Search for the Θ^+ pentaquark in the missing mass spectrum of the reaction $\gamma^* D \to \Lambda(1520)X$ at HERMES

Grigor Aslanyan *

September 11, 2005

Abstract

This report presents the analysis of the photoproduction reaction $\gamma^* D \to \Lambda(1520)X$ at HERMES. The polarized and unpolarized deuterium data of the years 1998, 1999 and 2000 were used. Most attention is paid to the reconstruction of the Λ and $\overline{\Lambda}$ from the proton and kaon. The missing mass technique allows us to determine the invariant mass spectrum of X and to look for Θ^+ production associated with the $\Lambda(1520)$. The statistics were too low to be conclusive.

1 Introduction

In the theory of strong interaction, quantum chromodynamics (QCD), hadronic states with baryon number 1 and strangeness +1 are not prohibited by any known law. In terms of quark structure this type of particles can only be built from a minimum of five quarks. It is impossible to construct them from two or three quarks, like all other hadrons so far observed.

Starting from the early stages of quark models, such type of states were proposed to exist. Experimental searches for these exotics (so called because they were previously unobserved) which, started in the early 70's, did not yield any significant success. The new trigger for experimenters was the work of Diakonov *et. al* [1] in 1997 when, based on a completely different approach than quark models, they predicted the existence of a set of such exotic particles, grouped as a baryon antidecuplet. The first experimental report [2] of such an exotic state Θ^+ with minimal quark content $uudd\overline{s}$ came

*Yerevan State University, Yerevan, Armenia

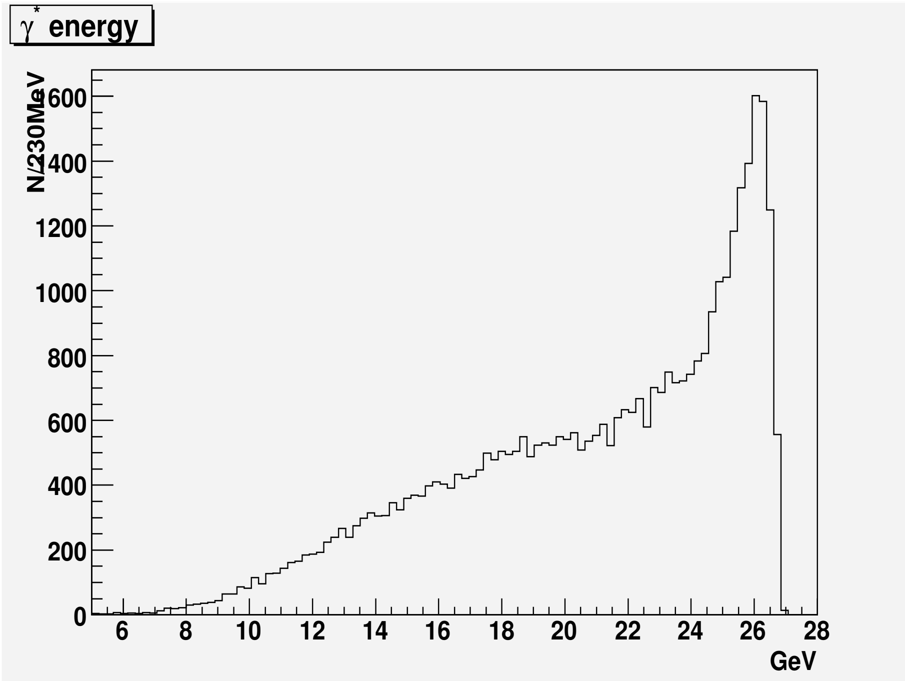

Figure 1: γ^* energy distribution.

from the LEPS experiment in Japan in 2003. Although now more than 15 experiments reported seeing candidates for such a state, decaying via the pK_s or nK^+ channel, including HERMES [3], a similar number of experiments reported null results.

So far the most succesfull experiment is LEPS, which reported three positive results for the Θ^+ in photoproduction on ^{12}C and D targets in the K^+n final state. The last report [4] from LEPS is devoted to the reaction of $\gamma D \rightarrow \Lambda(1520)\Theta^+$, and indeed the report claims to see Θ^+ in missing mass of $d(\gamma, Kp)$. Our report is aiming to repeat this type of analysis. In HERMES we can study photoproduction reactions by detecting the scattered lepton simultaneously with the other particles. We can then define the four momentum of the virtual photon γ^* (Fig. 1 shows the energy distribution for γ^*).

2 DATA set, Particle Identification(PID) and event selection

2.1 Data sample

To select the reaction on deuteron and to have the RICH detector available, the data sample was restricted to include only polarized and unpolarized deuterium data from 1998 till 2000. The runlist was chosen using the latest LOGRUN files which are marked by the HERMES DQ group as analyzable (see *http://www-hermes.desy.de/groups/daqlgrp/* for details). The runlist contains a total of 44944 runs.

2.2 Event selection and kinematic cuts

Events were selected from the μDSTs using the following criteria:

1. Events were required to contain at least three tracks:
   one lepton identified using the PID detectors response: $PID3+PID5 > 0$ and two oppositely charged hadrons using the cut $-100 < PID3 + PID5 < 0$.

2. Using the link between the track and the RICH we require that one hadron is identified by the RICH as a proton (antiproton) and another one as a $K^{\pm}$.

3. The proton momentum is required to be in the range $4.0 < P_p < 9.0$ GeV.

4. The kaon momentum is required to be in the range $2.0 < P_K < 15.0$ GeV.

5. The identified lepton is required to be an electron for the 1998 data and positron for the 1999 and 2000 data.

6. The distance of closest approach (DCA) between the proton and kaon tracks is required to be less than 0.4 cm.

7. The mid-point of this DCA segment is required to be less than 0.8 cm away from the z axis.

8. The z coordinate of that mid-point is required to be in the range $-18 < z < 18$ cm.

9. The DCA between reconstructed Λ and electron is required to be less than 1.5 cm.

10. The mid-point of this DCA segment is required to be less than 0.8 cm away from the z axis.

11. The z coordinate of that mid-point is required to be in the range $-18 < z < 18$ cm.

12. The reconstructed Λ decay length is required to be less than 7 cm.

13. Events with reconstructed invariant mass of $\Phi(1020)$ in the range $1.01 < M_{K^+K^-} < 1.03$ GeV, if we interpret the proton as a kaon, are discarded.

The cuts are described in detail in the next section.

3 Applied cuts

3.1 $\Lambda(1520)$ invariant mass

First we need to reconstruct the $\Lambda(1520)$ and $\overline{\Lambda}(1520)$ invariant masses. From the proton and kaon momentum vectors and masses we can reconstruct their four momenta, then adding them we can get the four momentum of Λ:

$$P_\Lambda = P_p + P_K \tag{1}$$

Then we need to separate the events corresponding to p^+K^+, p^+K^-, p^-K^+ and p^-K^-. In Fig. 2 are shown the four plots corresponding to these four different cases, when no cuts are applied. First two of them correspond to Λ and $\overline{\Lambda}$. The other two are just plotted for comparison. We can recognize a small peak for Λ, but for $\overline{\Lambda}$ we can say nothing. In this and the following figures the fitting results for Λ are shown with third order polynomial background and an appropriate gaussian, where sigma is fixed at 6 MeV. Fitting is not done for $\overline{\Lambda}$, because we can hardly see any events for this particle.

