Two RICH detectors as Velocity Spectrometers in the CKM Experiment

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Outline

- CKM Physics
- The CKM Detector Systems
- Pion RICH and Kaon RICH
- Summary

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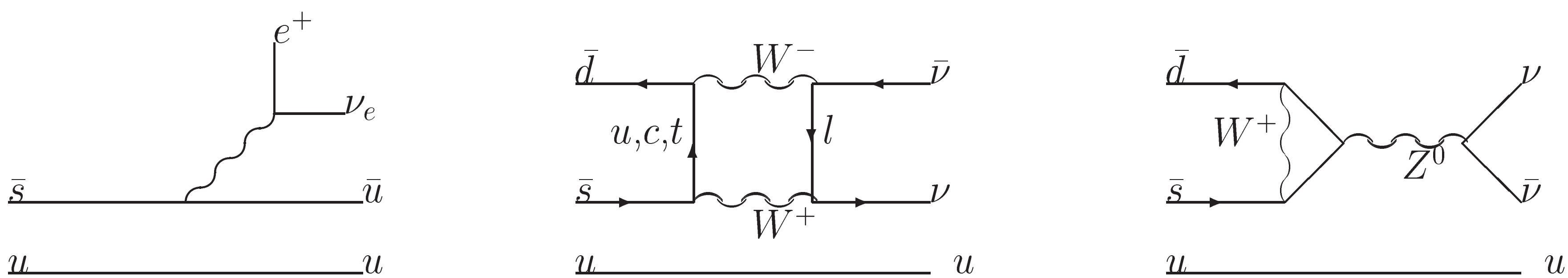
Quantitative Access to CKM parameters

- Goal is to test the Standard Model hypothesis that a single phase in the CKM matrix is the sole source of $\mathcal{CP}$ 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…"[1]
- To falsify the Standard Model hypothesis the only foreseeable results with controlled errors are:
  - B physics: $B_d^0 \to \Psi K_s$, and probably x_s/x_d mixing.
  - K physics: $K^+ \to \pi^+ \nu\bar{\nu}$ and $K^0 \to \pi^0 \nu\bar{\nu}$.

[1] Wolfenstein at Kaon'99

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

Calculated[2] by weak isospin rotation from $K^+ \to \pi^0 e^+ \nu$



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

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

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

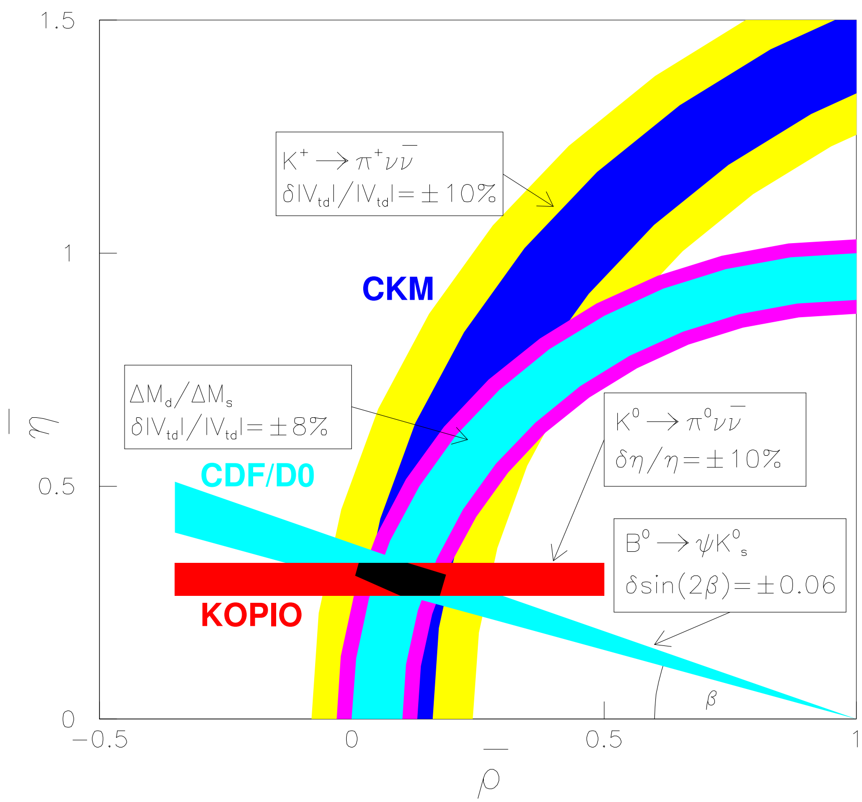
$$Br[K^+ \to \pi^+\nu\bar{\nu}] = 0.55 \times 10^{-10}[(1.35 - \bar{\rho})^2 + (1.05\bar{\eta})^2] = (0.75 \pm 0.29) \times 10^{-10}$$

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

[4] A.J. Buras, Proceedings Zacatecas 2001

- Total theoretical uncertainty of 8 % estimated by Buras, et al.[3]
- 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).



[3] A.J. Buras, Proceedings Zacatecas 2001

Brookhaven Experiments 787/949

- Stopped Kaon experiment.
- Have seen two events after several years of running.

$$\mathrm{BR}(K^+ \to \pi^+ \nu \bar{\nu}) = 1.57^{+1.75}_{-0.82} \cdot 10^{-10}$$

- Have new experiment approved (E949), will run in 2002/3 (but financial problems at BNL)
- Hope to see about 5-10 events
- Fermilab part of our experiment joined E949, and Brookhaven part joined us.

A short estimate for an inflight decay experiment

- Branching Ratio 10^{-10}
- 100 Events
- Acceptance $\approx 1\,\%$

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

- Duty cycle of machine $30\,\%$ (Fermilab Main Injector)
- 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

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Measurement Principle

$BR(K^+ \to \pi^+ \nu\bar{\nu}) \sim 1 \cdot 10^{-10}$
$BR(K^+ \to \mu^+ \nu) = 0.635$
$BR(K^+ \to \pi^+ \pi^0) = 0.212$
$BR(K^+ \to \pi^+ \pi^+ \pi^-) = 0.056$

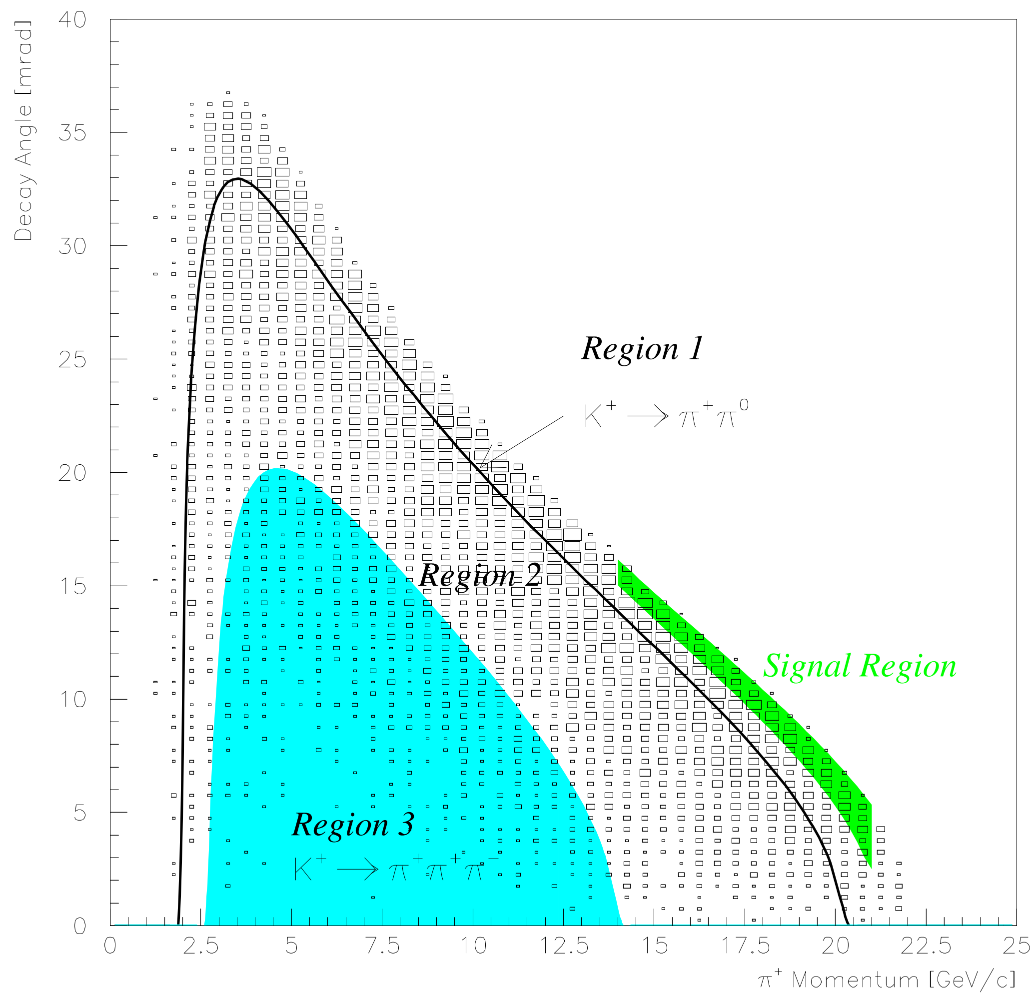
π^0 Rejection via Photon Veto System:
$< 1.6 \cdot 10^{-7}$

Kinematic rejection: $< 3 \cdot 10^{-5}$
From Velocity and Magnetic Spectrometers

