Proposal Presentation - Fermilab PAC

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Charged Kaons at the Main Injector

A Proposal for a Precision Measurement of the Decay $K^+ \to \pi^+ \nu\overline{\nu}$ and Other Rare K^+ Processes at Fermilab Using the Main Injector

R. Coleman, P.S. Cooper*, M. Crisler, C. Milstene†,E. Ramberg, R. S. Tschirhart
Fermi National Accelerator Laboratory, Batavia, IL, USA

A. Kohzevnikov, V. Kubarovsky, V. Kurshetsov, L. Landsberg, V. Molchanov, V. Obraztsov, V. Polyakov, D. Vavilov, O. Yushchenko
Institute of High Energy Physics, Serpukhov, Russia

J. Engelfried, A. Morelos
Instituto de Fisica, Universidad Autonoma de San Luis Potosi, Mexico

K. Lang, J.L. Ritchie*
University of Texas at Austin, Austin, Texas 78712

† Resident at Fermilab, on leave from Tel Aviv University.

* Cospokesmen: P.S. Cooper, pcooper@fnal.gov, (630) 840-2629
J.L. Ritchie, ritchie@hep.utexas.edu, (512) 471-4488

OUTLINE

- Introduction
- $K^+ \to \pi^+ \nu \overline{\nu}$ Theory
- Related K^0_L and B-system Measurements
- Experimental Method
- Apparatus
- Background Simulation
- Summary of Detector Cost Estimates
- Schedule
- Conclusion

Introduction

- Brookhaven Experiment E787

  Stopped K^+ experiment

  Reported 1 event from 1 good year of data taking

  Background estimate 0.08 ± 0.03 events

  $\text{Br} = [4.2^{+9.7}_{-3.5}] \times 10^{-10}$

  Consistent with Standard Model $[0.9 \pm 0.3] \times 10^{-10}$

- CKM Goal - Measure V_{td} in $K^+ \to \pi^+ \nu \overline{\nu}$

  Decay in flight experiment at Fermilab Main Injector

  $\sim$100 $K^+ \to \pi^+ \nu \overline{\nu}$ events with <10 background events in 2 years data taking

  5% statistical, 10% total precision

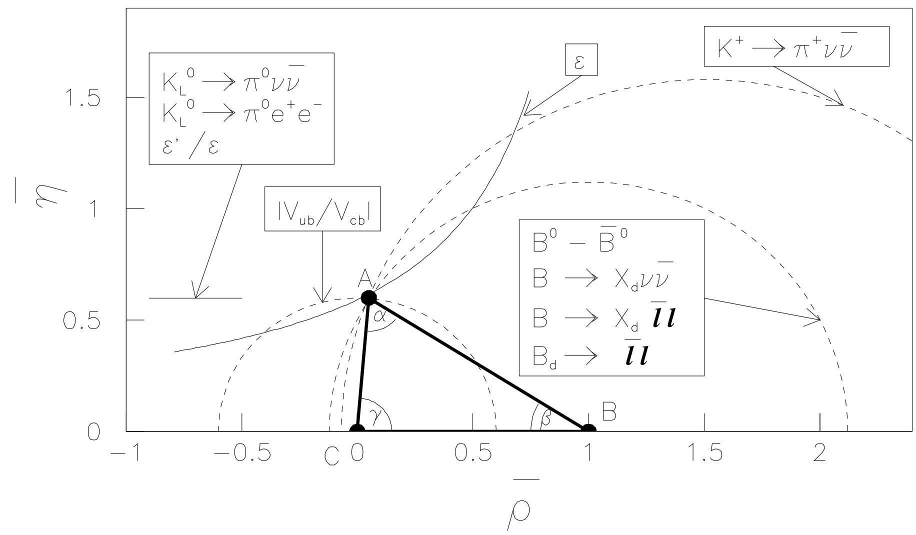


Figure 1: The ideal Unitarity Triangle. For illustrative reasons the value of $\bar{\eta}$ has been chosen to be higher than the fitted central value

$K^+ \to \pi^+ \nu\bar{\nu}$ Theory

Calculated by weak isospin rotation from $K^+ \to \pi^0 e^+ \nu$

$$\frac{B(K^+ \to \pi^+ \nu\bar{\nu}\ )}{B(K^+ \to \pi^0 e^+ \nu\ )} = \frac{3\alpha^2}{8\pi^2 \sin^4\theta_W} |V_{cs}^* V_{cd} D(X_c) + V_{ts}^* V_{td} D(X_t)|^2 \frac{1}{|V_{us}|^2} \tag{1}$$

