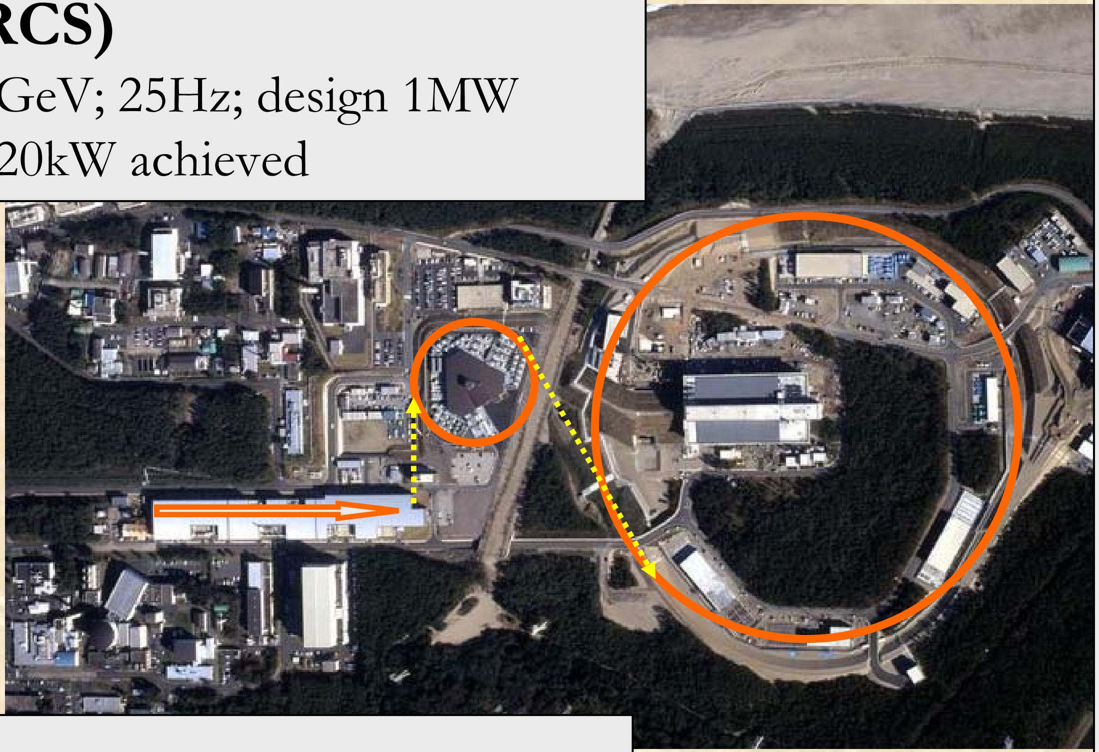
# J-PARC flavor program

Tadashi Nomura
(KEK)

# J-PARC accelerators

## Rapid Cycle Synchrotron (RCS)

- 3GeV; 25Hz; design 1MW
- 220kW achieved



## Main Ring (MR)

- 30GeV (Phase1)

- **Fast extraction**; design 750kW
  - 3.2sec cycle (shortened in near future)
  - **145kW** user op. achieved

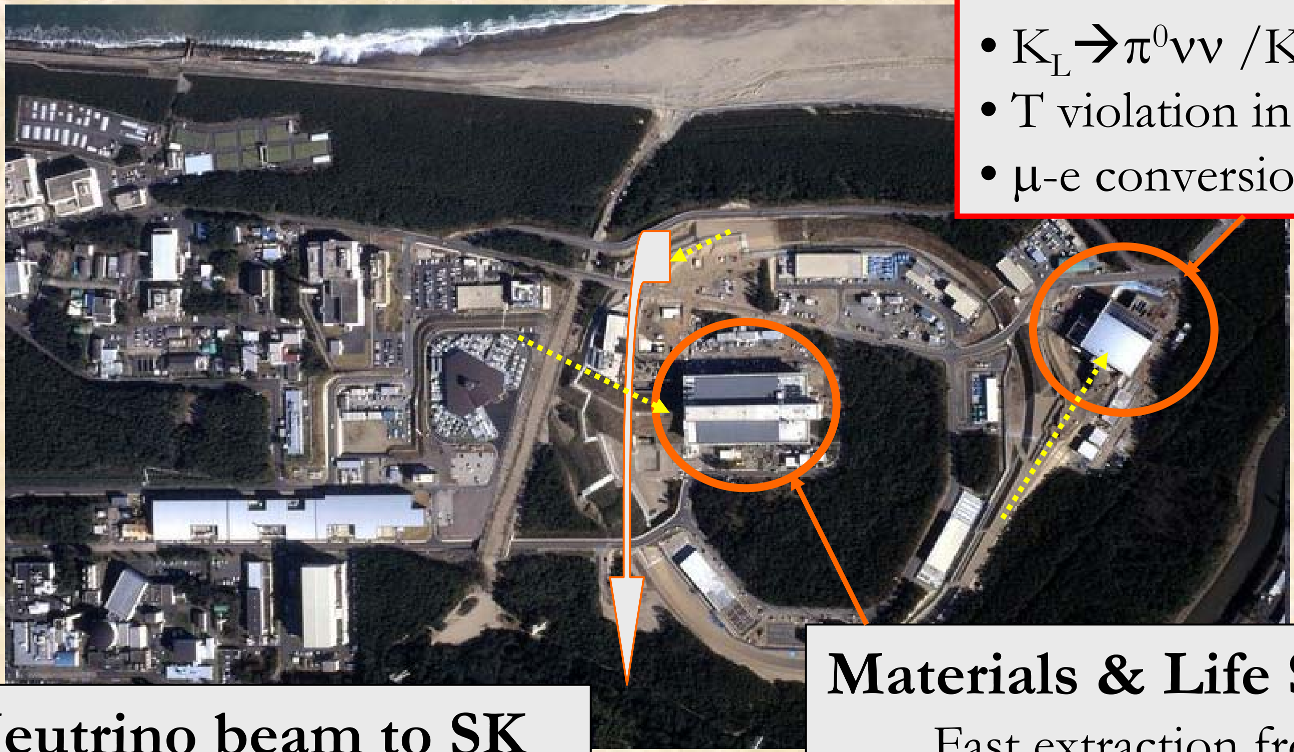
- **Slow extraction**; design 270kW
  - 2sec spill/6sec cycle
  - 3.6kW user op., so far
  - **99.5% extraction eff.** achieved
  - Spill structure by no means satisfactory

## Linac

- $H^-$; 181MeV/30mA; 25Hz

→400MeV/50mA in near future

# J-PARC flavor programs



**Hadron Hall**

Slow extraction from MR

- $K_L \rightarrow \pi^0 \nu\nu$ /KOTO
- T violation in $K^+ \rightarrow \pi^0 \mu^+ \nu$ /TREK
- μ-e conversion O($10^{-16}$) / COMET

my talk

**Neutrino beam to SK**

Fast extraction from MR

- T2K

E. Zimmerman's talk

**Materials & Life Science Facility**

Fast extraction from RCS

- μ-e conversion O($10^{-14}$) / DeeMe
- μ g-2, EDM

# A few words about the earthquake on March 11…

- J-PARC suffered significant damage.
  - *Fortunately, Tsunami didn't reach to J-PARC.*
  - *Mostly, damages of inter-building infrastructure and displacement of the equipments*
- We are continuing inspection of damages.
- Tentative recovery plan is,
  - Aim to restart accelerator operation in this year.
  - Aim to deliver beam to users for 2 months in this Japanese fiscal year.

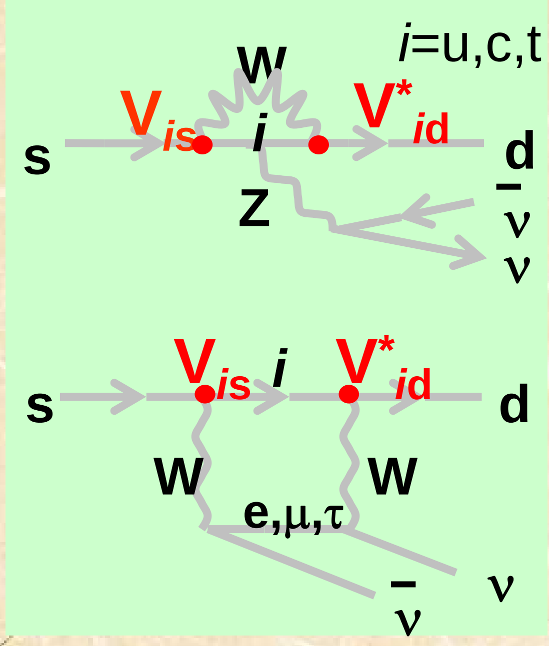
# KOTO: $K_L \rightarrow \pi^0 \nu\nu$ measurement

***KOTO** stands for "K0 at Tokai".*

- Stage 2 (full) approval
- On detector construction

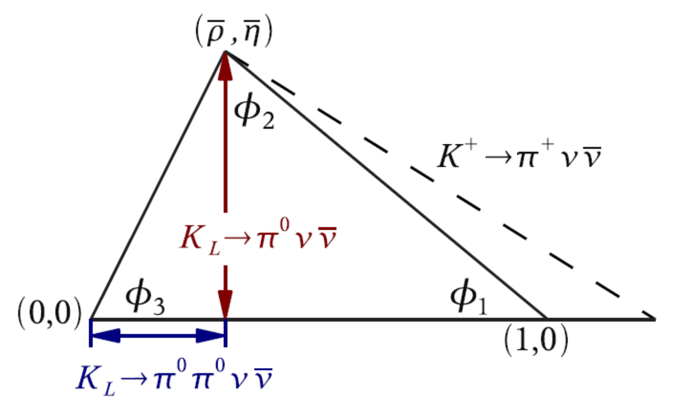
# $K_L \to \pi^0 \nu\nu$ in the Standard Model

