Determination of CKM Matrix elements with Rare Kaon Decays

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Jürgen Engelfried[1] (IF-UASLP)

Outline:

- Weak Interaction and CKM Matrix
- Measuring V_{td} with $K^+ \to \pi^+ \nu\bar{\nu}$
- Other measurements with rare decays
- Conclusion

[1]jurgen@ifisica.uaslp.mx, http://www.ifisica.uaslp.mx/~ jurgen

Important in Particle Physics:

- Parity

$$\mathcal{P}\Psi(\vec{r}) \rightarrow \Psi(-\vec{r})$$

  Strong and Electromagnetic Interaction conserve Parity

  Weak Interaction violates Parity (1957)

- Charge Conjugate $\mathcal{C}$
  - exchange sign of electric charge and magn. moment
  - exchange particle with antiparticle
- Time Reversal $\mathcal{T}$

Until 1964: All Interaction are invariant under $\mathcal{CP}$

$$\begin{array}{llll} K_L^0 \rightarrow \pi^0\pi^0\pi^0 & (21\%) & \mathcal{CP} = +1 & \\ \rightarrow \pi^+\pi^-\pi^0 & (13\%) & \mathcal{CP} = +1 & \\ \rightarrow \pi^+\pi^- & (0.2\%) & \mathcal{CP} = -1 & \mathcal{CP} \text{ Violation!!!} \end{array}$$

Weak Interaction

$\approx$ 1960 weak decay of strange particles

Why "strange"?

- produced abondandly
- long living

Explanation:

- produced in pairs by Strong Interaction
- decay by Weak Interaction suppressed
  eigenstates to Strong Interaction are mass **NOT** eigenstates to Weak Interaction

$\longrightarrow$ Cabbibo theory (1963)

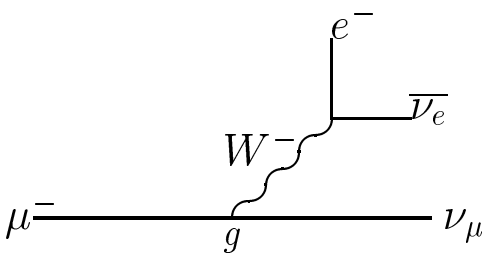
2×2 rotation matrix for quarks (not! for leptons)

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

$$\cos\theta_c = V_{ud}$$

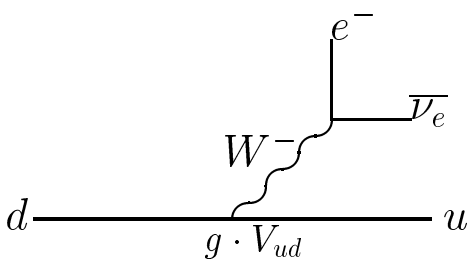
Examples for Weak Decays

$\mu^- \to e^- + \overline{\nu_e} + \nu_\mu$



beta decay: $n \to p + e^- + \overline{\nu_e}$.

On quark level: $d \to u + e^- + \overline{\nu_e}$



Some more History

$\approx$ **1970:** Are there more quarks? (most people: NO!)
If yes, how to change Cabbibo theory?

1972: Kobayashi and Maskawa: If there are 6 quark, we can describe CP Violation (3×3 matrix)

1973: "September Revolution" charm quark discovered (Brookhaven, SLAC)

1976: b quark (Fermilab)

1994: t quark (Fermilab)

Cabibbo-Kobayashi-Maskawa (CKM) Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Theory (Standard Model): Matrix is unitary and hermitian.

$$|V| = \begin{pmatrix} 0.9745 - 0.9760 & 0.217 - 0.224 & 0.0018 - 0.0045 \\ 0.217 - 0.224 & 0.9737 - 0.9753 & 0.036 - 0.042 \\ 0.004 - 0.013 & 0.035 - 0.042 & 0.9991 - 0.9994 \end{pmatrix}$$

Wolfenstein parameterization:

$$V = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Wolfenstein parameterization:

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$$\bar{\rho} = \frac{\rho}{A\lambda^3}$$
$$\bar{\eta} = \frac{\eta}{A\lambda^3}$$

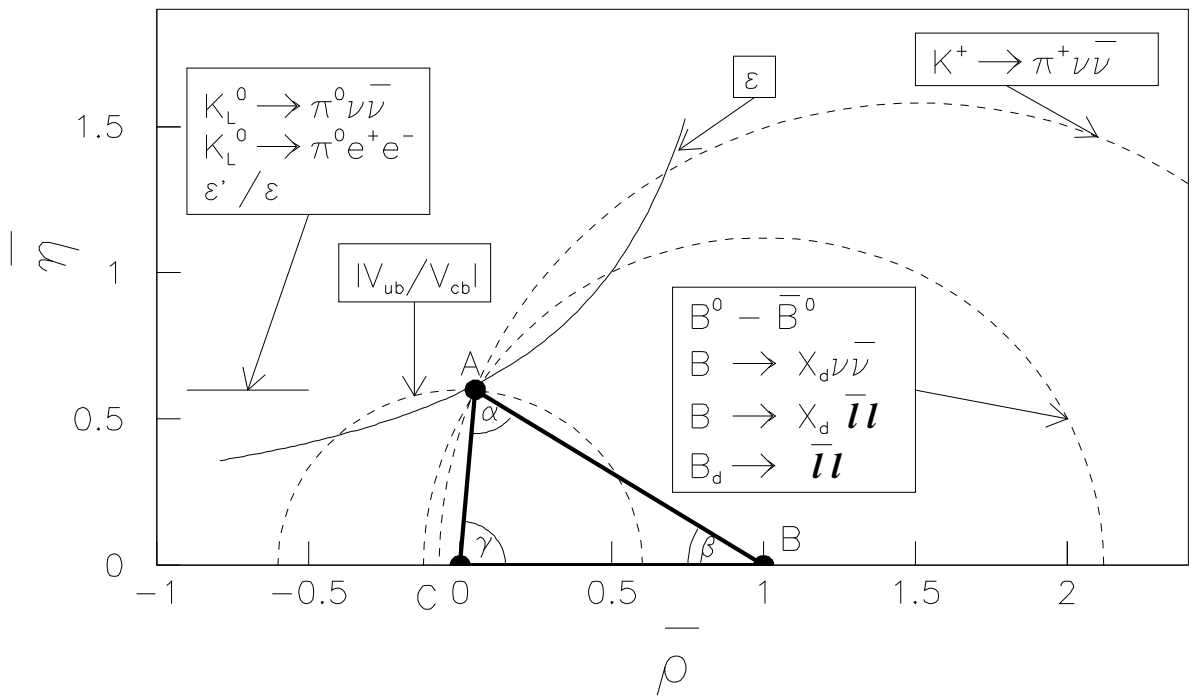


Figure 1: The ideal Unitarity Triangle. For illustrative reasons the value of $\bar{\eta}$ has been chosen to be higher than the fitted central value

