The Music of KOTO: $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

(KOTO: $\underline{K}^0$ at $\underline{\text{TO}}$kai, Japan)

Joseph Comfort
Arizona State University, Tempe

Heavy Quarks & Leptons
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Yukiko Matsuyama, Master Koto Player

Physics Issues

The symmetries of physics, applied to the very early universe, imply equal matter and antimatter densities.

But what we see is only matter (out to > 100 Mpc)!
(Small antimatter density is due to natural processes from cosmic rays.)

Why? What destroyed the symmetry?

It is known that CP is a broken symmetry. (One of Sakharov's criteria.)

CP violation is automatically built into the Standard Model.

Can CP violation do the job? **Do we need New Physics Beyond the SM?**

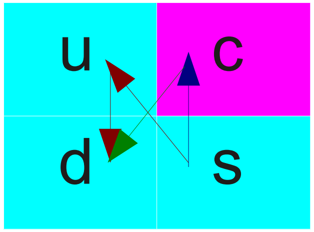
In addition, the KOTO decay mode is one of the 'golden' processes in flavor physics, due to the small theoretical uncertainties in the SM. Branching ratio is directly proportional to CPV parameter η^2.

A Little Historical Perspective

Neutral kaons have had a very large impact in the development of the Standard Model.

We start with normal matter (u,d quarks). → Generation 1

Associated Projection, e.g. $\text{pi}^{-}\ \underline{p} \rightarrow K^{0}\ \Lambda^{0}$ (s quark)
Strong suppression of $K_{L}^{0}\ (d\ s) \rightarrow \mu^{+}\ \mu^{-}$ (or $e^{+} e^{-}$)



GIM mechanism led to the c quark.

→ Generation 2

Observation of CP Violation: $K_{L}^{0} \rightarrow \pi\ \pi$
Proposal of CKM matrix. → Generation 3

<u>What is next?</u>

Relation of K_L to K^+

The decays K_L and K^+ to $\pi \nu \bar{\nu}$ are subject to the Grossman-Nir relation (based on isospin):

$$BR(K_L \text{ mode}) < 4.4 \text{ x } BR(K^+ \text{ mode})$$

Currently,

$BR(K^+ \text{ mode}) = (1.73 \pm 1.10) \text{ x } 10^{-10}$ (BNL 787/949)
$BR(K_L \text{ mode}) < 2.6 \text{ x } 10^{-8}$, 90% CL (KEK E391a)

So the K_L decay mode must be improved by a factor of about 20 – 100 to get below the Grossman-Nir relation.

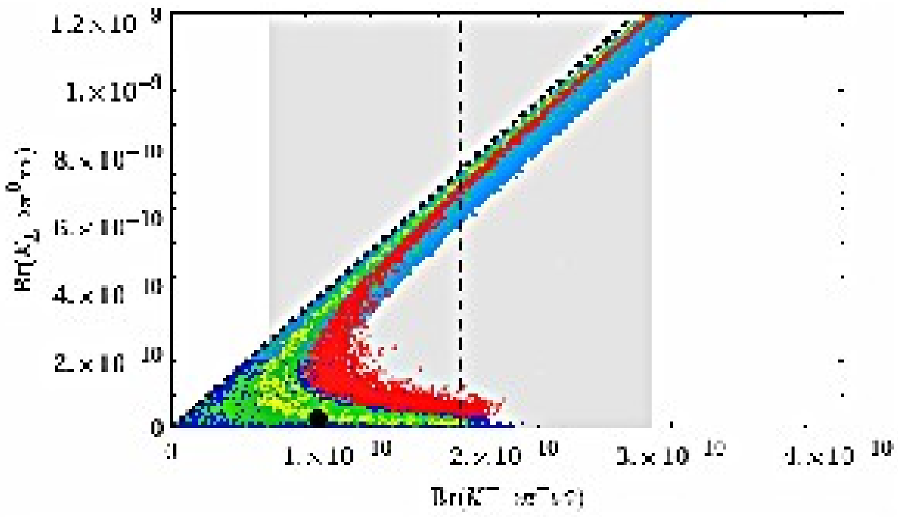
The KOTO experiment will do just that!

Note: The SM BR for the K^+ mode is $(8.5 \pm 0.7) \text{ x } 10^{-11}$.
K_L mode is $(2.4 \pm 0.4) \text{ x } 10^{-11}$.

Physics Beyond the Standard Model?

To get the the Standard Model level, the sensitivity of KOTO must be ~1000 times better than for KEK E391a.

But at 20-100 times improvement, KOTO is poised to see New Physics Beyond the Standard Model, if it exists.



Buras et al. have examined a 4-generation model. It can provide a K_L rate just below the G-N limit, and much above the SM value.

Requirements for the Experiment

- A detector of high acceptance, with a small hole through the center to allow beam to pass.

- Cover the decay region with hermetic photon veto counters that have very low inefficiency.

- Place detectors in high vacuum to minimize dead materials.

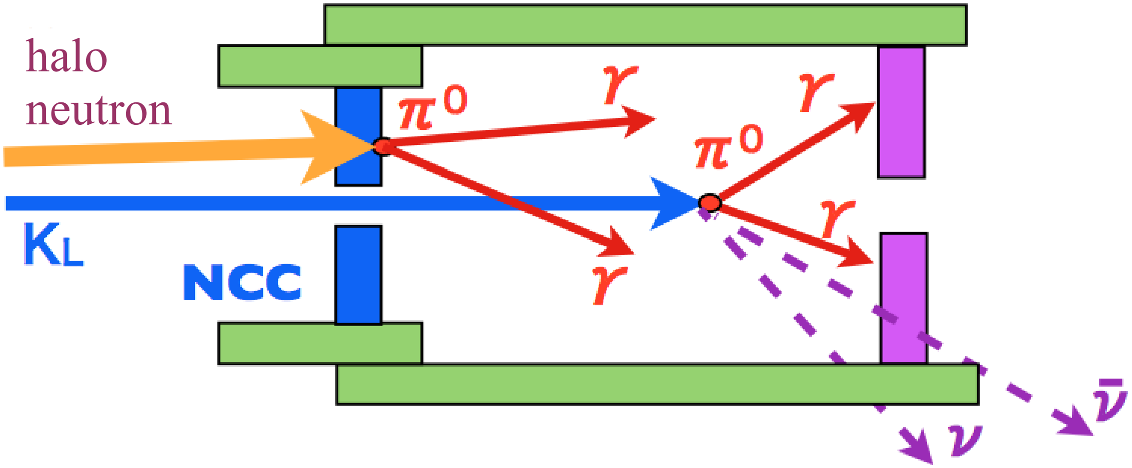
- Use a 'pencil' K_L beam.

- Require events to have only 2 photons that have the invariant mass of a π^0, and a large transverse momentum.

- Eliminate, eliminate, and eliminate backgrounds and unwanted events.

- These methods were developed for E391a, and will be extended for KOTO.

Strategy of the Experiment



- Use a large array of crystals to detect photons with good spatial resolution and very small energy loss out the end.

