The CKM Experiment: Using Rare Kaon Decays to determine CKM Matrix Elements

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Outline:

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

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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 $\mathcal{CP}$

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

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)

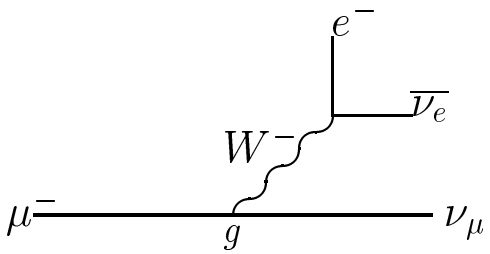
2×2 rotation matrix for quarks (not! for leptons)

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

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

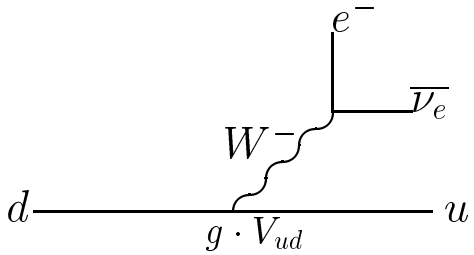
Examples for Weak Decays

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



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.

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

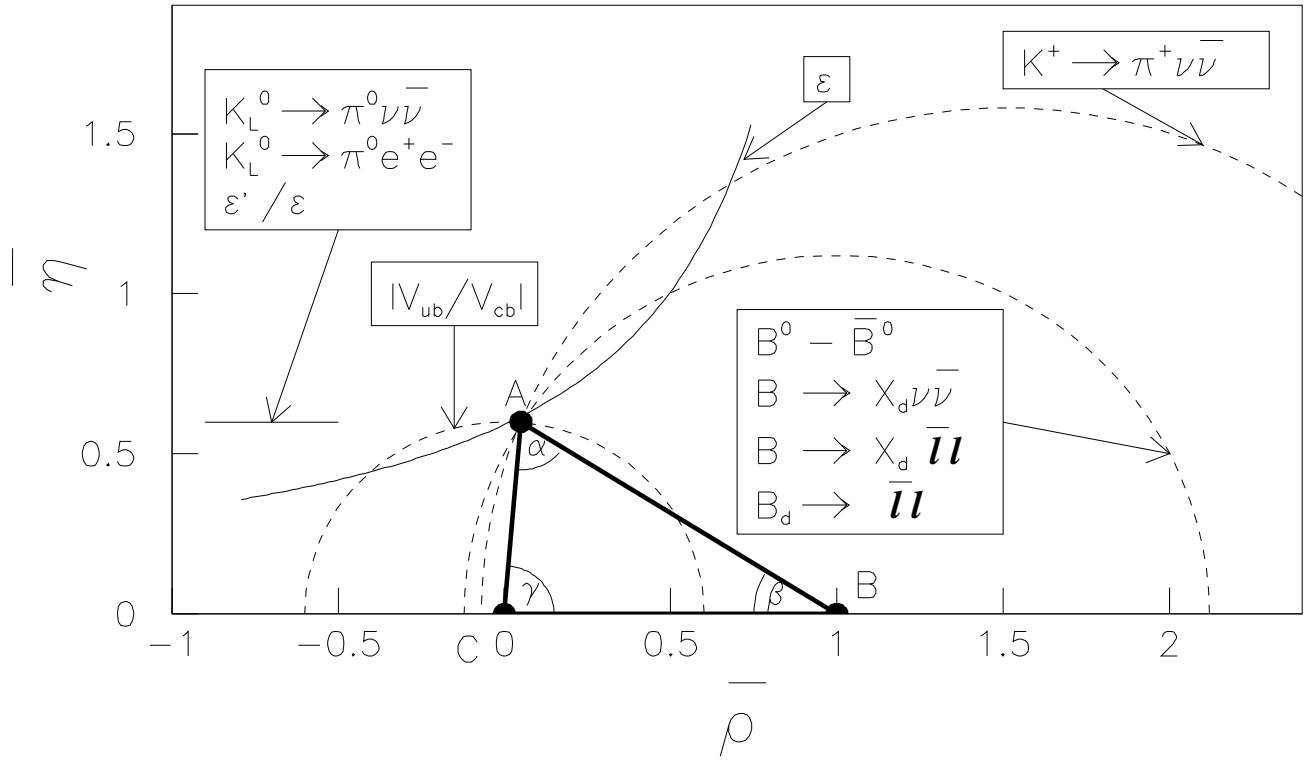
Wolfenstein parameterization:

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

Wolfenstein parameterization:

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

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



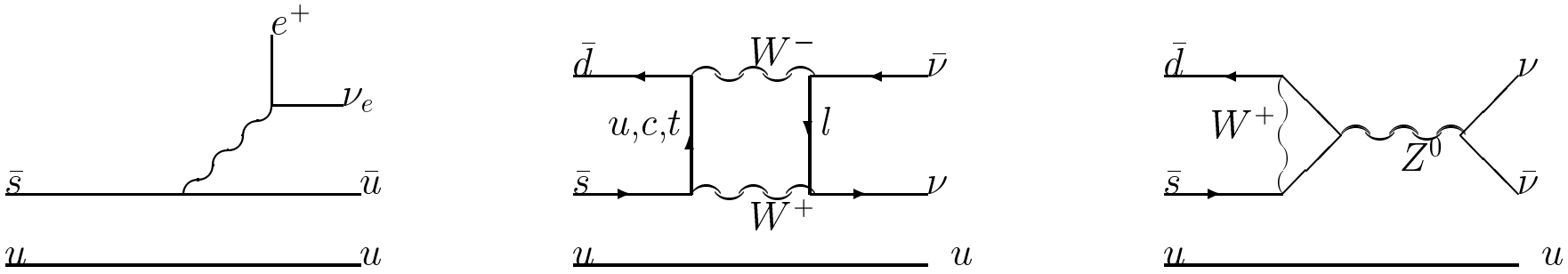
Quantitative Access to CKM parameters

- 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: $B_d^0 \to \Psi K_s$, 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 $K^+ \to \pi^0 e^+ \nu$



