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PROPOSAL FOR A NEW TEVATRON SEARCH FOR DIRECT CP VIOLATION IN THE 2π DECAYS OF THE NEUTRAL KAON

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The recent efforts of this collaboration have been the analysis of the extensive E731 data set for ε'/ε, the extraction of signals and limits for some rare kaon decays, preparations for E773, a sensitive CPT symmetry test, and preparations for E799, a dedicated rare kaon decay experiment. The collaboration sees as its long range future a

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continuation of this program of kaon experiments at the Tevatron, including another ε'/ε measurement, followed by the exploitation of a dedicated beam from the Fermilab Main Injector.

We will first present a status report on efforts now underway and then outline a proposal for a new Tevatron ε'/ε determination.

E731 analysis for ε'/ε

E731 was designed to measure the parameter of CP violation ε'/ε. The experiment had its major run in 1987/88 and over 5000 data tapes were recorded. The apparatus is shown in Figure 1; the experiment was configured in order to have minimal systematic uncertainty and in particular to be immune to changes in accelerator performance and other parameters over which the experimenter has little control. As is well known, both $2\pi^0$ and $\pi^+\pi^-$ decays need to be recorded for both K_L and K_S modes. For the majority of our running, either both charged modes or both neutral modes were recorded simultaneously and this greatly reduced a variety of systematics. For the last (approximately) 20% of the data, all four modes were taken at the same time. It is on this data set, which we call the "G-set," that we have done the full analysis. Our result was recently published; we found[1] $\varepsilon'/\varepsilon = -0.0004 \pm 0.0014(\text{stat.}) \pm 0.0006(\text{syst.})$, consistent with zero and two standard deviations below the earlier result[2] from CERN's NA31 group which found $\varepsilon'/\varepsilon = +0.0033 \pm 0.0007(\text{stat.}) \pm 0.0008(\text{syst.})$. This result has been fully described in the Ph.D thesis of J. R. Patterson.

In the Standard Model, the value of ε'/ε is expected to be non-zero but its precise magnitude depends upon, among other parameters, the value for the top mass: the higher the mass of the

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[1] A Determination of Re(ε'/ε) by the Simultaneous Detection of the Four $K_{L,S} \rightarrow \pi\pi$ Decay Modes, J. R. Patterson et. al., Phys. Rev. Lett. **64**,1491 (1990)

[2] First Evidence for Direct CP Violation, H. Burkhardt et. al., Phys. Lett. **206B**, 169 (1988)

top, the smaller is ε'/ε. Our result clearly favors higher values of M_t as is seen in Figure 2.

We have made substantial progress in the analysis of the full data. A result is expected in the first half of 1991. All of the remaining data has been reduced and the work at present is in the rather delicate calibration of the leadglass detector as well as in the understanding of the acceptance of the apparatus. In Figure 3 we show the $K_{L,S} \rightarrow 2\pi^0$ invariant mass distribution for the entire data set, without the final calibration constants. The K_L signal has about 300K events in it while the background (from $3\pi^0$ decays) is less than 0.5% and is smooth and well understood. The statistical error on ε'/ε will be about 0.0005. In Figure 4, we show the reconstructed vertex distribution for Ke_3 decays. Such plots can be used to estimate the systematic uncertainty from any misunderstanding of the acceptance of the apparatus; this was in fact our largest source of systematic uncertainty. As is seen in the figure, the ratio of data to Monte Carlo is consistent with being flat in z and the uncertainty is only about 0.02%/m. This is expected to lead to a systematic error on ε'/ε of less than 1×10^{-4} whereas for the G-set sample, it was 3×10^{-4}; thus we are confident that the systematic error for the full data set will be less than that for the G-set sample.

The analysis of the $\pi\pi$ modes in the 20% data set has given other results of interest. We have measured the K_S lifetime with comparable precision to that of the present world average: our result[1] is $\tau_S = (0.8902 \pm 0.0021) \times 10^{-10}$ sec. We have also determined the CPT violating phase difference[3] between η_{+-} and η_{00} : $\Delta\Phi = -0.3^0 \pm 2.4^0$(stat.) $\pm 1.2^0$(syst.). This result together with a result with similar precision from NA31 in a dedicated experiment resolves a long-standing earlier discrepancy which was $12^0 \pm 6^0$.

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[3] Test of CPT Symmetry Through a Determination of the Difference in the Phases of η_{00} and η_{+-} in $K \rightarrow 2\pi$ Decays, M. Karlsson et. al., Phys. Rev. Lett. **64**, 2976 (1990)

A closely related physics issue is the value of the mixing parameter ε itself. Its real part is determined from a measurement of the semileptonic charge asymmetry δ_e in Ke_3 decays. We have recorded over 10^8 such decays and, in addition to providing valuable acceptance checks, these will yield the best determination of δ_e. Our result from the 20% data sample is $\delta_e = (0.338 \pm 0.027)\%$, in agreement with the world average value of (0.330 ± 0.014) %.

E731 Analysis for other decays

Although E731 was designed exclusively to study CP violation in 2π decays, because of the attention to lack of bias and the necessarily high acceptance for 4-body kaon decays, we have found that we have excellent sensitivity for other not-well-studied decays. Indeed, it is this feature which has led us to embark on the dedicated rare kaon decay study, E799. Here we will briefly mention some of the modes we have been studying. Most of these results were reported recently at the Singapore conference.

1. $K_L \rightarrow \pi^0 e^+ e^-$

This mode is of considerable interest in that it is expected to have a sizable contribution from CP violating amplitudes. The standard model level is probably not greater than about 10^{-11} but there could always be a surprise. The predictions are more precise than for the 2π modes in that the matrix elements are reasonably well known. Our result[4], based upon the full data set, is $BR(K_L \rightarrow \pi^0 e^+ e^-) < 7.5 \times 10^{-9}$ (90% confidence). This can be compared to the upper limit of $< 5.5 \times 10^{-9}$ from the dedicated BNL 845 experiment[5]. The Brookhaven experiment is completed, and E799 should come near to the 10^{-11} level.

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[4] New Limit on $K_L \rightarrow \pi^0 e^+ e^-$, A. Barker et. al., Phys. Rev. **D41**, 3546 (1990)

[5] Improved Experimental Limit on $K_L \rightarrow \pi^0 e^+ e^-$, K. E. Ohl et. al., Phys Rev. Lett. **64**, 2755 (1990)

2. $K_L \to \pi^0\gamma\gamma$

This mode can give rise to a potential CP conserving background to the $\pi^0e^+e^-$ channel so it is important to measure it; additionally, there are predictions based upon chiral perturbation theory that need to be tested. Based upon the 20% data sample, we published[6] an upper limit of $<2.7 \times 10^{-6}$ (90% confidence) using data with $m_{\gamma\gamma} > 300$ MeV/c^2, which bettered the old limit by a factor of 100. More recently, the NA31 collaboration has reported[7] an observation of this decay with a branching ratio of $(2.1 \pm 0.6) \times 10^{-6}$ and we have a preliminary result from the entire data set which gives $(2.1 \pm 1.1) \times 10^{-6}$. Both results are for $m_{\gamma\gamma} > 280$ MeV/c^2. Our result from the full data set for $m_{\gamma\gamma} > 300$ MeV/c^2 is $(1.2 \pm 0.6) \times 10^{-6}$. (It is interesting to note that for the $2\pi^0$ mode, our background level is 0.3% or over a factor of 10 better than that for NA31 whereas for the $\pi^0\gamma\gamma$ mode, NA31 has significantly less background. The reason is that we have 11 planes of photon vetoes to provide good detection efficiency for $3\pi^0$ background decays in which gammas miss the leadglass detector. However, the background to the $\pi^0\gamma\gamma$ signal is largely $3\pi^0$ events where two of the photons lie on top of (fuse with) two other photons, and the NA31 liquid argon detector, with its 1 cm strips, has superior ability to resolve two close-by gammas.)

