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A High Rate Transition Radiation Detector for Particle Identification in a Hadron Beam *

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Abstract

A Transition Radiation Detector (TRD) was built for the purpose of tagging beam particles in a high rate (~2MHz) 250 GeV/c hadron beam during data taking for Experiment 769 at Fermilab. The availability of a good "tool kit", including a Monte Carlo program which could reliably predict the detector performance, made it possible to design and build the TRD in approximately one year. Pion or proton samples, each with a small contamination due to the other, could be selected with high efficiency by making cuts on the number of planes of the TRD registering hits for each incident beam particle. The detector is expected to work well to separate kaons from pions in the 500 GeV/c negative beam for E791.

Introduction

A Transition Radiation Detector was built to separate pions from kaons or protons in the incident 250 GeV/c charged hadron beam for E769 at Fermilab. This is the first reported use of a TRD for beam particle identification in a running experiment[1], although several authors have demonstrated the ability to separate pions from the heavier hadrons in test beams at similar energies using prototype TRD's[2,3,4,5].

The Physics objectives of E769 are to measure the dependence of open charm hadroproduction on the atomic number of the target material, the kinematic variables x_F and p_t of the produced charm particle, and the flavor of the incident beam particle. A Differential Isochronous Self-Focusing Cerenkov Counter (DISC)[6] that had been used successfully to identify beam particle type for previous experiments at Fermilab in this energy regime was refurbished for use in E769, and it was decided to set it at a pressure to give a positive tag for kaons. While this single tagging element would have sufficed to identify pions and kaons in the negative beam which was 91% pions, 7% kaons, and 2% anti-protons, two tagging detectors were required for particle identification in the positive beam, which was 59% pions, 35% protons, and 6% kaons. The decision to build a TRD as the second tagging detector was motivated by several factors, among them the fact that a future run at higher energies was anticipated for which the DISC, with a limiting resolution of $\Delta\beta \geq 4 \times 10^{-7}$, would no longer be capable of separating pions from kaons. The response of the TRD, by contrast, grows with energy since the number of TR photons produced by an incident beam particle depends on its Lorentz factor, γ. There is a saturation effect which keeps this response from growing indefinitely. The energy at which this occurs depends on the materials chosen for the radiator foils and inter-foil gaps and the relative thickness of the foils and gaps. Since these parameters are rather tightly constrained by the available materials and available space, this detector can be regarded as typical of practical TRD's. The response expected for the E769 TRD is displayed in Figure 1, which shows the average number of photons produced in the radiators and detected in the xenon-filled proportional chambers as a function of energy for pions, kaons, and protons as predicted by the Monte Carlo program[7] which will be discussed further in what follows. Saturation is not included in the program calculations and thus it has been put in by hand according to the formulae in Reference 8. Also, all numbers have been multiplied by the measured efficiency of 83% for the detection of x-rays at TR energies in the chambers when the electronics threshold was set to 4 keV. This efficiency was determined by exposing a prototype chamber to x-ray sources. Figure 2, which shows the events from a typical E769 positive beam data run plotted along two axes, one of which is the number of DISC photomultiplier tubes (of 8 total) that fired, and the other of which is the number of TRD planes (of 48 total) that registered a hit above the 4 keV threshold, demonstrates the power of the two detectors used together to separate the particles by species. During the course of data taking, several calibration runs were taken for the TRD with the DISC pressure set to tag pions or protons rather than kaons as for the normal data tapes.

Since the decision to build a TRD for E769 was made only about one year in advance of data taking, the time available for design and construction was short. Fortunately, there was a good "tool kit" with which to work. This included the Monte Carlo program[7], which had been written by University of Maryland personnel to predict the performance of a prototype TRD they had built and operated in a test beam. Since there was no a priori reason to believe the results of the program, it was tested by using it to simulate the TRD that had been built at the Leningrad Nuclear Physics Institute for E715 at Fermilab[9]. This TRD had operated successfully to identify electrons with high efficiency and with a large rejection factor for pions at energies ranging from 5-80 GeV. The Monte Carlo predictions were found to be in good agreement with the measured performance of the E715 detector. Also available in the "tool kit" was the design for a multiwire proportional chamber (MWPC) with 1 mm. wire spacing and $\sim$ 3mm. anode-cathode distance, which was suited for use at the expected high rates ($\sim$2 MHz) because of the relatively short drift distances. A chamber with these design parameters had been built as a prototype for the beamline MWPC's used throughout Fermilab[10] and it was quickly reassembled for use in the source tests. Despite its small size, the maximum drift time in this chamber was measured during the run to be approximately 120 ns, since xenon is a relatively slow gas. Also, chamber electronics could be built with a minimum of new design effort by making modifications to existing designs for CDF tracking chamber amplifier cards[11,12]. Since time was short it was not possible to expose prototype chambers and readout electronics to a test beam with the appropriate γ, of order 1800, which corresponds to an electron beam of about 1 GeV. Thus an x-ray source which outputs the k_α lines of various elements[13] was the last crucial item in the "tool kit". Since these x-rays bracketed the expected TR spectrum, it was possible to predict the detector response to TR photons under different conditions by performing tests on prototype chambers with this source varying the gas fill and the high voltage settings. The only elements of the system that could not be tested before the run were the radiators, which required actual beam particles in order to produce photons. But, these could easily be replaced should it be found that the TRD performance was below that expected based on the Monte Carlo results. (The radiators were, in fact, modified once during the run for reasons that will be explained below.)

