Rare K Decays:
Report from the Sensitivity Frontier.

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Fermilab

August 9th 2002

Lots of fine material borrowed from…

- C. Dukes, University of Virginia
- D. Jaffe, BNL.
- S. Chen, TRIUMF
- G. Lim KEK
- P. Cooper, FNAL
- CKM, KOPIO, and KEK-391 collaborations.

Evolution of the Frontier...

Branching Fraction: 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}, 10^{-7}, 10^{-8}, 10^{-9}, 10^{-10}, 10^{-11}, 10^{-12}, 10^{-13}, 10^{-14}

$K_L \to \pi^+\pi^-$ 1964, Discovery of CP violation.

$K_L \to e^+e^-\gamma$

1980, Dalitz Decays.

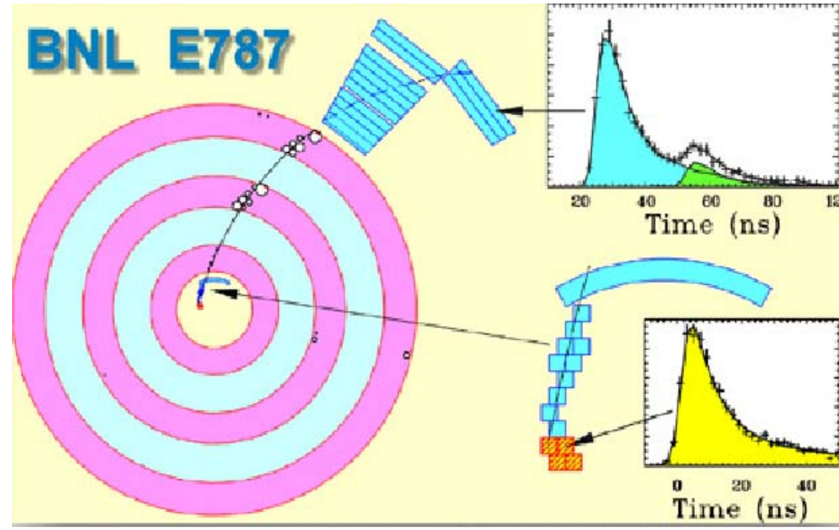
$K_L \to \mu^+\mu^-\gamma$

$K_L \to \mu^+\mu^-$ 1973, GIM Suppression.

$K^+ \to \pi^+\nu\bar{\nu}$ 1997, Birth of Quantitative CKM tests.

$K_L \to e^+e^-$ 1998, Rarest particle decay ever seen.

The Frontier: $K_L \to \mu^+ e^- < 4.7 \times 10^{-12}$ (90% CL)



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

Quantitative Tests of the CKM Formalism.

- The $K \rightarrow \pi l \bar{l}$ 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.

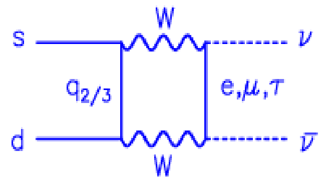
- Unfortunately the $\pi l^+ l^-$ final states, while easier to measure, have correspondingly high levels of radiative backgrounds, (e.g. $K_L \rightarrow e^+ e^- \gamma\gamma$)

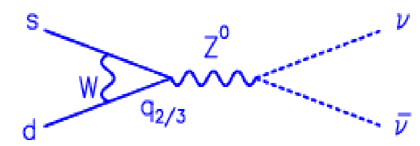
- Which leads us to the $K \rightarrow \pi \nu \bar{\nu}$ challenge…

K ➡ πνν in the Standard Model

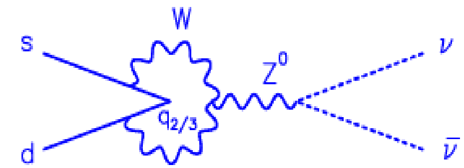
➢No Radiative Backgrounds.

(& No radiative signal!)



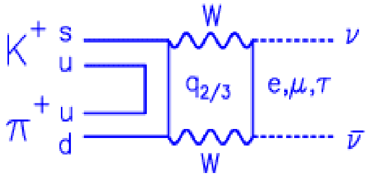


➢Leading diagrams



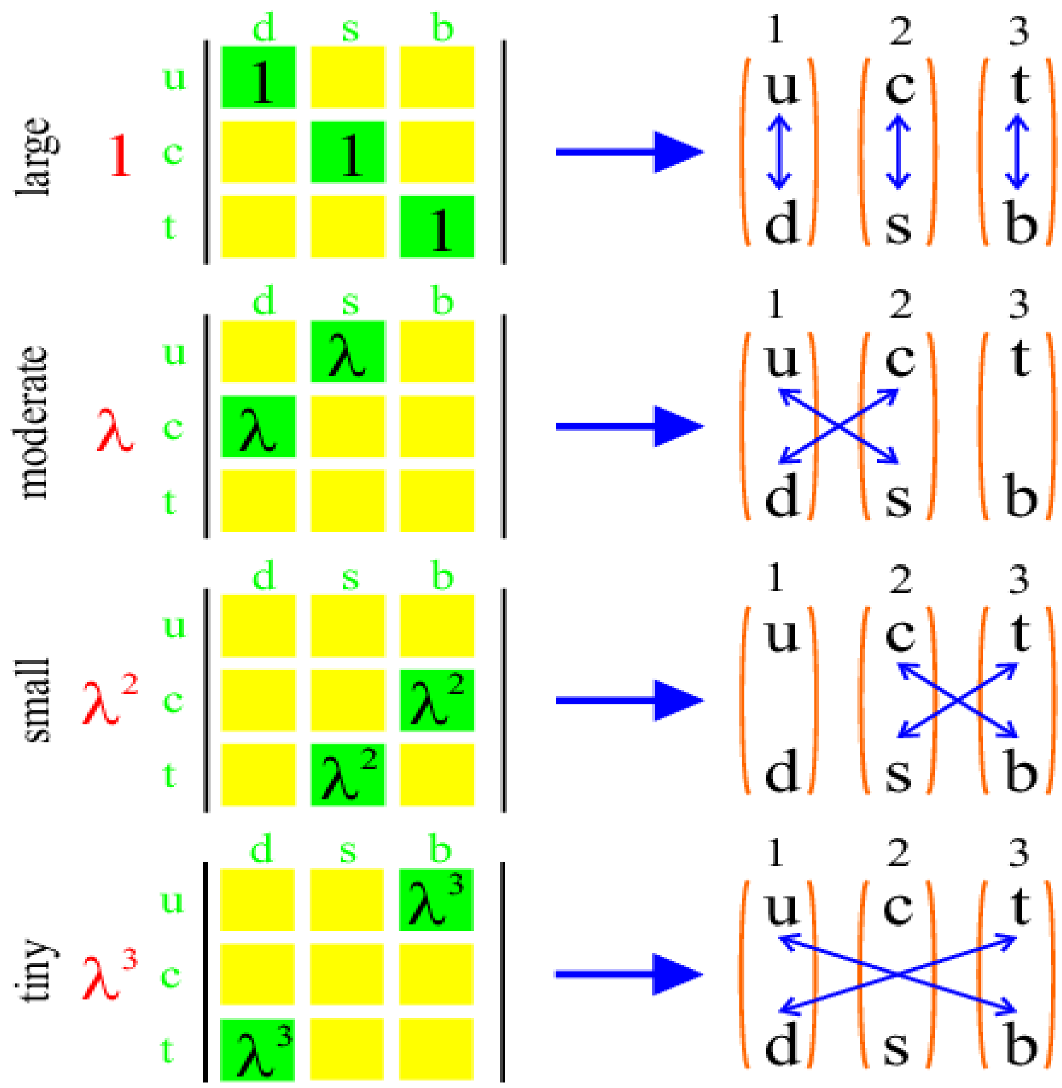
Direct sensitivity to V_{td}, and BSM physics such as SUSY that can be present in these loops.

Dressing up into hadrons:



Let’s review the quark level theory of these processes….

The CKM Matrix:



CKM Matrix Highly Constrained by Unitarity

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Unitarity implies:

$$V_{\rm CKM} V_{\rm CKM}^\dagger = V_{\rm CKM}^\dagger V_{\rm CKM} = 1$$

- Rows and columns normalized (weak universality):

$$\sum_{i=1}^{3} |V_{ij}|^2 = 1 = \sum_{j=1}^{3} |V_{ij}|^2$$

$$\sum_{i=1}^{3} V_{ji} V_{ki}^\dagger = 0 = \sum_{i=1}^{3} V_{ij} V_{ik}^\dagger$$

$\Rightarrow$ Matrix can be described by only 4 parameters!

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

where: $\lambda \approx 0.220$ and $A \approx \rho \approx \eta \approx 1$.

Important: Imaginary part η violates CP symmetry!

Properties of the CKM Matrix

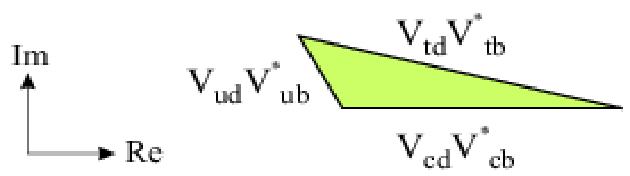
- Things rapidy get more complicated with increasing number of generations:

$$\begin{array}{lll} n_g = 2 & 1 \text{ angle} & 0 \text{ CP phase} \\ n_g = 3 & 3 \text{ angles} & 1 \text{ CP phase} \\ n_g = 4 & 6 \text{ angles} & 3 \text{ CP phases} \end{array}$$

- To have CP violation:

$$m_u \neq m_c \neq m_t \quad \text{and} \quad m_d \neq m_s \neq m_b$$

- Can represent 6 unitarity relations in terms triangles in the complex plane.

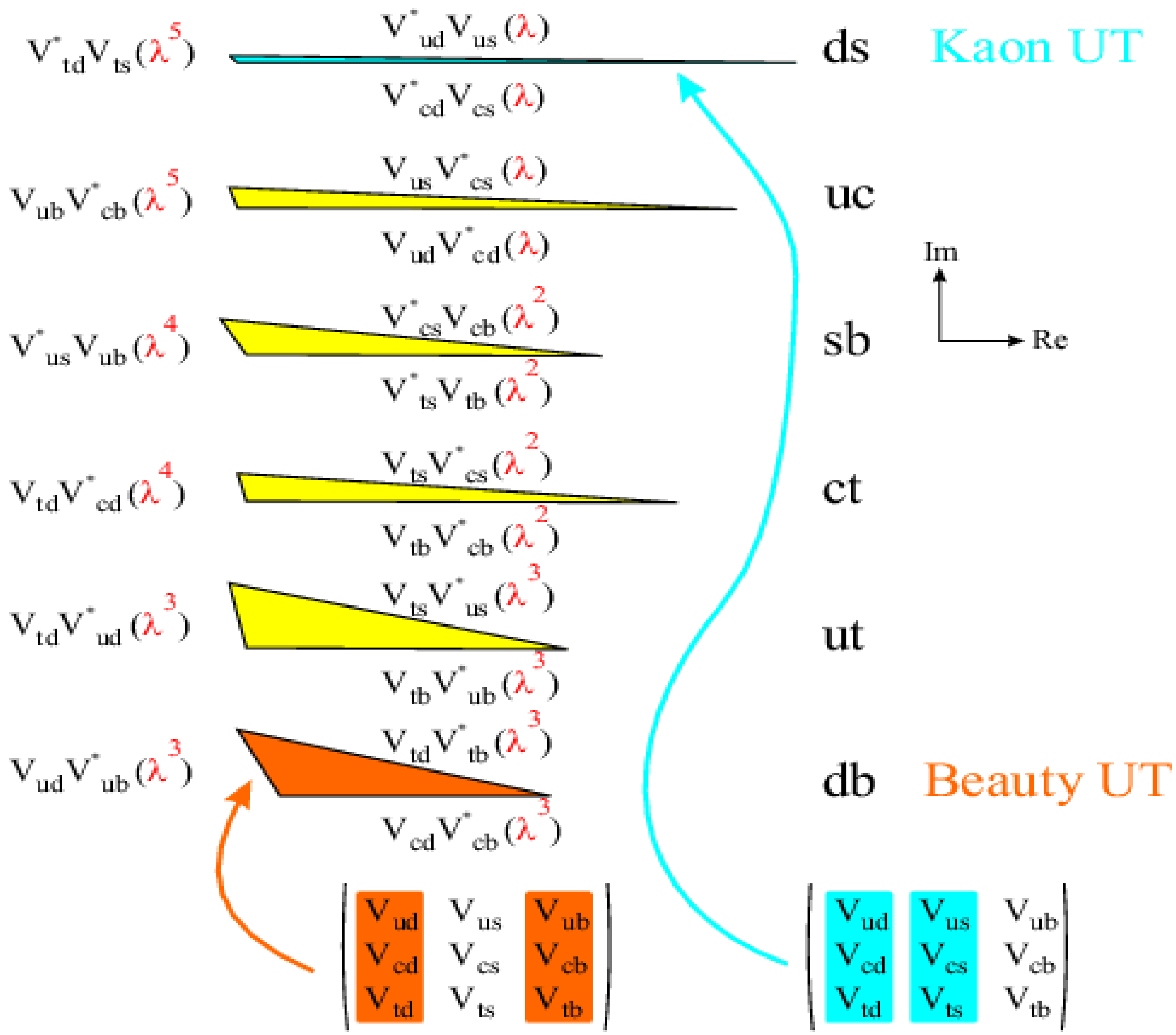


$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Note: area of all triangles is the same: $A^2\lambda^6\eta$
- Length of sides determined by measuring decay rates.
- Size of angles determined by measuring CP asymmetries.

One can measure the CP-violating phase in the CKM matrix without ever measuring a CP asymmetry!

The Unitarity Triangles



Status of CKM Matrix Elements

- 90% errors
- unitarity constraints
- PDG 2000
- one-loop level flavor-changing processes left out

3 generations

$$\begin{pmatrix} 0.9750 \pm 0.07\% & 0.223 \pm 1.5\% & 0.004 \pm 43\% \\ 0.222 \pm 1.3\% & 0.9742 \pm 0.07\% & 0.04 \pm 7\% \\ 0.009 \pm 55\% & 0.039 \pm 10.2\% & 0.9992 \pm 0.015\% \end{pmatrix}$$

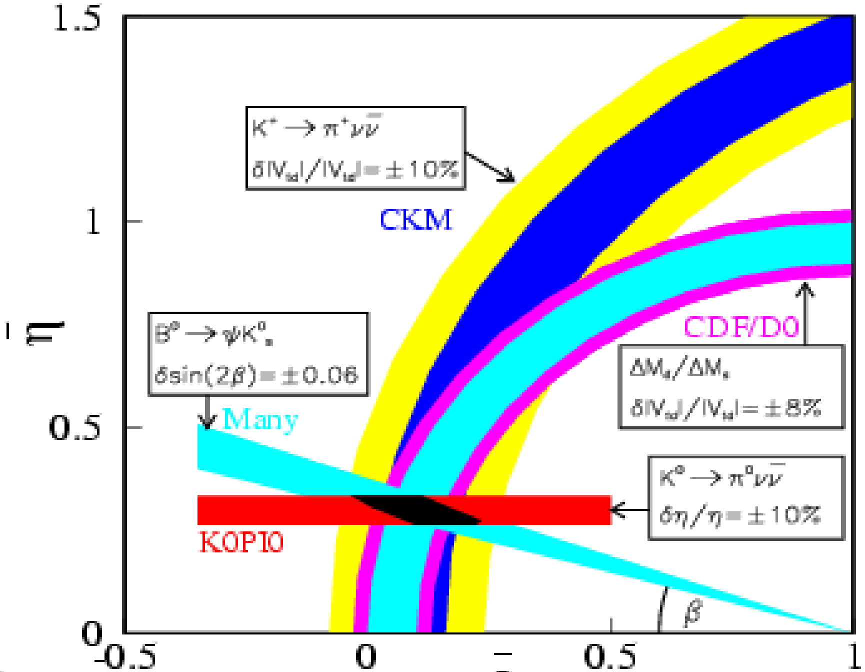
> 3 generations

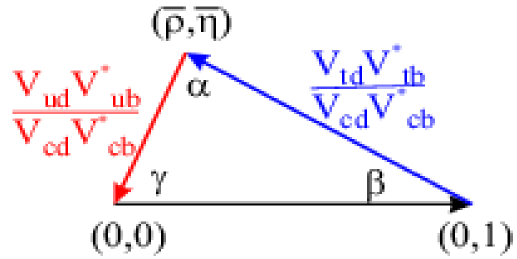
$$\begin{pmatrix} 0.9735 \pm 0.013\% & 0.219 \pm 1.6\% & 0.0035 \pm 43\% \\ 0.2185 \pm 4.3\% & 0.9675 \pm 0.9\% & 0.040 \pm 21\% \\ 0.045 \pm 100\% & 0.080 \pm 100\% & 0.53 \pm 87\% \end{pmatrix}$$

Testing the CP structure of the CKM Matrix:

- Four Gold-Plated accessible measurements have sufficient theoretical robustness that a contradiction could call the Standard Model into question:

$K^+ \rightarrow \pi^+\nu\overline{\nu}$	:	BNL787/949, CKM
$K^\circ \rightarrow \pi^\circ\nu\overline{\nu}$	:	KOPIO, KEK-e391a/JHF
$B_d \rightarrow J/\psi K_S$	:	Babar, Belle, CDF, D0, LHCb, Atlas, CMS, BTeV
$\Delta M_d/\Delta M_s$	:	CDF, D0, LHCb, Atlas, CMS, BTeV





B unitarity triangle

CKM structure of these modes…

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

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

V_{td}

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

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

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

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

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

Normalize to semileptonic process.

