Rare Kaon Decays: Progress and Prospects

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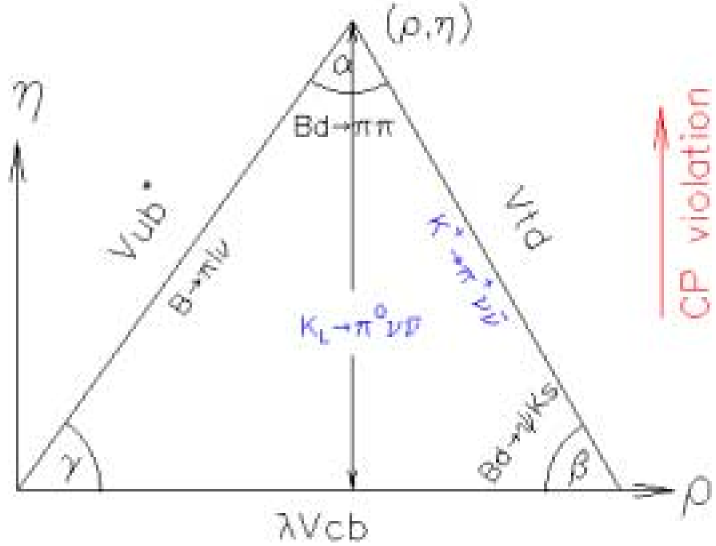
Overview of Rare Kaon Decays

State of the art: single event sensitivity, 10^{-12}

Exotic Searches	$K_L^0 \longrightarrow \mu\ e$ *LFV* $K^+ \longrightarrow \pi^+\ f$ *"Axions".*	**<4.7 10^{-12}**
SM Parameters and BSM Physics	$K_L^0 \longrightarrow \mu^+\ \mu^-$ $\lvert V_{td} \rvert$ $K^+ \longrightarrow \pi^+ \nu \bar{\nu}$ $\lvert V_{td} \rvert$ $K_L^0 \longrightarrow \pi^0\ e^+\ e^-$ *CP* violation $K_L^0 \longrightarrow \pi^0 \nu \bar{\nu}$ *CP* violation	**10^{-8}: 6200 events** **10^{-10}: 2 events**
Low Energy QCD Chiral Perturbation Theory	$K_L^0 \to e^+ e^-$ $K_L^0 \to \gamma l^+\ l^-$ $l = e, \mu$ $K^+ \to \pi^+ l^+\ l^-$ *...Radiative decays*	**10^{-11}: 4 events**

Standard Model CP Violation

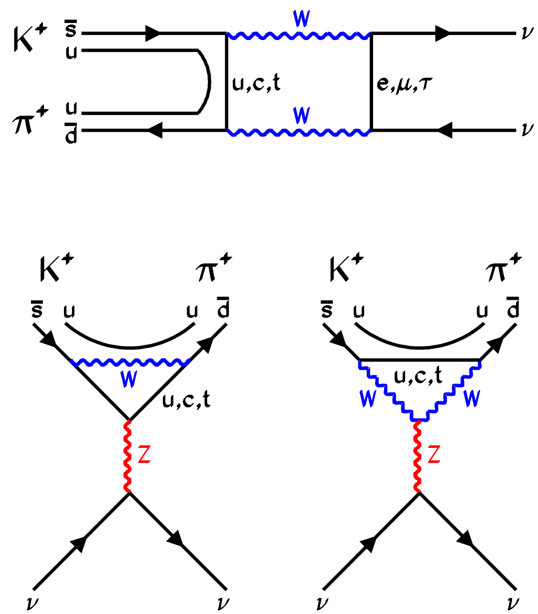


$$\left\{ \begin{array}{l} \text{"Jarlskog invariant"} \quad |J_{CP}| \\ 2A_{\triangle} = \left|\text{Im}V_{ts}^{*}V_{td}\right| \lambda\left(1-\frac{\lambda^{2}}{2}\right) \end{array} \right\}$$

Four super-clean processes will challenge the Standard Model:

$K^{+} \rightarrow \pi^{+}\nu\bar{\nu}$	$\lvert V_{ts}^{*}V_{td}\rvert$	E949, CKM
$K_{L}^{0} \rightarrow \pi^{0}\nu\bar{\nu}$	$\text{Im}(V_{ts}^{*}V_{td})$	KOPIO
$B_{d} \rightarrow \psi K_{S}$	$\sin(2\beta)$	BABAR, BELLE, CDF, D0
$\frac{x_s}{x_d}$	$\left\lvert\frac{V_{ts}}{V_{td}}\right\rvert$	CDF, D0, LHCB, BTEV

$K \to \pi\nu\bar{\nu}$ in the Standard Model



	$K^+ \to \pi^+\nu\bar{\nu}$	$K_L^0 \to \pi^0\nu\bar{\nu}$
Top Quark Dependence	$\lvert\lambda_t\rvert = \lvert V_{ts}^* V_{td}\rvert$	$\mathrm{Im}(\lambda_t) = \mathrm{Im}(V_{ts}^* V_{td})$
SM BR (10^{-11})	7.2 ± 2.1	2.6 ± 1.2
Est. Theory Uncertainty	7% (charm)	2%

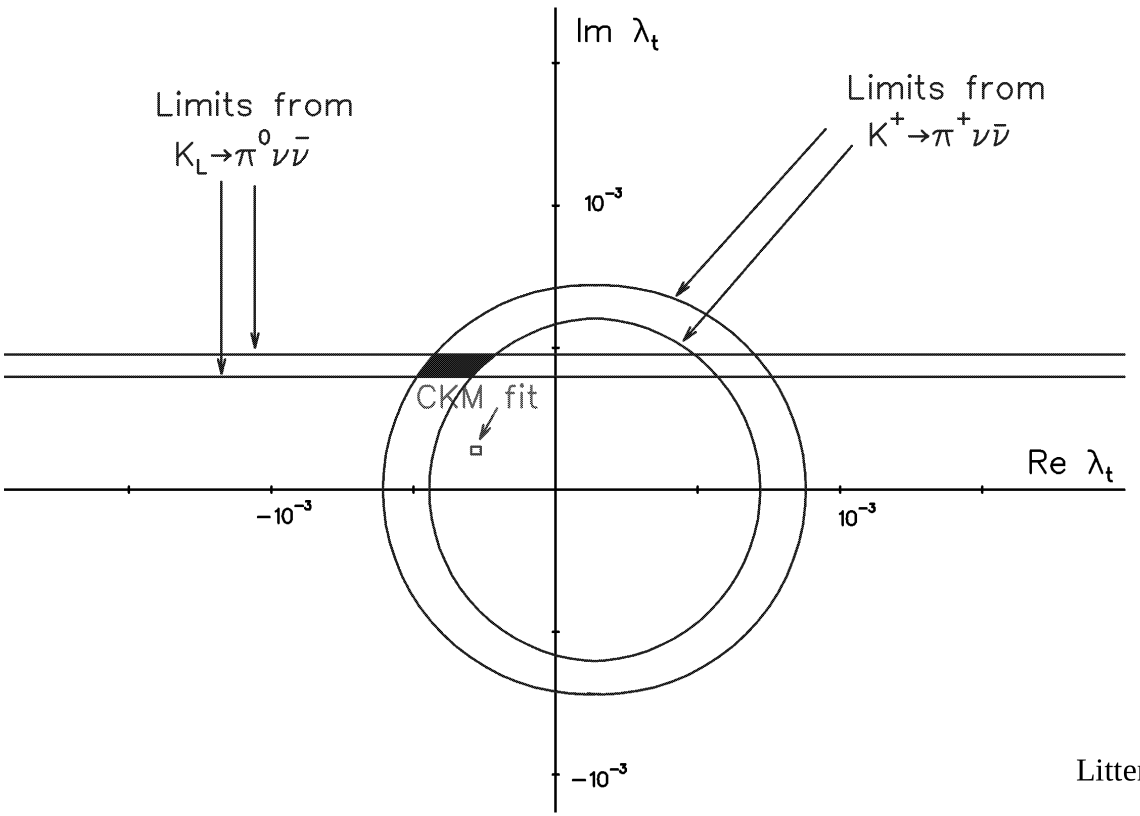
- Negligible long distance effects (10^{-13}).
- Hadronic matrix elements from isospin analog $K^+ \to \pi^0 e^+ \nu_e$.

Standard Model (*Buras*): $\mathrm{Im}\,\lambda_t = \mathrm{Im}V_{ts}^{*}V_{td} = \eta A^2\lambda^5$

$$\mathrm{R}(K_L^0 \to \pi^0 \nu\bar{\nu}) = 1.8\,x10^{-10}\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5}X(x_t)\right)^2$$

$$\sim 4.1\,x10^{-10}A^4\eta^2 = 2.6 \pm 1.2\,x10^{-11}$$

$$\mathrm{R}(K^+ \to \pi^+ \nu\bar{\nu}) \sim 1.0\,x10^{-10}A^4\left[\eta^2 + (\rho_0 - \rho)^2\right] = 7.2 \pm 2.1\,x10^{-11}$$

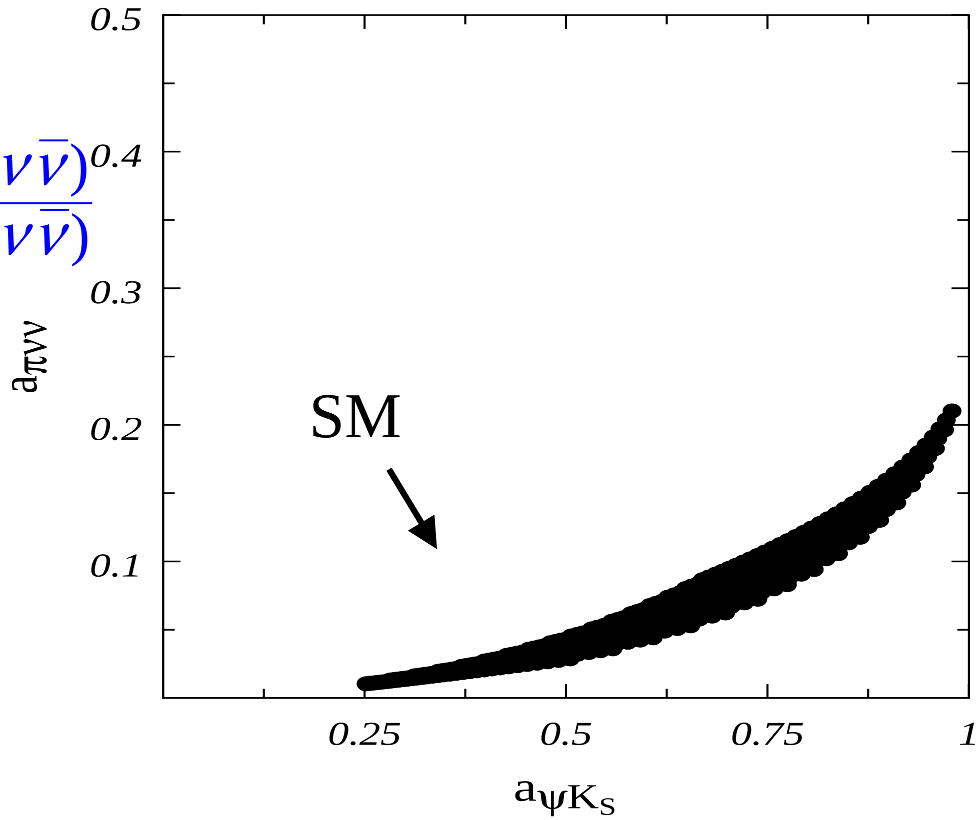


Littenberg

$\mathbf{B} \rightarrow \psi K_S$ *and* $\mathbf{K} \rightarrow \pi \nu \bar{\nu}$

