The KOTO Experiment at the J-PARC

Jiasen Ma 3/18/2011
LEPP Journal Club @Cornell

K0 at TOkai(KOTO) for the rare decay $K_L \to \pi^0 \nu \overline{\nu}$

- ~65 members from 5 countries, 16 institutions

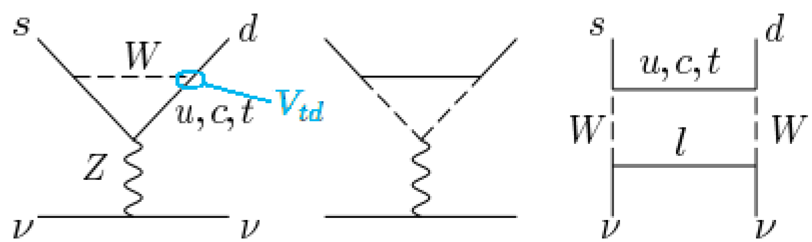
KEK
Kyoto
NDA
Osaka
Saga
Yamagata
Arizona State
Chicago
Michigan
JINR
National Taiwan
Cheju
Chonbuk
Kyungpook
Pusan National
Seoul

Outline

- Physics
- Strategy
- The pilot E391a
- How do we do it
- Timeline and summary

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

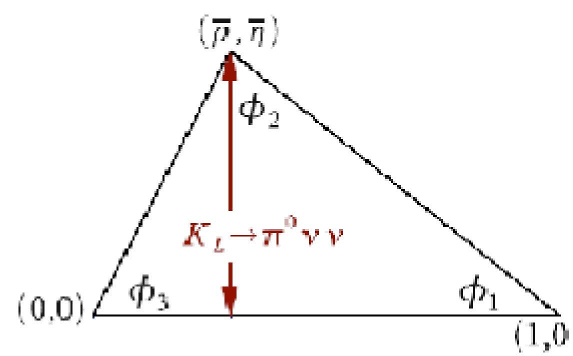
- Flavor changing neutral current at the loop level



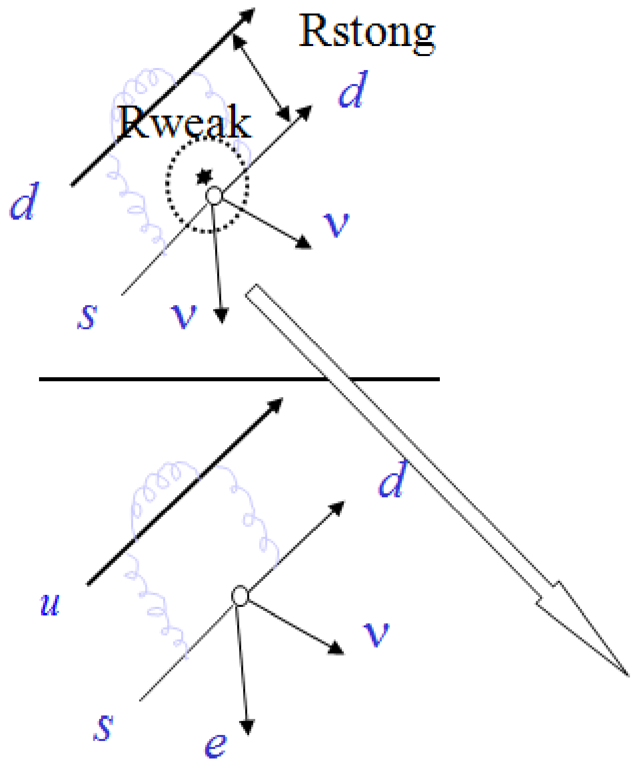
- A direct CP violation process

$$A(K_2 \to \pi^0 \nu \bar{\nu}) \propto V_{td}^* V_{ts} - V_{ts}^* V_{td} \propto 2i\eta$$

K_1 (or K_{even}) contribution negligible



Small Theoretical Uncertainty

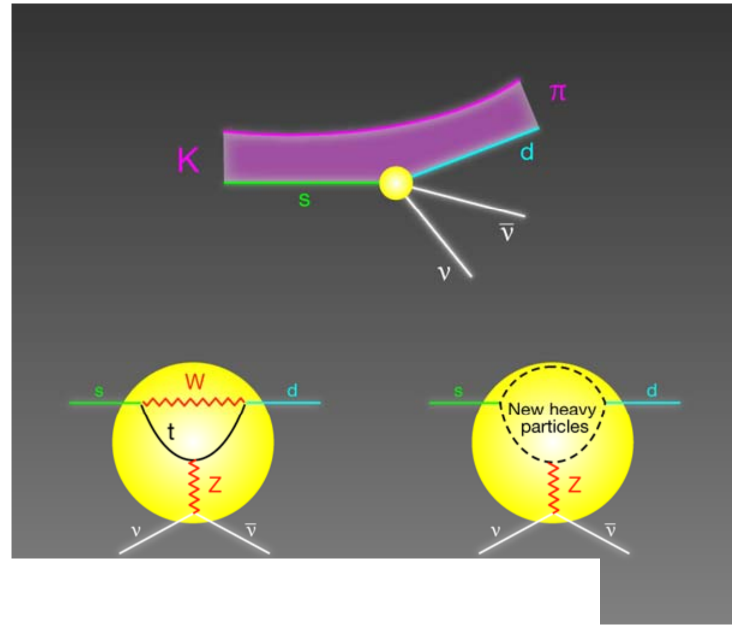


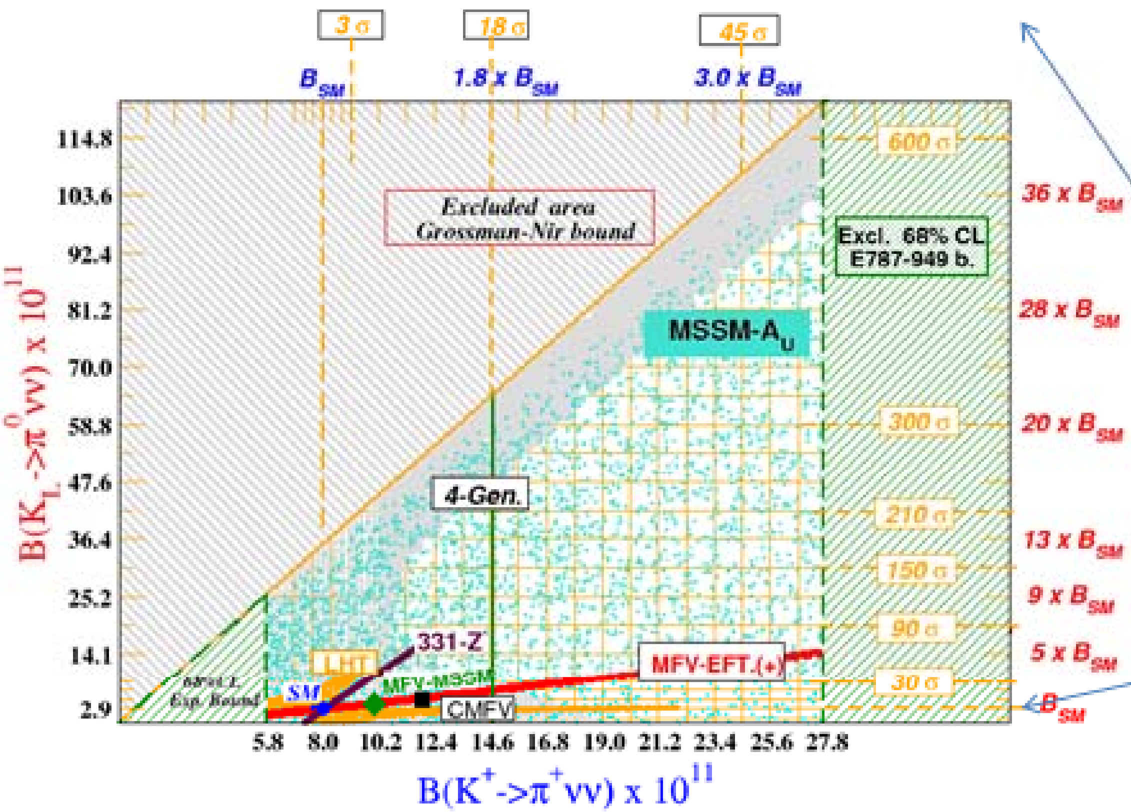
- The hadronic matrix element is substituted with known measurement.
- Uncertainty in the Standard Model prediction almost entirely comes from the CKM parameters, the top and W mass.

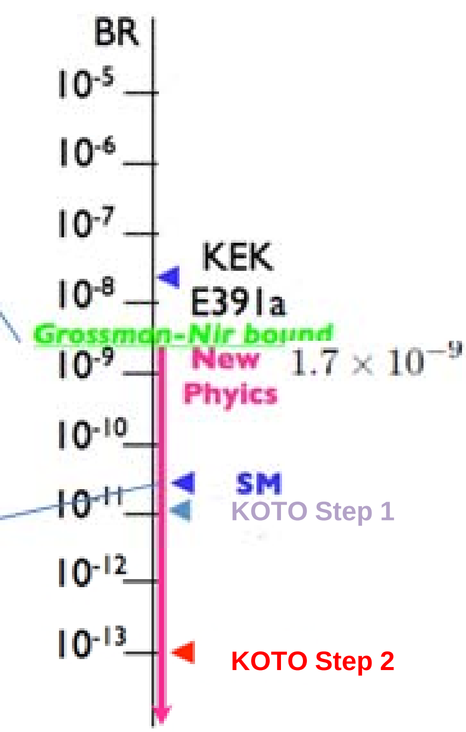
$$Br(K_L^0 \to \pi^0 \nu \bar{\nu}) = 6.87 \times 10^{-4} \times Br(K^+ \to \pi^0 e^+ \nu) \times A^4 \lambda^8 \eta^2 X^2(x_t)$$
$$= (2.49 \pm 0.39) \times 10^{-11}$$

Beyond standard model

- Large room for new physics with new heavy particles remains with the current branching ratio limits



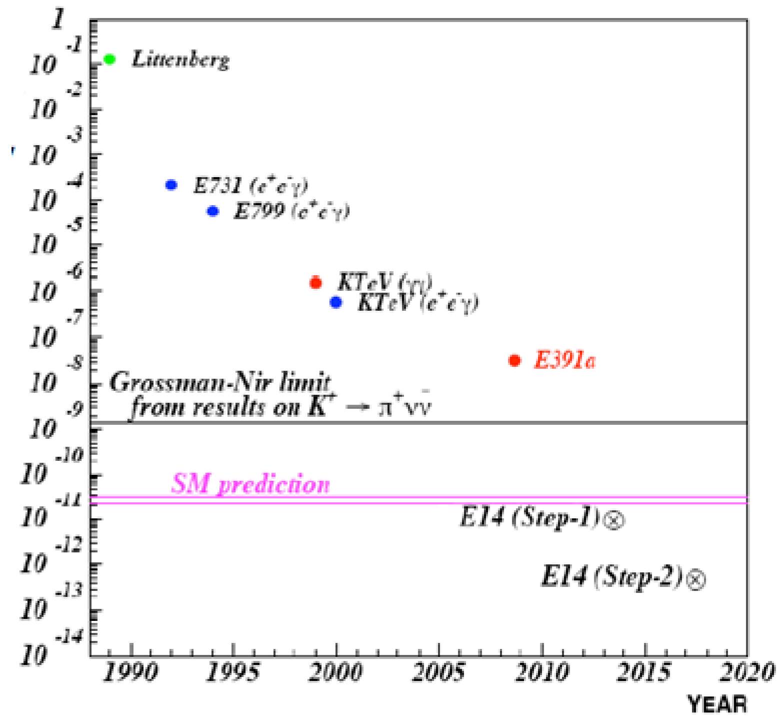




http://www.lnf.infn.it/wg/vus/content/Krare.html

A short history

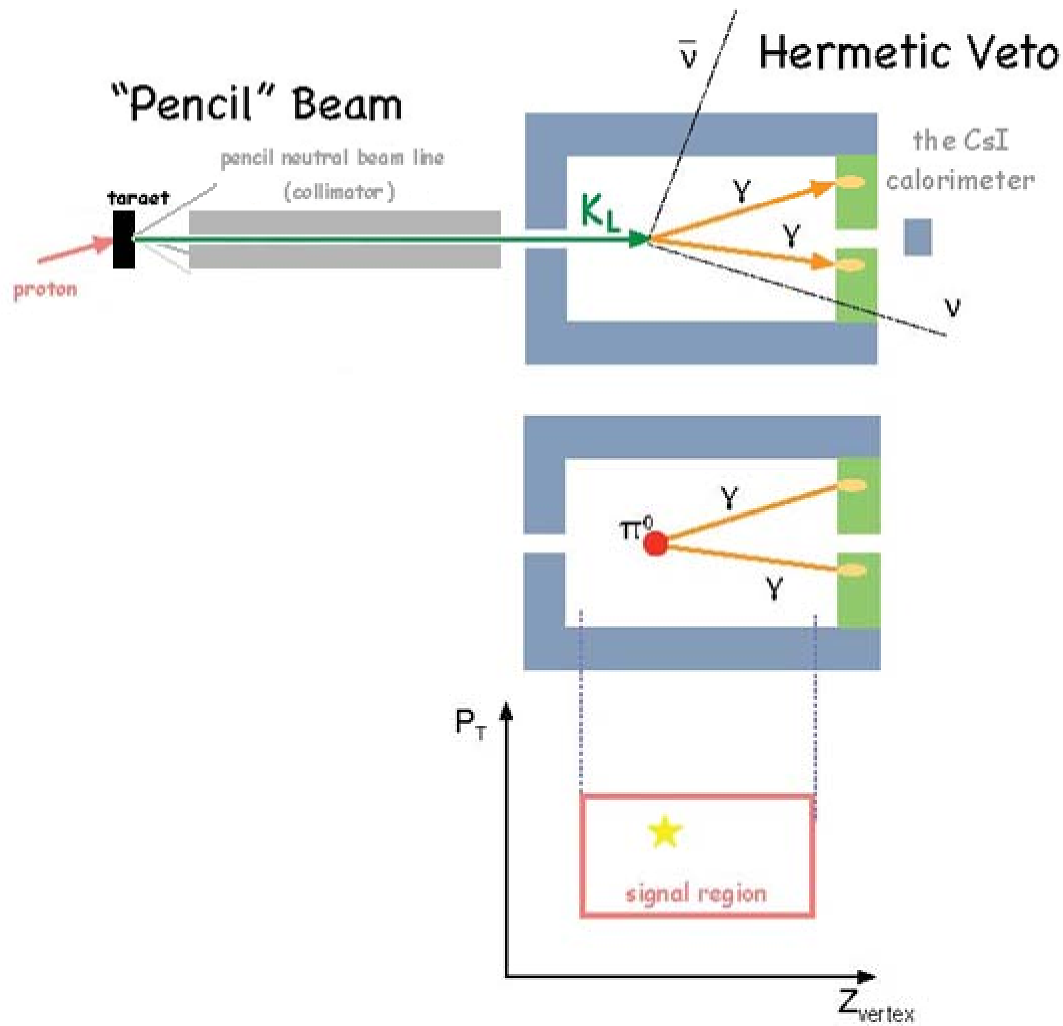
- Earlier searches using π^0 decaying into 2 γ's were crippled by limited veto abilities.
- A more sensitive search used the π^0 Dalitz decay. But acceptance is greatly sacrificed.



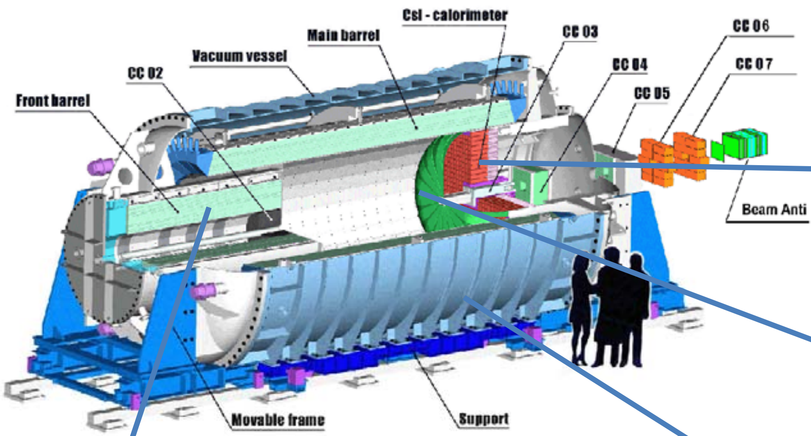
The Basic Strategy

- Pencil beam
- Hermetic veto
- Reconstruction of π^0 vertex and its transverse momentum assuming π^0 mass
- Daunting task to sort out two photons from one trillion events -> Step by Step

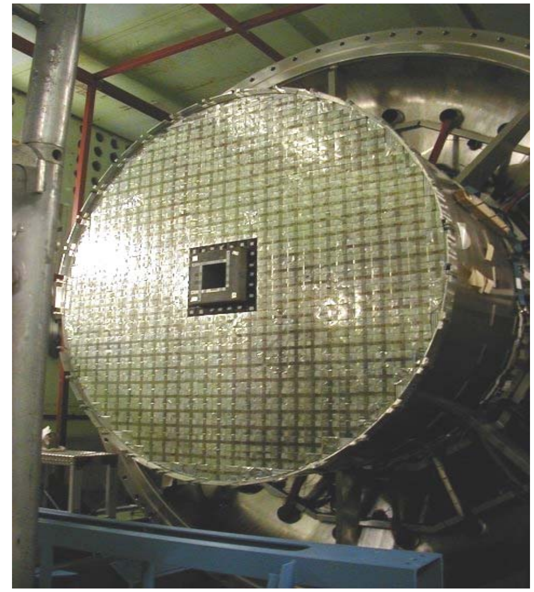
An over-simplified cartoon



Pilot E391a at KEK(2001-2005)



