CB Note No. 258.

# A Study of Hadronic Interactions in CBGEANT

# FLUKA vs GHEISHA

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**Abstract**

The results from a study on the behavior of the GEANT 3.21 Monte Carlo program are presented. The purpose was to study the different options available for hadronic interactions, and where possible to compare with data. Neutrons, $K^+$, $K^-$, $K_L$, $\pi^+$, and $\pi^-$ hadrons were studied at discrete momenta from 100 MeV/c to 1.0 GeV/c. The main conclusion is that the hadronic package currently employed in the CBGEANT Monte Carlo is wrong. It uses the wrong cross-sections and does not represent the data well. The choice between the correct version of GHEISHA and FLUKA is less clear, the pros and cons of which should be weighted by the user according to his/her application. Finally, there have been dramatic changes to the neutron transportation code between GEANT versions 3.14 and 3.21.

# 1 Introduction

This note addresses the problem of which of the hadronic packages supplied with the GEANT 3.21 [1] code is the most suitable for our energies and particle types, and hence, which should we recommend for use in the CBGEANT Monte Carlo code. GEANT 3.21 has three codes available, namely GHEISHA, FLUKA and MICAP. The later was extracted from a more general program (GCALOR) and is interfaced to FLUKA and GEANT and is meant to handle neutrons at energies below 20 MeV. However, at the moment it has a limited set of defined materials, and so it shall not be considered further. As GHEISHA has an optional "correction term", which modifies its behavior at low momenta, in the following it will be regarded as a separate package, GHEISHA_C. These packages, GHEISHA, GHEISHA_C, and FLUKA, are discussed in more detail below. Historically, GHEISHA has been the default hadronic package supplied with GEANT. Recently FLUKA has been added as an option. CBGEANT, at least until the current version 4.06/09, has always used the GHEISHA_C package.

In an earlier investigation of the $K_L$ interaction probability by Michael Kobel [2], he noted that there were inconsistencies between the input and output of the Monte Carlo. This was in fact due to the correction factor which he did not know was being applied, and which modified the cross-sections for CsI. It was also suggested that an upgrade to GHEISHA version 8.0 could provide more reliable results. In fact that was the version in use for GEANT 3.14, and there is no more recent code.

## 1.1 GHEISHA

GHEISHA (Gamma- Hadron- Electron- Interaction SH(A)ower code) [3] is a general code to handle the interactions, showers and tracking of all particle types within the materials of a user definable detector setup. Only the hadronic interaction part of GHEISHA has been interfaced to GEANT. Originally the program was optimized to describe the properties of some specific experiments, and the author has warned that quite different detector configurations and/or incident particle types may require the addition of more detailed atomic or nuclear interaction effects.

In general, the elastic and inelastic cross-sections are parameterized using data from interactions of $\pi^+$, $\pi^-$, $K^+$, $K^-$, $K_L$, p and $\overline{p}$ on free protons. The parameterization uses the naive quark parton model to describe all cross-sections on free protons in terms of various quark scattering amplitudes. These amplitudes are then determined by a global fit to all cross-section data on free protons. To determine cross-sections on heavy nuclei the optical model is invoked. The black disk model is used, but the coefficients have small, momentum and particle dependant correction terms.

The extrapolation to other materials seems to fit the data quite well for momenta above 1.0 GeV. However, in most cases the parameters and cross-sections have not been compared with momenta in our range. In several places the author has warned that certain approximations are reasonable above for example 500 MeV/c or 1.0 GeV/c, and hence one might suspect that the code is not that suitable for momenta of only a few hundred MeV/c. Only in the case of neutrons has an attempt been made to get accurate cross-sections at low momenta. Likewise, the generation of secondary particles in inelastic reactions are reasonably well described with a multiplicity distribution function for momenta above 6 GeV. At lower momenta, individual final state reaction cross-sections are used rather than a parameterization, although again, this has only been tested for momenta above 500 MeV/c.

## 1.2 GHEISHA_C

In the GEANT manuals, there is a recommendation that if one is using inorganic scintillators then one should use the correction term GHCOR1 which modifies "slightly" the hadronic cross-sections by a multiplicative factor. In recent discussions with the author, it was determined that this correction factor was only added to make the data of one experiment fit the Monte-Carlo better and that it was never meant to be generally applied. He was of the opinion that it should not be used without good reason. It has little effect at momenta above 1 GeV, where it was intended to be used, but can be quite large at lower momenta as shown in figure 1.

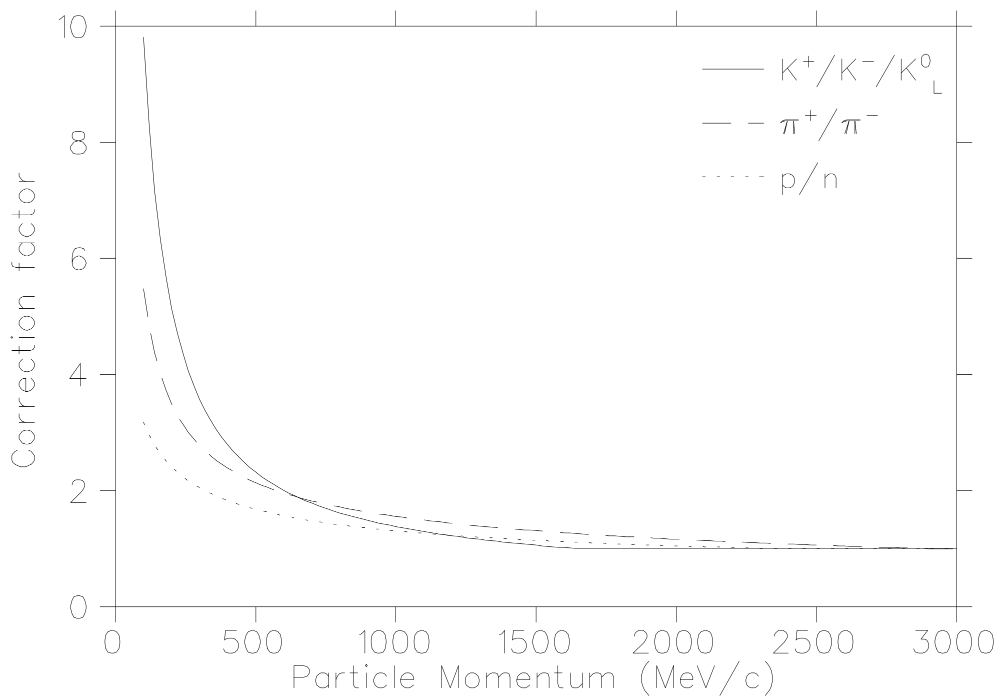



Figure 1: Correction factors applied to CsI as a function of particle type and momentum.

This correction term is amplifying the GHEISHA cross-sections in our momentum range by factors of at least 2, and is particularly bad for low momentum kaons.

## 1.3 FLUKA

FLUKA (FLUctuating KAskade) [4] is a stand alone program which simulates showers from high energy particles. Originally it was limited to very high energies, by Crystal Barrel standards, but recently much work has been done in the low energy regime. We have not tried to understand the inner workings of FLUKA. It uses many many models in different energy regimes, such as the"pre-equilibrium emission and evaporation model" which is applied at energies below 300 MeV. Suffice it to say that their various models have been used along with modern data on total, elastic and inelastic cross-sections as low as 20 MeV. They also use data on multiplicity distributions and claim to properly treat interactions of antibaryons and stopping particles like the $\pi^-$.

The FLUKA authors claim to be able to simulate inelastic collisions in detail, from energies of several TeV to about 20 MeV. Tests show that this claim is justified, $\pm \approx 20\%$, in their bench tests to measure neutron fluence and dosage in calorimeters irradiated with 24 and 200 GeV hadron beams (protons or $\pi^+$).

## 2 Generation and Analysis Procedure

Except where explicitly mentioned, all Monte Carlo was generated with GEANT 3.2100, along with correction cradle version 0.0100. This was linked to the CBGEANT code which will soon be released as version 5.00. Six different hadrons were investigated, namely $\pi^+$, $\pi^-$, $K^+$, $K^-$, $K_L$, and neutrons. For each particle, the three possible hadronic interaction packages, FLUKA, GHEISHA and GHEISHA_C were tested, with 10000 events each at each momentum point. Single particles were generated monoenergetically at momenta of 100, 200, ... 1000 MeV/c. They were generated equally in space with a vertex distribution representative of the antiproton stopping distribution in the Crystal Barrel hydrogen target. (Card SETV 9). In all cases a magnetic field of 1.5 Tesla was used. Altogether, this represents $1.8 \times 10^6$ Monte Carlo events, stored on 6 exabytes, available to anybody who is interested.

