COSY-TOF RESEARCH ON Θ^+ *

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Using the TOF detector at the COSY storage ring the hadronic reaction $pp \to \Sigma^+ K^0 p$ was measured exclusively at a beam momentum of 2.95 GeV/c. A narrow peak was observed in the invariant mass spectrum of the $K^0 p$ subsystem at $1530 \pm 5\,\mathrm{MeV}/c^2$ with a significance of 4–6 standard deviations, depending on background assumptions. The upper limit of 18 $\pm 4\,\mathrm{MeV}/c^2$ (FWHM) for its width is given by the experimental resolution. Since a resonance in this subsystem must have strangeness $S=+1$ we claim it to be the Θ^+ state for which very recently evidence was found in various experiments. To come to a final decision on the existence of the Θ^+ very recently COSY-TOF performed a measurement which will give results with strongly improved statistical accuracy.

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1. Introduction

As presently understood, QCD does not forbid the existence of states other than quark–antiquark and three-quark systems as long as they form color singlets. In numerous theoretical publications the possible existence of exotic systems including pentaquark states has been worked out based on specific assumptions and production scenarios also. One of the most cited publications concerning pentaquark states by Diakonov, Petrov and Polyakov [1] is based on the soliton model assuming an antidecuplet as third rotational excitation in a three flavor system. The corners of this antidecuplet are occupied by exotic pentaquark states with the lightest state having a mass of $\approx 1530\,\mathrm{MeV}/c^2$, strangeness $+1$, spin 1/2 and isospin 0. This state, originally known as Z^+, has more recently been renamed Θ^+. In this model

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the mass of the Θ^+ is fixed by the N^* resonance at $1710\,\mathrm{MeV}/c^2$, which is assumed to be a member of the antidecuplet. The most striking property of the Θ^+ resonance is the predicted narrow width of $\Gamma < 15\,\mathrm{MeV}/c^2$, which according to Ref. [1] is connected with a narrow width of the $1710\,\mathrm{MeV}/c^2$ N^* resonance of 50 MeV or less. With the predicted quark content for the Θ^+ of $uudd\bar{s}$ this pentaquark resonance is expected to decay into the channels K^+n and K^0p. The first report on the discovery of a narrow resonance in the expected mass region came from the LEPS Collaboration at SPring8 [2] where in the γK^- missing mass spectrum of the reaction $\gamma n \to K^+K^-n$ on ^{12}C a narrow resonance was observed at $1.54 \pm 0.01\,\mathrm{GeV}/c^2$ with an upper limit for the width of $\Gamma = 25\,\mathrm{MeV}/c^2$. In the meantime several other experiments have presented observations in the mass region between about 1525 and $1555\,\mathrm{MeV}/c^2$ [3–9].

In this contribution we report on the search for the Θ^+ resonance using the COSY-TOF experiment. Within the framework of the hyperon production program at COSY-TOF [10, 11] the reaction $pp \to \Sigma^+K^0p$ has been measured exclusively. Data were taken predominantly at a beam momentum of $p_{\mathrm{beam}} = 2.95\,\mathrm{GeV}/c$, corresponding to an excess energy of 126 MeV. This limits the invariant mass spectrum of the K^0p system between the threshold value of $1436\,\mathrm{MeV}/c^2$ and an upper value of about $1562\,\mathrm{MeV}/c^2$. Accordingly an optimal ratio between a possible resonance signal around $1530\,\mathrm{MeV}/c^2$ and the non resonant background is expected [12]. A deviation from a smooth invariant mass spectrum of the K^0p system was already observed in a first measurement performed in 2000, but the extracted event sample was too small for a definite statement [11]. To improve the statistical significance a second production run at the same beam momentum was performed in 2002.