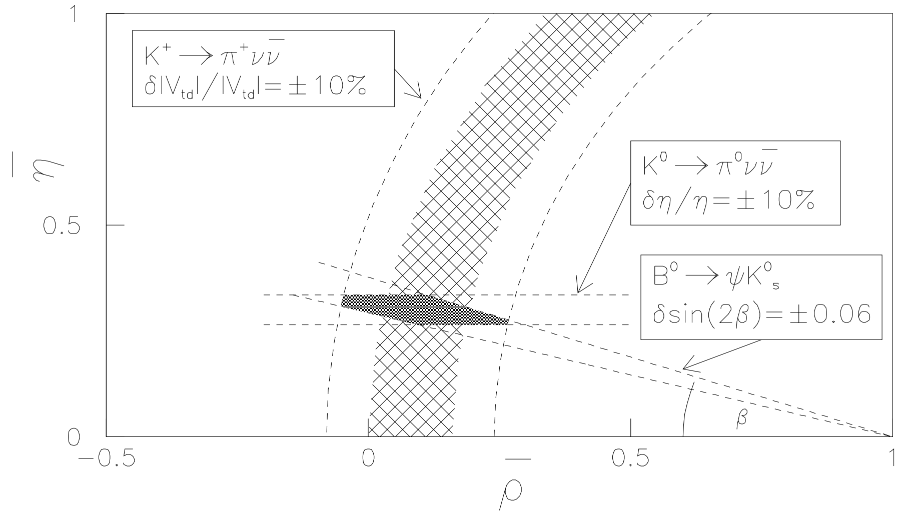
$$Br[K^+ \to \pi^+ \nu\bar{\nu}\ ] = [0.44 \pm 0.15] \times 10^{-10}[(1.4 - \bar{\rho})^2 + \bar{\eta}^2] \tag{2}$$

Total theoretical uncertainty of 8% estimated by Buras, et al.

Dominated by uncertainty in charmed quark mass

Structure of K^+ is put in with measured K_{e3}^+ branching ratio

All other corrections are small and calculated (NLO QCD, isopsin, long distance contributions)



Related K_L^0 and B-system Measurements

- Testing the Standard Model description of CP Violation [η]
- Confirming the Standard Model description of CP Violation

  All measurements for which the theory is reliable can contribute

  Both B sector & K sector have to give the same answer

- Falsifying the Standard Model description of CP Violation

  Only foreseeable measurements with controlled theoretical errors

  Three of these are: $K^+ \to \pi^+ \nu\overline{\nu}$ $K_L \to \pi^0 \nu\overline{\nu}$, and $B^0 \to \psi K_s^0$

Experimental Method

- Signal- $K^+ \to \pi^+ \nu \overline{\nu}$
- Backgrounds - $K^+ \to \pi^+ \pi^0$ and $K^+ \to \mu^+ \nu_\mu$ most obvious
- Observables

  Momentum of the K^+

  Momentum of the π^+

  Angle between the K^+ and the π^+

  These are combined as M^2_{miss}, the missing mass squared recoiling against the π^+

  Particle ID for both charged tracks

  Absence of anything else in time in the event

- Sensitivity - High rates are required

  Acceptance for this class of experiments is $\sim$1%

  10^{-12} Single event sensitivity $\to 10^{14}$ K^+ decays

  In $\sim 2 \times 10^7$ live seconds (2 years) $\to$ $\sim$5 MHz of decaying K^+. This implies a 30 MHz K^+ rate in CKM.

- Resolution - σ_p/p $\sim$1%, σ_θ/θ $\sim$1%, σ_t $\sim$1 nsec, are required to control the dominant backgrounds.
- Mismeasurement - REDUNDANCY is required for all measurements to control scatters, noise and accidentals. The largest source of background from from scatters in the last measurement before or the first measurement after the decay volume
- Vetos - for photons and muons

