Charged Kaons at the Main-Injector

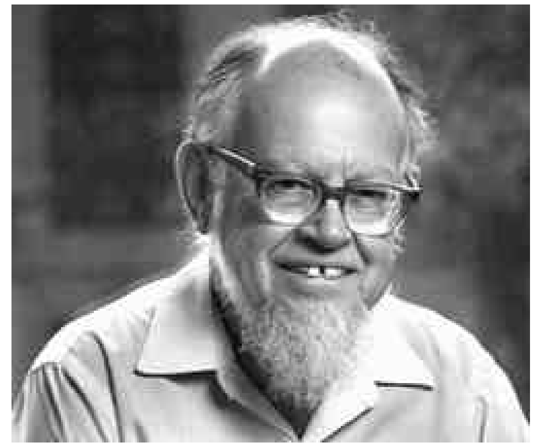
R. Tschirhart, Fermilab *March 26th, 2003*

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 ρ and η 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.''



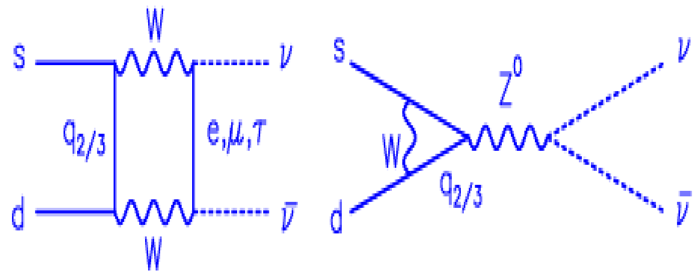
Lincoln Wolfenstein, CMU

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.**

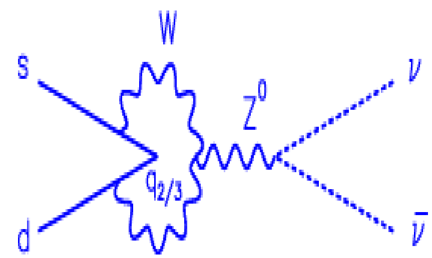
Primary Physics Goal of CKM:

Precision Measurement of K^+® $p^+ n \bar{n}$.

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

CKM

- 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.

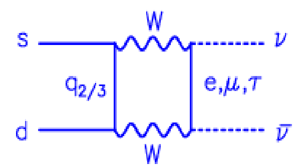
- Unfortunately the $\pi l^{+} l^{-}$ final states, while easier to measure, have correspondingly high levels of radiative backgrounds, (e.g. $K_L \Rightarrow e^{+}e^{-}\gamma\gamma$).

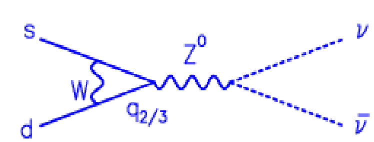
- Which leads us to the $K \Rightarrow \pi\nu\bar{\nu}$ challenge…

K ⇨ πνν in the Standard Model

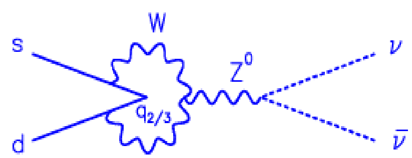
- No Radiative Backgrounds.

  (& No radiative signal!)



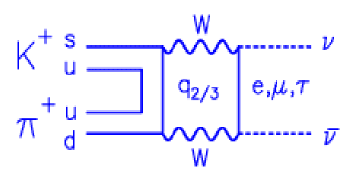


- Leading diagrams



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…

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

V_{td}

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

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

$$K_+ \equiv r_+ B \quad K_0 \equiv r_0 B \tau(\mathrm{K}^0_\mathrm{L}) / \tau(\mathrm{K}^+)$$

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

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

$$B \equiv \frac{3\alpha^2 \mathcal{B}(\mathrm{K}^+ \to \pi^0 e^+ \nu)}{2\pi^2 \sin^4 \theta_\mathrm{W}}$$

Normalize to semileptonic process.

