# Rare Kaon Decays and CP Violation

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# Kaon and rare kaon decays

- Charged and neutral kaons

$$K^+ = u\bar{s}, K^0 = d\bar{s}$$

$$K^0 \rightarrow 50\% K_S^0, 50\% K_L^0$$

First evidence of CP violation observed in $K_L \rightarrow \pi^+\pi^-$ in 1964!

- Rare kaon decays in this talk

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

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

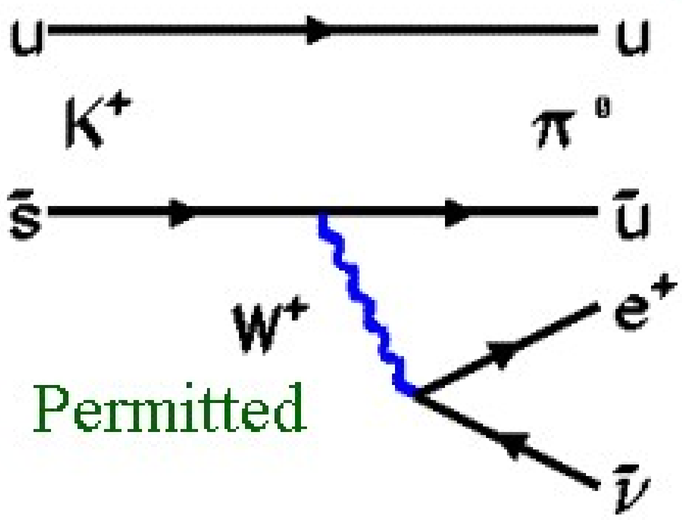
$$K_S^0 \rightarrow \pi^0 \nu\bar{\nu}$$

CP Violation

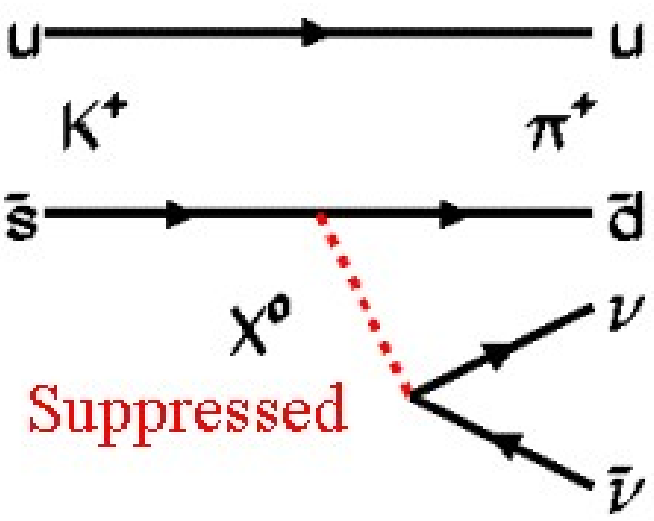
**Decay rates ~ Vtd and η**

# History of rare Kaon decays

**Decay via flavor-changing charged current**



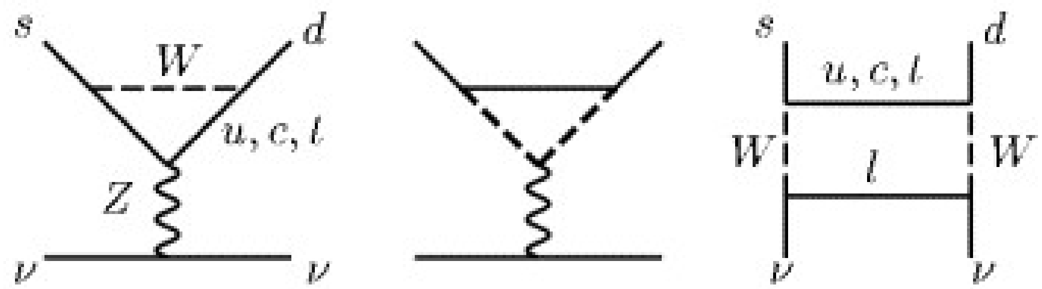

**Decay via flavor-changing neutral current (FCNC)**




- **By early 1970's, FCNC forbidden in view of the old theory.**
- **Discoveries of the neutral current, Charm, Bottom and Top quark open a door for the decays with FCNC.**

# Rare Kaon decay in SM

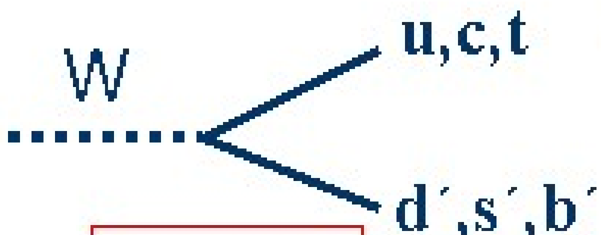
- Decay via penguin and box diagrams




$$\text{幅度} \sim \sum_{q=u,c,t} \frac{m_q^2}{m_W^2} V_{qs}^* V_{qd}$$

- Least problems among hadronic decays
  - Hadronic matrix element 利用同位旋对称 $K^+ \to \pi^0 e^+ \nu_e$
  - Negligible long distance effects 因末态中微子不与虚光子耦合
  - No significant QCD correction
- Theoretical ideal for new physics discovery
  - Accurate calculation in SM and its extension
  - Rates sensitive to fundamental parameters

# CKM and CP violation




Q'=UQ

弱本征态 → 质量本征态

CKM

**CKM Matrix** **Wolfenstein Parametrization**

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \simeq \begin{bmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

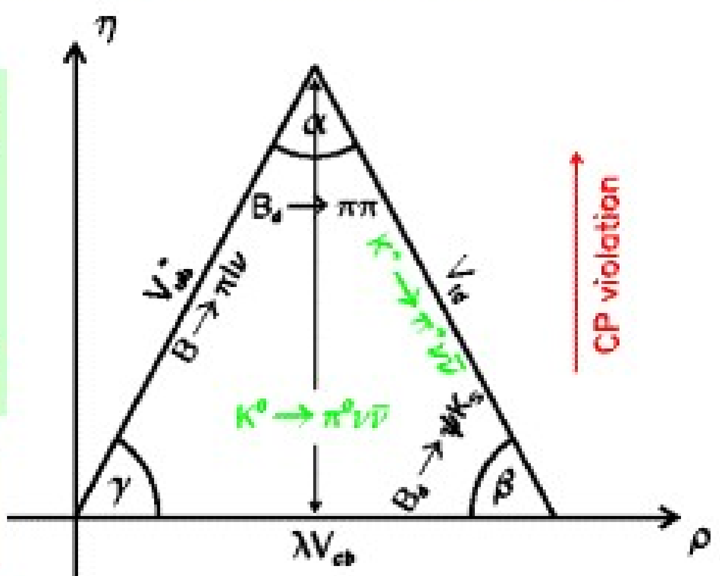
**CP violation: $J_{cp} \approx A^2\lambda^6\eta \neq 0$**

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ A^4 X^2(x_t)[\eta^2 + (\rho_0 - \rho)^2]$$

$$B(K_L^0 \to \pi^0 \nu\bar{\nu}) = \kappa_L A^4 X^2(x_t)\eta^2$$

$$B(K_S^0 \to \pi^0 \nu\bar{\nu}) = \kappa_L A^4 X^2(x_t)\eta^2 \frac{\tau_{K_S}}{\tau_{K_L}}$$ Too small

