Proposal to Measure the Branching Ratio for the Decay, $K_S^0 \to \pi^0 e^+ e^-$

P. Gu, P. Haas, B.K. Kim, S.K. Kim, J. Matthews, S.S. Myung,
S. Schnetzer, R. Stone, G. Thomson*, Y. Zou
Rutgers University

A. Barker, D. Harris, K. McFarland, B. Schwingheuer, S. Somalwar,
Y. Wah, B. Winstein, R. Winston
University of Chicago

E. Swallow
Elmhurst College

G. Bock, R. Coleman, J. Enagonio, R. Ford, R. Hsiung, D. Jensen,
E. Ramberg, K. Stanfield, R. Tschirhart, ~~T. Yamanaka~~
Fermilab

G. Gollin, J. Heuer, W. Hogan, J. Ross, H. Thomas
University of Illinois

K. Arisaka, W. Slater
UCLA

Abstract

We propose to measure the branching ratio for the decay $K_S^0 \to \pi^0 e^+ e^-$. This decay is important because it can be used to predict the indirect CP violating contribution to $K_L^0 \to \pi^0 e^+ e^-$. We will bring a proton beam to the E799B detector in the MC beam line, strike a target at the entrance of a hyperon magnet to form a K_S^0 beam, and use the same detection apparatus as E799B (whose aim is to measure the K_L^0 branching ratio) to minimize systematic errors. We expect to achieve a single event sensitivity of about 1×10^{-11}. The theoretical estimates for this branching ratio are between 5×10^{-10} and 5×10^{-9}, so we should see between 50 and 500 events.

E799B will collect data in the first two thirds of the 1993 fixed target running period. We want this K_S experiment to take data in the last third of that running period.

An important secondary objective of this experiment would be to collect a large number of $3\pi^0$ and $\pi^+\pi^-\pi^0$ decays near the target, and measure the CP violation parameters η_{000} and η_{+-0}. We could collect about 120 M decays of each type, and reach a sensitivity of $\delta\eta \sim 0.7 \times 10^{-3}$.

* Scientific Spokesperson: Gordon Thomson (201)932-4566: FNAL::THOMSON.

1 Introduction

Our collaboration has embarked on a program of experiments [1] to find direct CP violation in the decay $K_L^0 \rightarrow \pi^0 e^+ e^-$. This decay has contributions from indirect CP violating and CP conserving amplitudes as well, which must be understood before the direct CP violating amplitude can be determined. One can make an accurate prediction of the indirect CP violating contribution by measuring the branching ratio for the (CP conserving) decay $K_S^0 \rightarrow \pi^0 e^+ e^-$. This is what we propose to do.

In the 1993 fixed target running period we will run E799B, which should find at least a few K_L decays. We would like the K_S measurement to follow E799B, in the same running period. We estimate that E799B will take eight months to complete, and that the K_S experiment will require four months. To complete both of these experiments the 1993 run will have to be long, and preferably be split in the middle at the time we would make the changeover. The length of the 1993 run is a very important parameter. If the run is too short the result might be to seriously compromise both experiments. We do not want this to happen, and we feel that the acceptance of this proposal should include a committment on the part of Fermilab to have a sufficiently long run in 1993. Because of other experimental plans of our group, it would be very disadvantageous to have the K_S experiment rolled over into the next fixed target run.

Recently, a background in the $\pi^0 e^+ e^-$ channel has been found[2] that must be dealt with. This is $K_L \rightarrow \gamma\gamma$, with an internal conversion and bremsstrahlung to give $\gamma\gamma e^+ e^-$. By making judicious cuts, (demanding that the two γ's add up to a π^0, and by cutting on the Dalitz plot) one can reduce this background to the 1×10^{-11} level. To do this a new electromagnetic calorimeter must be built with five times better energy resolution. The result would be a signal to noise ratio of perhaps 2:1, if the K_L decay happens at about the expected level. In neighboring bins in $\gamma\gamma$ invariant mass, there are about 17 times more background events, making it possible to accurately predict the level of the background under the π^0 mass.

Seeing a few events does not pin down direct CP violation in this rare decay mode, background or no background. To do this a more sensitive experiment must be done, perhaps at the Main Injector. An experiment sensitive at the 10^{-14} level has been discussed in P804. This experiment could achieve a 6σ measurement of the direct CP violating contribution to the K_L decay, if the direct CP violating branching ratio is 3×10^{-12} (the typical value predicted by the standard model). The effect of the background is merely to reduce the number of σ's by $\sqrt{1.5}$, which is not a big effect. This expected accuracy places a constraint on how well we must measure the K_S decay. A single event sensitivity of 1×10^{-11} would match that of the Main Injector K_L experiment.

It is worth mentioning that the K_S experiment is much easier at the Tevatron than at the Main Injector. The energy of the kaon beam grows linearly with proton energy, but the shielding required to contain the proton showers grows only logarithmically, so at the higher energy, decays at shorter proper times are visible, and more K_S decays can be collected.

[1] See the proposals for E799 by T. Barker et al., and P804 by W. Molzon et al.

[2] H. B. Greenlee, Yale preprint YAUG-A-90/3, submitted to Physical Review D.

Being sensitive to $10^{11} K_S$ decays, the experiment will have unprecedented sensitivity to other interesting physics. Foremost on the list must be η_{000} and η_{+-0}. Here we will collect more than 100 M events of both types. We will also be able to search for CP violation in the decay $K_S \rightarrow \pi^+\pi^-\gamma$, investigate the short proper time behavior of the semileptonic charge asymmetry, and search for other rare K_S decays.

2 Theoretical Predictions

The most interesting of the three amplitudes that contribute to the decay $K_L \rightarrow \pi^0 e^+ e^-$ is the one coming from direct CP violation. To extract it, one must subtract the branching ratios of the other sources. All are expected to be about the same size. If you measure B_{Short}, the branching ratio for $K_S \rightarrow \pi^0 e^+ e^-$, the predicted K_L branching ratio from indirect CP violation is $B_{indirect} = B_{Short} \times |\epsilon|^2 \times \tau_L/\tau_S = B_{Short} \times 0.0030$. To extract the CP conserving part of the K_L branching ratio, since it comes from a two photon exchange diagram, one measures the branching ratio for $K_L \rightarrow \pi^0\gamma\gamma$, where the two γ's do not add up to a π^0. Then a theoretical estimate of the contribution can be made. The $\pi^0\gamma\gamma$ branching ratio has been measured by the NA31 group at CERN, and in E799A we hope to measure it even better.

Gilman and Wise[3], in 1980, predicted that the K_S branching ratio would be between 1.5 and 3×10^{-9}; Gilman's student, Claudio Dib, quotes 2×10^{-9} in his recent Ph.D. thesis[4]. Ecker, Pich, and DeRafael[5] used chiral perturbation theory, and by normalizing to the measured branching ratio for $K^+ \rightarrow \pi^+ e^+ e^-$, they come to two solutions, 5×10^{-10} and 5×10^{-9}. All authors stress the model-dependence of their calculations, and say that a measurement of the K_S branching ratio must be made.

We have recently surveyed the calculations for the direct CP violating branching ratio for the K_L decay, and have arrived at a "best" estimate of 0.33×10^{-11}. Bruce Winstein has rewritten the calculation in a way that the top quark mass mostly cancels out, and this is his result. Claudio Dib's calculation would say that 0.33×10^{-11} is the correct value at a top quark mass of about 100 GeV/c^2, and the branching ratio grows with top quark mass, to reach 1×10^{-11} at 200 GeV/c^2. If the K_S branching ratio is 2×10^{-9}, the indirect CP violating contribution would be 0.6×10^{-11}, and if the CP conserving contribution were the same, then in a Main Injector experiment, sensitive at the 10^{-14} level, we would see 2530 events in the π^0 mass bin, including a background of 1000 events. The uncertainty in this number would be 51 events. We would then measure the direct CP violating contribution to an accuracy of $330/51 = 6.5\sigma$. Here I am neglecting complications due to phases among the three amplitudes, which would have to be sorted out by examining the Dalitz plot or by doing an interference experiment. To subtract the indirect CP violating part, we must measure the K_S branching ratio to comparable accuracy; i.e. to 51/600= 9%. To do this we need 123 K_S events. If we reach 1×10^{-11} sensitivity, we will have made a measurement accurate to 7%, so 1×10^{-11} should be our goal. This calculation is weakly dependent on the value of the K_S branching ratio.

[3] F.J. Gilman and M.B. Wise, Phys. Rev D21, 3150 (1980).

[4] C.O. Dib, Ph.D. Thesis, Stanford University, 1990 (unpublished).

[5] G. Ecker, A. Pich, and E. deRafael, Nucl. Phys. B291, 692 (1987).

3 The Experiment

Since one cannot regenerate enough K_S's from the Meson Center K_L beam, we must transport primary protons to a new target just in front of the decay region of E799B, strike that target, and have a magnetic collimator to define the K_S beam and absorb the primary protons. The detection apparatus of E799B would be used for the K_S measurement. At the time E799B ends, we would have the shielding for the K_S beam already in place, with the necessary magnets staged just out of the beam. Then the magnets would be rolled in, and the K_S measurement made.

A beam of 1×10^{10} protons/pulse would be transported through the existing dump and brought to the K_S target. Since the MC beam runs in a stable manner for intensities greater than about 1×10^{11} protons/pulse, about that number of protons must be brought through the switchyard. After that point, the proton beam intensity must be reduced to 1×10^{10}. A pinhole collimator could be used (a diffracted beam from a target could be used also). We choose 1×10^{10} protons/pulse to hit the K_S target because shielding for more than this intensity would be quite expensive. Magnets would be needed to control the angle at which the protons hit the K_S target.

An important element of the experiment is the magnet that forms the K_S beam and absorbs the protons. Following previous experiments at Fermilab that have studied K_S's, we would use a hyperon magnet. This is a magnet generating a high field, with a collimator inside that is designed to transmit a well defined neutral beam, and stop and absorb all charged particles. The hyperon magnet in the Proton Center beam has a 35 kGauss field, and is 7.2 m long. The best magnet for this application would have a similar field and be 5 m long. The 2 m saved is worth 20% more accepted K_S decays. To make an intense K_L beam, one typically strikes the target at 3 - 5 mrad. For this experiment, 1 mrad would be better, because more kaons go into the beam solid angle, and their spectrum is stiffer. The rates are not particularly high so neutrons are not a problem. Instead of a lead filter to remove γ's from the beam, we would use a high-z target placed just inside the field of the hyperon magnet. The collimator would have a solid angle of 5 μster. Fig. 1 shows a plan view of the collimator in the hyperon magnet.