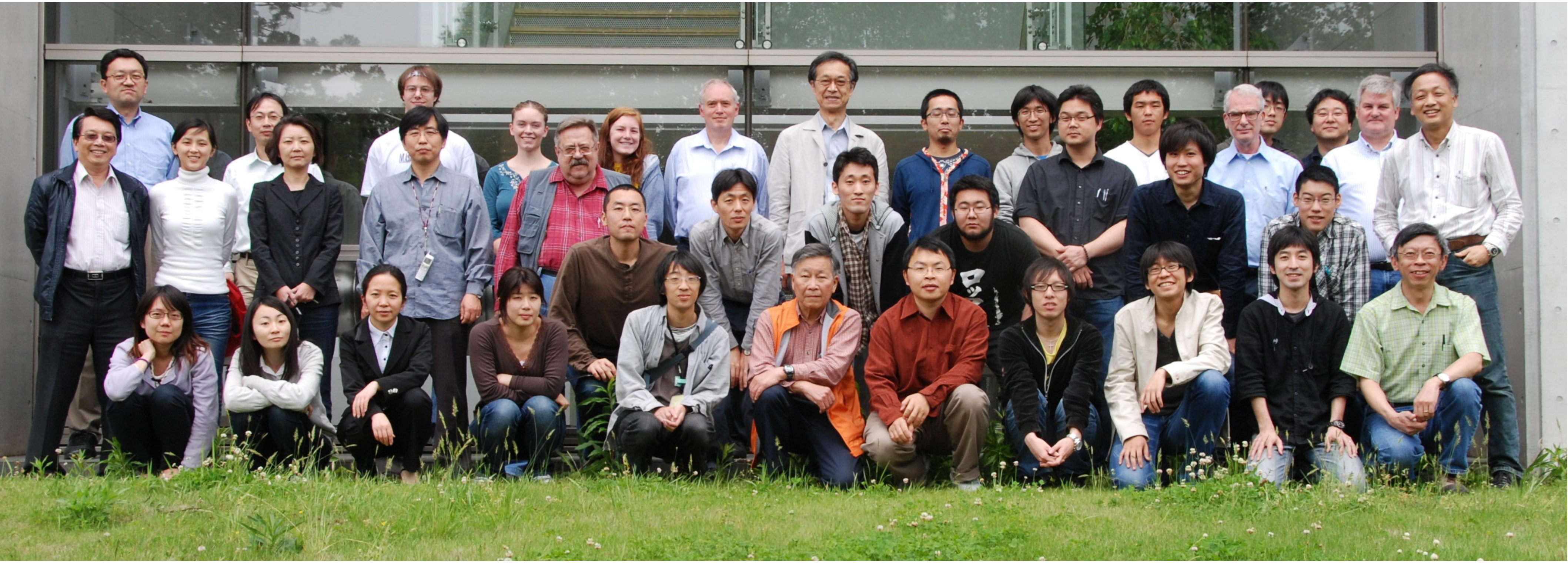
- Project back from the photon hit positions towards the beam line to determine the position in the kaon decay region.

- The two photons must have the invariant mass of a π^0 .

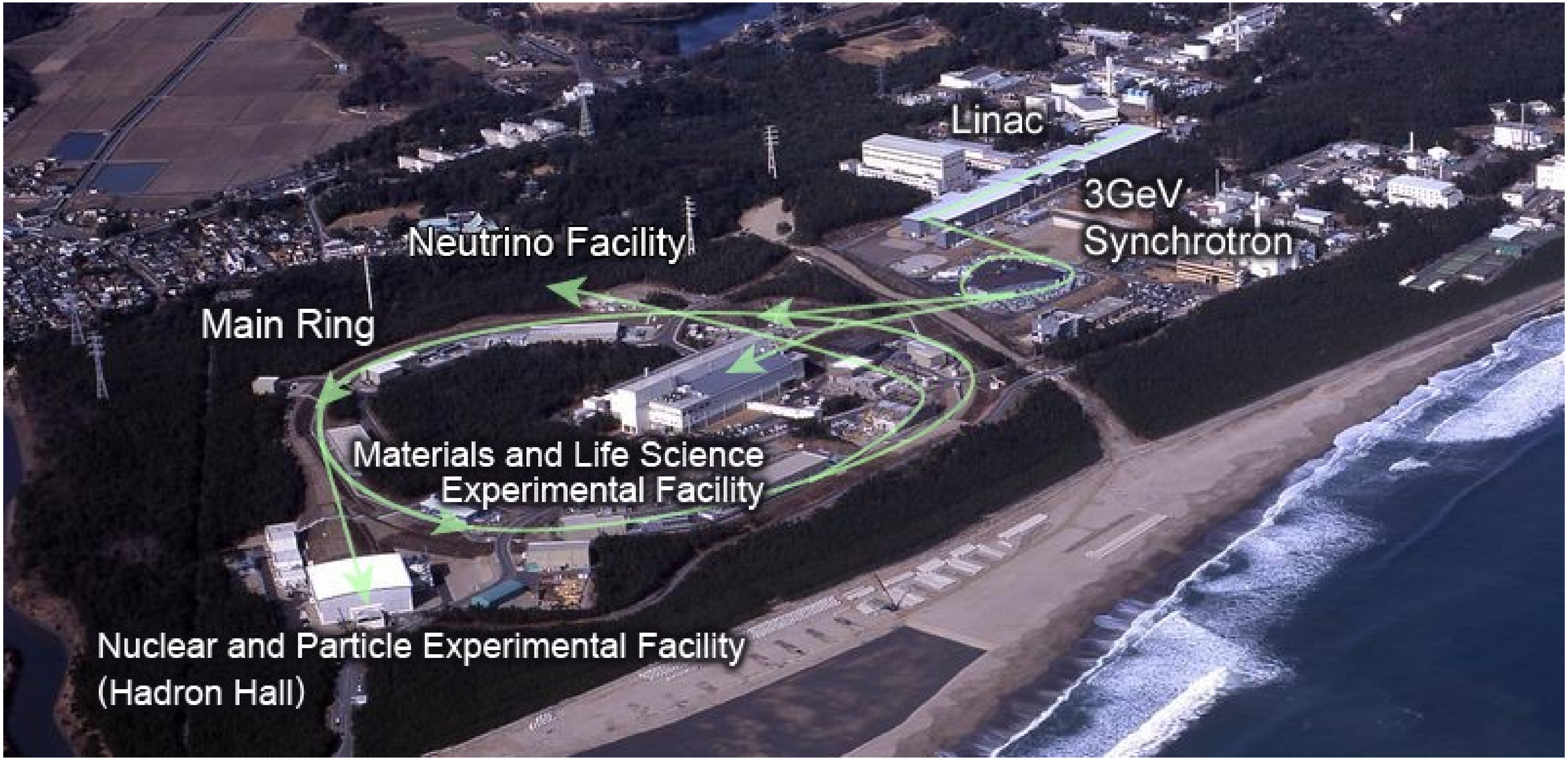
- Select a (high) range of transverse π^0 momenta, corresponding to the momentum carried by the neutrinos, to suppress backgrounds.

KOTO Collaboration

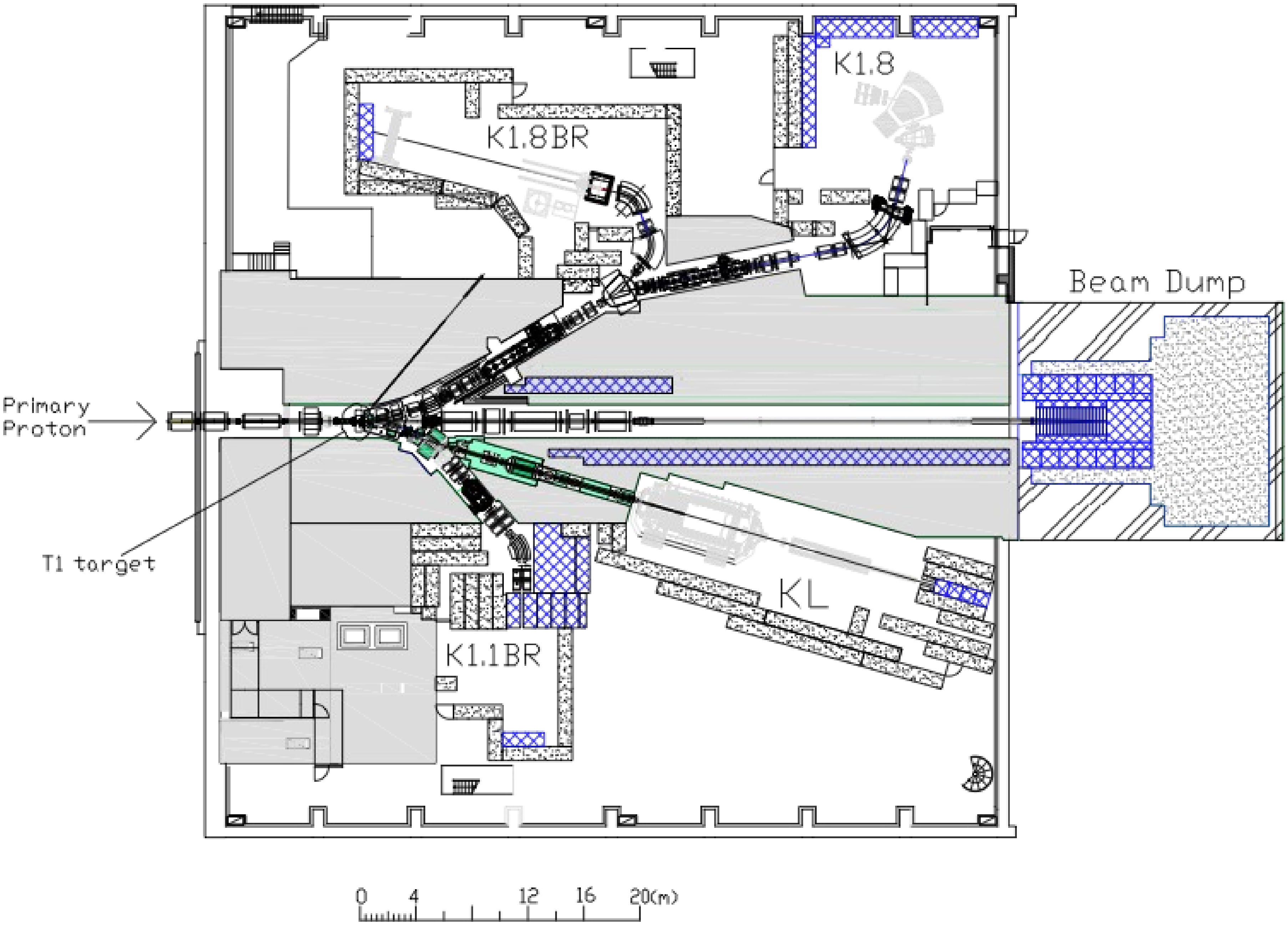
Japan: KEK, Kyoto, NDA, Okayama, Osaka, Saga, Yamagata
USA: ASU, Chicago, Michigan
Korea: Cheju, CNU, KNU, Pusan, U. Seoul
Taiwan: NTU
Russia: JINR