黄金等式: $(\sin 2\beta)_{\pi\nu\bar{\nu}} = (\sin 2\beta)_{J/\Psi K_S}$



# Experimental status

- **Charged kaon experiments**

  1) E787 and its successor E949 (unfinished)

  2) CKM (cut)

- **Neutral kaon experiments**

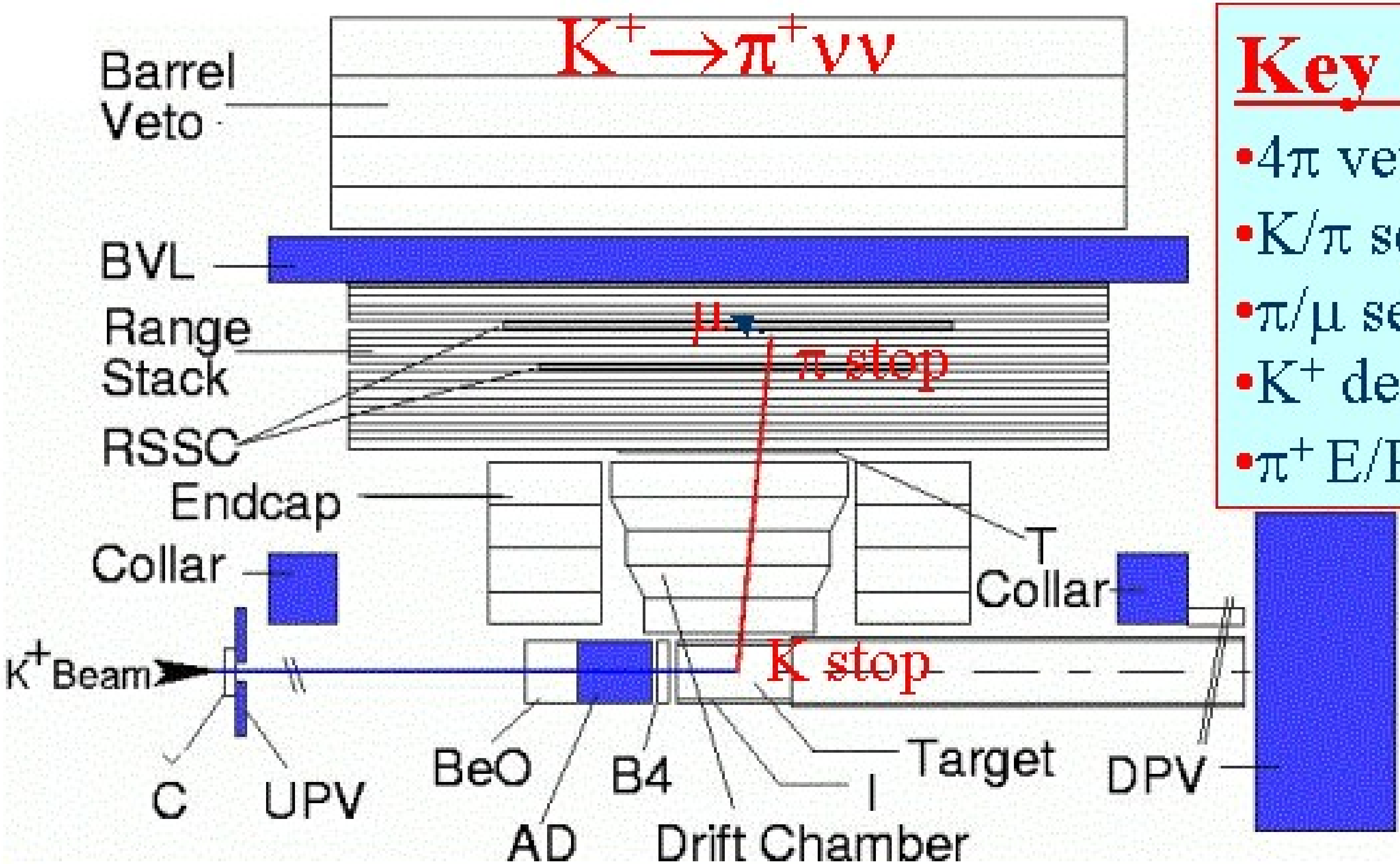
  1) KTeV (finished)

  2) E391a (on-going)

  3) KOPIO (R&D, started in 2011)

  4) JAPAC $K_L$ experiment (under discussion)