- Flavor changing neutral current with Z penguin and box diagram
- Top in the loop, Sensitive to $V_{td}$
- **Small theoretical uncertainty**

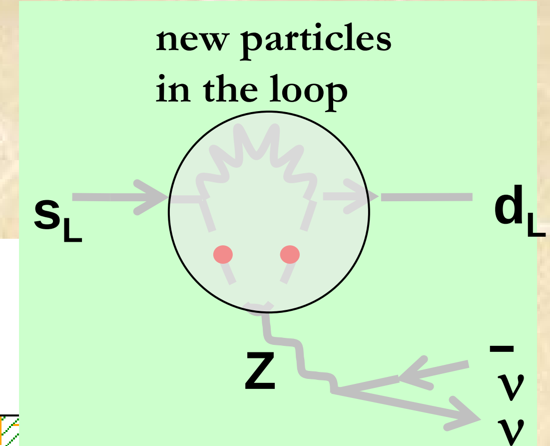


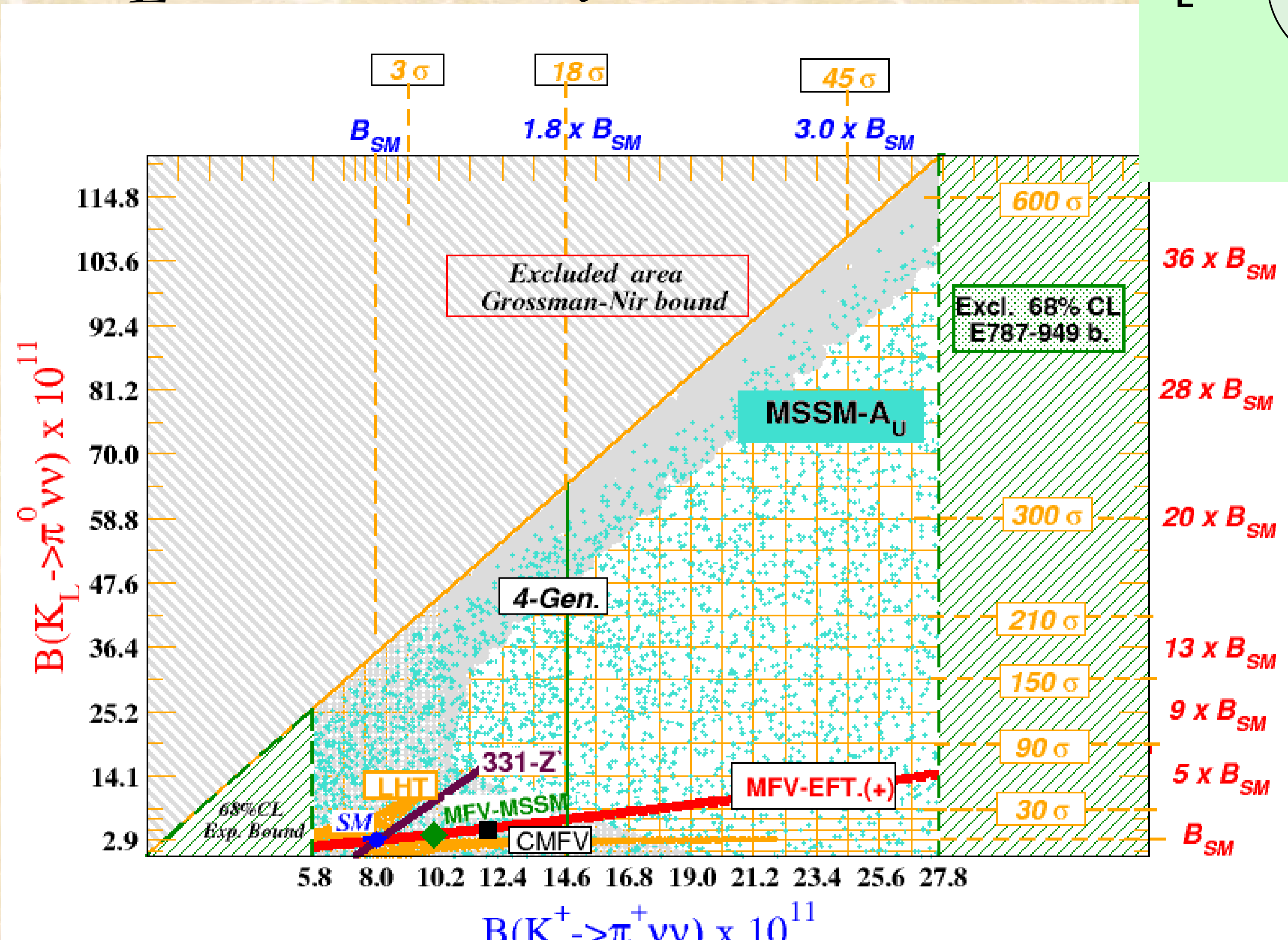

$$B(K_L \to \pi^0 \nu\nu) = \kappa_L \left( \frac{\mathrm{Im}(V_{ts}^* V_{td})}{\lambda^5} X_t \right)^2$$
$$= (2.43^{+0.40}_{-0.37} \pm 0.06) \times 10^{-11}$$

1st error: input parameter (Vcb:54%, $\eta$:39%, $m_t$:6%)
2nd error: remaining theoretical uncertainty (Xt(QCD):73%, $\kappa_L$:18%, …)



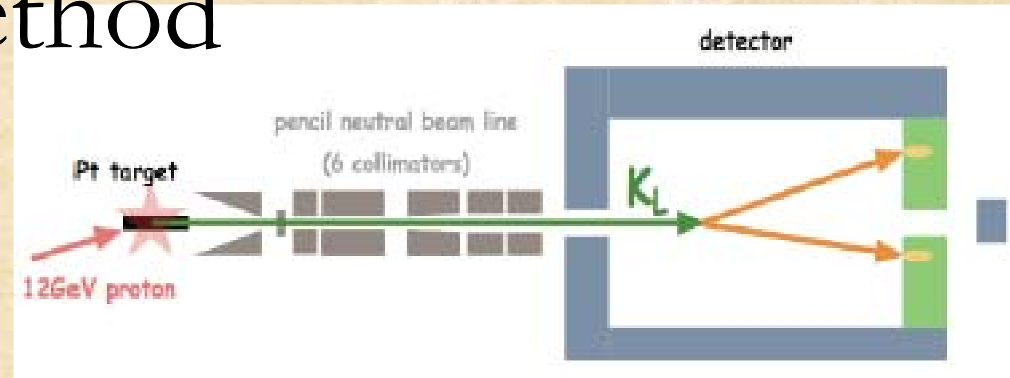
# $K_L \rightarrow \pi^0 \nu\nu$ beyond the SM



# Experimental method

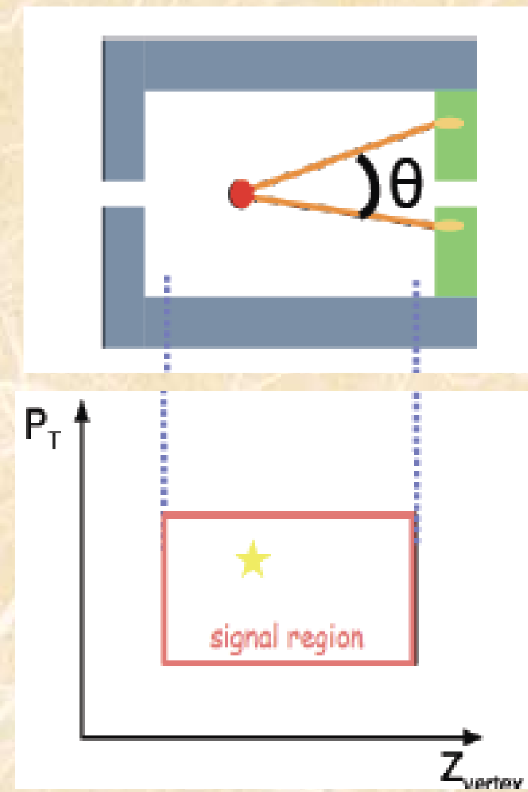
1. Detect two photons
   (CsI calorimeter)
   and nothing else
   (hermetic veto)




