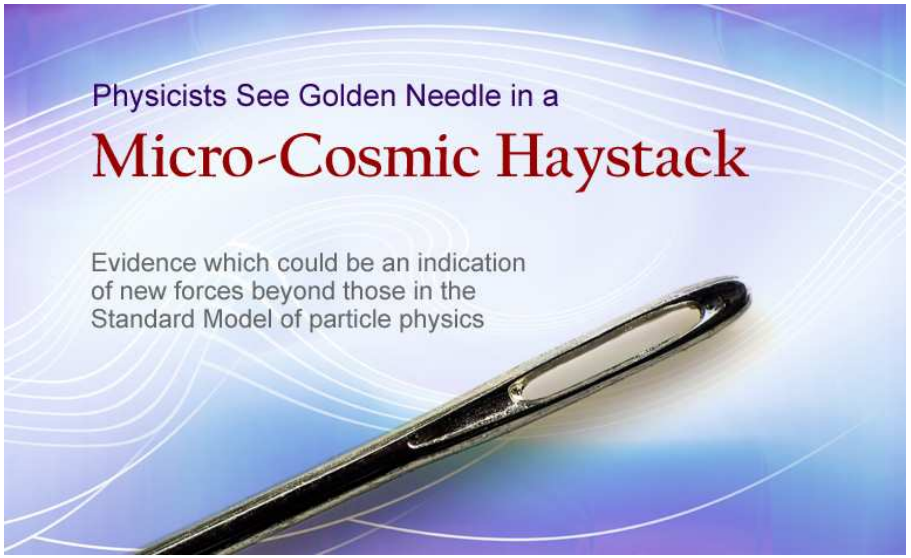
Rare Kaon Decays

- a review of results, 2004

Takeshi K. Komatsubara
(KEK-IPNS)



FPCP 2004 @ Daegu

October 8, 2004



Outline of "not just $\pi\nu\bar{\nu}$" [44 slides, 40 minutes]

1. introduction
2. violations of the Standard Model (SM)
   - Lepton Flavor violation
   - T-violating transverse muon polarization in $\mathbf{K}^{+}_{\mu 3}$
3. Flavor Changing Neutral Current (FCNC) processes
   - $\mathbf{K}^{0}_{L}$ / $\mathbf{K}^{0}_{S} \to \pi^{0}\ell^{+}\ell^{-}$ $[\,\ell = e, \mu\,]$
   - $\mathbf{K}^{+} \to \pi^{+}\nu\bar{\nu}$, $\mathbf{K}^{0}_{L} \to \pi^{0}\nu\bar{\nu}$
4. future kaon programs

<< Acknowledgments to the collaborations >>

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

$\surd$ data taking completed

$*$ future program: construction not started

The upper limits in this talk are **at 90% C.L.**

Branching Ratio (Fraction)

$$\text{B.R.} = \frac{\Gamma_f}{\Gamma_{all}} = \tau \times \frac{2\pi}{\hbar} \int d(\text{PhaseSpace}) \cdot |M_f|^2$$

well-done $\%\ \sim\ 10^{-3}$ $<$ main decay modes $>$

- determinations of Lifetimes, Decay Constants, Form Factors, ...
- Were these really "well done" ??

⟵ Sasha Glazov (DESY)

medium $10^{-3}\ \sim\ 10^{-7}$

- hadronic interactions at low energy, radiative decays, ...
- understanding the background sources to rare decays

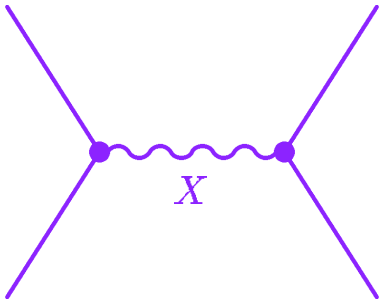
⟶ Fabio Bossi (Frascati)

rare $10^{-7}\ \sim\ 10^{-12}$

Branching Ratio (Fraction)

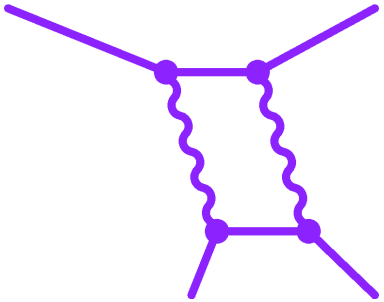
$$\text{B.R.} = \frac{\Gamma_f}{\Gamma_{all}} = \tau \times \frac{2\pi}{\hbar} \int d(\text{Phase Space}) \cdot |M_f|^2$$

- $|M_f|^2$ is zero in the "TOE"
- tree diagram, $m_X \gg m_{EW}$



⟵ violations of the SM

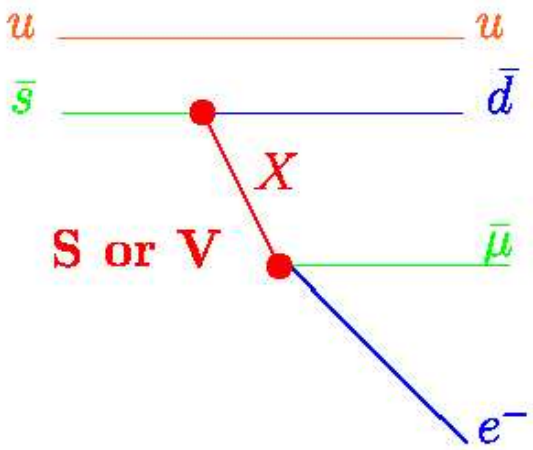
- no tree diagram, loop diagram with suppression mechanism



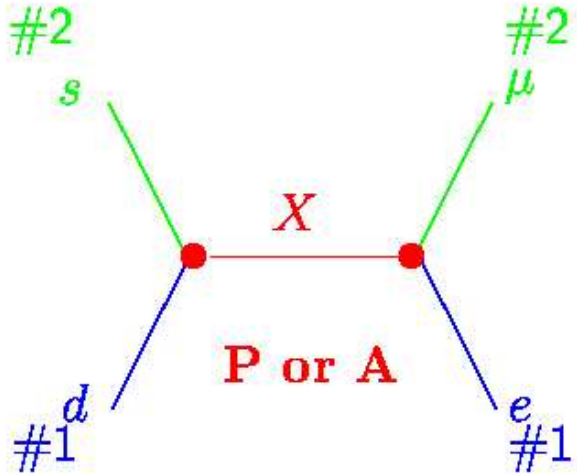
⟵ SM parameters, CP violation

Rare decay modes can be
"just around the corner"
(just below the current experimenal limit) !

Lepton Flavor Violation in K decays



$K^+ \to \pi^+\mu^+e^-$ (BNL-E865)
$K^0_L \to \pi^0\mu^\pm e^\mp$ (FNAL-KTEV)



$K^0_L \to \mu^\pm e^\mp$ (BNL-E871)

- Involving both quark and lepton sectors at tree level
  $\Longleftarrow$ Generation Puzzle of the SM

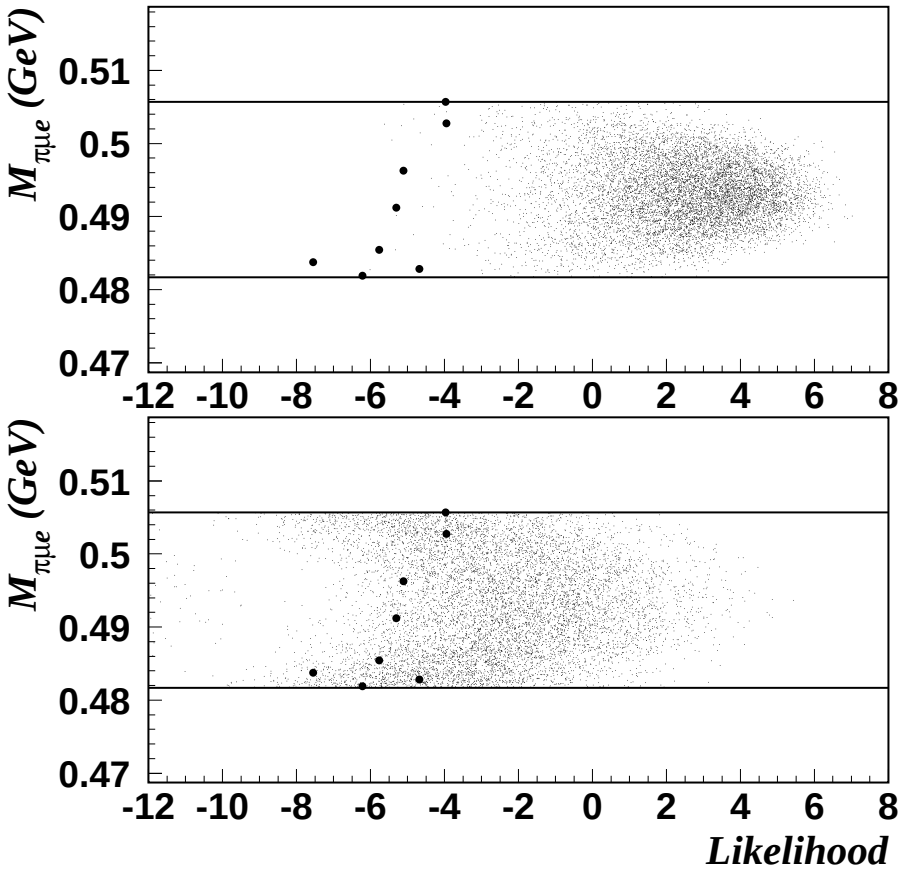
$$\underline{\text{B.R.} = O(10^{-12}) \Longleftrightarrow M_X = O(100\text{TeV}/c^2)}$$

Technicolor, Composite, Leptoquark, ...

* Δm^2-$\sin^2 2\theta$ region of ν oscillation: $K^0_L \to \mu e < 10^{-25}$

three-body LFV decay (1) $K^+ \to \pi^+\mu^+e^-$ by BNL-E865

E865 1998 dataset



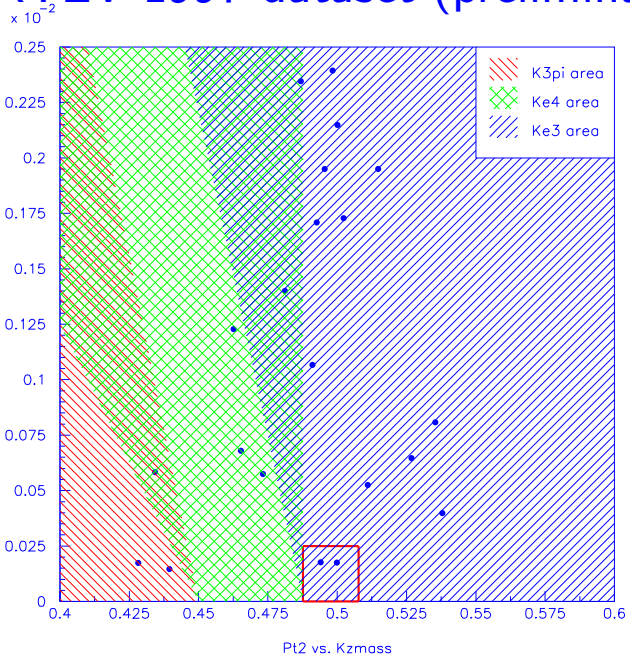
- un-separated K^+ beam
- PID ($\pi^\pm/e^\pm$ and π^+/μ^+)
- multiple K^+ decays
  → "accidental background"
  (K^+ reconstruction at the target, remove out-of-time events)
  - Bgd level: 8.2 ± 1.9
- Likelihood analysis
  → 90% C.L. limit: 2.4 events

Data	BR
1998	$< 2.2 \times 10^{-11}$
95+96 + E777	$< 2.8 \times 10^{-11}$
Combined	$< 1.2 \times 10^{-11}$

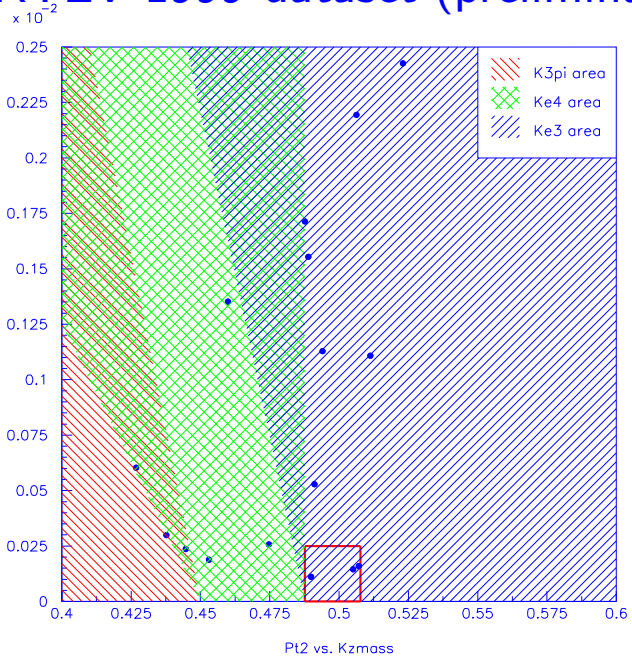
presented by A.Sher at DPF2004;
article in preparation

three-body LFV decay (2) $K_L^0 \to \pi^0 \mu^\pm e^\mp$ by FNAL-KTEV

KTEV 1997 dataset (preliminary)



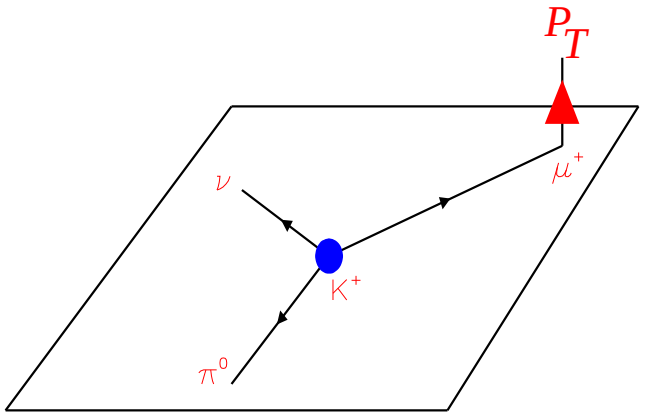
KTEV 1999 dataset (preliminary)



