# Rare Opportunity:
# Seeking New Physics with $K \to \pi\nu\bar{\nu}$

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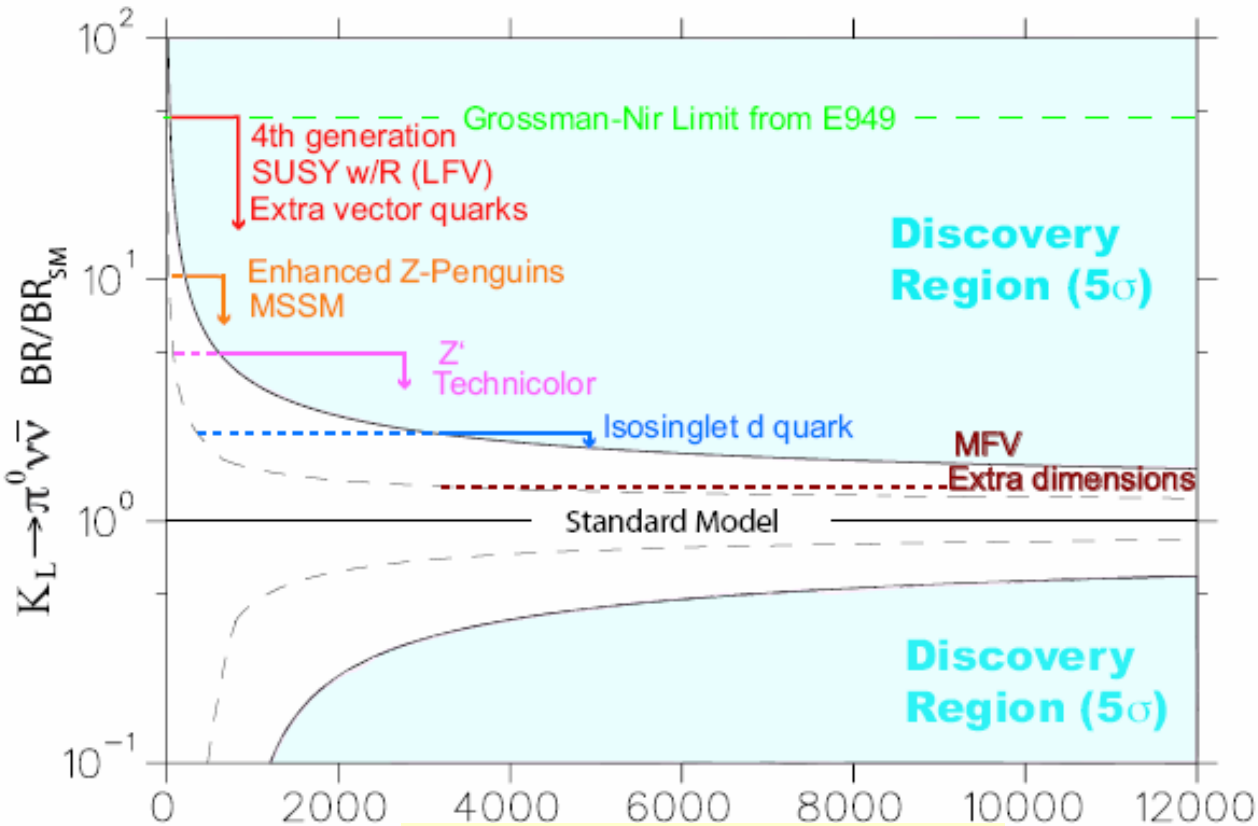
# $K_L^0 \to \pi^0 \nu\bar{\nu}$ Discovery Potential

$K_L^0 \to \pi^0 \nu\bar{\nu}\left(BR / BR_{SM}\right)$ *vs.* Events Observed

Experiment Sensitivity for SM Events

O(100) → O(1000)



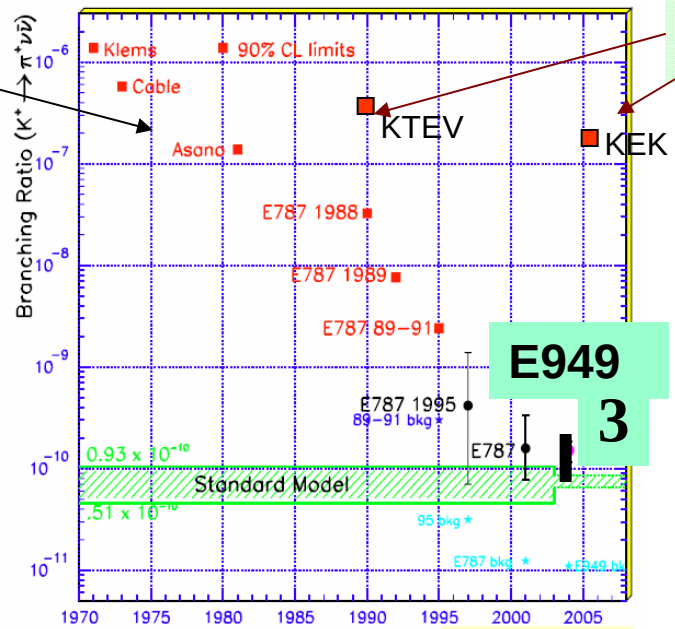

Run Duration (Hours*)

