Charged **K**aons at the **M**ain-Injector

An Experiment to Observe $K^+ \to \pi^+ \nu \bar{\nu}$

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Introduction

A measurement of the rate of the rare kaon decay $K^+ \to \pi^+ \nu \bar{\nu}$ constitutes a direct measurement of the magnitude of the V_{td} matrix element in the CKM matrix. Such a measurement with sufficient statistics to be limited by theoretical uncertainties would, by itself, put significant constraints on the remaining unknown parameters of the standard model. In combination with another independent measurement of the unknown CKM parameters ρ and η both the real and imaginary parts of V_{td} would be determined to within quadratic ambiguities. This would conclusively resolve whether some, all or none of the CP violation observed in the neutral kaon system is the result of the standard model.

The goal here is to describe and experiment to observe ~100 $K^+ \to \pi^+ \nu \bar{\nu}$ decays assuming a 1×10^{-10} branching ratio which can be done today with existing detector technology.

Theory

The branching ratio for the $K^+ \to \pi^+ \nu \bar{\nu}$ decay was first calculated by Inami and Lim [1] as an isospin rotation from K_{e3} ($K^+ \to \pi^0 e^+ \nu$) decay. The result of that calculation for each light neutrino type is:

$$\frac{B(K^+\to\pi^+\nu_l\bar{\nu}_l)}{B(K^+\to\pi^0 e^+\nu)} = \frac{\alpha^2}{8\pi^2\sin^4\theta_W}\left| V^*_{cs}V_{cd}\ D(X_c) + V^*_{ts}V_{td}\ D(X_t)\right|^2 \frac{1}{|V_{us}|^2} \qquad (1)$$

$$D(X) = \frac{1}{8}\left\{1 + \frac{3}{(1-X)^2} - \frac{(4-X)^2}{(1-X)^2}\right\} X\ln(X) + \frac{X}{4} - \frac{3X}{4(1-X)} \qquad (2)$$

$$X_j = \left(\frac{m_j}{m_W}\right)^2 \qquad j = c, t \qquad (3)$$

Ellis and Hagelin [2] evaluated the QCD corrections for this decay. These corrections are, in their words, "...numerically significant, relatively free of theoretical ambiguities, and constitute the most important class of radiative corrections to this process." Unlike CP violating measurements in the neutral kaon or B systems there is no theoretical uncertainity introduced by the structure of the initial hadron. More carefully said, the structure of the kaon factors out of this calculation since the ratio of two kaon decay amplitudes is calculated. The structure of the kaon is put in with the measured K_{e3} branching ratio. Rein and Sehgal [3] have evaluated the long distance contribution to the $K^+\to\pi^+\nu\bar{\nu}$ decay amplitude and find that these terms contribute 0.7×10^{-13} to the branching ratio. This is less than 1% of the lowest value predicted by the standard model. We will ignore the QCD and other corrections here for reasons of clarity. It is straight forward to include them. Rein and Sehgal [3] also noted that since the calculation is done by analogy to that for the $K^+\to\pi^0 e^+\nu$ decay mode the distributions for the two modes should be identical. Particularly the Dalitz plot projection of the missing neutral mass squared ($M^2_{\nu\nu}$) should be identical to the $M^2_{e^+\nu}$ distribution in $K^+\to\pi^0 e^+\nu$ decays. This is an important test of the validity of the calculation.

The Wolfenstein parameterization of the Cabibbo Kobayashi Maskawa (CKM) matrix [4] is:

$$V_{jk} = \left|\begin{matrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{matrix}\right| \qquad (4)$$

where $\lambda = 0.2205(18)^5$ is the usual Cabibbo angle and $A=0.82(10)^5$. Using these forms for the CKM matrix elements in equation (1) gives the following form for the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ amplitude in terms of measurable and known quantities:

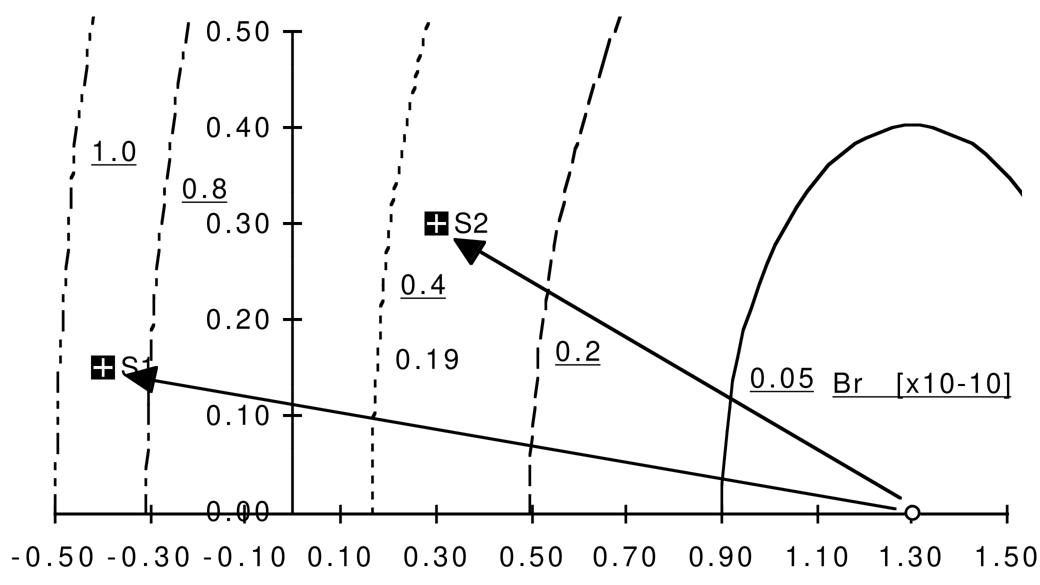
$$\frac{4\pi\sin^2\theta_w}{\sqrt{6}\alpha}\left[\frac{B(K^+\rightarrow\pi^+\nu\nu)}{B(K^+\rightarrow\pi^0 e^+\nu)}\right]^{\frac{1}{2}} = \left[(1-\frac{\lambda^2}{2})D(X_c) + A^2\lambda^4(1-\rho-i\eta)D(X_t)\right] \tag{5}$$

Using present values for the parameters of equation (5) and the charmed and top quark masses; 1.3 (3)[GeV]^5 and 174(16) [GeV]^5 respectively, in order to evaluate the D functions gives:

