Project X Kaon Experiments

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Rare Decays in the LHC Era

New Physics found at LHC

$\Rightarrow$ New particles with unknown flavor- and CP-violating couplings

Precision flavor-physics experiments needed to help sort out the flavor- and CP-violating couplings of the NP.

New Physics NOT found at LHC

Precision flavor-physics experiments needed -> sensitive to NP at mass scales beyond the reach of the LHC (through virtual effects).

Quark Gen.	Processes to Study NP
1	μ-e Conversion, $\pi \to e\nu$
2	$K^+ \to \pi^+ \nu\bar{\nu}$, $K_L^0 \to \pi^0 \nu\bar{\nu}$
3	$b \to s\gamma$, other rare decays

$K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L^0 \to \pi^0 \nu\bar{\nu}$ have special status because of their small SM uncertainties and large NP reach.

$\mu - e$ Conversion and $K^+ \to \pi^+ \nu\bar{\nu}$ are immediate priorities.

* Huge gains in sensitivity are experimentally accessible.

* Smooth transitions to the Day-1 Project-X Intensity Frontier program.

Rare K Physics at Project X

$K^{+} \to \pi^{+}\nu\bar{\nu}$ (Wide range of New Physics accessible.)

$K_{L}^{0} \to \pi^{0}\nu\bar{\nu}$ (New Physics including pure CPV effects.)

$K^{+} \to \pi^{0}\mu^{+}\nu$ (Transverse Polarization -T violation)

$K^{+} \to e^{+}\nu / K^{+} \to \mu^{+}\nu$ (Universality, LFV, Pseudoscalars...)

$K^{+} \to \mu^{+}\nu_{H}$ (Heavy neutrinos)

$K_{L}^{0} \to \pi^{0}ee / \pi^{0}\mu\mu$ (CP Violation)

$K_{L}^{0}, K^{+} \to LFV \quad e.g. \quad K_{L}^{0} \to \mu e$

K^{0} Interferometry (Plank scale physics)

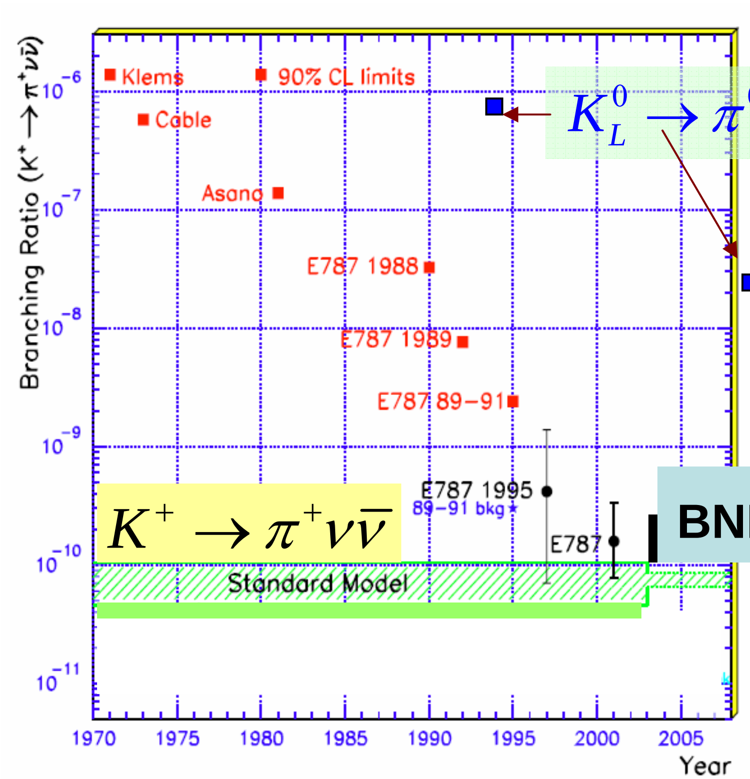
$K \to \pi l\nu$ ... (Universality, Chiral PT)

...