*AGS

# Experiments

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

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




**E949**

**3**

**KEK-> J-PARC?**

**NA62?** **100**

**Project X? 1000???**

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

# The Challenges

- $B(K_L \to \pi^0 \nu\bar{\nu}) \sim 3\times10^{-11}$ ;
  need huge flux of K's -> high rates
- Weak Kinematic signature ($\pi^0$ +2 particles missing)
- Backgrounds with $\pi^0$ up to $10^{10}$ times larger
- Veto inefficiency on extra particles must be $\leq 10^{-4}$
- Neutrons dominate the beam
  - make $\pi^0$ off residual gas – require high vacuum
  - halo must be very small
  - hermeticity may require photon veto in the beam
- Need convincing measurement of background

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

Background suppression factor needed: $10^{10}$

## Primary Backgrounds

| Mode | Branching Ratio |
|---|---|
| $K_L^0 \to \pi^0 \pi^0$ | $0.93 \ x \ 10^{-3}$ |
| $K_L^0 \to \pi^- e^+ \nu \gamma$ | $0.36 \ x \ 10^{-2}$ |
| $K_L^0 \to \pi^+ \pi^- \pi^0$ | 0.1255 |
| $K_L^0 \to \pi^0 \pi^0 \pi^0$ | 0.2105 |

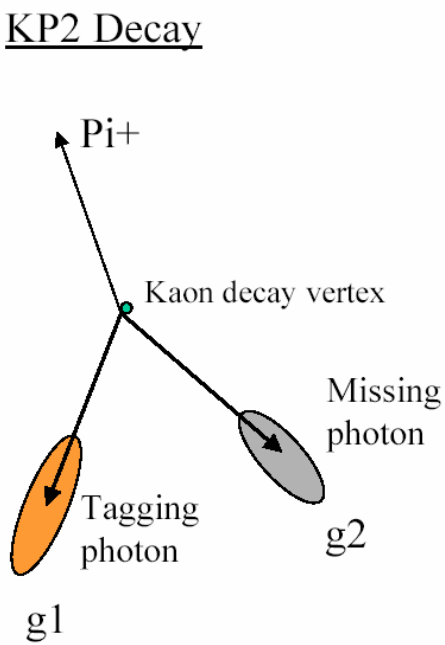
Others

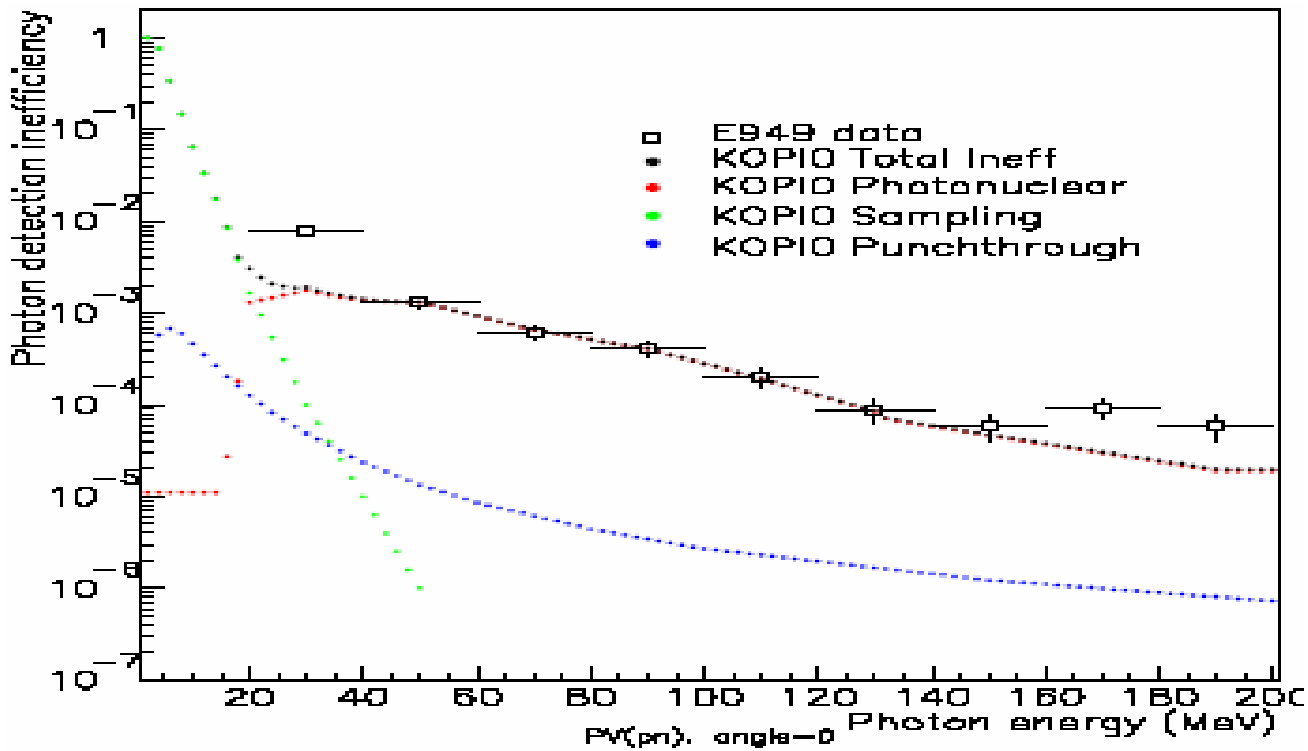
# Photon Veto Efficiency Estimates and Simulations based on improved E949 Measurements supplemented by FLUKA calculations

Photon Detection Efficiency limited by

- Photonuclear interactions ("$\gamma \rightarrow$ n")
- Sampling Fluctuations
- Punch-through