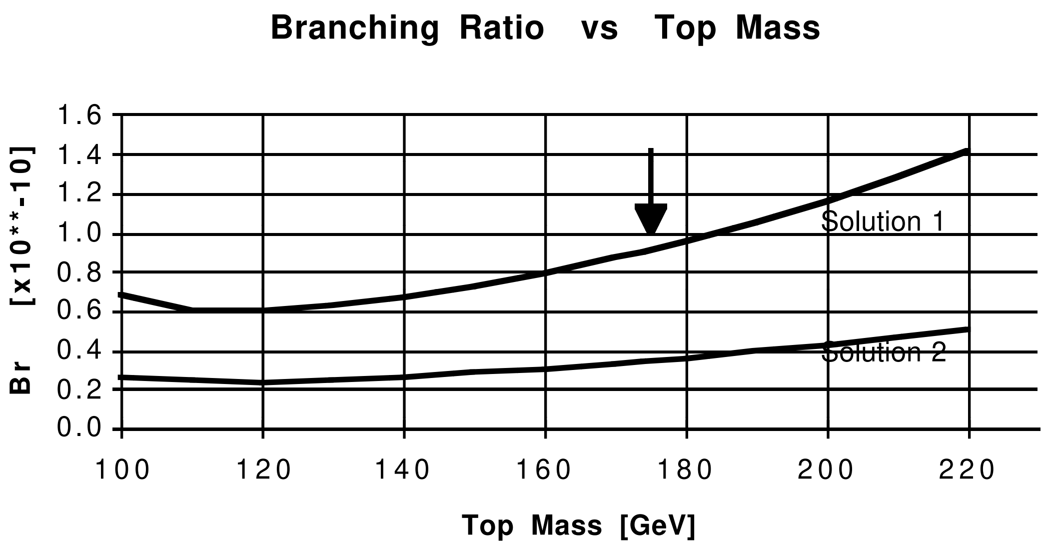
$$B(K^+\rightarrow\pi^+\nu\nu) = (0.31\text{x } 10^{-10})\left[(1.30-\rho)^2 + \eta^2\right] \tag{6}$$

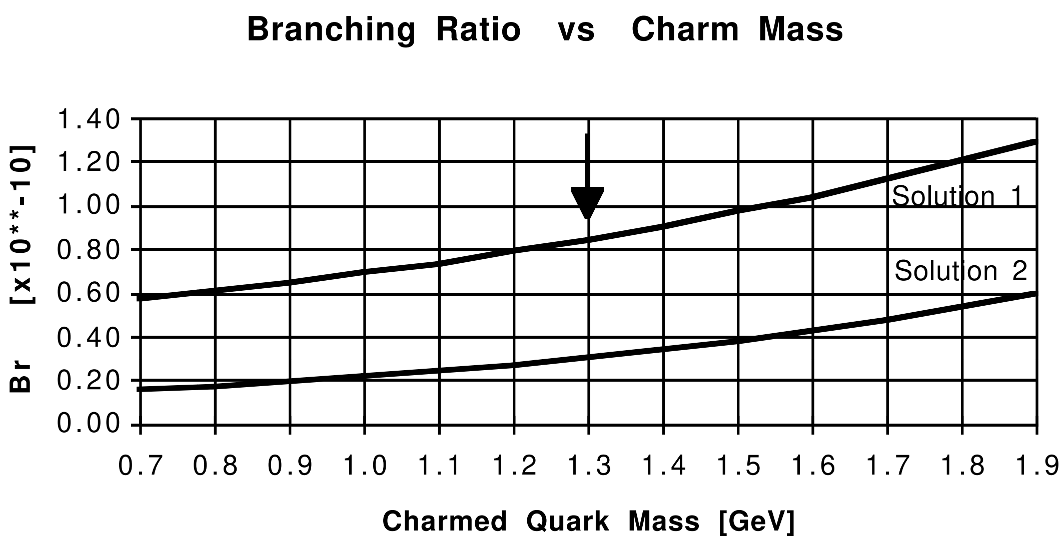
A measurement of $B(K^+\rightarrow\pi^+\nu\nu)$ defines an annulus in the (ρ,η) plane centered about the point $(\rho,\eta)=(1.30, 0)$. The shift of the center from $\rho=1$ is due to the contribution of the charmed quark to the decay (the first term on the right hand side of equation (5)). If $B(K^+\rightarrow\pi^+\nu\nu)$ is measured to 10% then the radius of the annulus is statistically determined to 5%.

Rho - Eta Plane



This result is shown graphically on the (ρ,η) plane in the figure above. The two points on the figure are the two possible standard model allowed solutions from Gerard's recent review [6]. These two solutions correspond to $B(K^+ \to \pi^+ \nu\nu)$ values of 0.91×10^{-10} and 0.34×10^{-10} respectively. The variation of the branching ratio with the top and charmed quark masses for these two solutions is shown in the following two figures.





Gerard's two solutions (reproduced from [6] in the figure below) have significant uncertainties both in the underlying experimental measurements and the theory. The choice of solution 1 or 2 is determined by the unknown and, so far, incalculable parameter f_B. If f_B was known exactly the experimental uncertainties from Gerard's plots are of order 0.1 in both ρ and η. As we show below, this experiment will measure ρ