3. $K_{L,S} \to \pi^+\pi^-\gamma$

These modes are of possible interest for a variety of reasons. The K_S decays with a well identified gamma in the detector ought primarily to arise from an inner bremstrahlung process and be therefore relatively uninteresting. However, for the K_L decays, because the 2π mode is suppressed due to CP symmetry, the inner bremstrahlung process ought also to be suppressed so that any direct emission term can be detected. This is indeed the case as is shown in Figure 5 where the gamma energy in the center-of-mass for each

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[6]A Search for $K_L \to \pi^0\gamma\gamma$, V. Papadimitriou et. al., Phys. Rev. Lett. **63**, 28 (1989)

[7]Observation of the Decay $K_L \to \pi^0\gamma\gamma$, G. D. Barr et. al., CERN-EP/90-69, May 1990 (Submitted to Physics Letters B)

type of decay is shown; the direct piece is clearly seen. These studies lead to the following inner bremstrahlung branching ratio results: BR($K_S \rightarrow \pi^+\pi^-\gamma$; $E\gamma > 50$ MeV) = $(2.41 \pm 0.06) \times 10^{-3}$; BR($K_L \rightarrow \pi^+\pi^-\gamma$; $E\gamma > 20$ MeV) = $(1.45 \pm 0.09) \times 10^{-5}$. Then, from over 2000 direct decays, we have determined the direct emission branching ratio to be BR($K_L \rightarrow \pi^+\pi^-\gamma$; DE) = $(2.20 \pm 0.09) \times 10^{-5}$. These results, which are still preliminary, are more precise than the previous world averages and they will shortly be submitted for publication.

Finally, it is possible to observe the classic interference pattern for $K_{L,S} \rightarrow \pi^+\pi^-\gamma$. This is done by looking at the proper time distribution of decays downstream of our regenerator; it enables us to determine the CP violating parameter $\eta_{+-\gamma}$ for the first time. While one expects that the result will be consistent with η_{+-} , it is worth a check; our result is $\eta_{+-\gamma} = 0.0020 \pm 0.0002$(stat.) $\pm$ 0.0003(syst.). Thus we have a multi-standard deviation determination of a new CP violating parameter. Unfortunately, at the current level of precision, little more is learned about the underlying mechanism.

4. $\pi^0 \rightarrow e^+e^-$

For this suppressed decay mode of the neutral pion, there are several marginally consistent results, some claiming a signal, others reporting upper limits, all in the range of a few times 10^{-7}. This is a few times the level at which a signal is expected using the 2γ mode and unitarity. Our contribution comes from a measurement which is not yet definitive, but it uses a new technique which promises a clean observation in the future. The technique is to use $K_L \rightarrow 3\pi^0$ decays where we have effectively 3 tagged neutral pions in an event which has a distinctive signature (6 clusters) and is very well reconstructed and constrained. We look for 6 cluster events with two tracks each having good E/p. An analogous search is done in $\pi^+\pi^-\pi^0$ decays although the sensitivity there is somewhat less. Our result, which is background free, is BR($\pi^0 \rightarrow e^+e^-$) < 2.3×10^{-7} (90% confidence).

5. $K_L \to \pi^0 \pi e \nu$

To date, there have been only about 15 of these neutral Ke4 events observed. The mode offers the possibility of a study of CP nonconservation, mostly from non-Standard Model effects. However, in order to do this one needs significant statistics to be able to determine the various form factors. In our current sample, we have observed about 800 events over a background of about 150; this leads to the result BR($K_L \to \pi^0 \pi e \nu$) = (6.0 ± 0.2(stat.) ± 0.4(syst.)) x 10^{-5}, somewhat different from the predicted[8] value of 3.2 x 10^{-5}. After completion of a study of the angular distributions, this result will be submitted for publication.

6. $K_L \to 3\pi^0$ quadratic decay parameter

We have collected the largest sample of $3\pi^0$ decays to date; about 15 x 10^6 of these were recorded to monitor the performance of the detector. We have used some of these events to make a determination of the quadratic slope term in the Dalitz plot for the first time. This quantity is closely tied to the second order term in the Chiral Lagrangian and can be used to confront the lattice gauge calculations. The all-neutral decay mode offers a very clean way of measuring the quadratic slope term, since, because of the symmetry of the final state, there is no linear term and consequently there are no corrections to the quadratic term. Our result, based upon a partial analysis, is (-6 ± 14) x 10^{-4} per unit R^2 (R^2 is the distance from the center of the Dalitz plot in units of m_π^2).

<u>New Tevatron ε'/ε experiment: E731'</u>

For the longer range as mentioned above, our group has unanimously chosen to propose a new experiment at the Tevatron to measure ε'/ε. Our result is consistent with zero, and a result from the full data set is imminent. There is every reason to attempt to gain another factor of about 5 at the Tevatron, especially in that we believe

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[8]Current-Commutator Calculation of the K_{l4} Form Factors, S. Weinberg, Phys. Rev. Lett. **17**, 336 (1966)

that essentially the same technique will work for us. Thus our goal is to achieve a measurement in the range of 1.0 x 10^{-4} statistical error and smaller systematic uncertainty. The CERN group has also proposed a new effort, to run in 1994, 95, and 96, and they are going to use an entirely new approach. Their goal is a statistical uncertainty of 1.5 x 10^{-4}. They have adopted features of our technique: two beams, stationary K_S source, magnetic analysis, and simultaneous collection of all four modes.

Although the Standard Model predictions have considerable error, and will have even when the top quark is discovered, nevertheless the phenomenon of CP non-conservation has been seen only in one place and it badly needs needs further exploration. The real issue here is the establishment of another non-zero effect, not (yet) the confrontation of theory with a precise measurement. It will probably be at least 10 years before an experiment with the sensitivity required to see the effect in the decays of B mesons could be viable so that, for the next decade at least, it is true that the avenues in the kaon system - namely ε'/ε and $K_L \rightarrow \pi^0 ll$ - are likely the best bets.

In order to execute this experiment, we will need to make many improvements. These will benefit the rare decay experiment as well.

1. Improvements to the beam.

For the purposes of this document, we will assume that this experiment will be run in the MC beamline where we are now located. However, it would be advantageous to consider moving our detector to an area which can handle higher Tevatron beam intensities as well as the very intense 120 GeV beam forseen at the Main Injector.

We should first reduce the muon flux at the apparatus. Muons dominate the rate responsible for chamber current; we will need at least a factor of 10 improvement.

The beam stability, halo, and profile should be improved.

We will need to be able to take up to 5 x 10^{12} protons per pulse, a factor of about 2.5 increase over what we have run at before.

We will also need to have our area upgraded to be able to handle the additional radiation in the portacamps, etc.

As we will run the new experiment, call it E731', with charged and neutral modes taken simultaneously, we will base our rate estimates on the G-set data sample of E731. The statistical levels together with the assumed relative yields for E731' are shown below.