CsI Calorimeter



Front Barrel with CC02

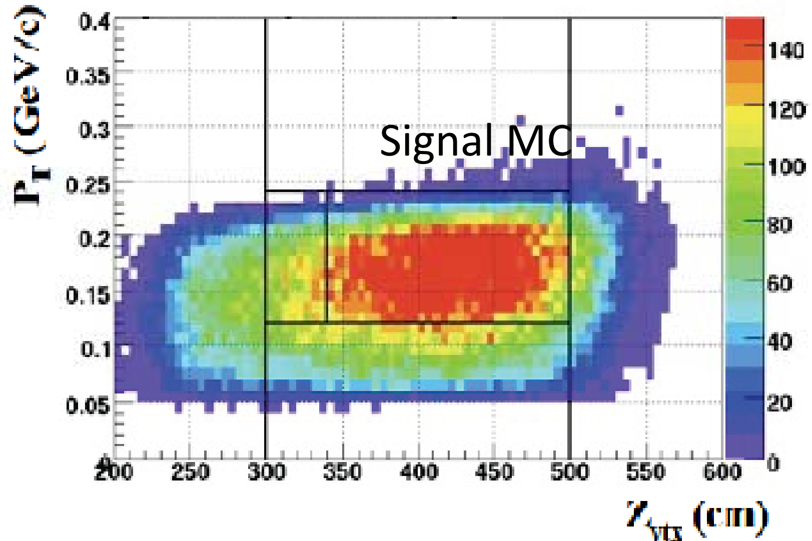
Main barrel

Charged Veto

- Decay region in high vacuum(10^{-7} Torr)

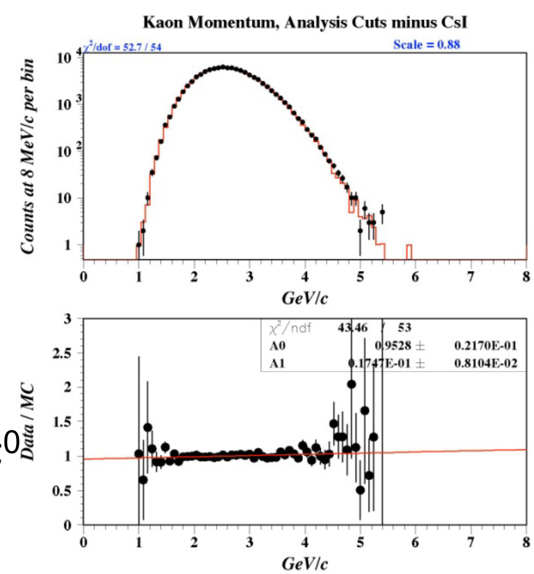
MC $K_L \rightarrow \pi^0 \nu \overline{\nu}$ after Reconstruction

- Signal Simulation



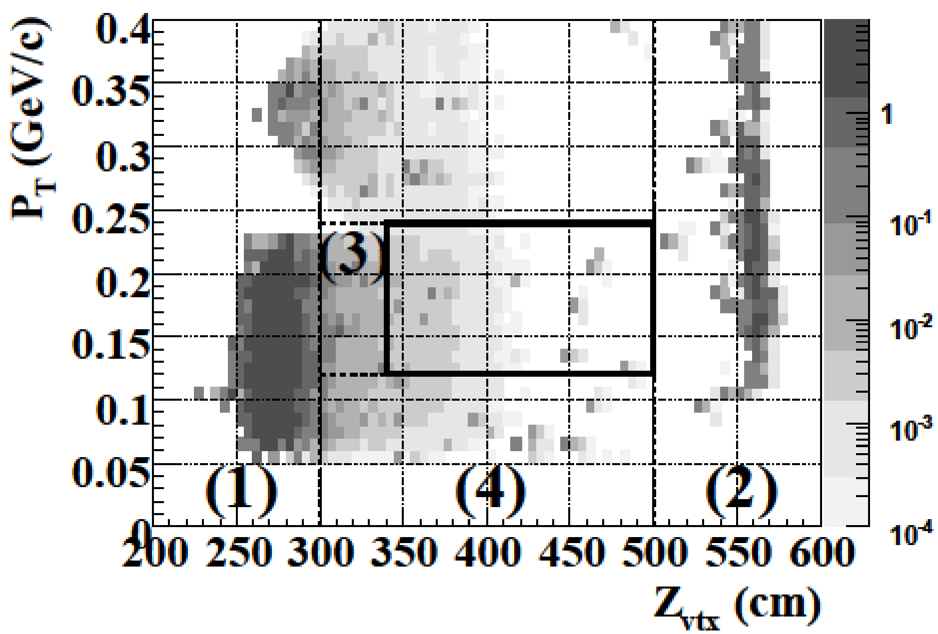
Acceptance 1%, largely due to shower shape cut.

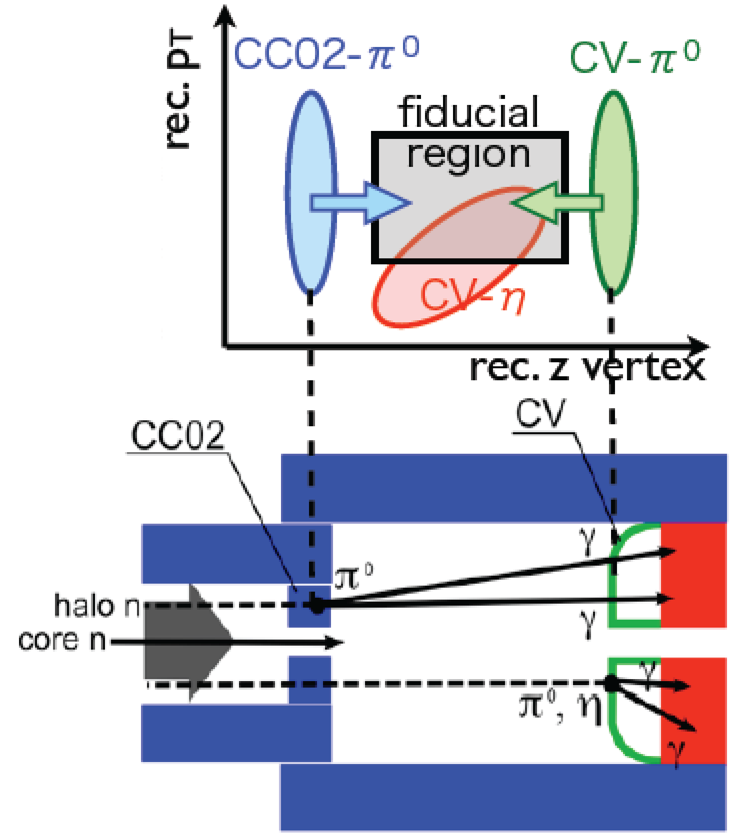
Kaon beam parameters were checked using other neutral decay modes



Momentum from $K_L \rightarrow 3\pi^0$

E391a Background Simulation-Neutron Related





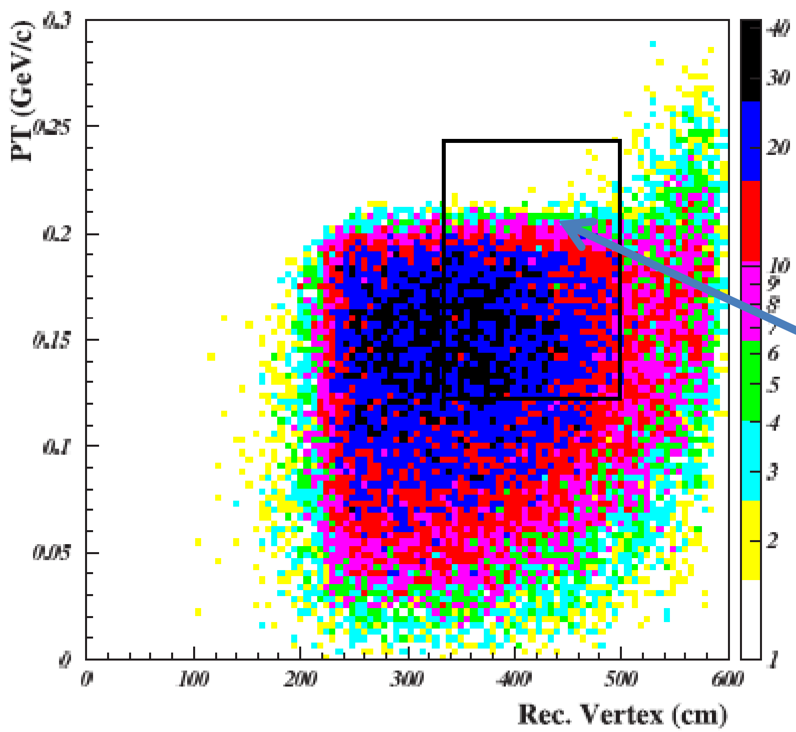
Neutron interactions with detector close to the beam are the E391a main background sources

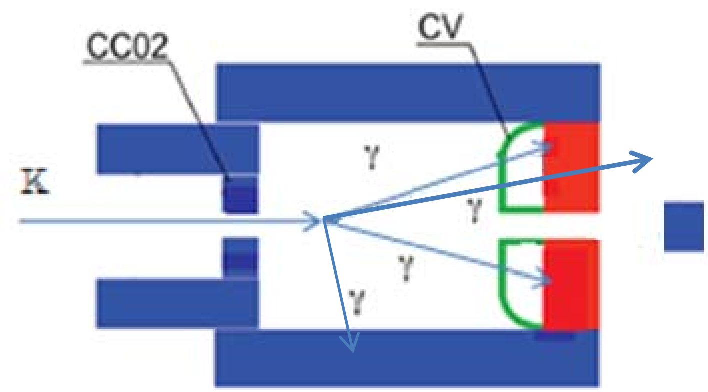
BG	Estimation
CC02 ‘pi0’	0.6+/-0.4
CV-eta	0.2+/-0.1
CV-pi0	<0.3

At a sensitivity of $1.1\mathrm{x}10^{-8}$

E391a Background Simulation: K_L->2 π^0

- Soft photons are lost in MB and energetic photons punch through $16X_0$ of CsI



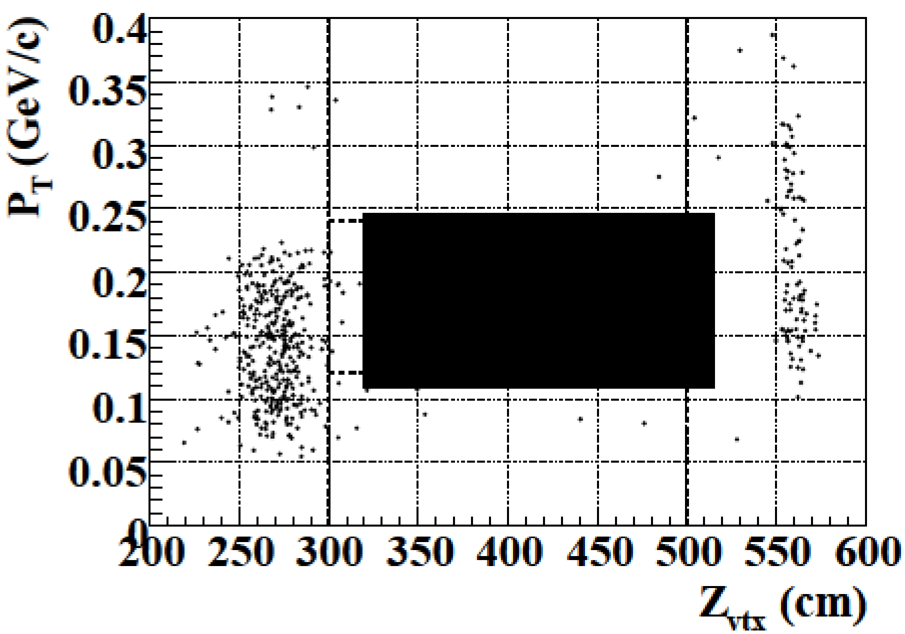


E391a K_L->2 π^0 background expected 0.024+/-0.018

Scale not normalized

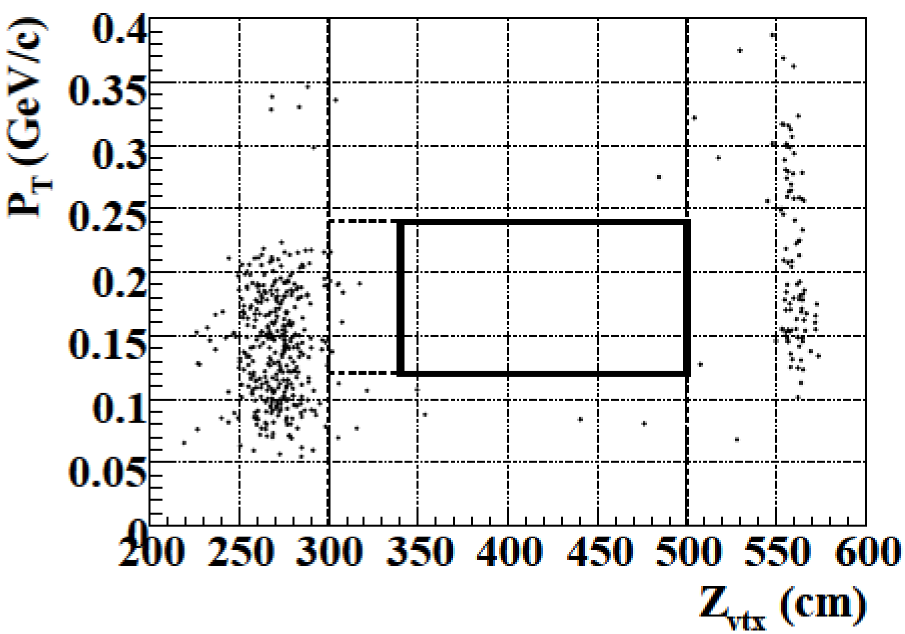
Pilot E391a Result

- Data plot of blind analysis



Pilot E391a result

- Data plot of blind analysis, open the box
- BR($K_L \to \pi^0 \nu \overline{\nu}$)<2.6x10^{-8}(90% CL)



- Main background: halo neutron interaction

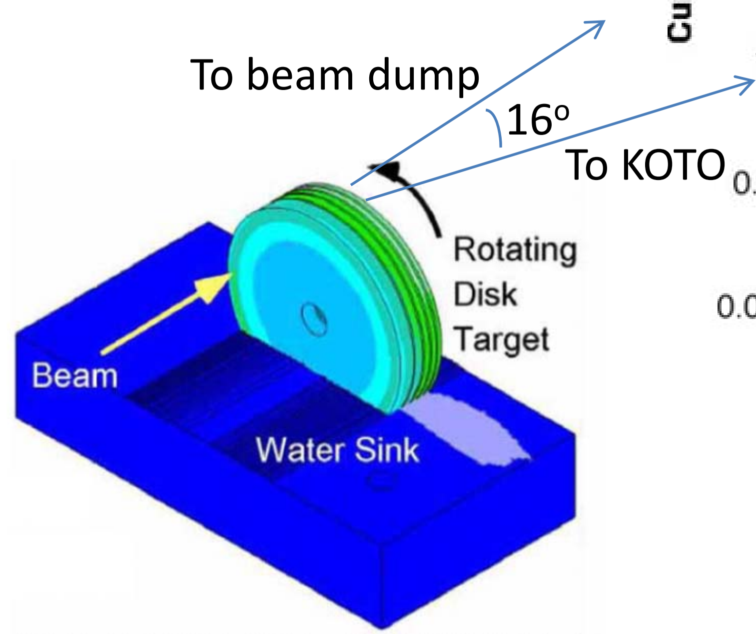
How do we improve from E391a

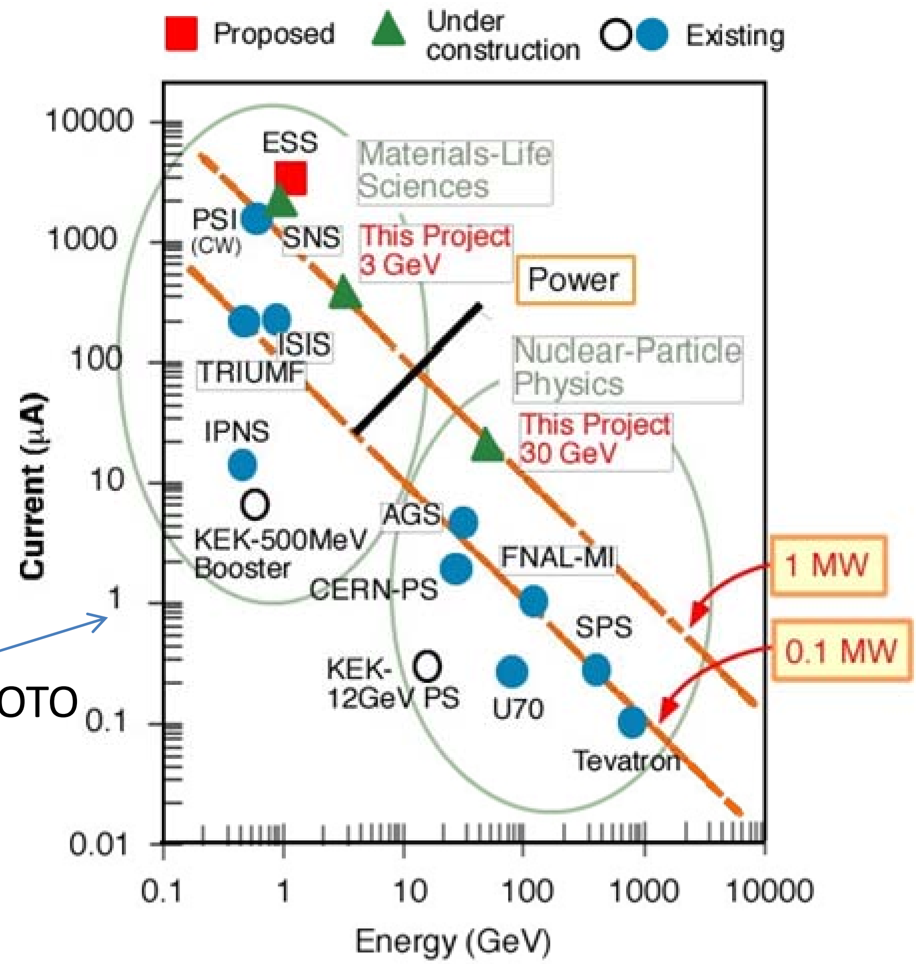
- More K_L ,less halo neutron $\rightarrow$ Beam
- Background and acceptance $\rightarrow$ Calorimeter and electronics
- Background $\rightarrow$ Main veto detectors