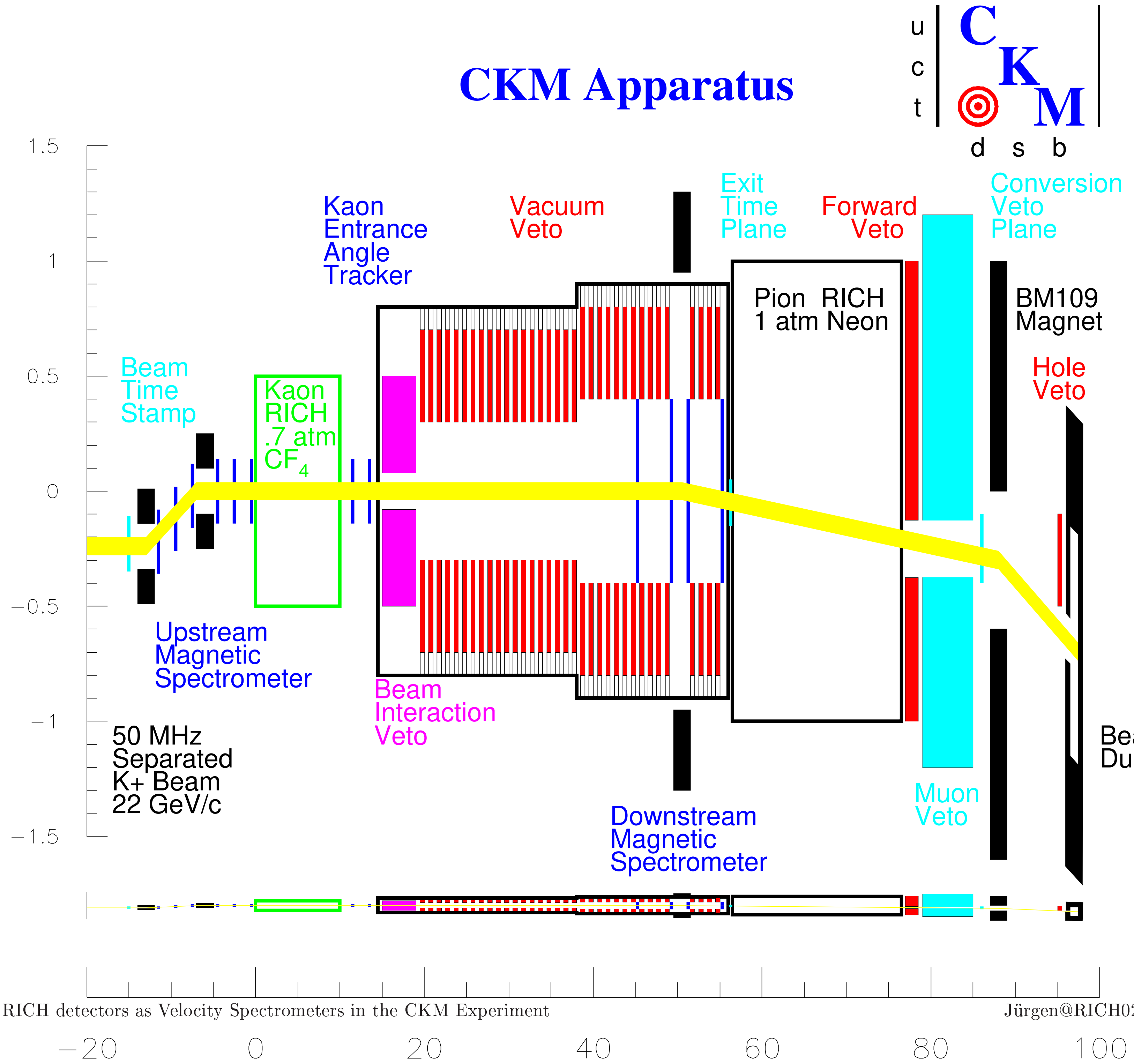
Calculating missing mass:

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

Resolution in Missing mass:
$\sim M^2_{\pi^0}/10$ for $K^+ \to \pi^+ \pi^0$



CKM Apparatus



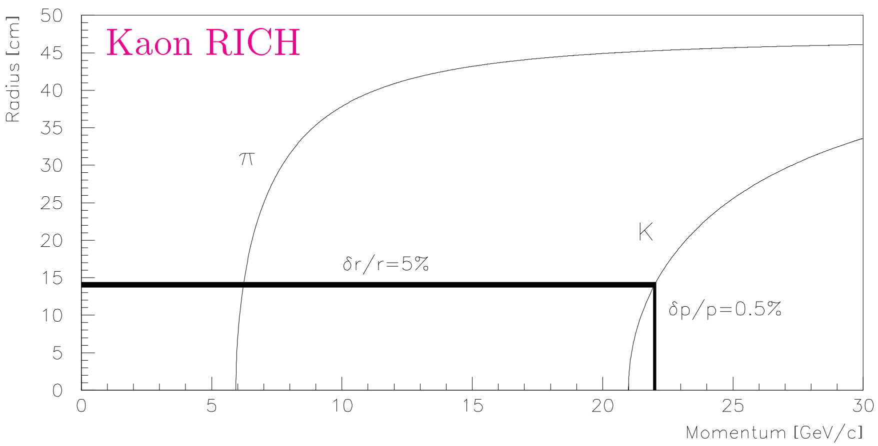
Apparatus

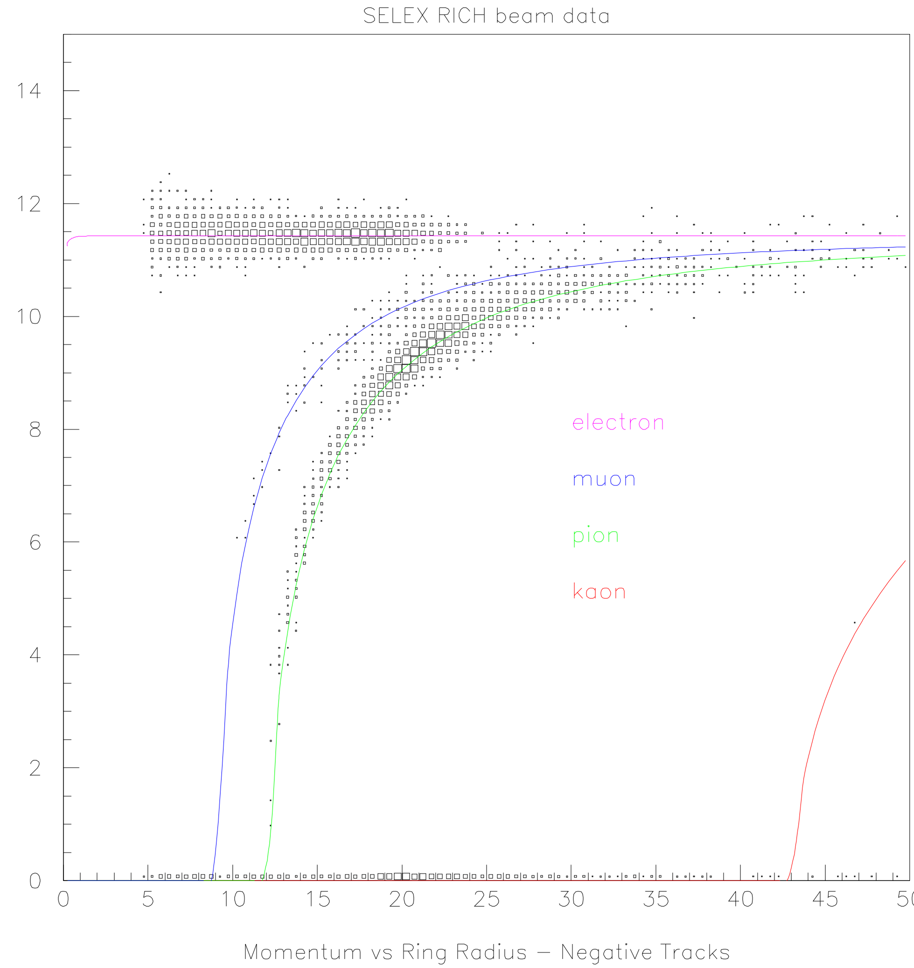
- Requirements
  - Redundancy in measurements to defy non-Gaussian behaviors
  - 2×10^{-7} direct π^0 rejection
  - 1×10^{-5} direct μ^+ rejection
  - Rate capability to handle 5 MHz of K^+ decays
  - Resolution - $\sigma_p/p \sim 1\,\%$, $\sigma_\theta/\theta \sim 1\,\%$, $\sigma_t \sim 1\,$nsec, are 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
- Photon Veto System
- Muon Veto System
- "Conventional" Magnetic Spectrometer
- "Velocity Spectrometer"