The analysis procedure was very simple and used a minimum number of cuts. The standard offline DECStation code was used, which at the time was

- CBOFF 1.23/05
- GTRACK 1.21/10
- BCTRAK 2.00/06
- LOCATER 1.52/06

For neutral hadrons, multiplicities of PEDs and tracks were studied, along with their correlation to the generated particle direction. Also PED energies etc., were looked at. No cuts were applied except as required to compare with other data analyses, as detailed in the relevant sections below.

For charged hadrons, exactly 1 good track was required, but any number of bad tracks could be present. Results were looked at with and without these bad tracks. A good track was defined to be one with at least 10 JDC hits, of which the first started before layer 5 in the JDC and for which the tracking error code was less than 29. This selection was chosen in order to make comparisons with the colinear studies described in the next sections.

Except for neutrons, the PED cuts EPEDBC and ECLUBC were set to 20 MeV. For neutrons, these were processed once at 20 MeV, and once at 10 MeV.

# 3 Charged Kaons

## 3.1 Charged Kaon Cross-sections

In figure 2, the total hadronic cross-sections for $K^+$and $K^-$ in CsI are plotted. In each case they are extracted from the GEANT 3.21 lookup tables and are plotted for the three different packages. One sees that the cross-sections are not at all consistent below 1.0 GeV/c. The abrupt step in the FLUKA curve is due to the fact that the inelastic and elastic cross-section data are known over different momentum ranges. The sharp kink in the GHEISHA_C curve is due to a cut on the maximum allowable size of the correction term.

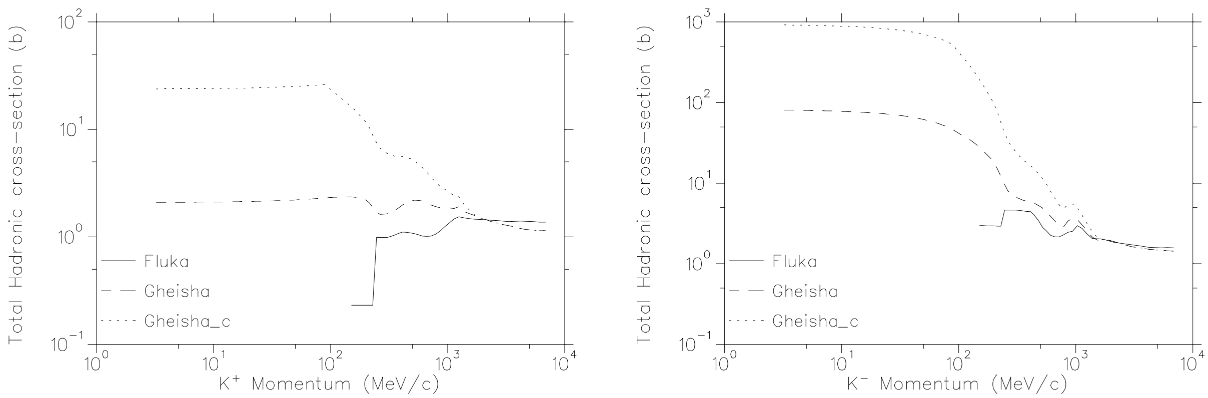



Figure 2: Total $K^+$ and $K^-$ hadronic cross-sections in CsI from GEANT.

## 3.2 Analysis Results

In the left side of figure 3 the fraction of good tracks which can be matched to PEDs in the crystals is plotted for $K^+$ between 100 and 1000 MeV/c. Two features are readily apparent; all the hadronic packages agree well, and there is a substantial hole at 200 MeV/c.

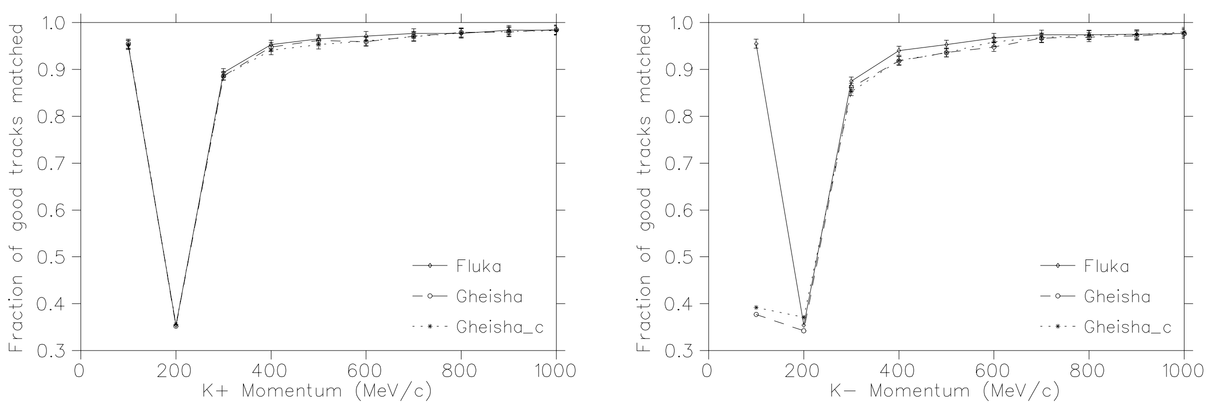



Figure 3: Monte Carlo results for $K^+$ (left) and $K^-$ (right). Plotted is the fraction of good tracks which can be matched to a PED in the barrel.

The hole can be explained by the following scenario. At 200 MeV/c the kaons have a sufficient range to enter the JDC, but generally stop in the outer walls of the JDC or the aluminum before the crystals. Since they stop before the crystals, the subsequent decay and interaction products do not match well with the projected track intersection point, and so these tracks are mostly not matched. If one plots the opening angle between the position the track would intersect with the crystals and the nearest unmatched ped, there is a broad clustering near $\cos\theta = 1.0$, but relatively few above the cut of $\cos\theta > 0.98$

At 100 MeV/c on the other hand, the charged kaons simply do not make it out of the target area. The positive kaons stop and decay, mainly via the two dominant decay modes of $K^+ \rightarrow \mu^+ + \nu_\mu$ and $K^+ \rightarrow \pi^+ + \pi^0$. The $\mu^+$ and $\pi^+$ have a relatively high momentum and give good matched tracks in the JDC and barrel. Hence these events appear to have good matched tracks, although the tracks themselves are not kaons.

However, when one looks at the corresponding plot for $K^-$, one sees that in GHEISHA, this suppression is still present at 100 MeV/c, see figure 3, which is vastly different from the prediction of FLUKA. This can be understood as in GHEISHA the $K^-$ have a very high inelastic cross-section at low momenta, and this process dominates even the ionization losses. The resulting hadronic cascade yields a few low momenta particles which then behave according to the 200 MeV/c scenario described above. In FLUKA however, the hadronic cross-sections are zero at these low momenta, and so the stopping and decay of the $K^-$ dominates, analogous to the case for 100 MeV/c $K^+$.

In the following plots, the hadronic split-offs are looked at. As single particles have been generated in the Monte Carlo, any unmatched PED is deemed to be a hadronic split-off. Figure 4 shows the number of unmatched peds per track expected for $K^-$ and $K^+$ respectively.

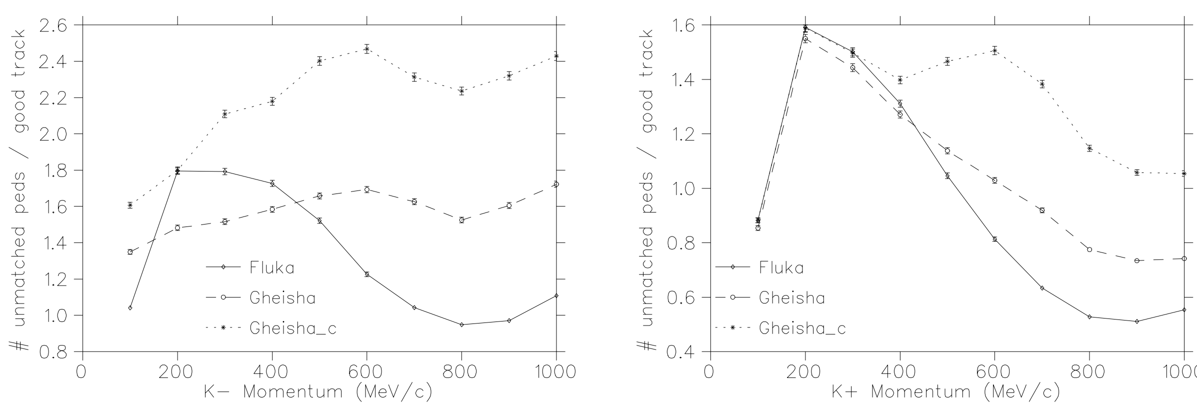



Figure 4: Monte Carlo results for $K^-$and $K^+$. Plotted is the number of split-offs per track. Note the difference in scales.

