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A Study of _Direct_ CP Violation in the Decay of the Neutral Kaon via a Precision Measurement of $|\eta_{oo}/\eta_{+-}|$

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ABSTRACT

In this proposal, we describe an experiment to measure the ratio R of the CP violating amplitudes $|\eta_{oo}|$ and $|\eta_{+-}|$ to a precision of better than 1% thereby improving the present results by about one order of magnitude. If the CP violation is confined to the mass matrix, R = 1.0 exactly. Recent theoretical considerations which unify the CP violating interaction with the CP conserving weak and electromagnetic interactions among six quarks predict R differing from 1.0 by sizable amounts.

I. Introduction and Motivation

We propose to study the contribution of direct CP violation in the decay $K_L \rightarrow 2\pi$ (whose size is governed by ε') in contrast to the dominant contribution (ε) which arises from the CP impurity of the K_L.

Let us define $|K_2>$ and $|K_1>$ to be the CP eigenstates in the K^o system:

$$|K_2> \equiv \frac{|K^o> - |\overline{K}^o>}{\sqrt{2}} \qquad CP = -1$$

$$|K_1> \equiv \frac{|K^o> + |\overline{K}^o>}{\sqrt{2}} \qquad CP = +1$$

Then allowing for CP non-conservation, the observed decay eigenstates, K_L and K_S, can be written:

$$|K_L> = \frac{|K_2> + \varepsilon|K_1>}{(1 + |\varepsilon|^2)^{1/2}}$$

$$|K_S> = \frac{|K_1> - \varepsilon|K_2>}{(1 + |\varepsilon|^2)^{1/2}}$$

where ε is the small (complex) amplitude specifying the CP impurity of the decay eigenstates.

Suppose now that there is no direct CP violation, i.e., the K_2 does not decay to two pions. Then clearly

$$\frac{\text{amp } (K_L \rightarrow 2\pi)}{\text{amp } (K_S \rightarrow 2\pi)} = \varepsilon$$

In particular, if we define

$$\eta_{+-} = \frac{\text{amp } (K_L \rightarrow \pi^+\pi^-)}{\text{amp } (K_S \rightarrow \pi^+\pi^-)}$$

$$\eta_{oo} = \frac{\text{amp } (K_L \rightarrow 2\pi^o)}{\text{amp } (K_S \rightarrow 2\pi^o)}$$

we would have

$$\eta_{+-} = \eta_{oo} = \varepsilon.$$

This is the so-called "super-weak" prediction which confines the CP violation entirely to an impurity in the decay eigenstates.

To consider the case where $K_2 \rightarrow 2\pi$ is allowed, we must decompose the $\pi\pi$ final states into an I = 0 and I = 2 part. Using the standard notation[1] for the neutral kaon system, we find

$$\eta_{+-} = \varepsilon + \varepsilon' \qquad (1)$$

$$\eta_{oo} = \varepsilon - 2\varepsilon' \qquad (2)$$

where

$$\varepsilon' \equiv \frac{\text{Im } (A_2/A_o)}{\sqrt{2}} \; e^{i\left(\frac{\pi}{2} + \delta_2 - \delta_o\right)}, \qquad (3)$$

$$A_2 \equiv \text{amp } (K^o \rightarrow 2\pi \; (I = 2))$$

$$A_o \equiv \text{amp } (K^o \rightarrow 2\pi \; (I = 0))$$

and δ_2 and δ_o are the strong interaction π-π phase shifts due to the final state I = 2 and I = 0 interactions, respectively. Thus we see that if there is a relative phase difference between $\Delta I = 1/2$ violating and conserving parts of the $K^o \rightarrow 2\pi$ amplitude, direct CP violation will occur with the experimental signature that

$$R \equiv \left|\frac{\eta_{oo}}{\eta_{+-}}\right| \simeq 1 - 3 \text{ Re}(\varepsilon'/\varepsilon) \qquad (4)$$

II. Previous Results

What are the present limits on the size of ε'? Two previous experiments have directly determined R with results of $1.03\pm.07$ (Ref. 2) and $1.00\pm.06$ (Ref. 3).

We note also the precision measurement[4] of the phase of η_{+-}: $\phi_{+-} = (45.9\pm1.6)^\circ$. The phase of ε can be calculated (in a model where $\varepsilon' = 0$) in terms of Δm and Γ_S so that in principle the measurement of ϕ_{+-} can yield a limit on the ε' contribution (see expression 1). However, in practice, the phase measurement is not sensitive simply because of the phase of ε', governed exclusively by the π-π phase shifts,[5] (expression 3), is nearly the same as the phase of ε: $\arg(\varepsilon')=(37\pm5)^\circ$. Thus the present experimental limit is

$$|\varepsilon'| \lesssim .02|\varepsilon|$$

III. Current Predictions for ε'

Kobayashi and Maskawa,[6] in 1973, proposed a model for the weak interactions which involved six quarks. This model had the virtue (and raison d'etre) that there were, in the transition matrix, three real angles (Cabibbo angles) and one complex phase, the latter accounting for CP non-conservation.

After the discovery of the J/ψ as a signature for a fourth quark together with the then mounting evidence[7] for a new lepton pair (τ,ν_τ), Ellis et al.[8] studied the implications of the Kobayashi-Maskawa model for both conventional and rare K-decays, as well as for charmed particle decays. CP violation was induced at every weak vertex connecting a strange quark with a charmed or top quark. Their conclusions regarding ε' were

$$|\varepsilon'| \lesssim \frac{1}{450} |\varepsilon|$$

the uncertainty resulting from the unknown mass splitting between the c and t quarks. In words, the 6-quark model closely approximated models in which $\varepsilon' = 0$.

Since that analysis, there have been two developments: one experimental and the other theoretical. First, the Upsilon[9] was discovered: this has the consequence, in the now conventional view, that $m_t >> m_c$. Secondly, a class of diagrams involving gluon exchange ("Penguin diagrams") which contribute to direct CP violation (i.e. to ε') have been recalculated[10] and found to yield large effects. These diagrams reportedly explain the $\Delta I = 1/2$ enhancement in non-leptonic K-decay and then induce, in the Kobayashi-Maskawa model, a relative phase between A_o and A_2 (defined previously). (See in particular Gilman and Wise[11] and references therein to the work of Shifman et al.). The model is constrained by the known value of ε, but the resulting prediction for ε' is still somewhat dependent upon the value of m_t and other parameters. Nevertheless, for "reasonable" choices, $|\varepsilon'|$ is on the order of a few percent of $|\varepsilon|$ or more!