2. Experimental setup and analysis

In the production runs in 2000 and 2002 reported the time-of-flight spectrometer COSY-TOF was used in its 3 m version [13]. The extracted proton beam ($\sim$ 1mm diameter) hits a liquid hydrogen target with a length of 4 mm. The geometrical reconstruction of the related tracks and vertices is mainly realized by the start detector system, a scheme of which is shown in Fig. 1 together with an event of the type $pp \to \Sigma^+K^0p$ with a subsequent decay of the K^0 as a K_{s} into a $\pi^+\pi^-$ pair and the delayed decay of the Σ^+ into a $n\pi^+$ pair. The events of interest are identified by these delayed decays. The reconstruction of the K^0_{s} and its decay vertex occurs via the tracks of its decay products $\pi^+\pi^-$ by two scintillating fiber hodoscopes. The decay kinematics and angular distributions allow a clear separation from the remaining background, which is dominated by the reaction $pp \to K^+\Lambda p$.

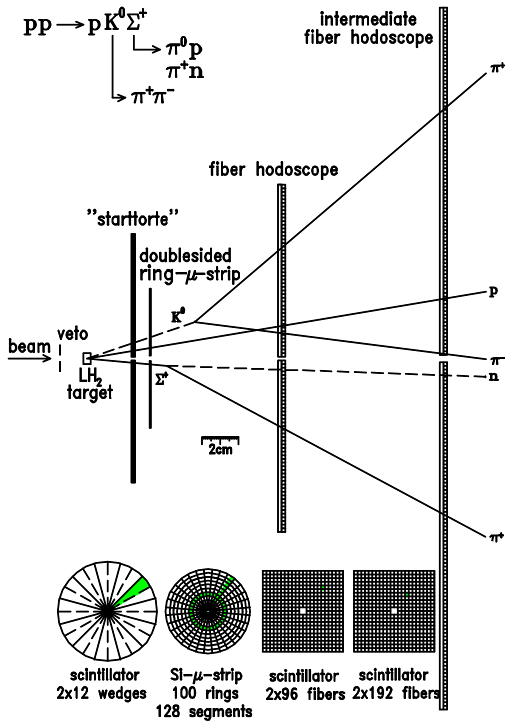

Fig. 1. Scheme of the Start detector system together with an event of the reaction $pp \to \Sigma^+ K^0 p$.

The Σ^+ hyperon together with its delayed decay into πN is characterized by a track with a kink and is detected via a double sided silicon micro-strip detector close to the target. That also means that in the actual situation there is a unique particle identification from the event pattern.

The momenta of the reconstructed particles are calculated directly from the extracted directions ("geometry spectrometer") using momentum and energy conservation. Since there are usually several possible geometrical combinations and hence kinematical solutions for each event, a missing mass analysis is applied for both the mass of the Σ^+ using the tracks of the primary reaction products and the mass of the K^0_s determined by using the information of the tracks of its decay products. This contains two over-constraints. To find the best solution, both masses are required to be best-fitted simultaneously. Events outside the phase space of the reactions of interest were rejected. Geometrical cuts on the tracks and decay vertices were used to suppress the background. By varying these cuts and performing Monte Carlo simulations in parallel it was carefully checked that the restrictions used do not influence the results concerning the observables of the reaction of interest.

Both measurements show clear mass distributions peaking at the related masses of the Σ^+ ("primary mass") and K^0 ("secondary mass"), respectively, and they are identical. A corresponding plot of the combined sample of the years 2000 and 2002 is shown in Fig. 2. To get very clean samples for further investigations of the reaction of interest cuts on the resulting mass peaks have been applied. This is demonstrated in Fig. 3 where again the spectra of the two runs are summed up. In the upper part the cuts are indicated which lead to the spectra in the lower part. Finally, these cuts shown on the K^0 mass and the Σ^+ mass lead to two samples of 421 and 518 events for the two runs, respectively, and accordingly 939 events for the total sample which is used for further analyses.

