

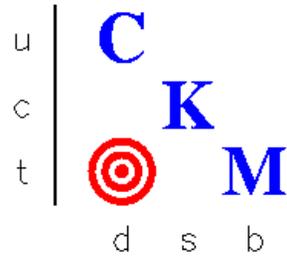
# Charged Kaons at the Main-Injector

*R. Tschirhart, Fermilab March 26th, 2003*

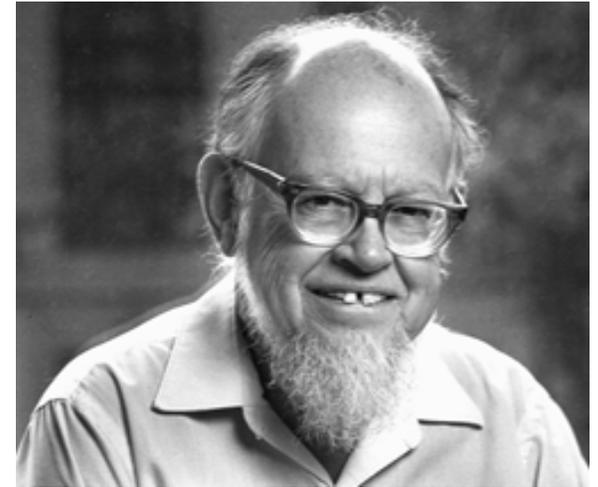
*Presentation to P5 Visiting Panel.*

CKM Physics Goals & State of the  
 $K \rightarrow \pi \nu \bar{\nu}$  Field.

# Why are we doing this?



“I invented  $\rho$  and  $\eta$  and I don't care what their values are so why should you?? The *physics* here is to determine if the breadth of CPV phenomena are really described by this simple description.”



Lincoln Wolfenstein, CMU

The work of many authors has shown that theories beyond the Standard Model (e.g. SUSY) typically contain much more CPV, and often very different manifestations between the B and K systems. **Particularly in FCNC interactions.**

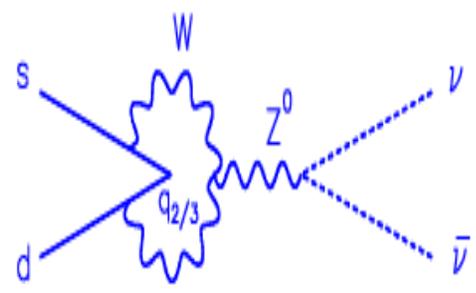
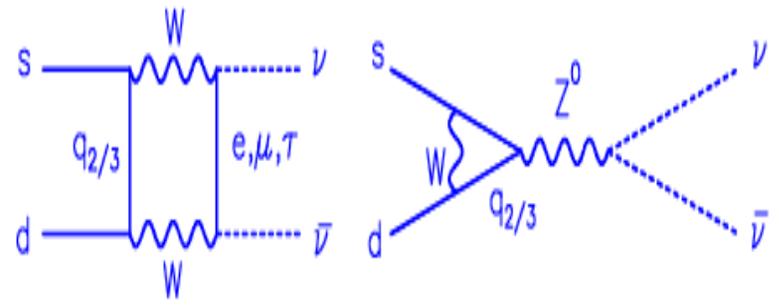
u	C
c	K
t	M
	⊙
	d s b

# Primary Physics Goal of CKM:

## Precision Measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ .

This decay is determined by loop processes to high order in the SM, and hence has a reach for *new physics at the EW scale and beyond*.

The SM rate can be calculated with a high degree of confidence, and hence any deviation in the measured rate is a signal for new physics.



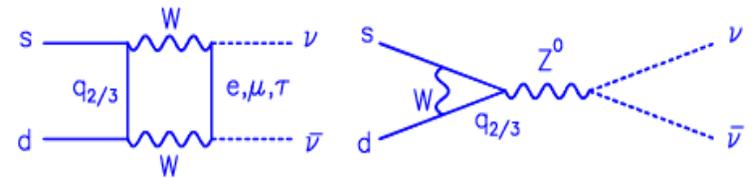
# WHY $K \rightarrow \pi \nu \bar{\nu}$ ?

u	C
c	K
t	⊙ M
	d s b

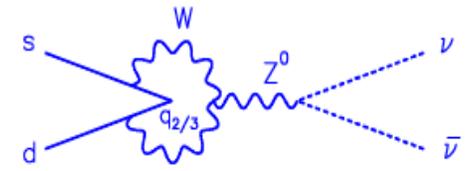
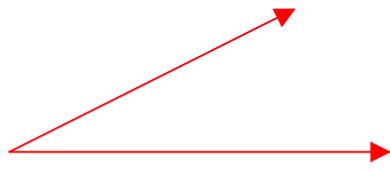
- The  $K \Rightarrow \pi \nu \bar{\nu}$  decay modes allow access to quark level physics since dependence on hadronic physics can be removed by normalizing to the well measured  $K \Rightarrow l^+ \pi \nu$  processes. This is new ground for kaon physics.
- Unfortunately the  $\pi l^+ l^-$  final states, while easier to measure, have correspondingly high levels of radiative backgrounds, (e.g.  $K_L \Rightarrow e^+ e^- \gamma \gamma$ ).
- Which leads us to the  $K \Rightarrow \pi \nu \bar{\nu}$  challenge...

# $K \rightarrow \pi \nu \nu$ in the Standard Model

➤ No Radiative Backgrounds.  
(& No radiative signal!)