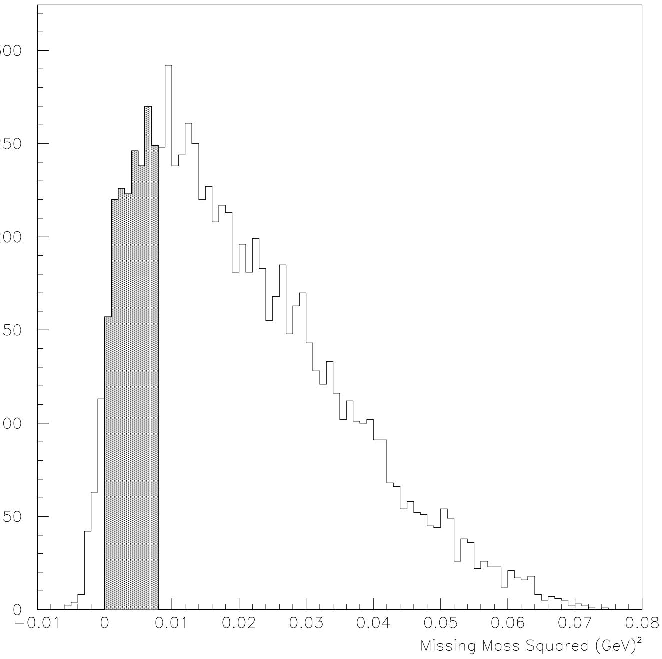
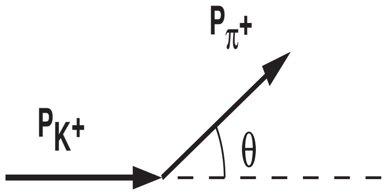


Figure 29: Measured missing mass squared (M^2_{combined}) in $K^+ \to \pi^+\nu\overline{\nu}$ events. The signal region is shaded.



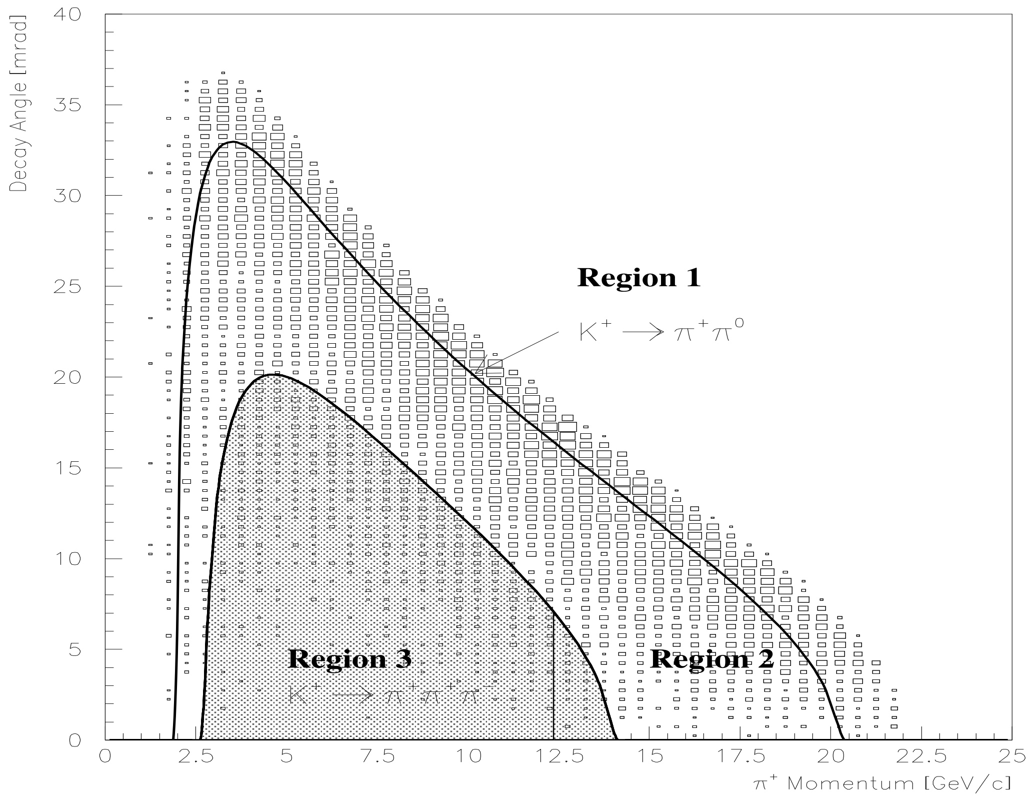


Figure 3: Decay angle versus momentum for $K^+ \to \pi^+\nu\overline{\nu}$ events. Three distinct analysis regions are shown.

Apparatus

- Requirements

  Redundant 1% $M^2_{\rm miss}$ resolution

  2×10^{-7} π^0 rejection

  1×10^{-5} μ^+ rejection

  Rate capability to handle 5 MHz of K^+ decays

- Detector Technology - Use proven systems to the maximum extent possible.

- Separated Beam - RF separated 22 GeV/c K^+ beam

  Same beamline as proposed by CP/T.

