Rare K Decays

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Thanks to many: D. Jaffe, T. Komatsubara, D. Bryman

Historical Perspective

Kaon decays have a parallel history along with the development of the standard model.

Phase	Observation	BR sens	Physics
Early	Long life	1	Strangeness
	Decays of K^+, K_L, K_S	0.1	Parity violation
1960s	Semileptonic	$> 10^{-3}$	Meson Dynamics
	Hadronic	$> 10^{-3}$	CP violation
1970-80s	FCNC	$> 10^{-7}$	GIM, Standard Model
1985-present	ϵ'/ϵ		Direct CP
	radiative decys	$\sim 10^{-8}$	Low Energy QCD
	Forbidden Searches	$\sim 10^{-11}$	Limits on Non-SM
Future	Precision	$\sim 10^{-13}$	SM or New

Progress has been in phases partly driven by acceleractor and detector technology. New phase is about to begin.

Focus of this talk:

- $K_L/K_S \to \pi^0 l^+ l^-$ $[l = e, \mu]$
- $K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$

Measuring $K^0_L \to \pi^0 \ell^+ \ell^-$

$$\mathcal{B}(K^0_L \to \pi^0 \ell^+ \ell^-) = \left(C_{mix} \pm C_{int} \frac{Im\lambda_t}{10^{-4}} + C_{dir}\left(\frac{Im\lambda_t}{10^{-4}}\right)^2 + C_{CPC}\right) \times 10^{-12}$$

$\ell\ell$	C_{mix}	C_{int}	C_{dir}	C_{CPC}	$\mathcal{B}(K^0_L \to \pi^0 \ell^+ \ell^-)$	$\mathcal{B}(K^0_L \to \gamma\gamma\ell\ell)$
e^+e^-	$15.7\|a_S\|^2$	$6.2\|a_S\|$	2.4	0	$(3.7^{+1.1}_{-0.9}) \times 10^{-11}$ (+)	6×10^{-7}
					$(1.7^{+0.7}_{-0.6}) \times 10^{-11}$ (−)	10^{-10} with cuts
$\mu^+\mu^-$	$3.7\|a_S\|^2$	$1.6\|a_S\|$	1.0	5.2	$(1.5 \pm 0.3) \times 10^{-11}$ (+)	1×10^{-8}
					$(1.0 \pm 0.2) \times 10^{-11}$ (−)	?

$\mathcal{B}(K^0_L \to \pi^0 e^+ e^-)$ measurement: Effective $\mathcal{B}$ of main background to ee mode can be reduced with cuts, optimistically assuming signal/background of 1/2.5, implies a $\sim 10\%$ measurement of $\mathcal{B}$ would require 350 $\pi^0 ee$ events or 7×10^{15} K_L with a 1% acceptance (including the decay probability). This would take a year at J-PARC (2×10^{14}p/spill) with 10^9 K_L /3.4s.

Additional possibilities to extract more information from these decays using Dalitz plot information, μ polarization and/or K_L-K_S interference.

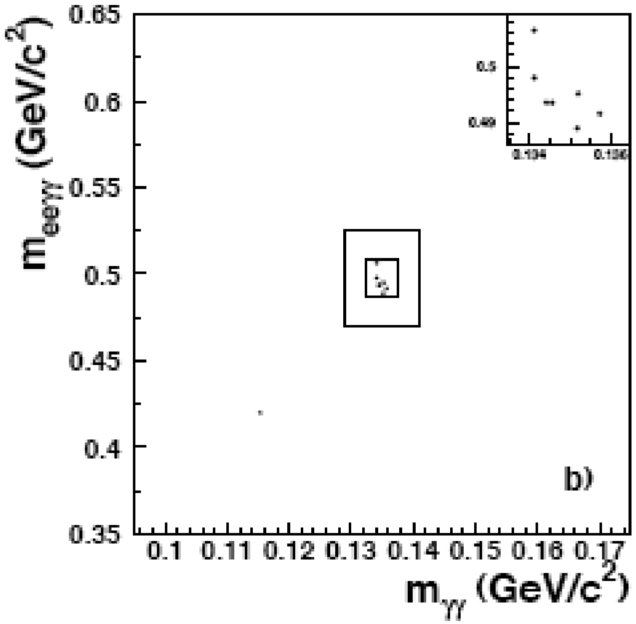
Ref: Isidori, Smith, Unterdorfer EPJ **C36** (2004) 15, $|a_S| = 1.2 \pm 0.2$, uncertainties in C coefficients omitted from table.

$$B(K_S \to \pi^0 e^+ e^-) \simeq 5.2 \times 10^{-9}\, a_S^2,$$
$$B(K_S \to \pi^0 \mu^+ \mu^-) \simeq 1.2 \times 10^{-9}\, a_S^2.$$

