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First Result on a New Measurement of ϵ'/ϵ in the Neutral Kaon System

M. Woods, K. Nishikawa(a), J.R. Patterson, Y.W. Wah, B. Winstein,
R. Winston, and H. Yamamoto
The Enrico Fermi Institute and the Department of Physics
The University of Chicago, Chicago, Illinois 60637

E.C. Swallow
Department of Physics
Elmhurst College, Elmhurst, Illinois 60126 and
The Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637

G.J. Bock, R. Coleman, Y.B. Hsiung, K. Stanfield, R. Stefanski, and T. Yamanaka
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

G.D. Gollin, G.L. Grazer, and J.K. Okamitsu
Department of Physics
Princeton University, P.O. Box 708, Princeton, New Jersey 08544

and

P. Jarry, R. Daudin, P. Debu, B. Peyaud, and R. Turlay
Departement de Physique des Particules Elementaires,
Centre d'Etudes Nucleaires de Saclay, F-91191 Gif-sur-Yvette Cedex, France

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A new beam line and detector were constructed to increase statistical precision and greatly reduce systematic uncertainty on the ratio of the CP-nonconserving parameters ϵ'/ϵ. Major improvements are discussed together with a result from a first run: $\epsilon'/\epsilon = 0.0032 \pm 0.0028$ (statistical) ± 0.0012 (systematic). The precision is better than earlier measurements yet the result is still consistent with the superweak mechanism (which predicts zero) and that due to Kobayashi and Maskawa. Significantly more data are being collected.

CP non-conservation was first[1] observed in the $\pi^+\pi^-$ decay of the long-lived neutral kaon (K_L); this and many subsequent measurements point to a very small asymmetry in the mixing of K^0 and $\bar{K}^0$, parameterized by $|\epsilon| \simeq 2.3 \times 10^{-3}$.

A natural way of incorporating the asymmetry into the charged current weak interaction was advanced by Kobayashi and Maskawa[2] (KM) and, especially since the subsequent discovery[3] of the bottom quark, this has provided increased motivation for further studies. The KM mechanism has as one consequence a second manifestation of CP non-conservation in the $K^0(\bar{K}^0) \to 2\pi$ decay itself, parameterized[4] by the ratio ϵ'/ϵ. This is in contrast to the superweak[5] model. However, the effect is small (in the range $0.001 \lesssim |\epsilon'/\epsilon| \lesssim 0.007$) and the theoretical uncertainty is considerable.[6]

This experiment seeks to isolate such an effect by measuring the decay rates of K_L and K_S to charged and neutral pions:

$$\frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)} \simeq 1 + 6 \text{ Re } \epsilon'/\epsilon$$

Recent published experiments[7,8] had sensitivities to the above double ratio in the range of .03 to .04 and found no deviation from unity.

The technique which our group[7] has adopted in experiments at Fermilab allows simultaneous detection of K_L and K_S decays with a double neutral beam derived symmetrically from a single target; the K_S are provided by coherent regeneration from material (the regenerator) placed in one of the K_L beams. The experiment is run in two distinct modes: charged, where $\pi^+\pi^-$ are detected, and neutral, where $2\pi^0$ are detected. This approach provides good control of systematic uncertainties:

(a) Since K_L and K_S decays are detected simultaneously, time dependent losses cancel. Such losses come from triggering, accidental vetoing (e.g., from short term intensity variations), electronic drifts, and resolution changes.

(b) The momentum dependence of regeneration at high energies[9] results in nearly identical spectra for decaying K_L's and K_S's.

(c) Acceptance differences for decays from the two beams are negligible as the regenerator is frequently moved from one to the other.

K_L and K_S decays then differ only in the decay distribution along the beam so that good knowledge of the acceptance is needed. Background in K_L decays and contamination from diffractive and inelastic regeneration in K_S decays must be small and understood.

The experiment (E731) was performed in 1985 in the new Meson Center beamline at the Tevatron. The neutral beams (0.5mr × 0.5mr) were defined at 4.8mr from a Be target. A component of soft neutrons, common in previous neutral beams, was greatly reduced by an appropriate configuration of collimation and sweeping.

The detector is shown schematically in Figure 1. The regenerator was about 123m from the production target and the end of the decay region was defined by two closely spaced 1mm scintillators between which an 0.1rl lead sheet, serving as a converter for the neutral mode, could be placed ("conversion plane" in Figure 1).