$r_+ = 0.901 \quad r_0 = 0.944$

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

$$3.\ \Delta m_s / \Delta m_d = \xi^2 |V_{ts}/V_{td}|^2 \quad \xi = 1.16 \pm 0.06$$

$$4.\ \sin 2\beta \quad \beta \equiv \arg(-\mathrm{V_{cd}}\ \mathrm{V_{cb}^*}\ /\mathrm{V_{td}}\ \mathrm{V_{tb}^*}\ )$$

Expectation and Measurements…

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

Uncertainty dominated by current errors on **A,** ρ, and **η.**

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

Limit are at 90% CL.

The $K^+ \Rightarrow \pi^+\nu\nu$ Experimental Program

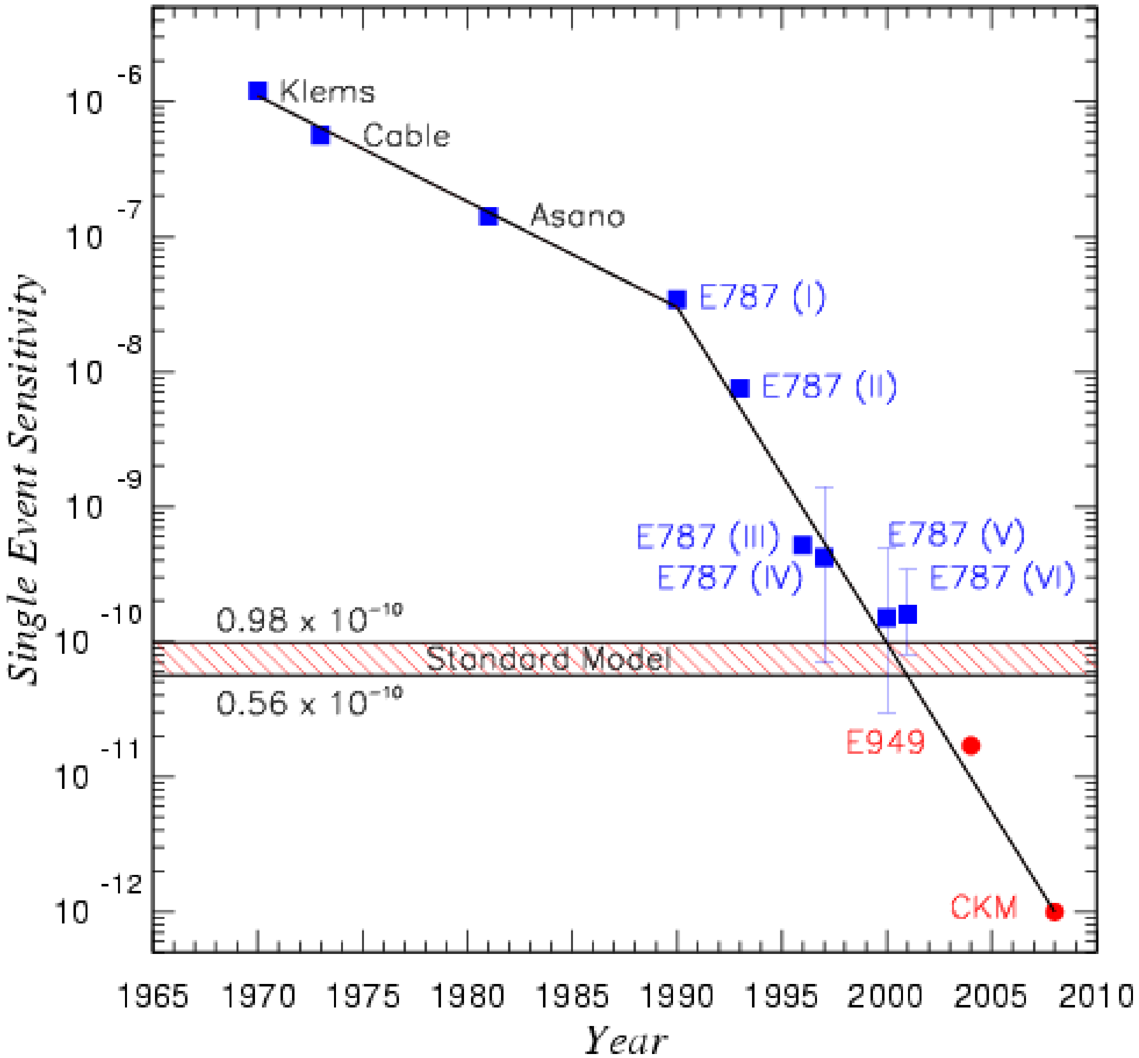
- BNL E787 completed. Flux of 5.9×10^{12} stopped kaons analyzed. Two candidate events found with a measured background of 0.15+/-0.05 events corresponding to:

$$B(K^+ \Rightarrow \pi^+\nu\bar{\nu}) = (1.57^{+1.75}_{-0.82}) \times 10^{-10}$$

- BNL E949 running, upgrade of E787. Expect an effective flux of 40×10^{12} stopped kaons corresponding to 5-10 SM events.

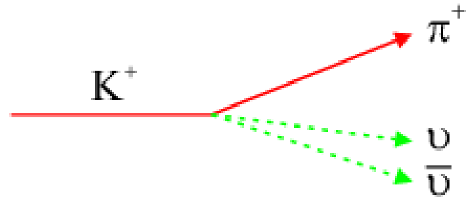
- Fermilab CKM (Charged Kaons at the Main injector) approved. Decay in-flight technique with a goal of 100 SM events over 10 background. This will match expected theory uncertainty. Physics Results in 200X.

Status of BR($K^+ \to \pi^+ \nu\bar{\nu}$)



Backgrounds a (the) Problem!

Signal



Tools

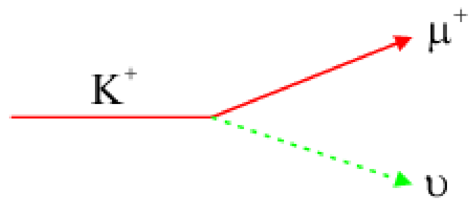
- momentum
- direction
- particle ID
- 3-body decay

For every 10 billion K+ decays we get:

1

(BR = $1\text{x}10^{-10}$)

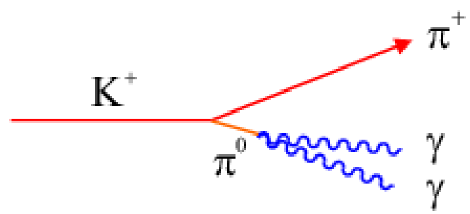
Backgrounds



- particle ID
- 2-body decay

6,350,000,000

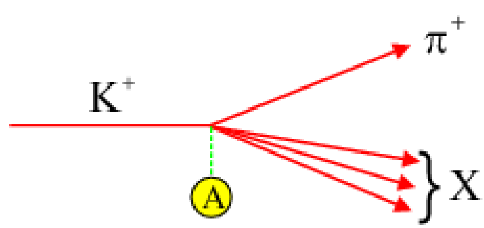
(BR = 0.635)



- particle ID
- 2-body decay

2,120,000,000

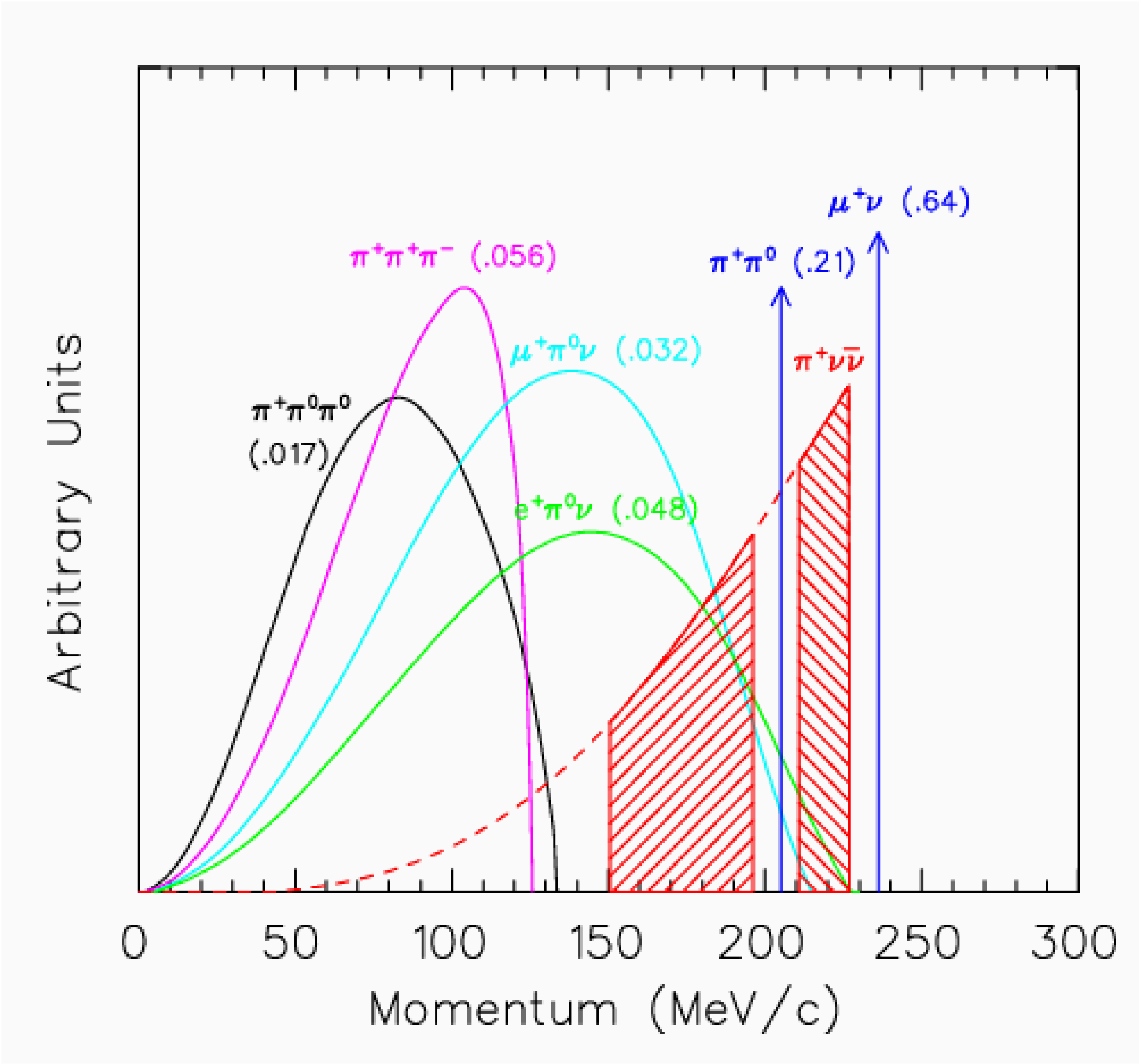
(BR = 0.212)



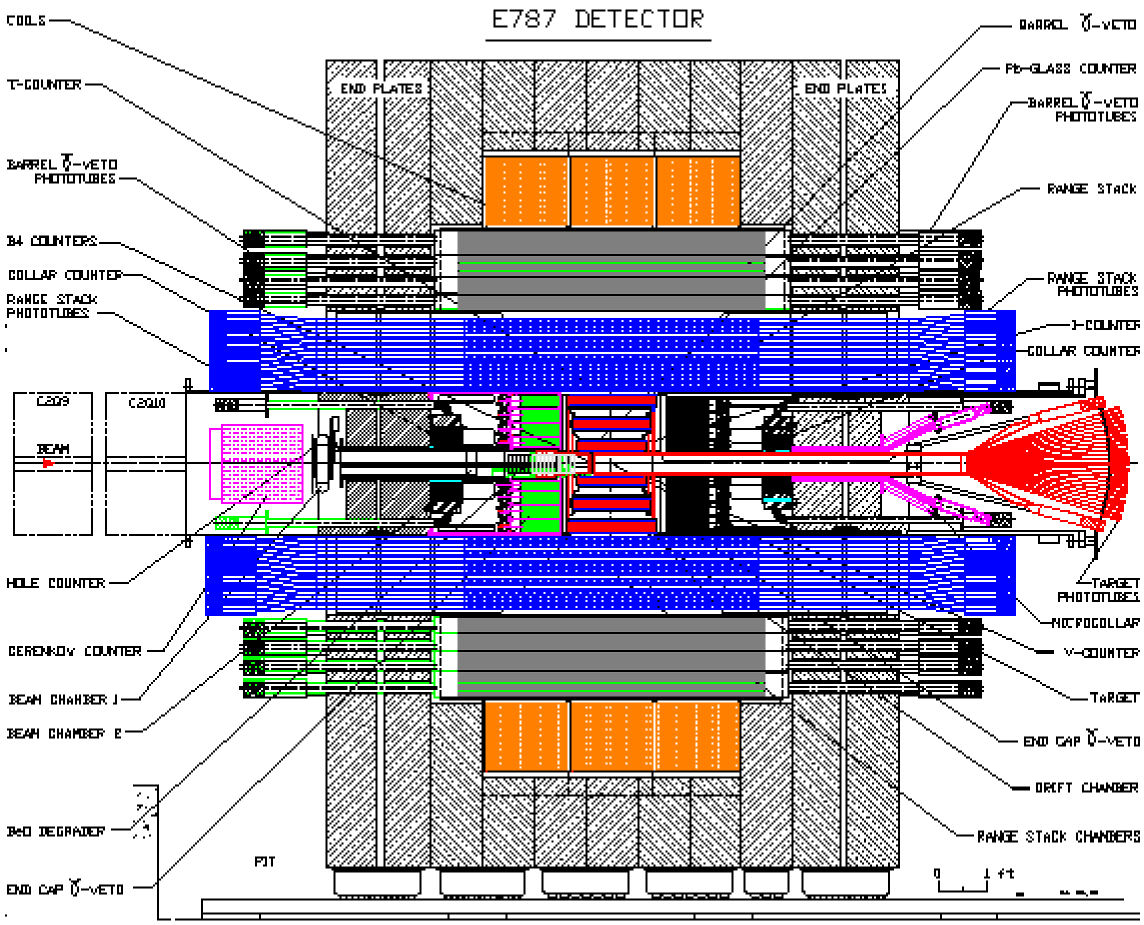
- γ-veto
- charged veto
- low material

lots!

Signal and Background Kinematics…

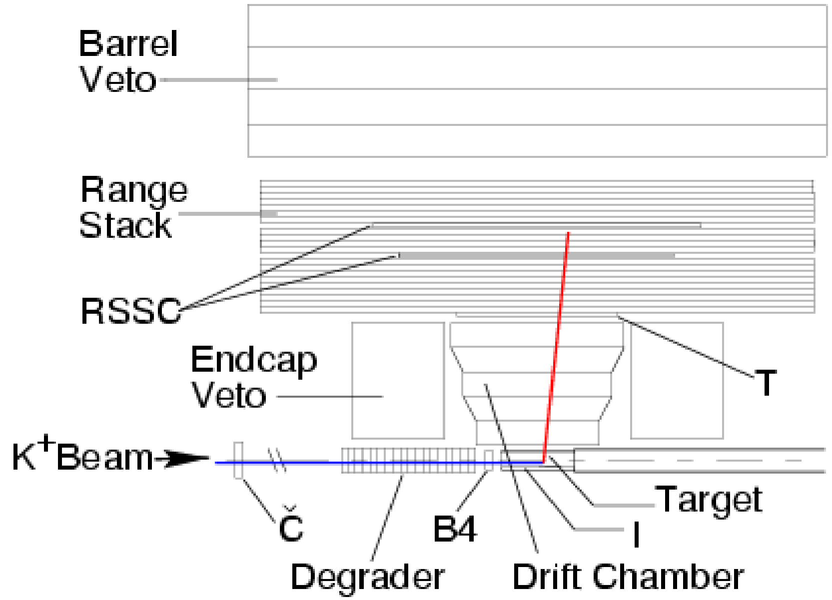


E787/E949: The definitive stopped K^+ detector.

