Charged Kaons at the Main Injector

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

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Goals

1. To be able to observe approximately 100 events for a 1×10^{-10} branching ratio in two years of running with the Main Injector.
2. To reduce all backgrounds to the level of a few events.
3. To limit capital costs to less than 10M$.

Theory

$$\frac{B(K^+\to\pi^+\nu\nu)}{B(K^+\to\pi^0 e^+\nu)} = \frac{\alpha^2}{8\pi^2\sin^4\theta_W}\left| V^*_{cs}V_{cd}\, D\left(\frac{m_c}{m_W}\right) + V^*_{ts}V_{td}\, D\left(\frac{m_t}{m_W}\right)\right|^2 \frac{1}{|V_{us}|^2}$$

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

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

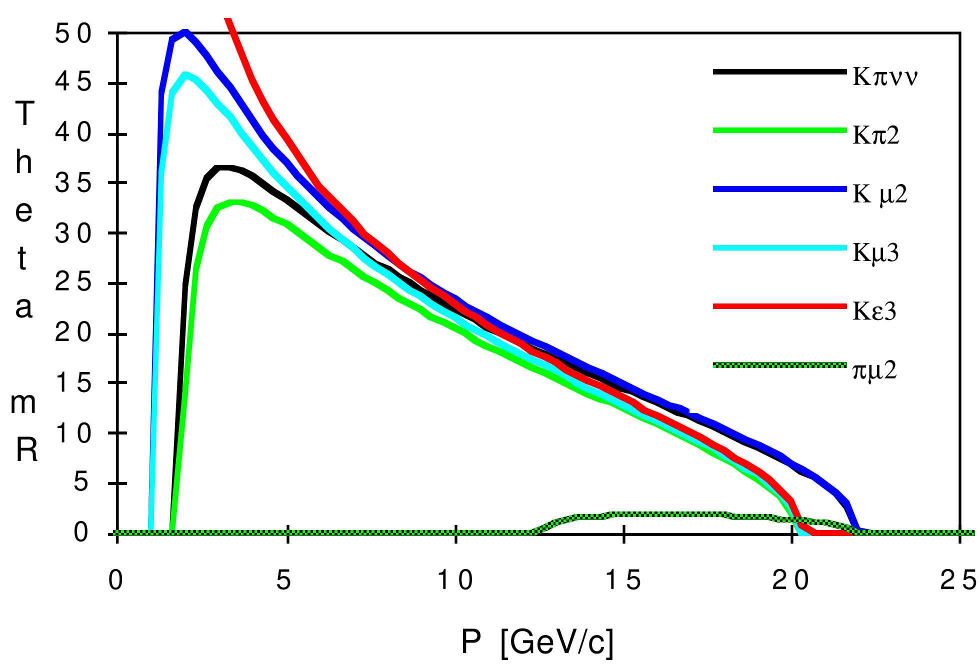
where λ = 0.2205(18) is the usual Cabibbo angle and A = 0.82(10) from V_{cb}.

$$B(K^+\to\pi^+\nu\bar{\nu}) = [(0.52 \pm 0.14) \times 10^{-10}]\left[(1.30-\rho)^2 + \eta^2\right]$$

Charged Kaon decay primer

Mode	Name	Br	P_t^{max} [GeV/c]	Class
$\mu^+ \nu$	$K\mu 2$	.63510	.2355	
$\pi^+ \pi^0$	$K\pi 2$	.21170	.2051	**background**
$\pi^+ \pi^+ \pi^-$	$K\pi 3$	.05589	.1254	
$e^+ \pi^0 \nu$	Ke3	.04820	.2284	
$\mu^+ \pi^0 \nu$	$K\mu 3$	.03180	.2151	background
$\pi^+ \pi^0 \pi^0$	$K\pi 3$	.01730	.1329	
$\mu^+ \nu \gamma$	$K\mu 2\gamma$	5.5×10^{-3}	.2355	background
$e^+ \pi^+ \pi^- \nu$	Ke4	3.9×10^{-5}	.1679	
$e^+ \pi^0 \pi^0 \nu$	Ke4	2.1×10^{-5}	.1730	
$e^+ \nu$	Ke2	1.5×10^{-5}	.2468	
$\mu^+ \pi^+ \pi^- \nu$	$K\mu 4$	1.4×10^{-5}	.1448	
$\pi^+ \nu \nu$	$K\pi\nu\nu$	1.0×10^{-10}	.2271	signal

