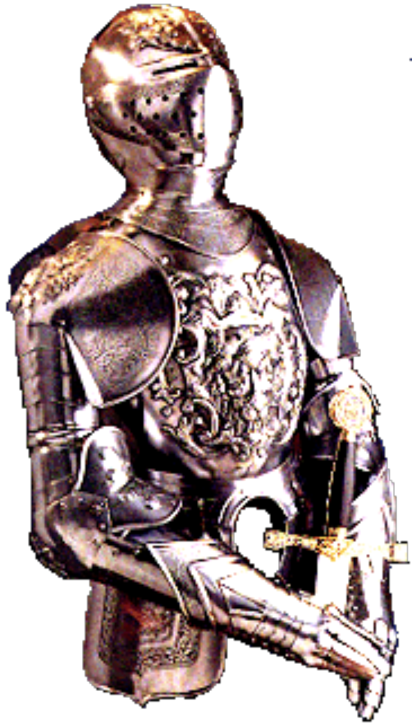


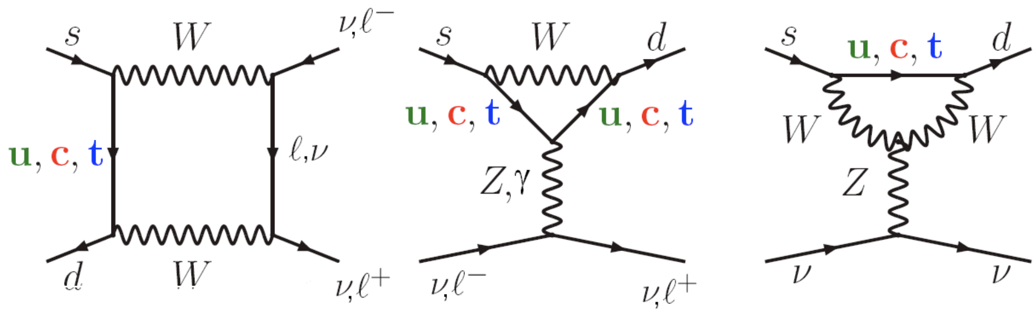
The Quest for $K \to \pi\nu\nu$

Monica Tecchio
University of Michigan

FPCP 2010
Torino, May 29th, 2010

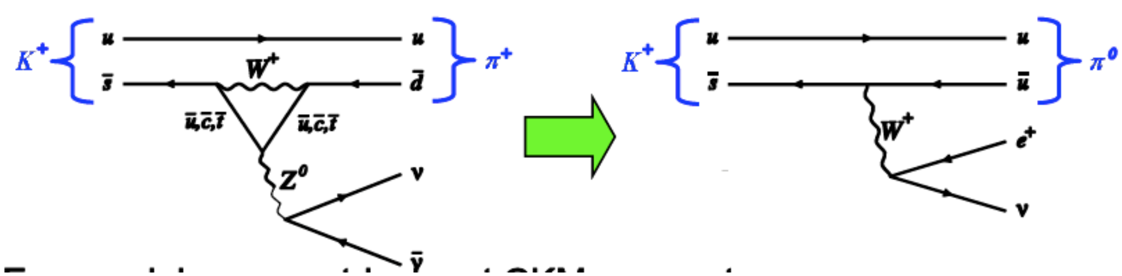
The Prologue

- The two rare kaon decays, $K_L \to \pi^0 \nu\nu$ & $K^+ \to \pi^+ \nu\nu$, are FCNC processes, forbidden at tree level and dominated by one loop diagrams



- They involve $\mathcal{O}(G_F^2)$ loops (W boxes and Z penguins) which can be predicted very precisely (2-5% level) in perturbation theory

- Relevant hadronic operator can be calculated from $K^+ \to \pi^0 e\nu$



The Prologue

- Theoretical calculations gives:

  $BR(K^+ \to \pi^+ \nu\nu) = (8.2 \pm 0.8) \times 10^{-11}$

  $BR(K_L \to \pi^0 \nu\nu) = (2.8 \pm 0.4) \times 10^{-11}$

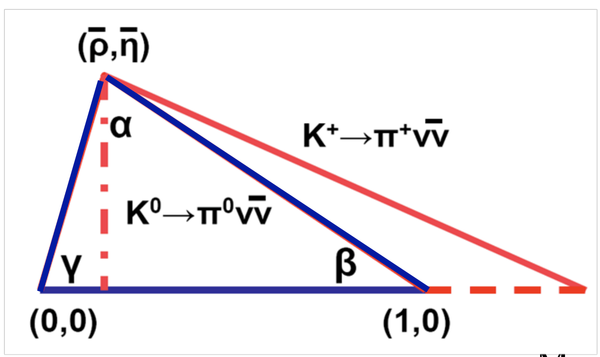
where the uncertainty is mostly parametric

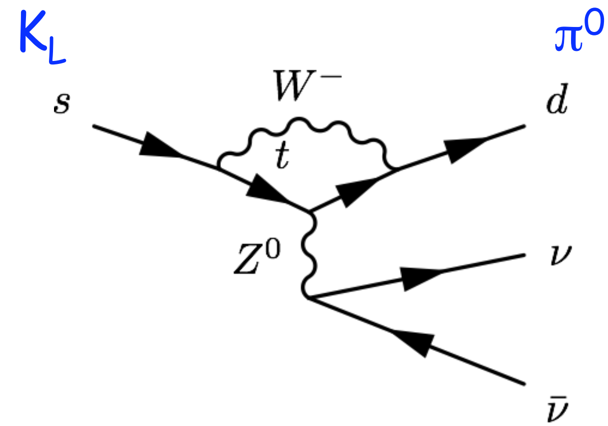
- Isospin symmetry (Grossman-Nir limit) :

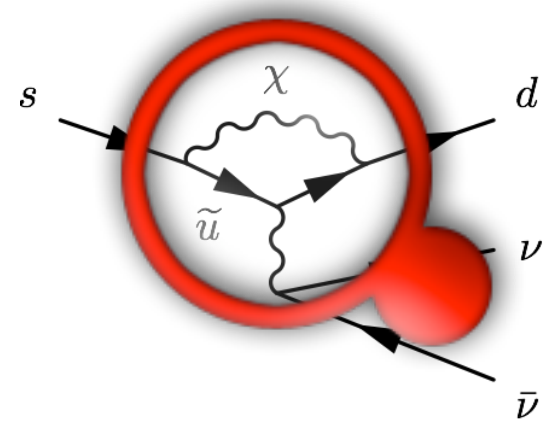
  $BR(K_L \to \pi^0 \nu\nu) \leq \tau_{KL}/\tau_{K+} \, BR(K^+ \to \pi^+ \nu\nu)$

- Very sensitive to New Physics

- Directly related to CKM unitarity triangle:

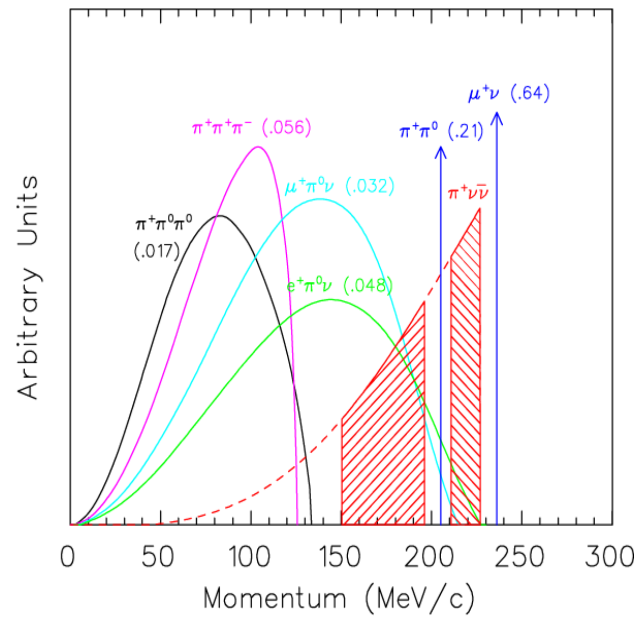


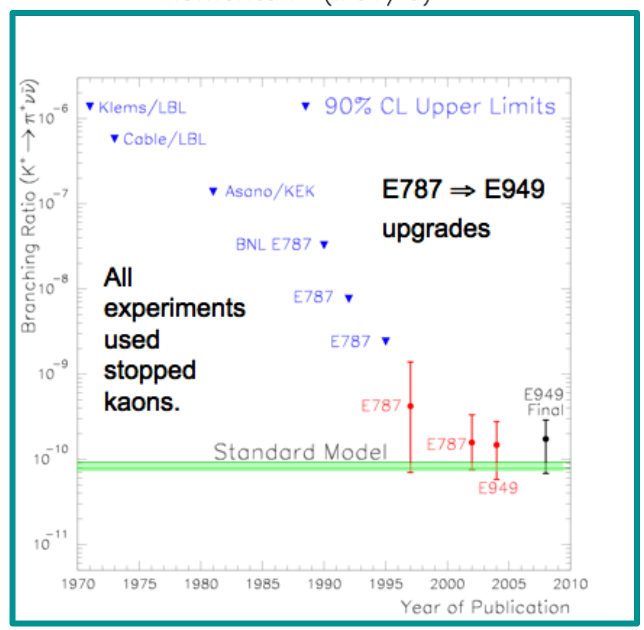




The Charged Quest

- $BR(K^+ \to \pi^+ \nu\nu) \sim 80 \times 10^{-12}$
- 3-body decay, only 1 visible, π^+, a common K^+ decay product
- Need particle ID for beam and daughter particles
- Backgrounds:
  - $K^+ \to \mu^+ \nu(\gamma)$
  - $K^+ \to \pi^+ \pi^0$
  - $K_L \to \pi^+ \ell^- \nu$, ℓ^- missed
  - Beam related backgrounds (can be different for kaon decay at rest vs kaon decay in flight)

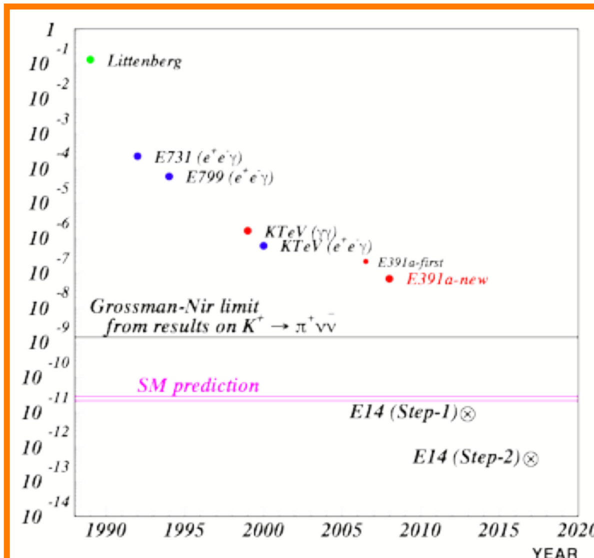




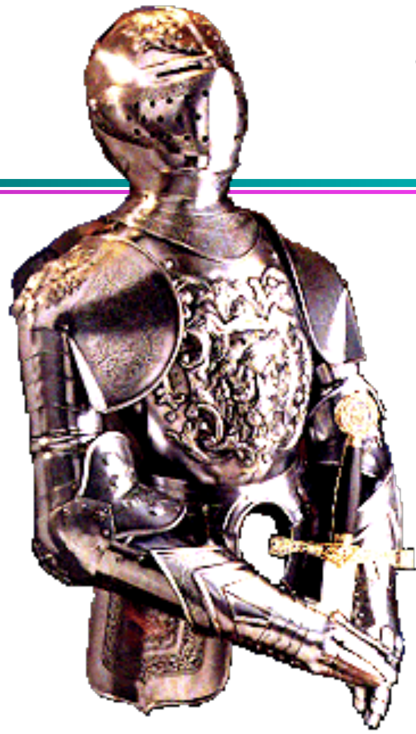
The Neutral Quest

- $B(K_L \to \pi^0 \nu\nu) \sim 30 \times 10^{-12}$
- Kinematic signature "nothing going into nothing"
- K_L decays with π^0 up to 10^{10} times larger than signal
- Veto inefficiency on extra particles, both charged particles and photons, must be $\leq 10^{-4}$
- Huge flux of neutrons in beam
  - can make π^0 off residual gas – requires high vacuum
  - halo must be tiny
  - hermeticity requires photon veto for beam

K_L Decay	BR
$\pi^\pm e^\mp \nu_e$	3.88×10^{-1}
$\pi^\pm \mu^\mp \nu_\mu$	2.72×10^{-1}
$\pi^0\pi^0\pi^0$	2.10×10^{-1}
$\pi^+\pi^-\pi^0$	1.26×10^{-1}
$\pi^\pm e^\mp \nu_e \gamma$	3.53×10^{-3}
$\pi^+\pi^-$	2.09×10^{-3}
$\pi^0\pi^0$	9.32×10^{-4}
$\gamma\gamma$	5.90×10^{-4}
$\pi^\pm \mu^\mp \nu_\mu \gamma$	5.70×10^{-4}
$\pi^0 \pi^\pm e^\mp \nu$	5.18×10^{-5}
$\pi^+\pi^-\gamma$	4.39×10^{-5}



Review of experiments



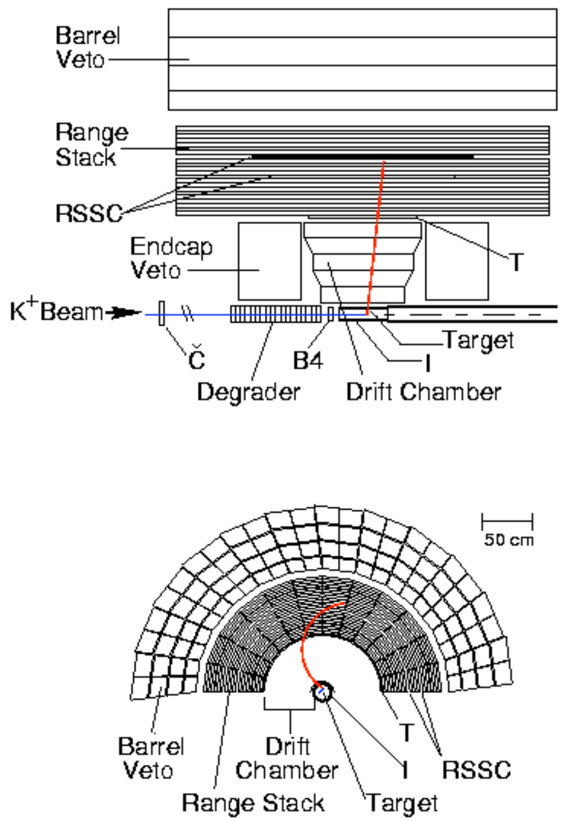
- $K^+ \to \pi^+ \nu\nu$
  - E787/E949 at BNL
  - NA62 at CERN
- $K_L \to \pi^0 \nu\nu$
  - E391a at KEK
  - KOTO at JPARC
- P993 at Fermilab
- Project X at Fermilab