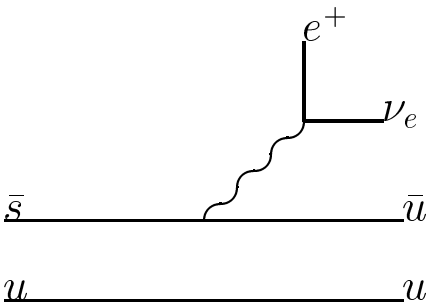
Quantitative Access to CKM parameters

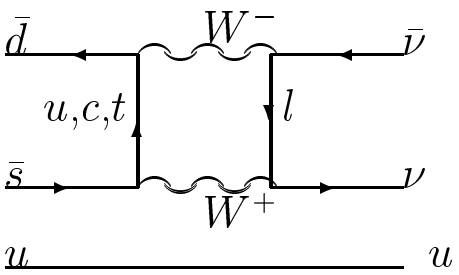
- Goal is to test the Standard Model hypothesis that a single phase in the CKM matrix is the sole source of CP violation.
- This means *over-constraining* the prediction, and testing for consistency. Paraphrasing Wolfenstein: "...I invented the parameters ρ and η, and I don't care what the values are so why should you?? The substance here is to *over-constrain* the model and test for consistency..."[2]
- To falsify the Standard Model hypothesis the only foreseeable results with controlled errors are:
  - B physics: $B^0_d \to \Psi K_s$, and perhaps x_x/x_d mixing.
  - K physics: $K^+ \to \pi^+ \nu\bar{\nu}$ and $K^0 \to \pi^0 \nu\bar{\nu}$.

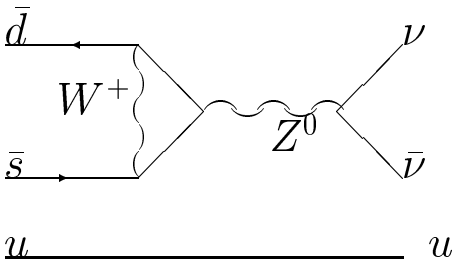
[2] Wolfenstein at Kaon'99

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

Calculated[3] by weak isospin rotation from $K^+ \to \pi^0 e^+ \nu$







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

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

$$X_j = \{\frac{m_j}{m_W}\}^2; \quad j = c, t.$$

$$\begin{aligned} Br[K^+ \to \pi^+ \nu\bar{\nu}] &= [0.44 \pm 0.15] \times 10^{-10} [(1.4 - \bar{\rho})^2 + \bar{\eta}^2] \\ &= (0.9 \pm 0.3) \times 10^{-10} \end{aligned}$$

[3] T. Inami and C.S. Lim, Progress of Theoretical Physics **65** (1981) 297-314

Total theoretical uncertainty of 8 % estimated by Buras, et al.[4]

Dominated by uncertainty in charmed quark mass.

Structure of K^+ is put in with measured $K^+ \to \pi^0 e^+ \nu$ branching ratio.

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

$\Longrightarrow$ We can measure V_{td} to 10 % if we can measure $Br[K^+ \to \pi^+ \nu\bar{\nu}]$ to 10 % (100 Events).

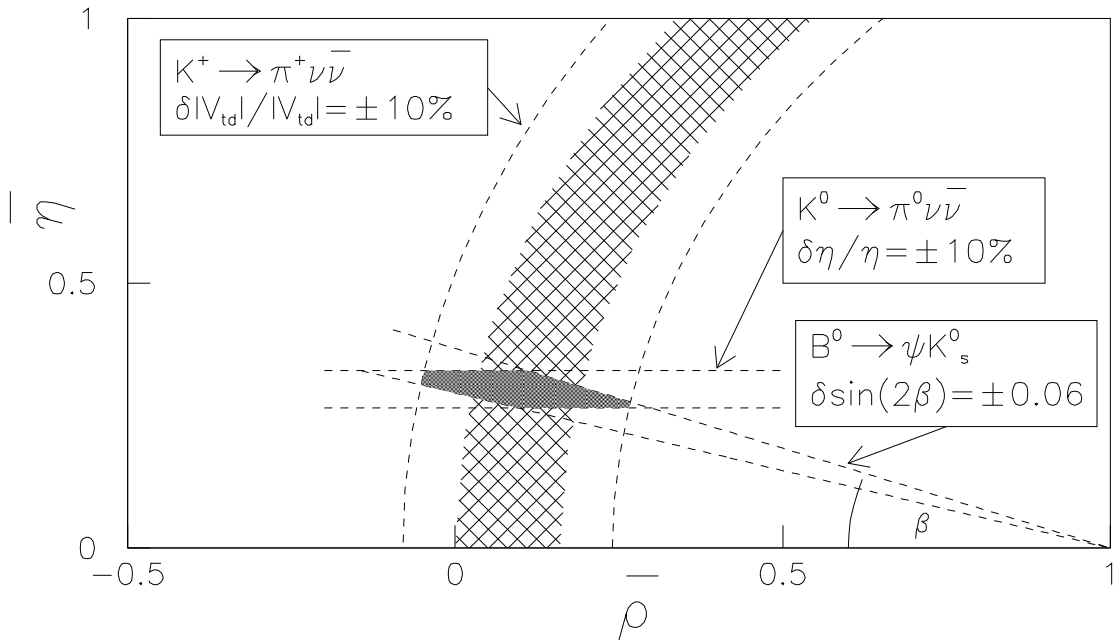


Figure 2: A possible outcome from measurements of $K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$ and $B^0 \to \psi K_s^0$. The hashed annulus indicates the statistical precision of a 100 event measurement, and the total band indicates the combined statistical and theoretical errors.

[4] A.J. Buras, hep-ph/971217

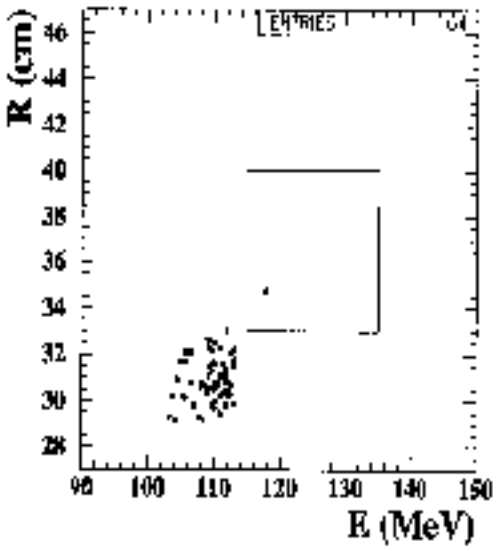
Brookhaven Experiment 787

- Stopped Kaon experiment.
- Have seen one event after several years of running.
- Have new experiment approved (E949), will run in 2001-2003
- Hope to see about 10 events
- Fermilab part of our experiment joint E949,
  and Brookhaven part joint us.

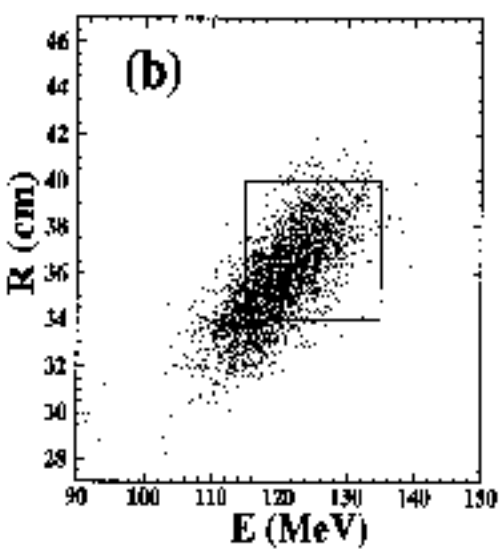
$K^+ \to \pi^+ \nu\bar{\nu}$ Event

- Background level = 0.07 events.