The detector, shown in Figure 2, would be the same as in E799B. It consists of a Vee spectrometer of four drift chambers, two in front of, and two behind the 100D40 magnet. Three transition radiation detectors would help identify electrons, and an electromagnetic calorimeter would catch photons and also help identify electrons. Trigger processors to pick out clusters in the calorimeter and to process tracking information from the drift chambers will be important in the trigger. These are being built for E799. We will probably have to build an addition to the track processor to identify $\Lambda \to p\pi^-$ decays.

The biggest addition to the apparatus will be a new electromagnetic calorimeter. Our aim is to reduce our resolution in π^0 mass from 4 MeV/c^2 to 0.8 MeV/c^2. It may be that the only detector that can be bought for a reasonable price would be made of undoped Cesium Iodide. The better resolution is necessary for a new ϵ'/ϵ experiment and for $K_L \to \pi^0 e^+ e^-$, and will greatly aid the present proposal.

Source	K_S Experiment	K_L Experiment
Total decays	677 kHz	520 kHz
K_S^0 decays	285 kHz	0
K_L^0 decays	11 kHz	520 kHz
Λ^0 decays	381 kHz	0
$\pi^+\pi^-\pi^0$	1.4 kHz	64 kHz
$3\pi^0$	2.4 kHz	113 kHz
$\pi e \nu$	4.2 kHz	201 kHz
neutron flux	11 MHz	172 MHz

Table 1: Calculated Rates

We have calculated the neutron and muon fluxes, and the rates of K_S, Λ^0, and K_L decays expected at a targeting angle of 1 mrad. We used the Malensek parameterization[6] for the kaon flux, and the Skubic parameterization[7] for the Λ's. In Skubic et al., kaon fluxes were also measured, and for the range $x > 0.2$, where Skubic had data, both parameterizations agree. For the neutron flux, we used a measurement of the neutron invariant cross section by Edwards et al.[8] at $p_t = 0$, scaled by the p_t dependence of ISR data. Table 1 gives the results of this rate calculation. The overall rates in the K_S experiment are similar to what is expected in E799B. The largest single contribution is from Λ decays. Because the protons from $\Lambda \rightarrow p\pi^-$ are tightly collimated in a cone around the beam, they could cause inefficiencies in the drift chambers due to space charge buildup. We calculated the rate/cm of wire to be $\leq$ 10 kHz, which is well below 20 kHz, the point where this effect becomes important. We are also building new drift chamber preamplifiers to allow us to reduce the drift chamber high voltage, and have fewer positive ions form near the sense wires, making us less sensitive to this effect. The expected neutron flux is well below E799B also.

In the K_L experiment, the muon flux from the target is quite high. In the K_S experiment we use two orders of magnitude fewer protons per pulse, so the muon flux might not be as serious. We performed a calculation of this muon flux using CASIM, a hadronic shower program that tracks muons that come from decays or direct production. In the context of planning the main injector kaon beam, we recently tested this program by trying to calculate the muon flux that was observed in E613, a beam dump experiment in the Meson Lab. CASIM's results were consistently a factor of two higher than the measured muon fluxes. The result of the calculation for the K_S experiment was that a flux of about 100 kHz/sq. ft. would be observed in the first photon veto counter ring, about 7m downstream of the target. The main muon lobes were just outside these counters to left and right. The highest flux in these lobes was 500 kHz/sq. ft. The muons were traveling away from the beam, and the flux became progressively smaller at locations further downstream. In the first drift chamber, the flux was about 1 kHz. These are acceptable rates.

We performed a Monte Carlo calculation of the acceptance of the apparatus. Because the K_S decays emphasize the high momentum end of the kaon spectrum, the acceptance is

[6] A.J. Malensek, Fermilab FN-341 (1981).
[7] P. Skubic et al., Phys. Rev. D18, 3115 (1978).
[8] R.T. Edwards et al, Phys. Rev. D18, 76 (1978)

better than in E799B, with 20% of decays above 50 GeV/c being accepted. The result is 57,000 accepted K_S decays/second. If we multiply by 20 sec/pulse, 60 pulses/hr, and 800 hr/experiment, we have 0.55×10^{11} kaons, or a single event sensitivity of 1.8×10^{-11}.

We have looked into the backgrounds that might be present in the K_S experiment. The $\gamma\gamma e^+e^-$ background that is a problem for the K_L experiment is not a problem for the K_S. In the E799 proposal several sources were considered, and we have calculated how these might change with a K_S beam. Most are not a problem with either beam, but the case of a $2\pi^0$ decay, with a double internal conversion (double Dalitz decay) is quite different in the two cases because the $2\pi^0$ branching ratio is a factor of 300 larger. More Monte Carlo work has shown that the single event sensitivity of this mode is ?????, and is not a problem. The other type of background that is different in the two beams is those involving random γ's hitting the electromagnetic calorimeter. We have calculated the equivalent single event sensitivity for the worst of these, $K_L \rightarrow e^+e^-\gamma$, with random γ's hitting the calorimeter. We determined the probability that random γ's hit the lead glass calorimeter of E621, which ran in quite similar conditions to the experiment we are proposing here. That probability was about 4 times higher than in E731. A file was made of the energies and positions at the calorimeter of random γ's from the E621 data, and these γ's were overlaid on Monte Carlo events of the $K_L \rightarrow e^+e^-\gamma$ decay, to see if they could be confused with the signal. This background came in at the ????? level, and is not a problem.

Two of us (G.T. and Y.Z.) were members of the Rutgers, Michigan, Minnesota collaboration that performed E621. This experiment sampled a large number of neutral kaon decays between 9 and 25 m from the production target. It has a sensitivity to $K_S \rightarrow \pi^0e^+e^-$ in the 10^{-9} range. About 1/7 of the E621 data has been examined, and one good event has been found. In this part of the data, the single event sensitivity is 3×10^{-8}. Figure 3 shows a scatter plot from one data tape from E621 (1/40 of the data set under examination), where all cuts have been made except the E/p cut to choose electrons. $K_{\pi 3}$ events, and $K_{\pi 2}$ and semileptonic decays (with two random gammas that add up to a π^0) can be seen in the figure. Figure 4 is the same data after applying an E/p cut (0.8< E/p <1.2), and is much cleaner. When all tapes are accumulated, one signal event remains, and 4 events show up in the K_{e3} area. We are currently calculating the probability that the one signal event is a K_{e3}. In E621 we tried to sweep charged particles off the glass, so most of the time we have only one particle hitting the glass, and only one E/p to evaluate. In addition we didn't have transition radiation detectors or an excellent electromagnetic calorimeter. In the experiment we are proposing here, the situation would be many orders of magnitude better, and this background would be absent.

We can calculate the improvement that the present experiment would have over our experience in E621. Table 2 shows the various factors that go into the calculation. Also shown is the result of the calculation for the present experiment using the beam intensity parameterization of Malensek. There is a factor of 1.9 discrepancy between the two calculations, which is probably an acceptable uncertainty. We believe the Malensek calculation is better because in E621 there are normalization uncertainties of about a factor of 2 that were never solved (fewer K_S and Λ decays were found than calculated), which contradicted the E8 group's experience, gained from previous hyperon experiments.

Item	Factor	Single Event Sensitivity
Data Set 3		3×10^{-8}
All E621	7	4×10^{-9}
Acceptance	6	7×10^{-10}
Solid Angle	10	7×10^{-11}
p<120	1.2	5×10^{-11}
Shorter H.M.	1.2	4×10^{-11}
Running Time	1.33	3×10^{-11}
Malensek		1.8×10^{-11}

Table 2: Projections from E621 to the Present Experiment

4 η_{000} and η_{+-0}, and other physics

We would also collect a large sample of $3\pi^0$ and $\pi^+\pi^-\pi^0$ decays in this experiment. This would let us measure η_{000} and η_{+-0}. Experiment 621 collected 2 M $\pi^+\pi^-\pi^0$ events, and the data is still being analyzed. No experiment has collected more than a few hundred $3\pi^0$ decays near the target. We could easily collect 100 M events of each type. This would allow us to determine η_{000} and η_{+-0} to a statistical accuracy of about $|\eta_{+-}|/10$ (The current limit in the Particle Data Group compilation[9] is $\eta_{000} < 0.30$). The systematic errors would be dominated by our ability to calculate the acceptance of the detector. Our group has a lot of experience in studying $3\pi^0$ decays. In the data analysis performed for the first run of E731 the understanding of the acceptance for $3\pi^0$ decays was at the $3 \times |\eta_{+-}|$ level. For the full E731 data set, about an order of magnitude better accuracy is being achieved, and with a new electromagnetic calorimeter, we would do even better.

Because the contribution to $3\pi^0$ decays from direct CP violation (called ϵ'_{000}) does not violate the $\Delta I = 1/2$ rule, it could be larger by a factor of 25 than in the case of 2π decays. In other words, ϵ'_{000} might equal $\epsilon/10$. To reach this level, a double beam experiment must be performed. It is possible to modify the Meson Center beam line to make two neutral beams, where one is a pure K_L beam and the other is a short, mixed K_L and K_S beam. One would use the pure K_L beam to measure the acceptance of the apparatus, and the mixed beam to search for the interference that signals CP violation. A double beam experiment would require a much larger investment in beam time, and would cost somewhat more.

Nancy Grossman, a graduate student on E621 from the University of Minnesota, has recently written her Ph.D. thesis on 1/7 of the E621 data. Her result is that $\mathrm{Im}(\eta_{+-0}) = 0.02 \pm 0.02 \pm 0.01$, where the first error is statistical and the second systematic. She used several constraints in deriving this result. She used the double beam geometry, a normalization constraint from $K_{\pi 2}$'s collected simultaneously with the $K_{\pi 3}$'s, and the fact that the real part of η_{+-0} is known to be equal to the real part of ϵ. Figure 5 shows the results of several η_{+-0} experiments, including E621. The Particle Data Group upper limit is $|\eta_{+-0}| < 0.35$ for experiments before E621.

[9] M. Aguilar-Benitez et al., Phys. Lett. B204, 1 (1988).

Another decay mode that would be interesting to investigate would be $K_{S,L} \rightarrow \pi^+\pi^-\gamma$. The branching ratio (for $k^* > 50$ MeV, where k* is the γ ray momentum in the center of mass) is 1.8 $\times 10^{-3}$. Two processes contribute to this decay, inner bremsstrahlung from the (CP conserving) $\pi^+\pi^-$ decay, and direct emission from the decay vertex. Direct emission has never been seen in K_S decay, although both processes have been seen in the K_L case. A CP violation parameter derived from the inner bremsstrahlung branching ratios for K_S and K_L is consistent with $|\eta_{+-}|$, as might be expected. It would be interesting to measure the direct emission branching ratio for the K_S, and look for interference between K_S and K_L.