Kaon Decay Kinematics [22 GeV/c]



Previous Measurements and Their Limitations

BNL E787 proposed 1983, running about 5 years

Sensitivity $Br[K^+ \to \pi^+\nu\overline{\nu}] < 2.4 \times 10^{-9}$ [90%CL]

Stopped Kaons 200 KHz, 4π magnetic detector

$\mathbf{P}_K = 0$, $\mathbf{P}_\pi$ by curvature and range

Particle ID by obsevring $\pi \to \mu \to e$ decay chain

4π photon vetos - Pb Scint + CsI

Limitation - the muon lifetime is **not** negotiable!

If the kaon stop rate ~1/2.2 μsec = 500 kHz

then events pile up in the detector

acceptance $\varepsilon \sim 0.6\%$, $Br = 1 \times 10^{-10}$

BNL beamtime 3×10^6 sec/year

$\Rightarrow$ Sensitivity ~ 1 event/year

This is a beautiful experiment - but it won't see 100 events

upgraded can reach 5×10^{-11} sensitivity by 1998

Another Idea

If decay at rest isn't sensitive enough then decay in flight is the only other choice.

Need: Short resolving time [2 μsec $\to$ 20 nsec]

Momentum and ID for both K and π.

High K flux [$10^5 \to 10^7$ K decays/sec]

Problems: Mass Resolution - to seperate different decay modes

Accidentals - measure time of everything to control

Interactions - minimum material in the beam

Solution: Non-magnetic spectrometers with pRICHs

$\Delta P_K/P_K = <1\%$ $\Delta P_\pi/P_\pi = \sim 1\%$ $\Delta M^2_{\nu\nu}/M^2_{\pi^o} = 10\%$

Measurement of velocity rather than momentum helps ID

Control pileup/accidentals with timing.
Easy to measure time of PMT pulses to 1 nsec

Material in beam is mainly radiator gas [$X_L = 12\%$, $I_L = 4\%$]

Apparatus

Beam

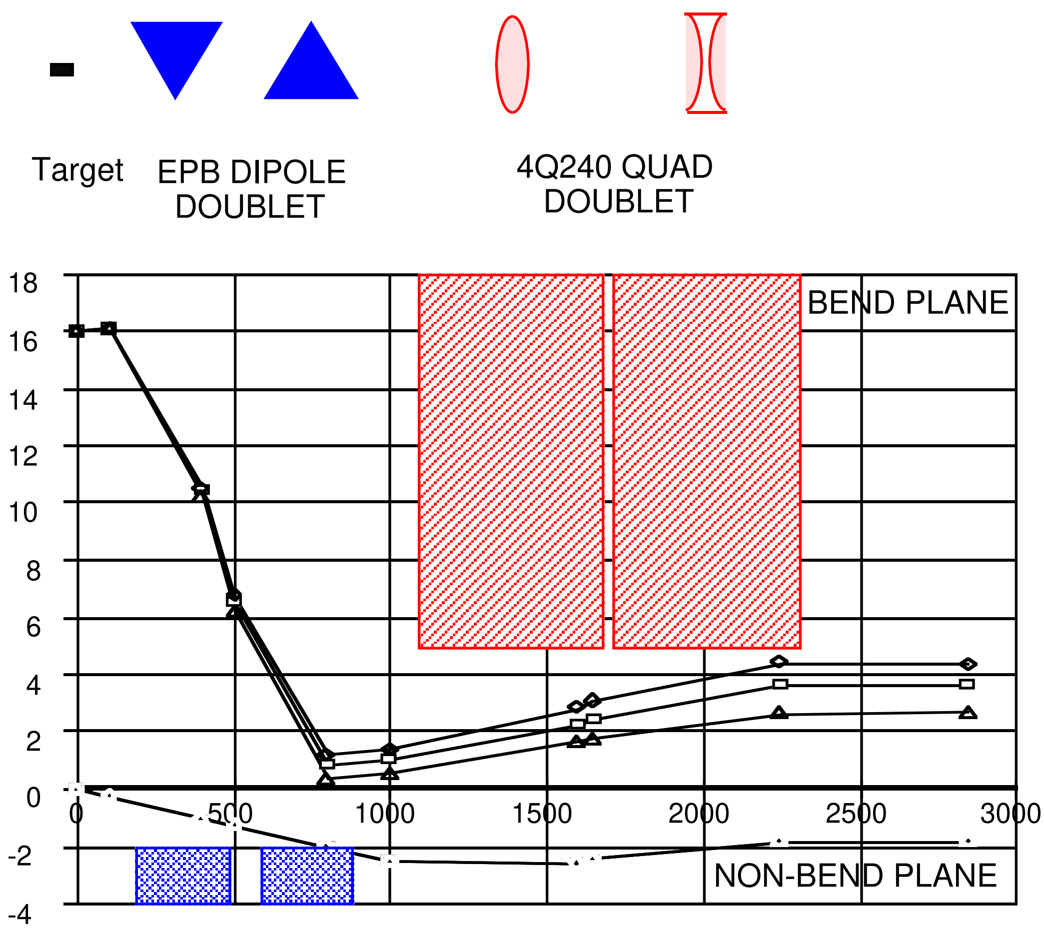
- >300 MHz unseperated positive beam at ~22 GeV/c