Fig. 3 shows the momentum distributions for the protons and kaons. For better identification of these particles we accept only the protons with momentum in the range $4.0 < P_p < 9.0$ GeV and the kaons with momentum in the range $2.0 < P_K < 15.0$ GeV. The Λ and $\overline{\Lambda}$ invariant mass distributions with these cuts applied, are shown in the same figure. With these cuts (and the others which will follow) we decrease the number of events for Λ, but they are needed to be sure that we see mostly $\Lambda(1520)$ events.

Next we take into account that HERMES used an electron beam in 1998 and a positron beam in 1999 and 2000. Therefore we expect electrons or

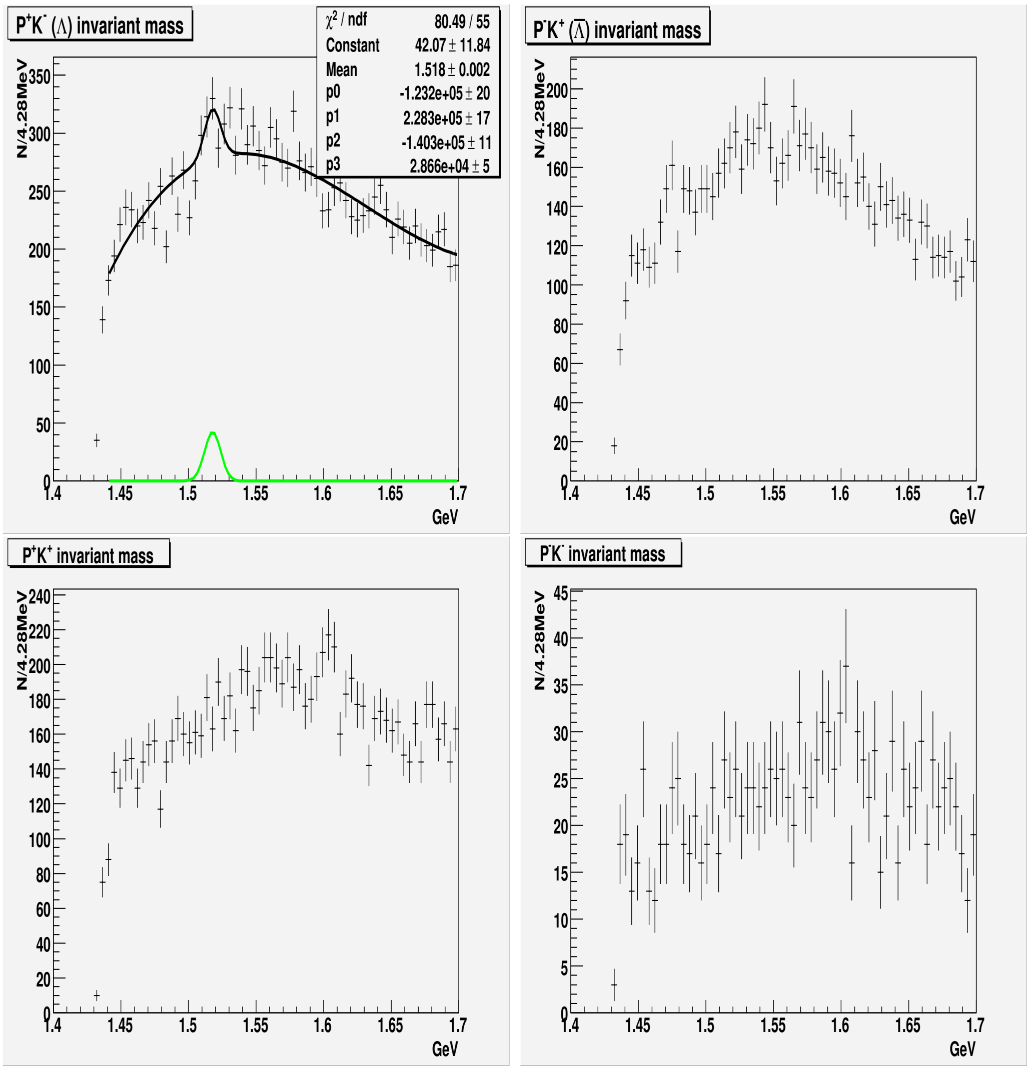

Figure 2: The Λ and $\overline{\Lambda}$ invariant masses (top left and right) and the reconstructed invariant masses for p^+K^+ and p^-K^- (bottom left and right) without applying any cuts. Number of events for Λ is 148 ± 42.

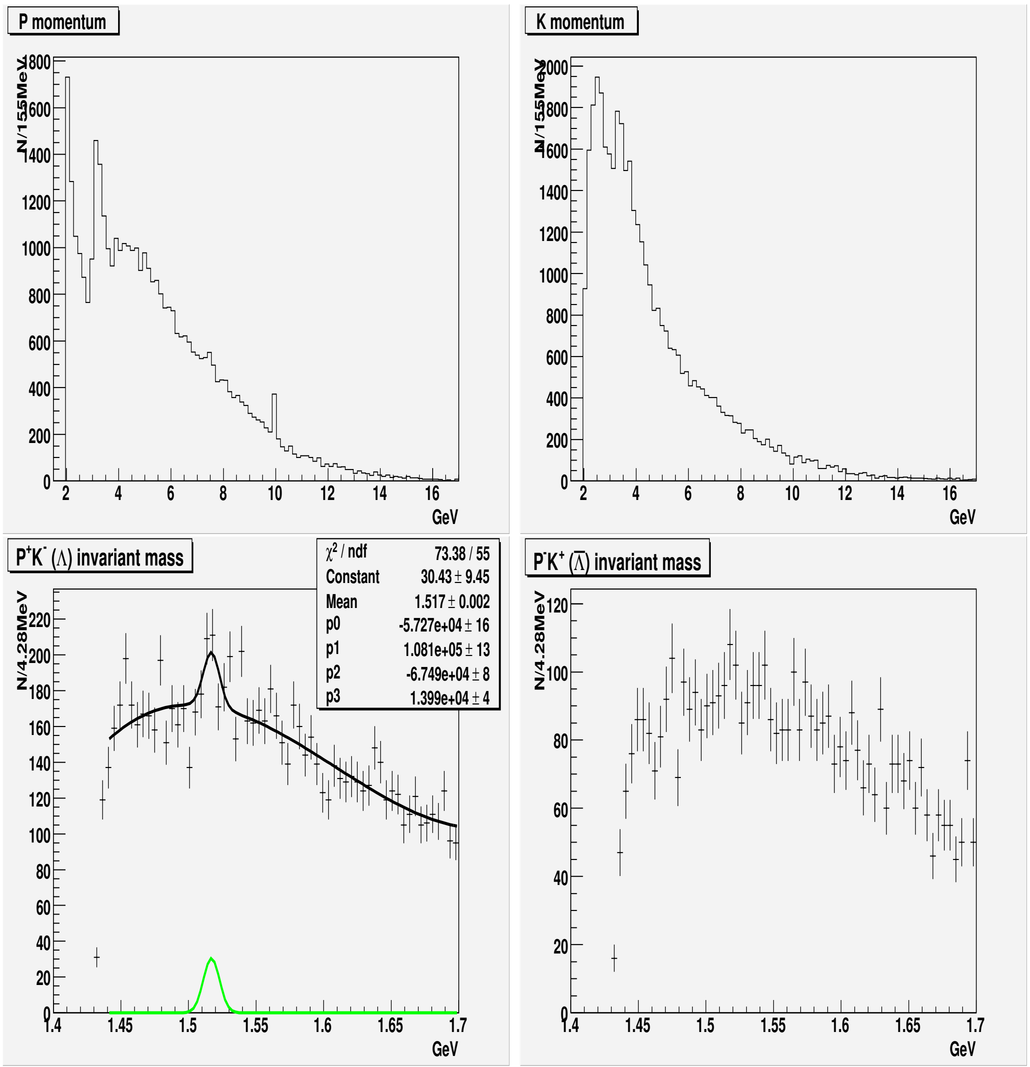

Figure 3: The proton and kaon momentum distributions (top left and right) and the Λ and $\overline{\Lambda}$ invariant masses (bottom left and right) with proton and kaon momentum cuts applied. Number of events for Λ is 107 ± 33.