Beam

The Primary Beam

- Proton intensity is improved by a factor of ~100
- Slow extraction from the main ring for KOTO

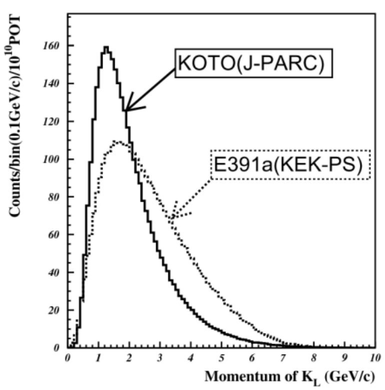


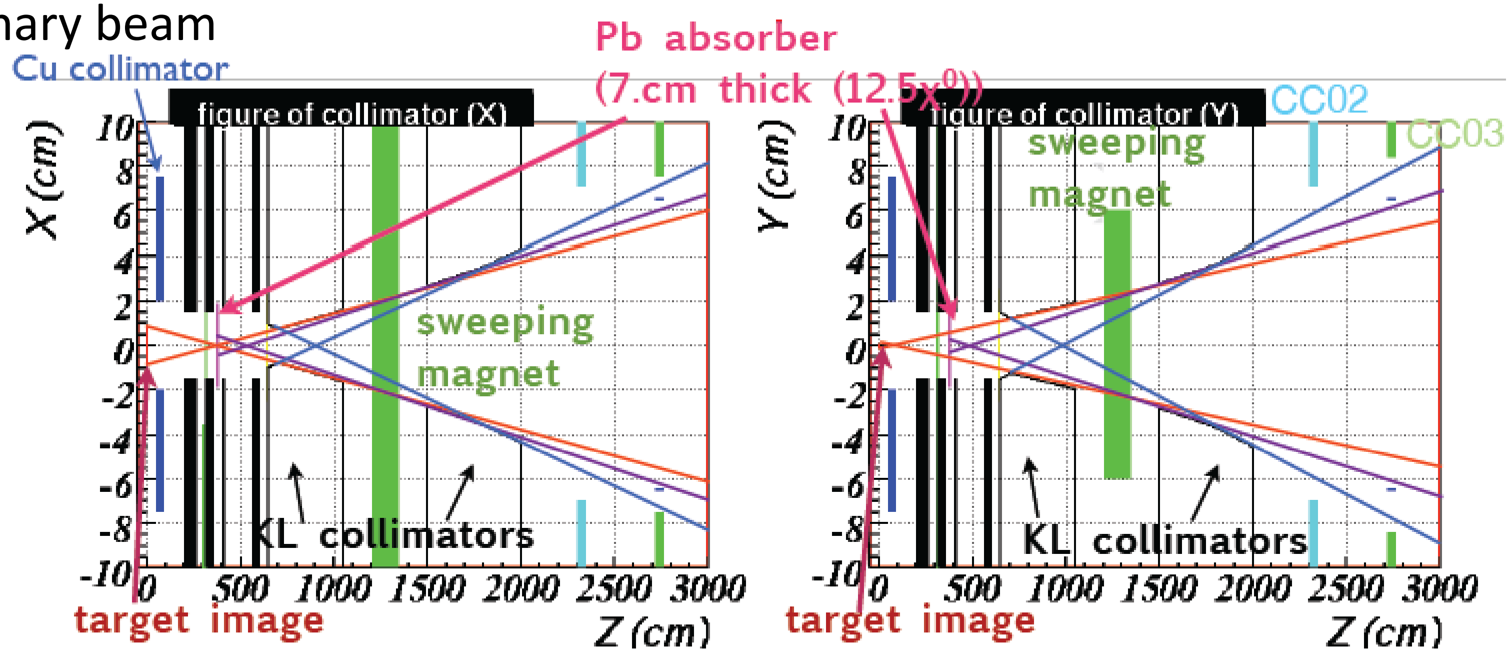


The Beamline Design

- A long beamline with large extraction angle

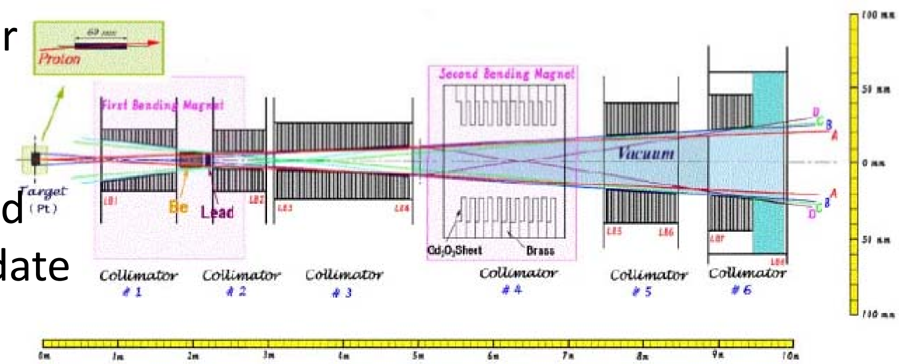
  ->to suppress hyprons, $K_{S...}$, to have soft Kaon momentum with higher energy primary beam





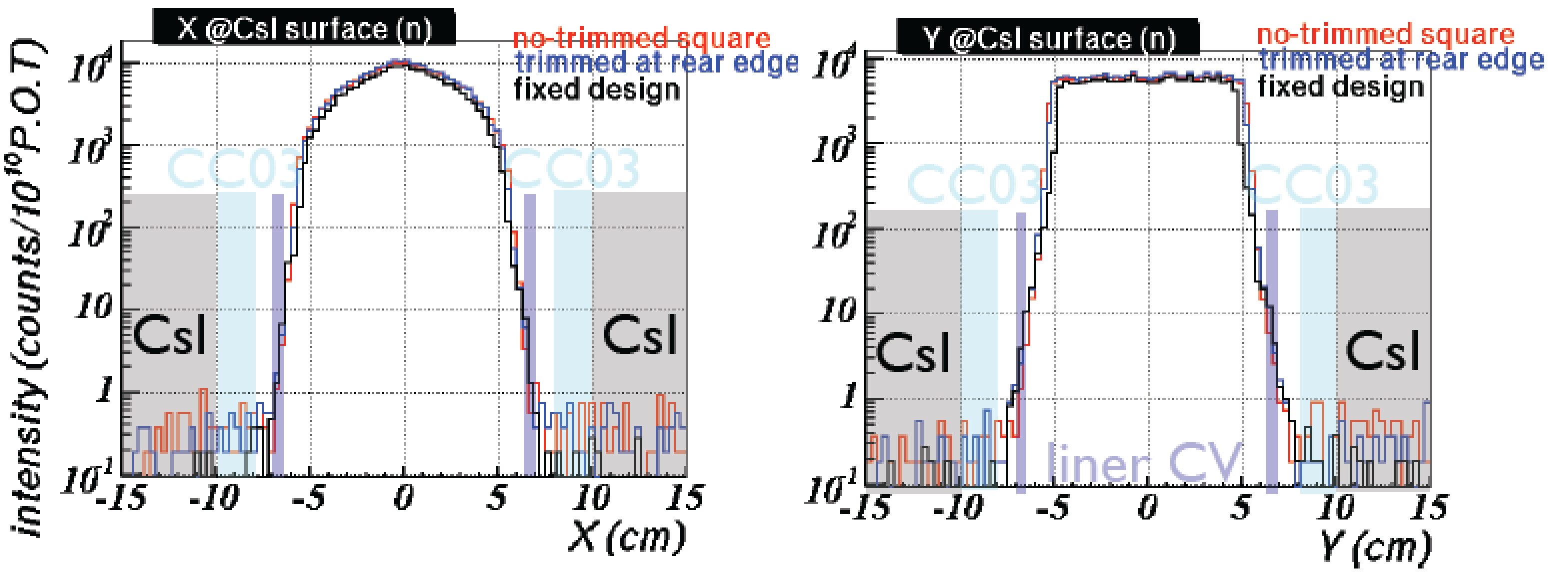
Halo neutron produced by scattering off the inner surface of collimators -> inner surface not facing the target

The downstream collimator was further optimized to reduce the multiple scattering and accommodate the lead absorber

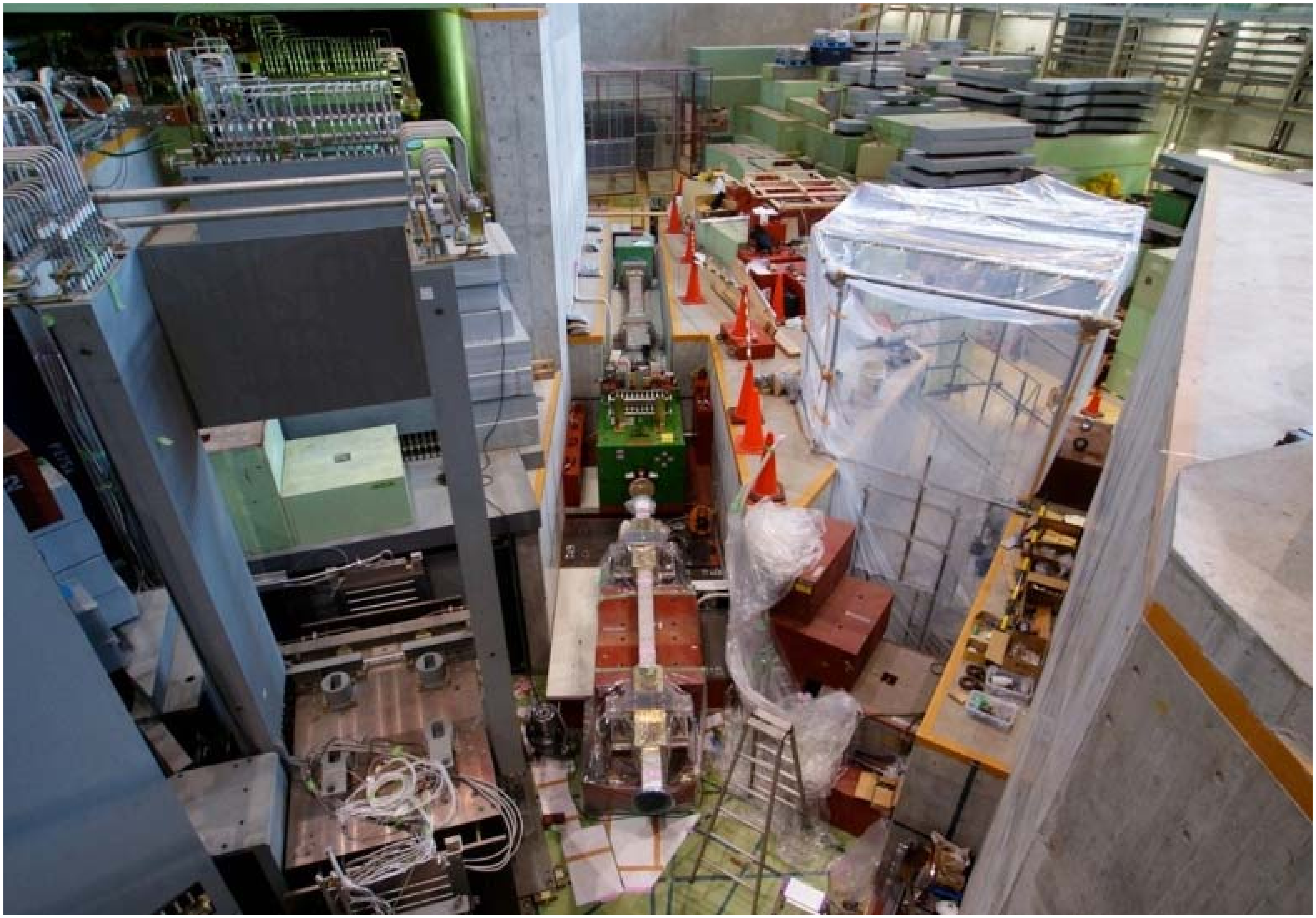


Beamline Simulation

- Neutron profile expected

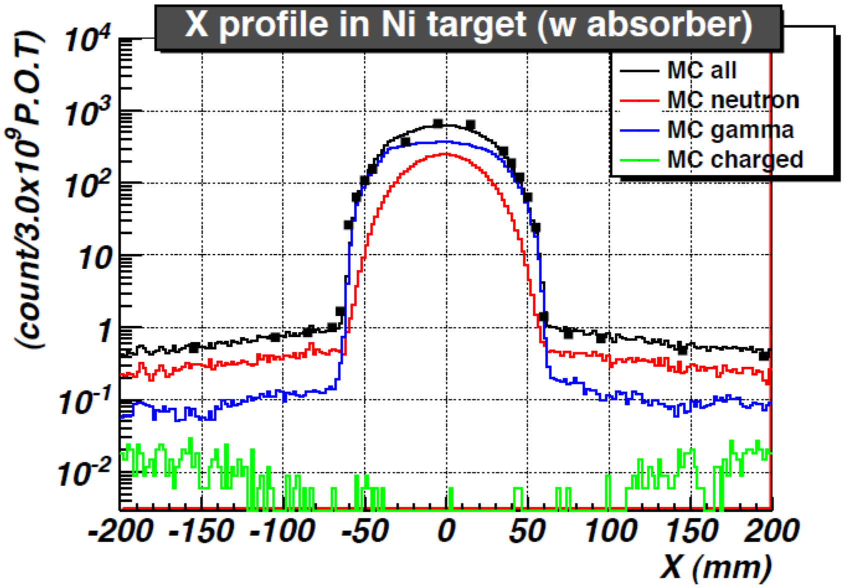


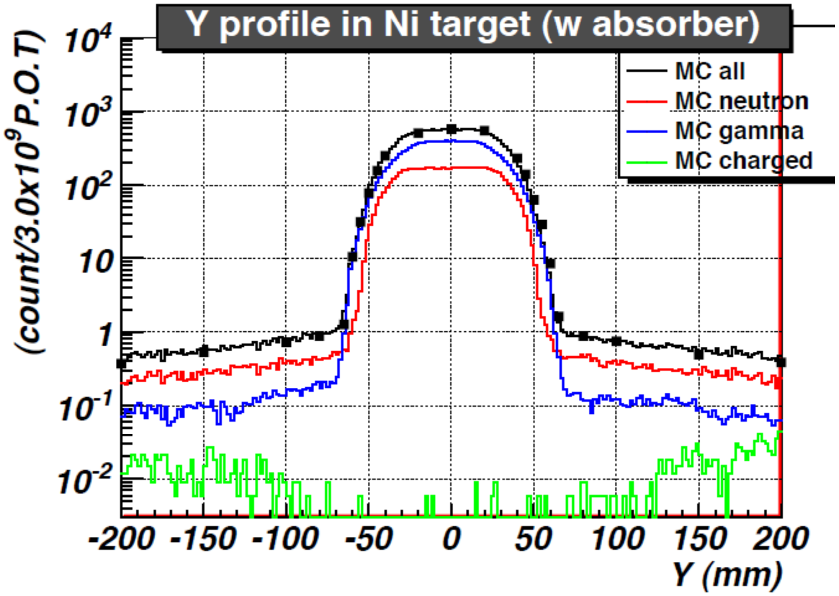
Picture of the Beamline



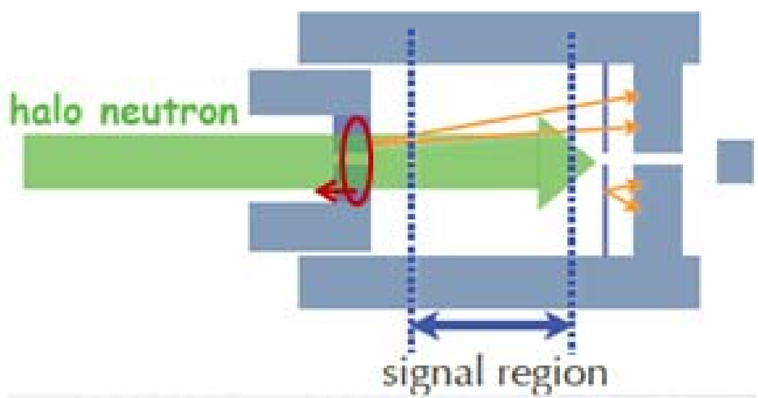
Beam Survey of Halo Neutron

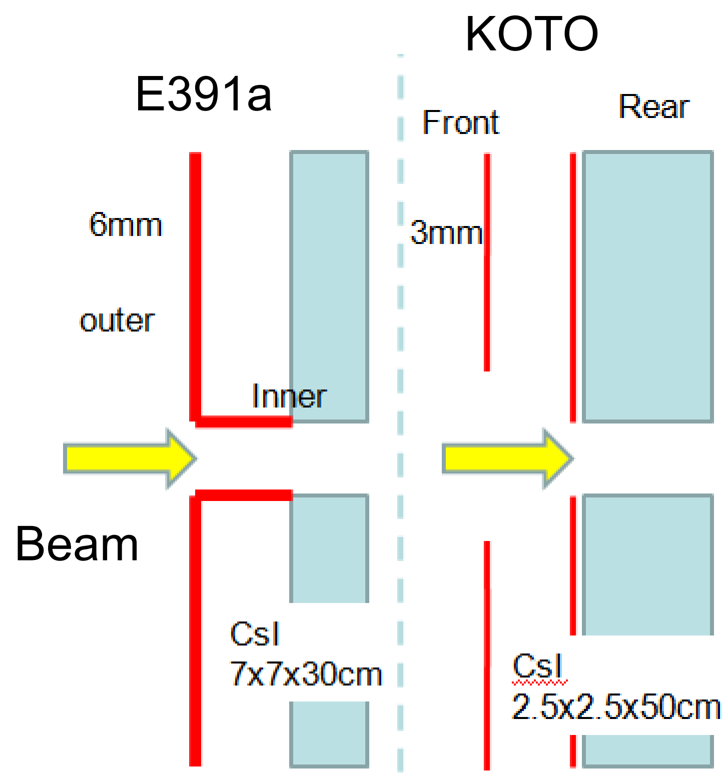
- Halo neutron measurement with
  two pieces of heavy scintillators
  -> look for hit in the downstream one