Differences sensitive to new physics – virtually free of uncertainties.

$$\frac{\Gamma(\mathbf{K}_L^0 \rightarrow \pi^0 \nu \bar{\nu})}{\Gamma(\mathbf{K}^+ \rightarrow \pi^+ \nu \bar{\nu})}$$



CP asymmetry in $\mathbf{B} \rightarrow \psi K_S$

Candidates:

* Low energy SUSY
* Minimal Flavor Violation
* Multiple Higgs
* New Physics in $B_d - \overline{B}_d$
* New Physics in $s \rightarrow d\ \nu\bar{\nu}$

(Nir and Worrah, Phys. Lett. **B319** 1998)

(Buras,1999)

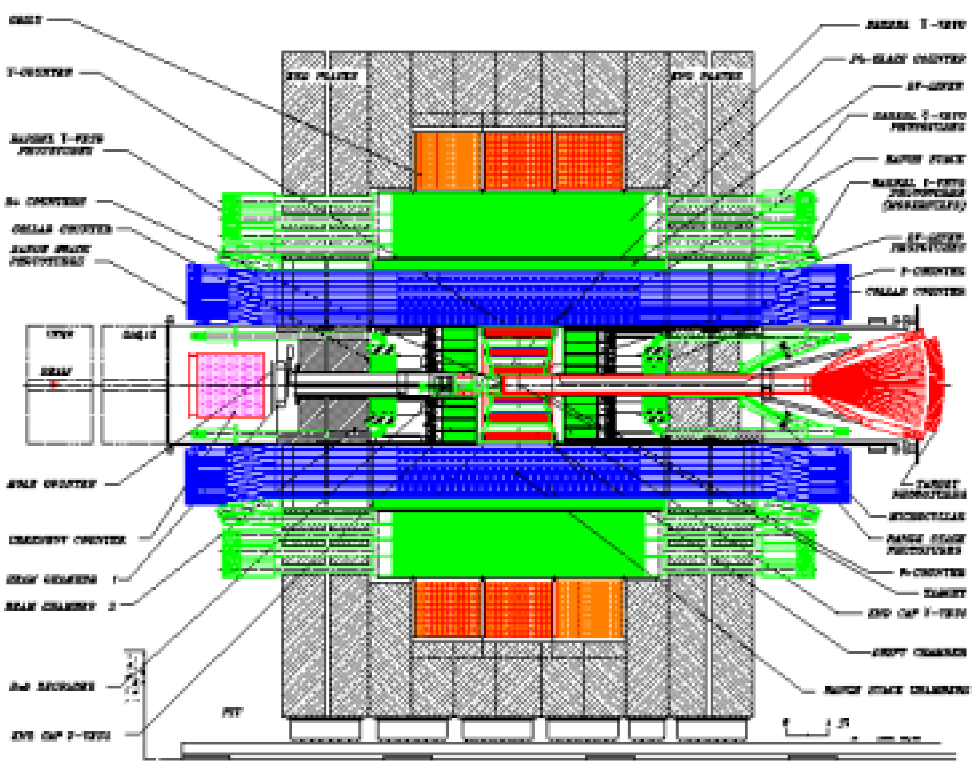
Comparison of Precision from Future K and B Measurements

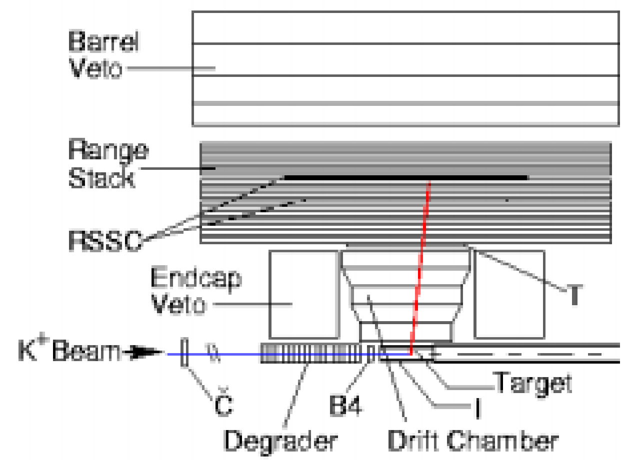
$\sigma(|V_{cb}|) = \pm 0.002(0.001)$

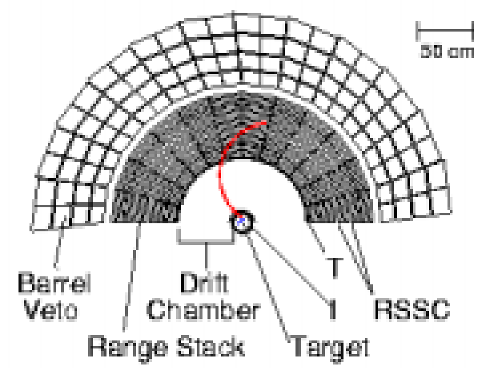
	$K \to \pi \nu \bar{\nu}$	**B-Factory Era**	**LHCB/BTEV**
$\sigma(\|V_{td}\|)$	$\pm 10\%(9\%)$	$\pm 5.5\%(3.5\%)$	$\pm 5\%(2.5\%)$
$\sigma(\bar{\rho})$	$\pm 0.16\,(0.12)$	± 0.03	± 0.01
$\sigma(\bar{\eta})$	$\pm 0.04(0.03)$	± 0.04	± 0.01
$\sigma(\sin 2\beta)$	± 0.05	± 0.06	± 0.02
$\sigma(\mathrm{Im}\,\lambda_t)$	$\pm 5\%$	$\pm 14\%(11\%)$	$\pm 10\%(6\%)$

BNL E787(E949)

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

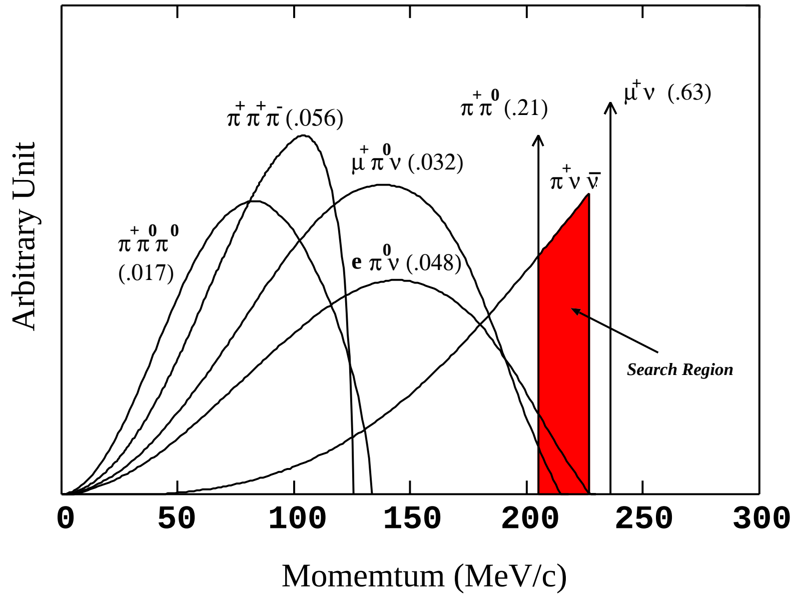






Special Features of Measuring $K^+ \to \pi^+ \nu \nu$

Background processes may exceed signal by $>10^{10}$



- Determine everything possible about the K^+ and π^+
  - * π^+/μ^+ particle ID better than 10^6 (π^+-μ^+-e^+)
- Eliminate events with extra charged particles or ***photons***
  - * π^0 inefficiency $< 10^{-6}$
- Suppress backgrounds well below the expected signal (S/N~10)

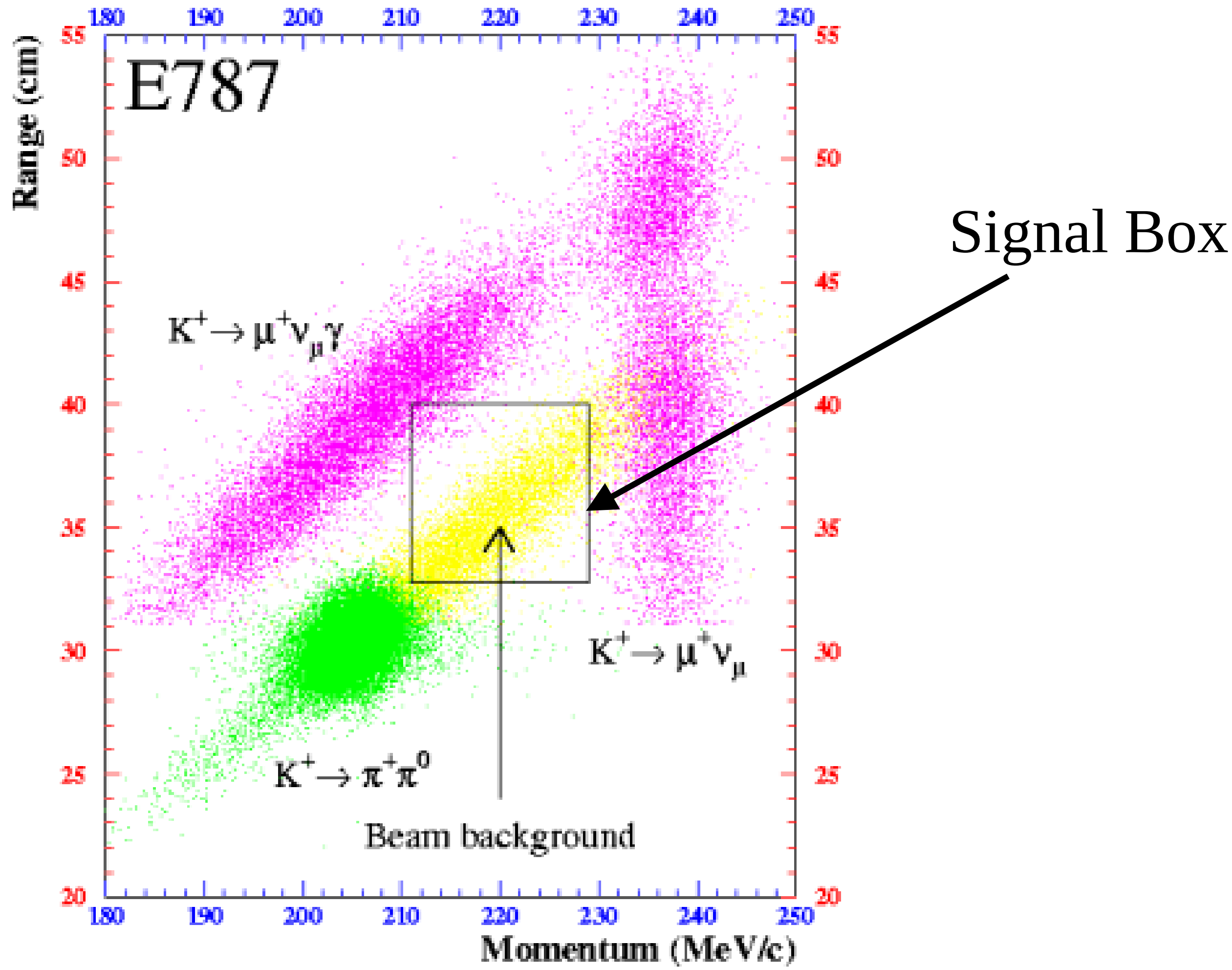
* Predict backgrounds *from data*: dual independent cuts