# E949/E787 experiment

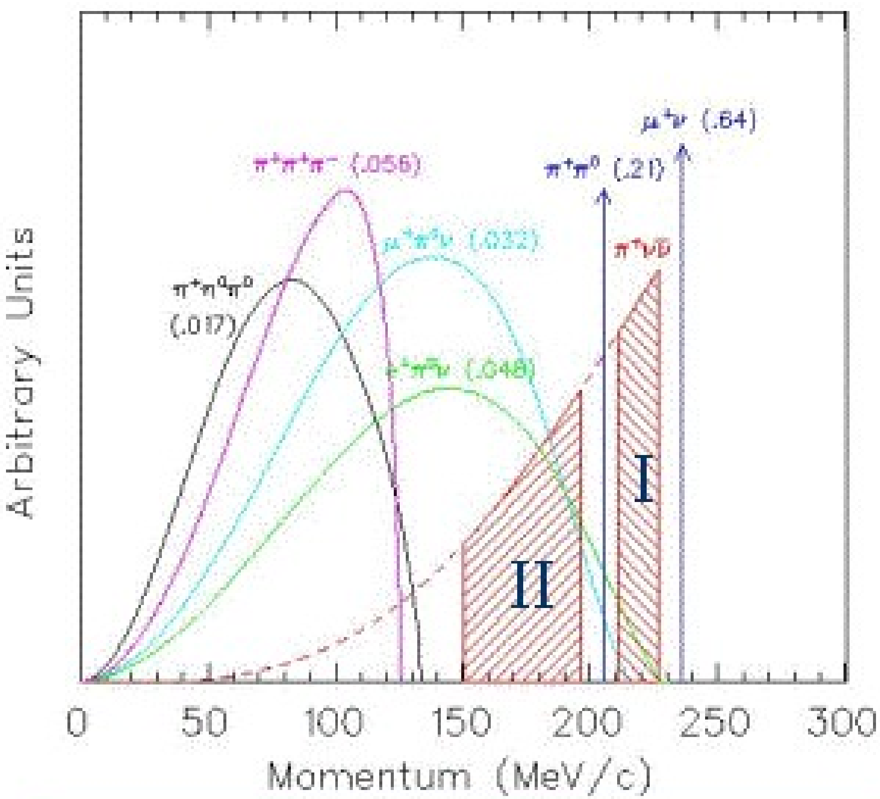


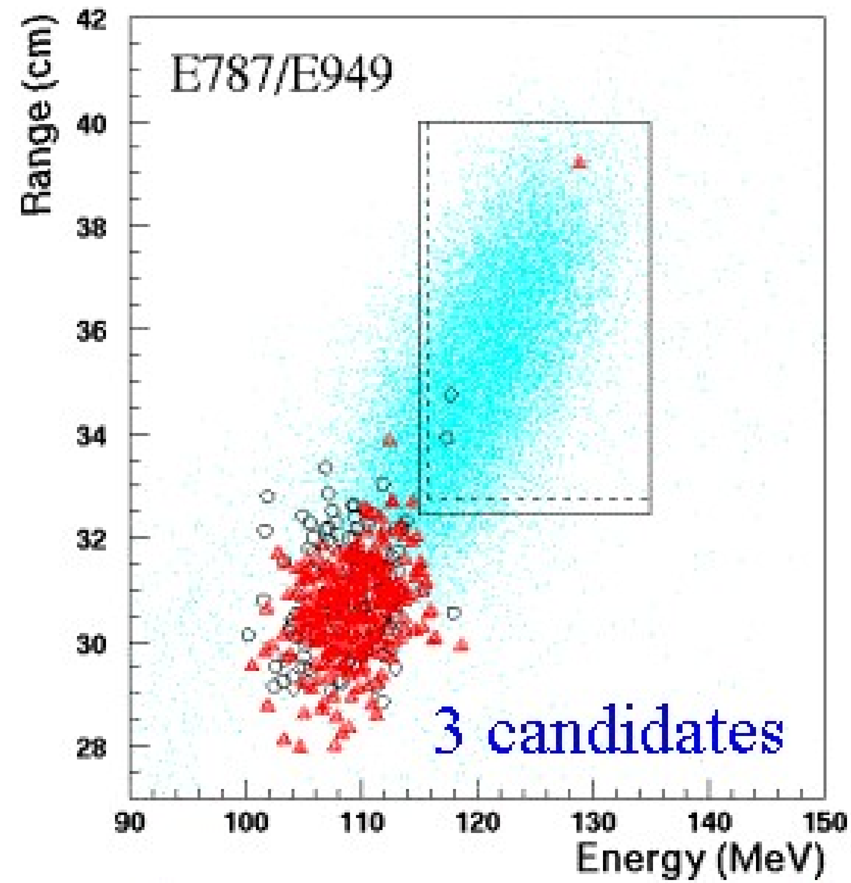

**Key issues**

- $4\pi$ veto ability
- $K/\pi$ separation
- $\pi/\mu$ separation
- $K^+$ decay at rest
- $\pi^+$ E/P/R

**About $7.8\times10^{12}$ $K^+$ stop at the detector centre**

# E787/E949 search region




$B(K^+ \to \mu^+ \nu_\mu) = 64.43\%$

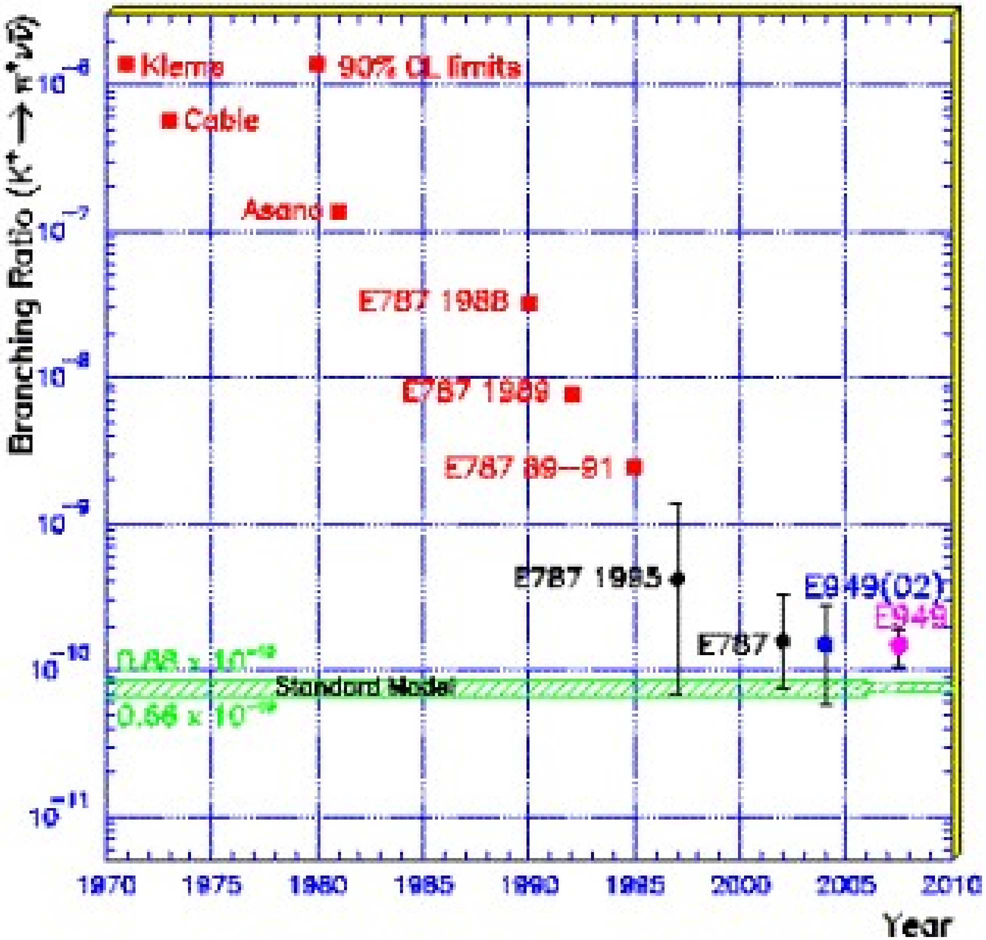
$B(K^+ \to \pi^+ \pi^0) = 21.13\%$

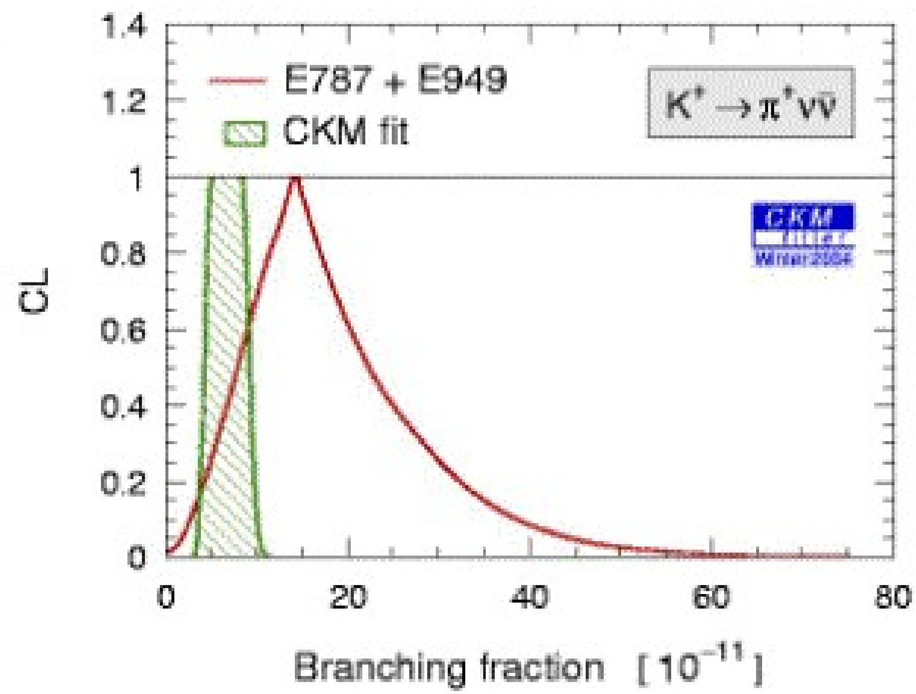
$B(K^+ \to \pi^+ \nu\nu)_{SM} = 0.75 \times 10^{-10}$