Velocity Spectrometer
Ring Imaging Cherenkov Counters

Design and Performance estimates based on data from SELEX RICH



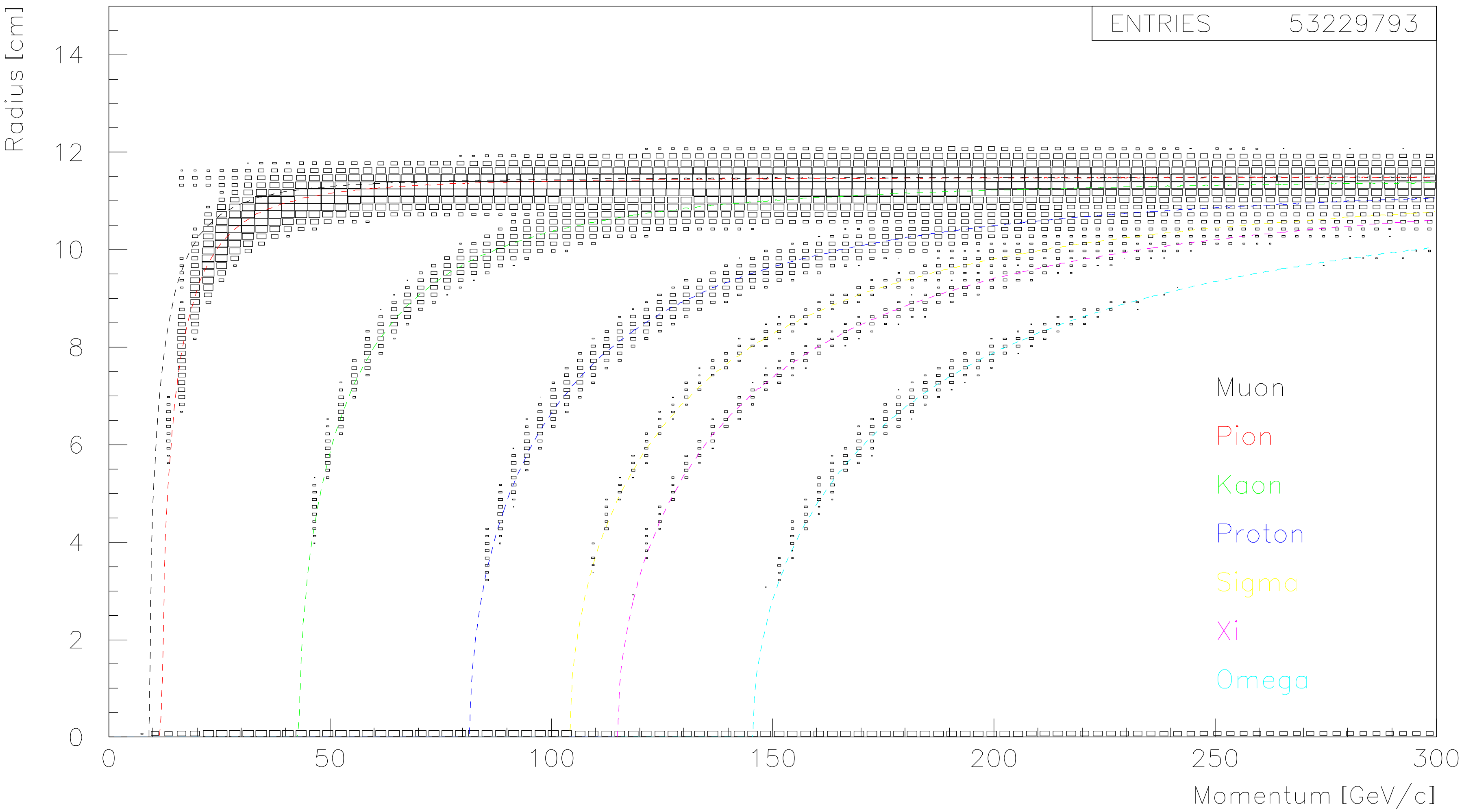


- Ring Radius: velocity
- Ring Center: angles
- Phototube Pulse Length $< 10\,\mathrm{nsec}$
- Time Resolution $< 1\,\mathrm{nsec}$ (HERA-B, CCLC)

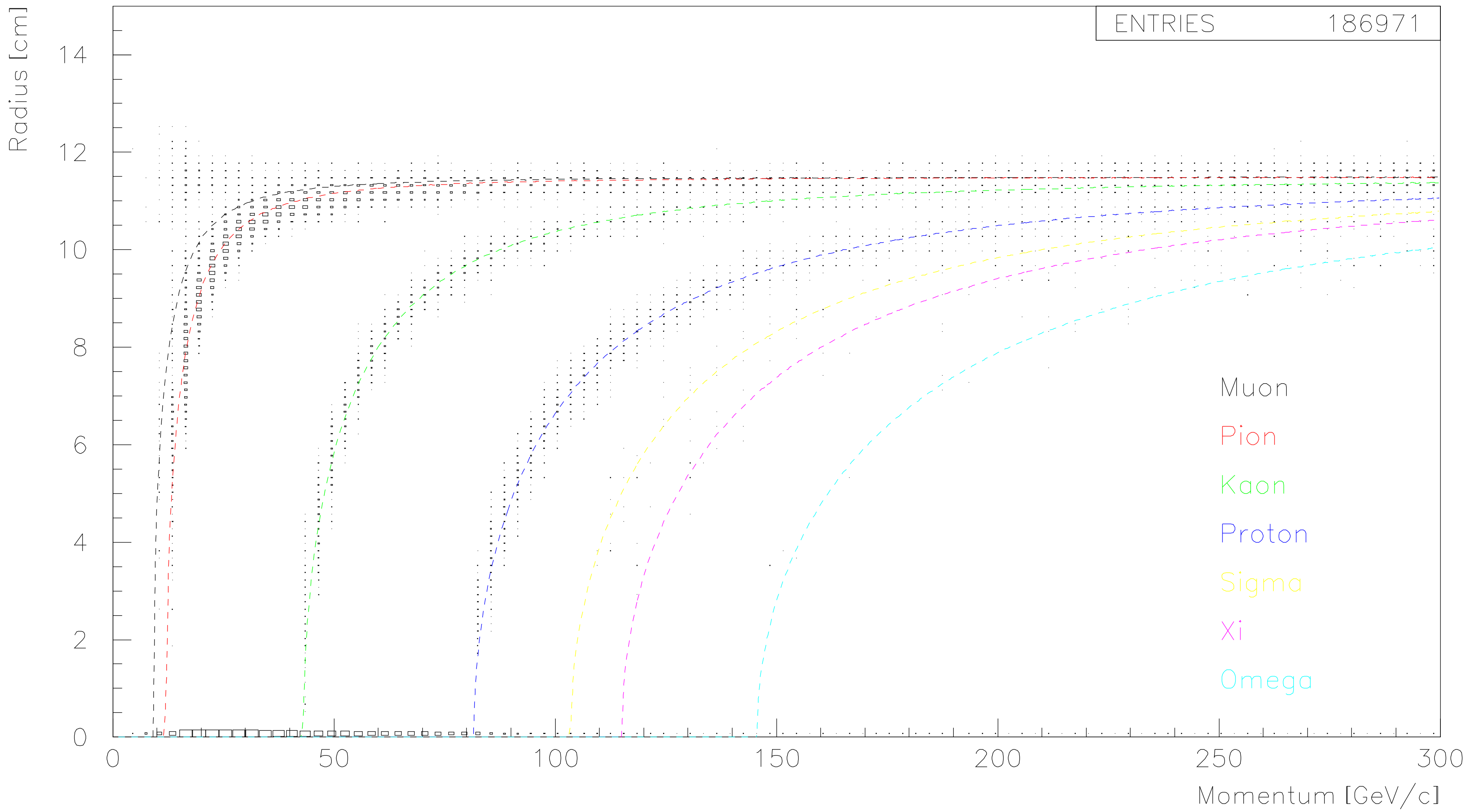
Cherenkov (Franck, Tamm) equation:

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

SELEX RICH: Particle Id negative tracks

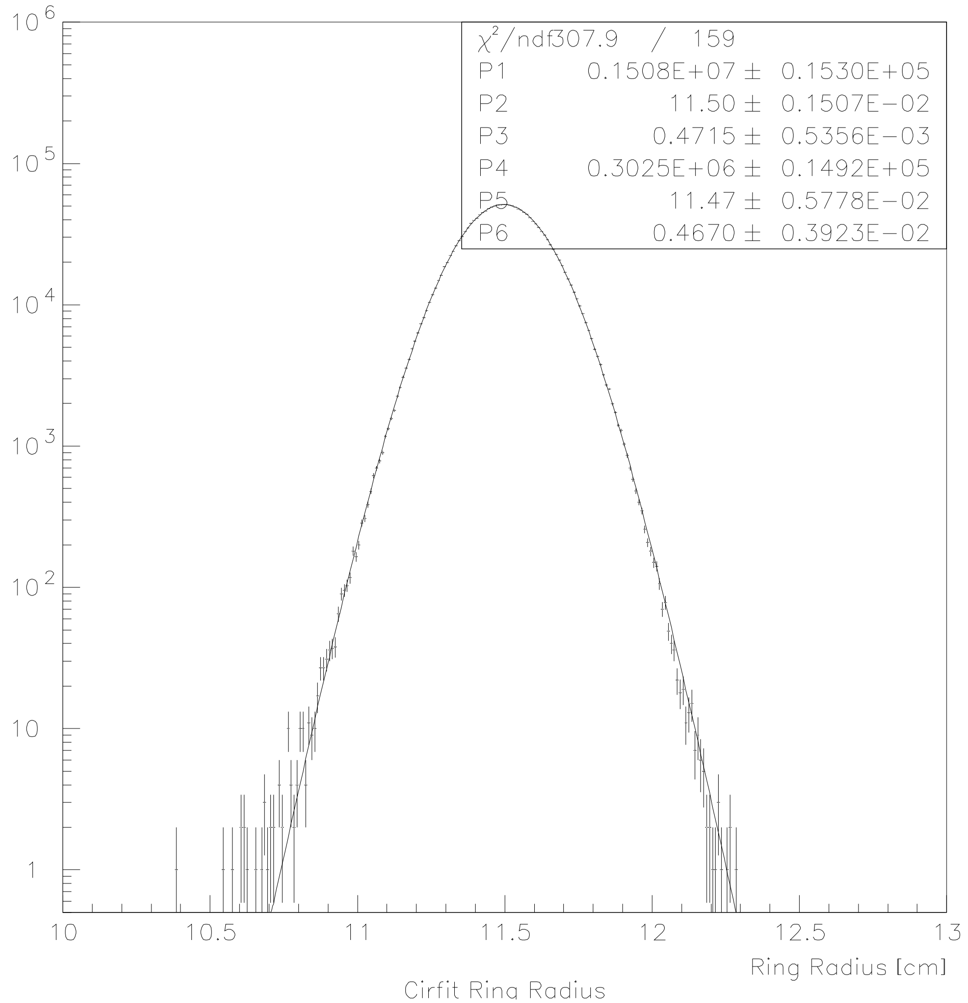


SELEX RICH: Particle Id positive tracks



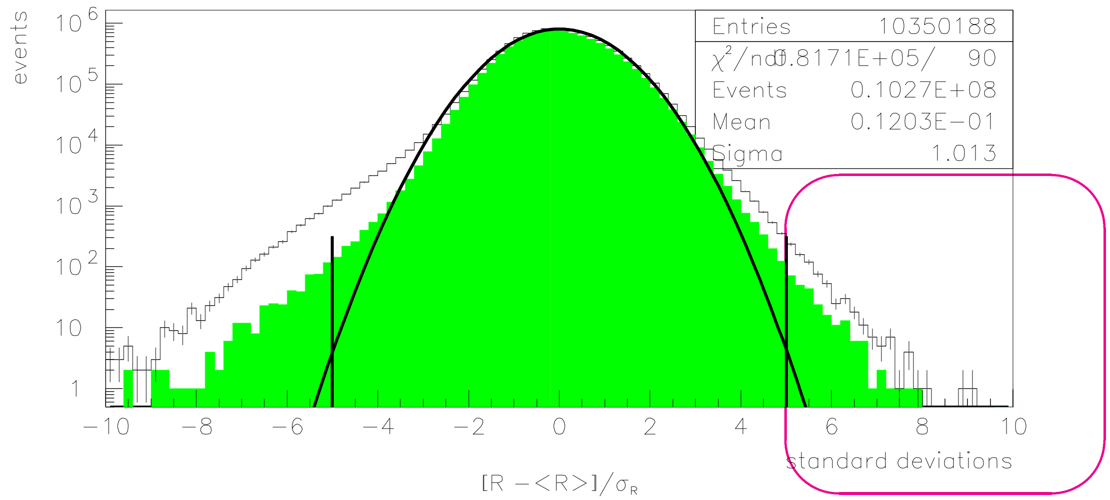
How Gaussian is the response?

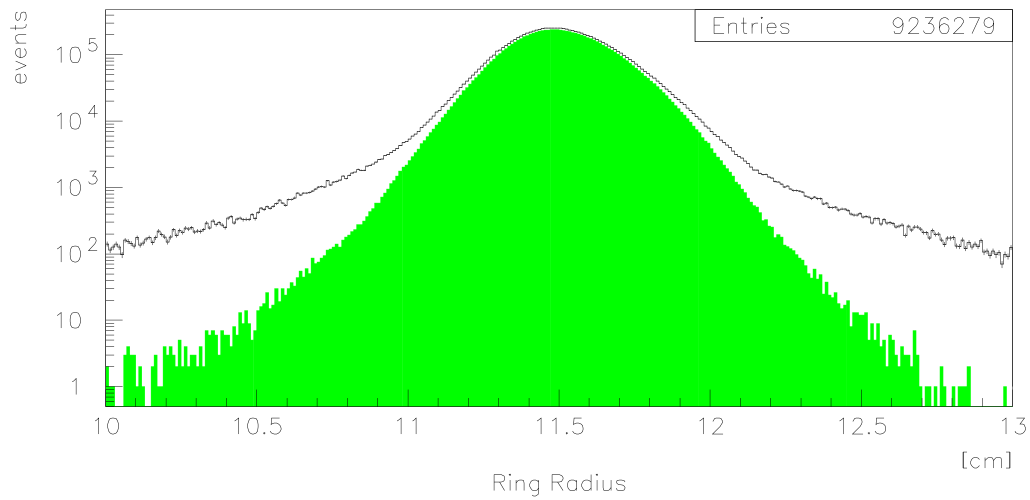
A Study with SELEX single beam tracks – Standard SELEX algorithm



Gaussian over nearly 5 orders of magnitude!

Study with SELEX single track data – Standalone





Solid histogram gives already enough rejection

NUCLEAR INSTRUMENTS AND METHODS 9 (1960) 55–68; NORTH-HOLLAND PUBLISHING CO.

A NEW TYPE OF ČERENKOV DETECTOR FOR THE ACCURATE MEASUREMENT OF PARTICLE VELOCITY AND DIRECTION*

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Department of Physics[**], *University of Rochester*

Received 22 June 1960

A new type of Čerenkov radiation detector is proposed, in which the light emitted by a single particle traversing a radiator is imaged, by means of a lens or mirror focused at infinity, on the cathode of an image-intensifier tube. The image is a ring, whose diameter measures accurately the Čerenkov cone angle, and thus the particle velocity. In addition the coordinates of the center of the circular image accurately indicate the orientation of the particle trajectory, though not its position. The sensitivity of presently available systems of cascaded image-intensifier tubes allows the photographic recording of the image produced by a single particle. The system is inherently insensitive to background noise. It can observe simultaneously several incident particles whose directions span a wide angle. It may be gated with microsecond coincidence resolving times. It can use condensed or gaseous radiators, with the former, chromatic dispersion is likely to limit the accuracy. For gas radiators, the attainable accuracy of velocity determination is estimated as $\delta\beta = \pm 0.0002$ or better, the accuracy of track orientation ± 0.001 radians. The range of velocity and orientation simultaneously observable depends on the angular field of view of the objective. Sources of error, the precision attainable, the design of practical systems and some possible applications are discussed.

1. Introduction

The Čerenkov light emitted by a fast-moving particle consists of rays parallel to the elements of a right circular cone. As observed by a detector, it seems to originate from a ring source at infinity whose angular diameter is that of the cone (fig. 1). It has justly been likened to the light from a ring of faint stars. If such light is collected by a telescope objective, an image of the ring is formed in the focal plane with a diameter given by

$$\ldots 2f \tan\theta \qquad (1)$$

where f is the focal length of the objective, and θ ... the half-angle of the cone of light.

Precisely such an arrangement may be used to collect the Čerenkov radiation from a fast particle, as shown in fig. 2. The light emitted by the particle may all be collected in a ring image. In principle, a photographic plate could then record the particle passage, but the light emitted is of course too weak to allow the photography of single particles. However, existing image-intensifier tubes, as now used in cascade for scintillation track-imaging, can record such ring images. Fig. 3 shows such a cascade system.

Fig. 1. (a) Čerenkov radiation emitted by a fast particle traversing a radiator ... a circular cone of parallel rays ... (b) The light from a ... ring source at infinity ... after passing through an aperture ... a ring image by a lens or mirror objective.

One can construct in this way a Čerenkov detector that measures accurately both the particle velocity,—even at very high speeds (β ... 0.99),—and the direction of motion of the particle. Furthermore, these measurements may be made on particles entering a large radiator at

* ... Atomic Energy Commission ... 31 ...

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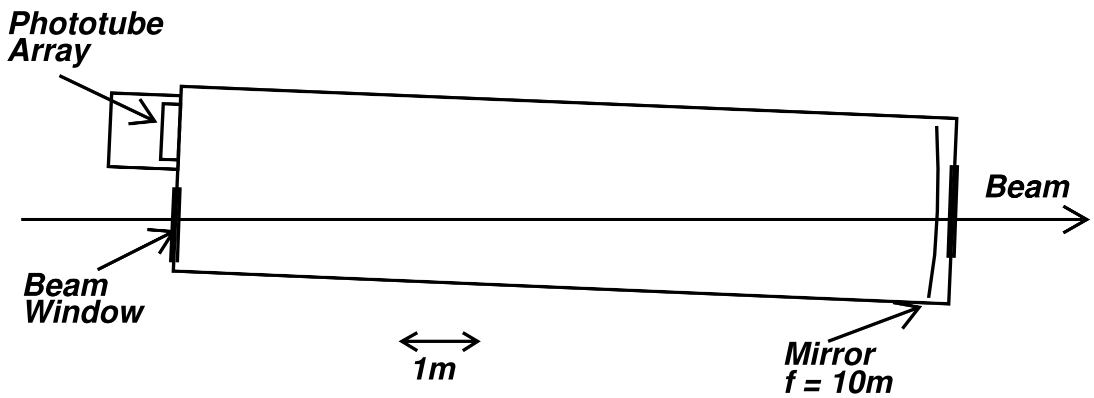
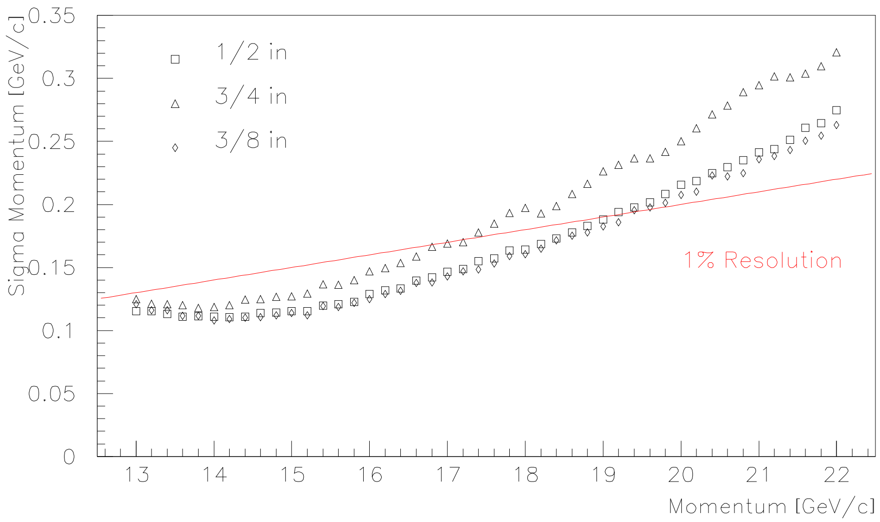
Pion RICH

Straight Copy of the SELEX RICH; Gas: Neon at atmospheric pressure.