E787/E949

1 ~700 MeV/c K^+ stopped in target, decays at rest

2 Identify and measure $\pi^+ \rightarrow \mu^+ \rightarrow e^+$

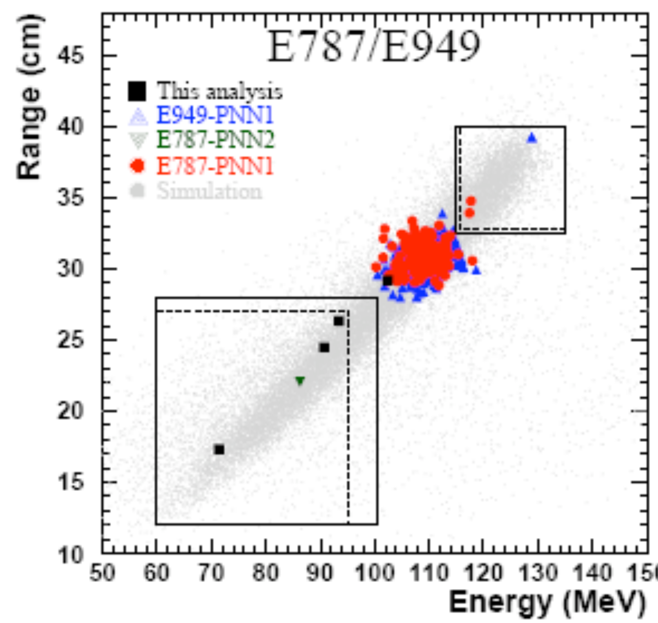
3 Veto on any other activity



- Search in two regions: PNN1 and PNN2 (above/below $\pi^+\pi^0$ peak)
- Combined result:

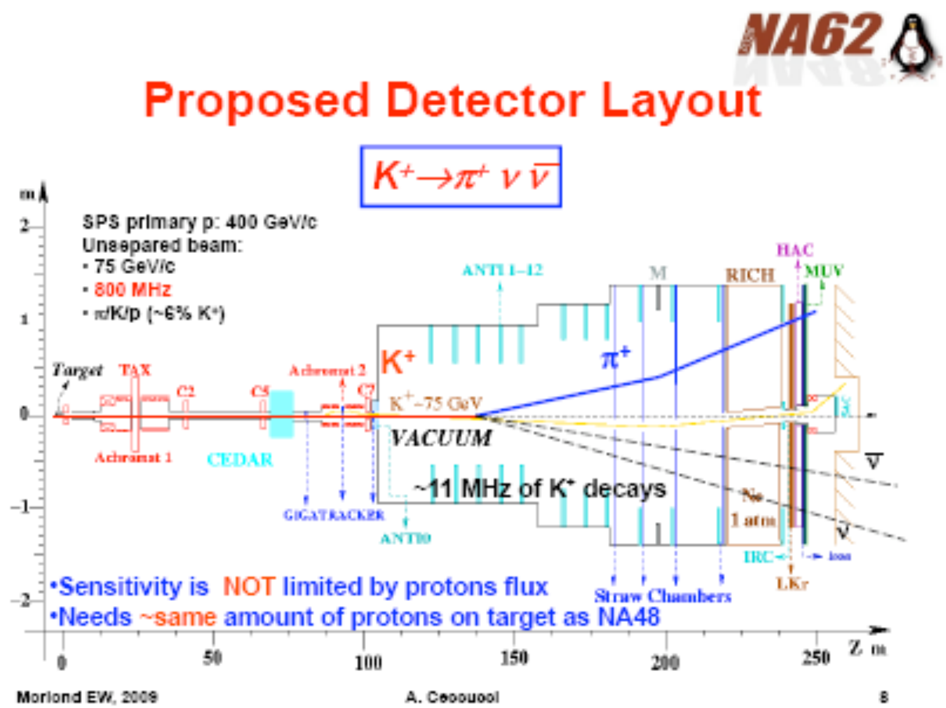
$BR(K^+ \rightarrow \pi^+ \nu \nu) = (17.3\ ^{+11.5}_{-10.5}) \times 10^{-11}$

with a probability of 0.001 for all 7 events to be due to background and 0.07 to be due to SM.



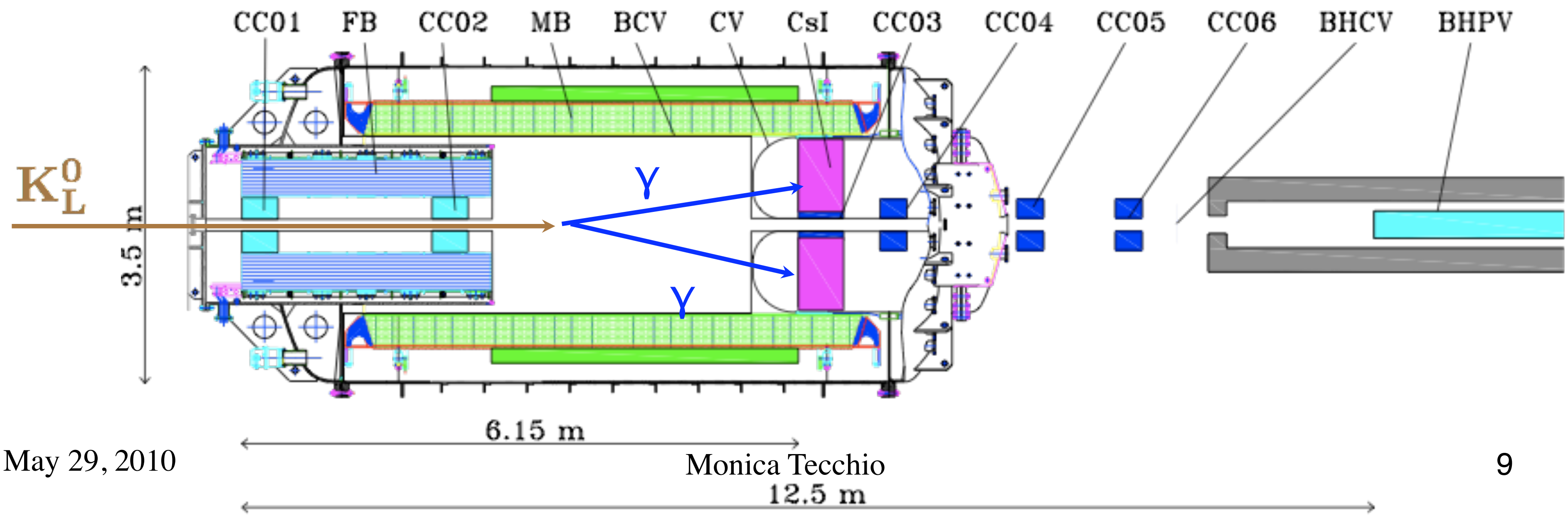
NA62

- New approach to $K^+ \to \pi^+ \nu\nu$ detection: use high momentum K^+ decay in flight
- Improves on E787/E949 sensitivity by avoiding background from source scattering and requiring low momentum π+ (below 2-body decay kinematic threshold)
- More on next talk