TABLE I: Statistics

Mode	G-set statistics	E731' stats
$K_L \to 2\pi^0$	55K	N
$K_S \to 2\pi^0$	215K	2N
$K_L \to \pi^+\pi^-$	45K	5N
$K_S \to \pi^+\pi^-$	170K	10N

The basis of the assumptions is the following. The ratio of 2/1 for regenerated to vacuum will result from an increase in the decay volume (for K_L decays). For the G-set, the charged triggers were prescaled by a factor of 8. The ratio of 5/1 for charged to neutral events arises from removing prescaling.

The error, then, on the double ratio will be $1.34/\sqrt{N}$. We will need about 0.00055 precision on the double ratio to obtain 1 x 10^{-4} precision on ε'/ε (there is a small amount of "dilution" from interference) so that our statistical goal becomes 6 x 10^6 $K_L \to 2\pi^0$ events or a factor of about 110 over that obtained in the G-set.

How can we improve this much? First of all, the G-set was a 3 week run so that by running for 24 weeks, we gain a factor of 8. Secondly, we can enlarge the decay region by a factor of two over the region used in E731 analysis so far (120m-137m). Thirdly, we expect to reduce the dead time for event collection: with better triggering, we should be able to pick up a factor of 1.7 relative to G-set running. This leaves a factor of 4 to go and this will have to come from increased intensity. The G-set was run at about 0.7 x 10^{12} so that we would need to run at about 3 x 10^{12} to achieve our goals. Since there will be some dead-time and other losses, we will set our goal towards being able to run at 5 x 10^{12} protons per pulse.

The attainment of this goal has major implications for the rest of the experiment and these will be dealt with below. First we will treat questions related to what is needed to be able to collect this amount of data and then we will treat the systematic issues.

The following table of rates will be useful in any extrapolation. It gives the kaon and neutron rates, higher level trigger rates, and some individual counter bank rates.

TABLE II: Raw Rates

Signal	Rate/10^{12}ppp E731 (17m decay region)	Rate/5x10^{12} E731' (34m decay region)	Rate/sec E731'
Kaons (≈neutrons)	1.0 x 10^7	5.0 x 10^7	2.5 x 10^6
K_L decays in decay region (30 - 160 GeV/c)	9.0 x 10^4	9.0 x 10^5	4.5 x 10^4
Regenerator Anti	1.2 x 10^7	6 x 10^7	3 x 10^6
B counter bank	3.2 x 10^7	7 x 10^7	3.5 x 10^6
B bank μ rate	2.0 x 10^7	1.0 x 10^7	5 x 10^5
4-cluster "trigger"	10^4	5 x 10^4	2.5 x 10^3
2-track "trigger"	8 x 10^4	3 x 10^5 **	1.5 x 10^4

** The rate increases from the less restrictive trigger for the enlarged decay region; we assume a factor of 5 reduction from the TRDs.

Another useful table sketches out the various loss factors that take us from the above kaon decay rate to the observed event rate.

TABLE III: G-set K_L Yields

K_L decays per pulse (10^{12}; 17m)	9.0×10^4
K_L decays/7×10^{11}	6.3×10^4
$2\pi^0$ decays	63
accepted $2\pi^0$ decays(19%)	12
$2\pi^0$ decays after veto losses (including offline)	7
$2\pi^0$ events to tape	4
$2\pi^0$ events after cuts	2.8
spills in G-set	20K
Total $2\pi^0$ events	56K
$3\pi^0$ decays	14.4K
accepted $3\pi^0$ decays (6%)	860
$3\pi^0$ events after cuts	215
Total $3\pi^0$ decays	4.2M
$\pi^+\pi^-$ decays	126
accepted $\pi^+\pi^-$ decays (50%)	63
$\pi^+\pi^-$ decays after prescale factor (8)	8
$\pi^+\pi^-$ events to tape	5
$\pi^+\pi^-$ events after cuts	2.3
Total $\pi^+\pi^-$ events	46K
Ke_3 decays	25K
accepted Ke_3 decays	12K
accepted after prescale factor	1.5K
Ke_3 decays to tape	800
Ke_3 after cuts	700
Total Ke_3 events	14M

2. Improvements to the apparatus.

The major improvements to the apparatus that are required are:

a) A new calorimeter, probably made from about 4000 CsI crystals.

b) A crude hadron calorimeter.

c) A better photon veto system to handle an enlarged decay region and provide more hermetic coverage.

d) New higher gain front-end amplifiers for the drift chambers.

e) TDC's and crude flash ADC's on each calorimeter channel.

f) A neutral cluster finder and trigger processor.

g) A new data acquisition system with parallel processing (Level 3).

The ε'/ε experiment will make use of the improvements already underway: a sophisticated track processor, a system of TRD's, and a totally active regenerator.

3. Improvements to the trigger.

As in E731, the majority of events written to tape would be of the high statistics modes: unfortunately, we will still need a great deal of these for systematic checks. (At the Main Injector, with a much larger acceptance and decay rate, we will be able to write mainly 2π events since we can separately determine the acceptance).

We will be writing about 2×10^4 events per spill where the 2π candidate triggers contribute the same as the high statistics ones. We will need a factor of 10 reduction in the four cluster trigger rate, presumably from an invariant mass calculation. We will also need a factor of 50 reduction in the charged trigger rate using the track processor which will find the number of tracks, match tracks with clusters in the calorimeter, and calculate E/p, invariant mass and

P_T^2 to select 2π events. As well, some of the reduction can come from Level 3.

Our total event rate corresponds to about 10^6 events to tape per hour. The experiment should run for 24 weeks at 100 hrs/week and 50 pulses per hour for a total of 120K pulses. We will be writing one 8mm cassette every hour or so. This is about twice the event rate to tape we had for charged-mode E731 running.

SYSTEMATIC ISSUES

We now turn to the achievement of a systematic error below 5 x 10^{-4} in the double ratio. We first list the contributions to the systematic uncertainty for the 20% data set analysis.

TABLE IV: Systematic Errors for ε'/ε

Effect	E731 Correction [%]	E731 Syst. Error (published) [%]	E731' Correction [%] Goal	E731' Syst. Error [%] Goal
$\pi e \nu$	0.31	0.06	0.03	0.005
incoherent regen. (charged)	0.13	0.01	0.025	0.005
$3\pi^0$	0.31	0.06	0.10	0.01
"cross-over"	4.66	0.14	0.45	0.01
incoherent regen. (neutral)	2.58	0.07	1.0	0.01
accidental effects (charged)	-	0.07	-	0.01
accidental effects (neutral)	-	0.07	-	0.01
energy scale/non. lin.	-	0.20	-	0.02
acceptance charged	0.45	0.18	≈2.0	0.02
acceptance neutral	3.97	0.18	≈5.0	0.02
TOTAL		0.38		0.04

We will discuss how each error will be reduced by the indicated amount.

1. Charged mode background ($\pi e \nu$)

Here we need a factor of about 10 in the uncertainty in the subtraction for residual semileptonic decays. This will be accomplished with the use of a system of TRDs (not used in E731) as well as with the improved resolution of the new electromagnetic calorimeter together with the new hadron calorimeter. Likely more than a factor of 10 will be attainable.