IV. Experimental Goals

We propose to measure $|\eta_{oo}/\eta_{+-}|$ to an accuracy of better than 1%. Our error on ε' (see expression 4) will then be better than $\pm .003|\varepsilon|$. In the following section, we outline the principle of the measurement.

V. Principle of the Measurement

In principle, to measure η_{oo} or η_{+-}, one need only measure the branching ratio of $K_L \to 2\pi$ by, for example, measuring the rate of $K_L \to 2\pi$ relative to semi-leptonic decays, and using "wallet-card" numbers for the K_S rates and lifetime. The major draw-back with such an approach is that, in the ratio $|\eta_{oo}/\eta_{+-}|$, the relative charged and neutral detection efficiences must be precisely known. Therefore we plan to measure, for each decay mode, the vacuum decay rate relative to the regenerated rate. This approach was already adopted by Ref. 2 and Ref. 3; what is different is that we will perform the measurments of vacuum and regeneration rates simultaneously by constructing a "double beam" similar to that employed in the measurement[12] of the K^o charge radius. An important source of systematic error, namely flux monitoring, is thereby eliminated.

Consider $N_L(P)$ K_L's of momentum P incident on a regenerator of X interaction lengths and regeneration amplitude ρ. Then the number of $K_S \to \pi^o\pi^o$ events decays z meters downstream of the regenerator will be (†)

$$I^R_{oo}(p,z) \propto N_L \; |\rho^2| e^{-z/\Lambda} \; e^{-X} \;\; \varepsilon_{oo}(p,z)$$

where Λ is the decay length of the K_S and ε_{oo} (p,z) the detection efficiency. Similarly, for the decays in a vacuum,

$$I^V_{oo}(p,z) \propto N_L |\eta_{oo}|^2 \varepsilon_{oo}(p,z) \qquad (5)$$

In these expressions R and V stand for regenerator and vacuum respectively. Thus the measured ratio of vacuum to regenerated events at each p and z is given by

$$\frac{I^V_{oo}(p,z)}{I^R_{oo}(p,z)} = \left|\frac{\eta_{oo}}{\rho}\right|^2 e^{z/\Lambda} \; e^X.$$

(Note that we have assumed equal fluxes incident on the vacuum and regenerator: this can be guaranteed by performing the measurements simultaneously and by frequent alternation of the regenerator between the two beams).

† Here the small contribution from interference with $K_L \to 2\pi^o$ is neglected. The correction for this is small and nearly identical in the charged mode so that the error thereby induced is negligible.

In fact we only need guarantee that the ratio of incident fluxes is identical in the neutral and charged mode).

In this expression, the flux and the detection efficiency drop out. Similarly, in the charged mode, we find

$$\frac{I^V_{+-}(p,z)}{I^R_{+-}(p,z)} = \left|\frac{\eta_{+-}}{\rho}\right|^2 e^{z/\Lambda_e x} ,$$

again independent of the charged efficiency, $\varepsilon_{+-}(p,z)$. Thus, if the same regenerator is used for both charged and neutral running, the ratio of ratios yields the desired quantity, in each p and z bin:

$$\frac{I^V_{oo}/I^R_{oo}}{I^V_{+-}/I^R_{+-}}(p,z) = \left|\frac{\eta_{oo}}{\eta_{+-}}\right|^2 \qquad (6)$$

The above somewhat idealized discussion is complicated by the following: the efficiency drops out of each ratio only in first order: the detection efficiency in any p and z bin (where p and z are measured quantities) depends weakly upon the true decay distribution (smearing due to resolution) so that in fact there is not perfect cancellation. The effect of resolution must be minimized and understood. The use of a high resolution photon detector is required for this reason as well as for the requirement of sufficient $K_L \to 3\pi^0$ rejection.

IV. Beam, Detector

The proposed experiment requires the M3 beam-line in the Meson Lab where the largest K_L flux is available. The neutron "background" which results from the small production angle is manageable. In addition, one can improve the K to neutron ratio with small changes in targeting angle.

Two well collimated sharply separated beams in vacuum are incident upon our apparatus. (See Figure 1.) In one of the beams, a regenerator is placed --110 cm of Carbon; the other contains no regenerator. Both beams are covered by a thin (1/32") anti-counter to veto inelastic events. The regenerator sits within a sweeping magnet.

In the spectrometer following the 50 m decay volume, one can detect either $K_L \to 2\pi^o$ in the vacuum beam together with $K_S \to 2\pi^o$ behind the regenerator or the corresponding charged pion decays. The detection of the latter does not differ significantly from previous FNAL regeneration experiments, so here we will concentrate on the more delicate detection of the neutral pion modes.

The crux of the apparatus consists of a high resolution gamma ray detector. Energy resolution of $\Delta E/E \simeq 15\%/\sqrt{E}$ (FWHM) and position resolution of $\lesssim 0.8$ cm (FWHM) are required so that in all probability a lead-glass array will be employed. Figure 2 illustrates how the K-mass width depends on the resolutions: improved energy resolution is of little benefit without good position resolution.

From the energy and position measurements of the 4-gamma rays, one can in fact fully reconstruct an event. The 4-γ invariant mass can be shown to be given (in the small angle approximation) by

$$M_{4\gamma}^2 = \sum_i \sum_{j \atop i \neq j} \frac{E_i E_j \theta_{ij}^2}{2} = \sum_i \sum_{j \atop i \neq j} \frac{E_i E_j r_{ij}^2}{2\, z^2}$$

where E_i is the energy of the i'th gamma, θ_{ij} the opening angle between the i'th and j'th gammas, r_{ij} the distance between the i'th and j'th gammas at the detector, and z the distance from the detector of the decay point. The numerator of the right-most quantity in the above expression is fully measured so that if z were known, $M_{4\gamma}$ could be calculated. The decay point z is determined by invoking the constraint that two sets of gammas must have the invariant mass of the π^0. Of the three possible pairings, the one which gives (for each π^0) the most consistent[13] z-determination is chosen, the best z is determined, and $M_{4\gamma}$ is then calculated. Figure 3a shows the resulting mass-distribution for Monte-Carlo events: the resolution is about 14 MeV (FWHM). Figure 3b shows that the vertex z can be determined by this method to within about 1.5 m(FWHM), (which is <1 K_S lifetime). The first moment of the energy distribution of the 4 gammas at the detector can also be calculated, to a precision of about 0.5 cm. This corresponds to the impact point of the kaon at the detector, had it not decayed.

