KOTO experiment: a measurement of the branching ratio of rare decay

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

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On behalf of KOTO collaboration
08/16/2013

Outline

- Overview
- Physics motivation
- Experimental strategy
- E391a challenges
- Detector status
- 1st physics run and the radiation accident

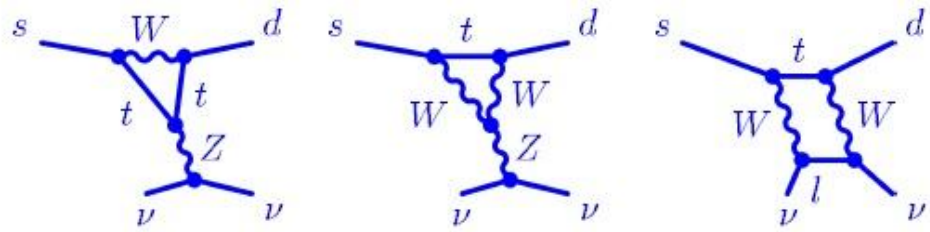
Overview

- KOTO (K^0 at Tokai) experiment is designed to measure the branching ratio of rare decay $K_L \to \pi^0 \nu \bar{\nu}$. The SM branching ratio prediction is 2.43(39)(06) $\times 10^{-11}$ (Phys.Rev.D.034030(2011)), with a very small theoretical uncertainty of 2.5%.
- The facility to generate K_L beam for KOTO is the 50 GeV proton synchrotron (Main Ring energy is 30 GeV) in J-PARC, Tokai-mura, Japan.
- Pilot experiment E391a (2001-2005) gave an upper limit: Br< 2.6 $\times 10^{-8}$ at 90% confidence level (Phys. Rev. D, 072004 (2010)), 3 orders of magnitude larger than SM predictions.

KOTO has a collaboration of 65 people from 16 institutes from 5 countries.

Physics Motivation I

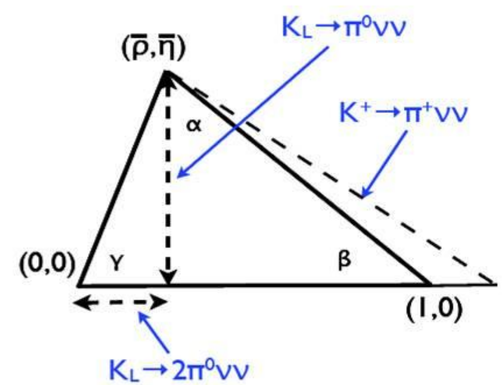
- Fundamental test of the Standard Model
  - It's a Flavor Changing Neutral Current (FCNC) process induced through electroweak penguin and box diagrams with *t* quark internal loop.



  - Direct CP violating process: branching ratio proportional to the square of the imaginary part of CKM matrix

(in Wolfstein parametrization to 3rd order of λ)

$$V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

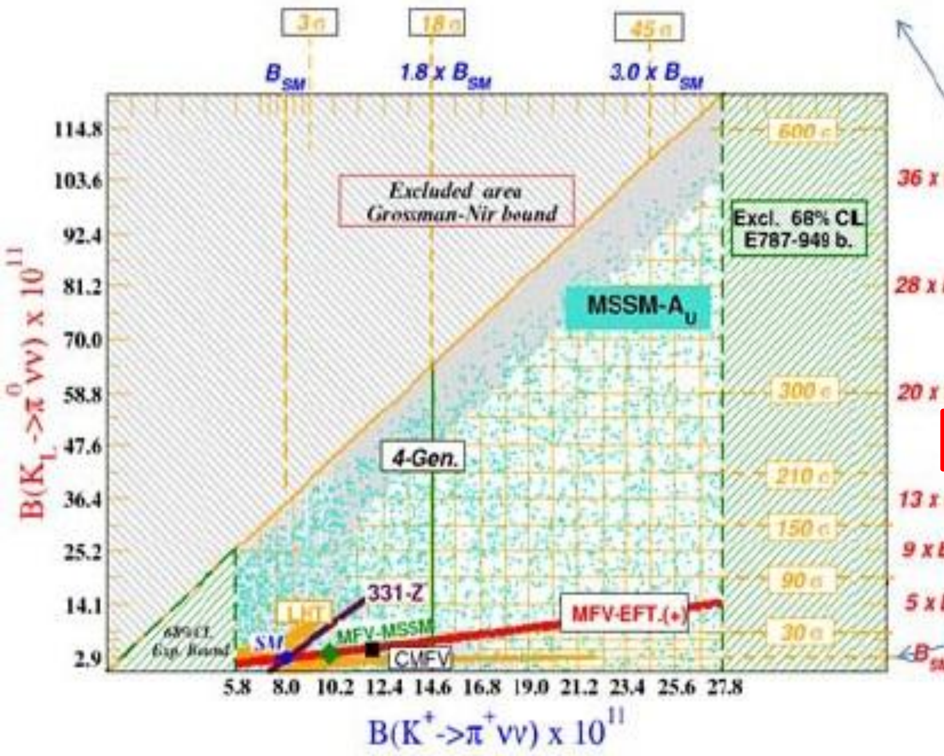


$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0.$$

$$Br(K_L^0 \to \pi^0 \nu\bar{\nu}) = 6.87 \times 10^{-4} \times Br(K^+ \to \pi^0 e^+ \nu) \times A^4 \lambda^8 \eta^2 X^2(x_t)$$
$$= (2.43 \pm 0.39 \pm 0.06) \times 10^{-11}$$

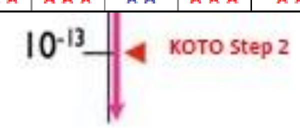
Physics Motivation II

- Beyond Standard Model (BSM) extensions
  - The decay is dominated by electroweak loop diagrams, thus sensitive to short distance (high energy scale) physics. Therefore, it's a good probe of high energy scale physics using a low energy process.



http://www.lnf.infn.it/wg/vus/content/Krare.html

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?