$K \to \pi\nu\bar{\nu}$: History and *Prospects*

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

$B_{SM}(K_{L}^{0} \to \pi^{0}\nu\bar{\nu}) = (2.8 \pm 0.4) \times 10^{-11}$



$K_{L}^{0} \to \pi^{0}\nu\bar{\nu}$

***J-PARC KOTO ***

BNL :7 events $K^{+} \to \pi^{+}\nu\bar{\nu}$

100

CERN NA62

1000

Project X

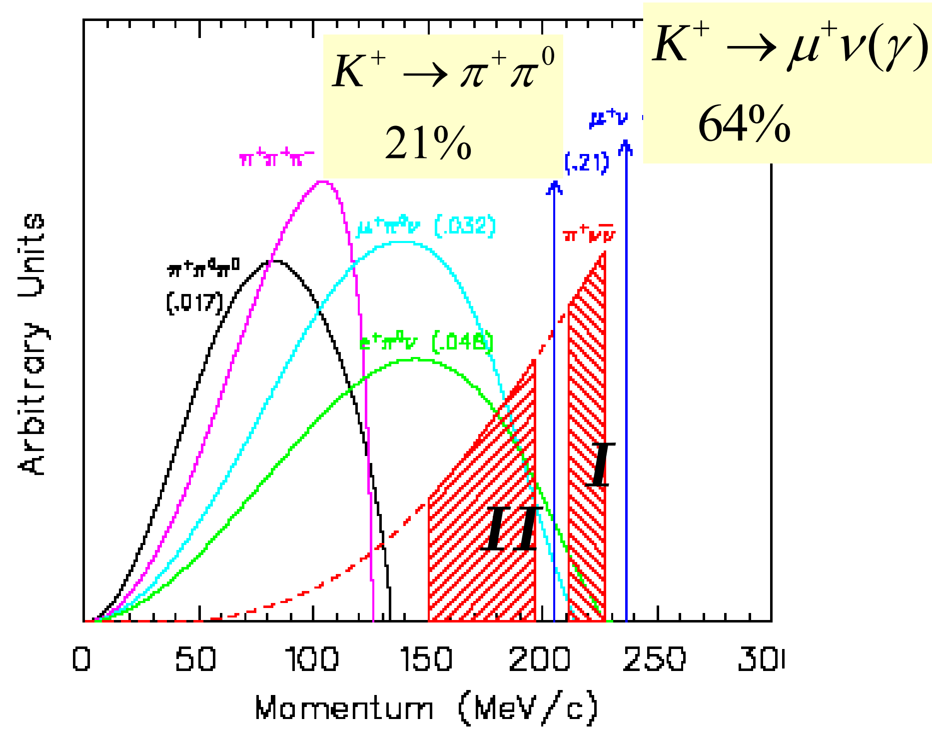
$K^{+} \to \pi^{+}\nu\bar{\nu}$

$K_{L}^{0} \to \pi^{0}\nu\bar{\nu}$

Special Features of Measuring $K^+ \to \pi^+ \nu \bar{\nu}$

$B_{SM}(K^+ \to \pi^+ \nu \bar{\nu}) = (8.5 \pm 0.7) \text{ x } 10^{-11}$

Experimentally weak signature with background processes exceeding signal by $>10^{10}$

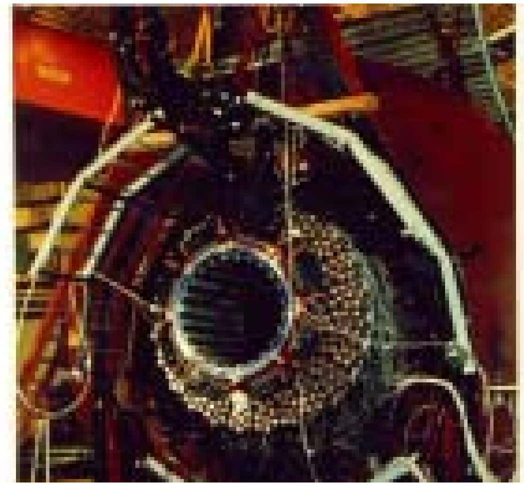


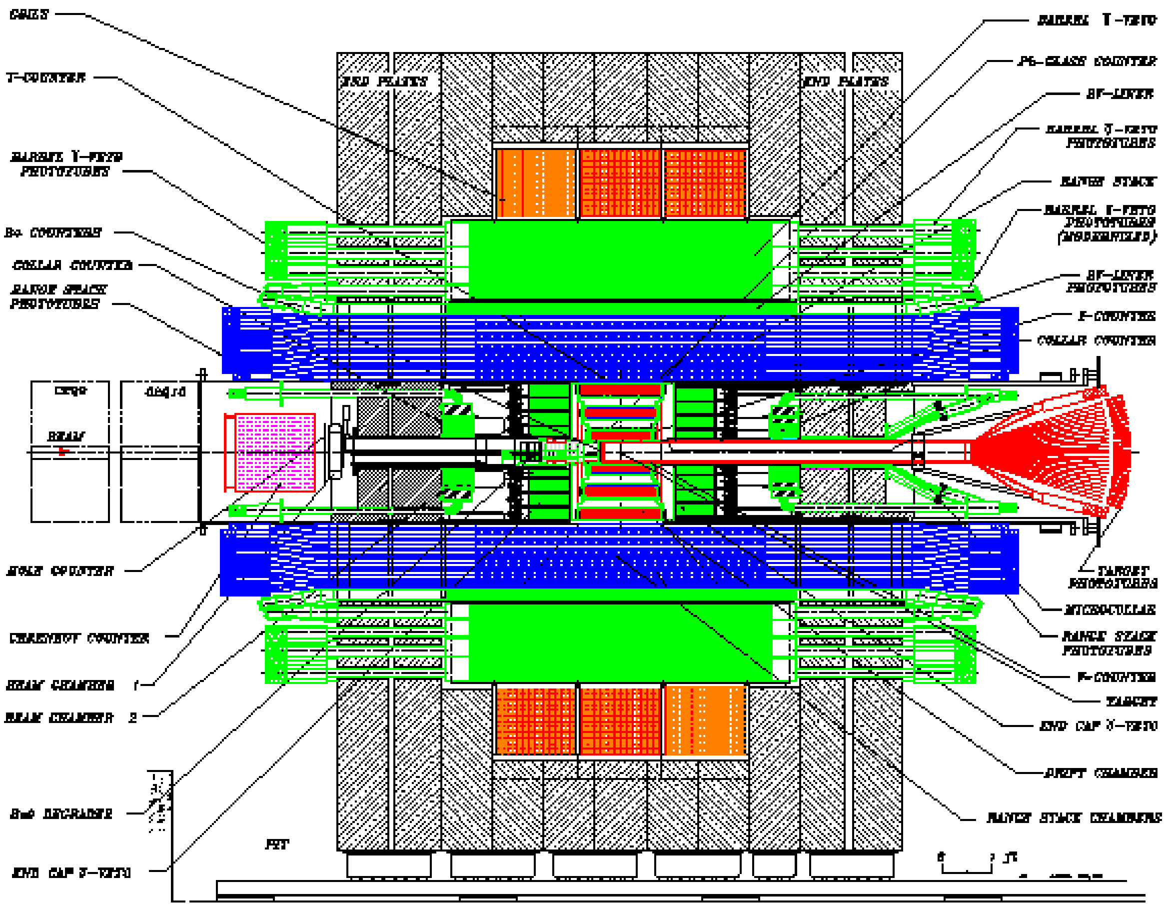
- Determine everything possible about the K^+ and π^+
  - * π^+/μ^+ particle ID better than 10^6 ($\pi^+ \to \mu^+ \to e^+$)
- Eliminate events with extra charged particles or ***photons***
  - * π^0 inefficiency $< 10^{-6}$
- Suppress backgrounds well below the expected signal (S/N~10)
  - * Predict backgrounds *from data*: dual independent cuts
  - * Use "Blind analysis" techniques
  - * Test predictions with outside-the-signal-region measurements
- Evaluate candidate events with S/N function