2. Reconstruct vertex
   using $\pi^0$ mass,
   assuming vertex on Z-axis

| narrow $K_L$ beam is a key → "pencil neutral beam" |
|---|

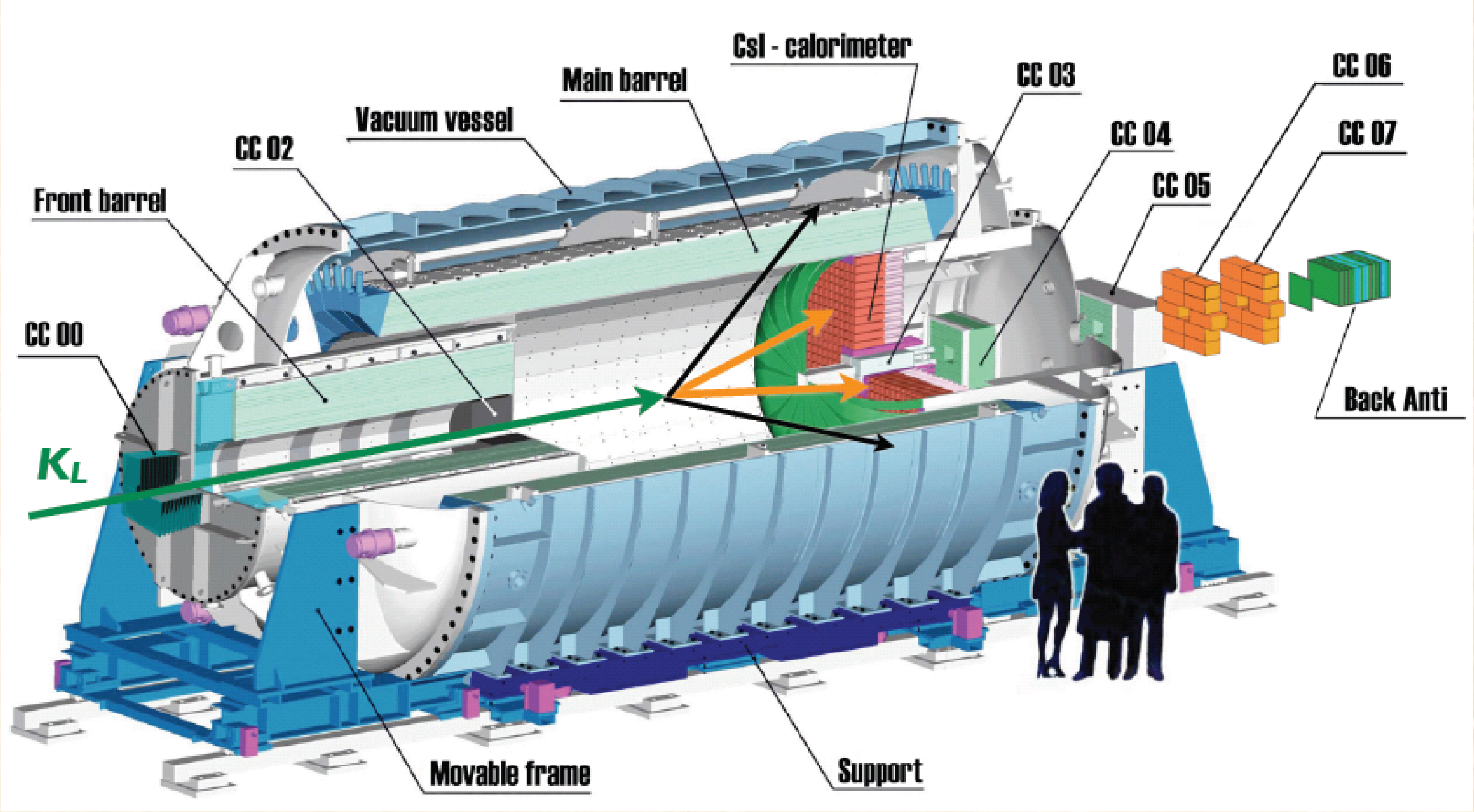
3. Calculate $\pi^0$ $P_T$




Our final plot

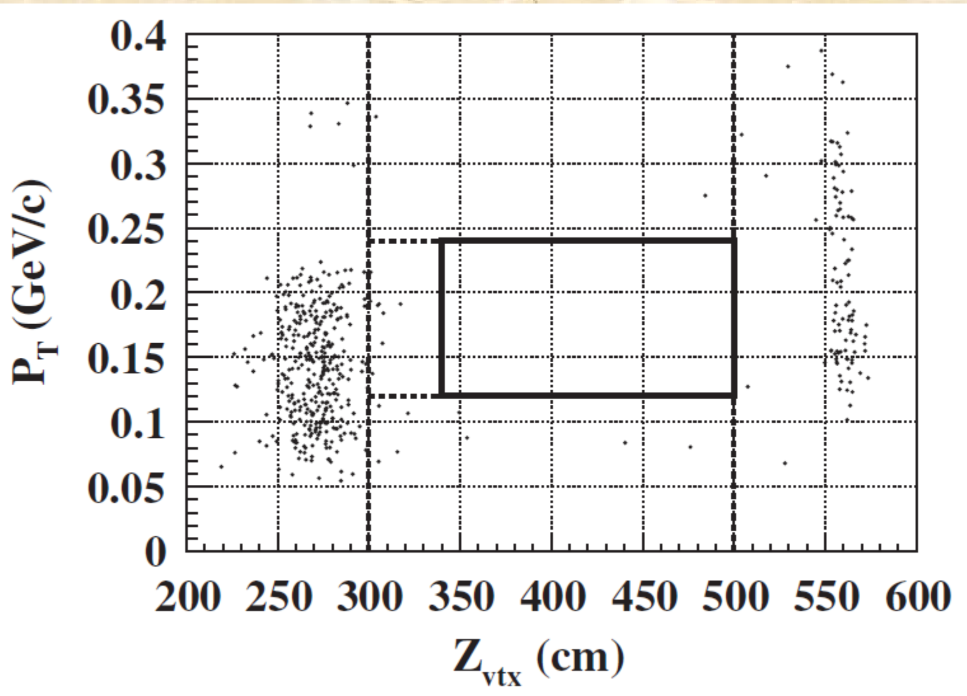
# KOTO Detector:
## partially improve predecessor's apparatus

**Predecessor: KEK-E391a**



# Lesson from previous experiment

KEK E391a final result:
Br<$2.6\times10^{-8}$ (90% CL)



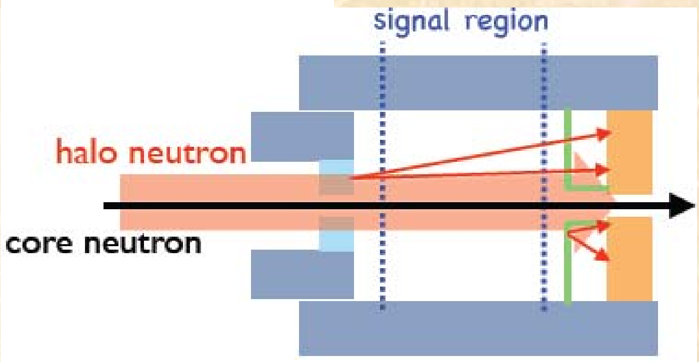

PRD81, 072004 (2010)

Knowledge about BG

# of BG estimated was 0.87

- Kaon BG
  - $K_L \rightarrow 2\pi^0$, with $2\gamma$ escaping detection
- Halo neutron BG
  - Interact with detectors placed near the beam and produce $\pi^0$, $\eta$ + mis-measure vertex