J-PARC Laboratory



Hadron Hall


K1.8
K1.8BR
Beam Dump
Primary
Proton
T1 target
KL
K1.1BR
0
4
12
16
20(m)

Production Target

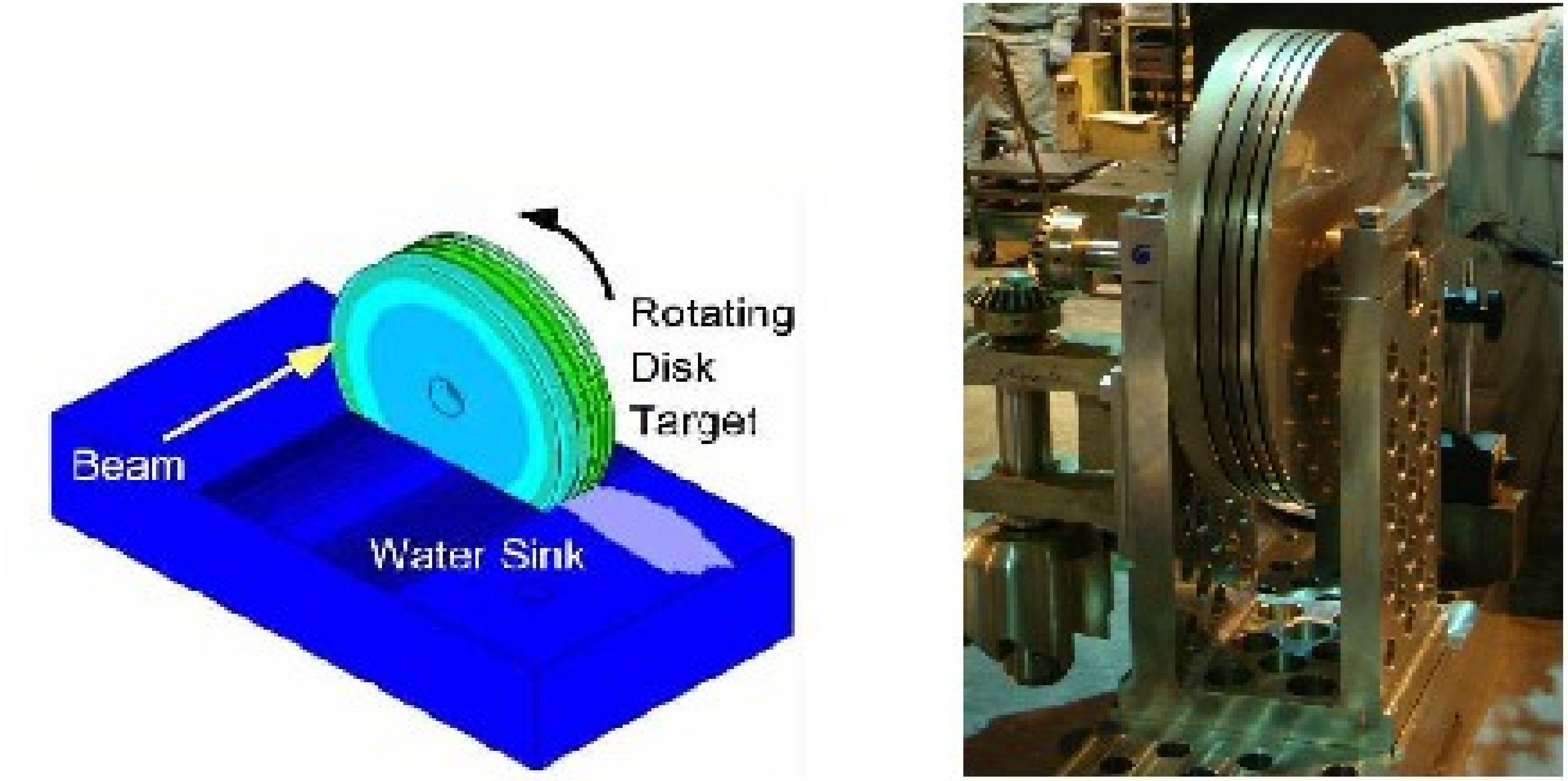
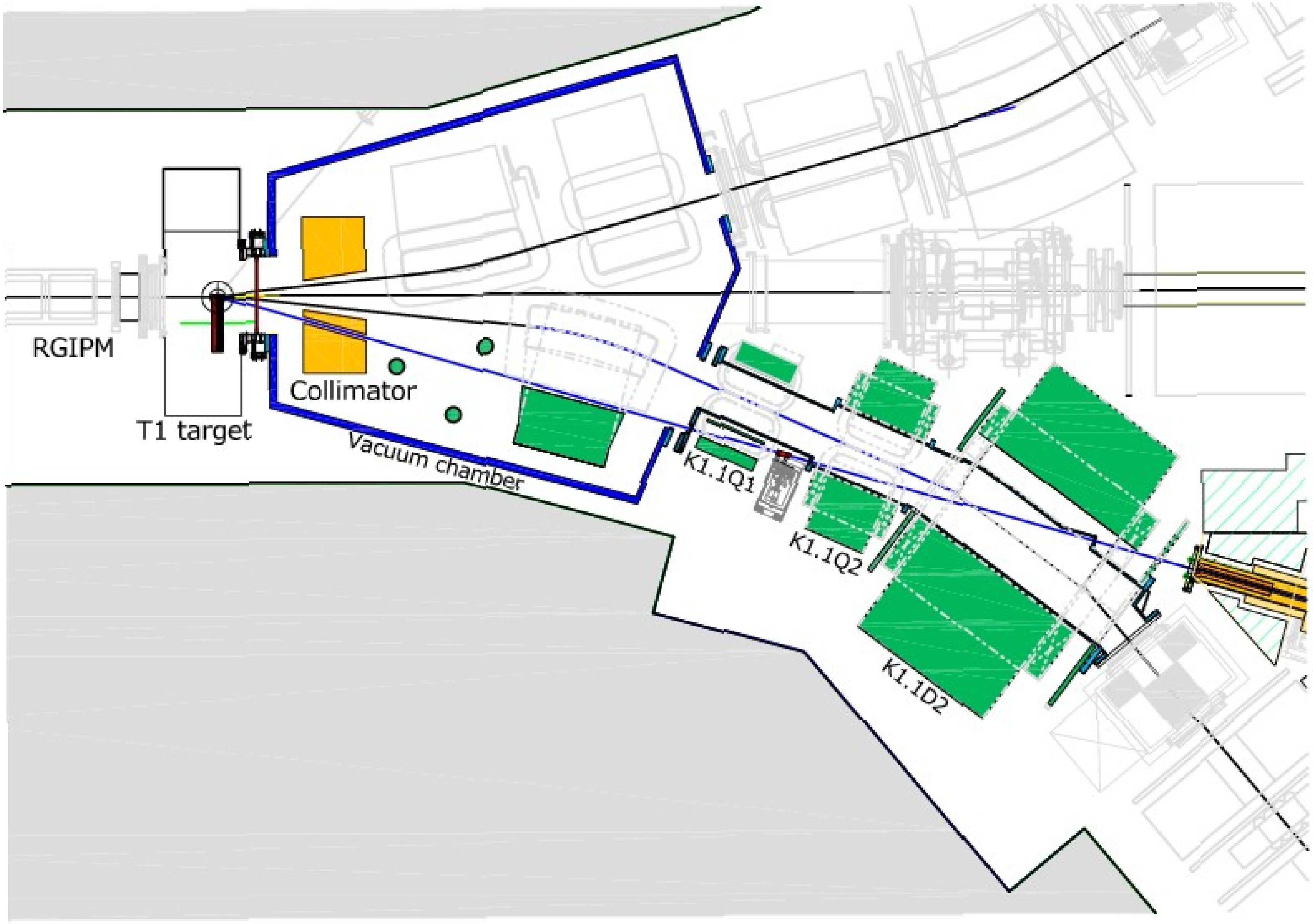


Figure 3: Schematic view of the T1 target (left) and a photo (right).