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

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

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

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

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

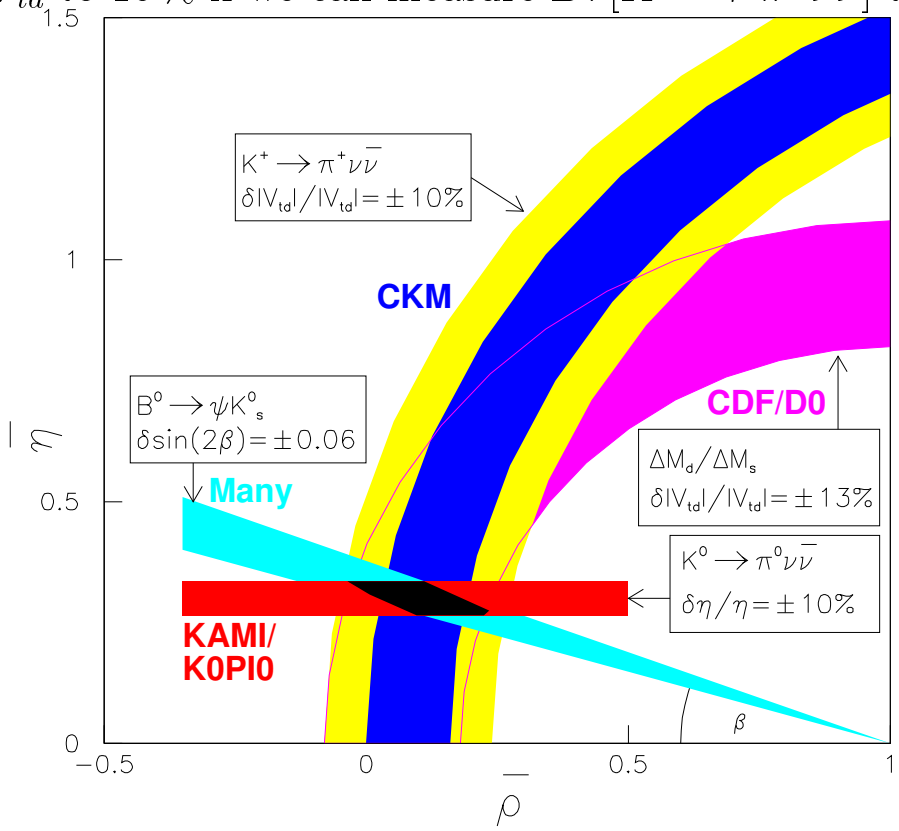
Total theoretical uncertainty of 8 % estimated by Buras, et al.[4]

Dominated by uncertainty in charm 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).



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

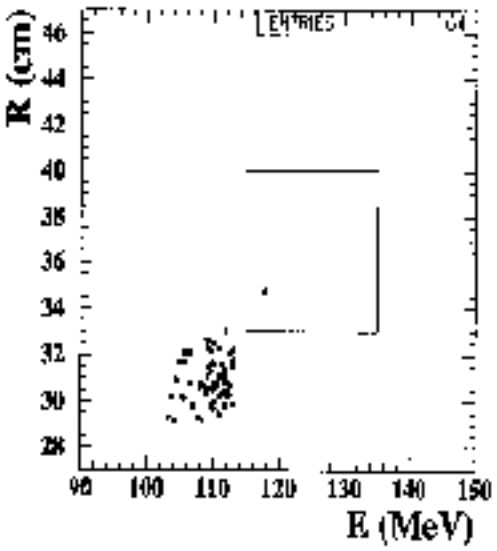
Brookhaven Experiment 787

- 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.

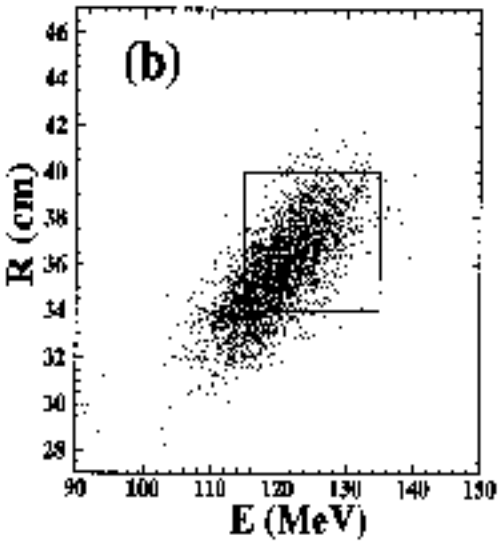
$K^+ \to \pi^+ \nu\bar{\nu}$ Event

- Background level = 0.07 events.

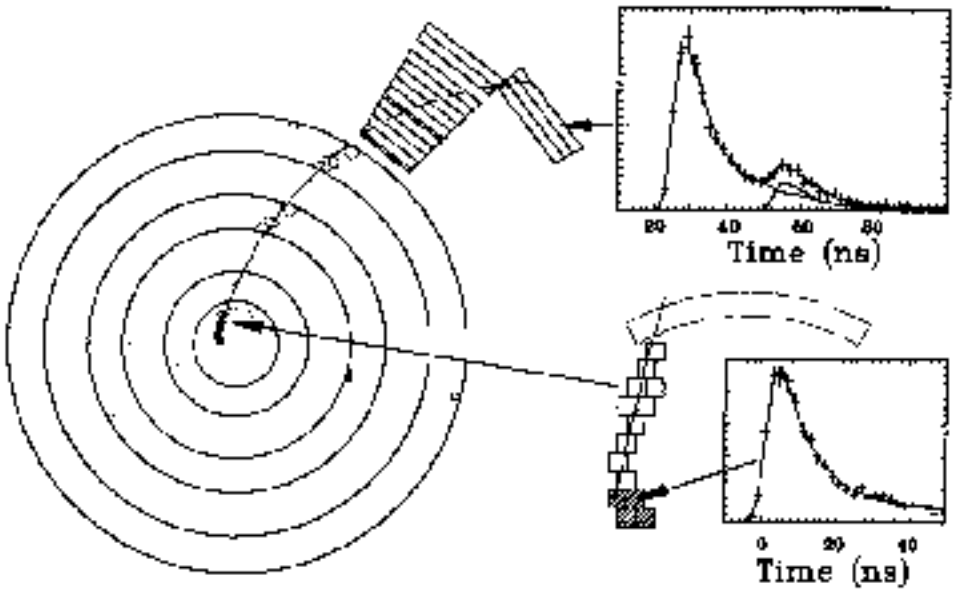
1995–97 Data



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

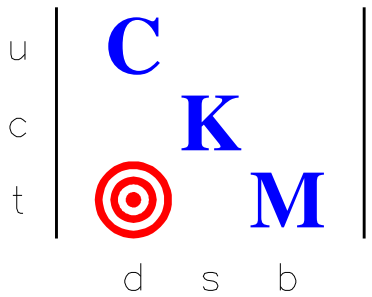
- $BR = 10^{-10}$
- 100 Events
- Acceptance 1 %