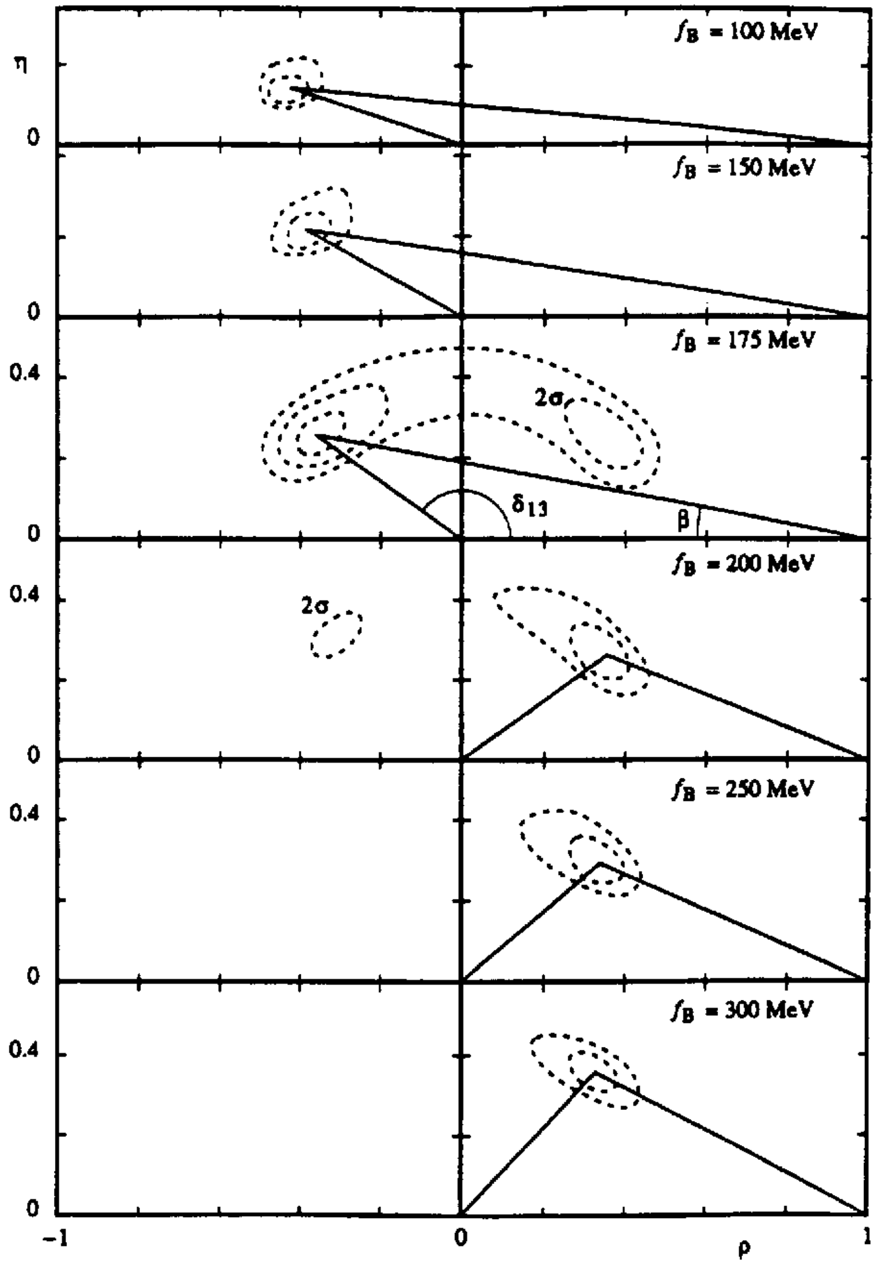


Fig.3 : Best fit results in the (ρ, η) plane for six values of f_B submitted by K.R. Schubert in [31]. The δ_{13} and β angles are defined in Eqs(2.21) and (3.44) respectively. $Vub/Vcb = 0.10 \pm 0.01$ and $B^B = 1$ are assumed. The contours show one and two standard deviations, in the 175 Mev case also three standard deviations.

with a precision of ±0.18 where the statistical component of this error is ±0.10. The balance of this error is due to experimental uncertainties in the other Standard Model parameters in equation 5. The area within the 0.05 contour in the (ρ,η) plane above shows the 90% CL upper limit we would set if we observed no events beyond background. Such a result of this experiment would leave the Standard Model in deep trouble. One can view this as either a confirmation that this experiment has the sensitivity to surely observe this mode or as an opportunity to illuminate a fundamental weakness of the Standard Model.

Previous Measurements and Their Limitations

The present upper limit for the branching ratio of $K^+ \rightarrow \pi^+\nu\bar{\nu}$ is $<5.2 \times 10^{-9}$ at 90% CL [7]. This result is from the E787 experiment at Brookhaven which is the only one actively searching for this decay at this time. E787 was proposed about ten years ago and has taken data for several years. The basic experimental technique used by E787 is to stop K^+s in a 4π magnetic detector measuring the momentum, energy and range of the decay pion. The charged decay track is identified as a pion by observing the $\pi \rightarrow \mu \rightarrow e$ decay chain. Additional background suppression is obtained with large solid angle photon detectors to reject events with additional photons. The overall acceptance of this detector for the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ decay mode is 0.55% [7].

We mean no criticism of E787. It is an experiment designed when the top was believed to be light and the width of the Z was unmeasured so that the number of light neutrino generations could have been 50. Their goal was to search for Physics beyond the Standard Model with 3 light neutrinos. The experiment was a heroic effort and has largely achieved its goals. We believe that its basic technique limits it from ever getting to the 100 event level given that the top is heavy and that the number of light neutrinos is now known to be three. A problem is that the observation of the $\pi \rightarrow \mu \rightarrow e$ decay chain is an absolutely critical part of the background rejection scheme required in a stopped kaon experiment and the muon just lives too long. E787 has published results with kaon stopping rates of 150 kHz and the acceptance quoted above [7]. With these parameters the running time to observe one event assuming a nominal standard model branching ratio of 1×10^{-10} is one year (1×10^{7} beam seconds). The E787 experimenters are trying to improve both their acceptance and rate capability. We believe that at best they may see a handful of events. This would be a major step forward. However, such limited statistics cannot yield an annulus on the $\rho-\eta$ plane with sufficient precision to apply important limits on the parameters of the standard model.

The logic of the experimental situation dictates a much higher kaon decay rate. We believe this requires just the opposite approach of E787, a decay in flight experiment with the minimum of material in the beam to reduce backgrounds from interactions. To achieve the 100 event level of sensitivity will require two orders of magnitude higher kaon decay rate at the same acceptance. A beam with ~10 MHz of decaying kaons will require a detector system with resolving times less than 100 nsec and very high rate capabilities. The acceptance can be maintained by going to a high energy beam where the Lorentz boost folds the kaon decay products into a small forward cone. The major drawback in a decay in flight experiment is that the kaon as well as the pion must be momentum analysed with high precision.

Similar experiments have been done in the past [8] and discussed for this decay mode in workshop studies[9]. In these cases the spectrometers are conventional magnetic spectrometers with either proportional wire chambers or drift chambers for charged particle tracking.

In the case of Brookhaven E777 [8] (of which one of us [psc] was a founding member) 200 MHz of unseparated +6 GeV/c beam yielded about 2 MHz of Kaon decays in the sensitive region of the apparatus. The acceptance for the decays studied was ~5% giving 100 KHz of accepted decaying kaons. The performance of MWPCs with their beam regions deadened limited the intensity to this level. The backgrounds observed were acceptably low for the three body all charged final states which were being studied in E777. The average good three body event had an extra track found in the MWPCs when operated with 25 nsec gates. These were mainly due to the geometry of the 6 GeV/c beamline. The incident Kaon was unmeasured but the requirement of three charged track forming a good vertex which reconstructed a kaon coming from the production target made the issue of accidental tracks unimportant. This would clearly not be the case for one charged particle final states. The basic lesson of E777 to be applied in this context is that even a conventional spectrometer with significant material [10] in the beam can be made to work in a 0.2 GHz beam.