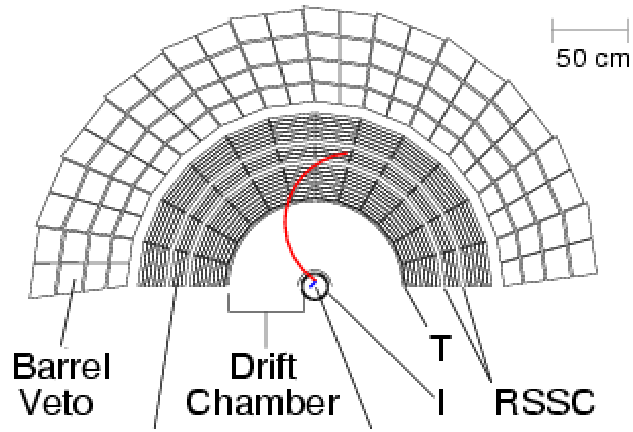


BNL E787/E949

Instrumentation:



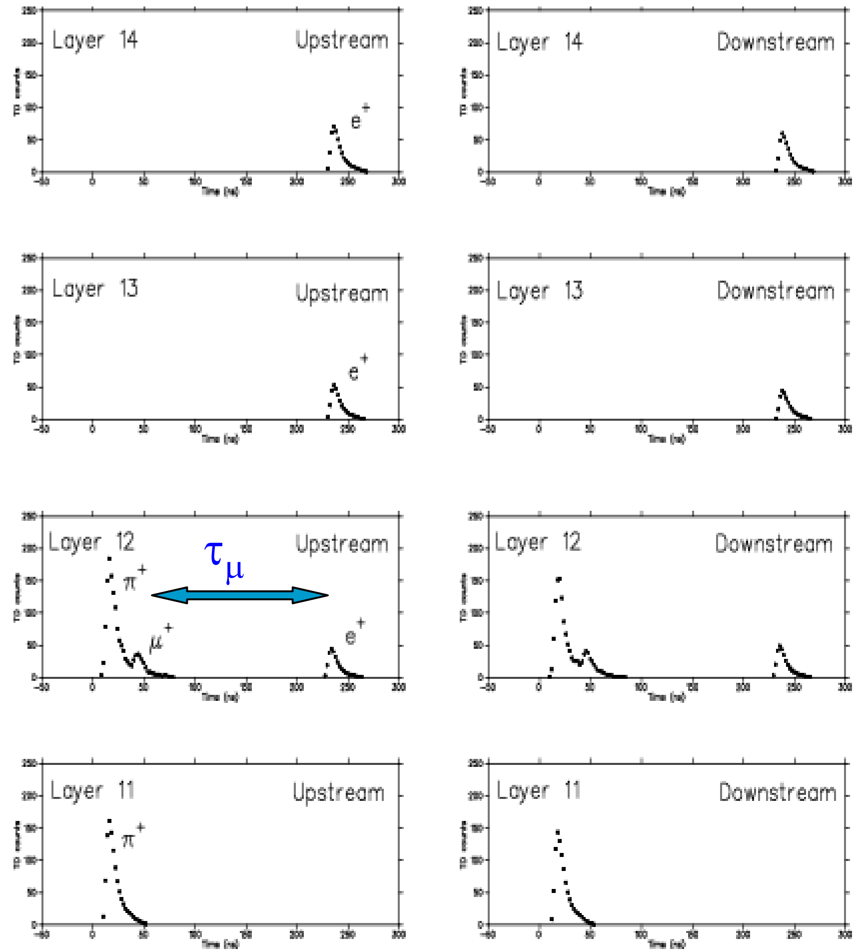
1-2 MHz of K+ stop in active target.



Instrumentation continued…

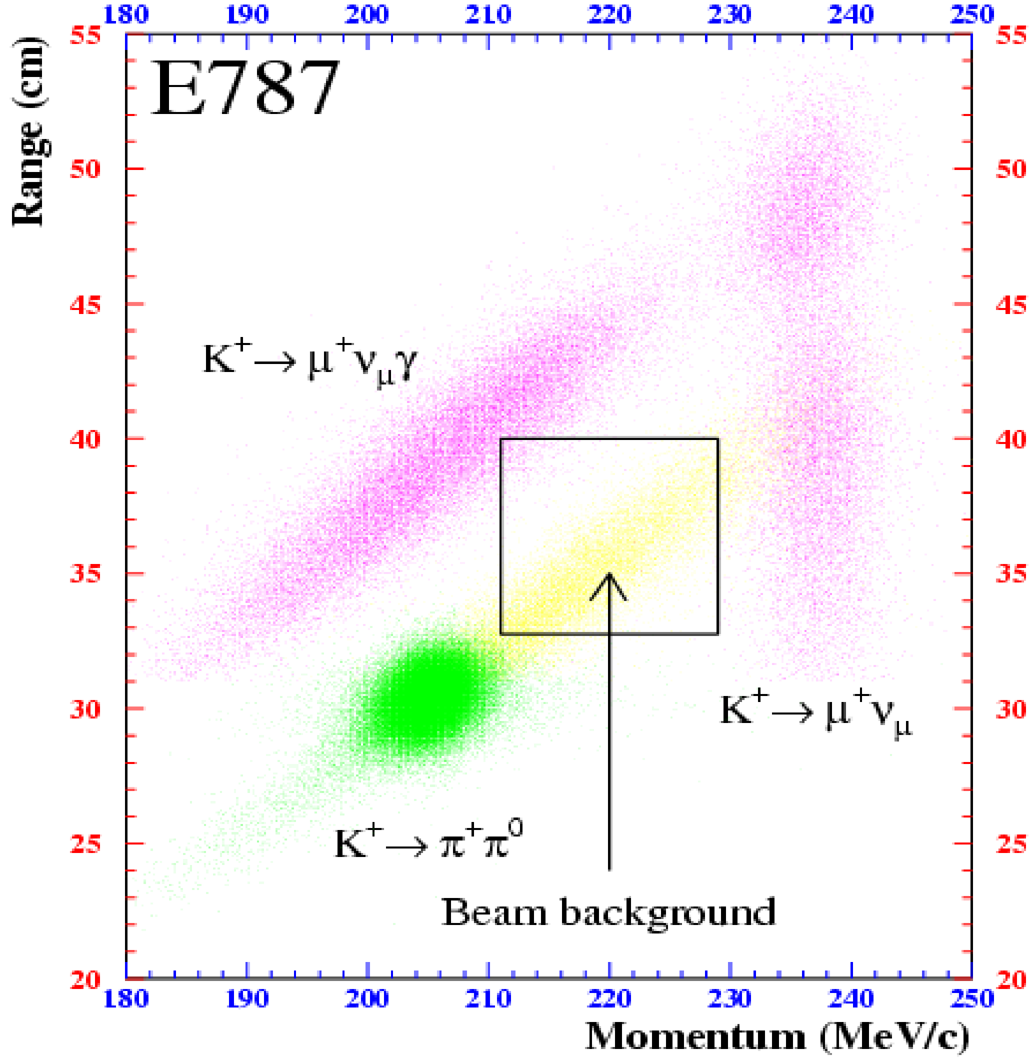
Particle ID exploits space and time topology of $\pi \rightarrow \mu \rightarrow e$ decay chain. This limits max rate to less than about $\sim\tau_\mu$ (1 μsec).

2.7 500 MHz transient digitizers (TD)



- **Pulse shapes from both ends of the plastic scintilators.**
- **Ability to identify the $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay**

3.1 Backgrounds in $\pi^+\nu\bar{\nu}(1)$ analysis

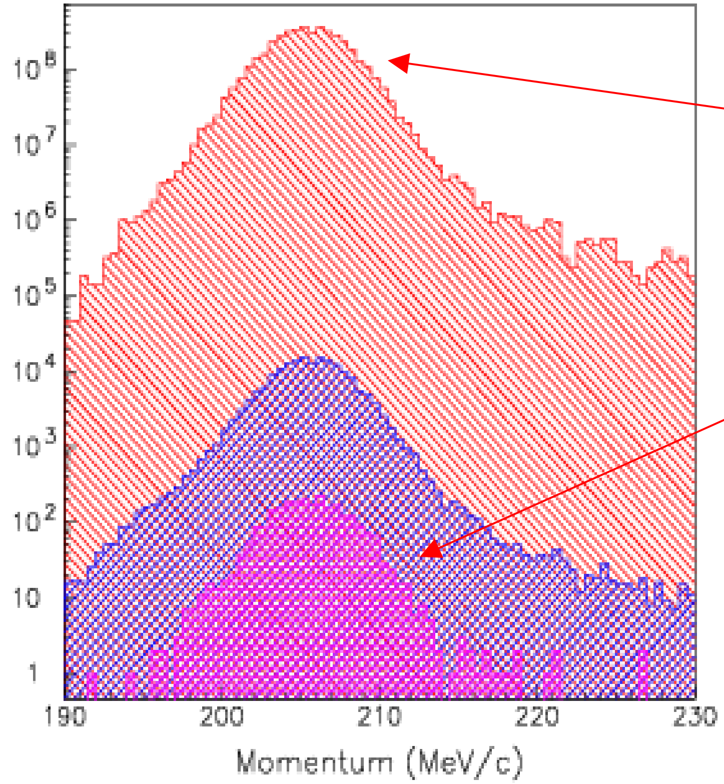


E787 Analysis Strategy.

- A priori identification of background sources.
- Suppress each background source with at least two independent cuts.
- Backgrounds cannot be reliably simulated: measure with data by inverting cuts and measuring rejection taking any (small) correlations into account.
- To avoid bias, set cuts using 1/3 of data, then measure backgrounds with remaining 2/3 sample.
- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- Use MC to measure geometrical acceptance for $K^+ \to \pi^+ \nu \bar{\nu}$. Verify by measuring $\mathcal{B}(K^+ \to \pi^+ \pi^0)$.
- "Blind" analysis. Don't examine signal region until all backgrounds verified.

Validating analysis cut inversion to determine background estimates from the data:

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



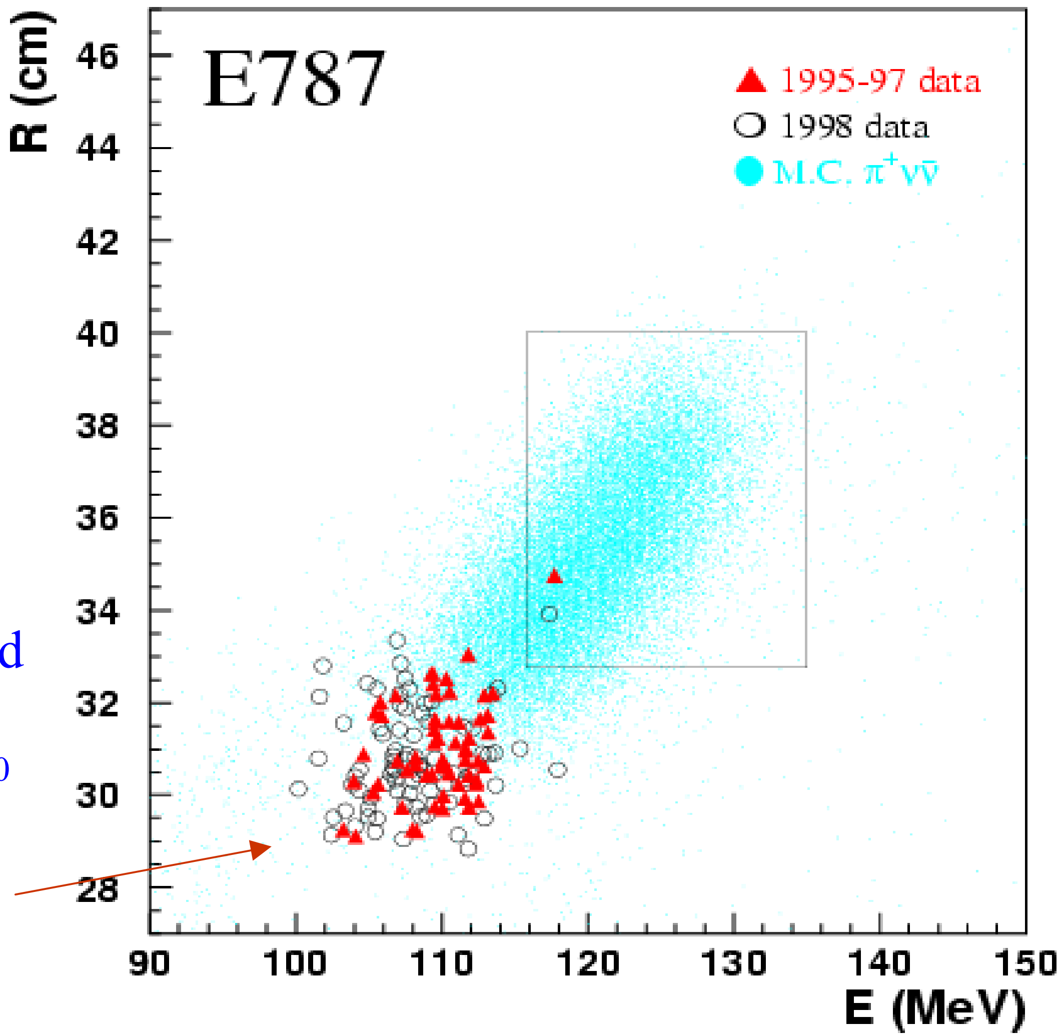
p_π before γ-veto.

p_π after γ-veto.

$(1-\varepsilon_{\pi 0} = 1.7\text{x}10^{-7})$

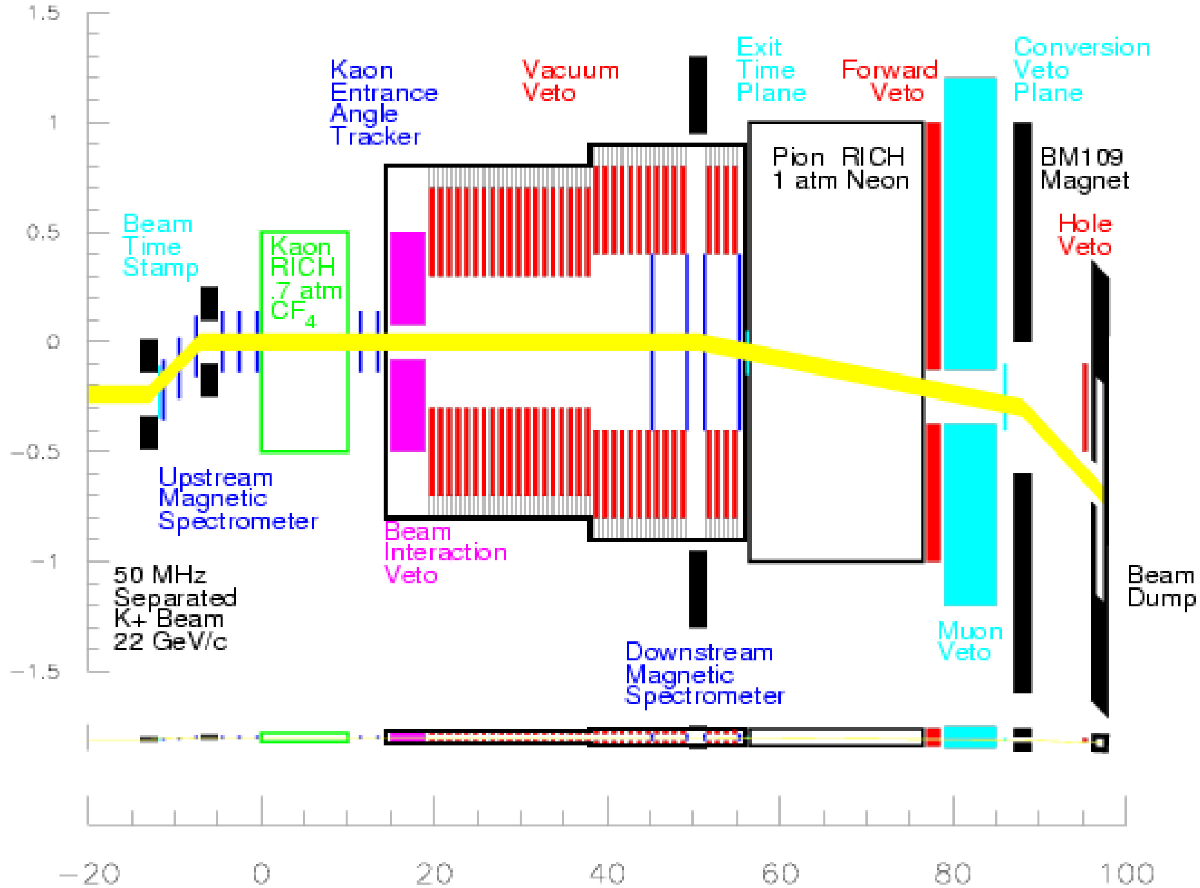
Demonstrated for BNL-787: π^+ momentum line shape unchanged
line γ cuts and full offline γ cuts.

On opening the box, two events are found…



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

The CKM Apparatus



- Decay in flight experiment: 22 GeV/c enriched K^+ beam.
- Philosophy: redundant measurements, proven technology.
- Good, redundant measurements of K^+ and π^+ momenta.
- Good, redundant particle ID for signal and backgrounds.
- Very high-rate, low-mass detectors.

Number of Kaons Needed

$$\textbf{Branching Ratio} \times \textbf{Acceptance}$$

$$1\times10^{-10} \times \left\{\begin{array}{ll} 0.12 & \text{decay region} \\ 0.034 & \text{acceptance/cuts} \\ 0.70 & \text{livetime/efficiencies} \end{array}\right\} = 2.74\times10^{-13}$$

$\Rightarrow$ 3.65×10^{14} K^+'s needed for 100 accepted $K^+ \to \pi^+\nu\bar{\nu}$ decays.