$\Longrightarrow 10^{14}$ 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}



Jürgen, UNAM 22Sep00. 14

Charged Kaons at the Main Injector

March 10, 2000

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

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Web Address: www.fnal.gov/projects/ckm/Welcome.html

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[5] 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

[5] Fermilab TM-2060

Beamline Picture from Leo

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"

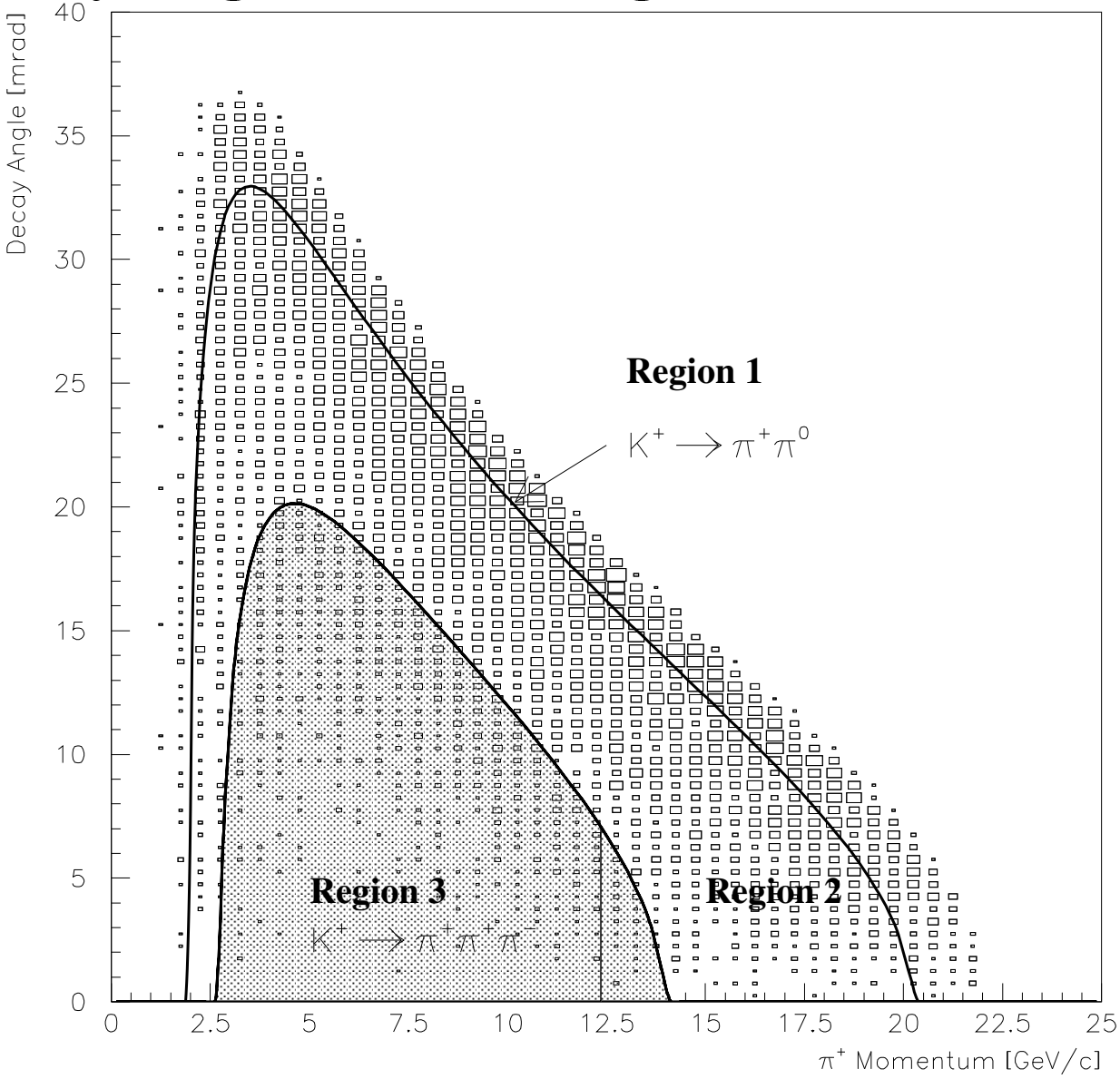
$$M^2_{miss} = M^2_K(1 - p_\pi/p_K) + m^2_\pi(1 - p_K/p_\pi) - p_\pi p_K \theta^2$$