2. Regenerator backgrounds (incoherent regeneration and "cross-over").

Since the 4 gammas are observed only at the position of the electromagnetic calorimeter, kaons which scatter in the regenerator can wind up in the vacuum beam. These are called "cross-over" events. For E731', the crossover is expected to be about 0.5%. This is a factor of 10 less than in E731 since the inelastics, which contribute about 80%, should be eliminated with a fully active regenerator and since the decay region is a factor of two longer (increasing the vacuum signal relative to the regenerated one). Our goal is to understand this correction to about 2% of itself whereas in E731 currently our understanding is at the 3% level. The incoherent events in the regenerated beam (those that scatter but remain in the regenerated beam) will be at the 1% level and we would like to understand these to 1% of themselves. This should be possible with the greatly increased statistics and using the simulataneously collected charged mode events where the full angular information is retained. We can also analyze the charged and neutral mode data symmetrically which would mean not using a P_T^2 cut in the charged analysis. The effective P_T^2 window for the beam region itself is about 2500 $(\mathrm{MeV/c})^2$ and the Ke3 background, given the improved electromagnetic resolution (CsI) and rejection (TRD's), should be at the level of only about 0.3%. Finally, particular attention must be paid to a smooth beam profile.

3. $3\pi^0$ background

The uncertainty in this background needs to be improved by a factor of 10. This can be accomplished by reducing the background significantly. The superior resolution of the electromagnetic calorimeter together with an upgraded photon veto system provide for such a reduction. Our background under the $2\pi^0$ mass peak is dominated by events with photon fusions; the ability to recognize these depends upon the granularity of the detector. The new detector will have about a factor of two finer (transverse) sampling so that the single fusion events will be reduced by a factor of four and the double fusion events by a factor of 16.

4.Accidental effects

We saw no systematic effect in E731 when overlaying accidentals on Monte Carlo events. However, because of the higher rate in E731' and the fact the accidental activity concentrates around the vacuum beam, there may very well be a small shift in the relative acceptance. There are two avenues of attack: first, we can measure the shift and, second, we can take measures to reduce the effect.

We can measure the effect with the high statistics modes. For example, with 500M $3\pi^0$ decays, assuming the same thickness regenerator and absorber, we should have about 30M $3\pi^0$ decays in the regenerated beam, allowing an absorption measurement with a precision of 2×10^{-4}. This data can be broken up to study rate dependence. Similar precision will be available with charged mode data. Since our goal is 1×10^{-4}, these samples will provide only checks, but the technique of overlaying accidentals should work very well.

The effect of accidentals can be reduced with the following measures.

(a) We will likely have TDC information for many of the calorimeter channels.

(b) We will likely have some flash ADC information for the calorimeter channels. For CsI, this is important for a subtraction of the slow component.

(c) The trigger plane at the end of the decay region (T/V), used in E731, will be removed (some clusters were created by neutrons scattering in T/V).

(d) There is good evidence that we had beam halo hitting the anti counter around the beam holes (CA) and making clusters. This will be improved.

5. Acceptance

As shown earlier (see Figure 4), we have been highly successful in the understanding of the detector acceptance. The correction for acceptance will be increased as a result of the enlarged decay region, but in order to achieve the required level of acceptance understanding for E731', we will only need another factor of about 2 or 3 improvement. It is likely that even with E731 data, we will achieve this.

6. Electromagnetic calorimetry

The remaining challenge is the reduction in the uncertainty in the neutral energy calibration by a factor of 10. This is the major reason for a high precision calorimeter. The improvement will come from the significantly better precision and from a better understanding of the sources of the photon line-shape that come from a scintillating device compared to a Cerenkov radiator.

We have done studies of new calorimetry candidates and we will briefly report on these here.

The new calorimeter is required to have the following characteristics: (1) energy resolution of order $1\%/\sqrt{E(\mathrm{GeV})}$ or better, (2) no significant radiation damage at 1000 Rad, (3) narrow output pulse and good timing resolution to reject accidental hits. Its configuration is shown in in Figure 6. This device would be doubled in size for the Main Injector experiments.

The current calorimeter for E731 consists of an 804-block leadglass array where each block has dimension $5.8 \times 5.8 \times 60\ \mathrm{cm}^3$ with its length parallel to the beam direction. The number of photo-electrons is 500/GeV which itself contributes $4.5\%/\sqrt{E}$ to the total electron energy resolution of $1.5\% + 5\%/\sqrt{E}$. The low light yield is primarily due to the fact that lead-glass is a Cerenkov radiator, and it will be necessary to use a scintillator to obtain photon statistics good enough for the next round of experiments. We have found that both CsI and BaF_2 generate 40000 or more photo-electrons per GeV even after the light yield is compromised to satisfy other requirements such as uniformity of response along the block. This corresponds to $0.5\%/\sqrt{E}$ energy resolution from photon statistics only.

Another important source of energy resolution is the coupling of longitudinal shower fluctuation to the light absorption within a block. The typical absorption of leadglass is 3% per radiation length and when this is coupled with longitudinal shower fluctuation of 1 radiation length (for electrons; for photons, it is even larger) it results in a constant term of 3% in energy resolution (for photons). In reality, leakage out the back partially compensates the absorption effect and the total contribution from shower fluctuation becomes dependent on energy (Fig. 7); the importance of uniformity of response, however, is clearly demonstrated.

With BaF_2, we have studied[9] the uniformity of response along the block with various wrappings and different methods for coupling of the phototube to the block. The absolute absorption length was measured to be 115 cm. However, with a careful teflon wrapping where small sections on both ends are left unwrapped, it was possible to obtain a uniformity consistent with being perfectly flat within the statistical errors of each point (Fig. 8). Also, the response curve is well simulated by a ray-tracing monte carlo indicating that the understanding of the response is good enough to control the curve more or less at will. Once it is installed, however, the resolution may degrade when the response curve deviates from being flat (e.g. due to radiation damage).

We have measured the timing resolution of BaF_2 and found it to be 160 ps even without correcting for pulse height. This is due to BaF_2's very fast (0.6 ns decay time) component. BaF_2 has also a slow component; this, however, can be effectively reduced to an acceptable level by a phototube with Cs-Te photocathode or Rb-Te photocathode,

[9]H. Yamamoto et. al., to be published.

the latter being a new photocathode material of which we have one prototype sample for evaluation. The fast timing also allows one to use a narrow gate (20 ns or less). The fast components of CsI are not as fast (10ns and 30ns) but probably adequate for E731'. If one adopts the fly's-eye configuration, BaF_2 blocks could be used near the beam holes where counting rate is high, with CsI filling the rest of the volume. Since CsI and BaF_2 have very similar radiation lengths and Molière radii, they can be used together without substantially complicating the analysis.

The literature on radiation hardness of BaF_2 and CsI is somewhat confusing due primarily to different grades of crystals used for tests. BaF_2, however, seems to be hard enough for the next round of experiments. More study is needed on the radiation hardness of CsI. One significant drawback of BaF_2 is that it is about three times as expensive as CsI. However, because of the interest in it for possible SSC experiments, there is the possibility of a dramatic reduction in price. One of the suppliers is discussing a figure of \$2.50/cc with their upper management; this development would be most welcome to us.

COSTS AND SCHEDULE

Costs for the major new items are estimated in the following Table.

TABLE V: Cost Estimate for E731'

CsI: 4000 crystals: 3.125cm x 3.125cm x 50cm @ $2/cc	$3.9 M
4000 PM's with UV glass @ $250	$1M
4000 PM bases @ $50	$200 K
4000 channels of ADC's @ $60	$240 K
4000 channels of TDC's @ $70	$280 K
4000 channels of flash ADC's	$400 K
Improvements to beam	$500 K
Fully active regenerator	$200 K
New decay tank and γ vetoes	$500 K
New drift chamber electronics @$100 / channel	$200 K
New drift chamber TDC's	$100 K
New DAQ with Level 3 (100MIPS)	$400 K
Hadron Calorimeter: 10 2.5m x 2.5m layers of 1/2" scintillator @ $50/ft^2	$35 K
200 PM's for HC	$60 K
Neutral cluster processor	$300 K
TOTAL:	$8.3 M

Schedule

We should be able to place the order for the CsI (if that is the chosen material) shortly after it has a beam test which will likely be in January of 1991. Thus we could have a good chunk of the calorimeter ready for the '93 run (depending upon when it actually occurs) but probably not all of it. We would employ as much of it as possible during the rare decay run in '93 and it would be completed for the folllowing Tevatron fixed target run.