Assume a 2-year run with a 1-s spill of 4×10^{12} protons every 3-s:
2 yr/run·39 wk/yr·120 hr/wk·3600 s/hr·1 spill/3 s = 1.12×10^{7} spill/run

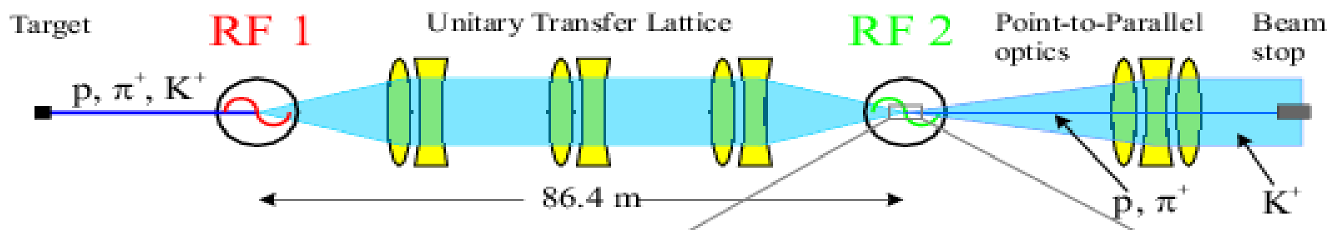
$\Rightarrow$ 32.5 MHz K^+ beam needed

⋆ Implications ⋆

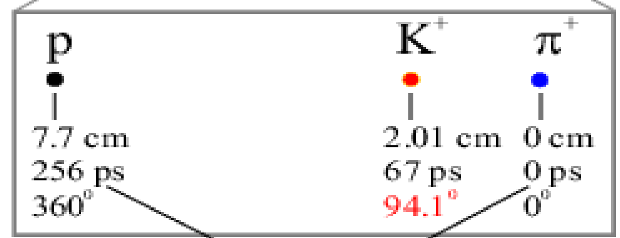
1. Protons required are a small fraction of the Main Injector capacity.
2. Unbunched beam *required*.
3. Enriched K^+ beam *required*.

Relative 22 GeV rates from 120 GeV protons: $\left\{\begin{array}{ll} 10 & \pi^+ \\ 4 & p \\ 1 & K^+ \end{array}\right.$

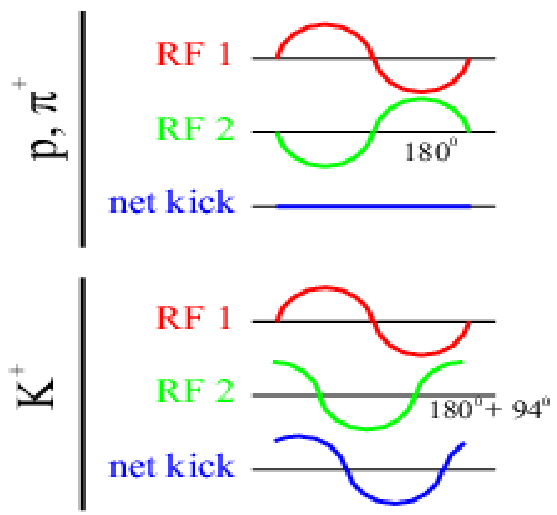
Enriching the Kaon Content of the Beam

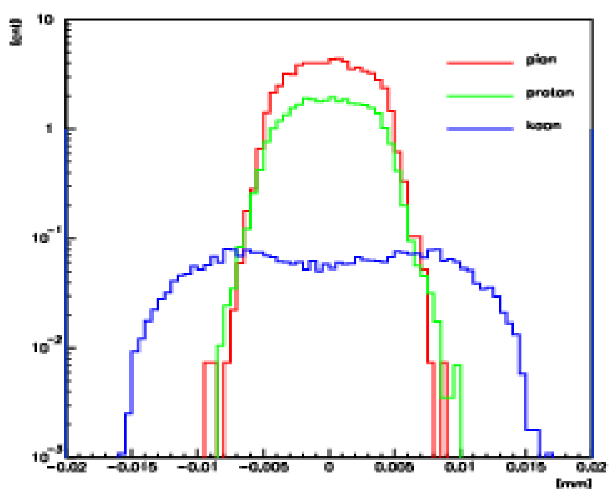


	v/c
π^+:	0.99998
K^+:	0.99975
p:	0.99909

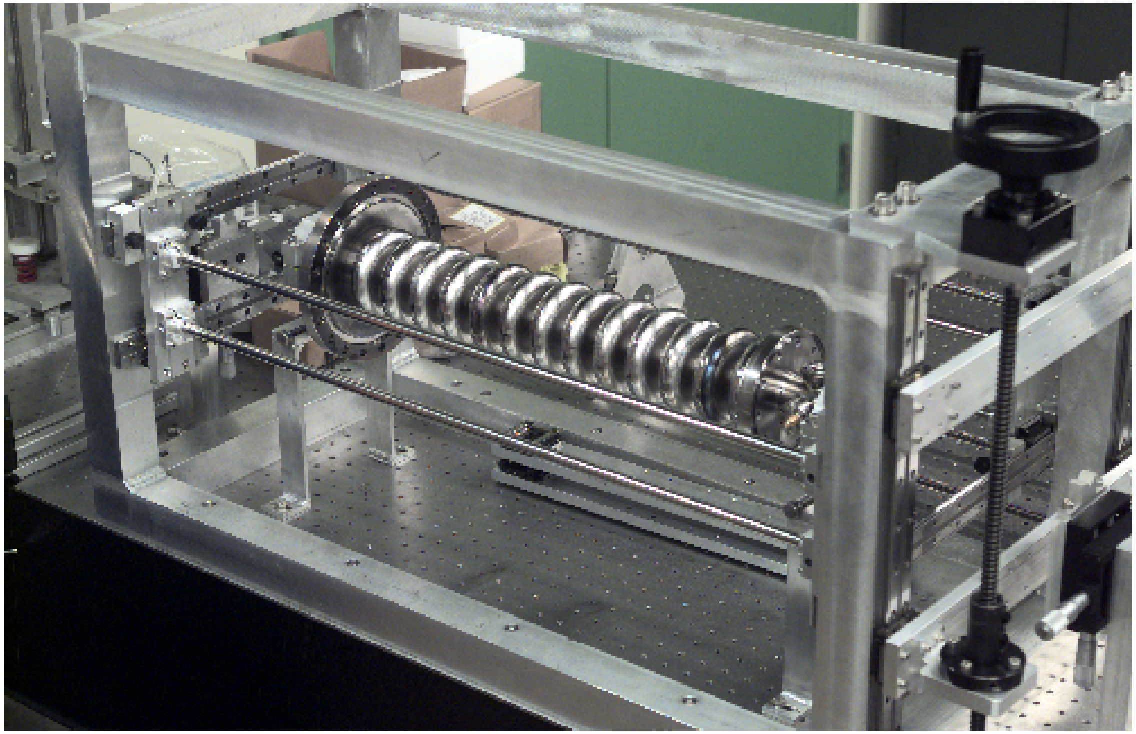


$$1/256\ \text{ps} = 3.91\ \text{Ghz}$$



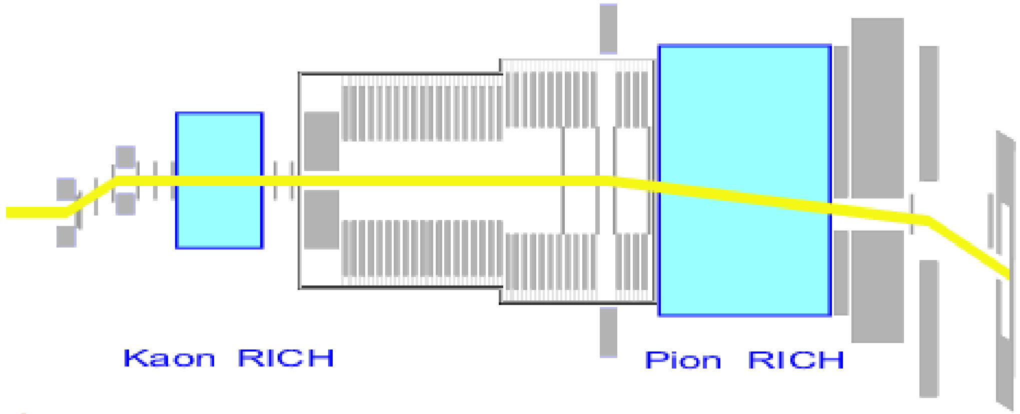


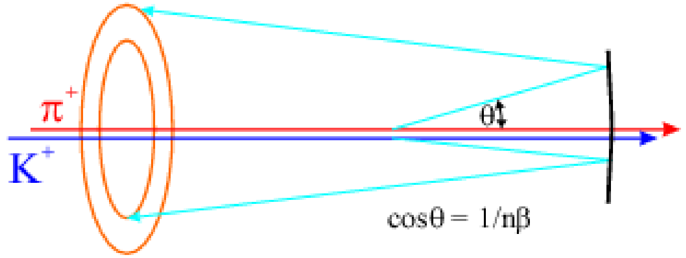
Prototype Superconducting RF Cell



- 13-cell *transverse field* prototype.
- Six 13-cell cavities per station: $p_T = 15$ MeV.
- Tesla R&D has been critical to the success of this development.
  - One-cell prototype has exceeded surface field requirement by $\times 2$.
  - Tuning and optimization of 13-cell cavity underway.

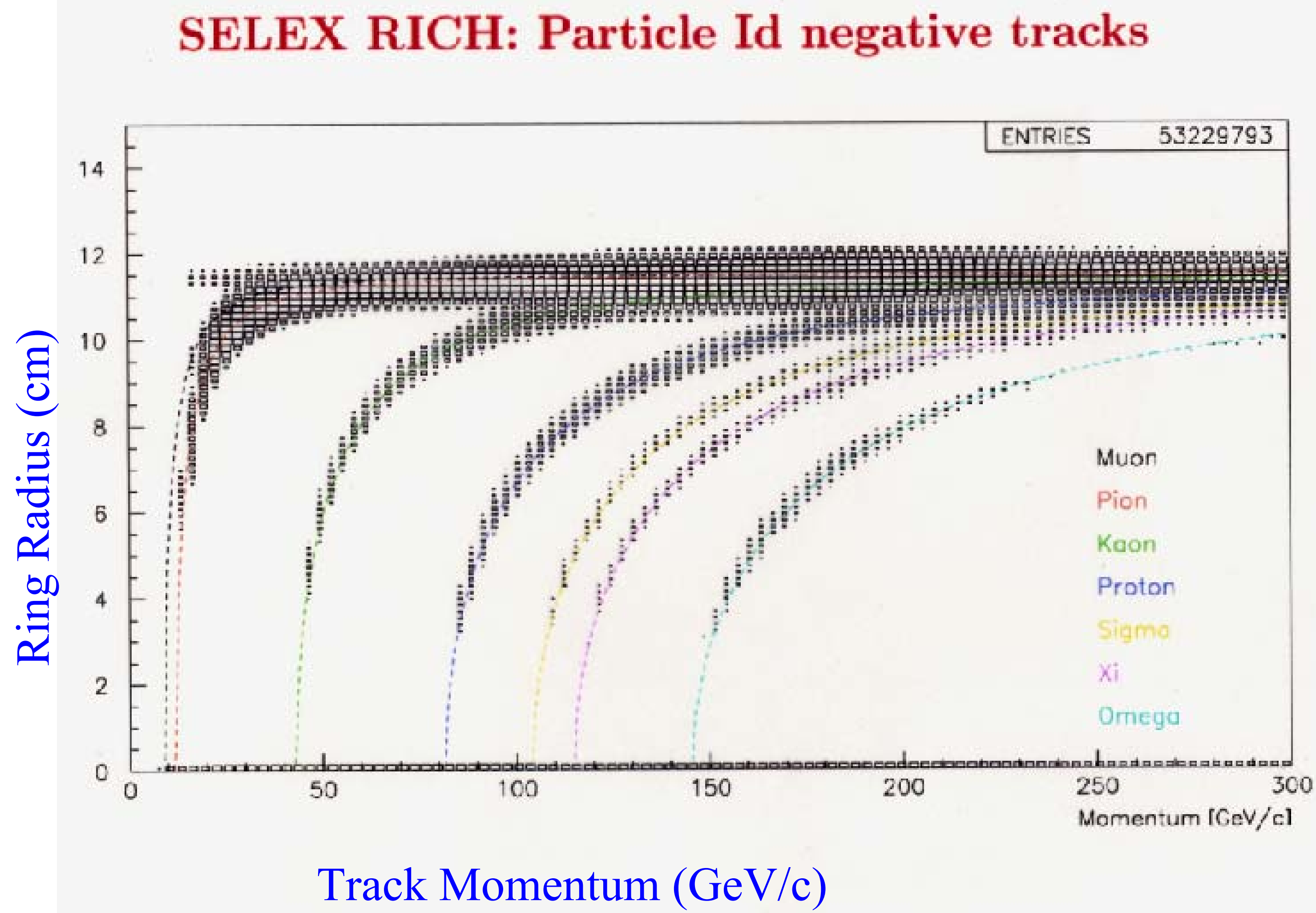
Ring Imaging Cherenkov Detector Systems



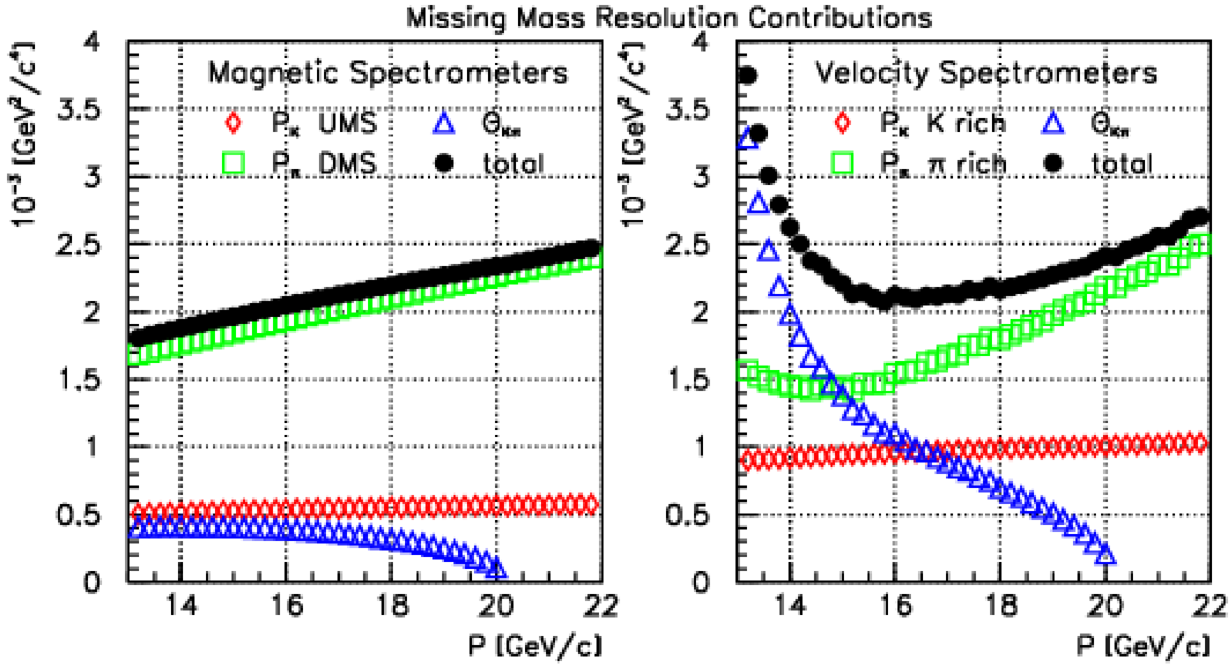


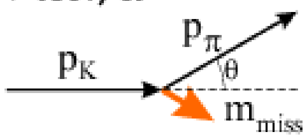
$$r = \frac{R}{2}\sqrt{2 - \frac{2}{n}\sqrt{1 + \left(\frac{mc}{p}\right)^2}}$$

- Vector velocity spectrometers.
- Provide totally independent measurement of momentum of K^+ and π^+.
- Provide (with magnetic spectrometers) particle ID for K^+, π^+, μ, p and e.
- Fast: phototube readout.
- Excellent momentum resolution.
- Based on successful SELEX RICH.