For negative kaons, all packages differ in their predictions, and one can only say that one should expect somewhere between one and two peds per track on average. For positive kaons, the expectation is lower, ranging between 0.5 and 1.6 peds per track. These can be compared with the colinear study of M. Burchell [5] who looked at colinear tracks into $\pi^+\pi^-$ and $K^+K^-$. Unfortunately, as he had two tracks to examine, he could not determine whether the split-offs arose from the negative or positive track, and could only determine a value per charged track. To facilitate the comparison, the two plots in figure 4 have been averaged to get the number of unmatched peds per kaon. The result is shown in figure 5. Burchell found 1.13 split-offs per track, at $P$ = 800 MeV/c, which is in good agreement with the results from GHEISHA.

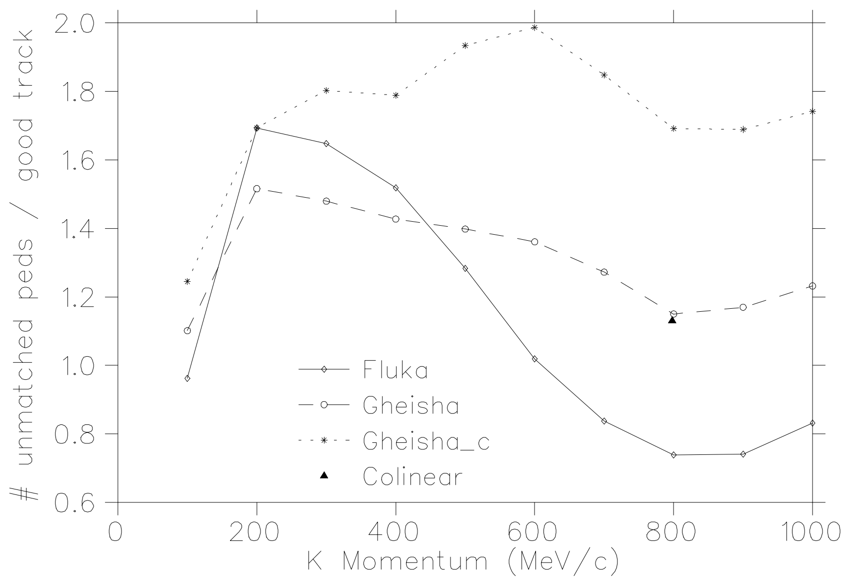



Figure 5: Combined Monte Carlo results for K$^-$and K$^+$. Plotted is the average number of split-offs per track. The value determined by Burchell from colinear data at $P$ = 800 MeV/c is also shown.

The split-off probabilities are plotted in figure 6. The results from GHEISHA and FLUKA are quite similar for positive kaons. However, for negative kaons, where hadronic cross-sections are large, the split-off probability from GHEISHA is fairly constant, about 65 to 70% at all momenta. On the other hand FLUKA fluctuates wildly between 45 and 85%. Again, this can be compared with Burchells colinear work, where he has that the

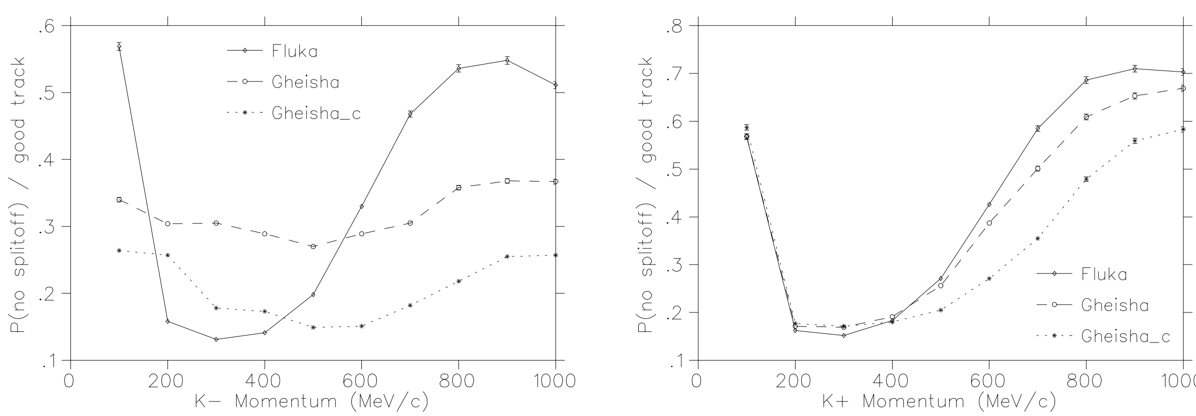



Figure 6: Monte Carlo results for K$^-$and K$^+$. Plotted is the probability that there were no split-offs associated with the track.

probability for no split-off from two tracks is 0.264 at 800 MeV/c. This can be compared with the product of the individual results for K$^+$ and K$^-$ as shown in figure 7. Burchells result favours GHEISHA slightly, while not agreeing particularly well with either.

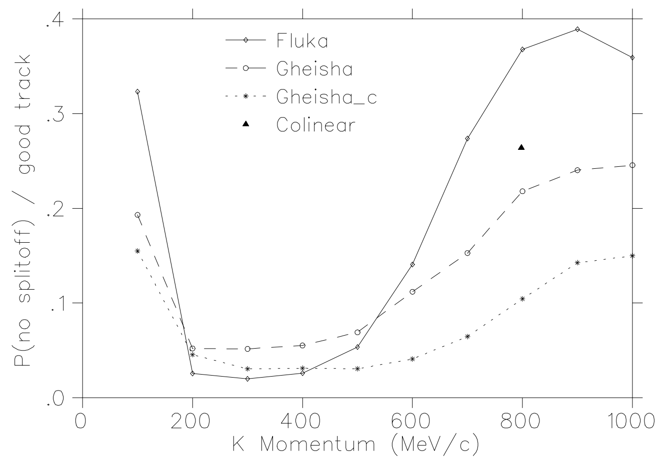



Figure 7: Combined Monte Carlo results for $K^-$and $K^+$. Plotted is the probability that neither track had a split-off.

# 4 Charged Pions

## 4.1 Charged Pion Cross-sections

For pions, the cross-sections are essentially charge independent so in figure 8 only the total hadronic cross-sections for $\pi^-$ in CsI are shown. One sees that GHEISHA_C is again quite different, but that FLUKA and GHEISHA agree quite well above about 200 MeV/c. Below 200 MeV/c, FLUKA is ill-defined, but in this region both packages have small cross-sections, so one can hope for similar results.

## 4.2 Analysis Results

In figure 9 the fraction of good pion tracks which can be matched to a PED in the crystals is plotted. One sees a good agreement between the different packages, and also with Burchels result from colinear $\pi^-\pi^+$ events, barely visible at $P = 928$ MeV/c. The dip at 100 MeV/c can be explained in the same way as the kaon dip at 200 MeV/c. In this case the increased penetrating power of the pions delays the onset of this effect until 100 MeV/c.

The details of the hadronic cascade are different for positive and negative pions, as can be seen in figure 10 where the average number of split-offs per track is plotted. FLUKA and GHEISHA are in reasonable agreement, $\pm \approx 20\%$, for $\pi^+$ interactions at all momenta. For $\pi^-$ interactions, their predictions diverge below 400 MeV/c.

Unfortunately the colinear data study is limited to pions of $P = 928$ Mev/c, which does not really probe the differences between FLUKA and GHEISHA. Non-the-less, if one averages between the $\pi^+$ and $\pi^-$ results to compare with the colinear result, one sees that at this momentum, FLUKA is preferred, see figure 11.