1 MeV Visible Energy Threshold



# Photon Veto Inefficiencies Assumed for JPARC $K_L^0 \to \pi\nu\nu$

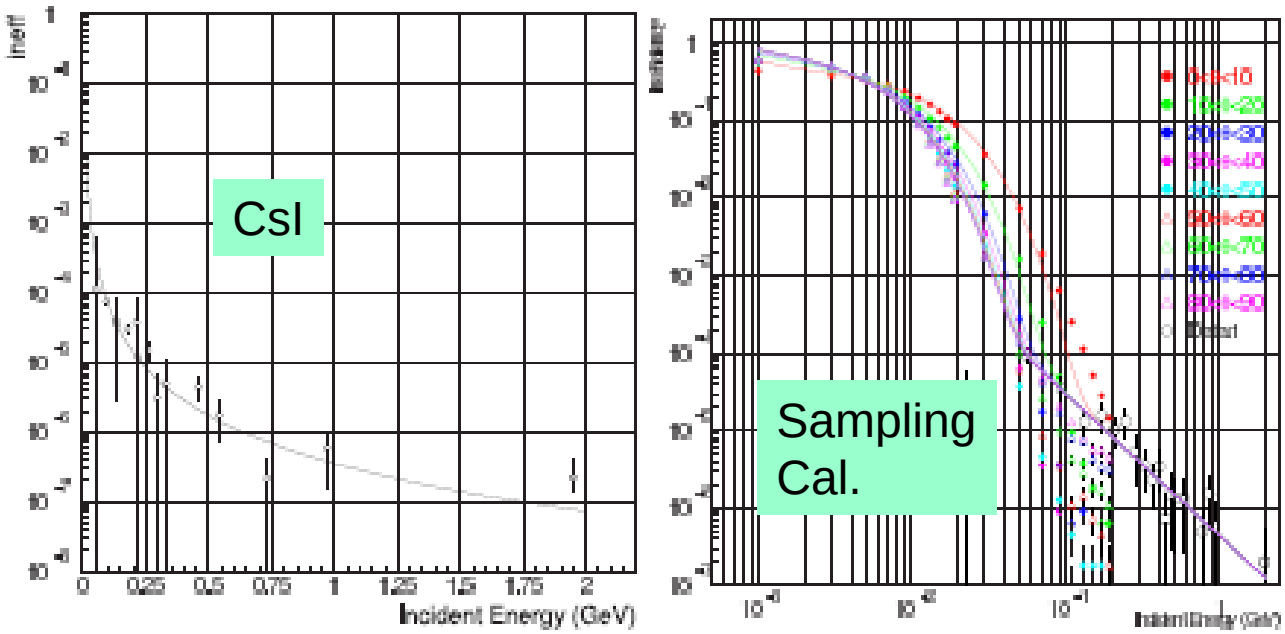
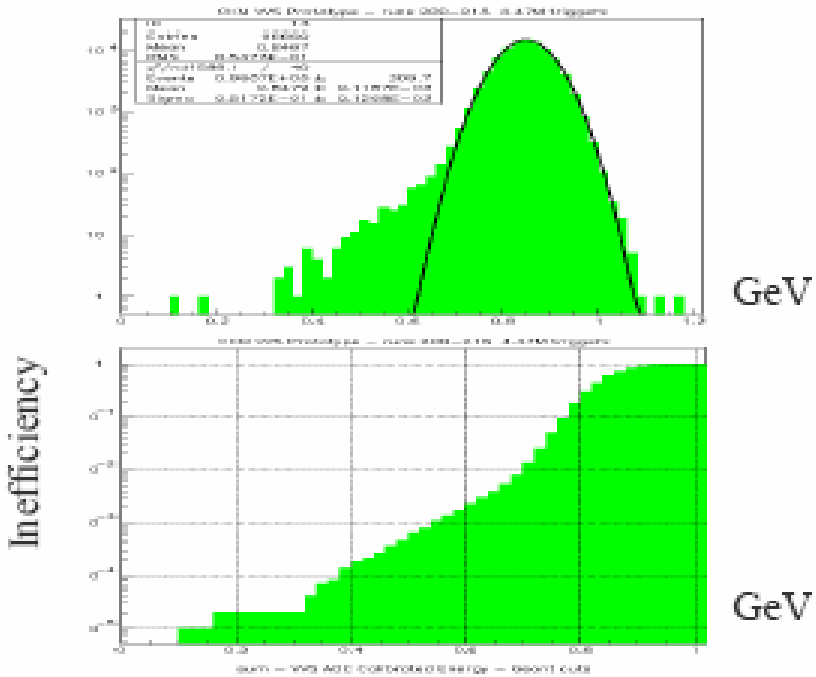



Figure 56: Photon detection inefficiencies for CsI crystals (Left) and a sampling calorimeter (Right) as a function of incident photon energy. The open black circles are experimental data for photonuclear interactions. Monte Carlo results for the inefficiencies due to punch-through and sampling fluctuations are shown in the Right figures as colored points. Different colors indicate different incident angles on the detector. The solid curves are the model inefficiency functions obtained by fitting the data and Monte Carlo results.