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

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

Charm Contribution

Expectation and Measurements…

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

Uncertainty dominated by current errors on $\mathbf{V_{cb}}$, r, and h.

	Uncert.	References
$\mathcal{B}(\mathrm{K}^+ \to \pi^+ \nu\bar{\nu})$	5%	PRL**88**,041803(2002)
		hep-ph/0101336
$\mathcal{B}(\mathrm{K}^0_{\mathrm{L}} \to \pi^0 \nu\bar{\nu})$	1%	PRD **61**,072006 (200?)
		hep-ph/9701313

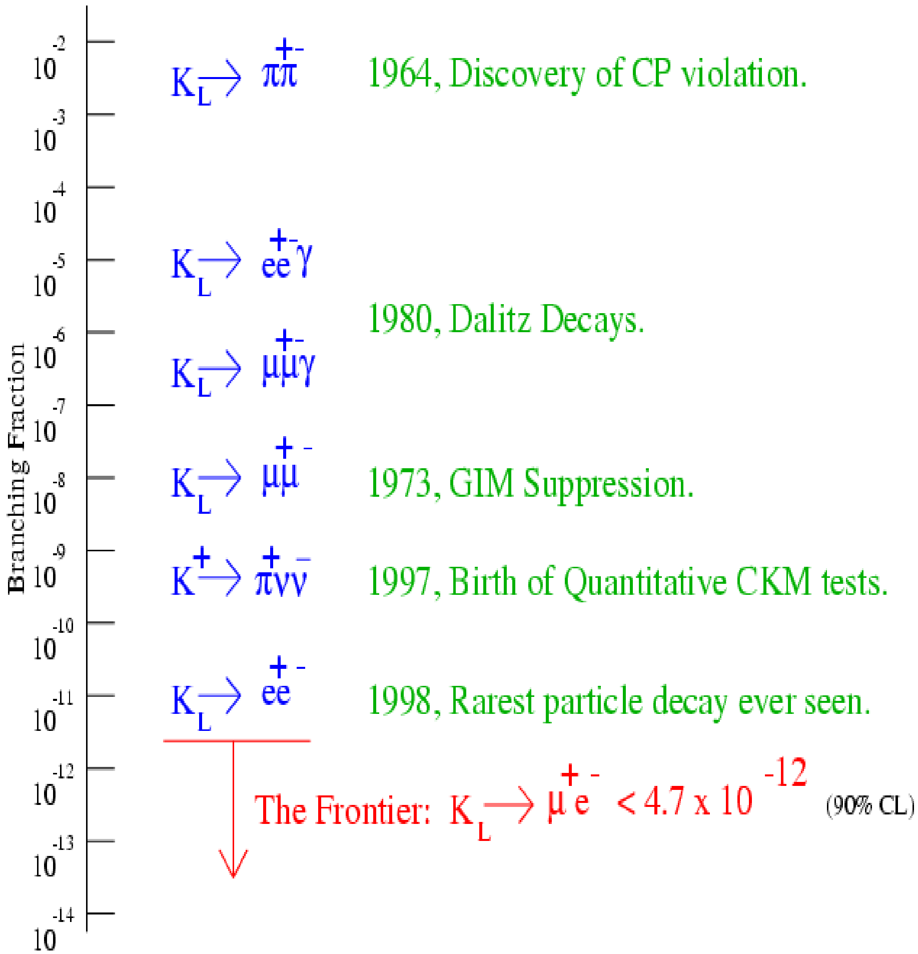
Limit are at 90% CL.