One can also calculate the probability that there was no split-off, which differs from the above, and again one sees, in figure 12, that GHEISHA and FLUKA are in reasonable agreement except for negative pions below 400 MeV/c.

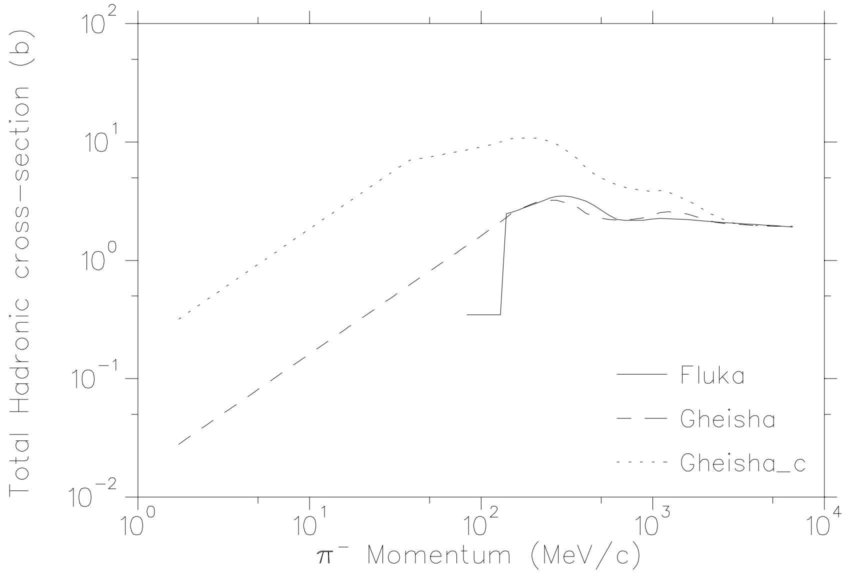



Figure 8: Total $\pi^-$ hadronic cross-sections in CsI from GEANT.

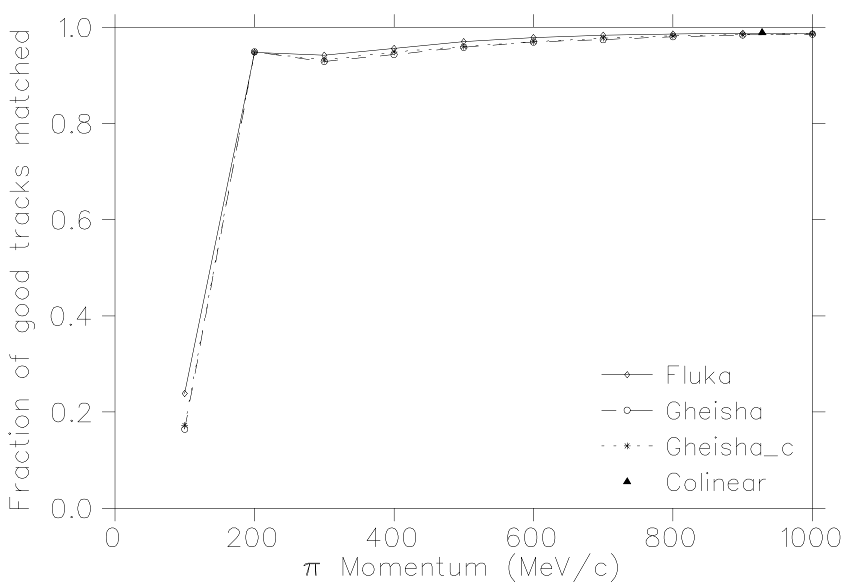



Figure 9: Monte Carlo results for pions. Plotted is the fraction of good tracks which can be matched to a PED in the barrel.

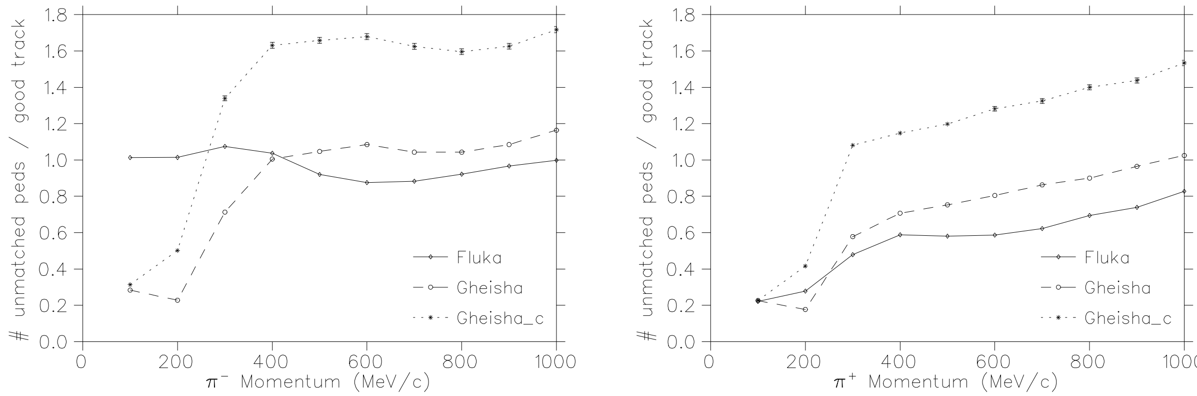



Figure 10: Monte Carlo results for $\pi^-$ and $\pi^+$. Plotted is the number of split-offs per track.

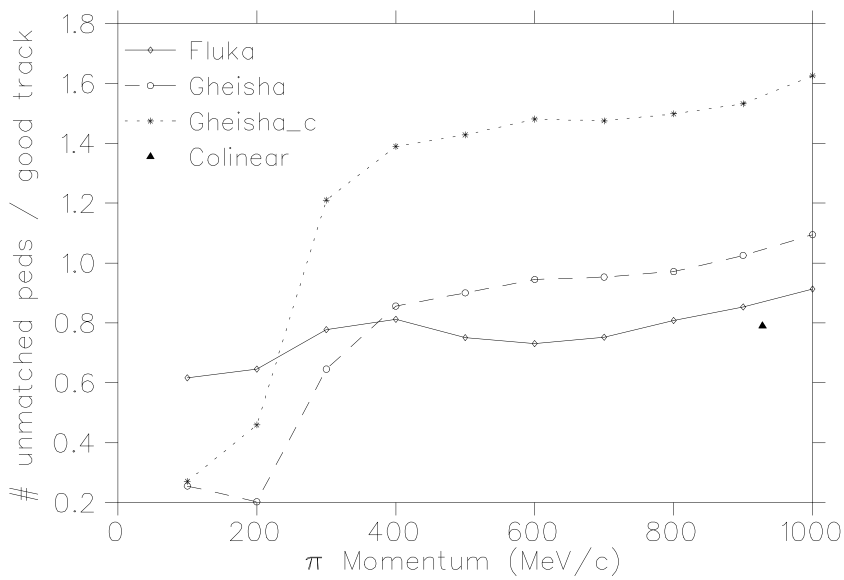



Figure 11: Monte Carlo results for pions. Plotted is the number of split-offs per good pion track.

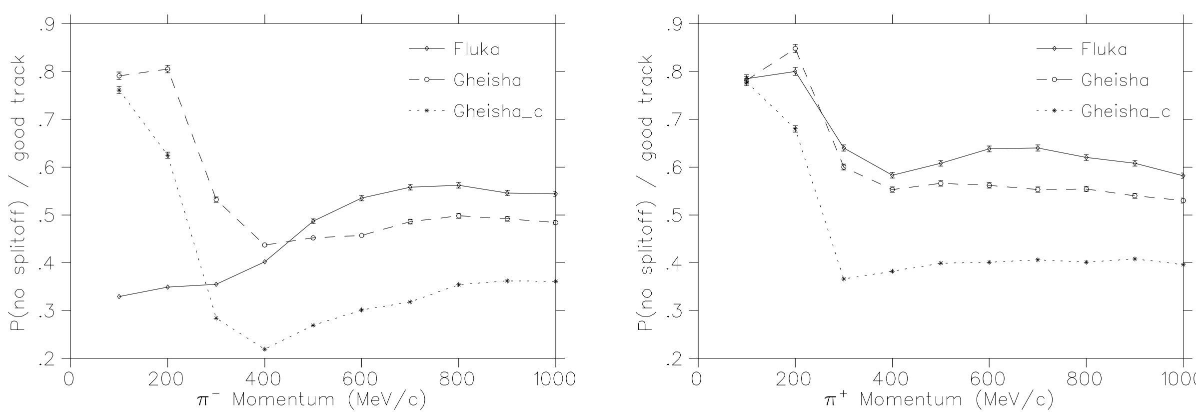
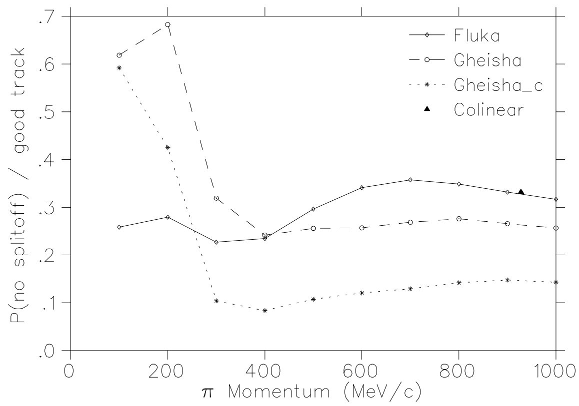



Figure 12: Monte Carlo results for $\pi^-$ and $\pi^+$. Plotted is the probability that there were no split-offs associated with the track.

