KOTO

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

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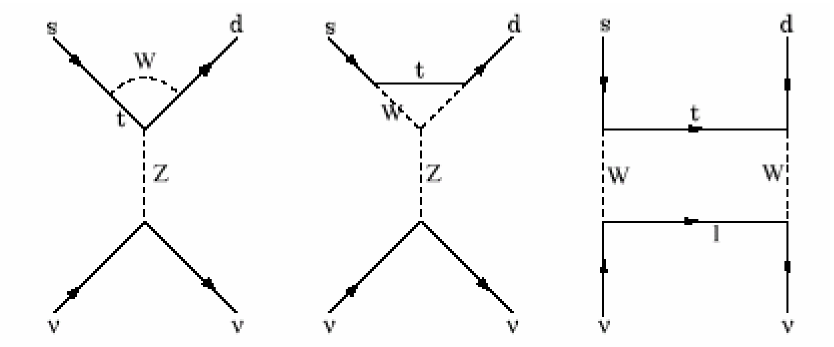
Goals

- Discover and measure the rate of $K^0 \to \pi^0 \nu \bar{\nu}$
- Flavor changing neutral current decay through second-order weak interactions



- Standard Model branching ratio is $(2.8 \pm 0.4) \times 10^{-11}$
- Measure 100 events at SM branching ratio
- Upgrade to E391a at KEK
- Approved as E14 at JPARC

C, P, and T Symmetry

- In order to explain the importance of $K^0 \rightarrow \pi^0 \nu\bar{\nu}$, we need to understand some important symmetries:
  - C: Charge conjugation symmetry. C flips the sign of all the additive quantum numbers of a particle (e.g. electric charge, baryon or lepton number, and flavor). Note that it does not affect the mass or chirality (handedness).
  - P: Parity symmetry. P inverts space and inverts the chirality of a particle, taking left-handed to right-handed.
  - T: Time reversal. T changes the flow of the direction of time.
- The combination of the three, CPT, is required for Lorentz invariance in Quantum Field Theory (QFT).

CP Violation

- CP is the combination of two discrete symmetries: Charge Conjugation (C) and Parity (P).
- CP violation is required to explain the baryon asymmetry of the universe (why we have more matter than antimatter). However, CP violation in the SM appears to be too small to explain baryon asymmetry by itself.
- CP violation emerges naturally in a three generation quark model with Weak flavor mixing in the form of the CKM (Cabibo-Kobayashi-Maskawa) Matrix.

Kaons

- Kaons are produced by strong interaction

$$K^0 = d\bar{s} \quad \bar{K}^0 = \bar{d}s$$

- The CP eigenstates are linear combinations of the strong interaction eigenstate

$$\left|K_1^0\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle - \left|\bar{K}^0\right\rangle\right) \qquad \left|K_2^0\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle + \left|\bar{K}^0\right\rangle\right)$$

- The weak decay eigenstates are

$$\left|K_S^0\right\rangle = \frac{1}{\sqrt{1+\left|\varepsilon\right|^2}}\left(\left|K_1\right\rangle + \varepsilon\left|K_2\right\rangle\right) \quad \left|K_L^0\right\rangle = \frac{1}{\sqrt{1+\left|\varepsilon\right|^2}}\left(\left|K_2\right\rangle + \varepsilon\left|K_1\right\rangle\right)$$