The Main Injector workshop[9] study for a "conventional" $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ experiment assumed a separated beam largely in order to limit the amount of background caused by the 10 pions and protons for every kaon in unseparated beam. The assumed separated beam was 30 MHz with a flux of accepted decaying kaons of 420 kHz which required a large fraction of the Main Injector proton intensity in order to make up for the separator and decay losses. This design would give 10 events at $Br=1x10^{-10}$ in a year of running.

Apparatus

Our proposal is to do the entire job of momentum measurement and particle identification for both the kaon and decay pion with a two low mass detectors; a pair of phototube ring imaging Cerenkov counters (RICH). The beam would be a 0.3 GHz unseparated positive beam at about 22 GeV/c. The beamline is relatively long (~100m) with quadrupoles so that the beam as it enters the first RICH is parallel (<50 μRad divergence) with a large area (10 x 10 cm^2). The rate of kaon decays in the decay volume would be about 3 MHz. Assuming the 4.7% acceptance after all cuts given by a simple Monte Carlo simulation and $Br=1x10^{-10}$ as before, the sensitivity is 150 events with missing neutral mass below M_{π° in one year (10^7 live seconds of beam). About half of these events would be in free of significant backgrounds.

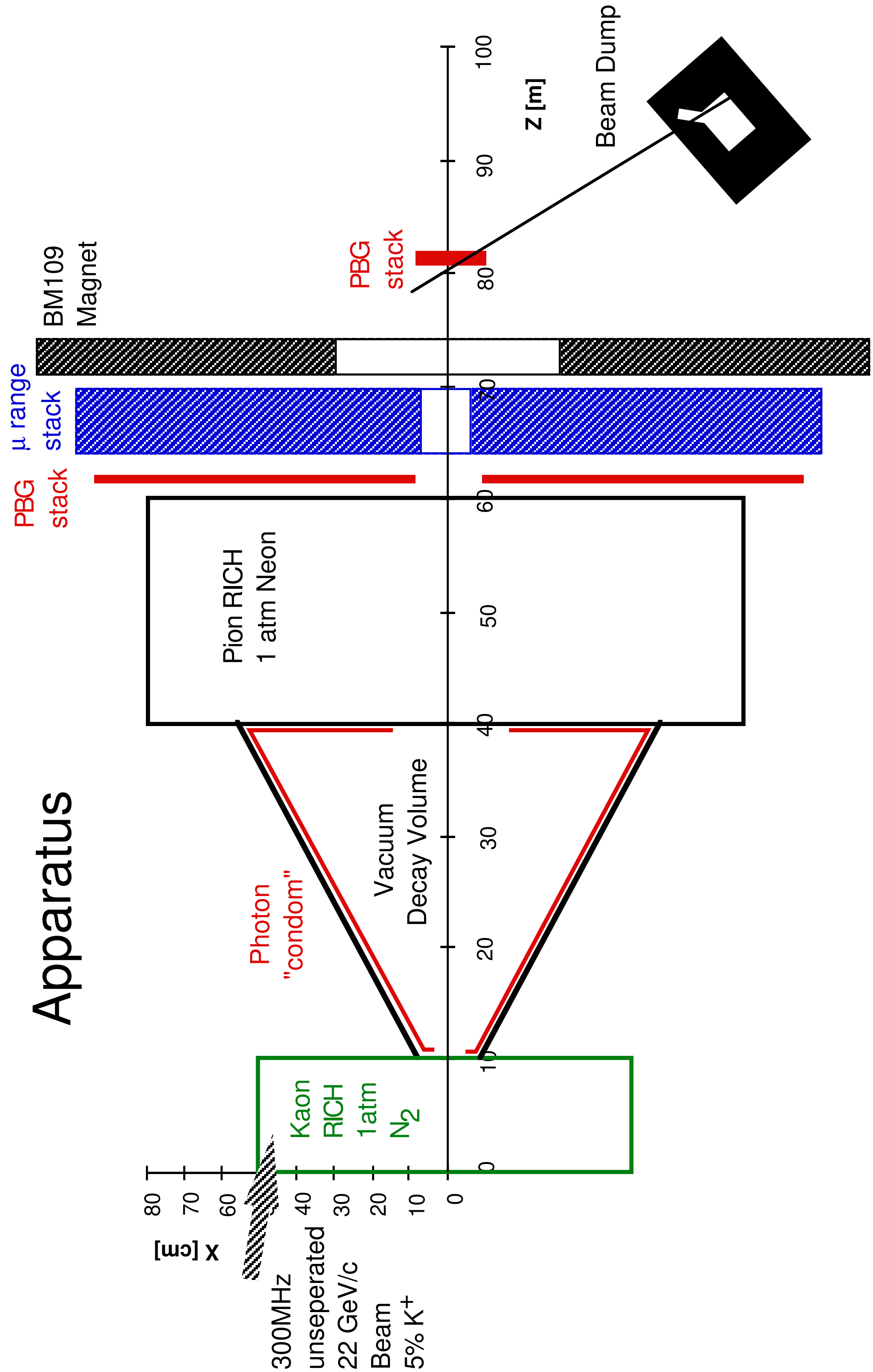
The figure below shows a complete schematic of the CMK apparatus.

Phototube RICH Detectors

The choice of a detector technology with as "rich" and varied a past as the ring imaging Cerenkov counter is admittedly unconventional. This choice is motivated by the near ideal match between the properties of the phototube RICHs pioneered by one of us [psc] with colleagues from E781 and the requirements of this experiment. A RICH measures the vector velocity of a charged particle with a minimum amount of material and with a resolving time limited only by the speed of the photo-detectors used. Cerenkov detectors measure velocity , not momentum. In a beam of narrow enough momentum bite particle ID is intrinsically included in the measurements.

