# CP violation in the K system and rare decays

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# Outline

- ***What have we been learning from Kaons lately?***
  - *The active experiments*
  - *Direct CP violation (see B. Peyaud's talk)*
  - *Rare decays ($K_L$, $K_S$, $K^{\pm}$), LFV limits, T-violation*
- ***Ongoing experiments***
  - *A wide spectrum of physics from kaons*
- ***A unique window on flavour physics***
  - *K ® p l l: why and how*
- ***Future projects and goals***

# “What have we been learning from kaons lately ?”

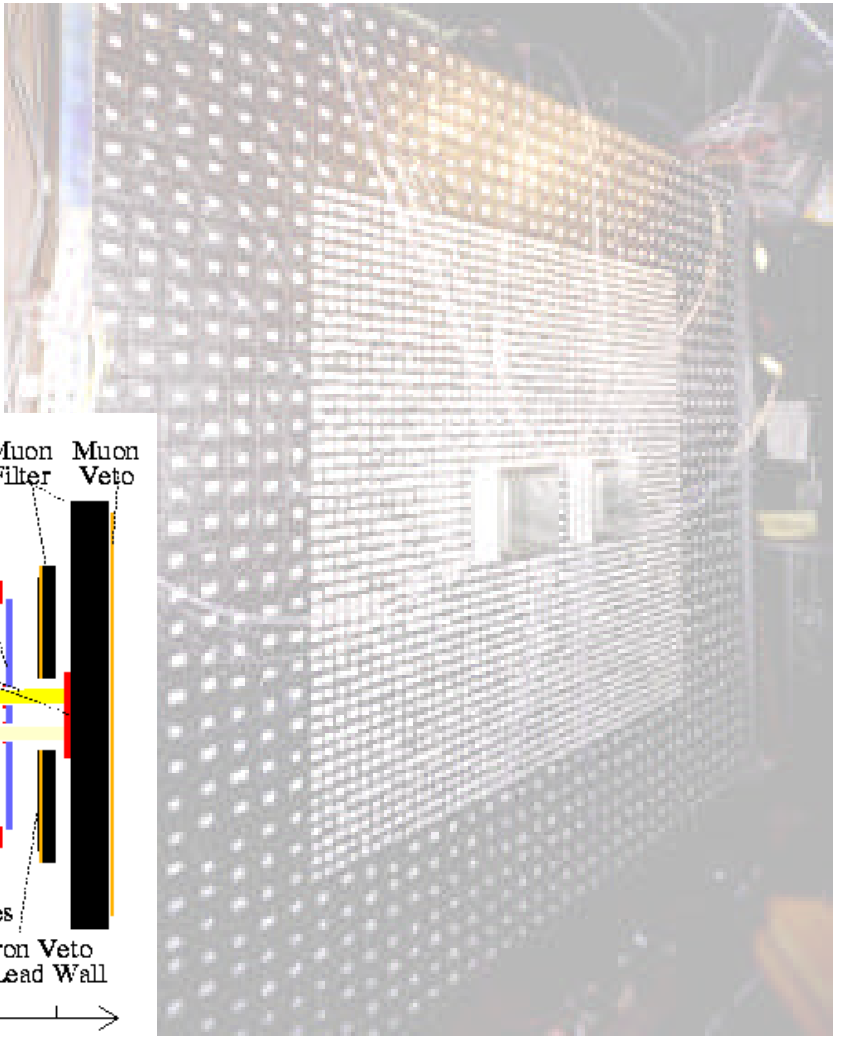
The K meson system was central in the shaping of the Standard Model: flavour, P violation, CP violation, charm, lepton-flavour violation and CPT limits,...

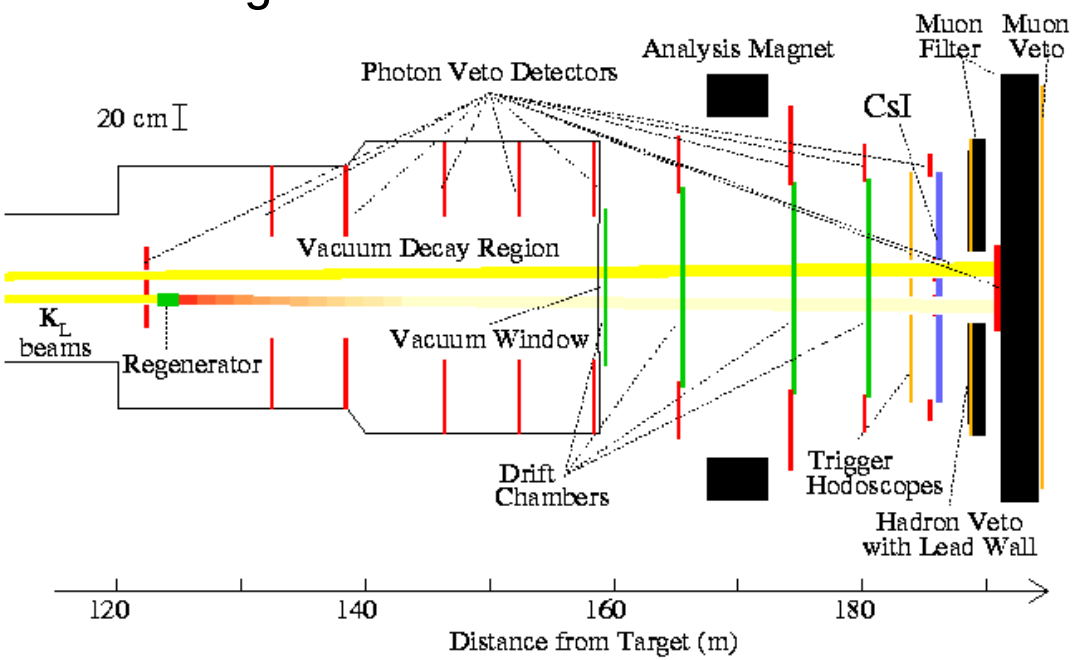
It is a “simple” subtle system:
lifetimes, BR, beams, backgrounds,...

Can we still learn something from it?

# KTeV at Fermilab

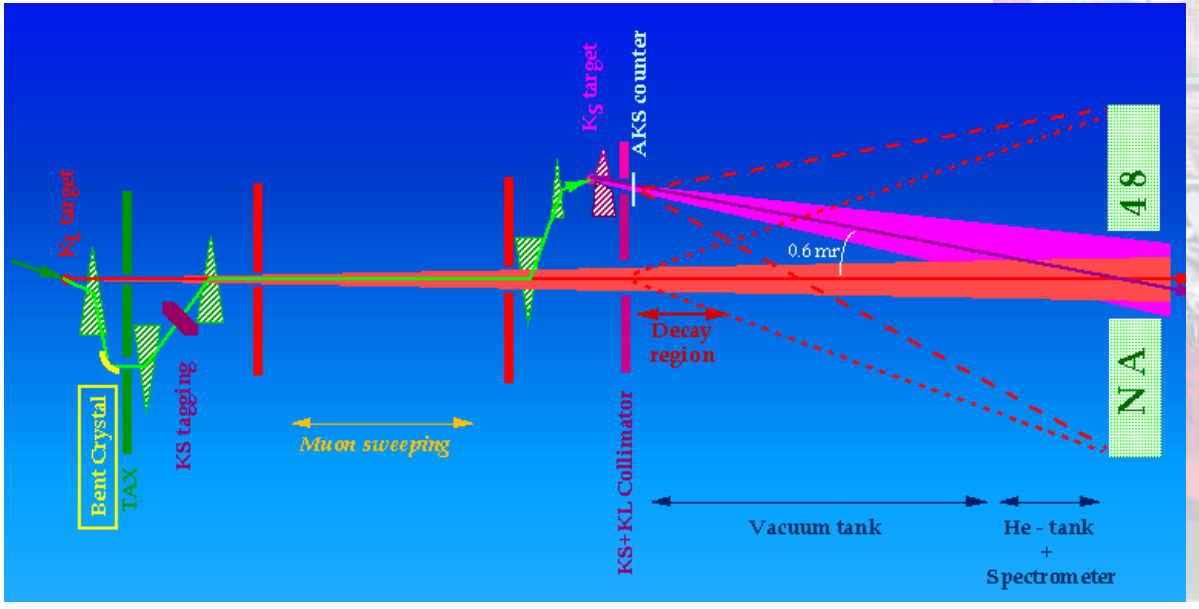
Main Injector (120 GeV) p
Double $K_L$ beam (<p>=70 GeV/*c*)
Regenerated $K_S$
Pure CsI calorimeter
Data taking in 1997 and 1999