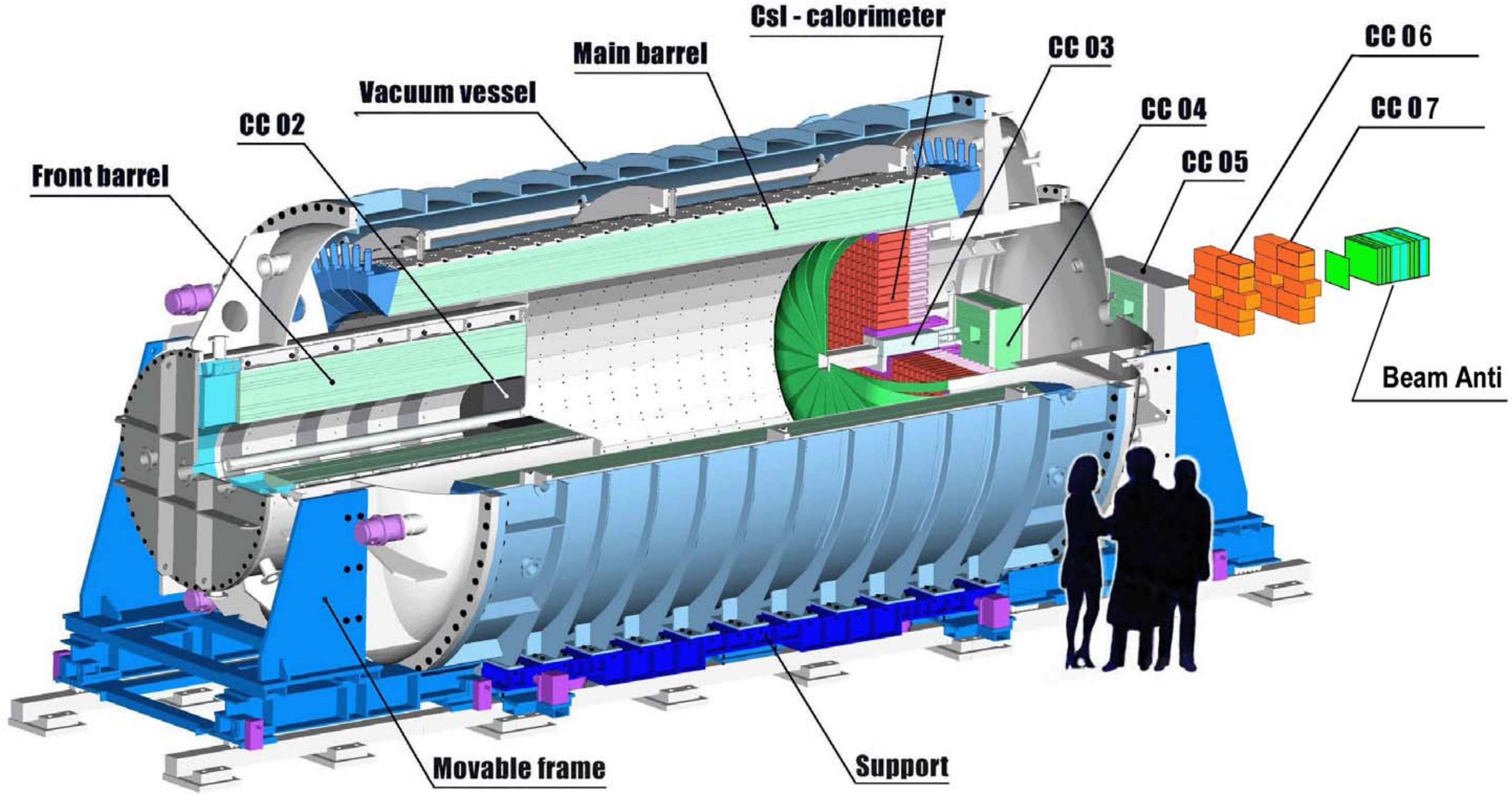
$K^0 \to \pi^0 \nu \bar{\nu}$

- Why measure $K^0 \to \pi^0 \nu \bar{\nu}$
- It can be calculated very accurately (6%)
- It is a CP – violating decay
- It only occurs in the standard model in second order processes
- It can probe new particles and new processes that are overwhelmed by first order standard model processes

Previous Measurements

- Fermilab E799-I in 1992, $BR < 2.2 \times 10^{-4}$
- Fermilab E799-II in 1999, $BR < 5.8 \times 10^{-5}$
- Fermilab KTeV in 2000, $BR < 5.9 \times 10^{-7}$
- KEK E391 in 2006 (one week), $BR < 2.1 \times 10^{-7}$
- KEK E391a in 2007, $BR < 6.7 \times 10^{-8}$
- Experiment E391 and E14 are the first experiments designed specifically to make this measurement