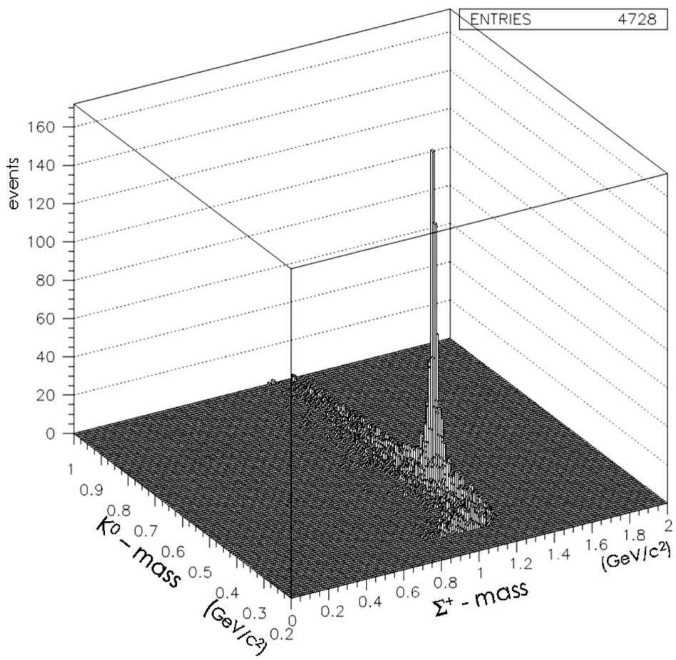

Fig. 2. Plot of the reconstructed Σ^+ mass *versus* the $K^0_{\rm s}$ mass for the combined sample.

Extensive Monte Carlo simulations were performed to control and to optimize the analysis chain. Moreover, they were used to deduce the resolution in the various observables. The resolution of the Σ^+ and the K^0 mass of the simulated data is in quantitative agreement with the real data. For the K^0p invariant mass which is relevant for the search for a possible narrow state an overall mass resolution of $18 \pm 3\,\mathrm{MeV}/c^2$ (FWHM) has been deduced from the simulations.

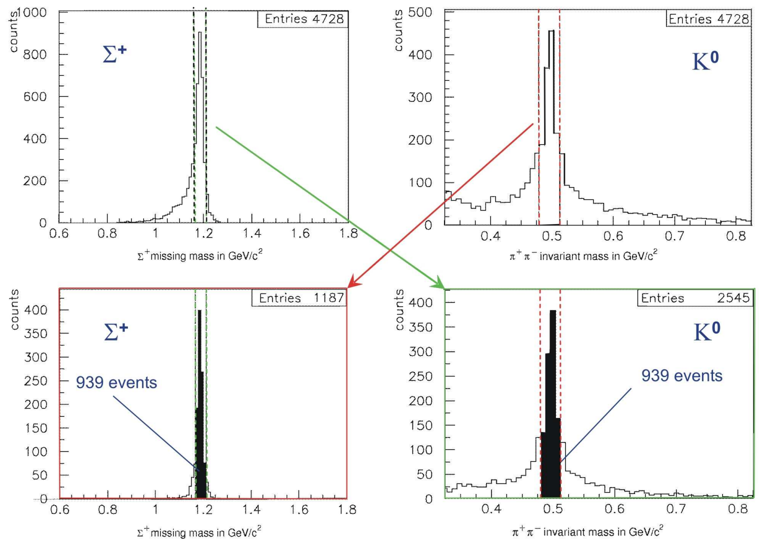

Fig. 3. Reconstructed masses of Σ^+ and K_s^0 for the summed data (years 2000 and 2002). In the upper spectra the cuts are indicated which lead to the lower spectra. For further explanation see text.