Currently, with low beam, nickel and platinum rod targets are being used.

Upstream Part of Beamline



KOTO Collimator

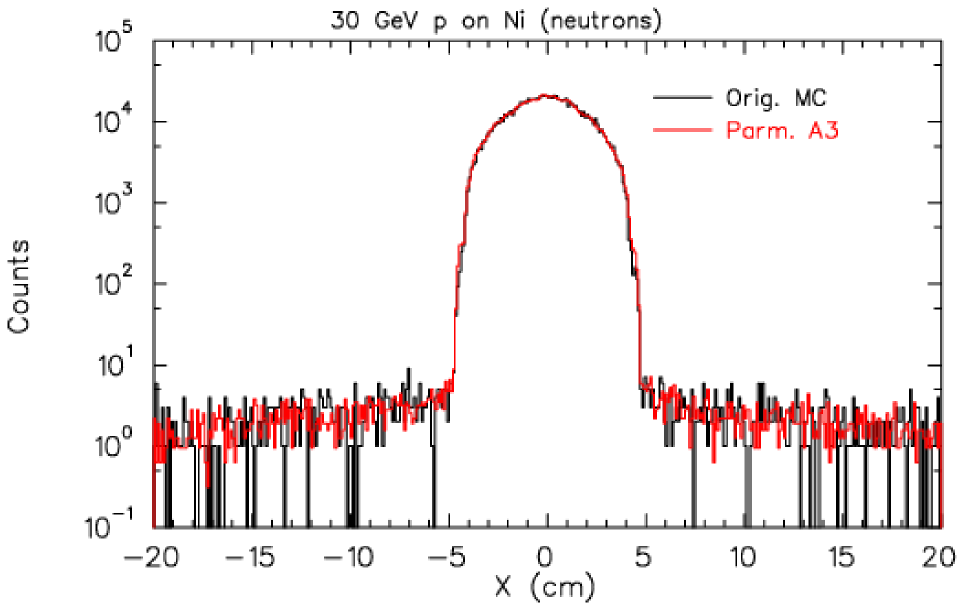
← Collimator 2

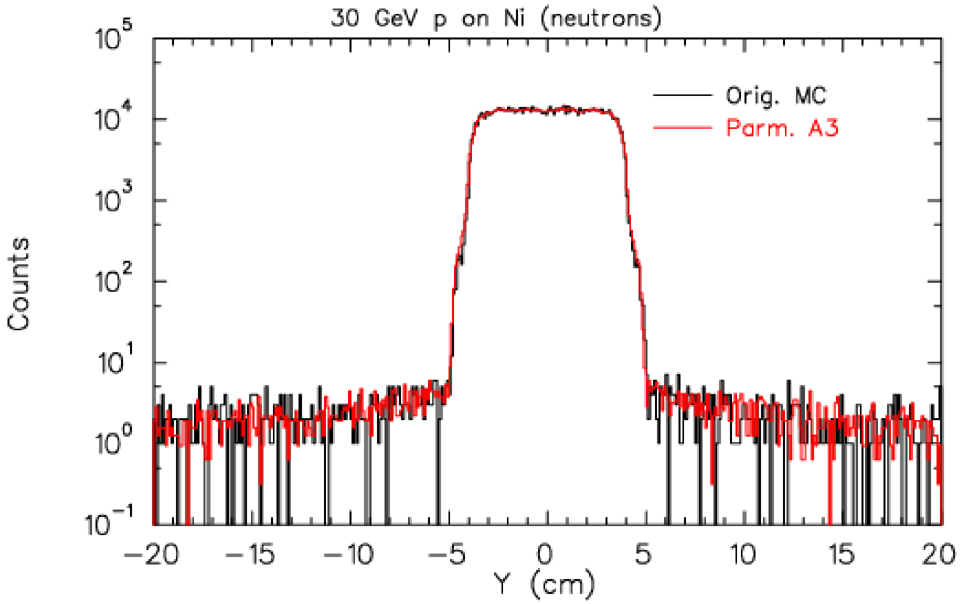
← Sweep Magnet

← Collimator 1

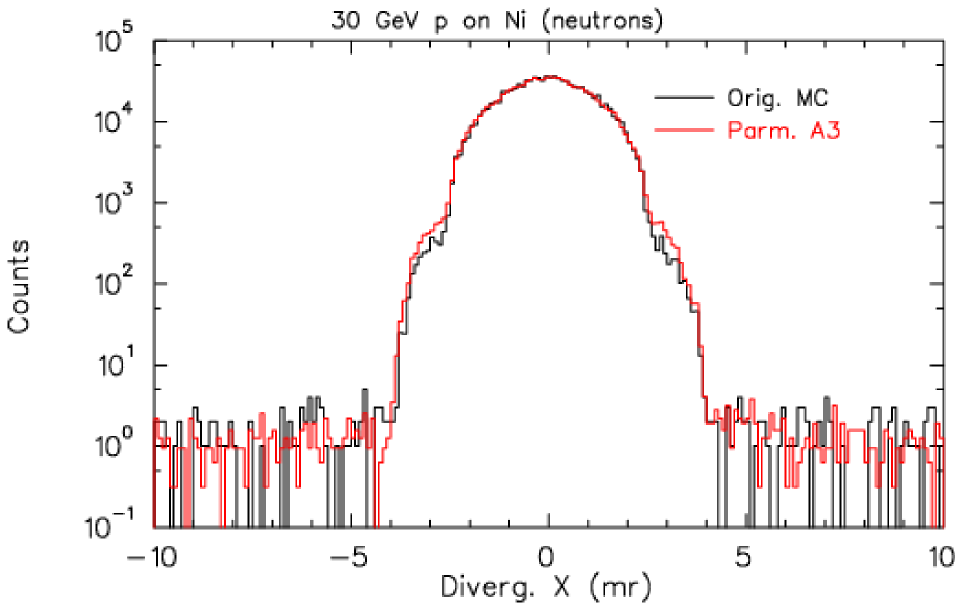