The charge asymmetry in semileptonic decays has never been measured in the few-τ_S proper time region. Here the asymmetry is quite large, and equals D, the dilution factor, at t=0. This would be a good way to measure D, and would also allow us to search for CPT violation. In the Stable Particle Summary Table of the Particle Data Group's compilation, there are 10 decays listed for the K_L that either violate separate lepton number conservation, or test flavor changing neutral currents, and only 2 for the K_S (and those are upper limits). We can search for many of these decays also.

5 Conclusions

We propose to use the time in the 1993 fixed target running period after E799B is completed to measure the branching ratio for the decay $K_S^0 \rightarrow \pi^0 e^+ e^-$. We would reach a single event sensitivity of 1×10^{-11}. Our group plans to perform the K_L^0 experiment, and to measure the $\pi^0\gamma\gamma$ branching ratio to determine the CP conserving contribution to the K_L decay. To complete the determination of the direct CP violating component, we must measure the K_S branching ratio, and this is the only time to do it.

In addition we would measure η_{000} for the first time. This would be very interesting as a study of CP violation, and also CPT conservation, because the largest uncertainty in the Bell-Steinberger relation comes from η_{000}.

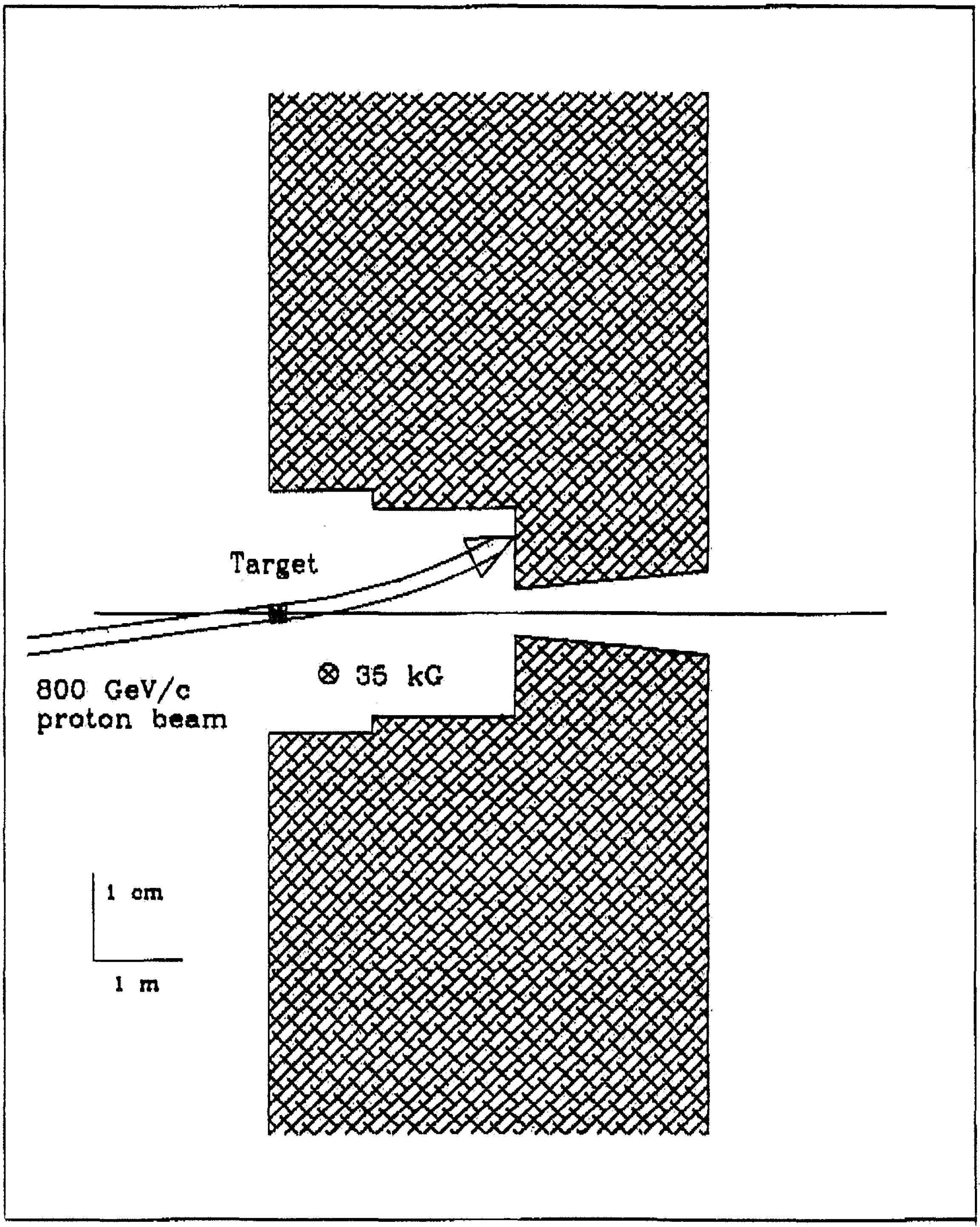

Figure 1. Collimator in Hyperon Magnet

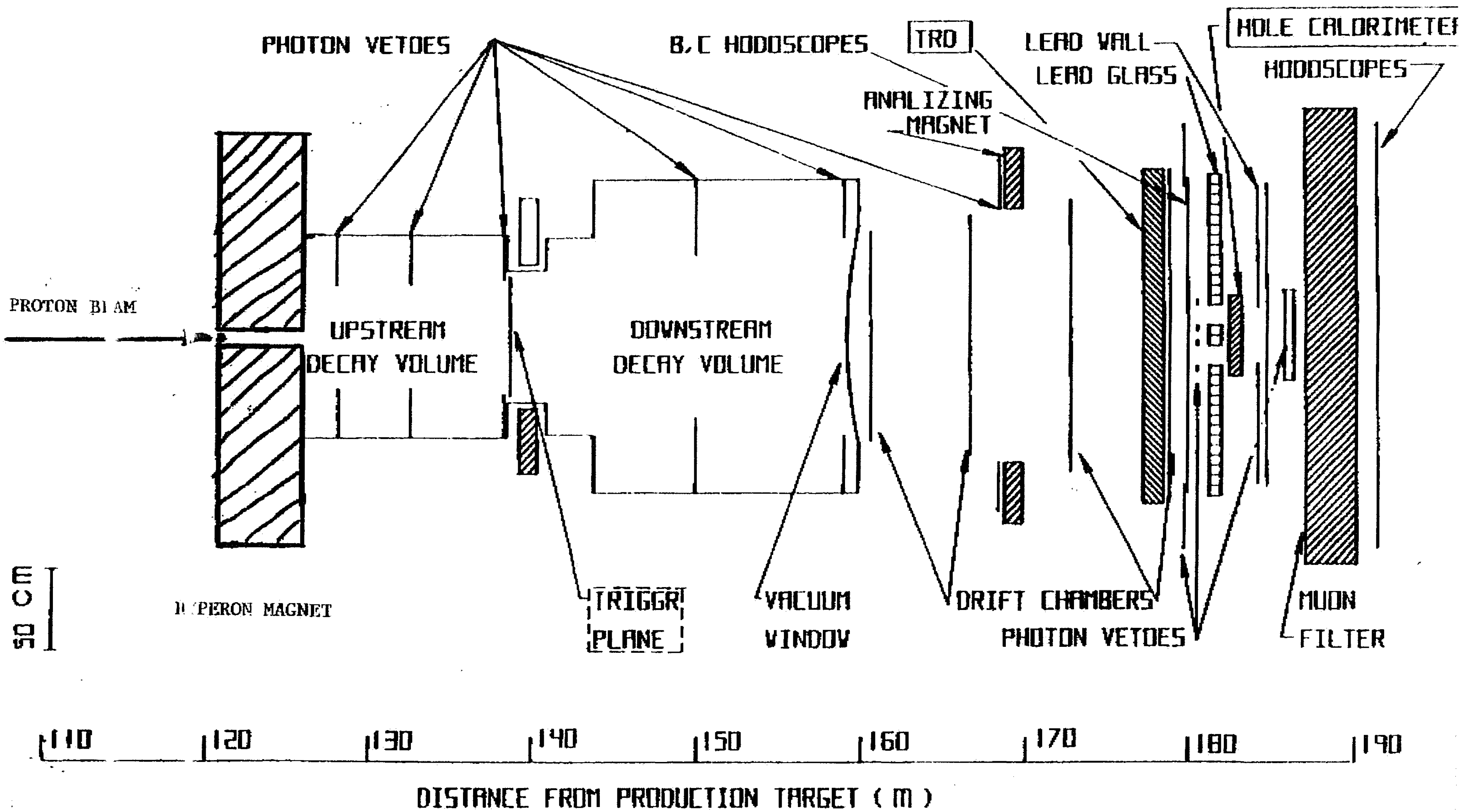

FIGURE 2 – APPARATUS LAYOUT

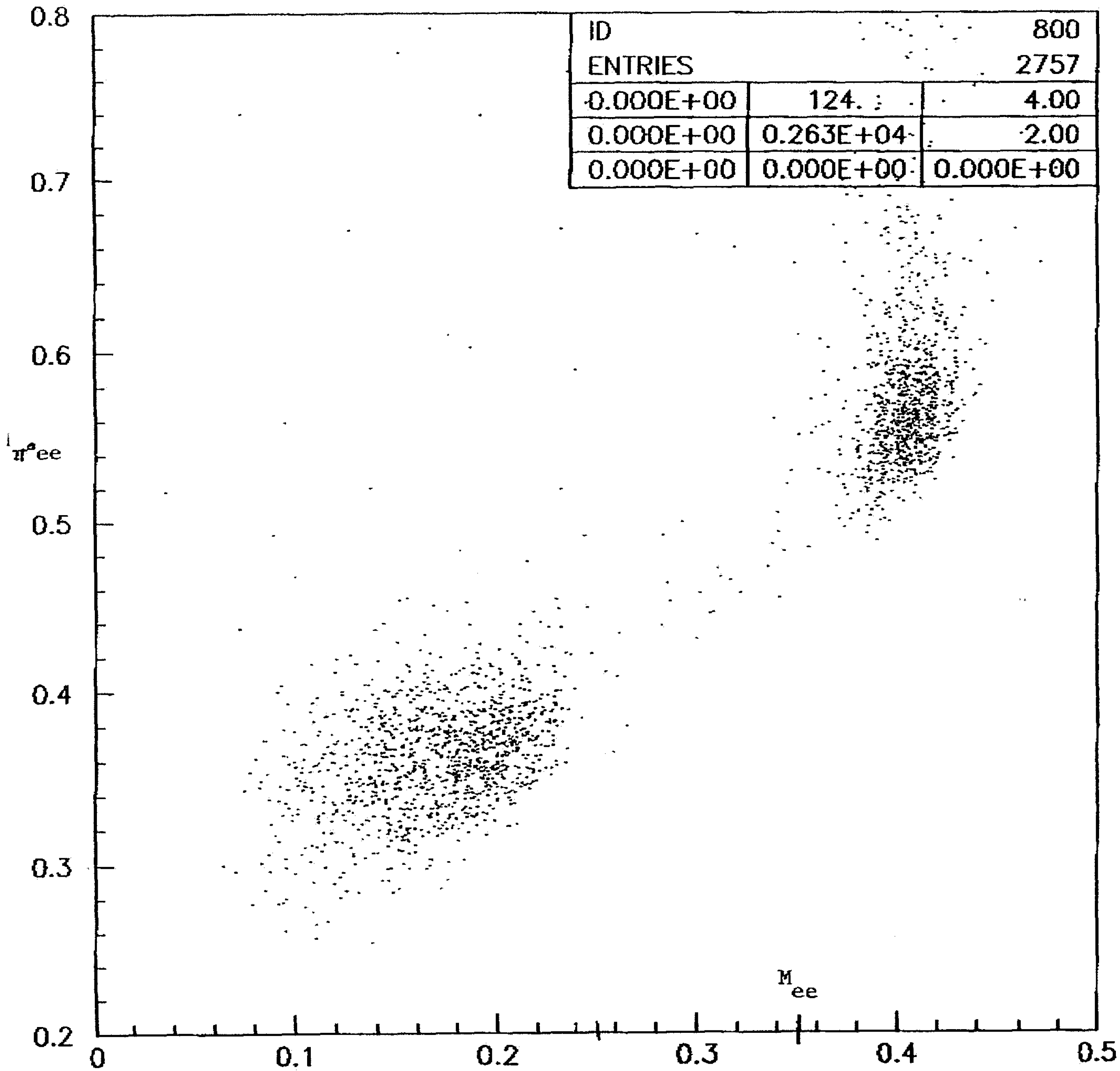

Figure 3. $M_{\pi^0 ee}$ vs. M_{ee}. No E/p cut.

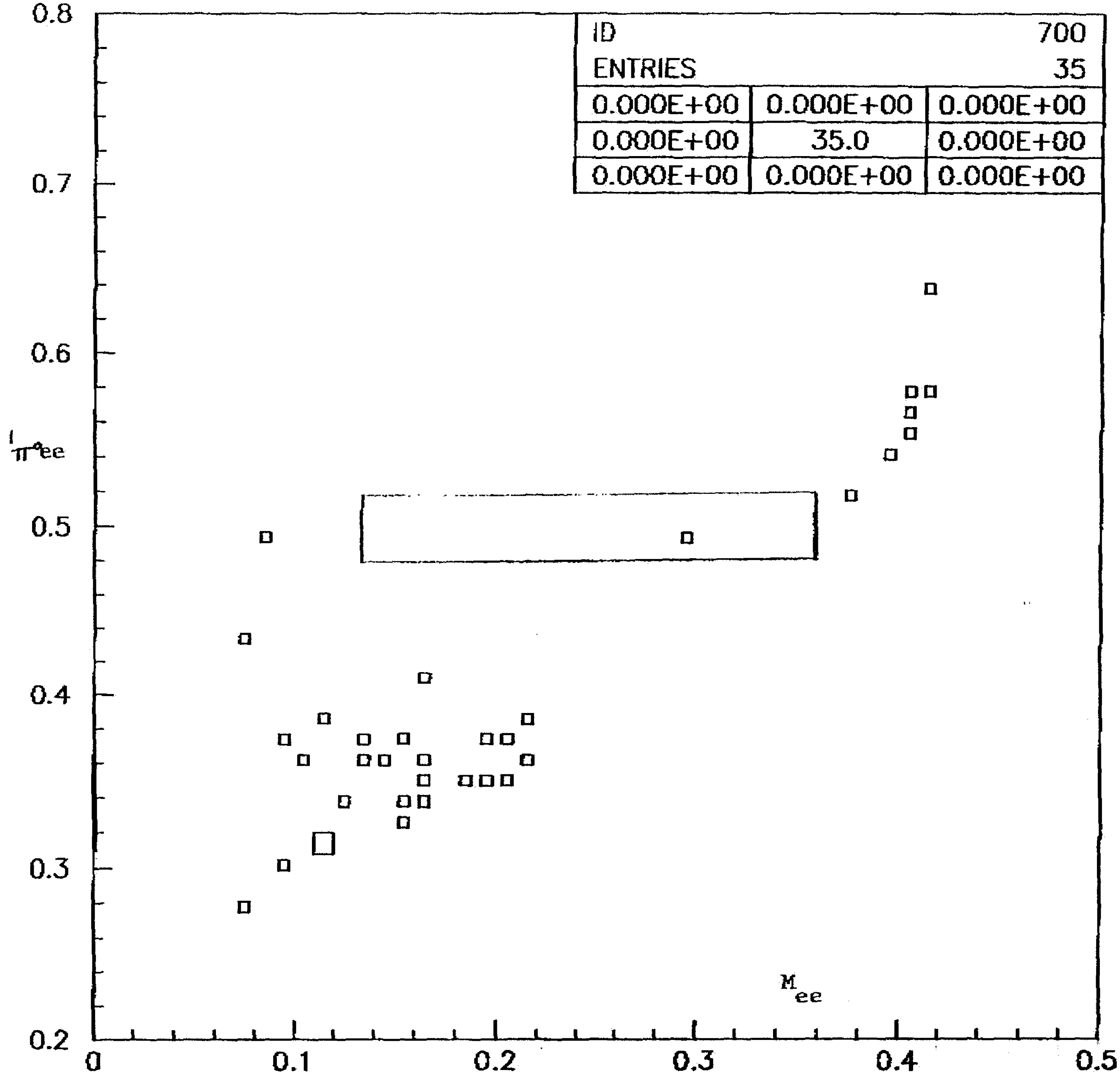

Figure 4. $M_{\pi^0 ee}$ vs. M_{ee}. Including E/p cut.

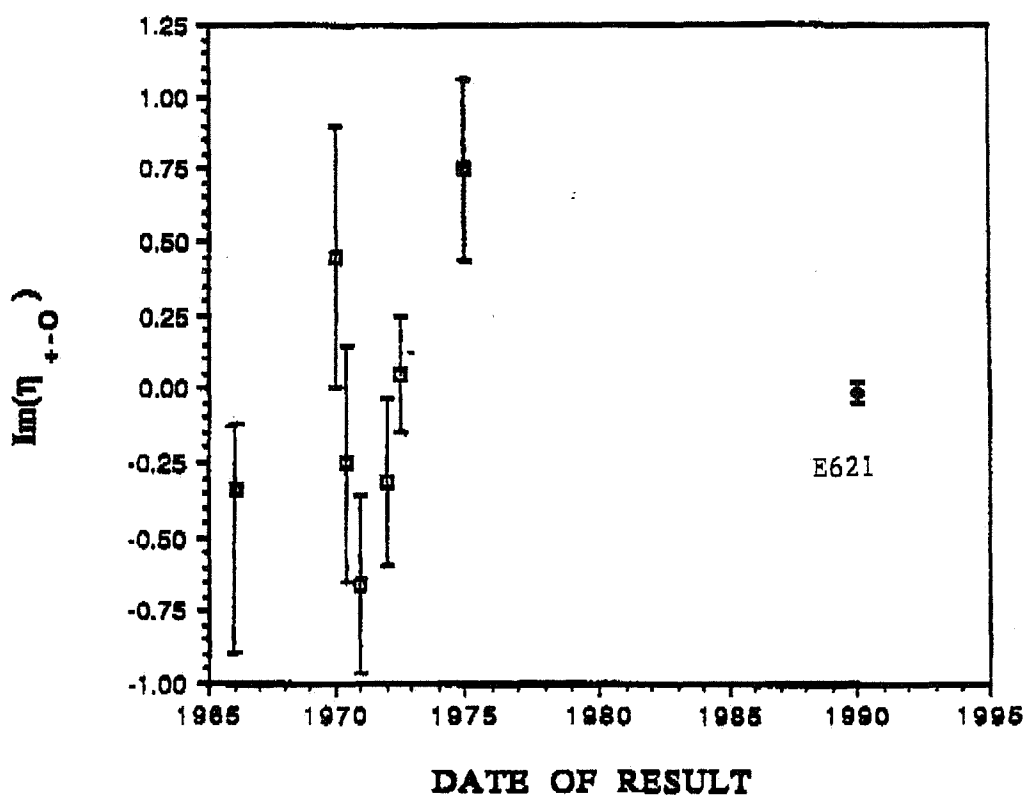

Figure 5. Experimental Result vs. Date of Result

Backgrounds in $K_S^0 \to \pi^0 e^+ e^-$

with contributions from:
S. Schnetzer, G. Thomson, T. Yamanaka, Y. Zou