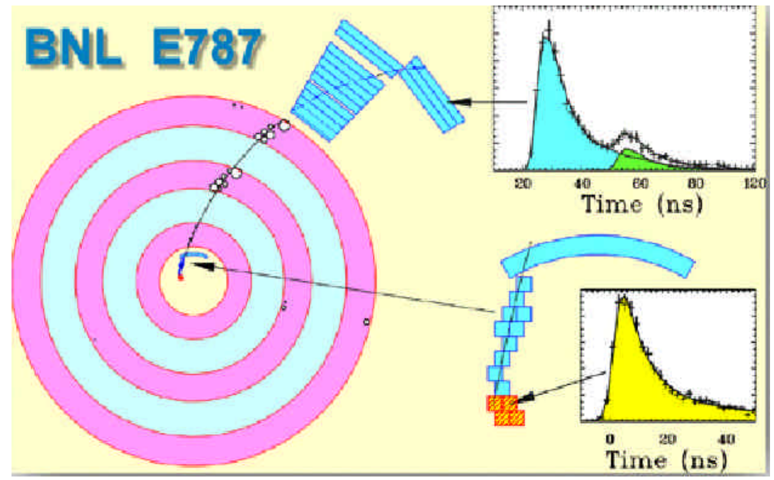
Theoretical Error Floor.

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 **13×10^{-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...





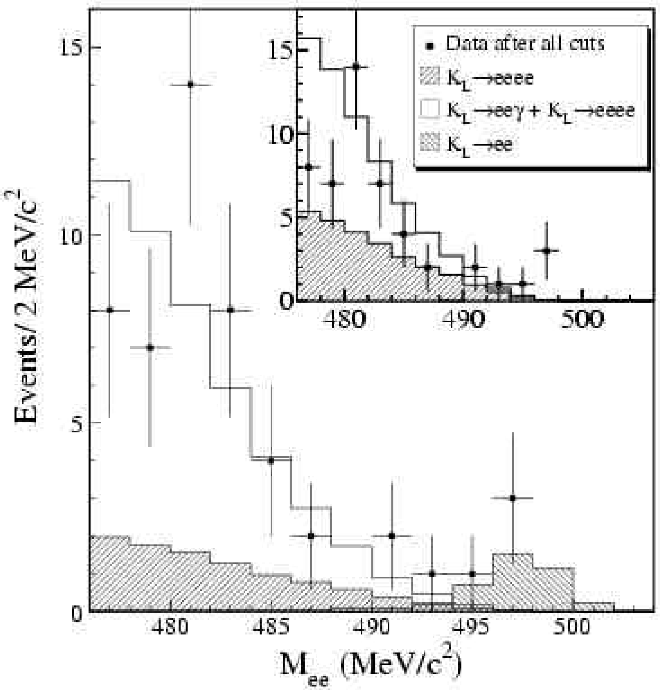
$B(K^+ \to \pi^+ \nu\bar{\nu}) = (16^{+18}_{-8})\mathbf{x}10^{-11}$

SM: $\mathbf{(8^{+3}_{-3})x10^{-11}}$

Postcards From the Frontier…

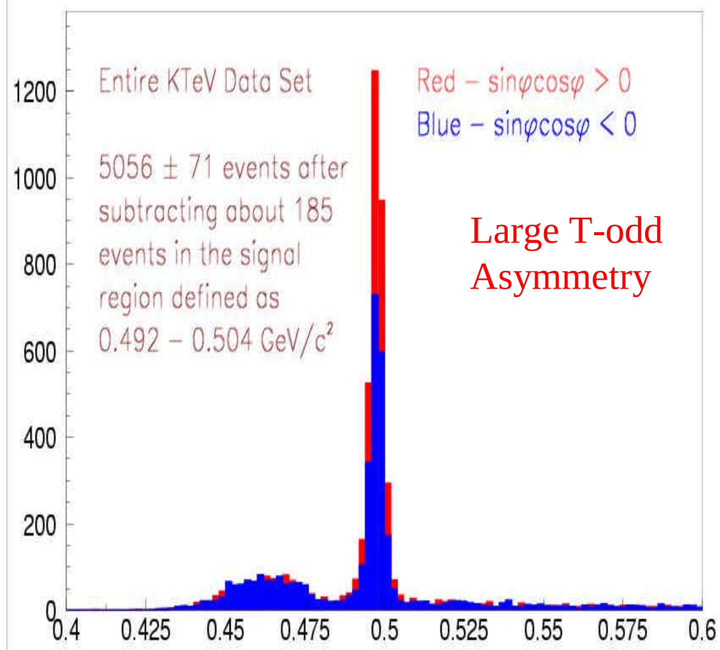
$K_L \rightarrow e^+e^-$ (BNL-871)