**Done in Region I**

**Not yet in Region II**

# Current limit from E787/E949

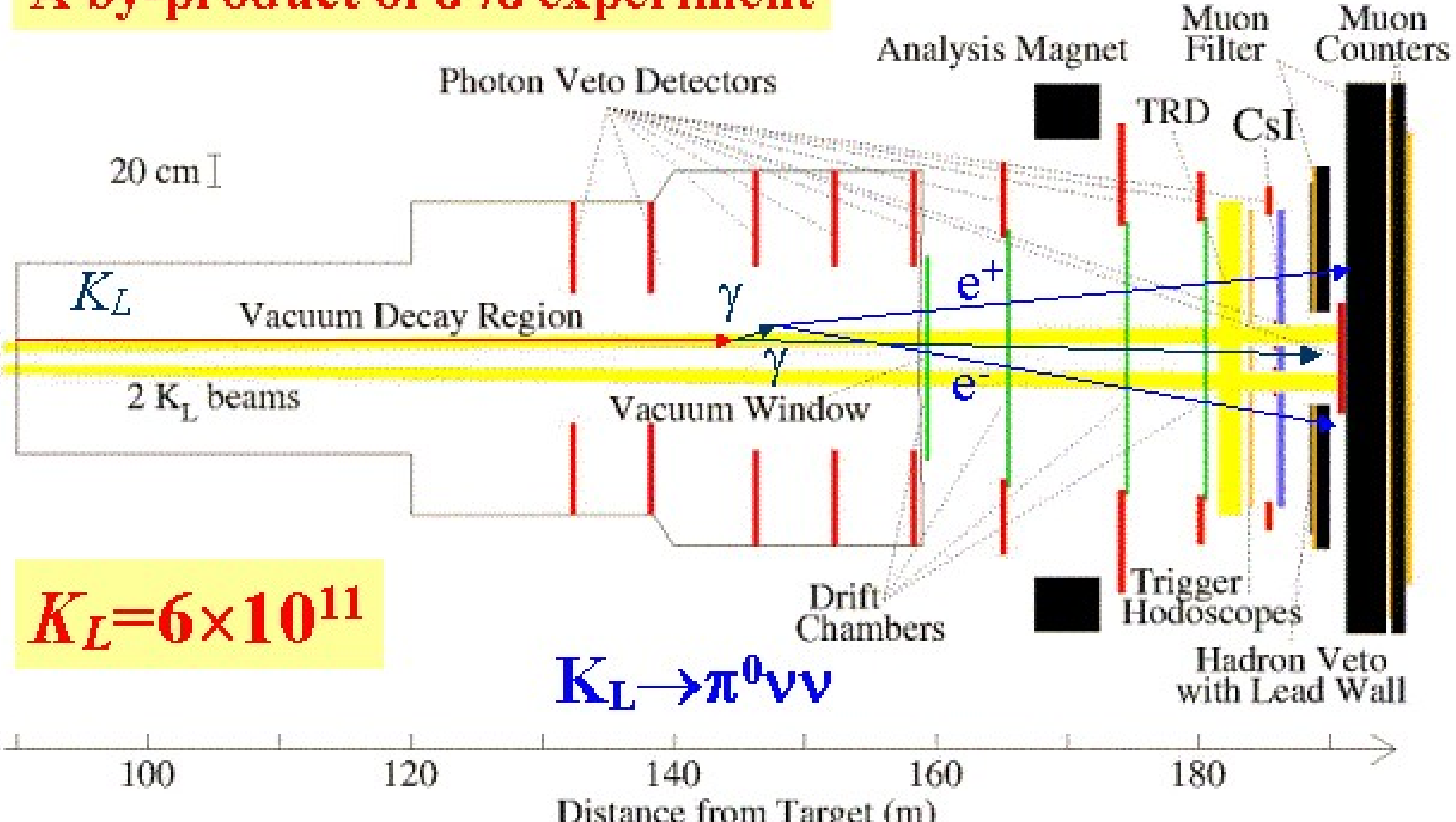



实验只拿到1/3的承诺束流，无法实现实验目标。

# KTeV experiment

**A by-product of ε′/ε experiment**

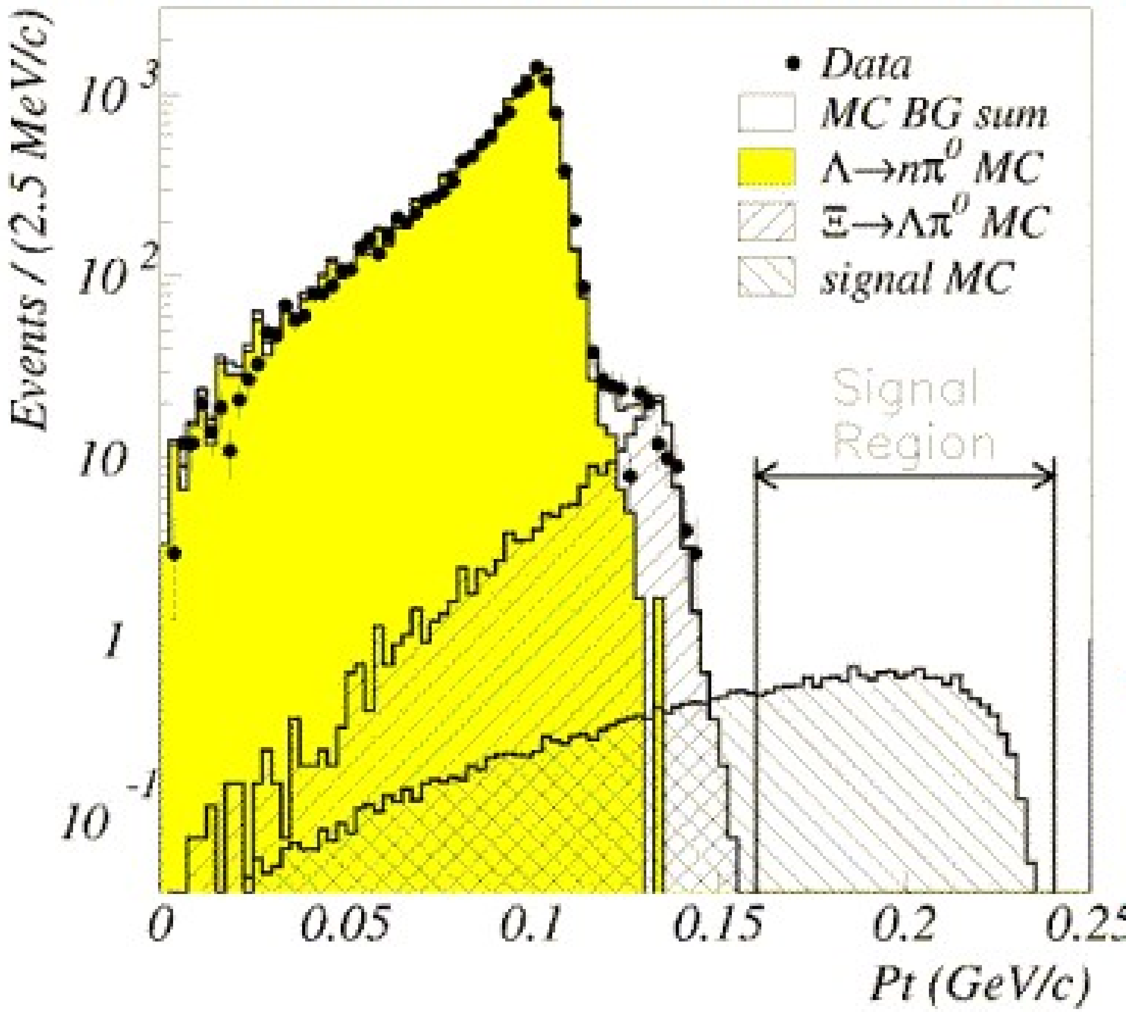



$K_L = 6\times10^{11}$

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

# Limit reached by KTeV

E799-II data, background limit $3.1\times10^{-8}$

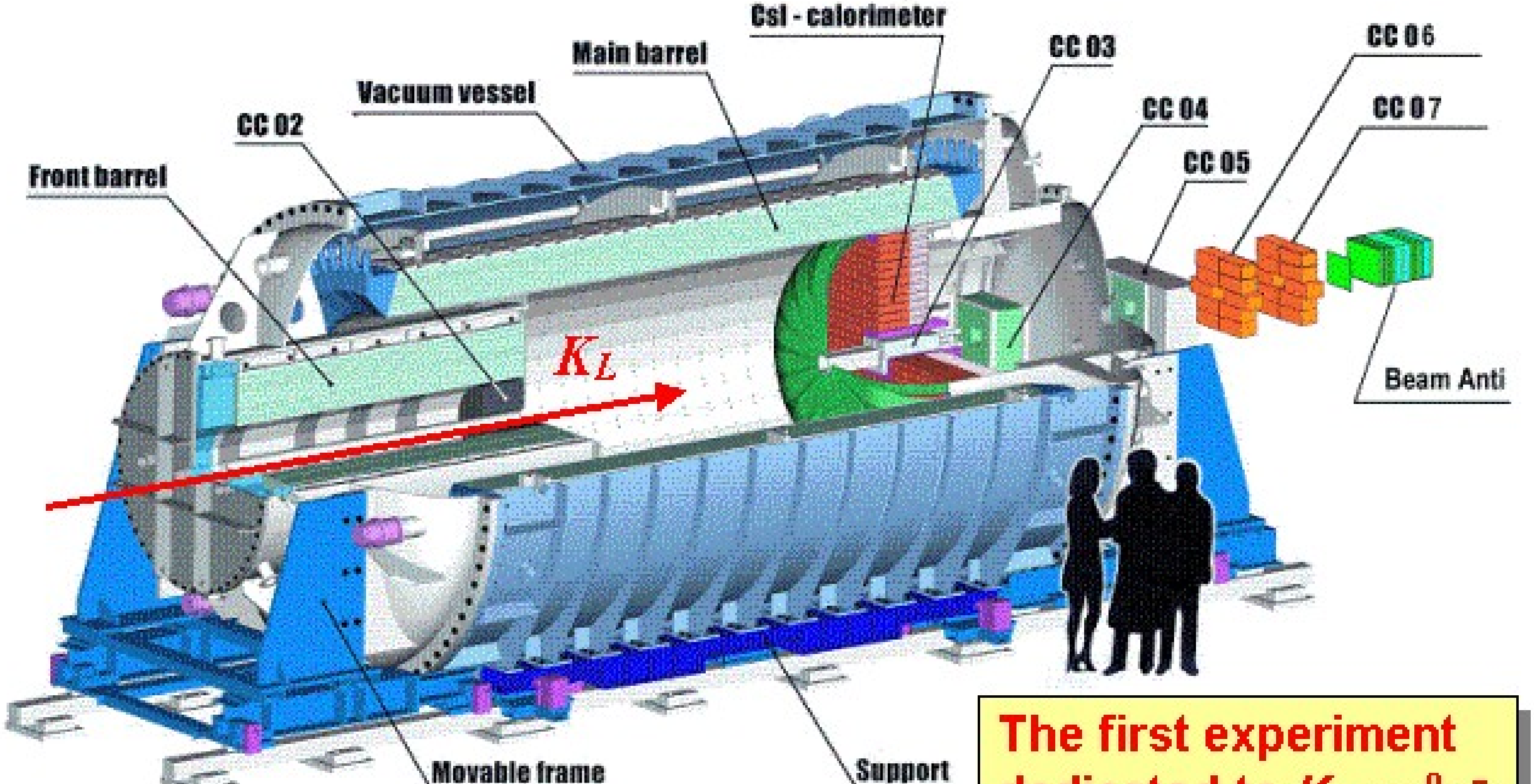