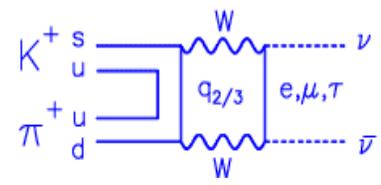


➤ Leading diagrams

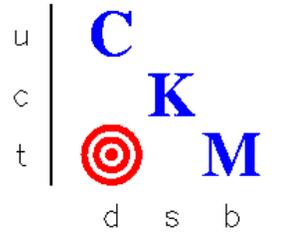


Direct sensitivity to  $V_{td}$  and BSM physics such as SUSY that can be present in these loops.

Dressing up into hadrons:



# CKM structure of these modes...



$$1. \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = K_+ \left( \left[ \frac{\mathcal{I}\lambda_t}{\lambda^5} X \right]^2 + \left[ \frac{\mathcal{R}\lambda_c}{\lambda} P_0 + \frac{\mathcal{R}\lambda_t}{\lambda^5} X \right]^2 \right)$$

$$2. \mathcal{B}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) = K_0 \left( \left[ \frac{\mathcal{I}\lambda_t}{\lambda^5} X \right]^2 \right) = K_0 (\eta A^2 X)^2$$

$V_{td}$

$$\lambda_i \equiv V_{is}^* V_{id}$$

$$K_+ \equiv r_+ B \quad K_0 \equiv r_0 B \tau(K_L^0) / \tau(K^+)$$

$$X \equiv X(x_t) \equiv \frac{x_t}{8(x_t-1)} \left( x + 2 + \frac{3x-6}{x-1} \ln x \right)$$

$$x_t \equiv (m_t/m_W)^2$$

$$B \equiv \frac{3\alpha^2 \mathcal{B}(K^+ \rightarrow \pi^0 e^+ \nu)}{2\pi^2 \sin^4 \theta_W}$$

Normalize to semileptonic process.

$$r_+ = 0.901 \quad r_0 = 0.944$$

$$P_0 = 0.40 \pm 0.06(\text{charm})$$

Charm Contribution

# Expectation and Measurements...

	Current	Theory
$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$	$(1.57_{-0.82}^{+1.75}) \times 10^{-10}$	$(0.8 \pm 0.3) \times 10^{-10}$
$\mathcal{B}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$	$< 5.9 \times 10^{-7}$ $< 4.4 \times \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$	$(0.3 \pm 0.1) \times 10^{-10}$

	Uncert.	References
$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$	5%	PRL88,041803(2002) hep-ph/0101336
$\mathcal{B}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$	1%	PRD 61,072006 (200?) hep-ph/9701313

Limit are at 90% CL.

Uncertainty dominated by current errors on  $V_{cb}$ ,  $\rho$ , and  $\eta$ .

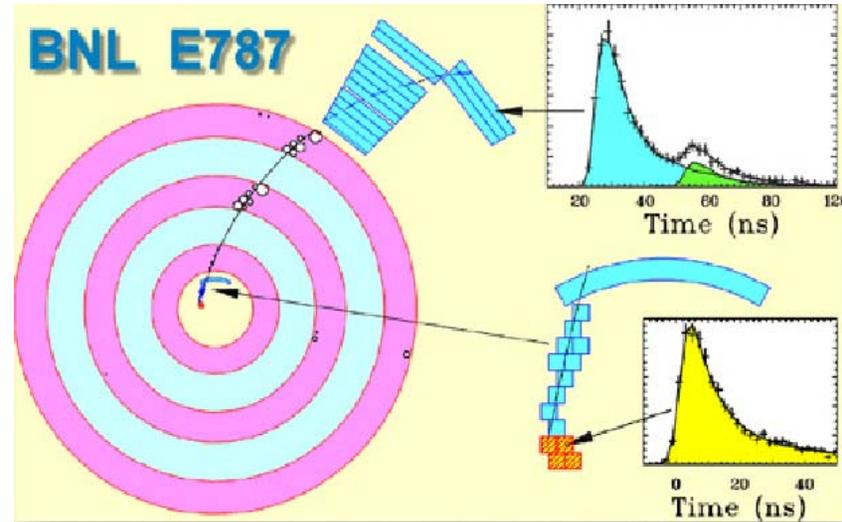
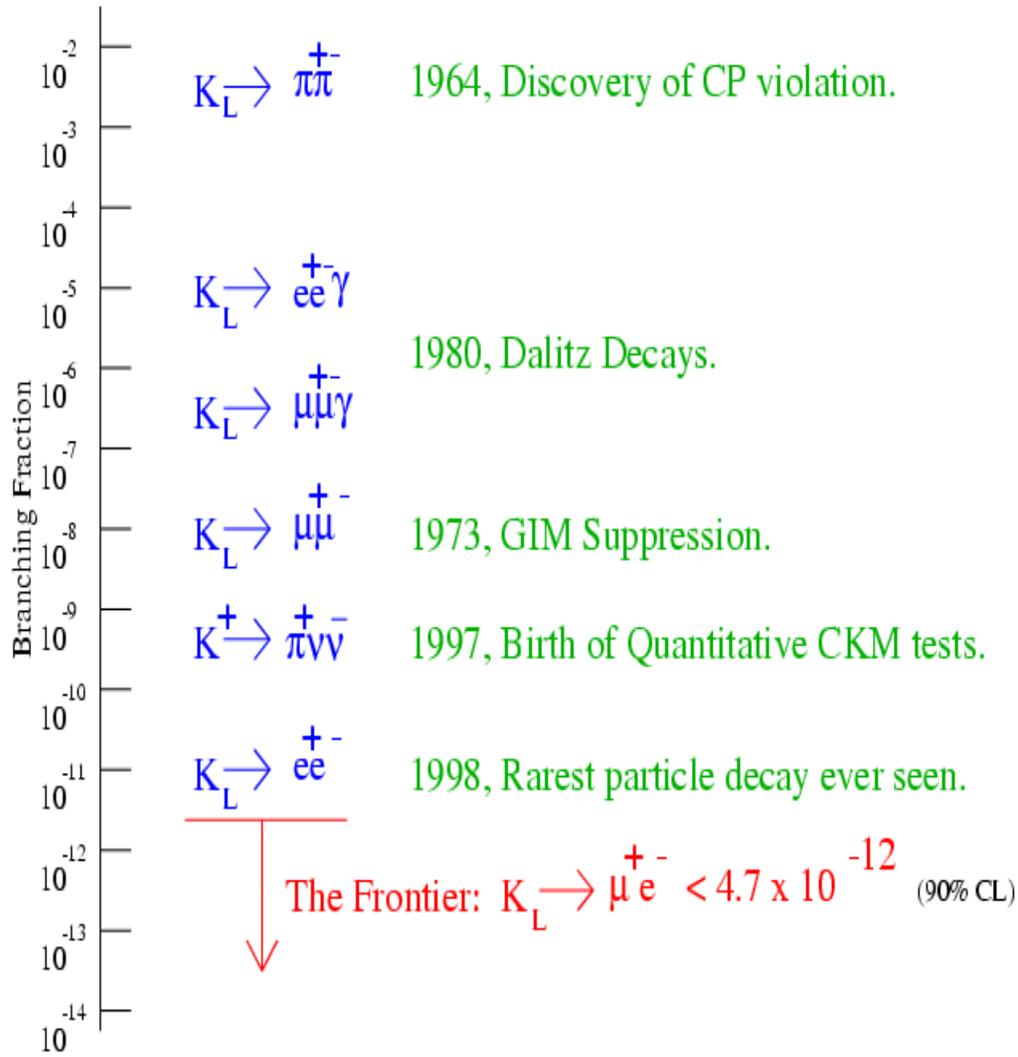
Theoretical Error Floor.