3. Results

To search for a possible resonance the data of the two runs have been investigated both separately and in sum. In Fig. 4 the invariant mass spectra of the K^0p system are shown. They cover the full kinematical range corresponding to the excitation energy of 126 MeV. The shape of all three spectra is very similar. Within statistical fluctuations the spectra from the 2000 (top figure) and 2002 (middle) runs are identical. There is a deviation from a smooth distribution in the spectra of both runs and in the spectrum of the summed sample (bottom) around 1.53 GeV/c^2 (indicated by the arrow in the summed spectrum). Assuming a smooth background as obtained by a polynomical fit excluding the region between 1.51 GeV/c^2 and 1.54 GeV/c^2 (dashed curves in Fig. 4) the significance of the signal can be deduced. Three different expressions for the significance of the peak in the summed spectrum (Fig. 4 bottom) have been considered. The first alternative is the naive estimation $N_\mathrm{S}/\sqrt{N_\mathrm{B}}$ where N_S is the number of events corresponding to the signal on top of the fitted background and N_B is the number of events corresponding to the background in the chosen area. In the present case this leads to a significance of $5.9\,\sigma$ on the basis of an intervall of $\pm$ 1.5 σ around the peak value of 1530 MeV/c^2. This estimator, however, neglects the statistical uncertainty of the background and, therefore, usually overestimates the significance of the peak. A more conservative method which is reliable

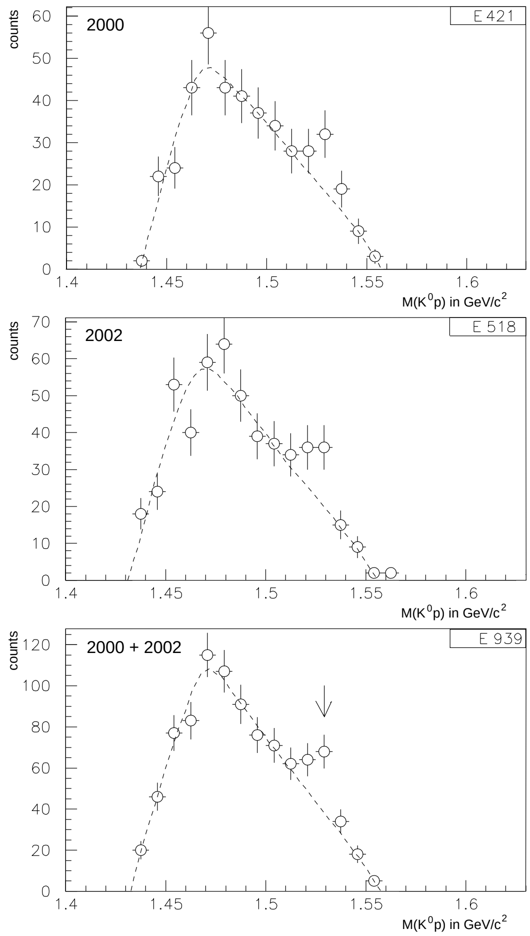

Fig. 4. Invariant mass spectrum of the K^0p subsystem obtained from the 2000 data (upper part), the 2002 data (middle part) and the sum of both together (lower part) with a fitted background.

for cases where the background is smooth and well fixed in its shape uses the estimator $N_{\rm S}/\sqrt{N_{\rm S}+N_{\rm B}}$. In our case this method leads to a significance of 4.7σ. The third expression taking into account the full uncertainty of a statistically independent background which should tentatively underestimate the significance of the signal is given by $N_{\rm S}/\sqrt{(N_{\rm S}+N_{\rm B})+N_{\rm B}}$. This leads to a value of 3.7σ.

Because the measurement presented and the event sample extracted from it cover the full phace space of the reaction products, an investigation of the corresponding Dalitz plot is possible. In Fig. 5 the Dalitz plot based on the 939 events of the summed spectrum of Fig. 4 is shown. The peak around

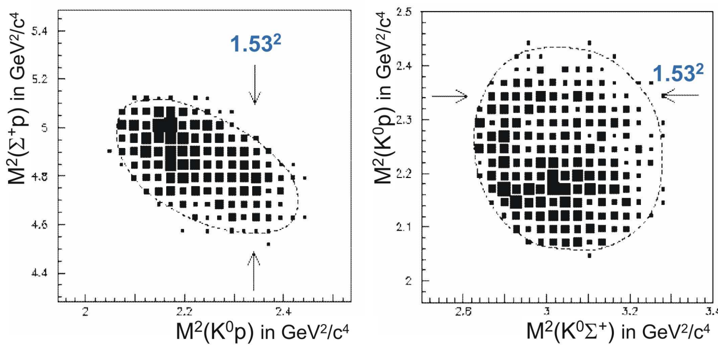

Fig. 5. Dalitz plots for the full sample at a beam momentum of 2.95 GeV/c. The dotted lines show the phase space limits. The arrows correspond to a mass for the K^0p system of 1.53 MeV/c^2.