**Key issues**

- Electrons tracks
- $\gamma$ Energy
- $\gamma$ direction
- Veto ability
- KL decay vertex
- High $P_t(\pi^0)$

$$B(K_L^0 \to \pi^0 \nu \bar{\nu}) < 5.9\times10^{-7}$$
$$@90\%C.L.$$

# E391a experiment




**The first experiment dedicated to $K_L \to \pi^0 \nu\bar{\nu}$**

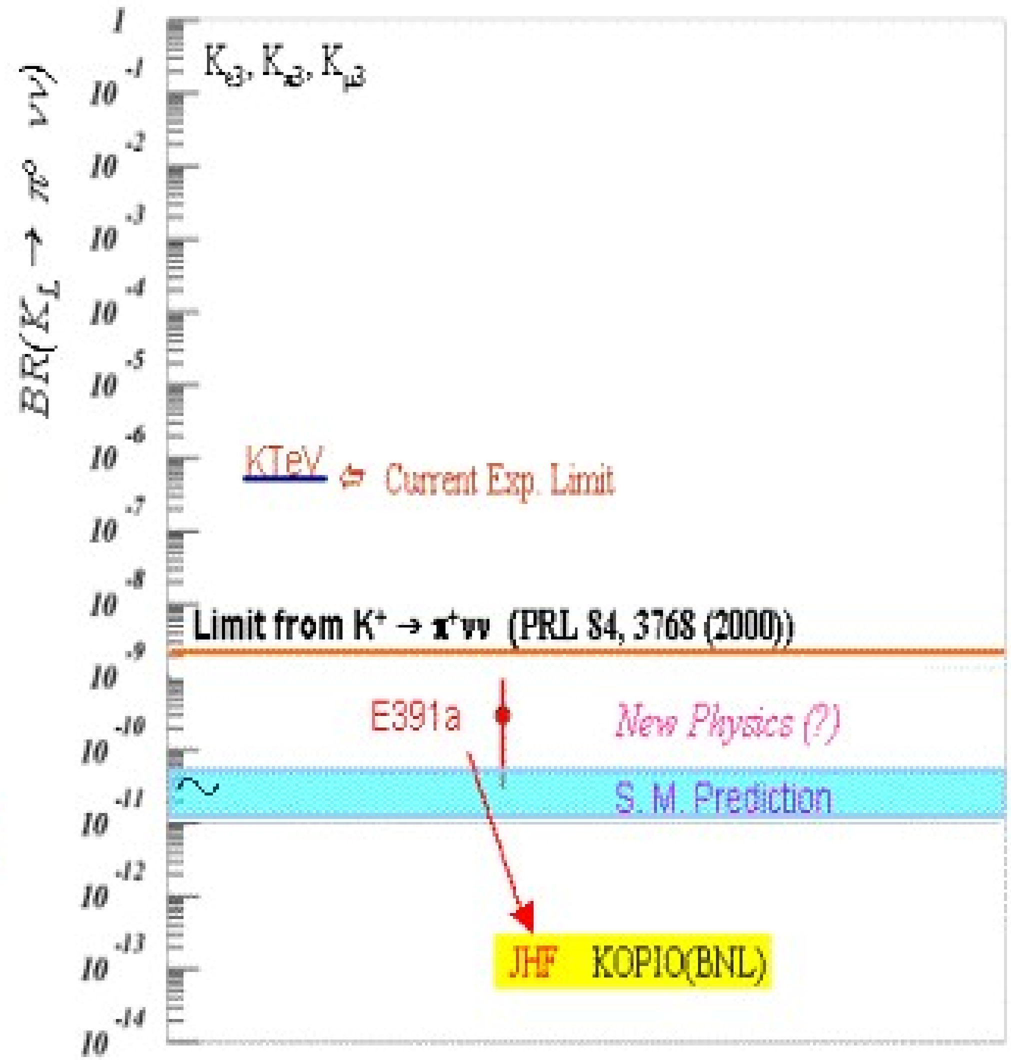
# E391a approach

## E391a: $O(10^{-10})$

- Pilot experiment
- Search for the decay in the region beyond the Grossman-Nir limit