First Observations of $K^0_S \to \pi^0 \ell^+ \ell^-$ by NA48/1

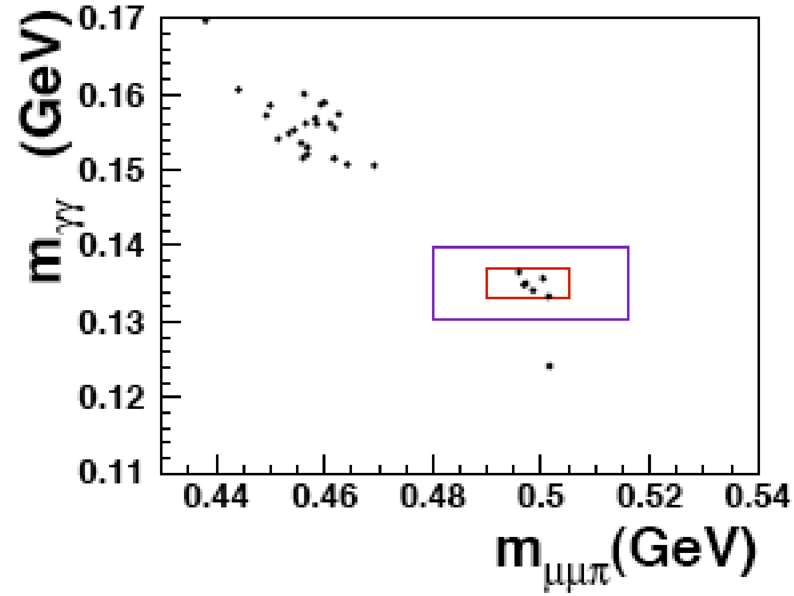
$K^0_S \to \pi^0 e^+ e^-$

PL B576 (2003) 43



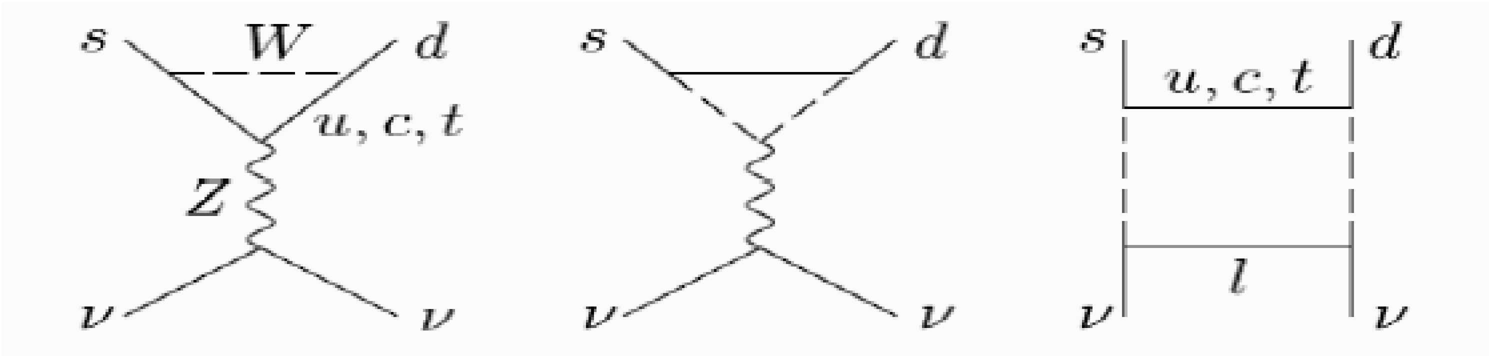
$K^0_S \to \pi^0 \mu^+ \mu^-$

PL B599 (2004) 197



Data	Bgd	observed	BR (vector matrix element, no form factor)
$K^0_S \to \pi^0 e^+ e^-$	$0.15^{+0.10}_{-0.04}$	7	$5.8^{+2.8}_{-2.3}(stat) \pm 0.8(syst) \times 10^{-9}$
$K^0_S \to \pi^0 \mu^+ \mu^-$	$0.22^{+0.18}_{-0.11}$	6	$2.9^{+1.5}_{-1.2}(stat) \pm 0.2(syst) \times 10^{-9}$

$K_L^0 \to \pi^0 \nu\bar{\nu}$ in the SM



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

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

$$\sim 4.1x10^{-10} A^4 \eta^2 = 3.0 \pm 0.6x10^{-11}$$

$$B(K^+ \to \pi^+ \nu\bar{\nu}) \sim 1.0x10^{-10} A^4 \left[\eta^2 + (\rho_0 - \rho)^2 \right] = 7.8 \pm 1.2x10^{-11}$$

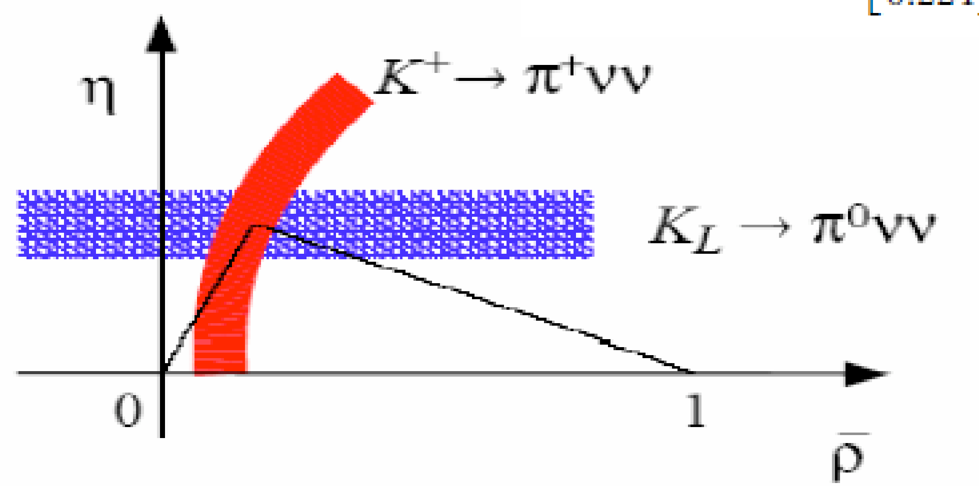
Errors from CKM parameter uncertainties

Intrinsic errors ~7% for K+, ~2% for K_L

Golden Relation: $\sin(2\beta)_{\psi K_S} = \sin(2\beta)_{K\to\pi\nu\bar{\nu}}$

Powerful tool to falsify SM or distinguish new physics scenarios

$$\mathrm{Im}\lambda_t = 1.39\cdot 10^{-4}\left[\frac{|V_{us}|}{0.224}\right]\left[\frac{1.53}{X(x_t)}\right]\sqrt{\frac{\mathcal{B}(K_L\to\pi^0\nu\bar{\nu})}{3\cdot 10^{-11}}},$$



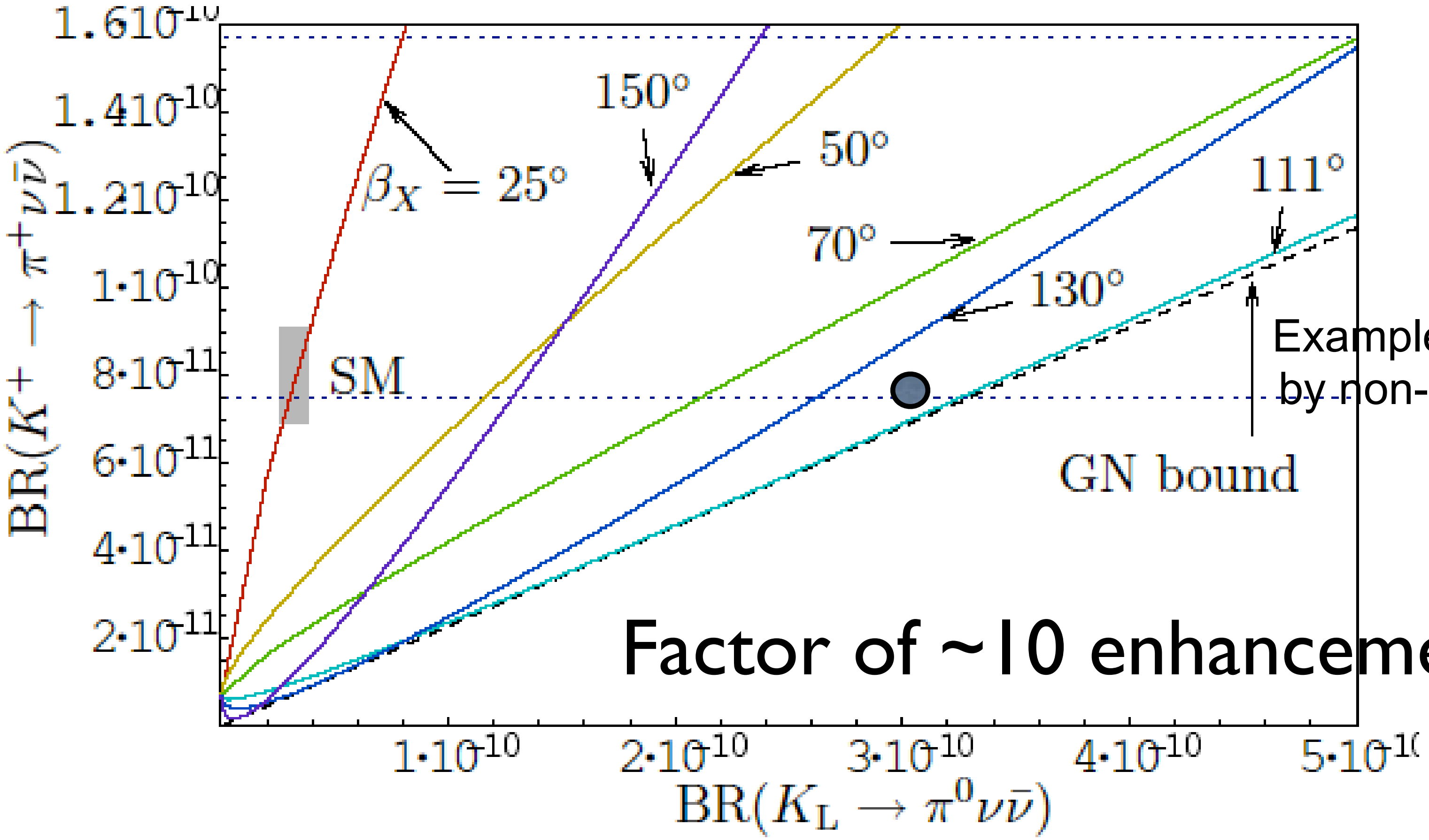
Buras, Isidori, D'Ambrosio, et al.