Description of the Detector

Since details of the Monte Carlo simulations and of the source testing that led to the final choice of design and operating parameters for the detector have been published elsewhere[1], only a brief description of the detector and associated electronics will be presented here. Figure 3 depicts one of the 24 modules of the TRD in plan view oriented such that the incident hadron beam entered from the left side of the figure. The 200-foil radiators were built by stacking 12.7 μm polypropylene foils alternately with 180 μm nylon net to maintain the gaps, which were flushed with helium. This was done to reduce the total amount of material in the beam. Also, helium has a lower plasma frequency than air which makes it a better gap material. Since the nylon net was found during the early part of the data taking run to attentuate the TR photons by approximately 50%, the radiators were removed and unstacked. They were restacked and replaced after cutting out the area of the nets traversed by the beam. Two MWPC planes with 1 mm wire spacing and 3.175 mm anode-cathode separation were placed following each radiator stack to detect the TR photons produced. The active area of these chambers was 7.62 cm square. The wires were .4 mil gold-plated tungsten and the cathodes .5 mil mylar with 140 Å aluminum on both sides. The active volume was filled with xenon, which has a short attentuation length for TR photons, bubbled through methylal at 0° C, which results in a mixture that is approximately 90% Xe. The xenon and helium volumes were separated by a 3.175 mm volume filled with nitrogen to prevent helium from leaking into the chamber and changing the gain. Care was taken to maintain the nitrogen and xenon volumes at the same pressure so that the cathodes would be flat and thus the gain would be uniform across the plane. The entire set of 24 radiator-chamber assemblies was 111 inches long, and the total amount of material presented to the beam by the TRD was 8.3% of an interaction length and 16.9% of a radiation length.

Figure 4 is a cartoon of the most important elements in the chamber electronics and readout system. The 64 wires in each plane were wire-or'd in groups of four into a common base, low-noise preamplifier designed by Radeka[11] for use in high-rate chambers. The signals then traveled on short coaxial cables to amplifier-shaper-discriminator (ASD) cards. These contained a pole-zero filter which shaped the pulses so that the signal resulting from capture of an Fe_{55} x-ray was ~26 ns wide. Following the filter was an amplifier with adjustable gain, which was tuned to impose system-wide uniformity. The amplified signals were input to fast LeCroy discriminators (MVL407) set to a threshold of 4 keV as determined in the source tests. These ASD cards were close copies of some that had been designed for use in CDF[12] where multiple hit capability in drift chamber cells was the goal. Here, the short integration times made it possible to use the method of cluster counting, which had been shown to give better discrimination among particle types than selection on the total integrated charge collected in each chamber plane[14]. All discriminator outputs from a single plane were input to a LeCroy 4564, which performed a logical OR of the 16 signals. The resulting plane-by-plane hit signals were input to a LeCroy 4448 latch gated by an event trigger, and the plane hit patterns were read out as part of the event data. Thus only one cluster could be registered per plane per event, but since the cluster probabilities were small, $\sim$.45 for the upstream plane and $\sim$.20 for the downstream plane of the pair, there was little loss in the TRD resolution from this choice of readout.

Detector Performance

Figure 5 shows the distribution in the number of TRD planes registering hits per event for events where the incident beam particle was not tagged by the DISC as a kaon in a typical positive beam data run, SQ1123. The proton peak averages to 3.2 planes/event and the pion peak to 14.5. Figure 6 shows the plane count distributions for DISC tagged samples where the events in a) are the tagged kaons from SQ1123, and in b) and c) are the tagged protons and pions, respectively, from TRD calibration tapes taken at approximately the same time in the data taking run. Although triggers which were within 120 ns (the TRD latch gate width, which was set to accommodate the maximum drift time in the chambers) of another were hardware suppressed, some events with two tracks going through the TRD were still recorded. These have almost all been eliminated from the distributions by making a cut on events with more than 9 (clustered) hits in the 8 planes of beam MWPC which were downstream of the TRD. However, there are still events with high plane counts remaining in the DISC tagged proton distribution. This high plane count tail appears to have the same shape as the two-track background derived from the same tape. Events with such high plane counts are well outside the range allowed by binomial statistics according to a Monte Carlo study in which the average plane count for each of the planes was input and plane hit counts were generated using these probabilities. These anomalous events constitute the only background to pions when a high enough plane count cut is imposed with the result that there is an approximately constant background of order 2% for all choices of the plane count cut above 10. Table I shows the efficiency for selection of either pions or protons and the background for each due to the other as a function of plane count cut as determined by making plane count cuts on the distributions shown in Figure 6 b) and c). The relative fraction of each in the positive beam is used in calculating the contaminations.

Table I

TRD Performance

Pions

# of TRD Planes That Fired	Pion Efficiency	Proton Contamination
≥ 8	.946	3.0%
≥ 10	.868	2.0%
≥ 12	.733	1.9%

Protons

# of TRD Planes That Fired	Proton Efficiency	Pion Contamination
≤ 6	.865	3.5%
≤ 7	.924	5.7%
≤ 8	.951	9.7%

A fit to the plane count distribution for the events not tagged by the DISC as kaons shown in Figure 5 was made using a trial distribution generated by adding together the pion and proton distributions shown in Figure 6 b) and c) in the appropriate ratios. Since the event trigger selection included the requirement that there be an interaction in the target, and since protons have a 50% larger inelastic cross section at 250 GeV/c than pions or kaons, the proton fraction in the beam has been multiplied by a factor of 3/2 relative to the other species and the three components renormalized to total 1. A small admixture of kaons (60% of the kaons but only 3% of the total in the summed distribution) has been included in the trial distribution, since approximately 60% of the kaons were outside the tightly collimated beam direction for which the DISC has good efficiency. Also added in is an assumed 2% residual two-track background modeled by using the plane count distribution for events with more than 9 clustered MWPC hits from SQ1123. The trial distribution has been normalized to the same total number of events as the data and is displayed as the dotted line in Figure 5. The resulting fit for this data tape was quite good, yielding chisquare of 43 over the 34 bins which contained data.