If one combines these results to compare with the colinear pion results, one sees that FLUKA is again favoured at these momenta, (see figure 13).



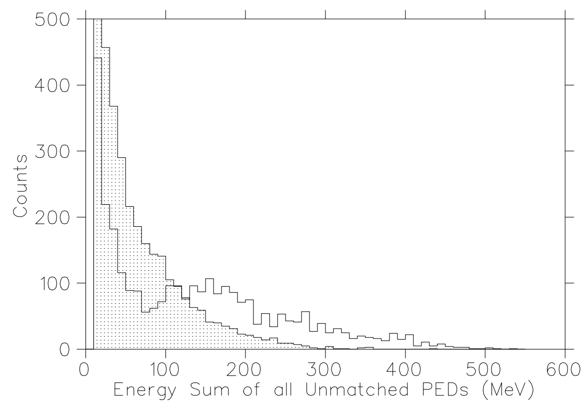




Figure 13: At left, combined Monte Carlo results for $\pi^-$ and $\pi^+$. Plotted is the probability that neither track had a split-off. At right, the energy deposited in the barrel for 600 MeV/c $\pi^+$. The shaded curve is from GHEISHA, the other from FLUKA.

Although the results for GHEISHA and FLUKA appear quite similar in the above plots, there is the possibility to distinguish between them based on other quantities which probe the details of the hadronic cascade. For example, figure 13 (right) shows the energy deposited in the barrel from unmatched PEDs originating from the interactions of 600 MeV/c $\pi^+$. There is a clear difference between the energy profiles in GHEISHA and FLUKA. A new look into the data of, for example, 4-prong $\pi^+\pi^-\pi^+\pi^-$ events might help clarify the situation.

# 5 Neutrons

## 5.1 Neutron Cross-sections

In figure 14 the total hadronic cross-sections for neutrons are plotted for the three different packages. One sees that where data exist, FLUKA and GHEISHA are in reasonable agreement. This is also true if one looks at the inelastic and elastic components separately. As usual, the GHEISHA_C cross-sections are quite a bit higher at lower momenta.

## 5.2 Analysis Results

The neutron data have been analyzed with both 10 and 20 MeV cuts for EPEDBC and ECLUBC. This was so that a comparison could be made with data extracted from the Pontecorvo reactions of Erich Schäfer [6] and the $\pi^0\pi^0\pi^0$n results from Jens Brose [7], both of which used 20 MeV cuts. Also, in previous Monte Carlo studies of neutrons by Farid Ould-saada [8] with version GEANT 3.14 and GHEISHA_C (the default), 10 MeV cuts were used. The neutron handling code has changed a lot between GEANT 3.14 and 3.21, so it is interesting to compare the two.

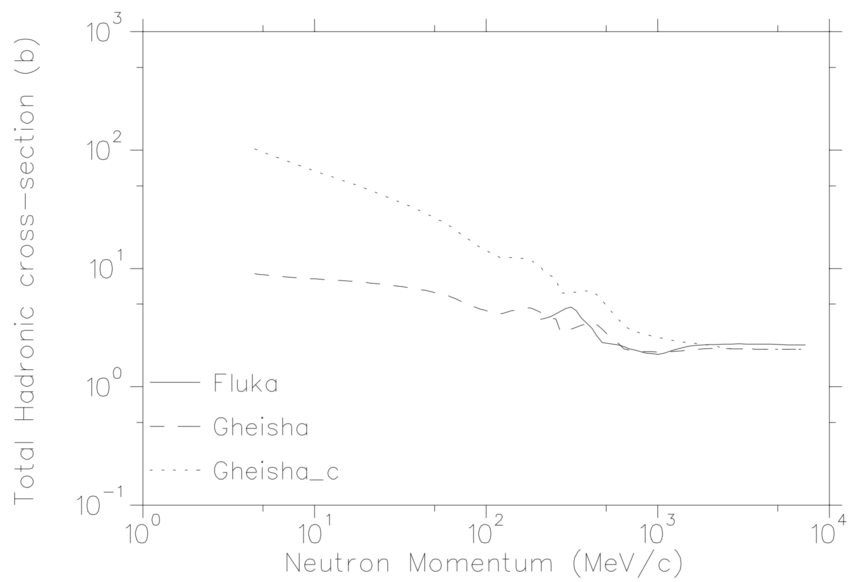



Figure 14: Total Hadronic cross-sections for neutrons in CsI, extracted from GEANT 3.21.

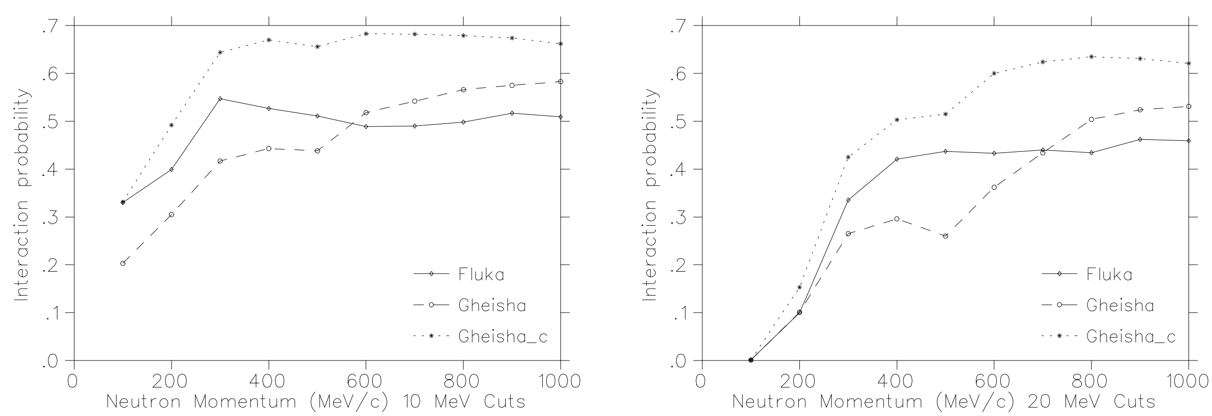



Figure 15: The neutron interaction probability according to GEANT 3.21. PED cuts were 10 MeV (left) and 20 MeV (right).

The neutron interaction probability, or the probability that at least one PED is detected in the barrel, is plotted in figure 15. FLUKA and GHEISHA are in qualitative agreement, although they differ in their predictions by about 10% between 400 and 500 MeV/c. The related quantity, the average number of PEDs per incident neutron, see figure 16, shows a similar qualitative agreement over the lower momentum range although they do start to disagree at higher momenta. There are clearly many low energy PEDs as evidenced by the much higher number of PEDs when using 10 MeV cuts rather than 20 MeV. The neutron detection efficiency is very sensitive to the PED energy cuts and hence, all analyses involving neutrons must take great care to ensure that all data and Monte Carlo are analyzed in a consistent fashion.

In order to make a comparison with the earlier work of Ould-saada a sequence of cuts analogous to his were applied. This involved the use of 10 MeV cuts, plus the removal of all events with charged tracks, plus the rejection of PEDs in crystal type 13, and the application of a primitive split-off rejection. The split-offs were defined to be those PEDs which were separated from other PEDs by less than $\cos\theta = 0.94$ and which contained less than 18% of the energy of the parent PED. After these cuts he looked at PED multiplicities. All of his work was done with GEANT 3.14, and used by default the correction term in GHEISHA. To compare the differences between 3.14 and 3.21, one should compare GHEISHA_C and GHEISHA_C_314 on the following plots with 10 MeV cuts.