Other Physics

Some interesting byproducts that would come from this run would be:

1. Measurement of τ_S to about 0.03%.
2. Measurement of Δm to about 0.15%.
3. Measurement of $\Delta\Phi$ to about 0.2^0.
4. Measurement of δ_e to about 5 times better than in E731.
5. 10^6 $\pi\pi\gamma$ events.

Conclusion

We believe that we can perform a significantly improved determination of ε'/ε at the Tevatron using essentially the same technique as in E731. The major new piece of equipment will be a high precision electromagnetic calorimeter of dimensions 2m x 2m. The calorimeter is crucial to the measurement. The time scale will be governed largely by the funding available and the delivery time for the new calorimeter material.

We should mention a few of other considerations. First, we do not know the schedule of the Main Injector; if it were on-line for a 1995 run, then we would prefer to make this measurement using a dedicated high intensity beam at 120 GeV/c. Second, we are still studying both BaF_2 and CsI; both look promising but the choice (or whether a hybrid detector is used) will be made only after our own beam tests. Finally, we do not yet have the final E731 result in hand. If somehow our result became as much as 3σ away from zero, then we would have to rethink this proposal. Needless to say, there is nothing that we have discovered to date that would significantly change our result.

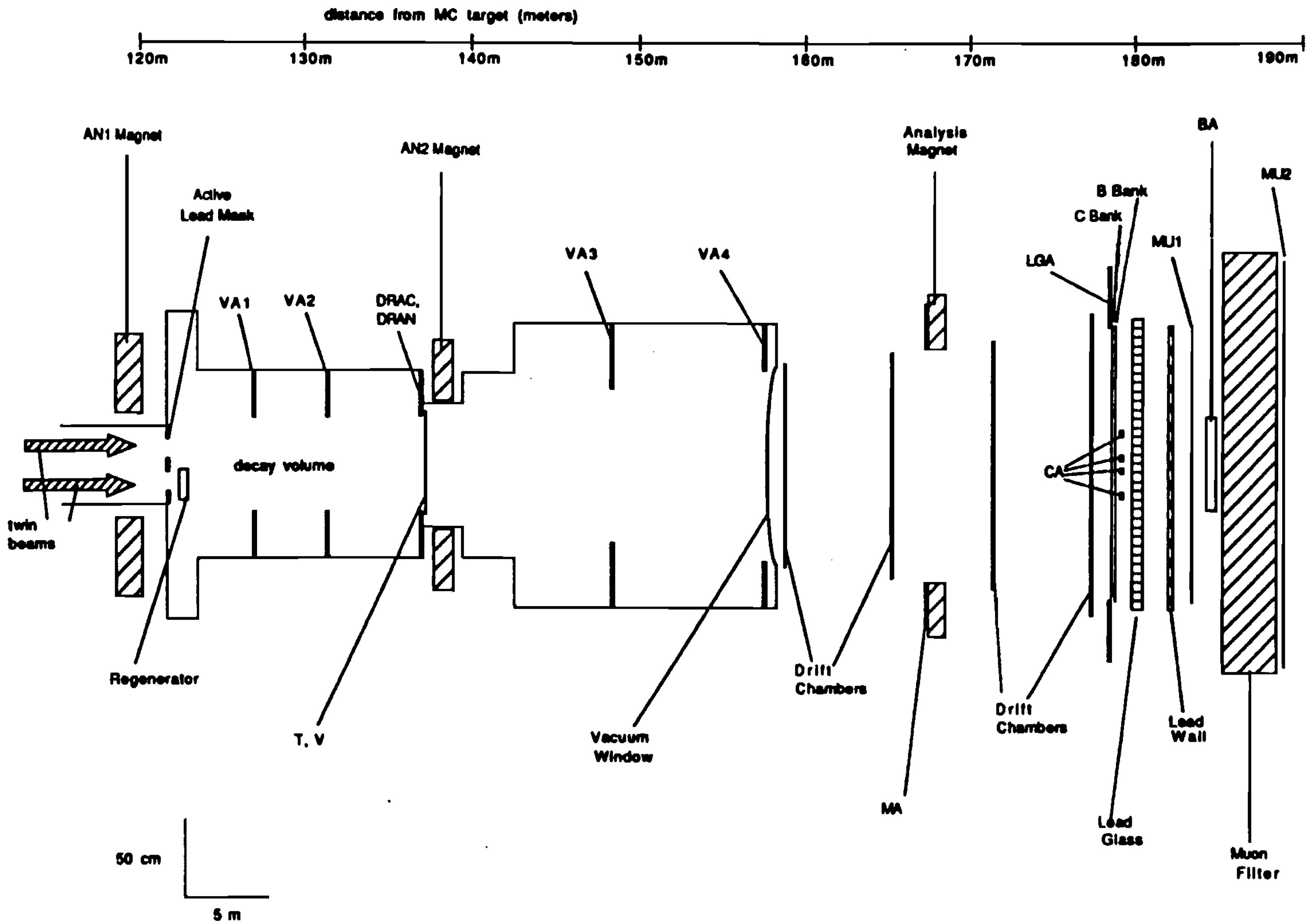

Figure 1 The decay volume and detector.

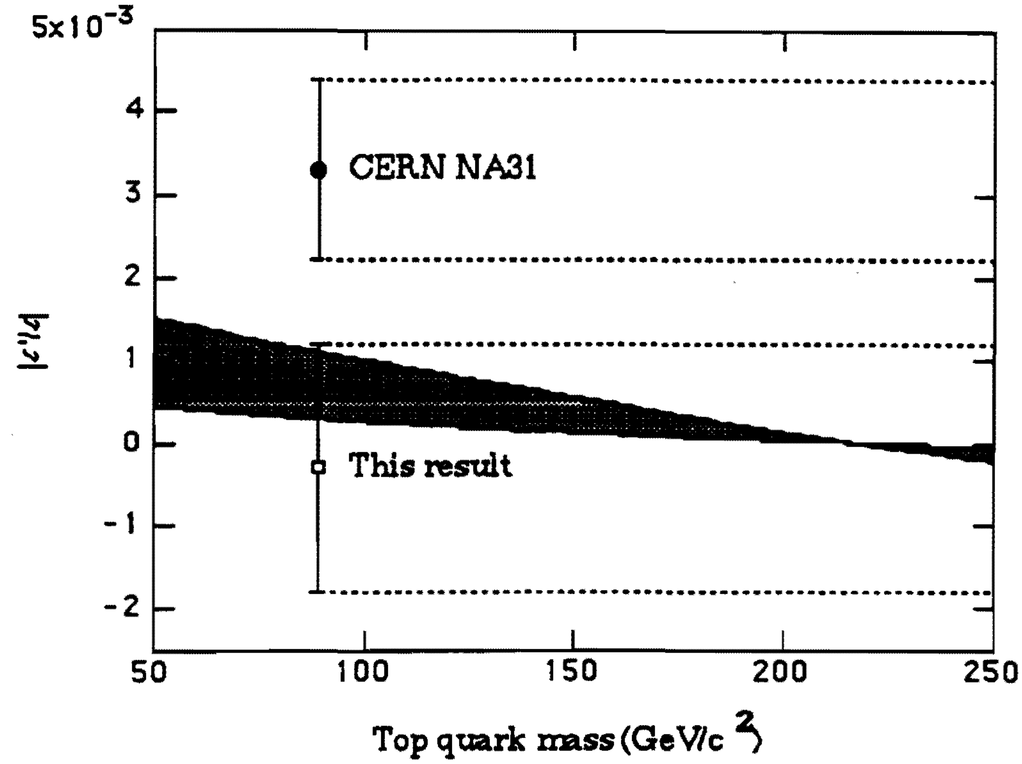

Figure 2 The value of $|\varepsilon'/\varepsilon|$ as a function of m_t. The shaded area is allowed by theory and the other CKM constraints. The solid circle is the result of CERN NA31 and the open square is the result of this experiment.