- $K_L^0\to\pi^0\nu\bar{\nu}$ (and $K^+\to\pi^+\nu\bar{\nu}$) – highly suppressed in SM and most of its extensions → opportunity for new physics.
- Most precisely calculated FCNC processes involving quarks in SM and in its extensions.
- Unique, clean access to the CP-violating and flavor breaking structure of new physics -- access to short distance effects.
- Even if SM holds at high precision, access to very high mass scales - complementary to highest energy colliders.

New CP-violating Phase θ_X : $\beta_X = \beta - \theta_X$

$$\frac{\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})}{\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{SM}} = \left|\frac{X}{X_{SM}}\right|^2 \left[\frac{\sin(\beta - \theta_X)}{\sin(\beta)}\right]^2 , \quad X = |X| e^{i\theta_X}$$

$B(K^+ \to \pi^+ \nu\bar{\nu})$ vs. $B(K_L^0 \to \pi^0 \nu\bar{\nu})$



New physics example: Minimum Flavor Violation

Buras et al. 2004

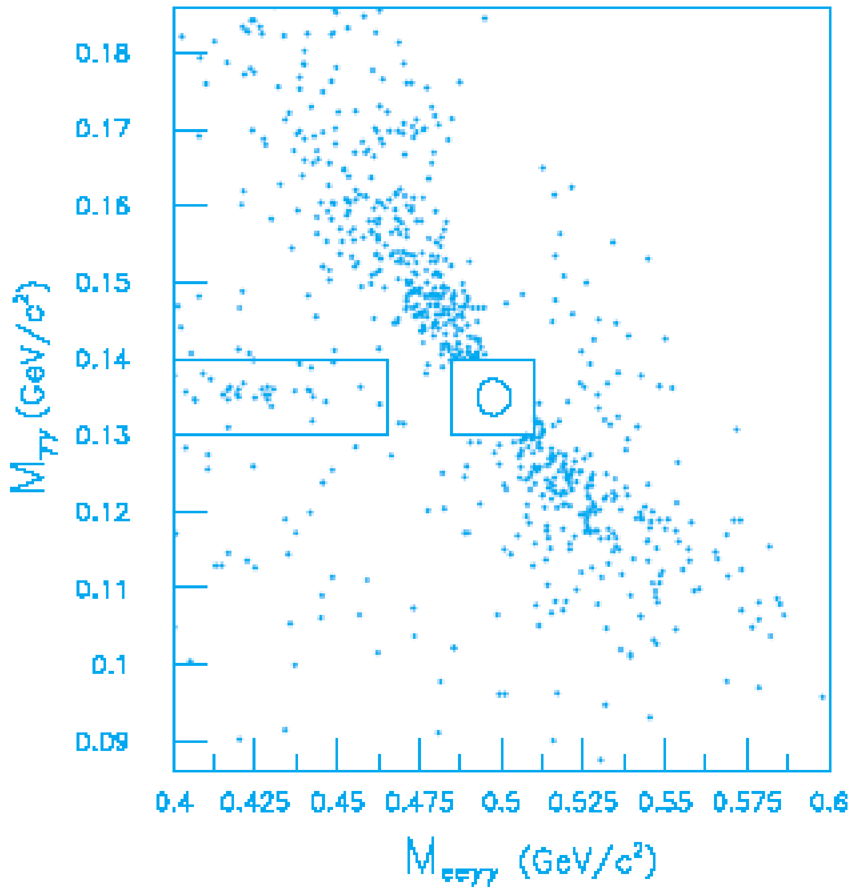
Status of experiments

KEK	PS (12GeV)	E246√	K^+ at rest
		E391a	K_L
J-PARC	PS (50GeV)	LoI's*	K_L K^+ at rest
BNL	AGS (25GeV)	E787√ / E949	K^+ at rest
		E865√	K^+ in flight
		KOPIO*	K_L
CERN	SPS (400GeV)	NA48/1√	K_S
		NA48/3*	K^+ in flight
FNAL	Tevatron (800GeV)	KTEV√	K_L
	Main Injector(120GeV)	CKM-P940*	K^+ in flight

√ data taking completed

∗ future program: construction not started

$K_L^0 \to \pi^0 e^+ e^-$ by KTEV



A radiative Dalitz decay:
$K_L^0 \to e^+e^-\gamma\gamma$, 5.8×10^{-7}
(when $M_{\gamma\gamma} = m_{\pi^0}$)
is the limiting background (pointed out by Greenlee, 1990).