* Use "Blind analysis" techniques

* Test predictions with "outside-the-box" measurements

- Evaluate candidate events with S/N function

Background Processes: Range vs. Momentum

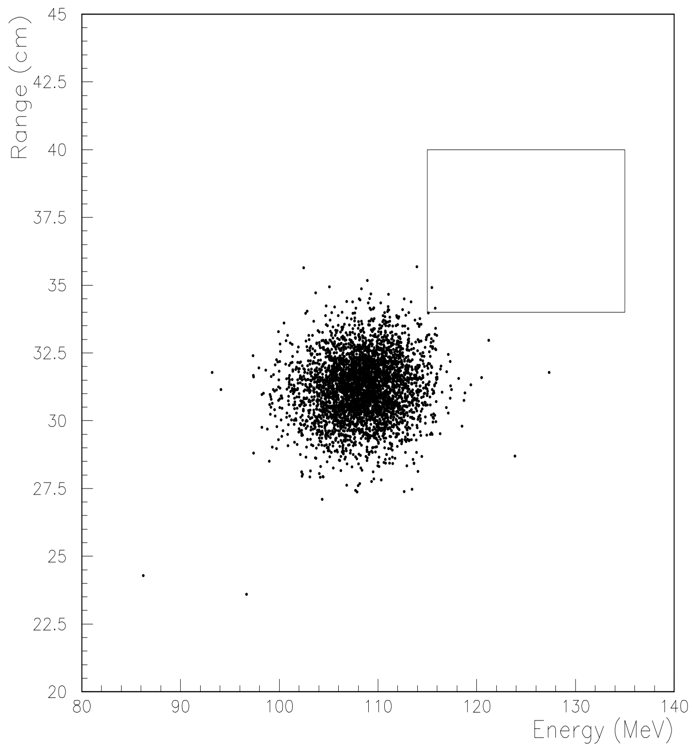


$K^+ \rightarrow \pi^+\pi^0$ Background Suppression

Dual cuts: γ Veto and Kinematics (P,R,E...)

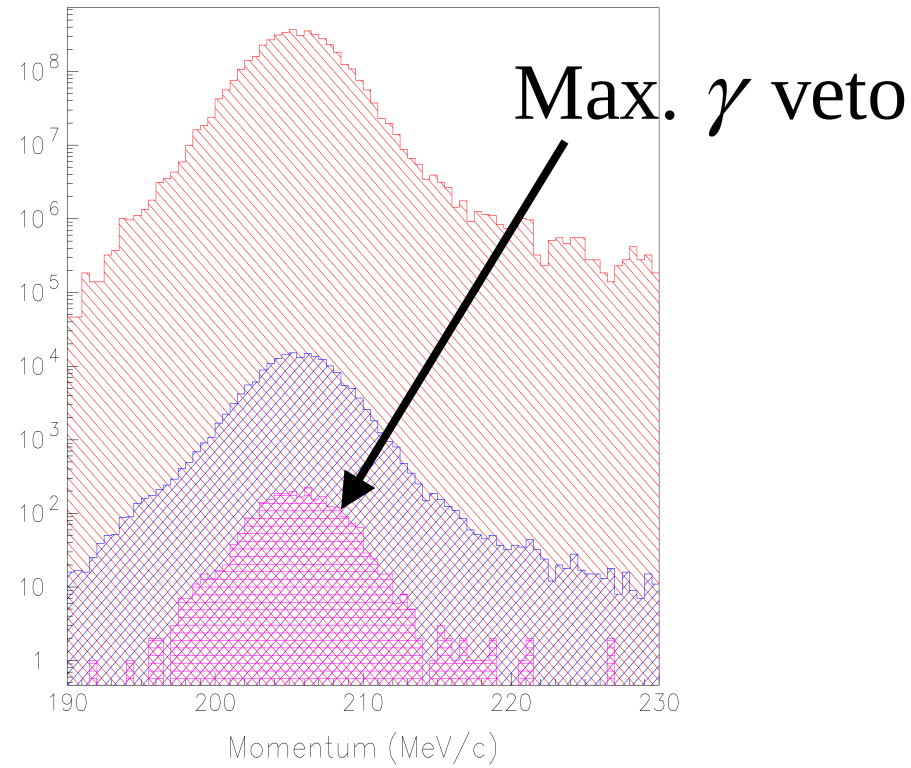
γ Veto Reversed

Range vs. Energy



γ Veto Applied

Momentum



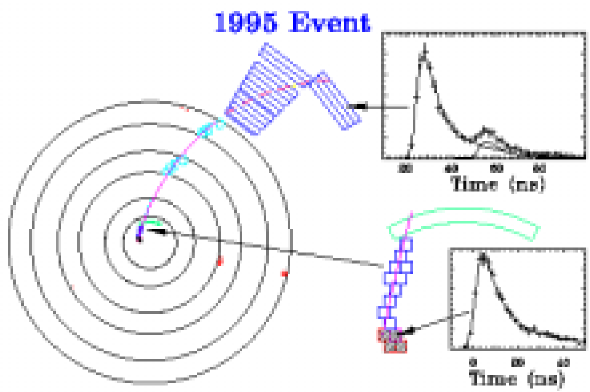
Check for correlations

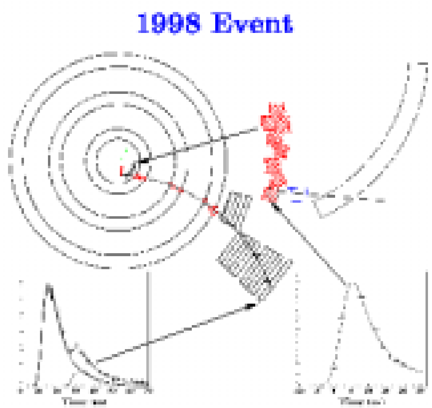
E787 Background Estimates

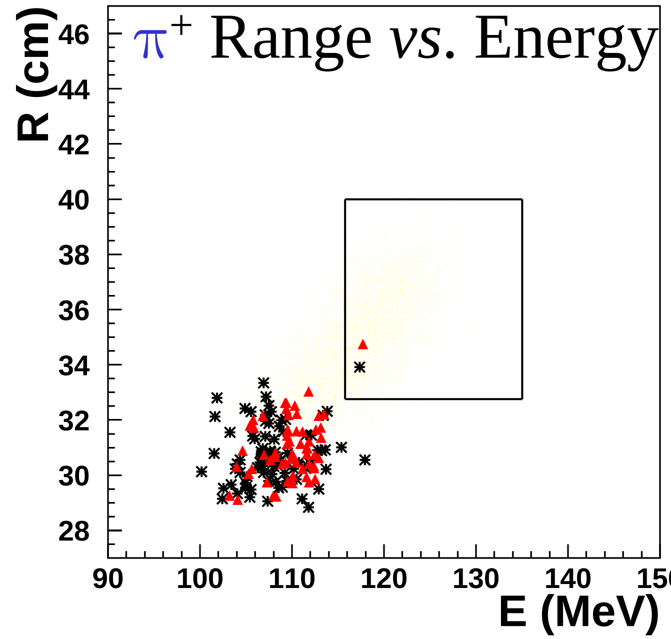
Source	Events
$K^+ \to \mu^+ \nu$	0.04 ± 0.01
$K^+ \to \pi^+ \pi^0$	$0.05 \pm^{0.04}_{0.03}$
Beam π	0.02 ± 0.02
Charge exch.	0.03 ± 0.01
Total	$0.15 \pm^{0.05}_{0.04}$

$N_{K^+} = 5.9\ x\ 10^{12}$ Efficiency $\boldsymbol{\varepsilon} = 2\ x\ 10^{-3}$

E787 2002: *Two* $K^+ \to \pi^+ \nu\bar{\nu}$ *Candidates*







Event	P (MeV/c)	R (cm)	E (MeV)	S/N
1995	218.2	34.8	117.8	35
1998	213.8	33.9	117.1	3.6

$N_{K^+} = 5.9\ x\ 10^{12}$ Efficiency $\boldsymbol{\varepsilon} = 2\ x\ 10^{-3}$

Estimated Background: 0.15±0.05 events

Branching Ratio

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

Consistent with SM: (0.72±0.21)x10^{-10}

Estimated probability of being due to background only : 0.02%

Limits on $\lambda_t \equiv V_{ts}^* V_{td}$ (Independent of B system, $\varepsilon_K, \varepsilon'$)

$$2.9\ x\ 10^{-4} < |\lambda_t| < 1.2\ x\ 10^{-4}\ \ (68\%\ C.L.)$$

$$-0.88\ x\ 10^{-3} < \mathrm{Re}(\lambda_t) < 1.2\ x\ 10^{-3}\ \ (68\%\ C.L.)$$

$$\mathrm{Im}(\lambda_t) < 1.1\ x\ 10^{-3}\ \ (90\%\ C.L.)$$

D’Ambrosio and Isidori, 2002
hep-ph/0112135

Impact of E787 and E949 on Flavor Physics

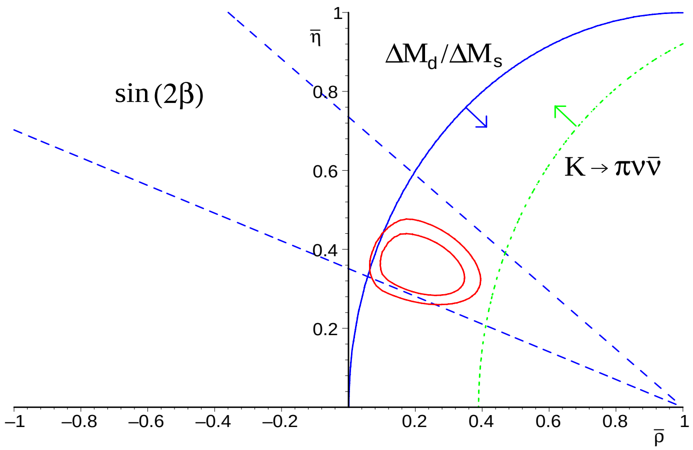


Figure 2: Allowed region in the $\bar{\rho} - \bar{\eta}$ plane using only theoretically *clean* observables: 90% C.L. interval imposed by $\sin(2\beta)$ (dashed); 90% C.L. limit from the upper bound on $\Delta M_{B_d}/\Delta M_{B_s}$ (full); 90% C.L. limit from the lower bound on $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ (dotted). For comparison the 68% and 90% C.L. ellipses from the global fit in Fig. 1 are also shown.