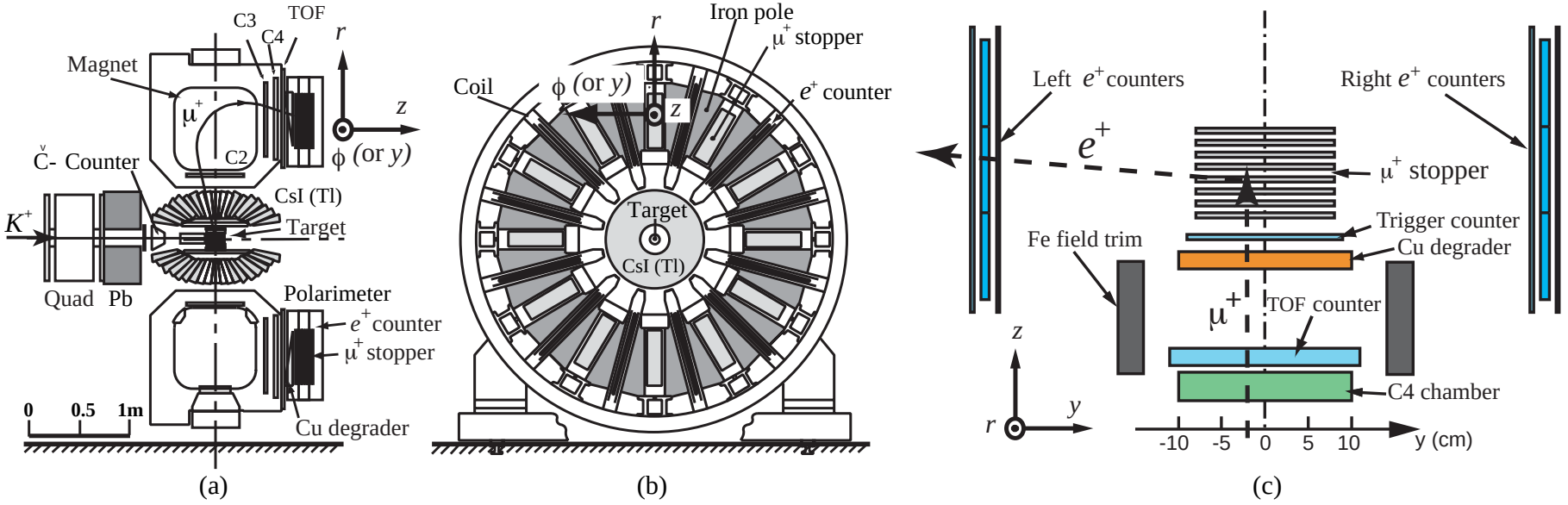
Data	Bgd	observed	BR
1997	0.53 ± 0.14	2	$< 4.40 \times 10^{-10}$
1999	0.48 ± 0.14	3	$< 5.33 \times 10^{-10}$
Combined			$< 3.31 \times 10^{-10}$

presented by A.Bellavance at BNL workshop in May 2004, article in preparation

T-violating P_t in $K^+ \to \pi^0 \mu^+ \nu$(B.R.=3.27%) at KEK-E246



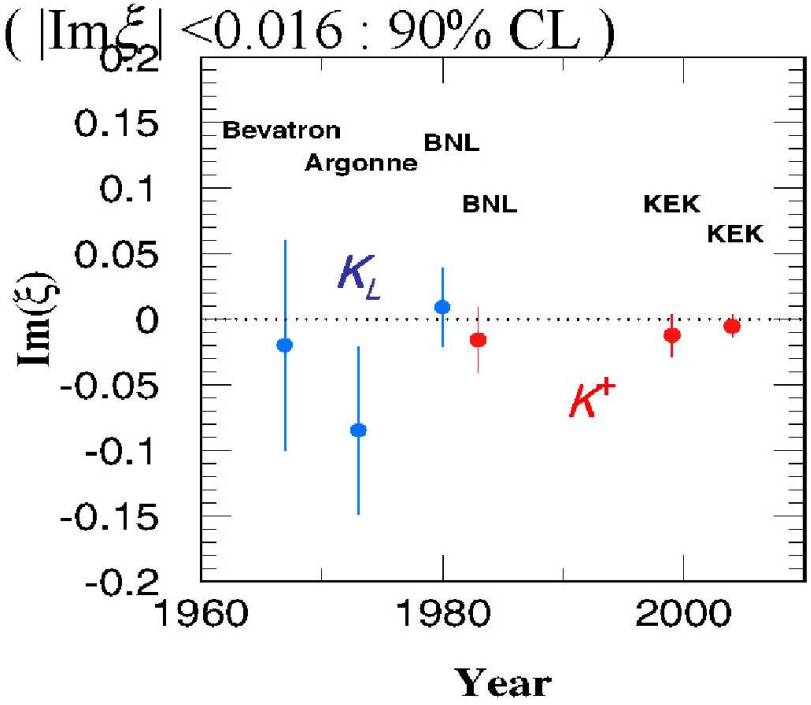
- $P_T \equiv s_{\mu^+} \times \dfrac{(p_{\pi^0} \times p_{\mu^+})}{|p_{\pi^0} \times p_{\mu^+}|}$: T-odd
  $\to$ an observable of CP violation
- spurious P_t from final state int: $< 10^{-5}$,
  P_t due to CPV in the SM is $\sim 10^{-7}$
  $\to$ sensitive probe of non-SM CPV



E246 results on P_t in $K^+ \to \pi^0 \mu^+ \nu$

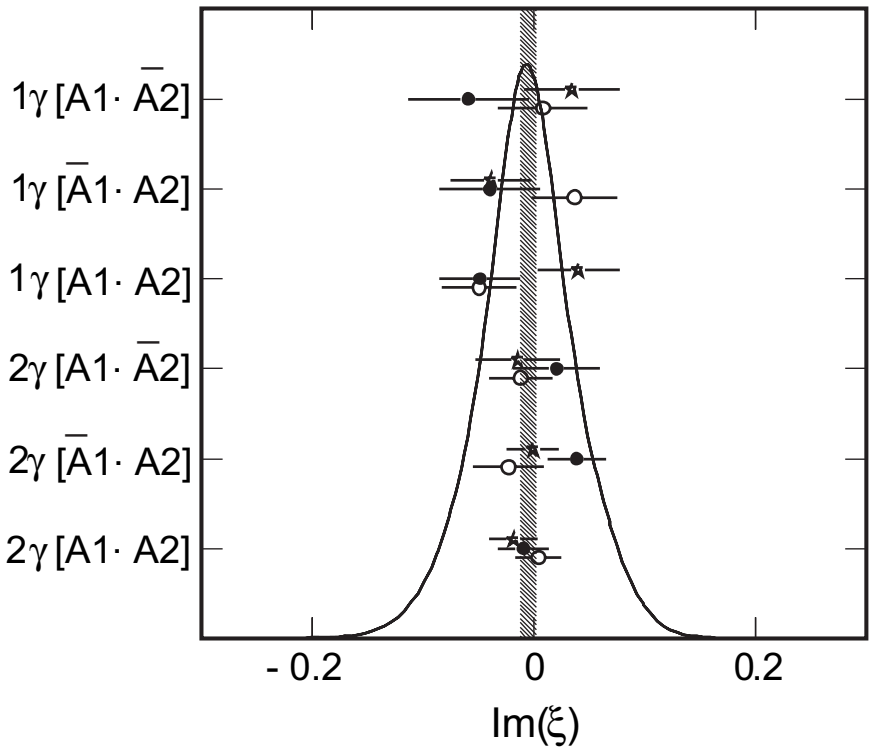
PRL 93(2004) 131601 (combining all the datasets: 1996-97, 98, and 99-2000)

- $P_t = -0.0017 \pm 0.0023_{stat} \pm 0.0011_{syst}$
  ($|P_t| < 0.50\%$)
- T-violating physics parameter $\boxed{Im(\xi)}$ ($\xi \equiv \frac{f_+(q^2)}{f_-(q^2)}$):
  $Im(\xi) = -0.0053 \pm 0.0071_{stat} \pm 0.0036_{syst}$



check of systematics

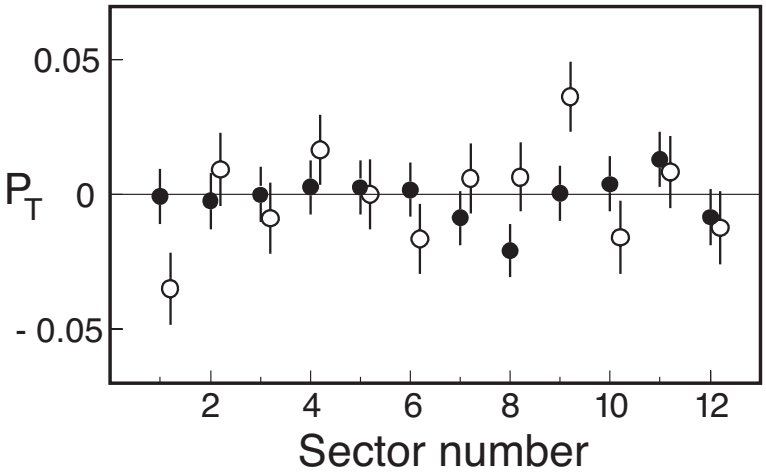
Consistency (datasets, π^0 tags)



●: 1996-97, ○: 98, ⋆: 99-2000

$\chi^2/d.o.f \;=\; 0.78$

Sector dependence



●: 2γ events

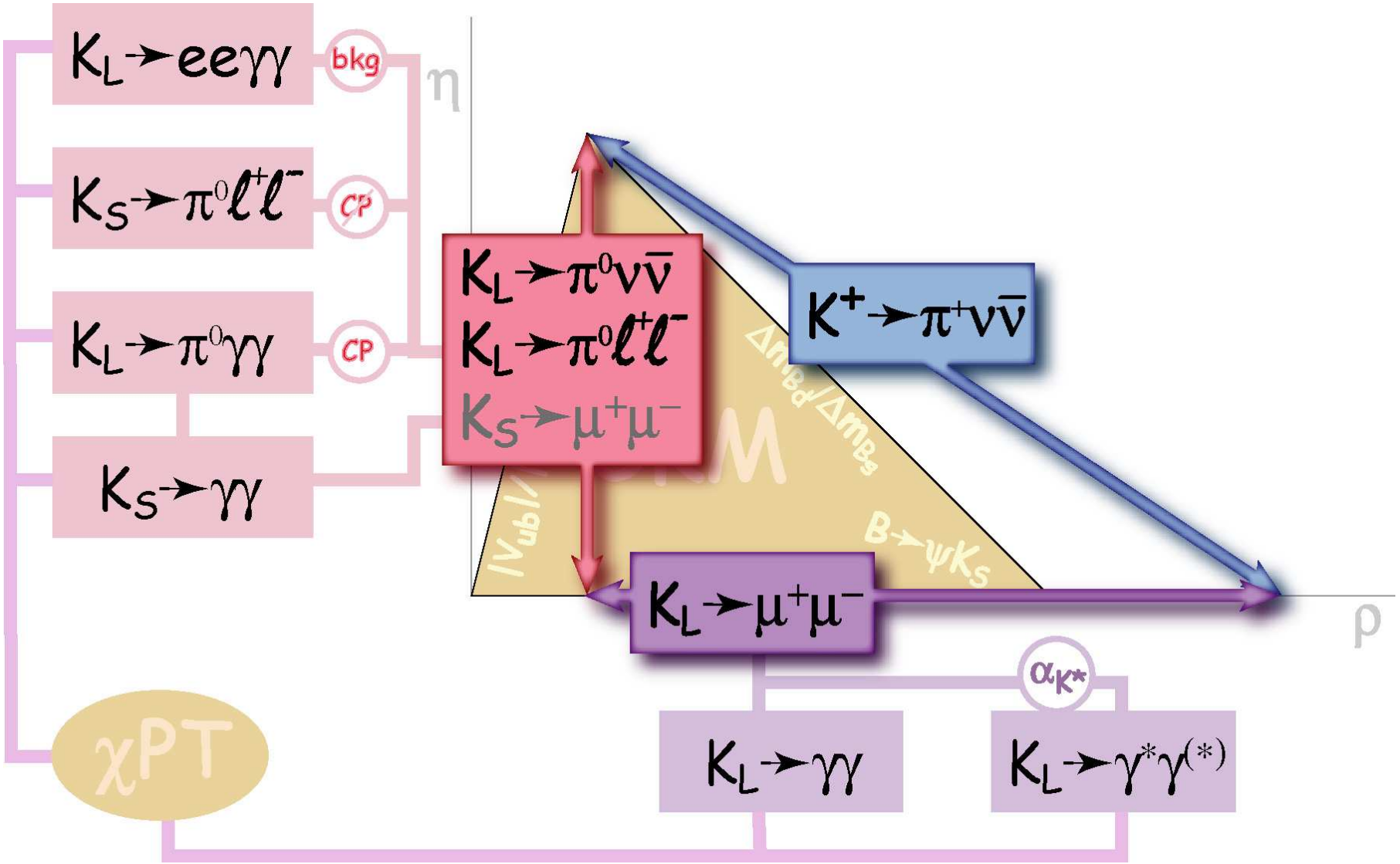
$\chi^2/d.o.f \;=\; 0.69$ (for ●)

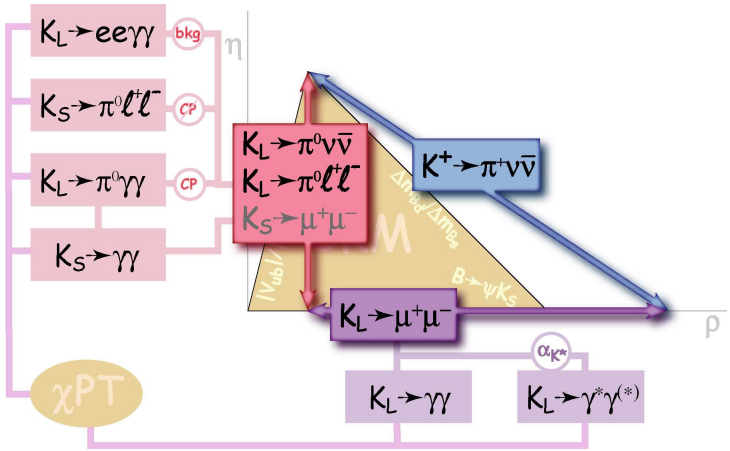
○: 1γ events

$\chi^2/d.o.f \;=\; 1.97$ (for ○)

Flavor Changing Neutral Current processes







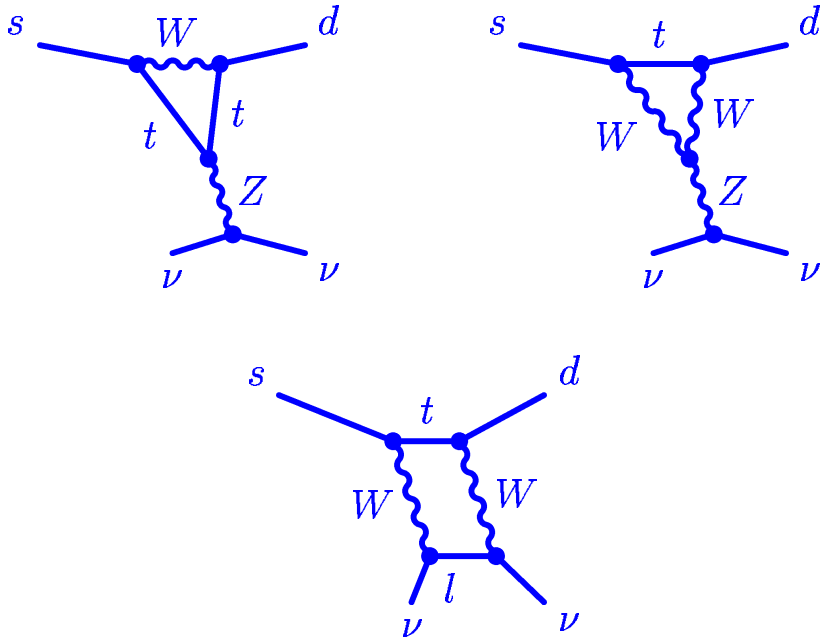
Cabibbo(1963)-Kobayashi-Maskawa(1972) matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} .975 & .22 & .002-.005 \\ .22 & .974 & .038-.044 \\ .004-.014 & .037-.044 & .999 \end{pmatrix}$$