Expected Performance at Higher Energy

The results discussed above were obtained toward the latter part of the data taking period after it was discovered that the high beam rates coupled with high gain operation of the chambers had damaged the cathodes by removing the aluminum surfaces, which were only 140 Å thick, over the beam area. Since the chambers were larger in active area than the beam, the array was simply raised by one inch, after which the TRD behaved as it had before the damage was incurred. The gains, however, were reduced to prevent this from happening again. Thus the performance of the detector is somewhat below the Monte Carlo predictions for these data. However, as shown in Figure 7, the data and Monte Carlo were in good agreement when the gains were tuned to the settings expected by the Monte Carlo. Figure 7 compares the hit probability per event for data and Monte Carlo for each plane in the TRD. The two upper curves are the pion data (solid line) and pion Monte Carlo (dashed line). The lower solid line is the response to protons, i.e., to minimum ionizing particles in the absence of TR. While the Monte Carlo systematically overpredicts the response of the more upstream planes and underpredicts the response of the more downstream planes to TR, the agreement for each module as a whole is good. The average number of planes registering a hit per pion event for these data is 18.8 compared to the prediction of 20.0.

Figure 8 shows the predictions of the same Monte Carlo program for operation of the TRD in the 500 GeV/c negative beam for E791. The beam has been assumed to be 98% pions and 2% kaons, which is the expected ratio at this energy[15]. Figure 8 b) displays the low plane count region of Figure 8 a) with a change of scale to demonstrate that the kaons can be well separated from the pions. The cathodes for the chambers are being rebuilt in preparation for E791 using aluminized mylar that has ten times the thickness of aluminum as on the originals ($\sim$ 1400Å) to enable operation for a longer period without a significant loss of performance. Also, analog output circuits, which were used to monitor the response to on-board Fe_{55} sources to establish gain uniformity from one chamber to the next for the duration of the running period, were sampling edge wires of the chamber and therefore were not sensitive to the beam damage. These will be re-routed to sample wires which are in the beam area for E791 so that any degradation in performance will be evident immediately.

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[14] T. Ludlam et al.,"Particle Identification by Electron Cluster Detection of Transition Radiation Photons", NIM 180 (1981) 413.

[15] R. Rubinstein, "Fermilab Research Program 1988 Workbook", May 1988, Figure 18, p. 25, gives relative fluxes for negatives at 500 GeV/c as measured in the MW beamline at FErmilab.