Dominant in KEK E391a

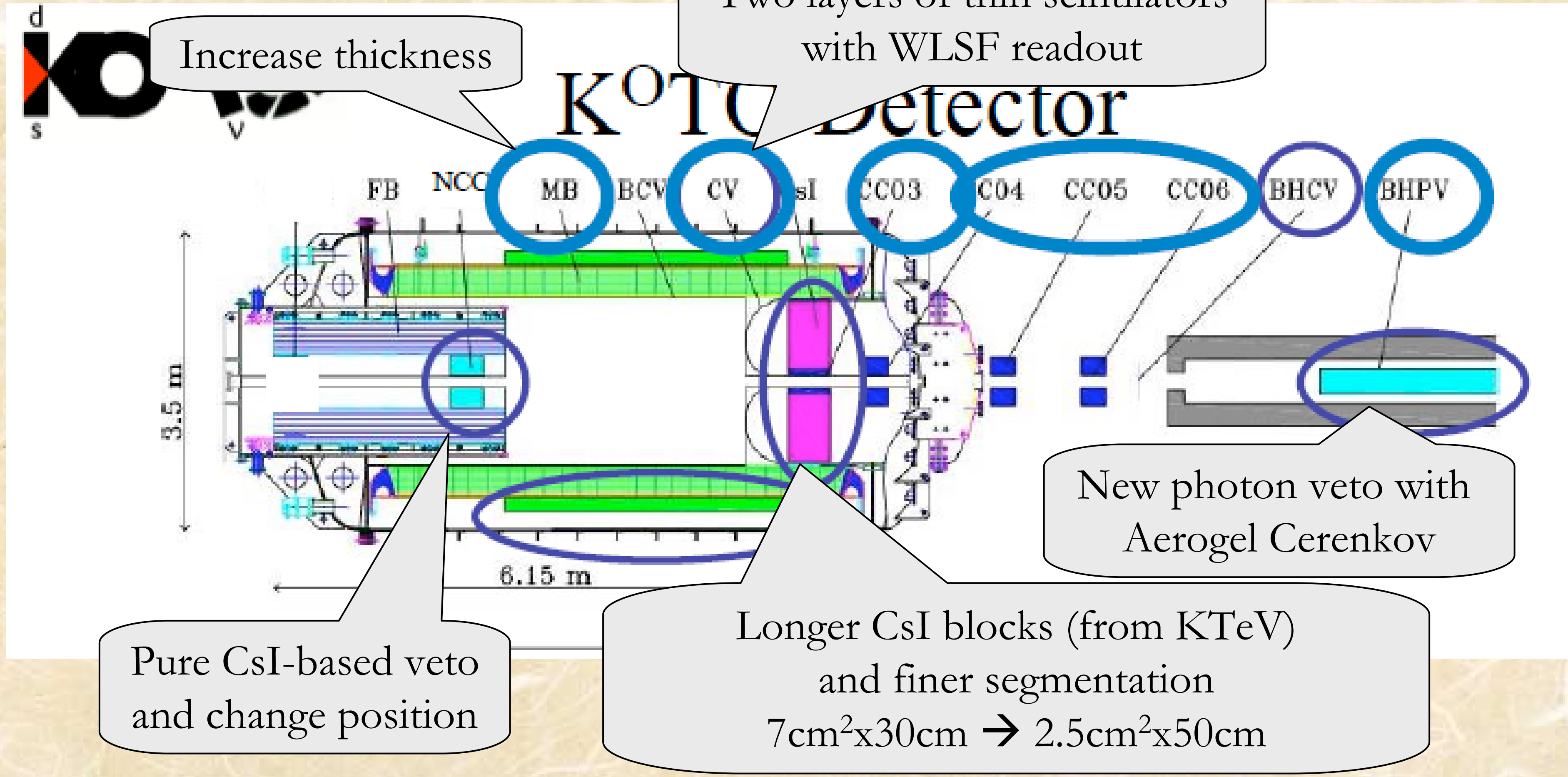


## Beamline improvement:

16 degree production → better K/n ratio

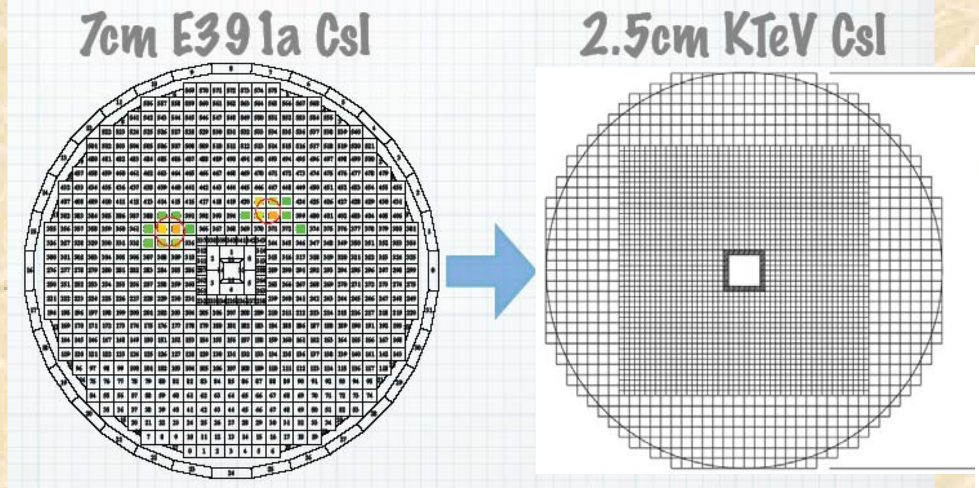
Newly constructed beamline → better halo/core ratio

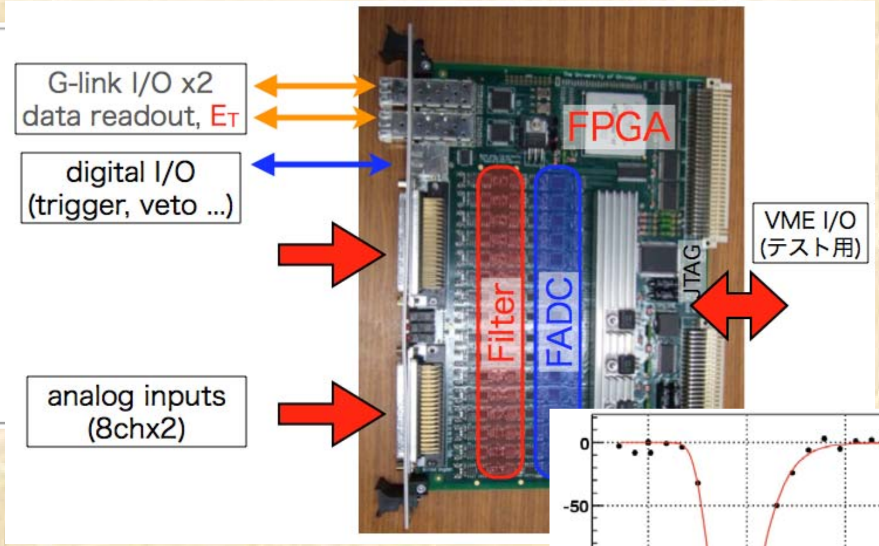
## Detector improvement:

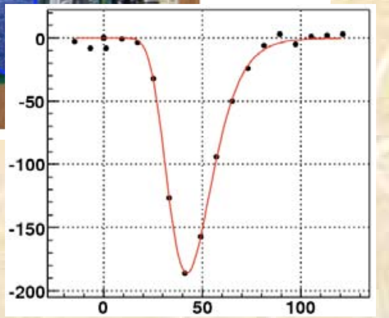


# Highlight: calorimeter upgrade

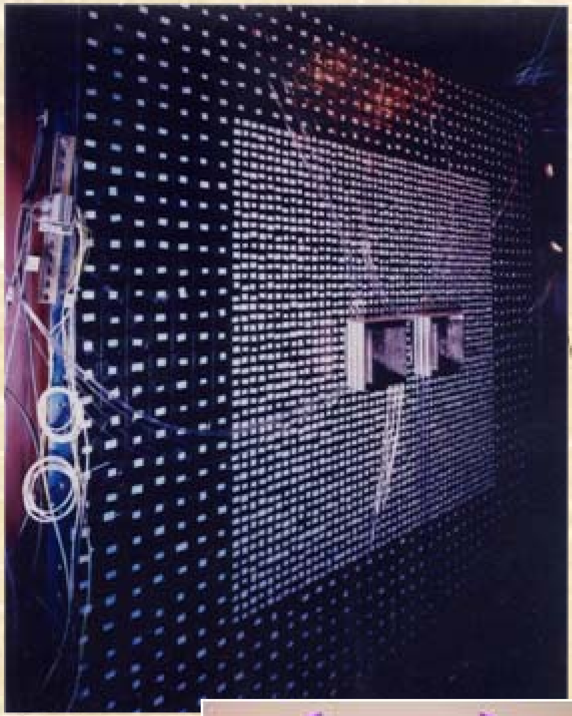
- Longer CsI crystals (30cm → 50cm)
  → more radiation length, reduce shower leakage
- Better segmentation (7cmsq → 2.5cmsq)
- Record waveforms of all crystals by 14bit 125MHz FADC



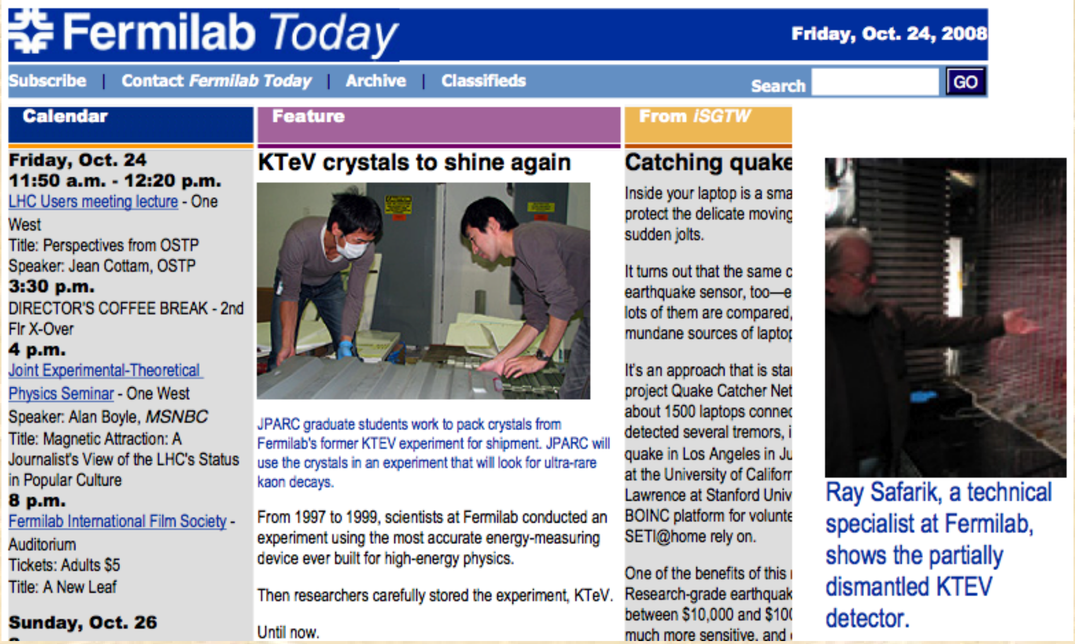



# KTeV CsI calorimeter




dismantled



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**

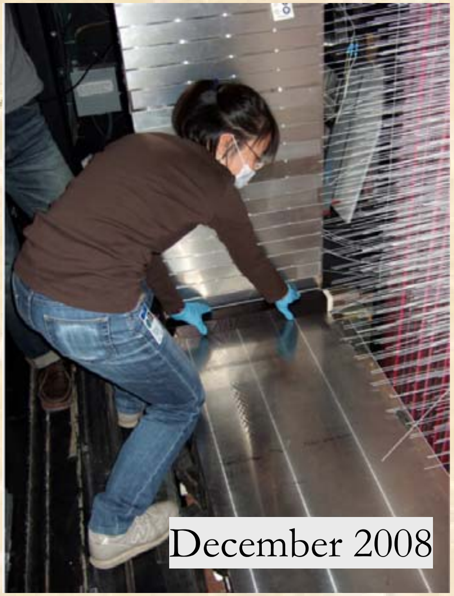
Inside your laptop is a sma protect the delicate moving sudden jolts.

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

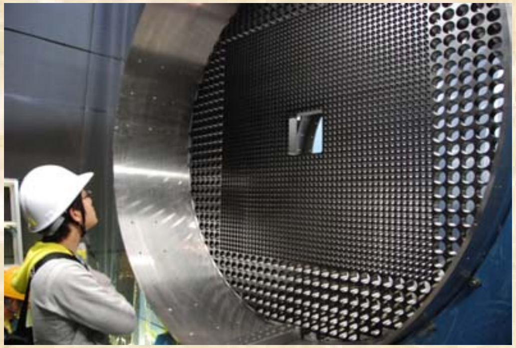
It's an approach that is star project Quake Catcher Net about 1500 laptops connec detected several tremors, i quake in Los Angeles in Ju at the University of Califorr Lawrence at Stanford Univ BOINC platform for volunte SETI@home rely on.

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.

