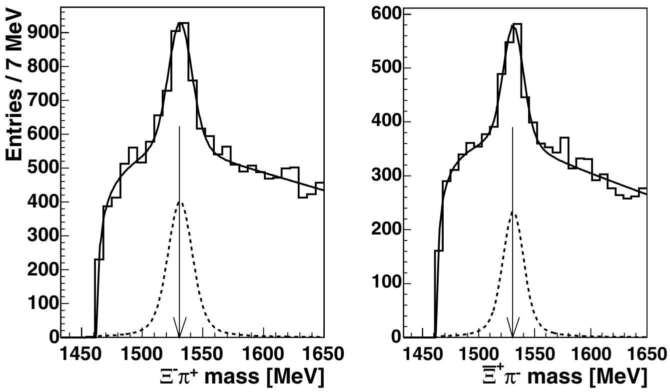

Fig. 4. The $\Xi^-\pi^+$ ($\overline{\Xi}^+\pi^-$) invariant mass spectra around 1530 MeV. Solid lines mark the fit results as described in the text, dashed lines mark the fitted signal shape only. Arrows indicate the $\Xi(1530)^0$ mass

tion point. All charged particles whose tracks point back to the primary interaction point, and which were not used in the earlier steps of the reconstruction or identified as muons, were assumed to be pions. They were combined with the Ξ^- or $\overline{\Xi}^+$ candidates in the mass range indicated in Fig. 2. The effective masses of the combinations were calculated assuming the nominal masses for the $\Xi^-(\overline{\Xi}^+)$. The mass spectra for the four charge combinations are shown in Fig. 3. The $\Xi(1530)^0$ ($\overline{\Xi}(1530)^0$) resonance signal is clearly visible. The invariant mass distributions around their nominal mass are presented enlarged in Fig. 4. The numbers of $\Xi(1530)^0$ and $\overline{\Xi}(1530)^0$ are given in Table 1. They were obtained by fits using a Voigtian (a convolution of a Breit–Wigner resonance curve and a Gaussian) for the signal and a background parametrised as $(m-m_0)^{p_1}\cdot\exp(-p_2\cdot m-p_3\cdot m^2)$.

The $\Xi(1530)^0$ ($\overline{\Xi}(1530)^0$) resonance has a natural width $\Gamma = 9.1$ MeV [1]. The observed widths of the $\Xi(1530)^0$ and $\overline{\Xi}(1530)^0$ signals in Fig. 4 are compatible

Table 1. Number of particles as obtained by fitting the mass spectra in Figs 1, 2 and 4. The errors take into account the uncertainty in the background parametrisation

	Yield of particles	Yield of antiparticles
$\Lambda/\overline{\Lambda}$	1 250 000±50 000	640 000±30 000
$\Xi^-/\overline{\Xi}^+$	18 000±900	10 600±600
$\Xi(1530)^0/\overline{\Xi}(1530)^0$	1 700±100	920±80

with the mass resolution of our spectrometer, $\sigma \approx 7$ MeV, expected from simulation. Assuming a similar width for the $\Phi(1860)$ signal, we determined upper limits for the signal of such a state.

The upper limits were obtained as follows: We estimated the expected background from a polynomial fit to the mass spectra of the like-sign pairs (cf. Fig. 3), excluding the region from 1825 MeV to 1895 MeV. We then investigated three intervals of 28 MeV width, staggered by 14 MeV, with the central interval centred at 1860 MeV. The numbers of entries in these intervals are denoted by n_1, n_2, n_3. With the estimated background for each interval, b_1, b_2, b_3, we determined the quantity $\max_{i=1,2,3}(3\sqrt{b_i}+\max(0,n_i-b_i))$ and thus deduced upper limits for a possible excess of events: 79 events for the $\Xi^-\pi^-$ and 89 events for the $\overline{\Xi}^+\pi^+$ final state at a confidence level of 99%. Also, no narrow peaks are visible around 1860 MeV in the spectra for the non-exotic unlike-sign pairs.

4 Discussion and conclusion

This negative result obtained in high-statistics quasi-real photoproduction is in line with other searches listed in Table 2.