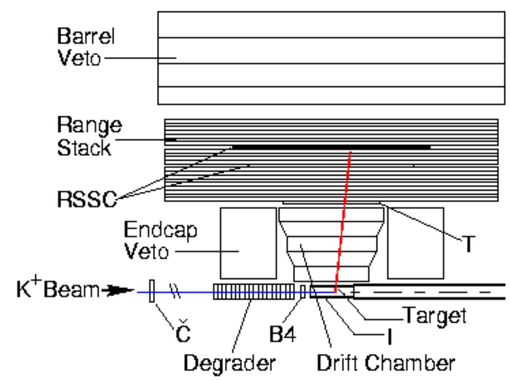
BNL 787/E949

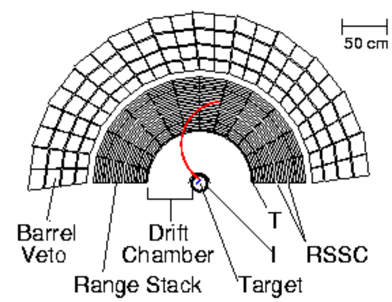
Measurement of

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

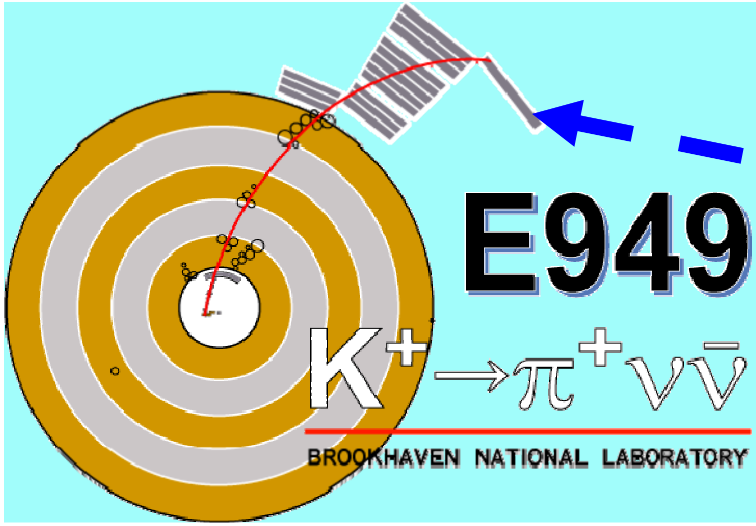


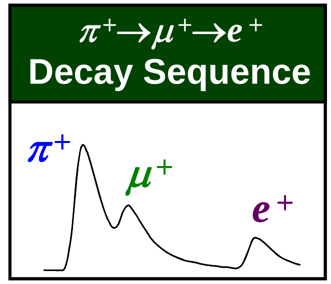




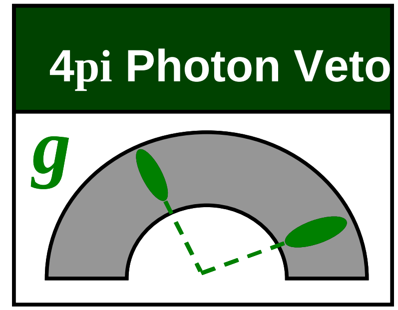


BNL E949: 3nd generation $K^+ \to \pi^+ \nu\bar{\nu}$ Experiment



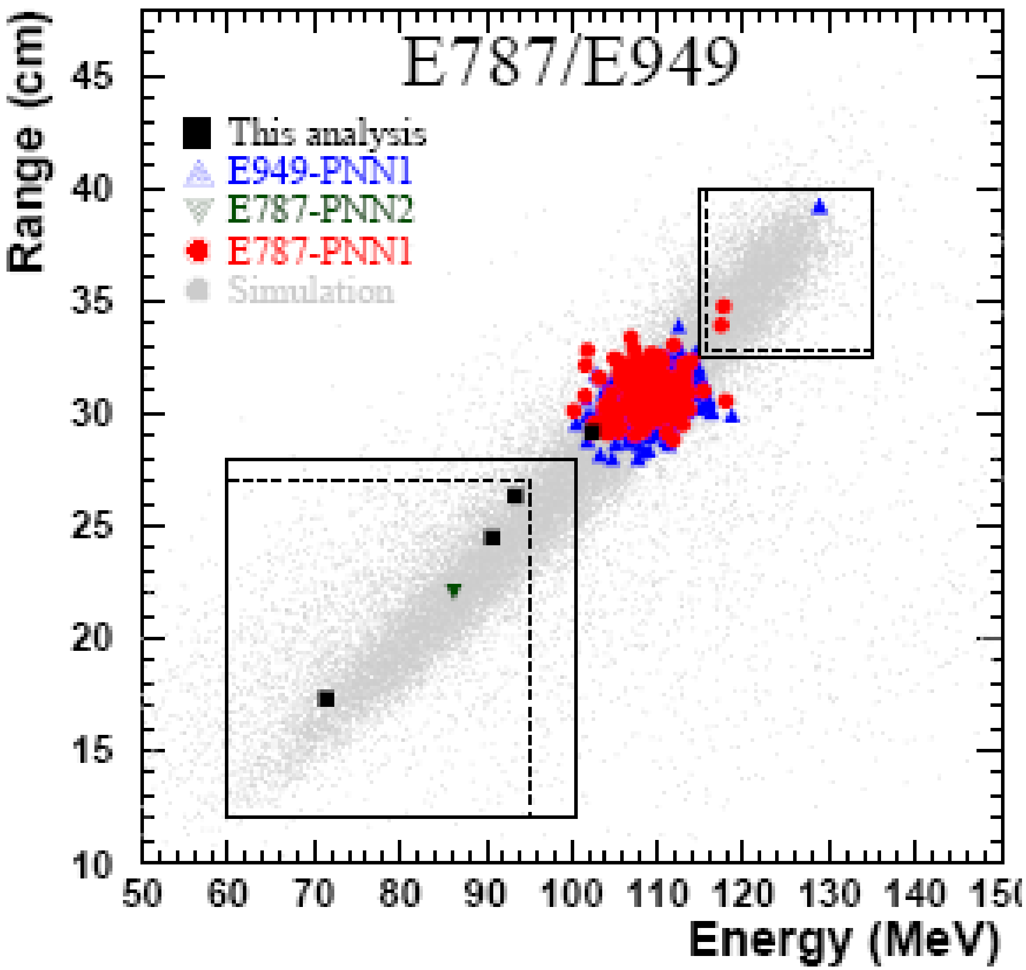


500 MHz digitizers



- **Measure everything possible**
- 710 MeV/c K^+ beam
- Stop K^+ in scintillating fiber target
- Wait at least 2 ns for K^+ decay (delayed coincidence)