  [BNL 777 was done in such a beam at 6 GeV/c]
- Kaons are just above Cerenkov threshold in Nitrogen
- **Main Injector -** Debunched beam required

  [or the accidentals have us for lunch!]
- $\Delta P/P = \pm 2.5\%$ $\Delta\theta = \pm 50\ \mu$rad, [parallel, large area]
- Secondaries/incident proton = ~6 x 10^{-3}

  $\Rightarrow$ ~5 x10^{11} protons/sec [~1% of MI intensity]

CKM Conceptual Beamline Design



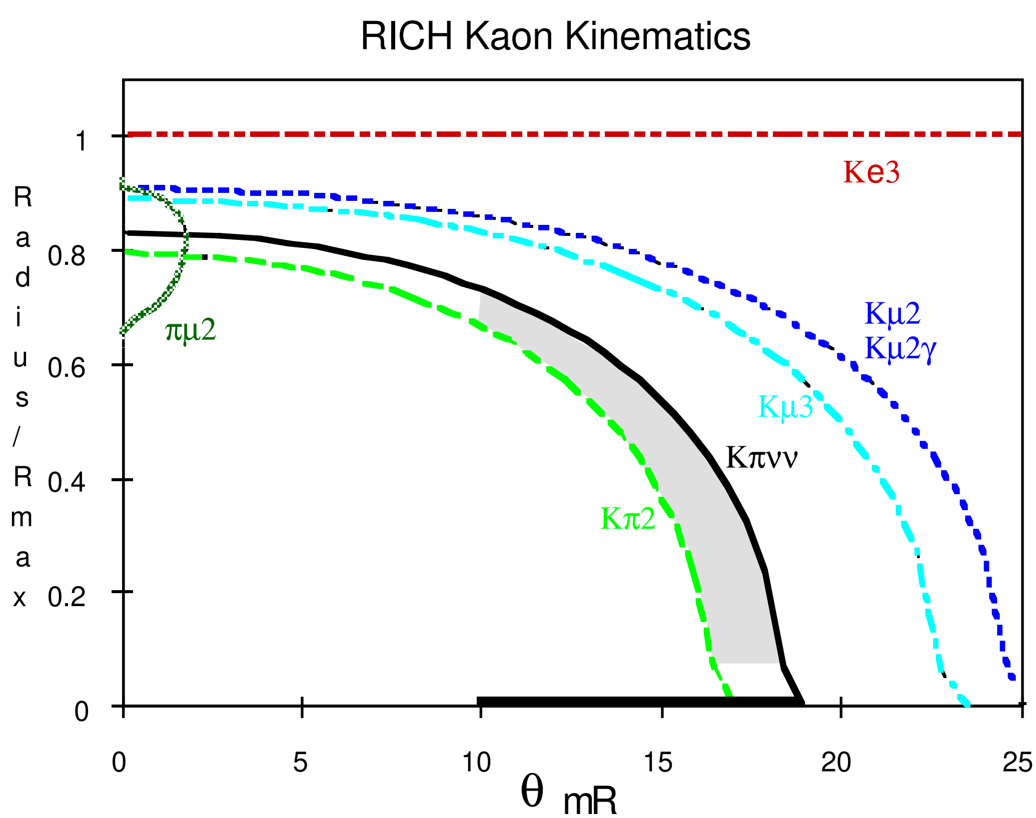
Detectors

A RICH simultaneously measures the incident angles of all radiating tracks and the associated velocities of those tracks. Cherenkov light is isochronous.