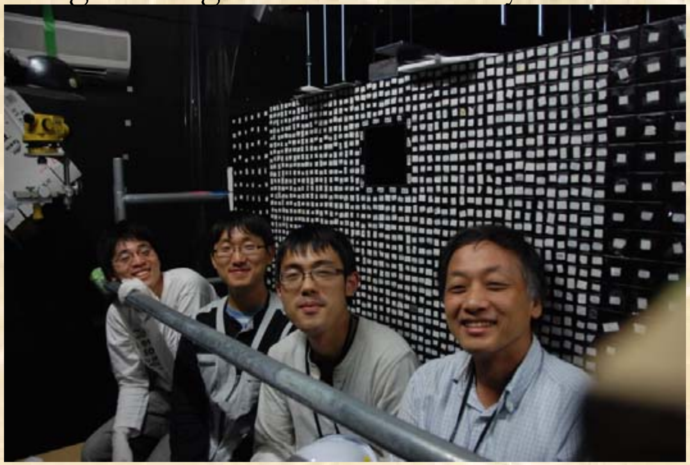

December 2008

May 2010



July 2010

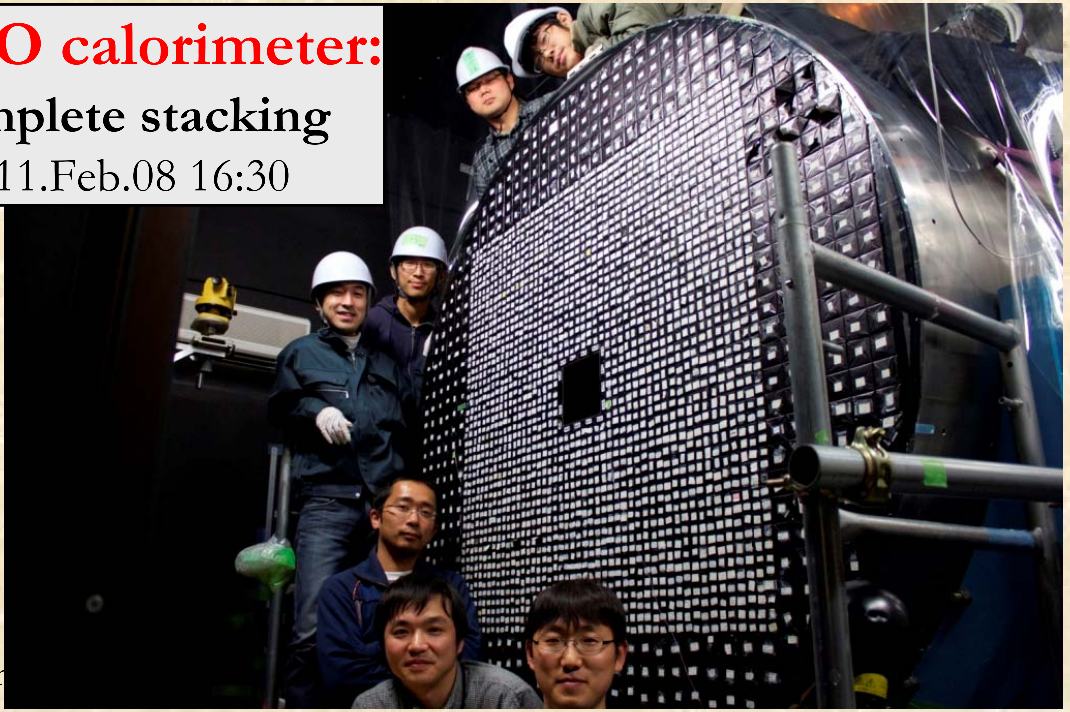
October 2010:
engineering run with 1774 crystals



**KOTO calorimeter:**

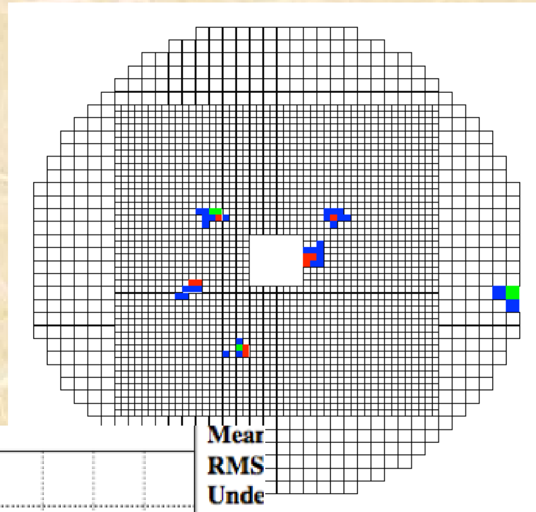
**Complete stacking**

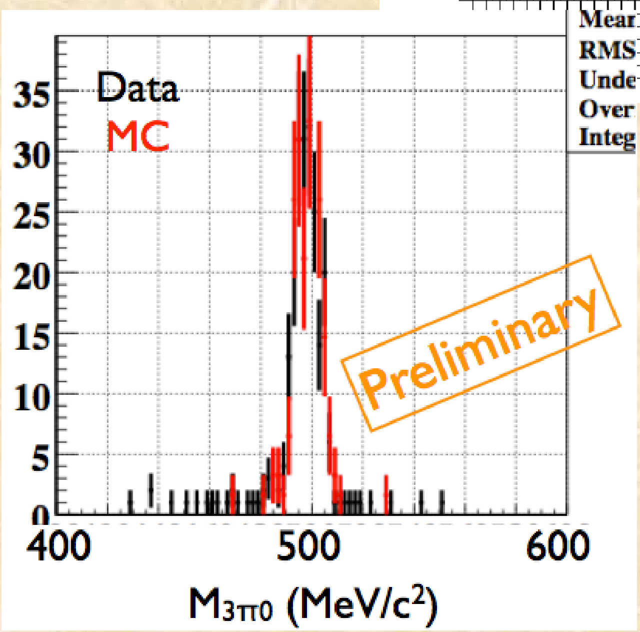
2011.Feb.08 16:30



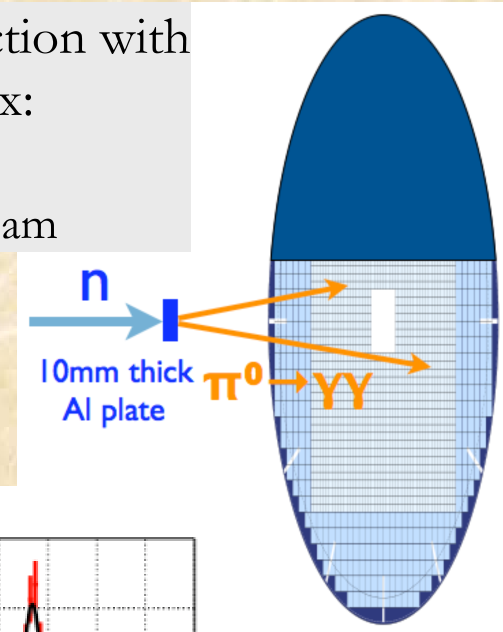
# Results from calorimeter engineering (Oct-Nov, 2010)

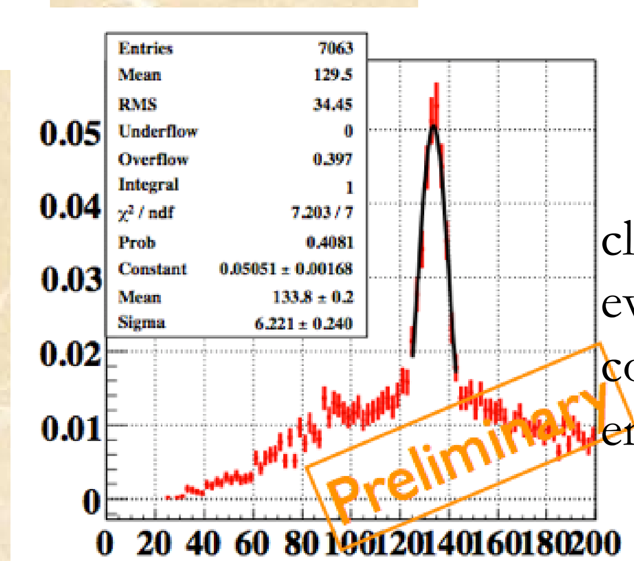
Event display of $K_L \rightarrow \pi^0\pi^0\pi^0$:
6 $\gamma$ clusters on calorimeter






$\pi^0$ reconstruction with know vertex:
Al thin target put inside beam




clear $\pi^0$ peak even with cosmic-ray based energy calibration

# KOTO Sensitivity and timeline

Note: As is considered before the earthquake. Will be updated.

- Goal: ~3 SM events / 3 years
  with S/N ratio ~ 2

  *** assuming design MR power ~270kW

COMPLETED
- 2009 Beamline survey

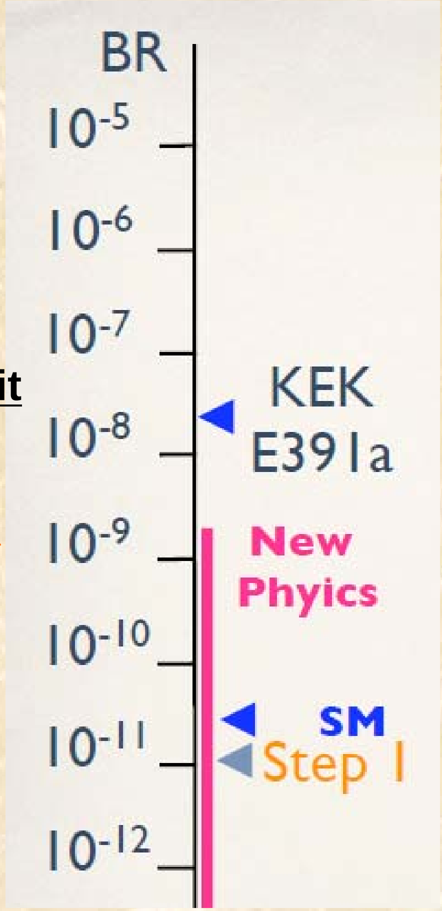
PARTIALLLY
- 2010 Calorimeter engineering
- 2011 Full engineering and
  Start physics run

  ➔ *1st milestone:*
  ***Grossman-Nir limit** by summer 2012*

~1YEAR DELAY ?
UNDER DISCUSSION

- Next step depends on scenario
  of accelerator's power upgrade.