$\Rightarrow$ phase space fiducial cuts

$< \sim$ 1/4 signal loss $>$

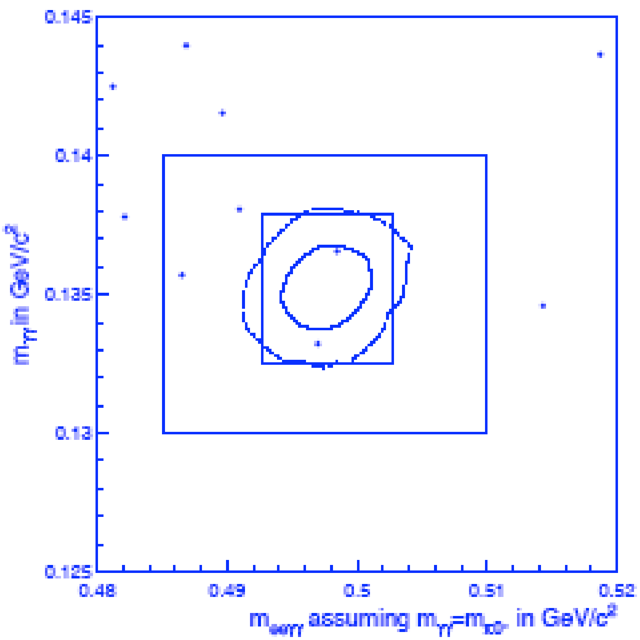
There are several distinctive regions in the $m_{\gamma\gamma}$ vs. $m_{ee\gamma\gamma}$ plane. In order to minimize human bias in the determination of the selection criteria, a blind analysis was performed. The box was the region covered up until cuts were finalized, and spans $130 < m_{\gamma\gamma} < 140$ MeV/c^2 and $485 < m_{ee\gamma\gamma} < 510$ MeV/c^2. The ellipse in the box is the signal region, which spans $\sim 2\sigma$ in the $K_L \to \pi^0 e^+ e^-$ signal Monte Carlo $m_{ee\gamma\gamma}$ and $m_{\gamma\gamma}$ distributions. In the $m_{ee\gamma\gamma}$ direction, the ellipse is $\pm$ 5.02 MeV/c^2 wide, and in the $m_{\gamma\gamma}$ direction it is $\pm$ 2.32 MeV/c^2 wide. The rectangular "strip" to the left of the box is dominated by backgrounds from $K_L \to \pi^0_D \pi^0_D$ and $K_L \to \pi^0 \pi^0_D \pi^0_D$ decays with accidental π^0s. Missing particles in these decays cause the reconstructed mass $m_{ee\gamma\gamma}$ to be low.

Make fit to extract signal/bck and make optimized phase space cuts

$$f\,(m_{ee\gamma\gamma}, m_{\gamma\gamma}) = A_0 + A_{\gamma\gamma} m_{\gamma\gamma} + A_{ee\gamma\gamma} m_{ee\gamma\gamma} + A_g\, g(m_{ee\gamma\gamma}, m_{\gamma\gamma})$$

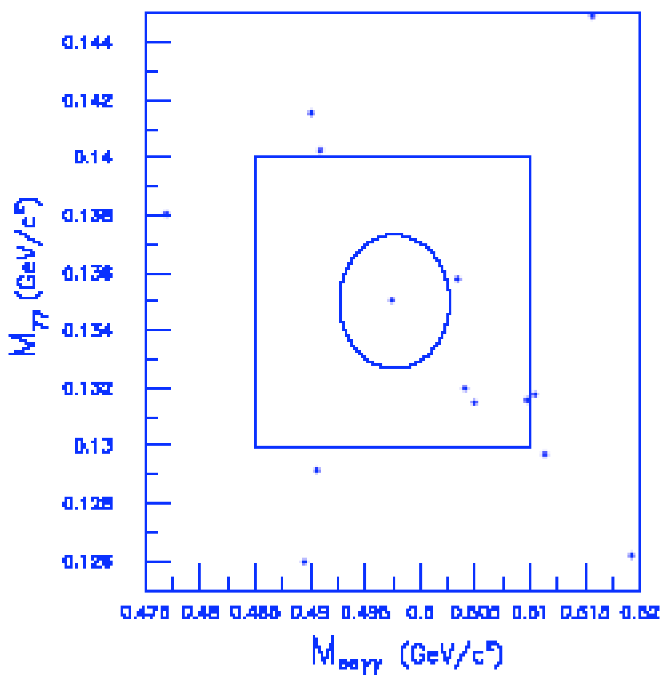
KTEV 1997 dataset

PRL 86 (2001) 397



KTEV 1999 dataset

PRL 93 (2004) 021805



Data	Bgd	observed	BR
1997	1.06 ± 0.41	2	$< 5.1 \times 10^{-10}$
1999	0.99 ± 0.35	1	$< 3.5 \times 10^{-10}$
Combined			$< 2.8 \times 10^{-10}$
SM prediction			$(2 \pm 1) \times 10^{-11}$

$K_L^0 \to \pi^0 \mu^+ \mu^-$ by KTEV

KTEV 1997 dataset

PRL 84 (2000) 5279

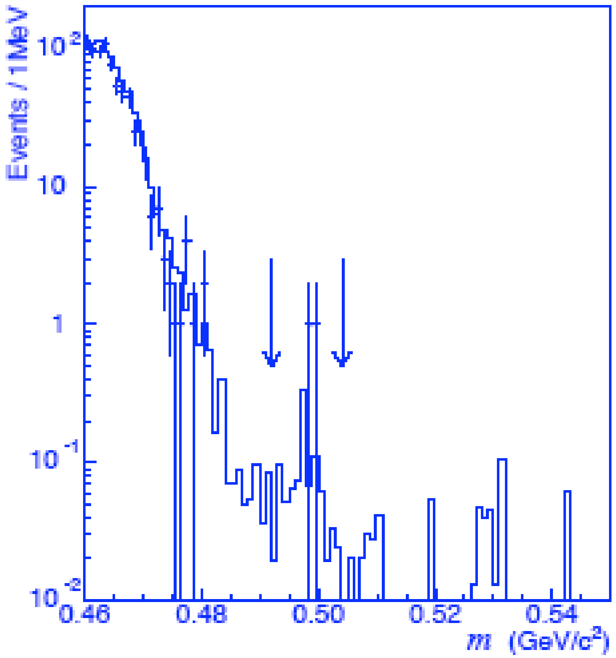
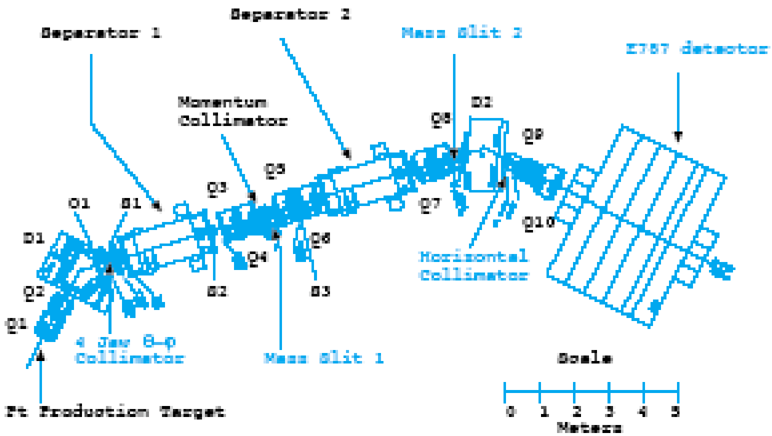


TABLE I. Summary of expected backgrounds in the signal region. "Acc." refers to particles from other sources which were accidentally time-coincident with the interesting decay; "D" and "P" refer respectively to decay in flight or punch-through. Limits are 90% C.L.; uncertainties are due to uncertainties in published branching ratios, simulation statistics, and the statistics of the normalization mode.