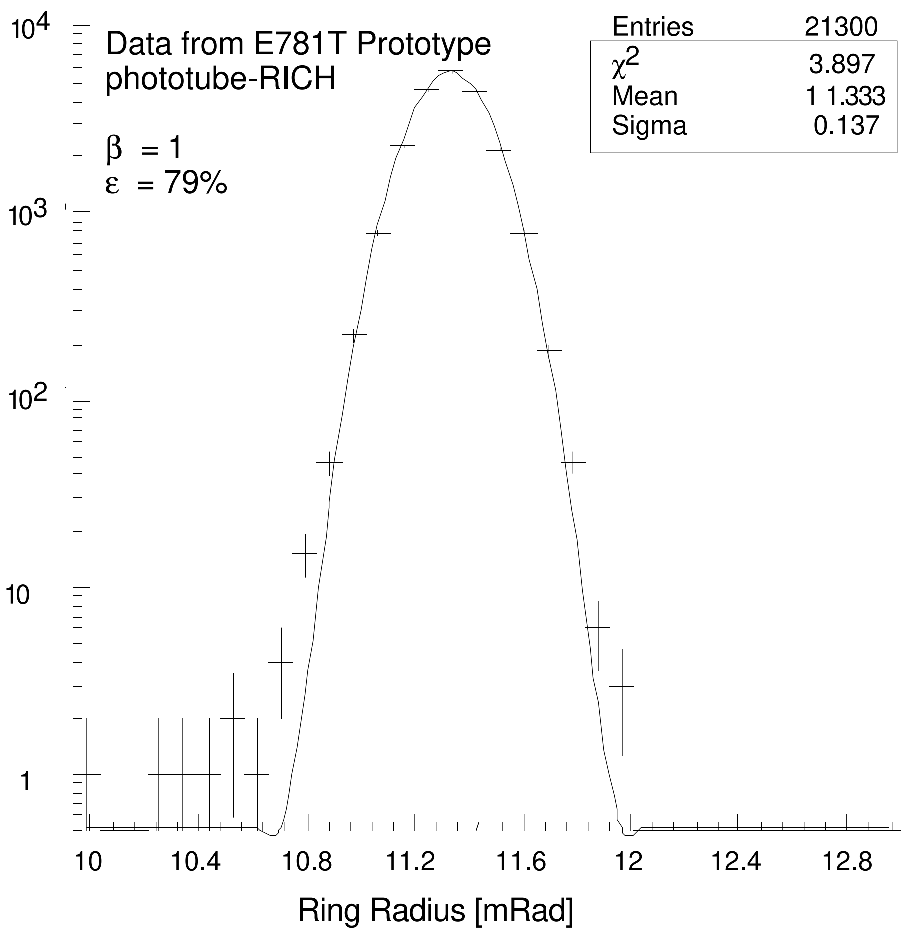
All the estimates and simulations used here are based upon measured results from a prototype phototube RICH we built and tested for E781 [11]. This 300 phototube prototype is the model for the first (kaon) RICH and probably could be used with only minor changes. A example of the results from this prototype are shown in the figure below. These data were taken downstream in a 400 GeV/c negative hyperon beam. The

Apparatus



300MHz
unseperated
22 GeV/c
Beam
5% K^+
X [cm]
80
70
60
40
30
20
10
0
Kaon
RICH
1atm
N_2
Photon
"condom"
Vacuum
Decay Volume
Pion RICH
1 atm Neon
PBG
stack
µ range
stack
BM109
Magnet
PBG
stack
Beam Dump
Z [m]
0
10
20
30
40
50
60
70
80
90
100

thresholds for $\pi^-/K^-/\bar{p}$ were 12/44/83 [GeV/c] respectively. The distribution shown is the ring radius for all single tracks observed after modest cuts on the χ^2 of the ring fit ($\chi^2/\nu<2.5$). The radius plotted here is the average angular distance from an MWPC measured track to each PMT in the event. The average track has 12.4 tubes assigned to a ring. The average number of PMTs fired by noise assigned to a ring is ~0.3 There are several effects which explain the events at low ring radius (upstream decays and interactions). The non-Gaussian tail on the high ring radius side is ~10 events out of 21300. These data were taken with a 100 nsec time gate on the PMTs. This non-Gaussian tail is consistent with the tube noise given this gate width. Provided that a trigger veto system controls upstream interactions and decays this type of detector will have nearly perfect Gaussian resolution function with the 100 times smaller effective gate width achieved by measuring the time of each PMT signal to ~1 [nsec]. These data were taken over a 12 day period and indicate the stability of this class of detector. The resolution (σ) is stable to ±1.5% and the ring radius is stable to ±27 [μRad] or ±20% of σ over this period.



The E781 RICH, with 2800 phototubes which is now under construction, is the model for the second (pion) RICH. The performance of this device will demonstrate the feasibility of scaling phototube RICH technology up to this size and provide important experience in maintaining the precision achieve with the prototype in large scale detectors.

The RICHs would operate at atmospheric pressure so that their beam windows can be very thin. The combination of radiator gas (nitrogen) and beam momentum (22 GeV/c) is chosen so that beam kaons are just above Cerenkov threshold in the first RICH. This kaon RICH is blinded to the beam pions by not instrumenting the device at large ring radius where pion Cerenkov light would hit the photocathode. The beam protons are below Cerenkov threshold are are therefore unseen. Kaons produce very small radius Cerenkov rings which make the identification of kaons unique (small rings centered on the beam direction) and the kaon momentum resolution very good (~0.5%). The kaon angles are measured from the center of the kaon ring but are better known from the beam divergence. Decay pions are measured in an analogous manner in the second RICH whose working gas is neon with a pion threshold of 12 GeV/c. Pion rings are larger and their ring centers are offset from the beam direction by the decay angle. The resolving time of a RICH is better than required. Cerenkov light is naturally isochronous (all cerenkov photons arrive at the photocathode at the same time). Sub-nanosecond timing on the signals from small phototubes is straight forward. The resolving time of a RICH is the width of a phototube pulse, about 10 nsec.

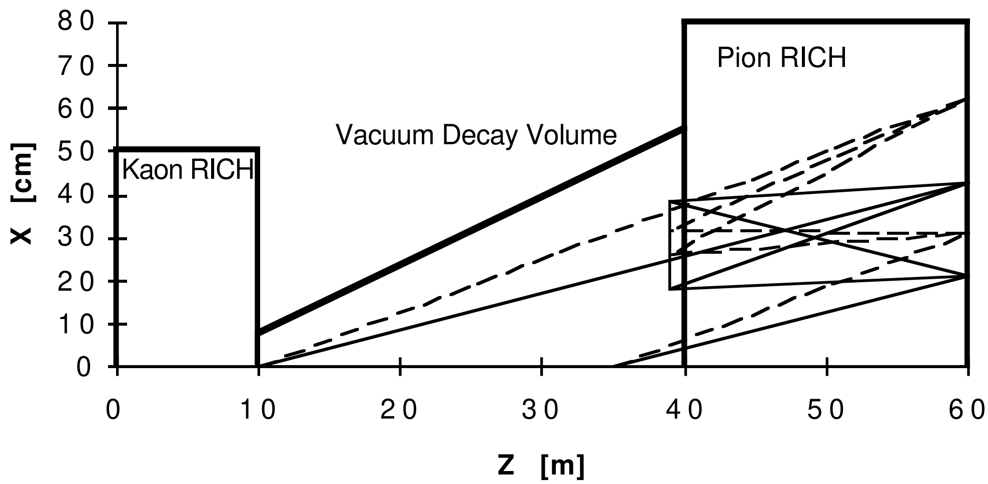
Decay Volume

Between the two RICHes is a 30m long vacuum decay volume whose walls are lined with a photon veto "condom". Only decays in this region are studied. The material in this region is ~5×10^{-6} interaction lengths and the interaction rate in this region is ~1kHz for a modest vacuum (100µm). The kaon decay rate in this volume is 3MHz. The vacuum window are modeled after the E731 "sailcloth" window with 0.25% radiation lengths and 0.2% interaction lengths each. Trigger scintillators will require decay tracks to emerge for this decay volume. The backgrounds due to interactions will be dominated by the limitations of this system rather than the actual interactions with the gas in the decay volume. A schematic of the apparatus is shown in the figure below. Charged particle and photon rays are shown for the largest and smallest pion angles (and momenta) of interest and both the beginning and end of the decay volume. The photon veto system is not shown here.