E787 and other clean observables (90% CL)

E949 at the E787 BR

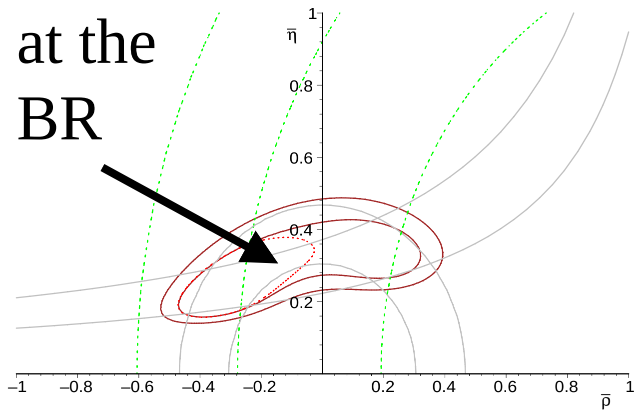


Figure 3: Allowed region in the $\bar{\rho} - \bar{\eta}$ plane with the inclusion of $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ and without B_d–$\bar{B}_d$ data. The two external contours denotes 68% and 90% confidence intervals; the inner (dotted) one is the 68% confidence interval under the assumption that experimental error in (1) is reduced by a factor two.

Possible E949 result favoring Non-SM

$K^+ \to \pi^+ \nu \bar{\nu}$ **_Future Prospects_**

BNL ***E949 (2002-)***

Upgrade of E787 detector

Improved photon vetos – truly hermetic coverage

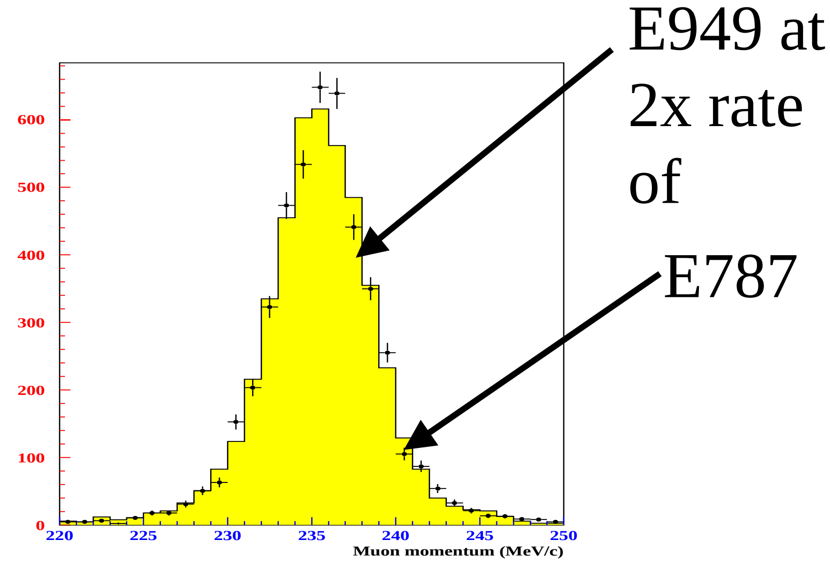
Access to the low momentum region

Sensitivity goal: $<10^{-11}$

Order of magnitude improvement beyond E787

Factor 5-10 below the SM prediction

μ^+ Momentum from $K^+ \to \mu^+ \nu$



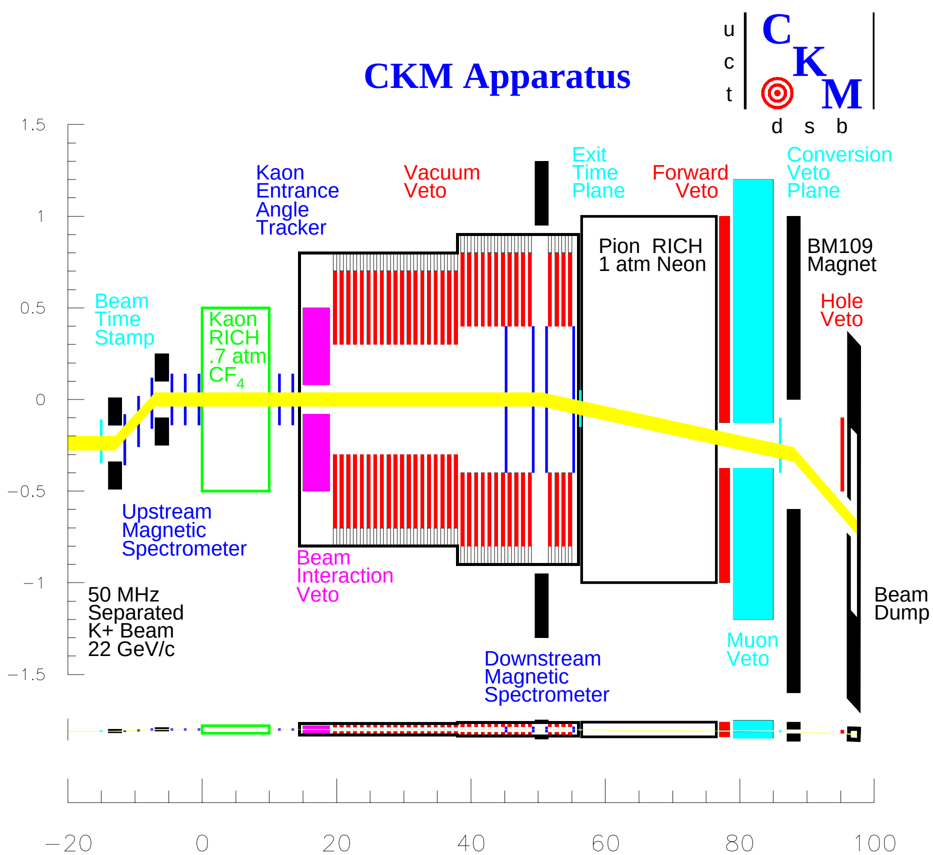
$K^+ \to \pi^+ \nu \bar{\nu}$

FNAL ***CKM (~2007-)***

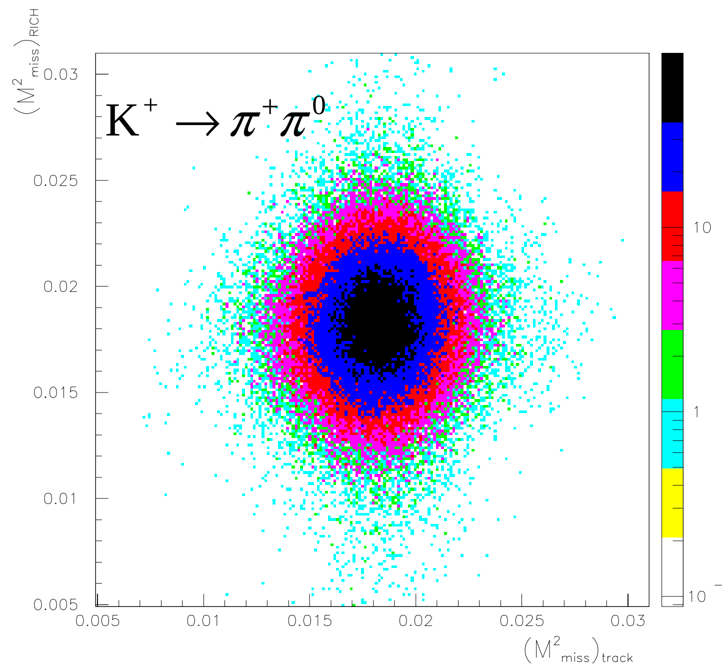
New *in-flight* technique - RF-separated K beam