# What about the charm contribution?

- Size of the charm contribution (40%), is known to **5-8%**.
- Extreme excursion of the charm quark mass limits the Standard Model branching fraction to less than  **$13 \times 10^{-11}$**
- 3-Loop *perturbative* calculations in progress (Buras et al), and Lattice efforts on charm mass can reduce charm quark contribution to **less than 5%**.

# Evolution of the Frontier...

u	C	
c	K	
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	d	s b



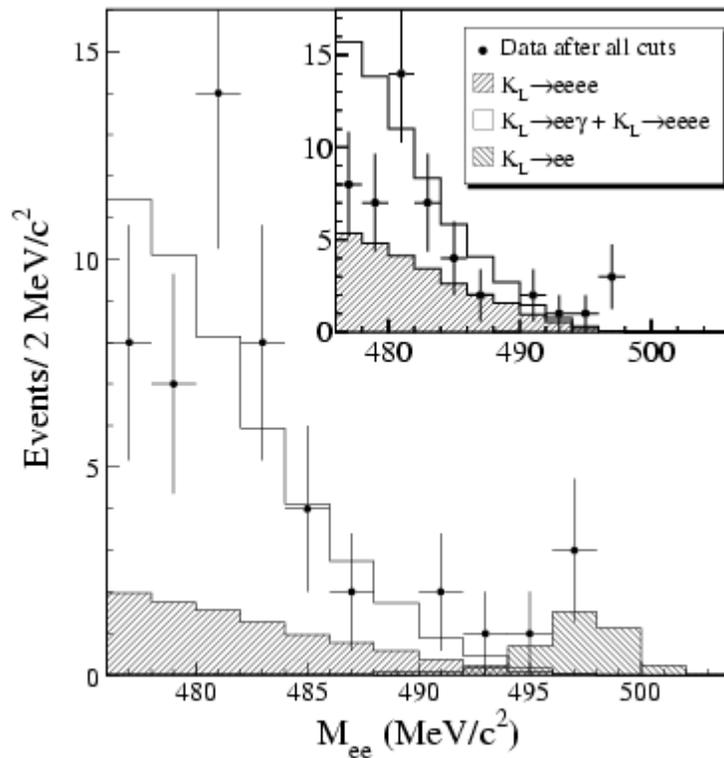
$$B(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (16^{+18}_{-8}) \times 10^{-11}$$

$$\text{SM: } (8^{+3}_{-3}) \times 10^{-11}$$

# Postcards From the Frontier...

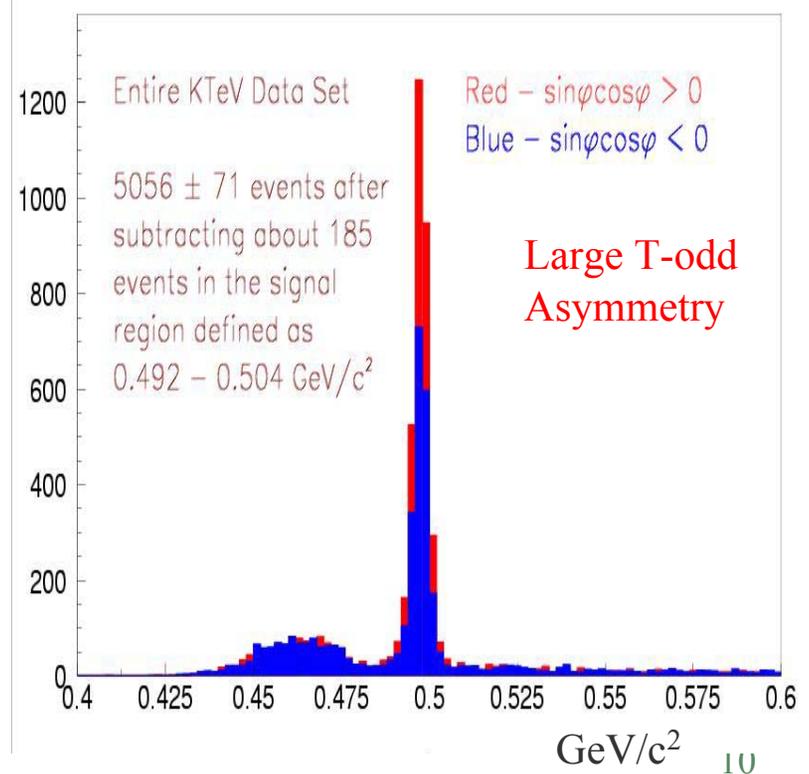
$K_L \rightarrow e^+ e^-$  (BNL-871)