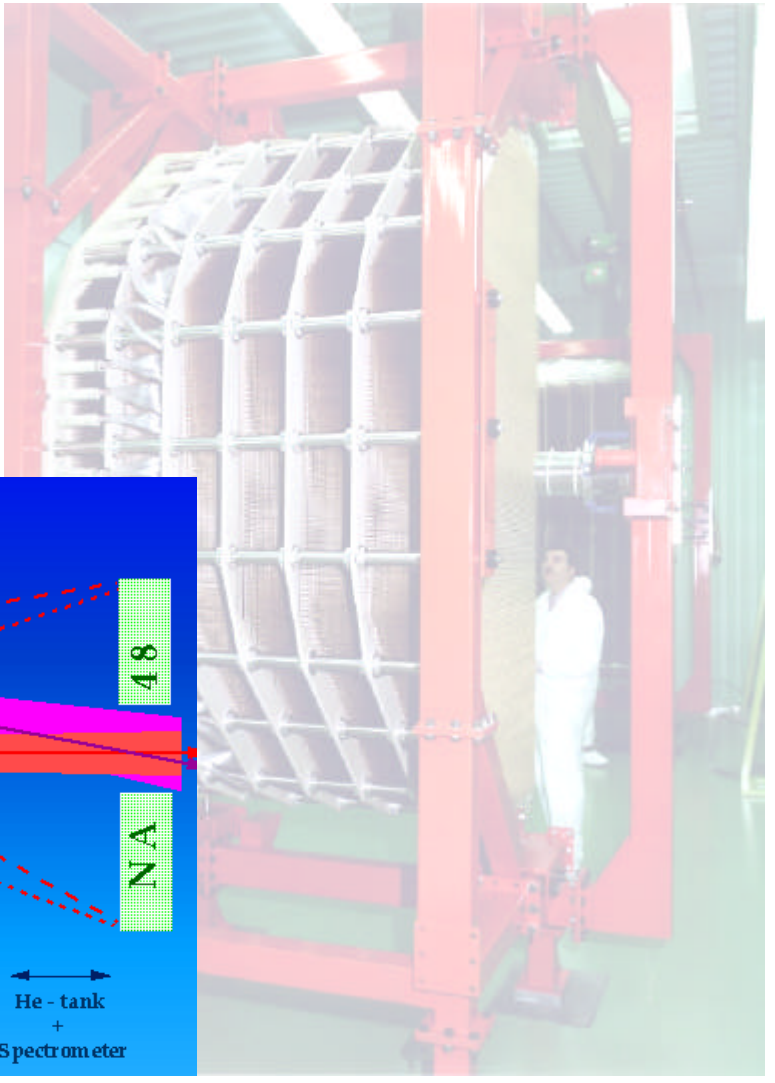




# NA48 at CERN

SPS (450 GeV) p
$K_S$ and $K_L$ beams (<p>=100 GeV/*c*)
Liquid Krypton calorimeter
1997-2001: $K_L$ and $K_S$
2000, 2002: NA48/1, intense $K_S$
2003-2004: NA48/2, $K^{\pm}$



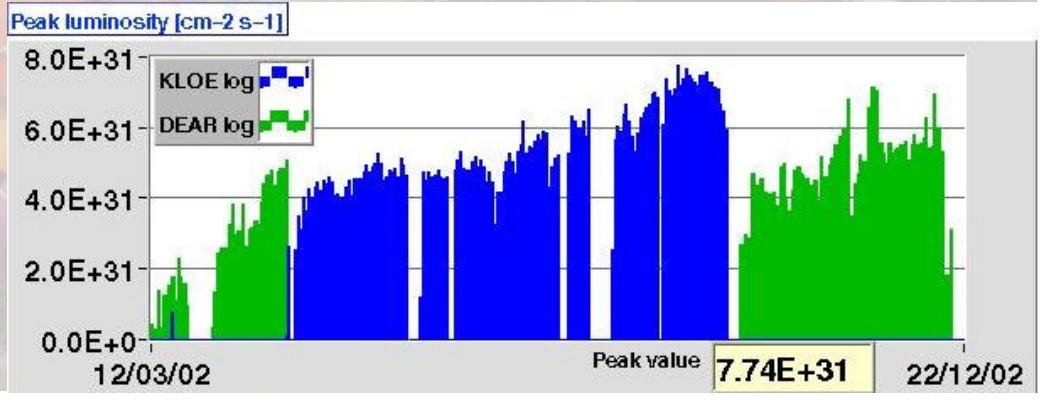



# KLOE at Frascati

DAFNE f-factory e+e-
Low luminosity at start, constantly improving
Peak luminosity: $8 \times 10^{31}$ cm$^{-2}$ s$^{-1}$ in 2002
Goal: $5 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
500 pb$^{-1}$ (1.5 $\times 10^{9}$ $\phi$) collected until 2002.

Currently running.

Good prospects for $K_S$, interferometry



# $K_L$ decays

Semileptonic charge asymmetry (*indirect* CP violation):
$2 \div 3 \cdot 10^8$ events (KTeV, NA48):

$$\delta_L(e) = (3.32 \pm 0.07) \times 10^{-3}$$

It measures e (hard to compute, *input* for theory), systematics limited

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Measurements of rare decays, tests of $\chi$PT (KTeV, NA48): such as

$$BR(K_L \to e^+e^-\gamma) = (10.13 \pm 0.04 \pm 0.06 \pm 0.29_{norm}) \times 10^{-6}$$

$$BR(K_L \to e^+e^-e^+e^-) = (4.07 \pm 0.12 \pm 0.11 \pm 0.16_{norm}) \times 10^{-8}$$

$$BR(K_L \to e^+e^-\mu^+\mu^-) = (2.69 \pm 0.24 \pm 0.12) \times 10^{-9}$$

More results expected from ongoing analysis.

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*Indirect* CP violation in $K_L \to p^+p^-e^+e^-$ (KTeV, NA48):
BR ~ $3.5 \cdot 10^{-7}$ Decay plane asymmetry ~ 14%

# $K_S$ decays: CPV

Search for $K_S \to 3\pi^0$: interf. $K_L$-$K_S$ at hadron machines, or F factories

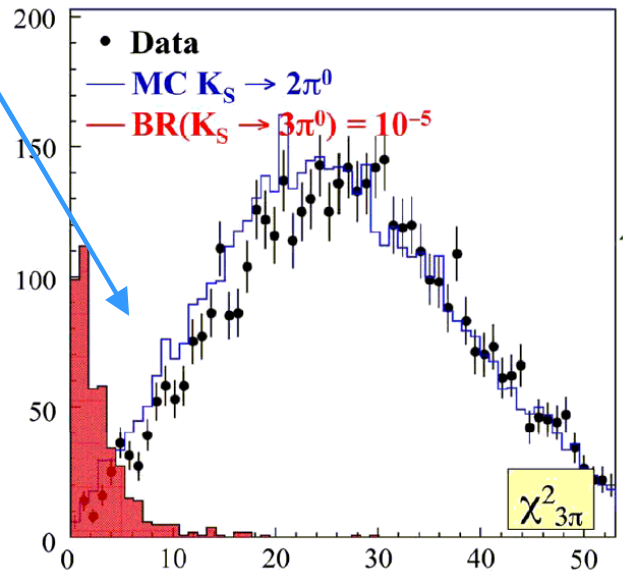
$BR(K_S \to 3\pi^0) < 3\times10^{-7}$ (90% CL) (NA48/1 prel.)

$BR(K_S \to 3\pi^0) < 2.1\times10^{-7}$ (90% CL) (KLOE prel. 450 pb-1, 4 ev. 3.2 bkg.)

Not yet reached indirect CP violation:
SM expectation: $3\times10^{-9}$

Dominates indirect CPT violation limits:

$$m(K^0) - m(\overline{K}^0) = (-1.7 \pm 4.2) \times 10^{-19} \text{ GeV}/c^2$$




Semileptonic $K_S$ decays (KLOE prel. 170 $pb^{-1}$):

$BR(K_S \to \pi e ?) = (7.09 \pm 0.07 \pm 0.08) \times 10^{-4}$

$K_S$ charge asymmetry (KLOE prel.):

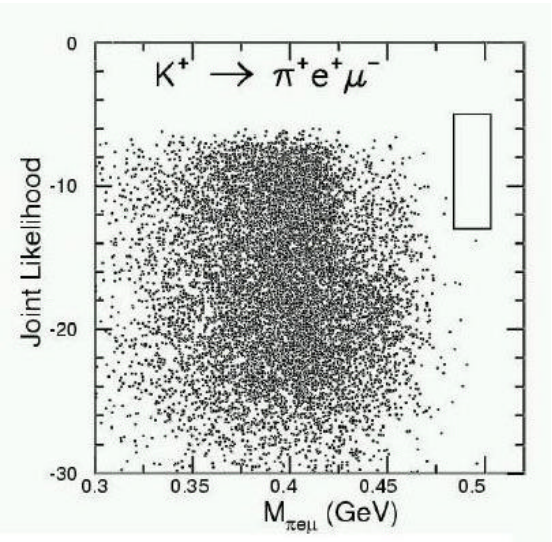
$\delta_S = (-2 \pm 9 \pm 6) \times 10^{-3}$ ($\to \pm 4?10^{-3}$, still far from CPT test)

# Lepton-flavour violation

Very intense activity led to stringent limits.

Further progress hindered by fluxes but also backgrounds.

No longer very competitive with μ system, no new experiments planned.




| Decay mode | BR limit (90% CL) |
|---|---|
| $K^+ \to \pi^+ \mu^+ e^-$ | $2.8 \times 10^{-11}$ |
| $K^+ \to \pi^+ \mu^- e^+$ | $5.2 \times 10^{-10}$ |
| $K^+ \to \pi^- e^+ e^+$ | $6.4 \times 10^{-10}$ |
| $K^+ \to \pi^- \mu^+ \mu^+$ | $3.0 \times 10^{-9}$ |
| $K^+ \to \pi^- \mu^+ e^+$ | $5.0 \times 10^{-10}$ |

Byproducts: limits on direct decays to exotic (s-)particles, Higgs.

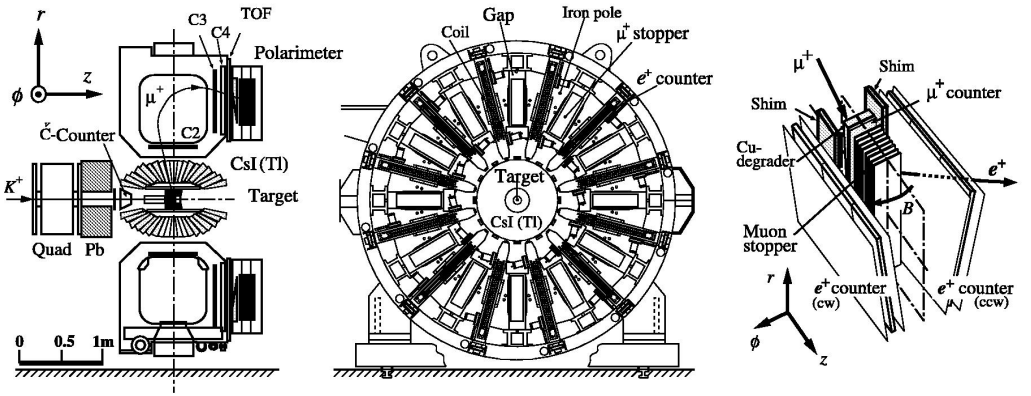
New results still expected from high-flux experiments.