# Photon Veto Inefficiency and Technology

- 0.3% VVS Prototype built
- Tested at JLAB in an $e^-$ beam
- Achieved $<1\times10^{-5}$ ($3\times10^{-6}$) veto inefficiency at 1 GeV (required $3\times10^{-5}$)



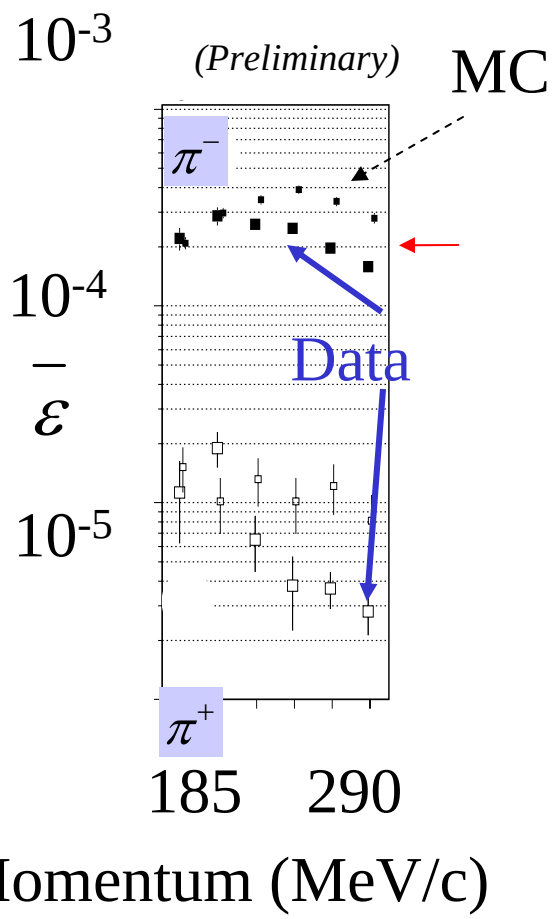
# Charged Particle Vetoing

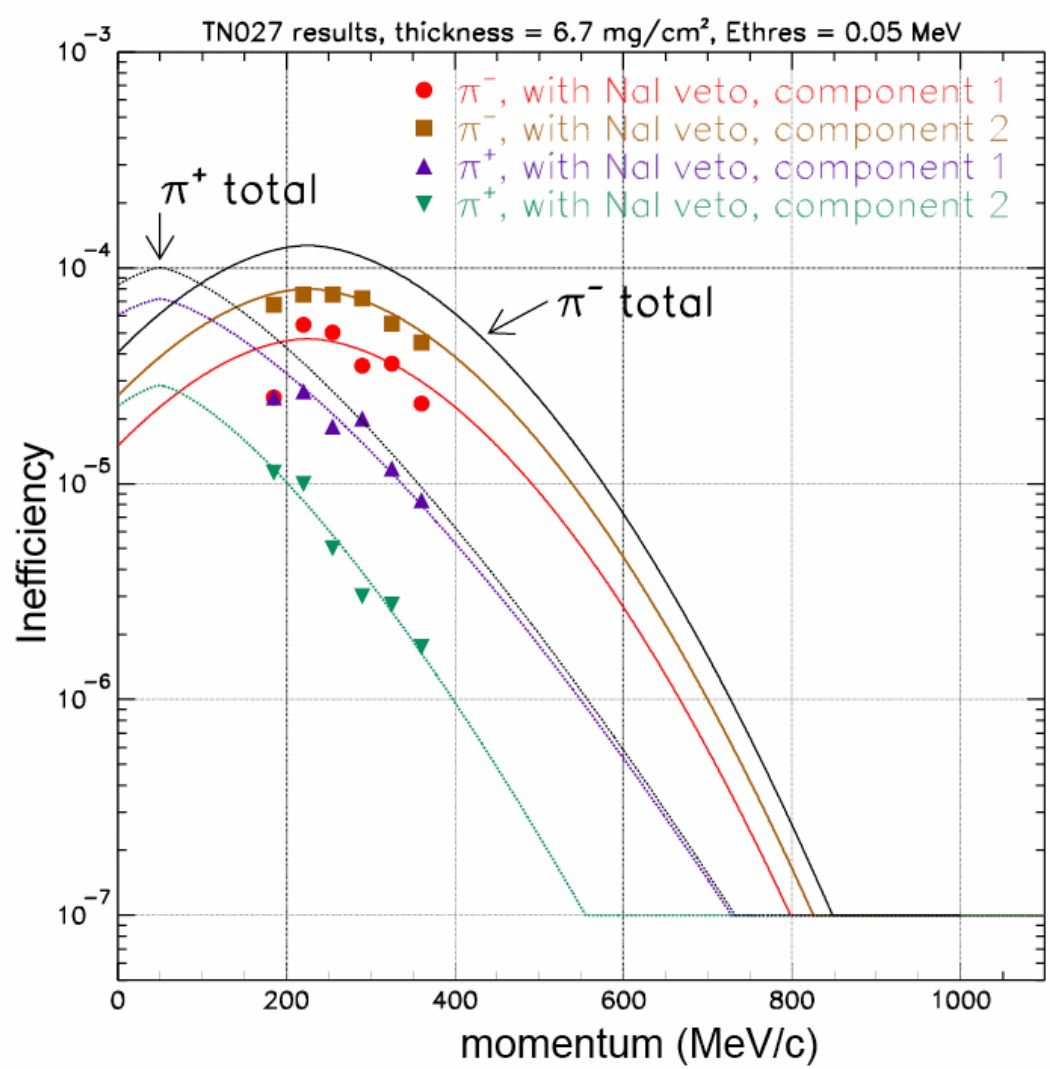
Example Background: $\mathbf{K}_L^0 \rightarrow \pi^- e^+ \nu \gamma$