  K^+ / π^+ > 2 to control rates in tracking detectors

  50 MHz total rate; 30 MHz K^+ , + π^+ + daughters

  Requires $\sim 5 \times 10^{12}$ MI protons/spill [15%]

- Magnetic Spectrometers

  UMS - 50 micron pitch, double sided Silicon strips using the last bending magnet in the beamline. Fiber planes to measure time

  KEAT - 50 micron pitch, double sided Silicon strips. To control scattering in Kaon RICH gas and mirror.

  DMS - Straw tubes deadened or absent in the beam. Straws are in the decay volume vacuum. 200 MeV/c P_t kick magnet. Fiber planes to measure time and cover beam region.

- Velocity Spectrometers

    Ring center + radius measures vector velocity

    Phototube RICH counters for Kaon and Pions

    Based on experience with Selex RICH

        Low noise

        Non-Gaussian resolution tails at a very low level

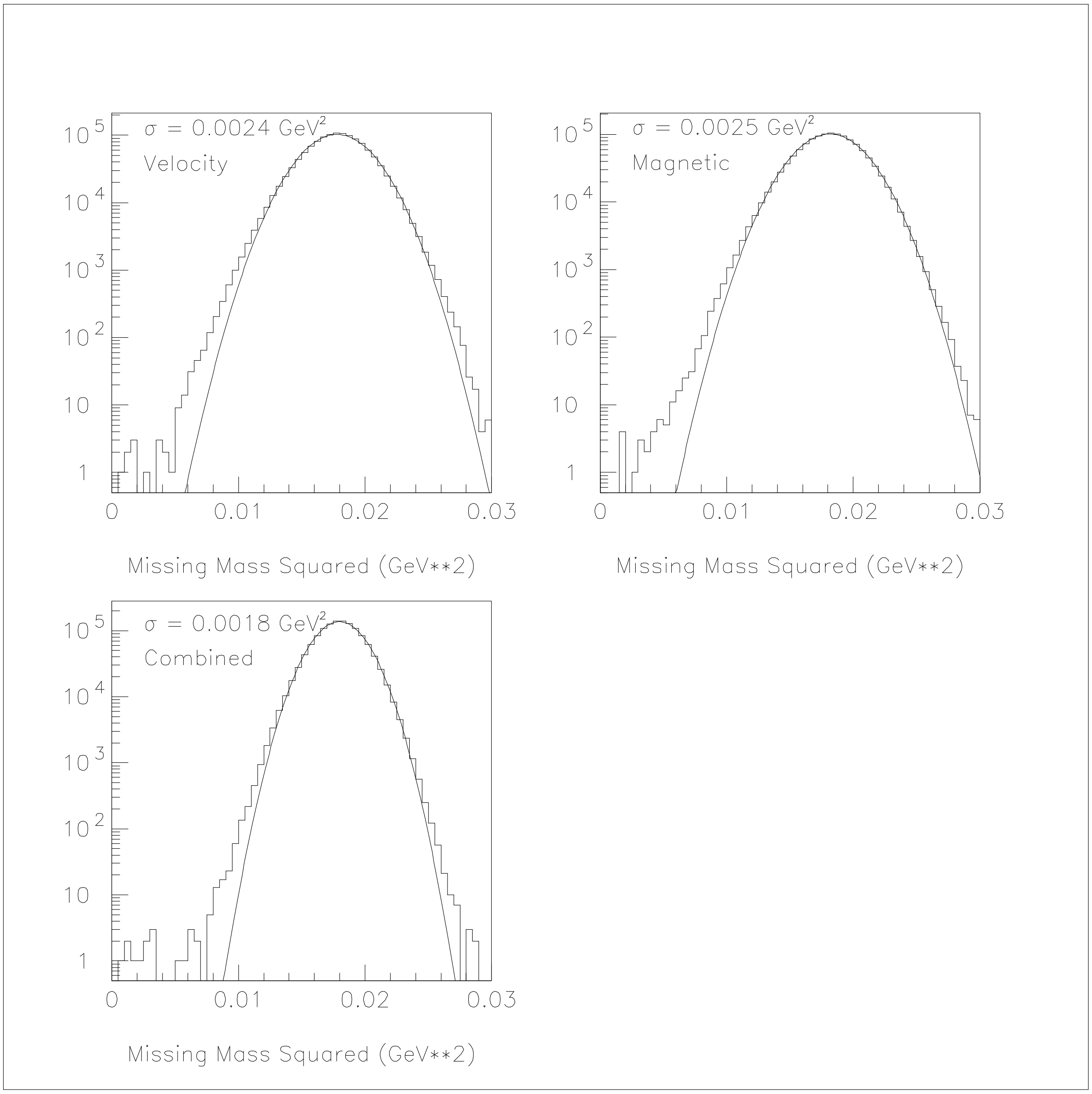
        Very high rate capability

        Time resolution to 1 nsec per PMT hit

    Kaon RICH $\Delta P/P \sim 0.5\%$

    Pion RICH $\Delta P/P \sim 1.5\%$

$K^+ \to \pi^+\pi^0$ 1×10^7 events simulated with all analysis cuts



$$M^2_{\text{miss}} = M^2_K(1 - p/p_K) + m^2(1 - p_K/p) - pp_K\theta^2 \qquad (11)$$