# T- violation: KEK E246

T-violation first measured by **CPLEAR**, compatible with indirect CP violation.

PT(μ) orthogonal to decay plane in 3-body decays (T-odd correlation).
Tiny FSI (EM) in SM: sensitive to New Physics
Stopped K experiments: systematics from detector mis-alignment, magnetic fields asymmetries and (large) in-plane polarization.

**KEK E246**:
660 MeV/*c* $K^+$ stopped in active fibre target.
Final result (8.3M $\pi^0\mu^+\nu$ decays, 1996-2000):




$$P_T(\mu) = (-1.7 \pm 2.3 \pm 1.1) \times 10^{-3}$$

$$\mathrm{Im}\,\xi = (-5.3 \pm 7.1 \pm 3.6) \times 10^{-3}$$

Experiment concluded. Also $10^5$ $\mu^+\nu\gamma$ decays (larger background, different sensitivity to New Physics) in 1996-98.

# Ongoing experiments

The study of kaon decays reaches a very wide and diverse range of physical issues

# $K^{\pm}$ decays: CP violation

Dalitz plot slope asymmetries in $K^{\pm} \to 3\pi$ decays:

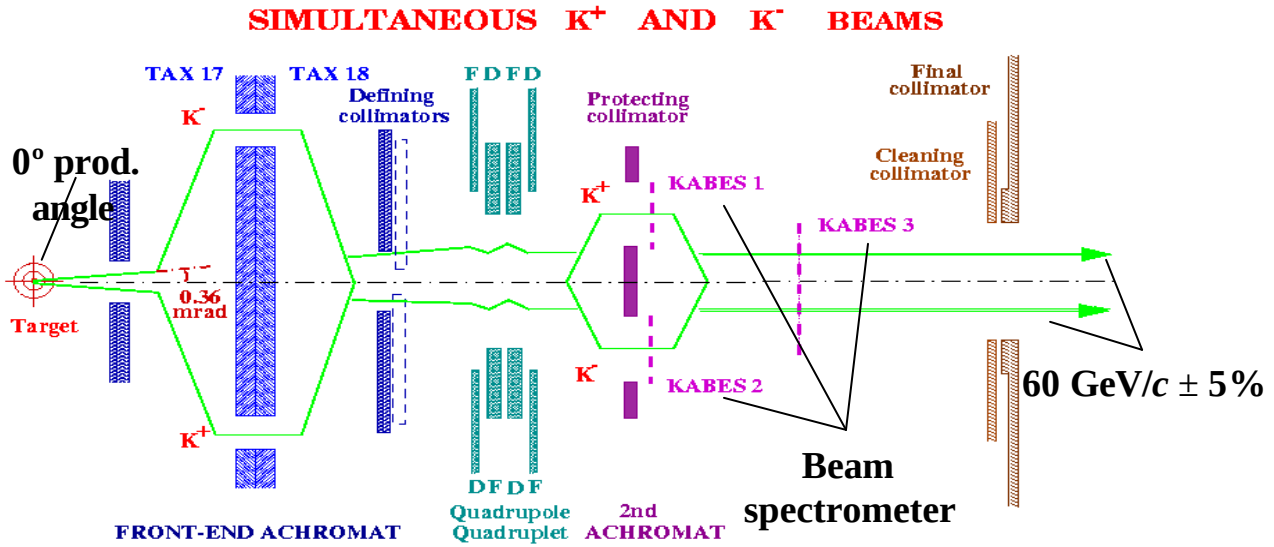
$|M(u,v)|^2 \sim 1 + gu + f(u^2,v^2)$ u,v: Dalitz variables

$p^{\pm}p^{+}p^{-}$ (BR = 5.6%): g ~ -0.22
$p^{\pm}p^{0}p^{0}$ (BR = 1.7%): g ~ +0.65

$A_g = (g_+ - g_-)/(g_+ + g_-) \; ? \; 0$
would indicate direct CP violation

Previous experiments' precision: few $10^{-3}$
Protvino experiment: $A_g(p^{\pm}p^{0}p^{0}) = (0.2 \pm 1.8 \pm 0.5)\cdot 10^{-3}$
SM predictions < $5\times10^{-5}$
Possible enhancements in models beyond SM

# $K^{\pm}$ decays: NA48/2




Run in 2003 and 2004

$10^{11}$ $K^{\pm}$ decays/year

$>10^{9}$ $K^{\pm} \rightarrow p^{\pm}p^{+}p^{-}$

$>5 \cdot 10^{7}$ $K^{\pm} \rightarrow p^{\pm}p^{0}p^{0}$ on tape in 2003

Goal: Ag in $K^{\pm} \rightarrow 3\pi$ decays at $O(10^{-4})$

First time *simultaneous* $K^{+}$ and $K^{-}$ narrow band beams, momentum analyzed ($10^{7}$ p/s) with MICROMEGA chambers

Systematics cancellation with simultaneous beams and frequent reversal of magnetic fields. Preliminary analysis: experiment is not systematics-limited.

Also: **OKA experiment** in preparation at Protvino: RF-separated 15 GeV/c beam, K+ or K- (alternated). Similar program/reach, first physics run in 2005

# $V_{us}$: Cabibbo angle

$|V_{us}| = 0.2196 \pm 0.0023$ (PDG2002)
$1 - \Sigma_i |V_{ui}|^2 = 0.0032 \pm 0.0014$ (violating unitarity at $2.2\sigma$)

Errors: 50% $V_{ud}$ (will reach $10^{-4}$) and 50% $V_{us}$ → Measure $V_{us}$ to $10^{-3}$

BR of semileptonic K decays is best handle on $V_{us}$:
it measures $|V_{us}|$ $f_+(0)$: theory input required

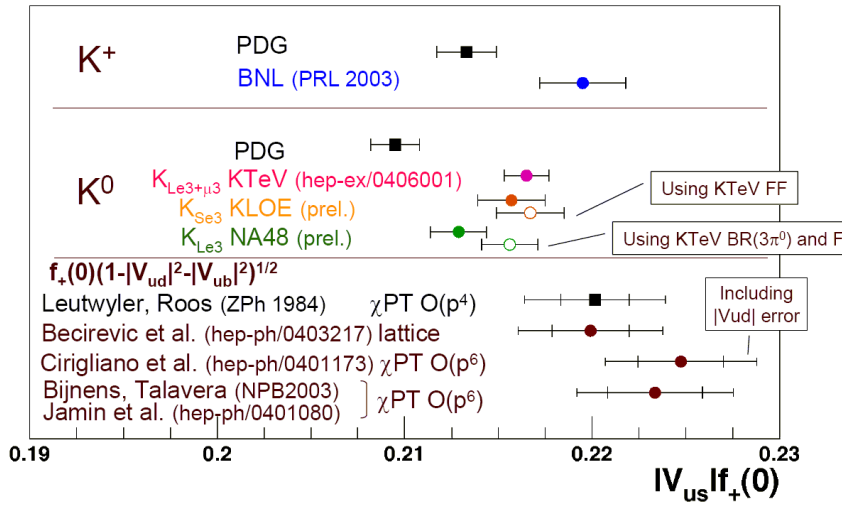
**BNL E865**: low-intensity 1 week run, 70K $K^+e3$ events,
partial $\pi^0_D$ reconstruction, radiative corr., 2.5% bkg.

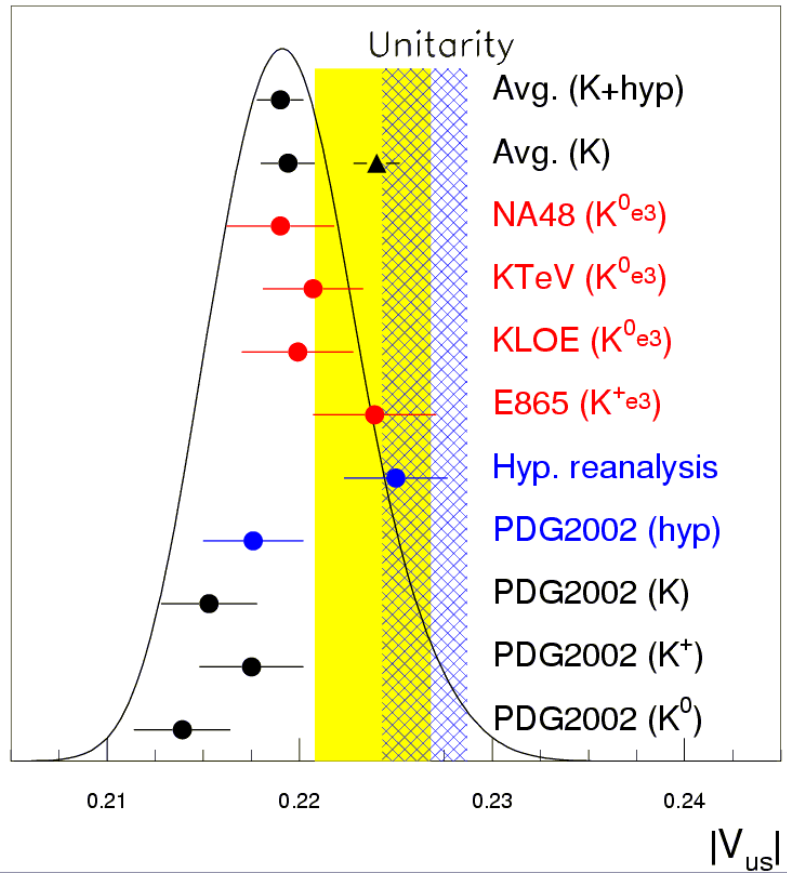
**KLOE** *preliminary* (170 $pb^{-1}$ $K_S$, 78 $pb^{-1}$ $K_L$) $K^0e3$ BR measurements.
Statistical error ~1% (0.5% on $V_{us}$).