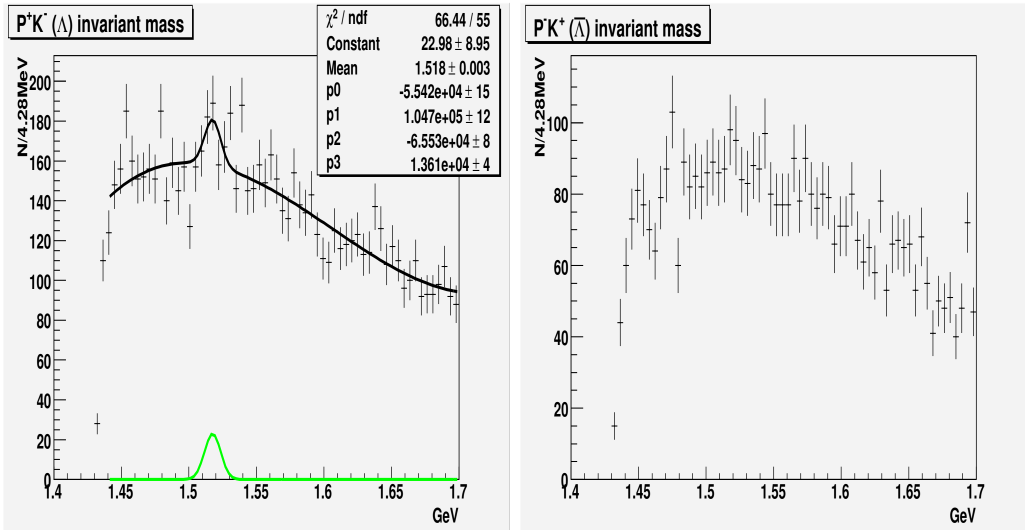

Figure 4: The Λ and $\overline{\Lambda}$ invariant masses with electron/positron charge cuts applied. Number of events for Λ is 81 ± 31.

positrons corresponding to these years, because, as already mentioned, we suppose that electron (positron) emits a virtual gamma and therefore does not change its state, so we can discard the positron events from 1998 data and electron events from 1999 and 2000 data. Invariant mass plots for Λ and $\overline{\Lambda}$ with this cut applied are shown in Fig. 4. Of course when we apply additional cuts, the previous cuts are kept.

In Fig. 5 we can see the distance of closest approach (DCA) of the distribution between the proton and kaon tracks. Another cut can be applied taking into account that these tracks should be close enough to each other. The best choice for this cut is DCA less than 0.4 cm. In the same figure are shown the invariant masses for Λ and $\overline{\Lambda}$ after this cut is applied.

We can apply another cut assuming that the mid-point of DCA between the proton and kaon tracks should be close enough to the z axis, which is along the direction of the beam. The distributions of the x and y coordinates are shown in Fig. 6. The best choice for this cut is $r < 0.8$ cm where $r = \sqrt{x^2 + y^2}$. In the same figure also the Λ and $\overline{\Lambda}$ invariant mass spectra are shown after applying this cut.

Because the target cell length is 40 cm and the middle of that cell z coordinate is 0, we discard the events for which z coordinate of the above mentioned mid-point point does not satisfy $|z| < 18$ cm (not 20 to be inside the main distribution of that z coordinate). The distribution of the z coordinate as well as the Λ and $\overline{\Lambda}$ invariant mass spectra with this cut applied

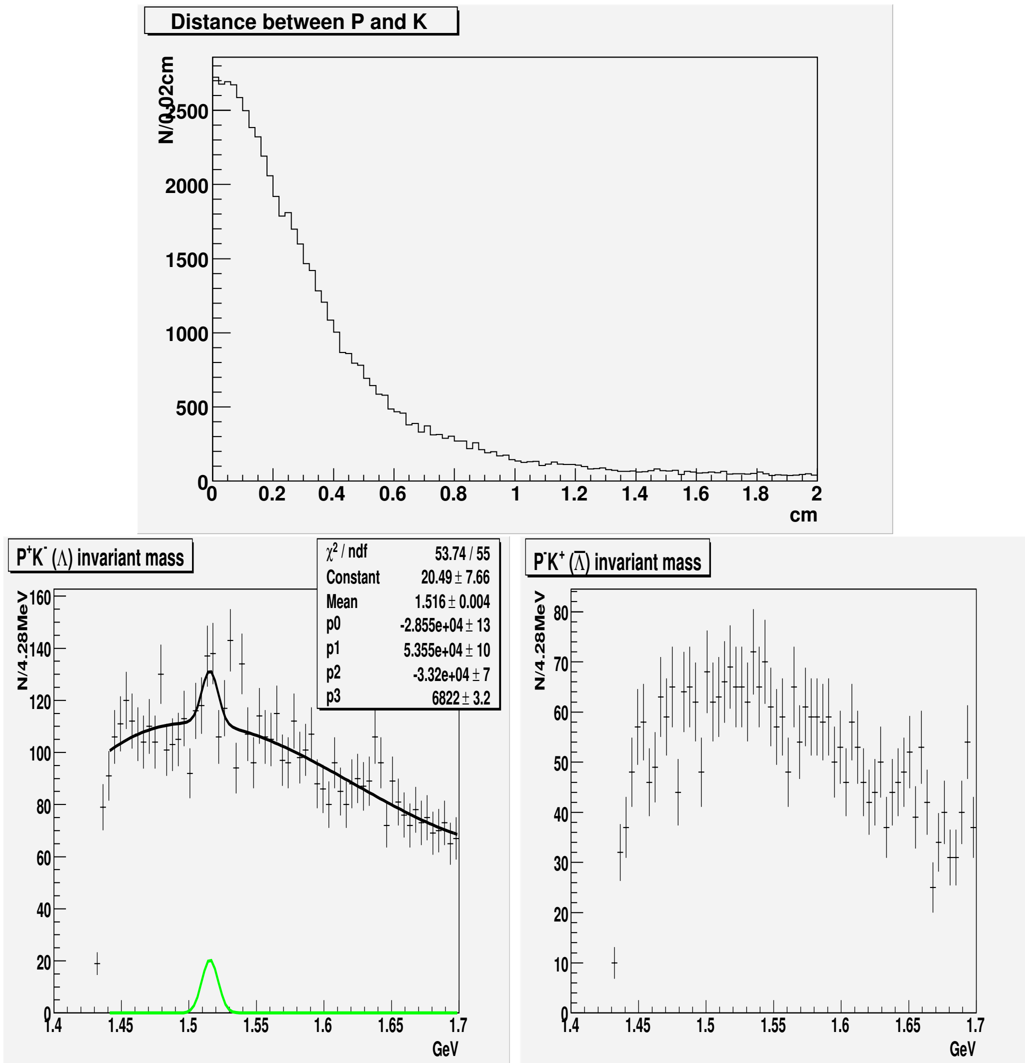

Figure 5: The DCA between the proton and kaon tracks (top), the Λ and $\overline{\Lambda}$ invariant masses (bottom left and right) with the DCA between the proton and kaon tracks less than 0.4 cm. Number of events for Λ is 72 ± 27.