**G-N limit**
30kW x
1month



# TREK:

T violation in $K^+ \rightarrow \pi^0 \mu^+ \nu$

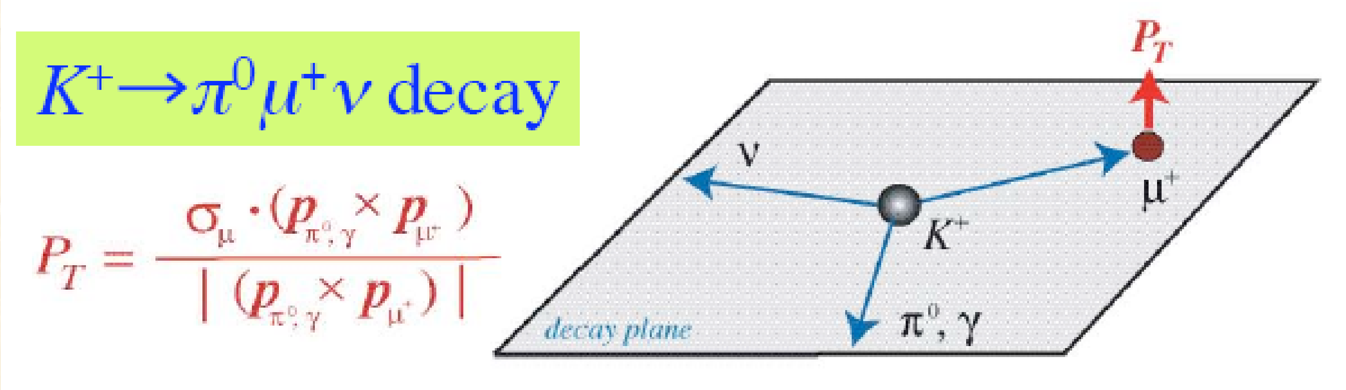
and "pre-TREK":

Measurement of $R_K = \Gamma(K^+ \rightarrow e^+ \nu) / \Gamma(K^+ \rightarrow \mu^+ \nu)$

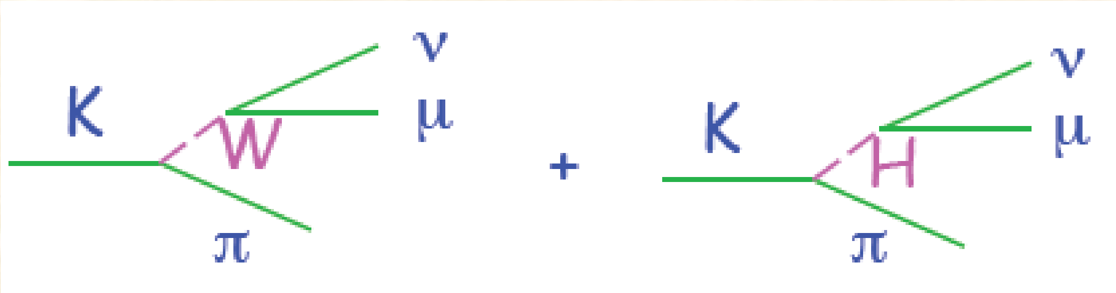
- Stage 1 (scientific) approval
- Beamline (not specific for TREK but versatile) partially constructed

# T violation: Measurement of muon polarization in $K^+ \rightarrow \pi^0 \mu^+ \nu$

- $P_T$ ; represented by T-violating triple product




- O($10^{-4}$) $P_T$ indicates contribution from BSM
  - SM~$10^{-7}$
  - FSI~$10^{-5}$

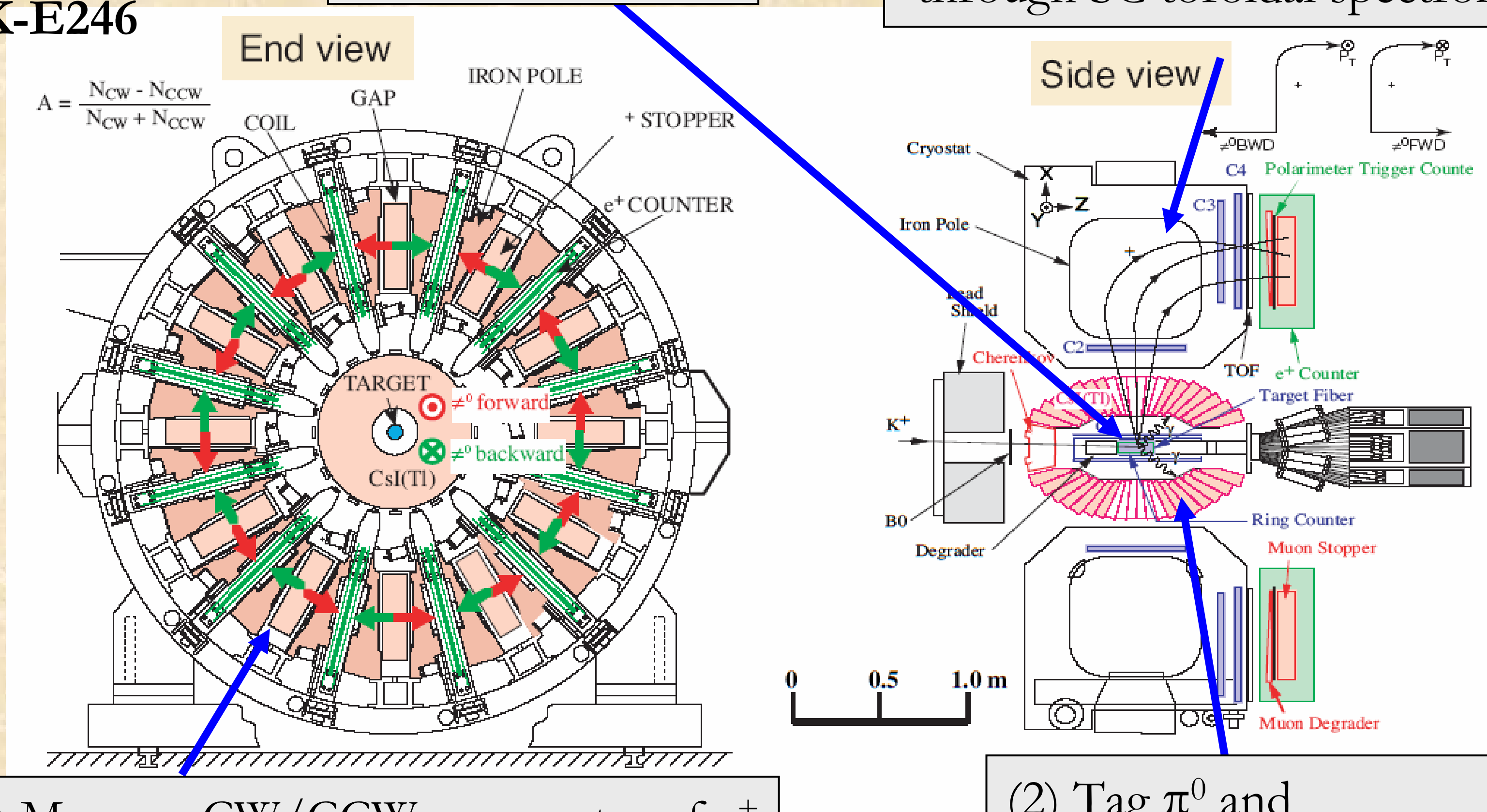


# TREK apparatus

**Predecessor:**
**KEK-E246**

(1) Use stopped $K^+$

(3) $\mu^+$ to polarimeter through SC toroidal spectrometer




(4) Measure CW/CCW asymmetry of $e^+$ in azimuthally symmetrical detector

(2) Tag $\pi^0$ and define direction (FWD/BWD)

# TREK goal and strategy

- Measure $P_T$ with $\delta P_T(\mathrm{stat}) \sim 10^{-4}$, $\delta P_T(\mathrm{syst}) \sim 10^{-4}$

  Current value: $(-1.7 \pm 2.3 \pm 1.1) \times 10^{-3}$ $\delta P_T \sim O(10^{-3})$

  - *$1 \times 10^7$ sec (~1year) running with 270kW beam*

- As "pre-TREK",

  $$R_K \equiv \frac{\Gamma(K^+ \to e^+ \nu)}{\Gamma(K^+ \to \mu^+ \nu)}$$ measurement are proposed

  - $\Delta R_K/R_K(\mathrm{stat}) = 0.2\%$
    - *50days run with 30kW power*
  - $\Delta R_K/R_K(\mathrm{syst}) = 0.1\%$

CERN NA62 value:
$(2.487 \pm 0.011 \pm 0.007) \times 10^{-5}$
$\delta R_K/R_K \sim 0.5\%$

**Phys.Lett.B698(2011)105**
and G. Ruggiero's talk

TREK: Stopped $K^+$ ←→ NA62: decay in flight

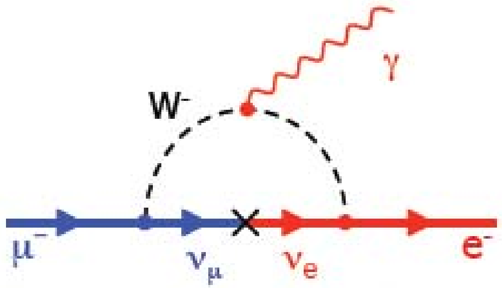
# μ-e conversion

- COMET: μ-e conversion $O(10^{-16})$
  - Stage 1 (scientific) approval

# Physics motivation

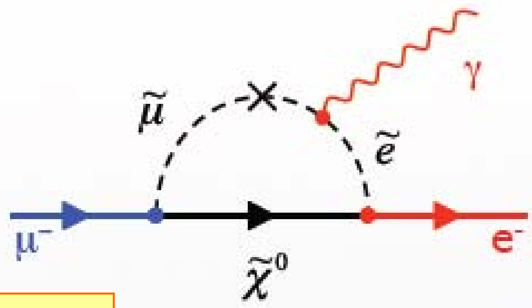
Exploring (and understanding) a new world...