**KTeV**: $K_Le3$ BR measurement.
Several BR measured, several very inconsistent with PDG.

**NA48** *preliminary*: $K_Le3$ BR measurement using BR($3p^0$) as input.
$K^+e3$ measurement and other BRs in progress.

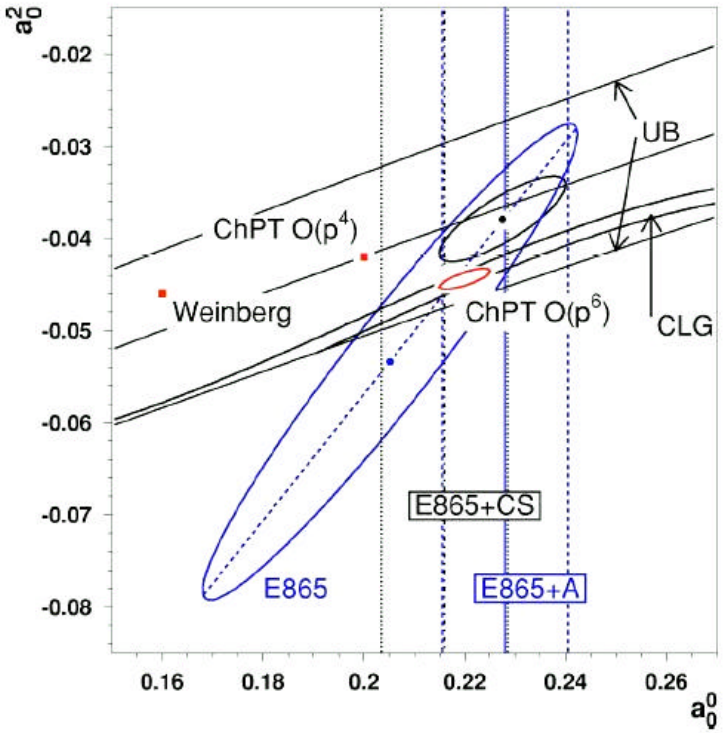
# $V_{us}$: Cabibbo angle




*Lots of new input to clarify situation*
(KTeV, KLOE, NA48, theory)

# pp **interactions and QCD**




Theory precision still not reached!

- Ke4 decays allow study of low-energy ππ dynamics.
- Asymmetry among di-pion and di-lepton planes sensitive to strong phase shifts.
- QCD quantity predicted with best precision (2-loop ChPT):
  $a_0^0 = 0.220 \pm 0.005$
- BNL E865: 400K $K^+e4$ events
  $a_0^0 = 0.216 \pm 0.013 \pm 0.003$
- NA48/2 goal: >1M events ($K^+e4$ and K? 3p distortions)
- DIRAC goal: $|a_0-a_2|$ at 6% (not kaons)

# A unique window on flavour physics

**CKM triangle constraints from charged currents (*tree*) or ? F=2 processes (*mixing*).**
**? F=1 physics has a different sensitivity to New Physics and in some special cases no irreducible theoretical errors.**

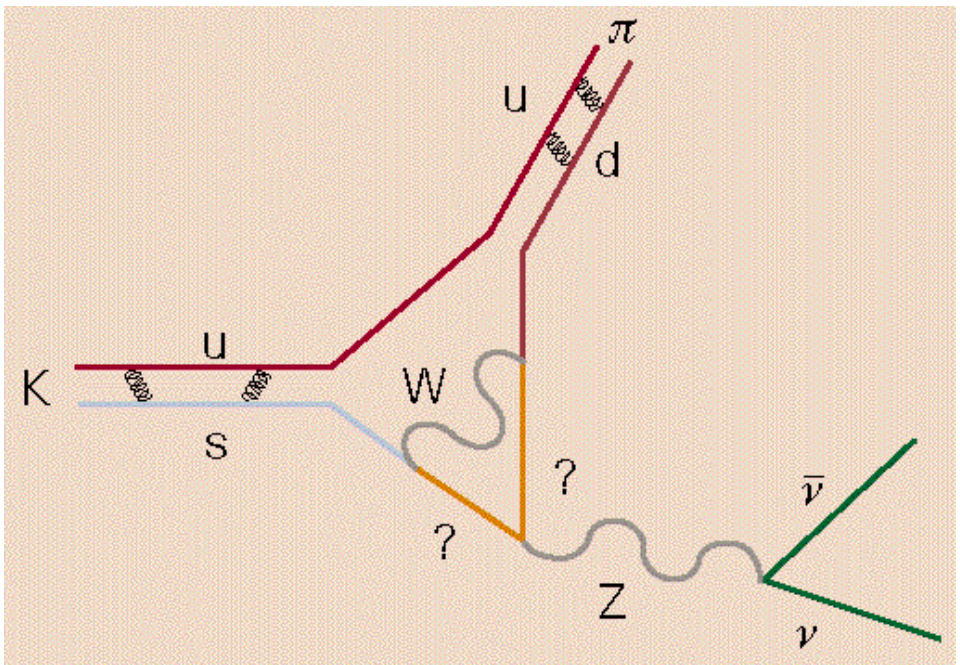
**FCNC rare decays:** $q_i \to q_j + (g,\ l^+l^-,\ ??)$

**suppressed in SM (GIM, CKM): 2nd order (*loop*)**

# Main goal: $K \to p l \bar{l}$

**(1) Semileptonic: main problem of estimating matrix element avoided (using known $K_{l3}$)**

**(2) Short distance physics dominates in loop: perturbative, SM under control at NLO, very sensitive to New Physics**




**(3) For l = ?: no long-distance contributions from ??**

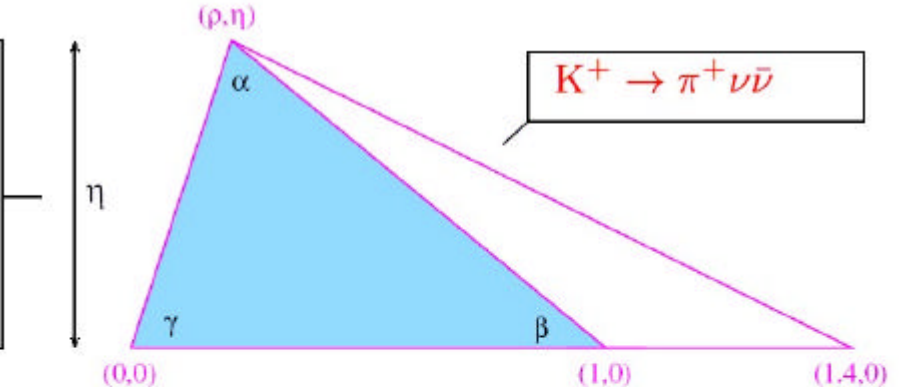
**(4) For $K_L$ (and l = ?): CP-violating, only top loop contributing (very accurate prediction)**

# Unitarity triangle from K

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

$K_L \to \pi^0 e^+ e^-$ { $K_S \to \pi^0 e^+ e^-$, $K_L \to \pi^0 \gamma\gamma$

**e, e'**




Required ancillary measurements

$K_L \to e^+ e^-$ { $K_L \to \gamma\gamma$, $K_L \to e^+ e^- \gamma$, $K_L \to e^+ e^- e^+ e^-$, $e^+ e^- \mu^+ \mu^-$

$V^*_{us} V_{ud} + V^*_{cs} V_{cd} + V^*_{ts} V_{td} = ?_u + ?_c + ?_t = 0$

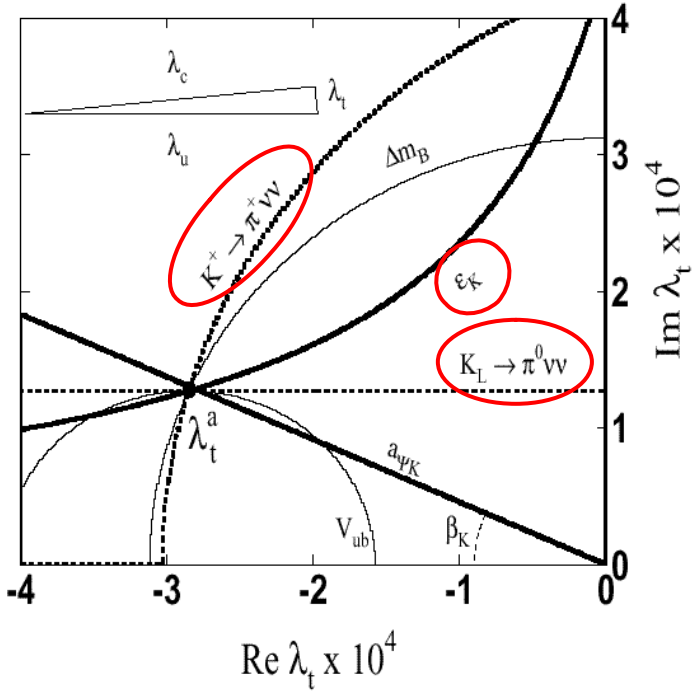
**Ke3**

$K \to p n \bar{n}$

**Height: Im($?_t$)**

$K_L \to p^0 n \bar{n}$

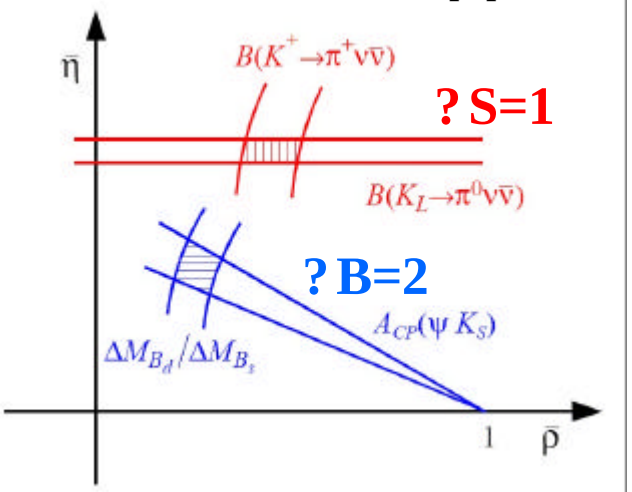
# Comparing K and B




Constraints from B and K physics (10% BR measurements):