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

- Wolfenstein parameterization (1983): $\lambda \equiv sin\theta_C = 0.22,\ A,\ \rho,\ \eta.$

FCNC in K decays: $s \rightarrow d$ transition



- induced in the Standard Model by $W^{\pm}/Z^0$ loop effects
- top-quark dominant (178.0±4.3 GeV/c^2)
- $\lambda_t \equiv V_{ts}^* \cdot V_{td}$

  $= -A^2\lambda^5 \bullet (1-\rho-i\eta)$

  $= -|V_{cb}|^2 \cdot \lambda \bullet (1-\rho-i\eta)$:

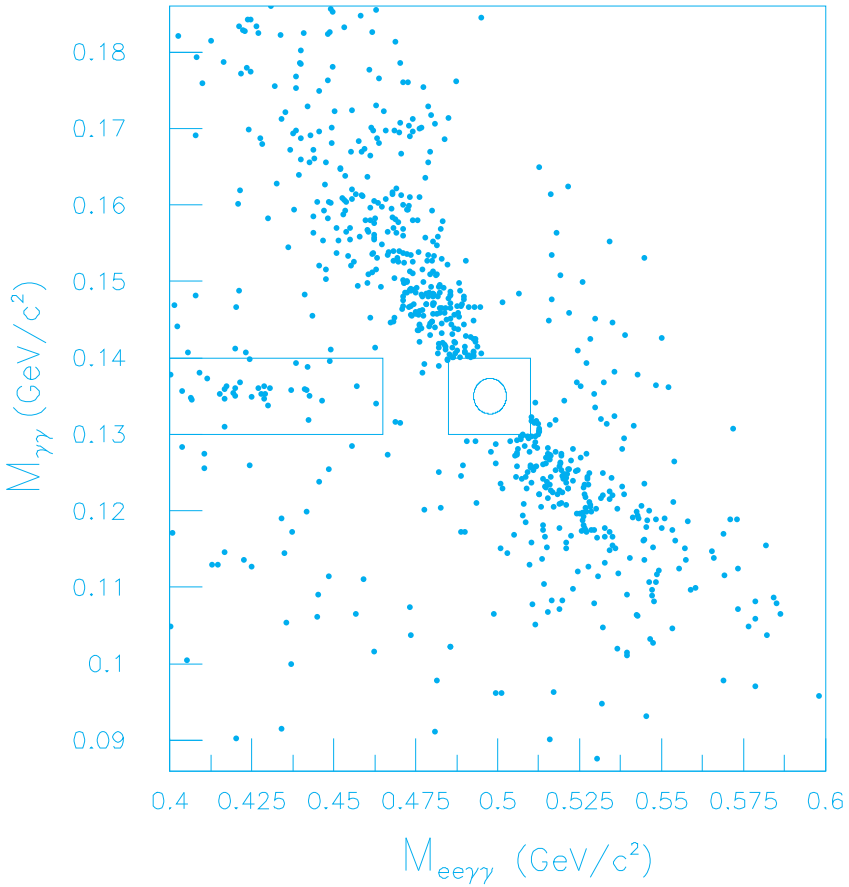
  rare [$|V_{cb}|^2 \cdot \lambda$], precious [ρ and η]

$\mathsf{K_L^0} \simeq \mathsf{K_2(CP-)} + \epsilon \cdot \mathsf{K_1(CP+)}$:

$\mathsf{A(K_2 \rightarrow \pi^0) \propto A(K^0 \rightarrow \pi^0) + A(\bar{K}^0 \rightarrow \pi^0)}$

$\propto \mathsf{V_{td}^* - V_{td} = 2\,Im(V_{td}) \propto \eta}$ [direct CP violation]

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



A radiative Dalitz decay:

$\mathbf{K_L^0 \to e^+ e^- \gamma\gamma}$, 5.8×10^{-7}

(when $M_{\gamma\gamma} = m_{\pi^0}$)

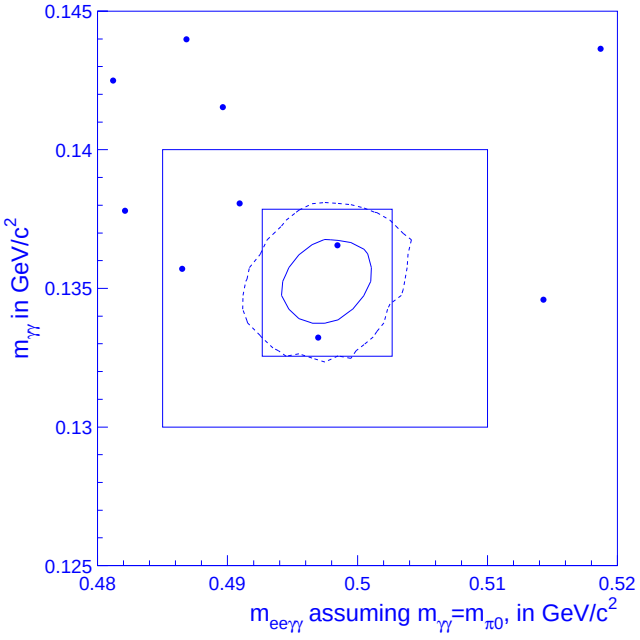
is the limiting background (pointed out by Greenlee, 1990).

$\Rightarrow$ phase space fiducial cuts

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

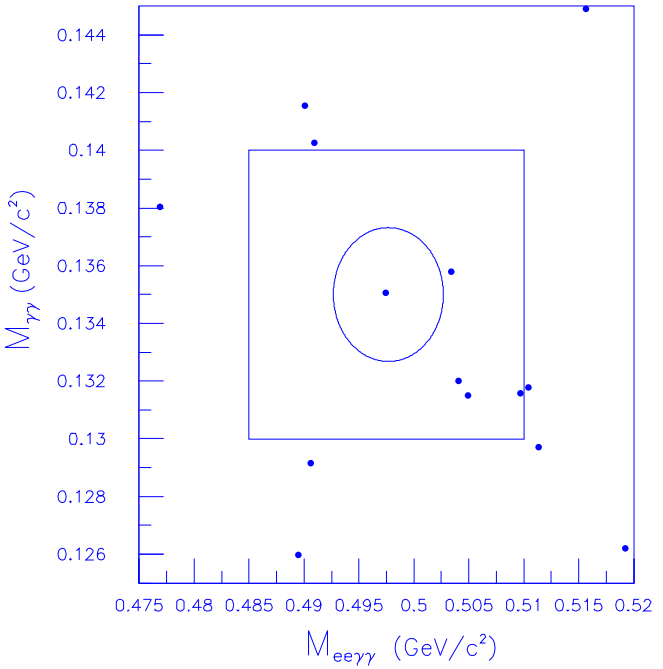
KTEV 1997 dataset

PRL 86 (2001) 397



KTEV 1999 dataset

PRL 93 (2004) 021805

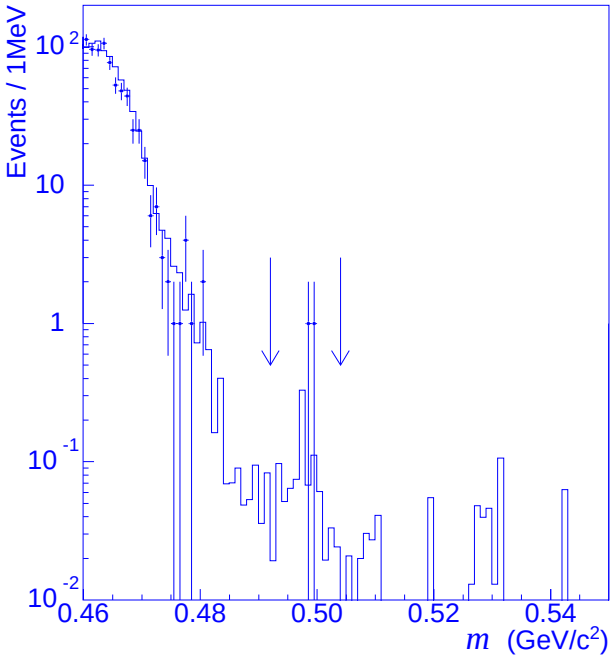


Data	Bgd	observed	BR
1997	1.06 ± 0.41	2	$< 5.1 \times 10^{-10}$
1999	0.99 ± 0.35	1	$< 3.5 \times 10^{-10}$
Combined			$< 2.8 \times 10^{-10}$
SM prediction			$(2 \pm 1) \times 10^{-11}$

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

KTEV 1997 dataset

PRL 84 (2000) 5279



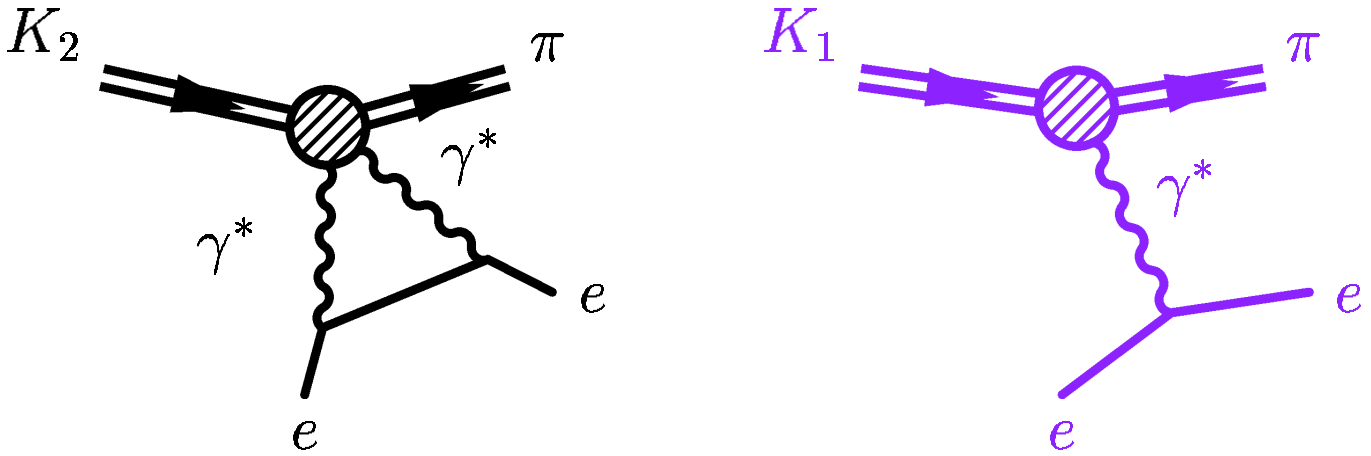
KTEV 1999 dataset

(coming soon)

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

$\mathbf{K_L^0 \to \pi^0 \ell^+ \ell^-}$: three contributions in the SM

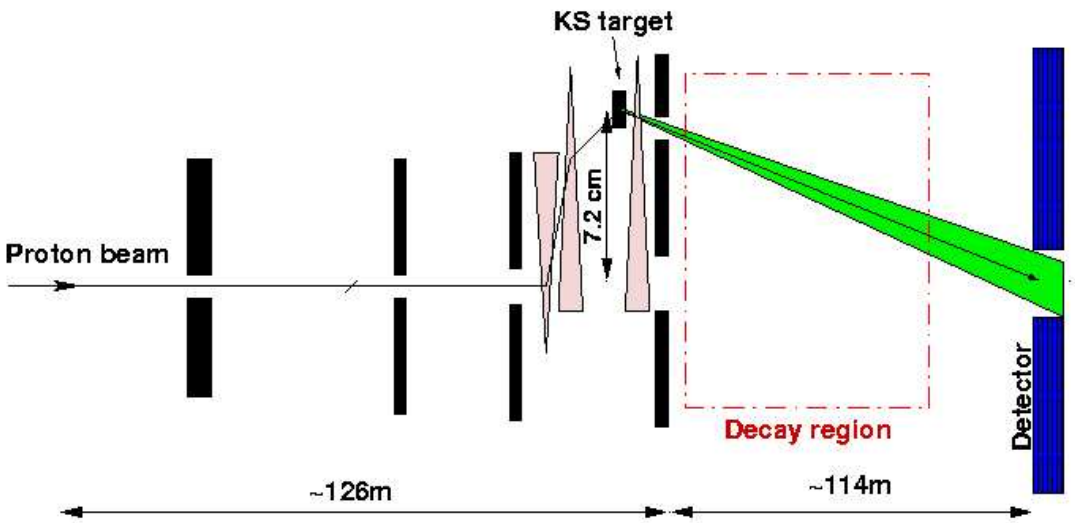
- direct CP violating
- CP conserving (K_2) and indirect(mixing) CP violating (K_1)

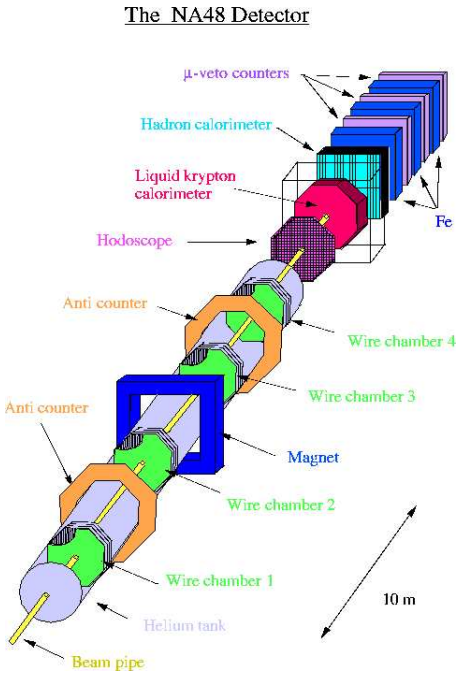


$K_S^0 \simeq K_1(CP+)$:

check the indirect CP violating effects in K_L
with K_S decays

CERN-NA48 K^0_s program



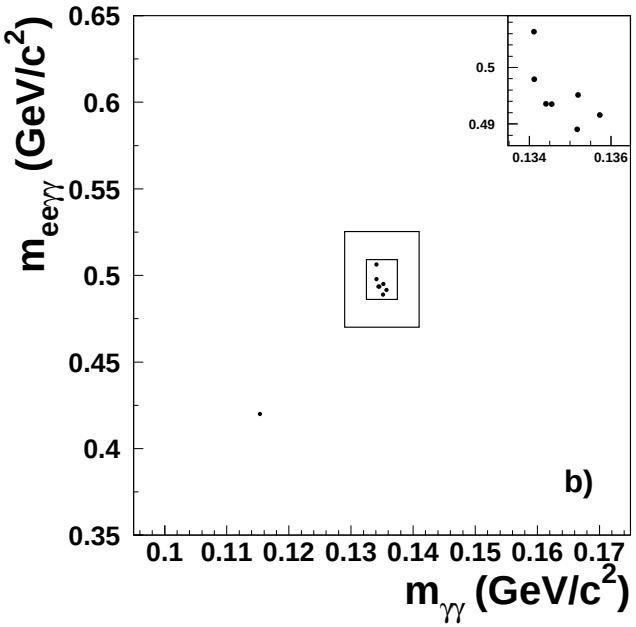


- 1999: 6×10^9 protons per pulse (ppp), 2 days
- 2000: no spectrometer; neutral modes
- 2002: K^0_s very high-intensity run <NA48/1>
  - 5×10^{10} ppp, 89 days
  - 4×10^{10} K^0_s decays in 40 - 240 GeV, 0 - 2.5 $c\tau_{K_S}$