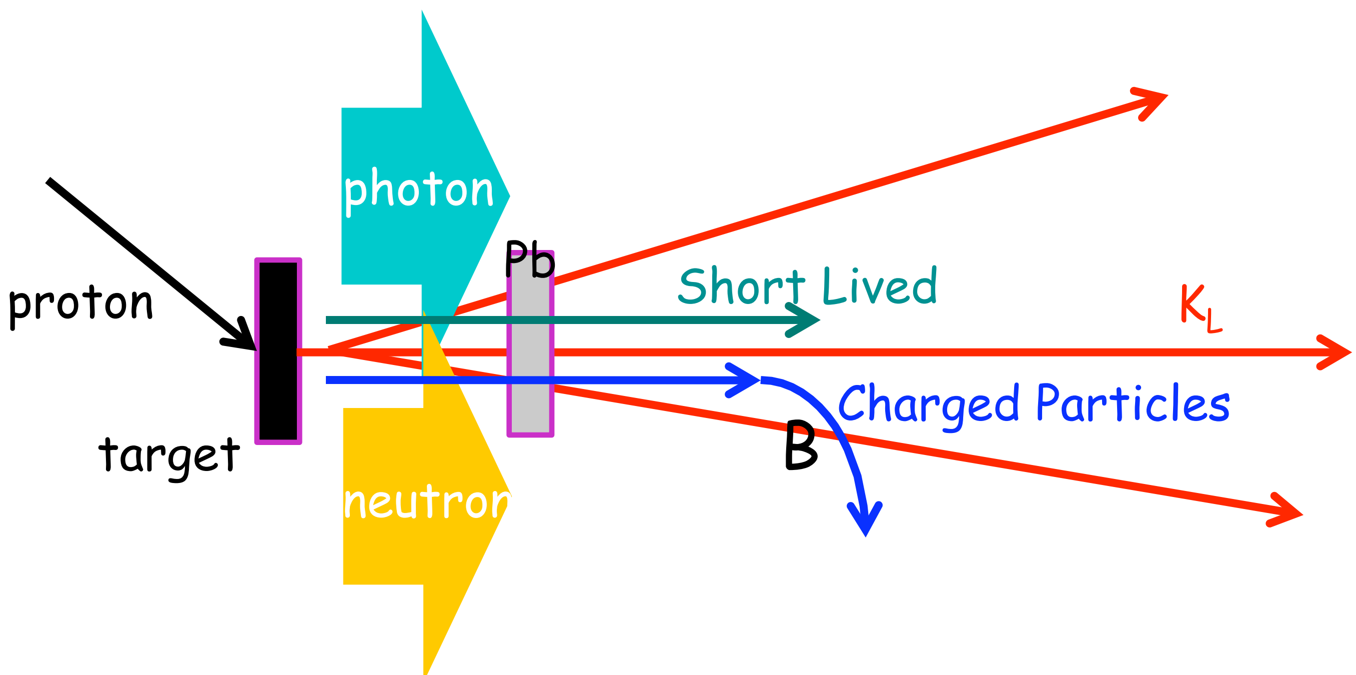
E391a

- First dedicated $K_L \rightarrow \pi^0 \nu\nu$ experiment looking for two photons and some missing momentum P_T
- Use 12 GeV proton beam at KEK-PS
- Three runs between Feb. 2004 and Dec. 2005



What does it take to catch a $K_L \rightarrow \pi^0 \nu\nu$?

- Clean K_L beam (off-axis beam line with photon absorber, sweeping magnet and long decay line)



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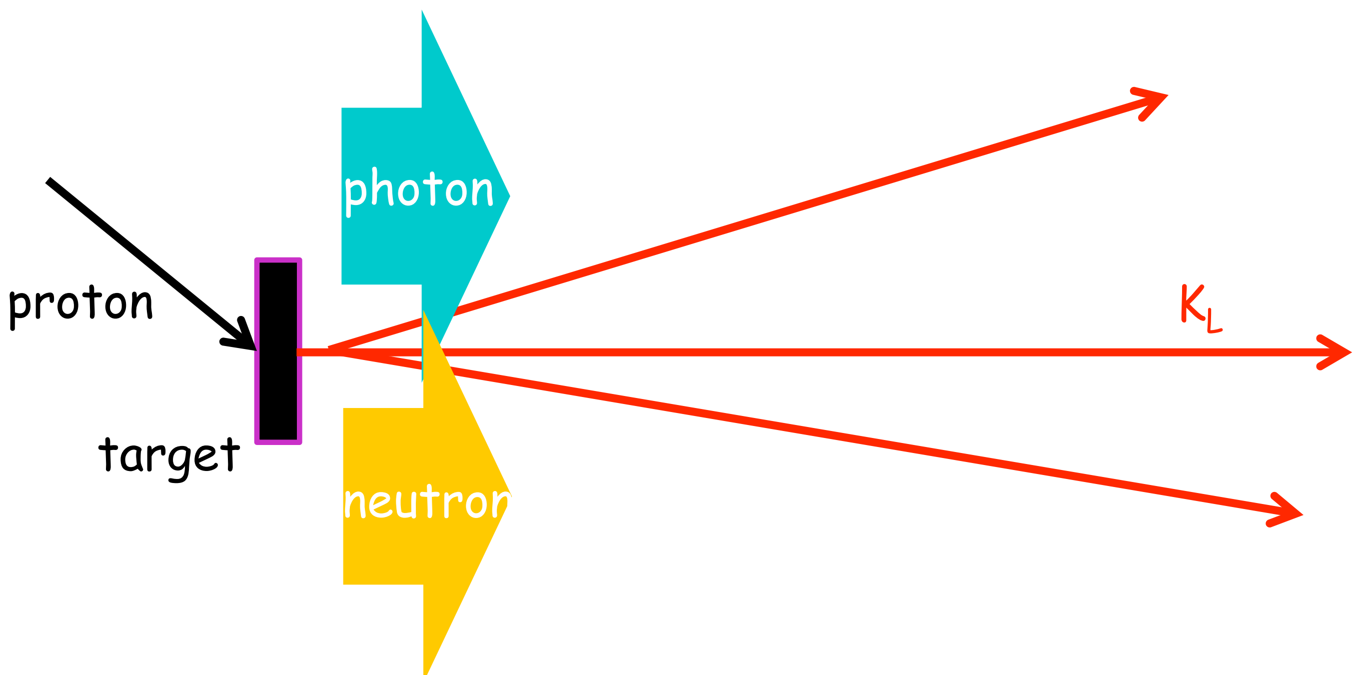
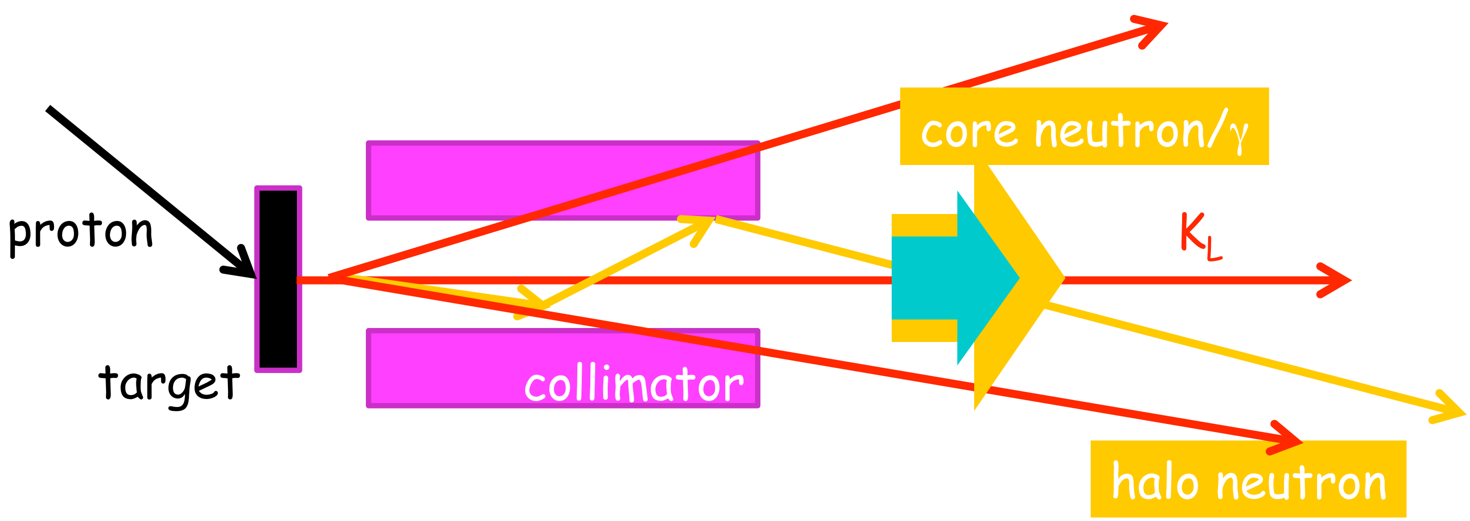