In order to significantly reduce background coming from $K_L \to 3\pi^0$ decays (to be discussed in a section VIII) we plan to convert one gamma ray in a thin (0.1 r) converter which follows an anti-counter immediately after the downstream window of the decay region. The wire chamber spectrometer will provide angle and momentum determinations for the converted pair which then provide, by extrapolation of the photon trajectory to the best z-value, information on the transverse decay point within the beam. Figure 4 shows the reconstructed beam profile. This point, together with the center of energy in the detector plane, allow a determination of the kaon angle (or t) with respect to the beam direction and thus, in the regenerated beam, diffraction regeneration can be effectively separated from coherent regeneration (see section IX).

An important ingredient in the rejection of background from $3\pi^0$ decays are the anti-counters (A in Fig. 1) along the decay volume and along the vacuum pipe that carries the beam through the apparatus and beyond. These veto the missing gammas which either go through the hole in the detector or miss outside.

VII. Rate Estimates and Running Time

For the spectrum and normalization of the K_L flux at $\theta = 1/4$ mr (the nominal M3 production angle), we have taken the results from reference 14. Preliminary results from E533 (π-μ Atoms) on the K_L flux in M3 are consistent with this choice. We find the following for a single beam:

3×10^{12} incident 400 GeV/c protons

$d\Omega$ given by a 4" x 4" beam at 1485'

K_L flux at detector (30 to 200 GeV/c) = 7.5×10^6/pulse

K_L decays in the 50 m region = 1.1×10^5/pulse

$K_L \to \pi^0\pi^0$ decays = 107/pulse, with a mean momentum of about 90 GeV/c.

For our proposed detector (including the conversion probability) we find an integrated acceptance of 0.7% so that we then expect

detected $K_L \to \pi^0\pi^0$ decays = 0.7/pulse

For the regenerated flux, we have used $\left|\frac{f-\bar{f}}{k}\right|$ for Carbon from reference 15 to calculate ρ for our 110 cm regenerator. We find, over the entire spectrum,

detected $K_S \to \pi^0\pi^0$ decays = 2.0/pulse

However, we very likely will not be able to have the full beam incident upon the regenerator; from the neutron flux measurements reported at zero degrees in reference 16, scaled to 400 GeV/c, we find

neutrons hitting regenerator $= 4.3 \times 10^8$/pulse.

From our experience in M4, we can run with 3×10^6 incident neutrons with appreciable dead-time, so that we will attenuate the regenerated beam to this intensity by using a Carbon or CH_2 absorber far upstream. This will result then (because of the difference in absorption cross sections for K_L's and neutrons) in a detected rate of $K_S \rightarrow \pi^o\pi^o$ of 0.2/pulse. (Note that if the absorber moves with the regenerator and if the <u>same</u> absorber is used in the detection of the charged mode, the "ratio of ratios" (expression (6)) is again $|\eta_{oo}/\eta_{+-}|^2$.

Since the regenerated events are concentrated within the first two K_S lifetimes, (i.e. typically within the first 10 m), in order to analyze the experiment as suggested by expression (6), we are only justified in using vacuum events also within the first 10 m. (It is very likely that we can sufficiently understand the acceptance, so that the whole decay region will be useful: several million $K_L \rightarrow 3\pi^o$ decays will be reconstructed just for that purpose). We here will adopt a conservative stance, expecting in that region a minimum of $\simeq 0.15$ vacuum events/pulse and $\simeq 0.2$ regenerated events/pulse.

We propose to run for 1000 hours on the neutral mode, collecting about 50,000 events of each type. This is to be compared with the total of 297 $K_L \rightarrow 2\pi^o$ events on which the previous results of refs. 2 and 3 are based. This will yield a <u>statistical</u> accuracy of 0.35% on $|\eta_{oo}/\rho|$.

To run the charged mode, we will remove the lead converter and trigger on two charged hadrons. As the efficiency for $\pi^-\pi^+$ is about an order of magnitude greater than $\pi^o\pi^o$, and the decay rate is a factor of two higher (branching ratios), the statistical error on $|\eta_{+-}/\rho|$ will be negligible.

To estimate the systematic error, we now consider in detail the background from $3\pi^0$'s, and the correction for diffraction regeneration.

VIII. $K_L \to 3\pi^0$ Background

This decay mode occurs at a rate of 228 times that for $K_L \to 2\pi^0$ so that one must have exceptionally good rejection in order to reach the desired precision. The $3\pi^0$ events which fake $2\pi^0$'s (i.e. having four energy clusters in the shower counter) are essentially of two classes: those where gammas miss the detector (either outside or inside), and those where six gammas hit the detector some being so close together (i.e. in the same lead-glass block) as to be indistinguishable from a single gamma. Monte-Carlo studies indicate that the background from the first class can be brought to the negligible level by the judicious placement of high efficiency anti-counters along the decay volume and downstream vacuum pipe.

The second class -- where two or more gammas "fuse" into one pseudo-gamma -- is more difficult to reject and here is where good position resolution is required. In fact, the exact form of the "front-end" of our gamma detector will be chosen so that the background from near-by unresolved gammas will be at a negligible level. Monte-Carlo studies of the fusion problem are in process: for now we have adopted the conservative view[17] that we will be able to resolve two gammas only if they strike our 1 m x 2 m detector more than 5 cm apart. Figure 5 then shows the resulting $M_{4\gamma}$ distribution indicating an $\approx 5\%$ background under the mass peak. From the direction of the converted gamma ray, we calculate p_T^2 for the kaon as described in section IV; Figure 5b illustrates the substantial rejection that can be obtained by demanding $p_T^2 < 4000\ (\text{MeV/c})^2$.

In addition, the p_T of the converted gamma is itself accurately determined ($\approx$10 MeV/c FWHM) so that by looking at events where p_T lies between 170 MeV/c and 230 MeV/c (the kinematic maxima for $3\pi^o$ and $2\pi^o$ decays, respectively), one can, if necessary, eliminate the $3\pi^o$ background as was done in ref. 2.

IX. Diffraction Correction

The choice of a two interaction length regenerator is optional for (at least) two different reasons: first, it yields the maximum rate of coherently regenerated K_S per incident K_L, and second, the number of singly scattered events is at a minimum as a result of the destructive interference between (a), regenerative scattering at a nuclear site and (b), elastic scattering at the same site with coherent regeneration along the kaon's path. (Since we are using coherently regenerated events as a monitor, it is important to have a minimal contamination of diffracted events near $p_T^2 = 0$.)