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

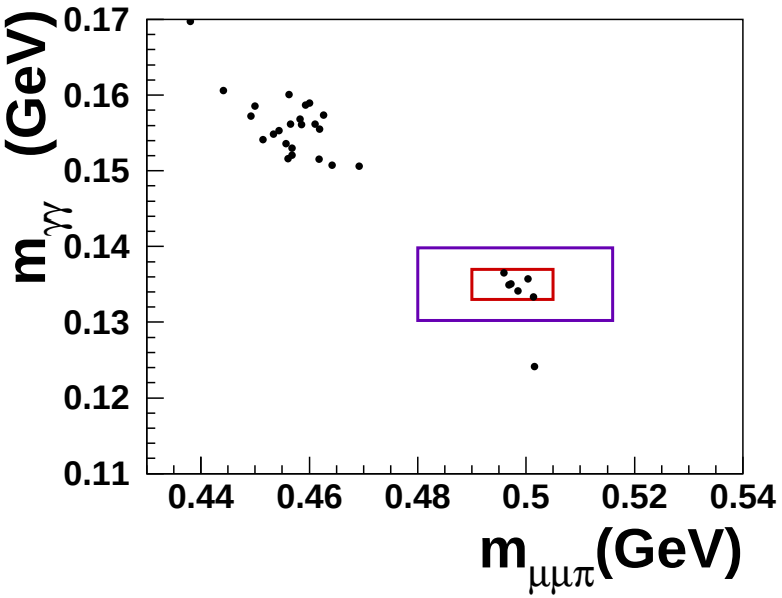
$K^0_S \to \pi^0 e^+ e^-$

PL B576 (2003) 43



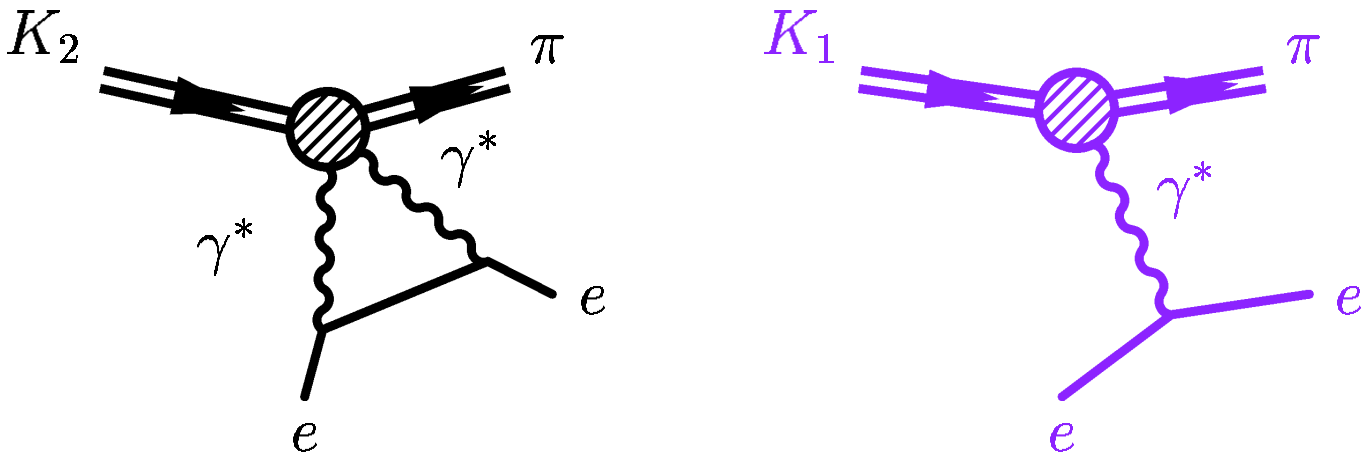
$K^0_S \to \pi^0 \mu^+ \mu^-$

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	$2.9^{+1.5}_{-1.2}(stat) \pm 0.2(syst) \times 10^{-9}$

- direct CP violating
- CP conserving (K_2) and indirect(mixing) CP violating (K_1)



⋆ Buchalla - D'Ambrosio - Isidori, Nucl.Phys.B672(2003)387
⋆ Isidori - Smith - Unterdorfer, Eur.Phys.J.C36(2004)57

	direct-CPV	←interference→	indirect-CPV	CPconserving
$\mathbf{K_L^0 \to \pi^0 e^+ e^-}$	5	± 9	17	(negligible)
$\mathbf{K_L^0 \to \pi^0 \mu^+ \mu^-}$	2	± 3	9	5

sub-dominant

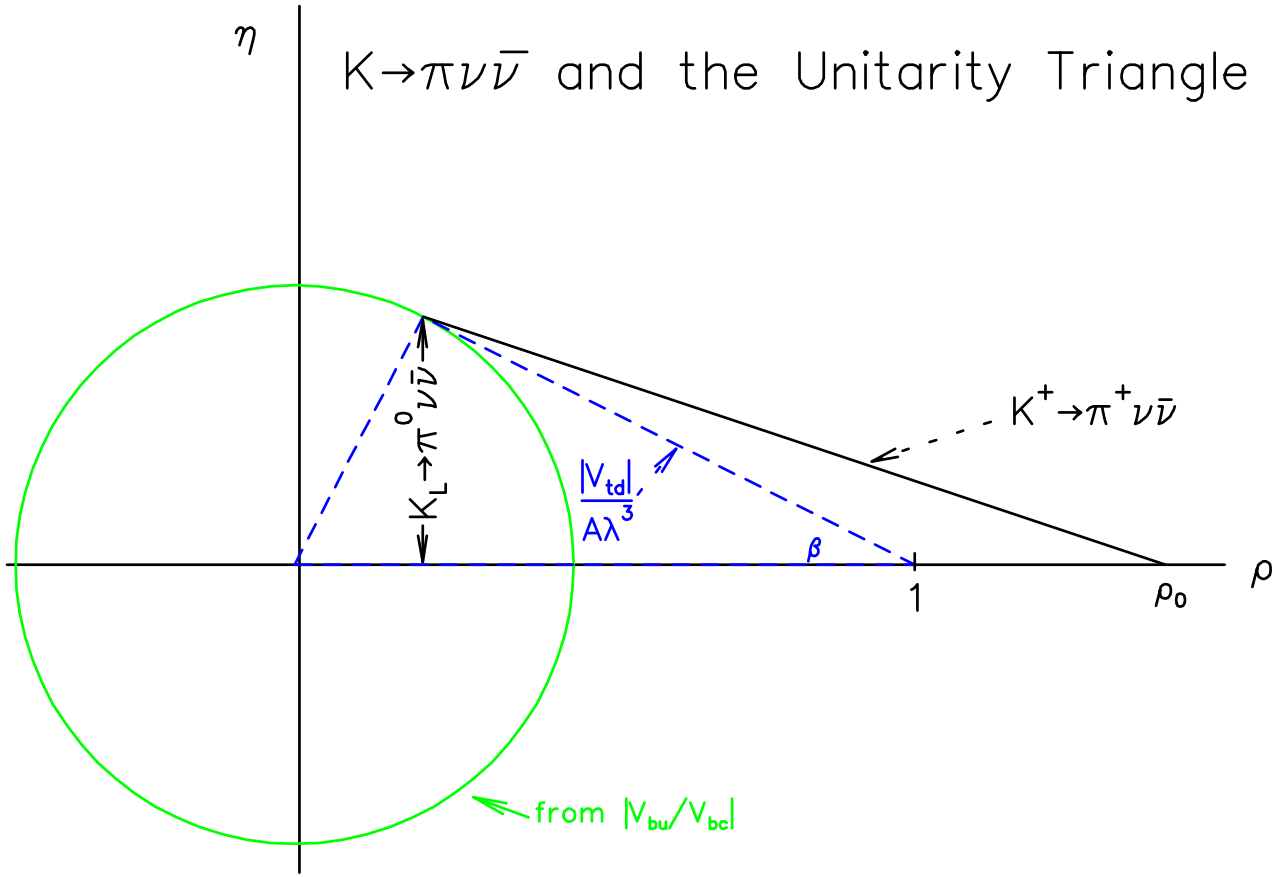
in 10^{-12}

B.R.($K \to \pi\nu\bar{\nu}$) in the SM

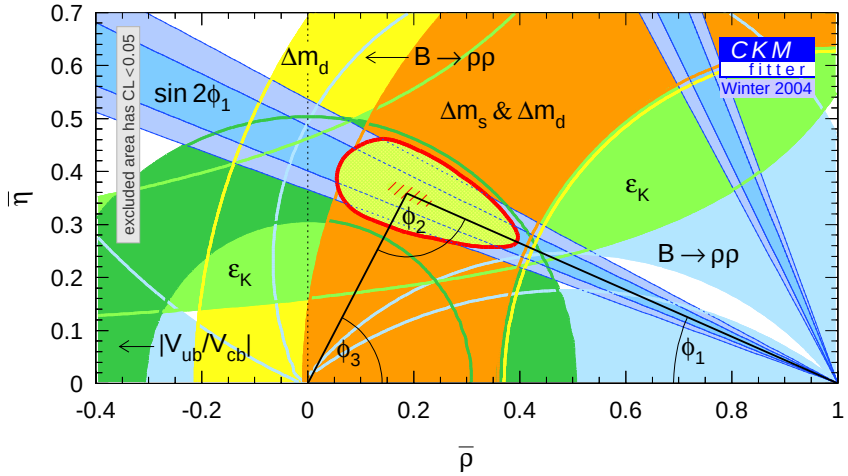
$|\Delta S|$=1 rare-decay processes

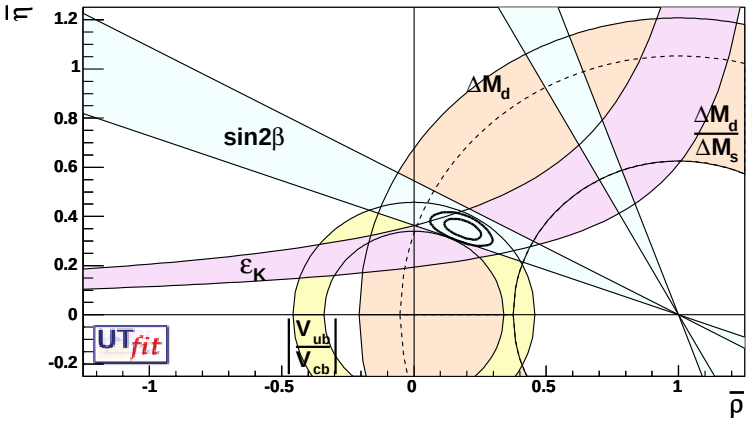
K^+ $\underline{4.84 \times 10^{-11}}$ • A^4 • $X(x_t)^2 \cdot [\ (\rho_0 - \rho)^2 + \eta^2\ ]$

K_L^0 $\underline{2.12 \times 10^{-10}}$ • A^4 • $X(x_t)^2 \cdot \eta^2$ ⇐pure direct CPV



(ρ, η) constraints





SM prediction	Buras et al hep-ph/0405132	accuracy	theoretical uncertainties
$K^+ \to \pi^+ \nu\bar{\nu}$	$(7.8 \pm 1.2) \times 10^{-11}$	±15%	±7% (NLO calculations)
$K_L^0 \to \pi^0 \nu\bar{\nu}$	$(3.0 \pm 0.6) \times 10^{-11}$	±20%	1-2%

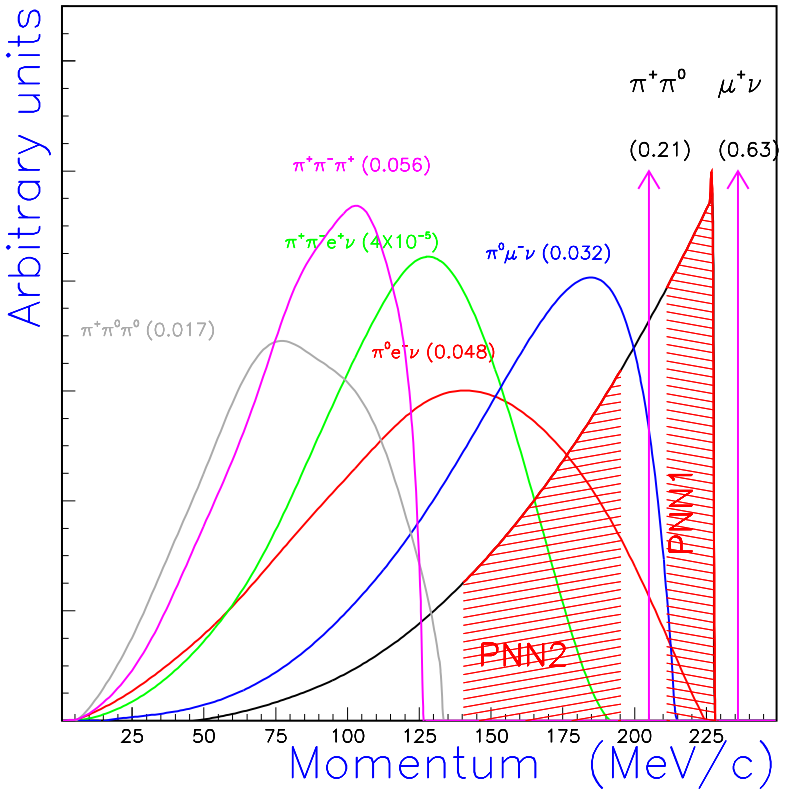
* NNLO QCD calculations are being perforemed.

Name	**"PNN2"**	**"PNN1"**
P_π (MeV/c)	[140,195]	[211,229]
Years	1996-97	1995-98
Stopped K^+	1.7×10^{12}	5.9×10^{12}
Candidates	1	2
Background	1.22 ± 0.24	0.15 ± 0.05
$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$	$< 22 \times 10^{-10}$	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$

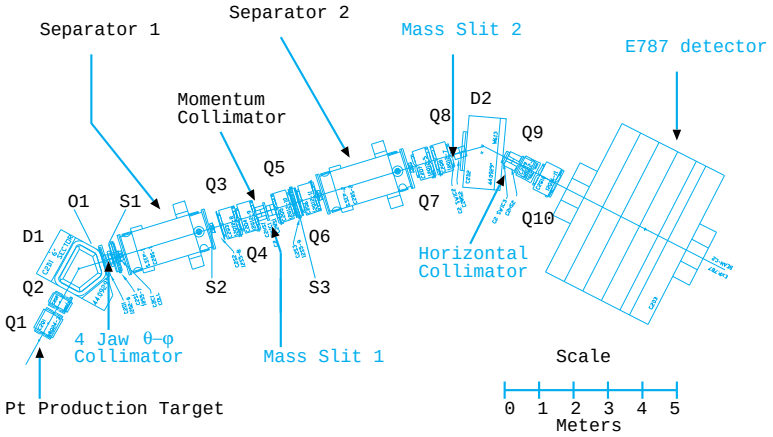
E787
$K^+ \to \pi^+ \nu\bar{\nu}$
results

PNN1: PRL **88**, 041803 (2002).