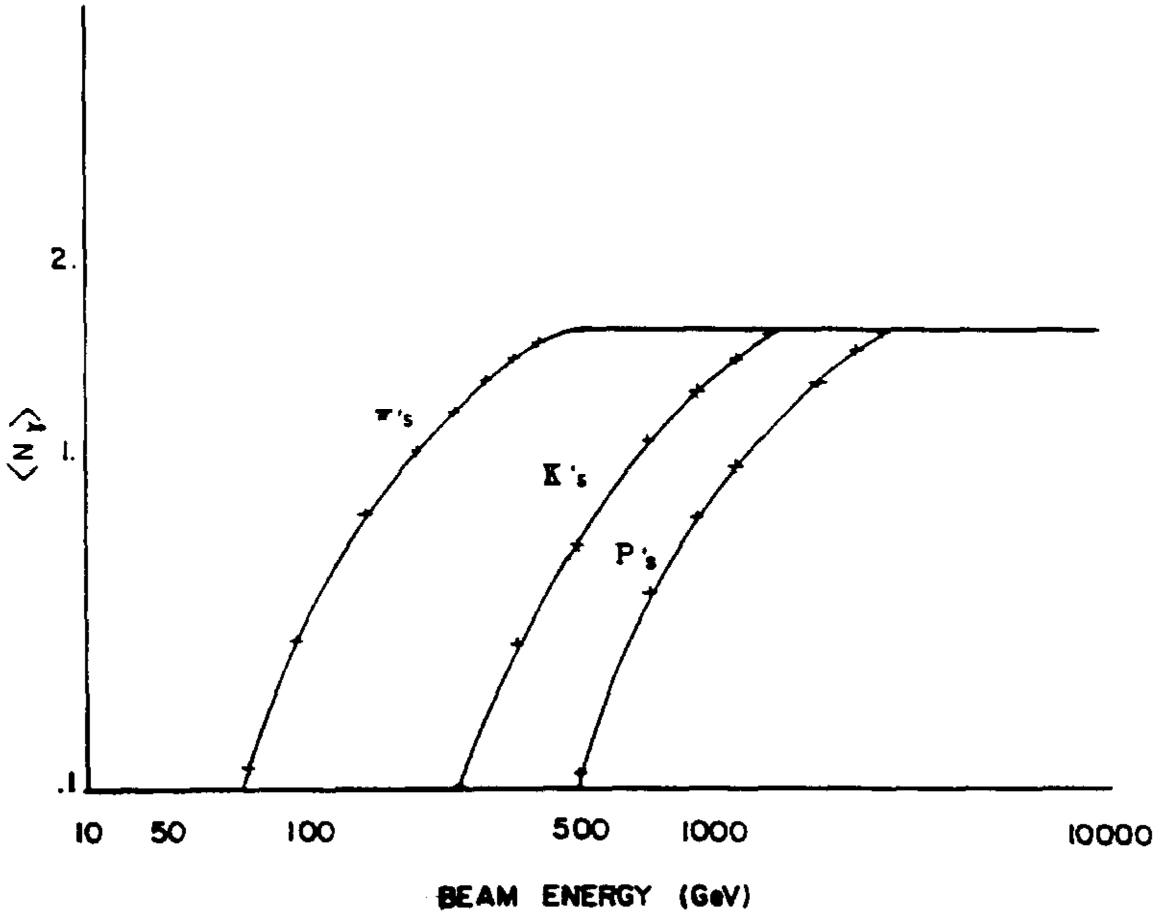

Fig 1. Average number of TR photons detected per module of the TRD for π's, K's, and p's as a function of beam energy. The efficiency factor of .83 measured in the source tests is included. γ_{sat} has been calculated using the formulae in Reference 8.

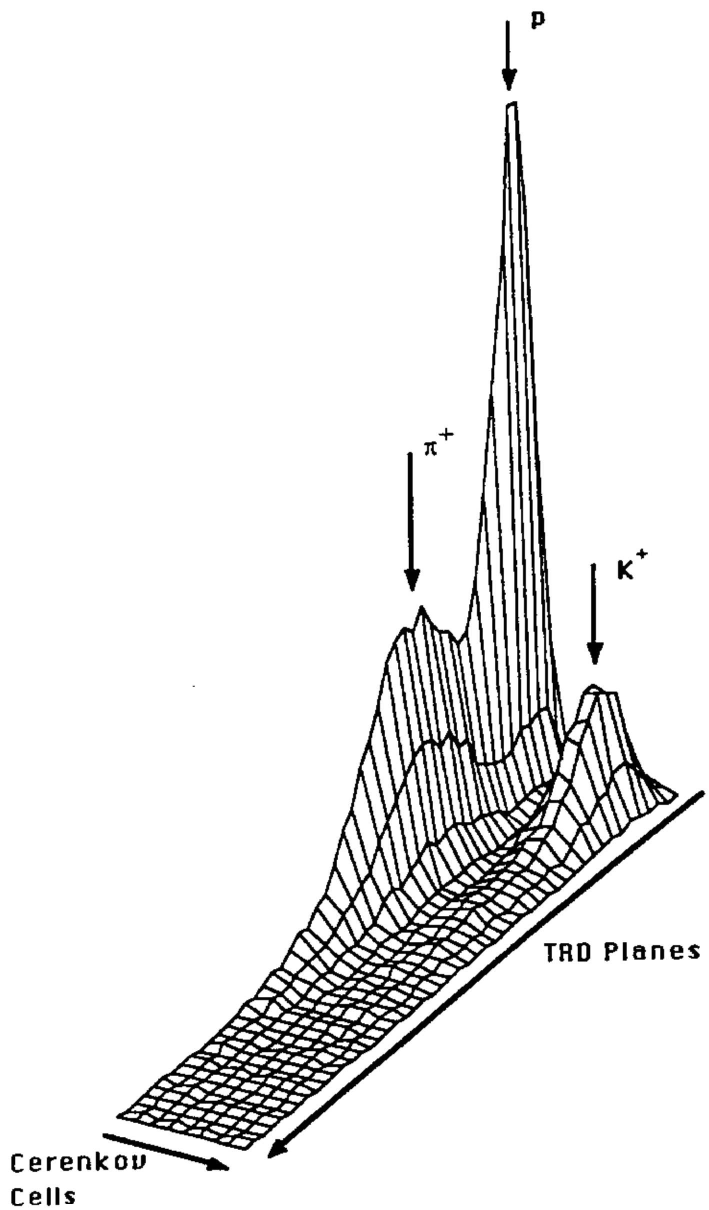

Fig 2. Distribution of events from a typical E769 positive beam data tape plotted along two axes, one of which is the number of TRD planes that fired and the other of which is the number of DISC photomultiplier tubes that fired.