1.53 GeV/c^2 identified in the K^0p invariant mass spectrum should show up in the ideal case as a band in the Dalitz plot at the corresponding squared mass around 2.34 GeV^2/c^4 as indicated by the arrows in both distributions. As expected due to the low number of events there is only a slight indication for a band. But more importantly in both distributions there is no indication of an artefact which could give rise to a faked signal in the K^0p mass spectrum. It should also be recognized that according to the low excess energy of 126 MeV the influence of a possible excitation of Σ^*-resonances is excluded. To correct for the efficiency of the detector and the analysis, Monte Carlo simulations were used. The correction function is very smooth giving some enhancement at the edges of the phase space. In Fig. 6 the efficiency-corrected K^0p invariant mass spectrum corresponding to the total sample is shown. In comparison to the uncorrected spectrum shown in Fig. 4 there is no major difference. Again there is a significant peak around 1.53 GeV/c^2 on top of a smooth background. For a more quantitative analysis a polynomial fit on the background and a Gaussian for the remaining signal are used (Fig. 6 dotted lines). This yields a peak value of 1530 $\pm$ 5 MeV/c^2. The deduced width of 18 $\pm$ 4 MeV/c^2 (FWHM) is in agreement with the value of the Monte Carlo analysis and accordingly only an upper limit for the physical width of the observed peak. Since a resonance in this subsystem must have strangeness $S = +1$ we claim it to be the Θ^+ state. This is the first evidence on the Θ^+ resonance from an elementary hadron–hadron reaction. The cross section of the observed peak around 1530 MeV/c^2 has been estimated by comparing with the measured total cross section of the reaction. The normalisation was deduced by comparison with the elastic pp scattering which was measured simultaneously. For the observed peak at 1530 MeV/c^2 we deduce a cross section of 0.4 $\pm$ 0.1 (stat) $\pm$0.1 (sys) μb.

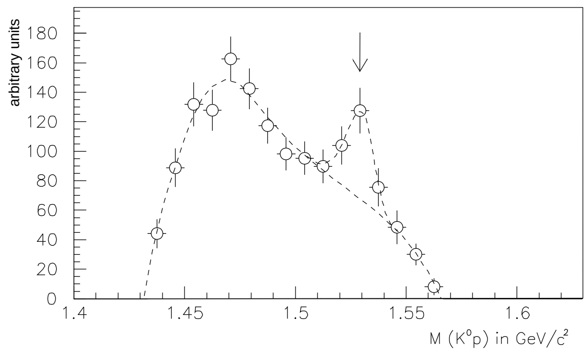

Fig. 6. Efficiency corrected invariant mass spectrum of the K^0p subsystem for the full sample.

This value is in rough agreement with theoretical estimations by Polyakov *et al.* [12] and Liu and Ko [14], where a total cross section in the order of 0.1–1μb is predicted for the Θ^+ production in the threshold region in pp and pn induced reactions. These results of the COSY-TOF experiment are published in [15].

4. Improved measurement

There is now evidence from several experiments on a narrow state in the systems K^0p and K^+n, in the mass region between about 1525 and 1555 MeV/c^2. However, this evidence comes from signals which contain about 50 events or even less. This means that none of these experiments has the statistical accuracy which is necessary to pin down the result with a precision required for a final proof of the existence. Moreover, especially in the high energy regime there are experiments which do not see a signal. For an experimental overview see [16].