The diffraction scattering angular distribution in our Carbon regenerator, including all orders of multiple scattering, has been generated with a Monte-Carlo. Figure 6 shows the reconstructed p_T^2 distributions for both coherent and diffracted events. The contamination within the first 4000 $(MeV/c)^2$ is seen to be 1.2% relative to the coherent signal. The uncertainty in this correction will be less than 5% of itself since we can extrapolate from larger p_T^2 values by a well known procedure.

From our experience with thick regenerators in M4, the actual non-coherent signal may be as much as a factor of two greater than here calculated as a result of attempting to suppress the inelastic regenerative scattering by a single anti-counter. We may attempt to equip the regenerator with several planes of anti-counters, but, even so, the error in the extraction of the number of coherent events should be negligible.

X. Equipment and Schedule

Of the major new equipment items, the experimenters would expect to provide the wire chambers, gamma detector, and assorted hodoscopes. We would expect that Fermilab provide the regenerator sweeping magnet and the vacuum chamber.

We expect to be able to begin data taking in the summer of 1980 by which time the present experimental program -- E533 and E584 -- should be completed.

XI. Conclusion

We have presented our capabilities to detect direct CP violation with a sensitivity one order of magnitude better than previous measurements. The improvement results from progress in the accurate detection of electromagnetic showers over the last several years, from the increased flux available, and from experience gained in previous Fermilab Kaon experiments requiring negligible systematic errors. No matter what the result, our understanding of CP non-conservation will be enhanced. The possibility of a large effect, as suggested by very recent theoretical considerations, is most tantalizing.

References and Footnotes

[1] See, for example, K. Kleinknecht, ANRS 26 (1976): 1-50.

[2] M. Banner et al., PRL 28, 1597 (1972).

[3] M. Holder et al., PL 40B, 141 (1972).

[4] C. Geweninger et al., PL 48B, 487 (1974).

[5] M. F. Losty et al., Nucl. Phys. B69, 185 (1974)

CERN-Munich Collaboration, 1974 Int. Conf. Meson Spectroscopy, Boston.

[6] Prog. of Theor. Phys. 49, 652 (1973).

[7] M. L. Perl et al., PRL 35, 1489 (1975).

[8] Nucl. Phys. B109, 213 (1976).

[9] S. W. Herb et al., PRL 39, 252 (1977).

[10] J. Ellis, private communication.

[11] The $\Delta I = \frac{1}{2}$ rule and violation of CP in the six quark model, F. Gilman and M. Wise, SLAC preprint.

[12] W. R. Molzon et al., PRL 41, 1213 (1978).

[13] We also define a X^2 which measures the degree of consistency of the two z determinations and is used to strongly suppress background.

[14] P. Skubic et al., Phys. Rev. D18, 3115 (1978). The spectrum was scaled to 400 GeV/c.

[15] A. Gsponer et al., PRL 42, 13 (1979).

[16] R. T. Edwards et al., Phys. Rev. D18, 76 (1978).

[17] Gabathuler et al., NIM 157, 47 (1978), find only 5% confusion for shower separation of $\simeq$3mm in our energy range, using analogue read-out MWPC.

Figure Captions

Figure 1 Schematic of experimental layout in the M3 beam-line.

Figure 2 The dependence of the resolution in the reconstructed 4-gamma invariant mass on spatial and energy resolution.

Figure 3 a) Reconstructed mass distribution.

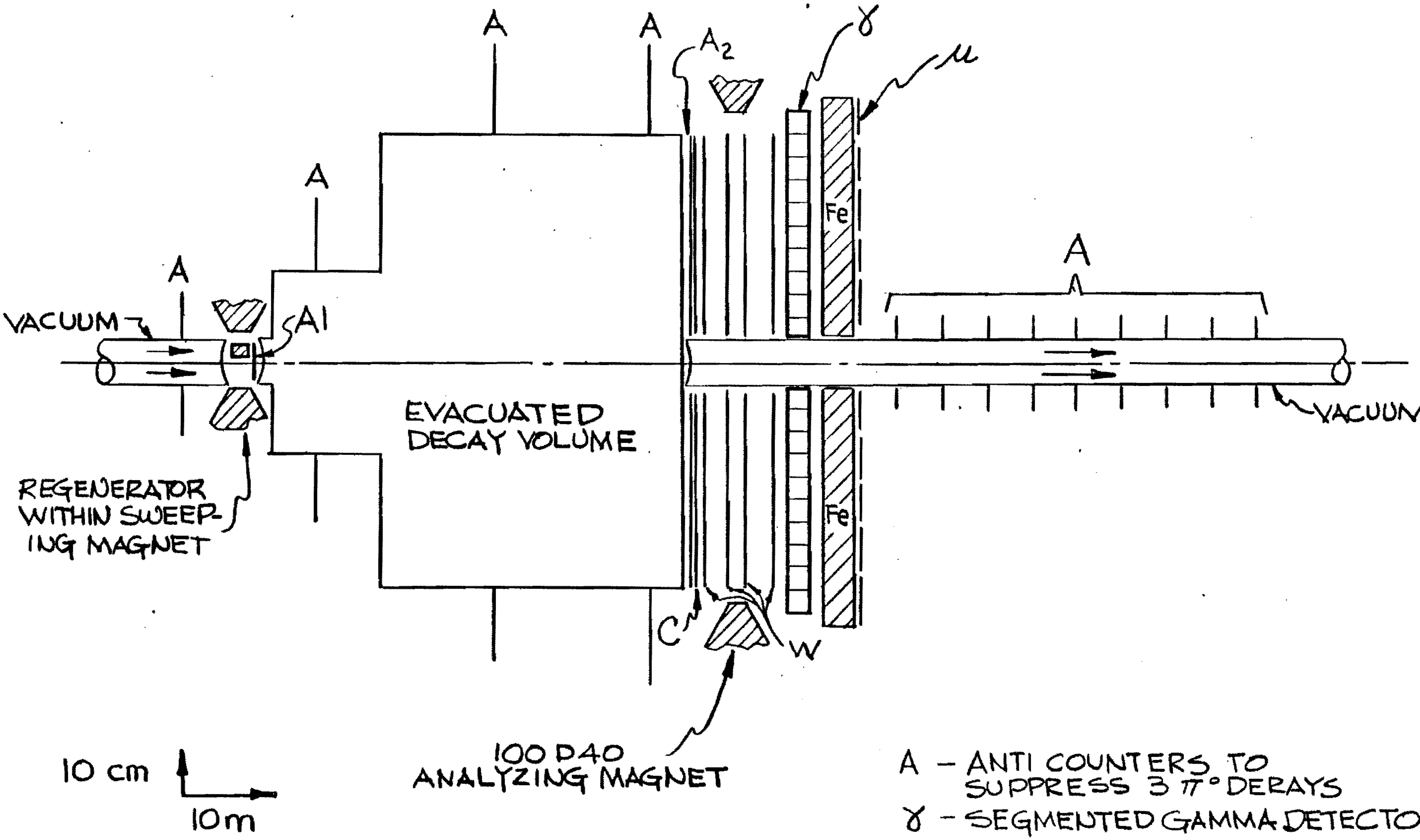
b) Longitudinal vertex resolution. Here we have used $\frac{\Delta E}{E} = \frac{12\%}{\sqrt{E}}$ (FWHM) and position resolution of 12 mm (FWHM).