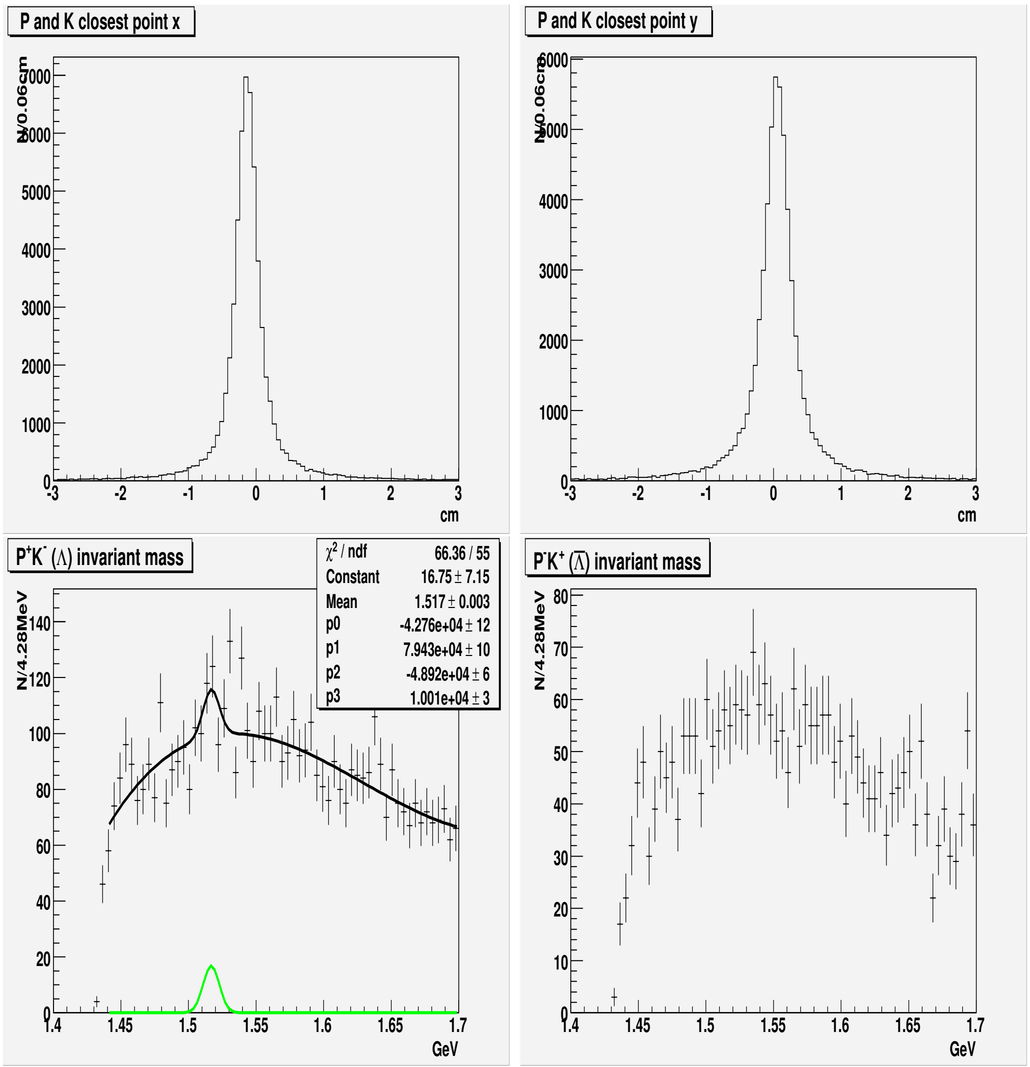

Figure 6: The proton and kaon DCA mid-point x and y coordinates distributions (top left and right), the Λ and $\overline{\Lambda}$ invariant masses (bottom left and right) with $r = \sqrt{x^2 + y^2} < 0.8$ cm cut applied. Number of events for Λ is 59 ± 25.

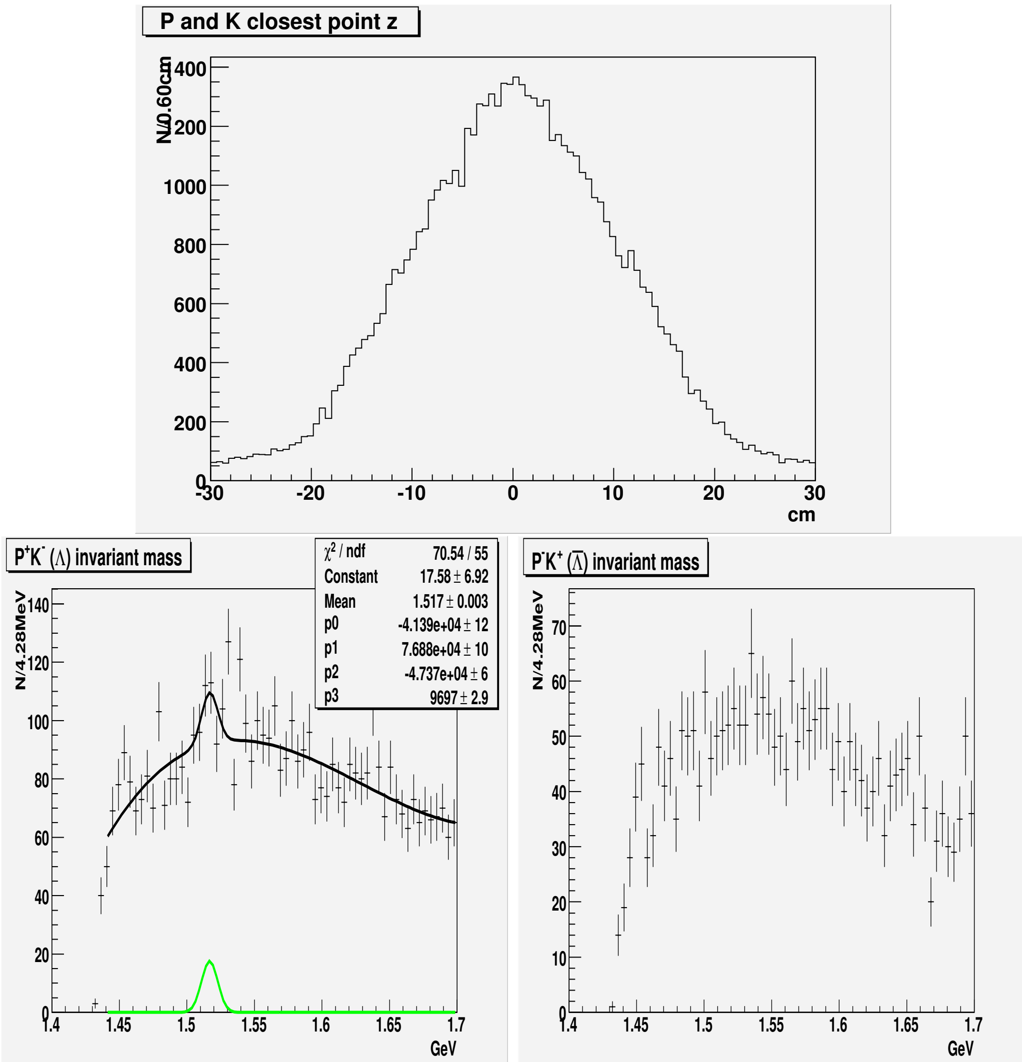

Figure 7: The proton and kaon DCA mid-point z coordinate distribution (top), the Λ and $\overline{\Lambda}$ invariant masses (bottom left and right) with $|z| < 18$ cm cut applied. Number of events for Λ is 62 ± 24.