What does it take to catch a $K_L \rightarrow \pi^0 \nu\nu$?

- Clean K_L beam (off-axis beam line with photon absorber, sweeping magnet and long decay line)
- Pencil size beam (highly shaped collimators to minimize halo particles generated by scattering off the collimator surface)



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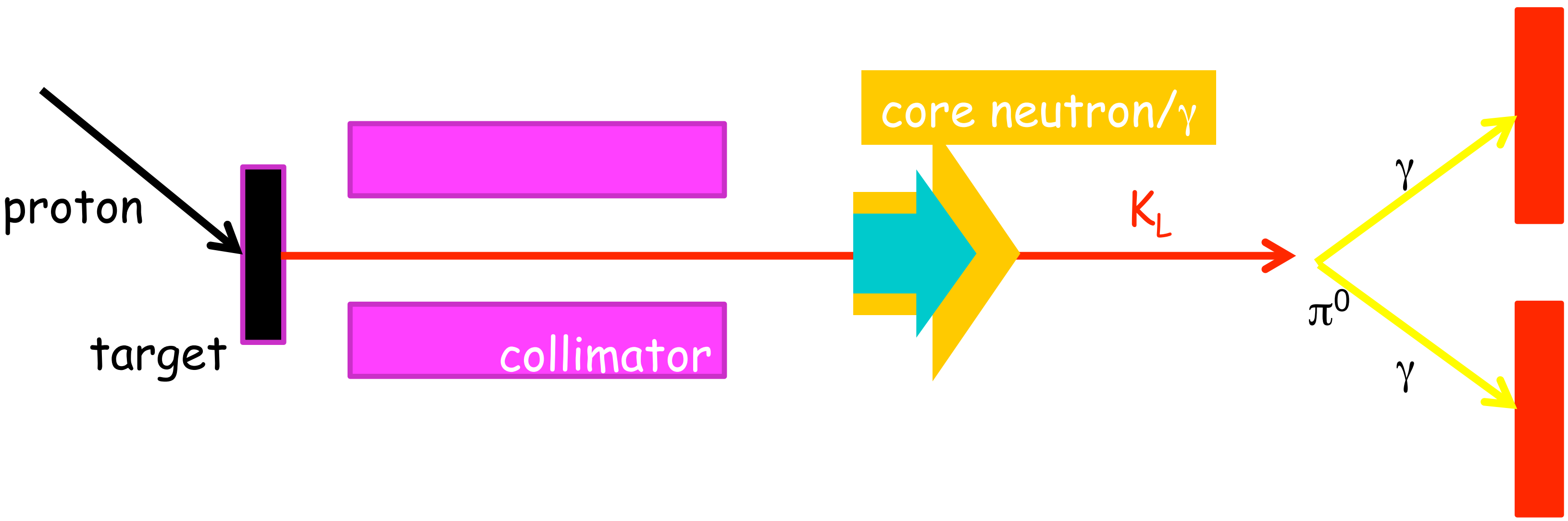

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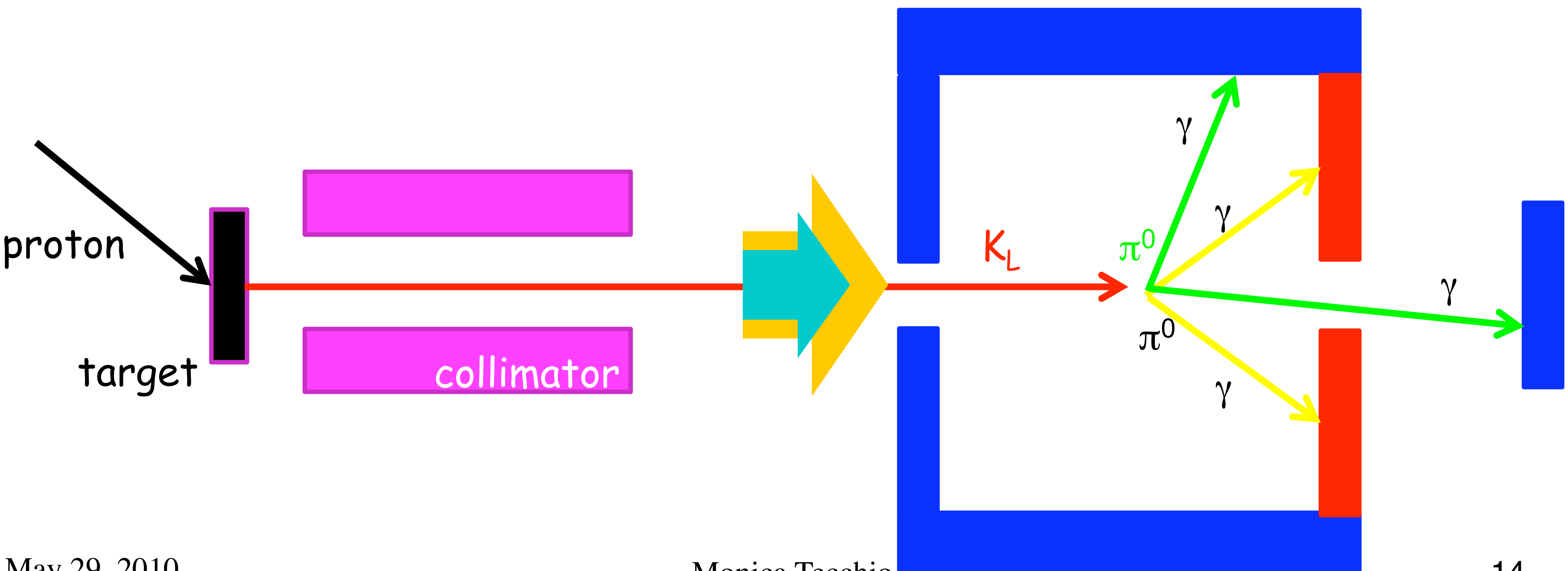
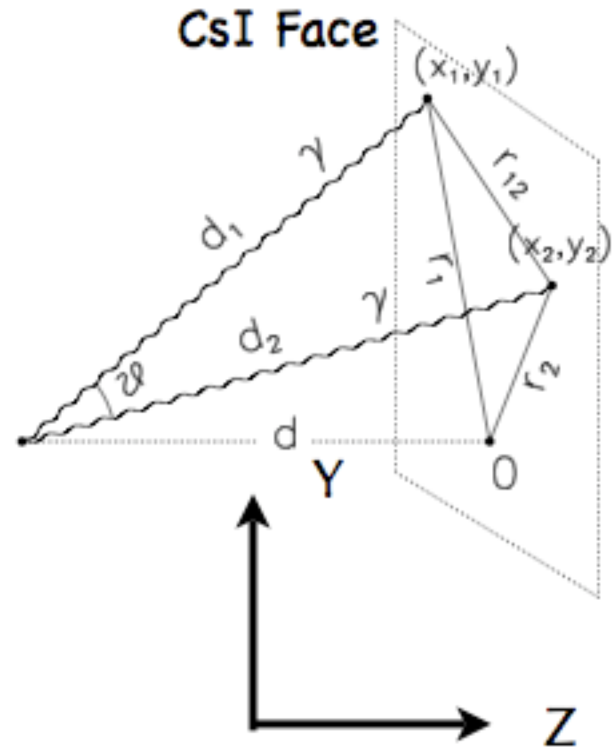