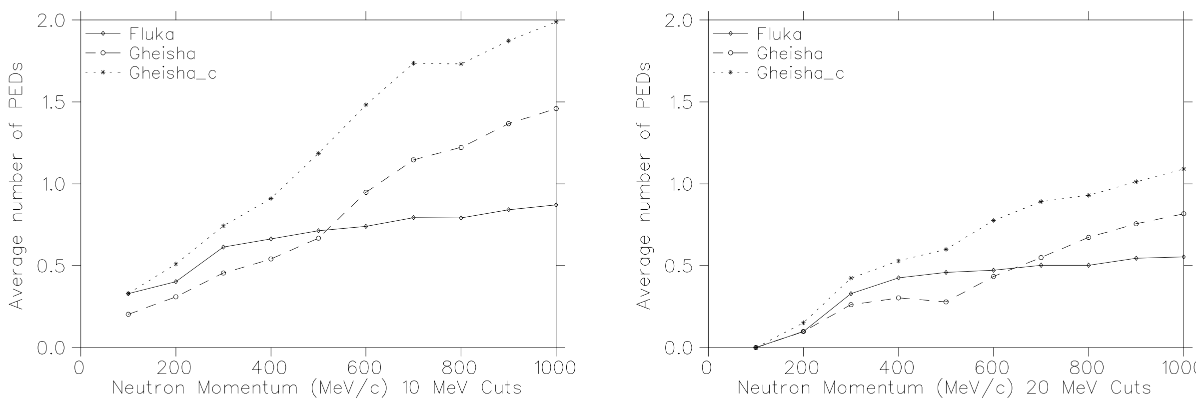



Figure 16: The average number of PEDs per neutron interaction according to GEANT 3.21. Pedestal cuts were 10 MeV (left) and 20 MeV (right).

After the application of these cuts, one sees in figure 17 the fraction of events with no PEDs, 1 PED, and multiple PEDs. One also sees that, quite naturally, the fraction of each PED multiplicity changes if one changes the PED cut from 10 to 20 MeV. It is immediately obvious that there have been enormous changes between 3.14 and 3.21. To ensure that this was not in fact some programing error on our part, Ould-saadas code was used to analyze GEANT 3.21 generated data. This test confirmed the differences between 3.14 and 3.21. In the old GEANT 3.14 there were far fewer PEDs created than with the 3.21 code.

In order to compare with results from the data analyses, it is important to realize that in these analyses each event was allowed to have at most one excess PED attributable to a neutron. The missing momentum was used to determine if there was a PED near the neutron interaction point or not. Neutrons which generated more than 1 PED were automatically excluded from these analyses. Hence a meaningful comparison with the data is possible if

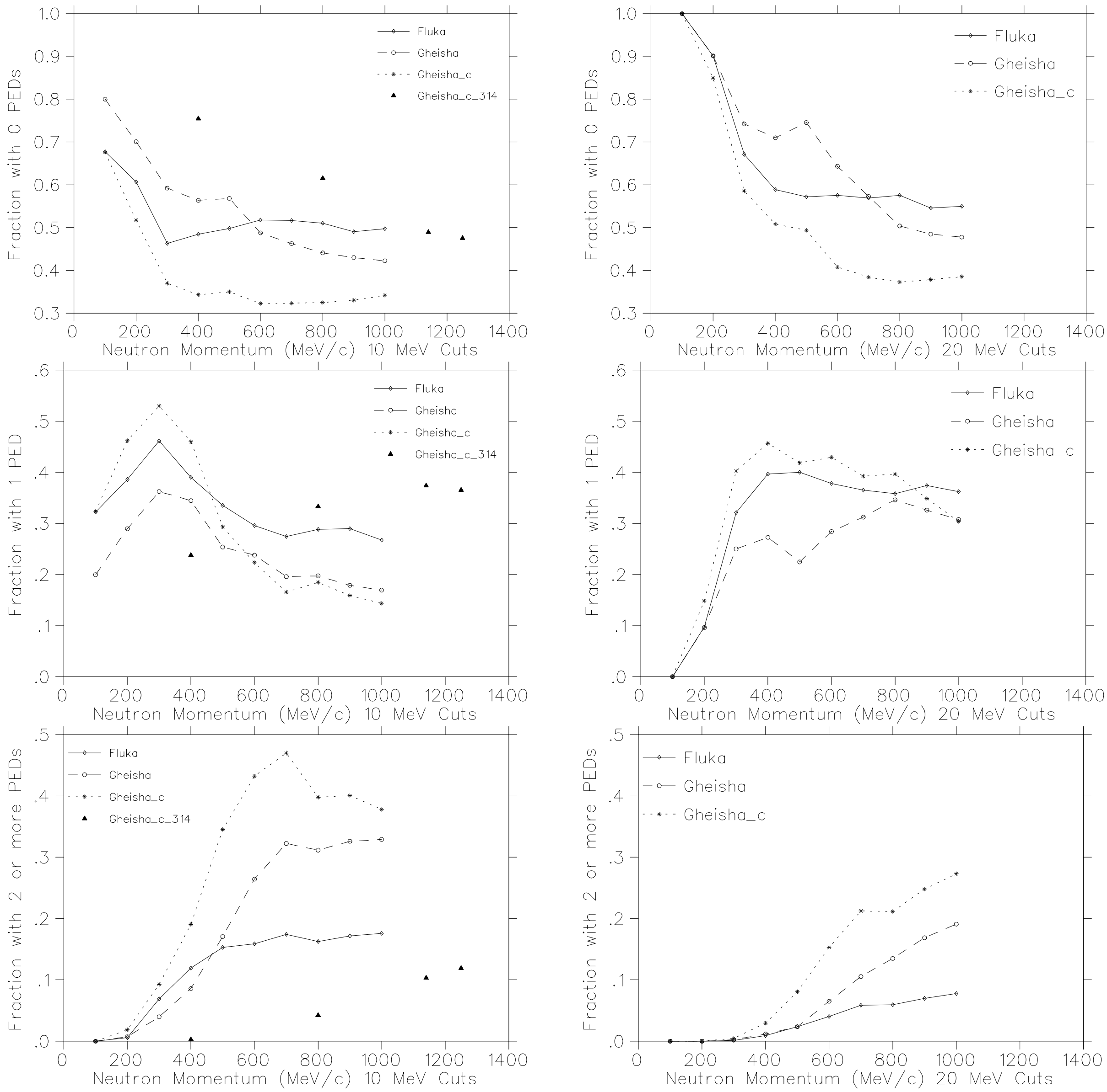



Figure 17: The fraction of neutron events with various PED multiplicities. Pedestal cuts were 10 MeV (left) and 20 MeV (right). With 10 MeV cuts, we also compare with the previous studies from GEANT 3.14.

one chooses to compare ratios of 0-PED and 1-PED events.

One set of data came from the Pontecorvo reactions studied by Erich Schäfer of $\bar{p}d \to \pi^0 n$ and $\bar{p}d \to \eta n$. These reactions produce monoenergetic neutrons with momenta of 1246 and 1183 MeV/c respectively. In the other data set, from the reaction $\bar{p}d \to \pi^0\pi^0\pi^0 n$ studied by Jens Brose, one has a continuous spectrum of neutron energies. These data are compared with the Monte Carlo predictions in figure 18. The error bars for the $\pi^0\pi^0\pi^0 n$ data have not been plotted, as the scatter gives a pretty good indication of the statistical spread, and the systematic errors are not known. In the data analysis, 20 MeV PED cuts were used.