Plastic Scintillator –

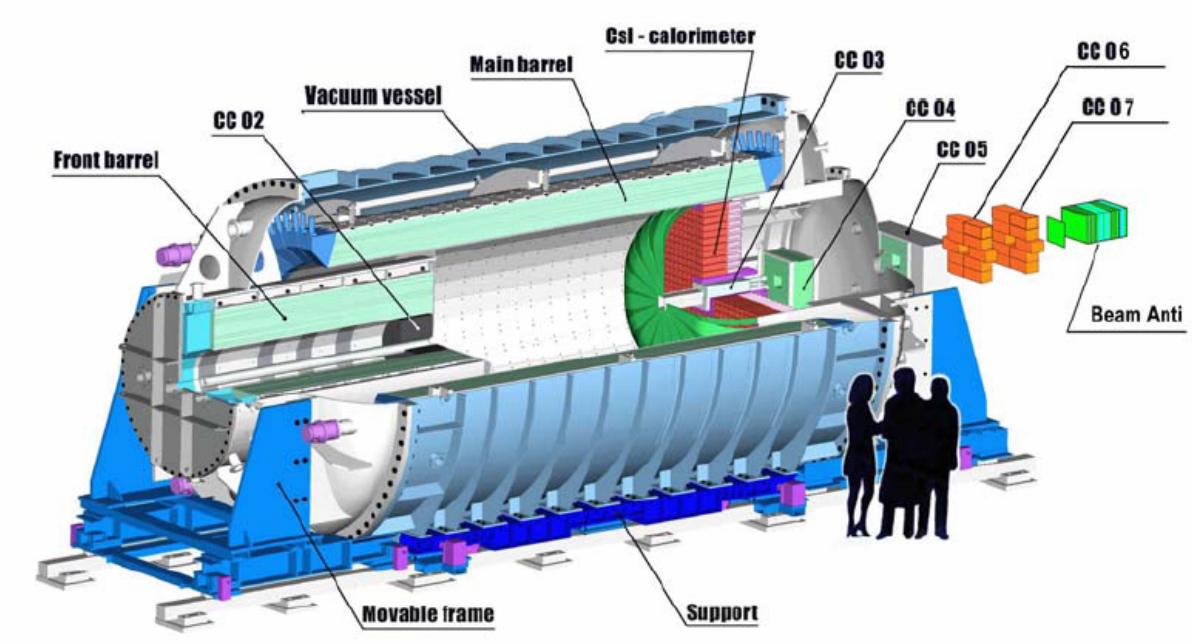
**backed up by γ vetoes!**

PSI Measurement



# KEK PS E391a >>> JPARC with KTEV CsI




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

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

2006 Result: $B(K_L^0 \to \pi^0 \nu\bar{\nu}) < 2.1 x 10^{-7}$ $(90\% CL)$

# Transverse Momentum $P_T$ *vs*. Vertex Position (Z)

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

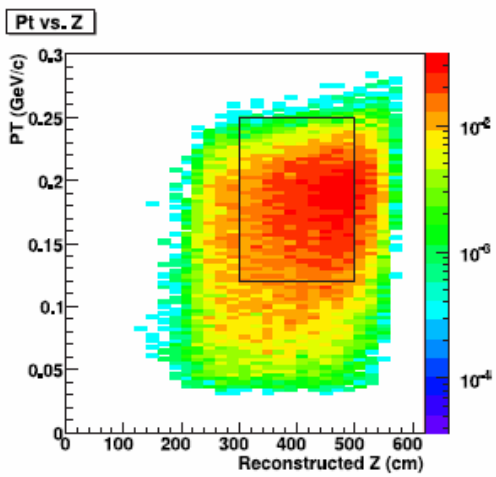



Figure 33: Distribution of $P_T$ vs. the reconstructed $z$ position for the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ signal events. The box shows the signal region.

$K_L^0 \rightarrow \pi^0 \pi^0$ "Odd"

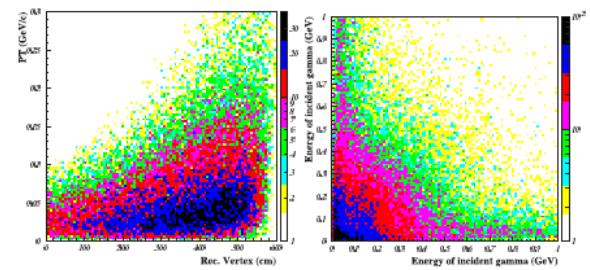



Figure 35: Left: reconstructed vertex and $P_T$ distribution for odd-pairing $K_L \rightarrow \pi^0\pi^0$ background. The reconstructed vertex is not correct which make the $P_T$ lower than the signal box. Right: Energy distribution of photons that enter the veto counters. Even though many events have low energies for both of the photons, the events are rejected through the high-$P_T$ selection. As a result, the photons needed to be rejected by the veto counters have distributions similar to those for even pairing.

$K_L^0 \rightarrow \pi^0 \pi^0$ "Even"

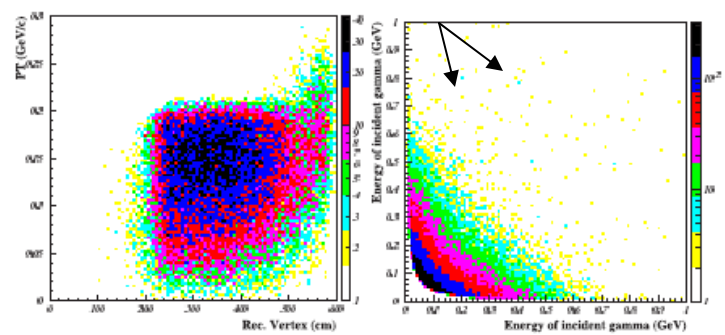



Figure 34: Left: reconstructed vertex and $P_T$ distribution for even pairing $K_L \rightarrow \pi^0\pi^0$ background. It has a distribution similar to that of the $K_L \rightarrow \pi^0\nu\bar{\nu}$ decay. Right: Energy distribution of gammas that enter the veto counters. At least one photon has sufficiently high energy to trigger the counter with a high detection efficiency.