- Measure π^+ momentum in drift chamber
- Measure π^+ range and energy in target and range stack (RS)
- Stop π^+ in range stack
- Observe $\pi^+ \to \mu^+ \to e^+$ in range stack
- Veto photons, charged tracks

Observation of $K^+ \to \pi^+ \nu\bar{\nu}$ Decay at BNL



E787/E949: 7 events observed

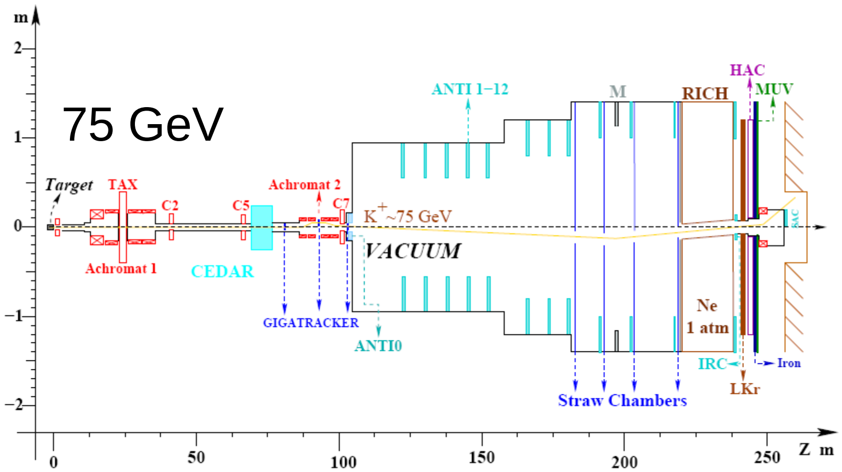
$B(K^+ \to \pi^+ \nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} x10^{-10}$

Standard Model:

$B(K^+ \to \pi^+ \nu\bar{\nu}) = (0.85 \pm 0.07) x10^{-10}$

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

CERN NA-62 first generation decay-in-flight experiment.