The regenerator was constructed of four identical sections each consisting of 19cm of B_4C, 1.76 cm of Pb, and six anticoincidence counters. The lead provided a sharp cutoff to the distribution of $K_S \rightarrow 2\pi^0$ decays. The anticounters signaled inelastic events: corrections for these dominated the systematic uncertainty in our previous effort[7].

Charged tracks were measured with a 2000 wire-16 plane drift chamber spectrometer. Electrons and photons were identified with a circular array of 804 lead-glass blocks.[7]

In the charged mode, a signal at the "conversion plane" and a two track signature in the A and B hodoscopes were required. A 2rl lead sheet upstream of the B-hodoscope (only used in the charged mode) suppressed Ke_3 decays with a pulse-height requirement. The hodoscope after 3m of steel provided $K\mu_3$ rejection.

In the neutral mode, 30 GeV electromagnetic energy and two tracks in the A and B hodoscopes consistent with a photon conversion were required - the magnet currents were chosen to separate and then recombine the pair at the lead glass. Background in this mode is dominated by $K_L \rightarrow 3\pi^0$ decays where photons miss, or merge with others in, the lead-glass. Ten planes of anticoincidence with sensitivity above about 100 MeV were employed. One, placed in the beams, signaled photons with $E > 5$ GeV; another recognized photons close to the beam holes through the lead glass.

The events were reconstructed[10] similarly to ref. 7. The chambers had plane resolutions of approximately 150μm, and the $K^0 \rightarrow \pi^+\pi^-$ mass resolution was 3.5 MeV (rms). High statistics lead glass calibration was done periodically with electron pairs: the resolution was $\sigma/E \cong 1.5\% + 5\%/\sqrt{E}$ and the $2\pi^0$ mass resolution was 6.1 MeV.

Table 1 gives the event totals and background levels; significant improvement over ref. 7 was obtained. The improved suppression of inelastic regeneration reduced the contamination under the coherent K_S peak in the neutral mode by a factor of about five. Figure 2 shows the $K_L \rightarrow 2\pi^0$ invariant mass distribution; the array of photon vetos reduced the background in this mode by more than a factor of five.

Background subtractions were made in each 10 GeV/c momentum bin (13 charged bins from 30 GeV/c and 11 neutral bins from 40 GeV/c). The ratios of K_S to K_L decays, after correction for acceptance, were simultaneously fit for three parameters: the B_4C regeneration amplitude, its power law momentum dependence, and ϵ'/ϵ. The fit gave $|(f-\bar{f})/k| \propto p^{-0.596\pm0.009}$, consistent with past work.[9,11] The result is $\epsilon'/\epsilon = 0.0032 \pm 0.0028$ where the (statistical) error is nearly a factor of two better than in ref. 7; χ^2 was 0.98 per degree of freedom.

The sources of systematic uncertainty are associated with the accidental activity in the detector, the relative energy calibration between the two modes, the background subtractions, and the acceptance corrections.

The integration time for the lead glass signals was 250ns; as a result, the neutral mode was most affected by accidental activity: nearly 10% of otherwise good decays were lost. Since the distributions of photons in the lead glass for K_L and K_S are not exactly the same and the accidental hits are not perfectly uniform, the combined effect could in principle give an asymmetry in the loss. From a study of accidental events superimposed on Monte Carlo data, however, it was determined that the asymmetry was less than 2% of itself. The resulting systematic error was 0.20% in the double ratio.

The $\pi^+\pi^-$ energy scale was determined using the well known values for the K^0 and Λ masses. A neutral mode energy scale error will shift the vertex; however, as no vertex cut was made, the corresponding systematic error was greatly reduced. The energy scale was initially determined for each block using only the electron calibration data. A final correction of $\simeq$ 0.5% was made to adjust the edges of the vertex distributions; the residual uncertainty was estimated at 0.2% leading to an uncertainty in the double ratio of 0.21%.

The sources of uncertainties in the backgrounds were as follows (see Table 1): the $3\pi^0$ contamination (Figure 2) was determined by fitting the background shape from a Monte Carlo; the major uncertainty came from imperfectly known efficiencies of some veto planes. The backgrounds in $K_L \rightarrow \pi^+\pi^-$ were well understood semileptonic decays ($\approx$ 85%) and a small ($\approx$ 15%) non kaon decay component.