Physics Motivation II

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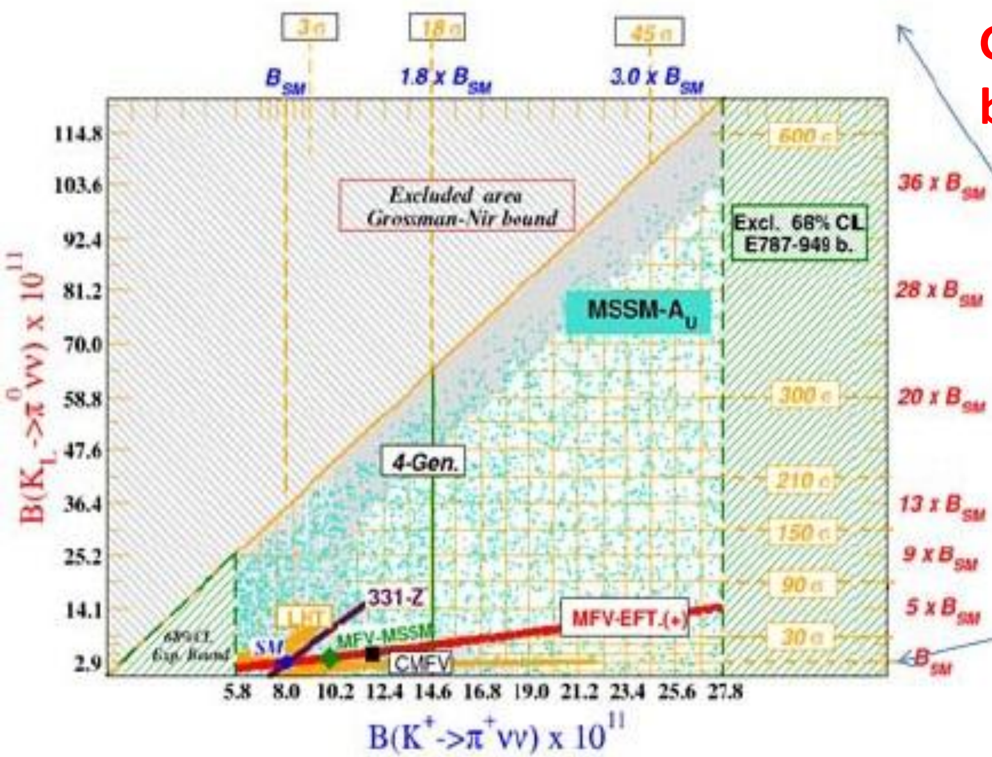
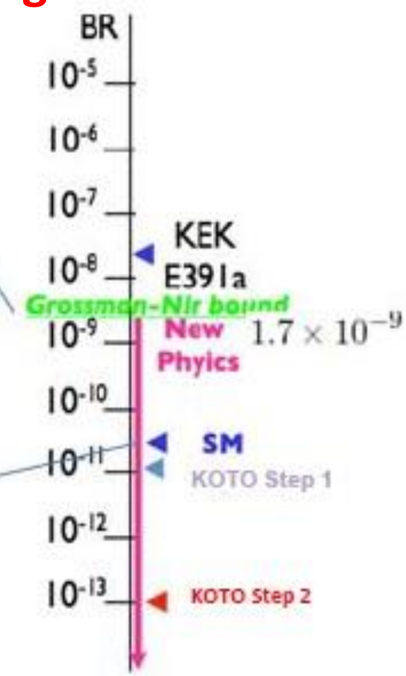


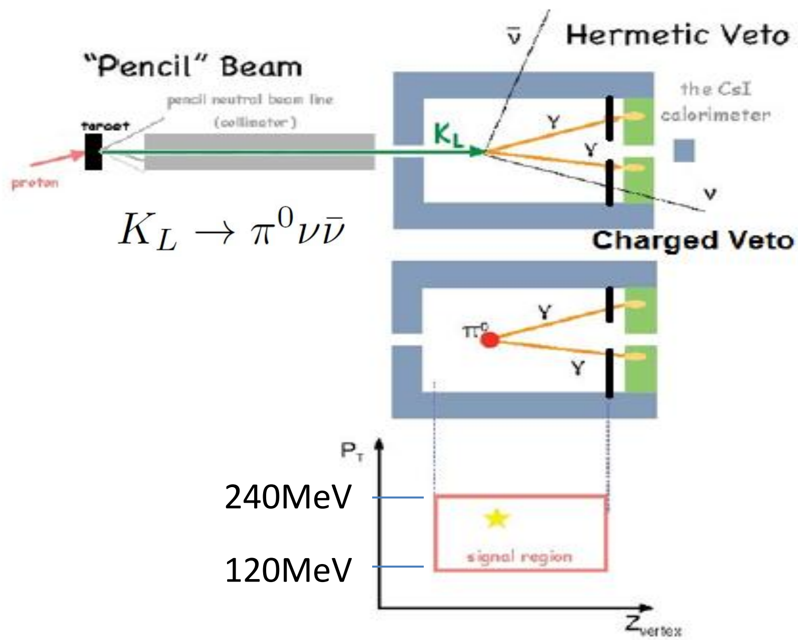
http://www.lnf.infn.it/wg/vus/content/Krare.html

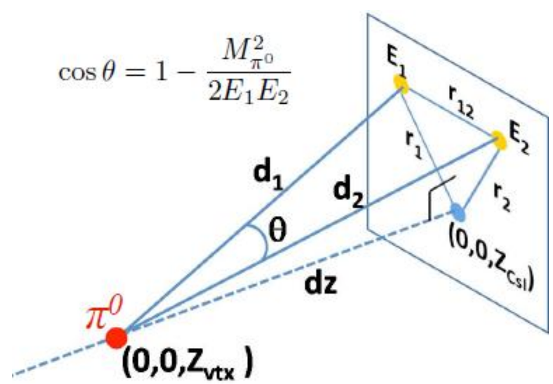
GOAL : 10^{-13} sensitivity of branching ratio measurement



Experimental strategy

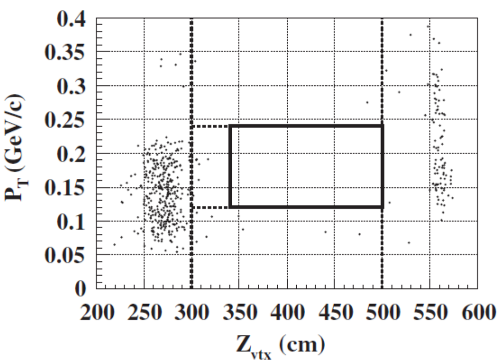
- Select events with only two photons and nothing else. (Calorimeter + hermetic veto)
- Using the information of deposit energy (E_i) and position (r_i) of the two photons, reconstruct the π^0 decay point (Z_{vertex})(which is the K_L decay point), and P_T.
- Define a signal region in P_T-Z_{vertex} plane to find the signal.
- K_L pencil beam: put a constraint on kinematic reconstruction

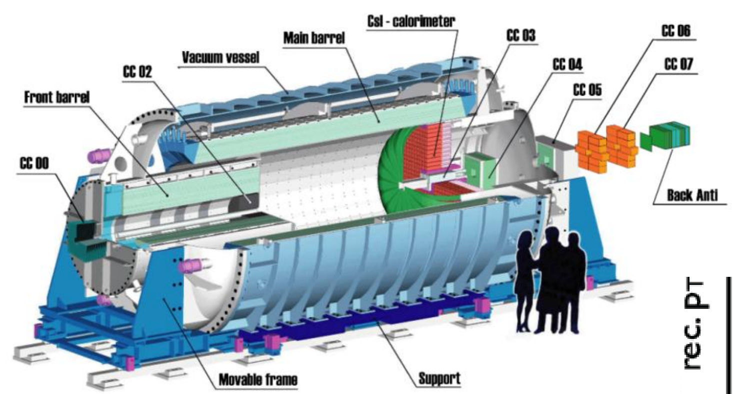




Pilot E391a and its challenges

- E391a gives an upper limit measurement of Br < 2.6×10^{-8} at 90% Confidencelevel. (Phys. Rev. D, 072004 (2010))
- Neutron interaction with detectors close to the beam is the biggest background. At a single event sensitivity of 1.1×10^{-8}.



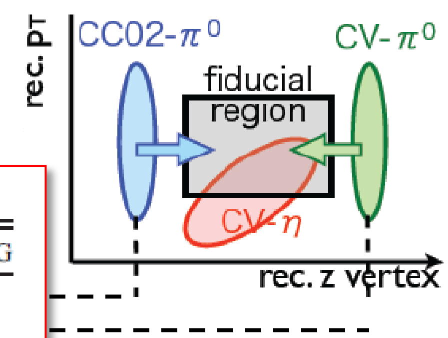


How to make an improvement of 1000 times to reach SM sensitivity

- Halo neutron suppression
- $K_L \to 2\pi^0$ background suppression
- New readout electronics

TABLE V. Estimated number of background events.