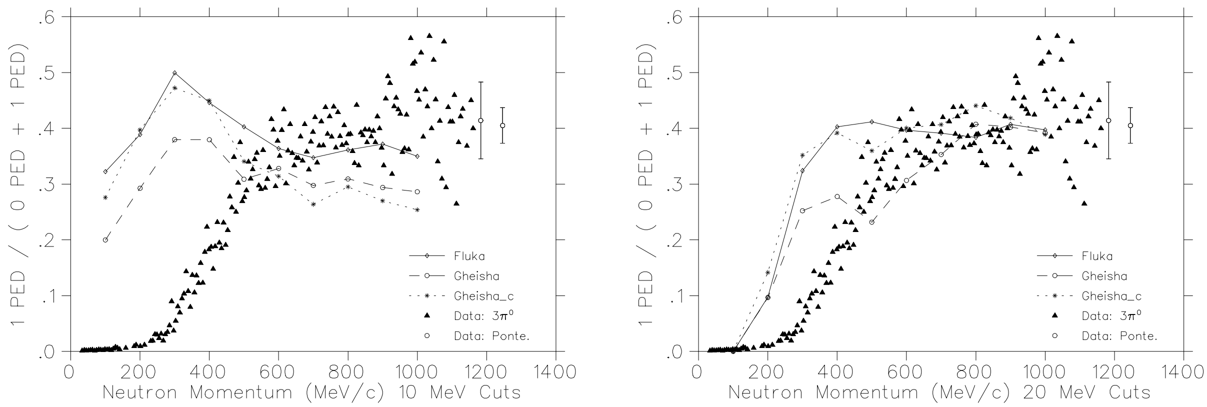



Figure 18: The ratio of events with 1 PED to the sum of 1 and 0 PED events to compare with results from the data analyses. Pedestal cuts were 10 MeV (left) and 20 MeV (right).

From the plot with the 20 MeV cuts in figure 18, one can see that the predictions are problematic in the region of momenta from 200 to 400 MeV/c, with the Monte Carlo predicting more PEDs than are seen in the data. One should be aware however, that the data results in this region probably represent more of a lower limit. This is because with 6 photons there is a fairly high probability that low energy neutron PEDs are misidentified as photon electromagnetic split-offs. Hence it may be that the neutron interactions are quite reasonably well described by GEANT 3.21, perhaps slightly favouring GHEISHA if one believes the results plotted in figure 18. One can see by comparison with the results with 10 MeV cuts, that this region is very sensitive to the PED energy and cuts in this region.

# 6 $K_L$ Interactions

## 6.1 $K_L$ Cross-sections

In figure 19 the total hadronic cross-sections for $K_L$ are plotted for the two different versions of GHEISHA. At the moment, due to a bug in FLUKA, the plotting of cross-sections from FLUKA is impossible. This appears to be due to the way it treats the $K_L$ as a mixture of $K^0$ and $\overline{K}^0$, which it doesn't resolve properly when plotting. The GEANT team claims that internally, the cross-sections for FLUKA are properly determined.

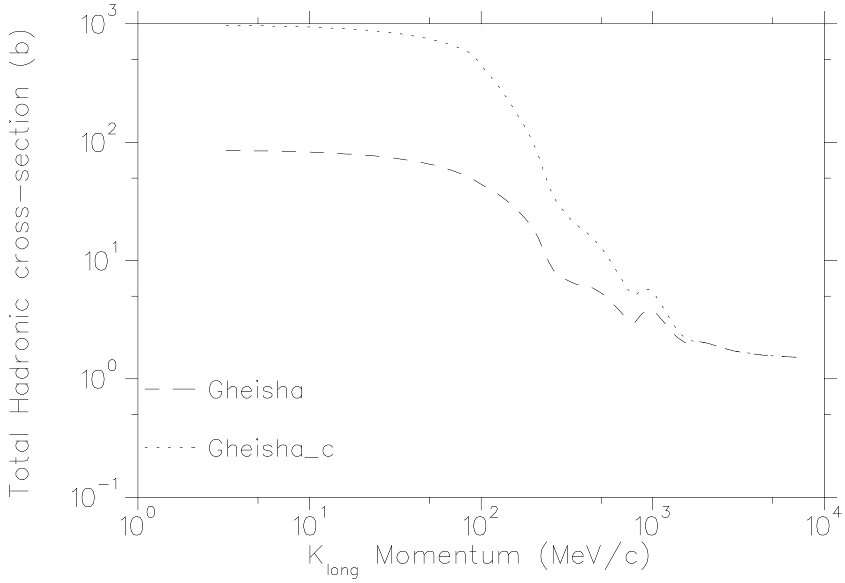



Figure 19: Total Hadronic cross-sections for $K_L$ in GEANT.

## 6.2 Analysis Results

The $K_L$ interaction probability, defined to be the probability that at least one PED is detected in the Crystal Barrel, is shown in figure 20. As most analyses with a $K_L$ in the final state have been from all-neutral data, the $K_L$ interaction probability shown here is from all-neutral data. Also shown is the value derived by Oliver Cramer [9] from $\bar{p}p \rightarrow K_S K_L$ data at rest. He looked at all-neutral events with at least 4 PEDs, and reconstructed the $K_S \rightarrow \pi^0 \pi^0$. He then attributed the remaining PEDs to the $K_L$. He had to use GEANT to determine the reconstruction efficiencies. However he calculated the efficiency for each PED multiplicity independently so that the dependence on the Monte Carlo was minimal.

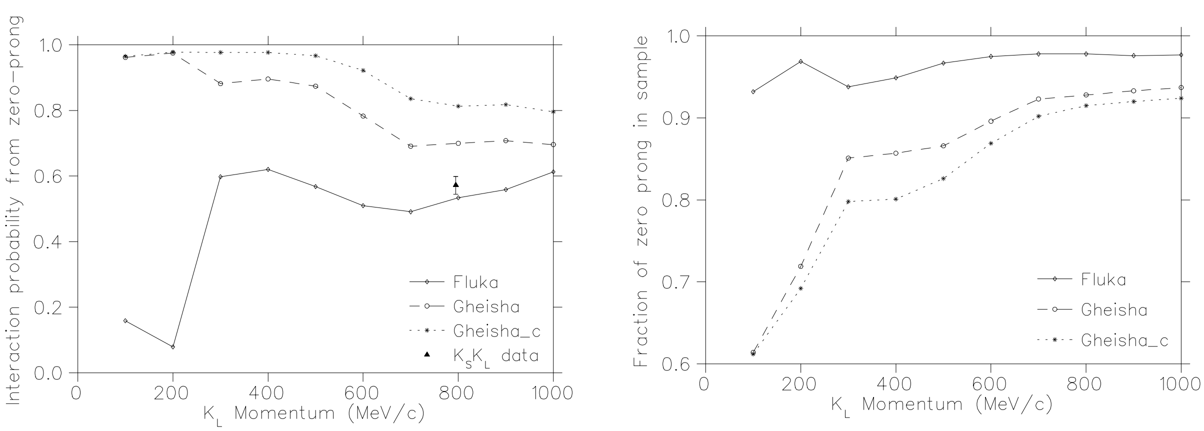



Figure 20: $K_L$ interactions: To the left is the $K_L$ interaction probability in all-neutral events. To the right is the fraction of all events which are all-neutral.

It is not a good assumption, especially at low momenta, to assume that $K_L$ interactions will not create charged tracks (see figure 20). In fact there are a significant number of tracks produced, especially at low momenta with the GHEISHA routines, as shown in figure 21, (at left). These have no particular orientation with respect to the $K_L$ direction, but are distributed evenly in space. If one looks at the number of hits in the JDC, (see figure 21, at right), it is clear that many of them are good long tracks. One can see the peaks corresponding to tracks from the origin, and to colinear like events. The peak at zero hits has been suppressed. Fortunately, these charged events appear to produce roughly the same number of PEDs as in all-neutral events, so that the actual variation in the interaction probability is only of order 5% compared with figure 20.

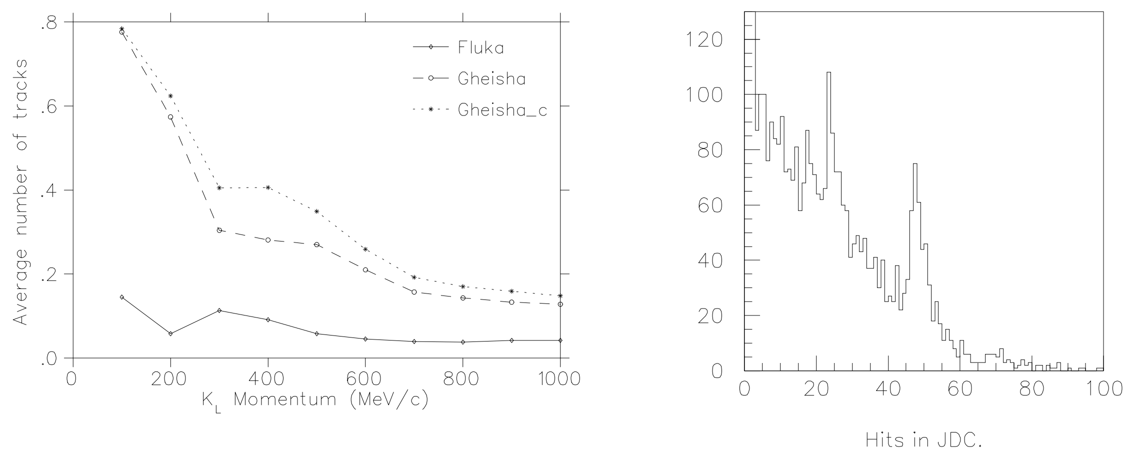



Figure 21: Charged tracks from $K_L$ interactions. To the left is the number of charged tracks per incident $K_L$. To the right, the number of hits in the JDC according to GHEISHA with 200 MeV/c $K_L$.