Schematic of E391 Detector



KOTO Collaboration

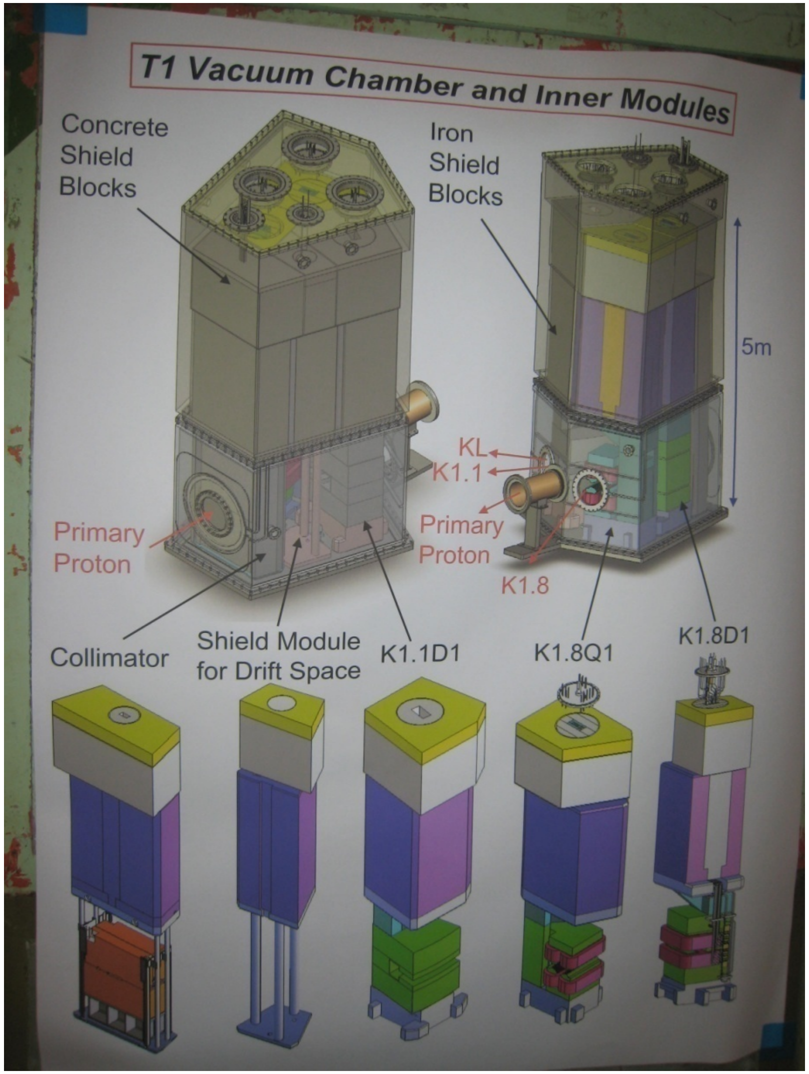
Looking down the Main Barrel

50 GeV Accelerator at JPARC

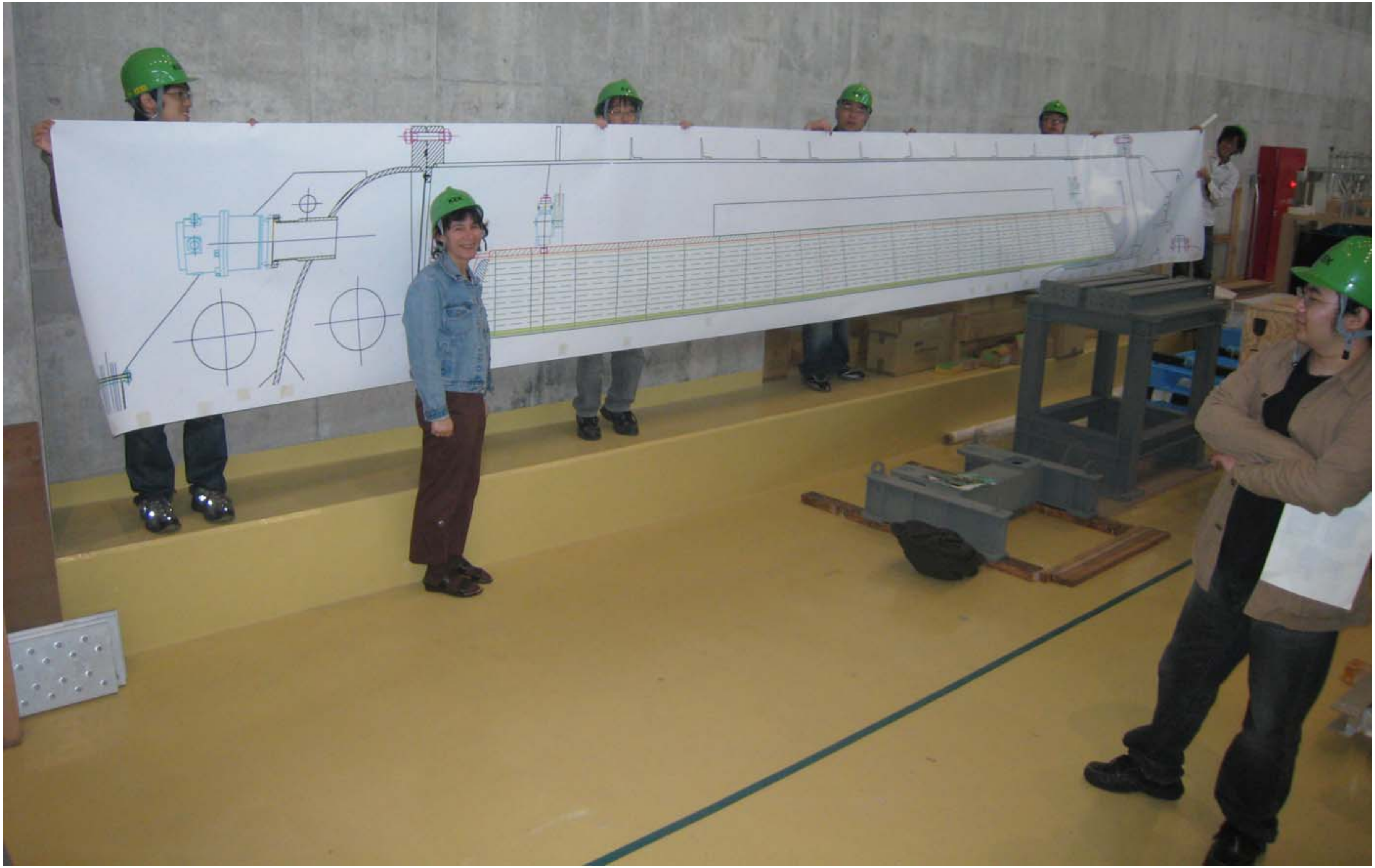
50 GeV beam line

Kaon Hall

Collimator


T1 Vacuum Chamber and Inner Modules
Concrete Shield Blocks
Iron Shield Blocks
5m
KL
K1.1
Primary Proton
Primary Proton
K1.8
Collimator
Shield Module for Drift Space
K1.1D1
K1.8Q1
K1.8D1