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

- Reduce all material to minimum
- Make redundant measurements

Background modes from Leo

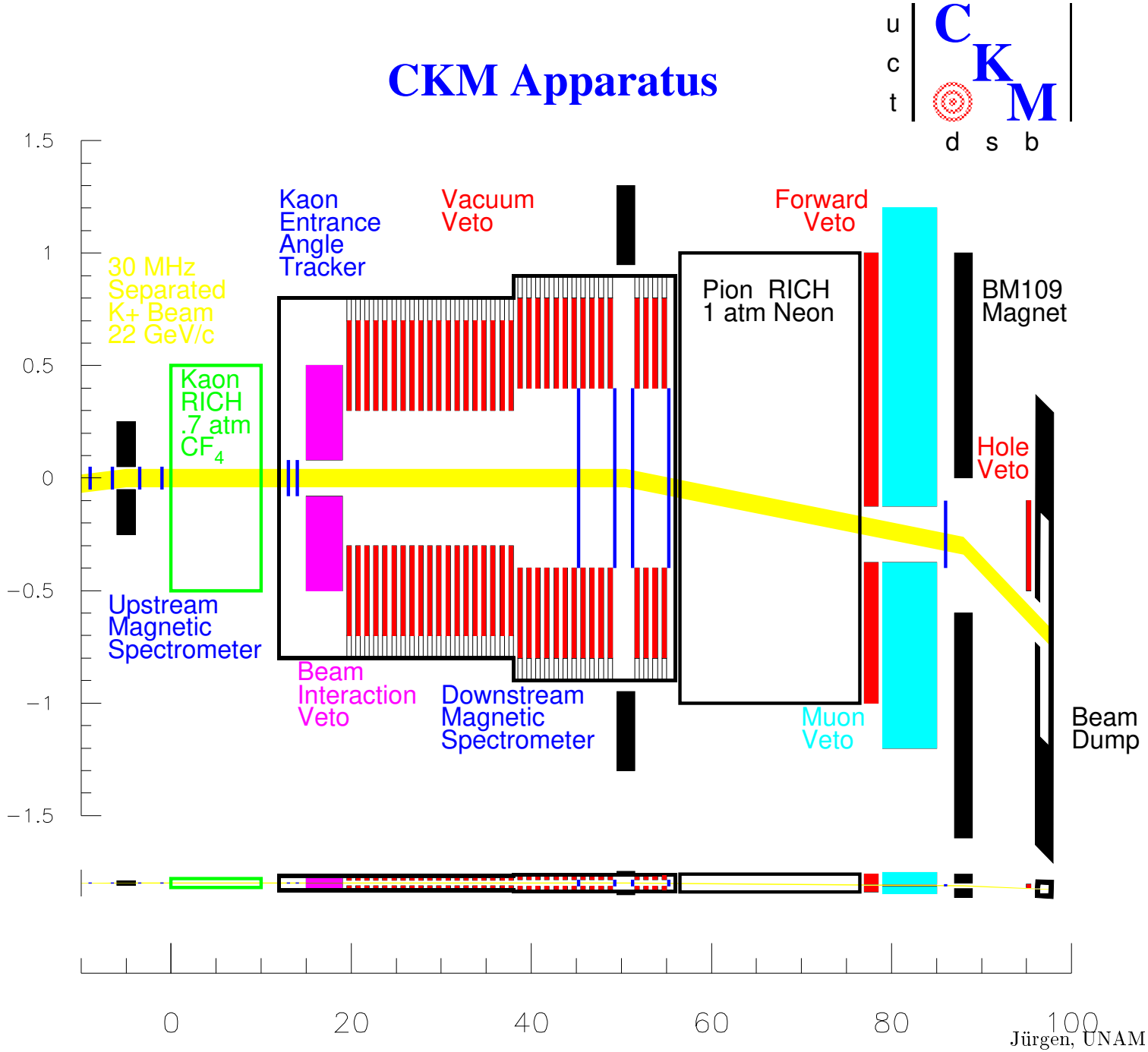
Decay angles and Backgrounds



Decay angles and Backgrounds (cont.)

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



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 or MWPCs using the last bending magnet in the beamline. Fiber planes to measure time.

  KEAT - 50 micron pitch, double sided Silicon strips or MWPCs. 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.

Straw Drawing from Leo

material budget from Leo

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:

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

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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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The SELEX phototube RICH detector

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Abstract

In this article, construction, operation, and performance of the RICH detector of Fermilab experiment 781 (SELEX) are described. The detector utilizes a matrix of 2848 phototubes for the photocathode to detect Cherenkov photons generated in a 10 m neon radiator. For the central region an N_0 of 104 cm^{-1}, corresponding to 13.6 hits on a $\beta = 1$ ring, was obtained. The ring radius resolution measured is 1.6%. © 1999 Published by Elsevier Science B.V. All rights reserved.

1. Introduction

The Fermilab experiment E781 (SELEX): a segmented large x_F Baryon spectrometer [1,2], which took data in the 1996/1997 fixed target run at Fermilab, is designed to perform high statistics studies of production mechanisms and decay physics of charmed baryons such as Σ_c, Ξ_c, Ω_c and Λ_c. The physics goals of the experiment require good charged particle identification to look for the different baryon decay modes. One must be able to separate π, K and p over a wide momentum range when looking for charmed baryon decays like $\Lambda_c^+ \to pK^-\pi^+$.

A RICH [3] detector with a 2848 phototube photocathode array has been constructed [4,5] to do this. The detector begins about 16 m downstream of the charm production target, with two analysis magnets with 800 MeV/c p_t-kick each in-between, and is surrounded by multi-wire proportional and drift chambers which provide particle tracking. The average number of tracks reaching the RICH is about 5 per event. First results from this detector can be found in Ref. [6].

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[1] Work supported by the US Department of Energy under contract NO. DE-AC02-76CHO3000.

[2] Deceased.

[3] Supported by the Russian Ministry of Science and Technology.