Sensitivity:  $2 \times 10^{-12}$



$K_L \rightarrow \pi^+ \pi^- e^+ e^-$  (KTeV)

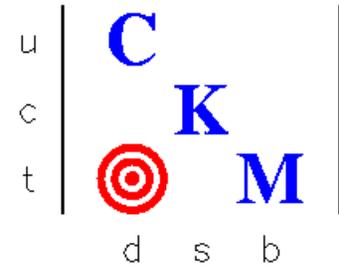
Sensitivity:  $6 \times 10^{-11}$



# The $K \rightarrow \pi \nu \bar{\nu}$ Experimental Program.

$\pi \nu \nu$	Experiment	Lab	Status	Signal	Background	S/N	SES	Comment
Measurements							/SM	
$K^0 \rightarrow \pi^0 \nu \nu$	<b>KTeV</b>	<b>FNAL</b>	complete	<b>0</b>	<b>0</b>	-	<b>10,000</b>	present upper limit
	<b>E391a</b>	<b>KEK</b>	running	?	~10	-	<b>10</b>	data in 2004
	<b>KOPIO</b>	<b>BNL</b>	approved	<b>50</b>	<b>25</b>	<b>2/1</b>	<b>0.02</b>	
	<b>KAMI</b>	<b>FNAL</b>	rejected	<b>100</b>	<b>25</b>	<b>4/1</b>	<b>0.01</b>	
$K^+ \rightarrow \pi^+ \nu \nu$	<b>E787</b>	<b>BNL</b>	complete	<b>2</b>	<b>0.15</b>	<b>13</b>	<b>1</b>	discovery
	<b>E949</b>	<b>BNL</b>	running	<b>5</b>	<b>0.5</b>	<b>10</b>	<b>0.2</b>	
	<b>CKM</b>	<b>FNAL</b>	approved	<b>100</b>	<b>&lt;10</b>	<b>&gt;10</b>	<b>0.01</b>	

# Measuring $|V_{td}|$ with $K^+ \rightarrow \pi^+ \nu \bar{\nu}$



## ○ $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is the best way to measure $|V_{td}|$

- Theoretical uncertainties are small ( $m_{\text{charm}}$ ) and robustly estimated. ( $\sim 8\%$ )
- Structure of  $K^+$  controlled by measurement, NO final state interactions.
- Need 100 signal events with  $< 10$  background (6%) to match theory error.

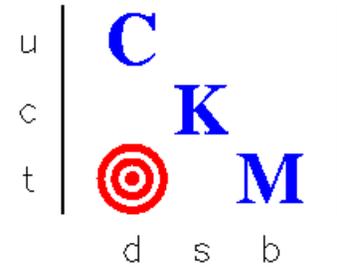
## ○ Experimental Challenge

- $\text{Br}[K^+ \rightarrow \pi^+ \nu \bar{\nu}] = 8 \pm 3 \times 10^{-11}$  (Standard Model)
- 2 clean events seen in BNL787 ( $\text{Br} = 16^{+18}_{-8} \times 10^{-11}$ )

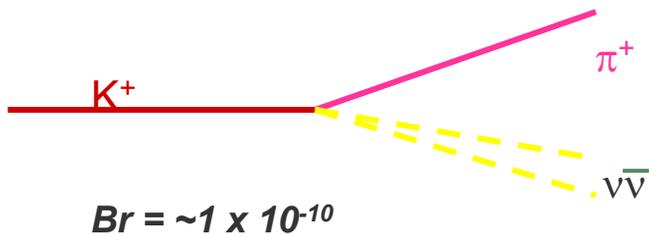
## ○ The tyranny of tiny decay rates

- $100 \text{ events} / 10^{-10} (\text{Br}) / 1\% (\text{acc}) = 10^{14}$  K decays must be studied
- $10^7 \text{ sec/year} \rightarrow 10^7 \text{ K decay /sec}$  to see 100 in 1 year
- Need to control background to  $10^{-11}$  of all  $K^+$  decays

# Backgrounds



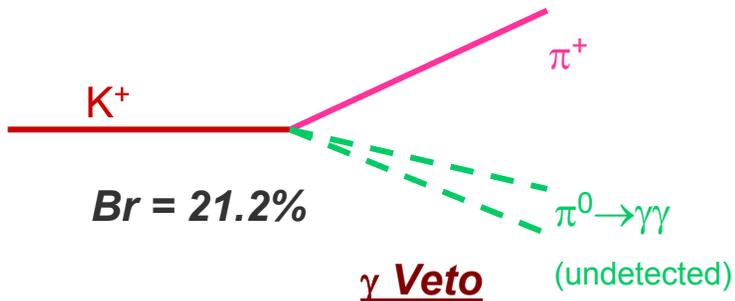
## What We Want:



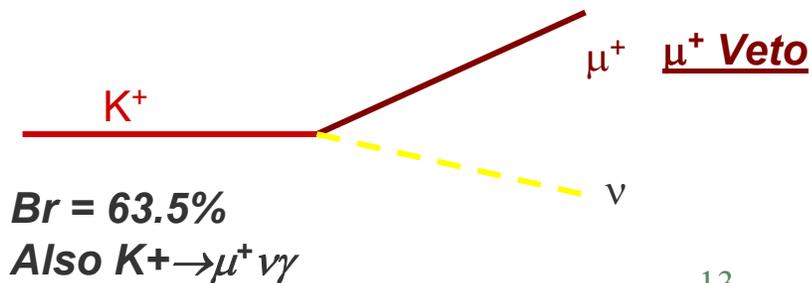
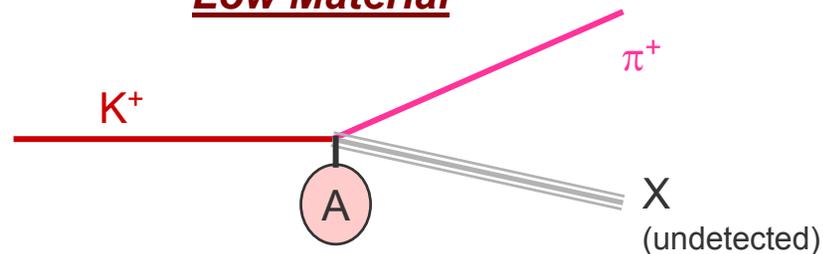
## Kinematics

Velocity, **M**omentum,  
position of  $K^+$  and  $\pi^+$

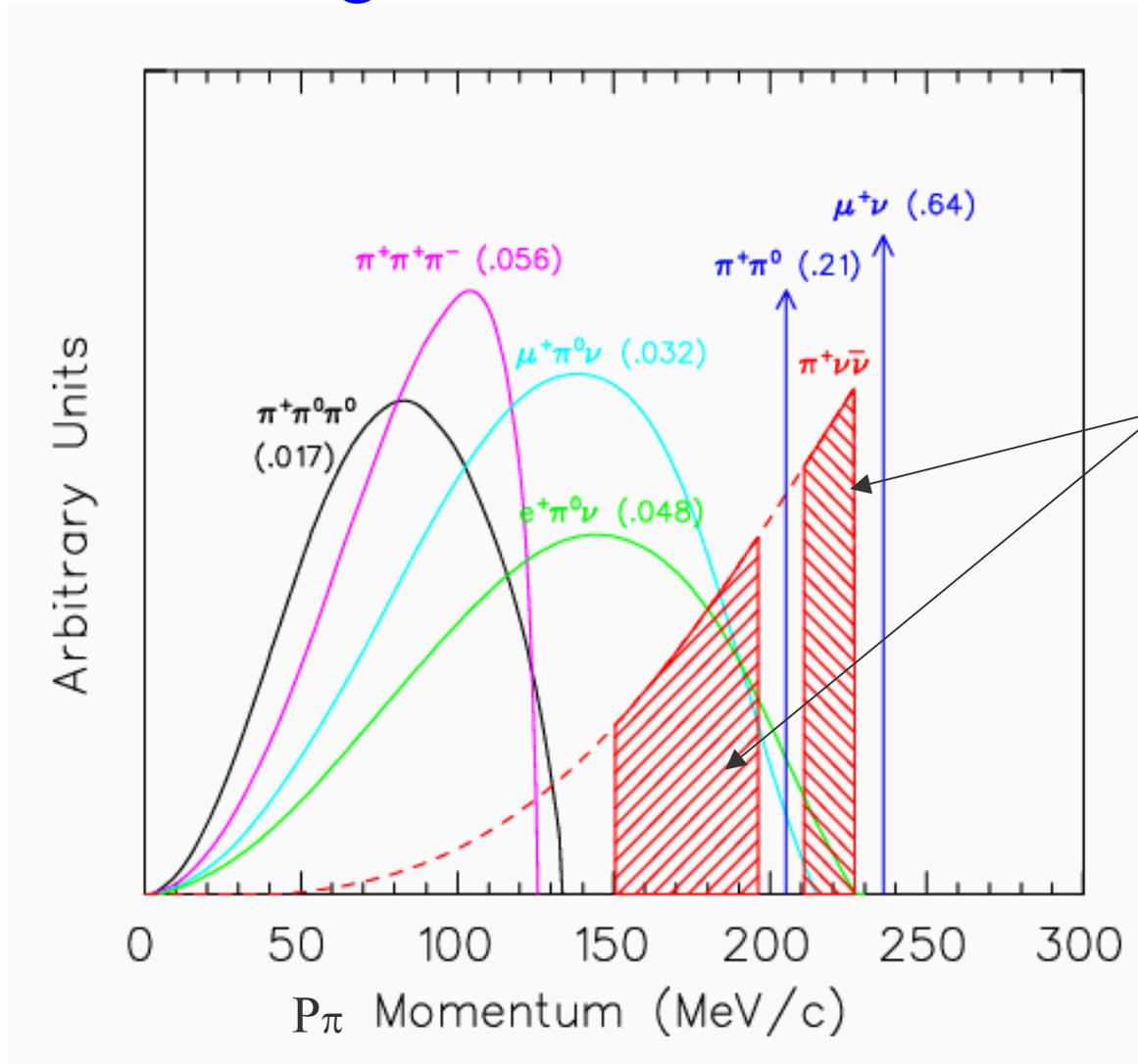
## What We'll Get:



## Charged Veto Low Material

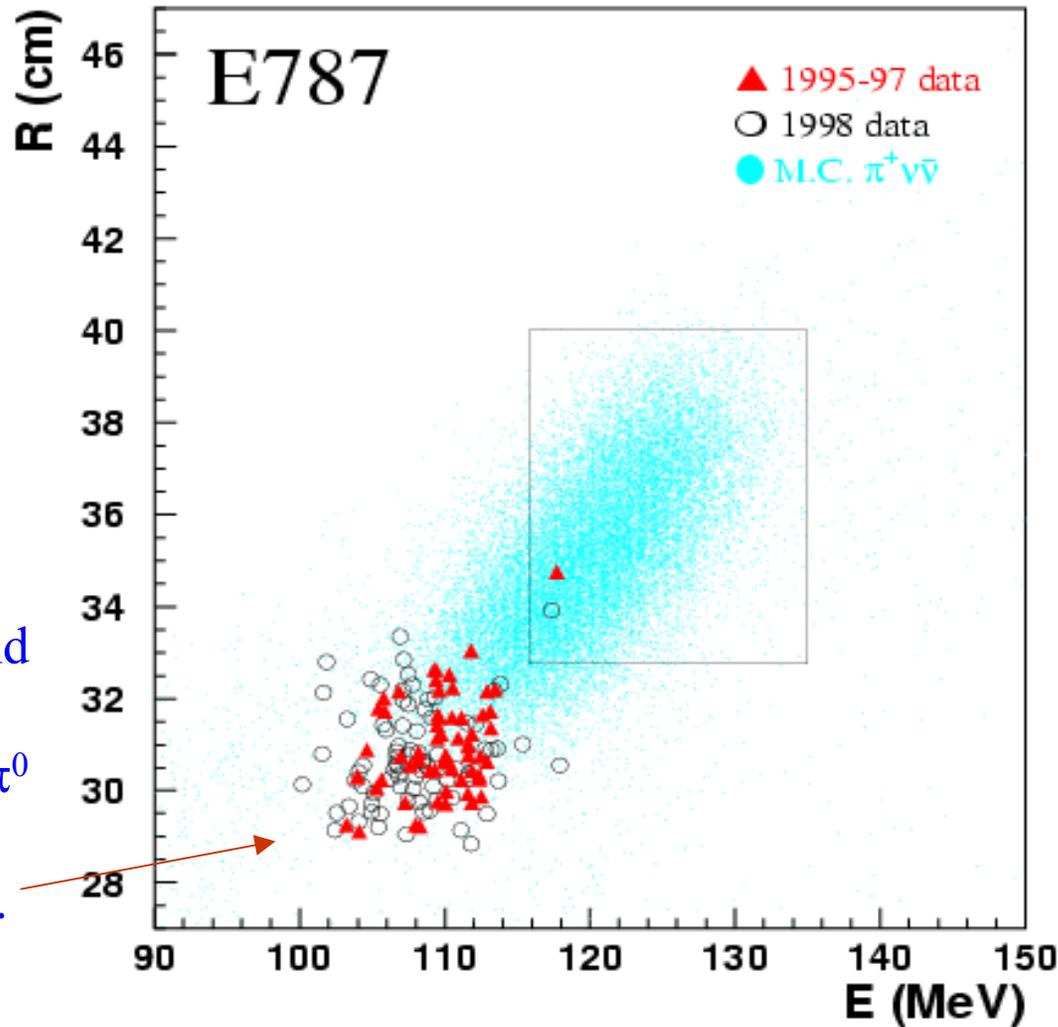


# Signal and Background COM Kinematics...



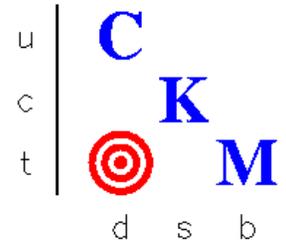
CKM has unique sensitivity to the Form Factor.

# Background Control at $2 \times 10^{-11}$ Level

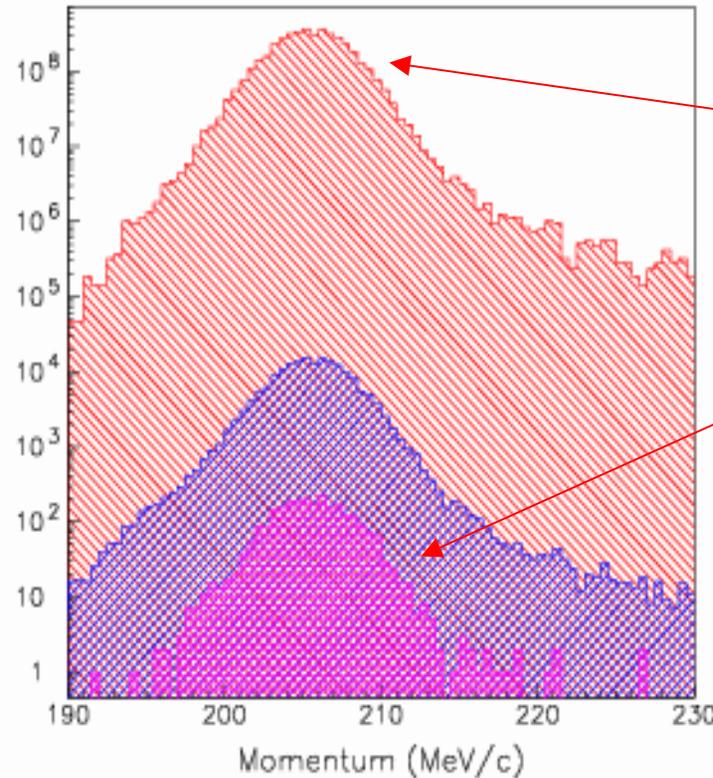


Background dominated by  $K^+ \rightarrow \pi^+\pi^0$  where  $\pi^0$  veto failed.