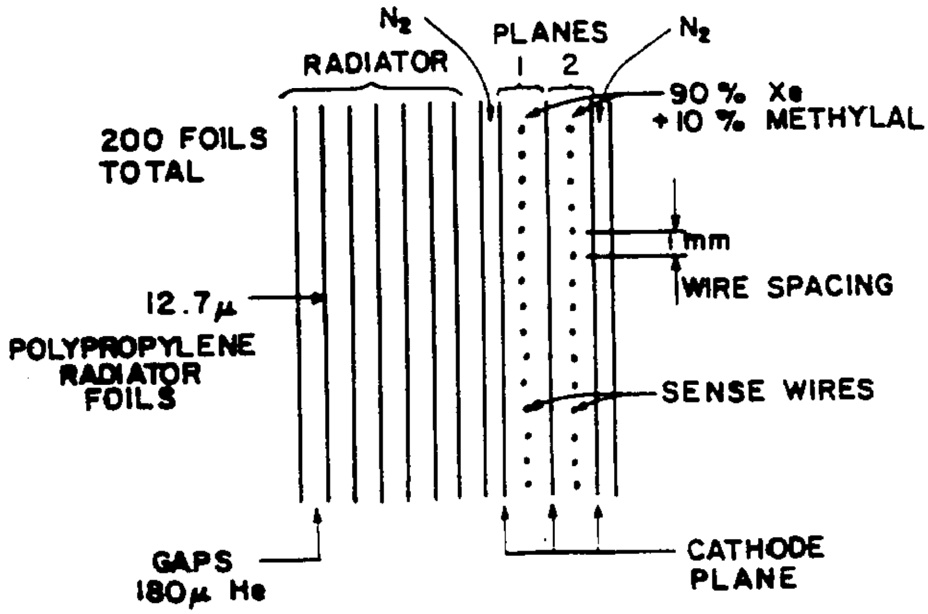

Fig 3. Schematic of one of the 24 radiator-chamber modules of the TRD.

TRD ELECTRONICS

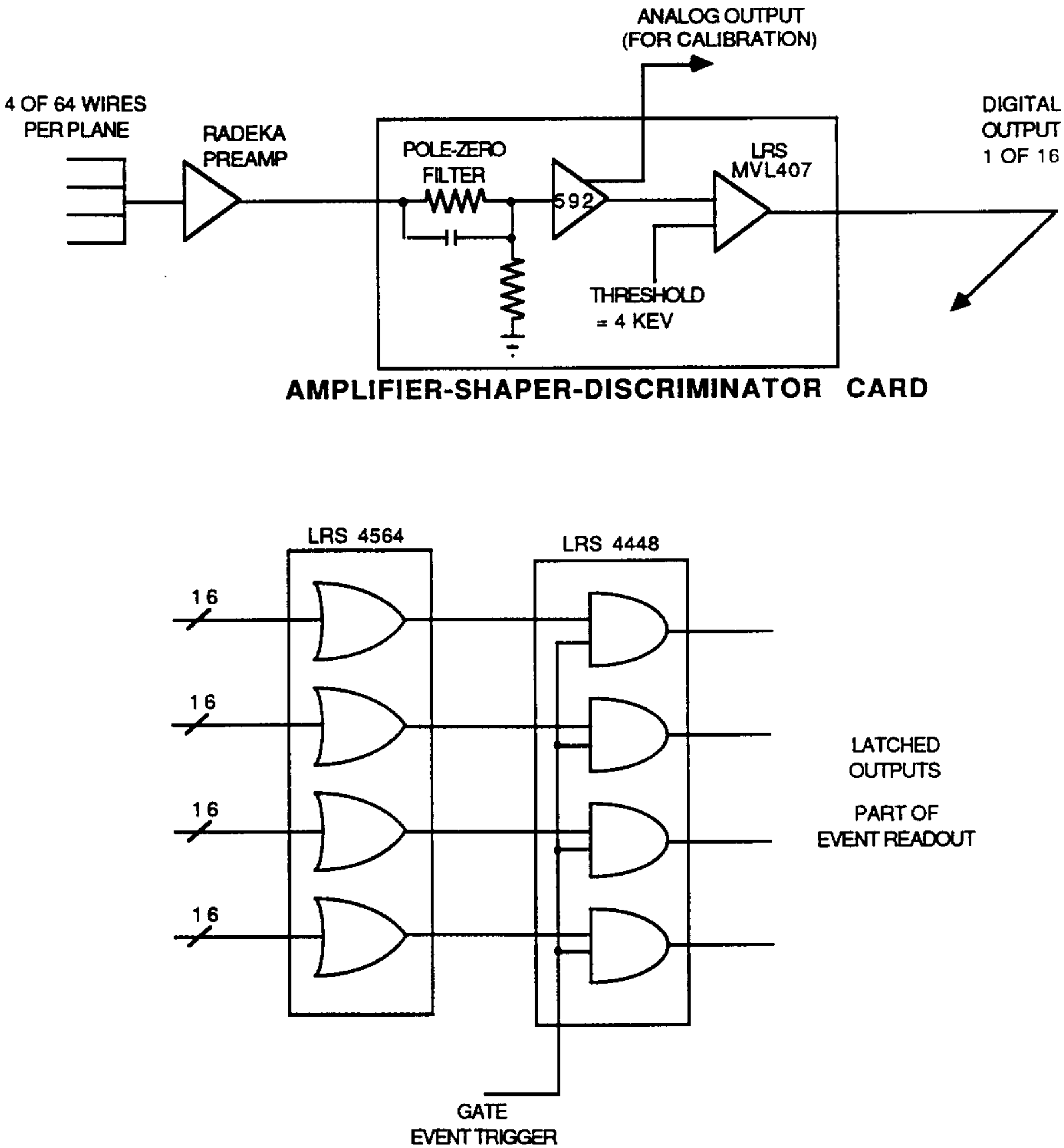

Fig 4. TRD front end electronics and read out system.