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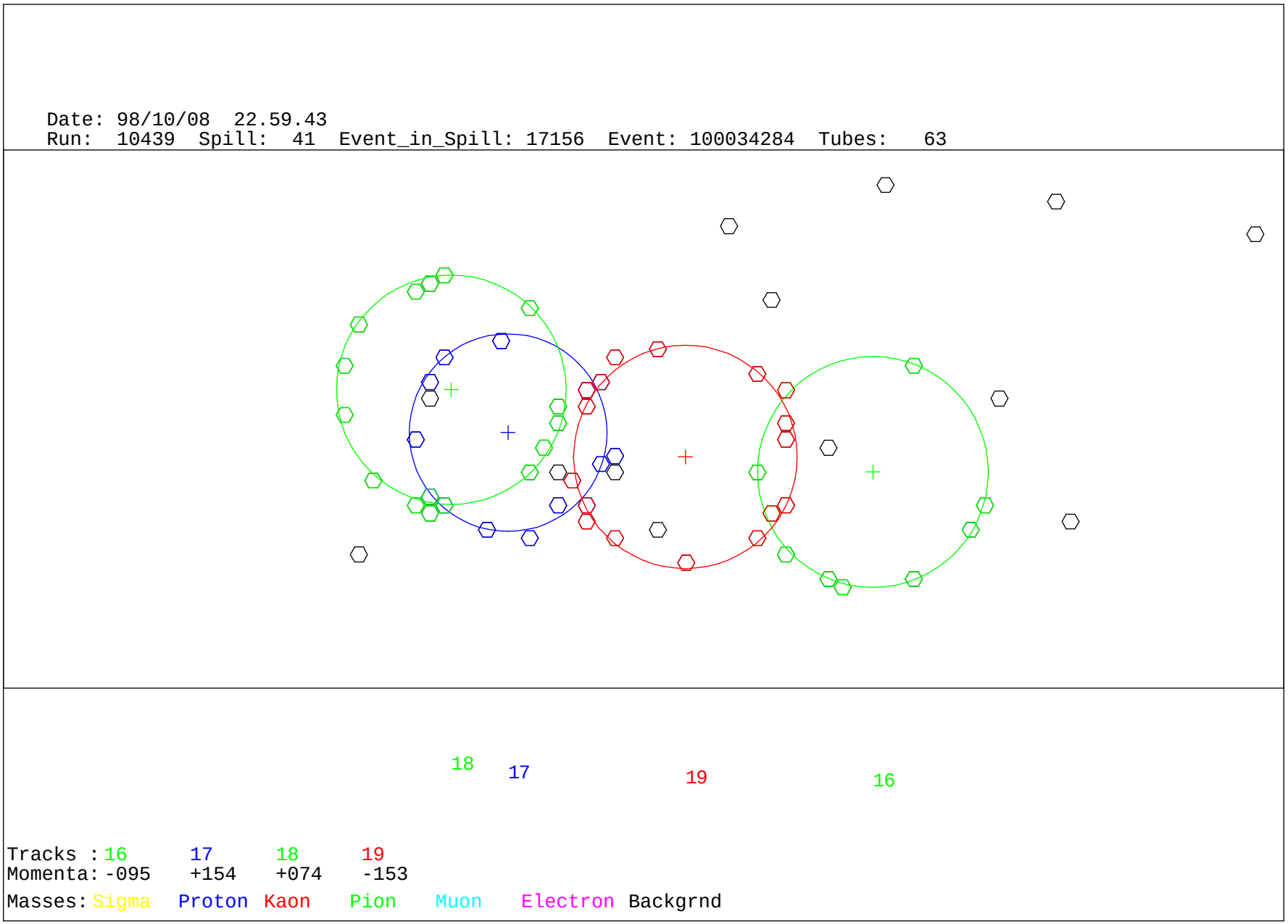
Date: 98/10/08 22.59.43
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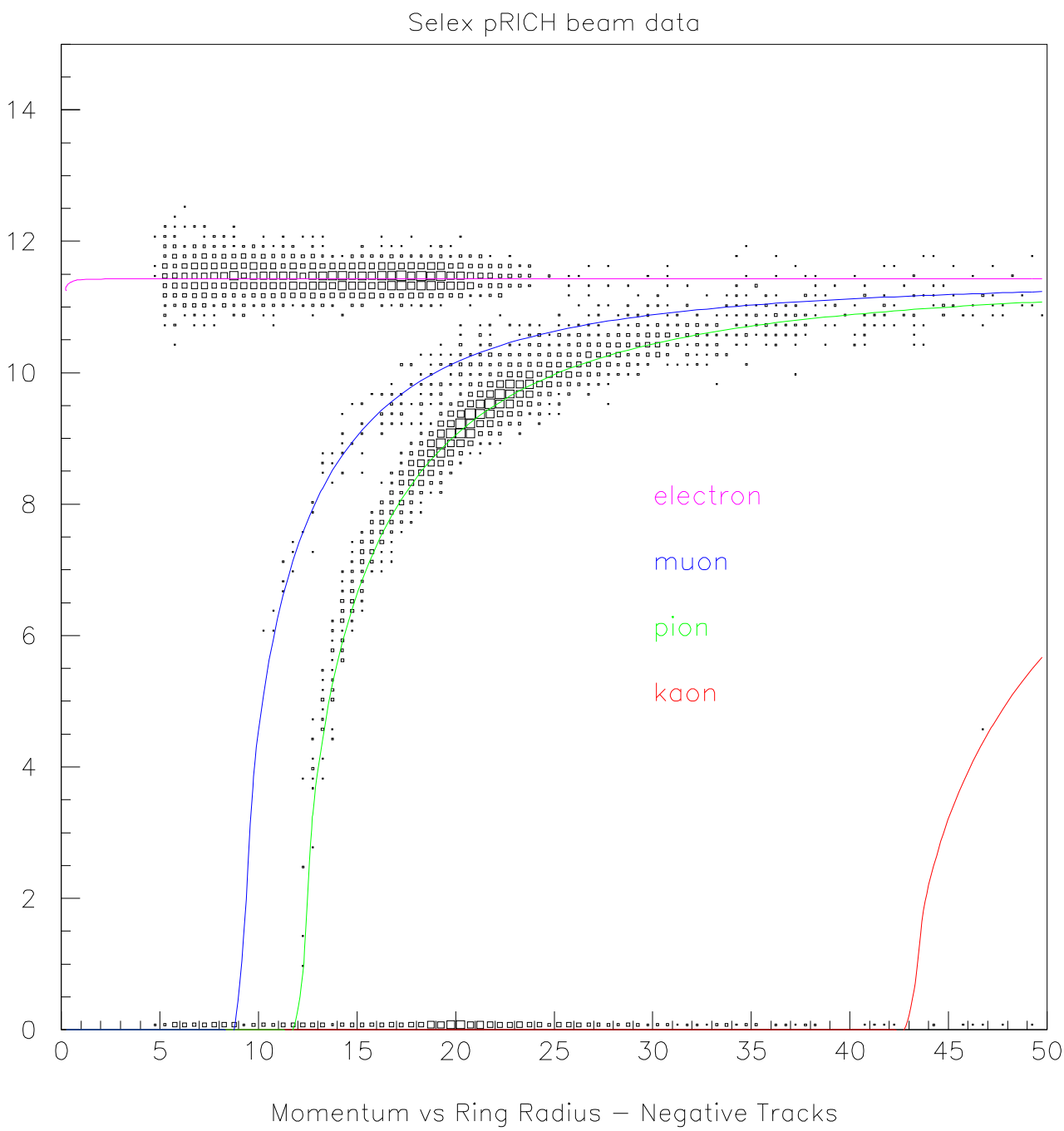
18
17
19
16
Tracks : 16 17 18 19
Momenta: -095 +154 +074 -153
Masses: Sigma Proton Kaon Pion Muon Electron Backgrnd