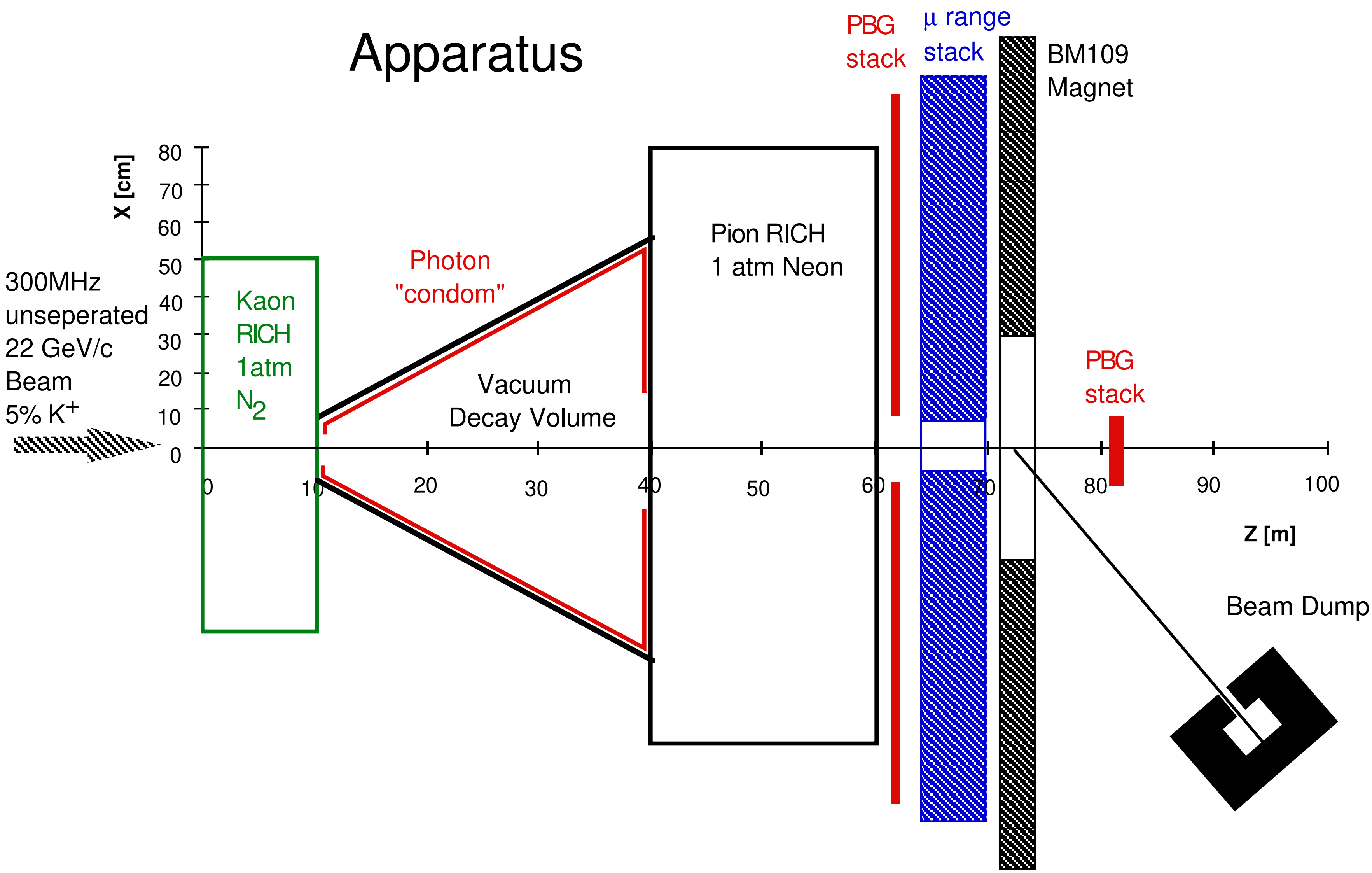
- N_2 pRICH at threshold to measure/identify Kaon ($\Delta P/P$~0.5%)
  Blind to beam (π, no PMTs at large radii; p are below threshold)