Neutron X and Y profiles at 2100 cm

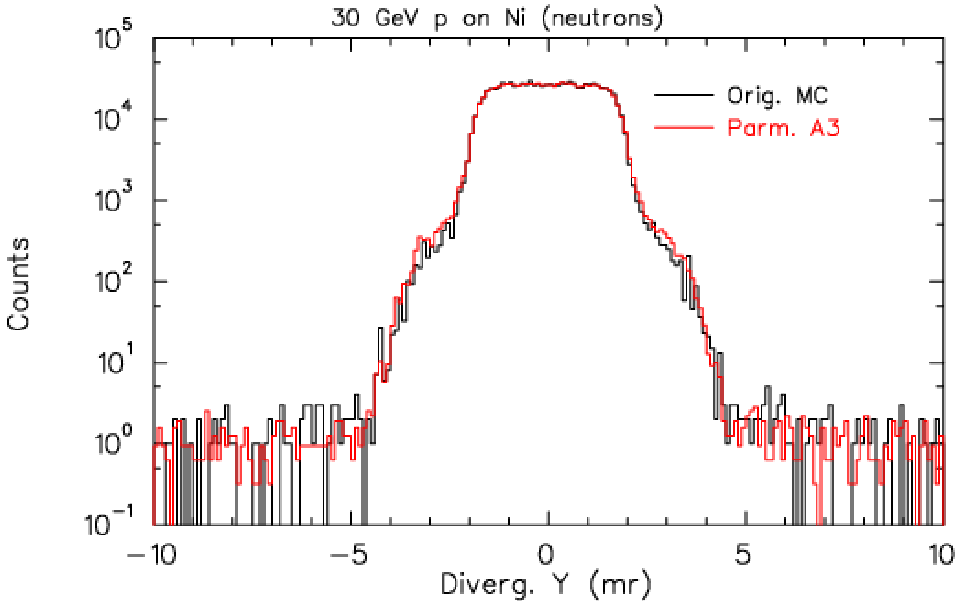
Coordinate





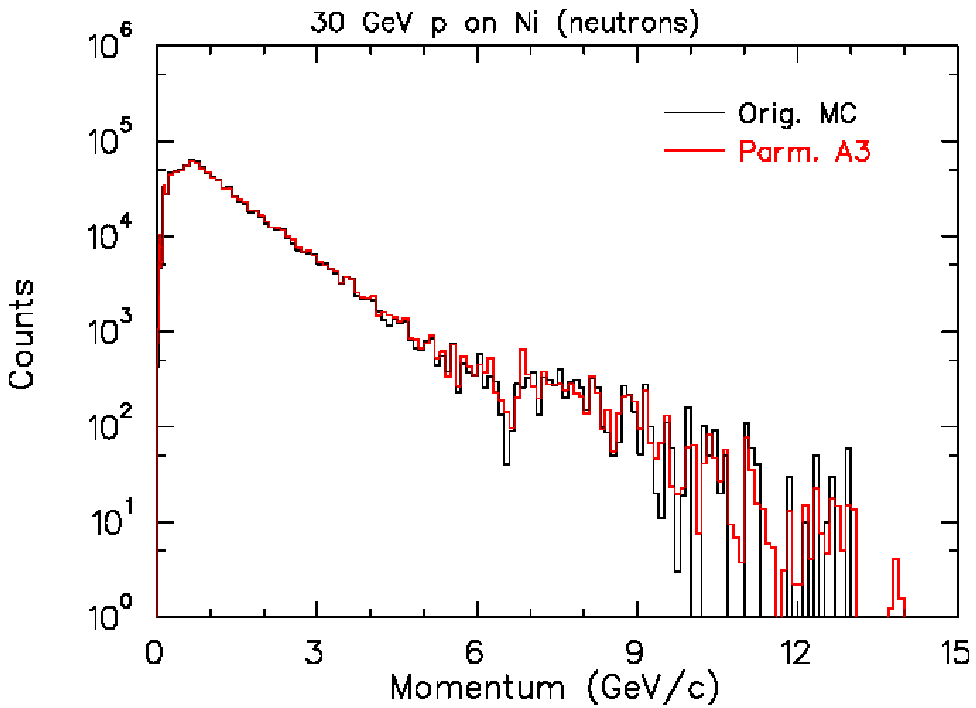
Divergence

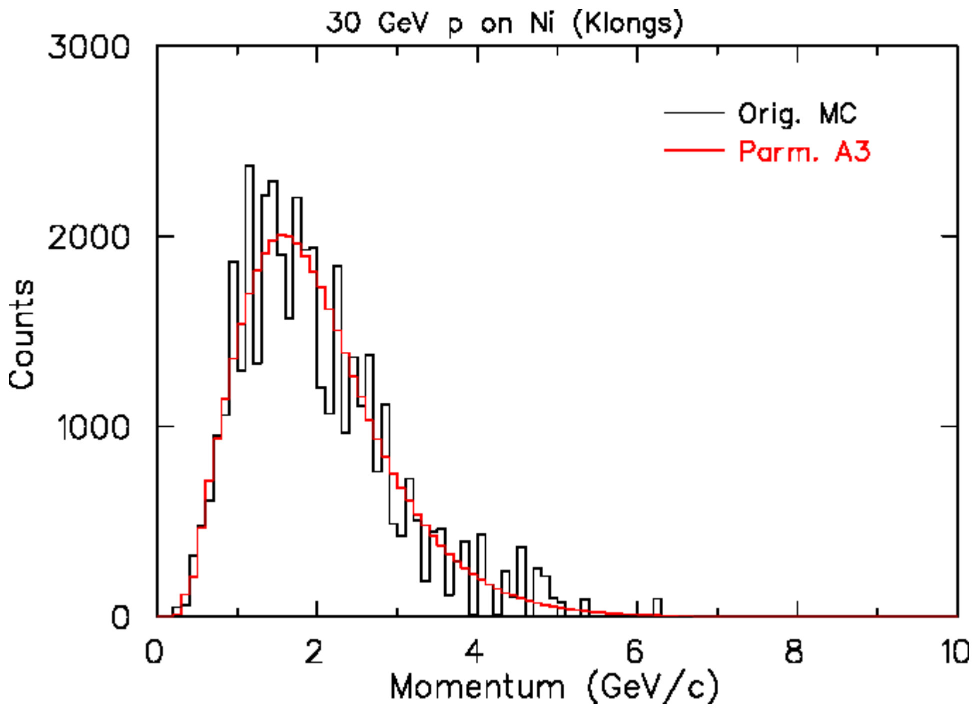




Neutron & K_L Momentum Profiles

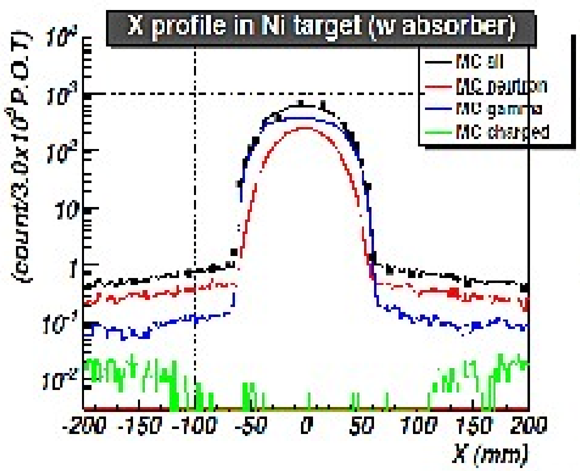
At 2100 cm – end of beam line/entrance to detector