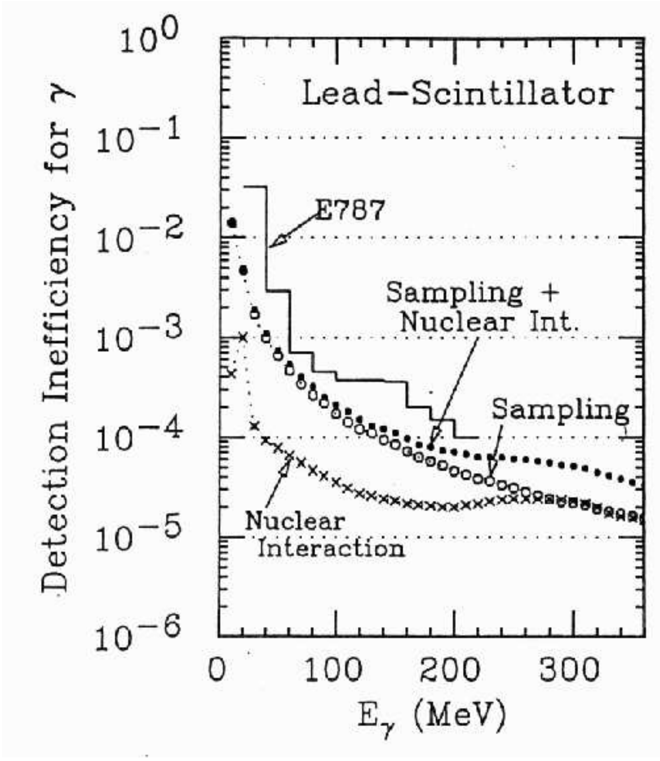


Figure 20: Measured photon detection inefficiency as a function of energy in lead-scintillator detectors

- Beam Interaction Veto
- Photon Veto Systems

  Three sub-systems; Vacuum, Forward and Hole vetos

  Must be Fast, hermetic and Rad-hard

  Requirements as achieved by BNL787. Above 1 GeV/c we need 3x better than BNL787 achieved.

  KAMI requires $\sim$ 30x lower inefficiency than CKM. These detector systems are a joint development with KAMI. (INS test)

  VVS Fine sampling Pb Scint after KTeV/KAMI

Energy Low-High (GeV)	(VVS) Inefficiency	(FVS) Inefficiency	(HVS) Inefficiency
0.0 - 0.02	4×10^{-1}	1	1
0.02 - 0.04	3×10^{-2}	5×10^{-1}	1
0.04 - 0.06	3×10^{-3}	5×10^{-2}	1
0.06 - 0.10	7×10^{-4}	5×10^{-3}	1
0.10 - 0.20	4×10^{-4}	2×10^{-3}	2×10^{-2}
0.20 - 0.40	1×10^{-4}	5×10^{-4}	5×10^{-3}
0.40 - 1.00	1×10^{-4}	2×10^{-4}	2×10^{-3}
1.00 - 3.00	3×10^{-5}	1×10^{-4}	2×10^{-3}
3.00 - 10.0	3×10^{-5}	3×10^{-5}	2×10^{-3}

Table 4: Required inefficiency performance of the CKM photon veto systems.

FVS

Reasonable calorimetry required to study backgrounds.

$\sigma_E/\mathrm{E} \sim (7-10)\%/\sqrt{E} + 2\%$

SHASLIK and SPACAL are both candidate technologies

- Muon Veto System

Reject μ^+ NOT identify π^+ .

Segmented range stack

Simulation with an algorithm based on shower length achieves a muon efficiency of less than 1×10^{-5} for a pion acceptance of 95%.