- Errors on ρ, $V_{td}$: better from B
- Errors on η, sin2β: similar to B- factories
- Error on $\lambda_t$: better from K

A. Buras, hep-ph/9905437




Comparing $V_{td}$ from $K^+ \to \pi^+ \nu\nu$ and

? $M(B_d)$ / ? $M(B_s)$

Comparing ß from BR(KL $\to \pi^0 \nu\bar{\nu}$) / BR($K^+ \to \pi^+ \nu\bar{\nu}$) and A($B_d \to J/?K^0$)

# $K \to p l \bar{l}$

*Experimental problems:*

BR $\approx 10^{-11}$, few (or no) kinematic constraints, backgrounds with BR x $10^{7}$

| | | | |
|---|---|---|---|
| $K_L \to p^0 e^+ e^-$ | $10^{-11}$ ($CPV_{dir}$ $3 \cdot 10^{-12}$) | $< 2.8 \cdot 10^{-10}$ (FNAL KTeV) | CPC+CPV, ee?? bkg. 3 ev. (2.05 bkg) |
| $K_L \to p^0 \mu^+ \mu^-$ | $10^{-11}$ ($CPV_{dir}$ $1 \cdot 10^{-12}$) | $< 3.8 \cdot 10^{-10}$ (FNAL KTeV) | CPC+CPV 2 ev. (0.87 bkg) |
| $K^+ \to p^+ n\bar{n}$ | $7.2 \cdot 10^{-11}$ (at 7%) | $1.47^{+1.30}_{-0.89} \cdot 10^{-10}$ (BNL E787+E949) | Dedicated expt. 3 evt. (bkg. 0.45) |
| $K_L \to p^0 n\bar{n}$ | $3 \cdot 10^{-11}$ (at 2%) | $< 5.9 \cdot 10^{-7}$ (KTeV, Dalitz decay) | CPV dir "*Nothing to nothing*" |

Dedicated experiments required

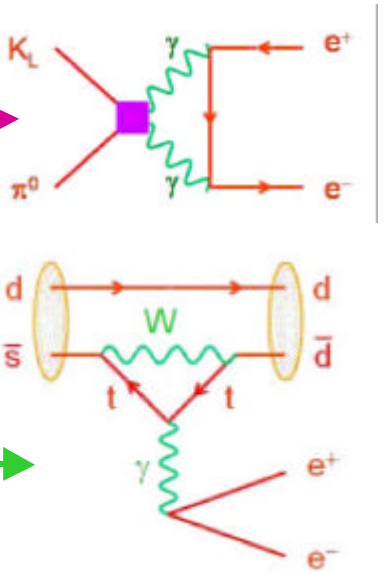
# $K_L \to \pi^0 l^+ l^-$

KTeV limits (90% CL):

$BR(K_L \to \pi^0 e^+ e^-) < 2.8\times10^{-10}$
$BR(K_L \to \pi^0 \mu^+ \mu^-) < 3.8\times10^{-10}$

3 contributions to these decays:

- **CP-allowed**: not predicted, derived from $K_L \to \pi^0$?? (NA48, KTeV)
- **Indirect CP violation**: not predicted, measured by $K_S \to \pi^0 l^+ l^-$ (NA48/1)
- **Direct CP violation**: predicted in terms of CKM phase

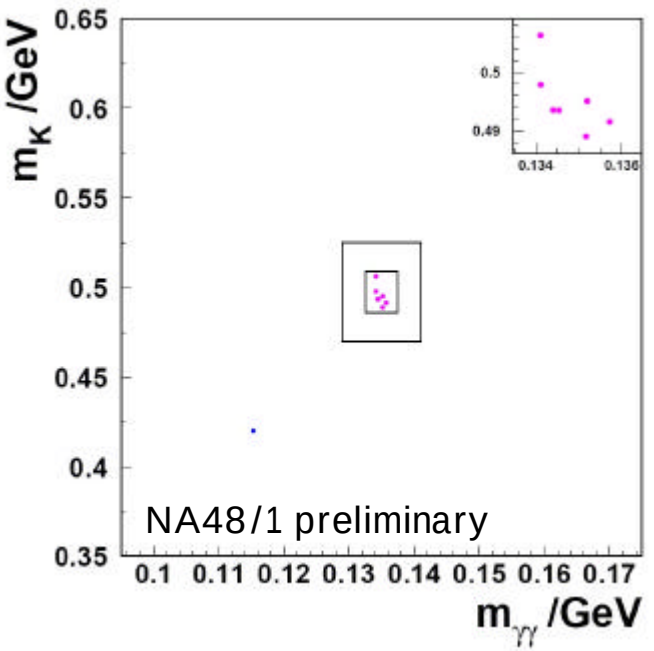



$$BR(K_L \to p^0 e^+ e^-)_{CPV} \approx 10^{-12}\left[15.3a_S^2 - 6.8a_S\,\mathrm{Im}(l_t)\times10^{-4} + 2.8\,\mathrm{Im}(l_t)^2\times10^{-8}\right]$$

$$l_t = V_{ts}^* V_{td} \qquad |a_S| \approx 1 \div 1.5 \quad \text{measured by } K_S \text{ (sign?)}$$

# NA48/1: $K_S \to \pi^0 l^+ l^-$

## $K_S \to \pi^0 e^+ e^-$




First measurement: 7 events

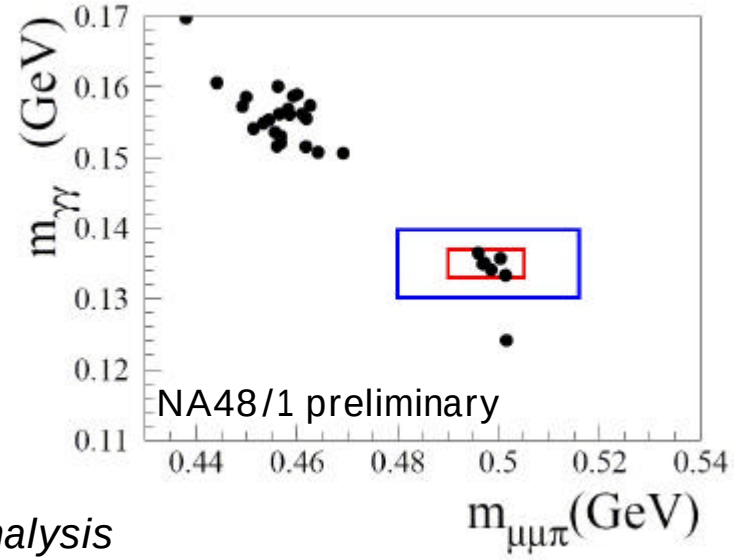
Bkg. $0.15\ ^{+0.10}_{-0.04}$ ($K_L \to ee\gamma\gamma$ and accid.)

BR = $(5.8\ ^{+2.8}_{-2.3} \pm 0.8) \times 10^{-9}$

*Blind analysis*

*Background-free*

## $K_S \to \pi^0 \mu^+ \mu^-$



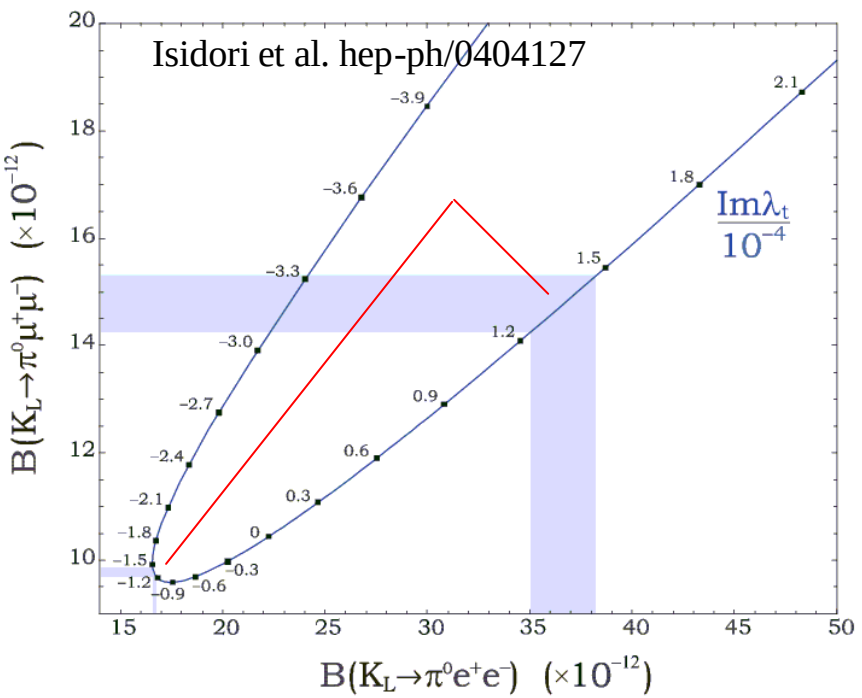

First measurement: 6 events

Bkg. $0.22\ ^{+0.19}_{-0.12}$ (accid.)