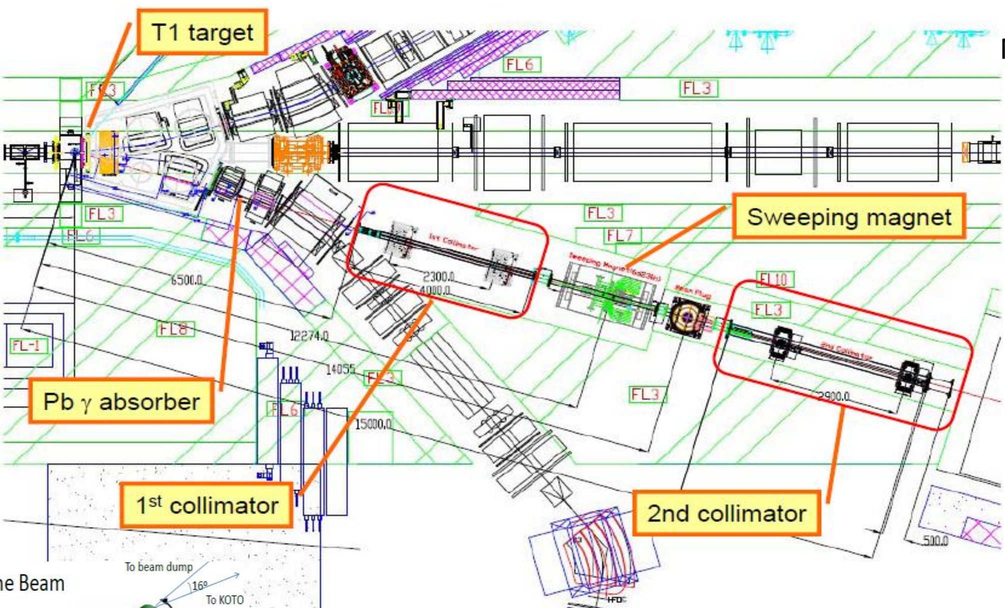
Background source		Estimated number of BG
Halo neutron BG	CC02-π^0	0.66 ± 0.39
	CV-π^0	<0.36
	CV-η	0.19 ± 0.13
K_L^0 decay BG	$K_L^0 \to \pi^0\pi^0$	$(2.4 \pm 1.8) \times 10^{-2}$
	$K_L^0 \to \gamma\gamma$	Negligible
	Charged modes	Negligible ($\mathcal{O}(10^{-4})$)
Other BG	Backward π^0	<0.05
	Residual gas	Negligible ($\mathcal{O}(10^{-4})$)
Total		0.87 ± 0.41

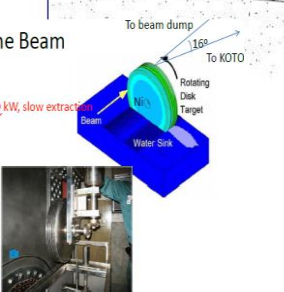


Beam line

- 30 GeV accelerator
  - Higher beam intensity, K_L yield
  - Large extraction angle
- Re-designed collimator systems to suppress halo neutron.

	J-PARC E14 KOTO	KEK-E391a
• Primary proton energy	30 GeV	12 GeV
• Proton intensity(/spill)	2×10^{14}	2.5×10^{12}
• Spill-length/repetition	0.7s / 3.3s	2s / 4s
• Extraction angle	16 deg.	4 deg.
• K_L yield(/spill)	8.1×10^{6}	3.3×10^{5}
• Average P_{KL}	2.1 GeV/c	2.6 GeV/c
• n/K_L ratio	6.5	45





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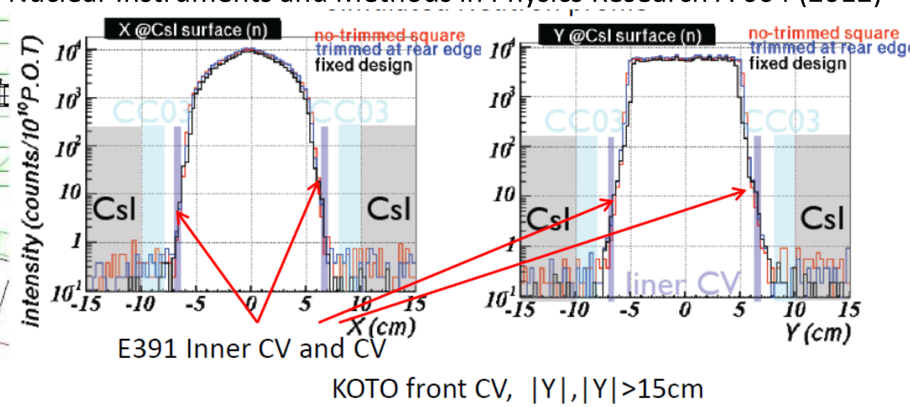
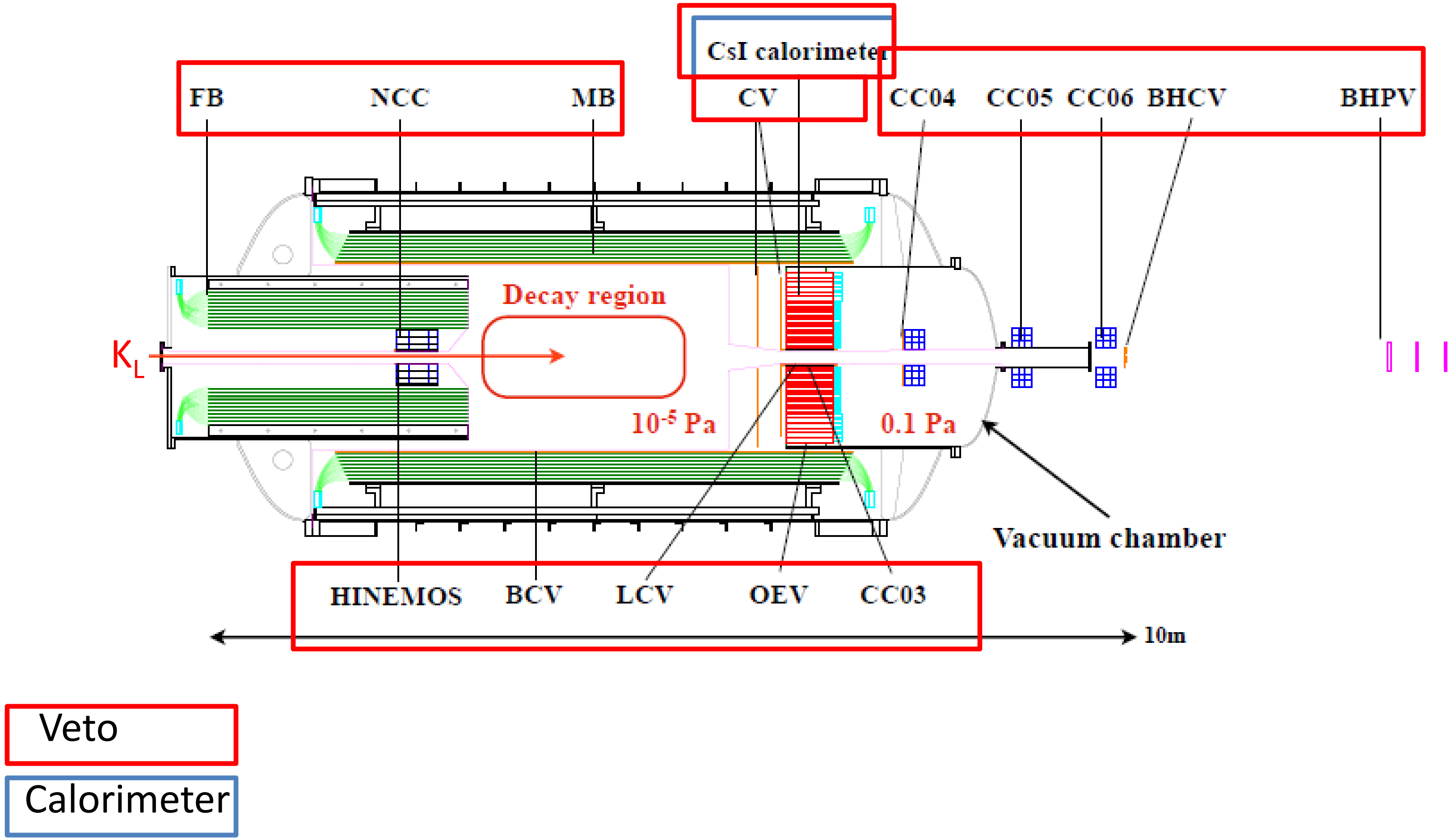