Figure 4 The reconstructed profile of the transverse vertex coordinates using the measured direction of the converted gamma ray. The relative position of the two beams is also shown.

Figure 5 a) The 4-gamma mass distribution with the $3\pi^{o}$ background.

b) The transverse momentum distribution of those events in a) satisfying $475 \leq M_{4\gamma} \leq 525$ (MeV/c^{2}).

Figure 6 Reconstructed transverse momentum distributions for both free and regenerated events.



A - ANTI COUNTERS TO SUPPRESS 3 π° DERAYS
γ - SEGMENTED GAMMA DETECTOR
W - WIRE PLANES
A1 - REGENERATOR ANTI COUNTER
A2 - ANTI COUNTER
C - γ10r CONVERTER
μ - MUON COUNTERS

Fig. 1

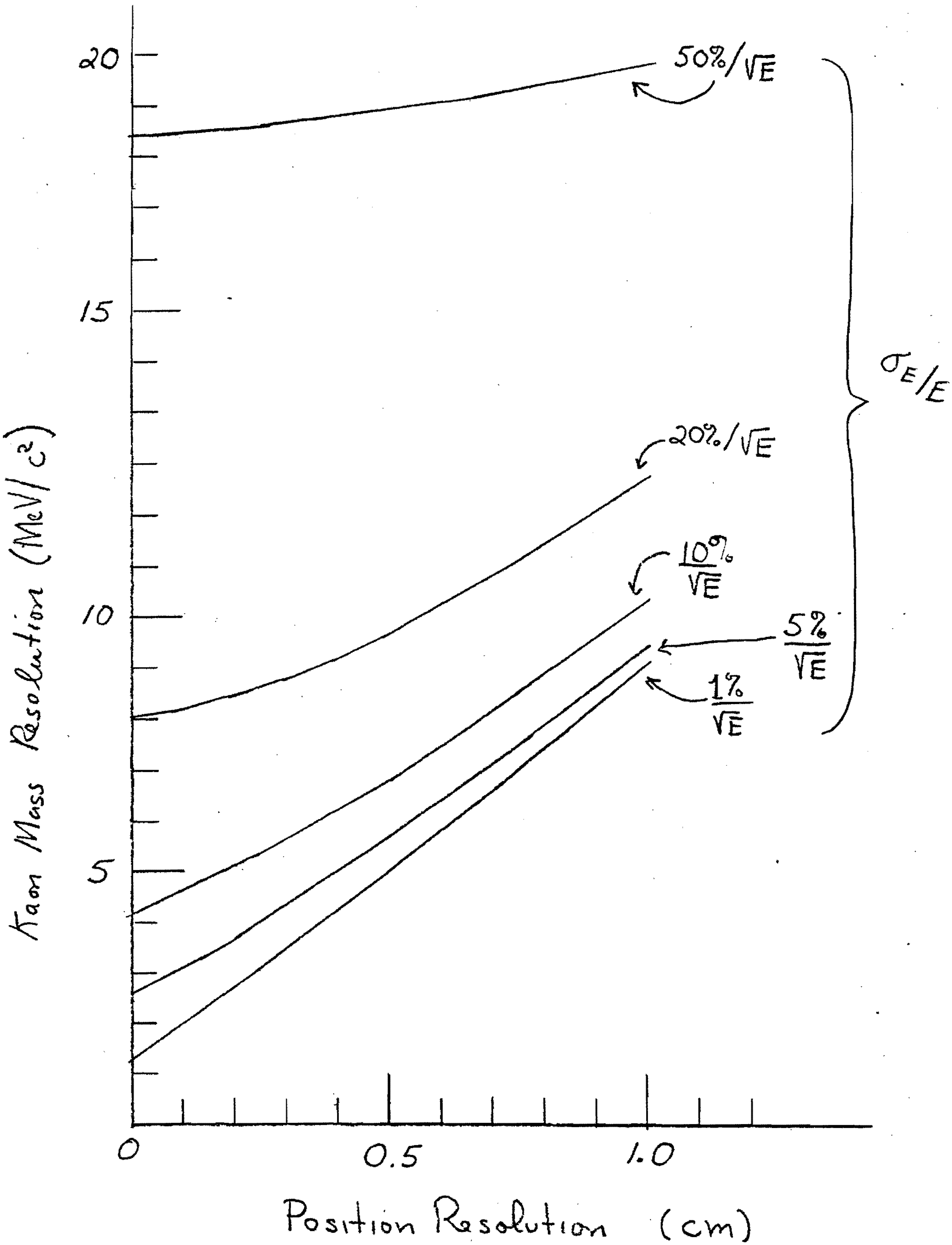

20
15
10
5
0
0.5
1.0
Kaon Mass Resolution (MeV/c²)
Position Resolution (cm)
50%/√E
20%/√E
10%/√E
5%/√E
1%/√E
σE/E