Sensitivity: $2\text{x}10^{-12}$



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

Sensitivity: $6\text{x}10^{-11}$



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

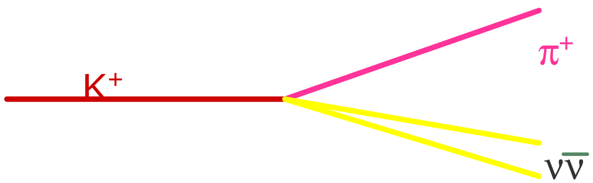
pnn Measurements	Experiment	Lab	Status	Signal	Background	S/N	SES /SM	Comment
K^0 ® p^0 nn	KTeV	FNAL	complete	0	0	-	10,000	present upper limit
	E391a	KEK	running	?	~10	-	10	data in 2004
	KOPIO	BNL	approved	50	25	2/1	0.02	
	KAMI	FNAL	rejected	100	25	4/1	0.01	
K^+ ® p^+ nn	E787	BNL	complete	2	0.15	13	1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

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

- $K^+ \to \pi^+ \nu \bar{\nu}$ is the best way to measure $|V_{td}|$
  - Theoretical uncertainties are small (m_{charm}) and robustly estimated. (~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
  - Br[$K^+ \to \pi^+ \nu \bar{\nu}$] = 8±3 x 10^{-11} (Standard Model)
  - 2 clean events seen in BNL787 (Br = 16^{+18}_{-8} x 10^{-11})
- The tyranny of tiny decay rates
  - 100 events / 10^{-10} (Br) / 1% (acc) = 10^{14} K decays must be studied
  - 10^7 sec/year ➔ 10^7 K decay /sec to see 100 in 1 year
  - Need to control background to 10^{-11} of all K^+ decays

Backgrounds

What We Want:



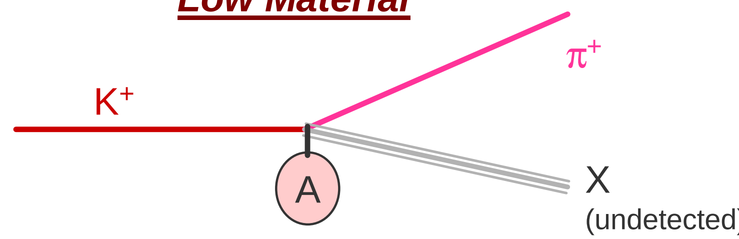
***Br* = ~1 x 10^{-10}**

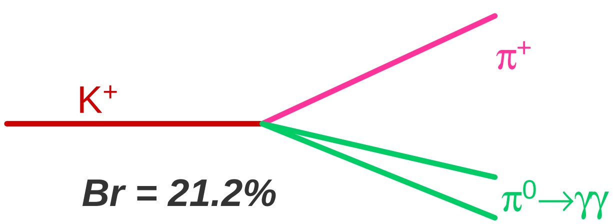
Kinematics

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

What We'll Get:

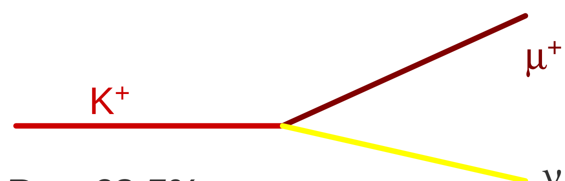
Charged Veto
Low Material





Br = 21.2%

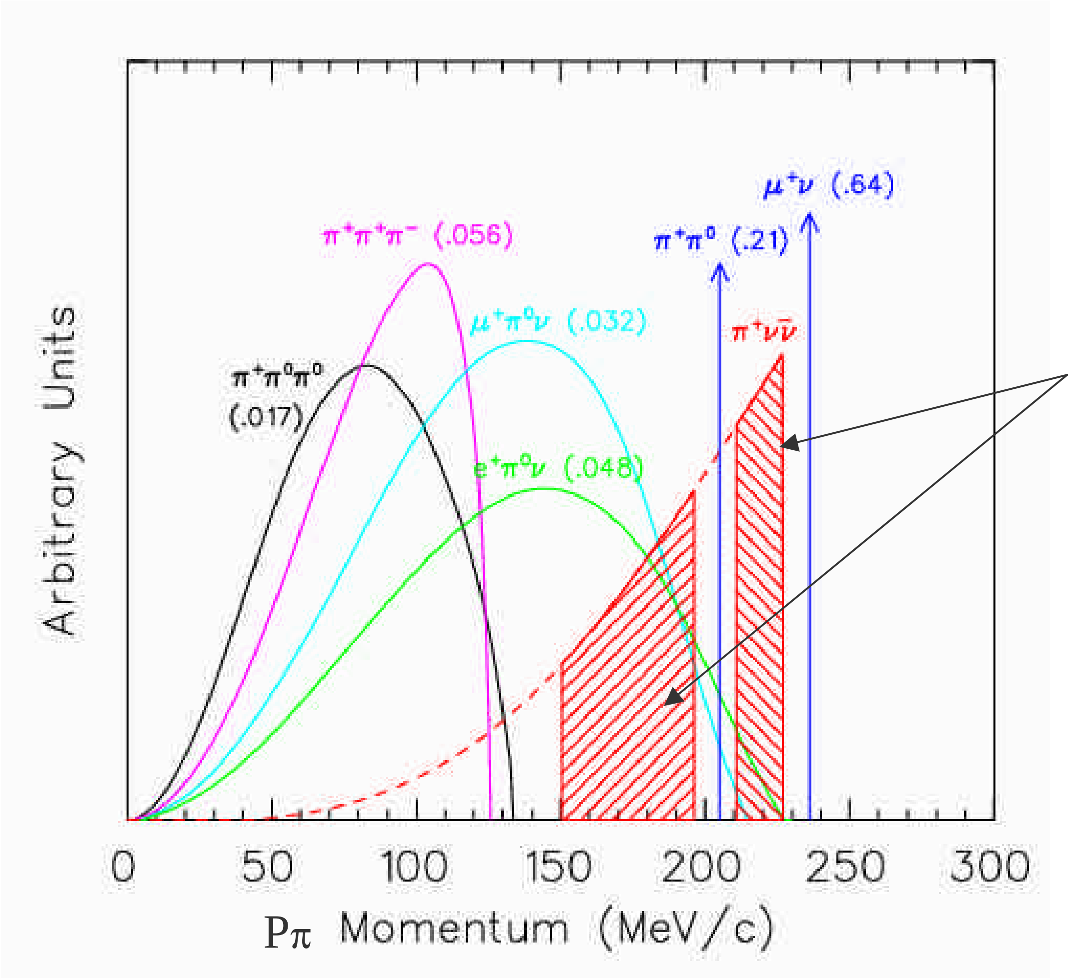
gVeto



m+ Veto

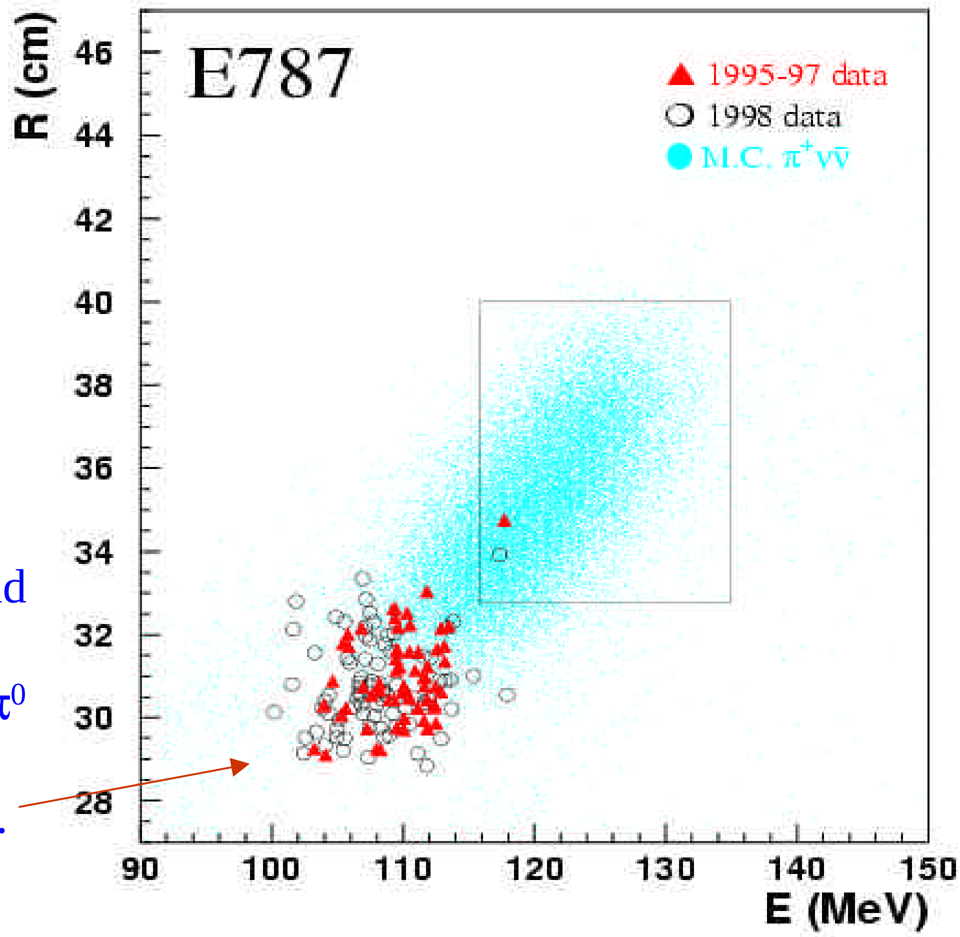
Br = 63.5%
Also K+® m+n g

Signal and Background COM Kinematics…



CKM has unique sensitivity to the Form Factor.