Veto Systems

The rest of the detectors consist of various vetos counter systems. Directly behind the pion RICH is a lead glass wall used to vetos all events with any deposition greater than is consistent with one minimum ionizing particle. This kills most events with electrons or photons from π^0s. This wall must have a hole to allow the beam out which need only be as large as the beam. Following the photon veto wall is a stack of steel large enough to absorb all the energy from a 22 GeV/c pion. Scintillator hodoscopes behind this stack are used as a trigger veto for the 2 MHz of $K^+ \rightarrow \mu^+\nu$ decays.

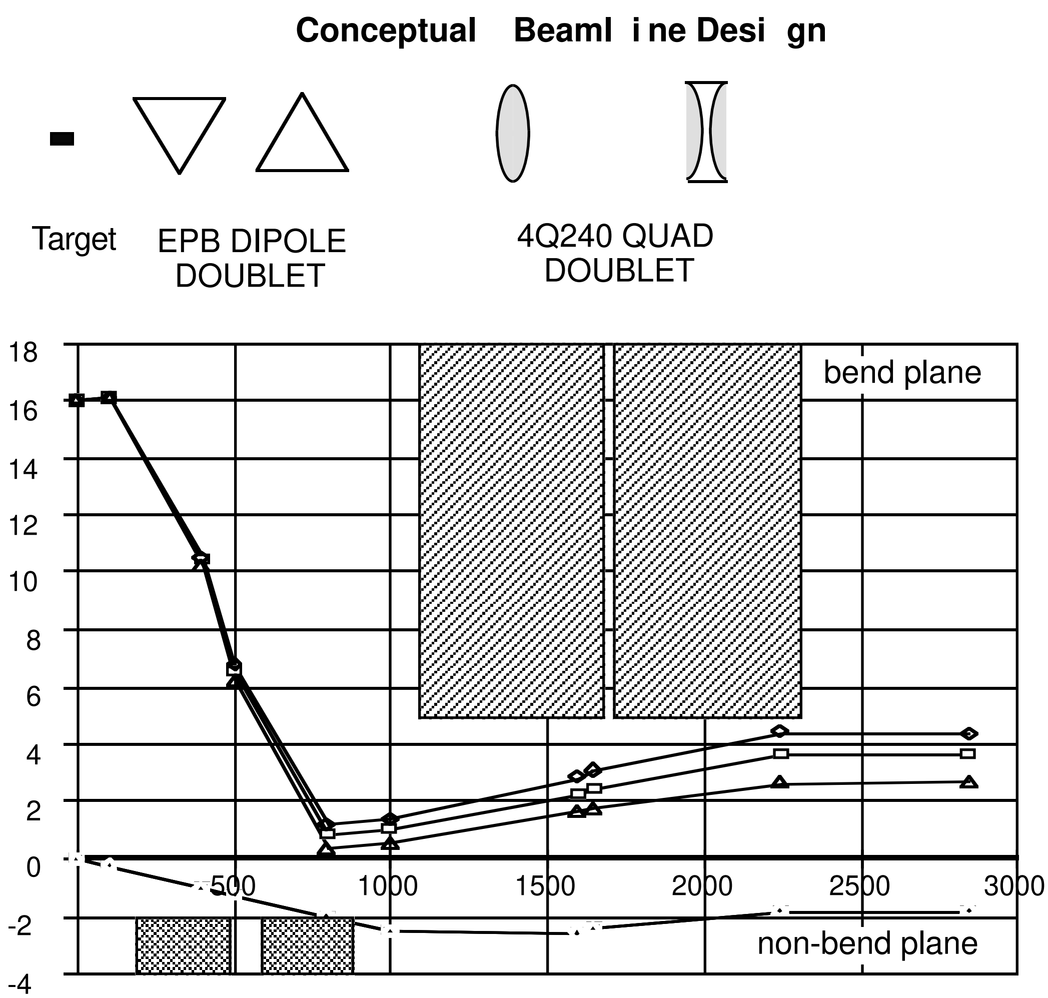
Apparatus Schematic



Beam

This measurement requires a high flux unseparated 22 GeV/c beam. Such a beam can be produced with either the 800 GeV/c protons from the Tevatron or the 120 GeV/c protons from the main injector. Since the duty factor is the same for both of these accelerators there is no difference in sensitivity between them. Main injector beam can be debunched so that accidental backgrounds are less severe by an order of magnitude. Accidentals are the largest potenital source of background after $K\pi2$ decays. To attempt this experiment with instantenous rates as large as 3 GHz would be folly. Therefore this is a main injector experiment.

The requirements for the beam are that it have a momentum bite of $\Delta P/P = \pm 2.5\%$ in order that the kaon is close enough to Cerenkov threshold to keep adequate kaon momentum resolution. The beam divergence should be ± 50 μrad. The transverse size of the beam as it enters the first RICH can be essentially of any convenient size; ±5 cm of a 4 inch beam pipe seems reasonable. The decay length of a 22 GeV/c kaon is 165 m so that a beam design with two underground enclosures separated by 100 m would allow the containment of radiation from the production target and the absorption of target associated muons in the earth between the two enclosures while losing only 45% of the kaons to upstream decays.



22 GeV/c beams are not typical at Fermilab. We have done a conceptual beamline design in order to assess feasibility and fluxes. This design (shown in the figure above) consists of a production target, an achromatic dipole doublet made of two EPB dipole magnets run with equal and opposite P_t kicks of 1 GeV/c followed by a 4Q240 quadrupole doublet focused at infinity. Limiting rays are shown in the bend and non-bend planes in the figure above.

This beam has a solid angle of ±3.5 mRad x ±1 mRad and a momentum bite of ±2.5%. The divergence downstream of the quads is ±110 μrad in the bend plane with a strong angle momentum correlation. A simple cascade simulation indicates that with a 30 cm (2 interaction length) Cu target the yield of this beamline is 6×10^{-3} particles per incident 120 GeV/c proton. Only 20% of this yield is due to the direct interactions of the primary protons. The balance is due to the cascade which is why the yield is optimized with a thick target. A yield of 0.01 implies that 5×10^{10} protons per second are required to produce a 0.3 GHz secondary beam.