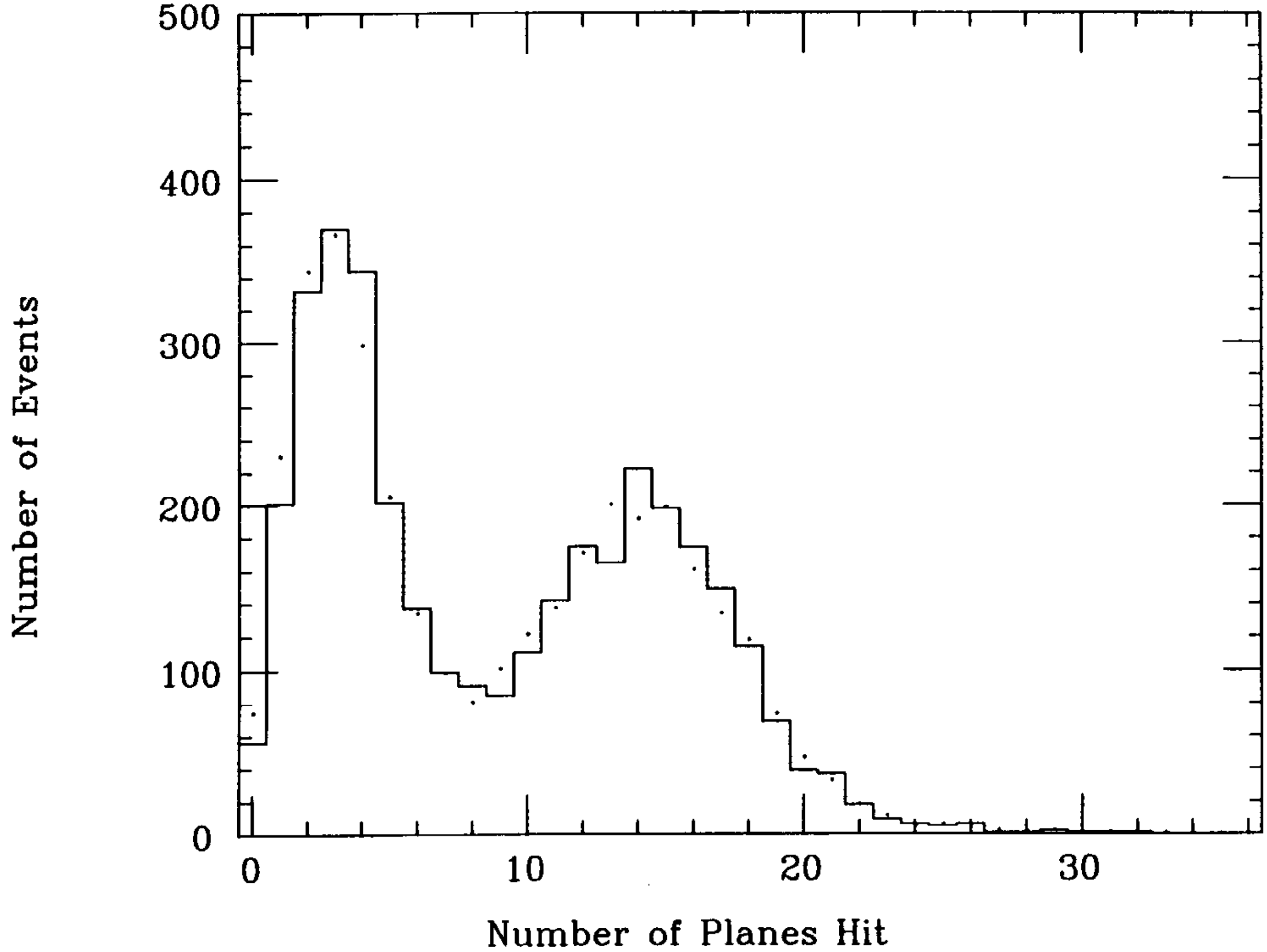

Fig 5. Number of TRD planes per event that registered a hit for events where the beam particle was not identified as a kaon by the DISC Cerenkov counter on a typical positive beam data tape, SQ1123. The dotted curve is the trial distribution made by summing the pion and proton distributions from the calibration tapes as described in the text. The trial distribution has been normalized to the same number of events as the data.