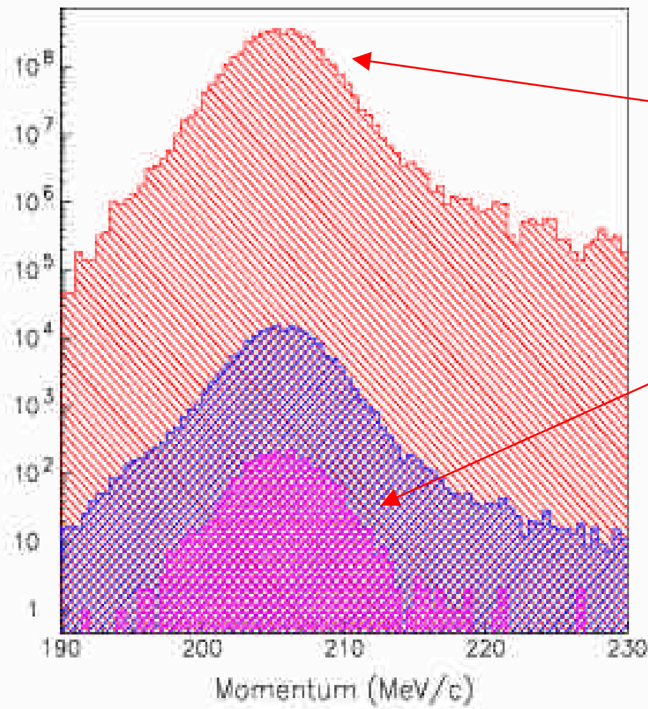
Background Control at $2x10^{-11}$ Level



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

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

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



p_p before γ-veto.

p_p after γ-veto.