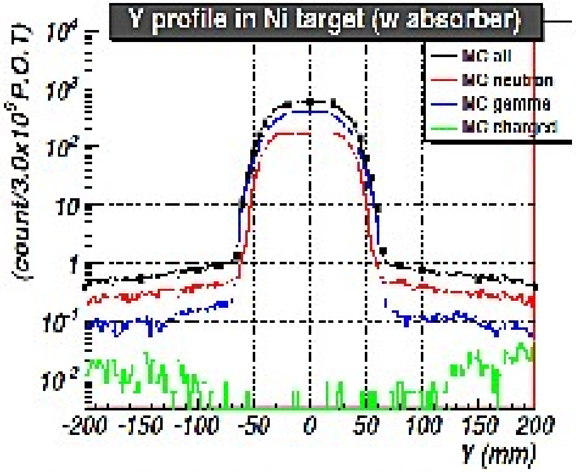




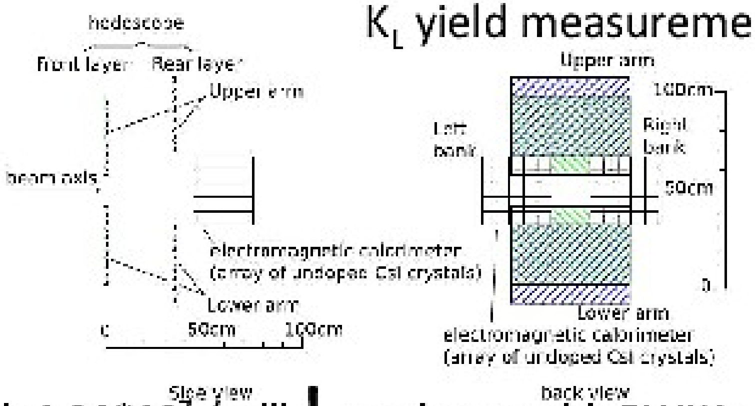
Beam Survey in 2009

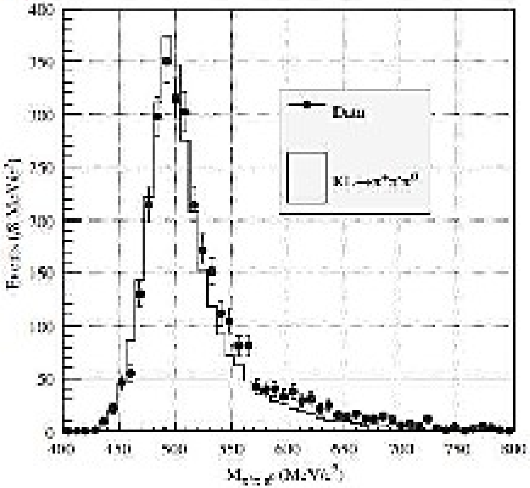
Halo suppression meets expectation





K_L yield measurement





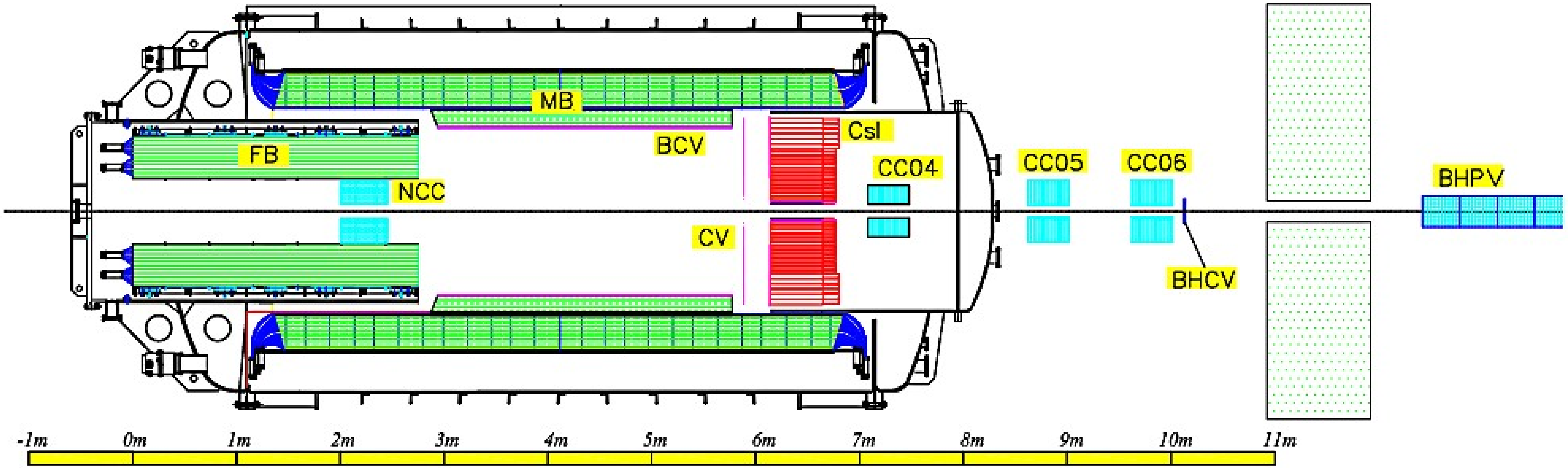
K_L yield: 1.94*10^7 /spill ! consistent with FLUKA;

2.4*GEANT4 QGSP-BERT-CHIPS (proposal assumption)

3 Snowmass year → <1.5

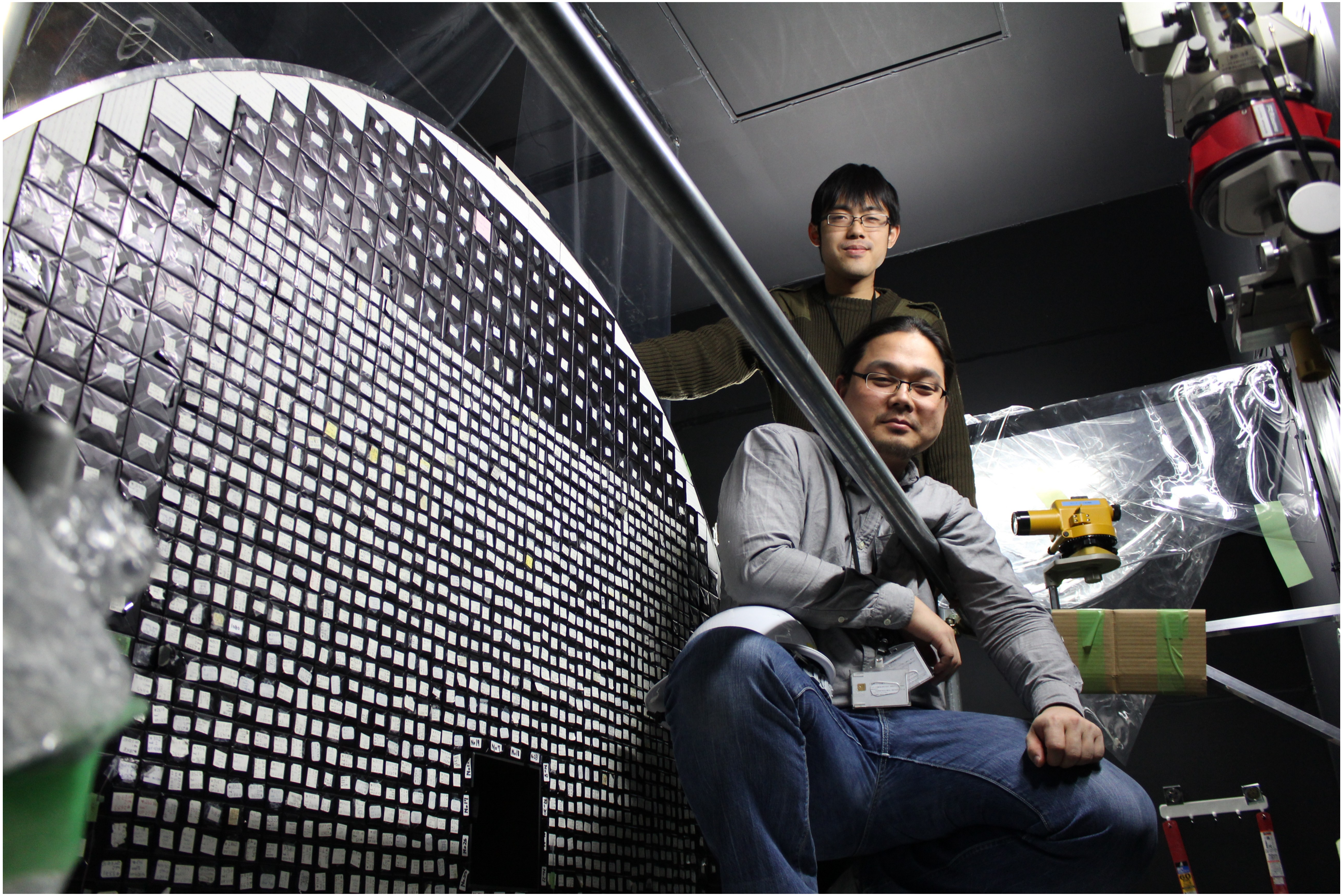
K. Shiomi, et al, Nucl. Instr. And Meth. A664, 264 (2012)

KOTO Detector



FB = Front Barrel
MB = Main Marrel
NCC = New Collar Counter
BCV = Barrel Charge Veto
CV = Charge Veto
CsI = CsI Crystals (50 cm, from KTeV)
CC0n = Collar Counters (Veto)
BHCV/BHPV = Beam Hole Charge/Photon Veto