What does it take to catch a $K_L \rightarrow \pi^0 \nu\nu$?

- Fully reconstruct π^0 and K_L
  - constrain 2γ system to π^0 mass, get the two photon opening angle θ
  - assuming K_L decay vertex on beam line, determine Z_{vtx} of π^0 decay

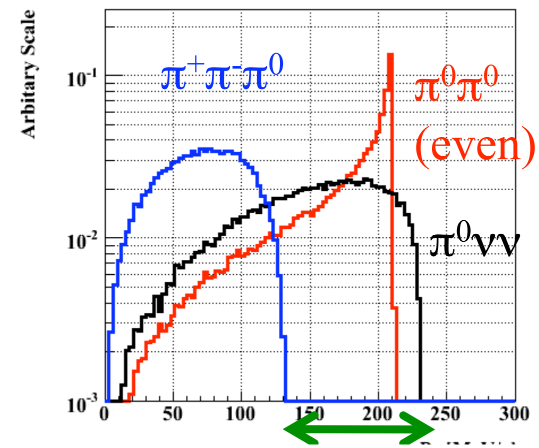


$$m_\pi^2 = (p_{\gamma_1} + p_{\gamma_2})^2 = 2\,E_1\,E_2 \times (1 - \cos\,\theta)$$

$$r_{12}^2 = d_1^2 + d_2^2 - 2\,d_1\,d_2 \cos\,\theta$$

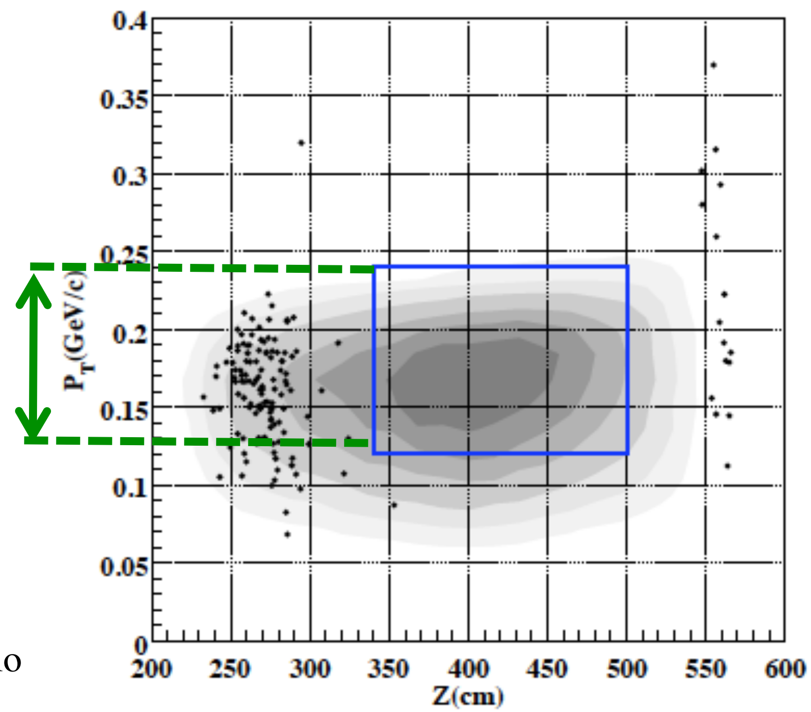
What does it take to catch a $K_L \rightarrow \pi^0 \nu\nu$?

- Fully reconstruct π^0 and K_L
  - constrain 2γ system to π^0 mass, get the two photon opening angle θ
  - assuming K_L decay vertex on beam line, determine Z_{vtx} of π^0 decay
- Define signal box in π^0 P_T-Z_{vtx} space using:
  - fiducіality cuts for Z_{vtx}
  - P_T above $K_{\pi 3}$ threshold and below (V-A) maximum of 231 MeV/c



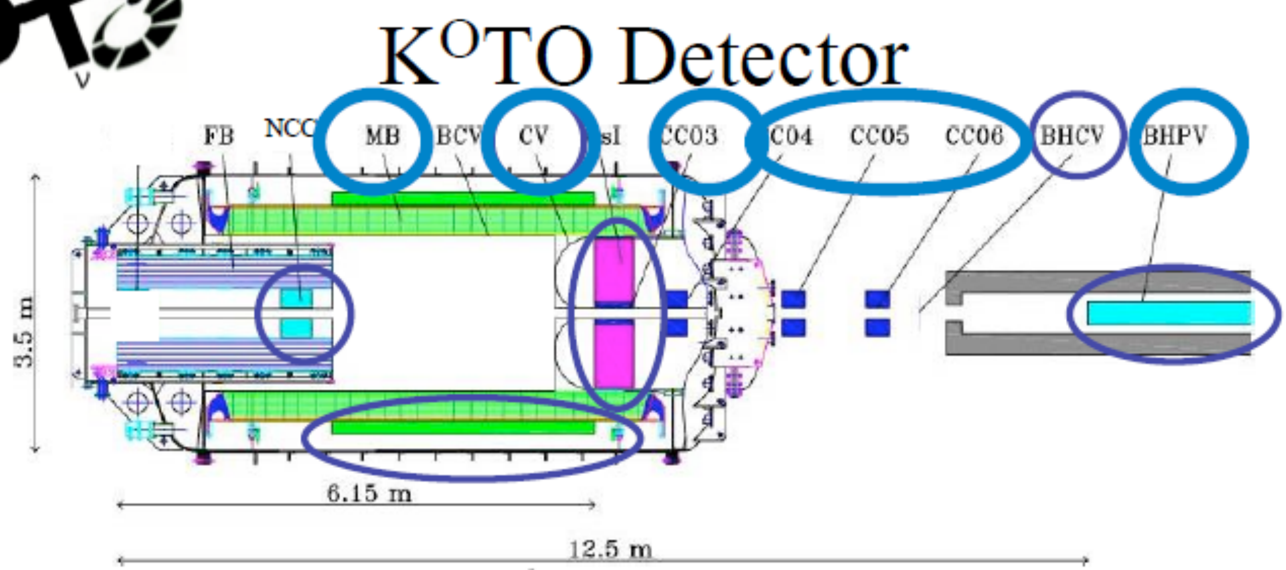
- SES(E391a) = 1/(flux*acceptance)
  = $(2.8 \pm 0.3)\times 10^{-8}$