BR = $(2.8\ ^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9}$

# $K_L \to p^0 l^+ l^-$

- $K_L$ measurements: CP-allowed contribution is *small*.
- $K_S$ measurements: indirect CP-violating term *dominates*.
- Sensitivity of BR to CKM phase depends on the (unmeasurable) *relative sign* of the two CP-violating terms. Theoretical predictions: *constructive* interference.




$$BR(K_L \to \pi^0 e^+ e^-)_{CPV} \times 10^{12} \sim 17\ (ind) \pm 9\ (interf) + 4\ (dir)$$

$$BR(K_L \to \pi^0 \mu^+ \mu^-)_{CPV} \times 10^{12} \sim 8\ (ind) \pm 3\ (interf) + 2\ (dir)$$

# $K^+ \to p^+ n \bar{n}$

BR(SM) ~ $10^{-10}$

Theoretical uncertainty ~ **5 - 7%**

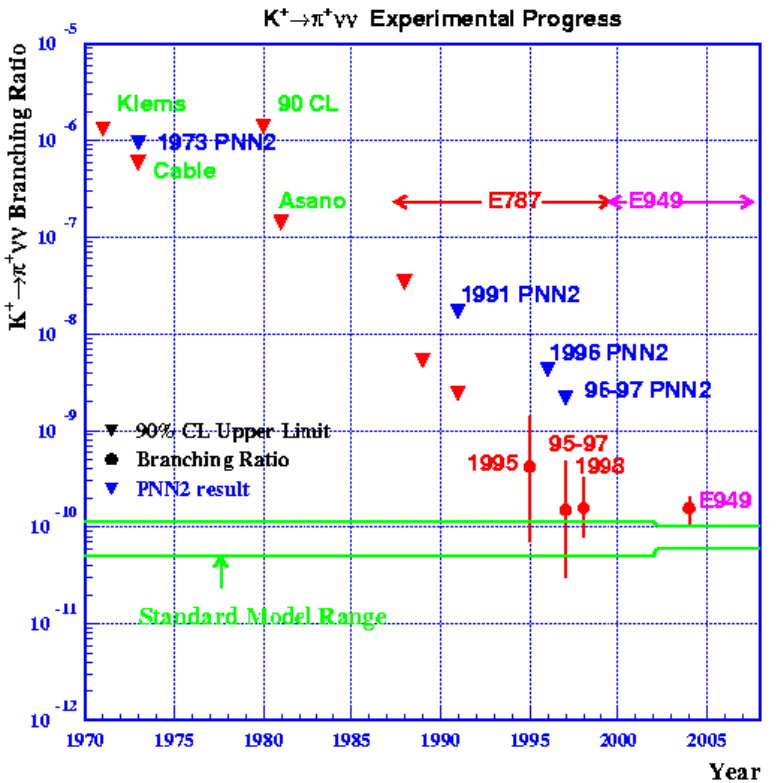
Background from K decays: $\mu^+\nu$ (0.63), and $\pi^+\pi^0$ (0.21), beam scattering, charge-exchange + Kl 3 and pion nuclear interactions.

No kinematic constraints.

VETO !!!

Background suppression $10^{11}$: redundancy is a must.

Measured @ BNL (3 events).



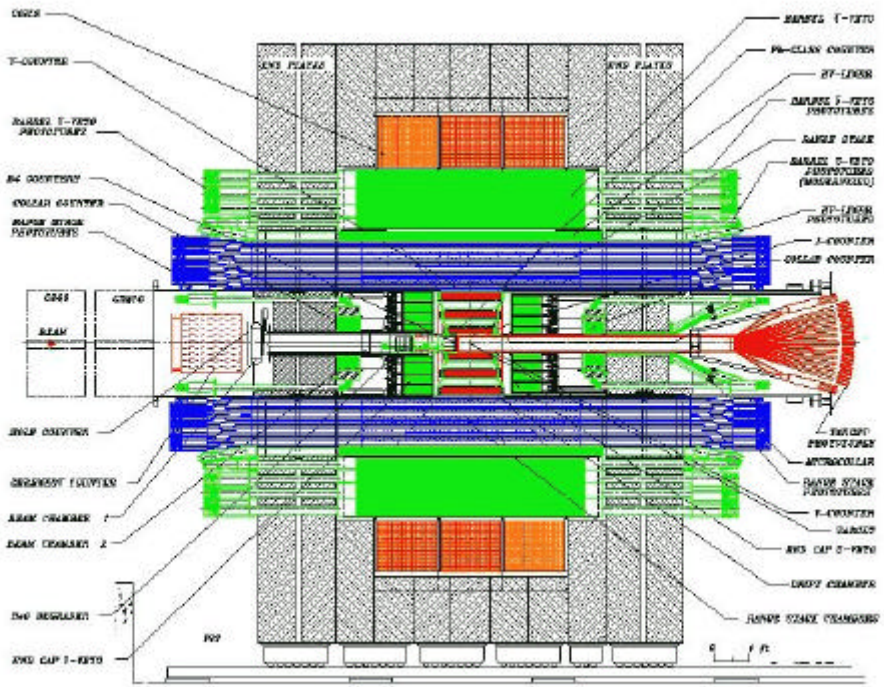
# BNL E787-E949: $K^+ \to p^+ n \bar{n}$

**E787**: 1989-1998
$K^+$ 800 MeV/c DC-separated
(K/p ~ 3), 5?$10^5$ K/$10^{12}$ p
Kaon ID: C, MWPC, dE/dx
Decay at rest, redundancy, $\pi \to \mu \to e$ decay chain.
Acceptance 0.2%

Final result: 2 events (0.15 bkg)

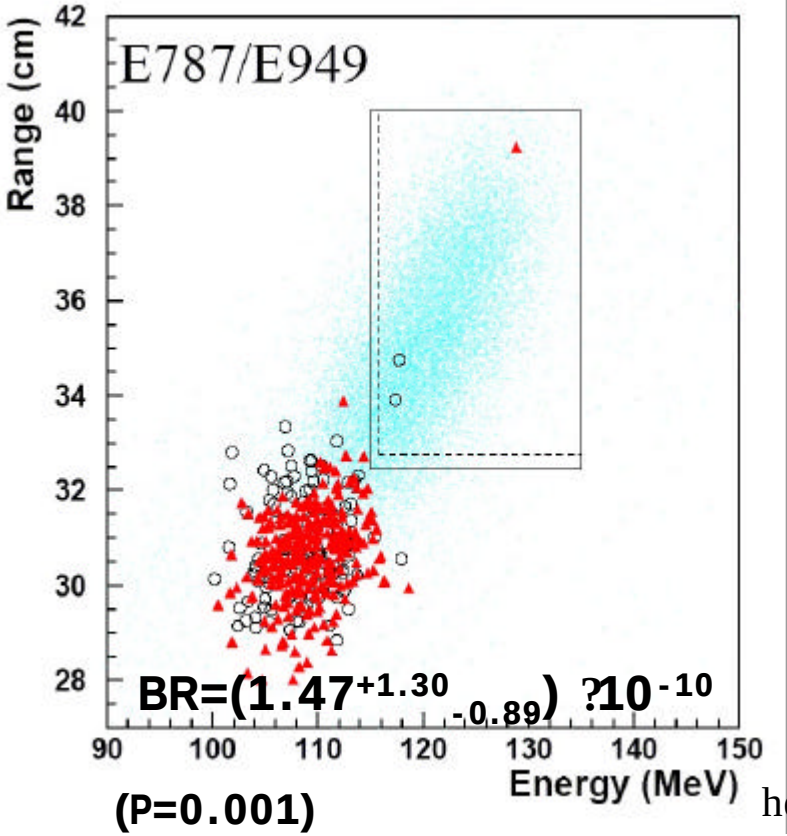
**E949**: upgrade (K/$\pi$ ~ 4), vetos, beam counters, *range stack*, calorimeter, trigger, DAQ.
Goal: 10 SM events in 60 weeks
11 week run in 2002 (1/5):
sensitivity ~ E787.

1 event. New run?



# E787-E949: data

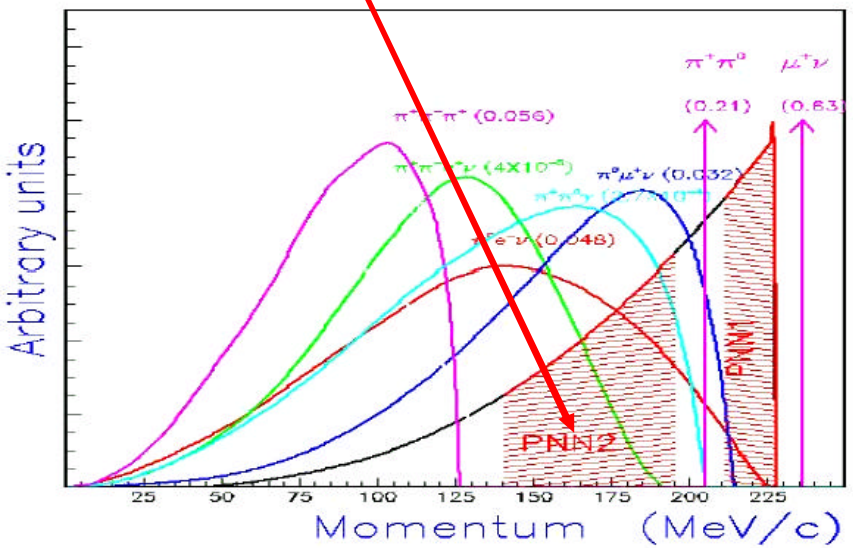
Region between two 2-body peaks ("smaller" background):




$BR = (1.47^{+1.30}_{-0.89}) \cdot 10^{-10}$

(P=0.001)

Study of region below $\pi^+\pi^0$ peak: higher background (nuclear p int.): S/B = 20 times worse




E787: 1 event (1.22 fondo)