# KEK PS E391a >>> JPARC

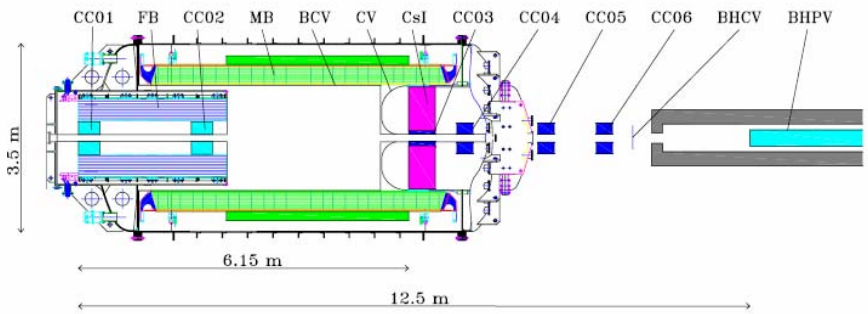



Figure 2: Schematic view of the E14 detector setup.

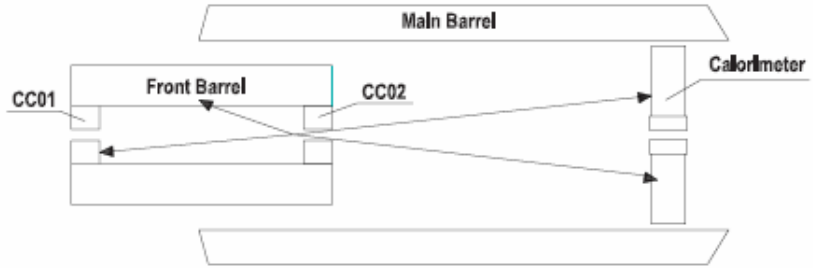



Figure 26: Schematic view of the role of the upstream decay chamber.

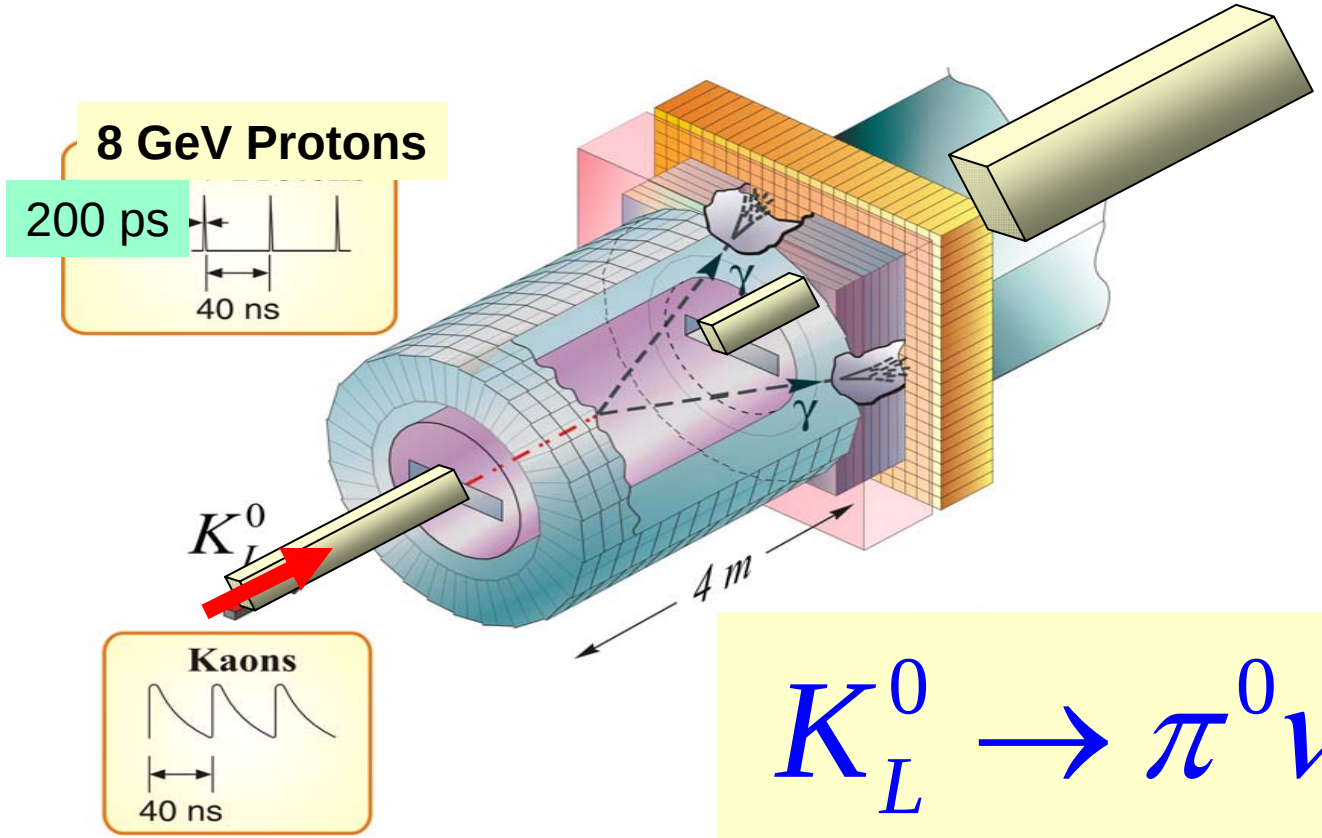
JPARC Phase 1 with KTEV CsI

Estimates: SM Signal 3.5

Background 2

JPARC Phase 2 Goal… 100 events S/N~5

# Another $K_L^0 \to \pi^0 \nu \bar{\nu}$ Experiment Concept




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

- Use TOF to work in the $K_L^0$ c.m. system
- Identify main 2-body background $K_L^0 \to \pi^0 \pi^0$
- Reconstruct $\pi^0 \to \gamma\gamma$ decays with pointing calorimeter
- $4\pi$ solid angle photon and charged particle vetos