- No events observed
  $BR(K_L \rightarrow \pi^0 \nu\nu) < 6.7 \times 10^{-8}$ (@ 90% CL)



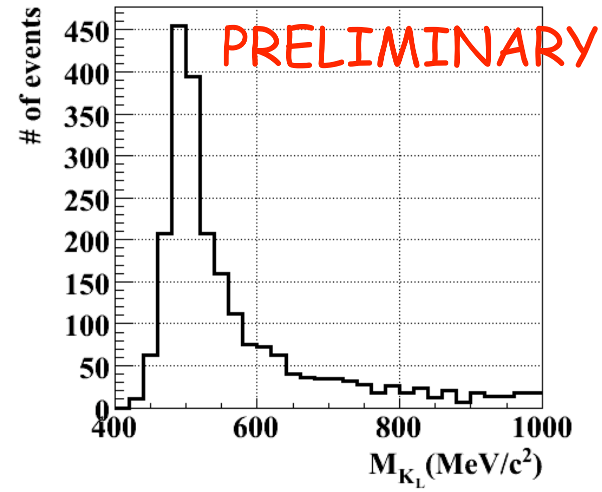
KOTO

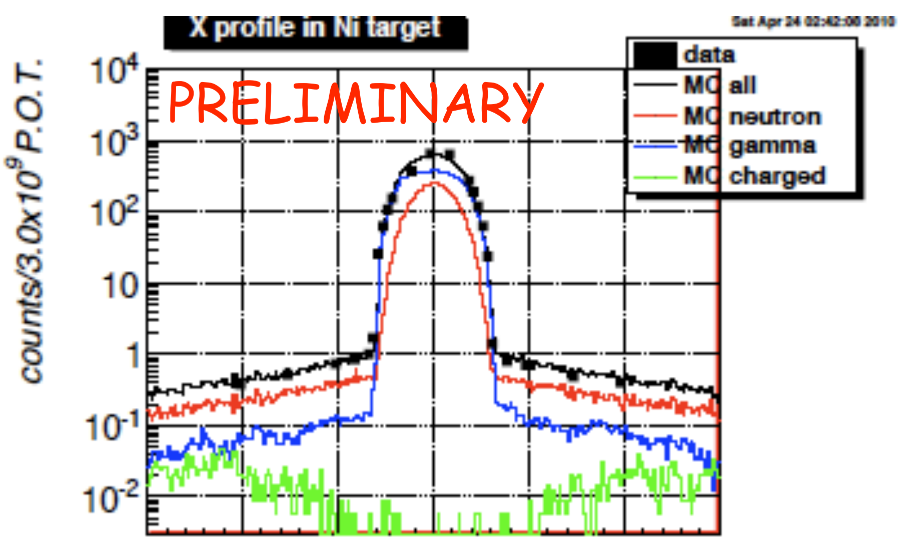
- KOTO (K^0 at Tokai) uses E391a concept and aims at SM sensitivity
- New 30 GeV proton beam at JPARC
- New 16° beamline (lower n momentun below η production threshold)
- Improved calorimeter (KTev CsI)
- New beam hole photon veto
- Improved readout and trigger
- Single Event Sensitivity: 9×10^{-12}

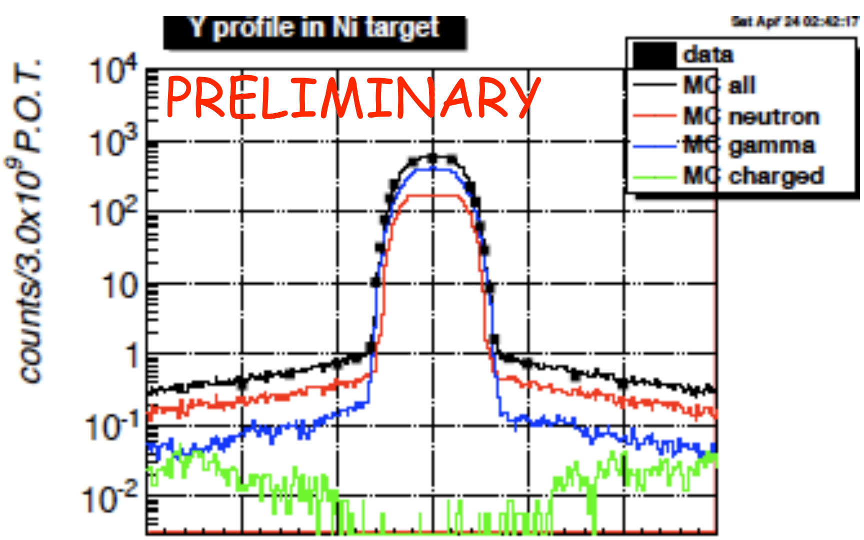


K0TO Preparation

- Beam Survey in Fall '09/Winter '10
- Measure beam shape and halo/core neutron ratio
- Measure K_L yield
- Good agreement with MC prediction