Particle ID : RICH

Sensitivity goal: $<10^{-12}$

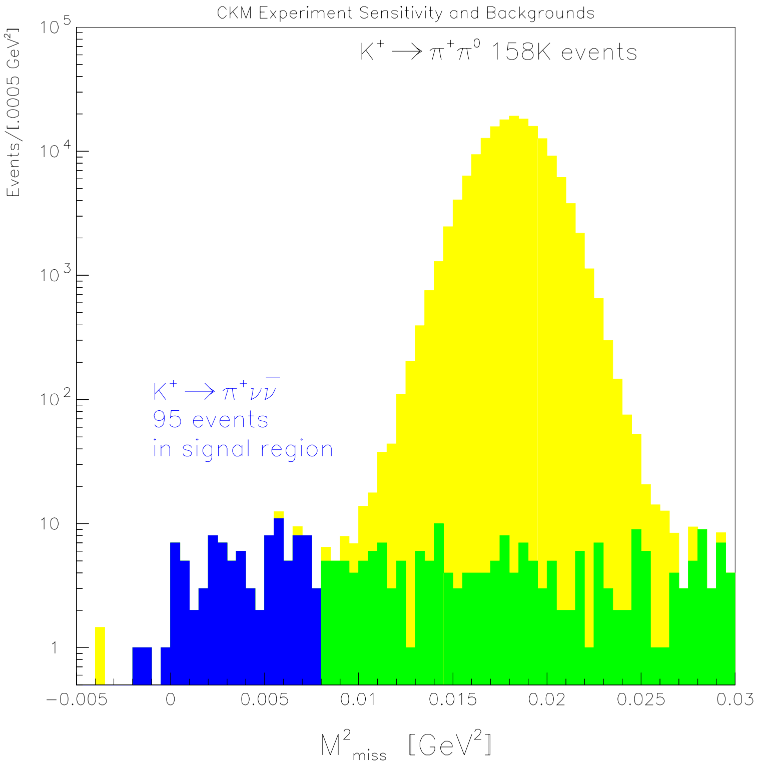


Momentum simulation:
RICH *vs* Tracking



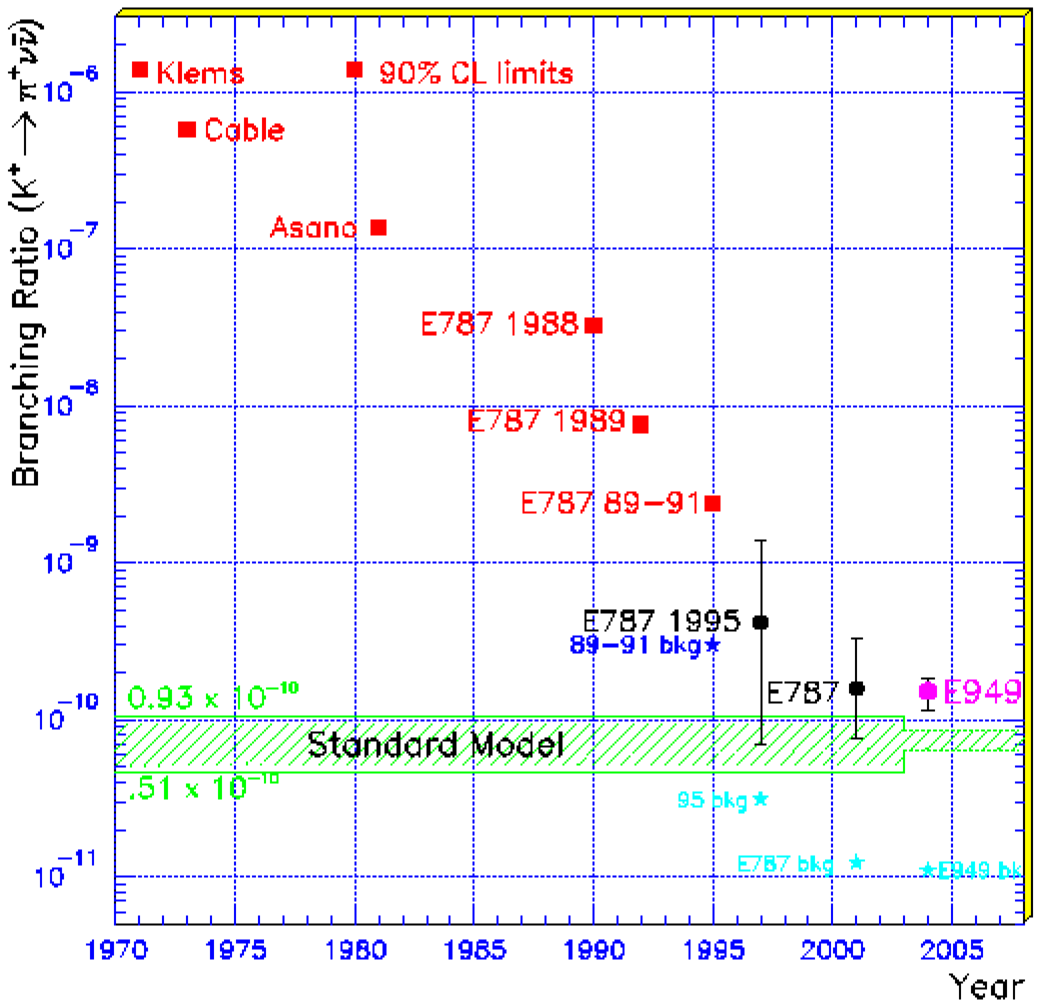
$M^2_{missing}$

CKM Goal: 100 events with S/N>7



Background source	Effective BR ($\times 10^{-12}$)
$K^+ \to \mu^+\nu_\mu$	< 0.04
$K^+ \to \pi^+\pi^0$	3.7
$K^+ \to \mu^+\nu_m u\gamma$	< 0.09
$K^+A \to K_LX, K_L \to \pi^+e^-\overline{\nu}_e$	< 0.14
$K^+A \to \pi^+X$ in trackers	< 4.0
$K^+A \to \pi^+X$ in residual gas	< 2.1
Accidentals (2 K^+ decays	0.51
Total	< 10.6

$K^+ \longrightarrow \pi^+ \nu \bar{\nu}$ Measurements vs. Year



CKM

$K^+ \to \pi^+ x$ and Global Family Symmetry

[Wilczek (1982), Gelmini et al. (1983), Feng et al. (1998)]

Motivation: Explain the replication of families

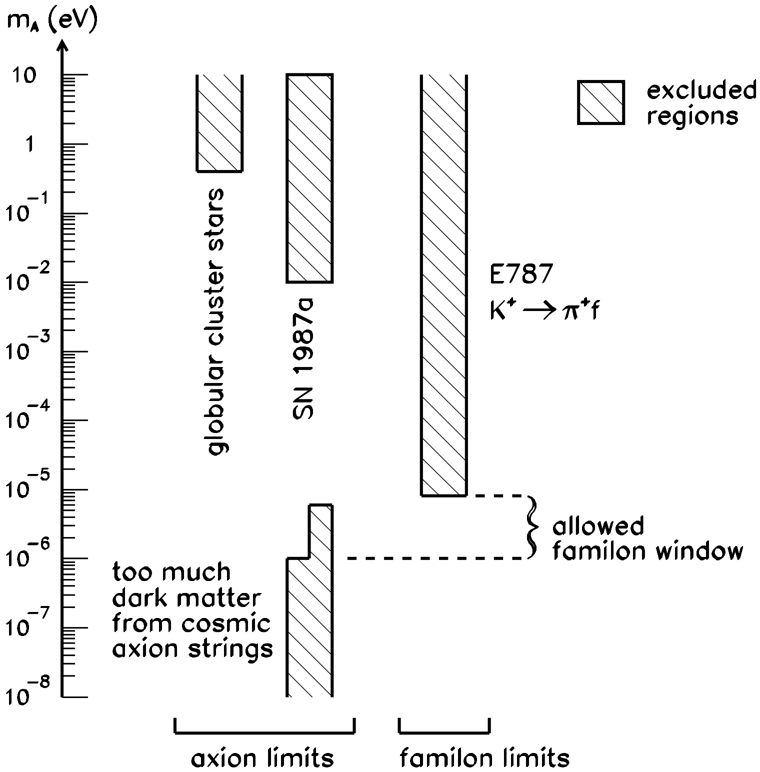
Postulate: Global Family Symmetry spontaneously broken at large mass scale (F)$\longrightarrow$ Goldstone Boson "FAMILON (f)".

$L_{eff} = \frac{1}{F} J_\mu \delta_\mu f$:: $\mu \to e + f$ and $s \to d + f$

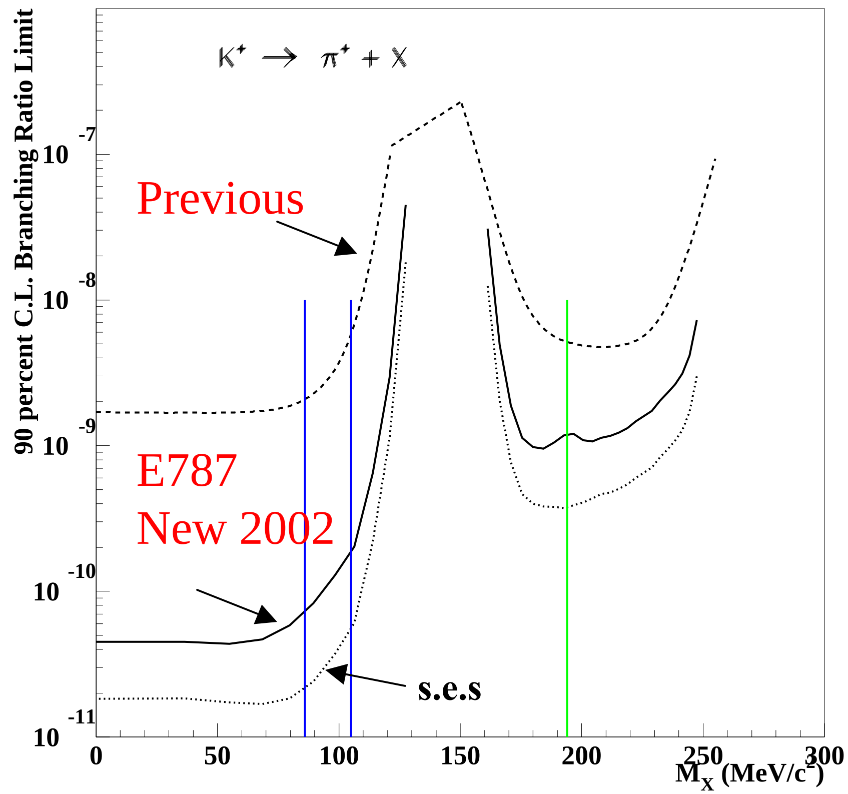
	GFS	Experiment	F Limit (GeV)
$B(K^+ \to \pi^+ f)$	$\frac{1.310^{14} GeV^2}{F^2}$	$< 5.910^{-11}$ (E787) (2002)	$> 210^{12}$
$B(\mu \to ef)$	$\frac{2.510^{14} GeV^2}{F^2}$	$< 2.610^{-6}$ (Jodidio)	$> 10^{10}$
$B(\tau \to ef)$	$\frac{2.510^{14} GeV^2}{F^2}$	$< 2.610^{-3}$ (ARGUS)	$> 310^{6}$
COSMOLOGY			$10^9 < F < 10^{12}$

Limits on K→π X

Familon / Axion mass



Branching Ratio *vs.* m_X



Probing CP Violation with Rare Kaon Decays

$$K_L^0 \longrightarrow \pi^0 \; e^+ e^-$$

Difficult to get at *short distance* physics due to long distance strong interaction effects and other complications**. Progress is being made.**

$$K_L^0 \to \pi^0 \nu \bar{\nu}$$

The Golden Mode! – but can it be measured?

SM Prediction: $\mathrm{R}(K_L^0 \to \pi^0 \nu \bar{\nu}) \sim 4.1 x 10^{-10} A^4 \eta^2 = 2.6 \pm 1.2 \, x 10^{-11}$

$K_L^0 \longrightarrow \pi^0 e^+ e^-$

$B_{\exp}(K_L^0 \to \pi^0 e^+ e^-) < 5.1x10^{-10}$ $(FNAL - E799\ 2001)$

- CP conserving part - two photon intermediate state .

  Can't be calculated reliably now. *Need* $K_L^0 \to \pi^0 \gamma\gamma$

- CP violating parts - single photon intermediate states

  - ⊙ Direct CP violation -- the goal !