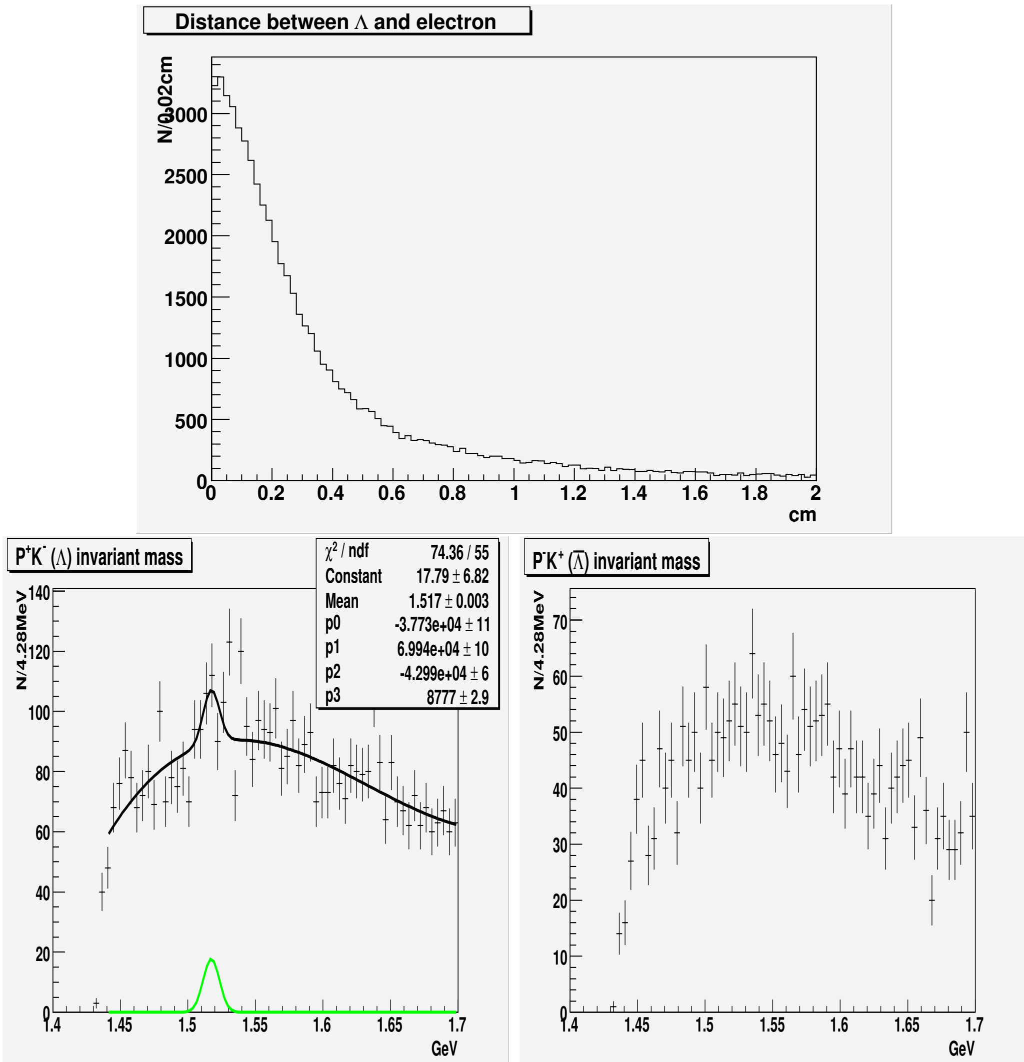

Figure 8: The DCA between the reconstructed Λ and electron tracks (top), the Λ and $\overline{\Lambda}$ invariant masses (bottom left and right) with the DCA between the reconstructed Λ and electron tracks less than 1.5 cm. Number of events for Λ is 62 ± 24.

