CB-Note 263

# $K_L$ -interaction in the Crystal Barrel Technical Report

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# 1 Introduction

The investigation of kaonic decay channels plays an important role in the $p\overline{p}$-annihilation at rest and at low momenta. It is therefore important to understand the interaction of the $K_L$ in the crystals.
The usual way to identify events involving a $K_L$ is to look for events where the $K_L$ did not interact and all other particles are detected. In this case a clear $K_L$ -peak will appear in the missing mass spectrum of the event. However, for the calculation of a branching ratio one has also to know the probability that the $K_L$ did not interact and, as it turns out that the Monte Carlo simulation of the $K_L$ -interaction by GEANT is not reliable, the $K_L$ -interaction probability has to be determined by the data.
Therefore a measurement of the interaction probability was required and it could be determined to $(57.2 \pm 2.7)\%$ in the channel $K_S K_L$ ($|\vec{P}_{K_L}| = 795$ MeV/c) [1] and to $(42 \pm 8)\%$ in the channel $K_S K_L \pi^0$ ($|\vec{P}_{K_L}| = 200$ - $700$ MeV/c) [6]. In the latter case the interaction seems to be constant over whole the momentum range.
Some features of the $K_L$ -interaction (energy deposit, shower size ...) were investigated in order to achieve a better understanding of the $K_L$ -interaction in the Crystal Barrel, which may help to explain the discrepancies between GEANT events and real data.

# 2 $K_L$ -interaction probability in the Crystal Barrel and BR ($p\overline{p} \rightarrow K_S K_L$)

The most precise result of the interaction probability was obtained by investigating the channel $K_S K_L$ . From that the branching ratio of $p\overline{p} \rightarrow K_S K_L$ could be determined.
However, as the interaction probability is expected to be momentum dependent, a second strategy has been developed to estimate the interaction probability in the larger momentum range of the channel $p\overline{p} \rightarrow K_S K_L \pi^0$ [6].
In the following a brief description of the $K_S K_L$ -analysis and of the way how to determine the $K_L$ -interaction probability for variable momenta is given.

## 2.1 The channel $p\overline{p} \rightarrow K_S K_L$ ($|\vec{P}_{K_L}| = 795 MeV/c$)

The analysis of the channel $K_S K_L$ uses the neutral $K_S$ -decay ($K_S \rightarrow \pi^0 \pi^0$) and allows an arbitrary number of $K_L$ -PEDs. So all events with at least 4 PEDs from the Nov.90 all neutral data (PED energy $>$ 20 MeV) are taken. The events must not show any charged track and their total energy must be within 700 and 2000 MeV. Now only those events with exactly 2 $\pi^0$ (PIOFND) and any additional number of PEDs are accepted. In case of only 4 PEDs a clear signal of the channel $K_S K_L$ can already be seen (Fig. 1a). To make sure that the $K_S$ -peak in the invariant $\pi^0$ $\pi^0$ -mass spectrum arises only from $K_S$ of the $K_S K_L$ -channel, all events with a $\pi^0$ $\pi^0$ -momentum not within 795 $\pm$ 75 MeV/c are rejected (Fig. 1b). Finally the total momentum of the two $\pi^0$ must not point in the direction of the detector holes and of crystal type 13 in order to investigate the interaction probability only of $K_L$ going properly through the crystals.

It has still to be distinguished between $K_L$ -PEDs and PEDs, which are produced by electromagnetic splitoffs of the $K_S - \gamma$. To do so, one looks for example at the 5 PED-events, reconstructs the $K_S$ and identifies the four PEDs of the four $K_S - \gamma$. If the fifth PED is due to an electromagnetic splitoff, it is expected to be found close to one of the $K_S - \gamma$ (max(cos(5.PED,$K_S$ -PED 1-4) $>$ 0.85), if it is due to a $K_L$ -interaction, it should be found in the opposite direction of the $\pi^0\pi^0$-momentum. The electromagnetic splitoffs lie in the upper left corner of Figure 1c and the respective events will be rejected.

The long life time of the $K_S$ leads to a shifted and asymmetric distribution of the measured $K_S$ -mass, so CBKFIT will reject about half of the remaining good events and is therefore not used.