    Same diagrams as $K \to \pi \nu \bar{\nu}$:

    $$R(K_L^0 \to \pi^0 e^+ e^-)_{CPV-dir} \sim 6.7\,x10^{-11} A^4 \eta^2 = 4\,x10^{-12}$$

  - ⊙ Mixing - *Need* $K_S^0 \to \pi^0 e^+ e^-$

    $$R(K_L^0 \to \pi^0 e^+ e^-)_{CPV-Mix} \sim |\varepsilon|^2 \frac{\tau_L}{\tau_S} R(K_S^0 \to \pi^0 e^+ e^-)$$

- Background : $K_L^0 \to \gamma\gamma e^+ e^-$

$$K_L^0 \longrightarrow \pi^0 \; e^+ e^-$$

- CP conserving part: two-photon intermediate state .

NA48 *Preliminary* results (2002):

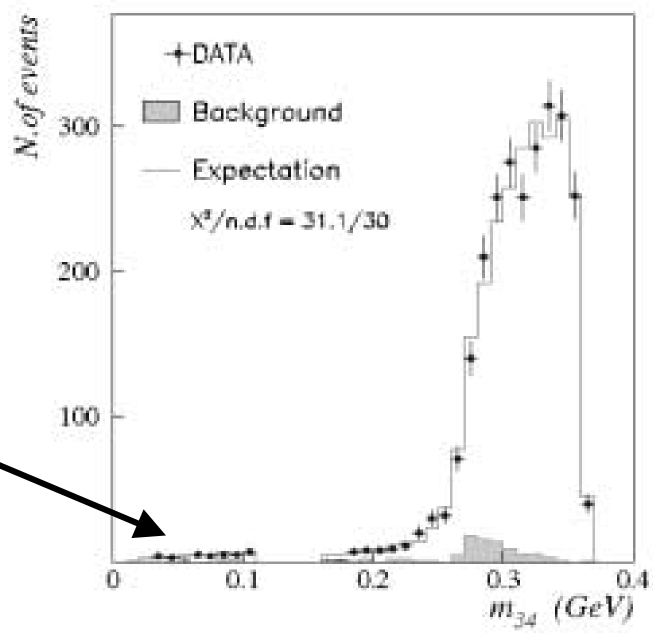
$$B(K_L^0 \to \pi^0\gamma\gamma) = (1.36 \pm 0.03_{stat} \pm 0.03_{syst} \pm 0.03_{norm}) \; x \; 10^{-6}$$

$KTEV_{1999}: 1.68 \pm 0.10) \; x \; 10^{-6}$

$(a_V = -0.72 \pm 0.05 \pm 0.06_{KTEV})$

$CHPT: 1.5 \, x \, 10^{-6}$, shape par.: $a_V \sim 0.7$

NA48 $K_L^0 \to \pi^0\gamma\gamma$



$$\left[\begin{array}{l} B(K_L^0 \to \pi^0\gamma\gamma)_{m_{\gamma\gamma}\in[30,110] \;\; y\in[0,2]} < 0.6 \; x \; 10^{-8} \\ a_V = -0.46 \pm 0.03 \pm 0.03 \pm 0.02 \;\; {}_{NA48} \end{array}\right]$$

$$\Downarrow$$

$$B(K_L^0 \to \pi^0 e^+ e^-)_{CPC} = (4.7 \pm 2.2) \; x \; 10^{-13}$$

$$K_L^0 \longrightarrow \pi^0 \; e^+ e^-$$

- CP violating part due to mixing:

$$R(K_S^0 \to \pi^0 e^+ e^-)^{CHPT}_{CPV-Mix} \sim 5.2(a_s)^2 \, x 10^{-9}, a_s \sim 1$$

NA48 (2001): $B(K_S^0 \to \pi^0 e^+ e^-) < 1.4 \; x \; 10^{-7}$

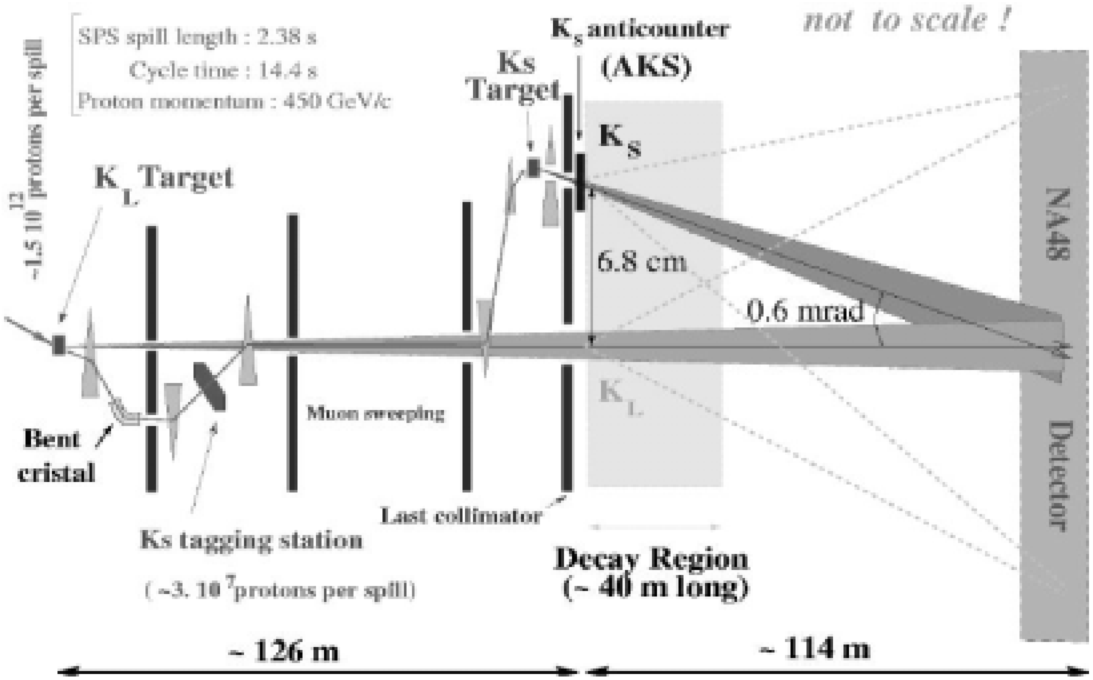
Use CHPT, $a_s < 5.2$: $B(K_L^0 \to \pi^0 e^+ e^-)_{CPV-Mix} < 4.4 \, x \; 10^{-10}$

- Background : $K_L^0 \to \gamma\gamma e^+ e^-$

$$B(K_L^0 \to \pi^0 e^+ e^-)_{K_L^0 \to \gamma\gamma e^+ e^-} \sim 3 \, x \; 10^{-10} \quad [Greenlee]$$

NA48/1 Rare K Decay Studies (2002-)

The K_L and K_S beams



- Upgraded detectors and beamline.
- 100 x intensity
- Improved K_S target
- S.E.S~ 10^{-10}

NA48/1 - Motivation

- $K_S \rightarrow \pi^0 l^+ l^-$, $l = e, \mu$
  - Bound Indirect CP Violation in the $K_L \rightarrow \pi^0 l^+ l^-$ decay to $< 10^{-12}$
- Search for CPV in K_S decays
  - $K_S \rightarrow 3\pi^0$, $K_S \rightarrow \pi^+\pi^-\pi^0$
- Study of time dependent CPV asymmetry in $K_{S,L} \rightarrow \pi^+\pi^-\gamma^*$
- Test of Chiral Perturbation Theory
  - $K_S \rightarrow \gamma\gamma$, $K_S \rightarrow \pi^0\gamma\gamma$, $K_S \rightarrow \pi^0\pi^0\gamma\gamma$
- Study K_S Dalitz and semi-leptonic decays
- Semi-leptonic and radiative neutral hyperon
  - $\Xi^0 \rightarrow \Sigma^+ e^- \nu$, $\Xi^0 \rightarrow \Sigma^+ \mu^- \nu$, $\Xi^0 \rightarrow \Sigma^0 \gamma$, $\Xi^0 \rightarrow \Lambda\gamma$

R. Sacco (2002)

Experiments seeking $K_L^0 \to \pi^0 \nu \bar{\nu}$

- Limit based on isospin and $K^+ \to \pi^+ \nu \bar{\nu} : < 1.7\, x 10^{-9}$ • $[Grossman, Nir]$

- KTEV (FNAL) result:

$$\mathrm{R}(K_L^0 \to \pi^0 \nu \bar{\nu}) \equiv \frac{\Gamma(K_L^0 \to \pi^0 \nu \bar{\nu})}{\Gamma(K_L^0 \to all)} < 5.9\, x 10^{-7}$$

- KEK E391a *goal* : s.e.s. $10^{-10} - 10^{-9}$

- KOPIO (BNL) *goal* : s.e.s. $< 10^{-12}$, >50 events

Primary Background: $\mathrm{K_L^0} \to \pi^0 \pi^0$ $\quad R(\mathrm{K_L^0} \to \pi^0 \pi^0) \sim 10^{-3}$

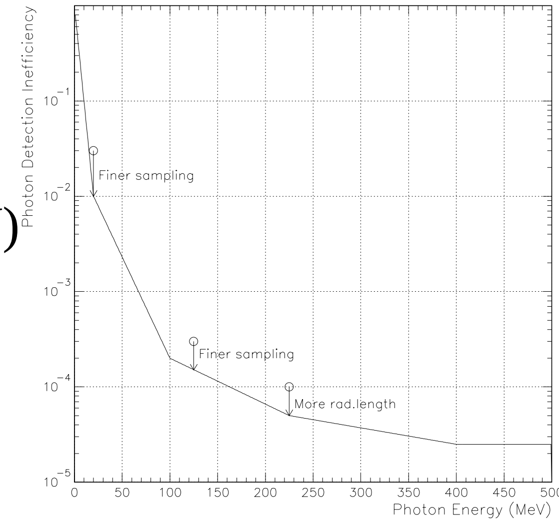
Photon Vetoing

E787

$\bar{\varepsilon}_\gamma \sim 10^{-2}$ (20-100 MeV)

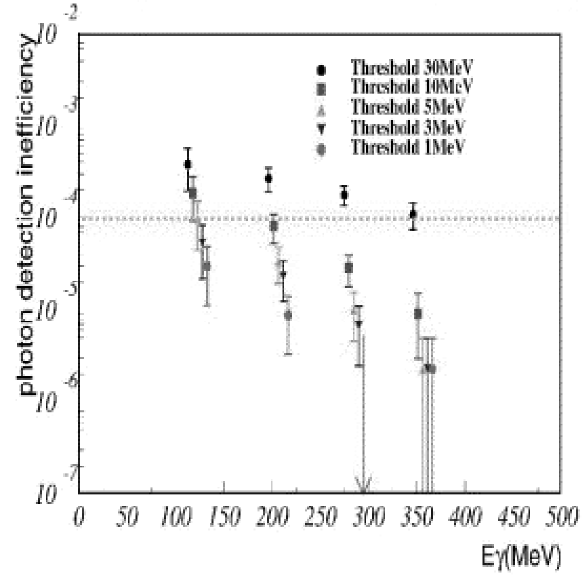
$\sim 10^{-4}$ (100-220 MeV)