$(1-\varepsilon_{\pi 0} < 1x10^{-6})$

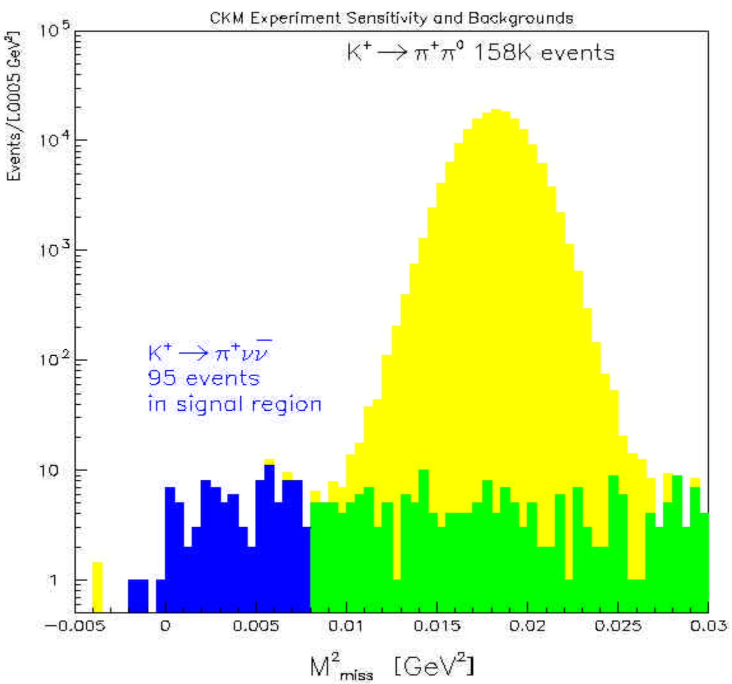
Demonstrated for BNL-787: π^+ momentum line shape unchanged
line γ cuts and full offline γ cuts.

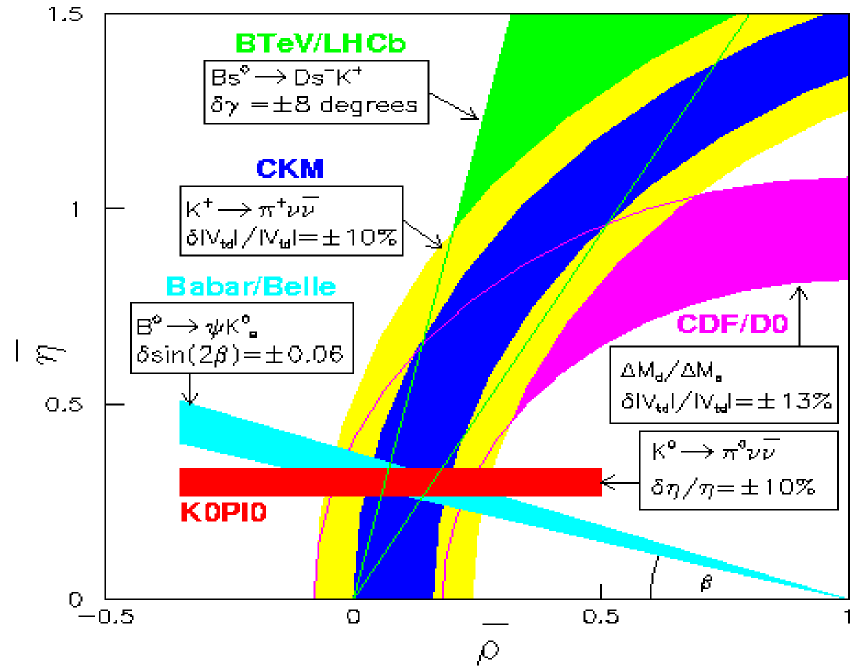
Evolution From the Discovery Program to Precision Measurement.