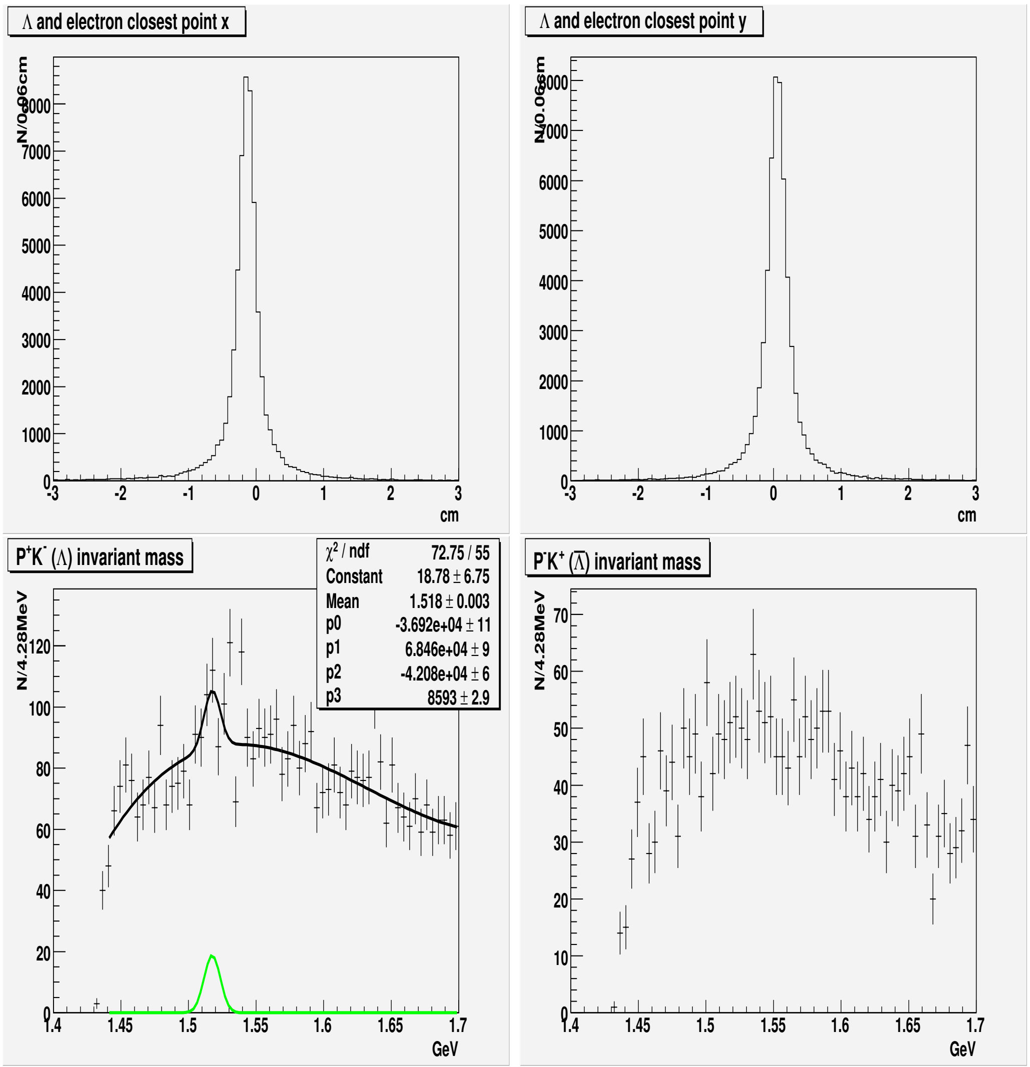

Figure 9: The reconstructed Λ and electron DCA mid-point x and y coordinates distributions (top left and right), the Λ and $\overline{\Lambda}$ invariant masses (bottom left and right) with $r < 0.8$ cm cut applied. Number of events for Λ is 66 ± 24.

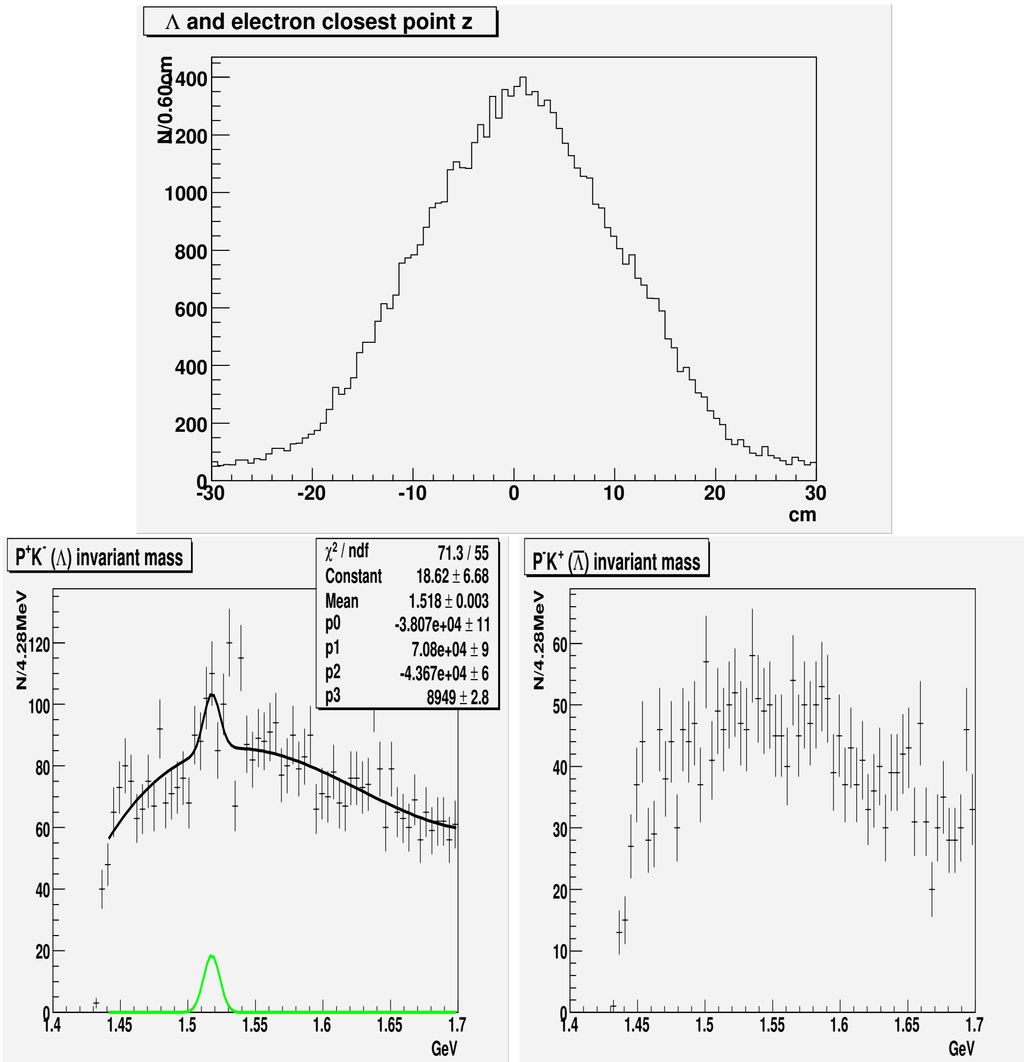

Figure 10: The reconstructed Λ and electron DCA mid-point z coordinate distribution (top), the Λ and $\overline{\Lambda}$ invariant masses (bottom left and right) with $|z| < 18$ cm cut applied. Number of events for Λ is 65 ± 23.