- Long vacuum decay volume
- Neon pRICH at measure/identify Pion ($\Delta P/P$~1%, $\Delta\theta_{K\pi}$~ 400 μRad)
  Thresholds: π, 12 GeV/c; K, 40 GeV/c; p, 80 GeV/c

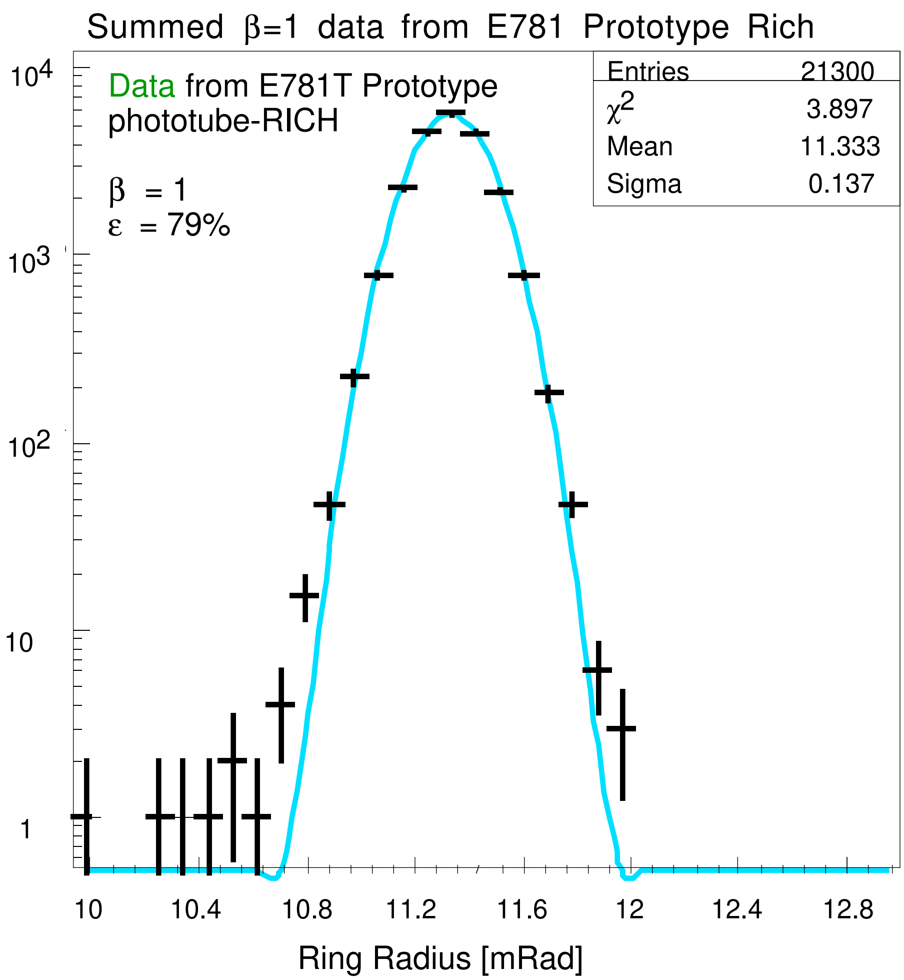
- Resolving time ~10 nsec (PMT pulse width) σ_t ~ 1 nsec
- Photon veto system to tag photons with inefficiency ~10^{-3}
- Muon range stack to tag muons with inefficiency ~10^{-4}



Apparatus



300MHz
unseperated
22 GeV/c
Beam
5% K+
X [cm]
0
10
20
30
40
50
60
70
80
Kaon
RICH
1atm
N2
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



Backgrounds

Mode	Br	Veto Inefficiency	Geometrical Efficiency	Events N_k=2.8 x 10^{13}
$\pi^+ \nu \nu$	1 x 10^{-10}	1	4.7%	158*
$\pi^+ \pi^0$	.21170	2 x 10^{-5}	18%	1107751
$\mu^+ \nu \gamma$	.00546	1 x 10^{-6}	0.15%	<25
$\mu^+ \pi^0 \nu$	.03180	1 x 10^{-9}	0.15%	<1