KOTO Experiment Hall

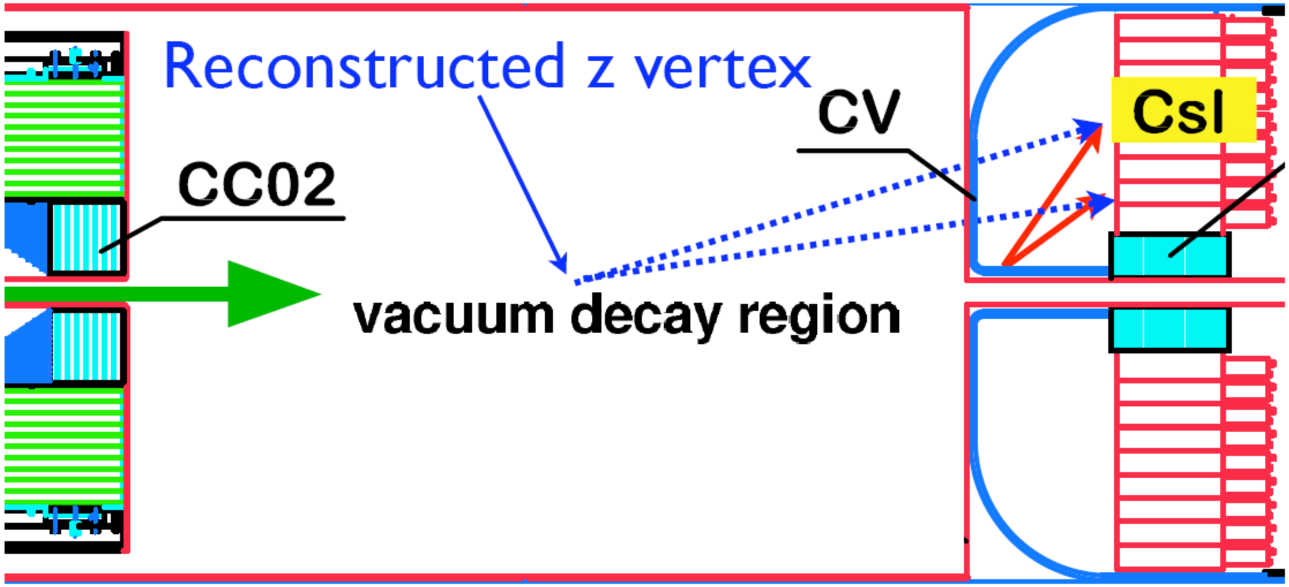


Measurement Principles

- Measure a π^0 with high transverse momentum
- Veto events with more than two photons
- Requires ‘pencil beam’, 4 cm diameter
- 2×10^{14} protons at 30 GeV per spill produces
  - 4.6×10^{6} K_L per spill
  - 3.0×10^{7} neutrons per spill
  - 2.0×10^{4} halo neutrons per spill
- Acceptance calculations and decay probability show we need 2×10^{13} K_L for each SM event

Background - neutrons

- Design beam to control halo neutrons which can create $\eta \rightarrow \gamma\gamma$ mimicking high P_t π^0 from beam line
- Introduce neutron collar counter to detect and veto neutrons
- Improve calorimeter energy and position resolution