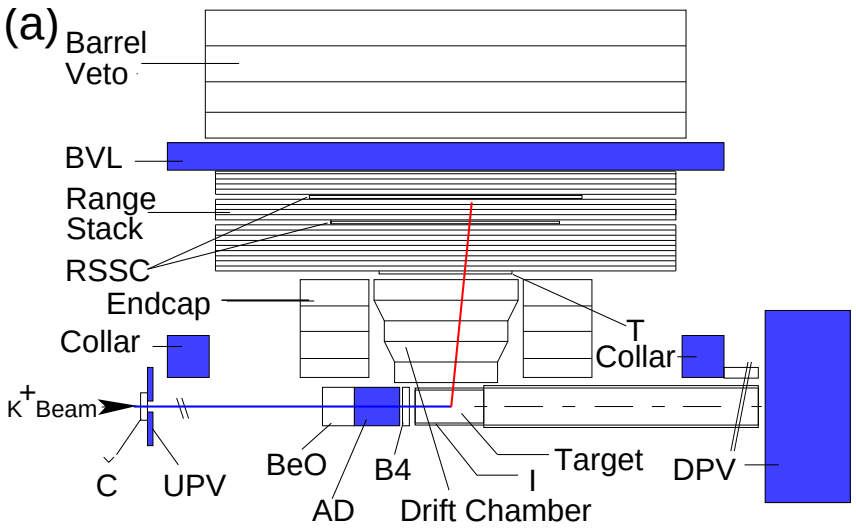
PNN2: limit at 90%CL is combined result from 1996 (PL **B537**, 211 (2002)) and 1997 (PRD **70**, 037102 (2004)) data.

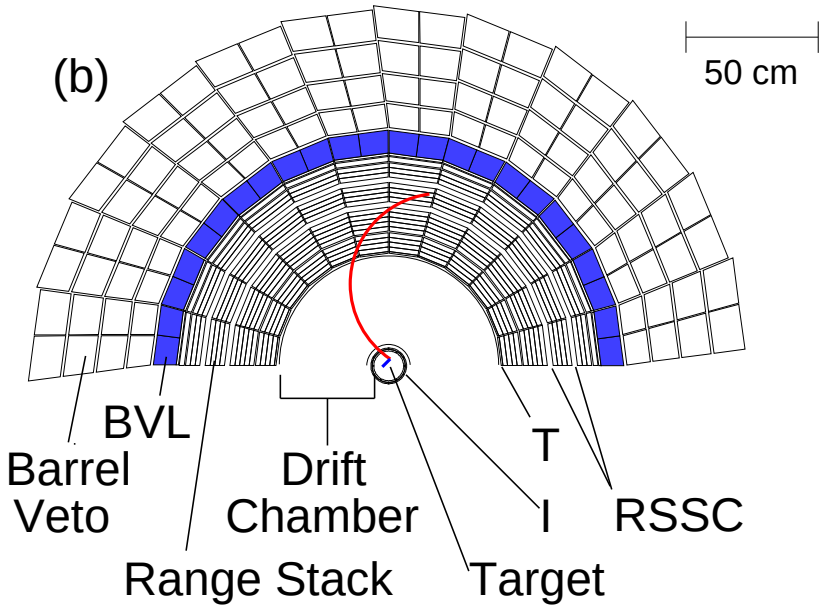


$K^+ \to \pi^+ \nu\bar{\nu}$ at BNL-E949

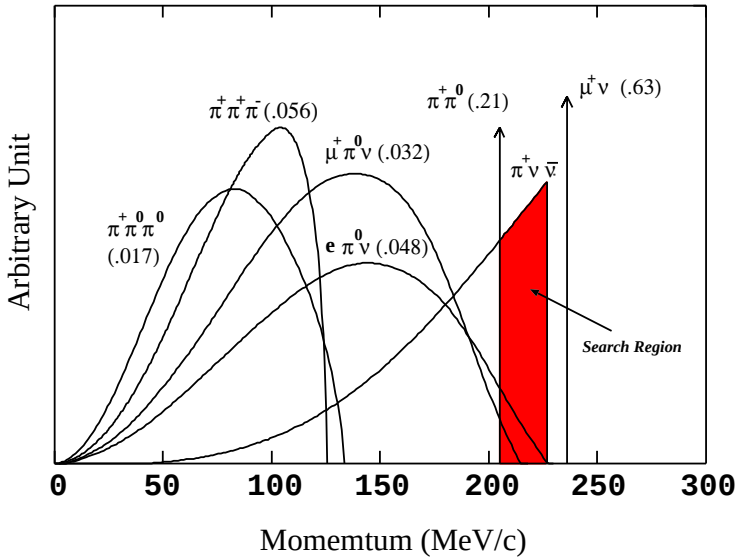


- AGS: 22GeV, 70×10^{12} protons/spill
- 2.2-sec spill in every 5.4 sec (duty cycle = 41%)
- 0.710 GeV/c, $K^+/\pi^+ = 3$





K^+ decay at rest $\rightarrow \pi^+ +$ "nothing"



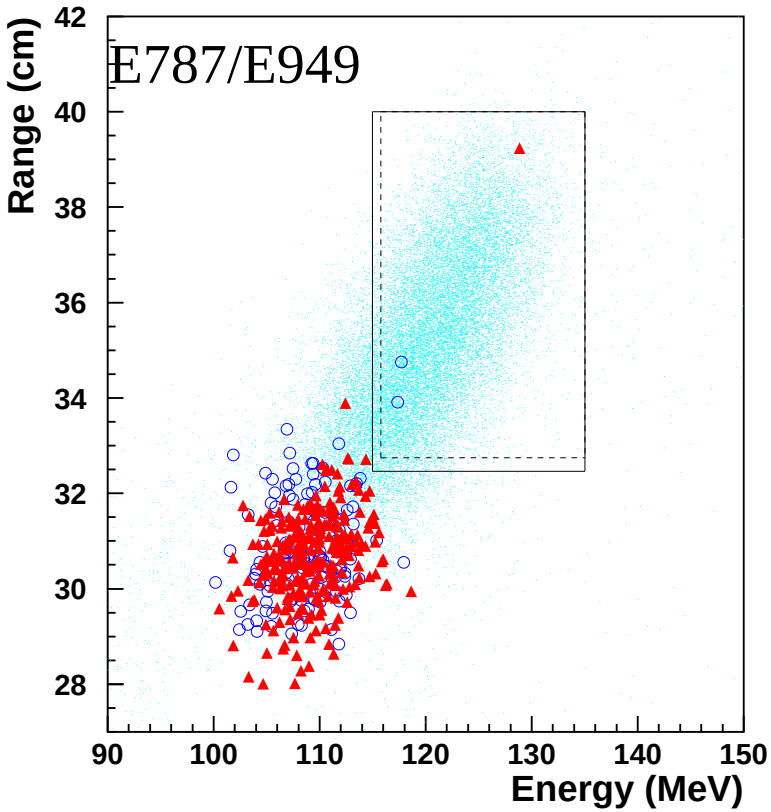
Background Rejection

- Kinematics of π^+
  - Momentum
  - Kinetic Energy
  - "Range" in plastic scintillators
- π^+/μ^+ separation
  $\Longleftrightarrow K^+ \rightarrow \mu^+\nu$
- extra particles (γ, ..)
  $\Longleftrightarrow K^+ \rightarrow \pi^+\pi^0$

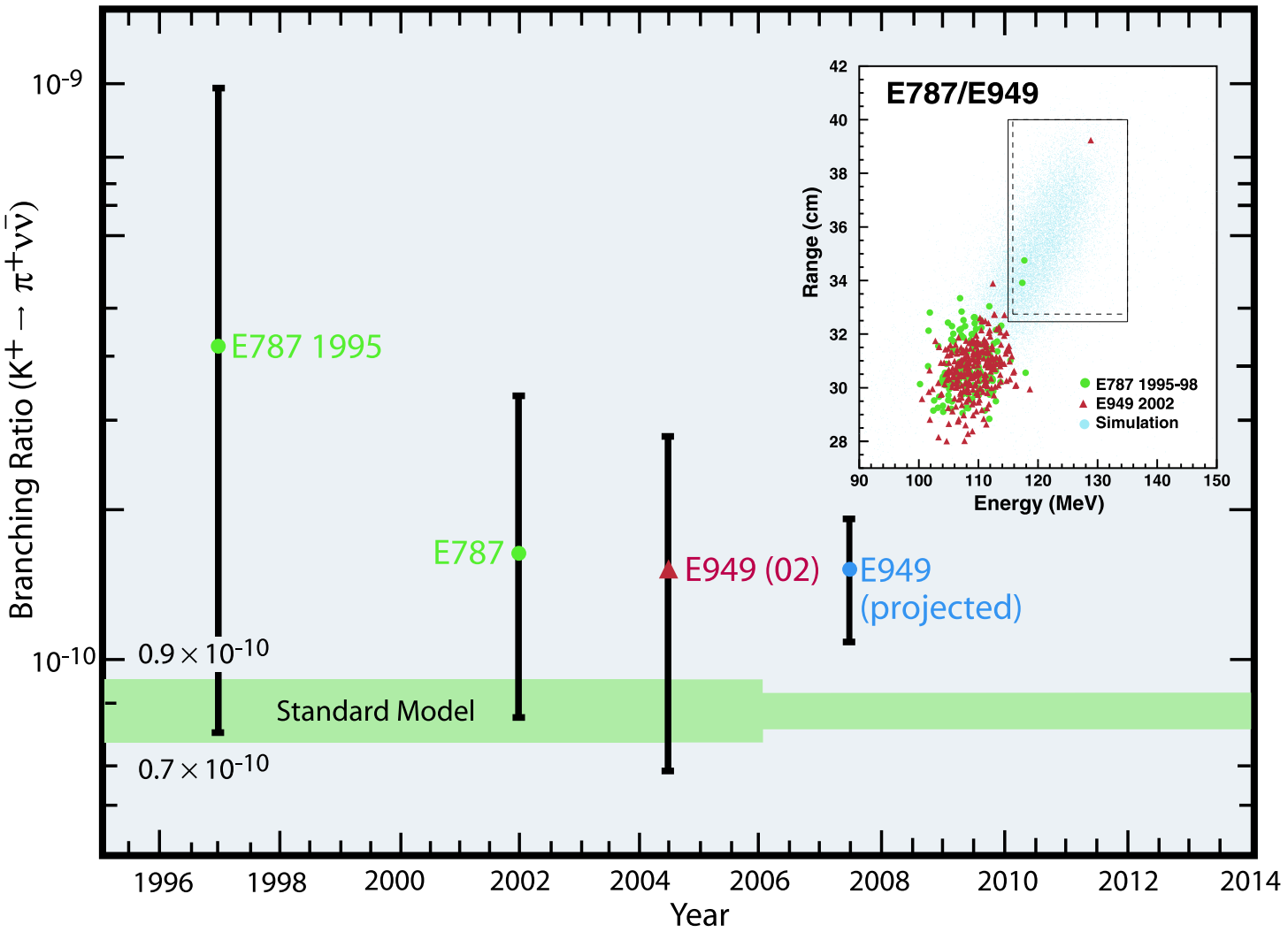
each weapon should have rejection of $\underline{10^6 \sim 10^7}$

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

E949 2002 dataset ($\sim$ 30% of E787), PRL 93 (2004) 031801



- π^+ Range vs Energy
- E949-2002 | E787 | MonteCarlo
- background: 0.30$\pm$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
- $P_b = 0.1\%$

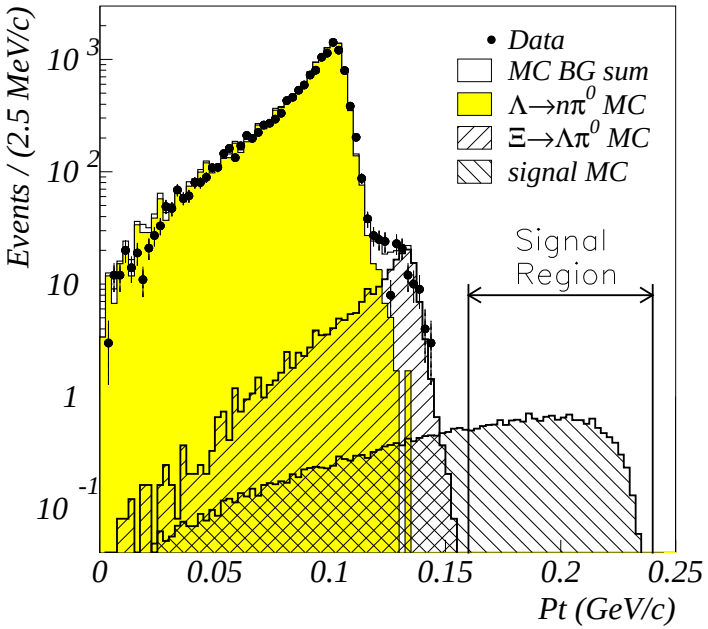


- waiting to take more data (12 weeks in 2002; proposal: 60 weeks)
- cosmic-ray run in August 2004 $\longrightarrow$ ready to resume.