Selex pRICH beam data
14
12
10
8
6
4
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45
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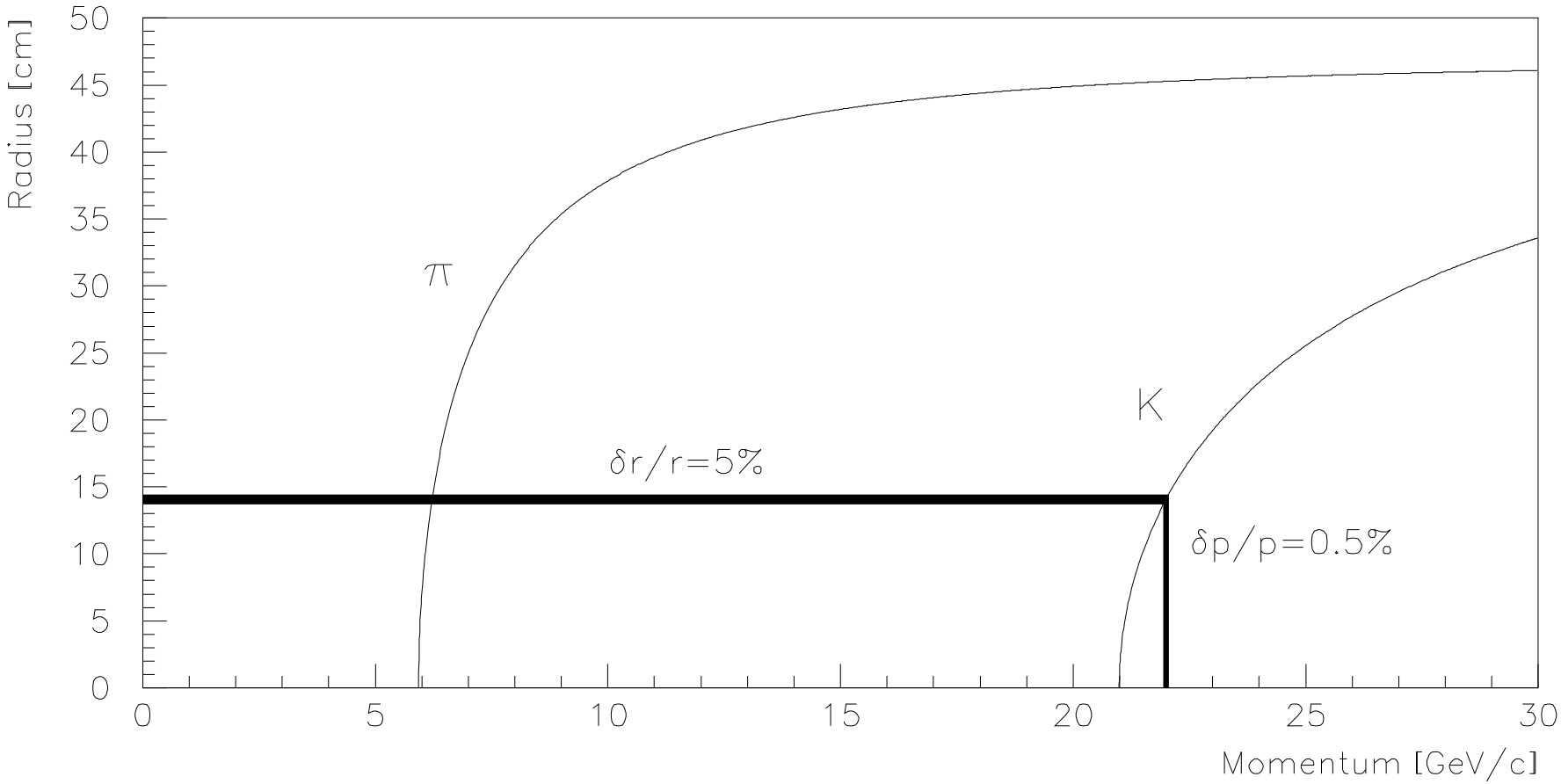
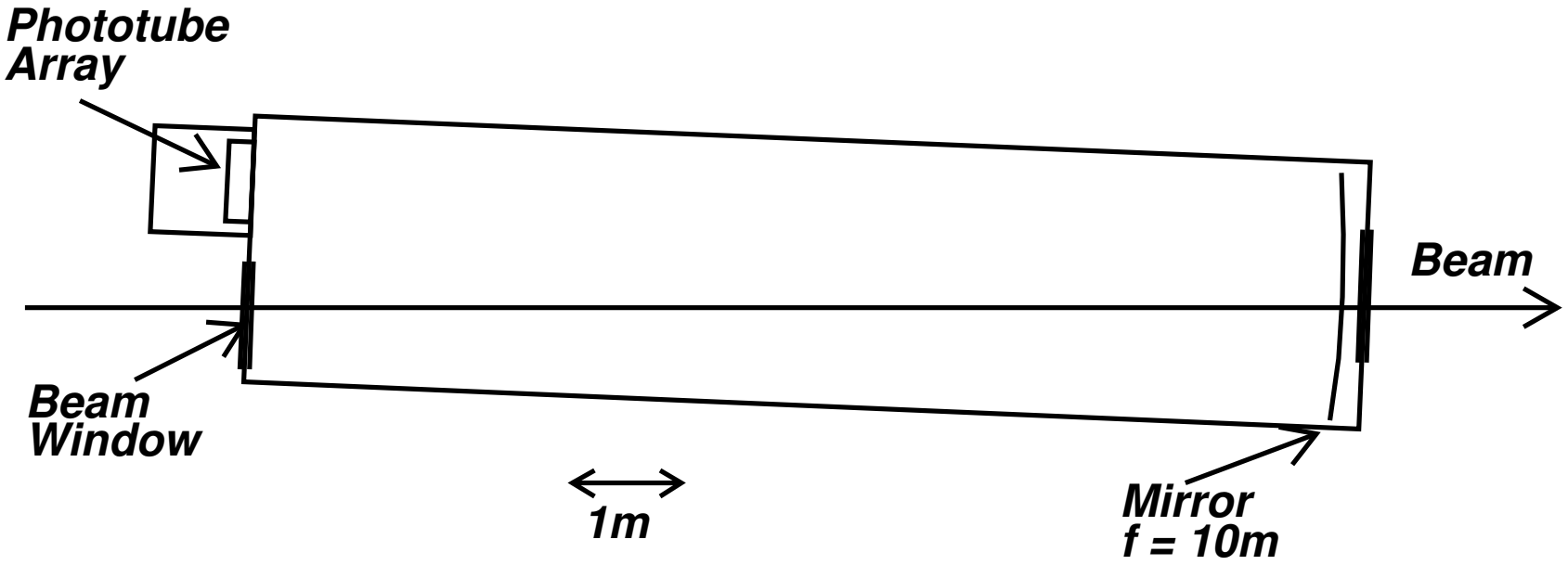
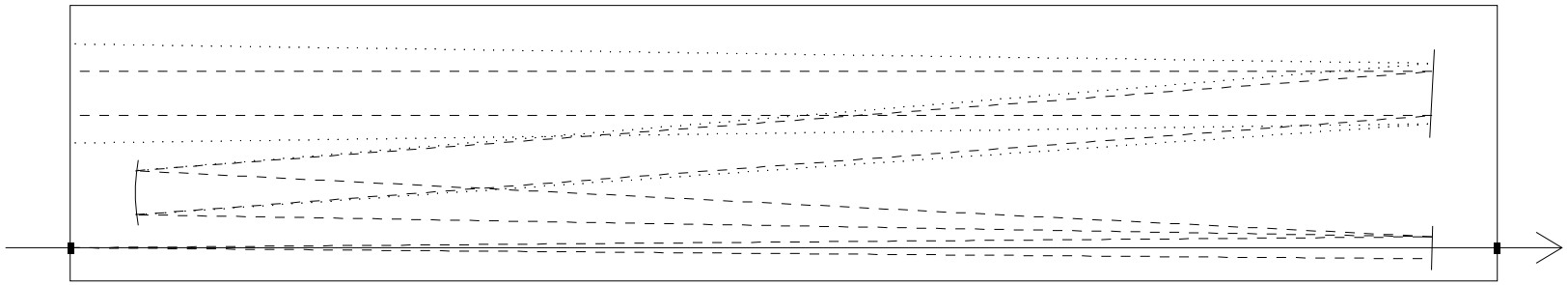
electron
muon
pion
kaon
Momentum vs Ring Radius – Negative Tracks


Radius [cm]
50
45
40
35
30
25
20
15
10
5
0
0
5
10
15
20
25
30
Momentum [GeV/c]
π
K
δr/r=5%
δp/p=0.5%

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.