μ Inefficiency = 1 x 10^{-4}

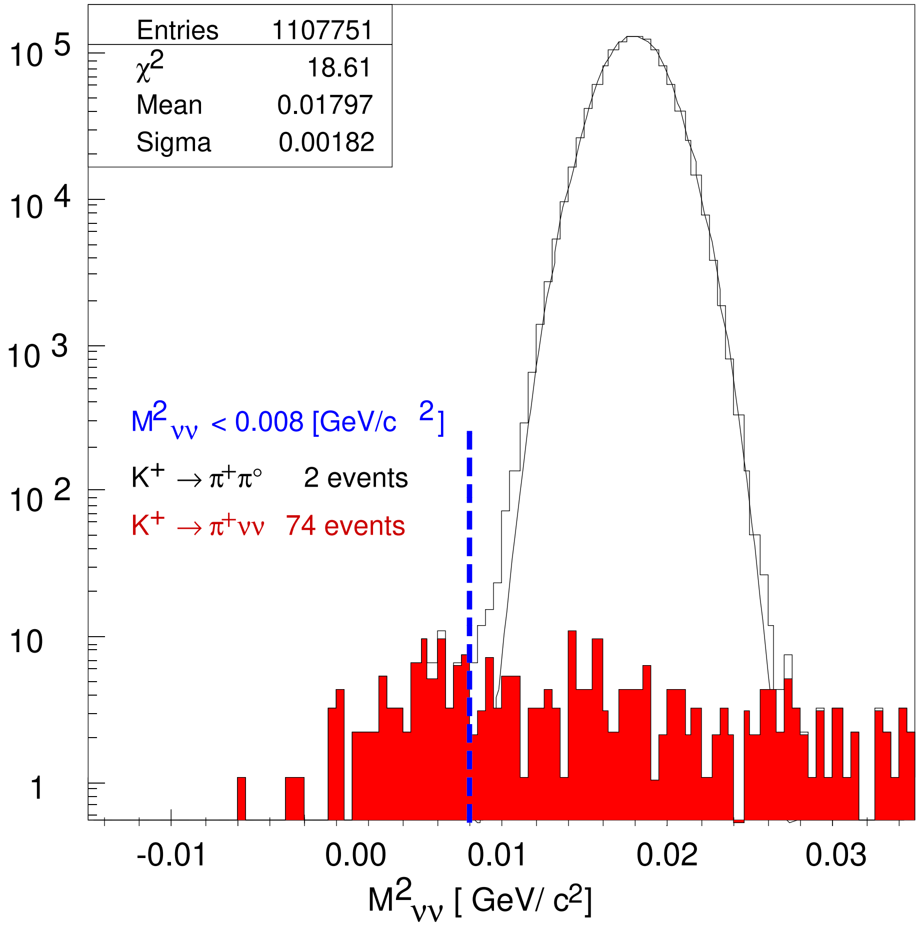
γ Inefficiency = 1 x 10^{-3}

π^0 Inefficiency = 2 x 10^{-5}

* $-.015$ [GeV^2/c^4] < $M^2_{\nu\nu}$ < $M^2_{\pi^o}$ = .0182 [GeV^2/c^4]