We have calculated the level at which we might see some backgrounds for the $K_S^0 \to \pi^0 e^+ e^-$ experiment. We started from the table of backgrounds and single event sensitivites in the E799 proposal,and calculated the relevant sensitivities for the K_S experiment by correcting for branching ratios, the probability of decays in the decay region, or for random gamma probabilities. Taku has used his Monte Carlo program for these calculations. It actually throws K_L decays, and in the near future we must redo some of these calculations for a version of the program modified for the K_S beam, targeting angle, etc. John Matthews, who has now passed the Rutgers qualifying exam, is working on this modification.

One decay mode that is worse for the K_S beam is $K_S \to 2\pi^0$ with a double Dalitz decay, because the K_S branching ratio is 345 times larger than that of the K_L. For the E799 proposal, Taku ran his Monte Carlo until a very small branching ratio was probed, and did not find any events. Because of the higher branching ratio in the K_S case he ran an order of magnitude more events, and showed that this background comes in at the ????? level.

For the backgrounds involving random gamma-rays, Taku had used random triggers from the E731 data. Upon extrapolating to 3×10^{12} protons per pulse, about 6% of events would have a random gamma in it, of average energy 6 GeV. Yu Zou looked into the $K_{\pi 2}$ triggers of E621, demanded that the two pions both miss the lead glass (about 10% of $K_{\pi 2}$'s), and measured a 12% random gamma probability. In that data, both upstream and downstream targets were being struck. We know that each target contributed about equally to the rates in the chambers, and if we assume that their contribution to the junk in the lead glass is also equal, we would have a random gamma probability of 6% here also. The average energy of the random gammas was 6 GeV. So the numbers are surprisingly similar. In each sample there is a long tail of high energy gammas, and the tail for E621 is longer.