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

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

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

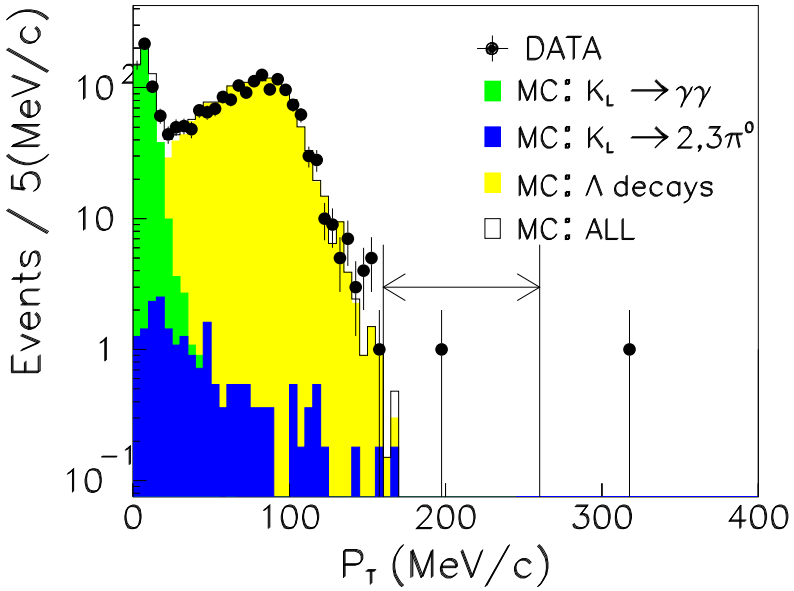


$< 5.9 \times 10^{-7}$

KTEV '97 PRD 61(2000)072006

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

background 3.5 ± 0.9 events



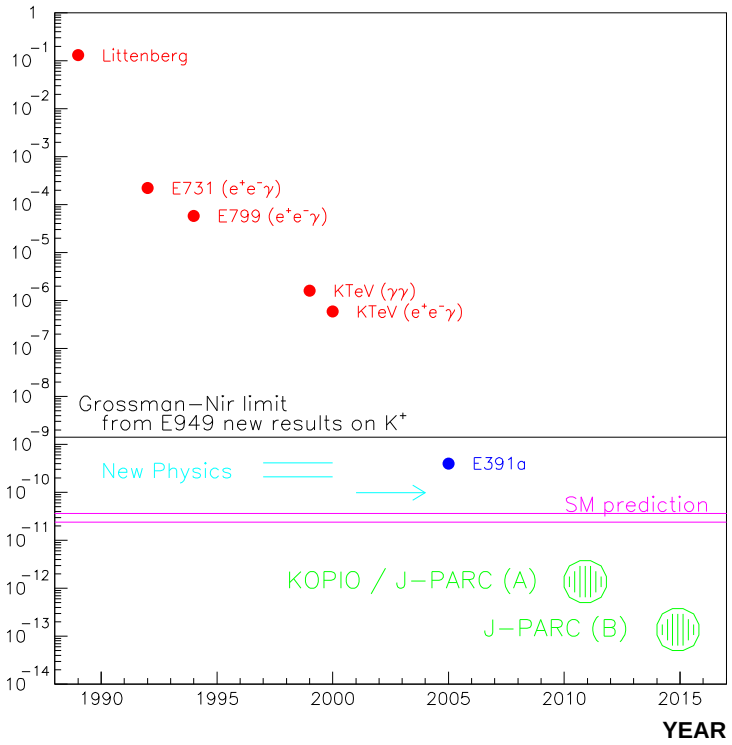
$< 1.6 \times 10^{-6}$

one-day PL B447(1999)240

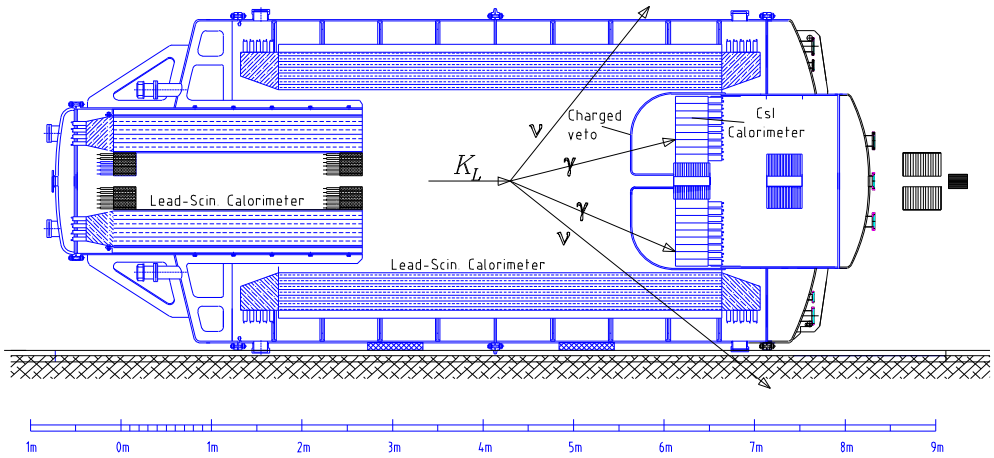
major background from $K_L \rightarrow \pi^0\pi^0$ (2 out of 4 γ's escape)

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

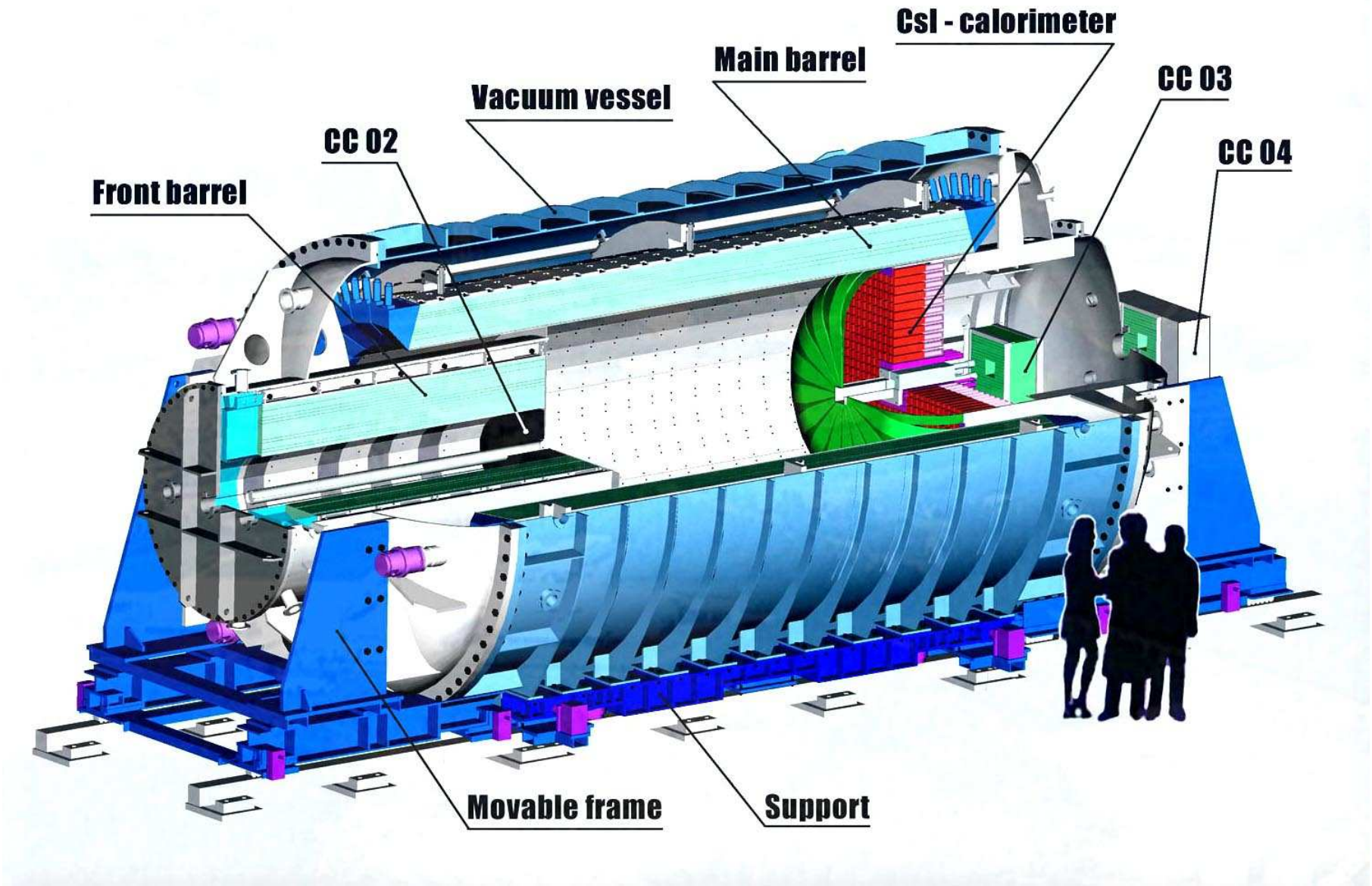
KEK-E391a: the first experiment dedicated to $K_L^0 \to \pi^0 \nu\bar{\nu}$



- collimated "pencil" beam
- 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

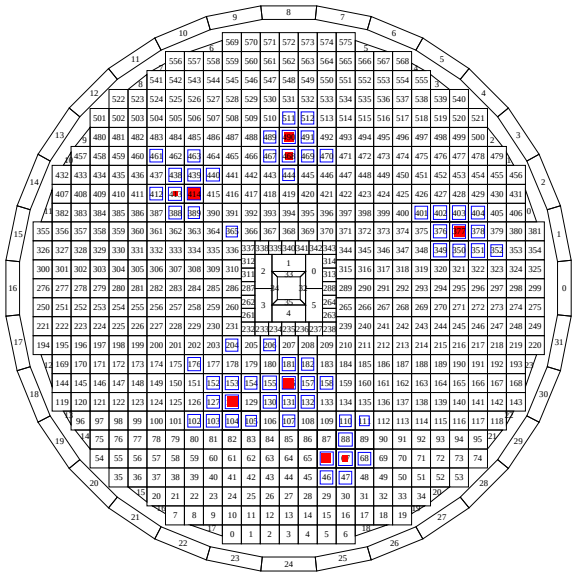


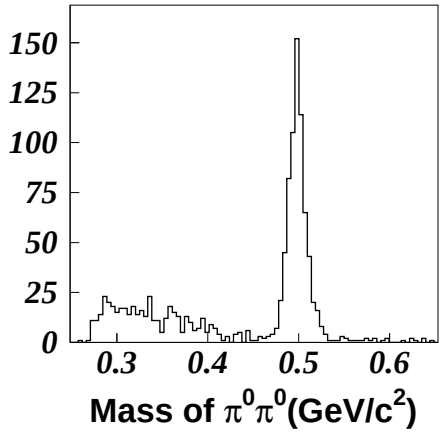
- KEK-PS: 12GeV,
  2.5×10^{12} protons/spill
- 2.0-sec spill in every 4.0 sec


CsI - calorimeter
Main barrel
CC 03
Vacuum vessel
CC 04
CC 02
Front barrel
Movable frame
Support

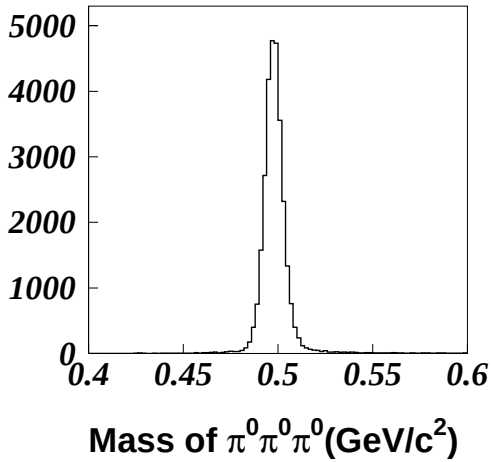
E391a Data Taking (from 18 Feb 2004)

		E391a
Ev size	Bytes	6K
		ADCs
Tr rate	Hz	500
Data flow	B/spill	6M
	B/Day	120G





$K_L^0 \to \pi^0\pi^0$

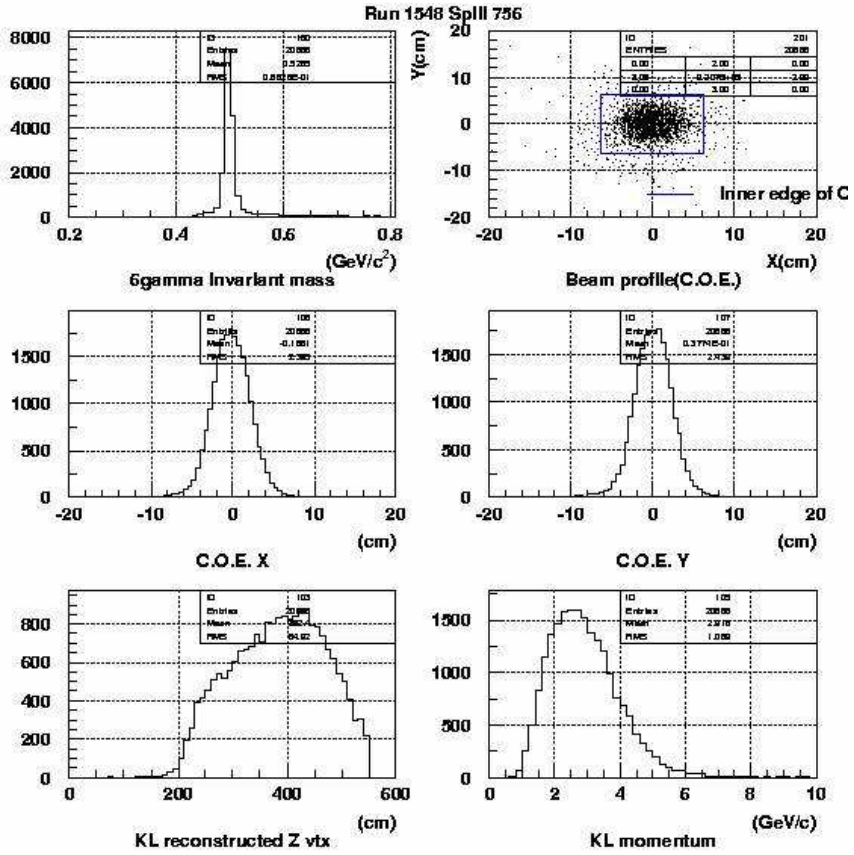


$K_L^0 \to \pi^0\pi^0\pi^0$

E391a Run-1 (until the end of June 2004)

- stable data taking
  - $N_{CLS} \geq 2$ w/vetoes : manageable Trigger rate
  - DAQ Live Time 75%
- Online accidental loss: 10%:
  - clean neutral beam
  - "pencil" concept: okay
- 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
  - break the KTEV upper limit
  - below the Grossman-Nir limit 1.4×10^{-9} from $K^+ \to \pi^+\nu\bar{\nu}$
- requesting Run-2 in 2005





future kaon programs

- JAERI and KEK Joint Project: J-PARC
  kaon program with the new 50GeV PS: see hep-ex/0409017
  - NP04 workshop (August)
- BNL: AGS
  Rare Symmetry Violating Processes Project
  - Workshop on Future Kaon Experiments at the AGS (May)
- CERN: SPS
  Future Fixed Target Programme at CERN: Villars meeting (last week)
  - HIF04 workshop (June)
- FNAL: Proton Driver + Main Injector
  - Fermilab Proton Driver Workshop (this week)



J-PARC	PS	LoI-05*	$\mathbf{K_L^0 \longrightarrow \pi^0 \nu\bar{\nu}}$ (high energy)
		LoI-04*	$\mathbf{K^+ \longrightarrow \pi^+ \nu\bar{\nu}}$ at rest
		LoI-19*	T-violation in K^+ decays at rest
		...	
BNL	AGS	KOPIO*	$\mathbf{K_L^0 \longrightarrow \pi^0 \nu\bar{\nu}}$ (low energy)
CERN	SPS	NA48/3*	$\mathbf{K^+ \longrightarrow \pi^+ \nu\bar{\nu}}$ in flight
FNAL	Main Injector	CKM-P940*	$\mathbf{K^+ \longrightarrow \pi^+ \nu\bar{\nu}}$ in flight

$*$ future program: construction not started

measurements of B.R.($\mathbf{K \longrightarrow \pi\nu\bar{\nu}}$) with $\sim$ 100 signal events