- Trigger and Data Acquisition Systems

$$\mathrm{Level}-1 = \mathrm{KRICH}(K^+\ )*\overline{\mathrm{KRICH}(\pi^+)}*\mathrm{PRICH}(\pi^+)*\overline{\mathrm{VVS}(\,1\,\mathrm{GeV})}*\overline{\mathrm{MVS}}$$

Trigger Source	Definition
$KRICH(K^+\ )$	At least six hit PMTs in the kaon RICH.
$KRICH(\pi^+)$	At least six hit pion arm PMTs of the kaon RICH.
$PRICH(\pi^+)$	At least eight hit PMTs in the pion RICH.
$VVS(\,1\,\mathrm{GeV})$	At least 1 GeV in the Vacuum Veto System.
MVS	At least one hit in the Muon Veto System. (Estimate of total $K_{\mu 2}$ and halo.)

Table 15: Level-1 trigger sources.

$K^+ \rightarrow \pi^+\pi^0$	155 kHz
$K^+ \rightarrow \pi^0 e^+\nu$	64 kHz
$K^+ \rightarrow \pi^+\pi^+\pi^-$	1 kHz
Total	220 kHz

Table 16: Level-1 trigger rates.

	CKM Requirement	KTeV Nominal	KTeV Maximum	SELEX Maximum
Spill length/Duty-factor:	1 sec/30%	20 sec/30%	20 sec/30%	20 sec/30%
Event rate to DPM:	200 kHz	10 kHz	24 kHz	5 kHz
Event size in DPM:	$\sim 1kB$	$7kB$	$64kB$	$6kB$
Data rate into DPM:	200 Mb/sec	70 Mb/sec	160 Mb/sec	30 Mb/sec
Level-3 recon. rate:	60 kHz	2 kHz	16 kHz	2 kHz
Level-3 rate to tape:	$\sim$ 1 kHz	300 Hz	4 kHz	0.2 kHz

Table 17: Comparison of estimated CKM data acquisition requirements and what has been achieved by KTeV and SELEX.

Loss Mechanism	Inefficiency
Trigger deadtime:	15%
MVS π/μ separation cuts:	5%
UMS/DMS tracking:	5%
Accidental losses at analysis:	5% $\rightarrow$ 9%
Double K^+ ambiguity in kRICH:	5%
Total miscellaneous inefficiency:	30% $\rightarrow$ 34%

Table 19: Miscellaneous inefficiency table.

Background Simulation

CKM Monte Carlo

- Beam K^+ generated according to Doornbos distributions
- Detailed simulations of RICH detectors
- Simple p_T kicks for magnets and gaussian resolutions for trackers
- Full Coulomb (multiple, plural, single) scattering and elastic hadronic scattering
- Particles tracked from beam RICH to Forward Veto, with π decay
- Photons tracked to matter and assigned energy/position dependent weights
- FRITIOF used as generator of inelastic hadronic interactions
- GEANT used to address some specific questions
- Cuts developed to preserve signal and reject background

Background Sources

- Kaon Decays
  - $K^+ \to \pi^+\pi^0$ is the major concern
  - $K^+ \to \mu^+\nu_\mu$ and $K^+ \to \mu^+\nu_\mu\gamma$ highly suppressed by RICH and μ-veto
  - Other modes ($K^+ \to \pi^+\gamma\gamma$, $K^+ \to \pi^+e^+e^-$, $K^+ \to e^+\nu\gamma$), with small BR's and powerful veto signatures believed small w.r.t. $K_{\pi 2}$
- Inelastic Interactions
  - Interactions producing a K_L followed by $K_L \to \pi^+e^-\nu$
  - Interactions in tracker producing a fast π^+
  - Interactions in residual gas
- Accidentals (induced by more than one beam particle)

Background Source	Effective BR ($\times 10^{-12}$)
$K^+ \to \mu^+ \nu_\mu$	< 0.04
$K^+ \to \pi^+ \pi^0$	3.7
$K^+ \to \mu^+ \nu_\mu \gamma$	< 0.09
$K^+ A \to K_L X$ followed by $K_L \to \pi^+ e^- \nu$	< 0.14
$K^+ A \to \pi^+ X$ in trackers	<4.0
$K^+ A \to \pi^+ X$ in residual gas (10^{-6} torr)	< 2.1
Accidentals (2 K^+ decays)	0.51
Total	< 10.6

Table 20: Background estimates in terms of effective branching ratio.