Trigger / DAQ

Every detector in this apparatus is a phototube. Every phototube will need an individual channel of readout electronics which provides the time associated with each pulse. The first level of trigger required is a combination of the correct range of phototube hits in the pion RICH in combination with vetos from the muon and photon veto systems. This trigger should fire at the 100 kHz level.

It is unclear, at this time, whether it is better to build dedicated electronics combining the trigger and time measurement system or to use a more conventional separated trigger and readout electronics.

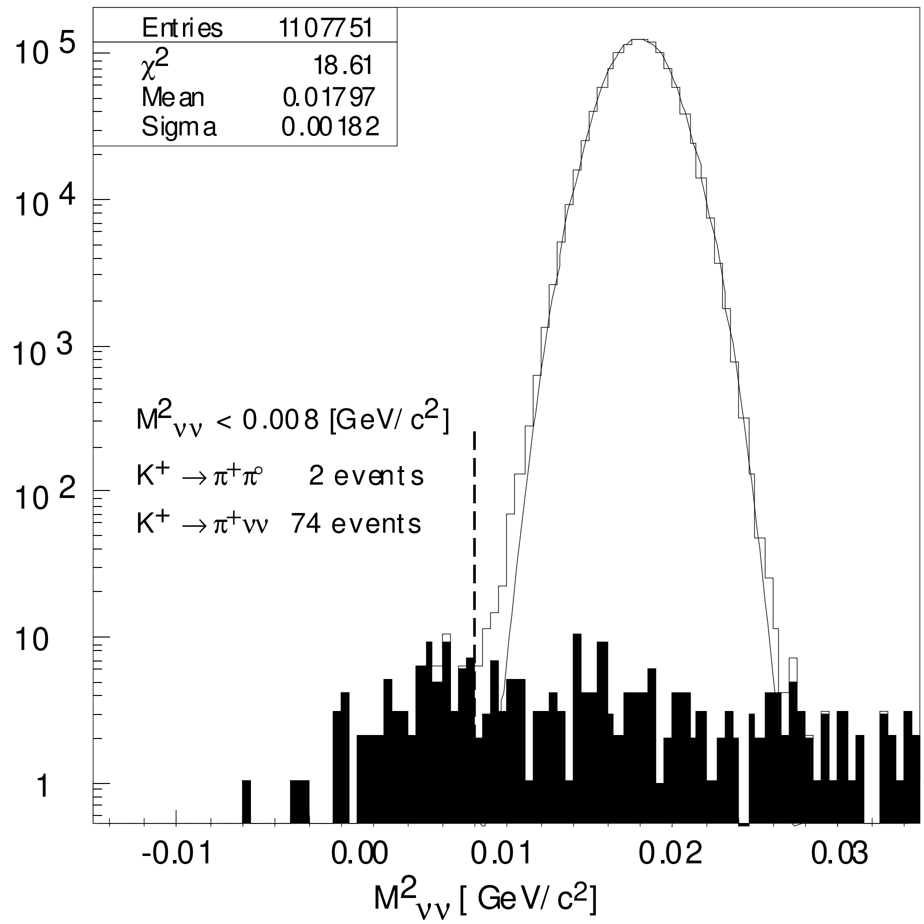
The lead glass blocks are also readout with ADC's with a 50 nsec or shorter gate for accepted triggers. Recall that the goal of the photon detectors is to veto any events inconsistent with a single minimum ionizing particle. The tails of the pulses aren't important at this level of resolution and any pileup causes only a small loss of good events. The total number of PMTs to be readout are 4000 , 100 of which require ADC's in addition to the time readout required of all channels. The total amount of data in a trigger, after sparsification is about 250 bytes.

Detector Simulation

We have simulated the response of this detector to the signal and the dominant background, $K^+ \rightarrow \pi^+ \pi^\circ$. We have included the RICH detector response as measured in the E781 test run and multiple scattering from the gas, windows and mirror in the beam. We have established a typical set of cuts in order to define a clean signal. These are:

Parameter	Cut	Efficiency
Kaon RICH PMTs fired	> 5	.98
PION RICH PMTs fired	> 7	.77
$P_{\pi+}$	> 16 [GeV/c]	.61

$M^2_{\nu\nu}$ error < 0.0032 $[GeV/c^2]^2$ .89



With these cuts we have an efficiency of 4.7% for all signal events with $M^2_{\nu\nu} < M^2_{\pi^\circ}$ and 2.2% of all signal events with $M^2_{\nu\nu} < 0.0080$ $[GeV/c^2]^2$. These efficiencies are with respect to all kaons decaying in the decay volume. In the plot below we show the $M^2_{\nu\nu}$ distribution for 2.8 x 10^{13} K^+ decays which corresponds to 10^7 live seconds of beam at 300 MHz. We have take the π° rejection from the veto systems to be 10^{-6}. We have achieved a $M^2_{\nu\nu}$ resolution of $M^2_{\pi^\circ}/10$. For an assumed branching ratio of 1×10^{-10} there survive 74 signal and 2 background events below the $M^2_{\nu\nu} < 0.0080$ $[GeV/c^2]^2$ cut.

Background Suppression

Kaon decays

The largest potential background is killed automatically by the detection with a Cerenkov counter. When the mass squared of the missing neutral system is calculated for a $K\mu2$ event with the muon assumed to be a pion a large unphysical negative value results. The backgrounds which must be controlled are $K^+ \rightarrow \pi^+\pi^0$, $K^+ \rightarrow \mu^+\nu\gamma$, 1 prong Kaon interactions and accidentals from either interactions or other decays. The total number of interactions lengths ito which the trigger is sensitive is ~1% giving a 3 MHz interaction rate matched to the 3 MHz kaon decay rate and 5 MHz of beam pion decays in the decay volume.