$BR < 2.2 \cdot 10^{-9}$ (90% CL)

hep-ex/0403036

# $K_L \to p^0 n \bar{n}$

CP-violating

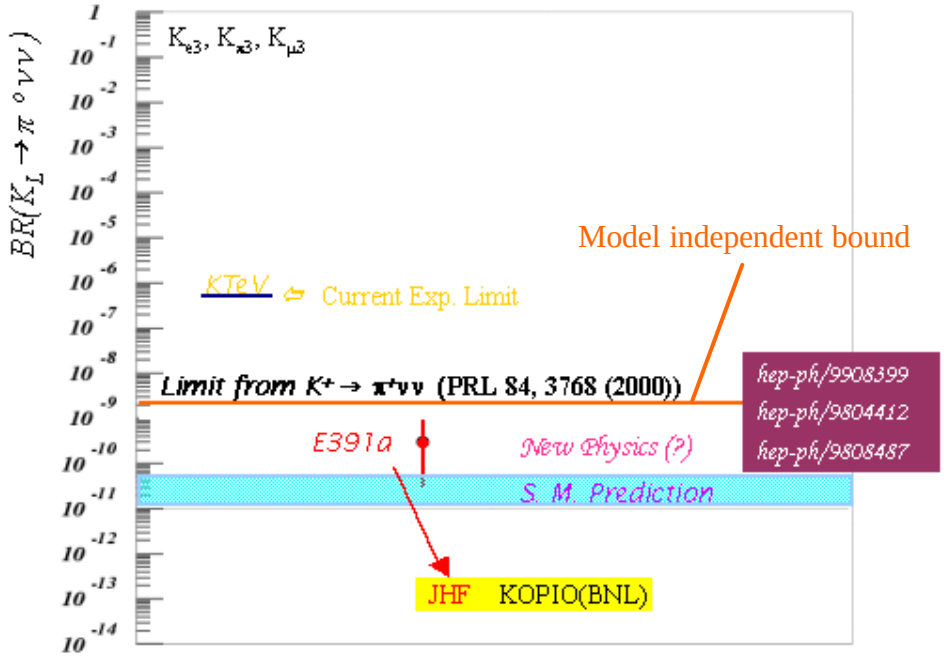
BR ~ $3 \cdot 10^{-11}$

Theoretical uncertainty ~ **1-2%**

Neutral bkg from $\pi^0\pi^0$ (BR 0.1%)
Missing $p_T$ cut, VETO!!!

**KTeV** limit: $10^{-7}$ ($\pi^0$ Dalitz decay).
1/2-day run 1996 with $\gamma\gamma$ (*pencil beam*): 1 bkg. event.

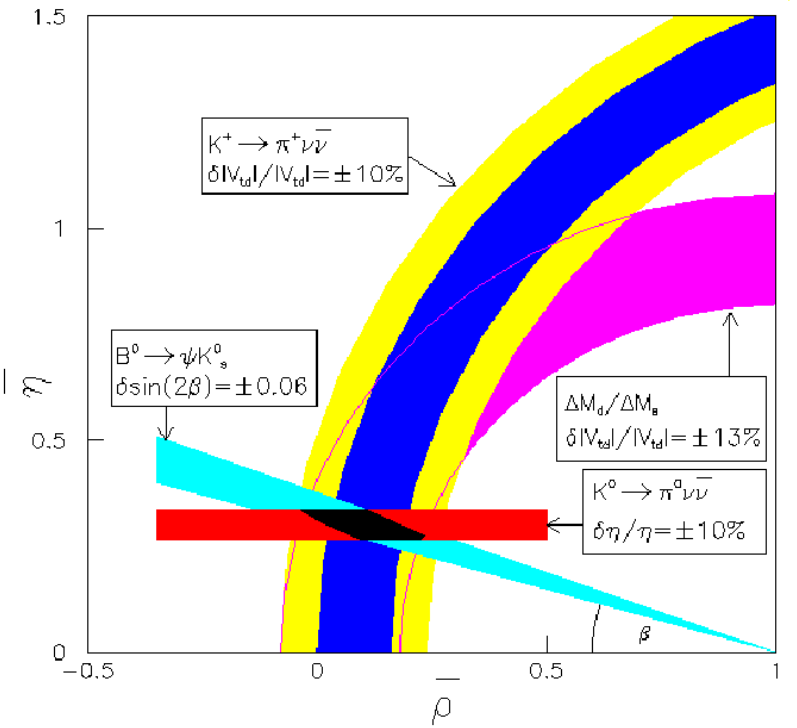
**KAMI** at FNAL (KTeV follow-up) with $K_L$ 10 GeV/c, acc. 6%, SES $2.3 \cdot 10^{-13}$ in 3 years, 100 SM events: not approved



# Future projects and goals

**Main focus on the measurement of ultra-rare decays: theoretically clean, highly sensitive, complementary to B**

**Also:**
**T-violation searches**
**CP asymmetries in charged K**



# $K^+ \to p^+ n \bar{n}$
# CKM a FNAL MI

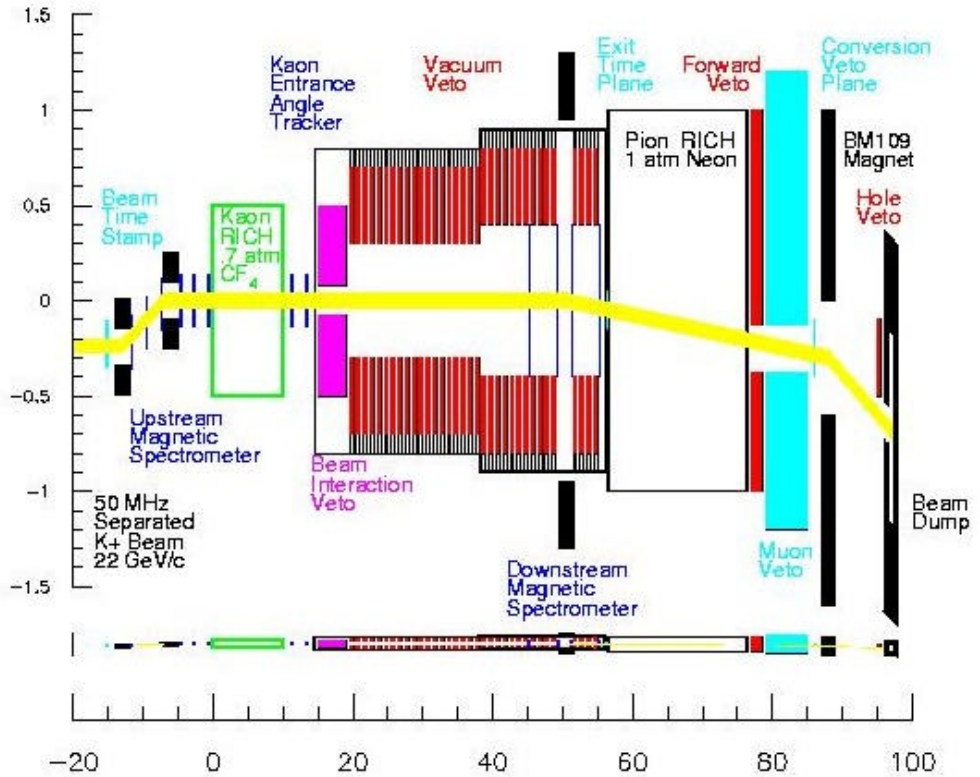
*New approach* : decay in flight
$K^+$ RF-separated beam (K/p ~ 4)
22 GeV/*c* (50 MHz)
$5 \cdot 10^{12}$ ppp (15% of MI), $3 \cdot 10^7$ K/spill

Redundancy (two RICH and two spectrometers), Pb/Sci + CsI calo (KTeV), ? vetos down to 10 MeV (ineff. $10^{-5} \div 10^{-7}$), acceptance 1.6%

R&D on (SC)RF cavities, photon vetos, *straws* in vacuum

Goal: 100 SM events in 2 years (S/B ≈ 10)

In 2003: not ratified because of high cost. Looking for cheaper solution (unseparated beam)



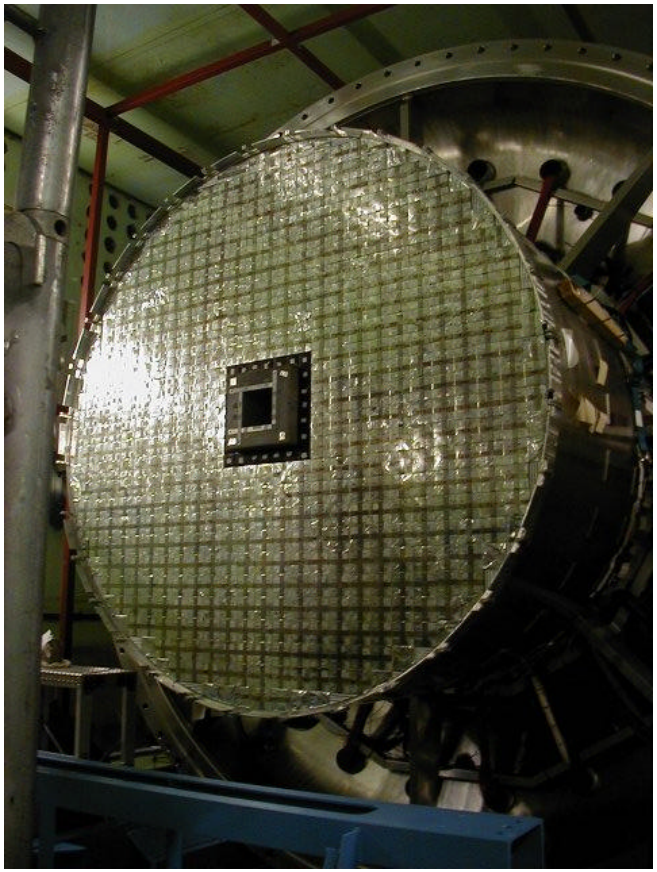
# Rare K decays at CERN?