- 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 ~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



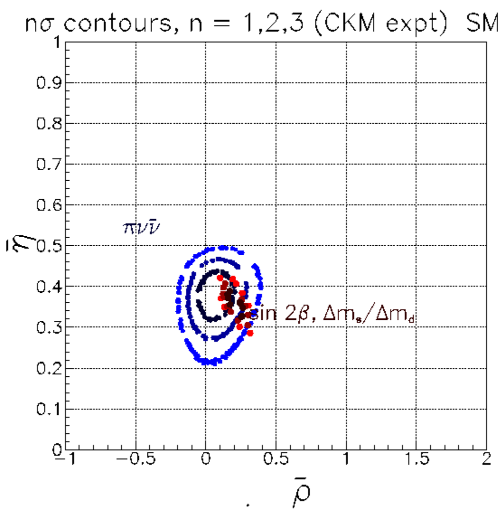


Challenging the Standard Model of CP-Violation with Golden Modes; Consider the Quartet:

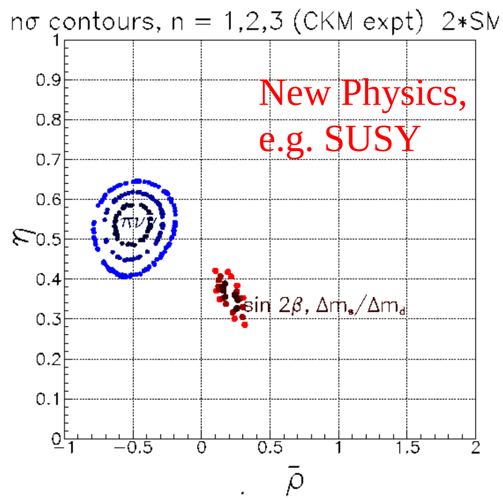
$$\sin(2\beta),\ K^0 \rightarrow \pi^0 \nu \bar{\nu},\ K^+ \rightarrow \pi^+ \nu \bar{\nu},$$

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

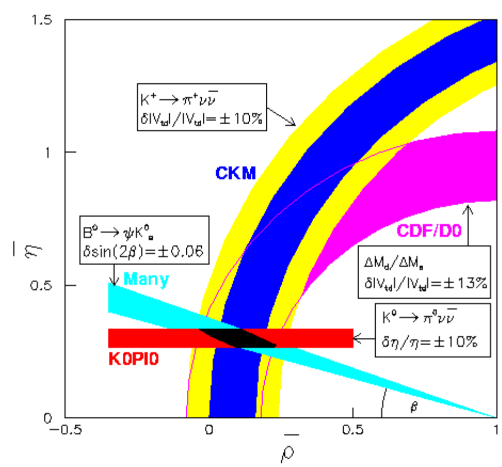
$\Gamma(\pi\nu\nu)$ = SM



$\Gamma(\pi\nu\nu)$ = 2xSM



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} (π_β 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 ~x(10-50).
- Precision tests of Chiral Pertubation Theory (e.g. $K^+ \rightarrow \pi\mu\mu$) & other rare K^+, π^+, π^0 decays.
- Plus a number of CP, T-odd, and CPT tests.

~30 PhD Theses

Summary…

- The $K \to \pi\nu\bar{\nu}$ 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 $K^+ \to \pi^+\nu\bar{\nu}$ 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 precison measurement of $\pi^+\nu\bar{\nu}$ and many other rare processes.