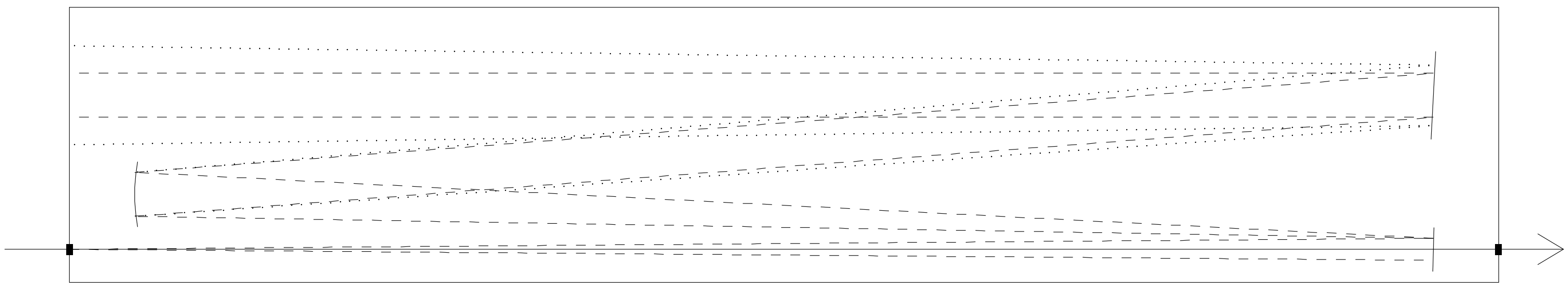


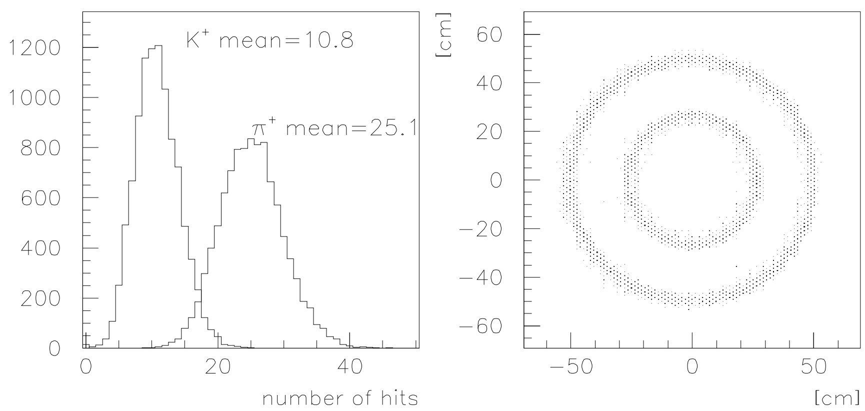
Change vessel length from 10 m to 20 m, Radius of Mirror(s) from 20 m to 40 m.



- Momentum Resolution $< 1\,\%$
- $\pi - \mu$ Separation $> 10\,\sigma$
- Rate per tube due to beam pions $< 400\,$kHz
- Rate per tube due to kaon decay products $< 90\,$kHz
- Resolution not limited by one factor (PM size, chromatic dispersion, mirror alignment)

Kaon RICH





- 11 m long vessel, N_2 (1 atm) or CF_4 (0.7 atm) as gas.
- double folded light path, $R = 40$ m
- Mirrors reflect only part of Cherenkov Photons from beam pions
- Pion and Kaon Rings nicely separated
- Rate per tube < 1400 kHz
- Resolution limited by chromatic dispersion
- Need to use Photomultiplier with glass window (cutoff 300 nm)

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
$\text{KRICH}(K^+)$	At least six hit PMTs in the kaon RICH.
$\text{KRICH}(\pi^+)$	At least six hit pion arm PMTs of the kaon RICH.
$\text{PRICH}(\pi^+)$	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.

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

DAQ: 100 MhZ “Shift Registers” with 1 nsec time resolution

Newest Idea: Triggerless. All data to a LINUX Farm

Simulation and Reconstruction

- All Detectors included in "CKM_GEANT", tuned on existing devices

Reconstruction algorithm

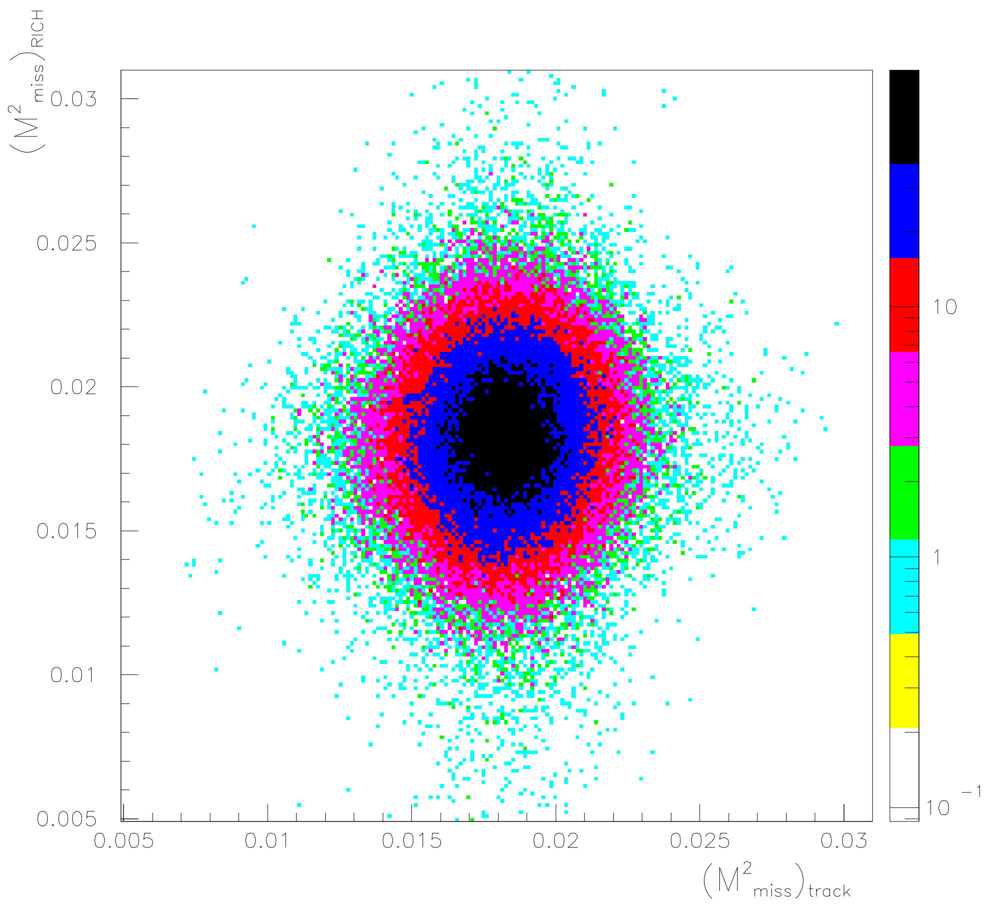
- Magnetic Spectrometers: Momentum measurement uses full info, angle just comes from KEAT
- RICHes: All PM hits get fit to one ring. No track info used. Outputs velocity and angles.
- Event Kinematics: Missing mass M^2_{miss} calculated for RICH and tracking system separately, later weighted by average resolution.