CsI Stacking Completed, 2/8/11



DAQ System Concepts

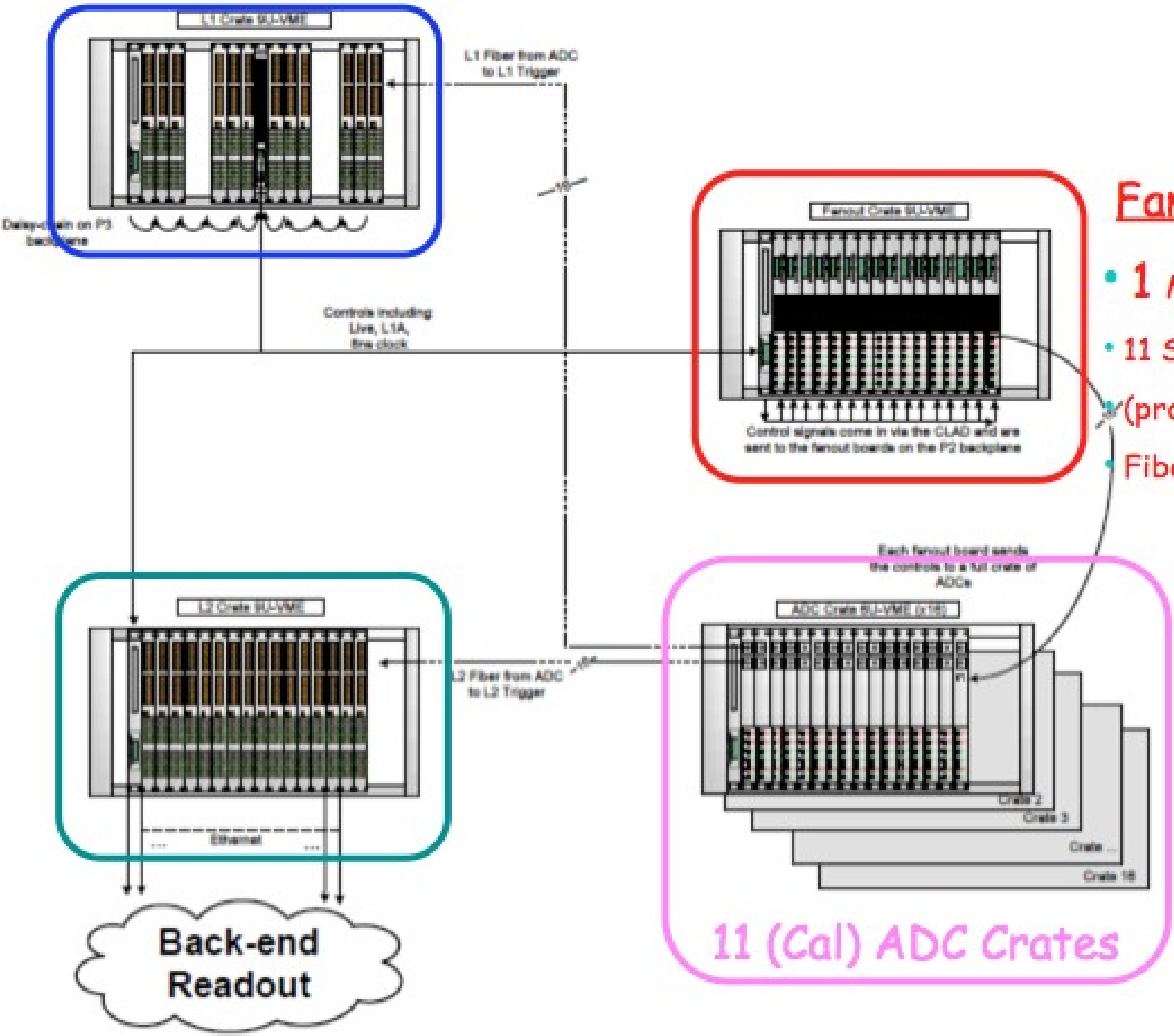
The DAQ electronics is custom-designed and built (Chicago and Michigan), with flexible FPGA firmware (ASU and UM).
The signals from 2716 CsI crystals and many other detector systems are digitized at 125 MHz (8 ns) over 48 time steps.
High-rate detectors (e.g., in the beam hole) are digitized at 500 MHz.
A ~Gaussian-shaping filter is used on the 125-MHz ADCs.
There are no TDCs.
The ADC data are pipelined to wait for a trigger signal.
2.5-GHz fiber is used for transfers to the trigger modules.

The data to Level-1 (L1) trigger boards are summed and compared to a set threshold (300or 500 MeV) to make a trigger.
The trigger is fanned out to the ADC boards with proper timing.

Upon receiving a trigger, the ADCs send the event data to the Level-2 (L2) system.

The L2s route the event segments to multiple PCs for event building.

DAQ and Trigger Structure



L1Trigger :

- 1 Master MACTRIS
- 1 Slave MACTRIS
- 11 Trigger boards
- Fiber-trans board

Fanout :

- 1 Master Fanout
- 11 Slave Fanout
- (processor)
- Fiber-trans. board

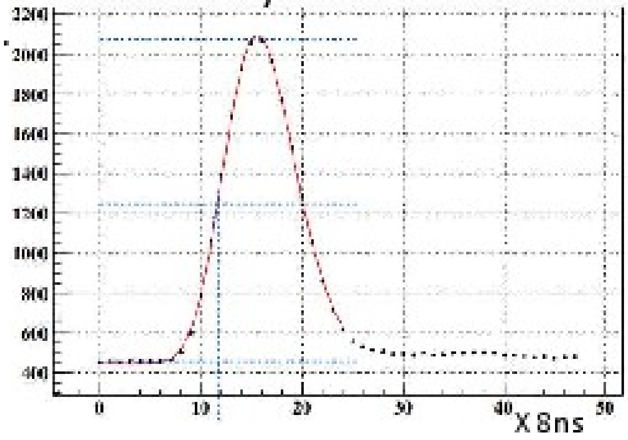
L2Trigger :

- 1 Slave MACTRIS
- 11 Trigger boards

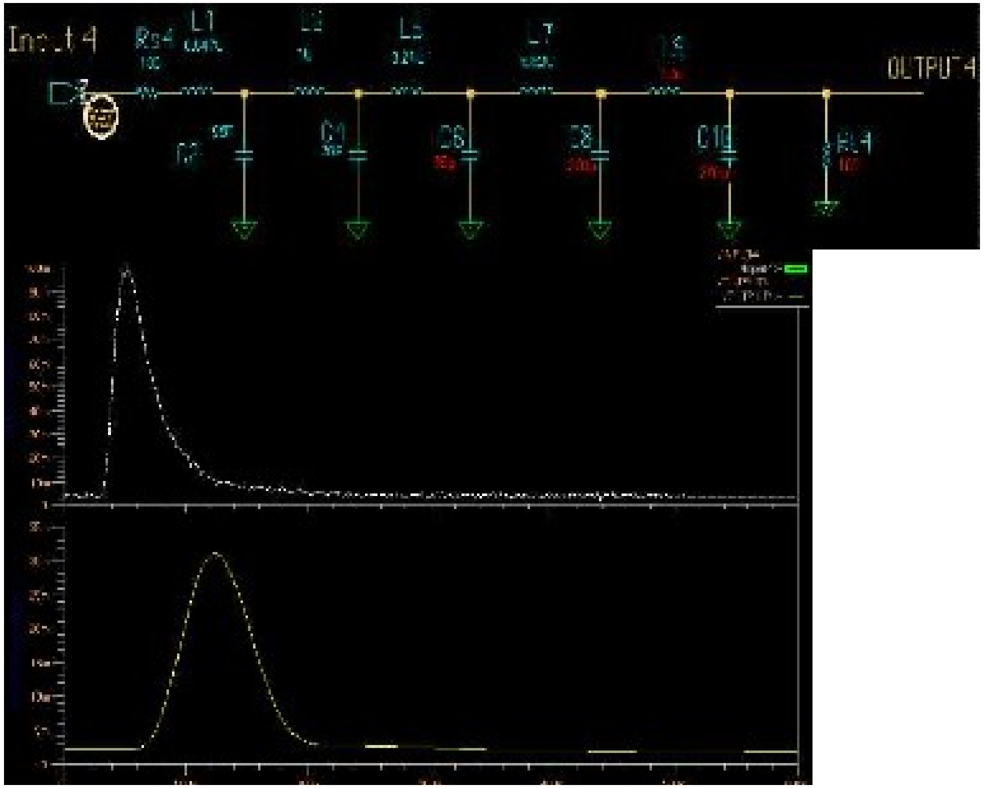
Event Timing

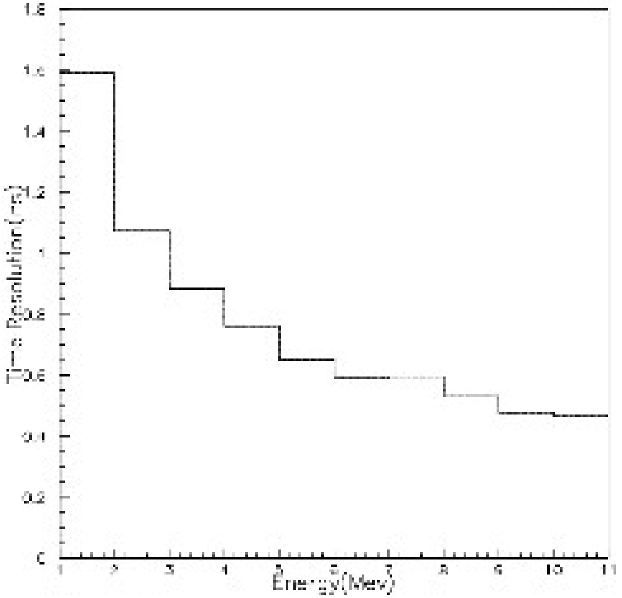
- Use the full waveform fitting to get the time instead of using threshold-TDC
- More waveform samples for the stretched quasi-Gaussian pulse.
- Time resolution is a function of the pulse smoothness(# of photo-electrons, energy). ~110ps at 200MeV in KOTO
- One system clock is very important for time measurement(~20 ps clock jitter)

CsI pulse data recorded by 125MHz FADC



SPICE Simulation and tuning of the filter





Expected time resolution from simulation

Data Size

Monte Carlo simulations, with vetos, estimate that ~70,000 events will trigger in 0.7 sec (100 kHz) of a beam spill at full beam intensity (300 kW, 2 x10^{14} protons on target).