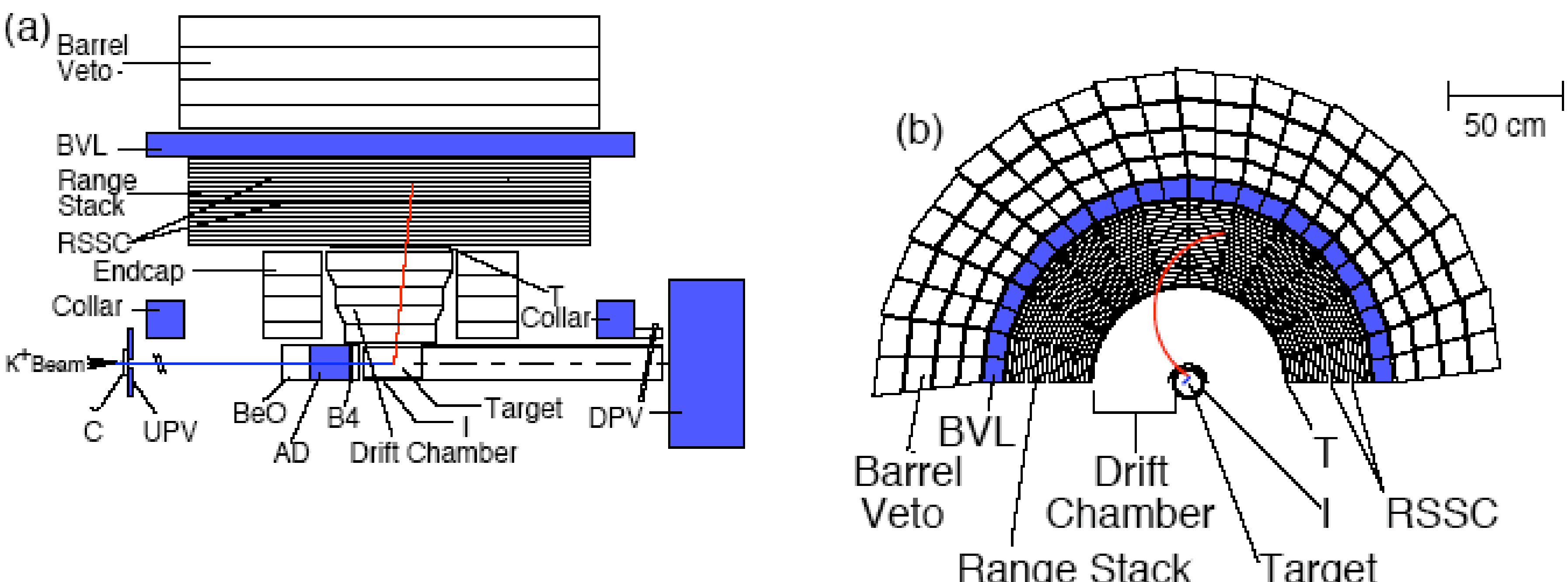
Decay mode	Expected number of events
$K_L \to \mu^+\mu^-\gamma\gamma$	0.373 ± 0.032
$K_L \to \mu^+\mu^-\gamma + \gamma(\text{Acc})$	< 0.029
$K_L \to \pi^+\pi^-\pi^0$ (DD)	0.252 ± 0.095
$K_L \to \pi^+\pi^-\pi^0$ (DP)	0.007 ± 0.007
$K_L \to \pi^+\pi^-\pi^0$ (PP)	0.007 ± 0.007
$K_L \to \pi^\pm\mu^\mp\nu + 2\gamma(\text{Acc})$ (D)	0.161 ± 0.093
$K_L \to \pi^\pm\mu^\mp\nu + 2\gamma(\text{Acc})$ (P)	0.063 ± 0.037
$K_L \to \pi^0\pi^\pm\mu^\mp\nu$ (D)	0.009 ± 0.009
$K_L \to \pi^0\pi^\pm\mu^\mp\nu$ (P)	< 0.009
Total	0.87 ± 0.15

Data	Bgd	observed	BR
1997	0.87 ± 0.15	2	$< 3.8 \times 10^{-10}$
1999			
SM prediction			$(1.5 \pm 0.5) \times 10^{-11}$

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at BNL-E949

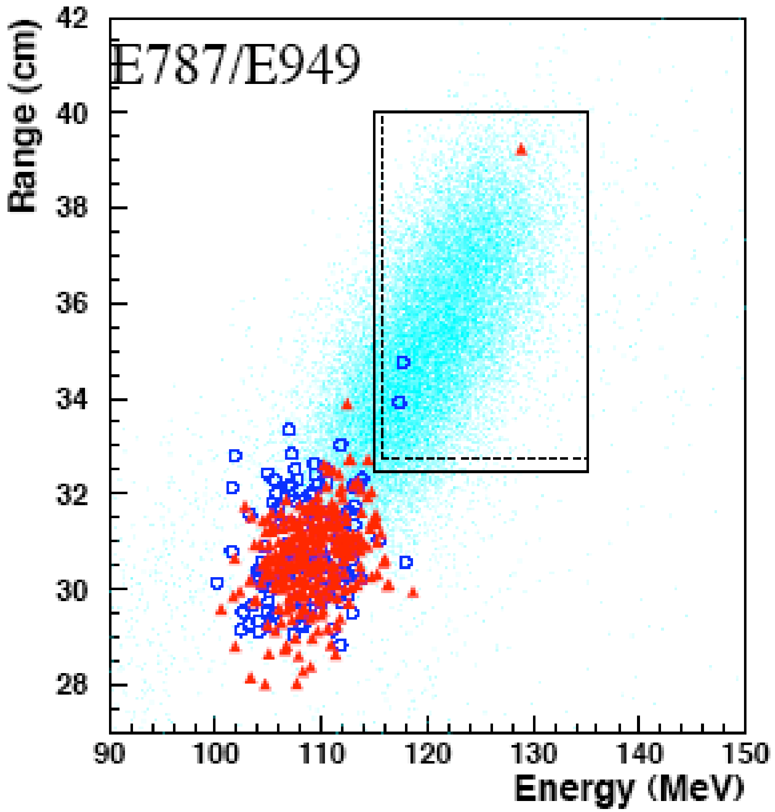


- AGS: 22GeV, 70×10^{12} protons/spill
- 2.2-sec spill in every 5.4 sec (duty cycle = 41%)
- 0.710 GeV/c, $K^+/\pi^+ = 3$