The rates in the new K_S experiment should be similar to E621. The random gammas come from:

- decays. This is a small fraction of the random gammas.
- neutrons in the beam. The neutron flux in E799C is much smaller than in E799B, so this should not be a problem.
- neutron boiloff. The end of a hadronic shower is a bunch of low energy neutrons that will boil off the downstream face of the dump magnet that formed the kaon beam. The solid angle of the apparatus from the dump is much larger for a K_S beam. This boiloff is independent of beam solid angle, however, so should not be larger than in E621, since we are using the same number of protons per pulse.

- collimator production. In E621 we had a collimator production problem, which is understandable from the design we used. We hope to improve this greatly in the new K_S experiment. Both Steve Schnetzer and Gordon Thomson are working on this by doing a GEANT calculation. We think this is a very important aspect of the new experiment's design. In short, we hope that this will be better than E621.

Of these items, only decays and neutrons in the beam depend on beam solid angle. From the energy histogram one would guess that decays and neutrons in the beam constitute about 10% of the total random gammas. So when we increase the solid angle of the beam for the K_S experiment, the random gamma probability should not increase by more than a factor of 2.

One worry is that the higher energy of decay gamma rays will make random coincidences that more readily fool the data analysis. So we are using the random gammas from E621 to overlay on Taku's Monte Carlo events to calculate background single event sensitivities.

Here is a list of each of the backgrounds in the E799 proposal, including the effects of using a K_S beam rather than a K_L beam.

- i), ii), and iii): $K_L \rightarrow 3\pi^0$ decay with missing γ's and Dalitz decays. These are suppressed by the ratio of decay probabilities (which is about 20).
- iv): $K_S \rightarrow 2\pi^0$ with a Dalitz decay. This is eliminated by a cut on the e^+e^- mass.
- v) and vi): $K_S \rightarrow 2\pi^0$ with double Dalitz decays. For this decay Taku found no successes in his Monte Carlo study. The level he reached was quite low for K_L's, but corresponds to a single event sensitivity of 4×10^{-10} for K_S's. He is now throwing more Monte Carlo events.
- vii): $K_S \rightarrow 2\pi^0$ with $\pi^0 \rightarrow e^+e^-$. This is a peak in the e^+e^- mass, and can be cut away.
- viii) and ix): $K_{\pi 3}$ and K_{e4} decays. Reduced by the ratio of decay probabilities.
- x): $K_L \rightarrow e^+e^-\gamma$ with random gammas. The E799 calculation was 5×10^{-12}. The K_L decay probability is much larger than the K_S one, so this is down by the ratio of decay probabilities (assuming the random gamma coincidence rate is the same). Taku is throwing Monte Carlo events of this type, and overlaying E621 random gammas to verify this.
- xi): $K_S \rightarrow \pi^+\pi^-\gamma$, with accidental γ. The K_S branching ratio is larger than the K_L by a factor of 70. This background might reach 1×10^{-11}.
- xii): K_{e3} plus two accidental γ's. This is down by the decay probability.

Finally, the infamous $\gamma\gamma e^+e^-$ background of Herb Greenlee is smaller by the ratio of decay probabilities, because the K_S branching ratio to $\gamma\gamma$ is a factor of 200 smaller than the K_L branching ratio.

In summary, a first look at the backgrounds in the $K_S^0 \rightarrow \pi^0 e^+ e^-$ experiment has revealed two possible backgrounds that might be a problem, and we are looking into exactly what levels at which they might arise. Our first guess is that these levels will be less than 1/10 of the expected branching ratio for $K_S^0 \rightarrow \pi^0 e^+ e^-$.

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Letter of Intent to Measure the Branching Ratio for the Decay, $K_S^0 \to \pi^0 e^+ e^-$

K. Arisaka, J. Kubic, D. Roberts, W. Slater, M. Weaver
UCLA

A. Barker, D. Harris, K. McFarland, B. Schwingheuer, S. Somalwar,
Y. Wah, B. Winstein, R. Winston
University of Chicago

E. Swallow
Elmhurst College

G. Bock, R. Coleman, M. Crisler, J. Enagonio, R. Ford, Y.B. Hsiung,
D. Jensen, K. Stanfield, R. Tschirhart,T. Yamanaka
Fermilab

G. Gollin, J. Heuer, W. Hogan, J. Ross, H. Thomas
University of Illinois

P. Gu, P. Haas, B.K. Kim, S.K. Kim, J. Matthews, S.S. Myung,
S. Schnetzer, R. Stone, G. Thomson*, Y. Zou
Rutgers University

Abstract

We propose to measure the branching ratio for the decay $K_S^0 \to \pi^0 e^+ e^-$. This branching ratio is needed to calculate the indirect CP violating contribution to $K_L^0 \to \pi^0 e^+ e^-$, in order to extract the direct CP violation from a measurement of the latter decay. We will bring a proton beam to the E799 detector in the MC beam line, strike a target at the entrance of a hyperon magnet to form a K_S^0 beam, and use the same detection apparatus as E799 (whose aim is to measure the K_L^0 branching ratio). We expect to achieve a single event sensitivity of about 1×10^{-11}. The theoretical estimates for this branching ratio are between 5×10^{-10} and 5×10^{-9}, so we should see between 50 and 500 events.

An important secondary objective of this experiment would be to collect a large number of $3\pi^0$ and $\pi^+\pi^-\pi^0$ decays near the target, and measure the CP violation parameters η_{000} and η_{+-0}. We could collect about 120 M decays of each type, and reach a sensitivity of $\delta\eta \sim 10^{-3}$.

* Scientific Spokesperson: Gordon Thomson (201)932-4566; FNAL::THOMSON.

1 Introduction

Our collaboration has embarked on a program of experiments [1] to find direct CP violation in the decay $K_L^0 \to \pi^0 e^+ e^-$. This decay has contributions from indirect CP violating and CP conserving amplitudes as well, which must be understood before the direct CP violating amplitude can be determined. The CP conserving amplitude arises from a two photon intermediate state, while the CP violating amplitudes come from a one photon exchange diagram. Since $K_L \sim K_2 + \epsilon K_1$, the CP violating amplitude has two contributions, the indirect CP violating amplitude coming from the small K_1 mixture in the K_L, and the direct coming from the K_2 part. Since the K_S is dominantly K_1, the $K_S^0 \to \pi^0 e^+ e^-$ decay can be used to determine the indirect CP violating part of the K_L decay. This is what we propose to do. We are submitting a letter of intent, not a proposal, because we have not had enough time to perform Monte Carlo studies of the experiment, in order to optimize the detector and learn about possible backgrounds.

The standard model predicts that all of these amplitudes are about the same size, and that $\epsilon'_{\pi ee}/\epsilon \sim 1$, making this decay mode a good place in which to search for direct CP violation. If studies of CP violation in the 2π decay modes prove to be inconclusive, then the $\pi^0 e^+ e^-$ decay mode will become even more important.

Recently, a background in the $\pi^0 e^+ e^-$ channel has been found[2] that must be dealt with. This is $K_L \to \gamma\gamma$, with an internal conversion and bremsstrahlung to give $\gamma\gamma e^+ e^-$. With a new electromagnetic calorimeter and by making judicious cuts, one can reduce this background to the few $\times 10^{-11}$ level, where it would not seriously compromise a high statistics K_L measurement.

Seeing a few events does not pin down direct CP violation in this rare decay mode, background or no background. To do this a more sensitive experiment must be done, perhaps at the Main Injector. An experiment sensitive at the 10^{-14} level has been discussed in P804. This experiment could achieve a 6σ measurement of the direct CP violating contribution to the K_L decay. This expected accuracy places a constraint on how well we must measure the K_S decay. A single event sensitivity of 1×10^{-11} would match that of the Main Injector K_L experiment.

It is worth mentioning that the K_S experiment is much easier at the Tevatron than at the Main Injector. The energy of the kaon beam grows linearly with proton energy, but the shielding required to contain the showers of the beam protons grows only logarithmically, so at the higher energy, decays at shorter proper times are visible, and more K_S decays can be collected.

Being sensitive to $10^{11} K_S$ decays, the experiment will have unprecedented sensitivity to other interesting physics. Foremost on the list must be η_{000} and η_{+-0}. Here we will collect more than 100 M events of both types. We will also be able to search for CP violation in the decay $K_S \to \pi^+\pi^-\gamma$, investigate the short proper time behavior of the semileptonic charge asymmetry, and search for other rare K_S decays.

[1] See the proposals for E799 by T. Barker et al., and P804 by W. Molzon et al.

[2] H. B. Greenlee, Yale preprint YAUG-A-90/3, submitted to Physical Review D.

2 Theoretical Predictions

The most interesting of the three amplitudes that contribute to the decay $K_L \rightarrow \pi^0 e^+ e^-$ is the one coming from direct CP violation. To extract it, one must subtract the branching ratios of the other sources. All are expected to be about the same size. If you measure B_{Short}, the branching ratio for $K_S \rightarrow \pi^0 e^+ e^-$, the predicted K_L branching ratio from indirect CP violation is $B_{indirect} = B_{Short} \times |\epsilon|^2 \times \tau_L/\tau_S = B_{Short} \times 0.0030$. To extract the CP conserving part of the K_L branching ratio, since it comes from a two photon exchange diagram, one measures the branching ratio for $K_L \rightarrow \pi^0\gamma\gamma$, where the two γ's do not add up to a π^0. Then a theoretical estimate of the contribution can be made. The $\pi^0\gamma\gamma$ branching ratio has been measured by the NA31 group at CERN, and in E799 we hope to measure it even better.

Gilman and Wise[3], in 1980, predicted that the K_S branching ratio would be between 1.5 and 3 $\times 10^{-9}$; Gilman's student, Claudio Dib, quotes 2×10^{-9} in his recent Ph.D. thesis[4]. Ecker, Pich, and DeRafael[5] used chiral perturbation theory, and by normalizing to the measured branching ratio for $K^+ \rightarrow \pi^+ e^+ e^-$, they come to two solutions, 5×10^{-10} and 5×10^{-9}. All authors stress the model-dependence of their calculations, and say that a measurement of the K_S branching ratio must be made.

3 The Experiment

Since one cannot regenerate enough K_S's from the Meson Center K_L beam, we must transport primary protons to a new target just in front of the decay region of E799, strike that target, and have a magnetic collimator to define the K_S beam and absorb the primary protons. The detection apparatus of E799 would be used for the K_S measurement.

A beam of 1×10^{10} protons/pulse would be transported through the existing dump and brought to the K_S target. Since the MC beam runs in a stable manner for intensities greater than about 1×10^{11} protons/pulse, at least that number of protons must be brought through the switchyard. After that point, the proton beam intensity must be reduced to 1×10^{10}. A pinhole collimator could be used (a diffracted beam from a target could be used also). Magnets would be needed to control the angle at which the protons hit the K_S target. We choose 1×10^{10} protons/pulse to hit the K_S target because shielding for more than this intensity would be quite expensive.