SELEX RICH: Particle Id negative tracks
ENTRIES 53229793
Ring Radius (cm)
0
2
4
6
8
10
12
14
0
50
100
150
200
250
300
Momentum [GeV/c]
Muon
Pion
Kaon
Proton
Sigma
Xi
Omega
Track Momentum (GeV/c)

Momentum and Velocity Spectrometer Resolutions Well Matched





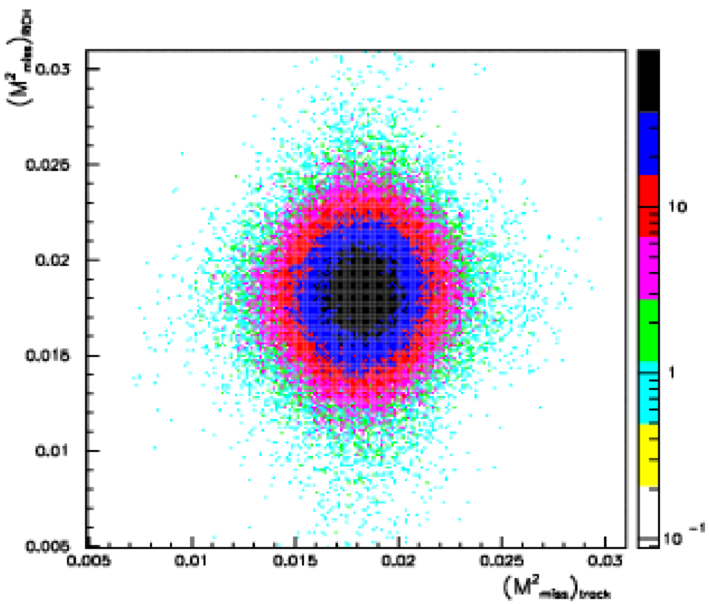
$M^2_{miss}\pi^0 = 18\text{x}10^{-3}$ Gev^2/c^4

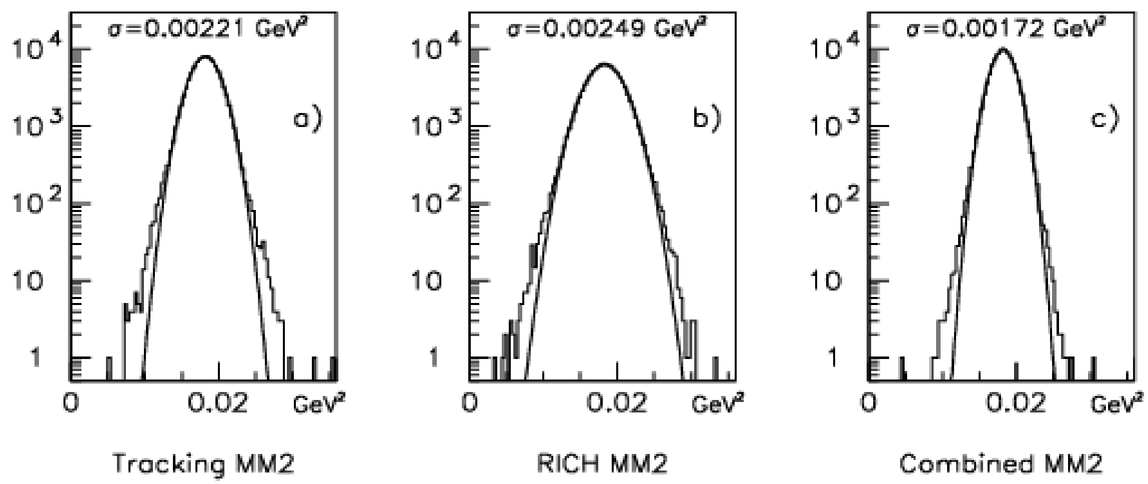
$$M^2_{\rm miss} = M_K^2\left(1-\frac{p_\pi}{p_K}\right) + m_\pi^2\left(1-\frac{p_K}{p_\pi}\right) - p_\pi p_K \theta^2$$

Little Correlation between Magnetic and Velocity Measurements

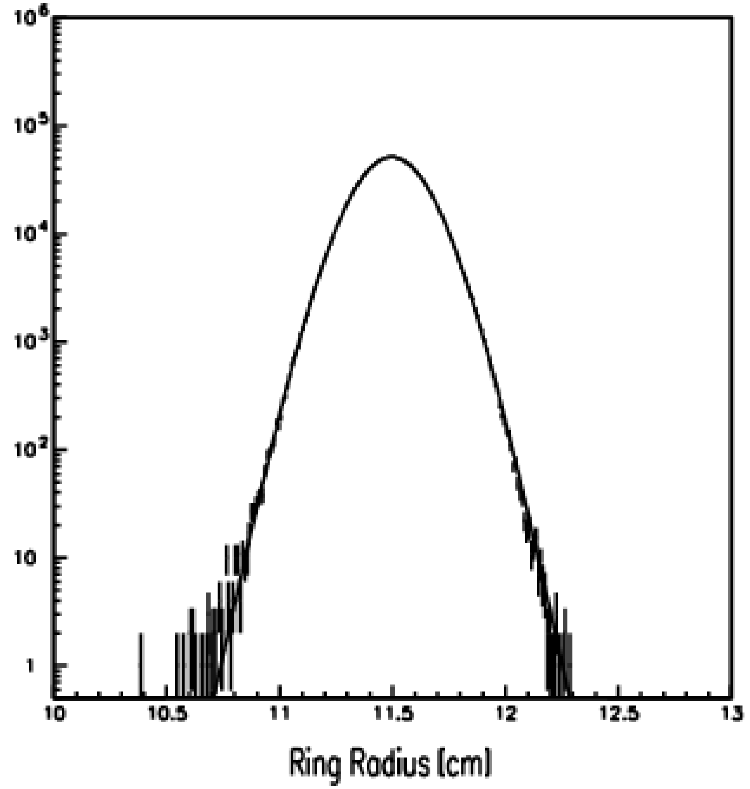
Full GEANT simulation of:

$K^+ \rightarrow \pi^+ \pi^0$ Bkg.



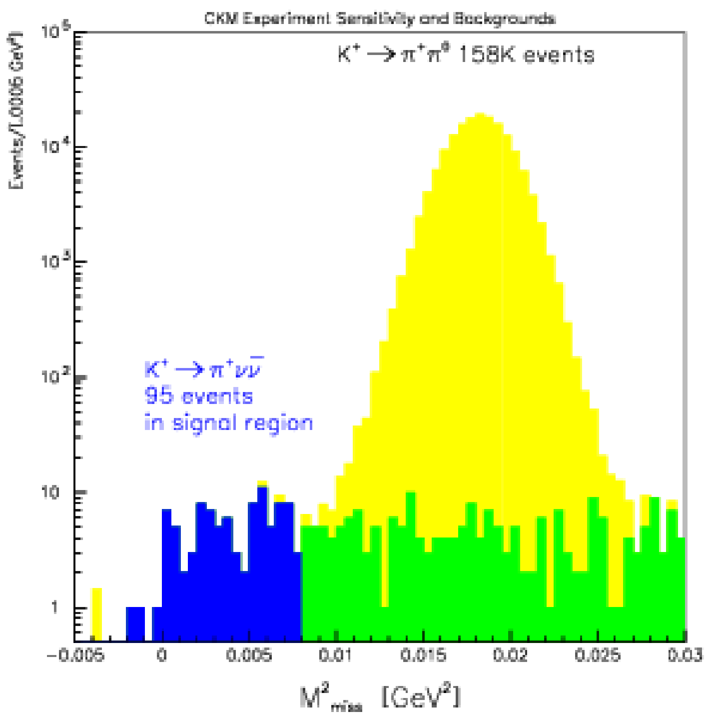


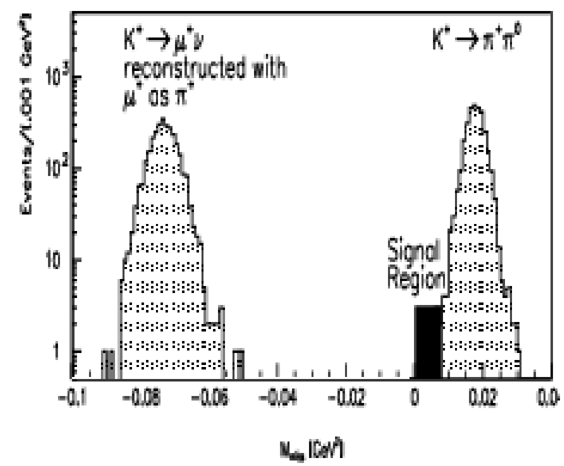
SELEX RICH Rings Gaussian over Five Orders of Magnitiude



β=1 Rings

CKM Sensitivity After Two Years





$$
\begin{array}{rrlcrl}
 & 1.123\times 10^{7} & \text{spill-s/2 yr run} & & & \\
\times & 31\times 10^{6} & \text{MHz kaon beam} & = & 3.5\times 10^{14} & K^+ \\
\times & 1\times 10^{-10} & \text{BR}(K^+ \to \pi^+\nu\bar{\nu}) & = & 3.5\times 10^{4} & K^+ \to \pi^+\nu\bar{\nu} \\
\times & 0.116 & \text{lifetime acceptance} & = & 4.0\times 10^{3} & K^+ \to \pi^+\nu\bar{\nu} \\
\times & 0.034 & \text{acceptance/cuts} & = & 137 & K^+ \to \pi^+\nu\bar{\nu} \\
\times & 0.070 & \text{livetime/efficiency} & = & 96 & K^+ \to \pi^+\nu\bar{\nu}
\end{array}
$$

The $K_L \rightarrow \pi^0 \nu\nu$ Experimental Program

- KTeV search complete. Flux of 0.33×10^{12} in-flight kaon decays analyzed. No events observed. Limit (90% CL) of $< 5.9 \times 10^{-7}$ established.
  Technique required Dalitz decay of π^0 ($\pi^0 \rightarrow e^+e^-\gamma$) to control backgrounds to 0.1 event level. New techniques required to reach SM level.

- KEK-E391a in construction, commissioning this Fall. Technique is based on fully hermetic photon veto coverage. Expected sensitivity of 1×10^{-10}. This is still x30 above SM level, but this experiment is vital to establish hermetic photon veto techniques. Proposed continuation to JHF in 200X.

- BNL KOPIO experiment approved. Novel techniques to measure K^0 momentum and photon directions. Expected sensitivity of 50 SM events over a background of ~20 events. Physics Results in 200X.

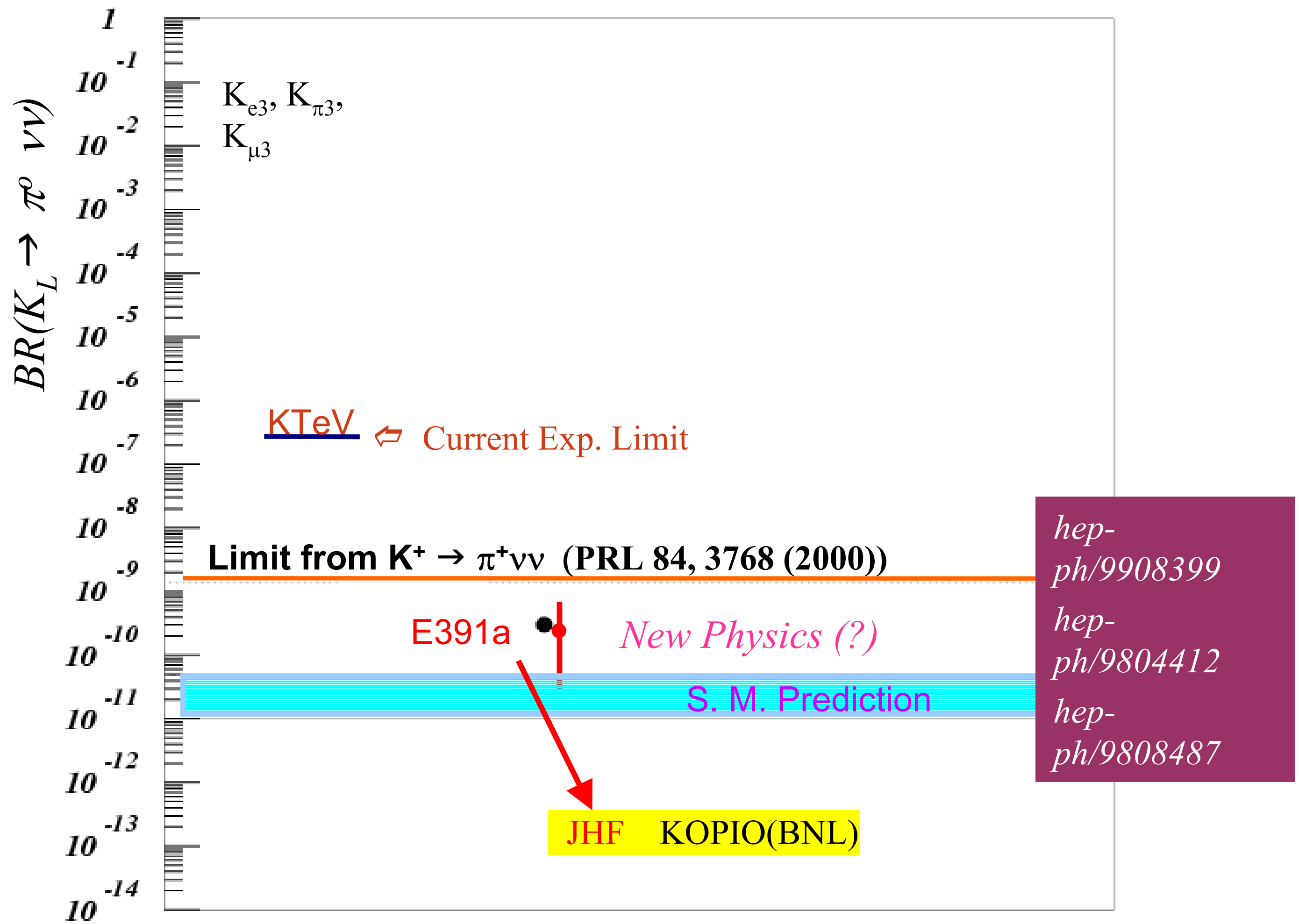
K_L Decay Modes…*Everything* is the enemy; some worse than others….

Decay Mode	Branching Ratio	Additional Particles
$\pi^o\pi^o\pi^o$	21.13 %	4γ
$\pi^+\pi^-\pi^o$	12.55 %	2Ch
$\pi^+\mu^-\nu$	27.18 %	2Ch
$\pi^+e^-\nu$	38.78 %	2Ch
$\gamma\gamma$	$5.86\text{x}10^{-4}$	
$\gamma\gamma\gamma$	$<2.40\text{x}10^{-7}$	1γ
$\pi^o\gamma\gamma$	$1.68\text{x}10^{-6}$	2γ
$\pi^o\pi^+e^-\nu$	$5.18\text{x}10^{-5}$	2Ch
$\pi^+e^-\nu\gamma$	$3.62\text{x}10^{-3}$	2Ch
$\pi^+\mu^-\nu\gamma$	$5.70\text{x}10^{-4}$	2Ch
$\pi^+\pi^-\gamma$	$4.61\text{x}10^{-5}$	2Ch
$\pi^o\pi^o\gamma$	$<5.60\text{x}10^{-6}$	3γ
$\mu^+\mu^-\gamma$	$3.25\text{x}10^{-7}$	2Ch
$e^+e^-\gamma$	$10.00\text{x}10^{-7}$	2Ch
$e^+e^-\gamma\gamma$	$6.90\text{x}10^{-7}$	2Ch

Decay Mode	Branching Ratio	Additional Particles
$\pi^o\gamma e^+e^-$	$<7.1\ \text{x}10^{-7}$	1γ 2Ch
$\pi^+\pi^-$	$2.06\text{x}10^{-3}$	2Ch
$\pi^o\pi^o$	$9.27\text{x}10^{-4}$	2γ
$\mu^+\mu^-$	$7.15\text{x}10^{-9}$	2Ch
e^+e^-	$9\ \text{x}10^{-12}$	2Ch
$\pi^+\pi^-e^+e^-$	$3.5\ \text{x}10^{-7}$	4Ch
$\mu^+\mu^-e^+e^-$	$2.9\ \text{x}10^{-9}$	4Ch
$e^+e^-e^+e^-$	$4.1\ \text{x}10^{-8}$	4Ch
$\pi^o\mu^+\mu^-$	$<5.1\ \text{x}10^{-9}$	2Ch
$\pi^o e^+e^-$	$<4.3\ \text{x}10^{-9}$	2Ch
$\pi^o\nu\nu$	$<5.9\ \text{x}10^{-7}$	
$e^+\mu^-$	$<4.7\ \text{x}10^{-12}$	2Ch
$e^+e^-\mu+\mu-$	$<6.1\ \text{x}10^{-9}$	4Ch
$\pi^o\mu^+e^-$	$<6.2\ \text{x}10^{-9}$	2Ch

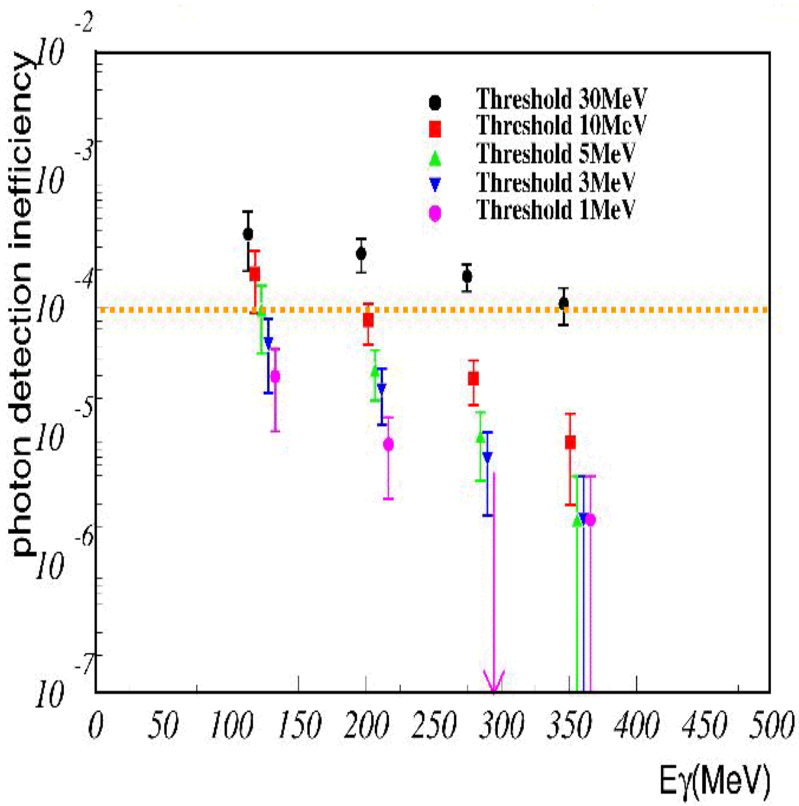
Where is the goal?