  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

VVS Inefficiency from Leo

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.)

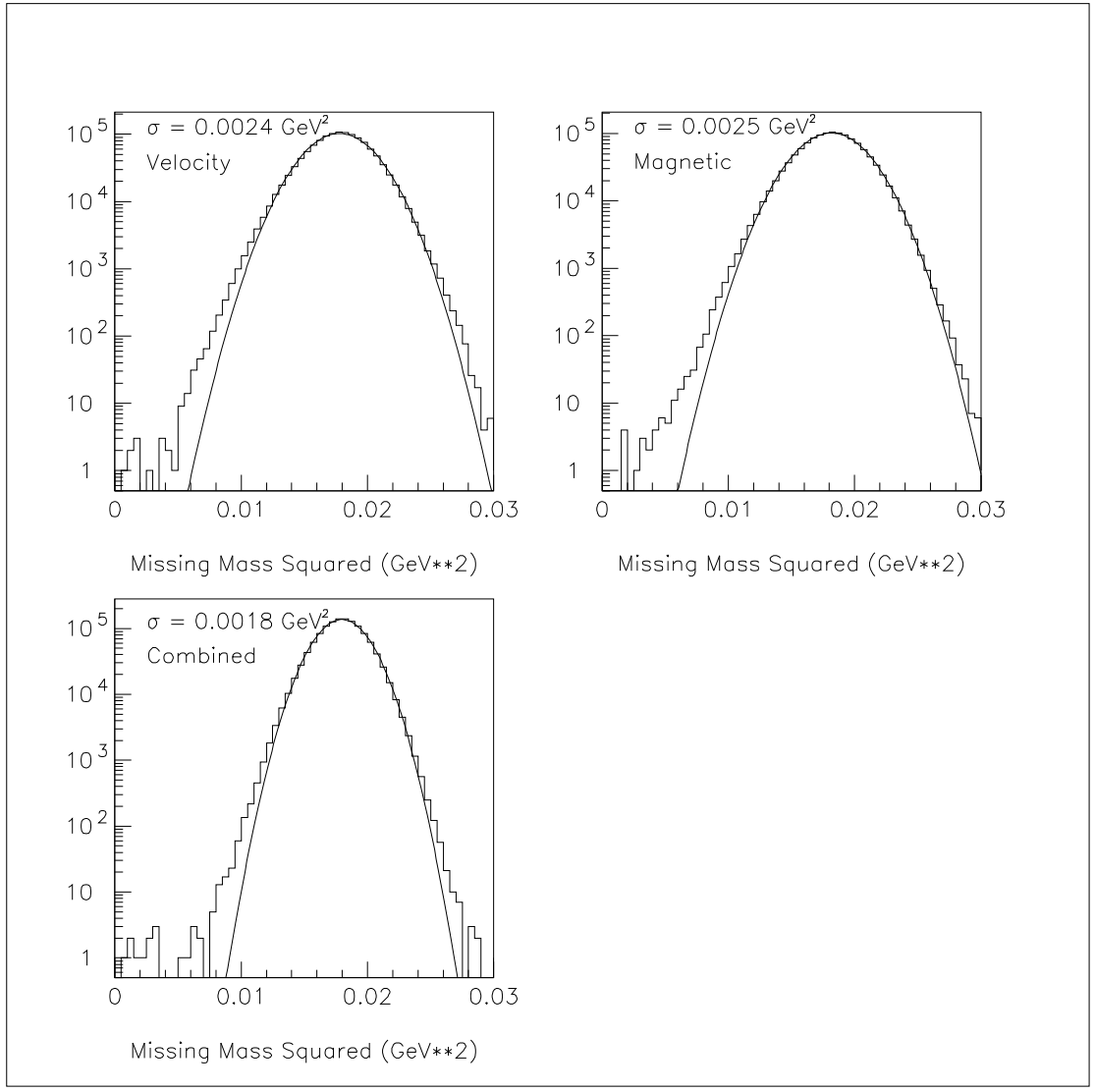
$K^+ \to \pi^+\pi^0$	155 kHz
$K^+ \to \pi^0 e^+ \nu$	64 kHz
$K^+ \to \pi^+\pi^+\pi^-$	1 kHz
Total	220 kHz

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 1: Miscellaneous inefficiency table.