Improved Measurement of the $K^+ \to \pi^+ \nu \bar{\nu}$ Branching Ratio

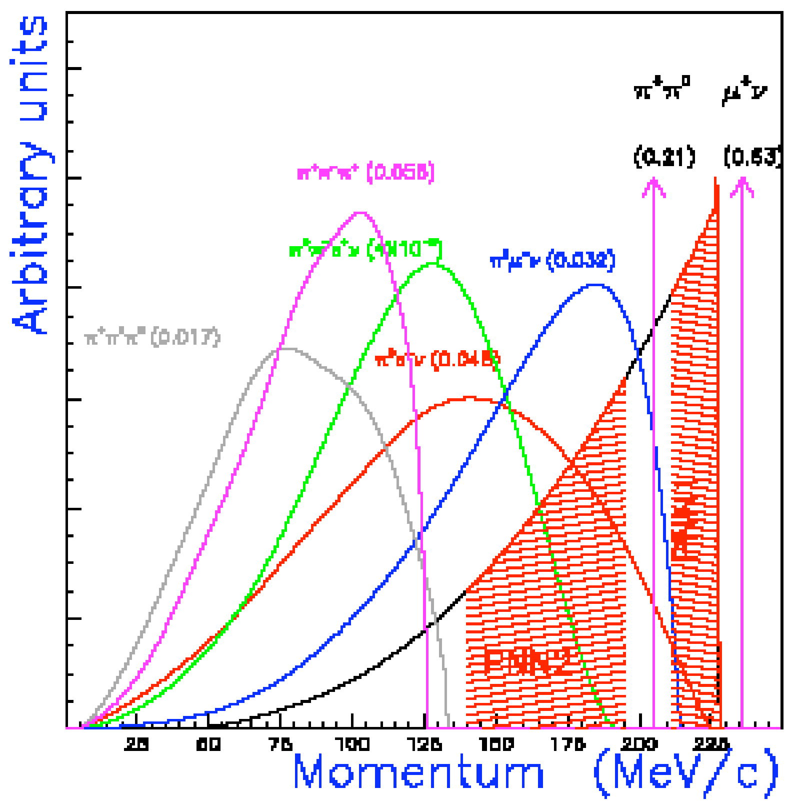
E949 2002 dataset (∼ 30% of E787), PRL 93 (2004) 031801



- π^+ Range vs Energy
- E949-2002 | E787 | MonteCarlo
- background: 0.30±0.03 events
  - "Blind" analysis
  - Likelihood analysis to the candidate events
- B.R. $= (1.47^{+1.30}_{-0.89}) \times 10^{-10}$ in 68%C.L. intervals
- $P_b = 0.1\%$

E787/E949 events

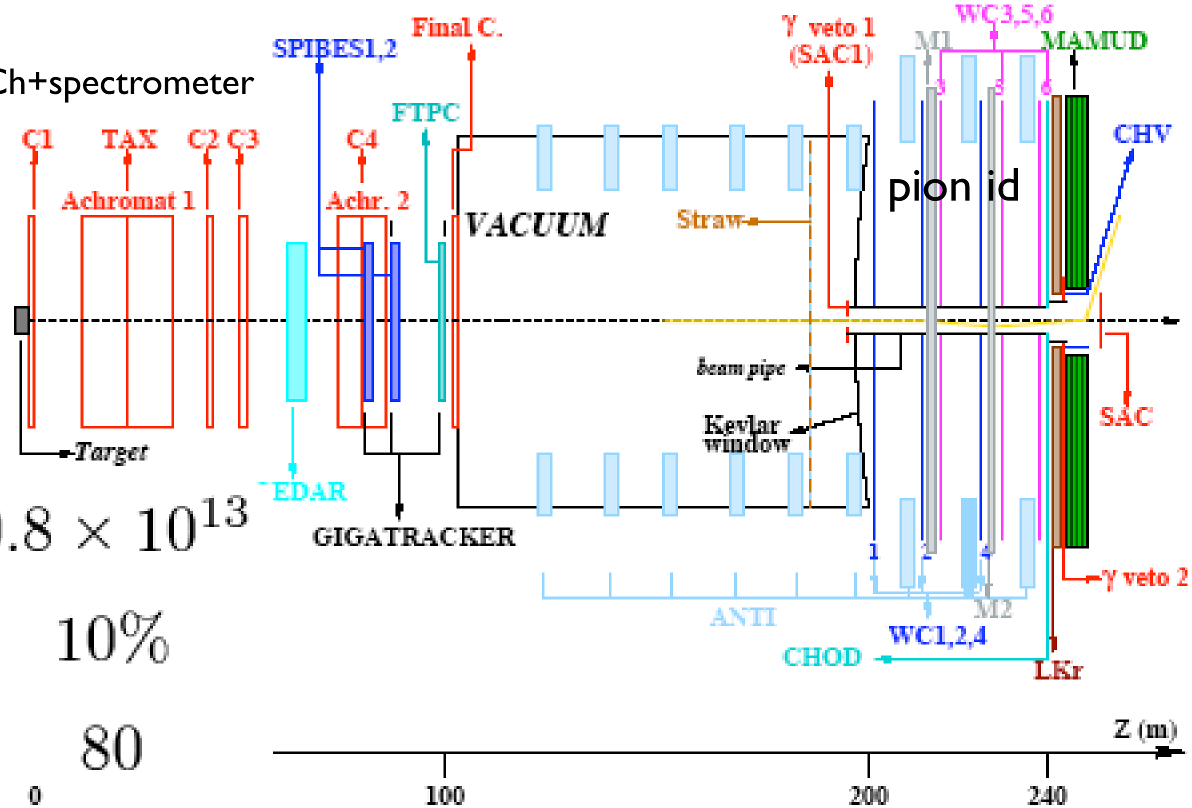
	PNN1		PNN2		
P_π (MeV/c)	[211,229]		[140,195]		
Years	1995-98 (E787)	2002 (E949)	1996-97 (E787)		2002 (E949)
Stopped K⁺	5.9×10^{12}	1.8×10^{12}	1.7×10^{12}		1.8×10^{12}
Candidates	2	1	1	**S/b = (BR·SES)/b** ≈ 0.1	GOAL: ~ 1
Background	0.15±0.05	0.30±0.03	1.22±0.24		
BR($K^+ \to \pi^+$__)	$(1.47^{+1.30}_{-0.89})\times10^{-10}$ (68% CL)		$< 22\times10^{-10}$ (90% CL)		?