Selection Cuts

- Aperture, Cleanliness
- Vertex
- Spectrometer agreement: Momentum/velocity measurements agree

Comparison of Momentum and Velocity Spectrometers

$1 \cdot 10^6 K^+ \to \pi^+\pi^0$ simulated Missing Mass Distributions

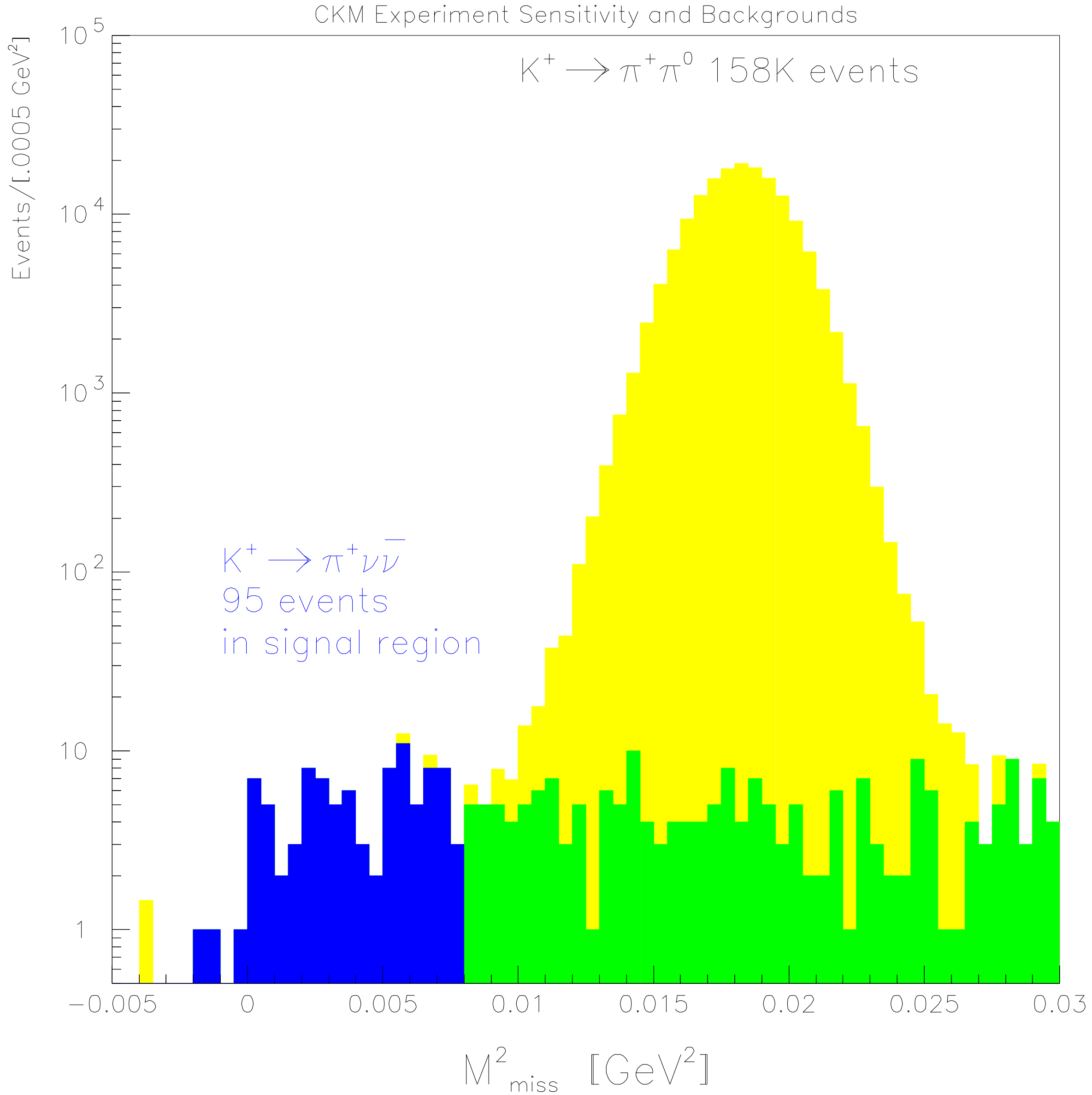


$$M^2_{\text{miss}} = M^2_K(1 - p_\pi/p_K) + m^2_\pi(1 - p_K/p_\pi) - p_\pi p_K \theta^2$$

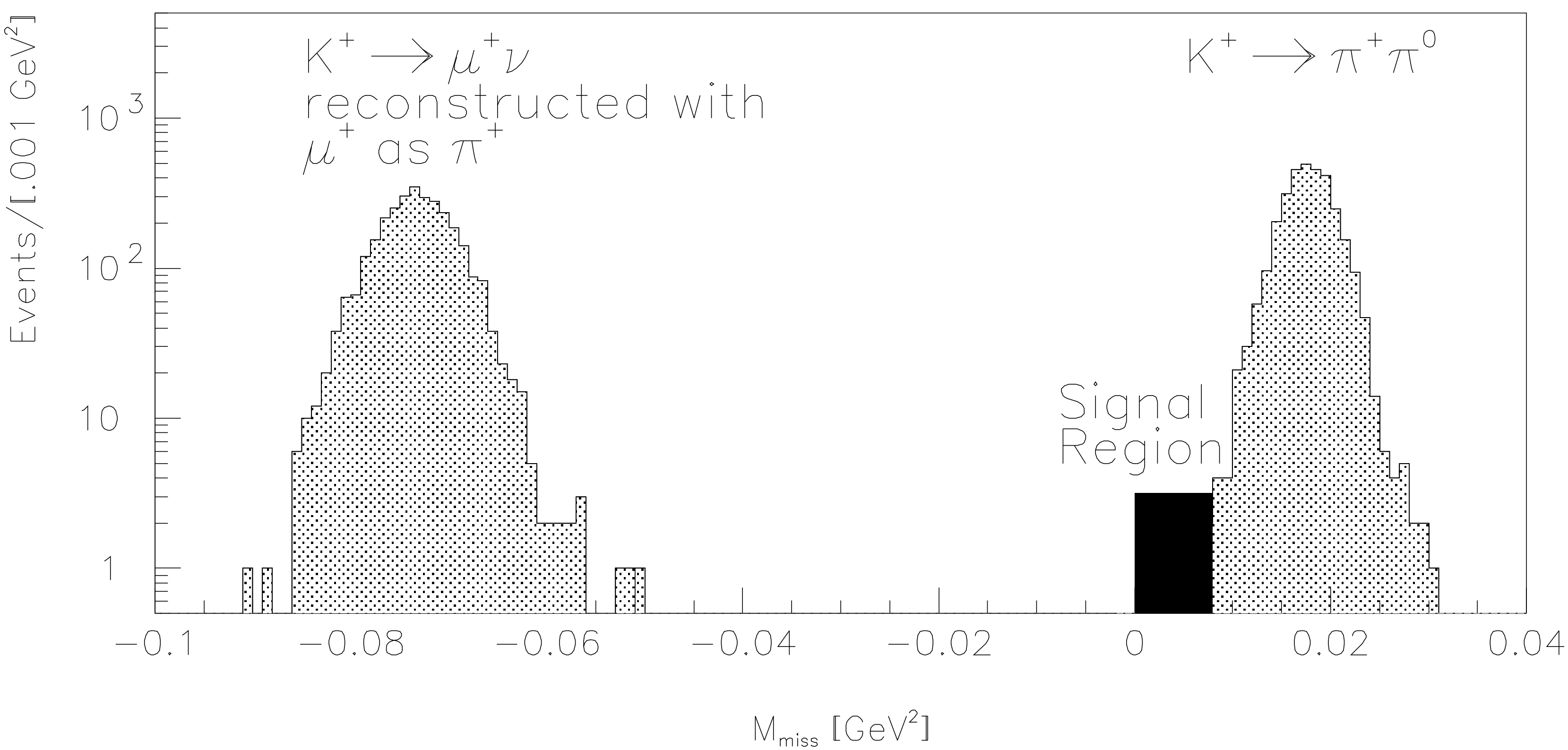
Simulated Background sources

Background Source	Effective BR ($\times 10^{-12}$)
$K^+ \to \mu^+ \nu_\mu$	< 0.04
$K^+ \to \pi^+ \pi^0$	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

The Final Signal Plot



And where are the μ^+ from $K^+ \to \mu^+\nu_\mu$?



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}
- Lepton Flavor Violating Decays
- $K^+ \to l^+\nu_l\gamma$: $\mathcal{T}_{\rm odd}$ Correlations
- $K^+ \to \nu\mu\gamma$: Test of Chiral Perturbation Theory

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:	2nd Edition of Proposal submitted
June 2001:	**Stage 1 Approval by Fermilab**
April 2003?:	Technical Design Report
2006??:	Running
2007-????:	Data analysis and publications.

Summary

- $K^+ \to \pi^+ \nu\bar{\nu}$ provides theoretically clean measurement of V_{td} to test $\mathcal{CP}$ Violation description in Standard Model.
- CKM experiment at Fermilab will measure $\approx$ 100 events

- Two RICH Detectors employed as "Velocity Spectrometer"
  - Modeled after the SELEX RICH
  - Can stand High Rates
  - Very low Noise ($<$ 1 kHz per Tube)
  - Good Time Resolution
  - Gaussian Resolution Function

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

Additional transparencies

RF Separated Beam

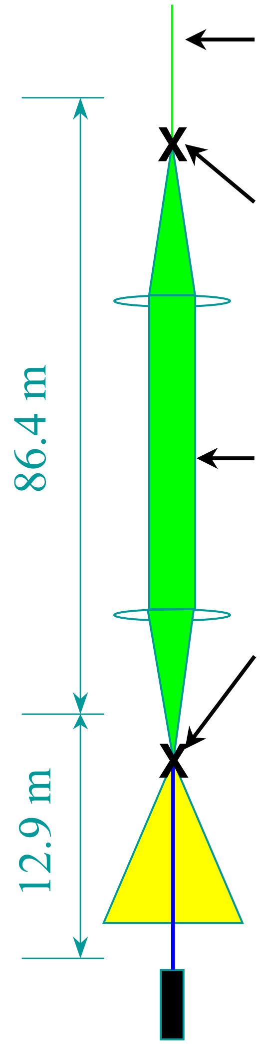
- Main Injector Beam 120 GeV. Put on a target, select 22 GeV
- Run two RF stations (same frequency, fixed phase)
- Tune phase shift so that pions and protons get two opposite transverse kicks, and kaons will get two in same direction).
- Put proper collimators
- Final beam contains mostly Kaons