The resulting number of $K_S K_L$ -events is obtained by fitting the $K_S$ -peak in the invariant $\pi^0$ $\pi^0$ -mass spectrum by one Gaussian on the left side of the peak, a second Gaussian with another width (due to the asymetrie) on the right side of the peak and a second order polynomial to describe the background. The fits are done by PAW/MINUIT, the fit region is taken as broad as possible (see limits in Figure 2), and $\chi^2$ is required to be less than one (respectively slightly larger,if necessary). This is done separately for events with 4 up to 9 PEDs (Fig. 2) and allows the determination of the number of $K_S K_L$ -events individually for any number of $K_L$ -PEDs (up to 5 $K_L$ -PEDs seen!). If a $K_L$ -interaction is allowed, the $K_L$ cannot be identified by their missing mass anymore and a large background will remain (for the 5-PED-events e.g. $\pi^0\omega \rightarrow \pi^0\pi^0\gamma, \omega\omega \rightarrow \pi^0\gamma\pi^0\gamma_{miss}$ or $\pi^0\pi^0\pi^0$ with one missing $\gamma$). The number of $K_S K_L$ -events in the peaks are listed in Tab. 1.

The reconstruction efficiency is determined by applying the same analysis on a well known number of $K_S K_L$ -events, which are produced by GEANT. As mentioned above this Monte Carlo simulation program seems to overestimate the $K_L$ -interaction probability in the Crystal Barrel and therefore more $K_L$ -PEDs than in real data will appear. This fact will lead to wrong results in the efficiency calculation, because events with more $K_L$ -PEDs have a lower chance to pass all the cuts. For example, more fake $\pi^0$ will be reconstructed for combinatorical reasons and it becomes more likely to find PEDs in crystal type 13.

To avoid these problems one has to create and analyse separately data sets with 4 $K_S$ -PEDs and n $K_L$ -PEDs (n = 0, 1, 2,...). Now the analysis of the Monte Carlo data becomes independent of the $K_L$ -interaction probability and one obtains the

reconstruction efficiency $\epsilon'(n)$ for $K_SK_L$ -events with 4 $K_S$ -PEDs and n $K_L$ -PEDs (n = 0, 1, 2,...). The total efficiency $\epsilon(n)$ is equal to $\epsilon'(n)$ times the probability that a $K_S$ leaves four PEDs in the crystals, which can be determined easily, as the electromagnetic interaction is very well simulated by GEANT.
The strong variation of $\epsilon(n)$ is shown in Tab. 1. The absolute number of $K_SK_L$ -events can now be calculated for any number of $K_L$ -PEDs. The errors in Tab. 1 are derived from the errors of the fit parameters as given by MINUIT.The interaction probability of $K_L$ with a momentum of 795MeV/c in the crystals is then given by the total number of $K_SK_L$ -events with more than one PED (17214 ± 678) divided by the total number of all $K_SK_L$ -events (30073 ± 798).

$$P_{int}(|\vec{P}_{K_L}| = 795MeV/c) = (57.2 \pm 2.7)\%$$

Taking into account the branching ratios for $K_S \rightarrow \pi^0\pi^0$ and $\pi^0 \rightarrow \gamma\gamma$ as well as the annihilations outside of the target ((3.9 ± 0.7) % [3]) and the in flight annihilations ((5.7 ± 1.1) % [3]), one obtains the branching ratio

$$BR(p\overline{p} \rightarrow K_SK_L) = (8.96 \pm 0.67) \cdot 10^{-4}$$

This result is slightly larger than those obtained by bubble chamber experiments: BR($p\overline{p} \rightarrow K_SK_L$) = $(7.1 \pm 1.0) \cdot 10^{-4}$ [4] and BR($p\overline{p} \rightarrow K_SK_L$) = $(8.0 \pm 0.5) \cdot 10^{-4}$ [5].