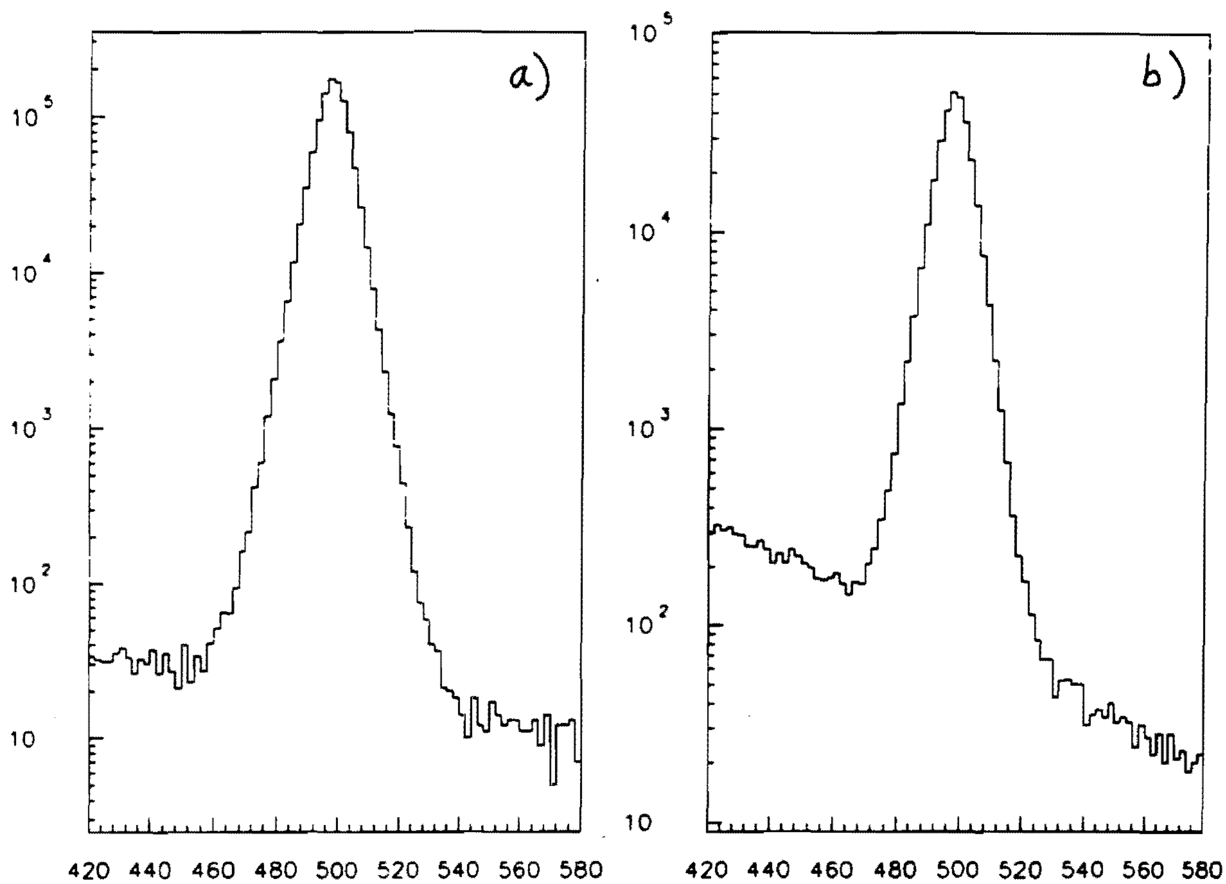

Fig. 3 $2\pi^0$ mass plots for K_S (a) and K_L (b) decays for the entire E731 data set.