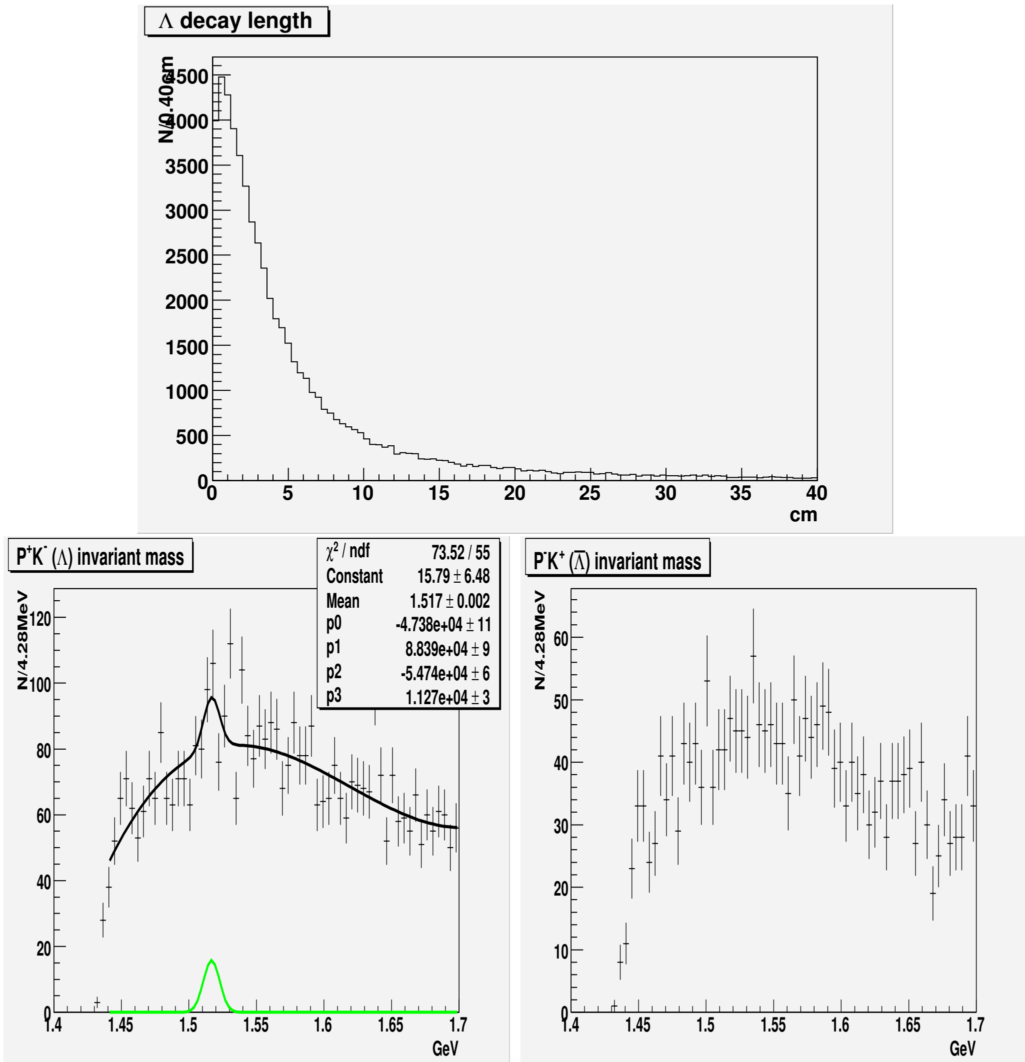

Figure 11: The distribution of the distance between the two mid-points (proton-kaon, Λ-electron) (top), the Λ and $\overline{\Lambda}$ invariant masses (bottom left and right) with this distance less than 7 cm. Number of events for Λ is 55 ± 23.

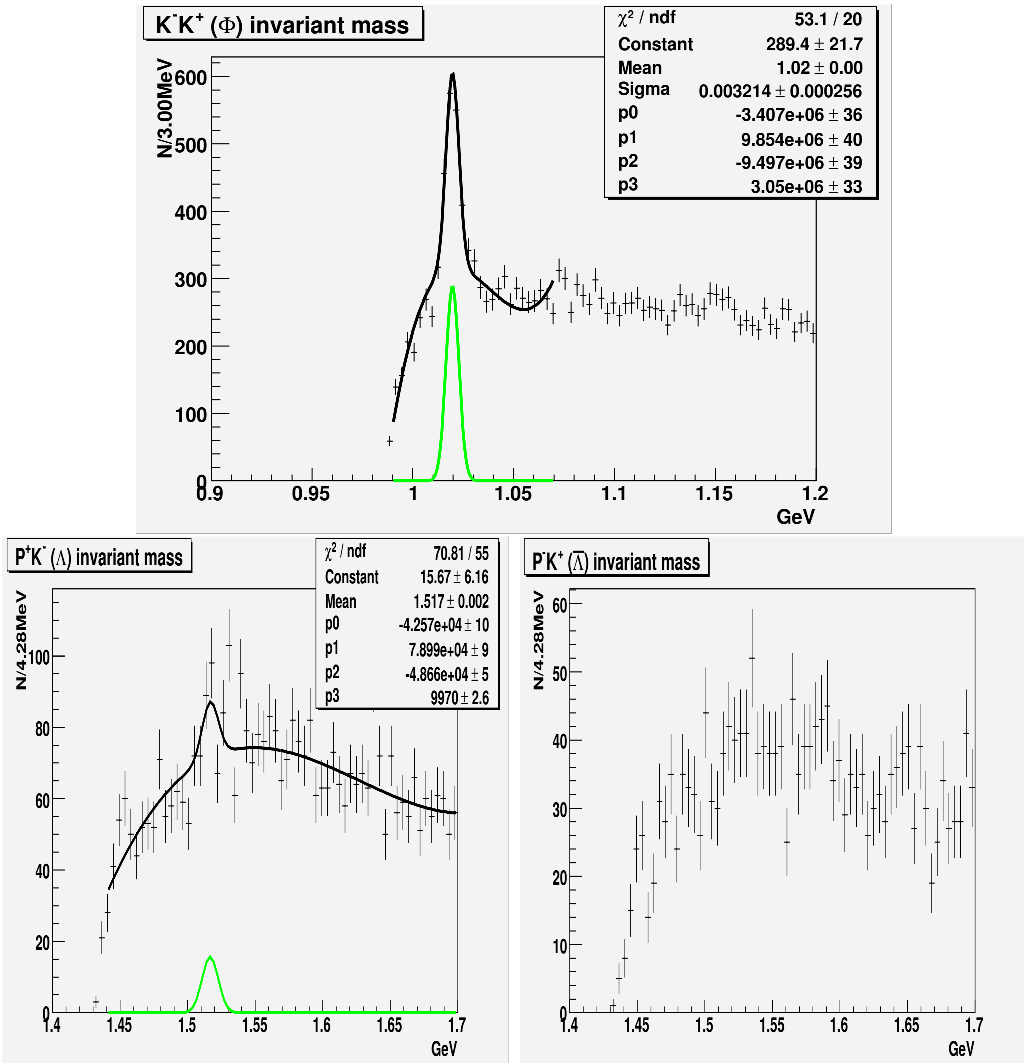

Figure 12: The invariant mass for the reconstructed $\Phi(1020)$ particle (top), the Λ and $\overline{\Lambda}$ invariant masses (bottom left and right) when events are discarded with Φ condition. Number of events for Λ is 55 ± 22.

are shown in Fig. 7.

The three cuts concerning the DCA between the proton and kaon tracks and its mid-point can also be applied to the reconstructed Λ and electron (positron) tracks. The best choice for the DCA between these tracks is less than 1.5 cm, for the distance of mid-point from the z axis is less than 0.8 cm, and $|z| < 18$ cm. The corresponding plots for these distance distributions as well as the invariant mass distribution spectra for Λ and $\overline{\Lambda}$ are shown in Fig. 8, Fig. 9 and Fig. 10.

The next cut refers to the distance between the two mid-points. It is called the decay length of Λ before decaying into a proton and a kaon. This distance distribution is shown in Fig. 11. We will discard the events for which this distance is more than 7 cm, because $\Lambda(1520)$ does not live long enough to move significantly. The corresponding distribution plots for the invariant masses of Λ and $\overline{\Lambda}$ with this cut applied are shown in the same figure.

As kaons may be misjudged as protons by the RICH detector, we can discard several events with the help of the reconstructed invariant mass of the $\Phi(1020)$ particle, decaying into K^+ and K^-. We interpret the proton as a kaon and calculate the invariant mass of the two kaons. Fig. 12 shows a nice peak for the $\Phi(1020)$ (we can calculate approximately 777 ± 58 events for $\Phi(1020)$). We can discard a number of events with misjudged protons by removing events with an invariant mass of K^+K^- in the range $1.01 < M_{K^+K^-} < 1.03$ GeV. Invariant masses for Λ and $\overline{\Lambda}$ are shown in the same figure.