Fig. 2

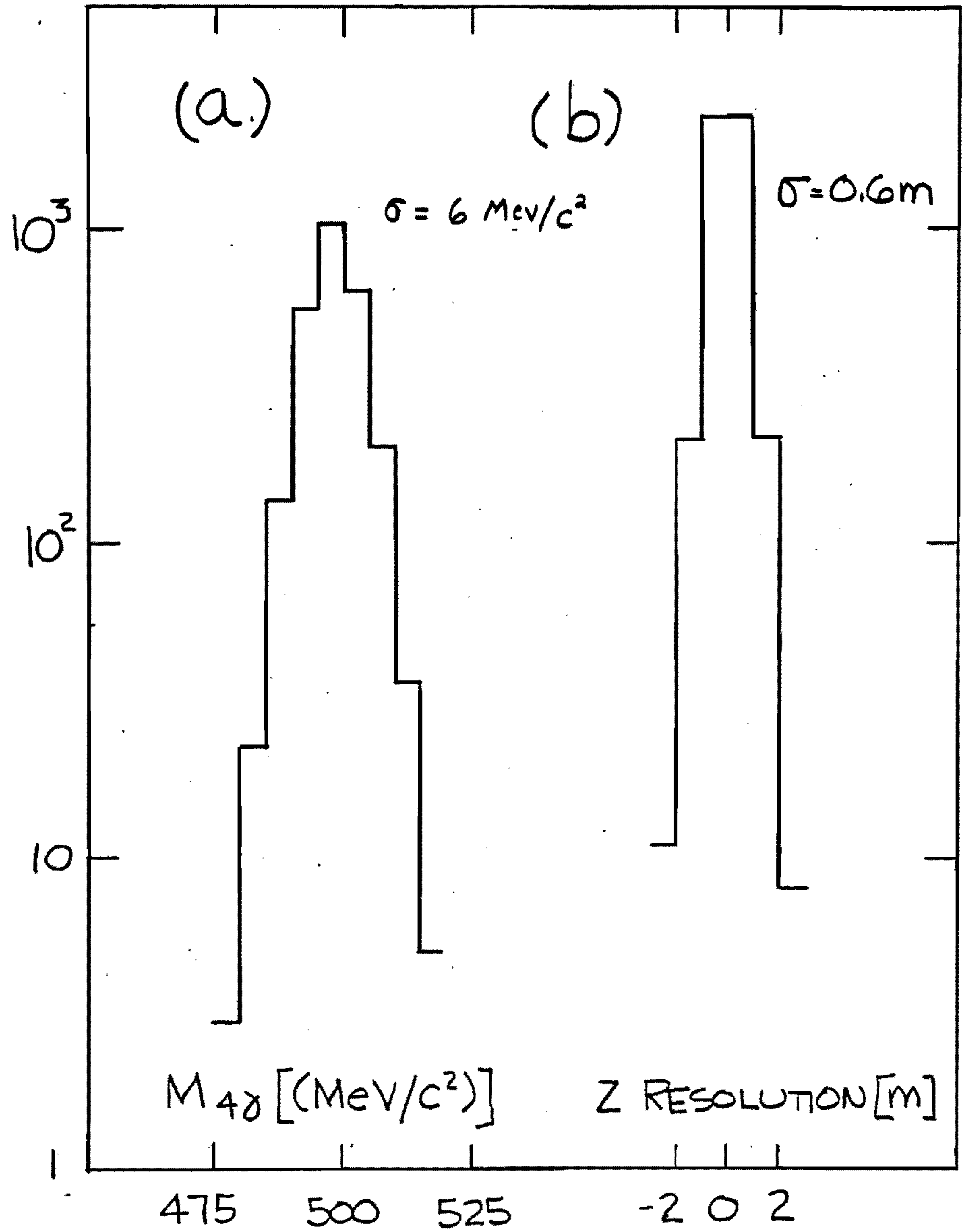