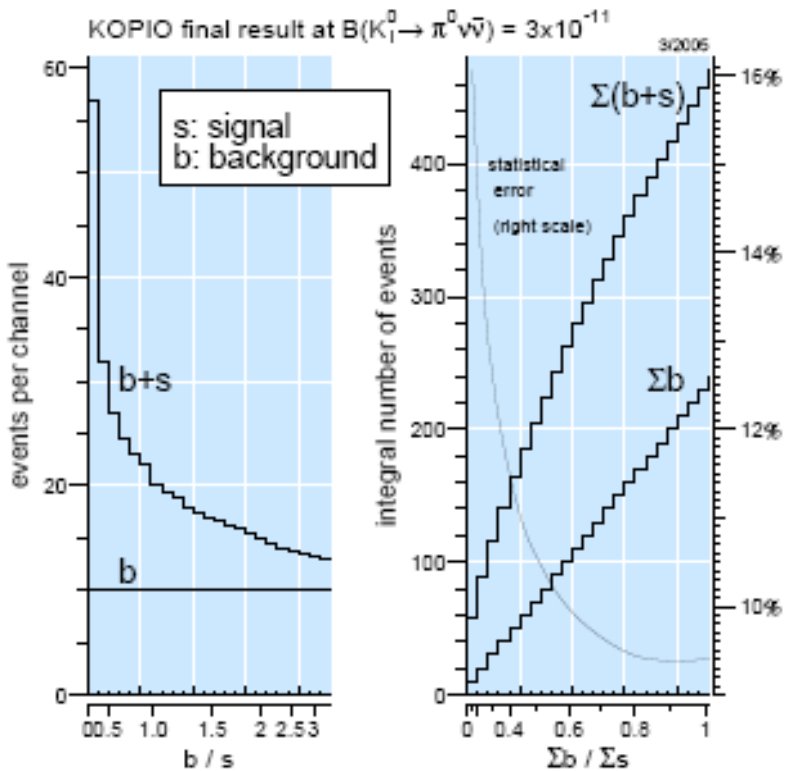



Fig. 13.28. Left: Events per channel where events are sorted into channels by B/S until a channel contains ten background events. The upper curve shows the total number of events expected in each channel. Right: The integrated number of events as a function of the total background to total signal ratio in each channel. The "statistical error" (right scale) shown is the square root of the integrated number of events divided by the total signal yield at each channel. This would be the relative uncertainty on a $K_L^0 \to \pi^0\nu\bar{\nu}$ branching fraction measurement if there were no uncertainty in the background yield and if the full power of the likelihood method were not employed.

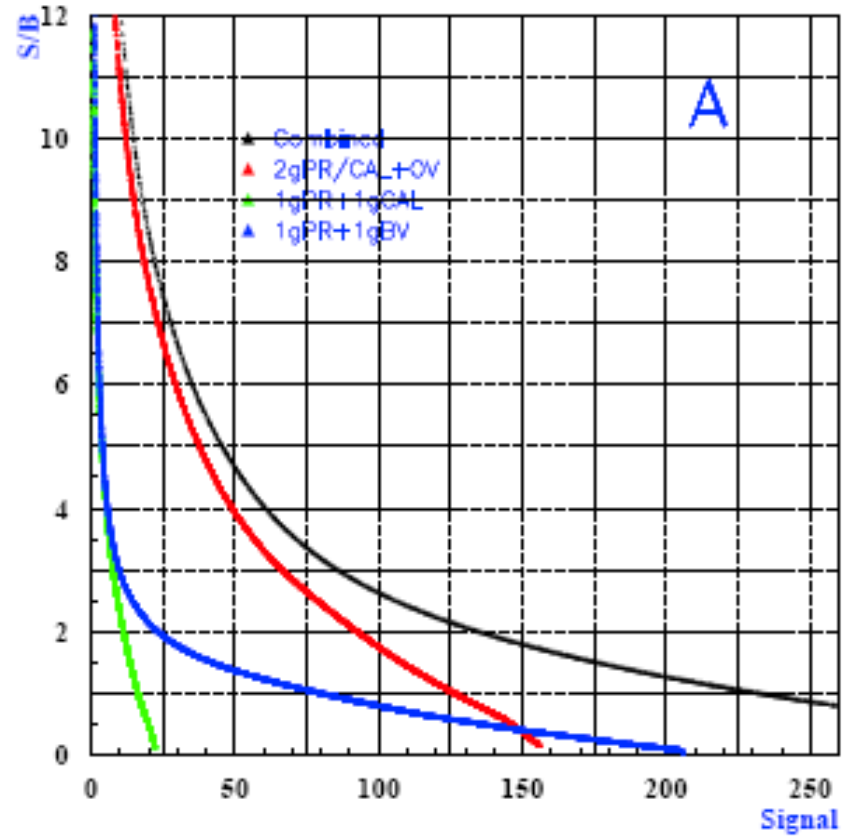



Fig. 13.19. The signal-to-background ratio ($S/B$) as a function of signal for all detection methods (black line) and for each of the three detection methods. The 2γPR method is shown in red, the 1γPR/CAL method is shown in green and the 1γPR/BV method is shown in blue.