$\bar{\varepsilon}_{\pi^0} < 10^{-6}$



KEK ***Photonuclear***

Inefficiency of γ detection



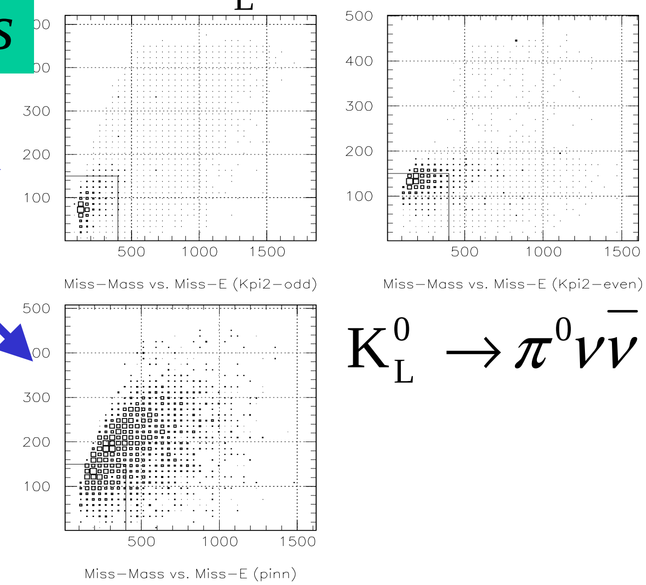
Photon vetoing & Kinematics:

Suppress events with low energy photons

Missing mass $(2E_1^{miss}E_2^{miss}cos\theta_{12})$ vs.
Missing energy $(E_1^{miss}+E_2^{miss})$

$\bar{\varepsilon}_{\pi^0} < (10^{-4})(10^{-4}) = 10^{-8}$

$K_L^0 \rightarrow \pi^0\pi^0$



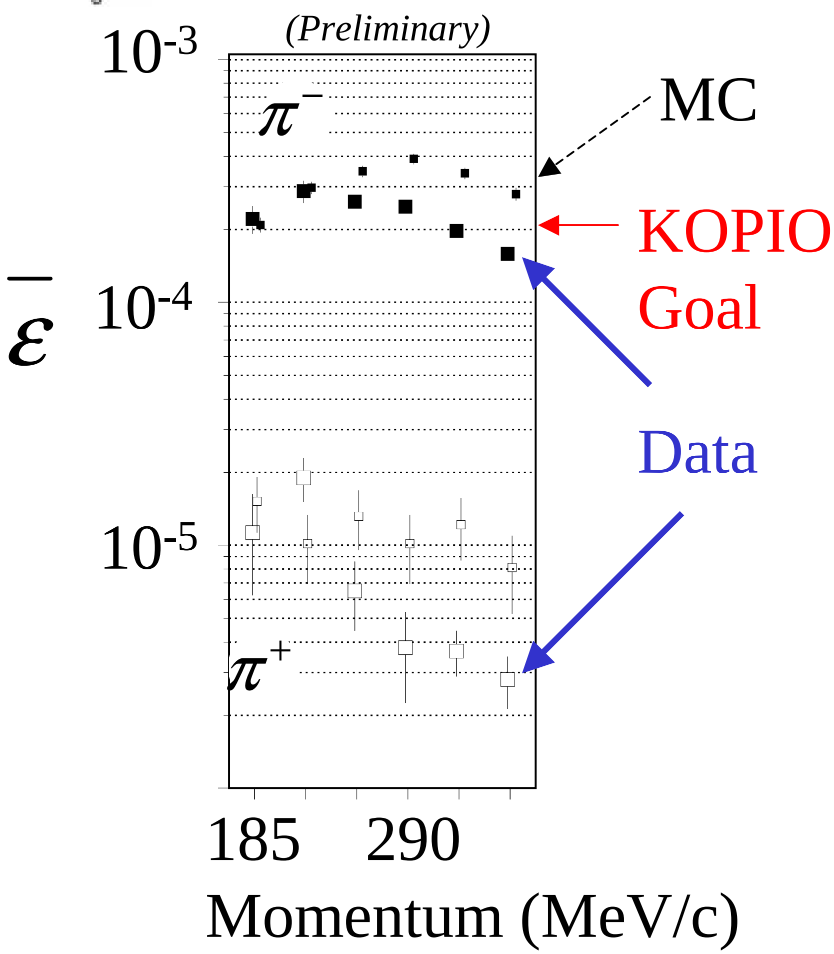
$K_L^0 \rightarrow \pi^0\nu\bar{\nu}$

Charged Particle Vetoing

Example Background: $\mathbf{K}_L^0 \rightarrow \pi^- e^+ \nu \gamma$

Plastic Scintillator

PSI Measurement



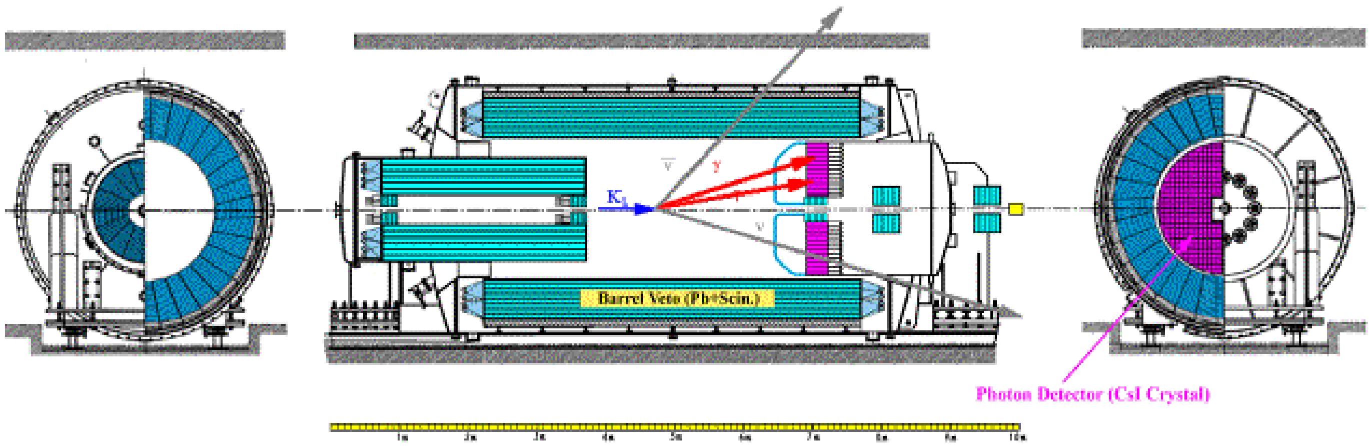
KEK: 1 GeV/c

Particle	$\bar{\varepsilon}$
e^+	$(3.2 \pm 0.9)\ x\ 10^{-4}$
π^+	$< 1.6x10^{-5}$
e^-	$< 1.3x10^{-4}$
π^-	$(6.0 \pm 0.6)\ x\ 10^{-4}$

NIM **A** 359, 478 (1995)

KEK PS

E391a Detector Setup



$K_L \rightarrow \pi^o \nu \nu$

$\pi^o \rightarrow \gamma\gamma \rightarrow$ pure CsI calorimeter

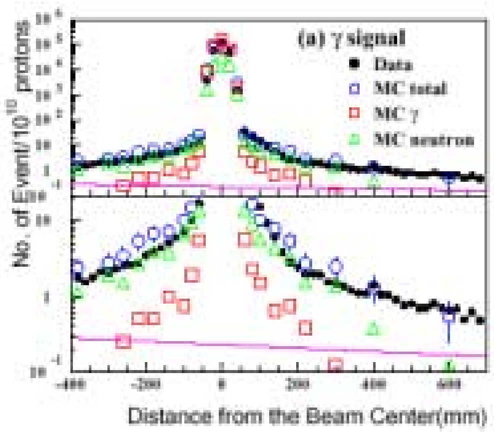
$\nu \nu \rightarrow$ *Nothing* $\rightarrow$ 4π veto system

Features:
* Pencil Beam
* High acceptance
* High P_T selection

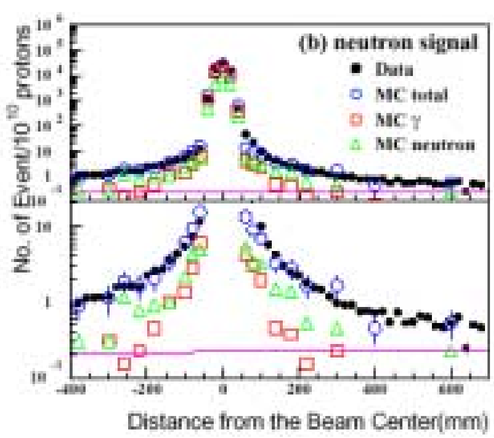
* Pilot Project for JHF
* Test reliance on extreme photon veto efficiency