The diffractive and inelastic components under the coherent peaks in the K_S samples were rejected by cutting on the momentum transfer, P_T^2, at the regenerator. (Of course the identical cut was applied to the K_L samples.) The distributions in this variable were very well understood for both decay modes and in fact they are the same in principle. The remaining background in the neutral mode was larger due to the poorer resolution (1500 $(\mathrm{MeV}/c)^2$) of the coherent peak; the error in the subtraction was dominated by resolution uncertainties.

The remaining systematic error comes from uncertainties in the acceptances for charged and neutral decays. Very important checks were provided by consistency in the acceptance corrected momentum spectra and regeneration power laws between the two modes. In the charged mode, where the resolution on the reconstructed vertex is excellent (15cm rms), the data can be analyzed in small bins with little statistical loss, and by fitting the ratios of regenerated to vacuum events, acceptance corrections are reduced significantly. For example, with 1.5m bins the overall correction is only 0.48%. From such studies the systematic error in the charged acceptance is estimated to be 0.25%.

In the neutral mode, the poorer vertex resolution (1.1m rms) and energy scale uncertainty complicate the use of small bins. Figure 3 shows the vertex distributions compared with the Monte-Carlo; agreement is excellent but an independent check is desired. There were only three apertures for photons so that the acceptance could be readily understood: the lead-glass array (including the hardware-defined inner edge around the beam holes), a lead mask just upstream of the regenerator (see Figure 1), and a thick lead aperture surrounding the conversion plane. In a typical momentum bin, the acceptance downstream of the mask varied with vertex by only about 1% per meter, the mean decay position for K_L and K_S events differed by less than 2m, and the acceptance correction was about 2%. For the region upstream of the mask, (~10% of the K_L data) the acceptance varied more sharply (by design). Both regions were studied with over 500,000 $3\pi^0$ decays having even greater acceptance variations; there was no disagreement with Monte-Carlo outside statistics. Furthermore, a consistent result was obtained discarding the upstream events although then the error from an energy scale uncertainty increased to about 0.4%. From these studies, the uncertainty in the neutral mode acceptance correction was estimated at 0.50%.

The total systematic error on the double ratio is given by combining all the above (uncorrelated) uncertainties in quadrature yielding an error of 0.75%. The result is $\epsilon'/\epsilon = 0.0032 \pm 0.0028$ (statistical) ± 0.0012 (systematic). Combining these errors in quadrature gives $\epsilon'/\epsilon = 0.0032 \pm 0.0030$. This is consistent with previous measurements while being more precise by nearly a factor of two; however, the superweak and KM models are both still viable. The experiment is running with upgrades and a significant increase in statistical precision is expected.[12]

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[a] present address: Institute for Nuclear Study, University of Tokyo

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9. See A. Gsponer et al., Phys. Rev. Lett. 42, 13 (1979).
10. The analysis and detector are fully described in the Ph.D. theses of P. Jarry and M. Woods (unpublished).
11. Here $f(\bar{f})$ is the forward $K^0(\bar{K}^0)$ scattering amplitude and k is the kaon wave number. The fit included interference with K_L decays.
12. Another experiment with a different technique at CERN (NA31) has the preliminary result $\epsilon'/\epsilon = 0.0035 \pm 0.0007$ (statistical) $\pm$ 0.0012 (systematic) $\pm$ 0.0004 (Monte-Carlo), and it also will acquire more data. See the review by I. Mannelli, to be published in the proceedings of the International Symposium on Lepton and Photon Interactions, DESY, Hamburg, July 1987.

Table 1. Event total, mass cut, and background summary for each mode

Mode	Events[a]	Mass cut	Background[b] [%]	Improvement[c]	Systematic error [%]
$K_L\to 2\pi^0$	6747	$\pm 3.3\sigma$	1.56	÷ 5.4	0.30
$K_S\to 2\pi^0$	21788	$\pm 3.3\sigma$	2.90	÷ 5.0	0.20
$K_L\to \pi^+\pi^-$	35838	$\pm 3.9\sigma$	1.23	÷ 2.5	0.18
$K_S\to \pi^+\pi^-$	130025	$\pm 3.9\sigma$	0.30	÷ 5.7	0.03

[a] After subtractions

[b] Residual non $\pi\pi$ background for K_L modes; diffractive and inelastic contribution for P_T^2 <250 (4000) [MeV/c]^2 for $\pi^+\pi^-$ ($2\pi^0$) K_S modes.