An important element of the experiment is the magnet that forms the K_S beam and absorbs the protons. Following previous experiments at Fermilab that have studied K_S's, we would use a hyperon magnet. This is a magnet generating a high field, with a collimator inside that is designed to transmit a well defined neutral beam, and stop and absorb all charged particles. The hyperon magnet in the Proton Center beam has a 35 kGauss field, and is 7.2 m long. The best magnet for this application would have a similar field and be 5 m long. The 2 m saved is worth 20% more accepted K_S decays. To make an intense K_L beam, one typically strikes the target at 3 - 5 mrad. For this experiment, 1 mrad would be

[3] F.J. Gilman and M.B. Wise, Phys. Rev D21, 3150 (1980).
[4] C.O. Dib, Ph.D. Thesis, Stanford University, 1990 (unpublished).
[5] G. Ecker, A. Pich, and E. deRafael, Nucl. Phys. B291, 692 (1987).

better, because more kaons go into the beam solid angle, and their spectrum is stiffer. The rates are not particularly high so neutrons are not a problem. The collimator would have a solid angle of 5 μster. Fig. 1 shows a plan view of the collimator in the hyperon magnet.

The detector, shown in Figure 2, would be the same as in E799. It consists of a Vee spectrometer of four drift chambers, two in front of, and two behind the 100D40 magnet. Three transition radiation detectors would help identify electrons, and an electromagnetic calorimeter would catch photons and also help identify electrons. To identify events that could be possible backgrounds, photon veto counters are placed around the decay region, and just outside the active area of the spectrometer. Trigger processors to pick out clusters in the calorimeter and to process tracking information from the drift chambers will be important in the trigger. These are being built for E799. The track processor will do a good job of identifying $\Lambda \to p\pi^-$ decays.

The biggest addition to the apparatus will be a new electromagnetic calorimeter. Our aim is to reduce our resolution in π^0 mass from 4 MeV$/c^2$ to 0.8 MeV$/c^2$. It may be that the only detector that can be bought for a reasonable price would be made of undoped Cesium Iodide. The better resolution is necessary for a new ϵ'/ϵ experiment and for $K_L \to \pi^0 e^+ e^-$, and will greatly aid the present proposal.

We have calculated the neutron and muon fluxes, and the rates of K_S, Λ^0, and K_L decays expected at a targeting angle of 1 mrad. We used the Malensek parameterization[6] for the kaon flux, and the Skubic parameterization[7] for the Λ's. In Skubic et al., kaon fluxes were also measured, and for the range $x > 0.2$, where Skubic had data, both parameterizations agree. For the neutron flux, we used a measurement of the neutron invariant cross section by Edwards et al.[8] at $p_t = 0$, scaled by the p_t dependence of ISR data. Table 1 gives the results of this rate calculation. The overall rates in the K_S experiment are similar to what is expected in E799. The largest single contribution is from Λ decays. Because the protons from $\Lambda \to p\pi^-$ are tightly collimated in a cone around the beam, they could cause inefficiencies in the drift chambers due to space charge buildup. We calculated the rate/cm of wire to be ≤ 10 kHz, which is well below 20 kHz, the point where this effect becomes important. We are also building new drift chamber preamplifiers to allow us to reduce the drift chamber high voltage, and have fewer positive ions form near the sense wires, making us less sensitive to this effect. The expected neutron flux is well below E799 also.

In the K_L experiment, the muon flux from the target is quite high. In the K_S experiment we use two orders of magnitude fewer protons per pulse, so the muon flux might not be as serious. We performed a calculation of this muon flux using CASIM, a hadronic shower program that tracks muons that come from decays or direct production. In the context of planning the main injector kaon beam, we recently tested this program by trying to calculate the muon flux that was observed in E613, a beam dump experiment in the Meson Lab. CASIM's results were consistently a factor of two higher than the measured muon fluxes. The result of the calculation for the K_S experiment was that a flux of about 100 kHz/sq. ft. would be observed in the first photon veto counter ring, about 7m downstream

[6] A.J. Malensek, Fermilab FN-341 (1981).
[7] P. Skubic et al., Phys. Rev. D18, 3115 (1978).
[8] R.T. Edwards et al, Phys. Rev. D18, 76 (1978)

Source	
Total decays	677 kHz
K_S^0 decays	285 kHz
K_L^0 decays	11 kHz
Λ^0 decays	381 kHz
$\pi^+\pi^-\pi^0$	1.4 kHz
$3\pi^0$	2.4 kHz
$\pi e \nu$	4.2 kHz
neutron flux	11 MHz

Table 1: Calculated Rates

of the target. The main muon lobes were just outside these counters. The highest flux in these lobes was 500 kHz/sq. ft. The muons were traveling away from the beam, and the flux became progressively smaller at locations further downstream. In the first drift chamber, the flux was about 1 kHz. These are acceptable rates. If the field in the hyperon magnet is horizontal, these muons can be directed up and down, and will not pose any radiation hazard.

We performed a Monte Carlo calculation of the acceptance of the apparatus. Because the K_S decays emphasize the high momentum end of the kaon spectrum, the acceptance is better than in E799, with 20% of decays above 50 GeV/c being accepted. The result is 57,000 accepted K_S decays/second. If we multiply by 20 sec/pulse, 60 pulses/hr, and 800 hr/experiment, we have 0.55×10^{11} kaons, or a single event sensitivity of 1.8×10^{-11}.

We are looking into the backgrounds that might be present in the K_S experiment. The $\gamma\gamma e^+e^-$ background that is a problem for the K_L experiment is not a problem for the K_S. In the E799 proposal several sources were considered, and we have calculated how these might change with a K_S beam. Most are not a problem with either beam, but the case of a $2\pi^0$ decay, with a double internal conversion (double Dalitz decay) is quite different in the two cases because the $2\pi^0$ branching ratio is a factor of 300 larger. We are now doing more Monte Carlo work to study this background.

The other type of background that is different in the two beams is those involving random γ's hitting the electromagnetic calorimeter. The two worst of these are $K_L \rightarrow e^+e^-\gamma$ and $K_L \rightarrow \pi e \nu$, with random γ's hitting the calorimeter. Our studies involve determining the probability that random gammas hit the calorimeter by looking at the data from E621, which ran at the same proton intensity, but with 1/10 the beam solid angle of what we are proposing here. We are using the same technique that was used in E799, of throwing Monte Carlo events for the processes listed above, and overlaying random gammas from the data, to count the events that might be confused with the signal. This process has been begun, but is not yet completed.

Two of us (G.T. and Y.Z.) were members of the Rutgers, Michigan, Minnesota collaboration that performed E621. This experiment sampled a large number of neutral kaon decays between 9 and 25 m from the production target. It has a sensitivity to $K_S \rightarrow \pi^0 e^+ e^-$ in the 10^{-9} range. About 1/7 of the E621 data has been examined, and one good event has

Item	Factor	Single Event Sensitivity
Data Set 3		3×10^{-8}
All E621	7	4×10^{-9}
Acceptance	6	7×10^{-10}
Solid Angle	10	7×10^{-11}
p<120	1.2	5×10^{-11}
Shorter H.M.	1.2	4×10^{-11}
Running Time	1.33	3×10^{-11}
Malensek		1.8×10^{-11}

Table 2: Projections from E621 to the Present Experiment

been found. In this part of the data, the single event sensitivity is 3×10^{-8}. Figure 3 shows a scatter plot from the E621 data, where all cuts have been made except the E/p cut to choose electrons. $K_{\pi 3}$ events, and $K_{\pi 2}, \pi\pi\gamma$, and semileptonic decays (with random gammas that add up to a π^0) can be seen in the figure. Figure 4 is the same data after applying an E/p cut (0.8< E/p <1.2), and is much cleaner. When all cuts are made, one signal event remains, and 1 event shows up in the K_{e3} area. We are currently calculating the probability that the one signal event is a K_{e3}. In E621 we tried to sweep charged particles off the glass, so most of the time we have only one particle hitting the glass, and only one E/p to evaluate. In addition we didn't have transition radiation detectors or an excellent electromagnetic calorimeter. In the experiment we are proposing here, the situation would be many orders of magnitude better, and this background would be absent.

We can calculate the improvement that the present experiment would have over our experience in E621. Table 2 shows the various factors that go into the calculation. Also shown is the result of the calculation for the present experiment using the beam intensity parameterization of Malensek. There is a factor of 1.9 discrepancy between the two calculations, which is probably an acceptable uncertainty. We believe the Malensek calculation is better because in E621 there were normalization uncertainties of about a factor of 2 that were never solved (fewer K_S and Λ decays were found than calculated), which contradicted the E8 group's experience, gained from previous hyperon experiments.

4 η_{000} and η_{+-0}, and other physics

We would also collect a large sample of $3\pi^0$ and $\pi^+\pi^-\pi^0$ decays in this experiment. This would let us search for CP violation in K_S decay by looking for interference between the K_S and K_L amplitudes in the proper time region $0.3\tau_S < t < 5\tau_S$. We would measure η_{000} and η_{+-0}, which are expected to be approximately equal to η_{+-}. The size of the interference is about 0.3% of the K_L decay rate, so very good statistics and control of systematic errors would be needed for the measurement.

Experiment 621 collected 2 M $\pi^+\pi^-\pi^0$ events near the production target, and no experiment has collected more than a few hundred $3\pi^0$ decays near the target. We could collect 100 M events of each decay mode. This would allow us to determine η_{000} and η_{+-0}

to a statistical accuracy of about $|\eta_{+-}|/3$ (The current limit in the Particle Data Group compilation[9] is $\eta_{000} < 0.30$). The systematic errors would be dominated by our ability to calculate the acceptance of the detector. Our group has a lot of experience in studying $3\pi^0$ decays. In E731, $K_L \rightarrow 3\pi^0$ decays were used to study the systematic errors in the Monte Carlo calculation of the acceptance for the $2\pi^0$ mode. In the present experiment, we would use the known time distribution of the $2\pi^0$ decays as a handle on the acceptance of the $3\pi^0$ mode. This is a somewhat harder task. The important parameter is how the acceptance error varies with the z of the kaon decay. This parameter is held under control very well in E731, although in the present proposal we may not be able to do quite as well.

Because the contribution to $3\pi^0$ decays from direct CP violation (called ϵ'_{000}) does not violate the $\Delta I = 1/2$ rule, it could be larger by a factor of 25 than in the case of 2π decays. In other words, ϵ'_{000} might equal $\epsilon/10$. To understand the acceptance at this level, a double beam experiment must be performed. It is possible to modify the Meson Center beam line to make two neutral beams, where one is a pure K_L beam and the other is a short, mixed K_L and K_S beam. One would use the pure K_L beam to measure the acceptance of the apparatus, and the mixed beam to search for the interference that signals CP violation. A double beam experiment would require a much larger investment in beam time, mostly in setting up and understanding the double beam. Although we are not proposing to do a double beam experiment now, with a modest upgrade at some time in the future, we could also make these measurements.