## 2.2 $K_L$ -interaction at variable momenta ($p\overline{p} \rightarrow K_SK_L\pi^0$)

The method to determine the interaction probability for a larger momentum range makes an explicit use of the detector holes. $K_SK_L\pi^0$-events are reconstructed out of the 6-PED-events in the same way as described in [6], but this time no cut on the momentum direction of the $K_L$ is applied. An event will pass the cut on the number of PEDs only if no $K_L$ -interaction has taken place. If the $K_L$ - momentum points into the direction of the crystals, only that fraction of the good events can be observed, which is compatible with the $K_L$ -interaction probability, whereas no interaction is possible, if the $K_L$ -momentum points into the direction of the holes. The ratio of reconstructed events with a $K_L$ -momentum pointing into the region covered by the crystals to those with a $K_L$ -momentum close to the z-axis is - after normalization to the size of the respective solid angles - equal to the average interaction probability of the $K_L$ over the total momentum range in that specific channel.
Fig. 3 shows where the $K_L$ -momenta of the reconstructed events are found and out of this the $K_L$ -interaction probability is determined to

$$P_{int}(|\vec{P}_{K_L}| = 200 - 700MeV/c) = (42 \pm 8)\%$$

The curve is not constant over the region covered by the crystals, as it is not yet acceptance corrected. Furthermore it needs more statistics in order to get a better resolution in the region of the hole. The data with the $K_S$ trigger from November 1993 were produced recently and with these amount of data this plot will be reproduced in the near future. Even with a smaller binning in the region of the holes, which is required evidently, the statistical error will then be reduced. Due to the lack of statistics it is not possible to get reasonable results for the interaction probability in subdivisions of this momentum range, but the new data can help to answer this question, too. In this channel the interaction probability seems to be constant over whole the momentum range, as it could be concluded by the density of the $K_L\pi^0$-band in the Dalitzplot, but more effort has to be done to make sure, that there is really no resonance in the cross section of $K_L$ in CsI, causing a dip in the Dalitzplot, which would look like a destructive interference.
Nevertheless this method has the advantage that it is applicable to different $K_L$ -channels and can be used as a normalization for the calculation of branching ratios, so that the exact knowledge of the momentum dependence of the $K_L$ -interaction is not required.

# 3 The Monte Carlo simulation

The interaction probability of the $K_L$ in the momentum range from 100 - 1000 MeV/c calculated by GEANT (Fig. 4b) shows two constant levels, one between 200 and 500 MeV/c at almost 100 % and another one above 750 MeV/c at approximately 85%. The shape of this curve does not at all agree with the results of the measurements given in 2.1 and 2.2. Furthermore GEANT produces much more $K_L$ -PEDs in the $K_SK_L$ -channel than can be seen in the real data (Fig. 4a). The discrepancies of the results obtained by the Monte Carlo simulation and by the analysis of real data is so large (see also next chapter), that one should not base any analysis on the $K_L$ -interaction simulated by GEANT.
A detailed study of hadronic interactions in GEANT and the different results using either GHEISHA or FLUKA is given in [10]. GEANT uses by default GHEISHA to handle the hadronic interactions, but this is recommended for $K_L$ -momenta above 1 GeV/c only. Below 1 GeV/c down to 300 MeV/c it is FLUKA, which seems to describe our data in a better (but not perfect) way. More and better information about the $K_L$ -interaction in this momentum range is needed to clarify the situation.

## 4 Features of the $K_L$ -interaction

From the $K_L$ -interaction with the protons and the neutrons of the CsI-crystals, mainly pions and Lambdas but also free neutrons and protons will arise as secondary particles.

Neutrons can deposit energy only via hadronic interaction, but they can also leave the detector by remaining invisible. Lambdas will decay into $p\pi^-$ or $n\pi^0$, if they do not escape unseen ($c\tau \approx 8cm$). The charged pions loose their energy via hadronic, but also via electromagnetic interaction and therefore the energy deposit will be influenced by the strength of the specific energy loss.

In order to investigate the PED-characteristics of a $K_L$ -interaction, it is necessary to extract events with at least one $K_L$ -interaction and without background. Possible methods to do so are described in [1], [8] and [9], here only the results are presented.

The distribution of the $K_L$ -energy deposits in the channel $K_SK_L$ (Fig. 5a) is very broad and in [1] it is shown that apparently the $K_L$ never deposit their full energy in the crystals, as the actual $K_L$ -energy of 938 MeV is never detected. The maximum energy deposit is at around 800 MeV. The clustersize is almost flat over the range from 2 crystals per cluster up to 20 crystals per cluster (Fig. 5c). The angle between the $K_L$ and the recoiling momentum is found to be nearly $180^0$ (Fig. 5e), but due to momentum conservation this angular distribution would not differ from events with a similar PED-topology, for example $\pi^0\omega \rightarrow \pi^0\pi^0\gamma$ and the two pions having a total momentum satisfying the respective cut in [1].