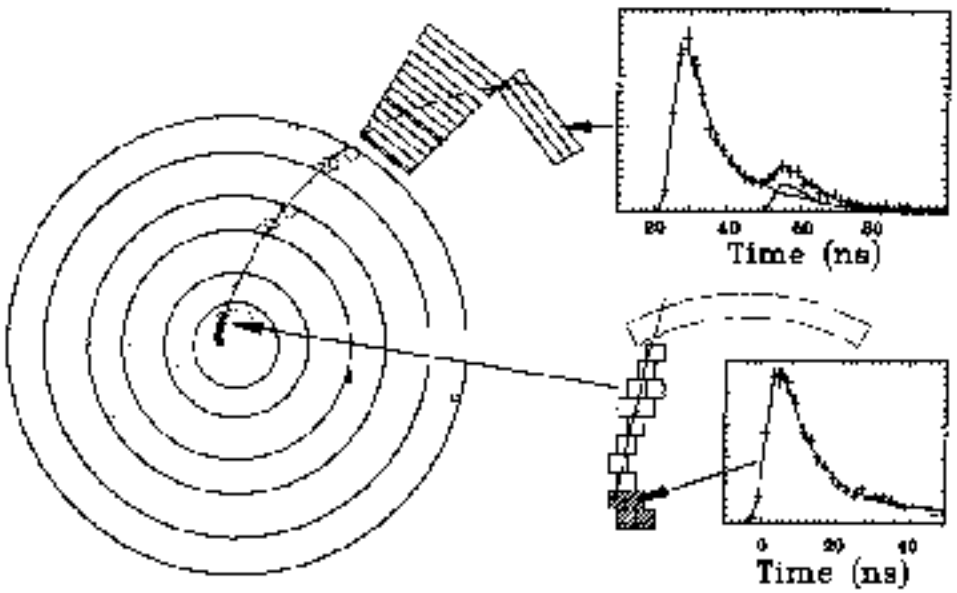
1995–97 Data



Monte Carlo



Event Display



- $\mathbf{BR}(K^+ \to \pi^+ \nu\bar{\nu}\ ) = 4.2^{+9.7}_{-3.5} \times 10^{-10}$ (PRL **79**)
- $\mathbf{BR} = 4.2/(2-3) \times 10^{-10}$ (1995–97)

A short estimate for an inflight decay experiment

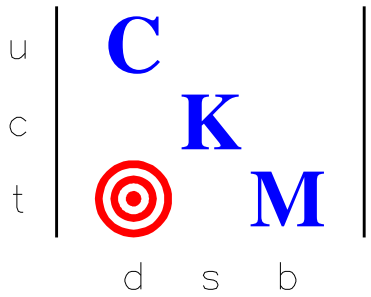
- $BR = 10^{-10}$
- 100 Events
- Acceptance 1 %

$\Longrightarrow 10^{14}$ live K^+

- Duty cycle of machine 30 % (Fermilab MI)
- Lifetime of machine and experiment 50 %
- 2 years of running time

$\Longrightarrow$ 30 MHz of K^+

In addition: Only a few background events
$\Longrightarrow$ Suppress background to 10^{-12}



Charged Kaons at the Main Injector

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

J. Frunk, S. Kettell, D. Strand
Brookhaven National Laboratory, Upton, NJ, USA

L. Belantoni, R. Coleman, P.S. Cooper[5], M. Crisler, C. Milstene[6], H. Nguyen, E. Ramberg, R.S. Tschirhart
Fermi National Accelerator Laboratory, Batavia, IL, USA

A. Kozhevnikov, 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 Física, Universidad Autónoma de San Luis Potosí, México

K. Lang, J.L. Ritchie[5]
University of Texas at Austin, Austin

E.C. Dukes, K. Nelson
University of Virginia

[5]Cospokesmen
[6]Resident at Fermilab, on leave from Tel Aviv University.

RF Separated Beam

- Main Injector Beam 120 GeV
- Put on a target, select 22 GeV
- Run two RF stations (same frequency, fixed phase)
- Tune phase shift so that Kaons get two opposite transverse kicks, and pions will get only one (or two in same direction).
- Put proper collimators
- Final beam contains mostly Kaons

- Problem: 1 sec spill from MI is "DC"
- $\Longrightarrow$ Superconducting RF
- We will use 3.9 GHz
- Project[7] approved (and funded!) at Fermilab to gain experience for TESLA

- 30 MHz K^+, 20 MHz others (mostly π^+)
- debunched, 22 GeV $\pm$ 1 %
- divergence $\approx 100\,\mu$rad
- Muon rate $\approx$ 30 MHz in 1 m $\times$ 1 m

[7] Fermilab TM-2060

Experimental Method

BIGGEST PROBLEM IS BACKGROUND

- Only measurable: K^+, π^+
- Biggest backgrounds: $K^+ \to \mu^+\nu$ (64 %) and $K^+ \to \pi^+\pi^0$ (21 %)

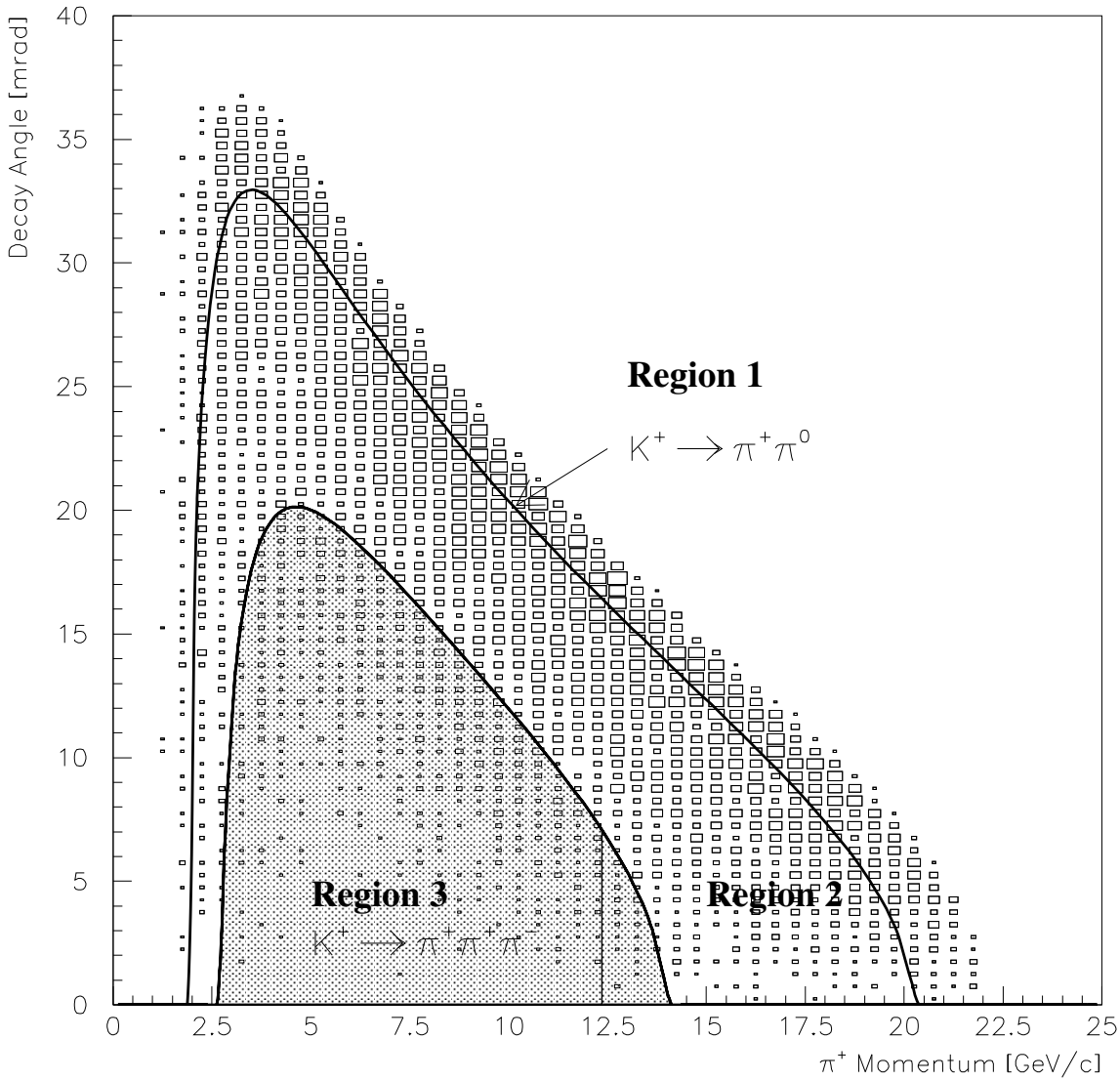
Calculate "Missing Mass"