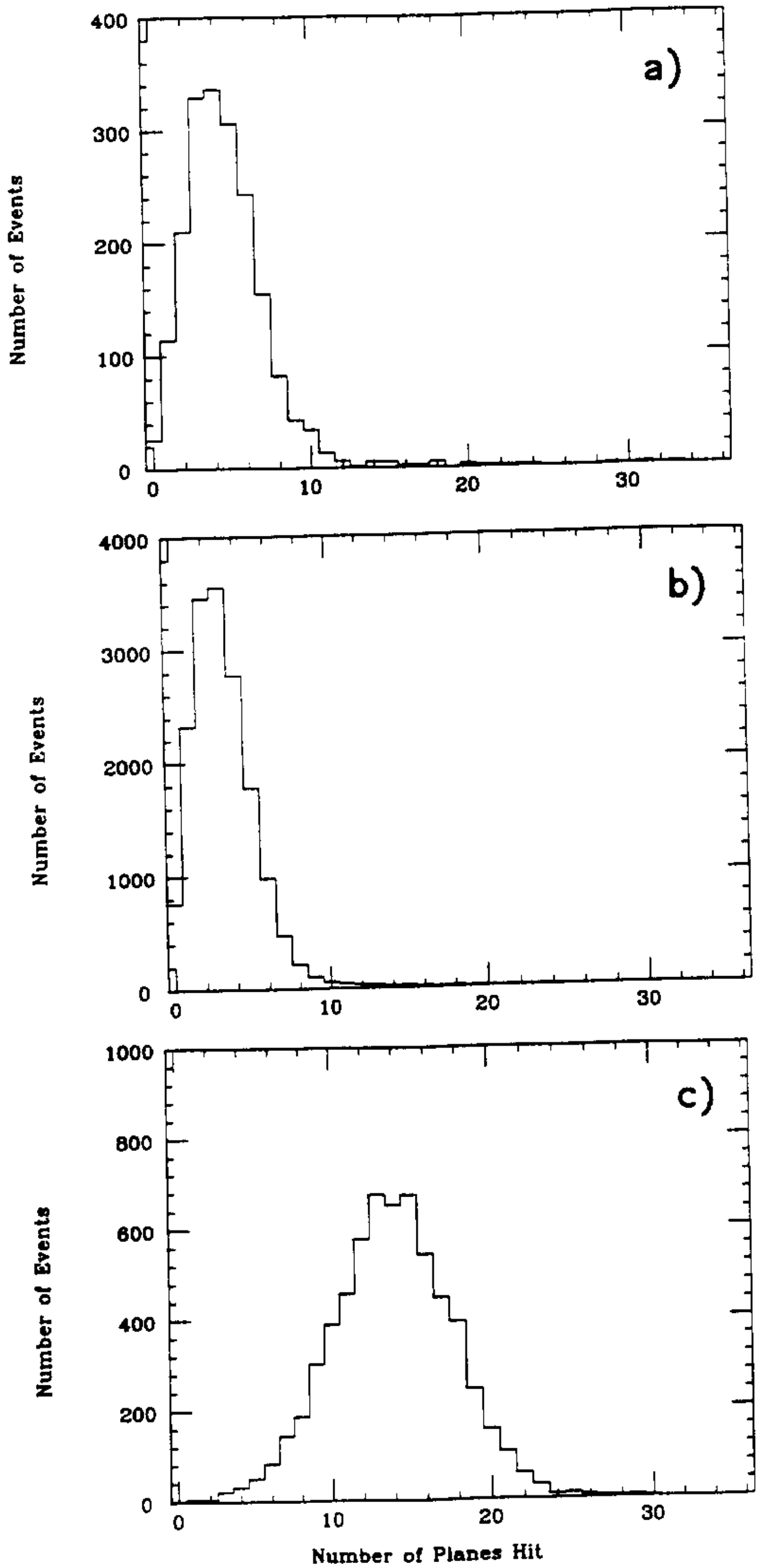

Fig 6. Number of TRD planes per event that registered hits for samples of DISC tagged events. The events shown in a) are the kaons from SQ1123. The events shown in b) and c) are the protons and pions, respectively, from calibration runs taken at about the same time in the data taking run.