- Builds on NA-31/NA-48
- Un-separated GHz beam
- Aim: 40-50 events/yr at SM
- Under construction; start >2013

$K_L^0 \to \pi^0 \nu\bar{\nu}$ at J-PARC

KOTO: 2nd try with ~same setup as KEK ($< 2.6 x 10^{-8}$)

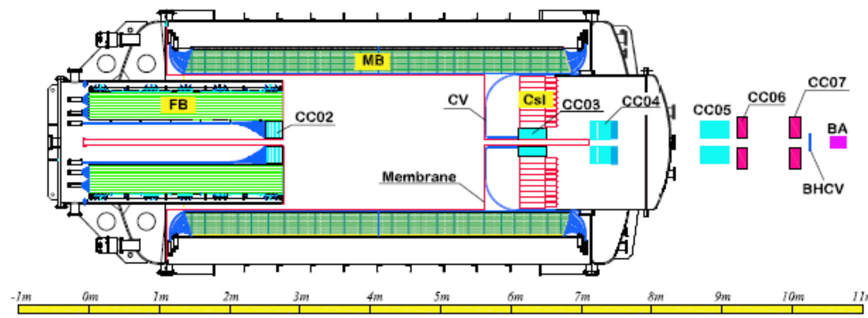
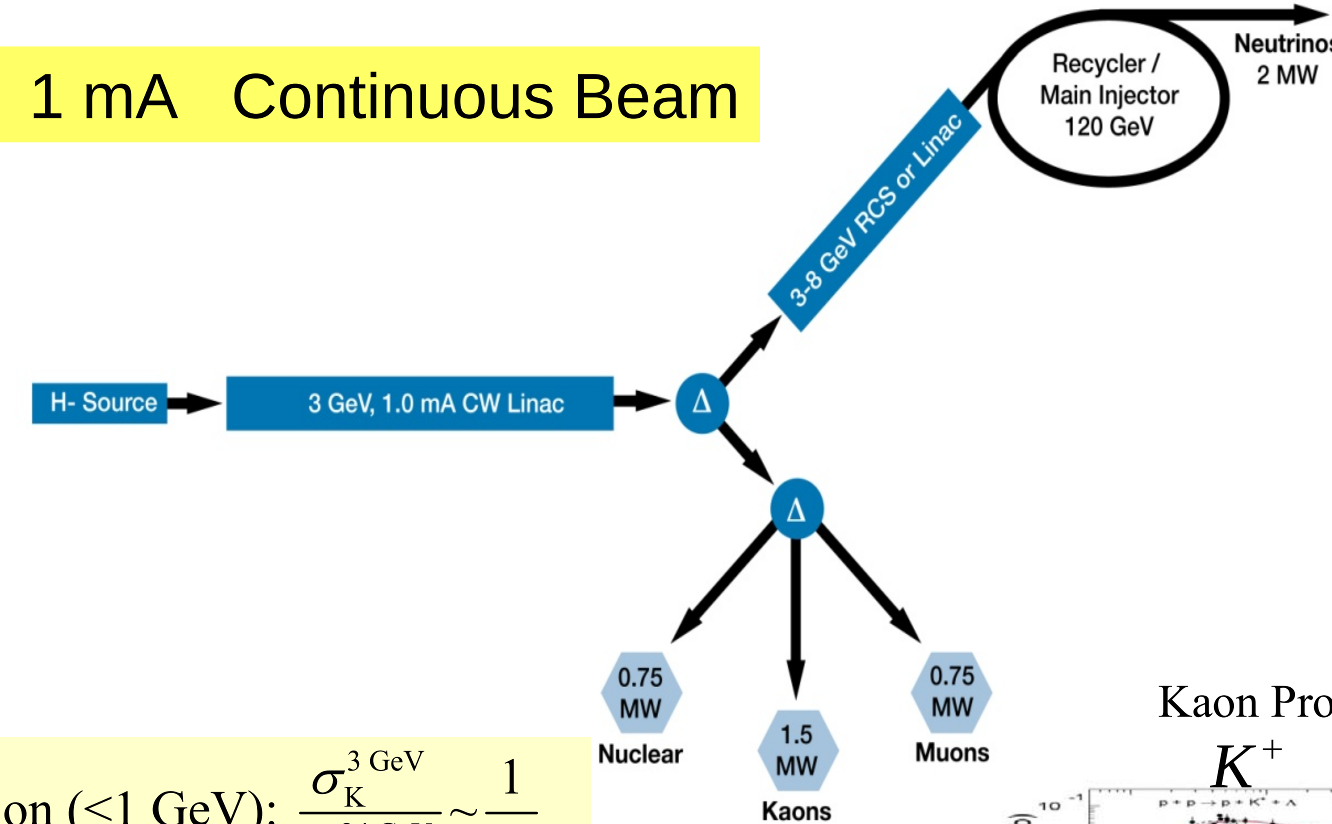


FIG. 1: Cross section of the E391a detector. K_L^0's enter from the left side.

- Improved J-PARC Beam line
- (Eventually) higher power
- Aim: 2.8 events (S/B~1) at SM
- Under construction; start >2011