LFV in charged sector strongly suppressed in SM with neutrino oscillations: i.e. BR($\mu \rightarrow e\gamma$)<$10^{-52}$.




SM: $B(\mu^- + N \rightarrow e^- + N) < 10^{-54}$

Same decay enhanced in new physics scenarios via new particles interactions: expected BR($\mu \rightarrow e\gamma$)~$10^{-12} \div 10^{-14}$ depending on NP parameters.




slepton mixing

**NP**: $B(\mu^- + N \rightarrow e^- + N) \sim 10^{-14} - 10^{-16}$

No contamination from Standard Model processes

A powerful probe for NP!

Current limit: $(\mu^- + Au \rightarrow e^- + Au) < 7\times10^{-13}$ by SINDRUM II

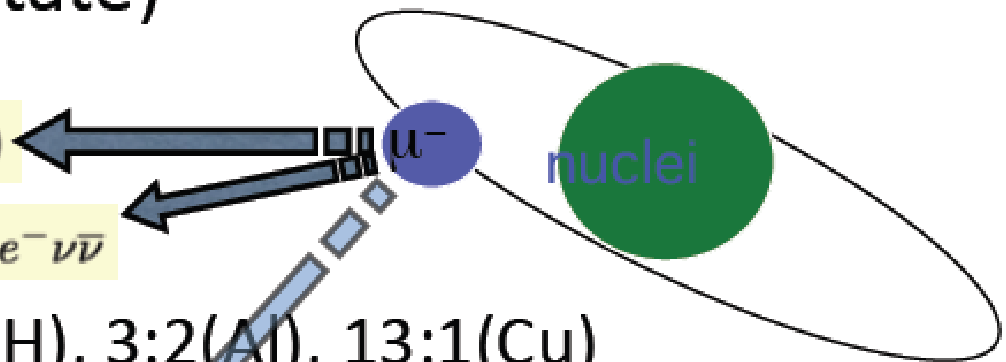
Slide from MEG's talk yesterday

# μ-e conversion

- Muonic Atom (1S state)

Muon Capture(MC)

$\mu^- + (A,Z) \to \nu_\mu + (A,Z-1)$




Muon Decay in Orbit (MDO) $\mu^- \to e^- \nu \bar{\nu}$

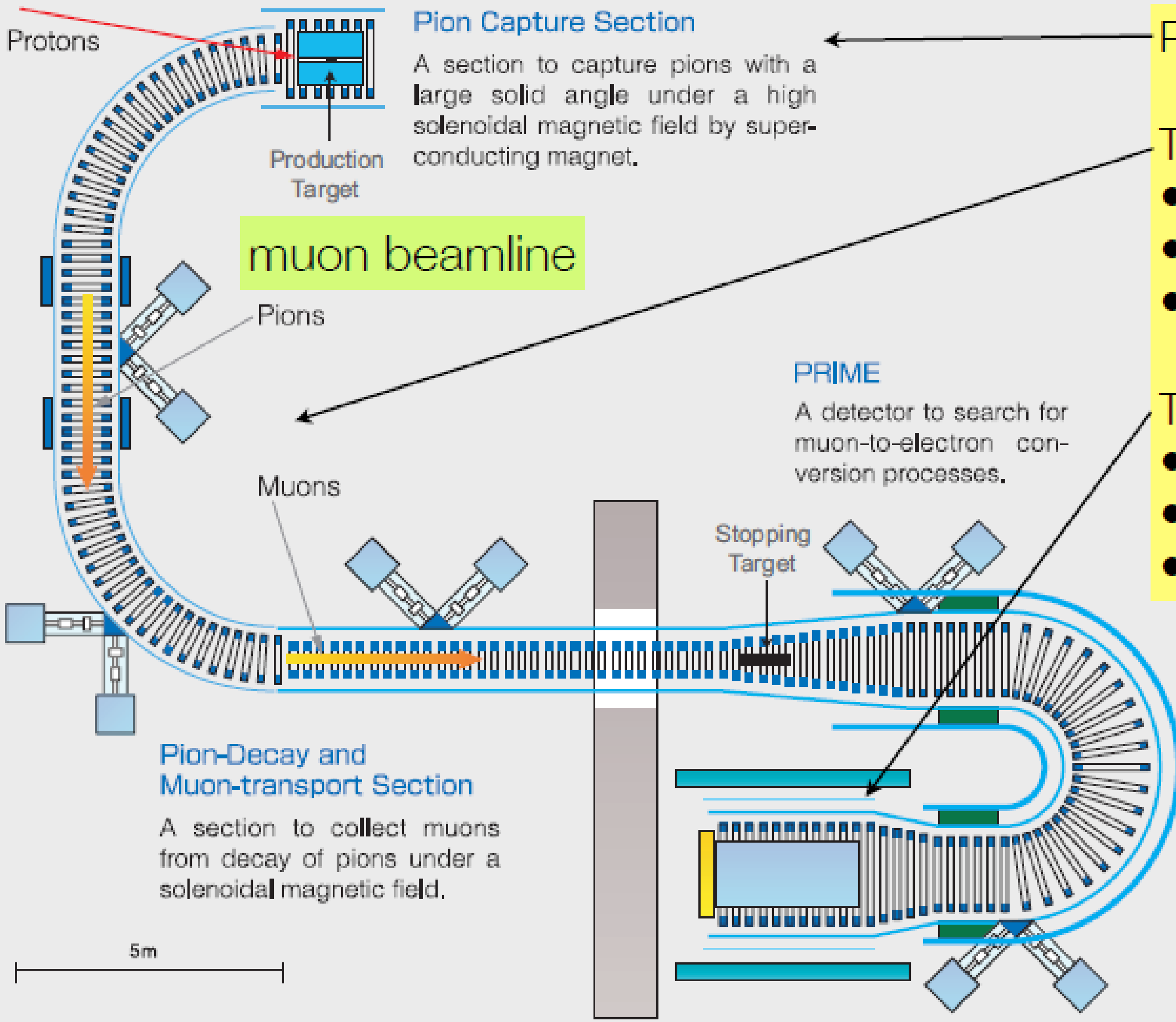
  - MC:MDO = 1:1000(H), 3:2(Al), 13:1(Cu)
  - τ(free μ-) = 2.2 μs
  - $\tau(\mu^-;Al)$ = 0.88 μs

- μ-e Conversion

$\mu^- + (A,Z) \to e^- + (A,Z)$ charged Lepton Flavor Violation (CLFV)

Signal: $e^-$ with $E_e \sim m_\mu$

# Layout of COMET




Proton Beam

The Muon Source
- Proton Target
- Pion Capture
- Muon Transport

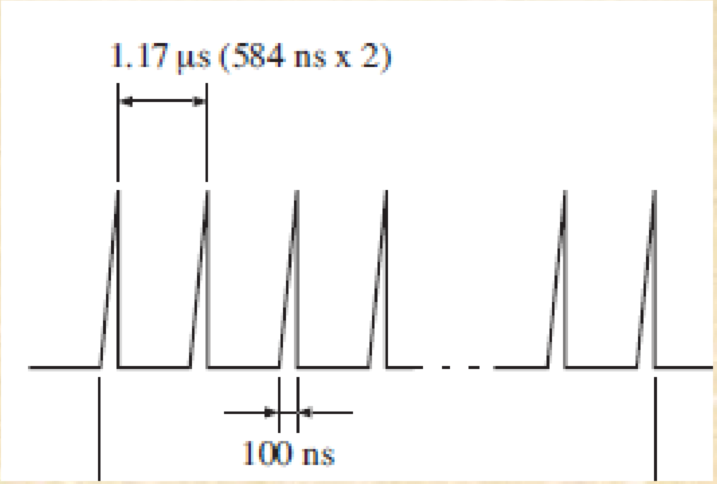
The Detector
- Muon Stopping Target
- Electron Transport
- Electron Detection

detector

# COMETsensitivity

- **$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}$**
  - $10^{11}$ muons/sec with
    - Pulsed slow extraction beam from MR
      (8GeV operation, beam power ~50kW)
    - Pion capture system surrounding the target to gain $\mu^-$ yield
  - $2\text{x}10^7$ sec running period
    - *Roughly, 4 years for construction, 1year for engineering, and 2 years for run (2017~?)*

# COMET: status
# "proof of principle"



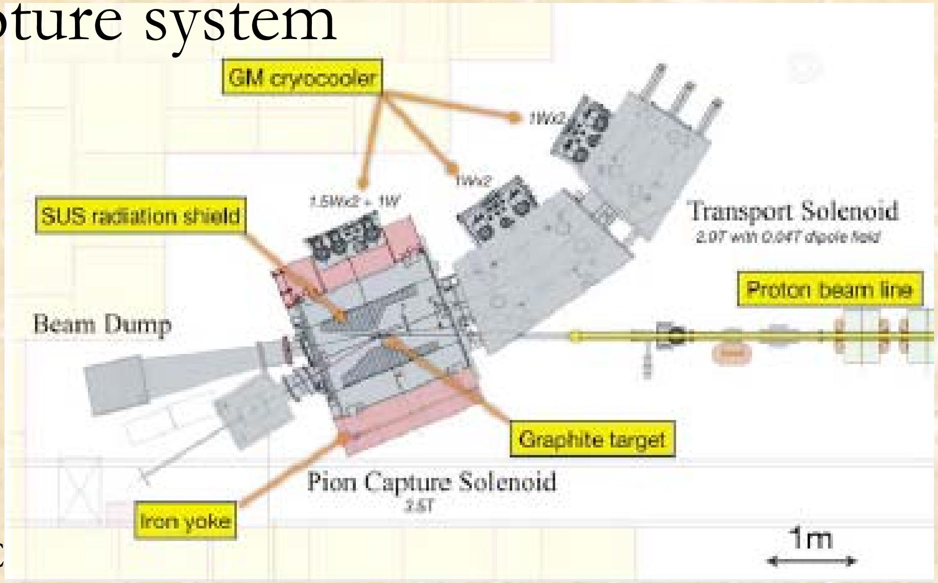

Bunched slow extraction

- Proton beam extinction
  - $10^{-9}$ required for $O(10^{-16})$ sensitivity

➔ *$10^{-7}$ in J-PARC MR confirmed.*
*Ideas to additional $10^{-6}$ improvement are there.*

- Demonstration of pion capture system at RCNP/Osaka U.