$$M^2_{miss} = M^2_K(1 - p_\pi/p_K) + m^2_\pi(1 - p_K/p_\pi) - p_\pi p_K \theta^2$$

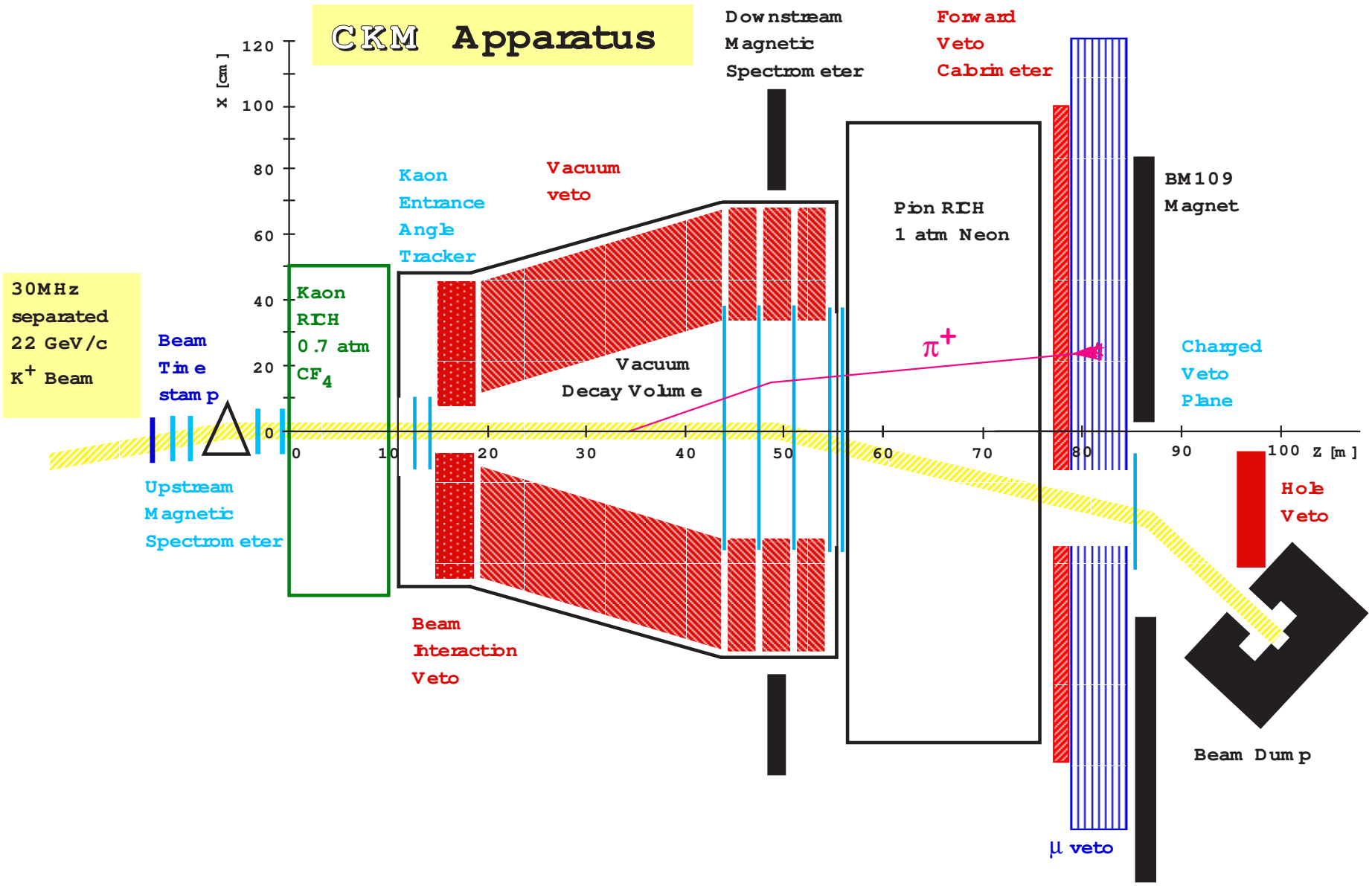
For 2-body decays, M_{miss} is fixed value. For signal, M_{miss} has distribution.

- Reduce all material to minimum
- Make redundant measurements

Decay angles and Backgrounds



Region	K-decay Backgrounds	Branching Ratio	Minimum $M_{\rm miss}$ (MeV)	Rejection Methods
1	$K^+ \to \mu^+\nu$	0.635	0	2-body kinematics, μ-veto
	$K^+ \to \pi^+\pi^0$	0.212	135	2-body kinematics, γ-veto
	$K^+ \to \mu^+\nu\gamma$	5.5×10^{-3}	0	μ-veto, γ-veto
2	$K^+ \to \pi^+\pi^0$	0.212	135	2-body kinematics, γ-veto
	$K^+ \to \pi^0 e^+\nu$	0.048	135	e-veto, γ-veto
	$K^+ \to \pi^0\mu^+\nu$	0.032	135	μ-veto, γ-veto
	$K^+ \to \pi^+\pi^0\pi^0$	0.017	270	γ-veto
	$K^+ \to \mu^+\nu\gamma$	5.5×10^{-3}	0	μ-veto, γ-veto
	$K^+ \to \pi^+\pi^0\gamma$	2.8×10^{-4}	135	γ-veto
3	Same as region 2, plus			
	$K^+ \to \pi^+\pi^+\pi^-$	0.056	279	charged particle veto


CKM Apparatus
Downstream
Magnetic
Spectrometer
Forward
Veto
Calrimeter
x [cm]
120
100
80
60
40
20
0
Kaon
Entrance
Angle
Tracker
Vacuum
veto
Pion RICH
1 atm Neon
BM109
Magnet
30MHz
separated
22 GeV/c
K+ Beam
Beam
Time
stamp
Kaon
RICH
0.7 atm
CF4
Vacuum
Decay Volume
π+
Charged
Veto
Plane
0
10
20
30
40
50
60
70
80
90
100 z [m]
Upstream
Magnetic
Spectrometer
Hole
Veto
Beam
Interaction
Veto
Beam Dump
μ veto

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

  Resolution - $\sigma_p/p \sim 1\,\%$, $\sigma_\theta/\theta \sim 1\,\%$, $\sigma_t \sim 1\,$nsec, are required to control the dominant backgrounds.