↓

## J-PARC: $O(10^{-13})$

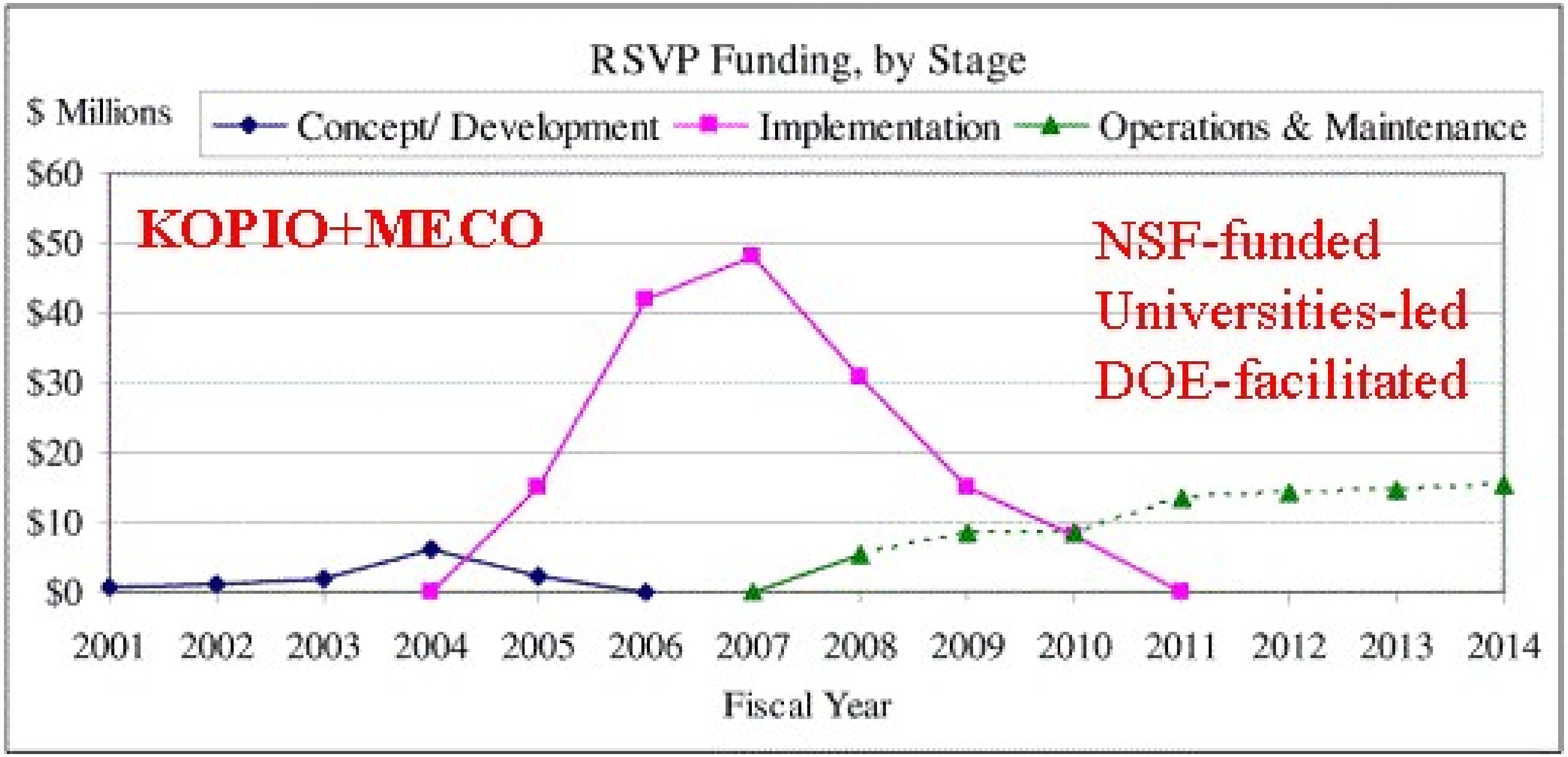


# KOPIO in RSVP project

**Rare Symmetry Violation Process**

**-- First Priority Project in NSF FY2006 Budget Request**

## $K^0$ to $PI^0$ → KOPIO



# KOPIO concept design

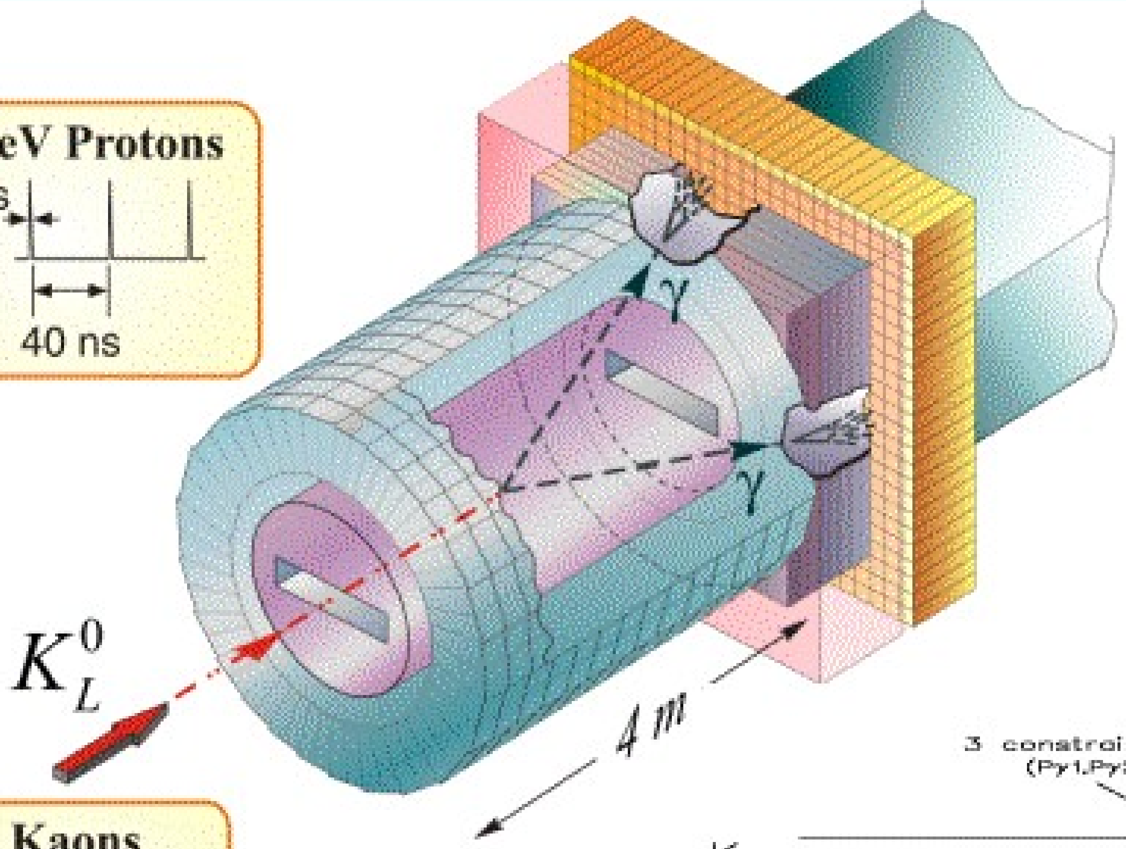