- Radiation hardness test of SC solenoid material



# Summary

- J-PARC; one of the best facilities for flavor physics
  - *Intensity frontier for fixed target, "dedicated" experiments*
- Comprehensive programs

  *T2K, long baseline ν osc. continues. And…*

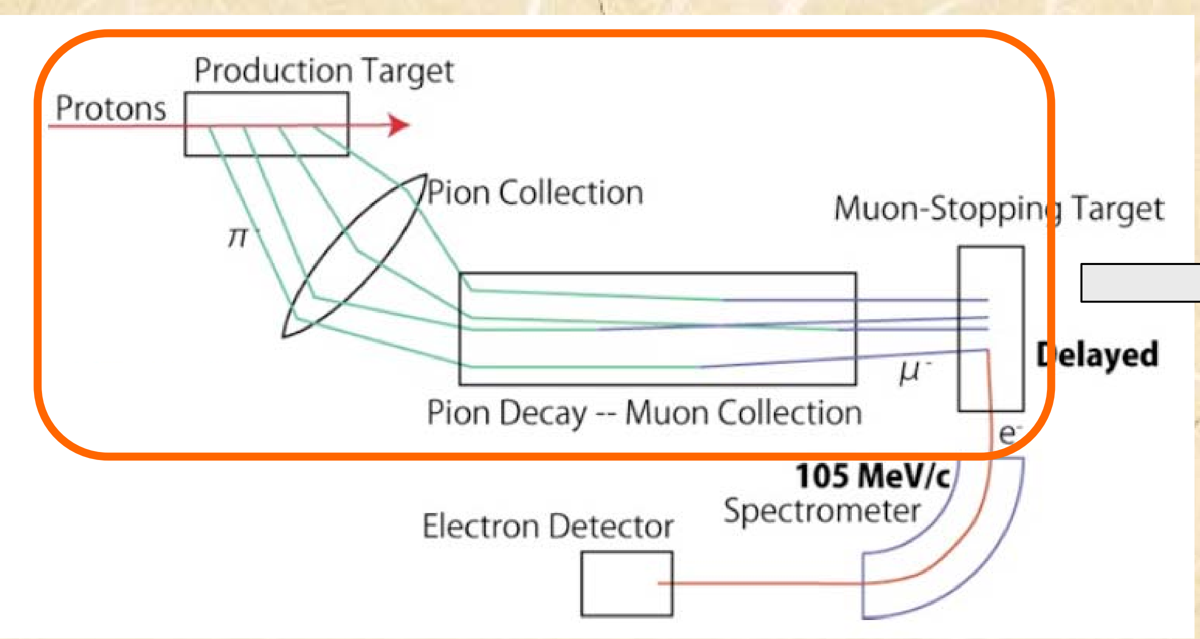
  - $K_L \rightarrow \pi^0 \nu\nu$ *experiment (KOTO) in preparation*
  - *T violation search in* $K^+ \rightarrow \pi^0 \mu^+ \nu$ *(TREK) under R&D*
  - *Two generation of μ-e conversion exp.(COMET, DeeMe), and other fundamental muon programs (g-2, EDM,…) are proposed*

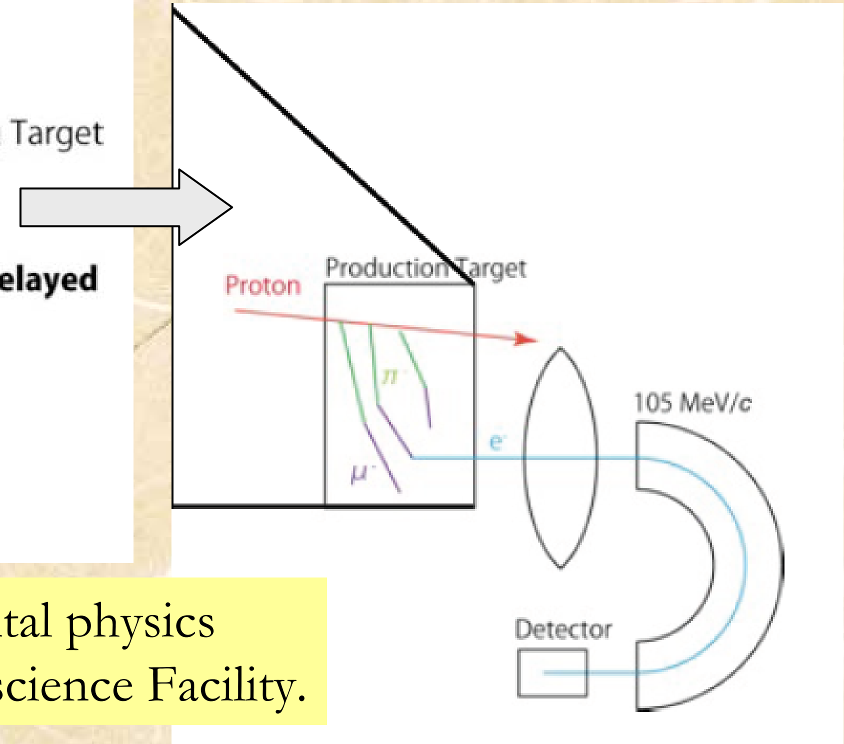
➔ making efforts to maximize physics outputs from J-PARC !!

# Extras

# DeeMe: yet another μ-e conversion

- "Detect 105MeV $e^-$ directly coming from target"
  ➔ compact configuration, less expensive




New multipurpose beamline for muon fundamental physics
is now under consideration in Materials & Life science Facility.

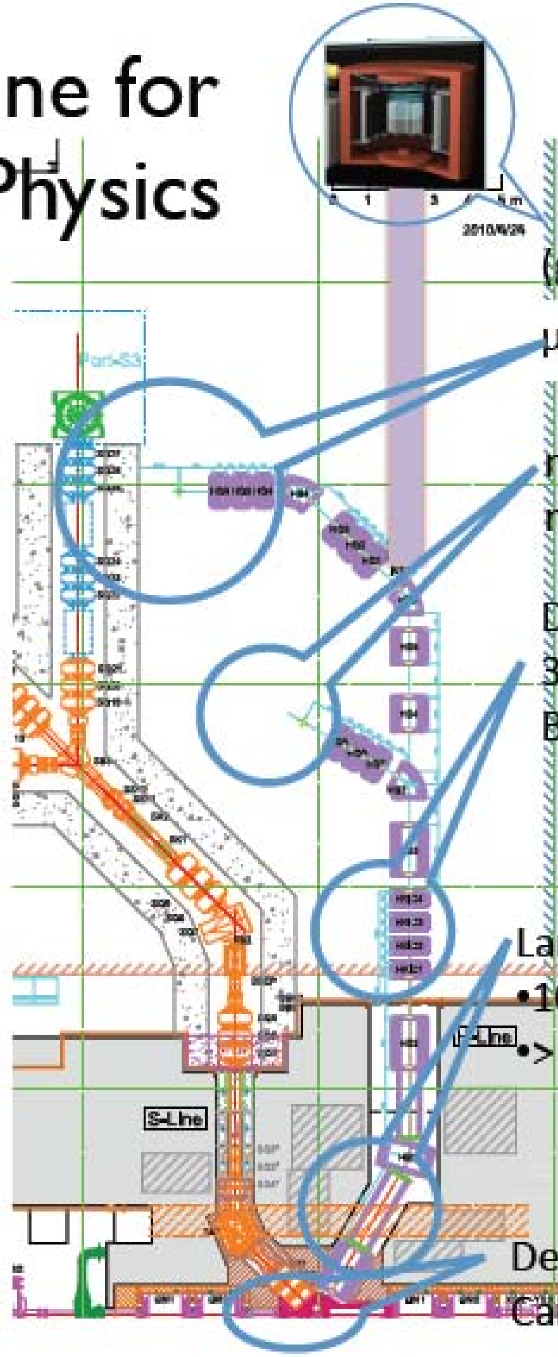
# DeeMe: sensitivity

- **<u>Sensitivity of B($\mu^-$+N → $e^-$+N)~$10^{-14}$</u>**
  - $1\text{x}10^{10}$ muonic atom formation/sec.
    - From 3GeV RCS, power ~1MW, *SiC* target
  - $2\text{x}10^{7}$ sec running period *corresponding to 1~2 years run*

*** Backgrounds due to prompt $e^-$ from late-arriving protons are severe ← Need extinction ~$10^{-17}$

# Multipurpose Beamline for Muon Fundamental Physics

- Compact Muon Storage Ring
  - <u>$(g\text{-}2)_\mu$: < 0.1 ppm</u>
  - <u>$d_\mu$: aiming $<10^{-24}$ e.cm</u>
  - off the magic momentum
  - ultra cold muon beam
    - no E field
    - extremely uniform B field
  - Totally different systematic errors from the BNL experiment.
- <u>Light-weight μ-e Conversion exp.</u>
- muonium HFS
- muonium-antimuonium Conv.



# New idea on μ g-2, EDM measurement

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

<Basic idea>

If no E,

- No need to be "magic momentum" and muon storage can be compact
- $\omega = \omega_{g\text{-}2} + \omega_{EDM}$

To do so,

- beam divergence should be small

➔Ultra cold muon at MLF

GOAL:

- $a_\mu \sim 0.1$ppm
- EDM~$5\times10^{-22}$ e