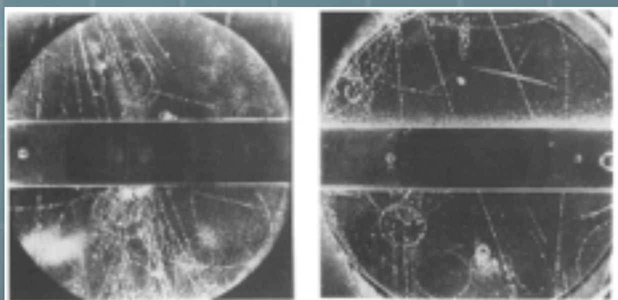
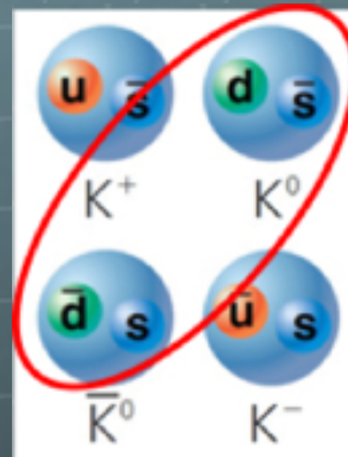
$K_L \rightarrow \pi^0 \nu\nu$ Experiment

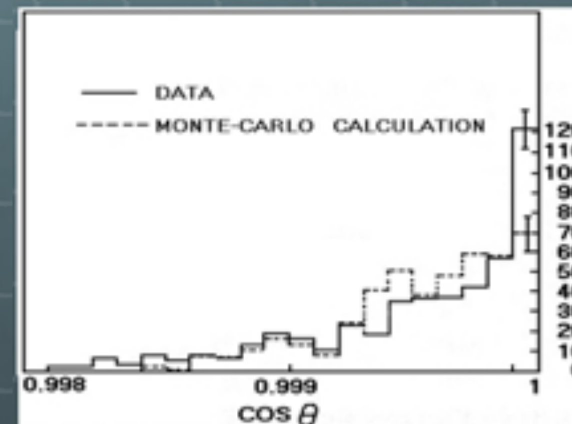
G.Y.Lim
IPNS/KEK

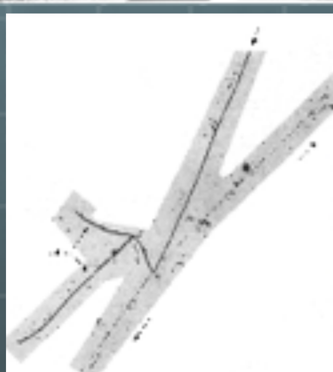
2015

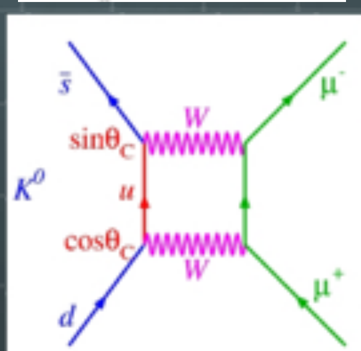
Studies on kaon decays - Cornerstone of the SM -