Nancy Grossman, a graduate student on E621 from the University of Minnesota, has recently written her Ph.D. thesis on 1/7 of the E621 data. Her result, which will soon be published, is that $\mathrm{Im}(\eta_{+-0}) = 0.02 \pm 0.02 \pm 0.01$, where the first error is statistical and the second systematic. She used several constraints in deriving this result. She used the double beam geometry, a normalization constraint from $K_{\pi 2}$'s collected simultaneously with the $K_{\pi 3}$'s, and the fact that the real part of η_{+-0} is known to be equal to the real part of ϵ. Figure 5 shows the results of several η_{+-0} experiments, including E621. The Particle Data Group upper limit is $|\eta_{+-0}| < 0.35$ for experiments before E621.

Another decay mode that would be interesting to investigate would be $K_{S,L} \rightarrow \pi^+\pi^-\gamma$. The branching ratio (for $k^* > 50$ MeV, where k^* is the γ ray momentum in the center of mass) is 1.8×10^{-3}. Two processes contribute to this decay, inner bremsstrahlung from the (CP conserving) $\pi^+\pi^-$ decay, and direct emission from the decay vertex. Direct emission has never been seen in K_S decay, although both processes have been seen in the K_L case. A CP violation parameter derived from the inner bremsstrahlung branching ratios for K_S and K_L is consistent with $|\eta_{+-}|$, as might be expected. It would be interesting to measure the direct emission branching ratio for the K_S, and look for interference between K_S and K_L.

The charge asymmetry in semileptonic decays has never been measured in the proper time region, $t < 2.7\tau_S$. Here the asymmetry is quite large, and at t=0 it equals D, the dilution factor, which is the difference over the sum of the number of K^0 and $\overline{K}^0$ decays. We are sensitive at $t=0.3\tau_S$, and can measure D this way. We will also have data out to about $15\tau_S$, will be able to see the interference between K_S and K_L, and in the high proper time

[9] M. Aguilar-Benitez et al., Phys. Lett. B204, 1 (1988).

region search for CPT violation. One of the best experiments that measured the semileptonic charge asymmetry in the interference region was by Gjesdal[10]. We could collect about 16 times as many semileptonic decays as that experiment.

In the Stable Particle Summary Table of the Particle Data Group's compilation, there are 10 decays listed for the K_L that either violate separate lepton number conservation, or test flavor changing neutral currents, and only 2 for the K_S (and those are upper limits). We can search for many of these decays also.

5 Conclusions

This is a letter of intent for an experiment to measure the branching ratio for the decay $K_S^0 \to \pi^0 e^+ e^-$. We would reach a single event sensitivity of 1×10^{-11}. Our group plans to perform the K_L^0 experiment, and to measure the $\pi^0\gamma\gamma$ branching ratio to determine the CP conserving contribution to the K_L decay. To complete the determination of the direct CP violating component, we must measure the K_S branching ratio.

In addition we would measure η_{000} for the first time. This would be very interesting as a study of CP violation, and also CPT conservation, because the largest uncertainty in the Bell-Steinberger relation comes from η_{000}.

[10] S. Gjesdal et al., Phys. Lett. 52B, 113(1974)