**25 GeV Protons**

200 ps

40 ns

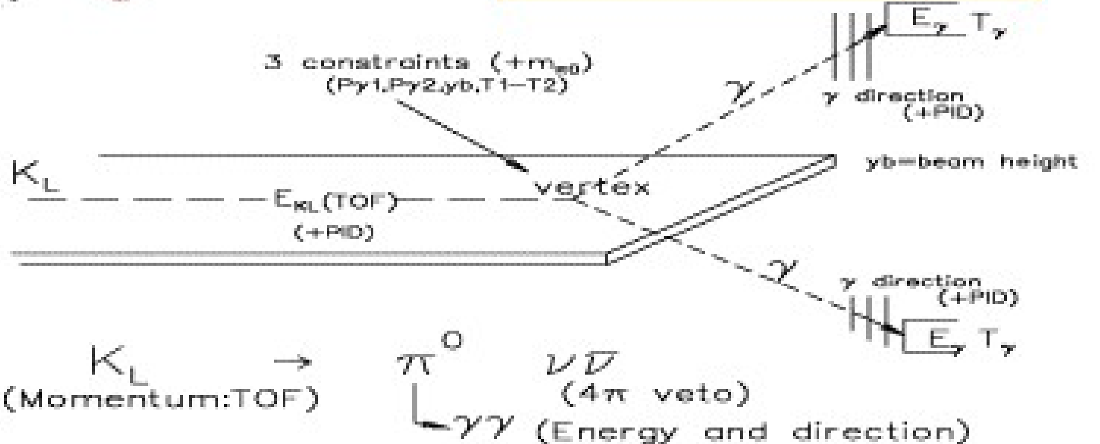
**Kaons**

40 ns

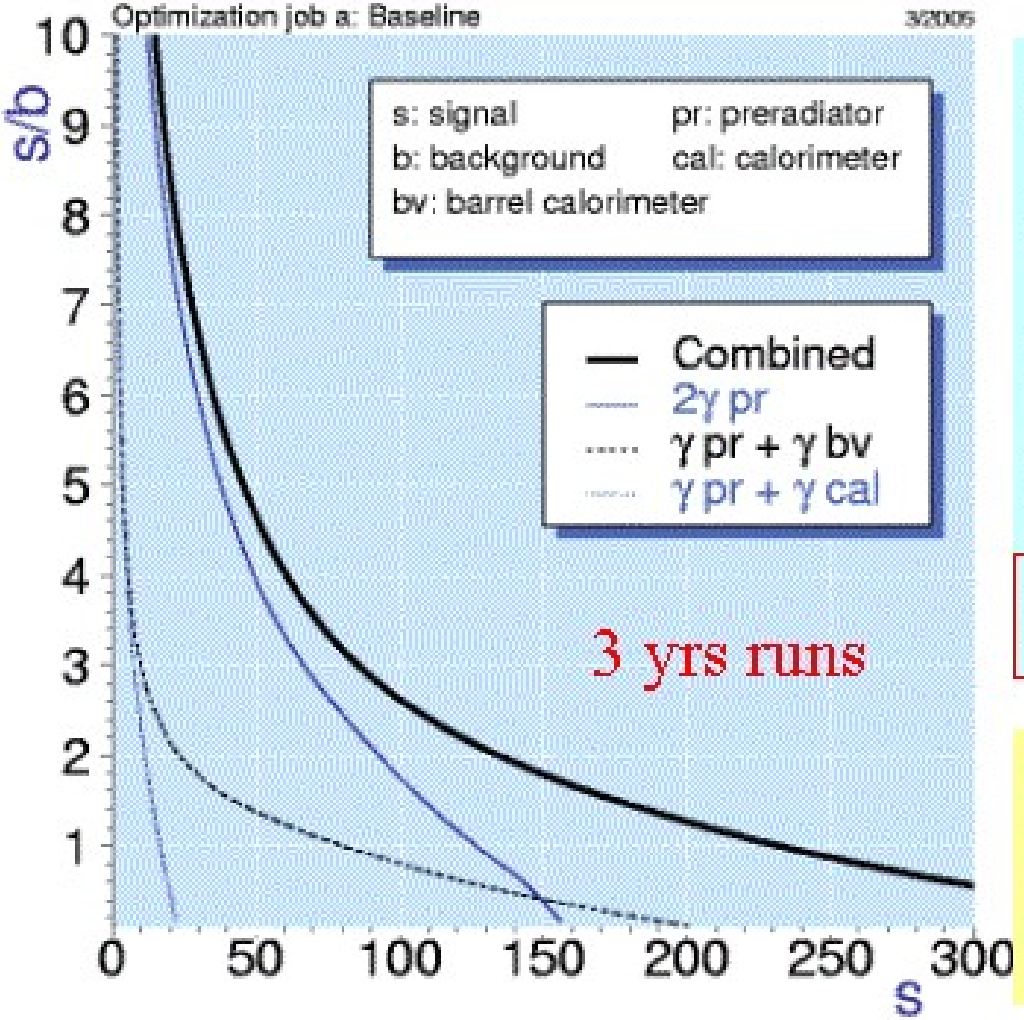



**Key issues**

- 4π veto ability
- γ direction
- γ energy
- γ hit time
- $\pi^0$ momentum
- $K_L$ momentum