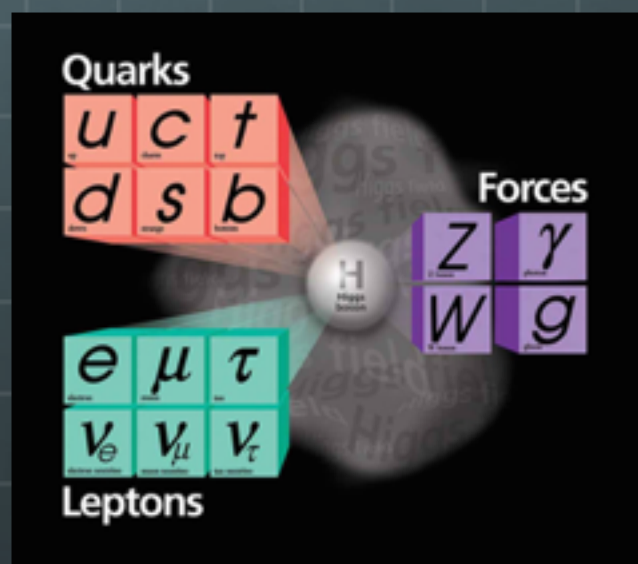


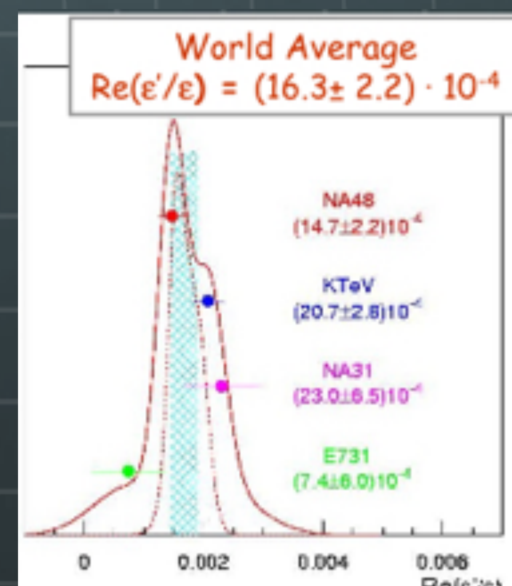












Search for new physics

- s-quark
  - Flavor structure
- ~ 500 MeV/c^2, ~10m in $c\tau$
  - High intensity secondary kaon beam
  - Stopped and in-flight decays of kaons
  - Small number of decay products

(parts of) K^0_L DECAY MODES

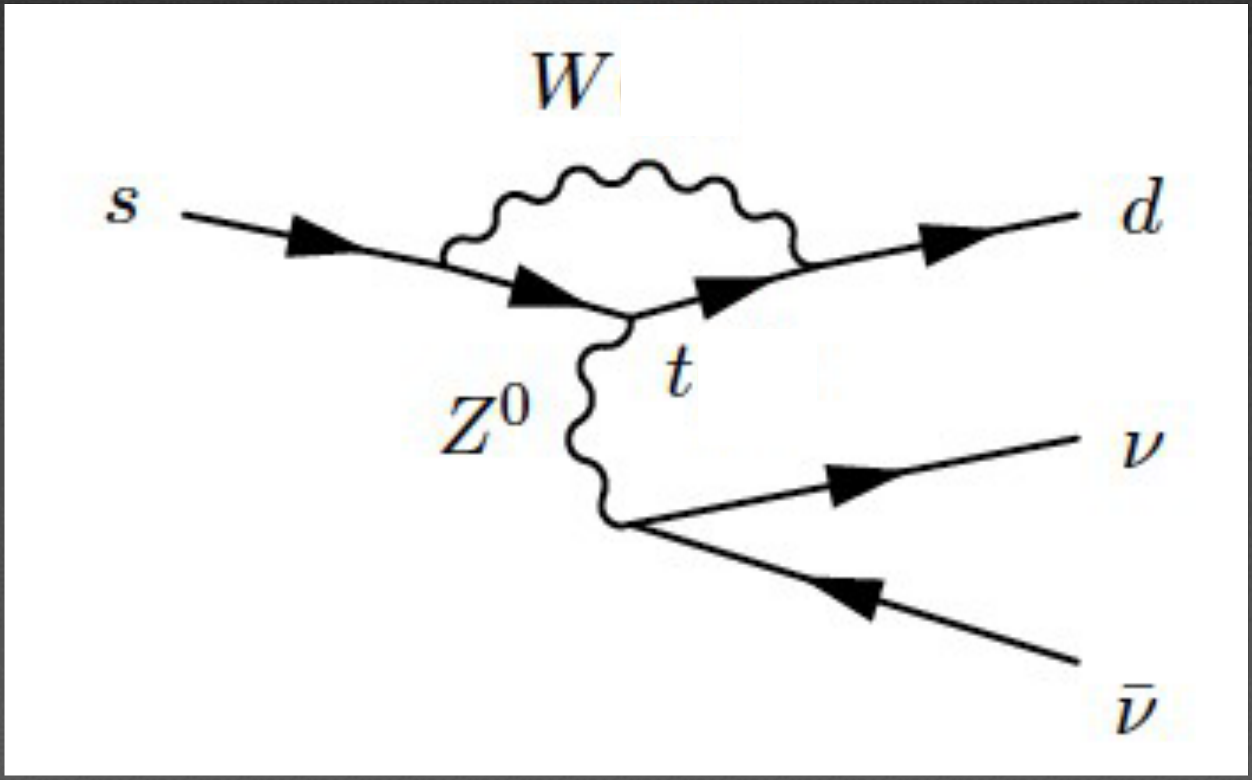
Charge conjugation × Parity (CP) or Lepton Family number (LF) violating modes, or $\Delta S = 1$ weak neutral current ($S1$) modes