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



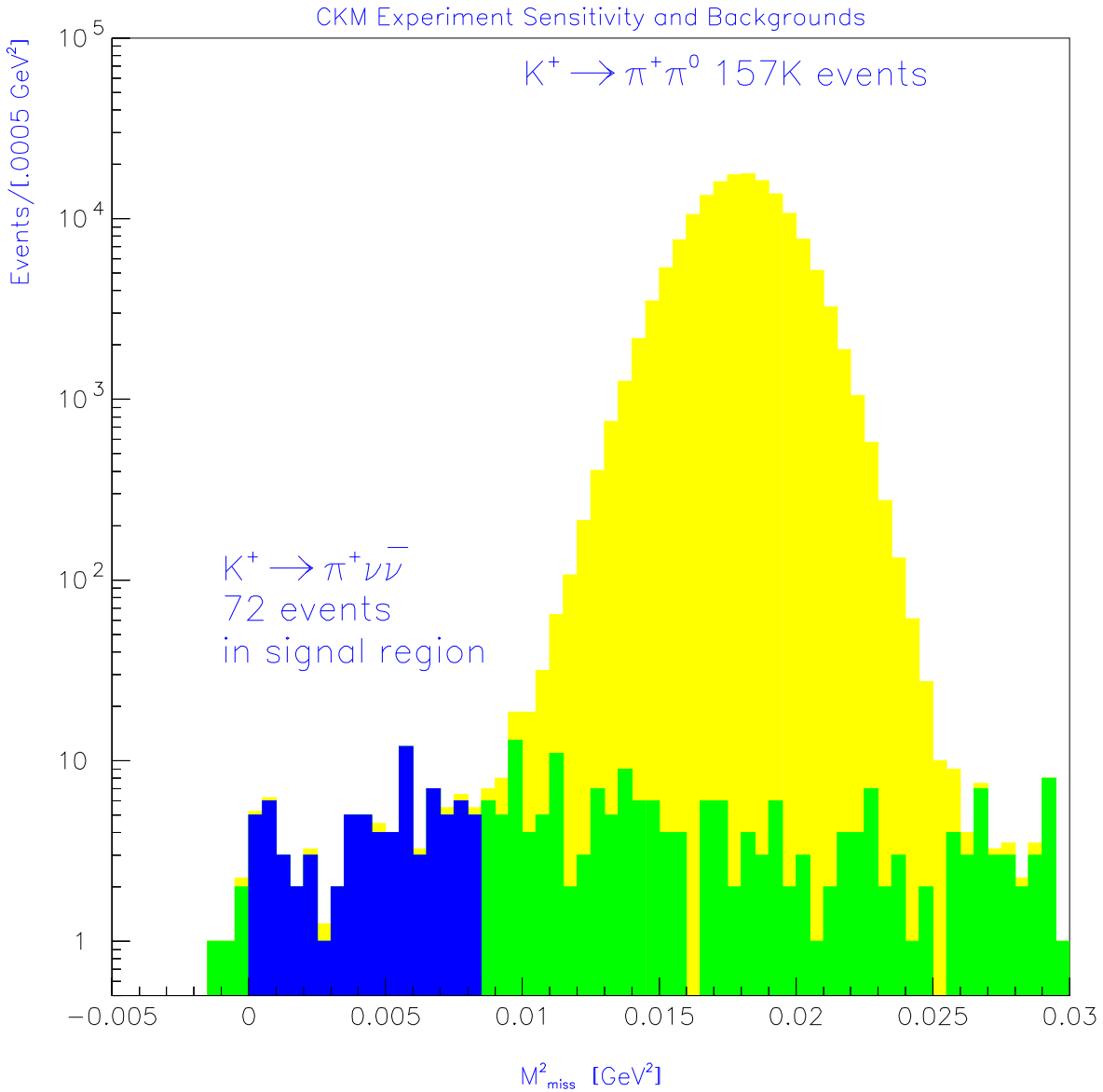
$$M^2_{\rm miss} = M^2_K(1 - p_\pi/p_K) + m^2_\pi(1 - p_K/p_\pi) - p_\pi p_K \theta^2$$

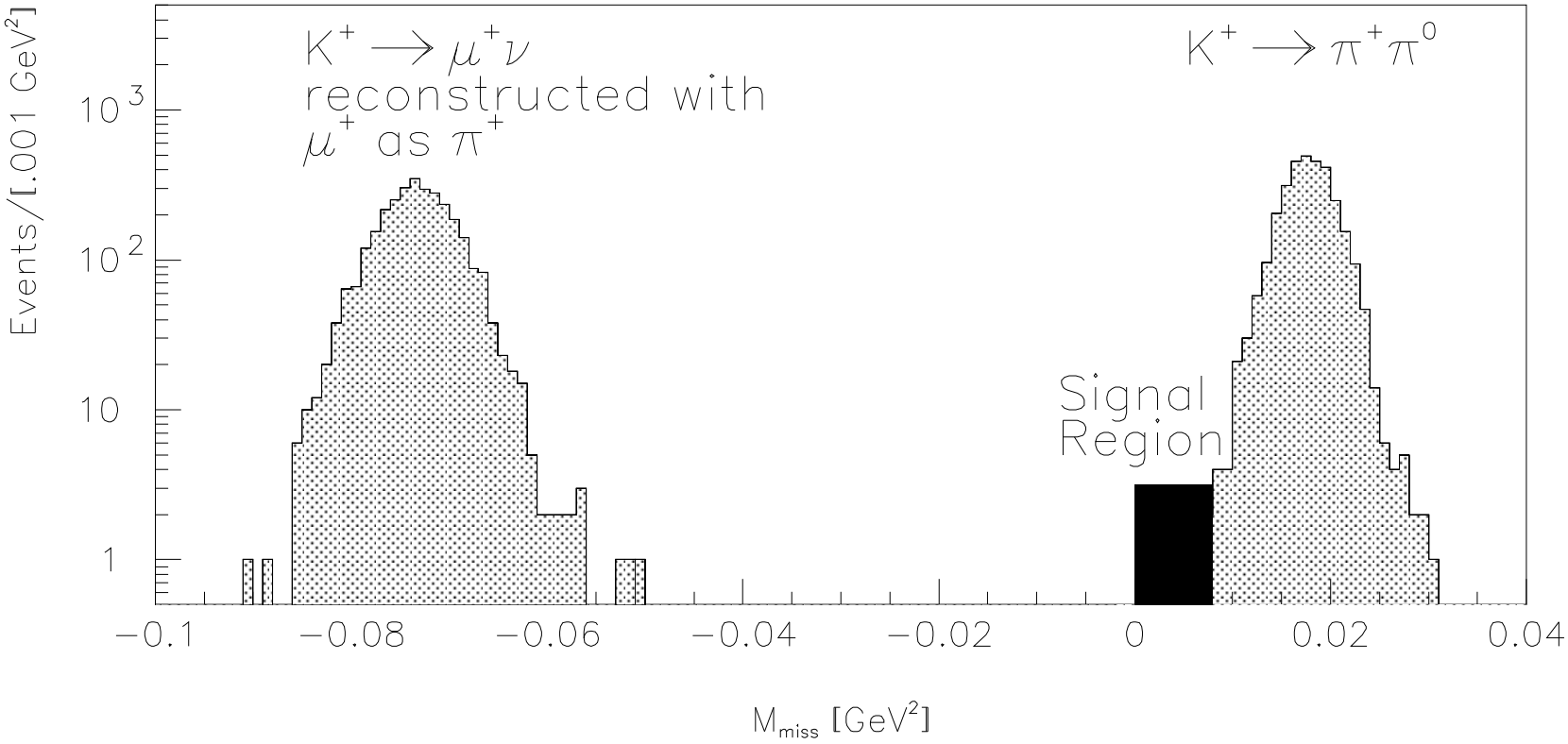
Simulated Background sources

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 2: Background estimates in terms of effective branching ratio.

The Final Signal Plot




$K^+ \to \mu^+\nu$
reconstructed with
μ^+ as π^+
$K^+ \to \pi^+\pi^0$
Signal
Region
Events/(.001 GeV^2)
10^3
10^2
10
1
−0.1
−0.08
−0.06
−0.04
−0.02
0
0.02
0.04
M_{miss} [GeV^2]

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.
- $K^+ \to \pi^0 e^+ \nu$, $K^+ \to \pi^0 \mu^+ \nu$ 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
2004-2006:	Running
2005-2008:	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`