By investigating events with more than one $K_L$ -PED, the behaviour concerning energy deposit and clustersize does not change, but the opening angle between the $K_L$ -PEDs can be seen now. It could be demonstrated that in most of the cases the cosinus of the opening angle of the $K_L$ -PEDs will be smaller than 0.85 for any number of $K_L$ -PEDs [1]. In Fig. 5d the distribution of these opening angles are shown for the case of two $K_L$ -PEDs.

The $K_L$ -energy deposit has also been investigated in the channel $K_LK^+\pi^-\pi^0$ [8]. The shape of the resulting curve (Fig. 5b) agrees with the one of Fig. 5a, except it shows less entries at low energies with respect to the total number of entries.

The investigation of data with various PED-cuts (July 90 : EPEDBC = 10 MeV, Nov 90 : EPEDBC = 20 MeV) [9] yields the result, that for the 20 MeV PED-cut less high energy $K_L$ are found. This can possibly be explained by the lower specific energy loss of the secondary charged pions, which are produced by the $K_L$ -interactions. The energy deposits may become so small, that no PED is seen. Until November 1990 the PED-reconstruction required a single crystal with an energy deposit larger than 20 MeV, which might not be produced by charged pions although their total energy deposit might be much larger than 100 MeV.

In accordance to that the $K_L$ -energy spectra of the channel $K_SK_L$ (Fig. 5a) shows much more entries at low energies than the one of the channel $K_L K^+ \pi^- \pi^0$ (Fig. 5b). The $K_L$ -energy in the two body decay is much larger, but a lot of the energy deposits are very small.

# 5 Conclusion

A lot of work has already been invested in $K_L$ -channels and a better understanding of the $K_L$ -interaction in the crystals has been achieved.
The interaction probability at 795 MeV/c could be determined with a high accuracy and hence also the branching ratio of the channel $K_S K_L$ . At lower momentum ranges the errors of the measurements are still much larger, but they can be reduced by making use of the much better statistics of the November 1993 data. It turned definitely out, that GEANT Monte Carlo for $K_L$ with a momentum of less than 1 GeV/c is far away from simulating the $K_L$ -interaction properly. Tony Noble showed that the GEANT default package to describe hadronic showers, GHEISHA, should not be used below 1 GeV/c. The FLUKA package seems to be more appropriate, but the situation will be much more clarified, once we have more and better information about the interaction of $K_L$ below 1 GeV/c.