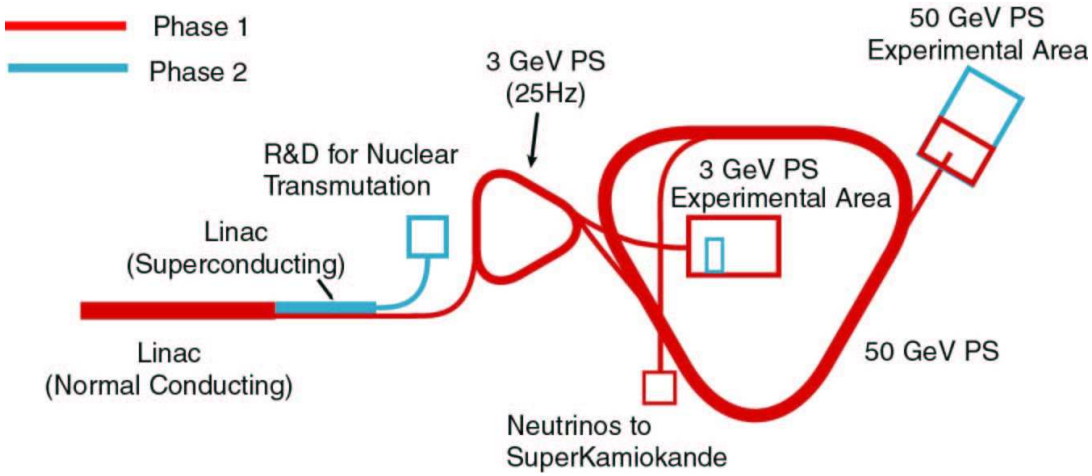
J-PARC







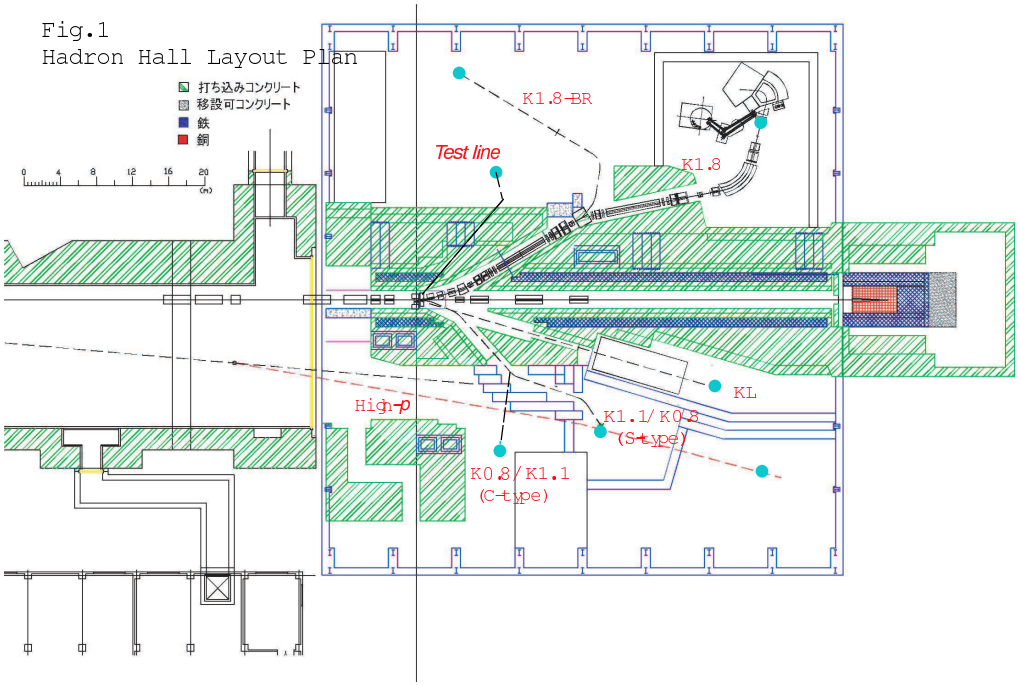
* Right photos were taken by TKK on 3 August 2004 at the J-PARC site



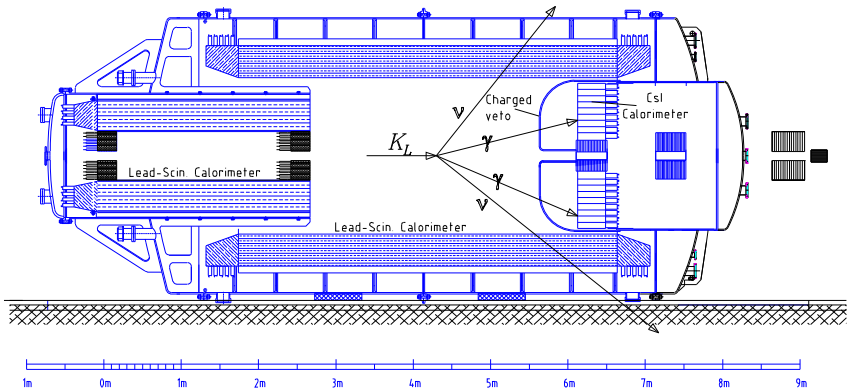
Slow Extraction

Phase-1 construction
finish in 2008

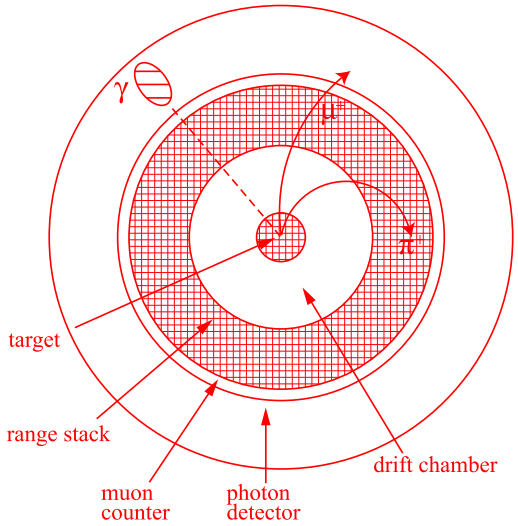
- 30GeV
- 200 $\times$ 10^{12} protons/spill
- every 3.42 sec (10 μA)



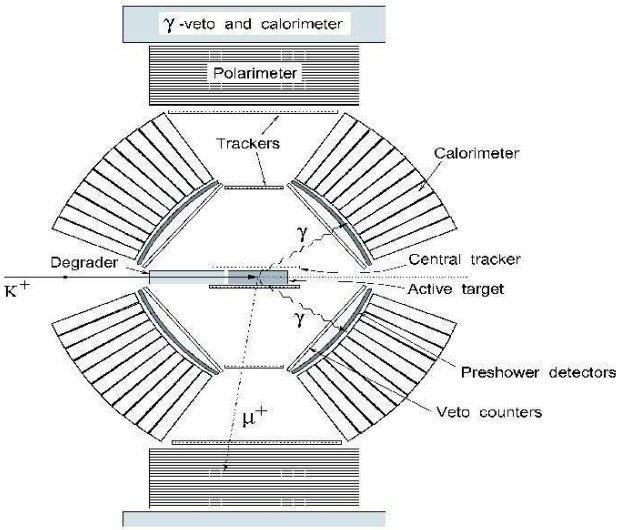
L-05: $K_L^0 \to \pi^0 \nu\bar{\nu}$



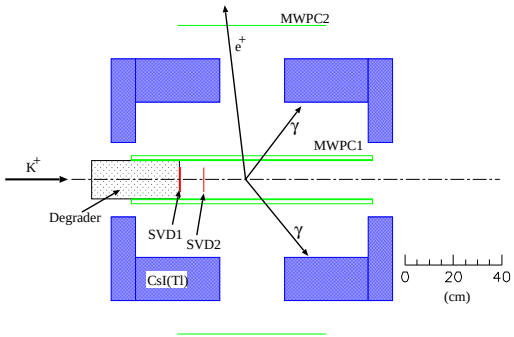
L-04: $K^+ \to \pi^+ \nu\bar{\nu}$



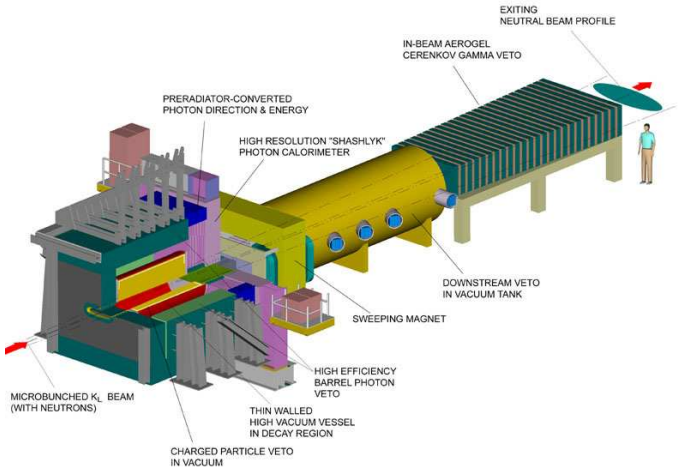
L-19/-16: $K^+ \to \pi^0 \mu^+ \nu$, $\mu^+ \nu\gamma$



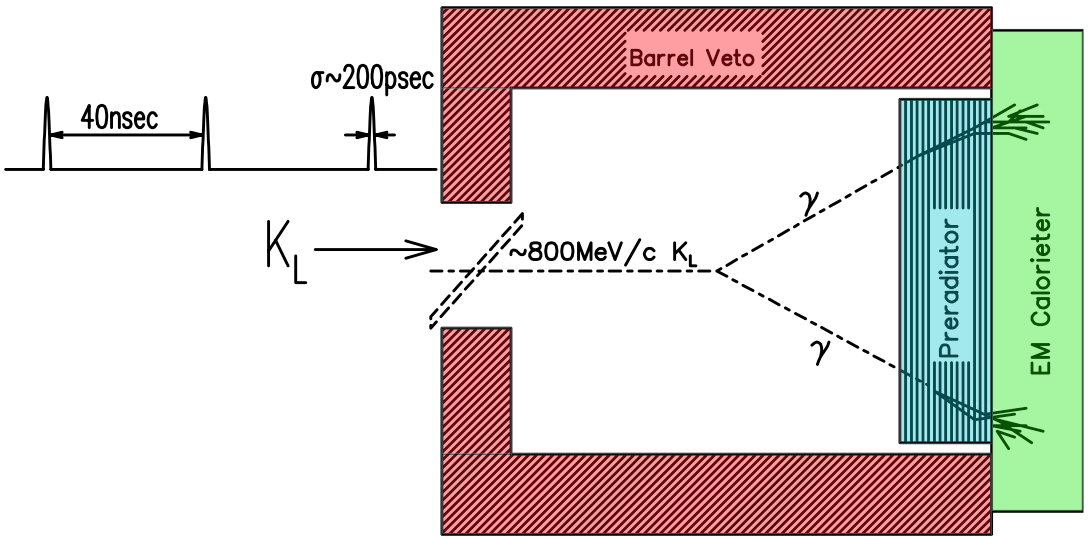
L-20: $K^+ \to \pi^0 e^+ \nu$



$K_L^0 \to \pi^0 \nu\bar{\nu}$: KOPIO experiment @ BNL

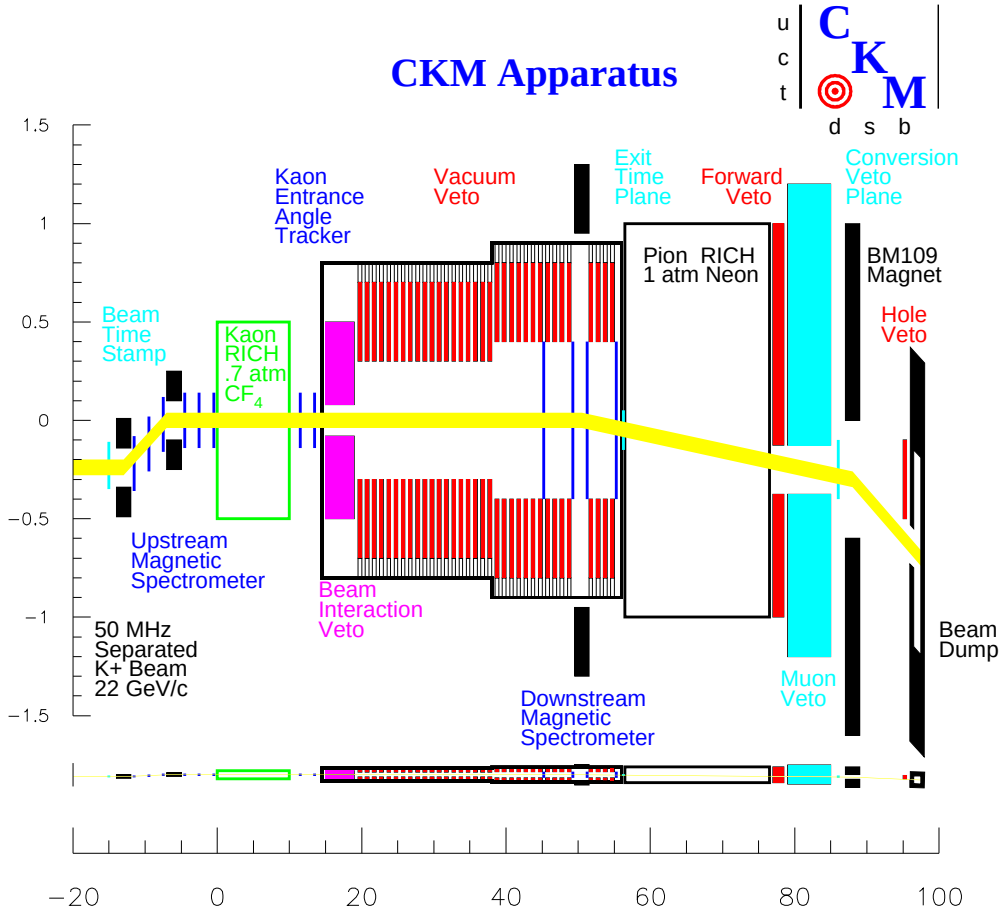


- RF-bunched, 0.8 GeV/c beam for TOF
- pre-radiator and Shashlik calorimeter:
  angle and timing measurements of each photon
- construction from FY2005,
  first physics run in FY2010 (being expected)