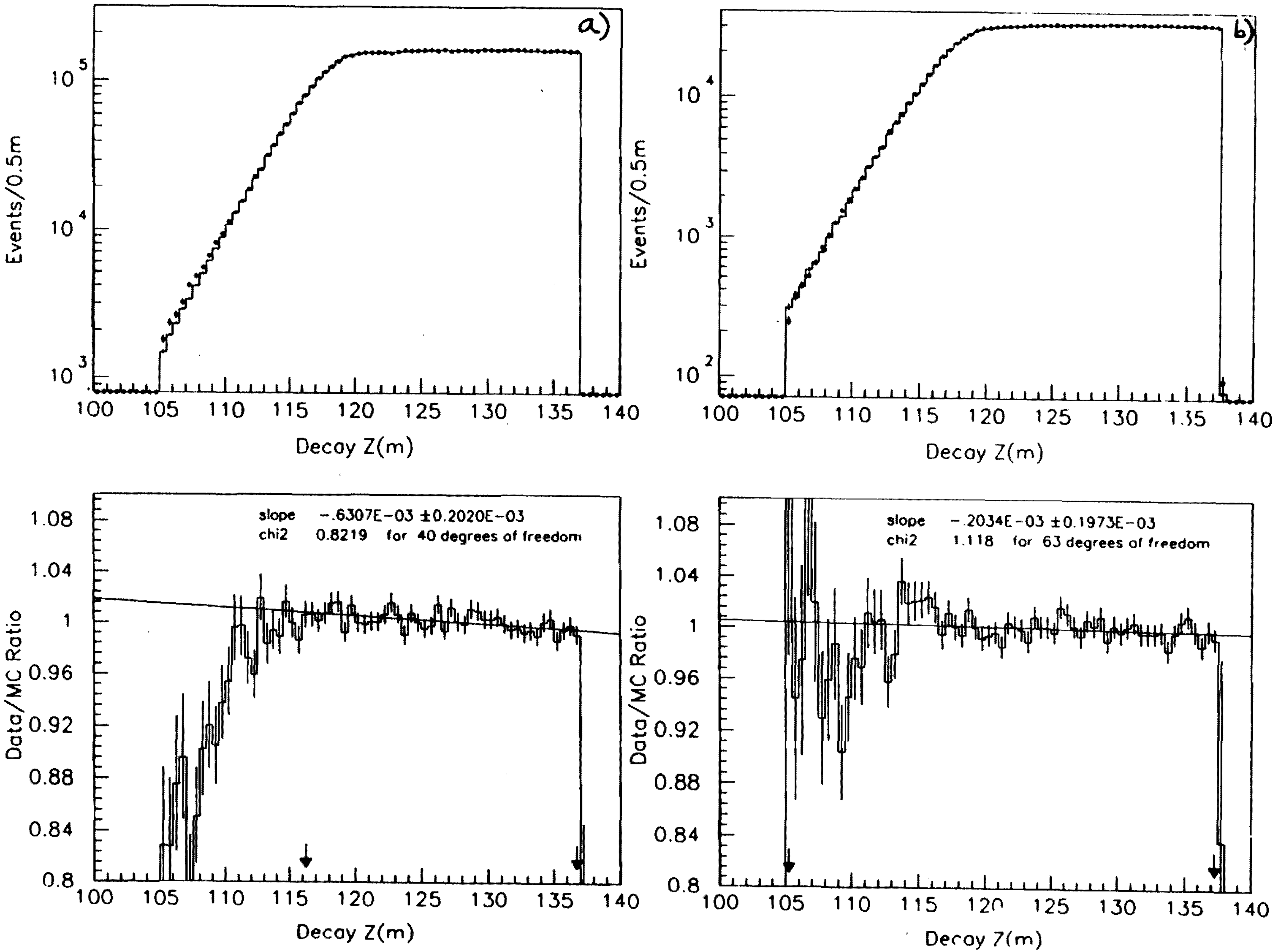

Fig. 4 Data/Monte-carlo comparisons for Ke_3 decays from a portion of the E731 data set. (a) shows the status at the time of publication while (b) shows our current status, with near final calibration constants

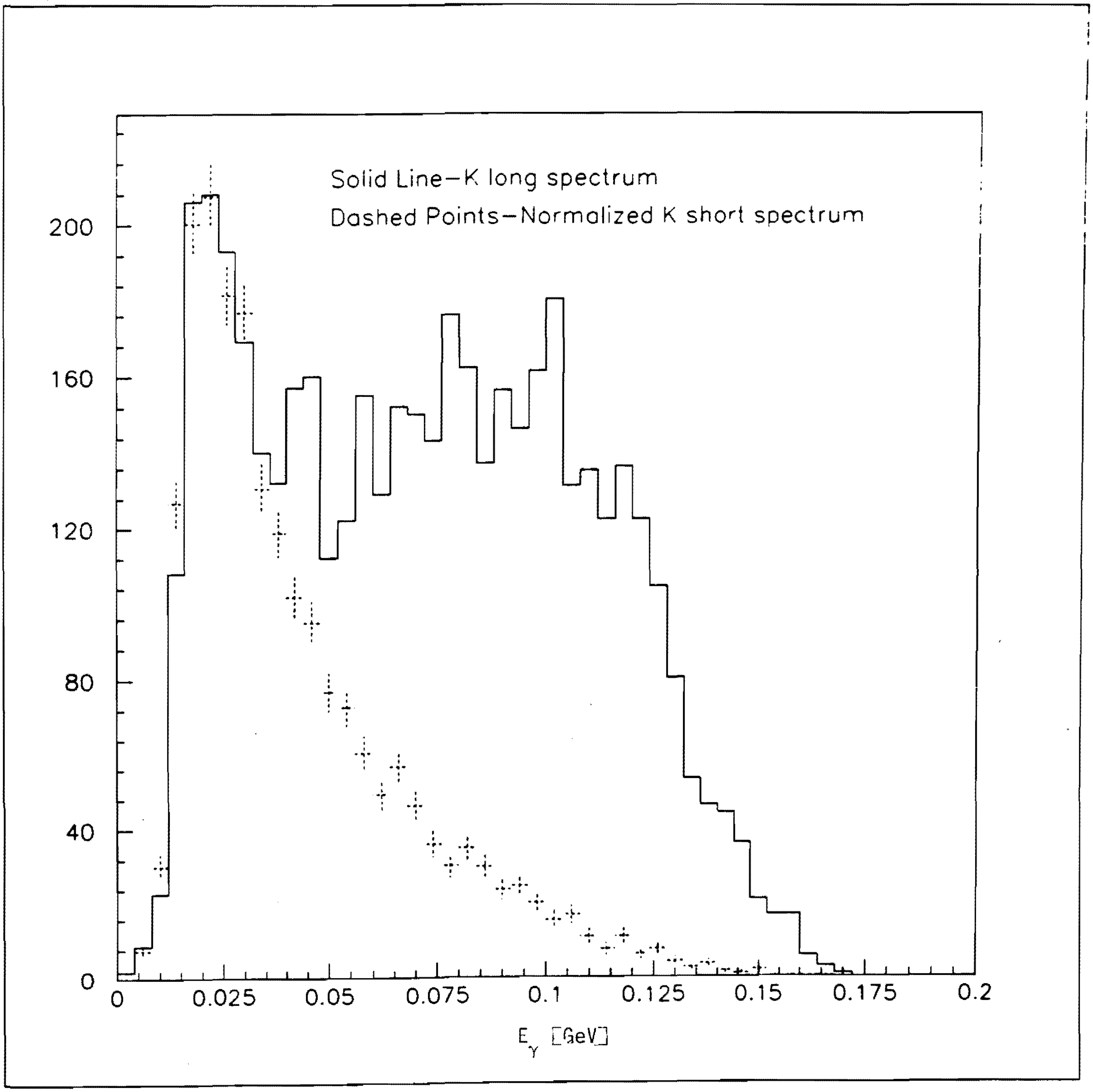

Fig. 5 E_γ distribution for $K_{L,S} \to \pi^+\pi^-\gamma$ events. The stiff direct component is clearly visible.