# Measuring Detector Performance and Background From the Data (E787):



2-body  $p_\pi$  from  
 $K^+ \rightarrow \pi^+ \pi^0$  decays:



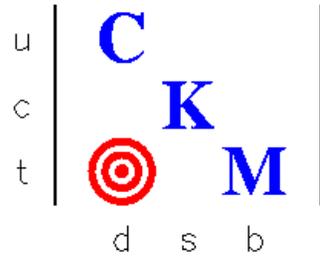
$p_\pi$  before  $\gamma$ -veto.

$p_\pi$  after  $\gamma$ -veto.

$$(1 - \epsilon_{\pi^0} < 1 \times 10^{-6})$$

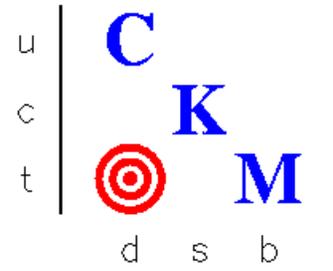
Demonstrated for BNL-787:  $\pi^+$  momentum line shape unchanged  
line  $\gamma$  cuts and full offline  $\gamma$  cuts.

# Evolution From the Discovery Program to Precision Measurement.

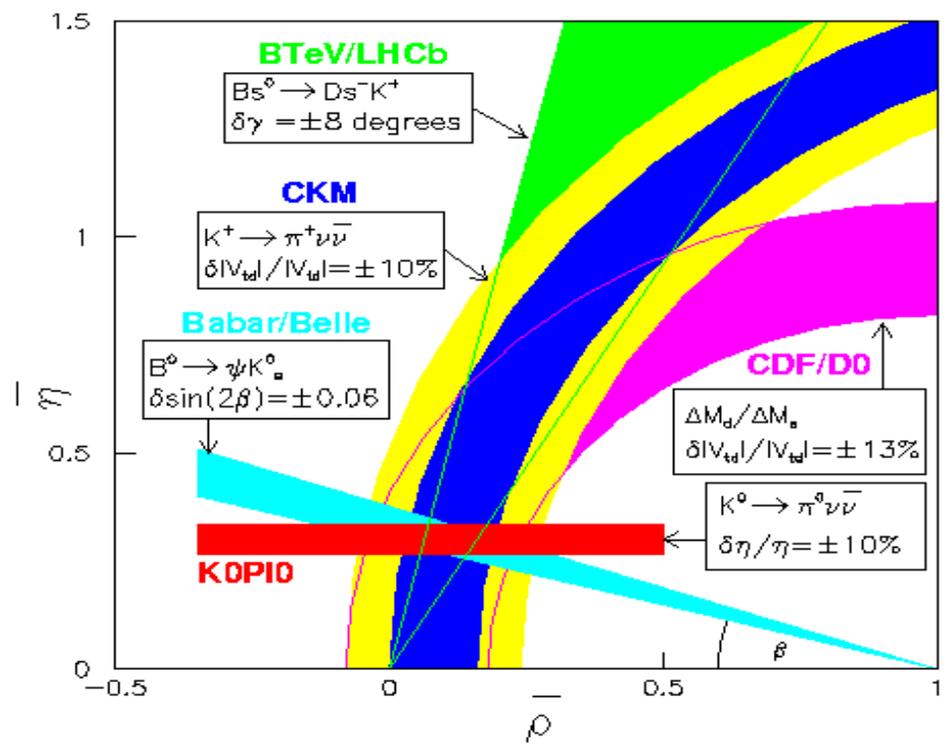
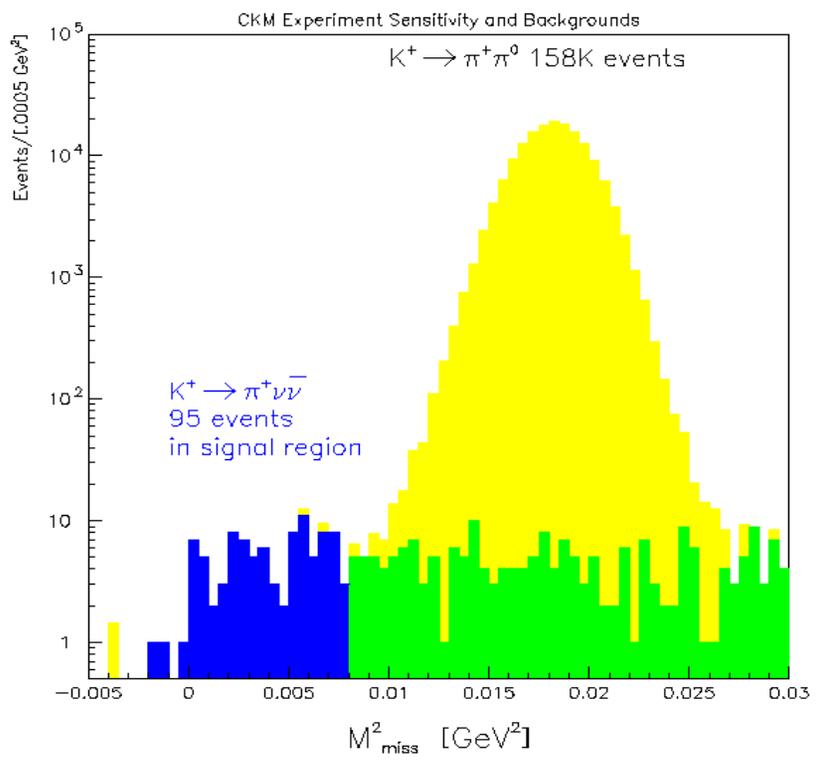


- The discovery program at BNL is fundamentally rate-limited by the  $\pi \rightarrow \mu \rightarrow e$  Particle-ID and requires effectively all AGS protons.
- The CKM detector elements are essentially isochronous, enabling ultra high-rate operation. The CKM precision measurement program requires  $\sim 15\%$  of the Main Injector capacity/pulse.
- A joint BNL-E949/CKM collaboration recognizes this evolution.