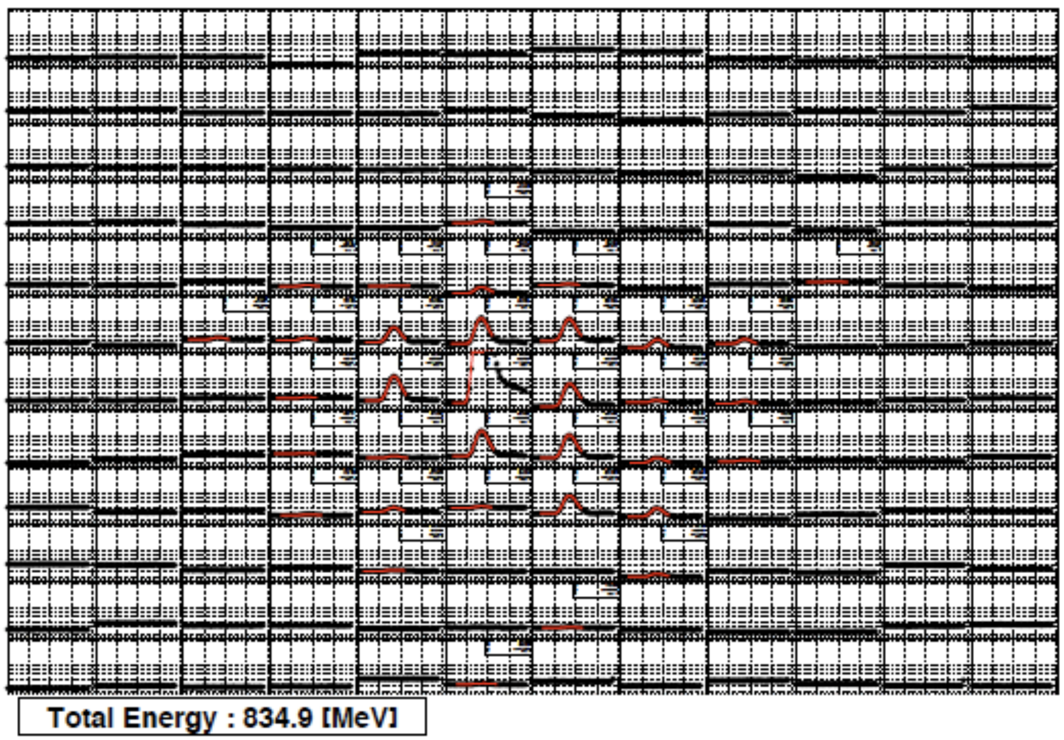


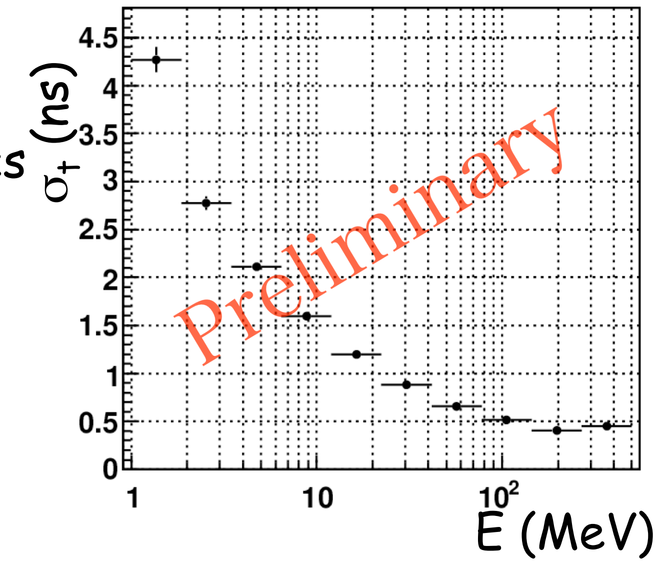


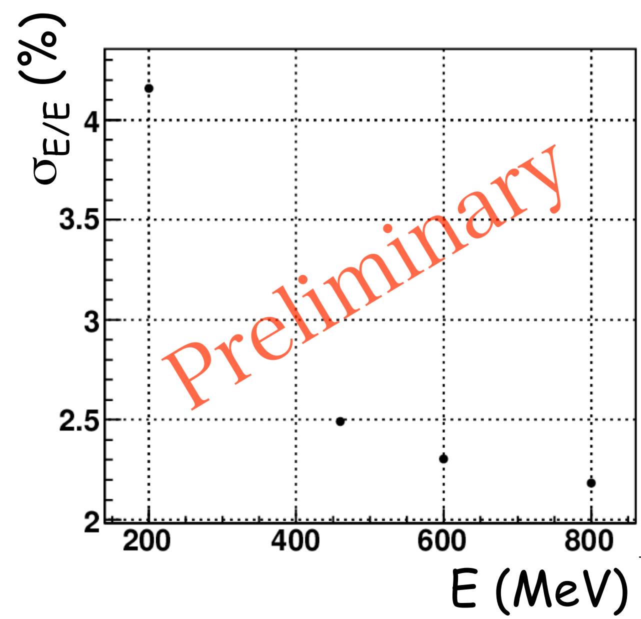
K0TO Preparation

Beam Test wit 144 (12x12) CsI crystals:

- Calibration of analog PMT readout
- Verification digital frontend/trigger electronics
- Study of time and energy resolution, shower containment

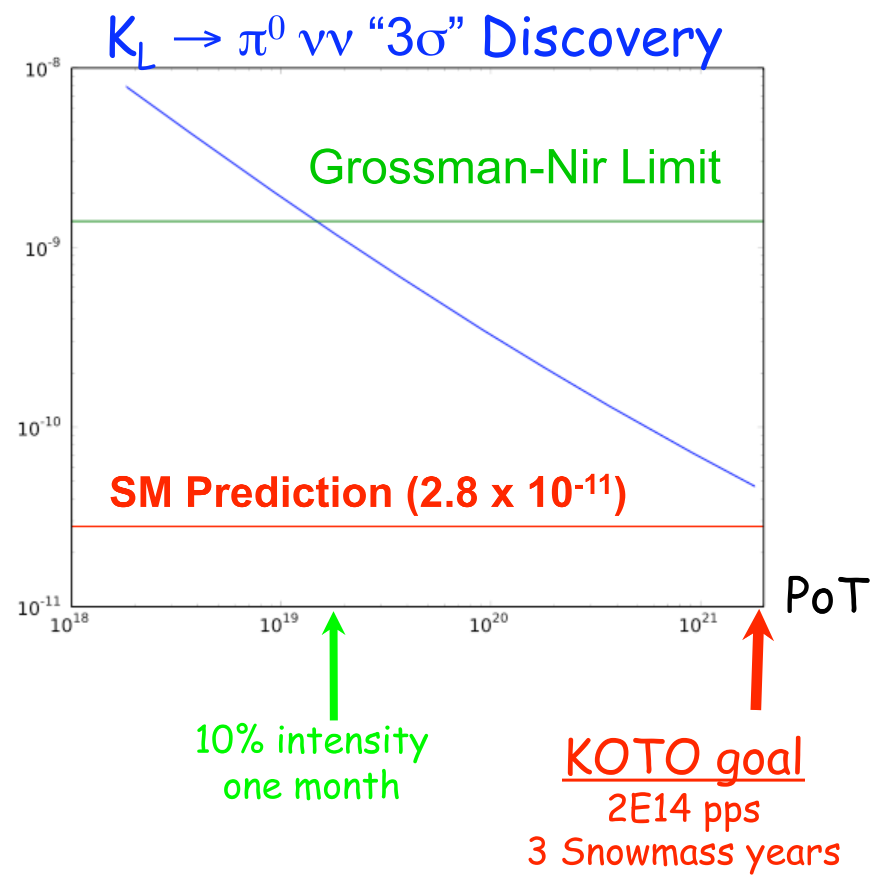






KOTO Schedule

- Fall 2010: partial engineering run for calorimeter (3000 ch. or 75% of readout)
- Fall 2011: commission vetos and first physics run
- Summer 2012: Grossman-Nir limit ($BR(K_L \to \pi^0 \nu\nu) < 1.5 \times 10^{-9}$) with 30 KW for 1 month
- SM limit for KOTO Step 1 with 300 KW
- 100 events for KOTO Step 2



P996 at FNAL

(see David Jaffe's poster)

Measure of BR($K^+ \rightarrow \pi^+ \nu\nu$) using E787/E949 concept (stopped kaon in target, hermetic tracking chamber + range stack to completely identify decay products)

- Use 150 GeV MI beam (10% of available current) + Tevatron as a stretcher → 95% d.f.
- New K^+ beam at P=550 MeV/c
- New modern detector with 10 times the E787/E949 acceptance
- Extrapolating E787/E949 backgrounds and sensitivity: 194 ± 85 evts/year
- Use existing experimental hall (B0) and CDF magnet

Project X

- Project X is a proposed high intensity proton facility at Fermilab with 8 GeV Continuous Wave linac plus Recycler plus Main Injector for simulataneous running of:
  - >2 MW proton beam for neutrino beam for long baseline neutrino oscillation experiments
  - 100-200 KW proton beam for kaon and muon precision experiments

- Physics proposal for ~10^3 evts charged and neutral $K\rightarrow\pi\nu\nu$ experiments with low-loss beam slow extraction technique providing 20-160 MHz spills with bunched beam (50 ps pulses) and high duty factor.

The Epilogue

- The quest for $K_L \rightarrow \pi^0 \nu\nu$ & $K^+ \rightarrow \pi^+ \nu\nu$ measurement at SM level is well under way.
- Immediate or long-term future experiments are being worked on/proposed.
- Rare and precise prediction ➔Extremely sensitive to new physics.
- The physics potential of this holy grail of flavor physics and CP violation is huge and worth pursuing!