To Further Reduce Neutron Background



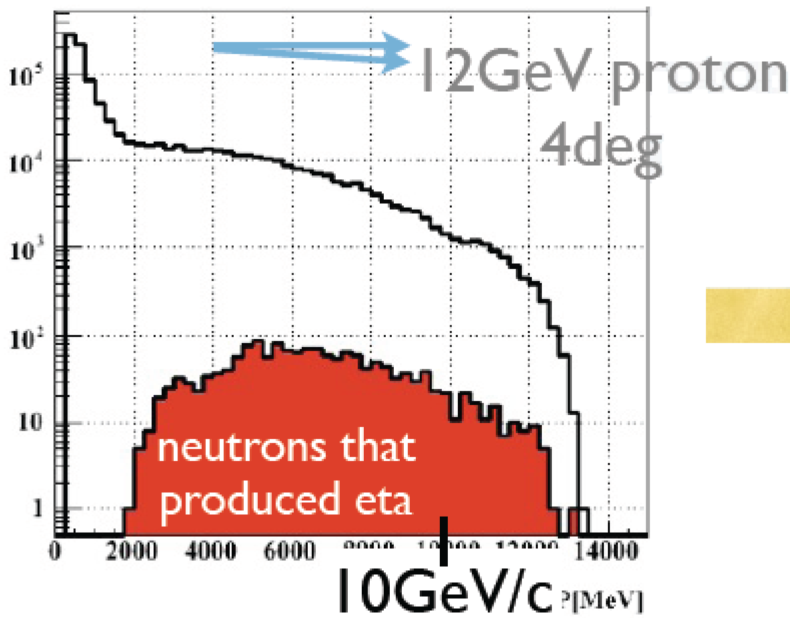


Move CC02 upstream and make it fully active

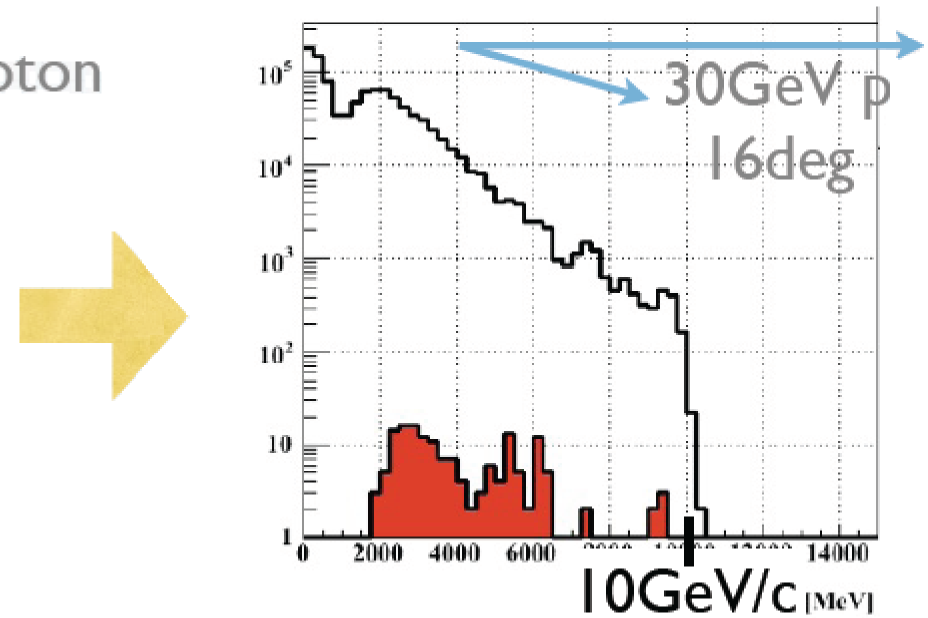
The new beamline and this configuration of CC02 and CV reduce the halo neutron to K_L ratio by a factor of ~230.

Comparison of halo neutron momentum

E391a at KEK-PS



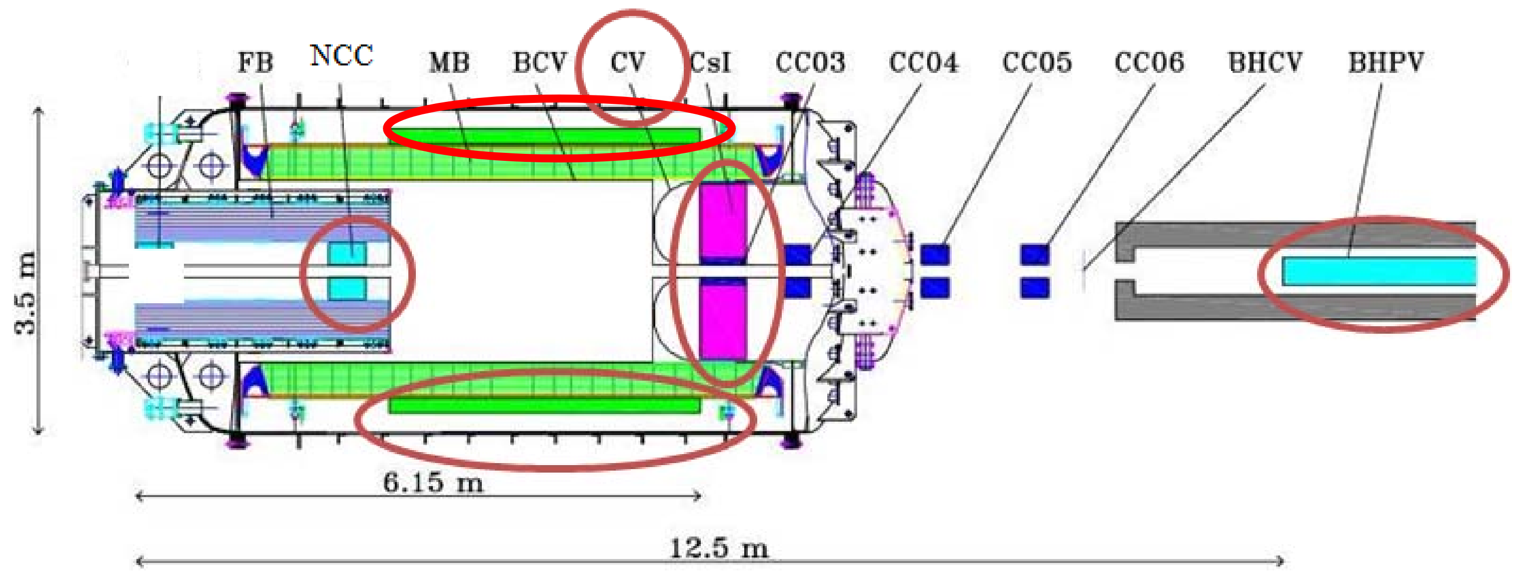
KOTO at J-PARC

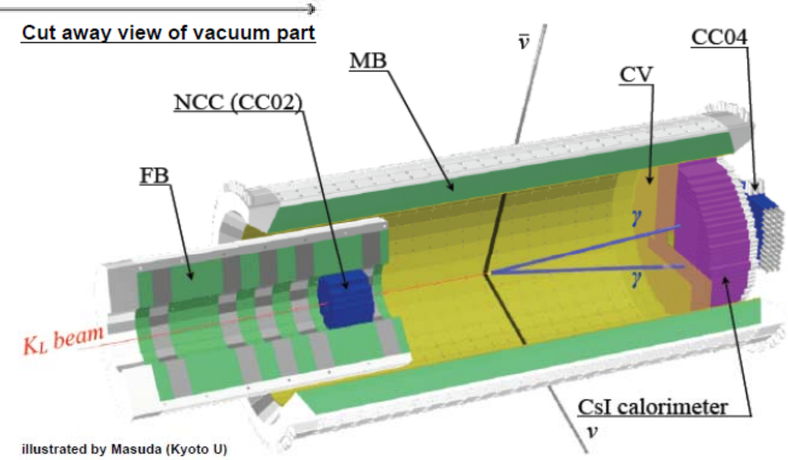


MC study of η particle production

The 10 GeV momentum cut off limits high energy Λ production at CC02

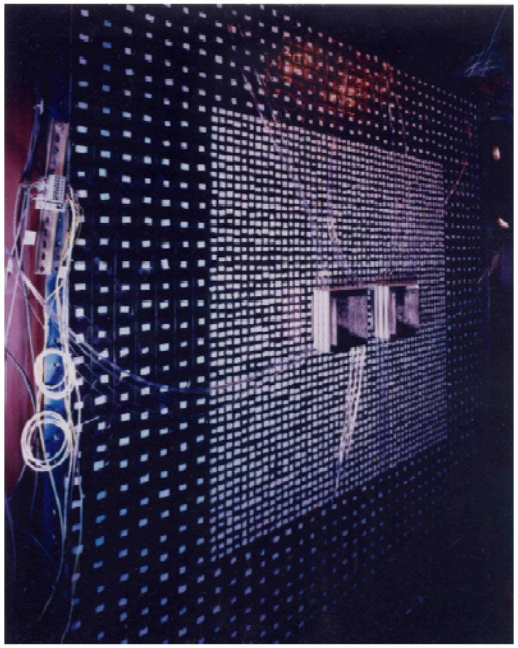
Detector Upgrades

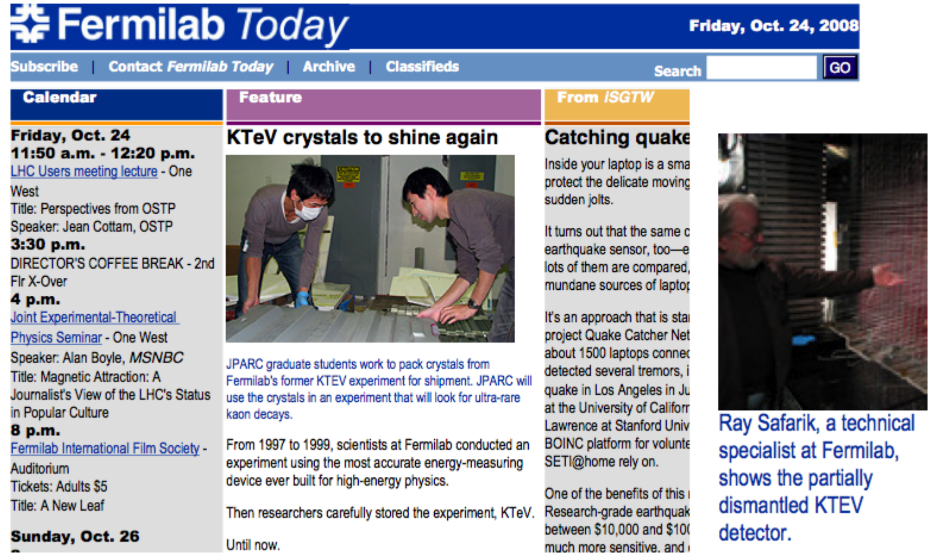




Calorimeter

KTeV
CsI calorimeter





Fermilab *Today* — Friday, Oct. 24, 2008

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Calendar

Friday, Oct. 24
11:50 a.m. - 12:20 p.m.
LHC Users meeting lecture - One West
Title: Perspectives from OSTP
Speaker: Jean Cottam, OSTP
3:30 p.m.
DIRECTOR'S COFFEE BREAK - 2nd Flr X-Over
4 p.m.
Joint Experimental-Theoretical Physics Seminar - One West
Speaker: Alan Boyle, *MSNBC*
Title: Magnetic Attraction: A Journalist's View of the LHC's Status in Popular Culture
8 p.m.
Fermilab International Film Society - Auditorium
Tickets: Adults $5
Title: A New Leaf

Sunday, Oct. 26

Feature

KTeV crystals to shine again

JPARC graduate students work to pack crystals from Fermilab's former KTEV experiment for shipment. JPARC will use the crystals in an experiment that will look for ultra-rare kaon decays.

From 1997 to 1999, scientists at Fermilab conducted an experiment using the most accurate energy-measuring device ever built for high-energy physics.

Then researchers carefully stored the experiment, KTeV.

Until now.

From *ISGTW*

Catching quake

Inside your laptop is a sma protect the delicate moving sudden jolts.

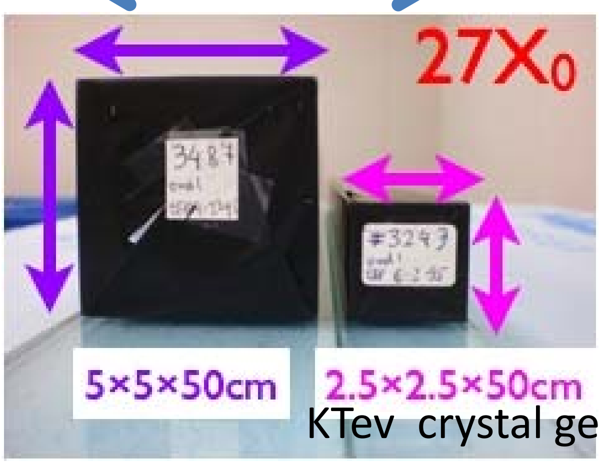
It turns out that the same c earthquake sensor, too—e lots of them are compared, mundane sources of laptop

It's an approach that is sta project Quake Catcher Net about 1500 laptops conne detected several tremors, i quake in Los Angeles in Ju at the University of Califor Lawrence at Stanford Univ BOINC platform for volunte SETI@home rely on.

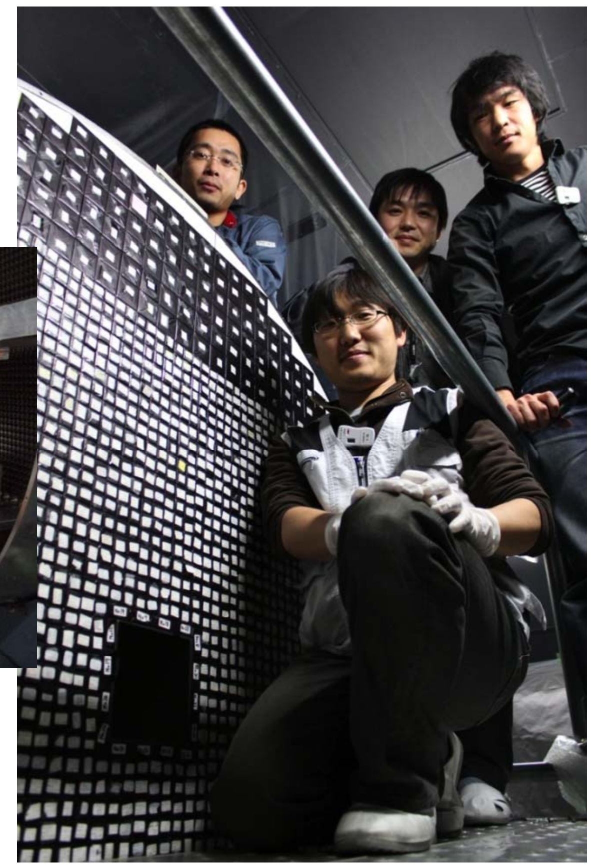
One of the benefits of this Research-grade earthquak between $10,000 and $10 much more sensitive, and

Ray Safarik, a technical specialist at Fermilab, shows the partially dismantled KTEV detector.

E391 CsI crystal 7cmx7cmx30cm **16X_0**



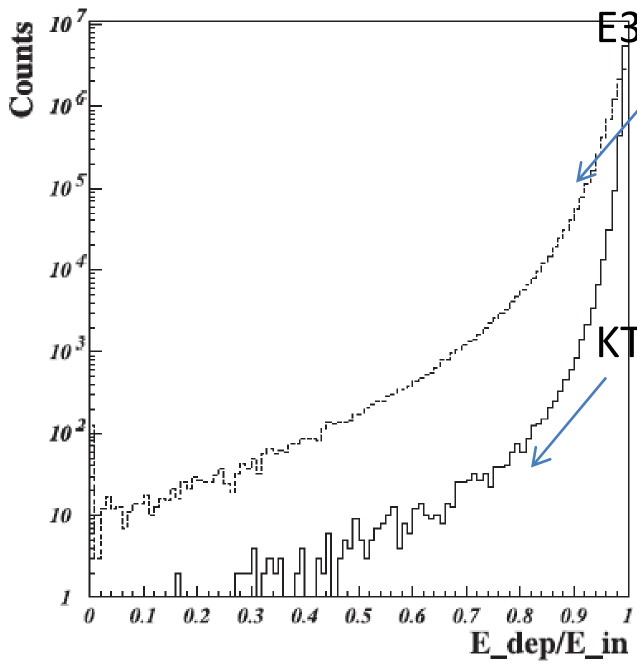
KTev crystal geometry

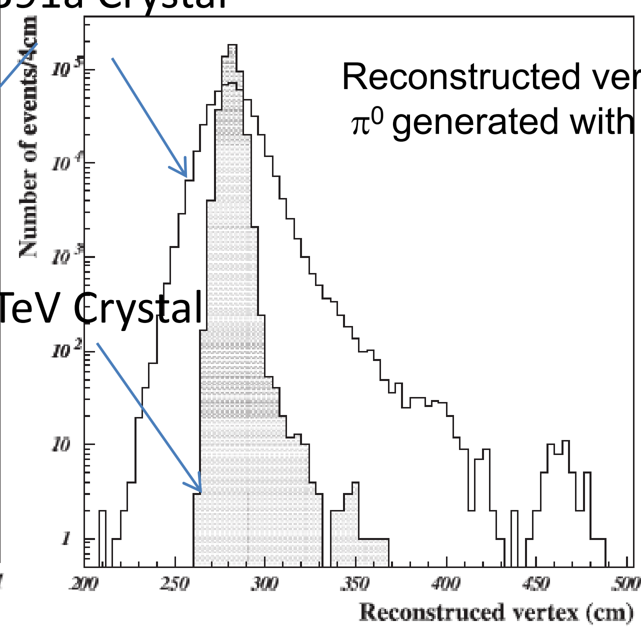


Feb,2011

Longer CsI Reduces Shower Leakage

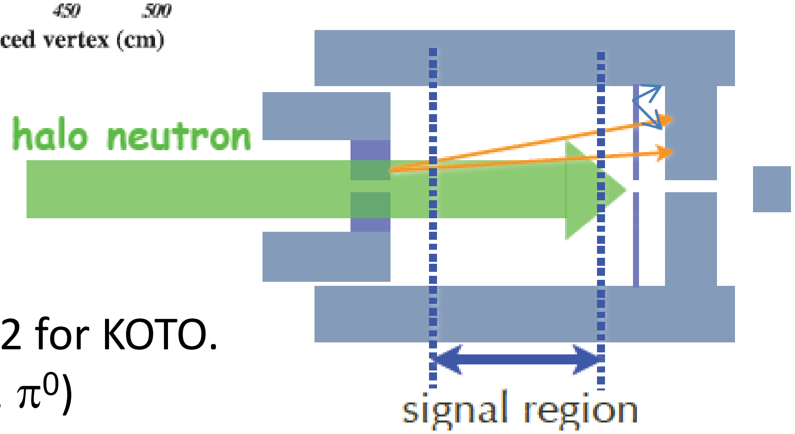
Better energy resolution suppresses the background caused by neutron interaction with veto counters





Reconstructed vertex of MC π^0 sample
π^0 generated with fixed position.