Fermilab Project X

3 GeV 1 mA Continuous Beam



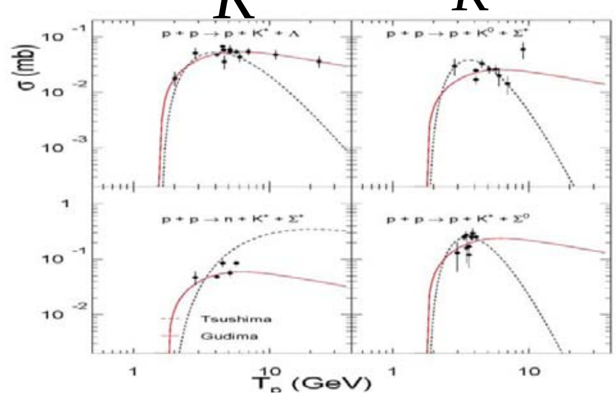
$$\text{K production (<1 GeV):}\quad \frac{\sigma_K^{3\ \text{GeV}}}{\sigma_K^{24\ \text{GeV}}} \sim \frac{1}{10}$$

$$\text{p beam intensity:}\quad \frac{\text{Proj. X}}{\text{AGS}} \sim 300$$

$$\text{K flux:}\quad \frac{\text{Proj. X}}{\text{AGS}} \sim 30$$

Kaon Production *vs.* T_P

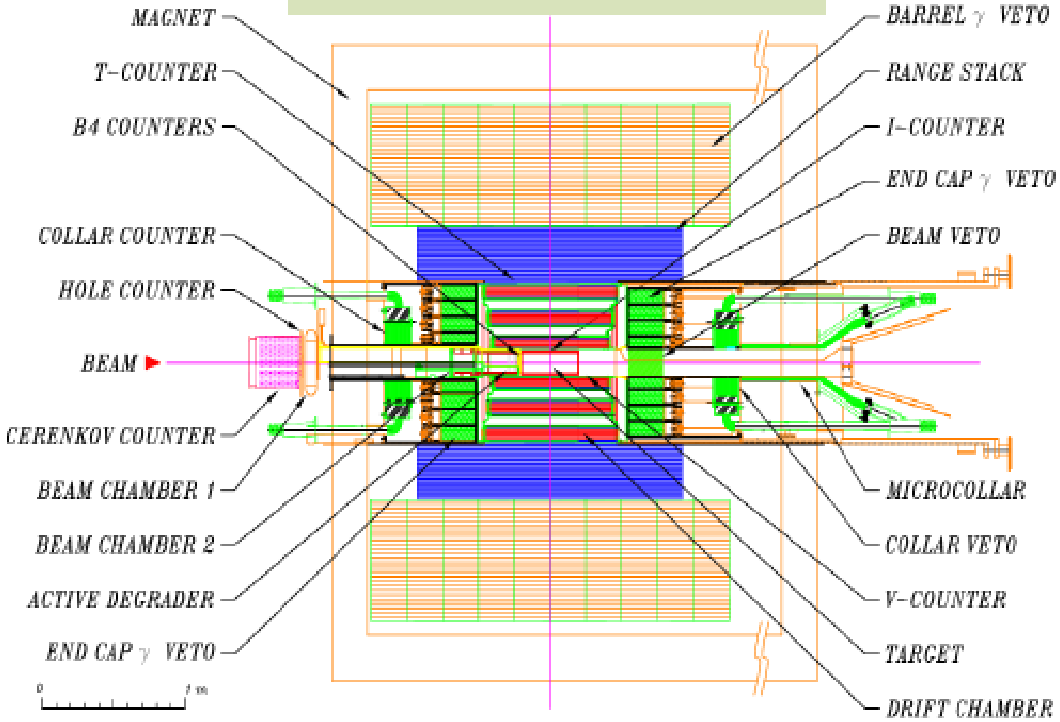
K^+ K^0



$K^+ \to \pi^+ \nu \bar{\nu}$ at Project X

340 events/year

4th Generation Detector



Incremental Improvements

- 450 MeV/c K stopping rate **x10** with comparable instantaneous rate as E949
- Larger solid angle – Acceptance **x 10**
- Finer segmentation, improved resolutions - **Reduced backgrounds**
- Overall >**250 x** sensitivity

Improvement Factors relative to BNL:

Detector Acceptance	$11.3 \pm^{3.3}_{2.3}$
Stopped K per year	24

Comparable or lower rates then in E949, despite much higher yield.