3.2 Missing mass of $d(\gamma^*, Kp)X$

Now it is time to reconstruct the invariant mass for X particle which is supposed to be the Θ^+ pentaquark in our case. The incoming electron (positron) has momentum equal to 27.5 GeV along the z axis. The difference of the electron four momentum before and after the interaction gives us the four momentum for γ^*. The four momentum for X can be calculated by the following equation:

$$P_X = P_{\gamma^*} + P_D - P_\Lambda \tag{2}$$

where P_D is the four momentum of the deutron, assumed at rest. The four momentum of Λ is calculated by formula (1) and the four momentum of the γ^* is calculated by the following equation:

$$P_{\gamma^*} = P_e^{before} - P_e^{after} \tag{3}$$

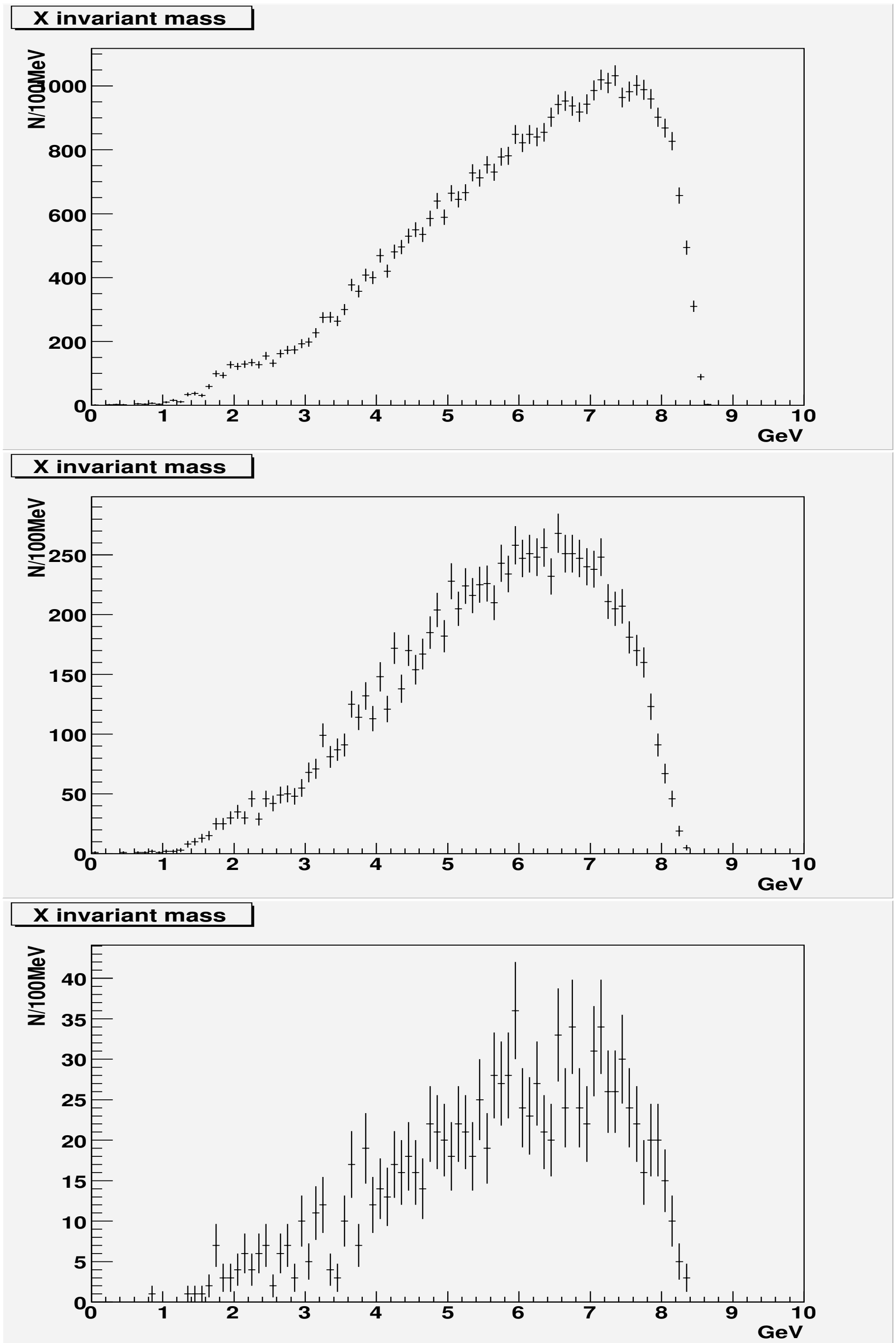

Figure 13: X invariant mass with no cuts applied (top), with the same cuts as for Λ, (middle), after selecting Λs in addition to the other cuts (bottom).

Finally, the four momentum of X can be calculated:

$$P_X = P_e^{before} + P_D - P_e^{after} - P_p - P_K \quad (4)$$

and then it is easy to calculate the invariant mass of X. Fig. 13 shows three plots for the invariant mass distribution of X. The first one is plotted with no cuts applied, the second one is plotted with the cuts used for reconstructing the Λ invariant mass, and the third one is plotted after selecting Λs with an invarint mass $1500 < M_{pK} < 1540$ MeV in addition to the cuts for Λ.

We can see that this mass is mainly distributed round $5-8$ GeV and there are only a few events in the region where Θ^+ is assumed to be. Therefore we need much higher statistics to try to see an evidence for that particle. Best of all would be plotting its invariant mass with all the cuts mentioned above (third plot in Fig. 13).

4 Results

Summarizing the results, we can see several events for the $\Lambda(1520)$ particle. A very small peak can be seen for the $\overline{\Lambda}$ on the plot where no cuts are applied, but it may be a statistical fluctuation as well. Applying cuts makes the peak for Λ clearer, but unfortunately we do not have large statistics and these cuts make it lower so the picture gets worse. After applying cuts very poor statistics is left for $\overline{\Lambda}$ and it does not make sense to try to see any events for that particle.

The missing mass $d(\gamma^*, pK)X$ is mainly out of the region of interest and there are only a few events in the region where Θ^+ is supposed to be, so we can not make solid conclusions.

5 Conclusions

1. $\Lambda(1520)$ events can be observed. Applying several cuts we can make the peak for that particle clearer.

2. A small peak can be seen for the $\overline{\Lambda}$ but we can not be sure that it is not a statistical fluctuation. Applying cuts makes the statistics for that particle very low and no events can be observed anymore.

3. The statistics of the missing mass distribution in the region where Θ^+ is supposed to be, are very low. No events can be observed.

4. We need to collect much more data to observe $\overline{\Lambda}$ events more clearly and to be able to apply the method described in this report for searching for Θ^+ pentaquarks.

6 Acknowledgements

I would like to acknowledge DESY and HERMES collaboration. I also acknowledge my supervisor Avetik Airapetian and Wouter Deconinck for great help during all my work and valuable advices.

A Programming and programs used

ADAMO μDSTs were converted to HBOOK files doing the first two cuts mentioned in section 2.2. To have an opportunity to use the object-oriented framework ROOT and *C++* programming language, we converted these HBOOK files to ROOT `TTree` objects with the `h2root` utility (provided with ROOT). For making the further programming easier we created a structure `ParticleData` which can handle all the information we get about the particles from the detectors. Several functions were created to calculate four momentum, invariant mass, DCA, and mid-point of DCA. All the histograms were created using the `TH1F` class. Fitting was done with options `IEBM` (use the integral of the function in the bin instead of the value at the bin center, perform better error estimation using the Minos technique, fix one or more parameters and the fitting function is "gaus", "expo", "poln", "landau", and improve fit results). Fitting was first done with a third order polynomial function then the resulting coefficients were passed to the main function (third order polynomial plus gaussian) as initial values. The width σ of the gaussian was fixed to 6 MeV, which corresponds to the decay width of $\Lambda(1520)$.

References

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