If all 48 time steps for all signals are kept, data can exceed 0.5 PB/day!
The L2 and PC stages are major bottlenecks.

Various ideas for data compression are being pursued.

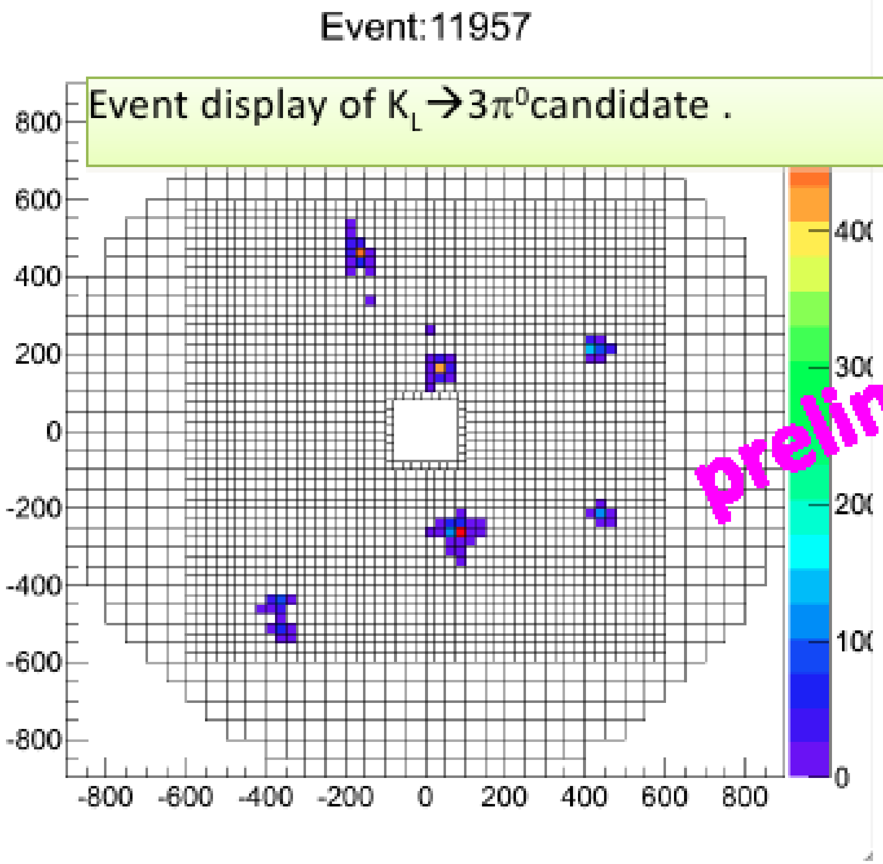
An option is to capitalize on the nearly fixed shape in time of the signal. A correlation coefficient can be computed between a reference peak and the data. Data above a threshold are passed. The method has excellent performance down into the noise level, and has been programmed into the ADC firmware, to exclude the many channels that have no measurable signals.

Ultimately, the 48 time steps will be replaced with fitted energy and time values.

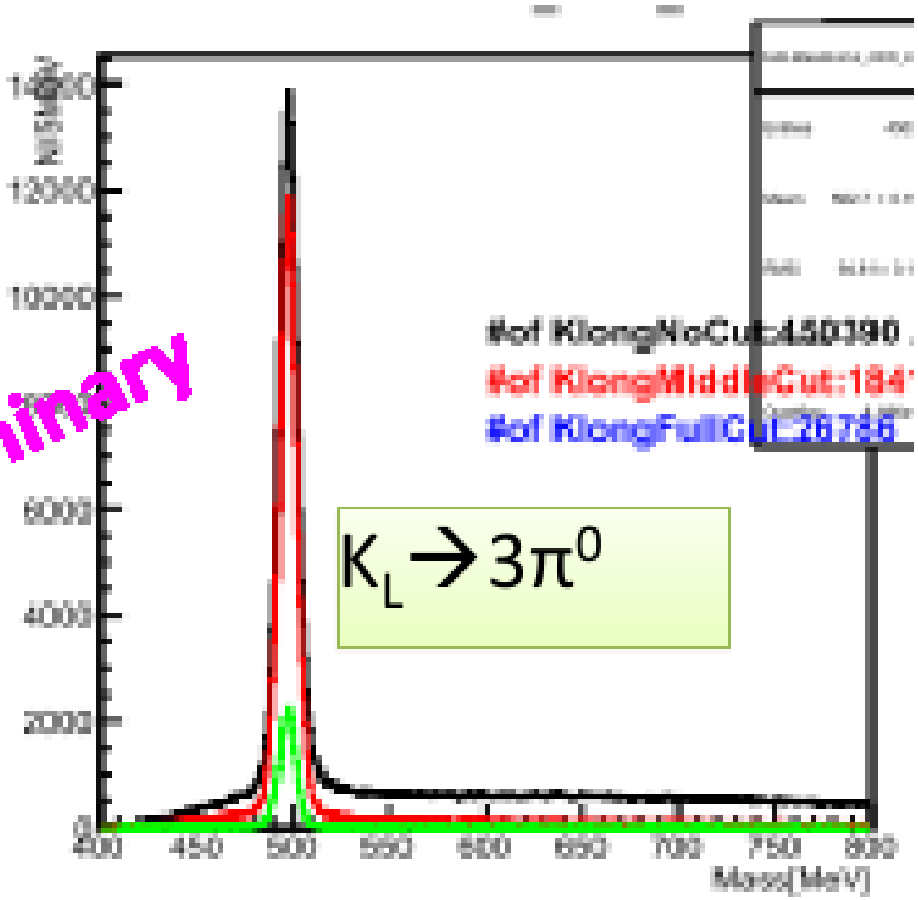
Engineering Run in Feb. 2012

J-PARC and KOTO have largely recovered from the earthquake.

In Februrary, an engineering run was made to realign the beam collimators and confirm the calorimeter and calibration methods.



Event display of $K_L \rightarrow 3\pi^0$ candidate .



$K_L \rightarrow 3\pi^0$

CV, June Test Run

- All the scintillator strips are fixed to the CFRP.
- All MPPCs are mounted and all strips and MPPCs are OK.
  - Checked with 90Sr and oscilloscope
- All preAmps are mounted and connected with MP
- Scintillator strips only

  (12um thick aluminized mylar)
- WLS fibers are inside → safer

Rough Timeline

Summer-Fall, 2012.	Installation of full detector.
Nov/Dec, 2012.	Engineering run (~4 weeks)
Early 2013.	Physics Run (~4 weeks), to reach G-N limit
Summer-Fall, 2013.	Shutdown for accelerator upgrade.
2014-2017.	Physics Runs, to reach SM level (a 'few' events)
~2016.	Start construction work on Stage 2.
~2020.	Engineering and physics runs, Stage 2

Summary

Kaons have had key roles in the development of the Standard Model
Took us from 1 generation to 2 and then to 3 (and maybe to 4).

CP violation is observed in several kaon decays.

The KOTO experiment can provide us with a direct measurement of the CP-violating parameter η in the Standard Model.

We are bringing innovative electronics to the task.

The experiment is very tough, but is progressing well.

The experiment is poised to soon break through a threshold for New Physics Beyond the Standard Model.

Stay tuned.