The Big Challenge: $K_L^0 \to \pi^0 \nu \bar{\nu}$

- $B(K_L \to \pi^0 \nu\nu) \sim 2.8 \times 10^{-11}$

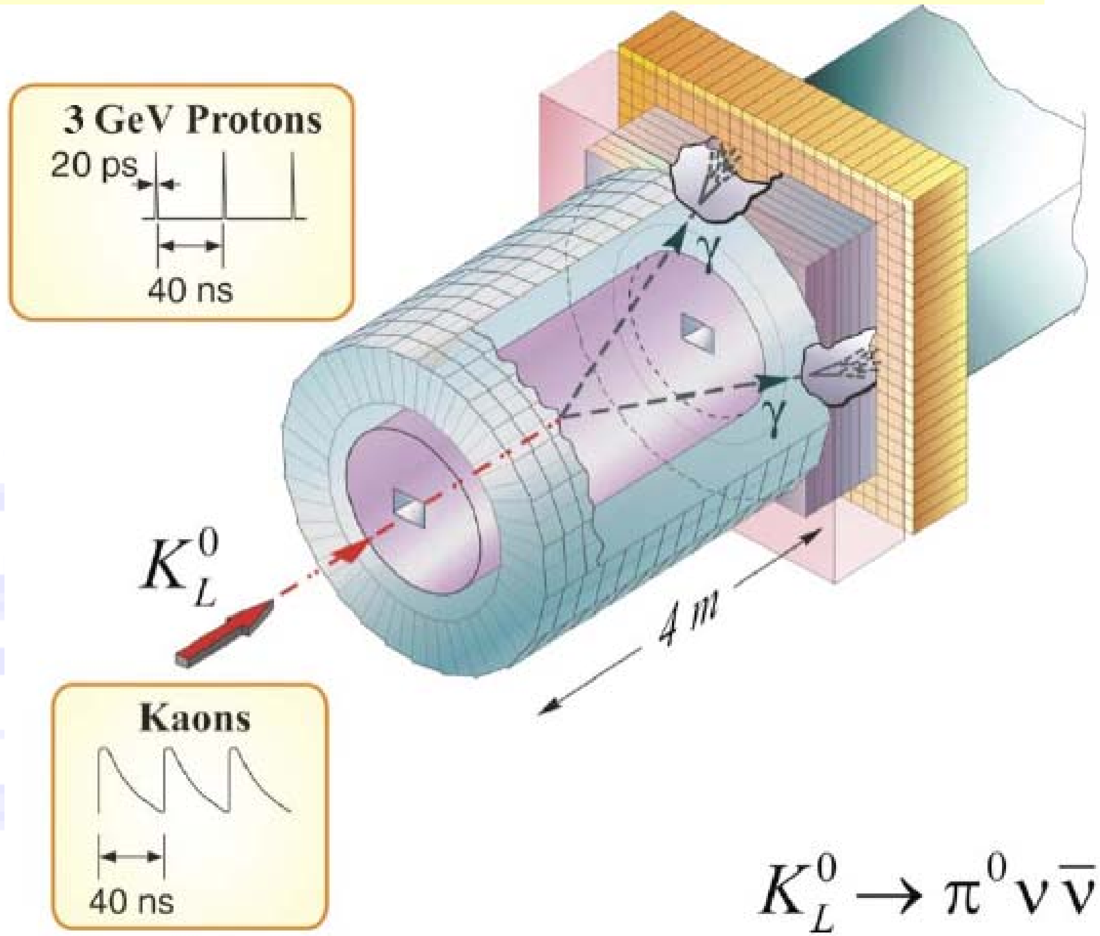
  Need huge flux of K's -> high rates
- Weak *neutral particle* kinematic signature

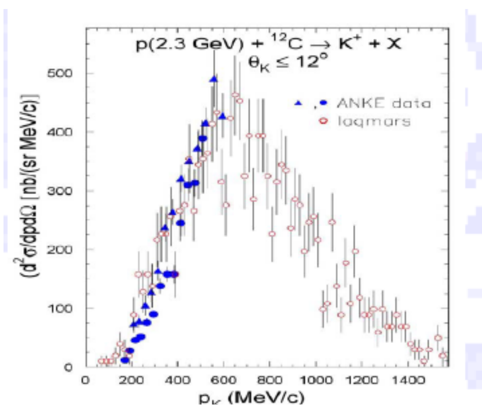
  2 particles missing
- Backgrounds with π^0 up to 10^9 times larger

  Principal problem: $K_L \to \pi^0 \pi^0$
- Veto inefficiency on extra particles must be $\leq 10^{-4}$
- Neutrons dominate the beam
  - make π^0 off residual gas – requires high vacuum
  - halo must be very small
  - hermeticity may require photon veto in the beam
- Need convincing measurement of background