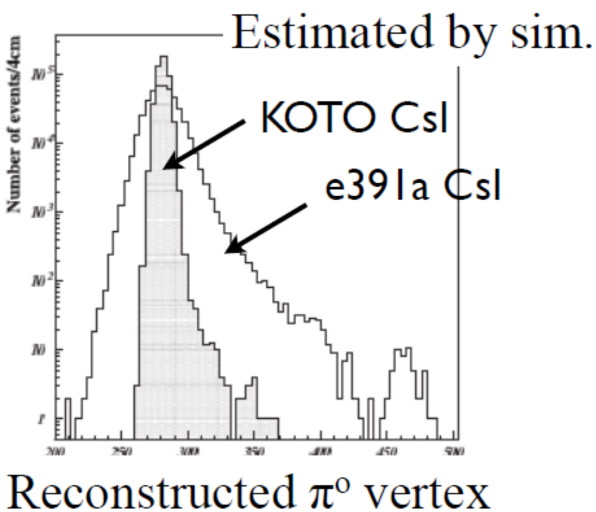
The ratio of halo neutron/K_L is suppressed by a factor >200, comparing with E391a

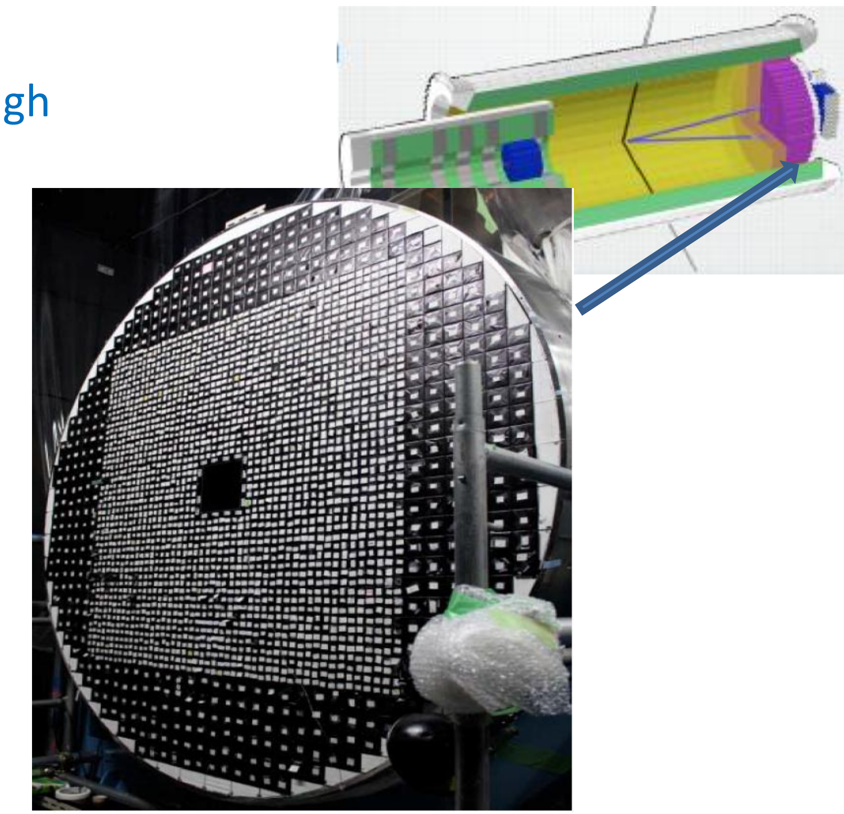
Detectors


CsI calorimeter
FB
NCC
MB
CV
CC04
CC05
CC06
BHCV
BHPV
Decay region
K_L
10^{-5} Pa
0.1 Pa
Vacuum chamber
HINEMOS
BCV
LCV
OEV
CC03
10m
Veto
Calorimeter

CsI Calorimeter

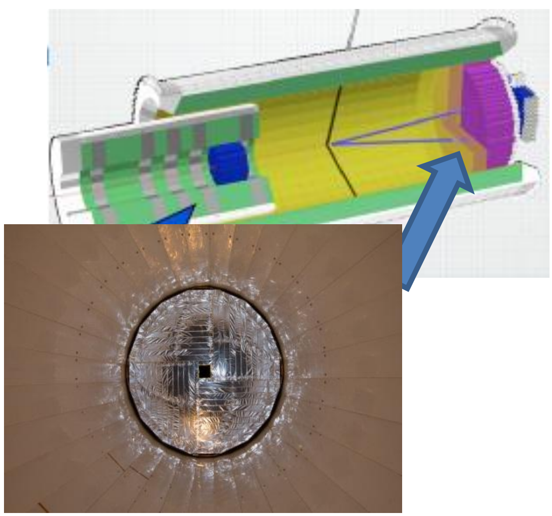
- CsI Calorimeter is the endcap detector to measure photon energy and position.
- Some upgrade from E391a:
- Finer granularity using KTeV CsI crystals. ->better position resolution
  - 25 * 25 mm^2 and 50 * 50 mm^2
  - 2716 readout channels in total
- Longer Length ->reduce photon punch-through
  - $16X_0$->27 X_0
- Improve π^0 reconstruction:





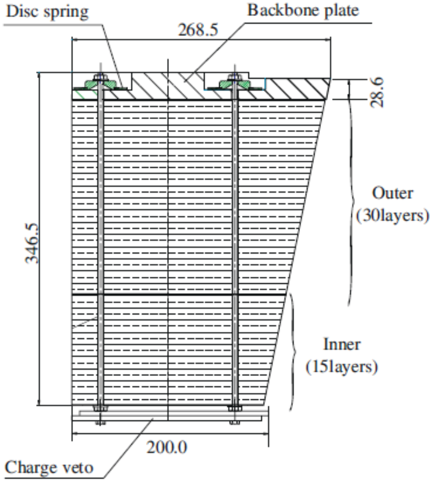
Charged Veto (CV)

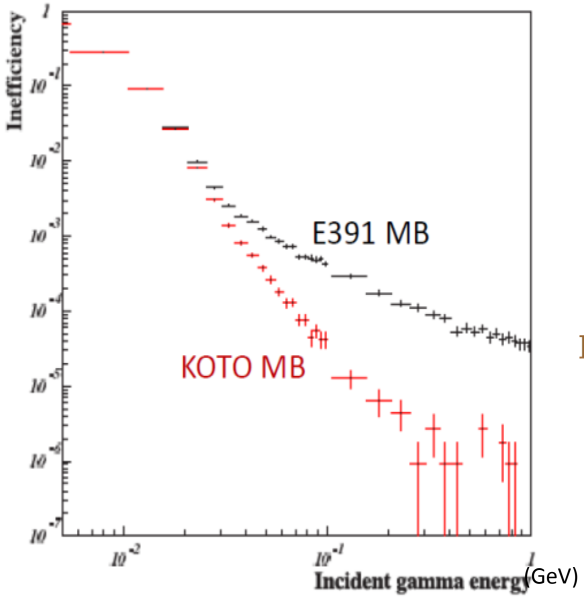
- Charged Veto is one endcap detector vetoing charged decay. Ke3, Kμ3, $\pi^+ \pi^- \pi^0$ decay.
- 2 planes of plastic scintillator
  - 2m diameter, 3mm thick
  - Wavelength Shift fiber and MPPC readout
  - Light material to reduce neutron interaction
  - $<10^{-6}$ inefficiency required