- Problem: 1 sec spill from MI is "DC". $\Longrightarrow$ Superconducting RF
- We will use 3.9 GHz
- Project[4] approved (and funded!) at Fermilab to gain experience for TESLA

- 30 MHz K^+, 10 MHz others (mostly π^+)
- debunched, 22 GeV $\pm$ 1 %
- divergence $\approx$ 100 μrad
- Muon rate $\approx$ 7.5 MHz in 1 m $\times$ 1 m

[4] Fermilab TM-2060

RF separated K^+ beams



Initial momentum-selected beam *$\Delta P/P \sim 2\%$*

RF deflection: *$A\sin(\omega t)$*
$A \sim 15$ MeV/c

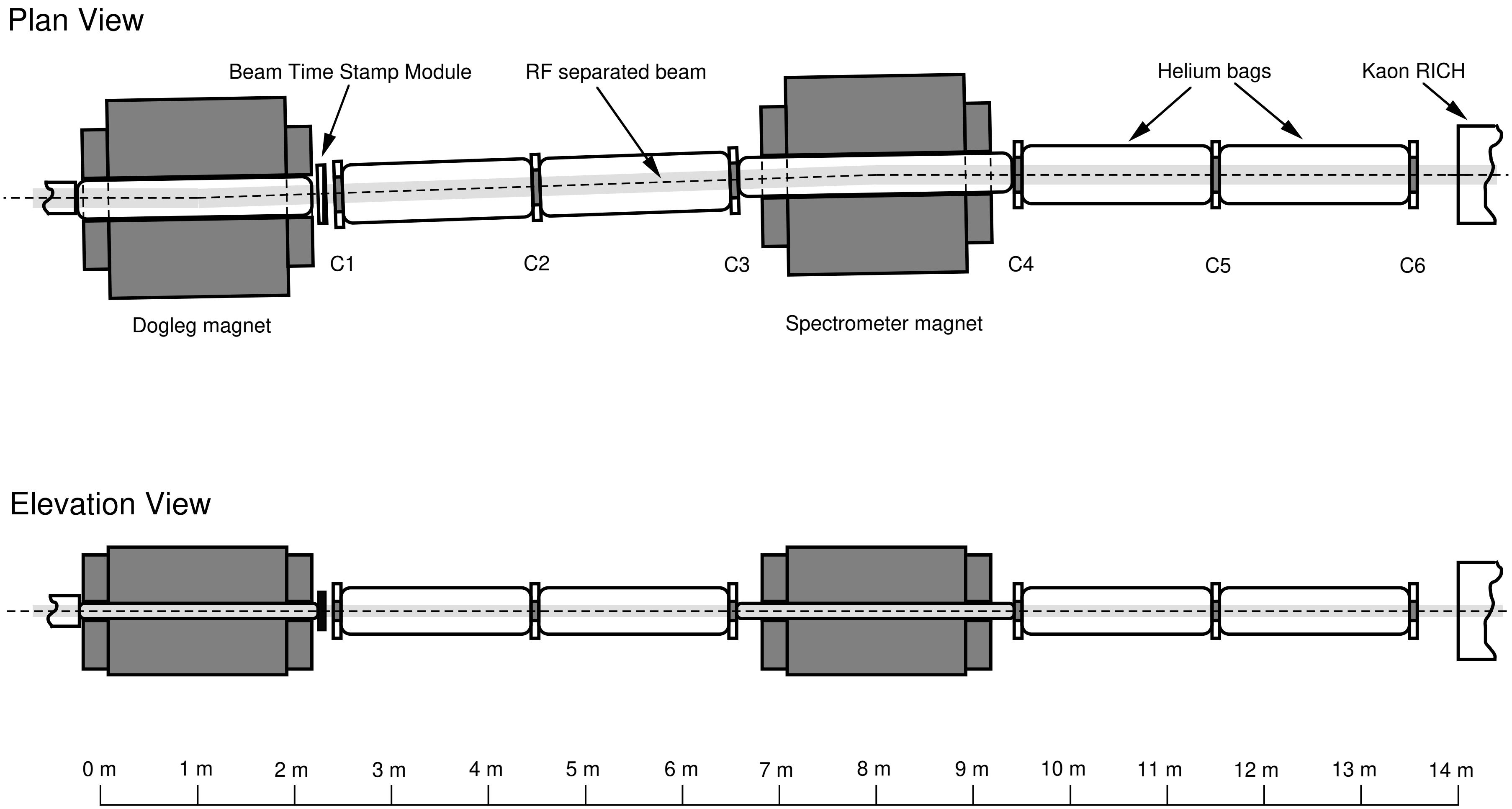
Transport $L = (\text{integer})\beta_\pi c\,/f$
Δt then integer multiple of $2\pi\omega$ for π^+

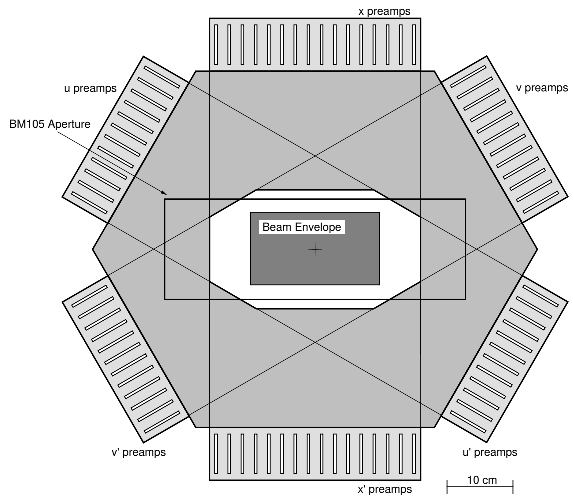
2nd RF deflection *e.g.* 180^o out of phase: *$-A\sin(\omega t+\omega\Delta t)$*

For π^+, no net deflection
For K^+, deflection is
$2A\sin(n\beta_K c/2f) \bullet$
$\cos(wt + n\beta_K c/2f)$

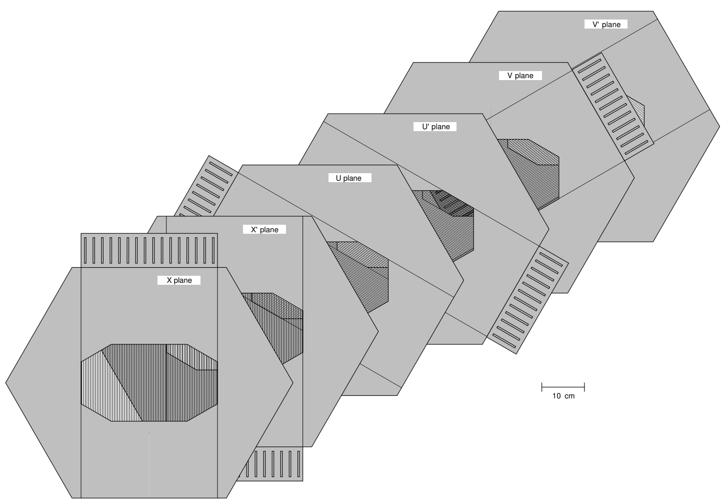
Stop π^+ with beam plug, collect K^+

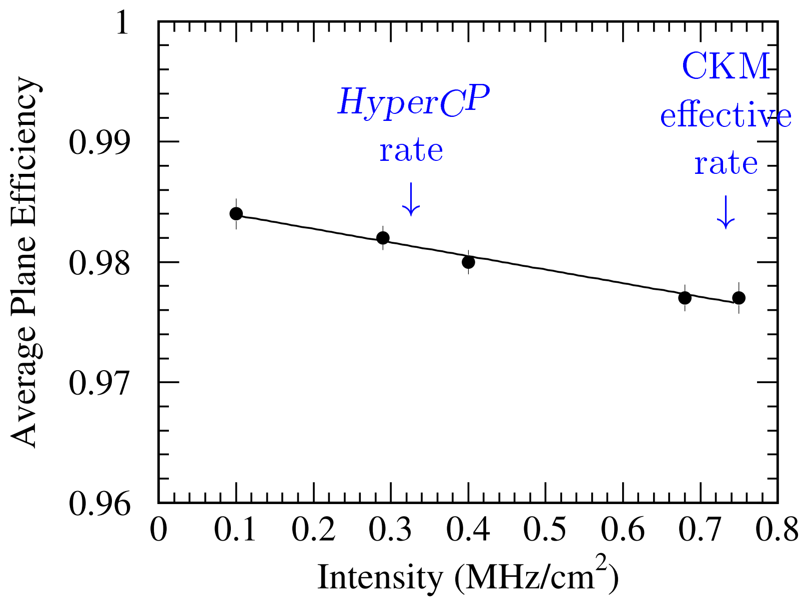
Upstream Magnetic Spectrometer (UMS)