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

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

- 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.

Apparatus (cont.)

- Velocity Spectrometers

  Ring center and 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

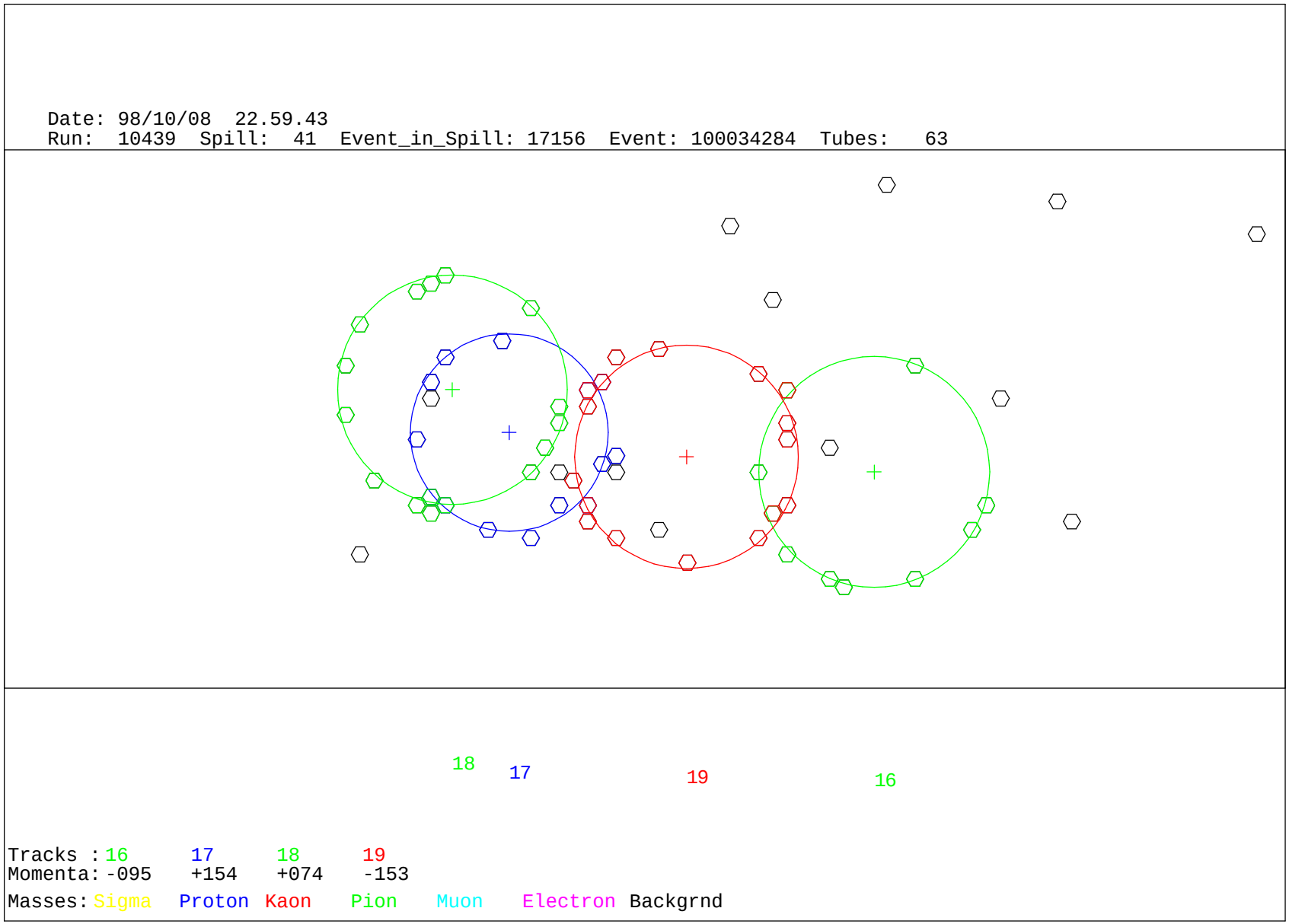
    Time resolution to 1 nsec per PMT hit