1 x 10^7 live beam seconds of data

Results - assuming Br = 1×10^{-10}, N_K = 2.8×10^{13}



Physics Reach

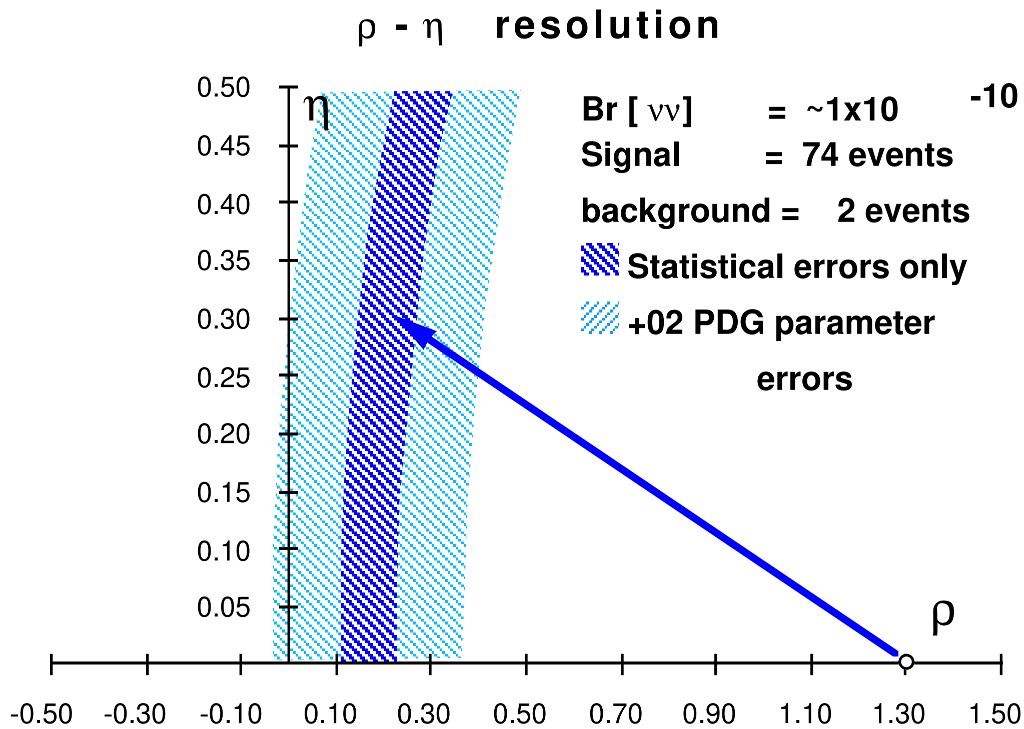
Contribution to radius resolution of annulus on the $\rho - \eta$ plane from

statisitcs (including background)

other standard model parameters

Resolution with guessed SM improvements by 2002

parameter	94 PDG value	radius % error	02 PDG value	radius % error
$\sin\theta_C$	0.2205(18)	3%	0.2205(18)	3%
A	0.82(10)	24%	0.82(4)	<u>10%</u>
M_t [GeV/c^2]	174(17)	9%	174(10)	<u>5%</u>
M_c [GeV/c^2]	1.3(0.3)	7%	1.3(0.3)	7%
Statistics	74(9)	6%	74(9)	6%
Total		27%		15%



Summary

RICH Velocity spectrometer adds new experimental dimensions

- Much improved resolving time allow much higher rates
- π/K/p beam seperation is "free"
- The "pixel" photocathode gives a remarkably gaussian resolution function
- Fast and efficient PMT RICHs are now really feasible

More work required to know if the experiment will really work.

- Study accidentals
- Simulate interaction backgrounds
- Optimized design to improve resolution. Add redundancy to control non-Gaussian resolution tails
- More realistic beam design

Proposal in the Fall provided goals can be met

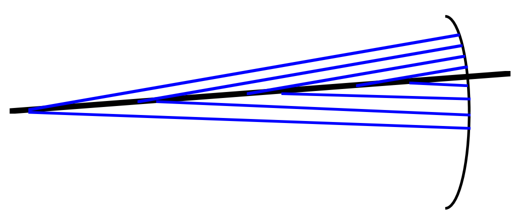
KTEV, SELEX and BNL E871 come first

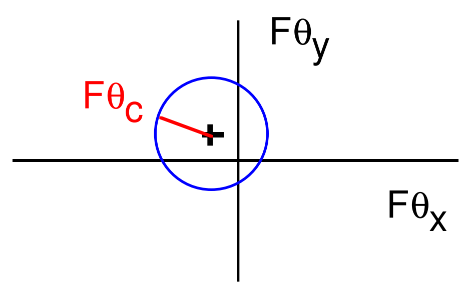
Ring Imaging CHerenkov counter primer

Cerenkov effect equations

θ_c	$= [\, 2\delta - 1/\gamma^2 \,]^{1/2}$	Cerenkov angle
δ	$= n - 1$	index of refraction
	$= 64 \times 10^{-6}$ (γ_{th}=88)	for Ne at 1 atm
N_{pe}	$= AL\sin^2\theta_c$	Photo-electrons observed
	L	length of radiator
	A ~ 150 /cm	Figure of merit

Cerenkov light is emitted at a constant angle θ_c to a track throughout the radiator. If this light is imaged by a spherical mirror to it's focal plane (where position is proportional to incident angle) a ring is formed whose center is given by the angle of the track and whose radius is $R = F\theta_c$ where F is the focal length of the mirror.





A RICH simultaneously measures the incident angles of all radiating tracks and the associated velocities of those tracks. Cherenkov light is isochronous. All photons arrive at the focal plane at the same time independent of where they were emitted.