# Issues and Prospects for $K_L^0 \to \pi^0 \nu \bar{\nu}$ Experiments

## Booster (20 kW) → Project X1 (200kW) → Project X2 (2000kW!)

- **High intensity, low energy micro-bunched beam**
  - Allows KL energy to be measured by TOF
- **Optimized beam structure to maximize probability for 1 $K_L$ decay/micro-bunch**
- **High duty factor: >80%**
- **Booster: $2 \times 10^{20}$ protons/yr; X1 (x100) X2 (x1000).**

- Measure γ energy, position, angle, time
- Hermetic veto (gammas and charged particles)
- Predict background from data
- Blind analysis & maximum likelihood techniques
  - As in BNL E787 & 949

# Straw "Person" Assumptions
## (For Comparison with KOPIO Design)

- 45 degree cross sections at 8 GeV are 0.5 x those at 24 GeV for 1 GeV kaons (>50% uncertainty – see Sergei's talk).
- Beam aperture 0.05 x the area of the KOPIO wide beam.
- Optimization for **1 $K_L$ decay/bucket** results in a large recovery factor.
- Detector acceptance increased relative to KOPIO by 50%: larger detectors (25%); improvede acceptance (25%).
- Minimal accidental losses (until X2).

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

Straw "Person" Order of Magnitude Estimates

| | FNAL Booster X0 | FNAL Proj X1 | FNAL Proj X2 |
|---|---|---|---|
| Events/yr | 50 | 300 | 600 |
| 5 yr. Precision(%) | 8 | 4 | 3 |

Rough estimates based on extrapolations from KOPIO design.

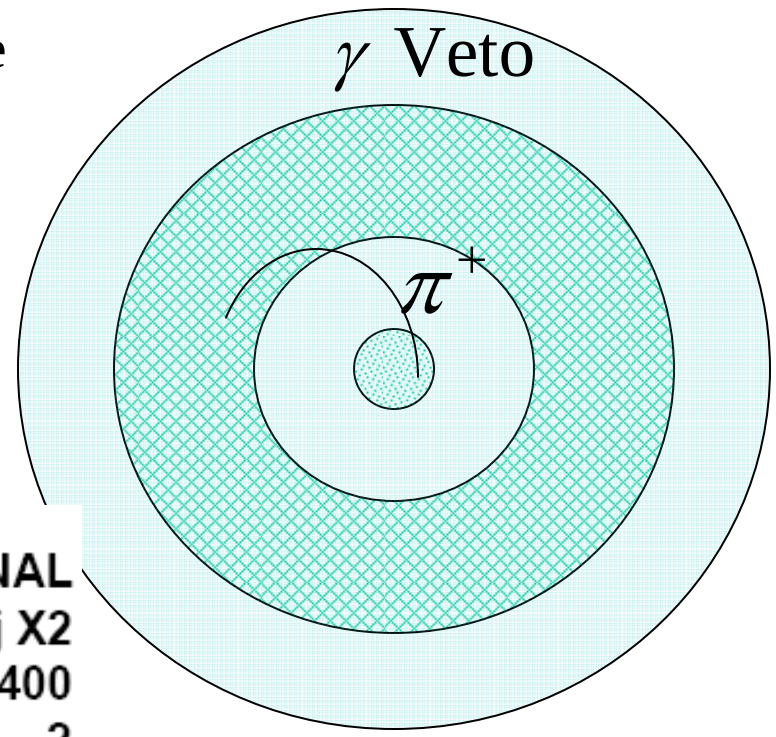
# Compact High Field Version of E787/E949

- Low $P_K$ (400 MeV/c) for high stopping efficiency
- Sci-Fi target and range stack for high rate $\pi \to \mu \to e$
- Increased acceptance, and improved momentum measurement suppresses $K^+ \to \pi^+\pi^0, \to \mu^+\nu$
- Improved homogeneous photon veto e.g LXe (Photon "tracking" to reduce accidental losses?)

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

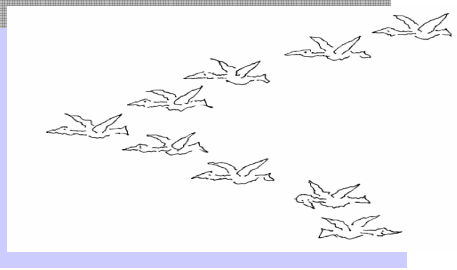
Straw "Person" Order of Magnitude Estimates

| | FNAL Booster X0 | FNAL Proj X1 | FNAL Proj X2 |
|---|---|---|---|
| Events/yr | 50 | 200 | 400 |
| 5 yr. Precision(%) | 6 | 3 | 2 |




3T field

# Summary



Rare Decays of $\mu, \pi,$ and $K$ offer unique, clean access to the flavor breaking and CP-violating structure of hypthetical new physics -- access to short distance effects and high mass scales are complementary to collider studies at the LHC.

Star Attractions: New Physics Sensitvity

- ($\mu \to e$ Conversion) and $\mu \to e\gamma$ **PSI-MEG** $\frac{1}{M_H^4}$
- $\frac{\pi / K \to e\nu}{\pi / K \to \mu\nu}$ PI E NU **PSI-PEN** **KLOE** **NA48/3** $\frac{1}{M_H^2}$
- $K_L^0 \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ $\frac{1}{M_H^2}$

**JPARC** **CERN P-326**

**FNAL ??**

**PROJX ??**