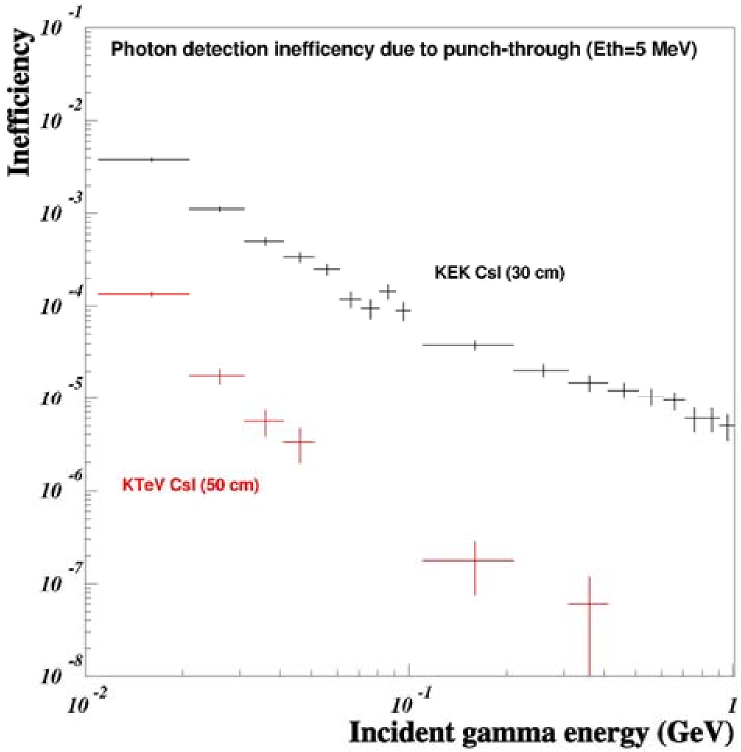
Energy in CsI as a fraction of incident photon energy

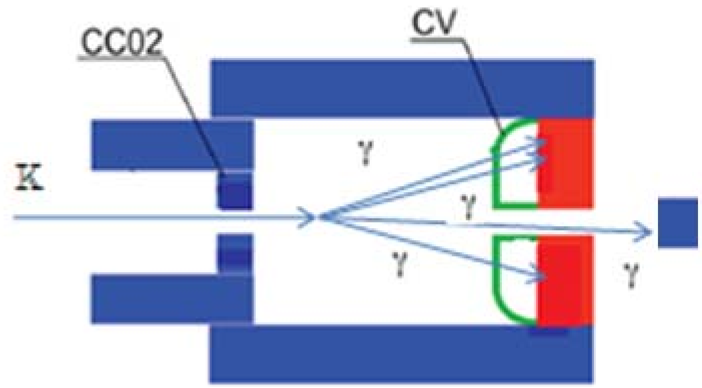


The halo neutron background is expected to be 0.2 for KOTO.
Main background become intrinsic K_L decay(K_L->2 π^0)

Effect on K_L->2 π^0 background(punchthrough)

- Calorimeter acts as a veto detector

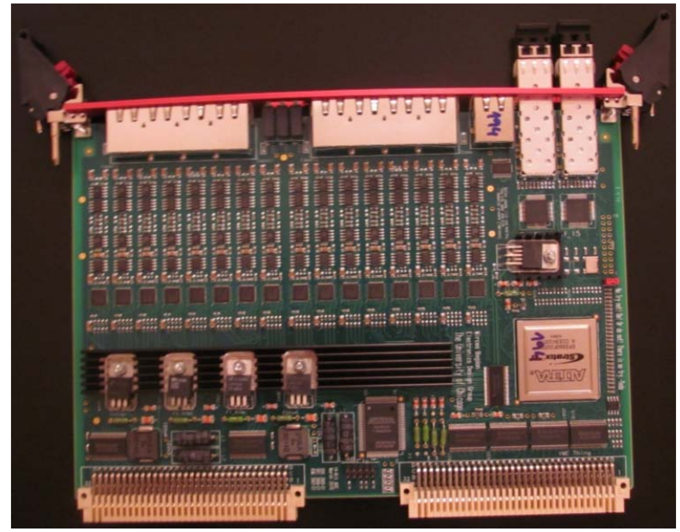




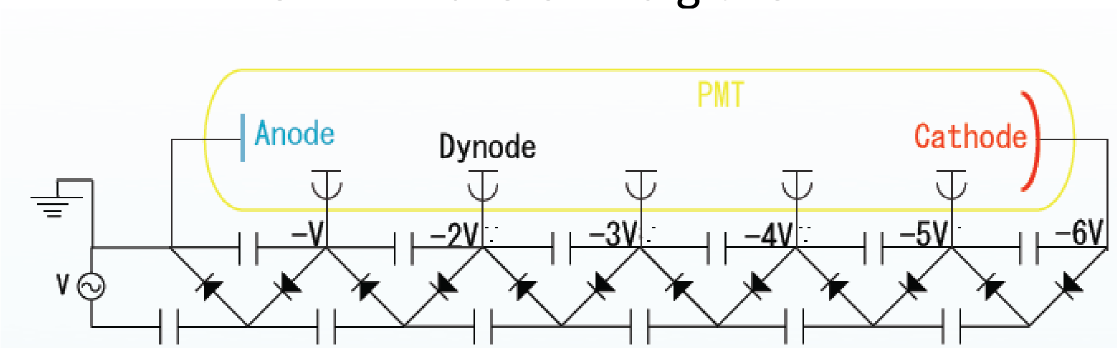
- Main mechanism for K_L->2 π^0 background becomes ‘even-paring’ events with two photon missing in veto detectors instead of CsI punch through.

Calorimeter Readout

KTeV Calorimeter → KOTO Calorimeter(Chicago)

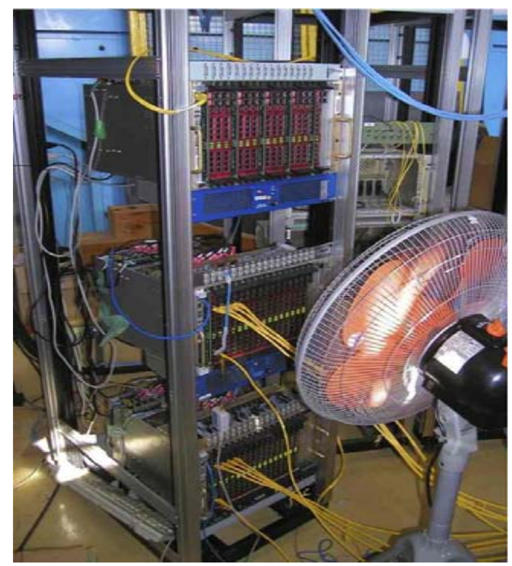


- New in KOTO: high rate, different energy range, vacuum, higher timing requirement, vacuum
- CW base ->low power
- Differential outputs to the
  125MHz waveform digitizer



Cockcroft-Walton

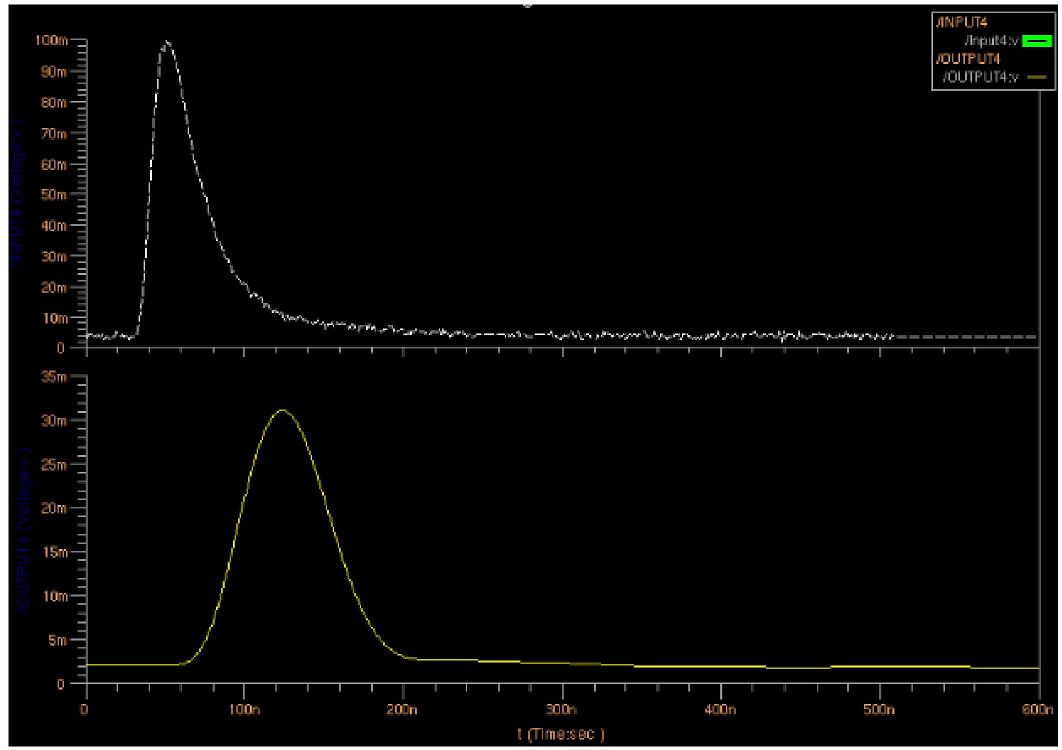
14bit 125MHz FADC



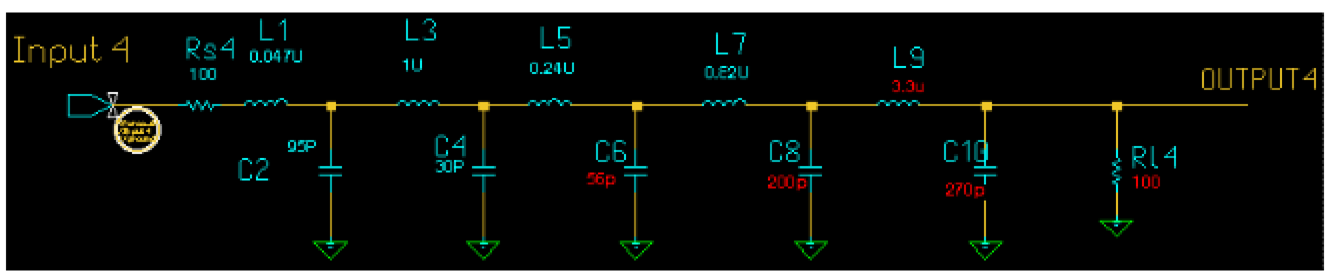
The Gaussian Filter in the FADC

- Challenge of sampling 3000 fast rising/falling pulses. **Cost and the amount of storage.**
- Solution: shape the CsI pulse into a qusi-Gaussian pulse.

CsI pulse(inverted). Yellow: filtered



Filter circuit

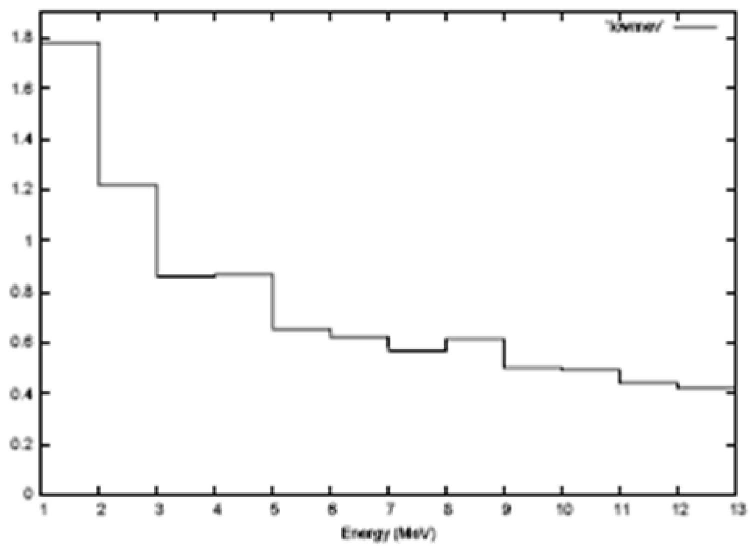


Timing Measurement with an ADC

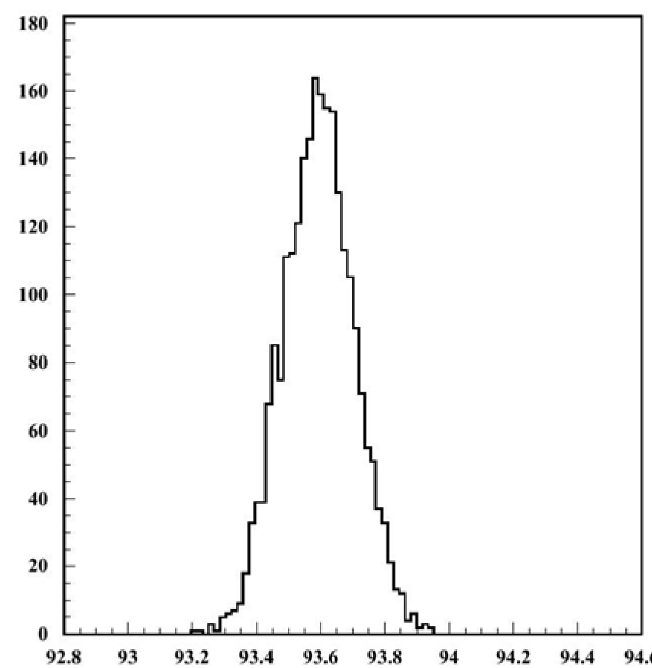
- Full pulse sampling allows fitting to determine the time of the pulse
- Timing measurement is important for veto and reducing acceptance loss. A good timing measurement also have the potential to find the angle of the photon. The angle measurement suppresses a large class of background.