[c] With respect to ref. 7.

Figure Captions

Figure 1 Detector schematic, elevation view.

Figure 2 Reconstructed $\pi^0\pi^0$ invariant mass for K_L. The $3\pi^0$ background shape determined from Monte Carlo is superimposed.

Figure 3 Reconstructed decay vertex for $K_{L,S} \to 2\pi^0$, data and Monte Carlo.

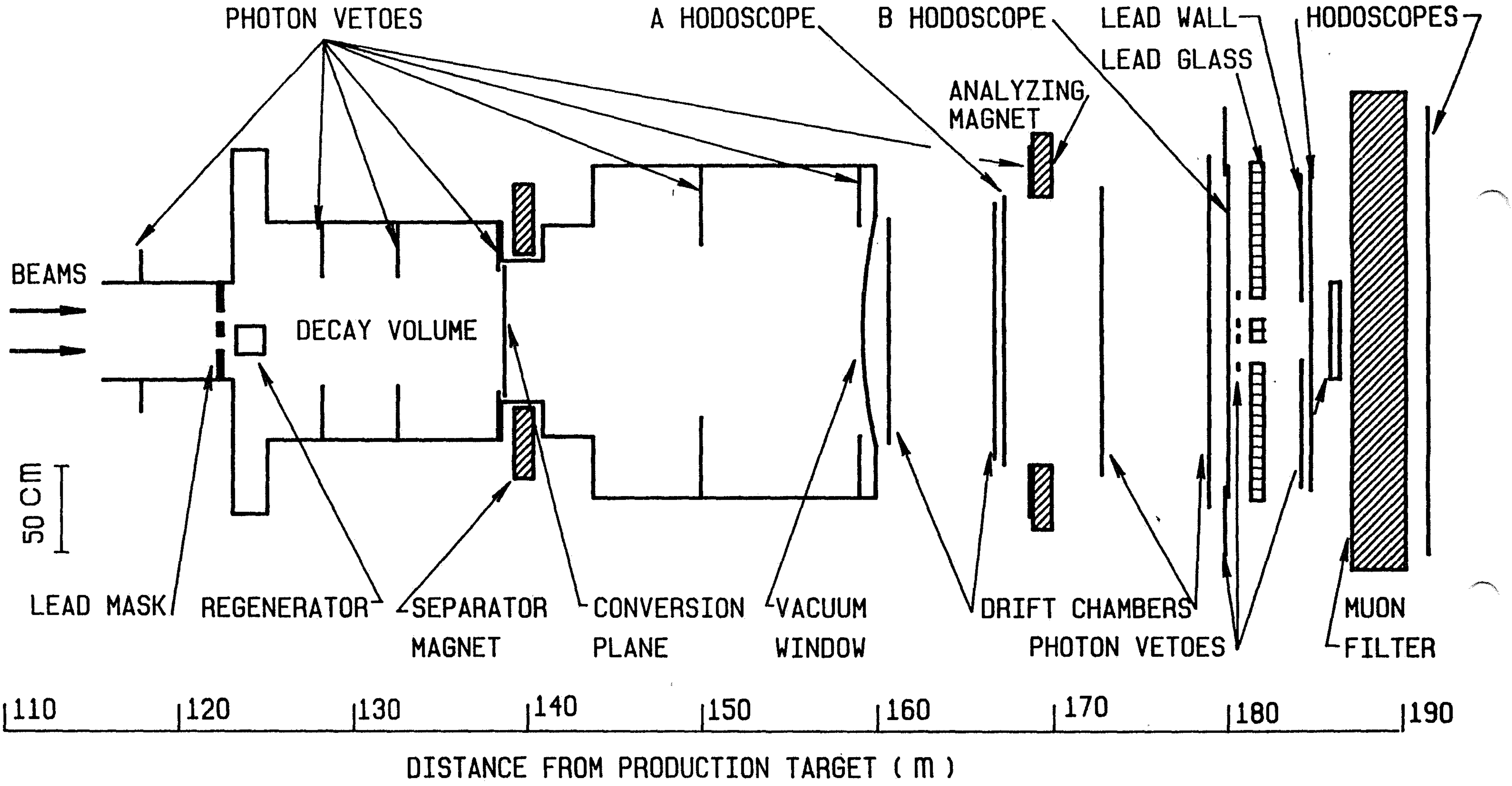
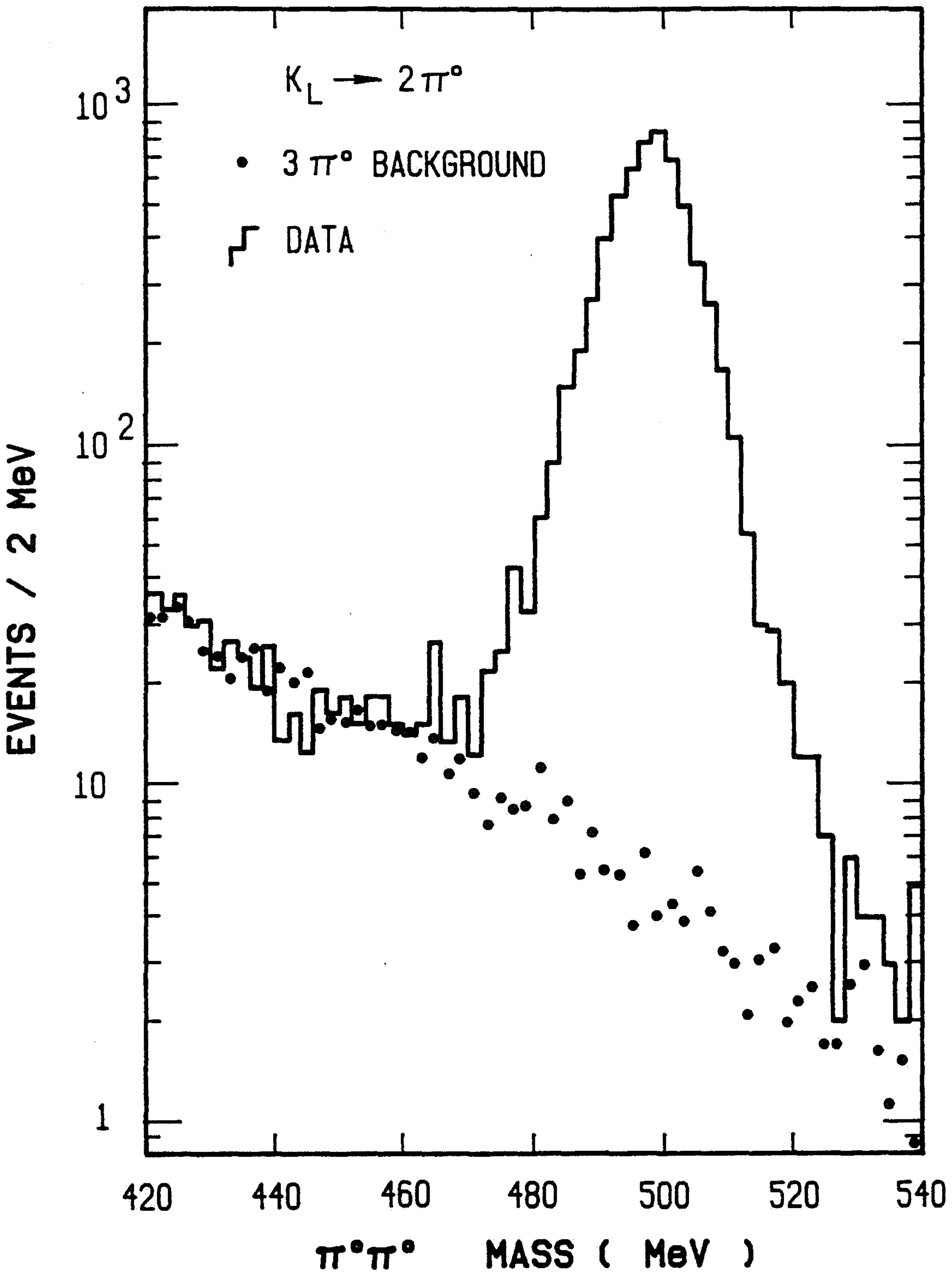