Project X : $K_L^0 \to \pi^0 \nu \bar{\nu}$ Experiment Concept

a la KOPIO



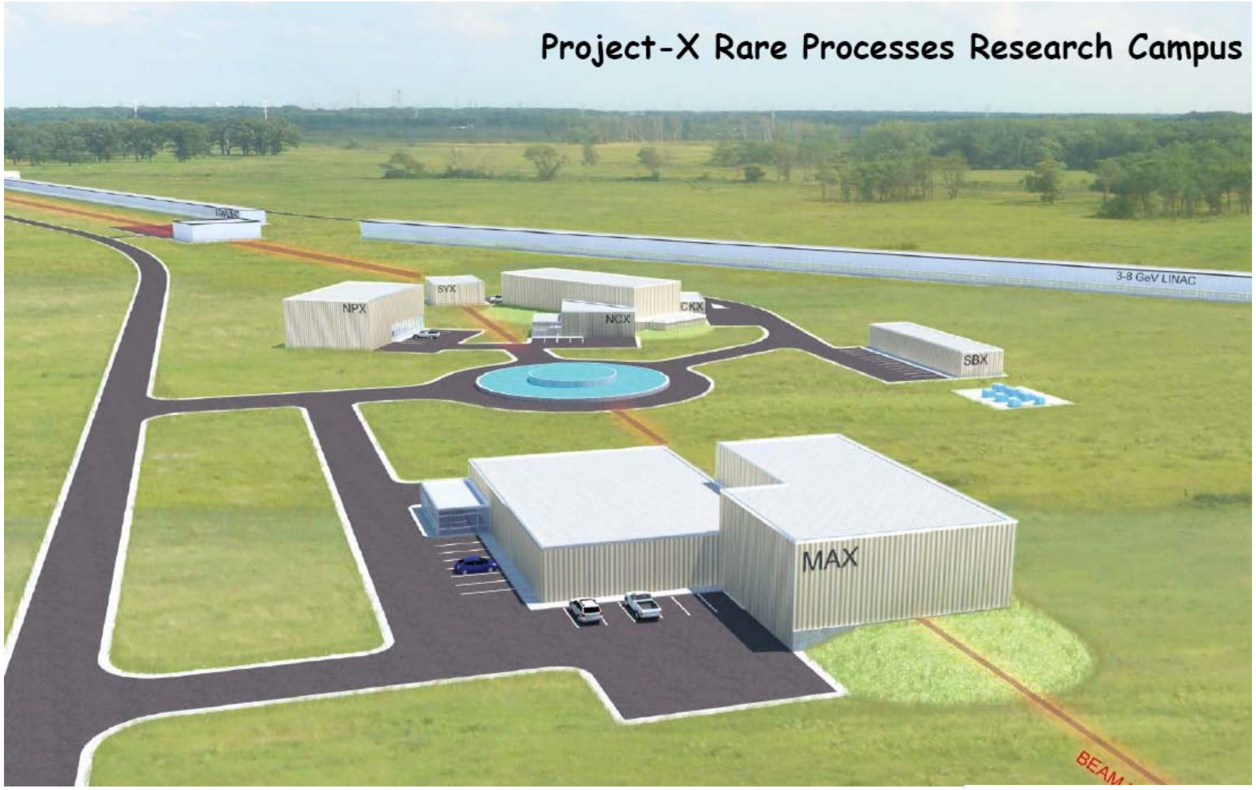


- Use TOF to work in the K_L^0 c.m. system
- Identify and eliminate main 2-body background $K_L^0 \to \pi^0 \pi^0$
- Reconstruct $\pi^0 \to \gamma\gamma$ decays with pointing calorimeter
- 4π solid angle photon and charged particle vetos

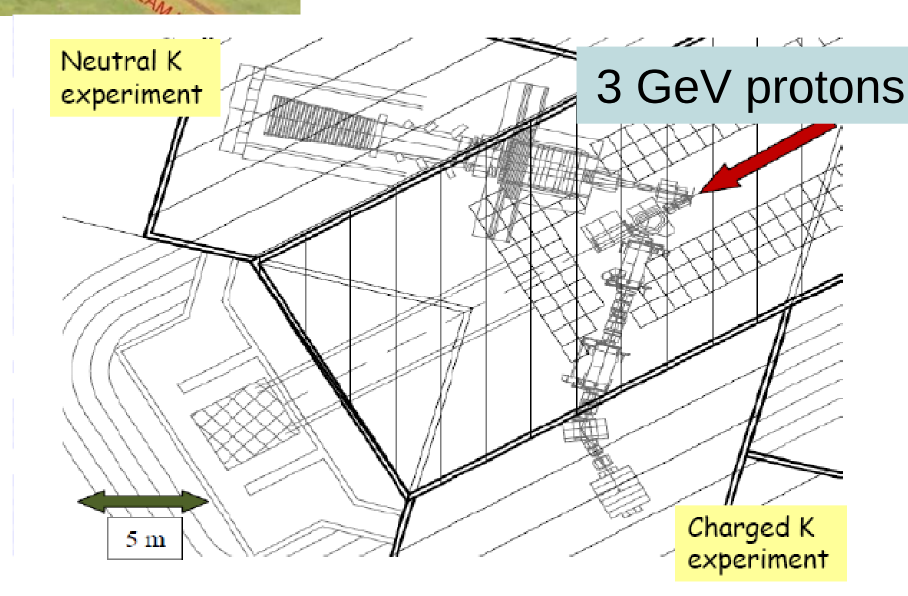
$K_L^0 \to \pi^0 \nu \bar{\nu}$ *At Project X :*

Ideal time structure for TOF-based experiment.

- ***High intensity allows small beam dimensions***
- Symmetrical beam, detector;
  geometric acceptance maximized
- 2-D beam kinematic constraint increases S/B
- Upstream backgrounds, backgrounds in the fiducial volume reduced
- Same micro-bunch event spoilage reduced
- Random vetos reduced due to high duty factor
- Beam veto may be unnecessary
- *Neutron rates high – could be problematic*



Project X Kaon Hall



Common target for

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

Experiments

$K \to \pi\nu\bar{\nu}$ Prospects

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

Now: $B(K^+ \to \pi^+\nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} x10^{-10}$

(7 events)

Future: Sensitivity at SM $(0.85 \pm 0.07) x10^{-10}$

Goals	NA62 CERN	FNAL MI	Proj.X
Events/ yr	40	100	340
S/N	5	5	5
Precision	10%	5%	3%

$K^0_L \to \pi^0\nu\bar{\nu}$

Now: $B(K^0_L \to \pi^0\nu\bar{\nu}) < 2.6\, x 10^{-8}$

Future: Sensitivity at SM $3\, x 10^{-11}$

Goals	KOTO * J-PARC	Proj.X
Events/yr	~1	"200"
S/N	~1	5-10
Precision		5%

* J-PARC plans a phase II to reach higher sensitivity.

Summary: K Physics at Project X

An unprecedented opportunity to find new physics with Rare Kaon Decays

- $K^+ \to \pi^+ \nu \bar{\nu}$ and $K_L^0 \to \pi^0 \nu \bar{\nu}$ can be measured with high precision.
  Ultimate experiments can be done covering all accessible non-SM physics.
  Complementary to LHC for studying flavor interactions at high mass scales.
- Many rare Kaon processes can be accessed to explore
  - New CP and T violation,
  - Universality,
  - Lepton flavor violation,
  - Searches for scalar and pseudoscalar interactions, exotics ....