$\mu^+\mu^-$	$S1$		$(6.84 \pm 0.11) \times 10^{-9}$
e^+e^-	$S1$		$(9\ ^{+6}_{-4}) \times 10^{-12}$
$\pi^+\pi^-e^+e^-$	$S1$	[r]	$(3.11 \pm 0.19) \times 10^{-7}$
$\pi^0\pi^0e^+e^-$	$S1$		$< 6.6 \times 10^{-9}$
$\pi^0\pi^0\mu^+\mu^-$	$S1$		$< 9.2 \times 10^{-11}$
$\mu^+\mu^-e^+e^-$	$S1$		$(2.69 \pm 0.27) \times 10^{-9}$
$e^+e^-e^+e^-$	$S1$		$(3.56 \pm 0.21) \times 10^{-8}$
$\pi^0\mu^+\mu^-$	$CP,S1$	[s]	$< 3.8 \times 10^{-10}$
$\pi^0e^+e^-$	$CP,S1$	[s]	$< 2.8 \times 10^{-10}$
$\pi^0\nu\overline{\nu}$	$CP,S1$	[t]	$< 2.6 \times 10^{-8}$
$\pi^0\pi^0\nu\overline{\nu}$	$S1$		$< 8.1 \times 10^{-7}$
$e^\pm\mu^\mp$	LF	[o]	$< 4.7 \times 10^{-12}$
$e^\pm e^\pm\mu^\mp\mu^\mp$	LF	[o]	$< 4.12 \times 10^{-11}$
$\pi^0\mu^\pm e^\mp$	LF	[o]	$< 7.6 \times 10^{-11}$
$\pi^0\pi^0\mu^\pm e^\mp$	LF		$< 1.7 \times 10^{-10}$

http://pdg.lbl.gov/2015/tables/rpp2015-tab-mesons-strange.pdf

Rare precess : $\Delta t \cdot \Delta E \sim \hbar$

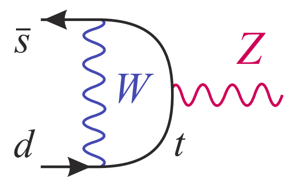
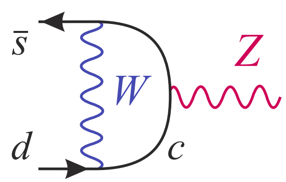
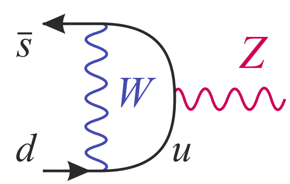
$K_L \rightarrow \pi^0 \nu\bar{\nu}$ & $K^+ \rightarrow \pi^+ \nu\bar{\nu}$