$K^+ \to \pi^+\nu\bar{\nu}$: Letter of Intent for NA48/3 @ CERN

75 GeV

$p/\pi^+/K^+$ MHz
160/480/48



Sensitive K decays	0.8×10^{13}
Acceptance	10%
pnn Total	80

- un-separated K^+ beam at ~75 GeV/c, $\pi^+\nu\bar{\nu}$ decay in flight
- testbeam run in August:
  rate-capable KAon BEam Spectrometer with Micromegas-type TPC's,

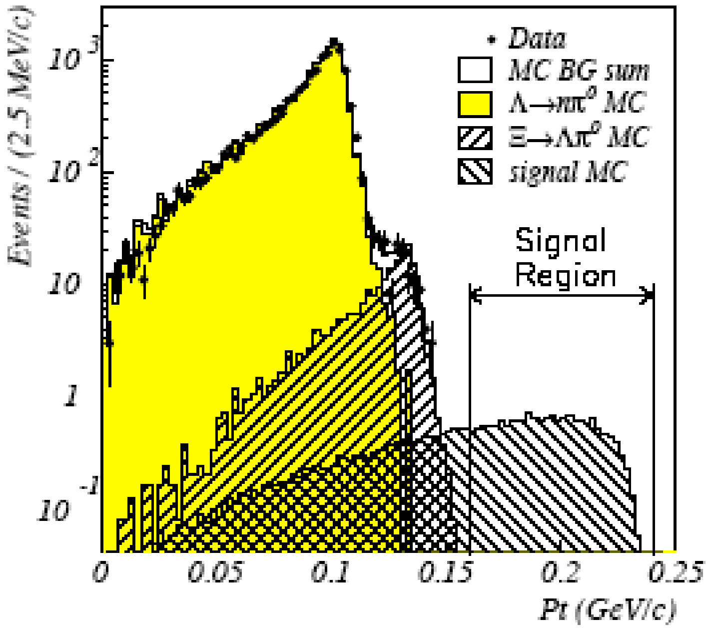
Signal/bkgd	2
$\sigma(\mathcal{B})/\mathcal{B}$	14%
Year	2009

E787/E949 acc~0.2%

in-flight K_L^0 decay $\to \pi^0$ + "nothing"

$[\pi^0 \to e^+e^-\gamma]$

background $0.12^{+0.05}_{-0.04}$ events

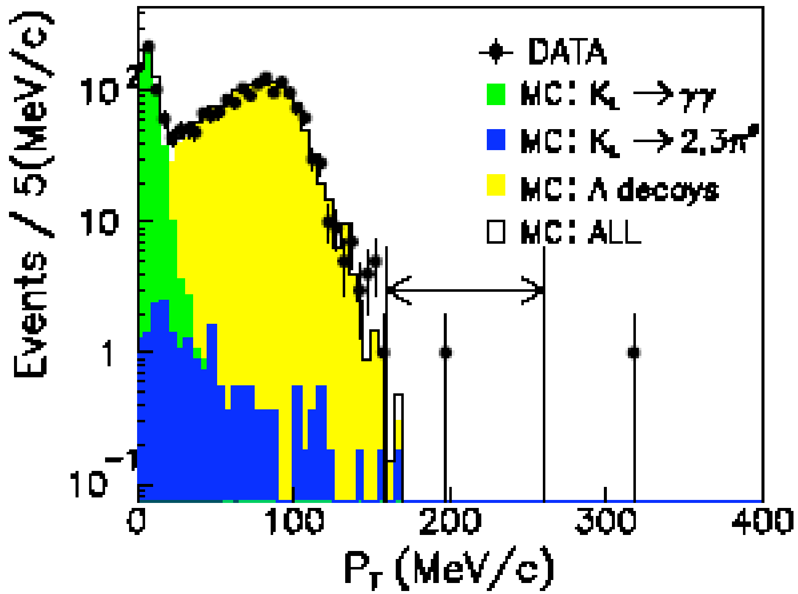


$< 5.9 \times 10^{-7}$

KTEV '97 PRD 61(2000)072006

$[\pi^0 \to \gamma\gamma]$ ← We need this !

background 3.5 ± 0.9 events



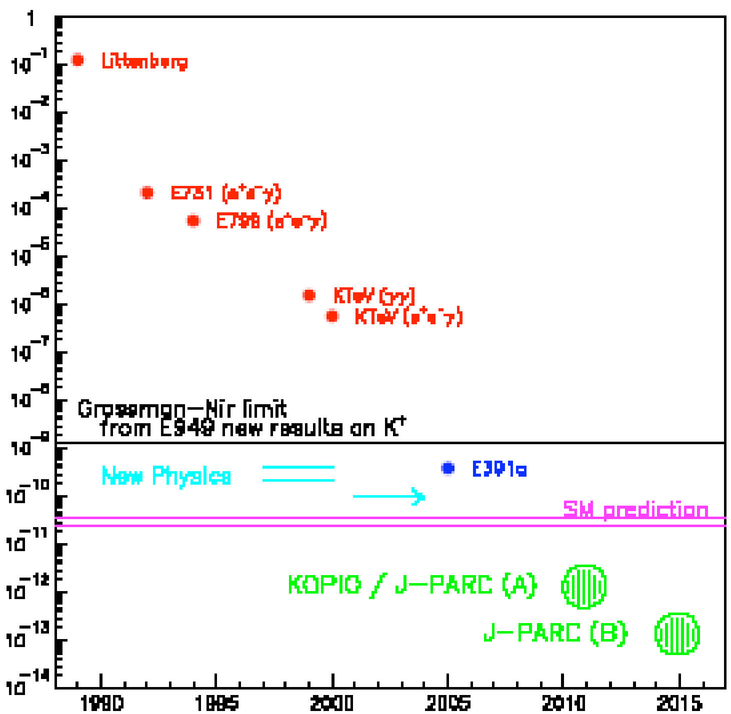
$< 1.6 \times 10^{-6}$

one-day PL B447(1999)240

major background from $K_L \to \pi^0\pi^0$ (2 out of 4 γ's escape)

photon detection with very-low inefficiency ($< 10^{-3} \sim 10^{-4}$)