G.Y. Lim;
KEK



Detector Inefficiency

Inefficiency of γ detection



Inefficiency for charged particles

G.Y. Lim; KEK

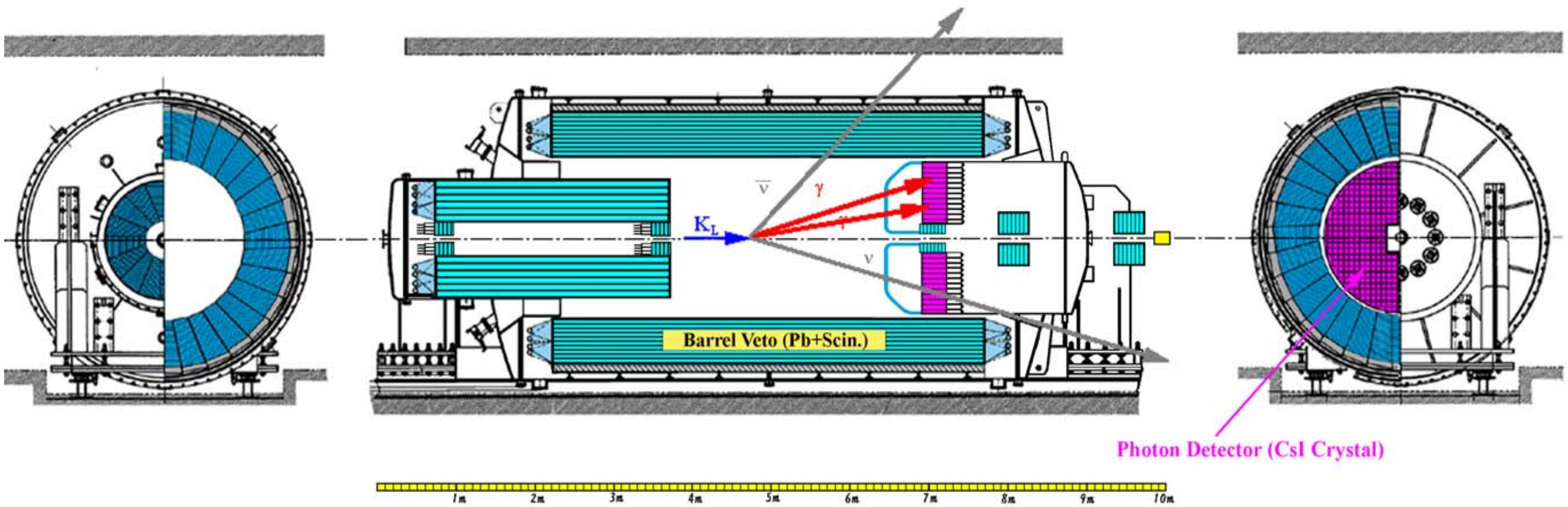
Particle	Total events	Tail events	Inefficiency (1)	Inefficiency (2)
e^+	4.7×10^4	13	$(2.8 \pm 0.8) \times 10^{-4}$	$(3.2 \pm 0.9) \times 10^{-4}$
π^+	6.1×10^4	0	$< 1.6 \times 10^{-5}$	$< 1.6 \times 10^{-5}$
e^-	4.1×10^4	5	$(1.2 \pm 0.5) \times 10^{-4}$	$< 1.3 \times 10^{-4}$
π^-	1.93×10^5	115	$(6.0 \pm 0.6) \times 10^{-4}$	$(6.0 \pm 0.6) \times 10^{-4}$
p	1.97×10^5	10	$(5.0 \pm 1.6) \times 10^{-5}$	$(5.0 \pm 1.6) \times 10^{-5}$

NIM A359 p478 (1995)

B.G. from $K_L \to \pi^- e^+ \nu$ Decay

→ *Veto charged particles*

E391a Detector Setup



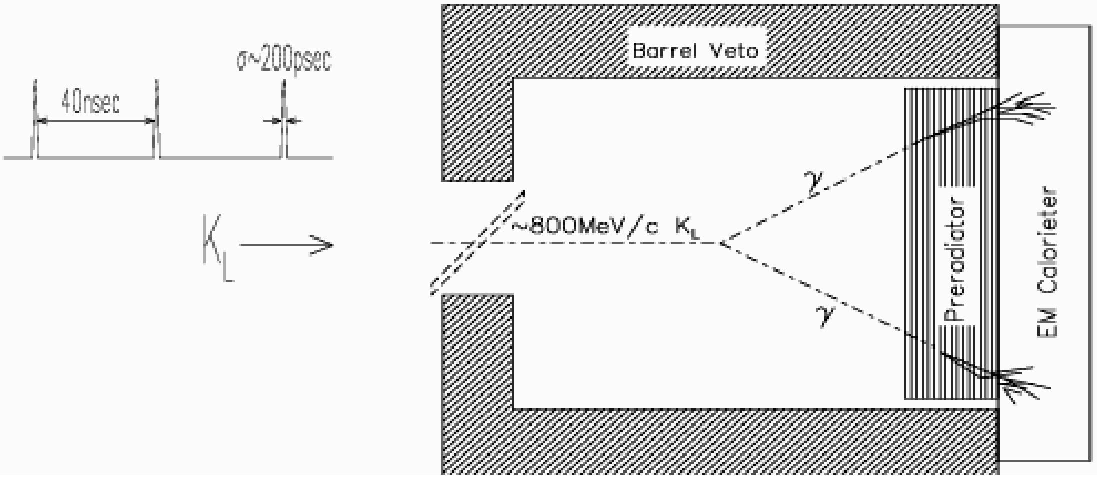
$K_L \rightarrow$ $\pi^o \nu \nu$ → *Nothing* → 4π veto system

π^o → $\gamma\gamma$ → pure CsI calorimeter

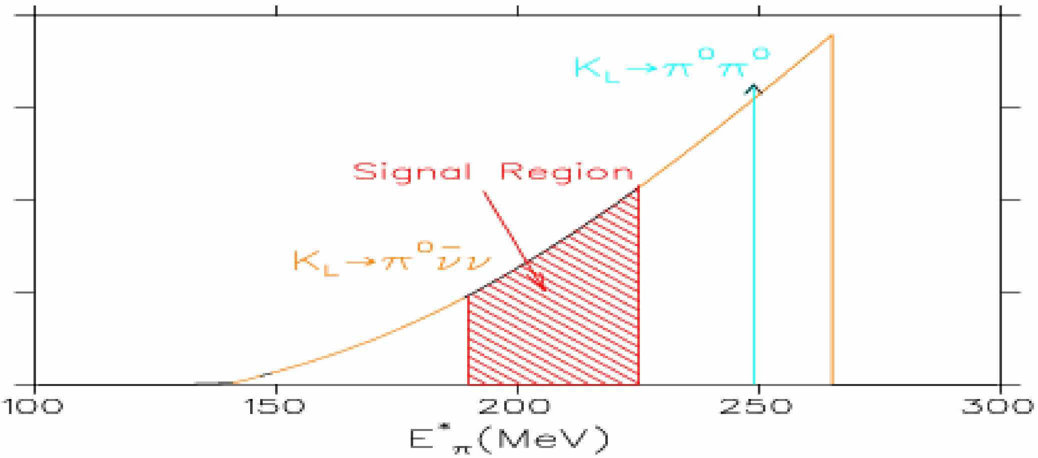
KOPIO: A Proposal to Measure $K_L^0 \to \pi^0 \nu \bar{\nu}$

Lessons from E787:

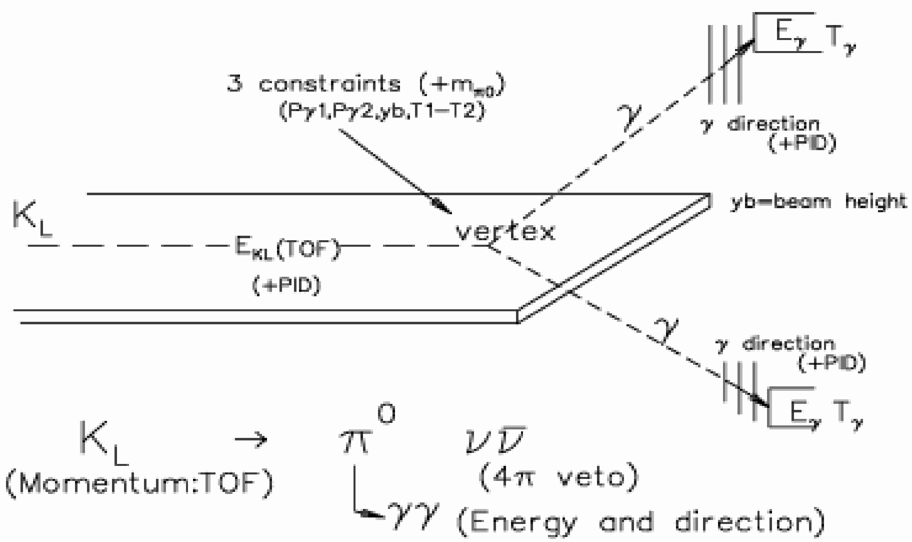
- Measure as much as possible:
  Energy, position and *ANGLE* of each photon.
- Work in the C.M. system :
  Use TOF to get the K_L^0 momentum.
- Photon Veto limited by photonuclear interactions at low energies.



- **Search for** $K_L^0 \to \pi^0 \nu \bar{\nu}$

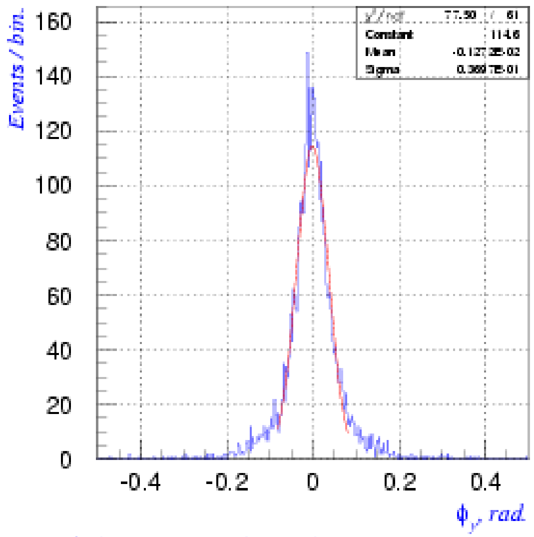


- **Measure all initial & final state quantities**

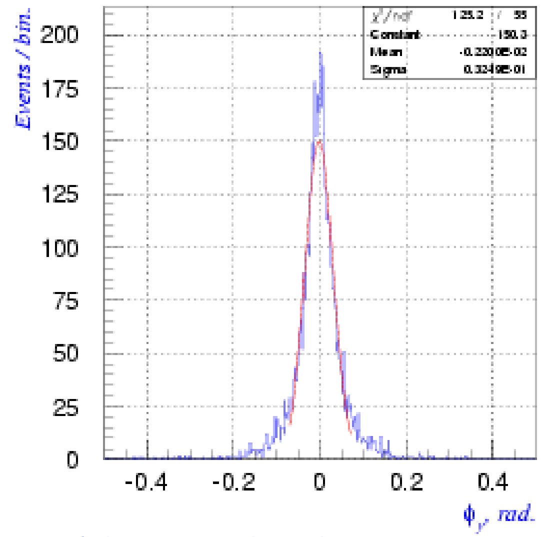


- **Measure Br to** $\sim 15\%$ **with** $S/N \sim 2$

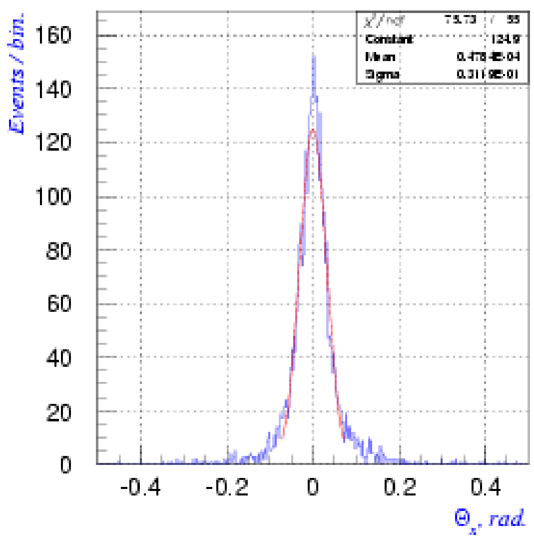
KOPIO. Preradiator Prototype Test. Gamma beam.



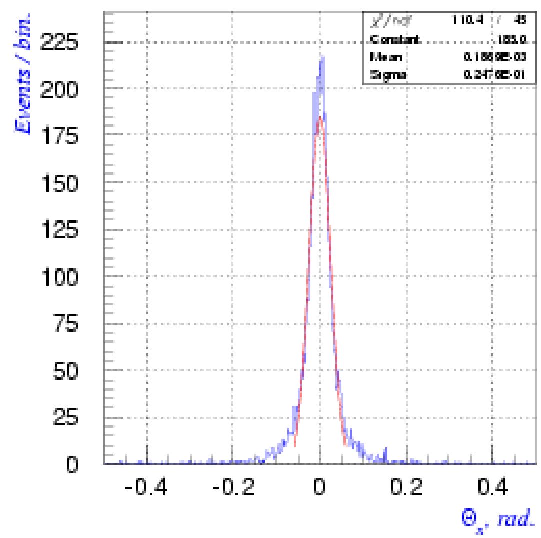
ϕ_y distribution of detected photons. $E_\gamma = 150$ MeV.



ϕ_y distribution of detected photons. $E_\gamma = 250$ MeV.

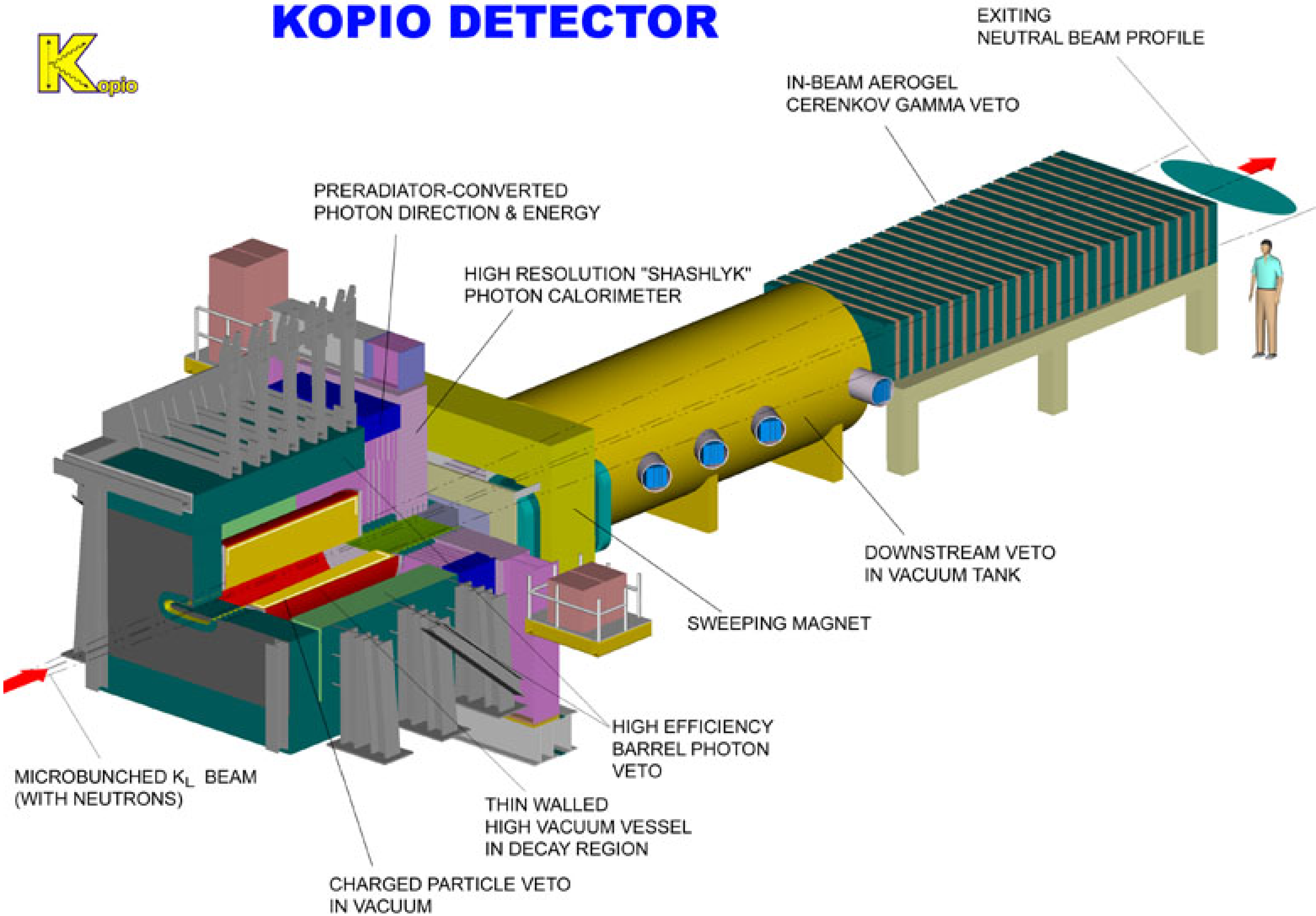


Θ_x distribution of detected photons. $E_\gamma = 150$ MeV.