Background - K_L

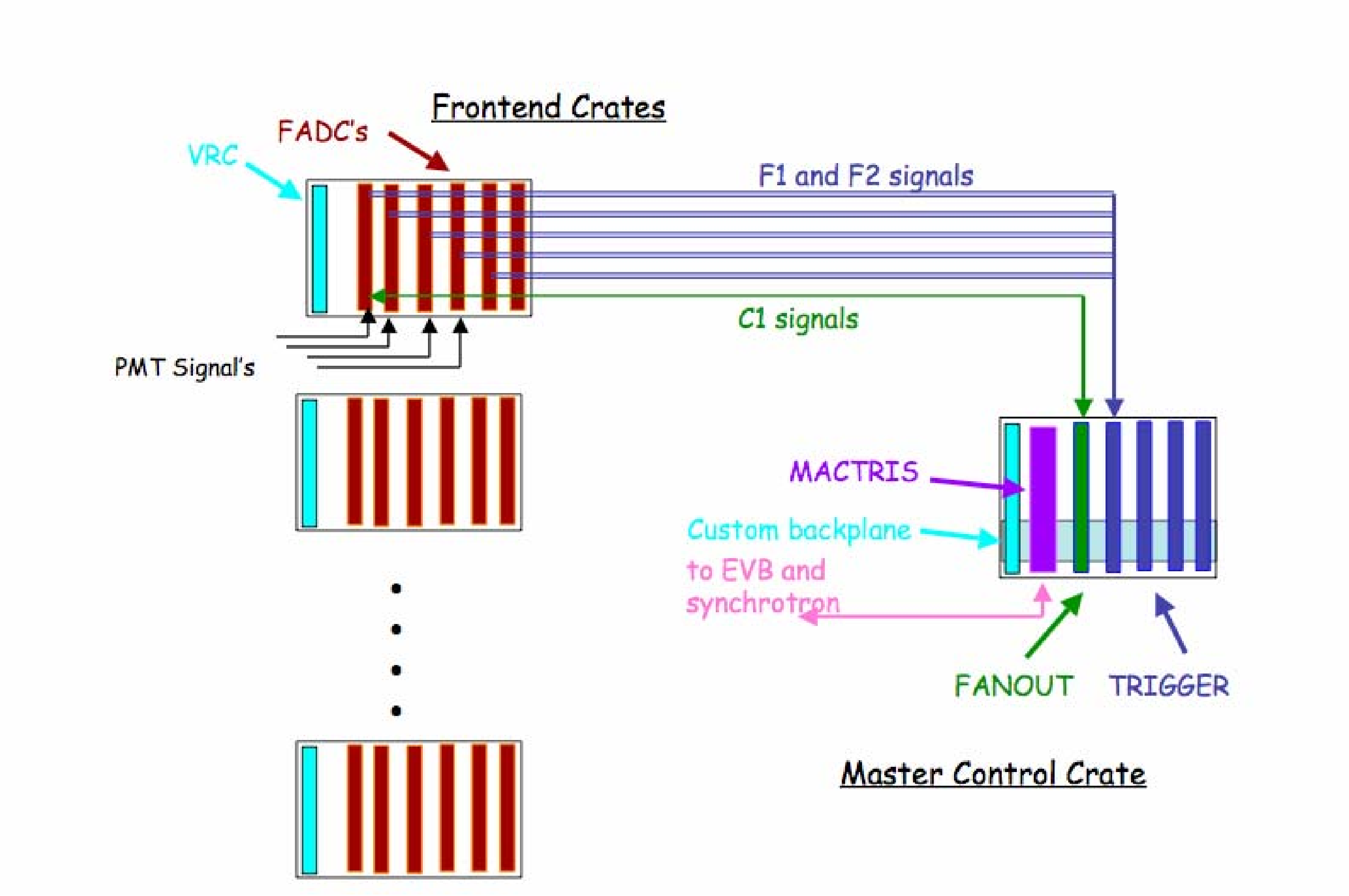
- Background from $K^0 \rightarrow \pi^0\pi^0$
  - Photons fuse in calorimeter
  - Photons are missed
- E14 will have smaller CsI crystals than E391
  - Crystals formerly used by KTeV
  - Have been shipped to Osaka
- New beam hole photon veto
  - Aerogel insensitive to neutrons
  - Photon inefficiency at 1 GeV is less than 10^{-3}
- Expect 100 signal events and 4 background events in Step 2

High Rate

- For Step 1 need 2×10^{13} K_L
- For Step 2 need 2×10^{15} K_L
- Building new electronics for high rate
  - 250 kHz trigger rate
  - Triggers do not create deadtime
  - Waveform digitization of calorimeter signals
  - 125 MHz, 14 bit, with sub-nanosecond resolution through waveform shaping (10-pole filter)
  - Two pulse resolution is 20 nanoseconds
- 3000 CsI and 1000 veto signals

DAQ Architecture

- 188 ADC boards, 12 ADC crates, one trigger crate



Conclusion

- KOTO will discover and measure the rate of

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

- Construction of new beamline at JPARC is well underway
- E391 is being moved from KEK to JPARC
- CsI crystals have been shipped to Osaka
- We are ready and eager to contribute to and participate in this experiment