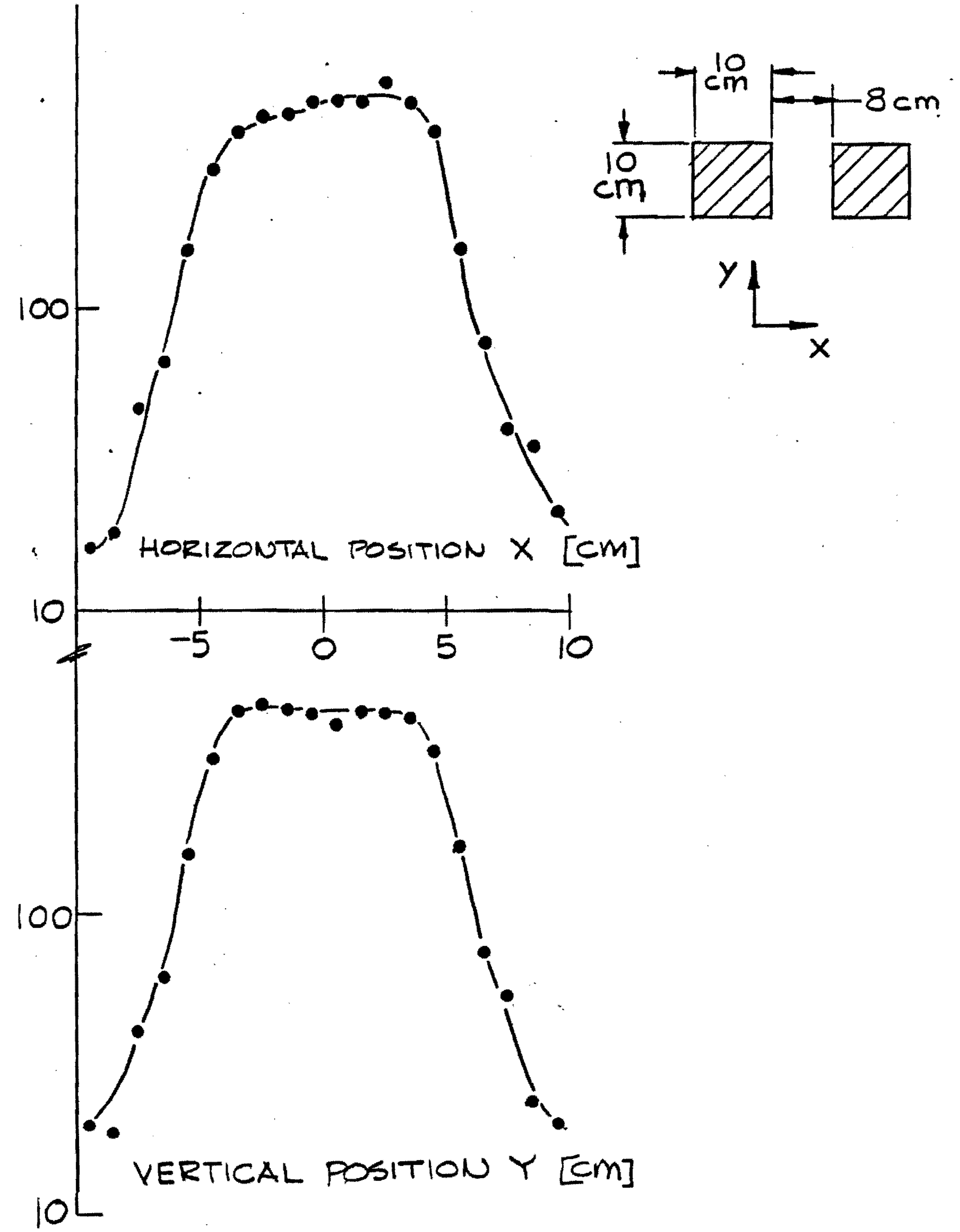
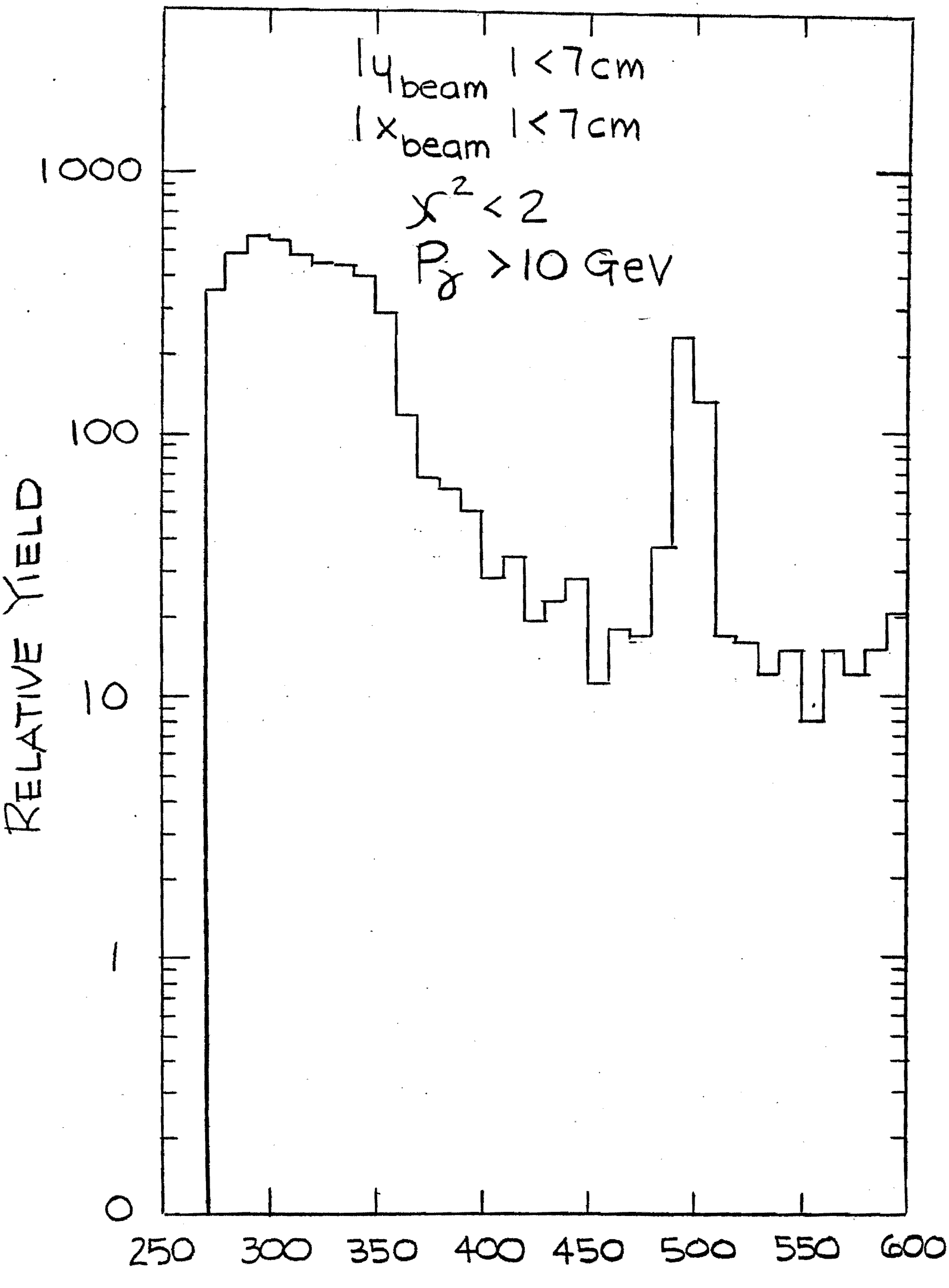