To get a final decision on the existence of the Θ^+ it is absolutely necessary to produce data samples with much higher statistical accuracy. In this respect COSY-TOF had a run in October/November 2004. Again the reaction $pp \to \Sigma^+ K^0 p$ was studied. To separate the region of interest around 1.53 GeV/c more from the kinematical limit of the K^0p mass spectrum a slightly higher beam momentum of $p_{\rm beam} = 3.05$ GeV/c was chosen. To improve the reconstruction efficiency there was an experimental upgrade concerning the fiber hodoscopes. The first two layer hodoscope was replaced by a three layer hodoscope with larger size. A photograph of the new one is shown in Fig. 7. The inner part (full line) corresponding to the size of the old hodoscope is now covered by three layers. The outer part (dashed line) with twice the size consists of two layers. From Monte Carlo simulations an increase of the reconstruction efficiency of more than 50%

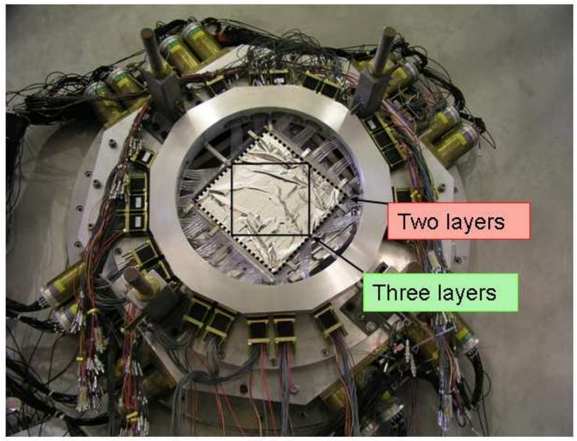

Fig. 7. New fiber hodoscope. The inner part (full line) is covered by three layers. The outer part (dashed line) consists of two layers.

is expected for the reaction channel of interest. Together with the higher luminosity the expected overall gain for the number of events for the new measurement compared to the published data is at least a factor of five. This can be estimated from the reaction channel $pp \rightarrow \Lambda K^+ p$ which has the same trigger condition and a similar event pattern with a delayed decay and which was measured simultaneously. This channel has a higher reconstruction efficiency in our detector. In Fig. 8 the spectrum of the reconstructed

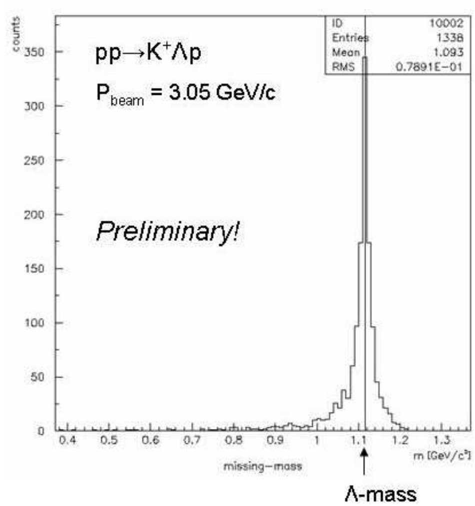

Fig. 8. Missing mass spectrum of the neutral particle in the reaction $pp \rightarrow \Lambda K^+ p$ at $p_{\mathrm{beam}} = 3.05\,\mathrm{GeV}/c$ from a subsample corresponding to a four hours run.

Λ missing mass is shown for a four hours run. The low background gives additional indication concerning the cleanliness of the expected data of the $pp \to \Sigma^+ K^0 p$ channel.

To control all steps of the analysis chain in an optimal way, independent analyses at several institutes are performed. These analyses are based on a common calibration database but use different codes which are partly emphasising different aspects of the detector. Moreover, improved Monte Carlo simulations will be used including background modelling.

5. Outlook

For a further search on the Θ^+ in the $K^0 p$ system we will investigate the reaction channel $pn(p) \to \Lambda K^0 p(p)$ using a liquid deuterium target. For this reaction our apparatus is optimally suited. In Fig. 9 a schematic of the start detector is shown together with a Monte Carlo event. This reaction channel has a unique signature of two "V's" corresponding to the delayed decays of the Λ and the K_{s} into charged particles. Again the corresponding increase of charged tracks is used as trigger condition. In a test run the trigger was successfully used and first event candidates could be identified.