*Ongoing study* for ultra-rare K decay program at CERN

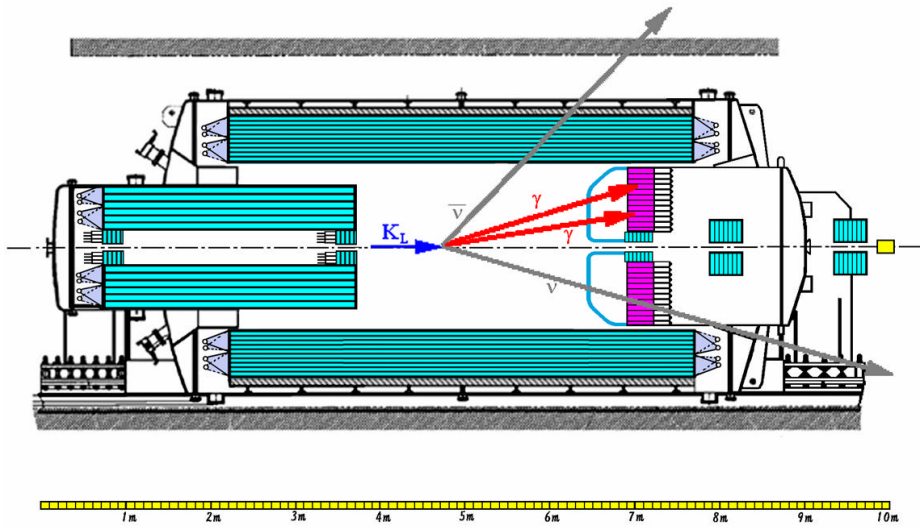
Focus on $K^+ \to \pi^+ \nu\bar{\nu}$ (not limited by SPS protons)

- In-flight decay at high energy (75 GeV): yield, resolutions, "easier" vetoing
- Unseparated beam: tracking K in 1 GHz beam (!)
- Double spectrometer, hermetic vetos
- New experiment, using parts of NA48
- Goal: 50 events (S/B ~ 10) in 2 years (2008 ?)
- First tests in 2004.

# KEK E391a



Pilot project at KEK-PS (2·10$^{12}$ ppp)
Collimated 2 GeV/*c* beam: K/p ~ 1/10
2.6·10$^{4}$ dec./s, $P_T$ cut to reject $\pi^0\pi^0$ and reduce veto needs to 10$^{-4}$ inefficiency.
Double decay chamber, 10% acceptance, old CsI calo and DAQ, new modular Pb/Sci vetos.
"Engineering run" in 2002
Data-taking in 2004: Goal SES 3·10$^{-10}$

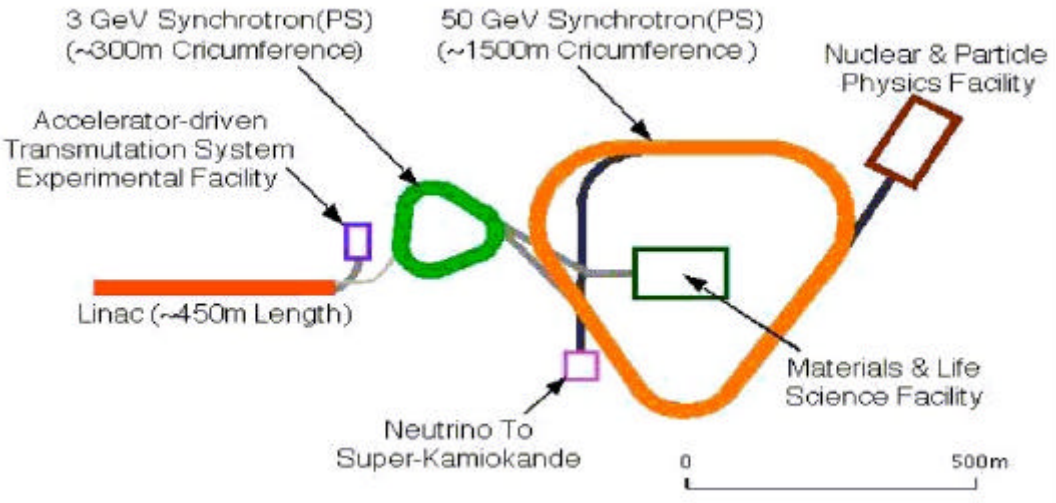


# J-PARC at Tokai

50 GeV (30 GeV phase I)
15 μA, 0.75 MW, $2\times10^{14}$ p/spill
0.7s/3.42 s (DC 20% !)

Phase II: 4 MW

Start physics in 2008




K physics program is **central**: 5 LoI

$K_L \to \pi^0\nu\nu$, $K^+ \to \pi^+\nu\nu$, T-violation, BR($K^+$), $K_{e3}$

2 kaon lines foreseen:

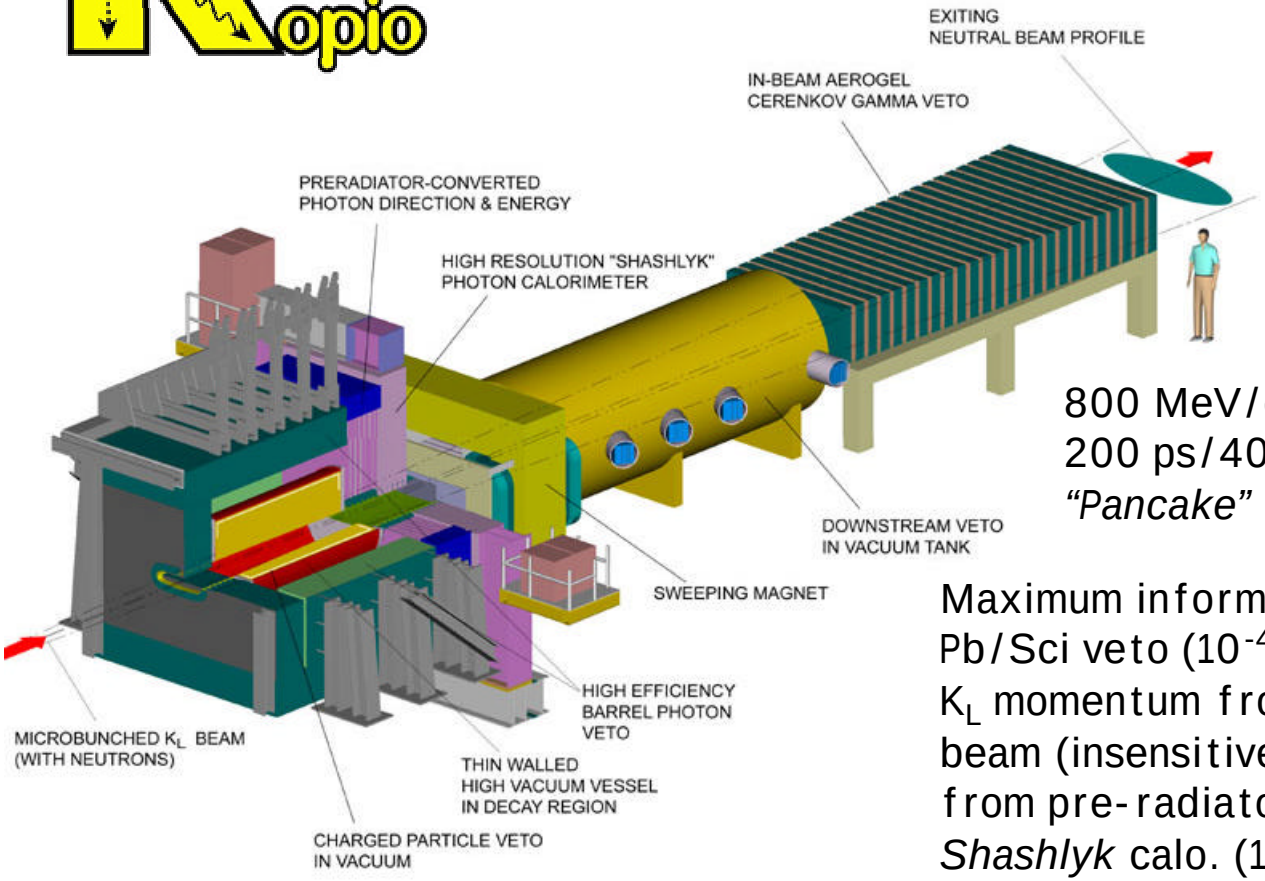
0.8 - 1.1 GeV $K^+$ and 2 GeV/c $K_L$ (?)

# $K \to p n \bar{n}$ at J-PARC

**$K_L$: follow-up of KEK-E391a**
**100 MHz *pencil beam* (accidentals, rate x500!), acceptance ~ 16%,**
**high energy (flux, resolution, acceptance, veto efficiency)**
**New calorimeters (CeF3 ?) and DAQ**
**Goal: >100 SM events (SES $3 \cdot 10^{-14}$ max, limit) in 3 years ($2 \cdot 10^{15}$ $K_L$)**

**$K^+$: BNL stopped-K technique**
**Low energy (600-800 MeV/c) DC-separated (K/p >3) beam**
**Decays at rest (>25% stop)**
**Incremental upgrade (x4) of detector, new spectrometer?**
**Goal: >50 SM events in 3 years (SES $2 \times 10^{-12}$: E949/5)**

# $K_L \to p^0 n \bar{n}$: KOPIO at BNL




800 MeV/c *microbunched* beam
200 ps/40 ns,
*"Pancake"* beam

Maximum information:
Pb/Sci veto ($10^{-4}$) complemented by:
$K_L$ momentum from TOF, aerogel C on beam (insensitive to n, $K^0$), $\gamma$ direction from pre-radiator (2 $X_0$ Sci+MWPC), *Shashlyk* calo. (18 $X_0$).
Funded in 2004, data-taking 2010
Goal: 40 SM events (S/B ≈ 2)

# K physics status

CERN: NA48 ($K_L$) NA48/1 ($K_S$) analysis, NA48/2 ($K^{\pm}$) run, future program under discussion
FNAL: KTeV ($K_L$) and HyperCP ($K^{\pm}$) analysis, CKM ($K^+$) study (?)
Frascati: KLOE ($K_{L,S}$, $K^{\pm}$) run, *upgrades ?*
BNL: E949 ($K^+$) analysis, data-taking(?), KOPIO ($K_L$) funded
KEK: E246 ($K^+$) analysis, E391a ($K_L$) run
Protvino: Analysis, OKA ($K^{\pm}$) in preparation
J-PARC: 5 LoI on K physics

- Several workshops, topical K conference in 2005
- Future program at CERN ?
- New high intensity proton drivers?

Pretty much alive!