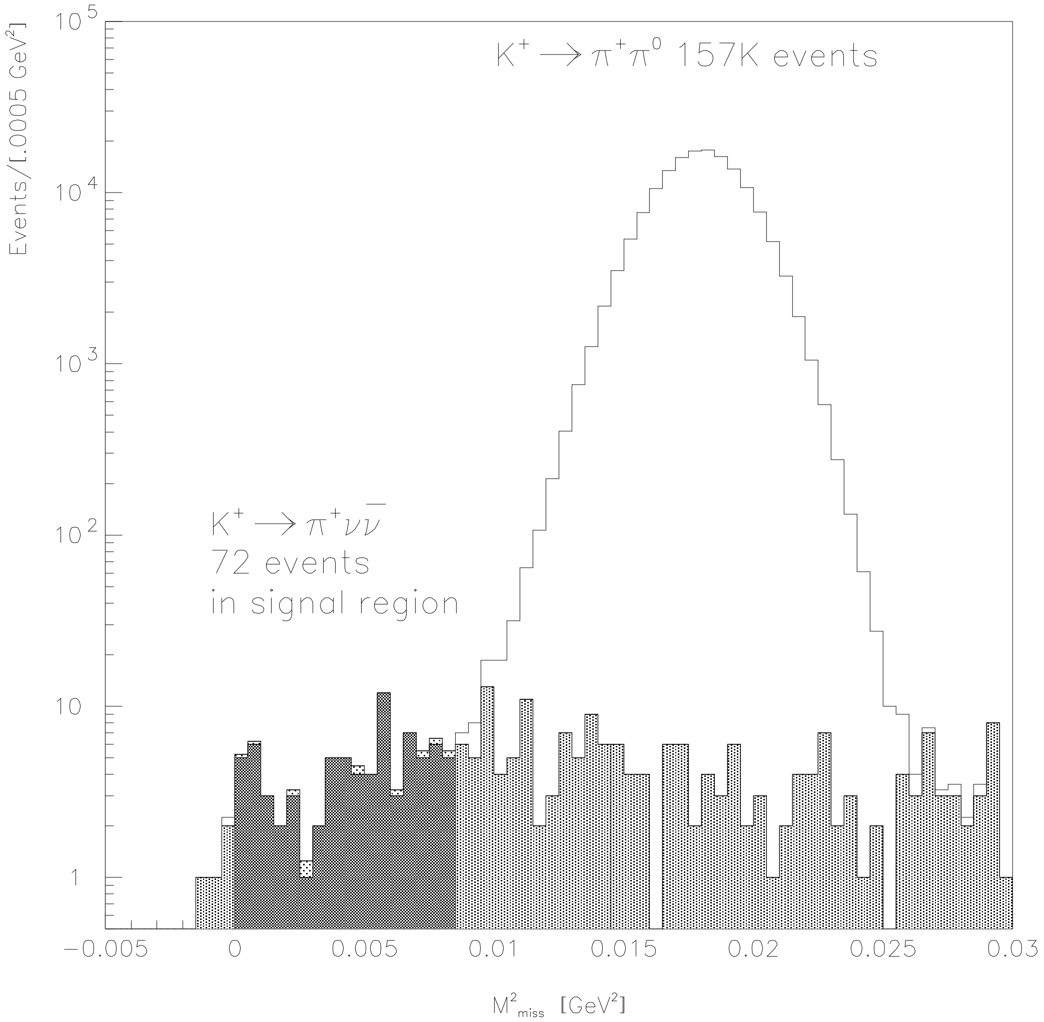


Figure 30: Missing mass squared (M^2_{combined}) for $K^+ \rightarrow \pi^+\pi^0$ events passing all cuts superimposed on the signal (light shading). The sensitivity shown in this plot corresponds to the experimental sensitivity of 72 $K^+ \rightarrow \pi^+\nu\overline{\nu}$ events in our mass window (single event sensitivity of 1.4×10^{-12}) which are indicated with the dark shading.

Summary of Detector Cost Estimates

Summary of Detector Cost Estimates	
Detector System	Sub-cost.
BTS System	\$335K
UMS System	\$170K
Kaon RICH	\$359K
KEAT System	\$80K
BIV System	\$228K
VVS System	\$2720K
DMS System	\$2100K
Pion RICH	\$1525K
FVS System	\$980K
MVS System	\$475K
CVP System	\$315K
HVS System	\$70K
Trigger System	\$300K
DAQ System	\$700K
Total	\$10357K
Separated Beam	\$4000K

Table 33: Cost estimate of the CKM detector systems.

Schedule

First stage (physics) approval

Second stage (technical and budgetary) approval — 1.5 year

Experiment construction — 2 years

Engineering run — 0.5 years

Data taking — 2 years

Analysis and publication — 1.5 years

Conclusions

- Present design with 2 year of data taking

    72 signal events from region 1

    $<$7.6 background events from region 1

    Region 2 sensitivity and backgrounds unevaluated

- Three goals set out in EOI are achieved

    1. Observe $\sim$100 events in 2 years of running

    2. Reduce all background to the few event level

    3. Limit capital costs to 10M$

- Good start on building a sufficient collaboration
- We are Seeking Scientific Approval to:

    Allow timely physics results wrt other pre-LHC experiments

    Generate both lab and outside resources for a full design

        Pre-engineering

        Small prototype testing

        Test beam studies as required

    Strengthen the collaboration

- Next Questions

    How clean and pure can we get the beam?