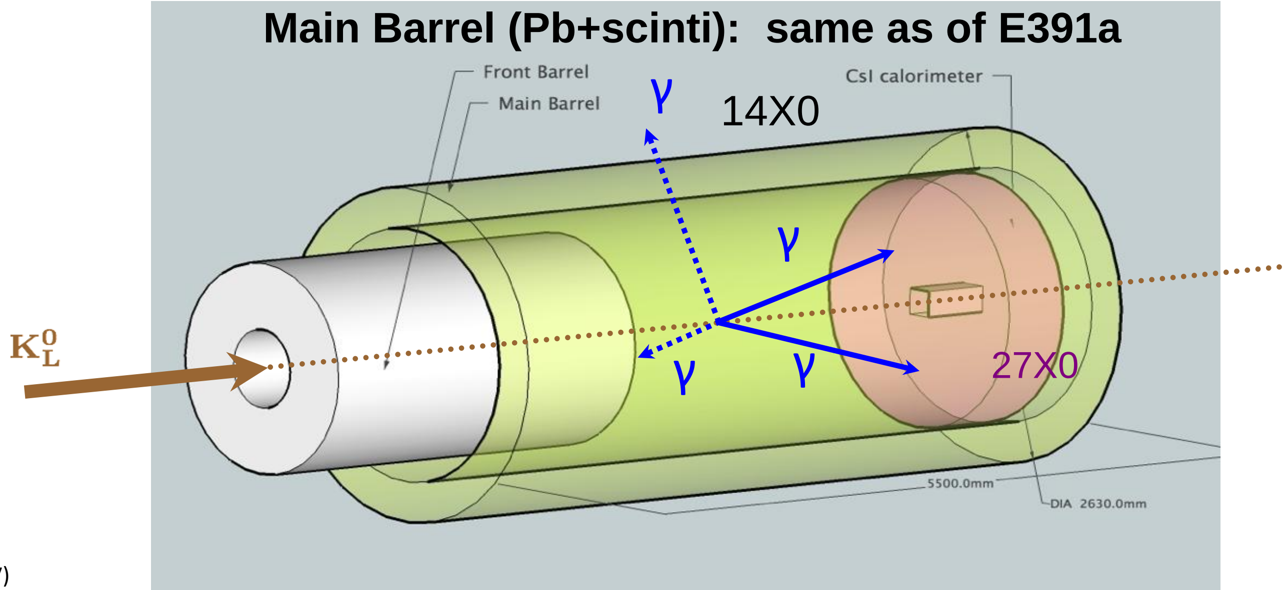
Main Barrel (MB)

- Main Barrel (MB) cover the decay region
  - Plastic scintillator and lead sandwich structure
  - WLS fiber and two end PMT readout
  - 14 X0
- Main background: $K_L \rightarrow 2\pi^0$ with one or two γ escaped MB.
- To reduce inefficiency, one MB upgrade is to insert 5 X0 thickness of Pb/scintillator.





Main Barrel photon detection inefficiency



Main Barrel (MB)

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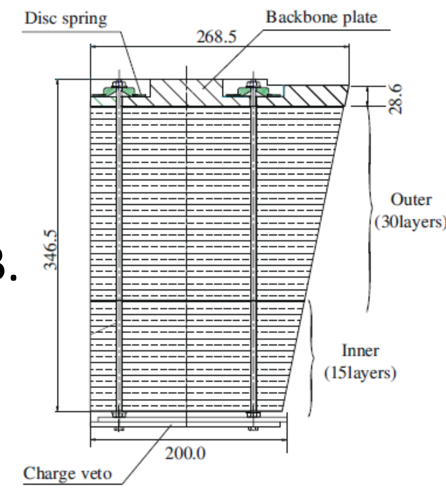
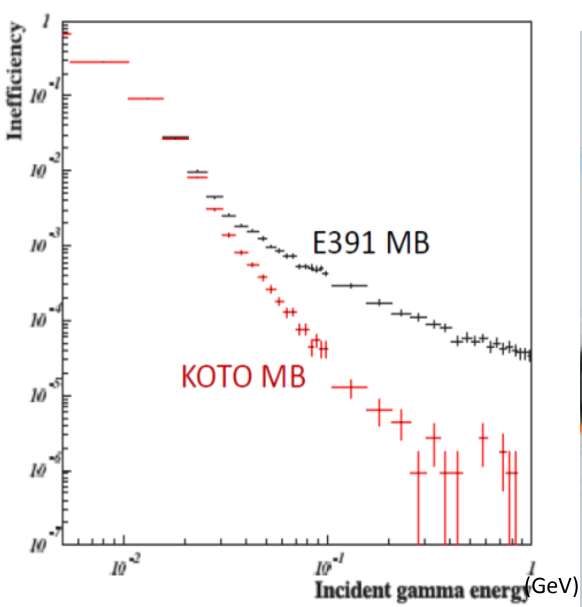
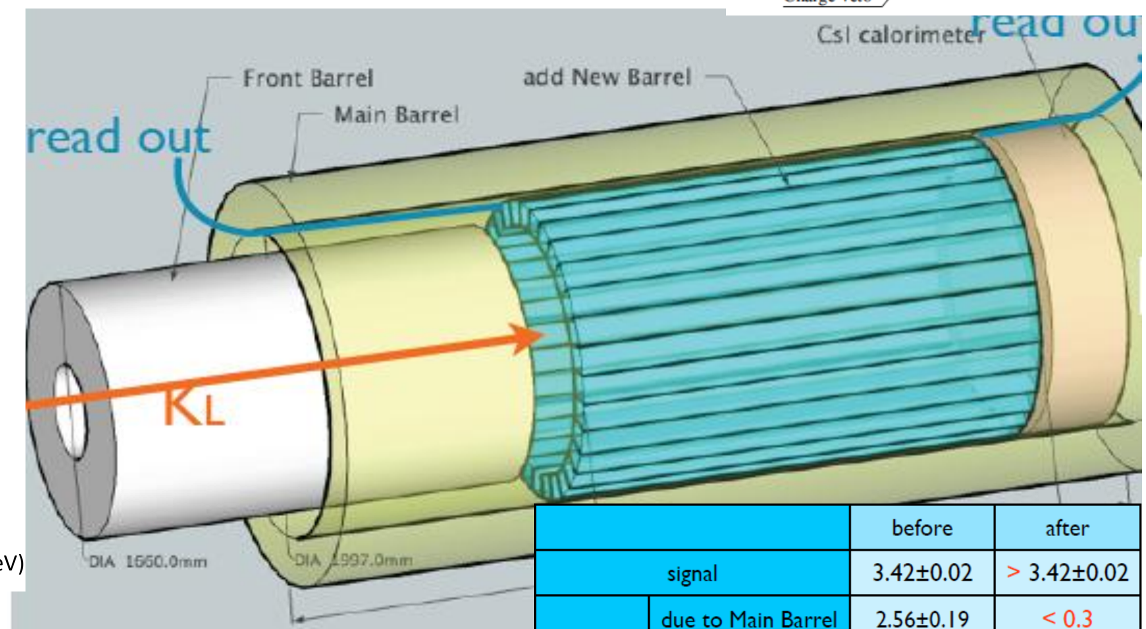