Flavor Changing Neutral Current

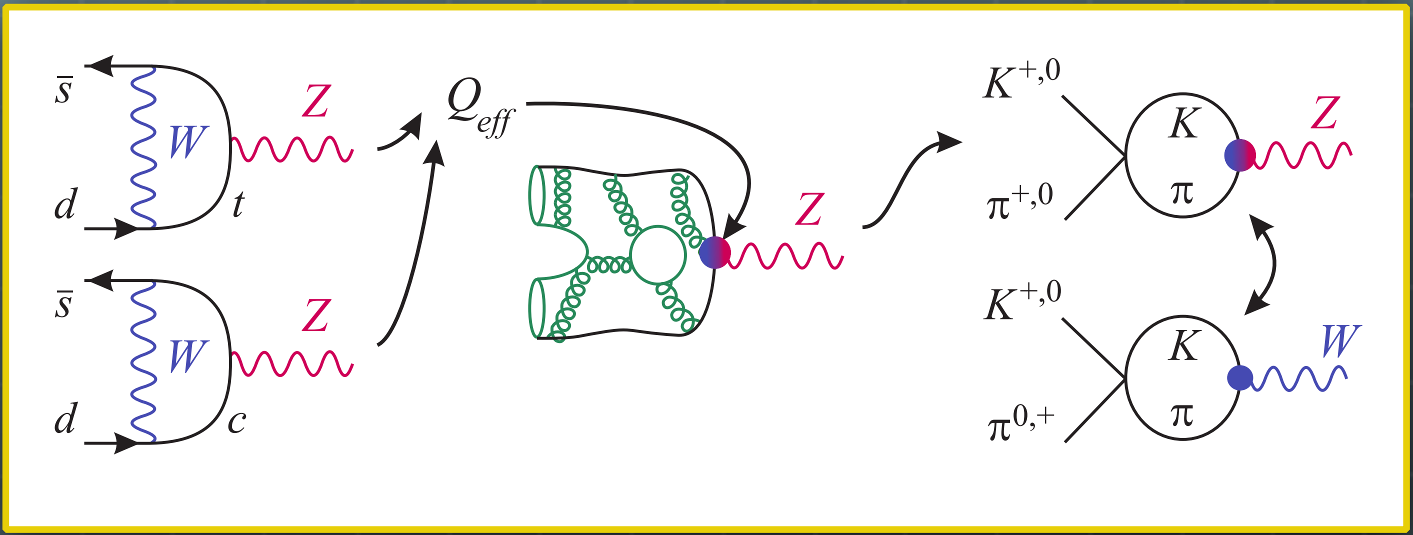
Highly suppressed process (in SM)

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

	$K_1 \to \pi^0 \nu\bar{\nu}$	$K_2 \to \pi^0 \nu\bar{\nu}$
	$\frac{m_t^2}{M_W^2}(\mathrm{Re}\, V_{ts}^\dagger V_{td} \sim \lambda^5)$	$\frac{m_t^2}{M_W^2}(\mathrm{Im}\, V_{ts}^\dagger V_{td} \sim \lambda^5)$
	$\frac{m_c^2}{M_W^2}(\mathrm{Re}\, V_{cs}^\dagger V_{cd} \sim \lambda)$	$\frac{m_c^2}{M_W^2}(\mathrm{Im}\, V_{cs}^\dagger V_{cd} \sim \lambda^5)$
	$\frac{m_u^2}{M_W^2}(\mathrm{Re}\, V_{us}^\dagger V_{ud} \sim \lambda)$	$\frac{m_u^2}{M_W^2}(\mathrm{Im}\, V_{us}^\dagger V_{ud} = 0)$