$K^+ \to \pi^+ \nu\bar{\nu}$: CKM(E921) experiment @ FNAL

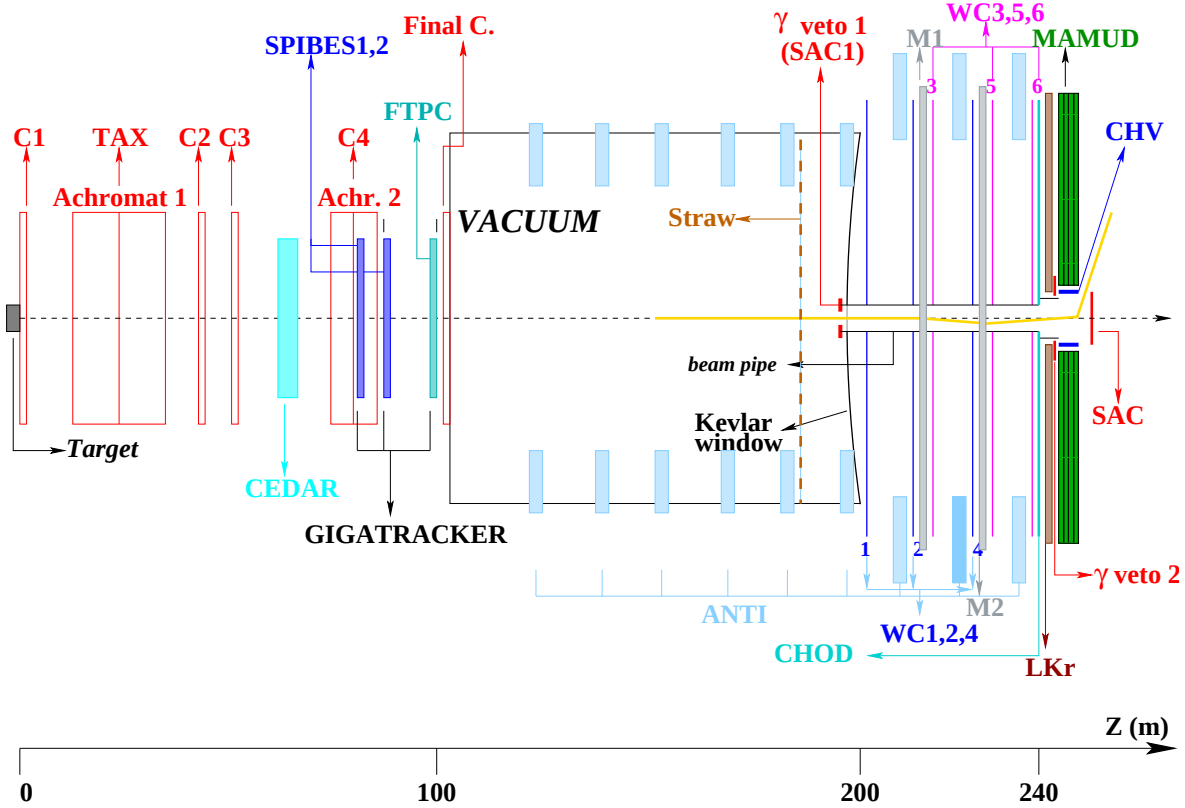
- RF-separated K^+ beam at 22 GeV/c, $\pi^+\nu\bar{\nu}$ decay in flight for the first time



... is being redesinged to P940,

which uses un-separated K^+ beam at $\sim$45 GeV/c in KTEV hall

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



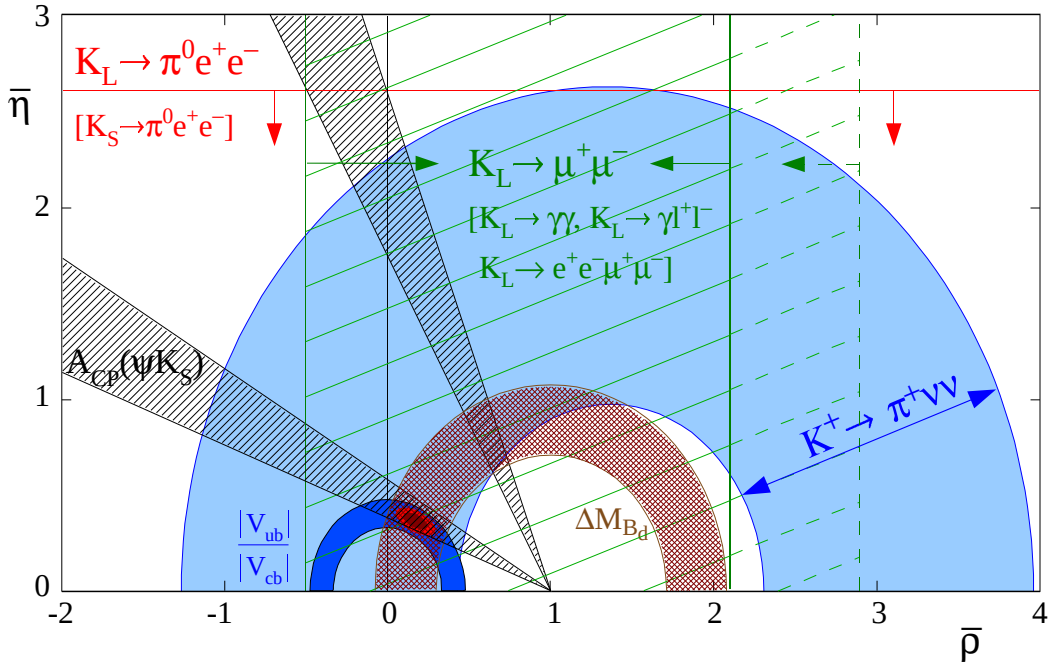
- un-separated K^+ beam at $\sim$75 GeV/c, $\pi^+ \nu\bar{\nu}$ decay in flight
- testbeam run in August:
  rate-capable KAon BEam Spectrometer with Micromegas-type TPC's,
  ...
- LoI presented at the Villars meeting

Conclusions: Rare Kaon Decays, 2004

- still NO explicit violations of the SM
- upper limits and measurements at $\boldsymbol{10^{-9} \sim 10^{-12}}$
  - first observation of K^0_S decays at $\boldsymbol{10^{-9}}$
- not just "opening the BOX" (Blind analysis - de facto standard);
  We started using **Likelihood analysis** in rare-decay searches,
  where both Signal and Noise are in small statistics.
- Future kaon programs will be "almost $\pi\nu\bar{\nu}$".
  - and the key will be high-intense and clean beamlines.

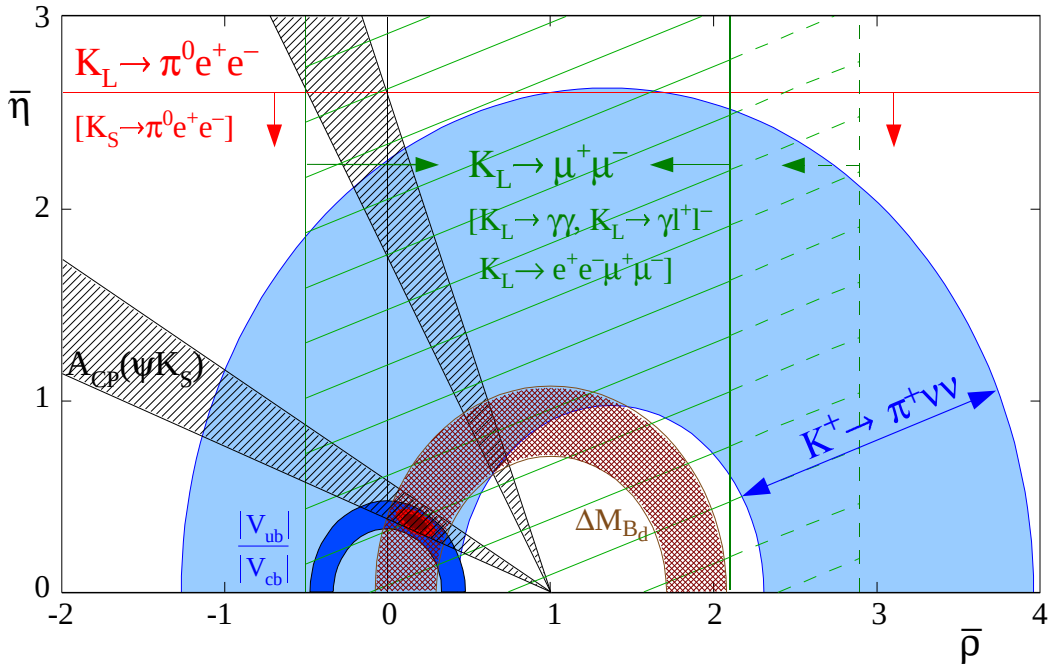


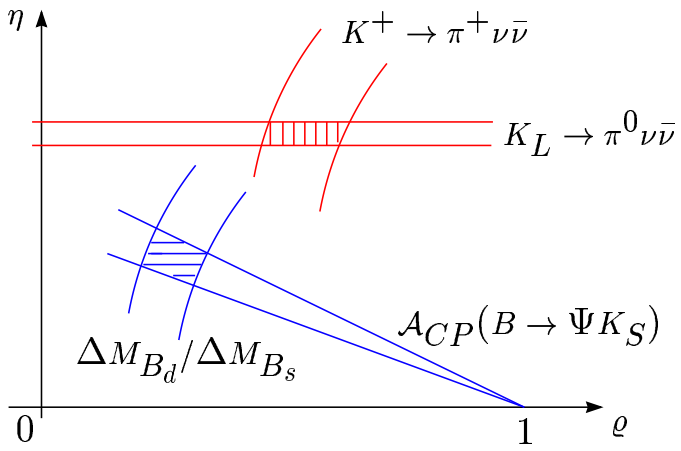
Isidori & Unterdorfer, JHEP01 (2004) 009



- exclude certain New Physics scenarios
- Why is New Physics so flavor-blind ??

Isidori & Unterdorfer, JHEP01 (2004) 009





backup slides

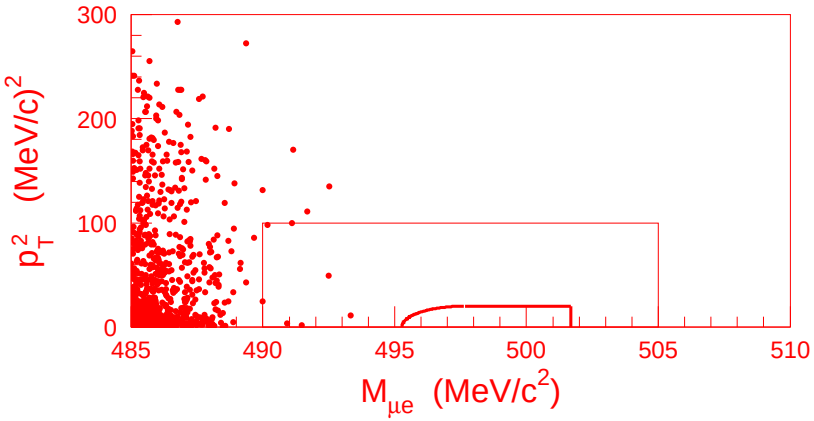
kaon decays that were not covered in this talk

- results from KLOE, which are covered by Fabio Bossi (Frascati)
- violations of the SM
  1. $K_L^0 \to \mu^\pm e^\mp$ from BNL-E871
  2. $K^+ \to \mu^+\mu^+\pi^-$ ($0\nu\mu\mu$, $< 3.0 \times 10^{-9}$) from E865
  3. $K_L^0 \to e^\pm e^\pm \mu^\mp \mu^\mp$ from KTEV
  4. $K^+ \to \pi^+\gamma$ from E787
- CP violation
  1. $K_L^0 \to \pi^+\pi^- e^+ e^-$ from KTEV
- FCNC
  1. $K_L^0 \to \mu^+\mu^-$, $\to e^+e^-$ BNL-E871
  2. $K_L^0 \to \ell^+\ell^-\gamma$, $\to \ell^+\ell^-\gamma\gamma$, $\to \ell^+\ell^-\ell^+\ell^-$ from KTEV, NA48
  3. "PNN2" of $\mathbf{K^+ \to \pi^+ \nu\bar{\nu}}$ from E787
- ...and the rare decays God only knows.

two-body LFV decay $K_L^0 \to \mu^\pm e^\mp$ at BNL-E871

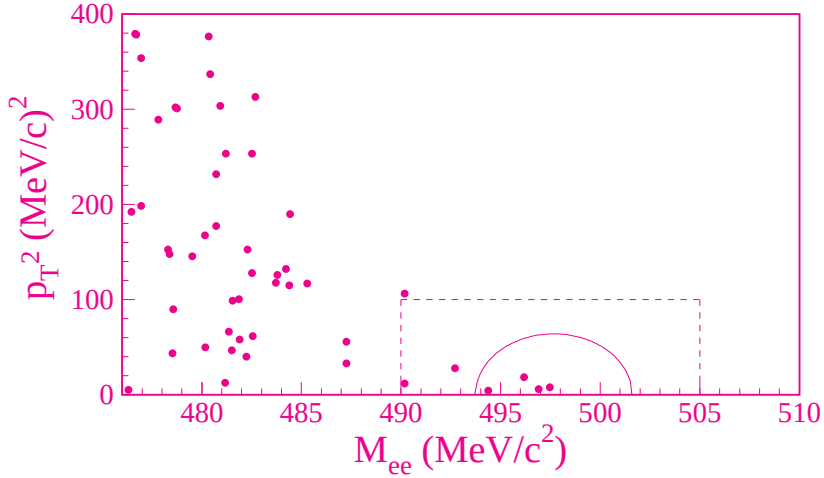
$< 4.7 \times 10^{-12}$

PRL 81(1998) 5734



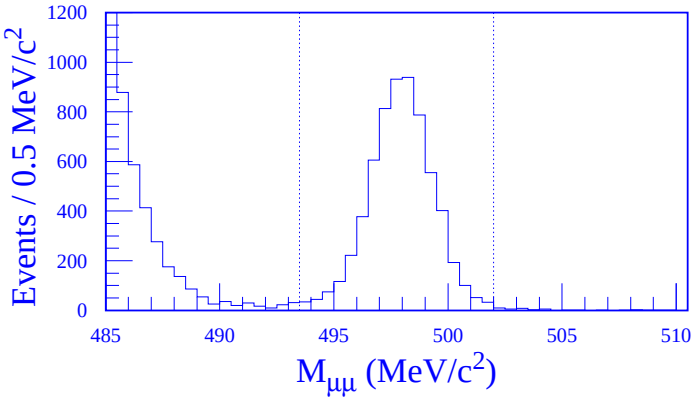
$K_L^0 \to e^+e^-$: 4 events

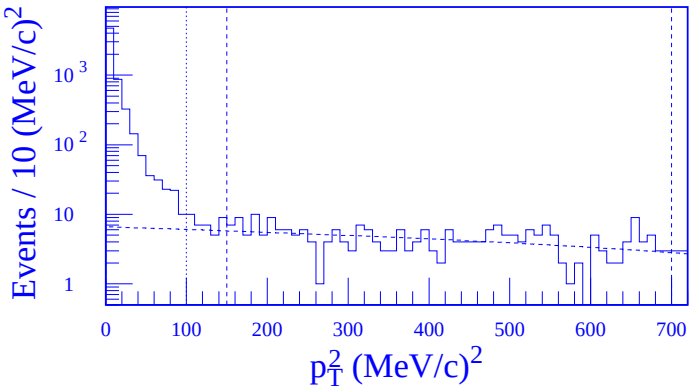
PRL 81 (1998) 4309



$K_L^0 \to \mu^+\mu^-$: 6.2K events

PRL 84 (2000) 1389





$B.R.(\mu^+\mu^-) = (7.18 \pm 0.17) \times 10^{-9}$

$B.R.(e^+e^-) = (8.7^{+5.7}_{-4.1}) \times 10^{-12}$