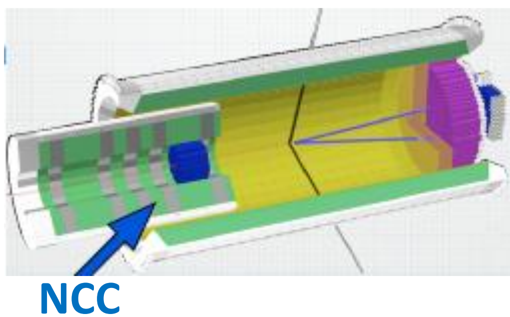
Main Barrel photon detection inefficiency

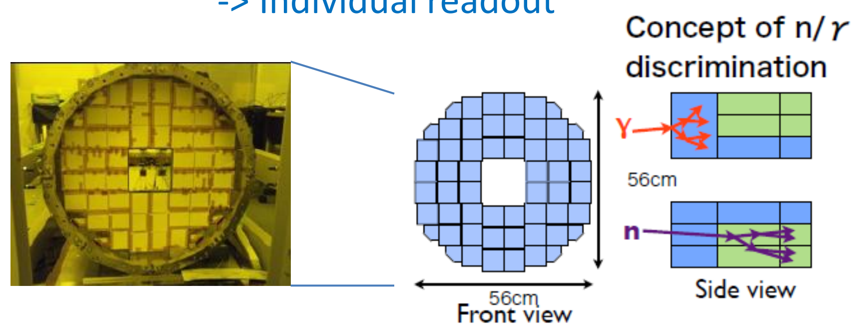


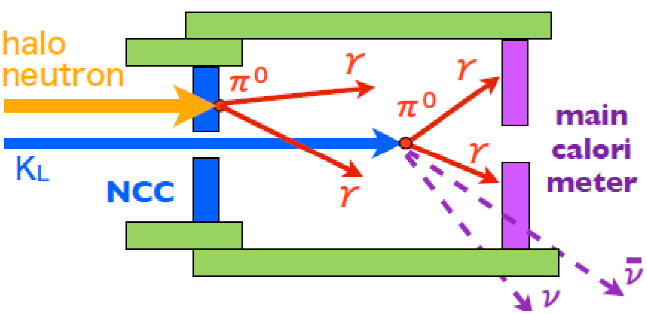
		before	after
signal		3.42±0.02	> 3.42±0.02
2π0 bkg	due to Main Barrel	2.56±0.19	< 0.3
	other detectors	0.24	0.24

Neutron Collar Counter (NCC)

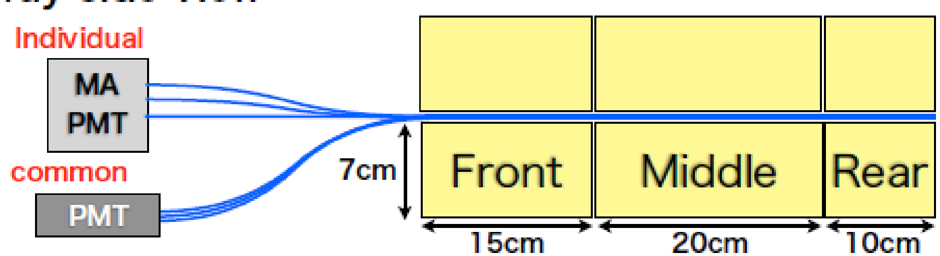
- NCC is the veto detector at the exit of FB close to the beam line.
- NCC is made up of undoped CsI crystals segmented along the z axis to differentiate neutron from photon based on shower shapes.
- Two functions:
  - veto events with halo-neutron interactions. ->Common readout
  - Measure the amount of halo-n and energy spectrum to estimate background.
    -> Individual readout



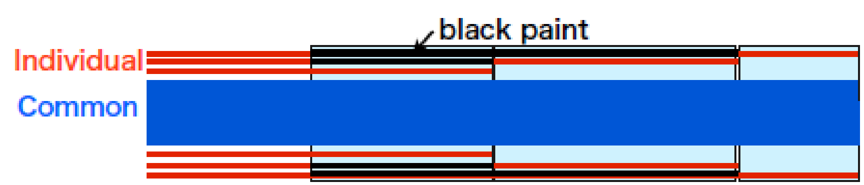




cutaway side view

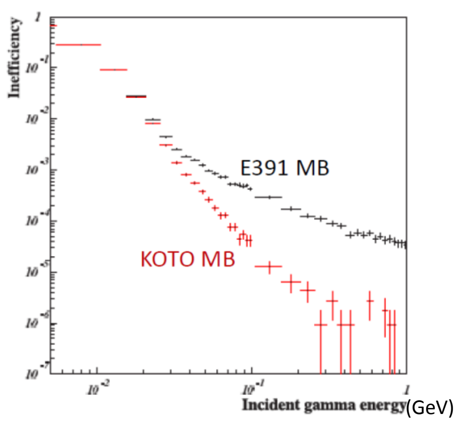


top view

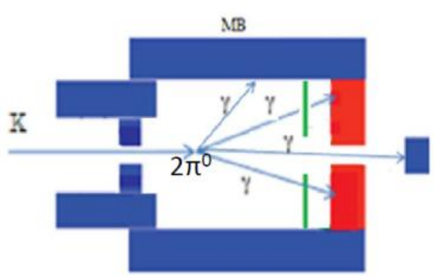


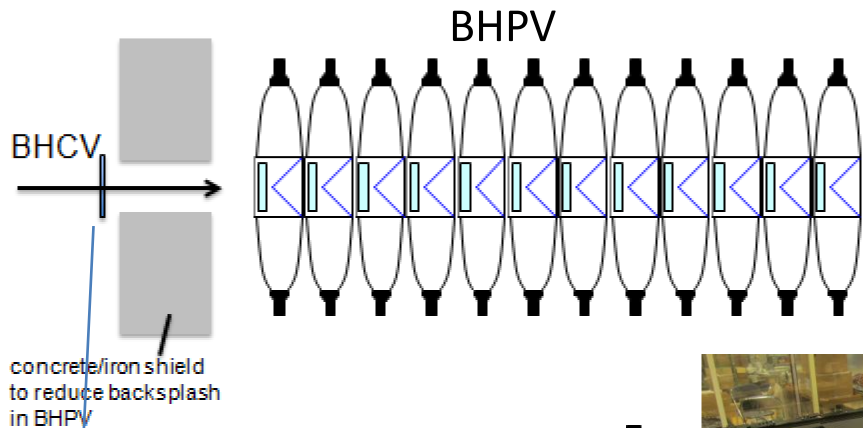
Beam Hole Charged Veto (BHCV) & Beam Hole Photon Veto (BHPV)

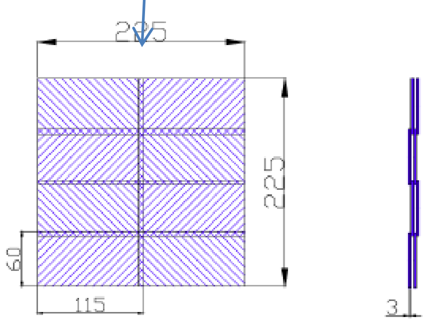
- BHCV and BHPV are beam hole detectors downstream to catch the particles escaping the beam hole so as to complete the hermeticity.
- Due to Main Barrel and CV inefficiency, the BHCV will catch the $\pi^+ \pi^-$ to reduce the $K_L \to \pi^+ \pi^- \pi^0$ background. BHPV will catch the extra photon to reduce the $K_L \to 2\pi^0$ background.
- BHCV: scintillator plate.
- BHPV: aerogel Cerenkov detectors.