Decays in flight

Accidentals

Interactions

Physics Results

If we assume that nature has the values for ρ and η near solution 2 shown in the figure below then the branching ratio for $K^+ \rightarrow \pi^+\nu\nu$ should be about 0.4×10^{-10} . This would yield us 30 signal plus 2 background events with the cuts established above. The resulting 1 σ allowed region on the (ρ,η) plane is shown in the

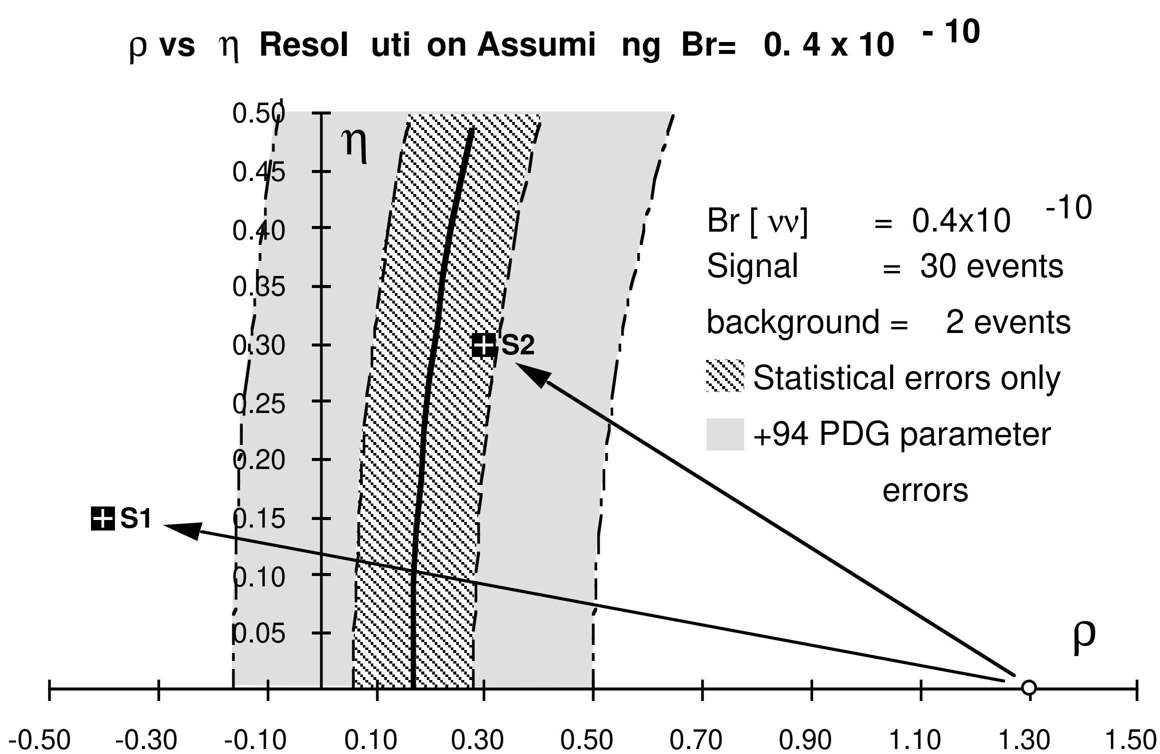


figure above. The hashed region is the 9% statistical error only. The shaded region includes the error due to the uncertainty in the measurements of the other standard model parameters require to evaluate equation 5. These uncertainties are dominated by a 24% contribution from $A^2 = [\,|V_{cb}|/|V_{us}|^2]^2$ followed by a 9% contribution from the top quark mass and a 7% contribution from the charmed quark mass. One can reasonably expect that the measurement of $|V_{cb}|$ and the top quark mass will be improved from work being done now at Fermilab, CLEO, LEP and elsewhere. As the geometry of the figure below clearly shows, this experiment is mainly sensitive to ρ and not η. If we assume that A^2 will be known to 10% and the top quark mass to 5% by the time that the data from this experiment are available then this experiment should yield a measurement of ρ with a precision of ± 0.18 or 16%. This error has contributions of 9% from statistics and 13% from experimental uncertainties in the other Standard Model Parameters.

Necessities

Budgets / Time Scale

A very rough first cut at a budget for this experiment is as follows:

	cost [K$]
4000 Hamamatsu R760 phototubes with bases @ $400/tube	1600
4000 channel of HV and readout electronics @ $100/channel	400
RICH mechanical, optical and gas systems	500
Veto systems	500
beamline	200
everything else	500
TOTAL	3700

The time scale for this experiment is dictated by the Main Injector. It requires a collaboration of several dozen physicists and students. It probably need two years of design and one year of construction for the experimental apparatus. It will very likely require more that one run in order to understand and tune the apparatus in order to have background in control at the 10^{-10} level and simultaneously achieve high relative efficiencies. Integrating 10^7 live beam seconds will require 2 calendar year of running.

Manpower

Conclusions

References

1. T. Inami and C.S. Lim, Prog.Theor. Phys. **65** (1981) 297.
2. J. Ellis and J.S.Hagelin, Physics Letter B **192** (1983) 201.
3. D. Rein and L.M> Sehgal, Phys. Rev. D **31** (1989) 3325
4. L. Wolfenstein, PRL **51** (1983) 1945.
5. Particle Data Group: Phys. Rev. D **50**,1173 (1994).
6. J.M. Gerard, *CP violation* in the proceeding of the Joint International Lepton-Photon Symposium & Europhhysics Conference on High Energy Physics, S. Hegarty, K. Potter, E Quercigh, ed., World Scientific (1991)
7. Search for the Decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, MS Atiya, et.al., PRL **70**,2521(1993), MS Atiya, et.al., NIM **A321**,129(1992), MS Atiya, et.al., Nucl. Phys. **A527**,727(1991), *Recent Results from BNL on Rare Decays of Kaons.*, W. Molzon, in Proceedings of the Joint International Lepton-Photon Symposium & Europhysics Conference on High Energy Physics, S. Hegarty, et.al, Ed., World Scientific, p 581, (1991). ,MS Atiya, et.al., PRL **64**,21(1990), .
8. *Search for Short Lived Neutral Particles Emitted in K^+ Decay*, N.J. Baker, et.al., PRL 59,2382 (1987), *A Search for the Decay $K^+ \rightarrow \pi^+ \mu^+ e^-$*, C. Campagnari, et.al., PRL 61,2062 (1988), *An Improved Limit on the Branching Ration of $K^+ \rightarrow \pi^+ \mu^+ e^-$*, A.M. Lee, et.al., PRL **64**,165(1990), *A Study of the Decay* , C. Alliegro, et.al., PRL 68,278 (1992)
9. *Report of the Working Group on K^+ Decay in Flight*, HS Collins, et.al., in the Proceedings of the Workshop on Physics at the Main Injector, S. Holmes and B. Winstein, Ed., Fermilab,p93, 1989.
10. E777 had about 5% of a radiation length of low Z material in the 200 MHz beam.
11. *A Phototube RICH Detector*, By M. Pommot Maia, (CNPQ, Brazil), P.S. Cooper, L. Stutte, (Fermilab), V. Solyanik, (IHEP, Serpukhov), I. Filimonov, A. Nemitkin (Moscow State Univ.) Published in NIM **A326**(1993)496-507.