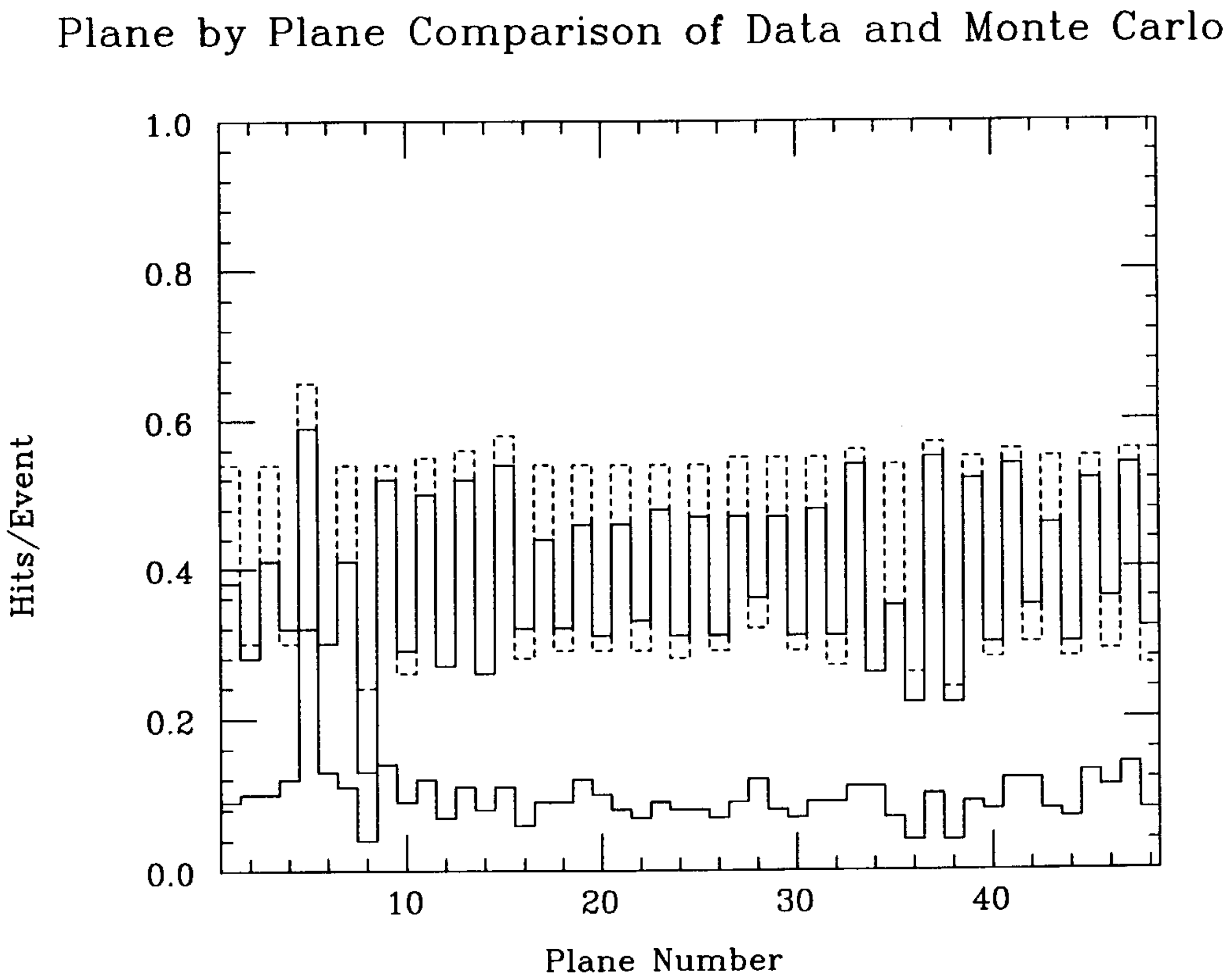

Fig 7. Hit probability per plane of the TRD per event for protons (lower solid line) and pions (upper solid line). The Monte Carlo prediction for the pion hit probability per plane per event is shown as the dashed line.

TRD Plane Count Distributions for Pions and Kaons at 500 GeV/c

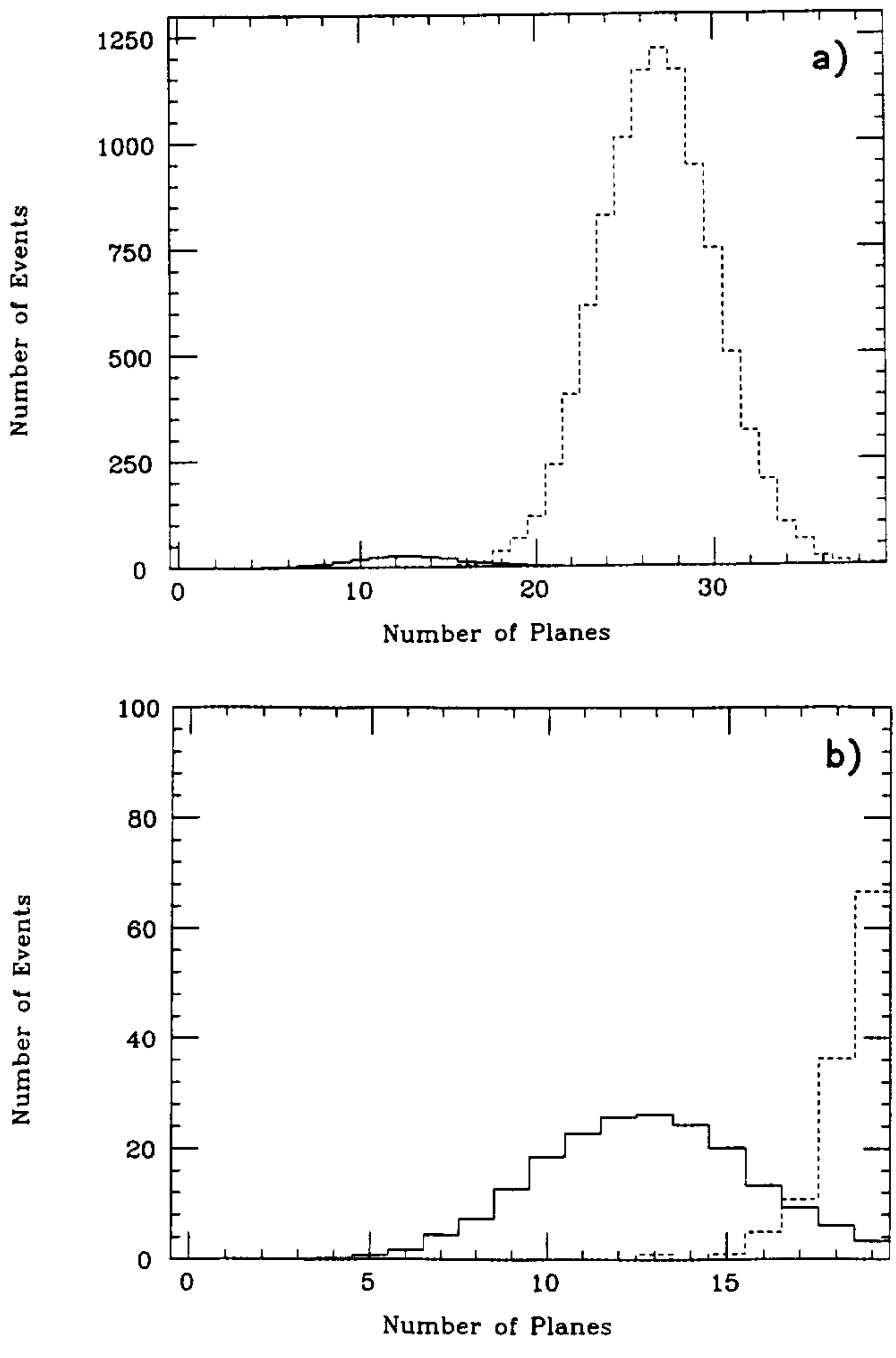

Fig 8. TRD plane count distributions for pions (dashed line) and kaons (solid line) as predicted by the Monte Carlo program for a 500 GeV/c beam incident. The kaons have been assumed to be 2% of the beam. b) is a detail of the low plane count portion of a) with a different scale to show in more detail the separation expected for the two species.