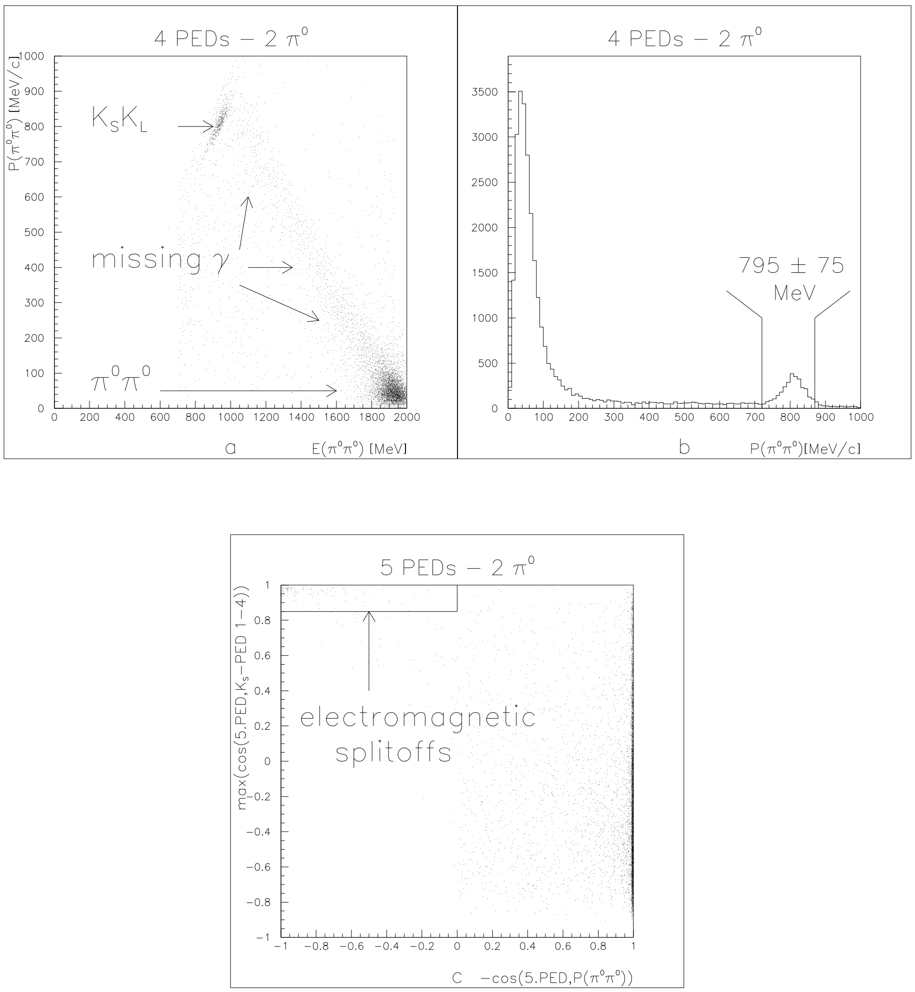


Figure 1: *(a): A clear signal of the channel $K_S K_L$ can be seen in events with 4 PEDs and two $\pi^0$. (b) The cut on the $\pi^0\pi^0$-momentum. (c) The electromagnetic splitoffs are placed in the upper left corner of this histogram.*

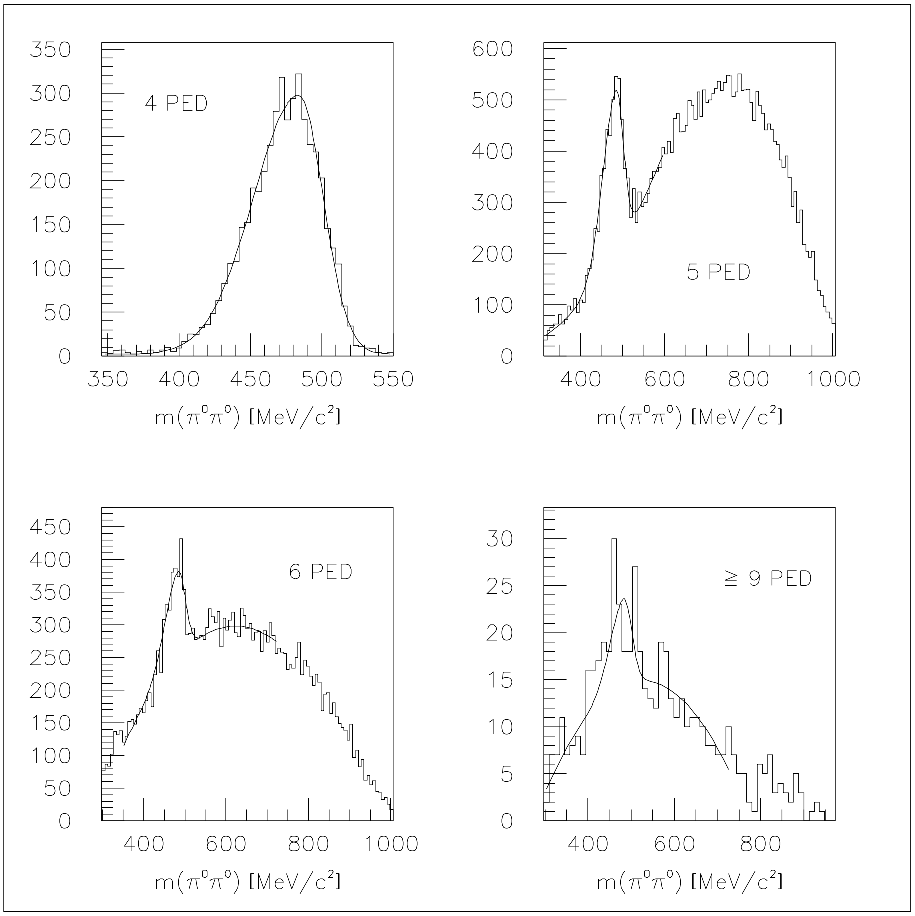


Figure 2: *The invariant $\pi^o\pi^0$-mass spectra show clear signals of $K_S$ from the channel $K_SK_L$ for any PED multiplicity.*