A graphical compilation of all search results is shown in Fig. 5. Note that some data [5–8,12] have been shown at conferences only and are not yet published in journals and therefore should be considered as preliminary. The circles and squares in Fig. 5 give the observed numbers of Ξ^- and $\Xi(1530)^0$ particles, respectively. The triangle indicates the yield of $\Phi(1860)$ observed by the NA49 Collaboration [3]. The arrows show the upper limits reported by the various experiments. Note that some limits are at 95% confidence level while others—like the data presented in this work—are at 99% confidence level. Also, the widths of the examined mass windows vary as the experimental resolutions are different. Thus a direct comparison of the various experimental limits has to consider systematic relative shifts by a factor of the order of two. The observed $\Xi(1320)^-/\Xi(1530)^0$ yield ratio varies by at most a factor of 2.5 between the different experiments. Assuming that the relative detection efficiencies for the various resonances are similar in the various experiments and ignoring possible differences in the production mechanism of a pentaquark, one can estimate the expected yields of $\Phi(1860)$ pentaquarks by scaling the observed numbers of $\Xi(1320)^-$ with the $\Phi(1860)/\Xi(1320)^-$ ratio reported by NA49. The

Table 2. Summary of $\Phi(1860)$ searches in inclusive production. The energies given in column 3 refer to the beam energy in case of fixed-target experiments and to $\sqrt{s}$ in case of collider experiments. The x_F values were calculated assuming a nucleon target

Experiment	Initial state	Energy [GeV]	approx. x_F for Ξ^-	Yield of Ξ^-	$\Xi(1530)^0$	$\Phi(1860)^{--}$
COMPASS	$\mu^+ A$	$E_{\mu^+} = 160$	> 0	18000	1700	< 79
NA49[3]	pp	$E_p = 158$	$-0.25...0.25$	1640	150	36
ALEPH [4]	e^+e^-	$\sqrt{s} = m_{Z^0}$		3450	322	< 24
BaBar [5]	e^+e^-	$\sqrt{s} = m_{\Upsilon(4S)}$		$250000^\dagger$	$24000^\dagger$	< 133
CDF [6]	$p\bar{p}$	$\sqrt{s} = 1960$		35722	2182	< 63
E690 [7]	pp	$E_p = 800$		512850	70000	< 200
FOCUS [8]	γp	$E_\gamma \leq 300$		800000	59391	< 170
HERA-B [9]	pA	$E_p = 920$	≈ 0	12000	1400	< 56
HERMES [10]	e^-D	$E_e = 27.6$		450	35	< 5
WA89 [11]	Σ^-A	$E_{\Sigma^-} = 340$	> 0.1	676000	60000	< 760
ZEUS [12]	ep	$\sqrt{s} = 310$		1561	$192^\dagger$	not seen

† sum of Ξ and c.c. state.

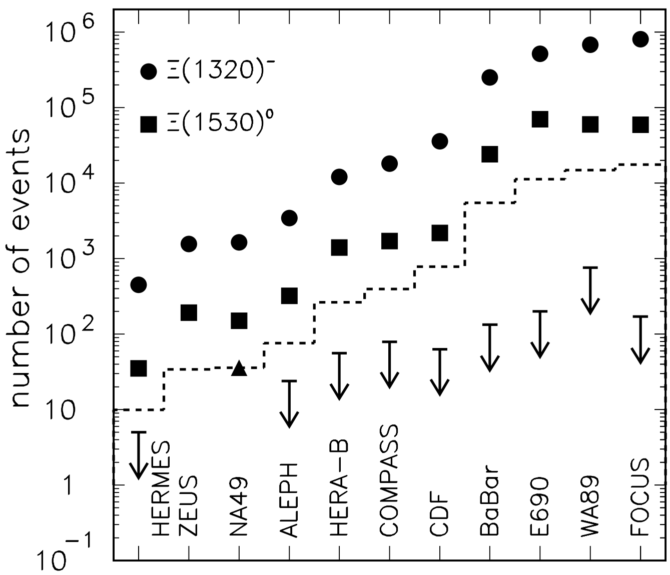

Fig. 5. Compilation of the data from Table 3.3. The dashed line shows the expected yield of $\Phi(1860)^{--}$ from [3] assuming the same $\Phi(1860)^{--}/\Xi(1320)^-$ event ratio in all experiments

result is shown by the dashed line in Fig. 5. It is obvious that the comparatively large $\Phi(1860)^{--}/\Xi(1320)^-$ production ratio reported in [3] is not supported by other experiments. A confirmation of the $\Phi(1860)$ existence is thus still missing.

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