Smaller pulses have irregular shapes

ns

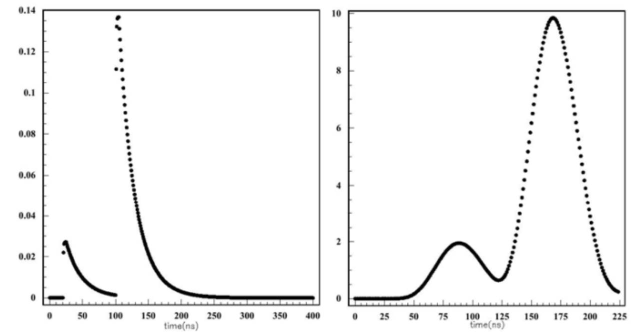


Timing Resolution, Low Energy Pulses

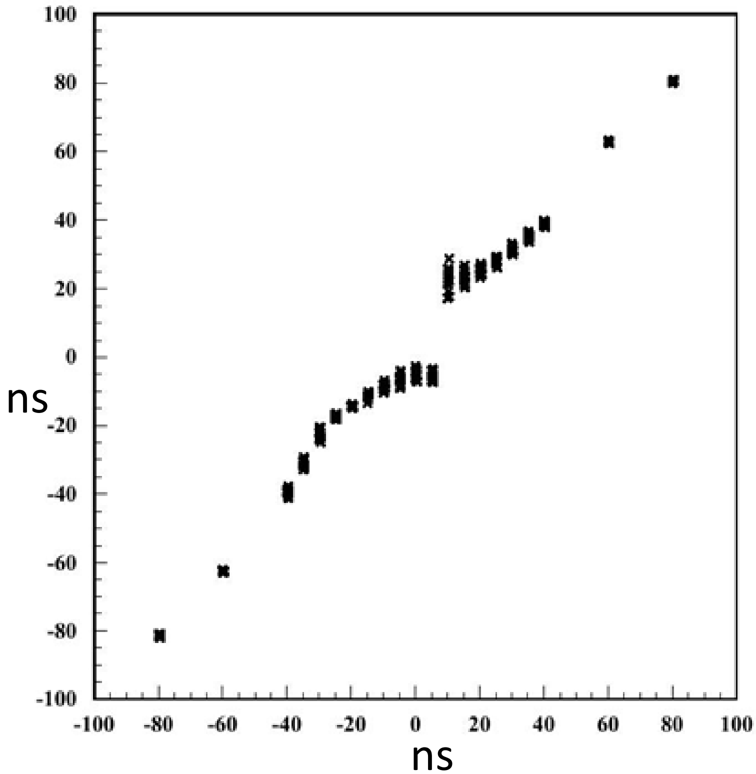


Timing resolution ~110ps at E=100MeV

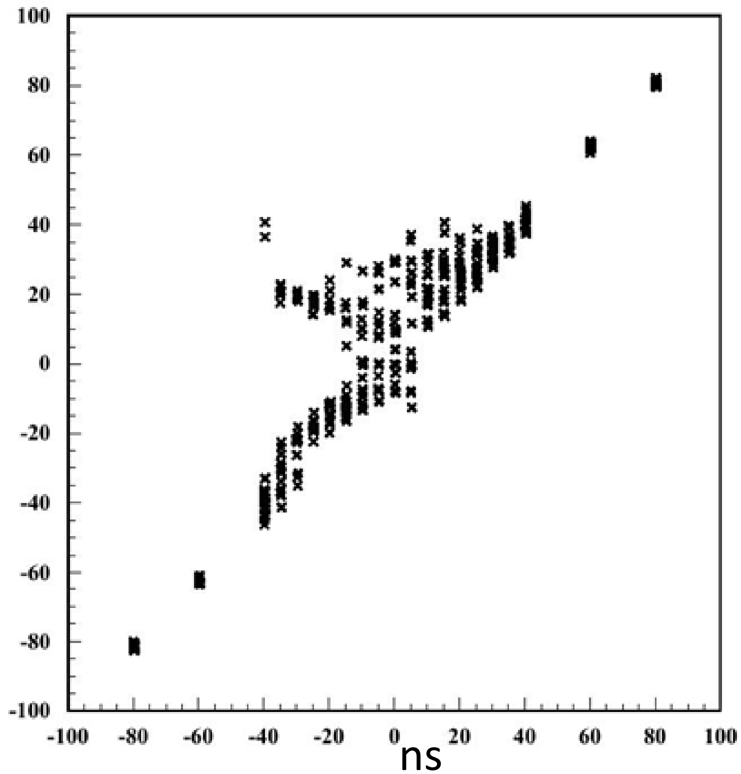
Two Pulse Separation



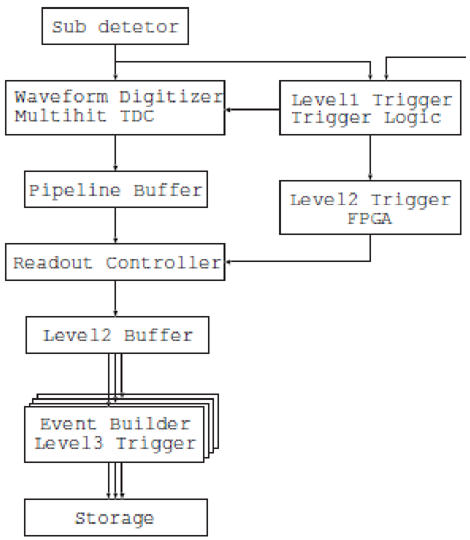
200MeV + 40MeV



2MeV + 10MeV

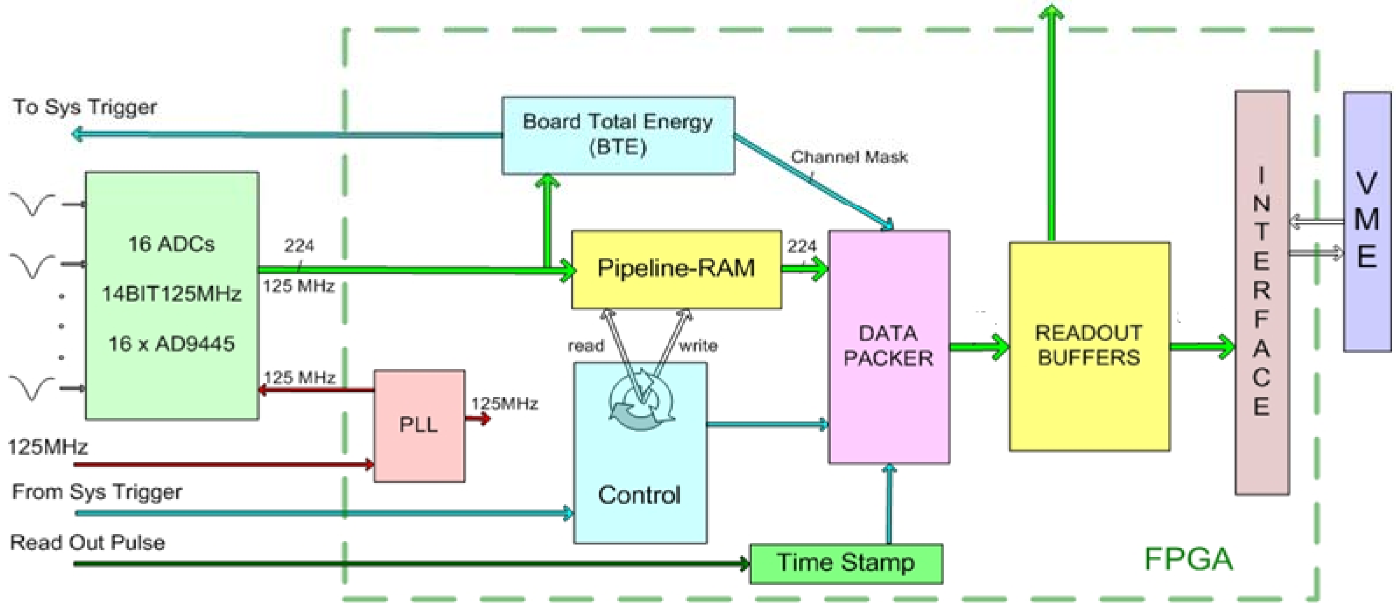


Readout and Architecture



Data Flow

Optical fiber readout



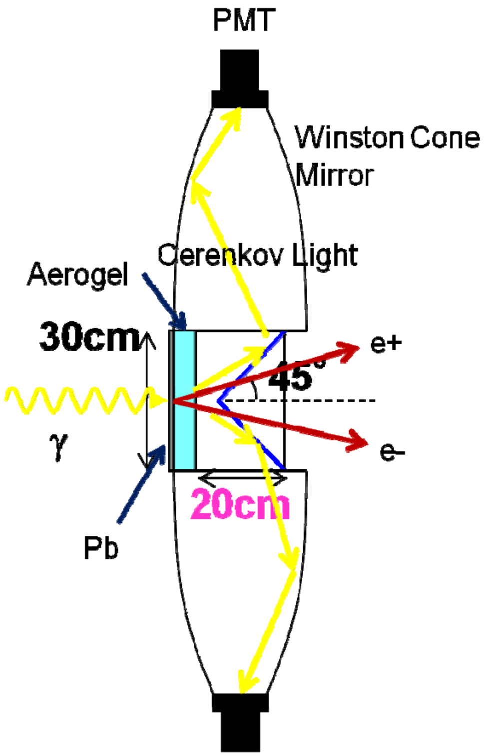
FADC

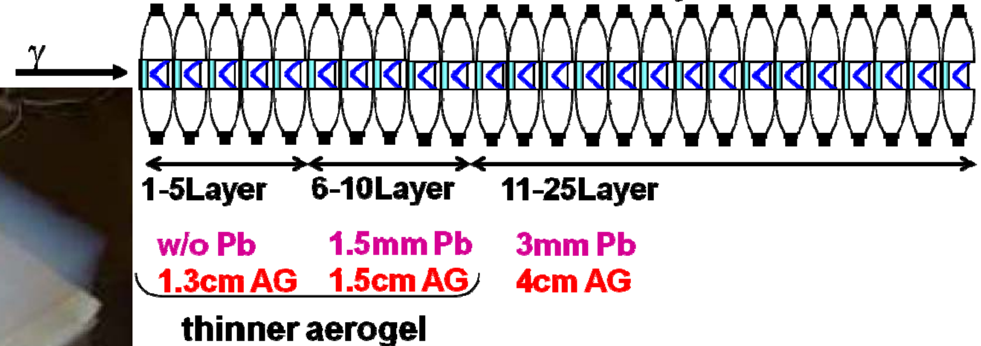
- Fully pipelined system with no delay cable
- With 48 samples for a pulse, the FADC board can send out data at a trigger rate of >100kHz. Data throughput: 20GByte/second
- Multi leveled trigger system

Major veto detectors

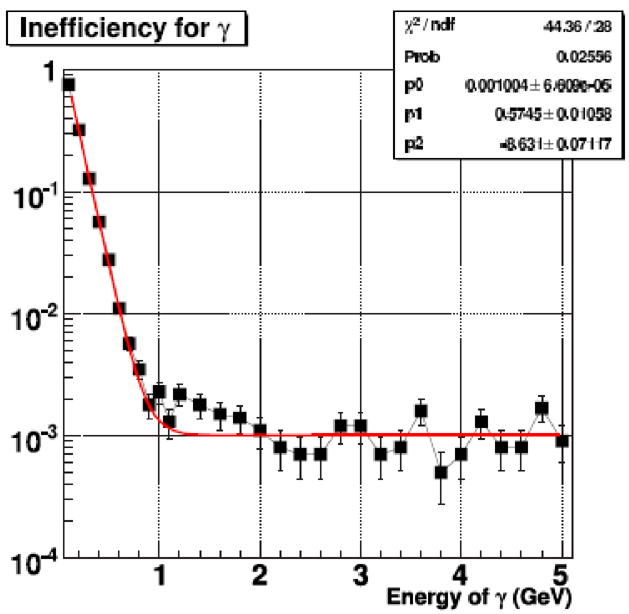
Catching photons down the beam hole

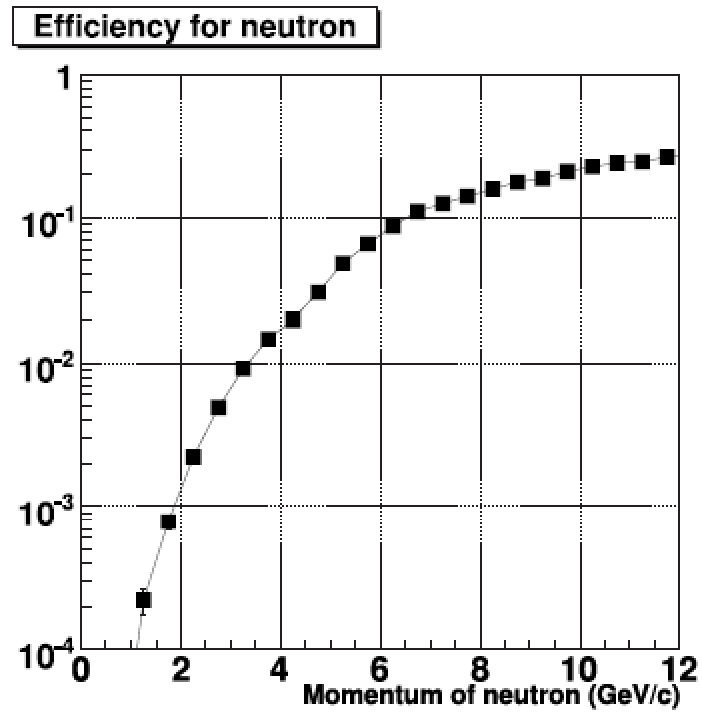
- Challenge: efficient for photon and inefficient for neutron
- Readout fast pulses: 500MHz FADC board(Chicago)





Expected Performance

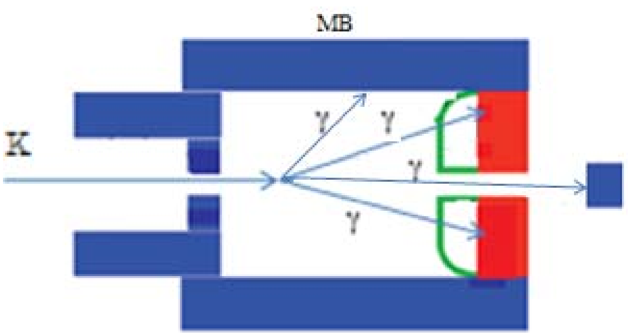




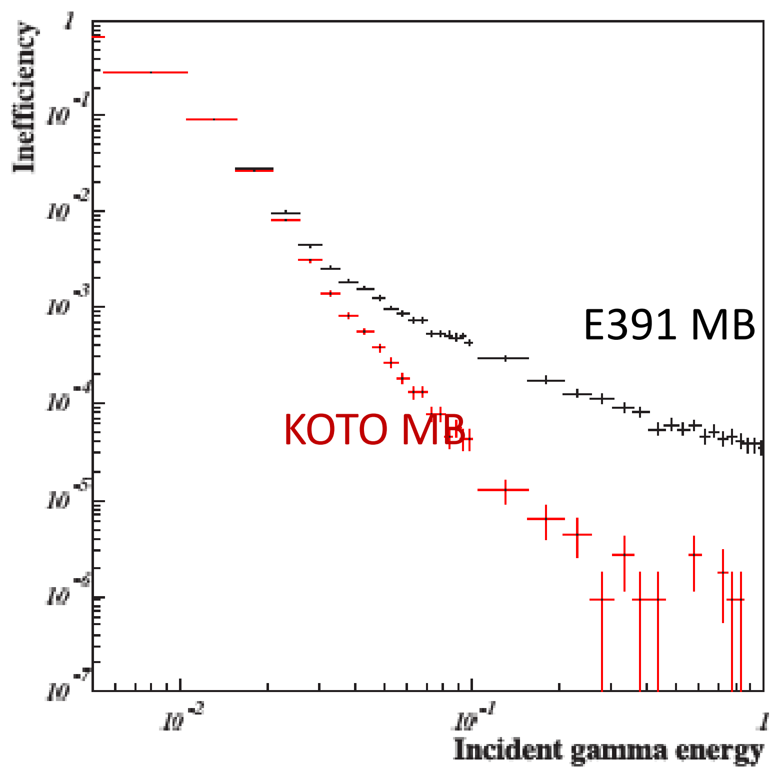
- Energetic photons go down the hole

KOTO Main Barrel(MB)

- With the improvement in the beam and Calorimeter, the main background comes from $K_L \rightarrow 2\pi^0$ with missing photons.
- Adding another $5X_0$ to the 14 X_0 E391a MBreduces $K_L \rightarrow 2\pi^0$ background by a factor of 2.



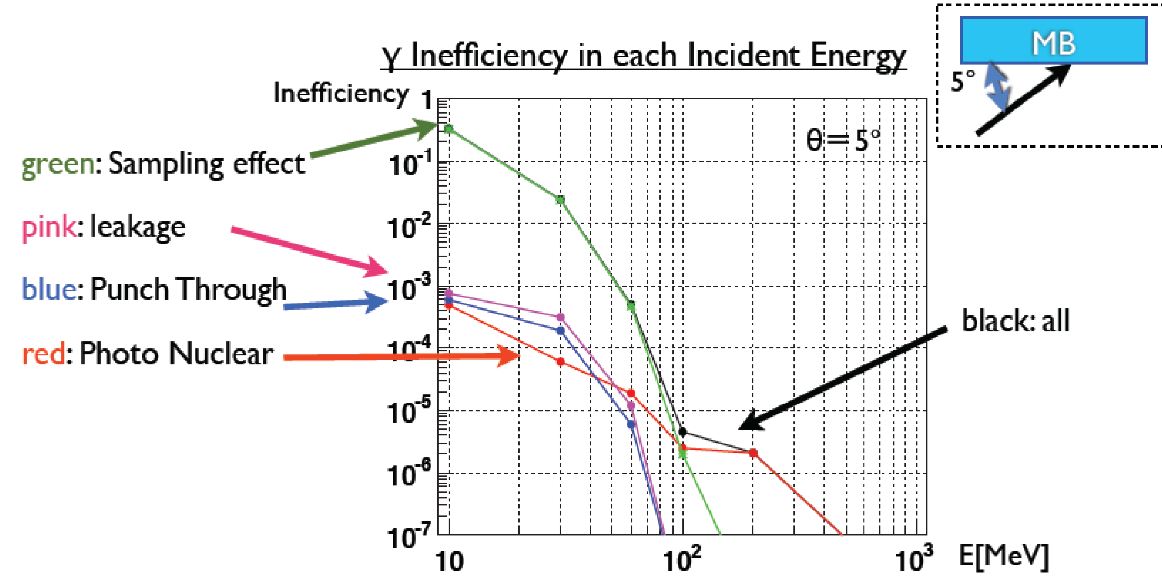
Photon Detection Inefficiency



How can we go further?

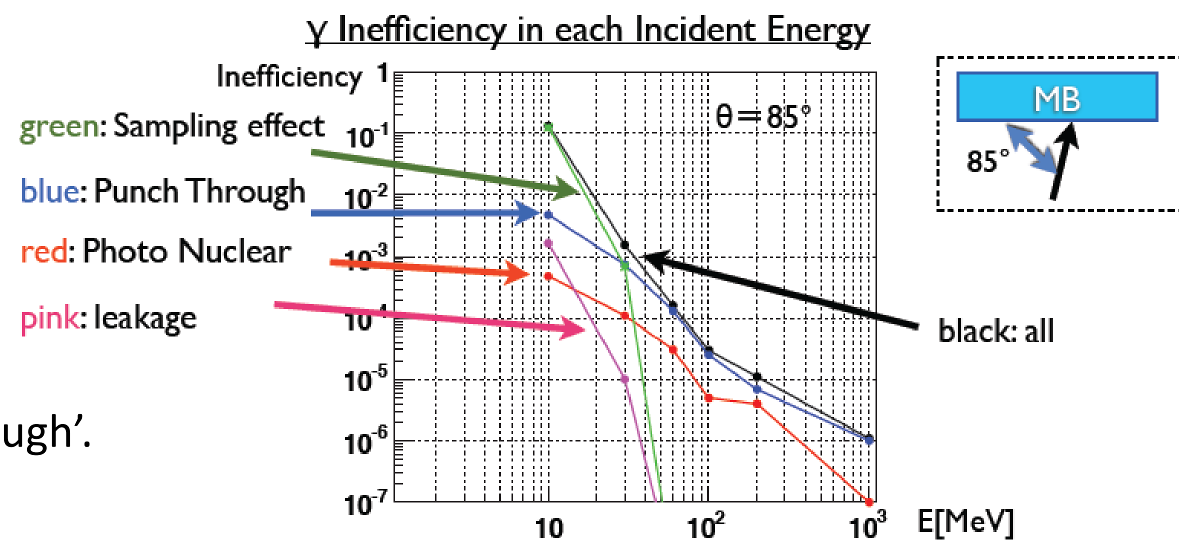
- MB Inefficiency Mechanism MC Study

Low energy sampling effect dominate



For perpendicularly incident photons, $19X_0$ isn't enough for punch though.