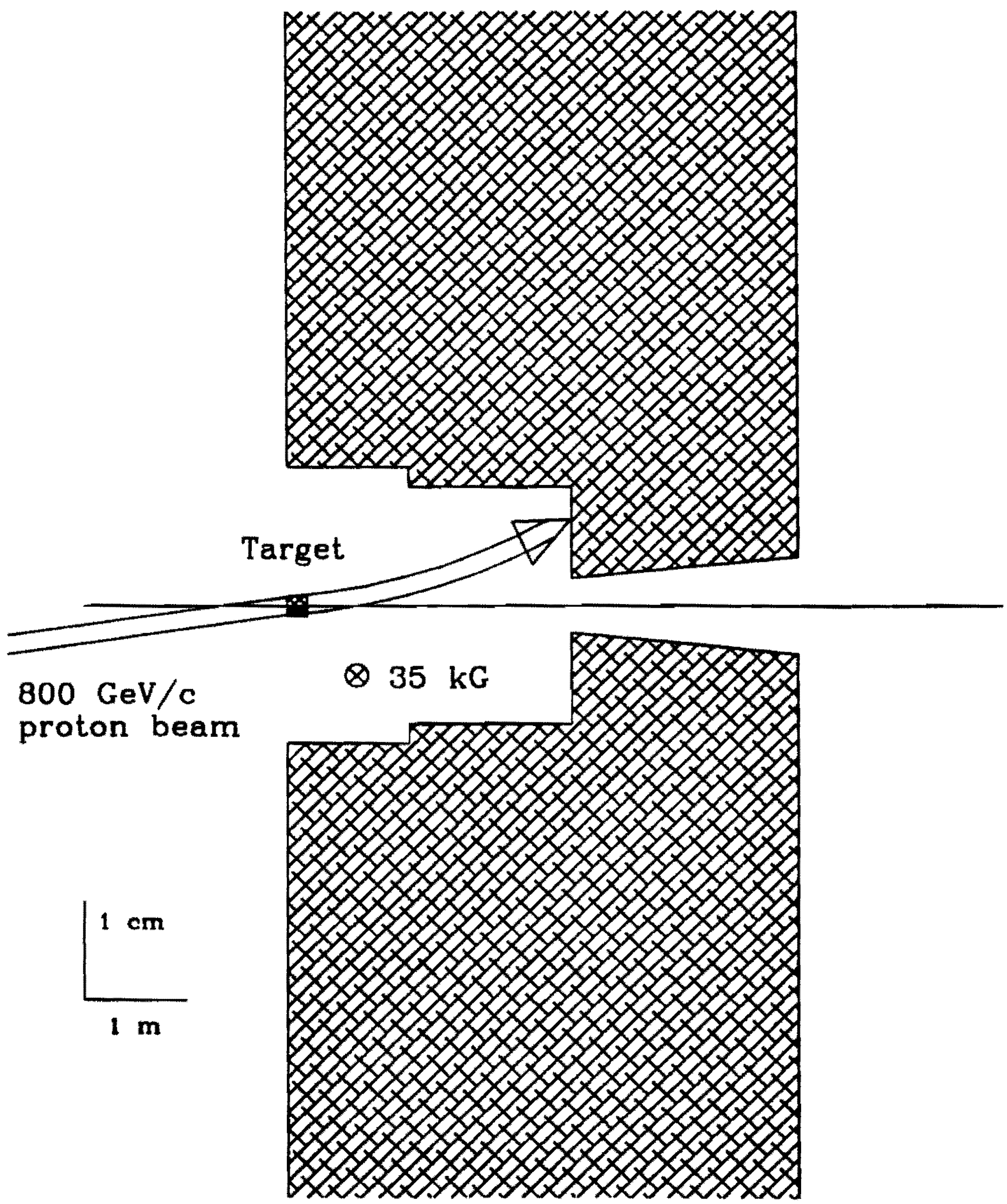

Figure 1. Collimator in Hyperon Magnet

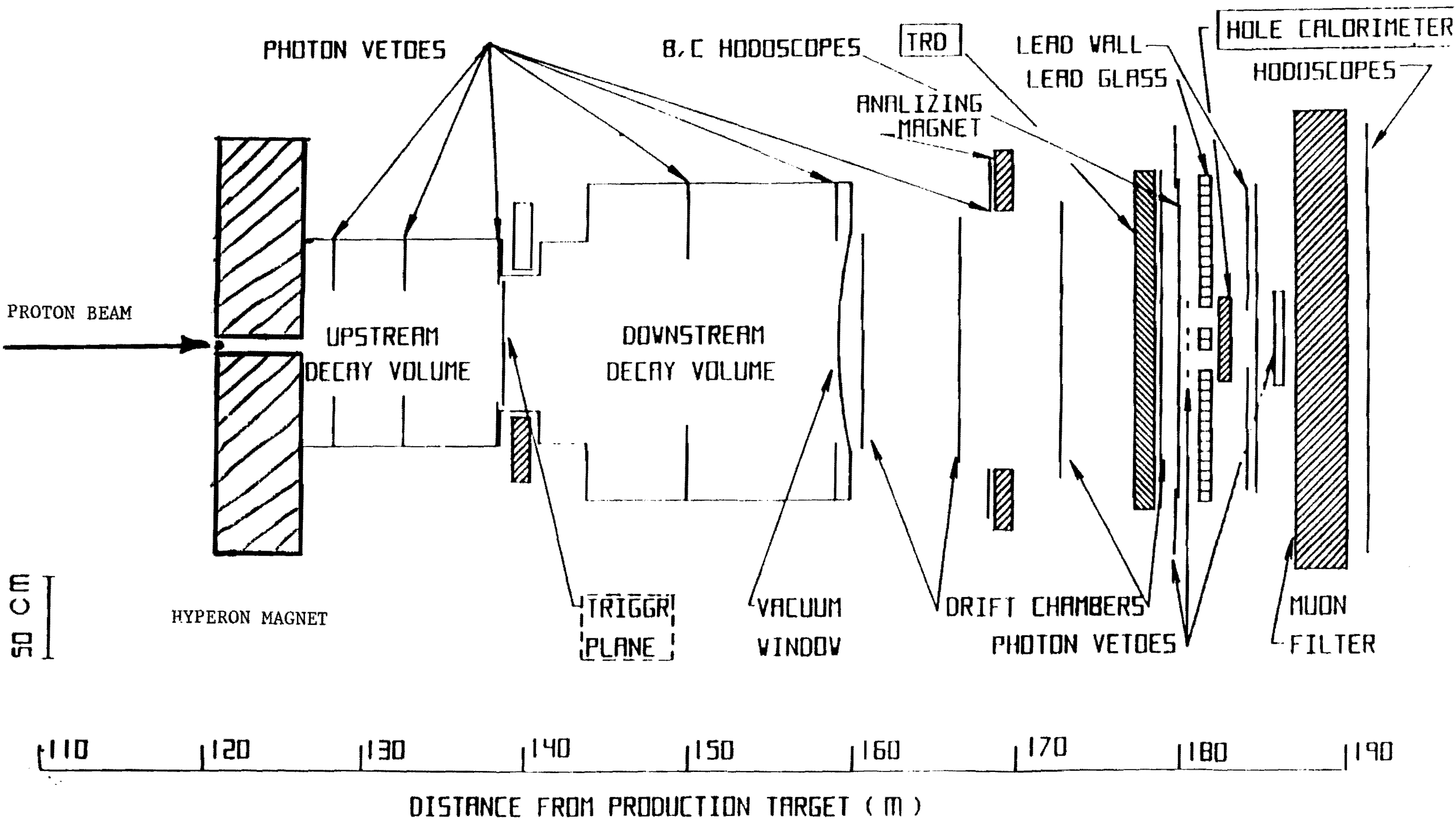

FIGURE 2 - APPARATUS LAYOUT

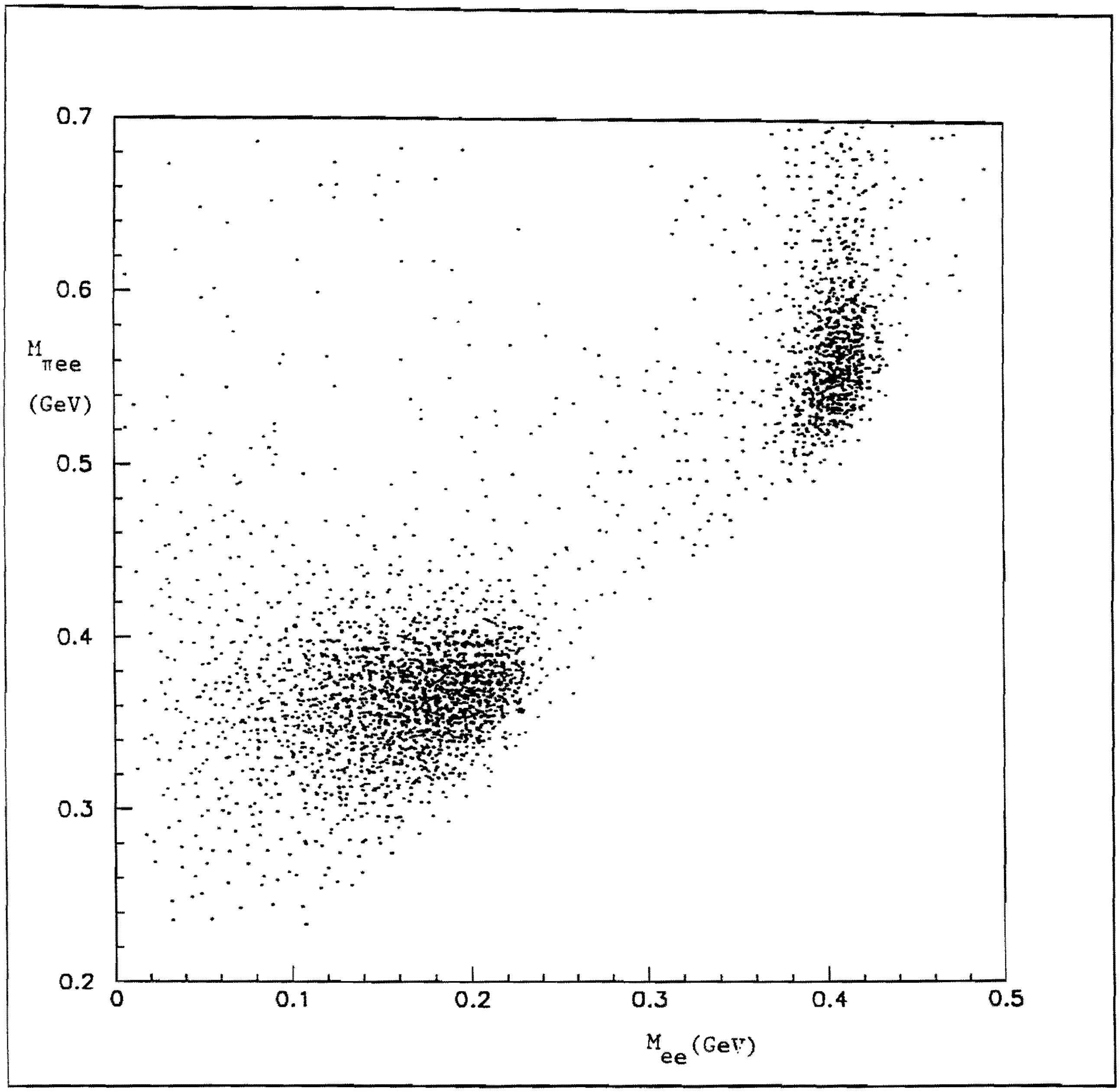

Figure 3. $M_{\pi ee}$ vs. M_{ee}. No E/p cut.

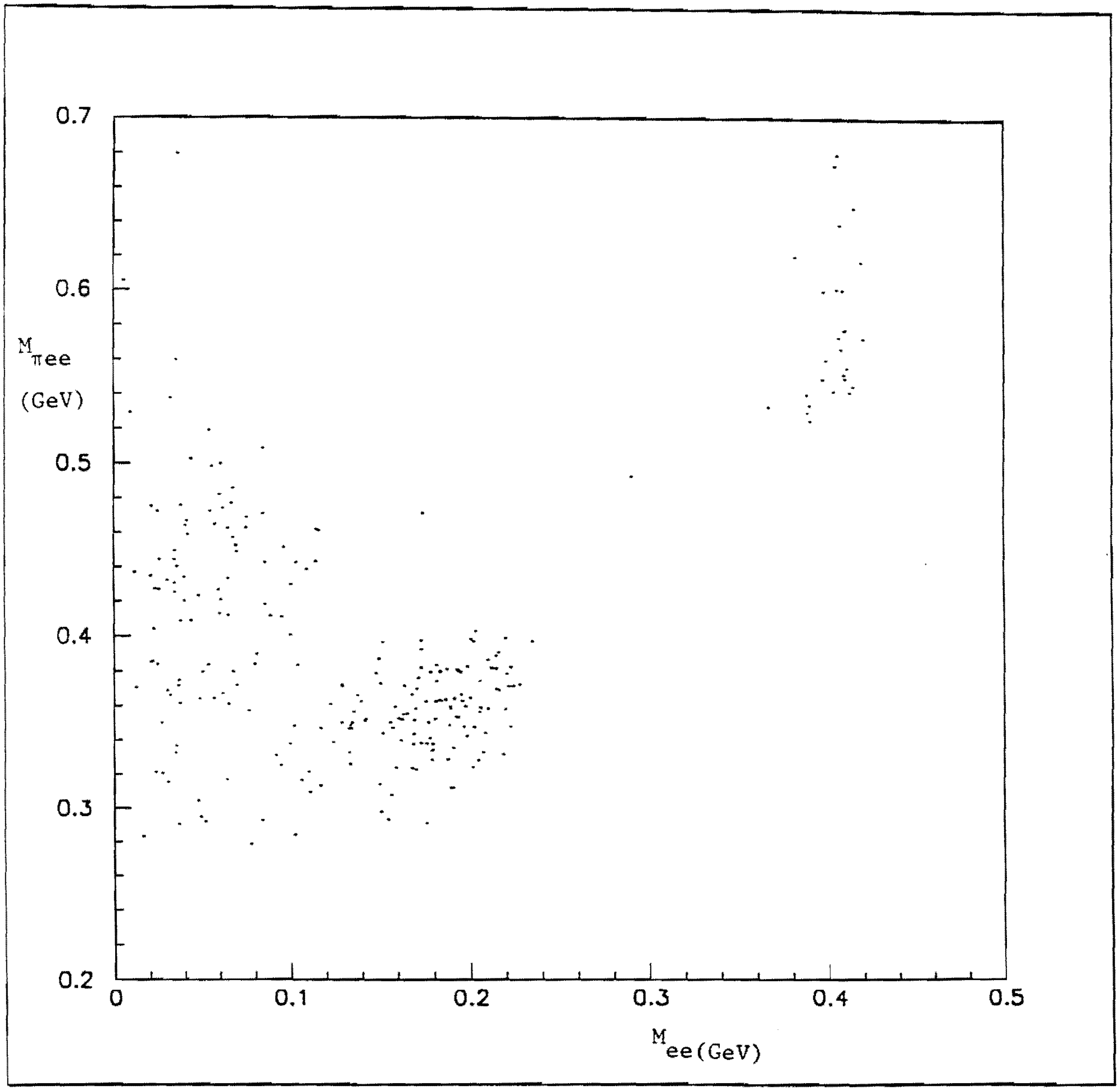

Figure 4. $M_{\pi ee}$ vs. M_{ee}. Including E/p cut.

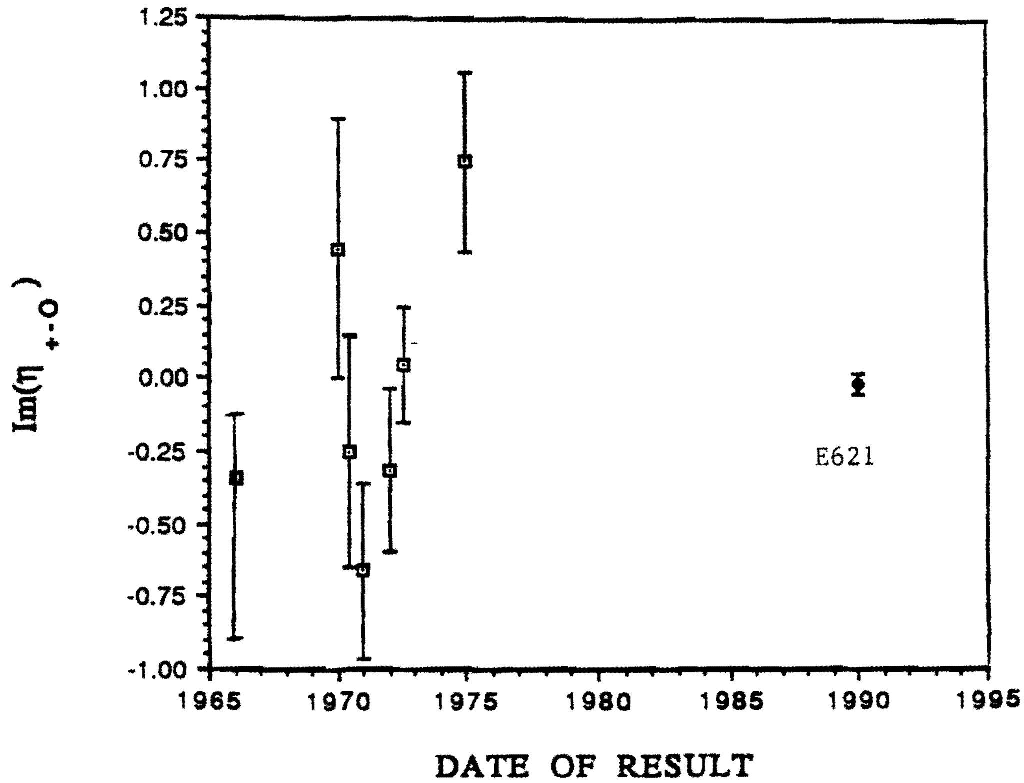

Figure 5. Experimental Result vs. Date of Result