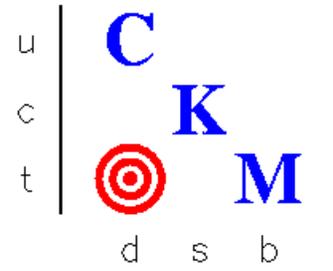
# When it all works



- 95 signal events with <10 background events
- In 2 years of data taking
- Together with others a critical test of Standard Model CP violation



# Challenging the Standard Model of CP-Violation with Golden Modes; Consider the Quartet:



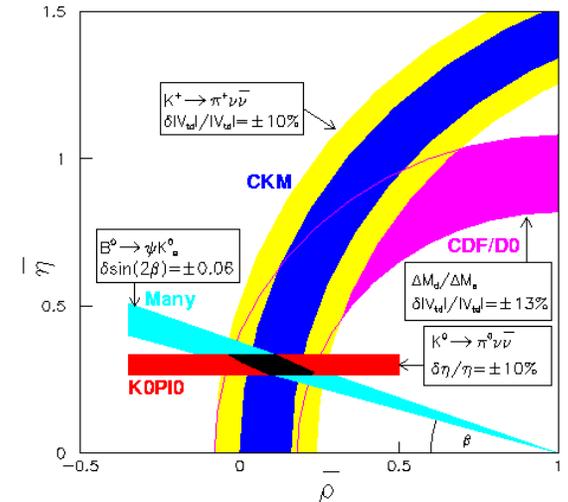
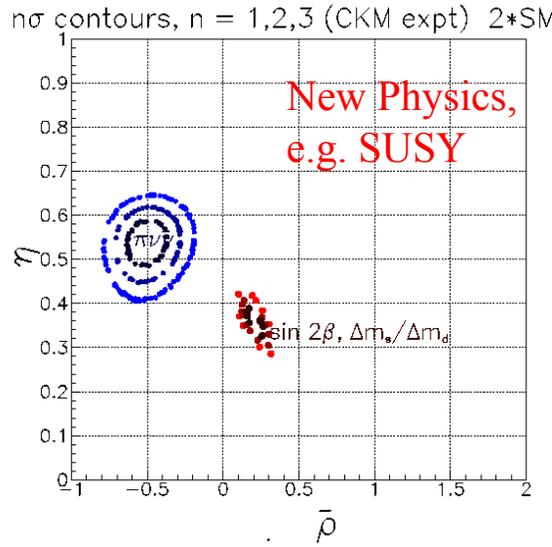
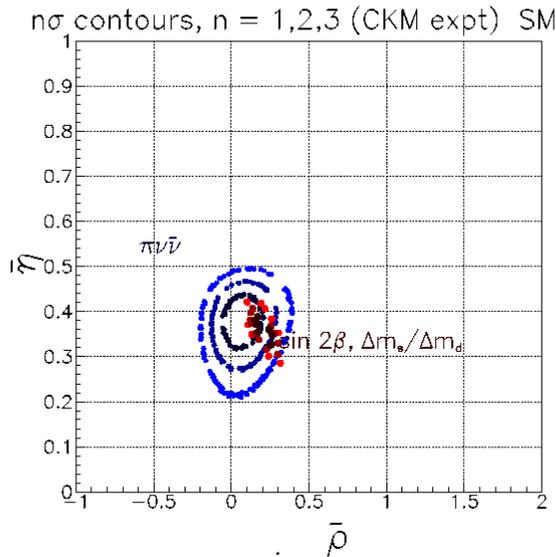
$$\sin(2\beta), K^0 \rightarrow \pi^0 \nu \bar{\nu}, K^+ \rightarrow \pi^+ \nu \bar{\nu},$$

$$\Delta m_d / \Delta m_s \text{ in } B_d^0 \text{ and } B_s^0 \text{ Decays}$$

$\Gamma(\pi\nu\nu) = \text{SM}$

$\Gamma(\pi\nu\nu) = 2 \times \text{SM}$

expected sensitivities



CKM Fitter Results, D. Jaffe (BNL).

# Other Probes of New Physics.

- Study of the  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  Form Factor.
- Precision Measurement of  $V_{us}$  (Ke3) and  $V_{ud}$  ( $\pi_\beta$  decay) to test unitarity:  $V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$ .
- Extend Sensitivity for Lepton Flavor Violation (e.g.  $K^+ \rightarrow \pi \mu e$ ) by  $\sim \times(10-50)$ .
- Precision tests of Chiral Perturbation Theory (e.g.  $K^+ \rightarrow \pi \mu \mu$ ) & other rare  $K^+$ ,  $\pi^+$ ,  $\pi^0$  decays.
- Plus a number of CP, T-odd, and CPT tests.

**~30 PhD  
Theses**

# Summary...

- The  $K \rightarrow \pi \nu \bar{\nu}$  processes are particularly sensitive probes of physics beyond the Standard Model. This opportunity has triggered a campaign to establish precision measurements.
- The recent discovery of  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  has provided a clear map of where the physics backgrounds are, which underwrites the viability of CKM.
- The CKM experiment is uniquely well suited to advance the State of the Art into a precision measurement of  $\pi^+ \nu \bar{\nu}$  and many other rare processes.