In figure 22 the PED distributions are examined. From GHEISHA one expects typically 1.5 PEDs per $K_L$ interaction, whereas from FLUKA only 1.0. Their predictions diverge at low momenta. From Cramers thesis an average PED multiplicity of about $1.11 \pm 0.04$ can be determined. This agrees reasonably well with the predictions of FLUKA.

There is also a result from Hans Peter Dietz's analysis [10] of the reactions $\overline{p}p \to K^0\overline{K}^0\pi^0$ and $\overline{p}p \to K^0\overline{K}^0\eta$. Here he finds an interaction probability of $(42 \pm 8)\%$ for $K_L$ in the momentum range of 200 to 700 MeV/c. Dietz claims that the interaction probability is fairly constant over this range. One can see that according to figure 20 this is quite consistent with the predictions of FLUKA, albeit a bit low.

One final comment on the $K_L$ interaction story. In the preliminary results for the channel $K_LK_L\pi^0$ which is being looked at in depth by Sven v. Dombrowski [11], it appears, although it is difficult to quantify, that the FLUKA generated Monte Carlo represents his Dalitz plot better. In his analysis he looks at 3-PED events, two of which are attributed to the $\pi^0$, and the other to an interacting $K_L$. The other $K_L$ does not interact. With FLUKA, as with data, the Dalitz plot is quite symmetric. On the other hand this symmetry is not well preserved when GHEISHA is used. This is due to the fact that in FLUKA the ratio of 0-PED to 1-PED events per $K_L$ is about 1 for most momenta so that the two $K_L$ have a similar momentum distribution.

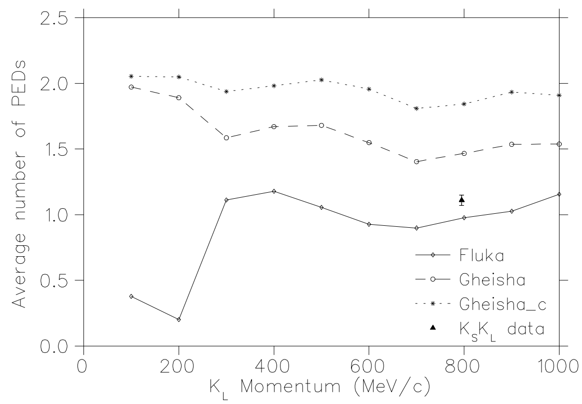



Figure 22: The average number of PEDs seen in the barrel per generated $K_L$.

He has also looked at the PED energy distributions in each case. Of course these are hard to compare as the momenta of the $K_L$ in the data are not phase space distributed and the statistics are poor. However one can see in figure 23 that FLUKA generated PEDs have the same overall characteristics as the data, including the spike at low energies, which is noticeably absent with GHEISHA.

Finally, from a sample of 10000 events each of $K_L K_L \pi^0$ generated with FLUKA and GHEISHA, and assuming about 20% background still in his Dalitz plot, one can make a preliminary estimate of the $\bar{p}p \to K_L K_L \pi^0$ branching ratio. These turn out to be $0.8 \times 10^{-3}$ for FLUKA, and $2.0 \times 10^{-3}$ for GHEISHA. The measured value for $\bar{p}p \to (K_L K_L + K_S K_S)\pi^0$ is about $1.5 \times 10^{-3}$. Taking half of this, one anticipates a $\bar{p}p \to K_L K_L \pi^0$ branching ratio of $0.75 \times 10^{-3}$, in agreement with the FLUKA result.

# 7 Conclusions

We have collected together the results from the analysis of kaon, pion and neutron interactions in our detector. Below is a summary of how the Monte Carlo packages performed when compared with available data.

- $K^+$ and $K^-$ : The Monte Carlo has only been checked against data at high momenta, where GHEISHA is slightly favoured over FLUKA. One possibility to check the cross-sections at lower momenta would be to look at the track matching for 100 MeV/c $K^+$ and $K^-$, or to look for $K^-$ decays from the target, predicted by FLUKA, and not by GHEISHA.

- $\pi^+$ and $\pi^-$ : Once again it is difficult to distinguish between FLUKA and GHEISHA, as they give similar results except for low momentum $\pi^-$. There is some possibility to distinguish between the two by looking at PED energies etc, but this necessitates a new look into the data.

- Neutrons: One can conclude first that there have been substantial changes to the handling of neutrons between the current version (CBGEANT with GEANT 3.14) and

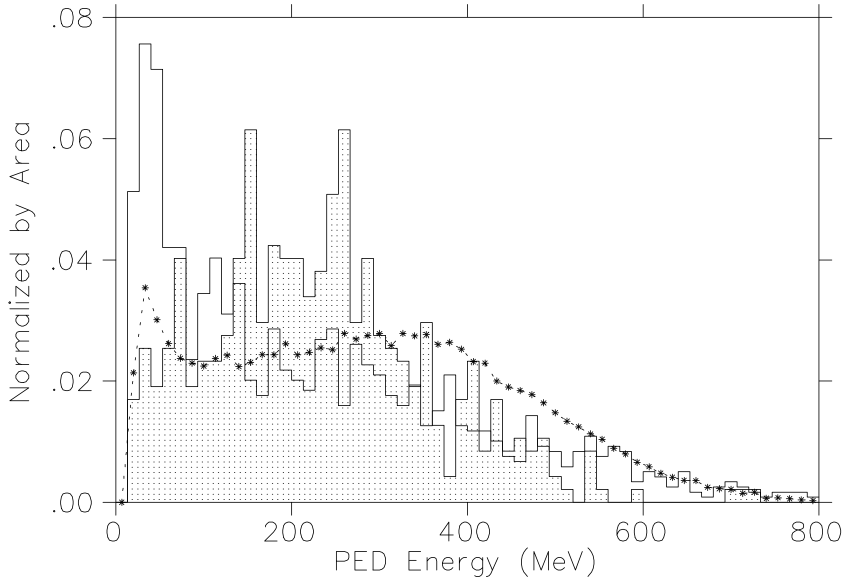



Figure 23: The PED energy distribution of PEDs not associated with the $\pi^0$ in $K_L K_L \pi^0$ data. The curve with asterisks is the data, the shaded histogram is derived from GHEISHA, and the plain histogram from FLUKA.

GEANT 3.12. In comparison with data, it appears that GHEISHA does a slightly better job at low momenta, while there is little difference at momenta above 700 MeV/c. In any case, in the most problematic region of 200 to 400 MeV/c, neither package agrees with the data.

- $K_L$ : Here it seems that nearly all tests, despite their rather rough nature, prefer FLUKA. This may be because in the GHEISHA parameterization the global fits are not really constrained to represent the $K_L$ data, (because there is so little of it). On the other hand, the behavior of FLUKA at very low momenta has not been tested, and in figure 20 one sees the rather dramatic and unexpected behavior of FLUKA below 300 MeV/c, presumably due to an abrupt change in the cross-sections.

It appears to be clear that GHEISHA_C gives an incorrect description of the data. It is difficult to choose between FLUKA and the standard GHEISHA, although depending on the application one may want to select one or the other, or try both. To this end the Monte Carlo has been changed so that the user can select either of the packages. For backwards compatibility, they may also use the correction term, although this is not recommended. GHEISHA will be established as the default, for no other reason than this is the standard default of GEANT.

Hopefully more data analysis will be done to compare with the Monte Carlo so that a clearer picture will emerge. If at least that happens, this study will have been a success. Also, we have many other results which have not been discussed here, as there was no data with which to compare, such as shower sizes, ped energies, etc. All of this exists, and the Monte Carlo tapes can easily be replayed if there is a specific interest to be looked at.

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