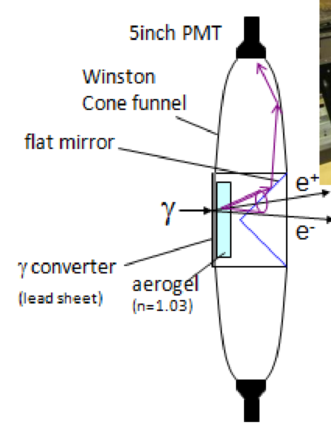


Main Barrel photon detection inefficiency



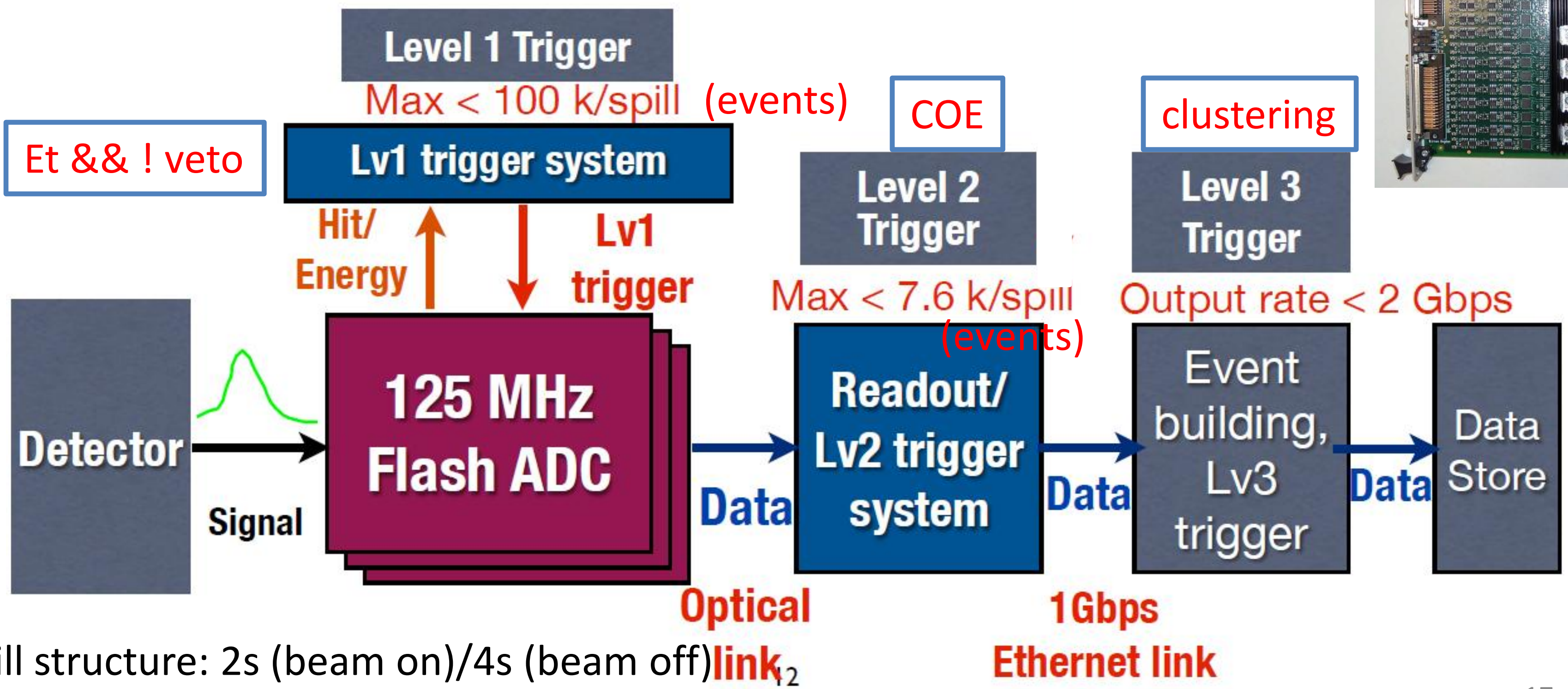






Data Acquisition system

- Challenges for rare decay experiment DAQ: high timing resolution; high data rate.
- Waveform sampling ADC front-end (0.1ns timing resolution)
- 3-tier pipeline trigger system



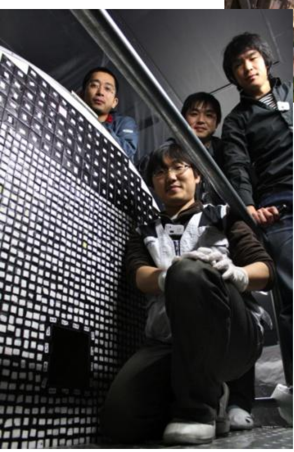
Spill structure: 2s (beam on)/4s (beam off)

Timeline of KOTO

2009

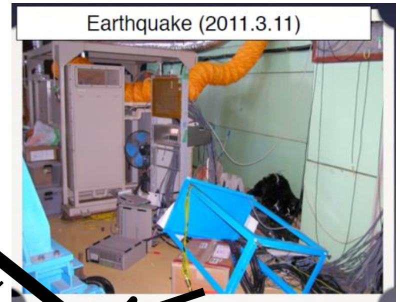
Beamline construction finished (2009 Aug)

2010



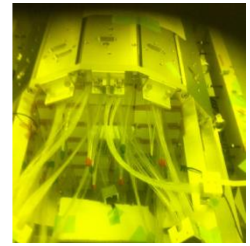
CsI calorimeter stacking finished (2010 Feb)

2011



2012

Charged Veto installation (2012 June)



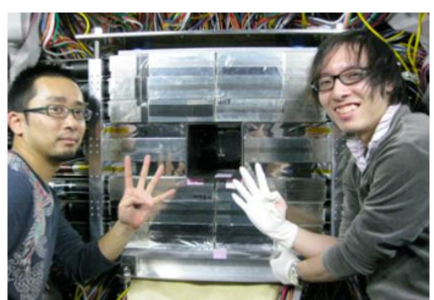
NCC installation (2012 Nov)

Main Barrel installation (2012 Dec)

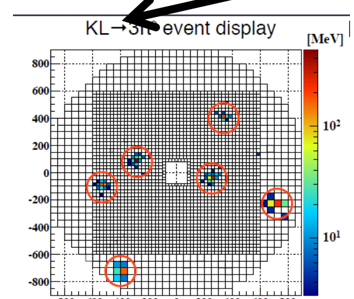
Closing vacuum chamber (2012 Dec)

FB installation (2012 Nov)

Sub detectors (CC04 etc.) Installation (2012 Dec)