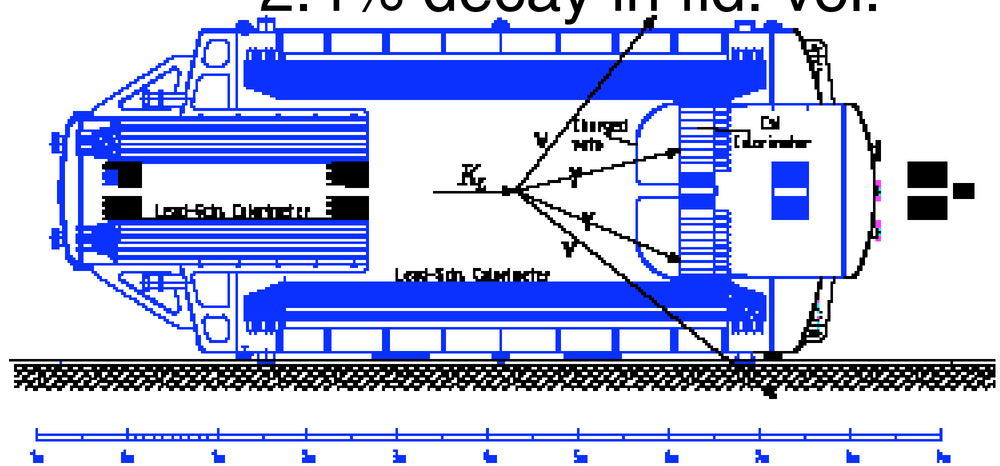
KEK-E391a: the first experiment dedicated to $K_L^0 \to \pi^0 \nu \bar{\nu}$



goal: Get below GN bound for new physics

- collimated "pencil" beam +-2mrad
- CsI calorimeter to detect $\pi^0 \to \gamma\gamma$
  - decay vertex along the beam line (m_{π^0} constraint)
  - the events with $P_T(\pi^0) > 120$ MeV$/c$
- calorimeters for perfect photon veto

P(k)~2-3GeV, 500k(30M) K(n) per pulse, 2.4% decay in fid. vol.



- KEK-PS: 12GeV, 2.5×10^{12} protons/spill
- 2.0-sec spill in every 4.0 sec

Run I 2004

- S.E.S (ratio to $K_L^0 \to \pi^0\pi^0\pi^0$): $\sim 4 \times 10^{-10}$ w/o very tight PV

- requesting Run-2 in 2005

KOPIO Concepts

Try to measure everything in K center of mass.

Kaon Beam:

42.5 degree take-off angle

Soft momentum spectrum [0.5,1.5 GeV]

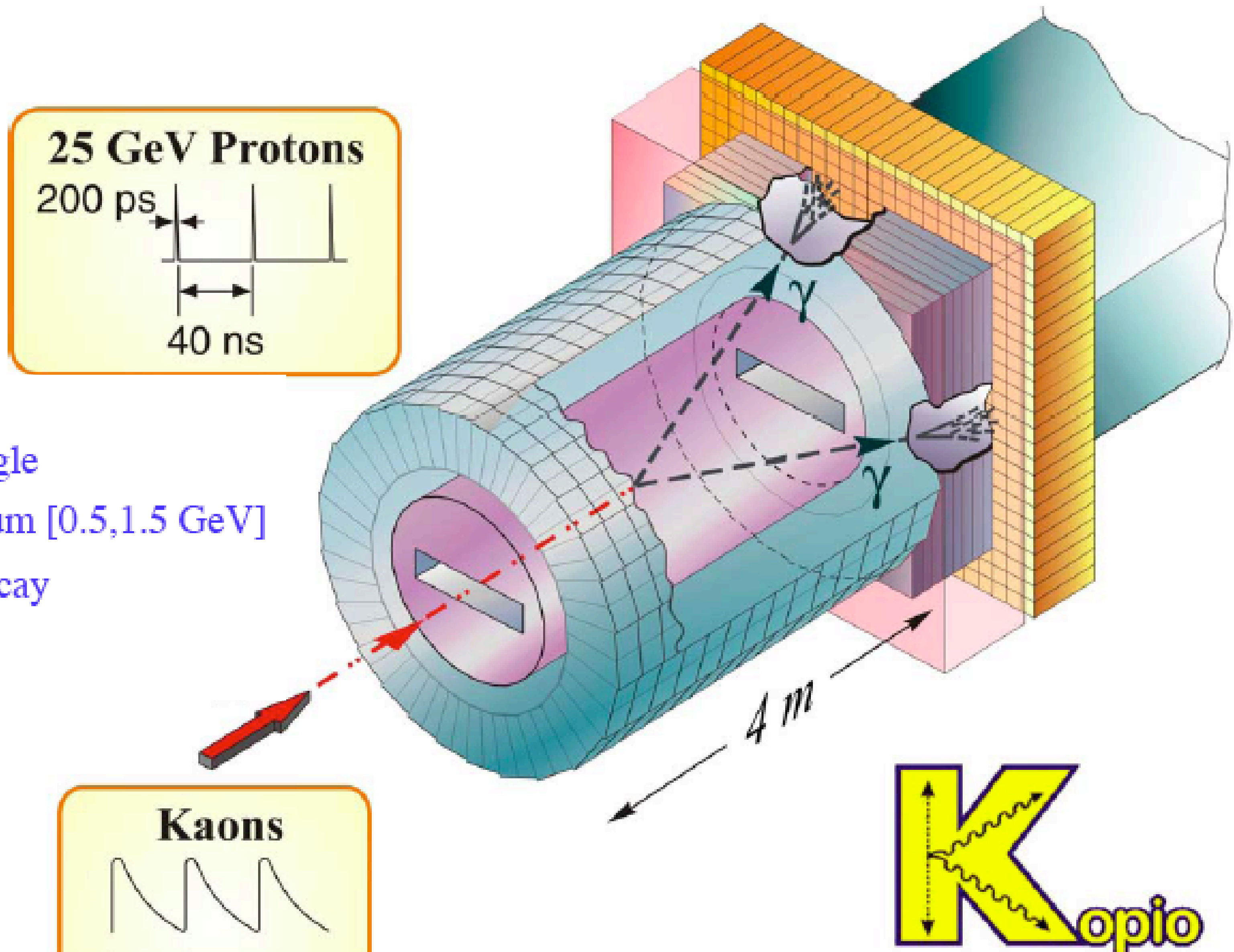
3×10^8 K_L / spill, 8 % decay

10 GHz neutrons

6000 hrs

~100 Signal

~20 bkg



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

Conclusions

- Situation with $K_L \to \pi^0 l^+ l^-$ is getting less murky because of the measurements from NA48 of $K_S \to \pi^0 l^+ l^-$.

  Is it good enough for a dedicated experiment ?

- Theory of $K^+ \to \pi^+ \nu\bar{\nu}$ ($\sim 10^{-10}$) and $K_L \to \pi^0 \nu\bar{\nu}$ ($\sim 3 \times 10^{-11}$) is very robust.

  New understanding of how $K_L \to \pi^0 \nu\bar{\nu}$ has sensitivity to new physics. (Bryman, Buras, Isidori, Littenberg, TUM-HEP-583/05)

- JPARC has many LOI for rare decays. 2×10^{14} protons/3.4sec

  Pencil beam for $K_L \to \pi^0 \nu\bar{\nu}$.

  Stopping beam for $K^+ \to \pi^+ \nu\bar{\nu}$.

- $K^+ \to \pi^+ \nu\bar{\nu}$: NA48/3.

  Perhaps incorporate some CKM features: ring imaging, separated beam. Seriously consider lower momentum (PNN2) region

- $K^+ \pi^0 \nu\bar{\nu}$: KOPIO waiting for funding.