(a)
(b)
σ = 6 MeV/c²
σ=0.6m
10³
10²
10
1
M 4γ [(MeV/c²)]
Z RESOLUTION [m]
475
500
525
-2 0 2

Fig. 3



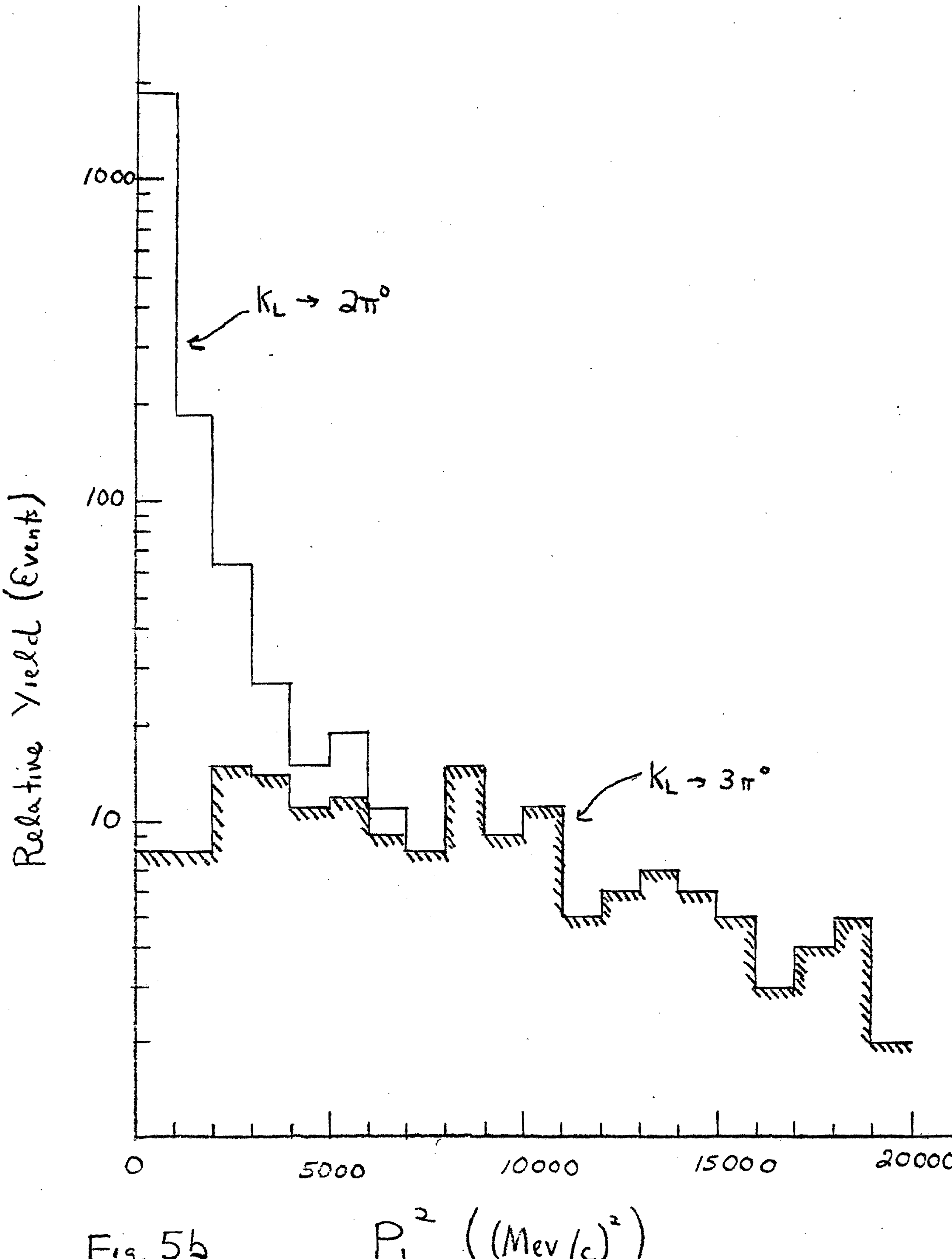
RECONSTRUCTED BEAM PROFILE

Fig. 4



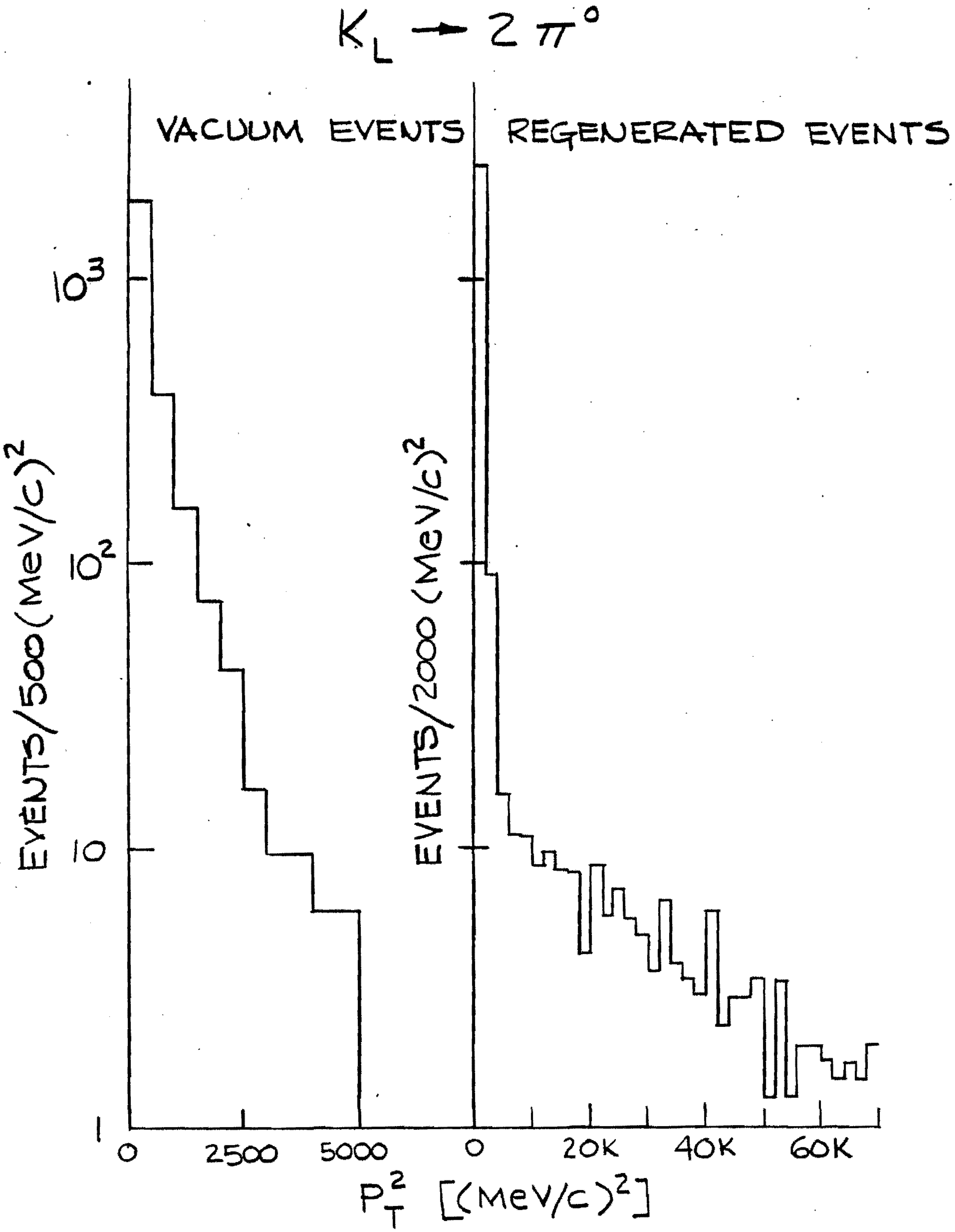
$|y_{beam}| < 7$ cm
$|x_{beam}| < 7$ cm
$\chi^2 < 2$
$P_\gamma > 10$ GeV
1000
100
10
1
0
RELATIVE YIELD
250
300
350
400
450
500
550
600

Fig. 5a



Relative Yield (Events)
1000
100
10
$K_L \to 2\pi^0$
$K_L \to 3\pi^0$
0
5000
10000
15000
20000
$P_\perp^2$ $((Mev/c)^2)$

Fig. 5b



$K_L \to 2\pi^0$
VACUUM EVENTS
REGENERATED EVENTS
EVENTS/500 (MeV/c)^2
EVENTS/2000 (MeV/c)^2
10^3
10^2
10
1
0
2500
5000
0
20K
40K
60K
P_T^2 [(MeV/c)^2]

Fig. 6