| n | $K_SK_L$ -events in peak | $\epsilon(n)$ | total number of $K_SK_L$ -events |
|---|---|---|---|
| 4 | 4527±105 | 35.2±0.8 | 12868±421 |
| 5 | 2767±84 | 33.4±0.5 | 8294±281 |
| 6 | 1150±84 | 24.6±0.5 | 4671±352 |
| 7 | 300±35 | 15.2±0.5 | 1972±237 |
| 8 | 115±24 | 8.2±0.7 | 1401±317 |
| ≥9 | 46±13 | 5.3±1.2 | 876±317 |
| Total | | | 30082±798 |

Table 1: *The number of $K_SK_L$ -events can be calculated for any number of additional $K_L$ -PED, taking into account, that $\epsilon$ varies with $n$.*

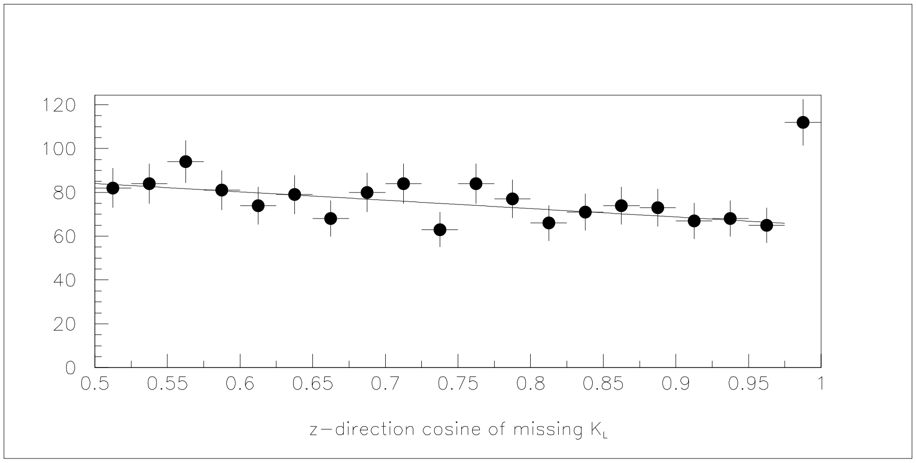


Figure 3: *The $K_L$ -angular distribution in $KK\pi$ shows an enhancement at the detector holes, which allows an estimation of the interaction probability. This plot will be improved by analysing the data with the $K_S$ -trigger.*

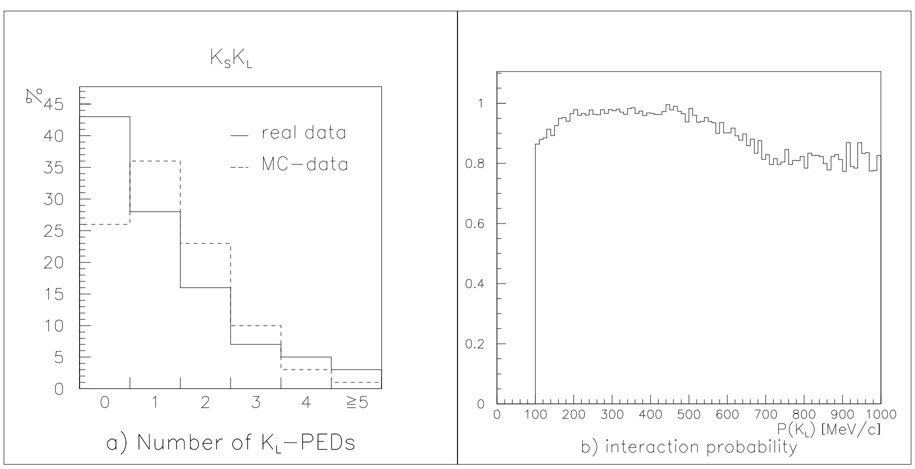


Figure 4: *(a) Distribution of $K_L$ -PED numbers obtained by Monte Carlo calculation and from real data (both normalized to a sum of 100%). (b) $K_L$ -interaction probability, calculated by GEANT for the momentum range 100 - 1000 MeV/c.*