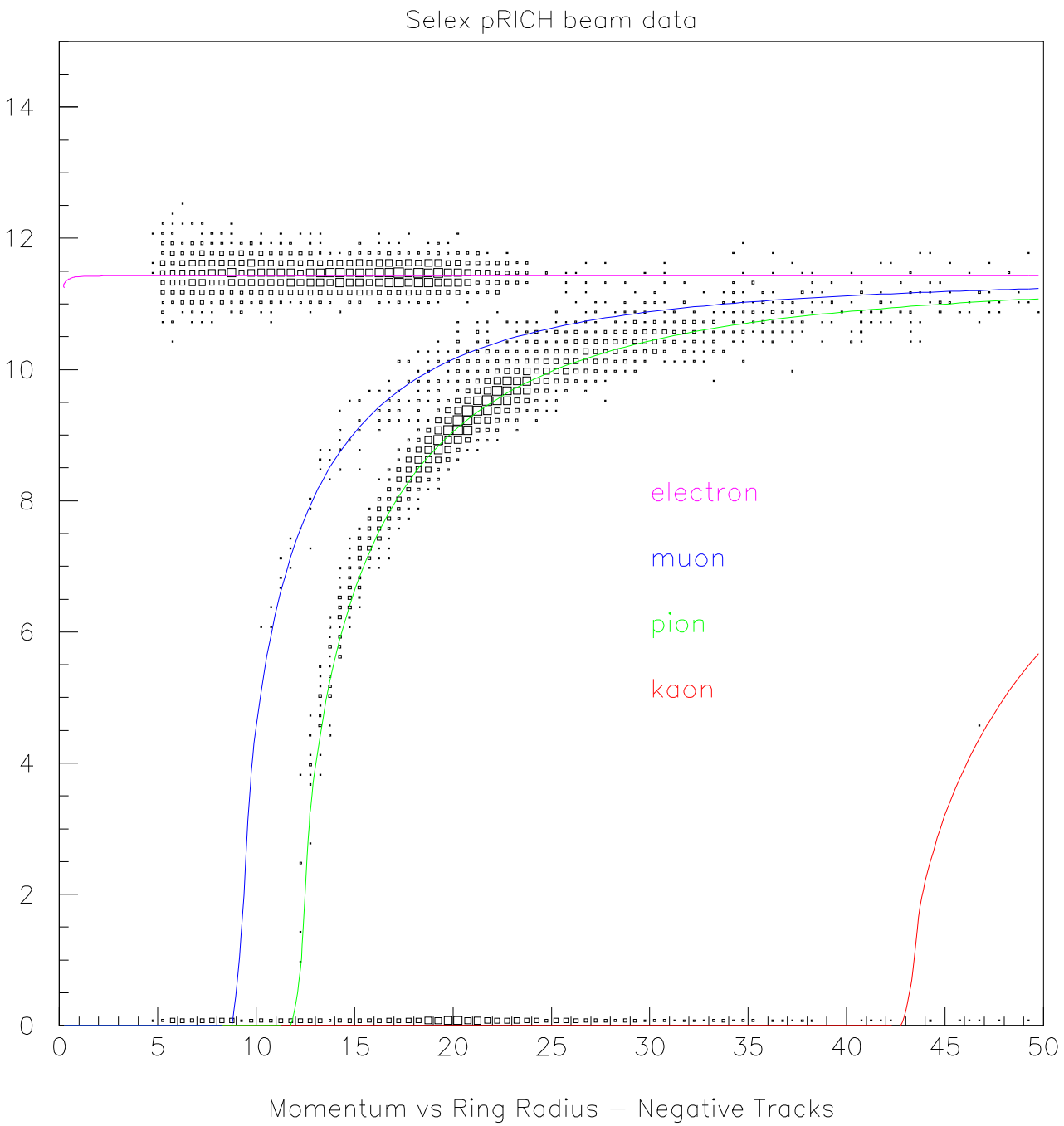
  Kaon RICH ΔP/P $\sim$0.5%

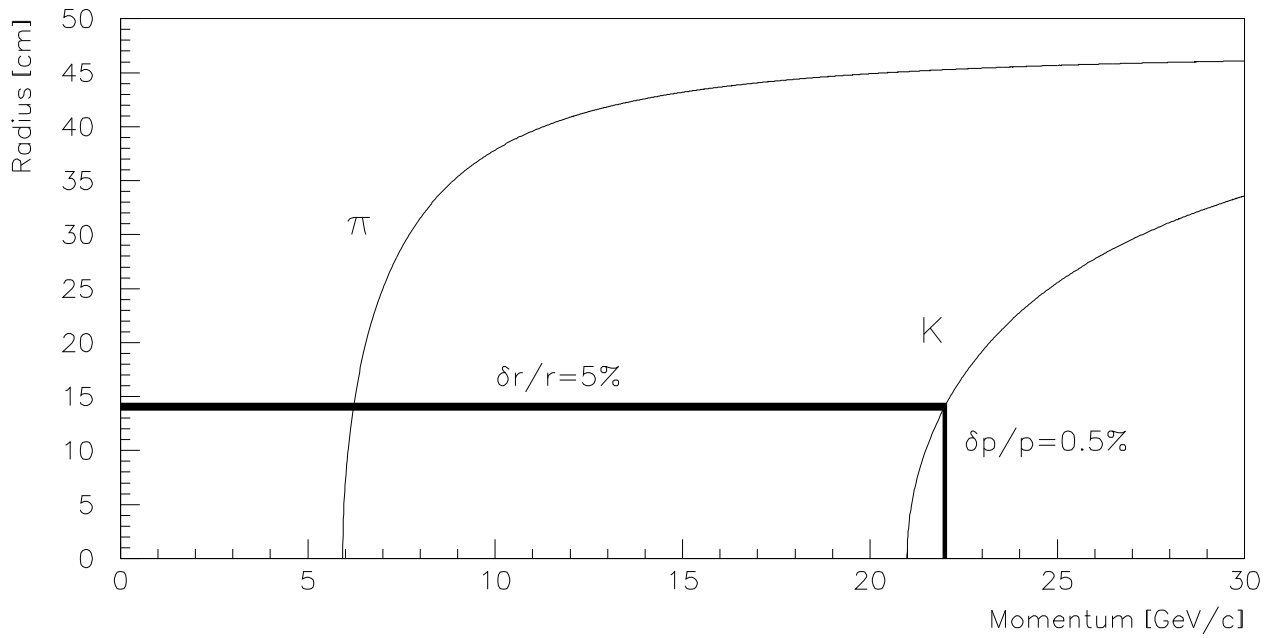
  Pion RICH ΔP/P $\sim$1.5%

Cherenkov (Franck, Tamm) equation:

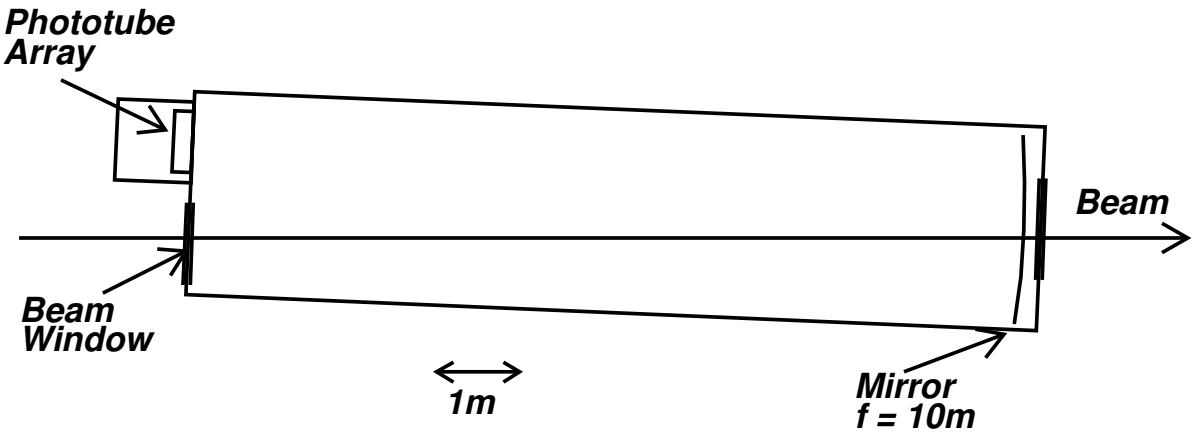
$$\cos\theta_c = \frac{1}{\beta n} \qquad \beta = \frac{v}{c}$$


Date: 98/10/08 22.59.43
Run: 10439 Spill: 41 Event_in_Spill: 17156 Event: 100034284 Tubes: 63
18
17
19
16
Tracks : 16 17 18 19
Momenta: -095 +154 +074 -153
Masses: Sigma Proton Kaon Pion Muon Electron Backgrnd

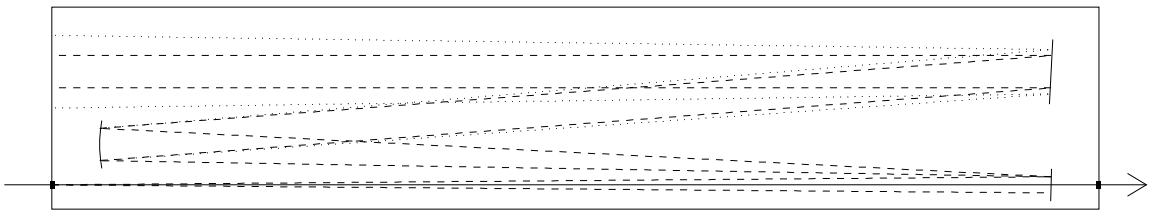

Selex pRICH beam data
14
12
10
8
6
4
2
0
0
5
10
15
20
25
30
35
40
45
50
electron
muon
pion
kaon
Momentum vs Ring Radius – Negative Tracks



Pion RICH: Like SELEX RICH, but with 20 m Vessel



Kaon RICH: 10 m Vessel, folded light path



Apparatus (cont.)