# Expected signal/background




$K_L^0 \to \pi^0\pi^0 : 0.9\times10^{-3}$

$K_L^0 \to \pi^0\pi^0\pi^0 : 0.21\times10^{-2}$

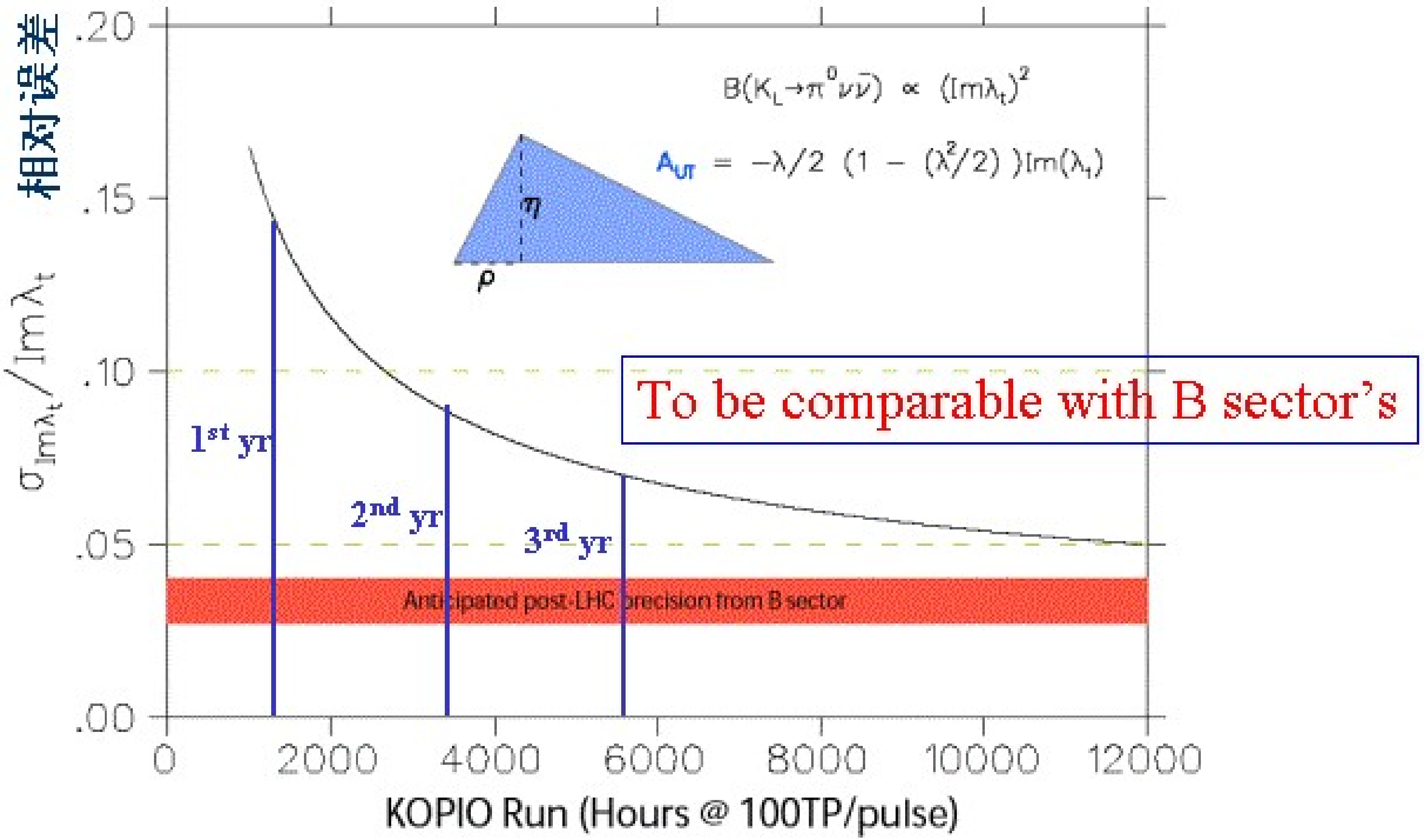
$K_L^0 \to \pi^+\pi^-\pi^0 : 0.13\times10^{-2}$

$K_L^0 \to \pi^\pm e^\mp \nu\gamma : 0.35\times10^{-3}$

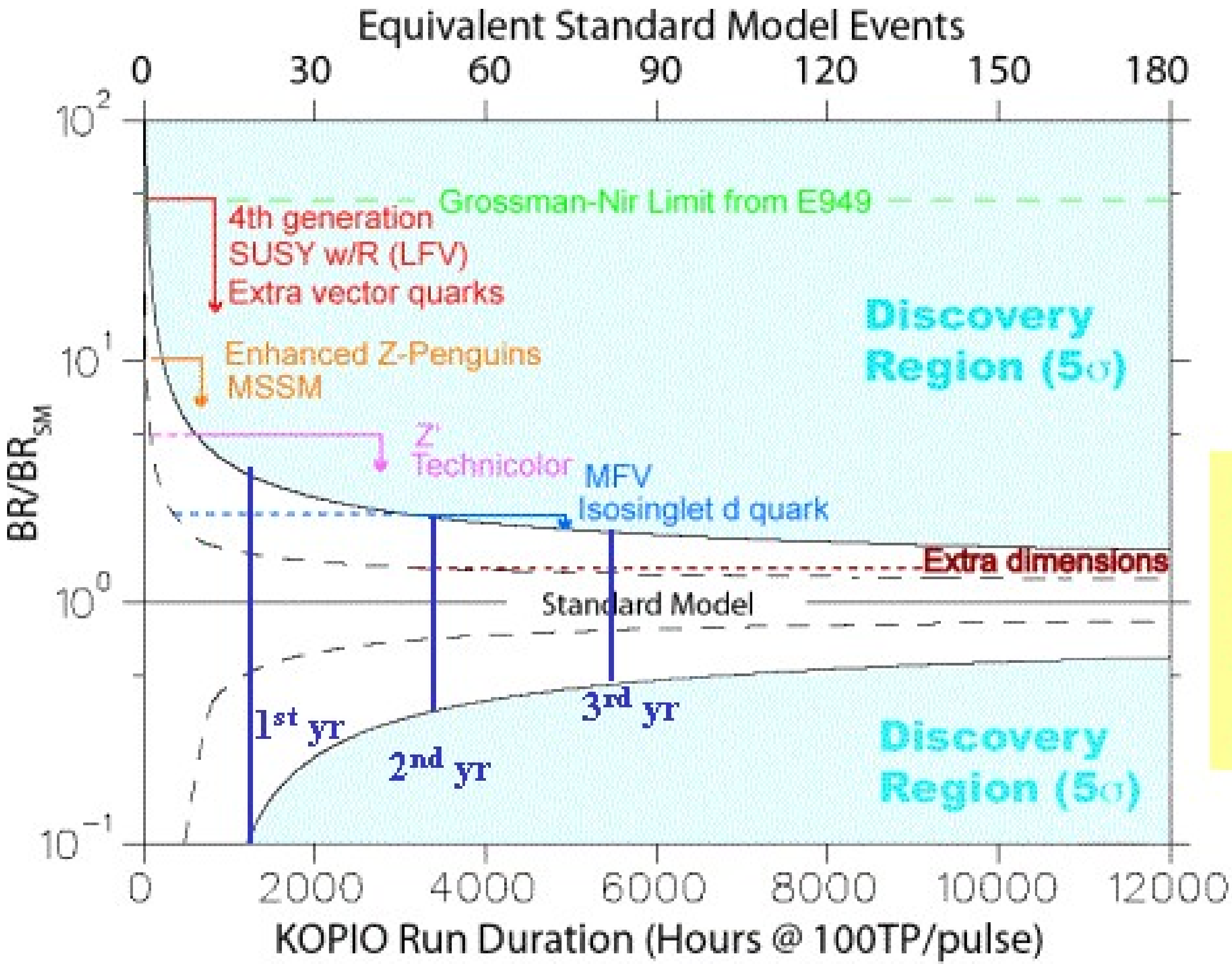
$K_L^0 \to \pi^0\nu\bar{\nu} : 0.3\times10^{-10}$

Best S/B ratio coming from both γ's hit the pre-radiator and the calorimeter.

# KOPIO's physics goal



# Sensitive to new physics




**Any deviation from SM will signal a new physics.**

# Summary

- Rare kaon decay is the theoretical ideal to test the Standard Model (SM) with potential to discover new physics beyond SM.
- Neutral rare kaon experiment: the best channel to study CP violation, but is rather challenge and needs more participants.
- Competition expected between BNL and J-PARC: another version of BaBar vs. Belle