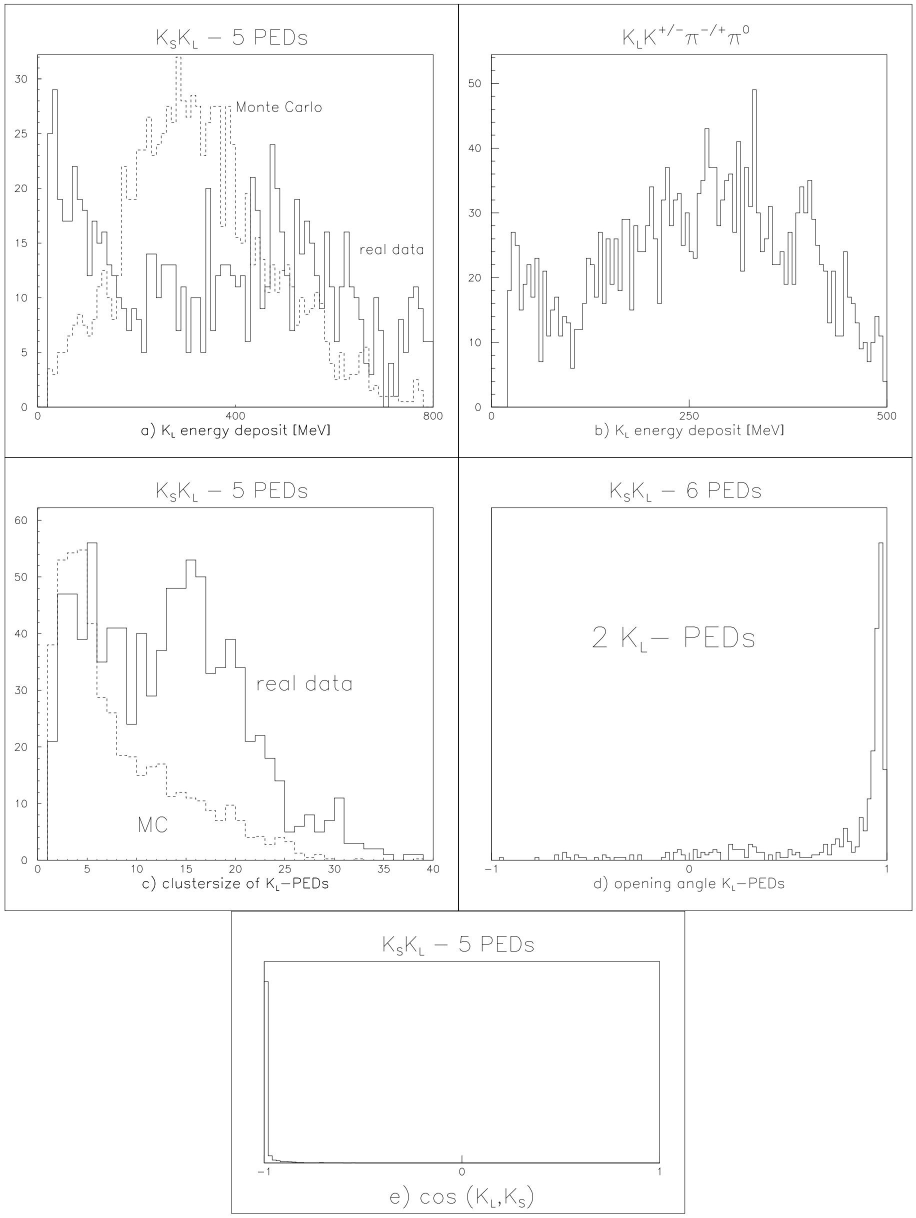


Figure 5: *(a) The distribution of the energy deposits of the* $K_L$ *in the channel* $K_SK_L$ *is very broad and differs very much from the one obtained by Monte Carlo. (b) The* $K_L$ *energy deposit distribution in the channel* $K_LK^+\pi^-$ *has the same structure as (a). (c) The distribution of the* $K_L$ *-clustersize is almost flat over a large range and differs also very much from the Monte Carlo prediction. (d) Opening angle between the 2* $K_L$ *-PEDs in the 6-PED-events. (e) Opening angle between* $K_L$ *and* $K_S$ *in the channel* $K_SK_L$ *.*

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