Θ_x distribution of detected photons. $E_\gamma = 250$ MeV.

KOPIO DETECTOR



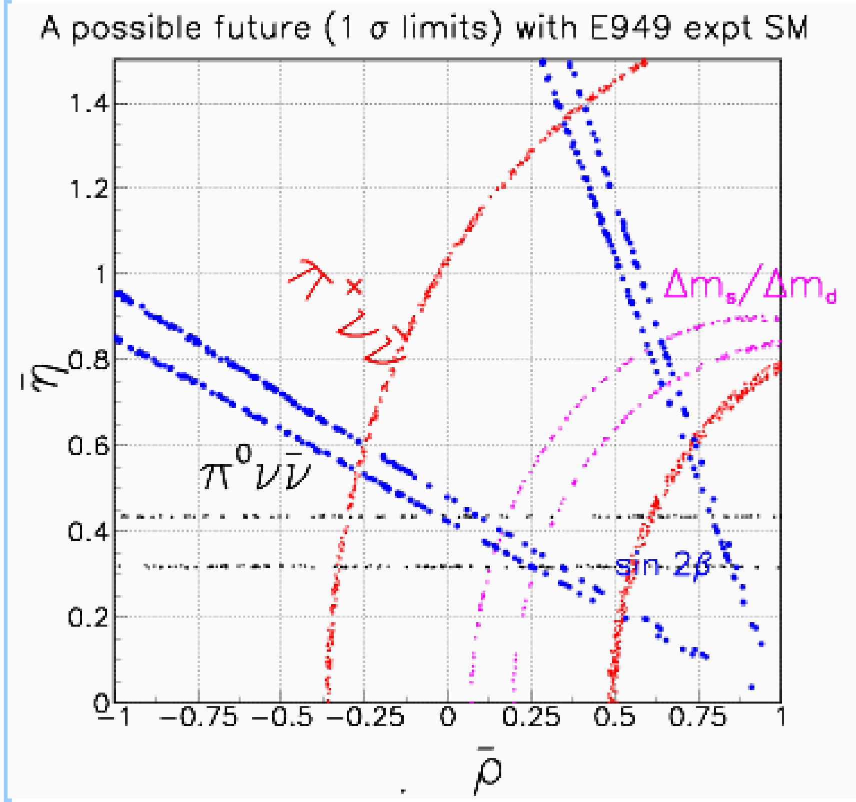
Let's consider a possible scenario of how B&K precision measurements can probe for physics beyond the Standard Model….

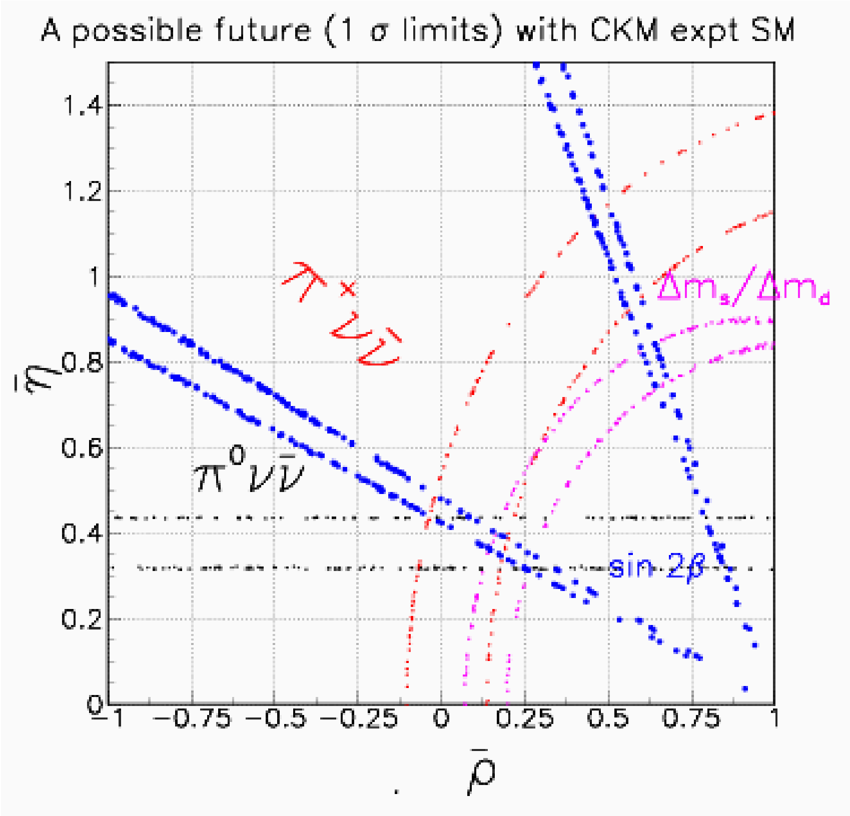
ASSUMPTIONS

- B measurements consistent with the SM:
  $\sin 2\beta = 0.75 \pm 0.02$ and $\Delta m_s / \Delta m_d = 17.0 \pm 1.7 \text{ ps}^{-1}$
- Two possible sets of K measurements.
  One consistent with SM, the other with both K branching ratios twice the SM prediction.
- Compare impact of E949 and CKM experiments.
- K experiments reach their projected sensitivities.

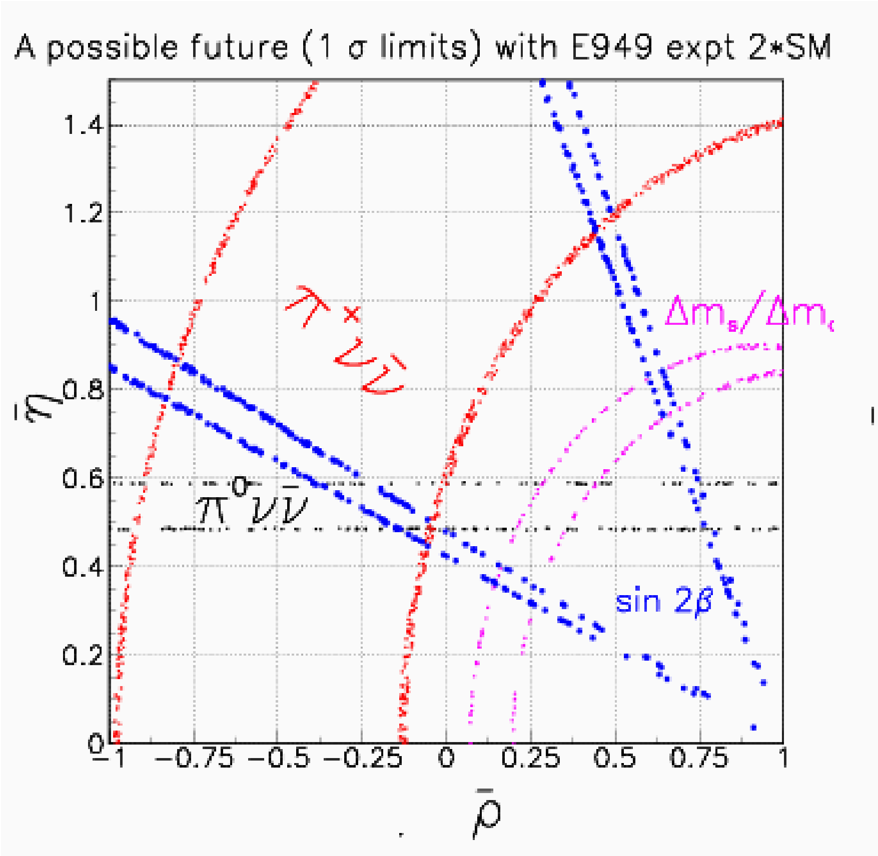
Treat all uncertainties as statistical using the Bayesian option of CKMfitter, hep-ph/0104062.

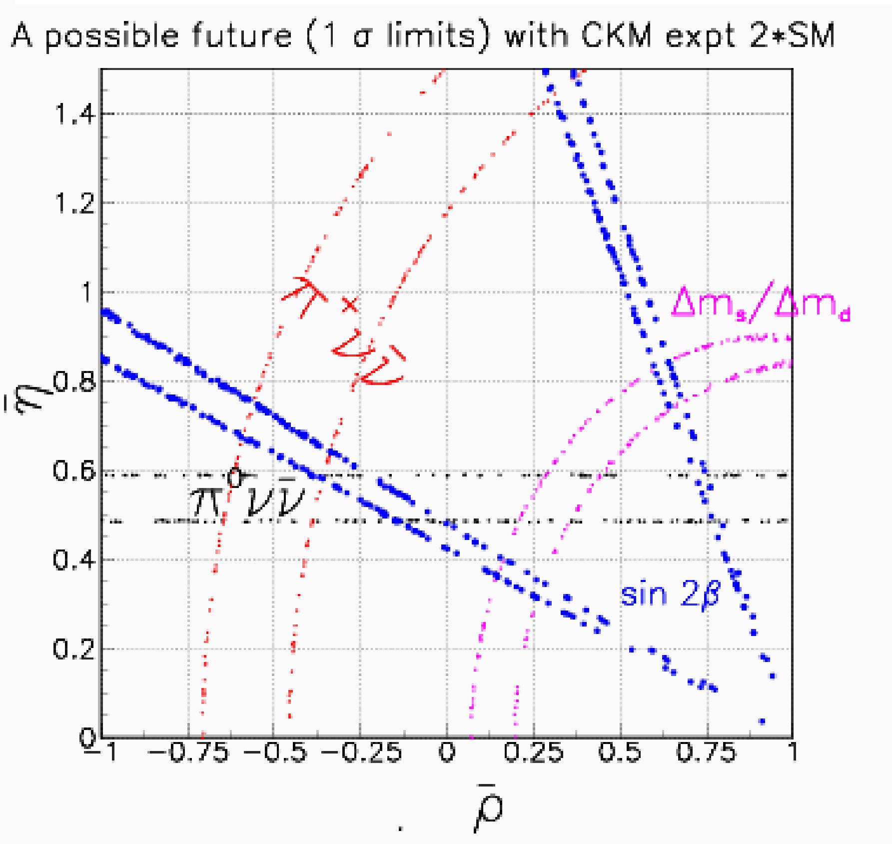
1-σ Bands for $K \to \pi\nu\bar{\nu}$ and $\sin 2\beta$ & $\Delta m_s/\Delta m_d$ at Standard Model Central Values:



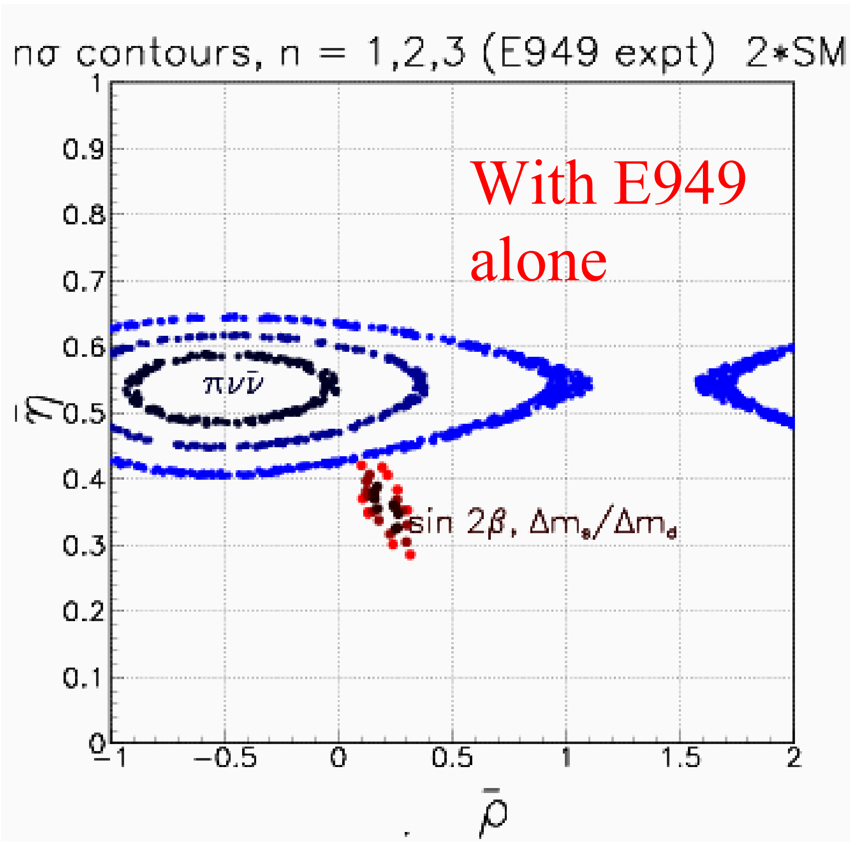


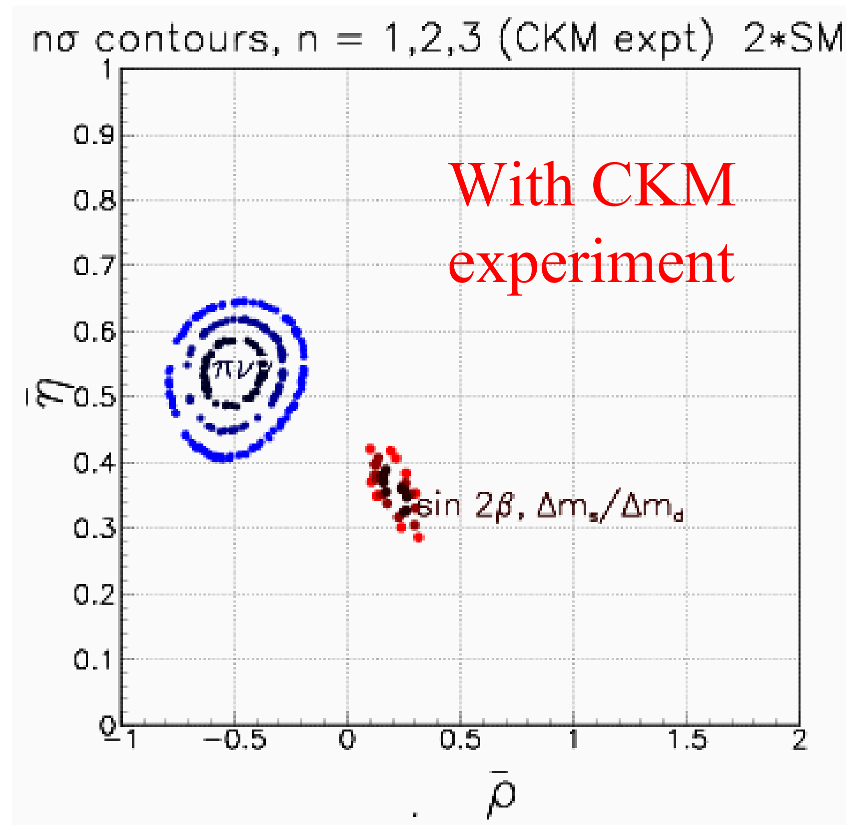
1-σ Bands for $K_L \to \pi^0 \nu\bar{\nu}$ and $\sin 2\beta$ & $\Delta m_s/\Delta m_d$ at SM level and $K^+ \to \pi^+ \nu\bar{\nu}$ at E787 central value:





σ-Contours for $K_L \to \pi^0 \nu\bar{\nu}$ and $\sin 2\beta$ & $\Delta m_s/\Delta m_d$ at SM level and $K^+ \to \pi^+ \nu\bar{\nu}$ at E787 central value:





Conclusions

- Rare kaon physics has matured to the point where the step from proven $1x10^{-11}$ sensitivity to $1x10^{-12}$ has been sensibly argued. This sensitivity is the key that will unlock the door to $K \rightarrow \pi \nu \bar{\nu}$.
- This step is fueled by ever increasing proton drivers ($7x10^{13}$ protons/pulse with the AGS!), very clean kaon beams, and innovative detector technologies.
- The CKM, KOPIO, and E391@JHF form a suite of promising experiments that can reach the $1x10^{-12}$ frontier in this decade.