PHOTON VETOES
A HODOSCOPE
B HODOSCOPE
LEAD WALL
HODOSCOPES
LEAD GLASS
ANALYZING MAGNET
BEAMS
DECAY VOLUME
50 cm
LEAD MASK
REGENERATOR
SEPARATOR MAGNET
CONVERSION PLANE
VACUUM WINDOW
DRIFT CHAMBERS
PHOTON VETOES
MUON FILTER
110
120
130
140
150
160
170
180
190
DISTANCE FROM PRODUCTION TARGET (m)

Figure 1



$K_L \rightarrow 2\pi^0$
● $3\pi^0$ BACKGROUND
DATA
EVENTS / 2 MeV
10^3
10^2
10
1
420
440
460
480
500
520
540
$\pi^0\pi^0$ MASS (MeV)

Figure 2

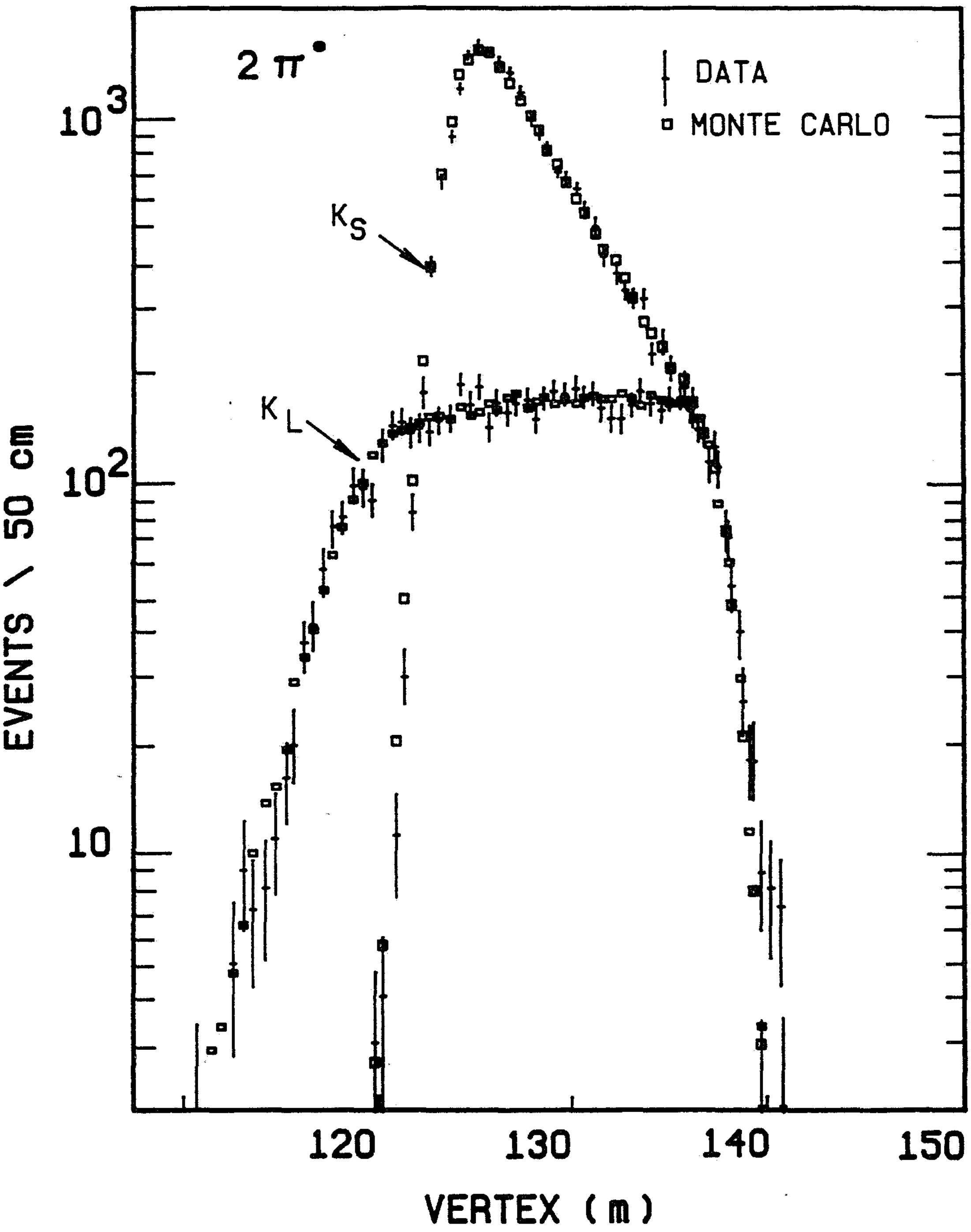

2 π°
DATA
MONTE CARLO
K_S
K_L
10^3
10^2
10
EVENTS \ 50 cm
120
130
140
150
VERTEX (m)

Figure 3