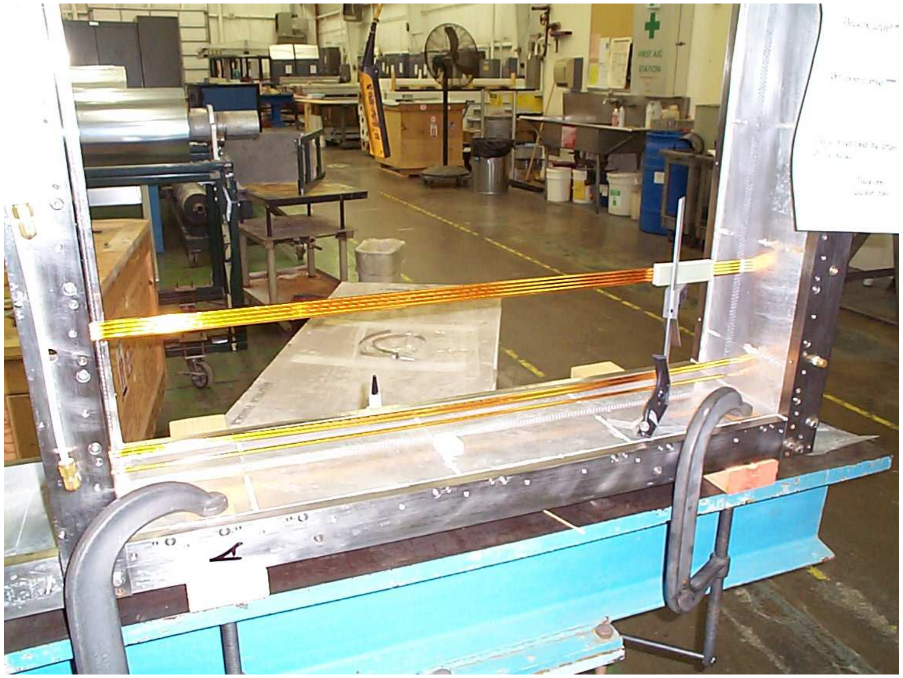
- Changed from 1st edition of proposal
- Modeled after *HyperCP* chambers
- 6 stations
- Each station has 6 views
- Wire pitch 0.8 mm
- Rate per wire < 610 kHz



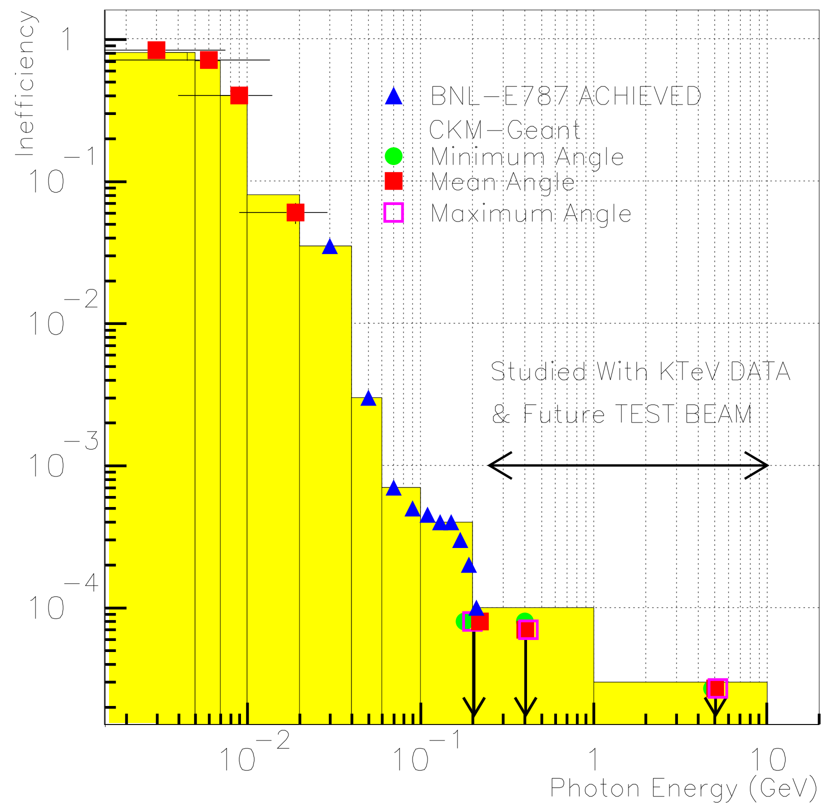


Downstream Magnetic Spectrometer (DMS)

- 4 planar straw drift chambers (after BNL E871)
- 5 / 8 / 8 / 8 views
- Each straw: 5mm diameter
- Drift time $\approx$ 25 nsec
- Deadened in beam
- Maximum rate 120 kHz per straw
- Situated in Vacuum



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.
- VVS: Fine sampling Pb/Scint after KTeV
  Prototype built to be tested this year
- FVS: Using KTeV CsI Calorimeter

Discrete Symmetries in Particle Physics

- Parity $\mathcal{P}$
- Charge Conjugate $\mathcal{C}$
- Time Reversal $\mathcal{T}$

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

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

Where is all the Antimatter?

Sacharov (1967?): Need 3 Conditions Matter/Antimatter Asymmetry:

- Violation of $\mathcal{C}$ and $\mathcal{CP}$
- Violation of Baryon Number
- Non-Equilibrium Condition in the Early Universe

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. $\longrightarrow$ Need only 3 real and one imaginary parameters

Current experimental values[5]

$$|V| = \begin{pmatrix} 0.9742 - 0.9757 & 0.219 - 0.226 & 0.002 - 0.005 \\ 0.219 - 0.225 & 0.9734 - 0.9749 & 0.037 - 0.043 \\ 0.004 - 0.014 & 0.035 - 0.043 & 0.9990 - 0.9993 \end{pmatrix}$$

Wolfenstein parameterization:

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

[5] PDG, 2000

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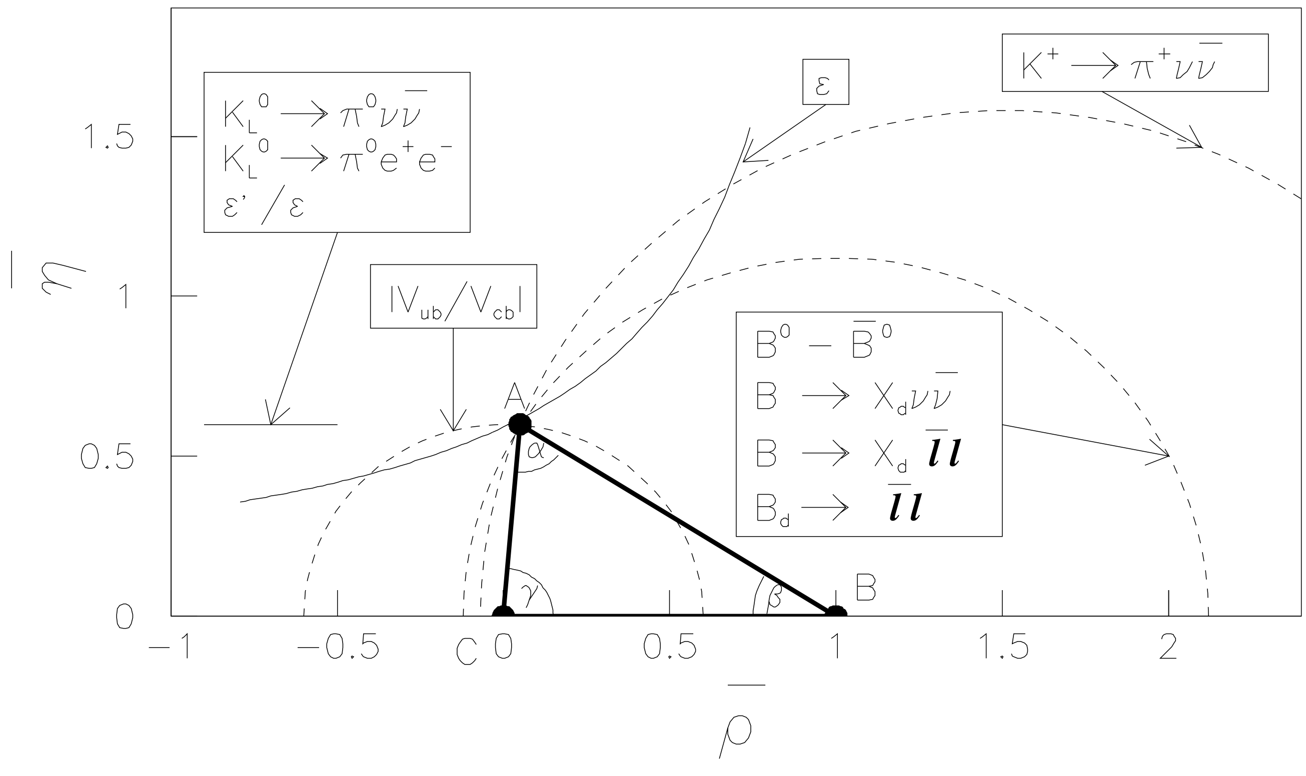

Magnetic Spectrometers

- UMS - MWPCs with 0.8 mm wire pitch using the last bending magnet in the beamline. Fiber planes to measure time.
  - Modeled after $HyperC^{P}$chambers
  - Rate per wire $< 610\,\mathrm{kHz}$
- KEAT - Same technology as UMS. To control scattering in Kaon RICH gas and mirror.
- DMS - Straw tubes deadened in the beam. Straws are in the decay volume vacuum!!
  - 4 planar straw drift chambers (after BNL E871)
  - Each straw: mm diameter
  - Drift time $\approx 25\,\mathrm{nsec}$
  - Maximum rate 120 kHz per straw
- 200 MeV/c p_t kick magnet. Fiber planes to measure time and cover beam region.

Apparatus (cont.)

- 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.
  - VVS: Fine sampling Pb/Scint after KTeV. Prototype built to be tested this year
  - FVS: Using KTeV CsI Calorimeter
- 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%.
  - Prototype being tested now in Protvino
- Magnet
  - We will use KTeV Magnet
- Beam Interaction Veto
- Beam Dump