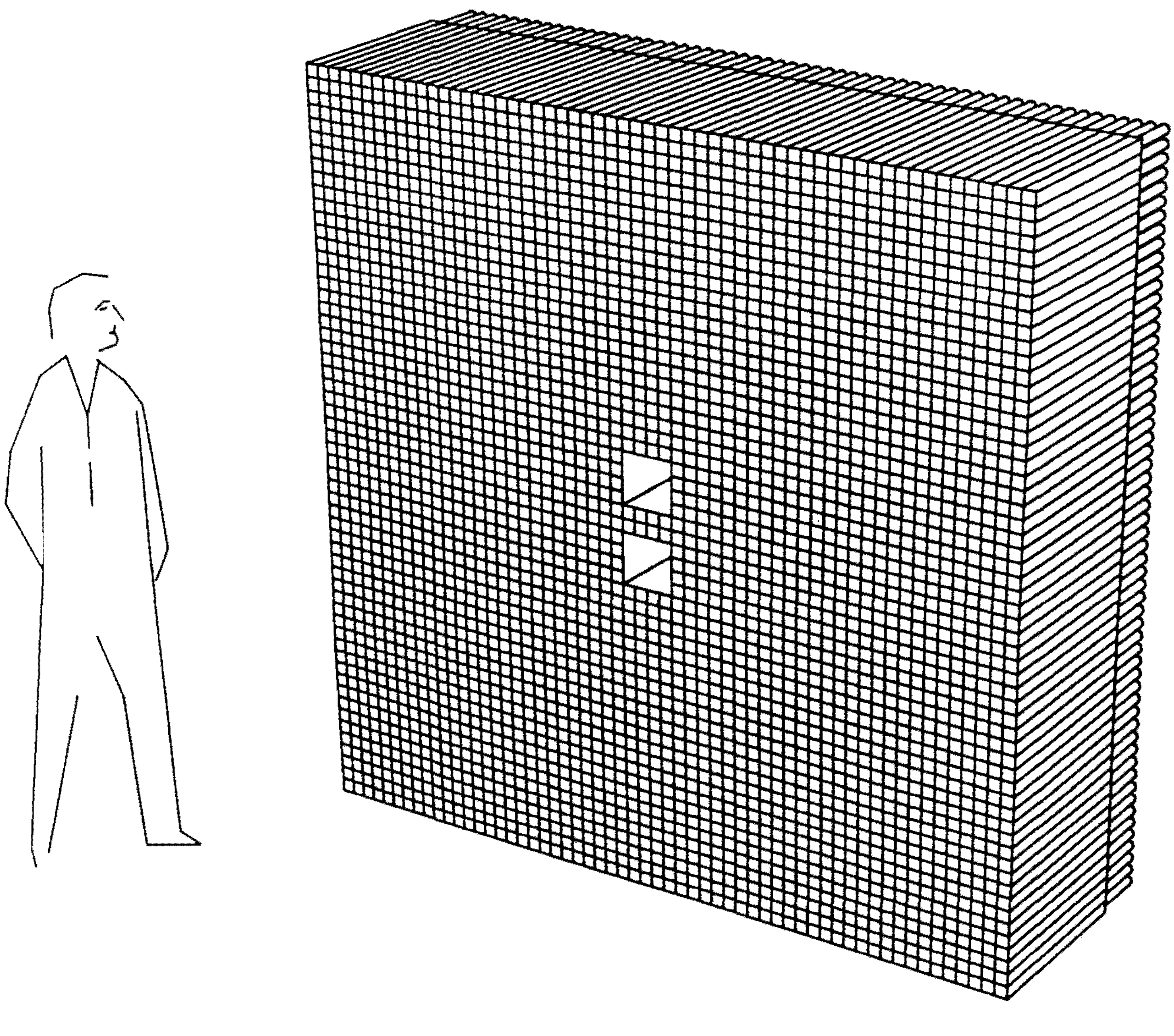

Fig. 6 Schematic of a new CsI array for a new ϵ'/ϵ experiment.

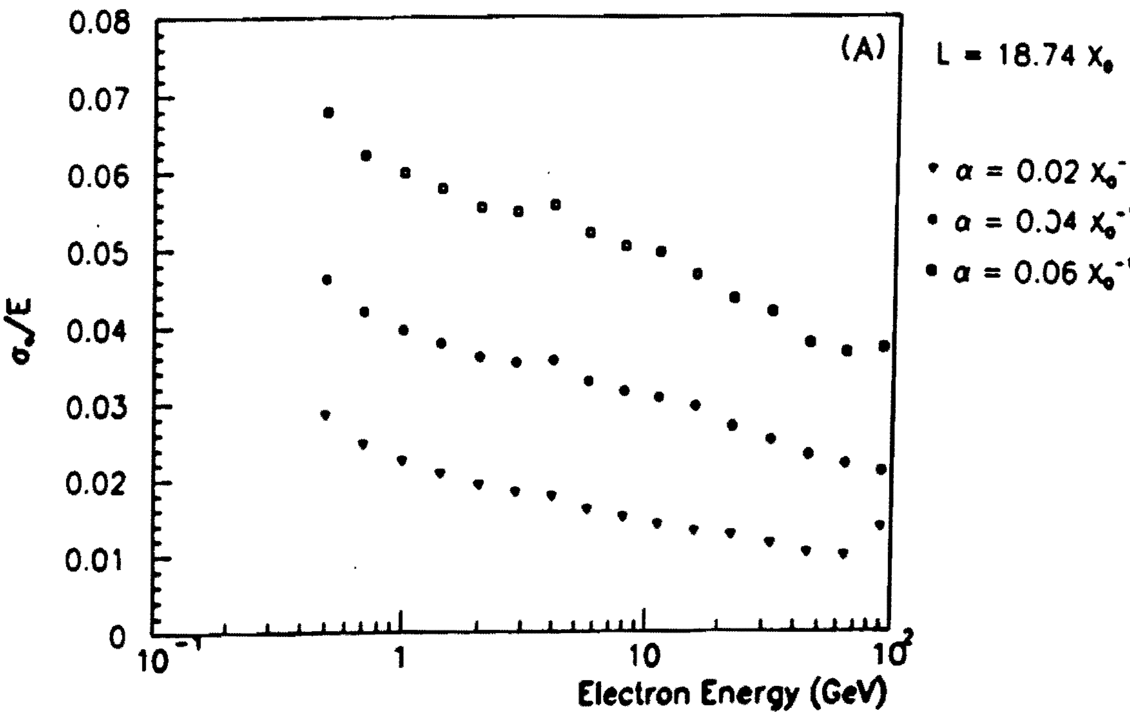

Fig. 7 **Energy resolutions due to shower fluctuation as functions of electron energy for different effective absorption per radiation length (α). The total length of block, 18.74 radiation length, is for the current leadglass block. The energy resolution strongly depends on the absorption.**

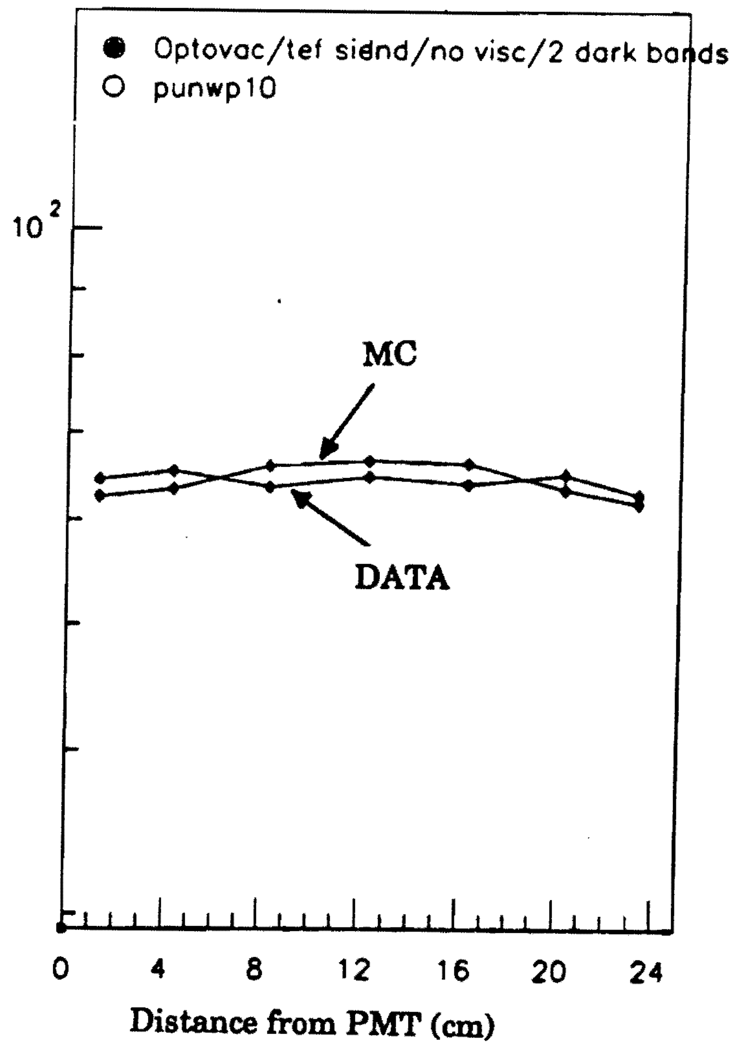

Fig. 8 Acceptance of scintillation photons as a function of distance from phototube. The data is consistent with being flat and is reasonably simulated by the ray tracing Monte Carlo. The measurement was performed with a muon telescope triggering on muons hitting the crystal transversely.