- 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.

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 1: Required inefficiency performance of the CKM photon veto systems.

VVS Fine sampling Pb Scint after KTeV/KAMI

FVS

Reasonable calorimetry required to study backgrounds.

σ_E/E $\sim (7-10)\%/\sqrt{E} + 2\%$

SHASLIK and SPACAL are both candidate technologies

Apparatus (cont.)

- 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%.

Apparatus (cont.)

- Trigger and Data Acquisition Systems

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

Trigger Source	Definition
KRICH(K^+)	At least six hit PMTs in the kaon RICH.
KRICH(π^+)	At least six hit pion arm PMTs of the kaon RICH.
PRICH(π^+)	At least eight hit PMTs in the pion RICH.
VVS(1 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 2: Level-1 trigger sources.

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

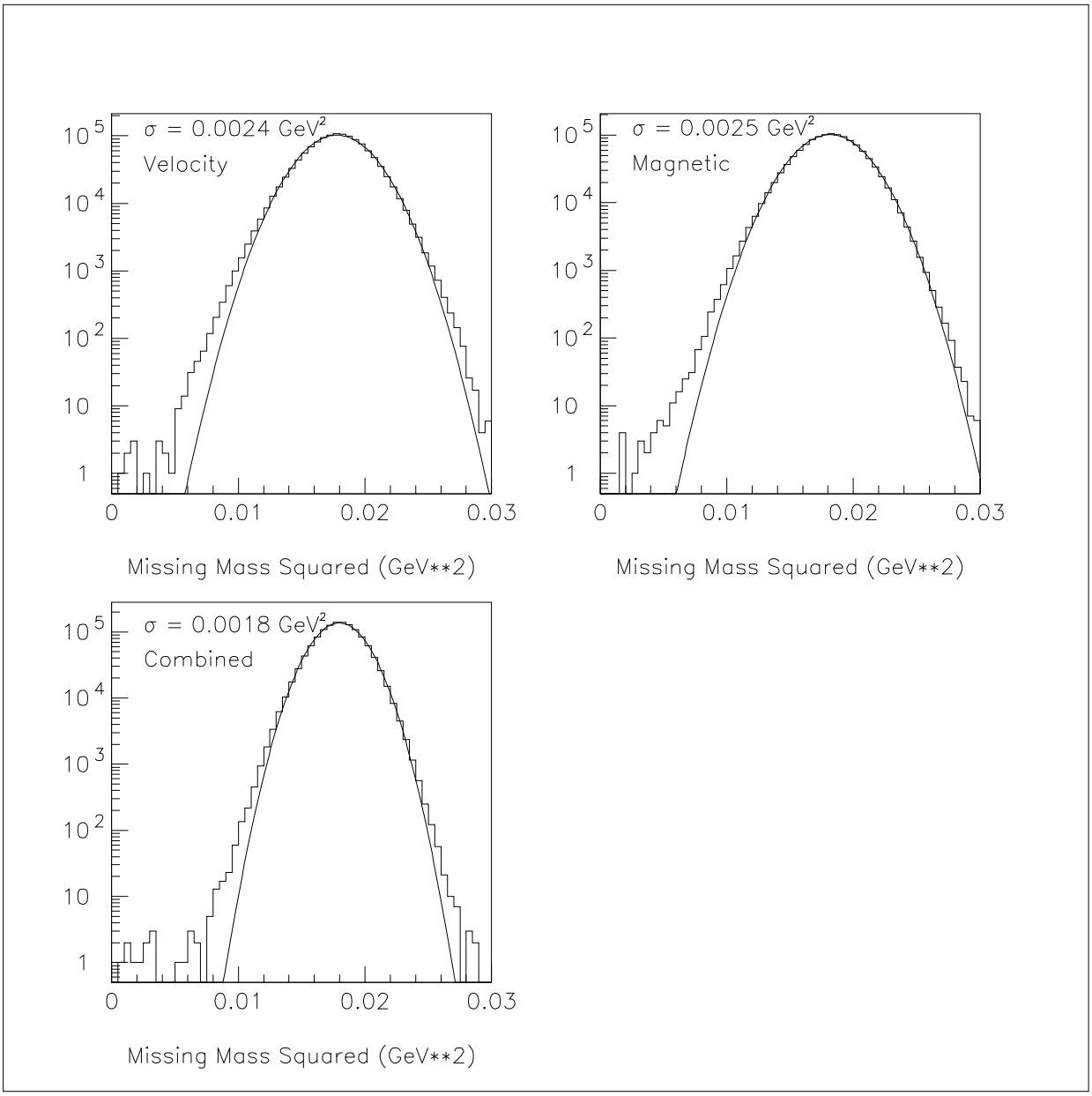
Table 3: Level-1 trigger rates.

Apparatus (cont.)

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 4: Miscellaneous inefficiency table.

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



$$M^2_{\rm miss} = M^2_K(1 - p_\pi/p_K) + m^2_\pi(1 - p_K/p_\pi) - p_\pi p_K \theta^2$$

Simulated Background sources

Background Source	Effective BR ($\times 10^{-12}$)
$K^+ \to \mu^+ \nu_\mu$	< 0.04
$K^+ \pi^+ \pi^0$	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 5: Background estimates in terms of effective branching ratio.