    What about Region 2 sensitivity and backgrounds?

    Can we demonstrate the photon veto requirements?

    How are we going to make 9000 straws work in a vacuum?

    Can we maintain our sensitivity with a more realistic simulation and analysis?

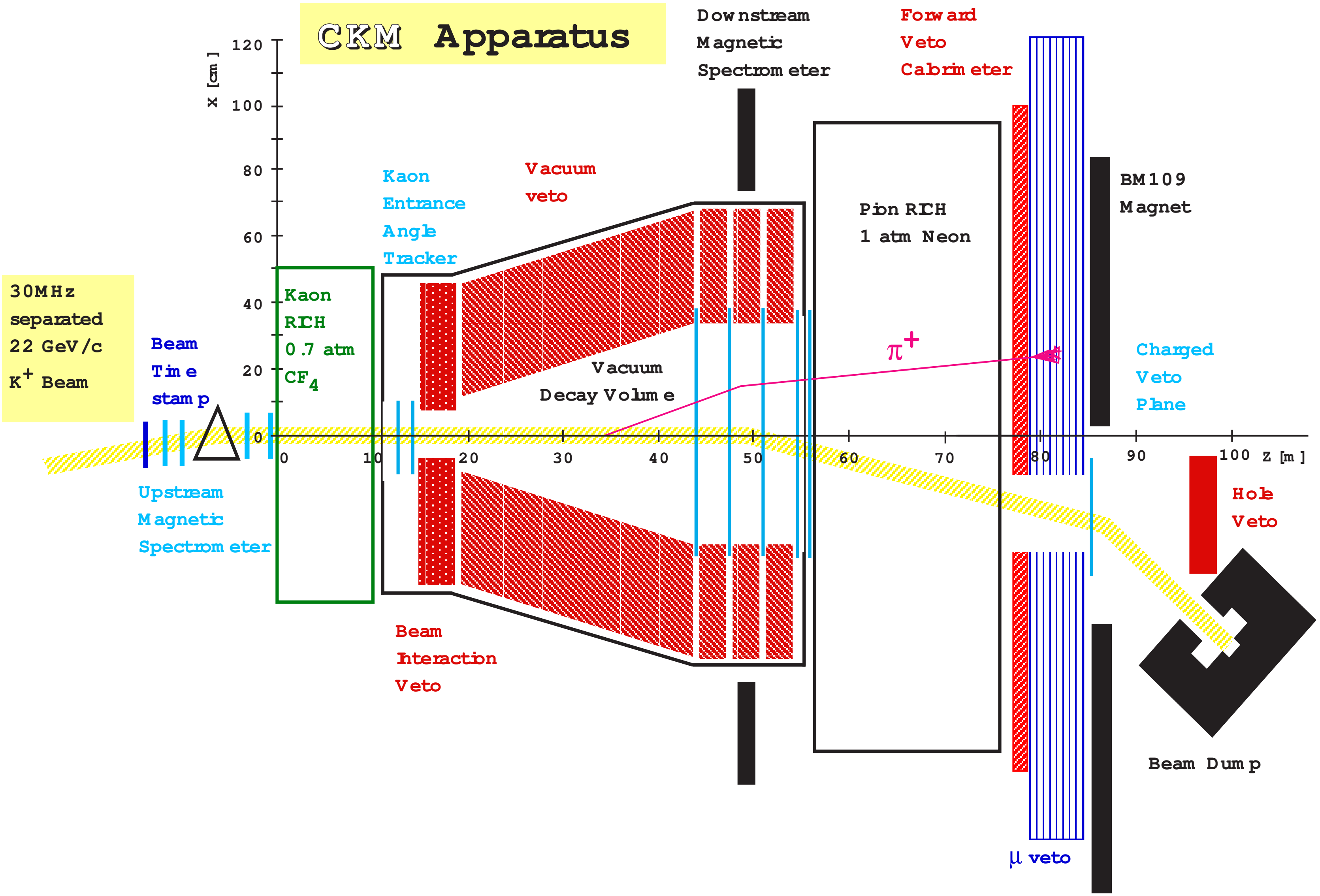


Figure 10: The CKM Detector.