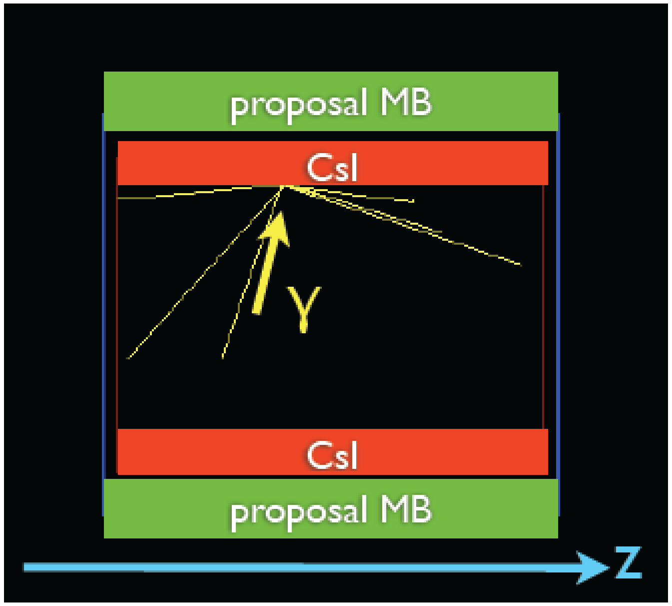
Not many such photons in MB, but many such photons in CsI. This explains why E391a $K_L \to 2\pi^0$ background comes from 'punch through'.

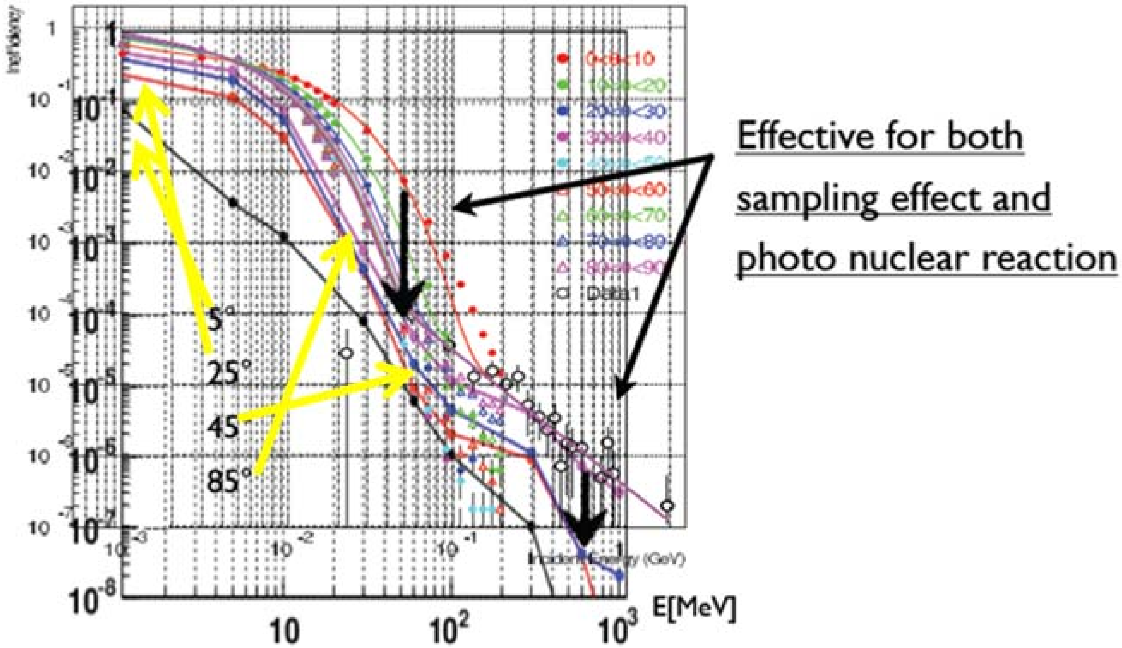


MB II(in plan)

- The inefficiency for photons with energy <30MeV is caused by the sampling effect in the Pb/scintillator sandwich structure.
- Using CsI in front of Pb/scintillator MB can further reduce the K_L->$2\pi^0$ background by 40%

3cm of CsI in front of CsI





Background and Sensitivity

	J-PARC KOTO	KEK-E391a	improvement
KL yield/spill	8.1×10^{6}	3.3×10^{5}	x30/sec
Run time	12 months	2 months	x6
Decay prob.	3.6%	2.1%	x2
Acceptance	4.7%	1%	x3.6
Sensitivity	0.8×10^{-11}	1.1×10^{-8}	x1300

With no CsI lining MB

Background source	#evts
$K_L \to \pi^0\pi^0$	1.8
$K_L \to \pi^+\pi^-\pi^0$	0.46
n + residual gas	0.04
n + upstream veto	0.13
accidental coincidence	0.10
sum	2.5

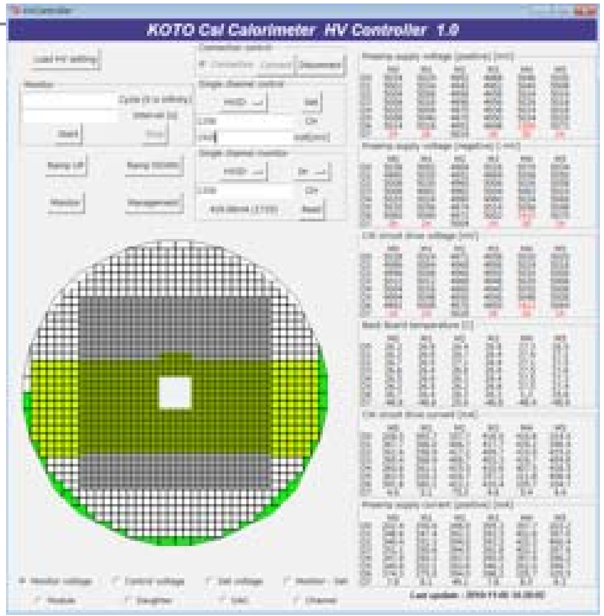
$K_L \to \pi^0\nu\bar{\nu}$ signal	3.5

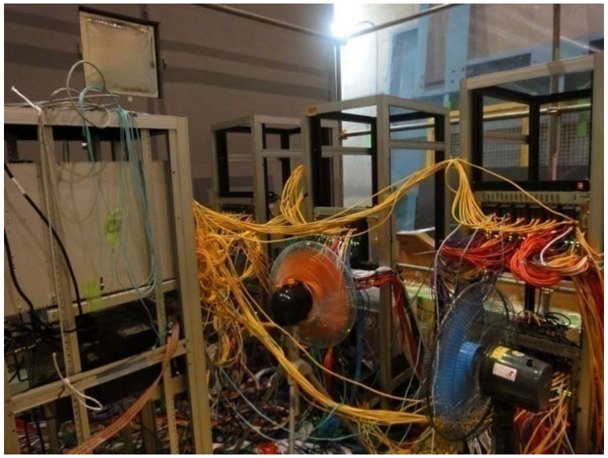
Timeline

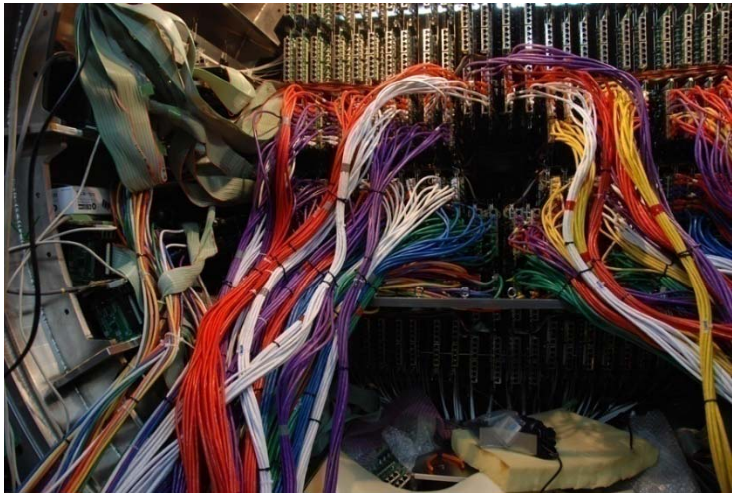
- Beamline construction done in 2009
- Engineering run in the fall of 2010

Engineering Run (10/2010-11/2010)

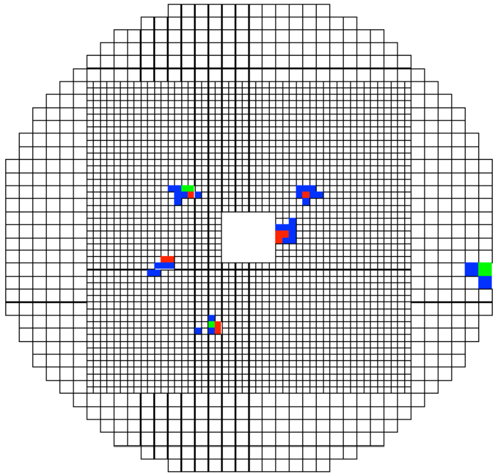
- With half of the calorimeter and 3-5kW primary beam
- spectrometer in front of the calorimeter
  ← calibration with momentum-measured electrons



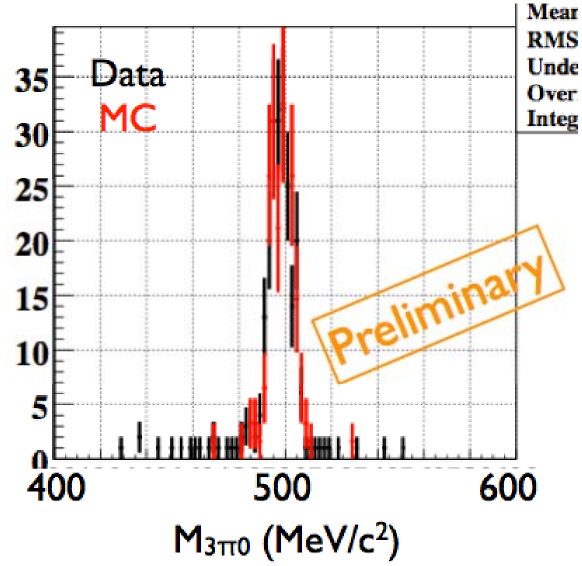




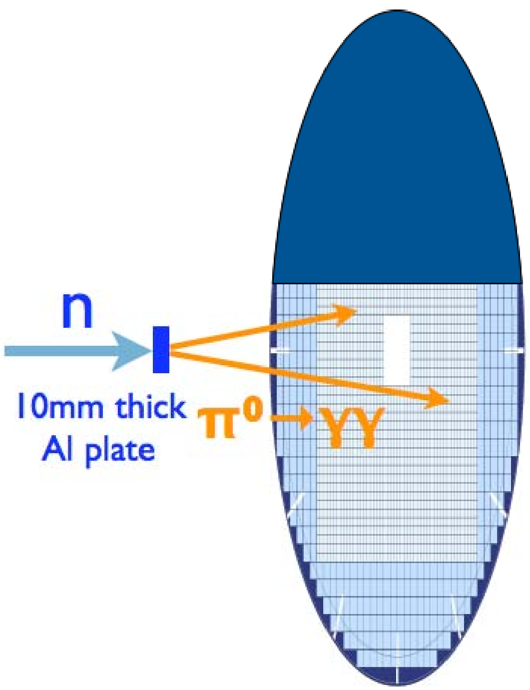
Results from Engineering Run

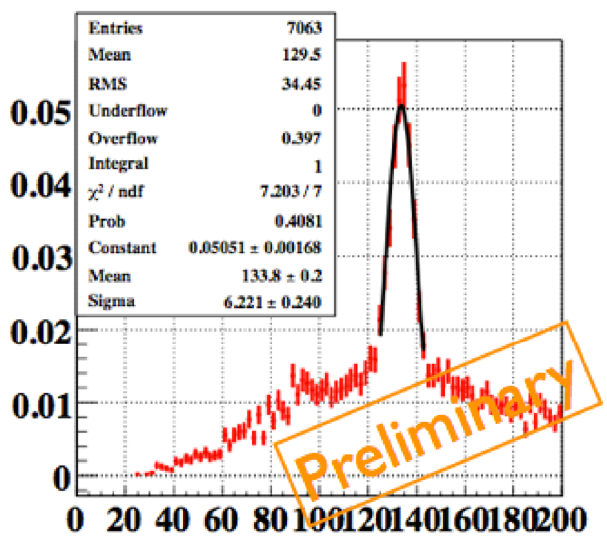


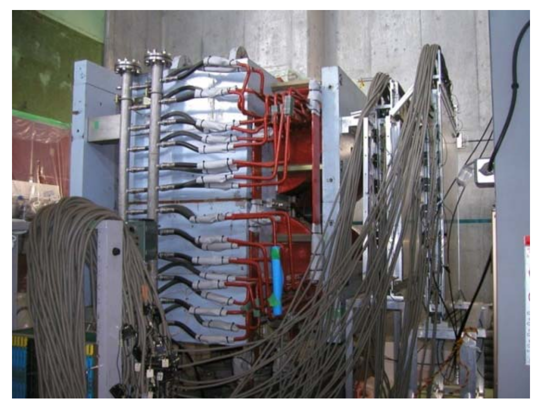
candidate of $K_L \to 3\pi^0$



spectrometer in front of the calorimeter
← calibration with momentum-measured electrons

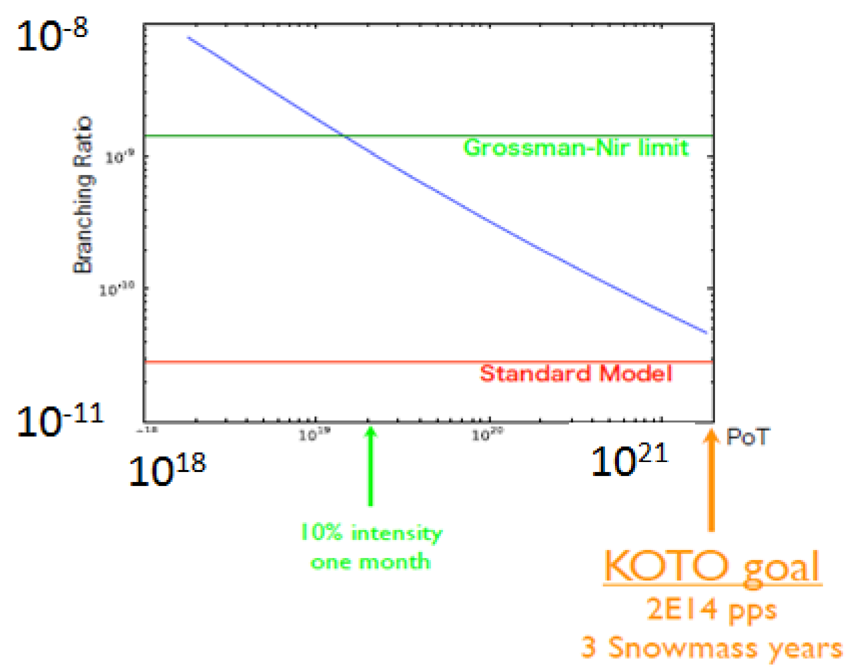




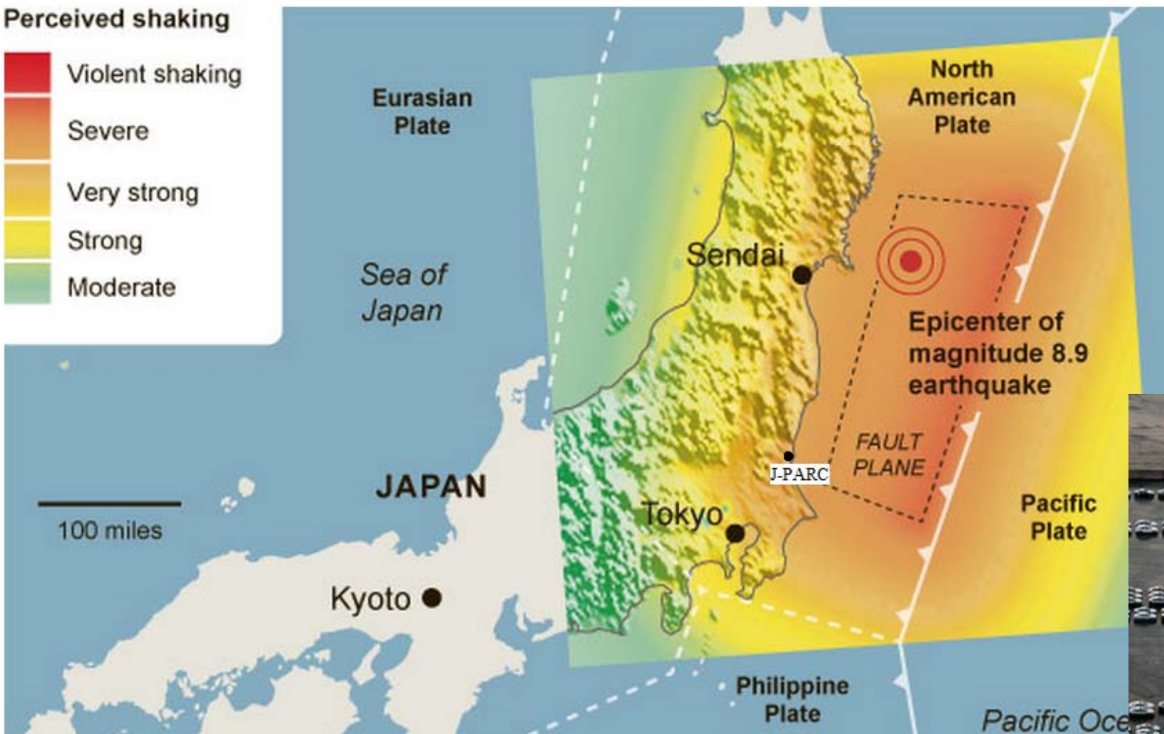


Timeline

- Beamline construction done in 2009
- Engineering run in the fall of 2010
- Calorimeter construction done in March 2011
- Full detector to be completed by the end 2011
- Physics run start in 2012(with 30 kW beam)



Report on 03/11/2011 Earthquake



2 miles from J-PARC

Need Electricity!