2013



2013 Jan engineering run

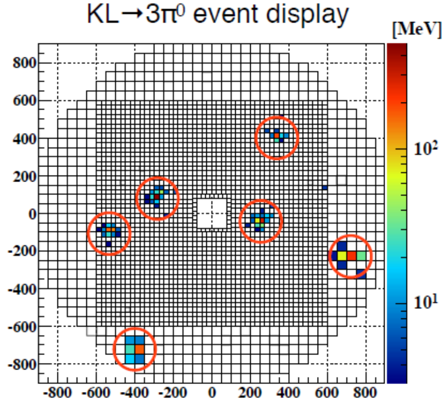
2014

1st physics run 2013 June

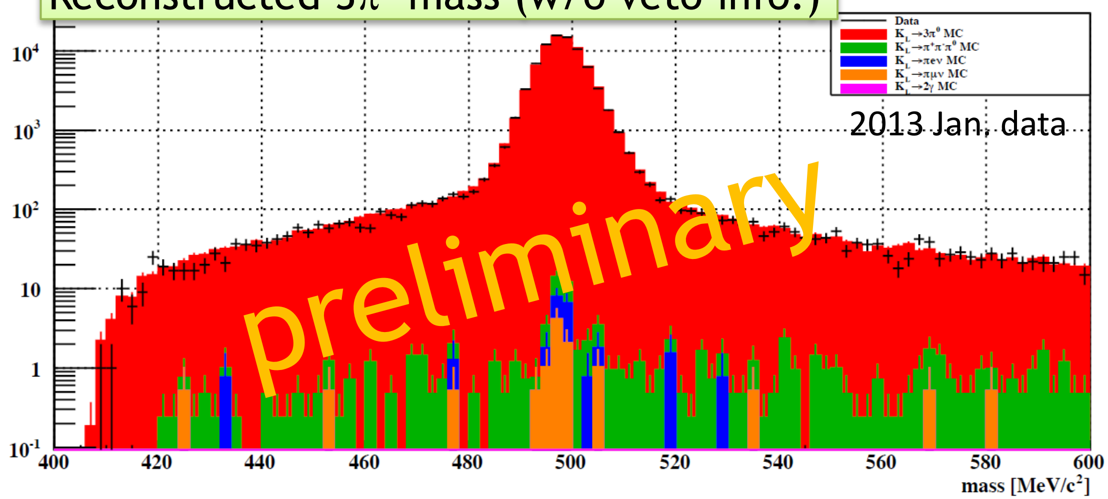
Results from 2013 January engineering run

- K_L->$3\pi^0$ reconstruction
  - Good statistics 20%
  - studying CsI performance, reconstruction method and MC.

KL→$3\pi^0$ event display

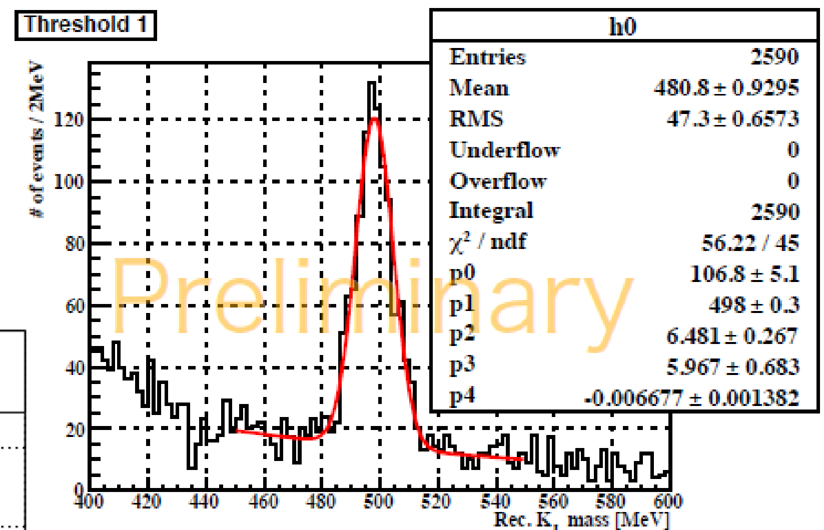


Reconstructed $3\pi^0$ mass (w/o veto info.)



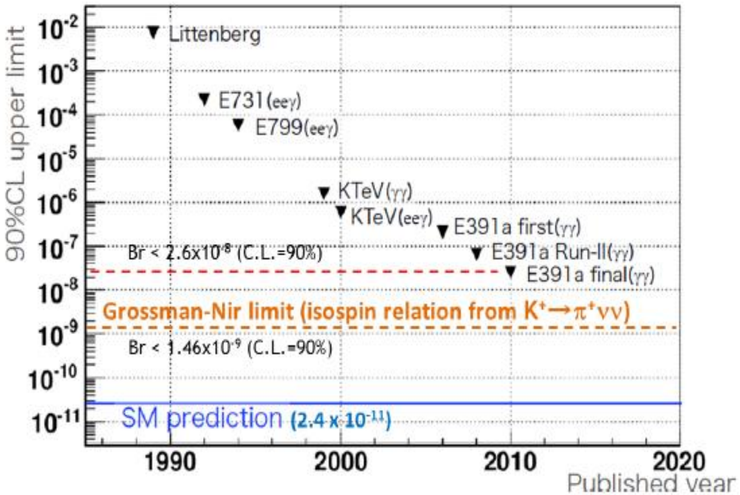
- K_L->$2\pi^0$ reconstruction
  - Main background
  - Good tool for studying veto performance

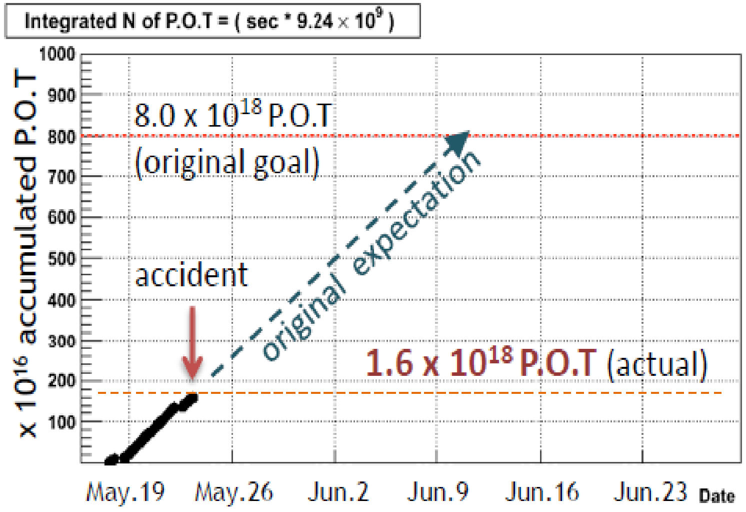
Rec. $2\pi^0$ mass distribution



1st Physics run (May-June 2013)

- The original plan for the KOTO physics run was to reach the Grossman-Nir bound sensitivity by running for a month.
- A radiation accident occurred in Hadron Hall on May 23rd. The data taking was terminated after an integrated Protons on Target (P.O.T) of 1.6×10^{18}.
- We estimate to have better sensitivity than E391a with this data set.





Conclusion

- KOTO experiment is dedicated to observe rare decay of $K_L \to \pi^0 \nu \bar{\nu}$ and measure its branching ratio at high sensitivity to test SM and BSM extensions.
- In 2012, all the sub-detectors were installed. And two engineer runs during 2013 January and April proves that all detectors are well understood.
- Physics run started in May, but was terminated early due to the radiation accident of the Hadron Hall on May 23rd. Accumulated POT was 1.6×10^{18} . From this data set, we expect to get better sensitivity than E391a.

backup

KOTO sensitivity estimate and BG budget

	GEANT4 value	new value
K_L^0 flux/ 2×10^{14} P.O.T	7.4×10^6	1.94×10^7
P.O.T	1.8×10^{21}	1.8×10^{21}
decay probability	4.0%	3.9%
geometrical acceptance	28%	27%
cut efficiency	23%	22%
acceptance loss	72%	76%
sensitivity	2.1×10^{-11}	1.0×10^{-11}
number of signal event	1.2	2.4

Table 7.2: Summary of the expected numbers of the signal and backgrounds.

	source	GEANT4 value	new value
signal	$K_L^0 \to \pi^0\nu\bar{\nu}$	1.16±0.01	2.39±0.03
K_L^0 decays	$K_L^0 \to 2\pi^0$	0.74±0.02	1.32±0.04
	$K_L^0 \to \pi^+\pi^-\pi^0$	0.05±0.01	0.11±0.01
	$K_L^0 \to \pi^\pm e^\mp \nu$	0.04±0.01	0.07±0.04
halo neutron	NCC-π^0	0.05±0.02	0.05±0.02
	CV-π^0	0.04±0.04	0.04±0.04
	CV-η	0.01±0.01	0.01±0.01
	S/N	1.25	1.49