The Final Signal Plot

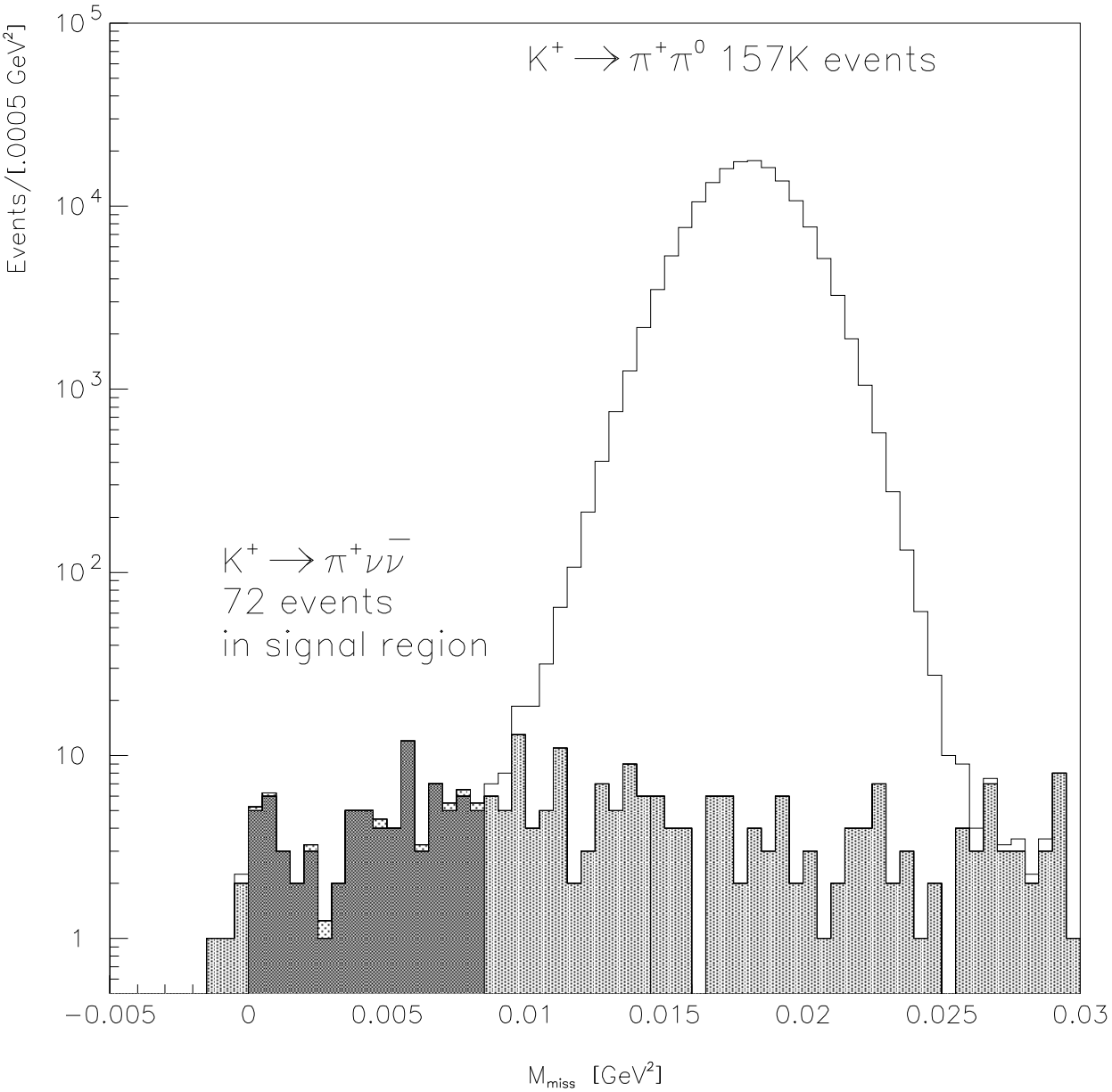


Figure 3: Missing mass squared (M^2_{combined}) for $K^+ \to \pi^+\pi^0$ events passing all cuts superimposed on the signal (light shading). The sensitivity shown in this plot corresponds to the experimental sensitivity of 72 $K^+ \to \pi^+\nu\bar{\nu}$ events in our mass window (single event sensitivity of 1.4×10^{-12}) which are indicated with the dark shading.

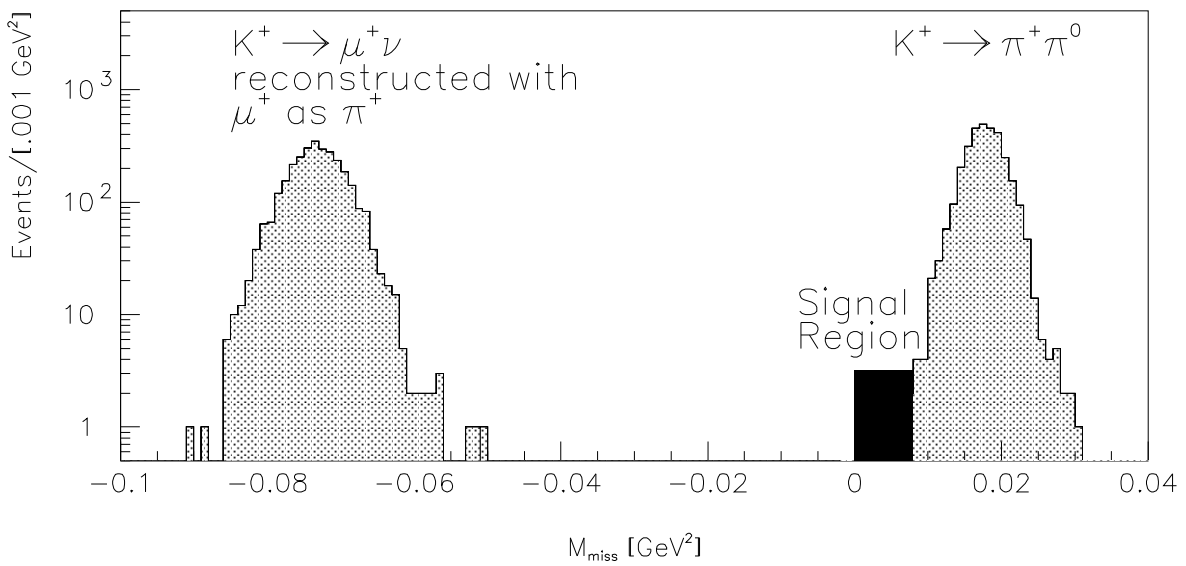


Figure 4: Missing mass of $K^{\pm} \to \mu^{\pm}\nu_{\mu}$ decays where the muon is reconstructed under the pion mass hypothesis.

Other possible measurements

10^{-12} in single event sensitivity is a long way.
There are a lot of interesting modes to be picked up.
This list is NOT finished, and is open to more suggestions.

These are just a few examples we where thinking of:

- $K^+ \to \mu^+\nu_\mu\gamma$ Form Factor: Test of Chiral Perturbation Theory
- $K^+ \to \pi^+e^+e^-$, $K^+ \to \pi^+\mu^+\mu^-$, Form Factor and Branching Ratio: Test of Chiral Perturbation Theory
- $K^\pm \to \pi^\pm\pi^+\pi^-$, $K^\pm \to \pi^\pm\pi^0\pi^0$, $K^\pm \to \pi^\pm\pi^0\gamma$, $K^\pm \to \pi^\pm\gamma\gamma$: Test of Chiral Perturbation Theory, Search for Direct CP Violation in $K^\pm$ decays.
- $K^+ \to \pi^0e^+\nu$, $K^+ \to \pi^0\mu^+\nu$ Branching Ratio: Measurement of V_{us}

Work in San Luis Potosí

- Design work on Kaon and Pion RICH
- Monte Carlo studies
- Construction of flat, thin mirror for Kaon RICH
- Tests and Classifications of Photomultipliers
- (Maybe:) Supervision of spherical mirror production (in Mexico?)

Schedule

April 1996: Expression of Interest (EOI)

April 1998: Proposal submitted

October 1998: Approved as an Fermilab R&D project

October 1999: R&D project financed

April 2001: Submission of Technical Proposal

2003-2005: Running

2005-2007: Data analysis and publications.

Conclusion

$K^+ \to \pi^+ \nu\bar{\nu}$ provides theoretically clean measurement of V_{td} to test $\mathcal{CP}$ Violation description in Standard Model.

CKM experiment at Fermilab will measure ≈ 100 events

UASLP is involved in detector R&D for this experiment

More information at
`http://www.fnal.gov/projects/ckm/Welcome.html`