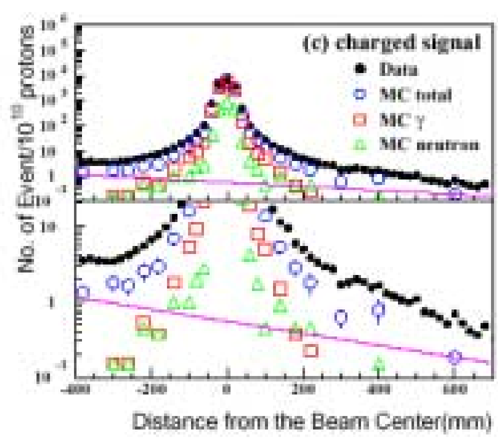
KEK Neutral Beam Measurements

H. Watanabe (2002)



Neutrons

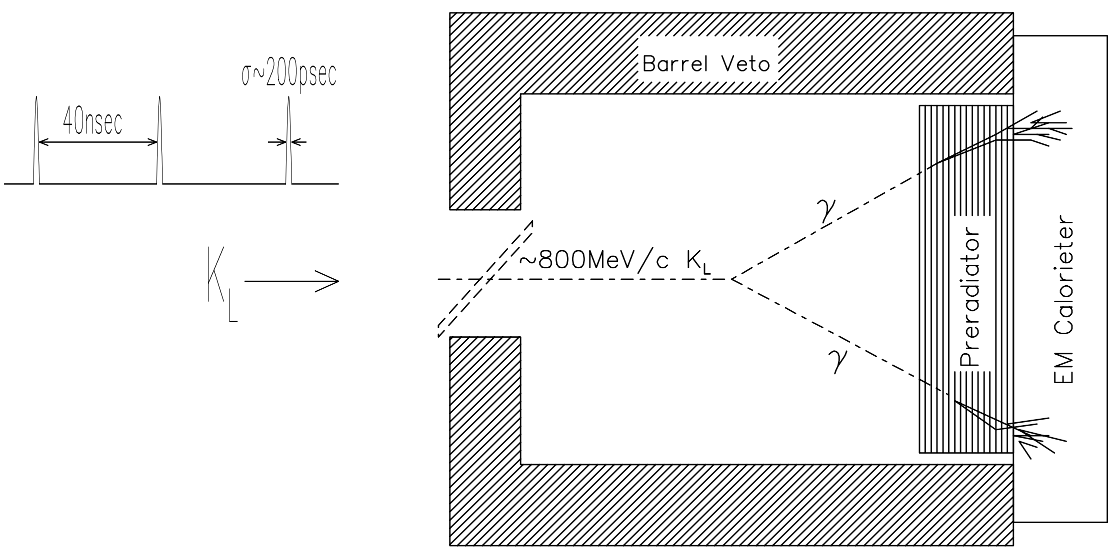


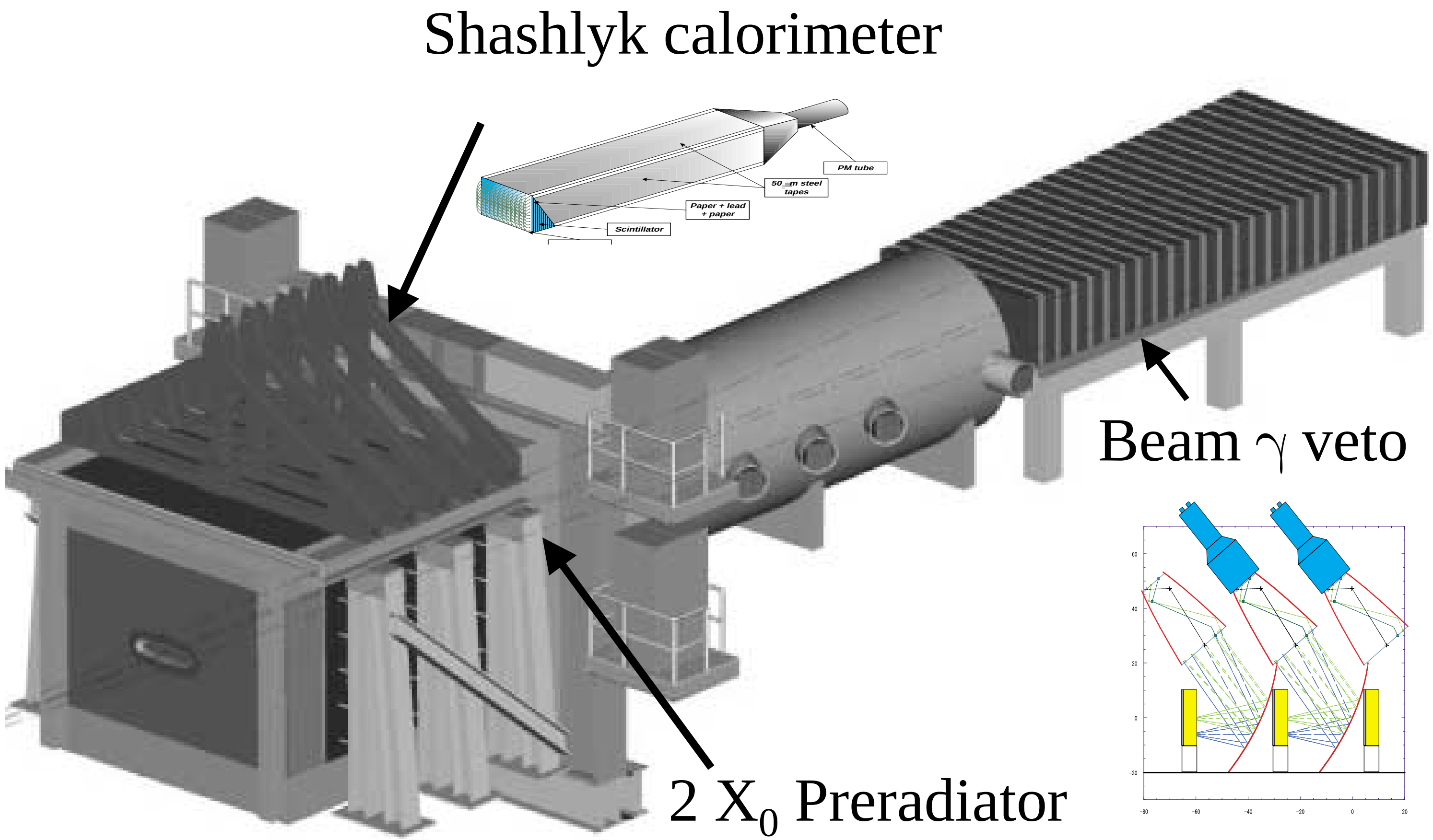


KOPIO: Measurement of $K_L^0 \to \pi^0 \nu \bar{\nu}$

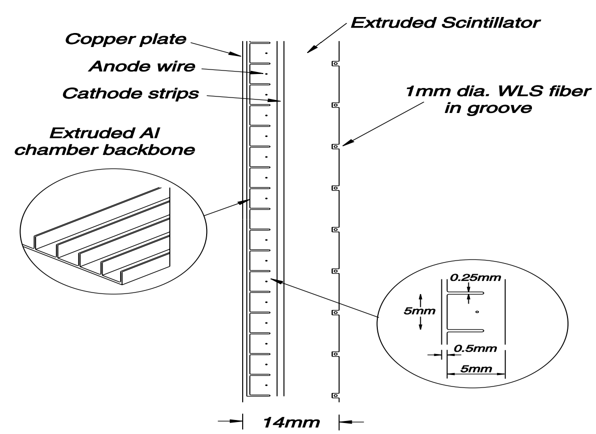
CONCEPTS

- 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.
- Maximize Photon Veto Efficiency
- Maximize Intensity of Microbunched Beam





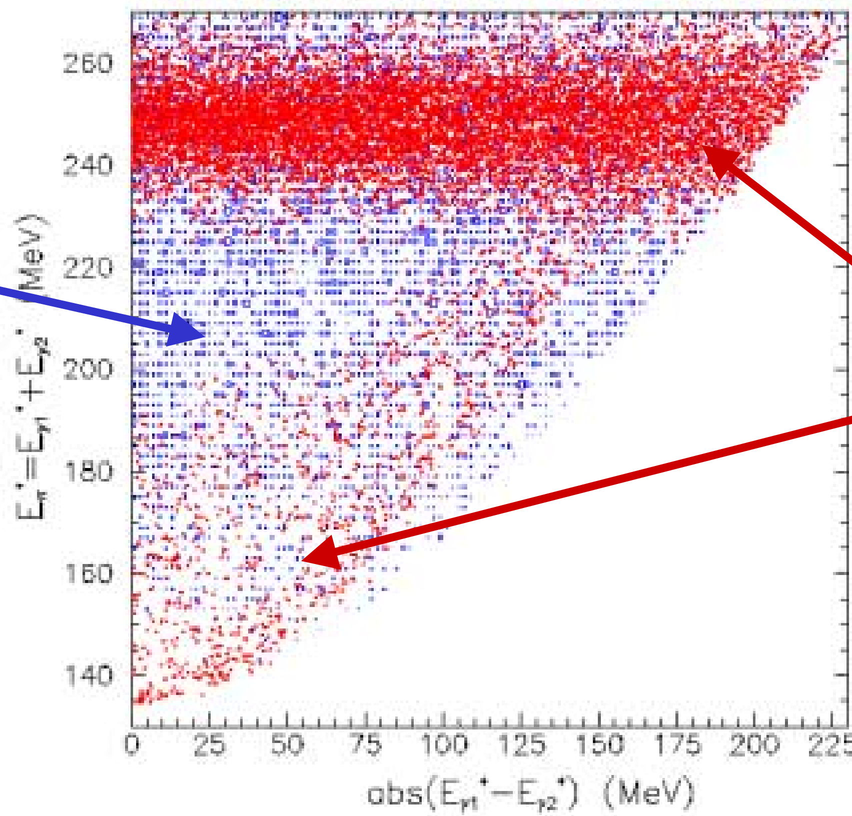
Parameter	Minimal Requirement	Expected Performance
E_γ resolution	$3.5\%/\sqrt{E}$	$2.7\%/\sqrt{E}$
θ_γ resolution (250MeV)	$(25-30)$ mr	23 mr
t_γ resolution	$100ps/\sqrt{E}$	$50ps/\sqrt{E}$
x_γ, y_γ resolution(250MeV)	10mm	$<$ 1mm
μ-bunch width	$300ps$	$200ps$
γ-veto inefficiency	$\overline{\epsilon}_{E787}$	$0.3\overline{\epsilon}_{E787}$



Kinematic suppression of backgrounds
Goal: >50 Events with S/N>2

$$E^*_{\pi^0} \; vs. \left| E^*_{\gamma 1} - E^*_{\gamma 2} \right|$$

$K^0_L \to \pi^0 \nu \bar{\nu}$



$K^0_L \to \pi^0 \pi^0$

Summary and Outlook

- $K^+ \to \pi^+ \nu\bar{\nu}$: 2 events seen

  $B(K^+ \to \pi^+ \nu\bar{\nu}) = 1.57 \pm^{1.75}_{0.82}\ x\ 10^{-10}$ (E787)

  Prospects: E949 (10 events) and CKM (100 events)

- $K^0_L \to \pi^0 \nu\bar{\nu}$ *Prospects* :

  E391a (s.e.s. $< 10^{-9}$) and KOPIO (50 events).

  JHF?

- Exotics: New results on $K^0_L \to \pi^0 x, K^0_L \to \pi^0 \gamma$ (E787)

  Soon, $K \to \pi\mu e$, *others* (KTEV/E799, BNL E865)

Summary and Outlook

- Radiative and semi-rare decays:

New results on $K_L^0 \to \pi^0\gamma\gamma, K_S^0 \to \pi^0 e^+e^-,$

$K_S^0 \to \pi^0\gamma\gamma$ (NA48), $K_L^0 \to \pi^0 e^+e^-$ (E799),

$K^+ \to \pi^+\mu\mu$ (HYPER-CP), $K_S^0 \to \pi^\pm e^\mp \nu$ (KLOE)

Soon, others (KTEV/E799, BNL E865, NA48, KLOE)

New Experiments:

NA48/1: Rare decays of K's and hyperons,

CPV in K_S decays

KLOE : ε'/ε, CPT, rare decays, test of CHPT