Spare Slides.

CKM Matrix Element Measurements

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

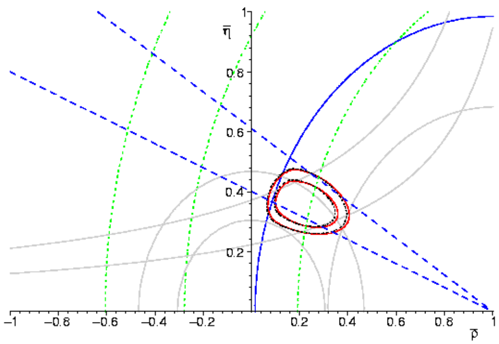
	Element	Value	Error	Method
1	$\|V_{ud}\|$	0.9735±0.0008	0.08%	nuclear β-decay neutron β-decay
2	$\|V_{us}\|$	0.2196±0.0023	1.1%	K_{e3} decays hyperon β-decays
3	$\|V_{cb}\|$	0.0402±0.0019	4.7%	$B \to \overline{D}^* l^+ \nu_l$ inclusive B decays
4	$\|V_{cd}\|$	0.224±0.016	7.1%	$\nu\overline{\nu}$ charm production
5	$\|V_{cs}\|$	1.04±0.16	15%	D_{e3} decays charm-tagged W decays
6	$\|V_{tb}^* V_{td}\|$	0.0083±0.0016	19%	ΔM_{B_d}
7	$\|V_{ub}/V_{cb}\|$	0.090±0.025	28%	$b \to u l^+ \nu_l$

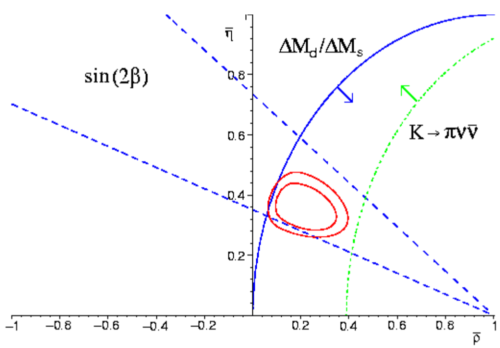
$K^+ \to \pi^+ \nu \bar{\nu}$: *a rising star on the stage of flavor physics*

G. D'Ambrosio and G. Isidori

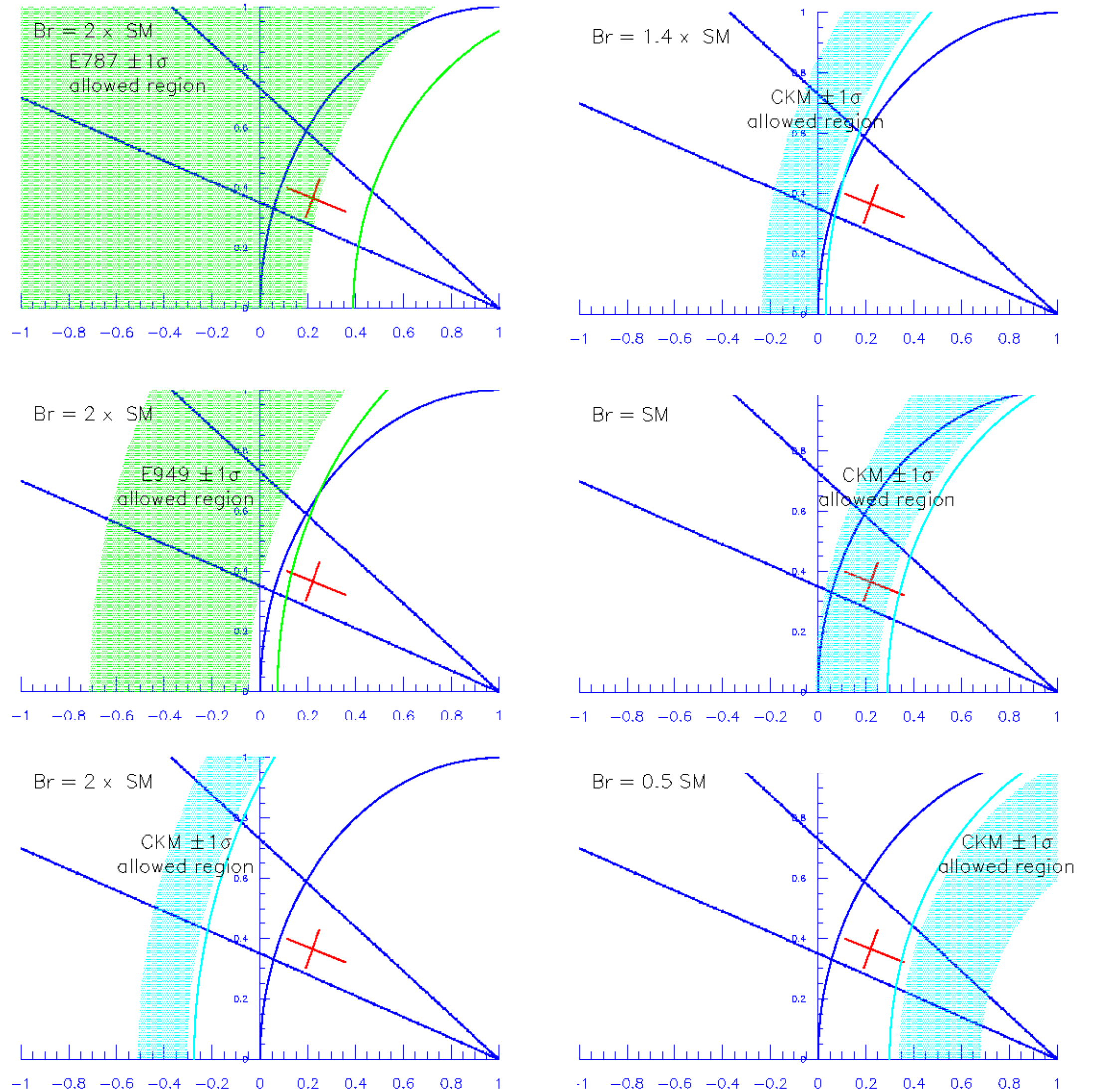
hep-ph/0112135

" Motivated by the new E787 (results) we analyze the present impact and future prospects opened by measurements of Br [$K^+ \to \pi^+ \nu\nu$] "



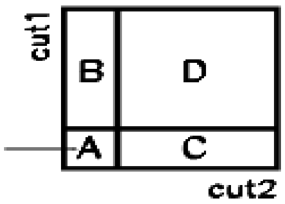


More cases (±1σ and 90% CL) for E787, E949 and CKM



3.5 Bifurcated Analyses

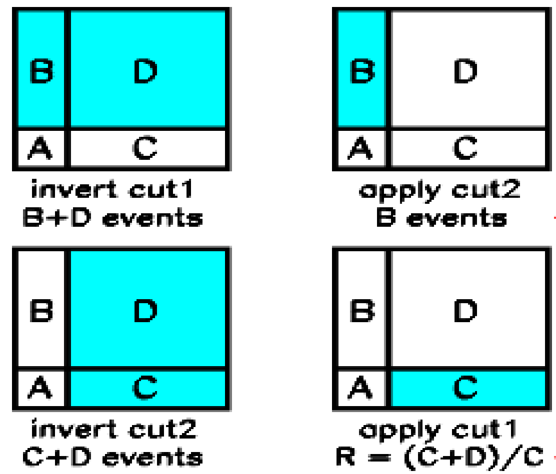
3.5.1 How does it work?



if cut1,cut2 uncorrelated,

$A/B = C/D$

$A = BC/D$



$N = B$

← Normalization branch

$bg = N/(R-1)$
$= BC/D$

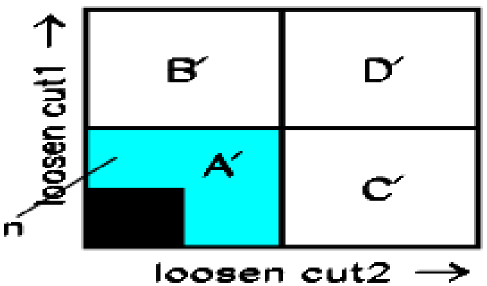
← Rejection branch

3.5.2 How can we check the correlation?

predict
$bg' = B'C'/D' - BC/D$

mask out box
and observe

outside−the−box region

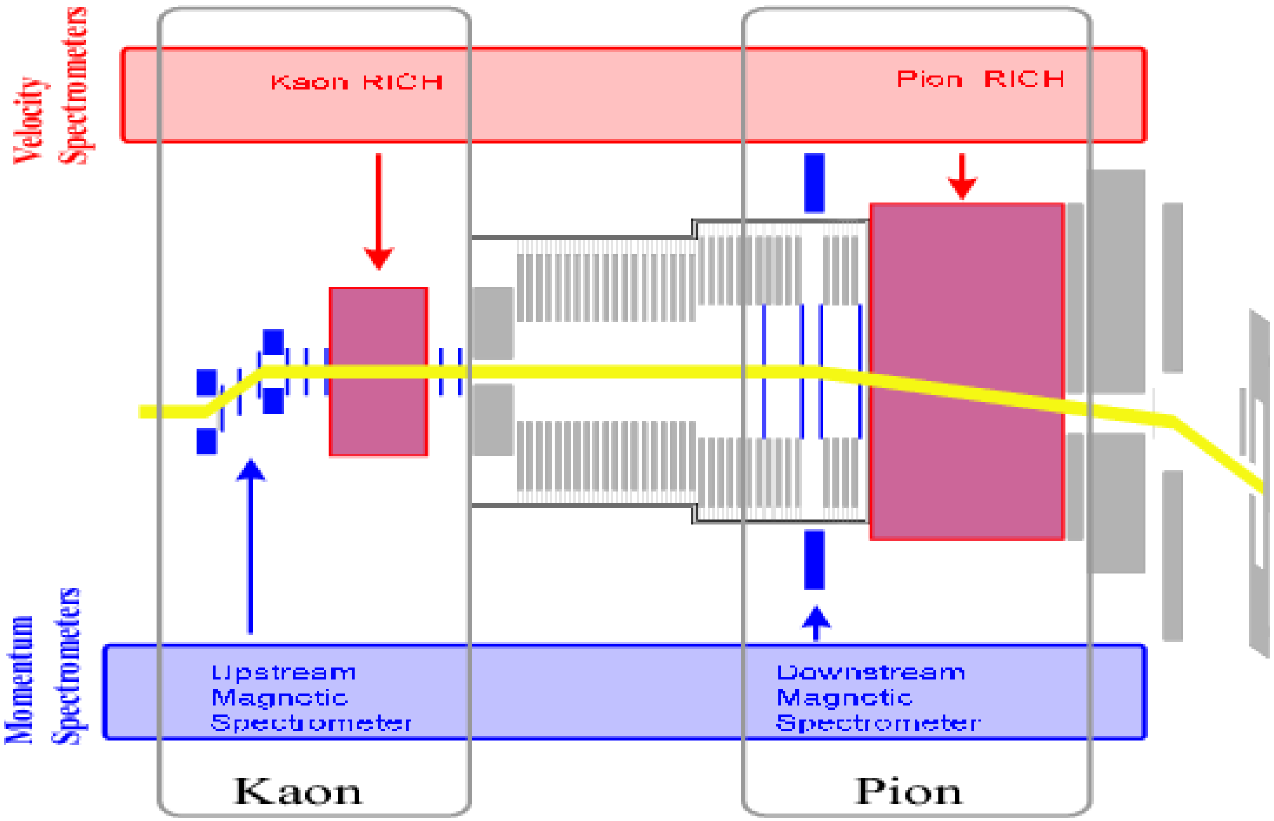


3.8 Consistency check

Bkg	1/3 1998	2/3 1998
$\pi^+\pi^0$	0.009 ± 0.009	$0.0120^{+0.0031}_{-0.0042}$
$\mu^+\nu_\mu(\gamma)$	0.025 ± 0.025	$0.0337^{+0.0435}_{-0.0240}$
1BM	0.003 ± 0.002	0.0039 ± 0.0012
2BM	0.004 ± 0.003	0.0004 ± 0.0001
CEX	$0.0157^{+0.0050}_{-0.0044}$	$0.0157^{+0.0050}_{-0.0044}$
Total	0.057 ± 0.027	$0.0657^{+0.0438}_{-0.0248}$

Bkg	1/3 1995-97	2/3 1995-97
$\pi^+\pi^0$	0.0224 ± 0.0074	0.0216 ± 0.0050
$\mu^+\nu_\mu(\gamma)$	0.0291 ± 0.0095	0.0282 ± 0.0098
1BM	0.0091 ± 0.0066	0.0054 ± 0.0042
2BM	0.0073 ± 0.0087	0.0157 ± 0.0149
CEX	0.0096 ± 0.0068	0.0096 ± 0.0068
Total	0.0764 ± 0.0177	0.0804 ± 0.0201

Momentum and Velocity Spectrometers

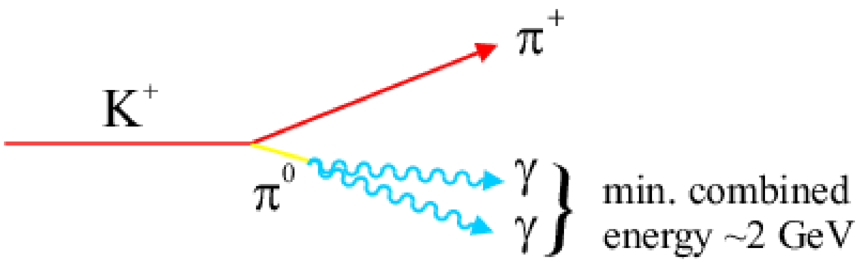


Photon Veto Requirements

Largest background: $K^+ \to \pi^+\pi^\circ$
($2\times10^9 \times$ signal!)

π° needs to be vetoed with an inefficiency of $< 1.6\times10^{-7}$

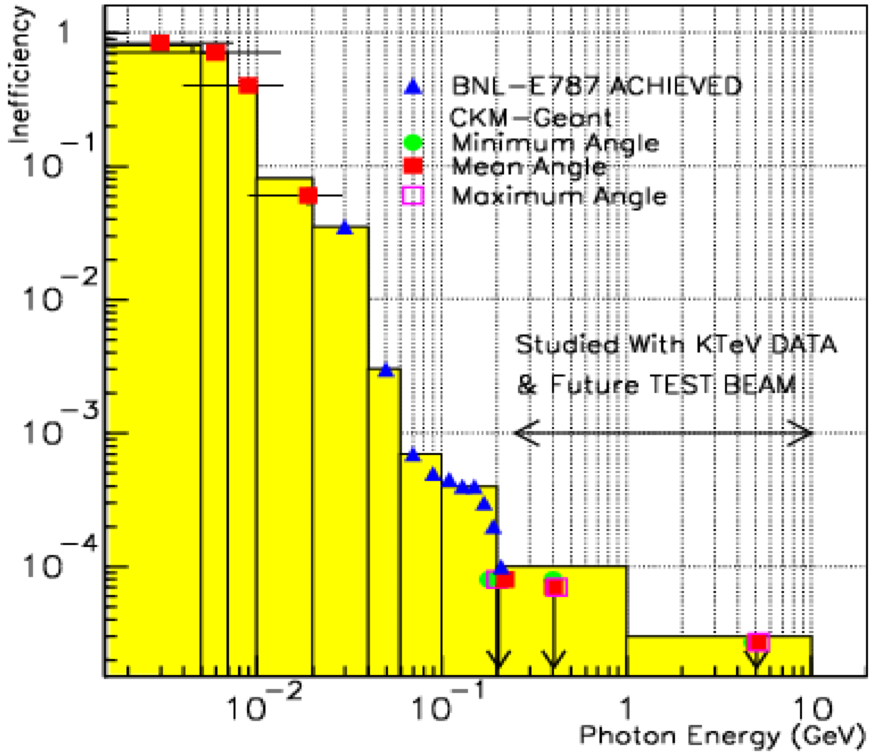
(note: BNL-787 achieved $\sim 1.7\times10^{-6}$ π° inefficiency)



Requirements:

- High level of hermiticity for high-energy γ's ($>$ 1 GeV).
- Modest efficiencies all the way down to $\sim$ 10 MeV.
- Superb efficiencies for high-energy γ's: ineff $< 3\times10^{-5}$.
- Robust, redundant readout system:
  - A single channel (2000 total) in VVS can be dead for no more than 6% of the time.

Required Vacuum Veto System (VVS) Inefficiency



- Shaded region plots required VVS inefficiency.
- Design assumes demonstrated performance of BNL-787 system (1 mm Pb/5 mm Scint.) for vetoing low energy (20–200 MeV) photons.