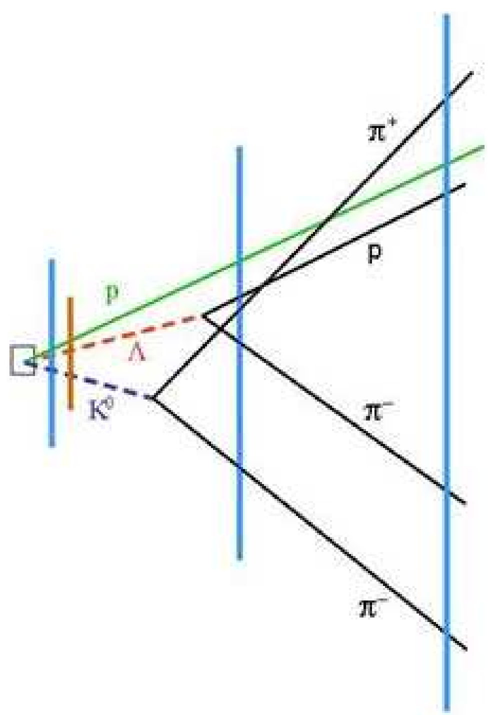

Fig. 9. Schematic of the start detector system together with a Monte Carlo event of the reaction $pn(p) \to \Lambda K^0 p(p)$.

Moreover, we started to investigate the reaction $pp \to \Lambda K^+ p$ to search for a possible double charged isospin partner of the Θ^+ in the subsystem K^+p. This can be done using data at various beam momenta between 2.75 and 3.30 GeV/c which were already taken.

A further point of interest is the investigation of the non-exotic partners in the antidecuplet. Here the investigation of N^* resonances in the region around 1700 MeV is of special interest. In our analysis of the reaction $pp \to \Lambda K^+ p$ we found clear evidence for contributions of N^* resonances. In the Dalitz plots corresponding to beam momenta above 3 GeV/c a strong resonances structure around 1710 MeV is seen. This is demonstrated in Fig. 10 where the Dalitz plot for preliminary data at a beam momentum of 3.3 GeV/c is shown together with the projection on the $K^+\Lambda$ subsystem. In the next step we want to analyse the Daltiz plots at various momenta to extract the widths of the contributing resonances. To disentangle the overlapping resonances we will also use a polarized beam which is available at COSY.

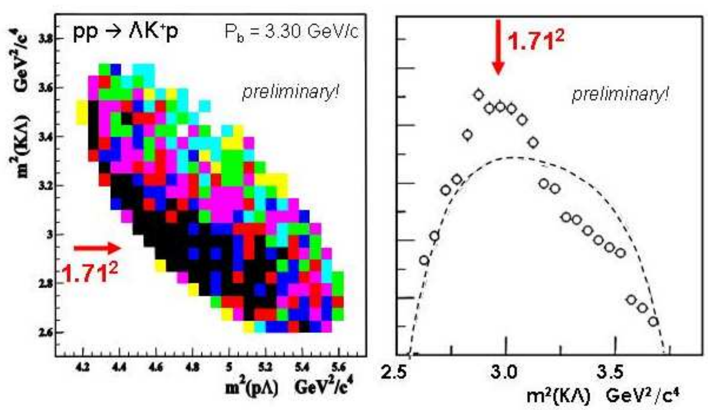

Fig. 10. Left-hand side: Dalitz plot of the reaction $pp \to \Lambda K^+ p$ at $p_{\text{beam}} = 3.3$ GeV/c. Right-hand side: Projection on the $K\Lambda$ subsystem together with phase space (dashed line).

In the case of confirmation of the Θ^+ by our ongoing analyses there are plans to measure the parity of this state [17]. For this a polarized beam will be used in combination with a polarized frozen spin target which was already successfully used in the experiment PS185 at LEAR [18].

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