Summary

- The KOTO experiment aims to discover the SM $K_L \to \pi^0 \nu \overline{\nu}$ events at Step 1
- Breach into the new physics from 2012
- Step 2(100 Golden events) after a good understanding of step 1

    go back to smaller angle

    longer decay volume->longer MB

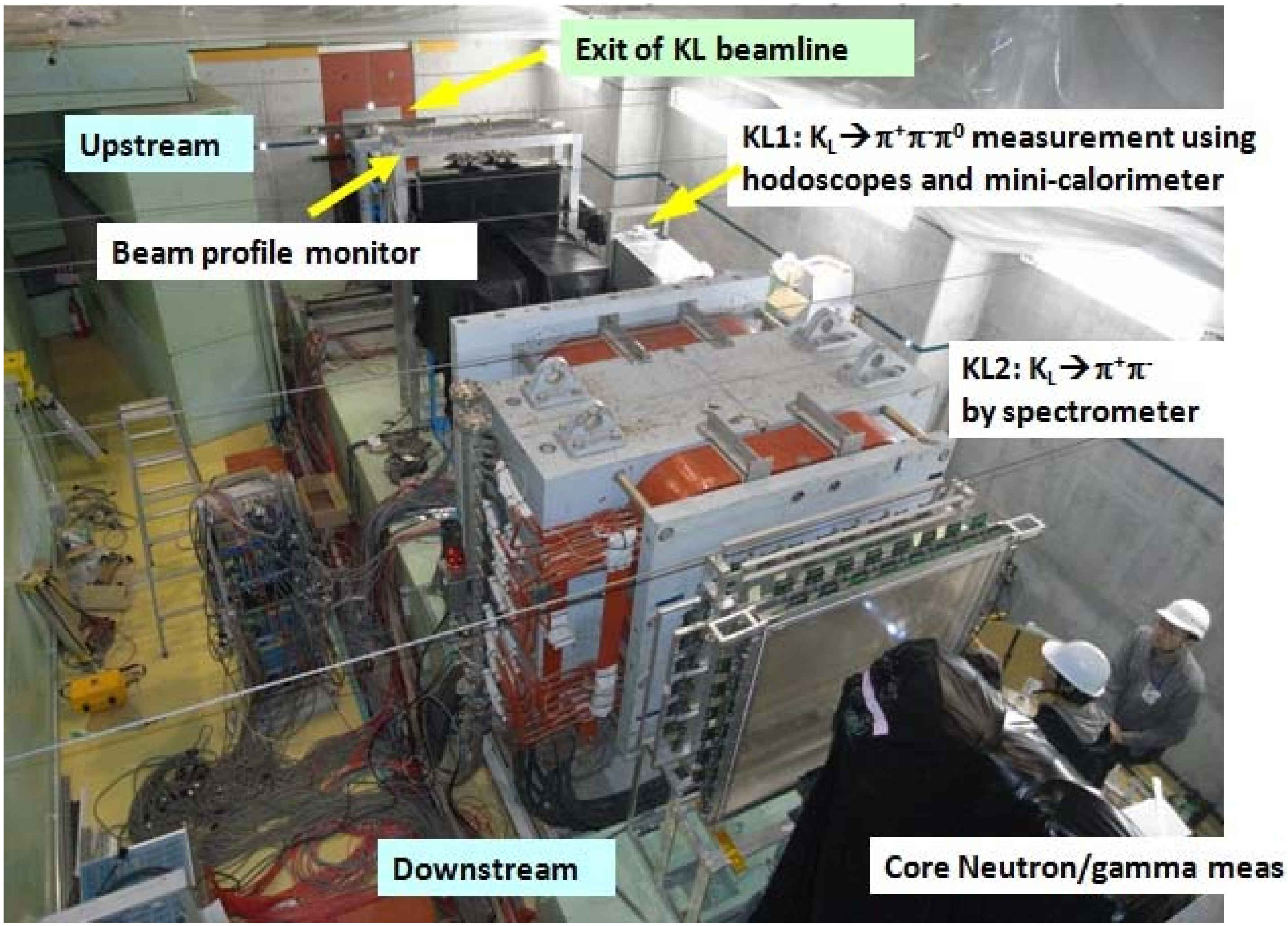
    bigger calorimeter

    retool the beamline

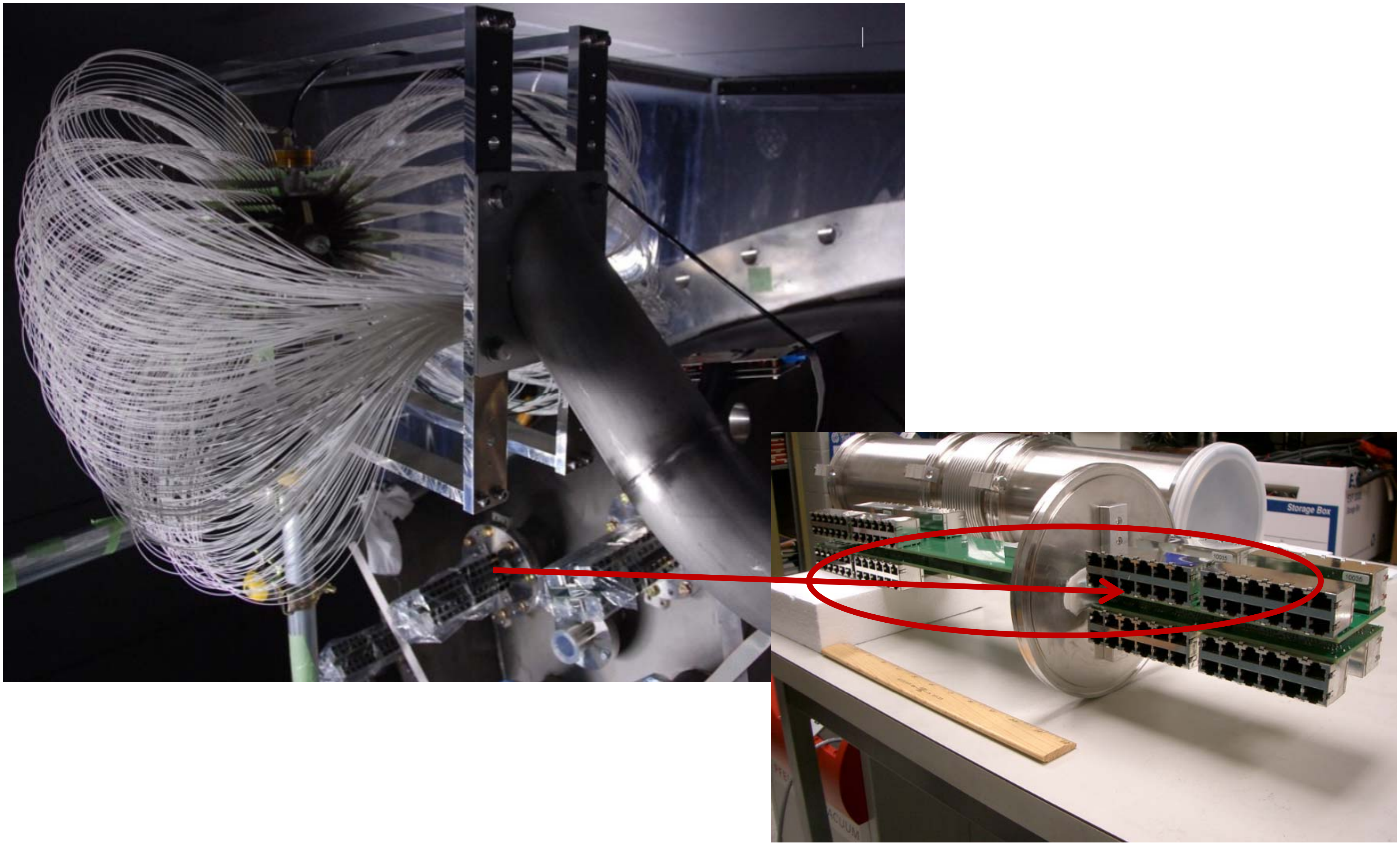
Backup

Beam Survey

With 1-3kW beam

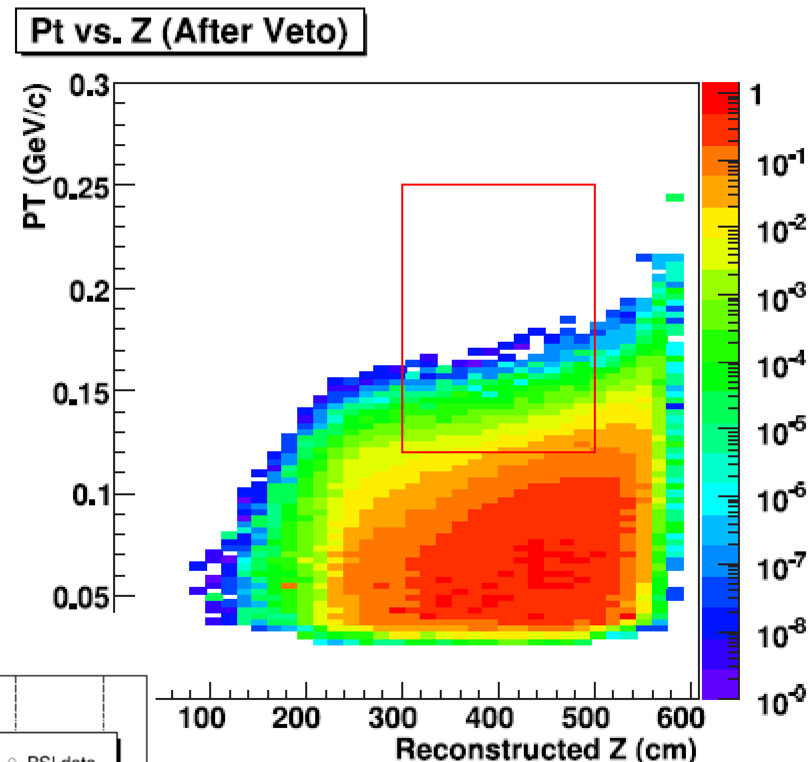


At the endcap

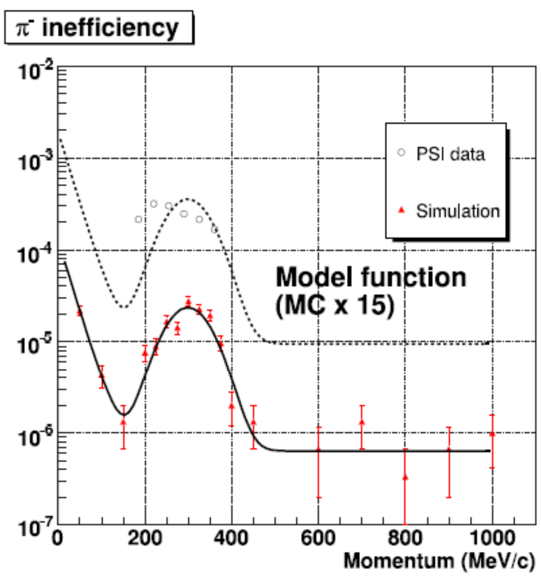


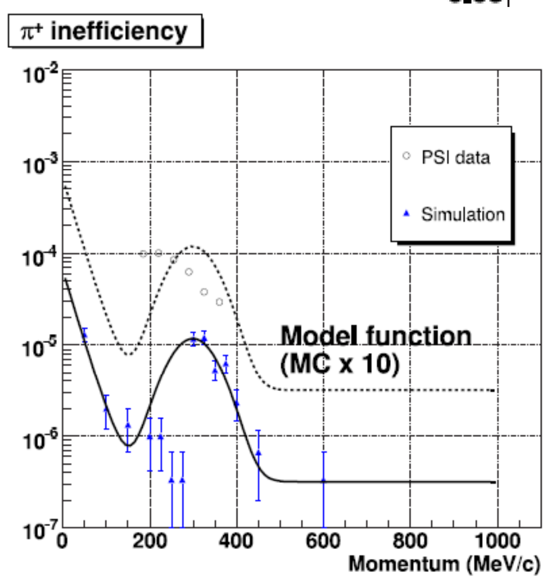
Background from K_L Charged Mode Decays

- Main contribution comes from Kpi3 decay. Ke3(pi-e+nu, bigger inefficiency) background is negligible because extra particles going into the calorimeter



K->pi+ pi- pi0 background

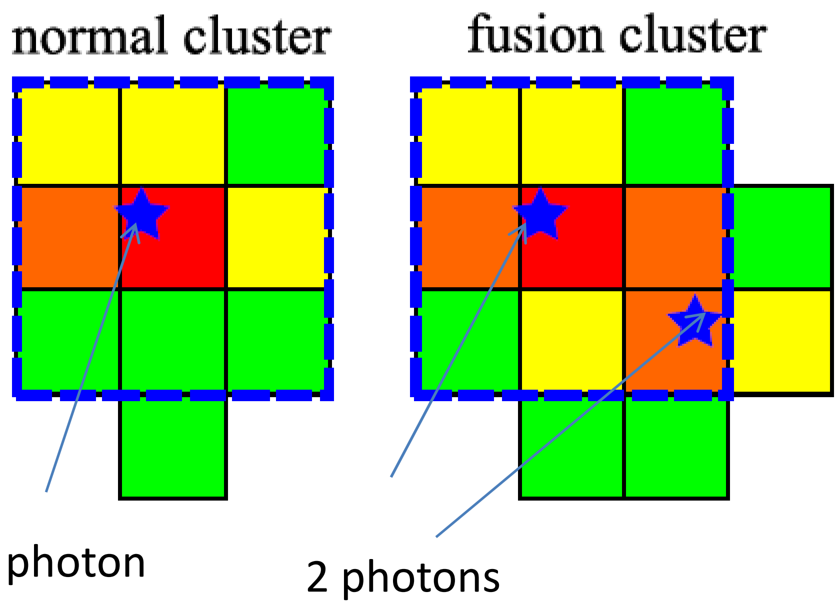


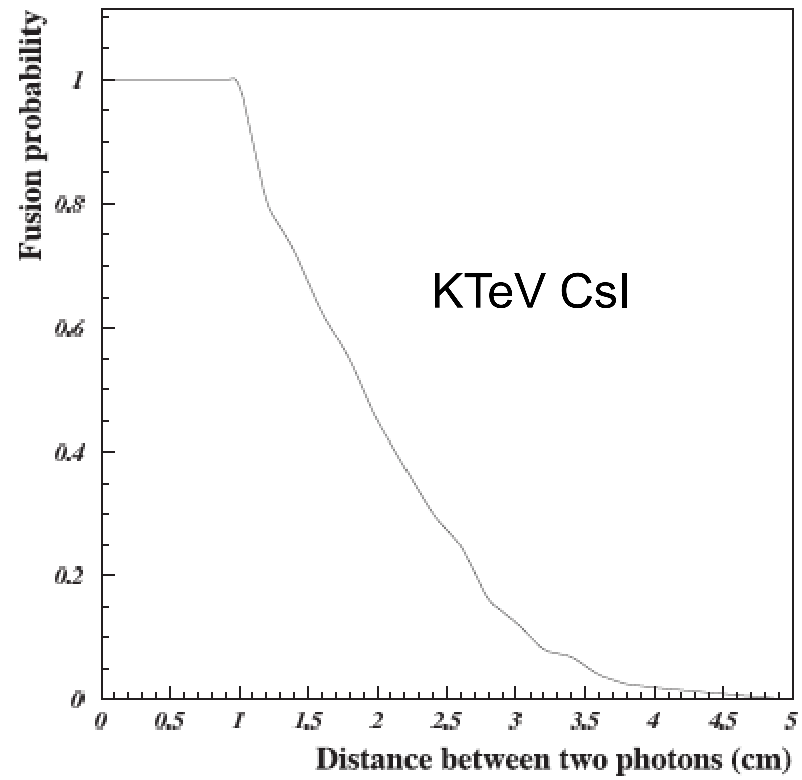


Inefficiency verified with CV prototype

Fusion

- K->2pi0 fusion background is about 10% of total background
- To reject fusion events, E391a suffered~60% acceptance loss. In KOTO, the fusion background is reduced with a small acceptance loss.





5cm distance between two photon to identify fusion using KOTO calorimeter; 15cm for E391a

Beam Parameter Summary

	J-PARC KOTO	KEK-E391a
• Primary proton energy	30 GeV	12 GeV
• Proton intensity(/spill)	$2x10^{14}$	$2.5x10^{12}$
• Spill-length/repetition	0.7s / 3.3s	2s / 4s
• Production target	Nickel disks	Pt rod
• Extraction angle	16 deg.	4 deg.
• KL yield(/spill)	$8.1x10^{6}$	$3.3x10^{5}$
• Average P_{KL}	2.1 GeV/c	2.6 GeV/c
• n/K_L ratio	6.5	45
• Halo neutron/K_L	$1.4x10^{-3}$	$3.3x10^{-1}$

CKM matrix and $K_L^0 \to \pi^0 \nu \bar{\nu}$

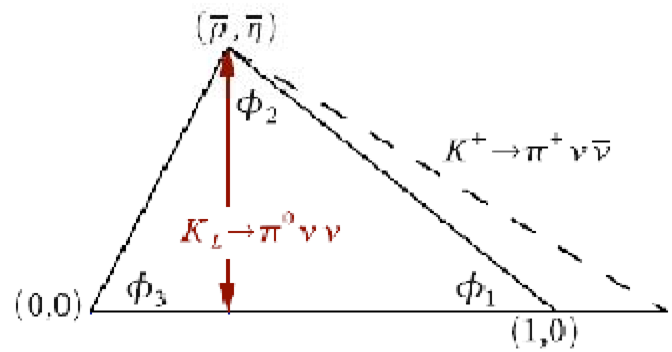
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKM matrix connects weak eigenstates and mass eigenstates

unitary

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

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



$$Br(K^0_L \to \pi^0 \nu \bar{\nu})_{SM} = \kappa_L \left[\frac{\mathrm{Im}(V_{ts}^* V_{td})}{\lambda^5} X \right]^2$$

$= (2.49 \pm 0.39) \times 10^{-11}$

κ is related to the isospin breaking correction and X is a function of m_t and α_s

(F. Mescia and C. Smith, PRD76, 074017(2007))