C. Smith, arXiv:1409.6162

Hadronic matrix elements



$K \rightarrow \pi\nu\nu$

$K \rightarrow \pi l \nu$

C. Smith, arXiv:1409.6162

The cleanest mode in theory

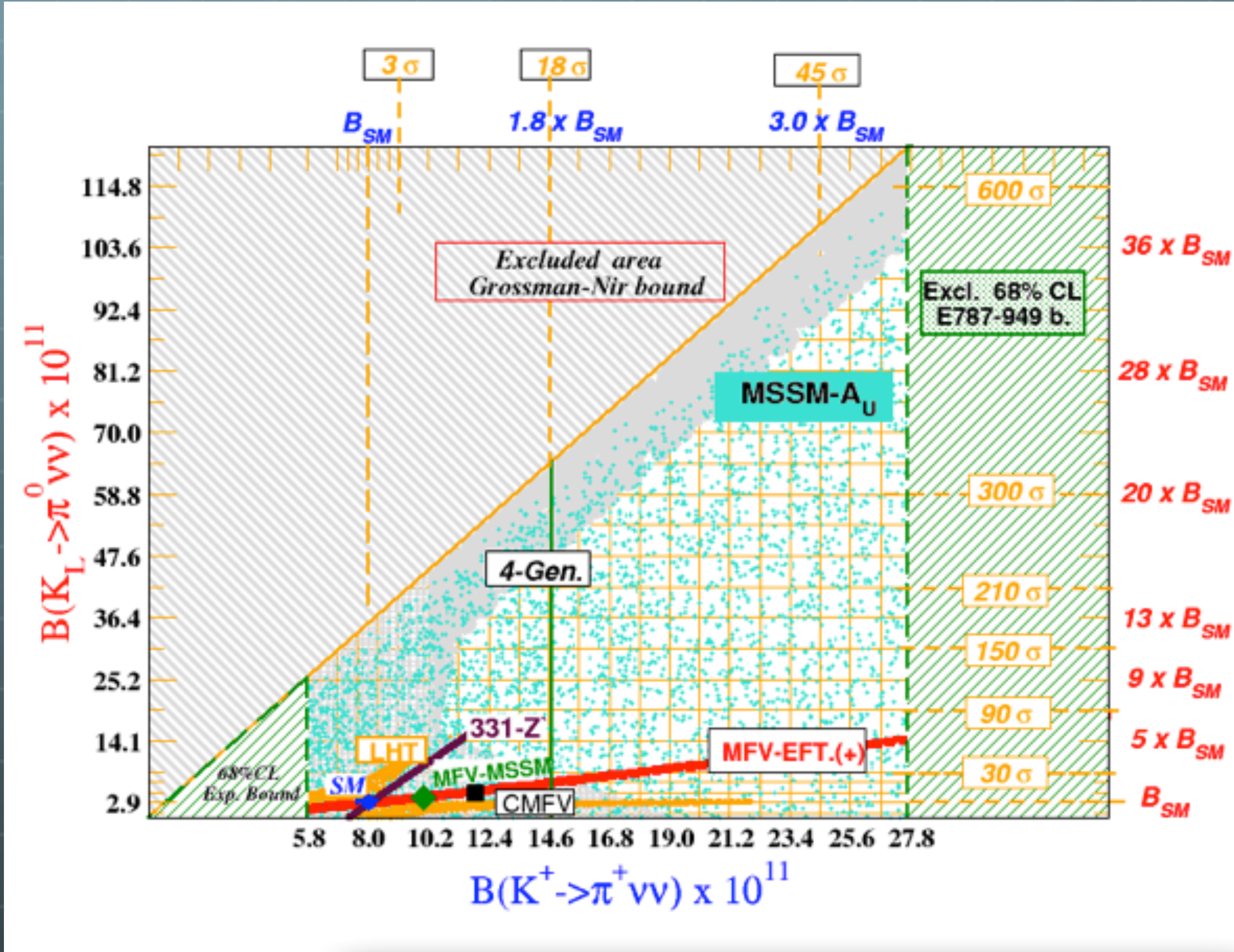
$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ (1 + \Delta_{\rm EM}) \cdot \left[\left(\frac{{\rm Im}\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{{\rm Re}\lambda_c}{\lambda} P_c(X) + \frac{{\rm Re}\lambda_t}{\lambda^5} X(x_t) \right)^2 \right]$$

$$\longrightarrow (9.11 \pm 0.72) \times 10^{-11}$$

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \cdot \left(\frac{{\rm Im}\lambda_t}{\lambda^5} X(x_t) \right)^2$$

$$\longrightarrow (3.00 \pm 0.31) \times 10^{-11}$$

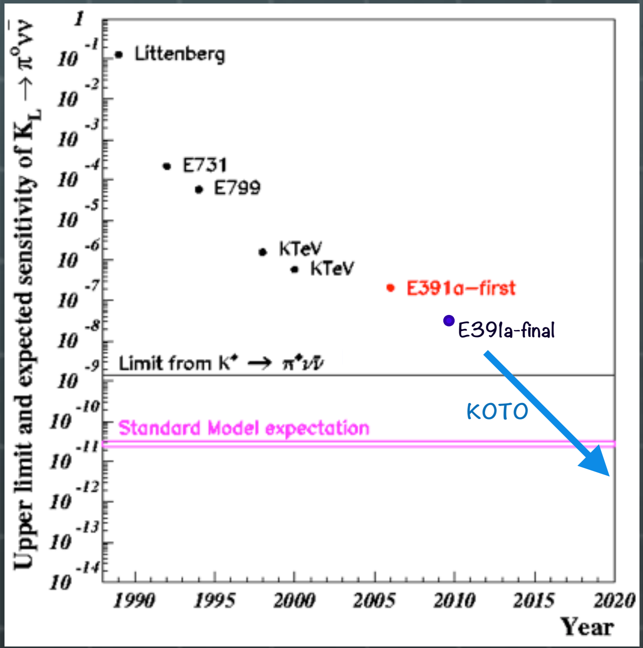
A. Buras, arXiv:1503.02693



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

Signal of the $K_L \to \pi^0 \nu\bar{\nu}$ Decay

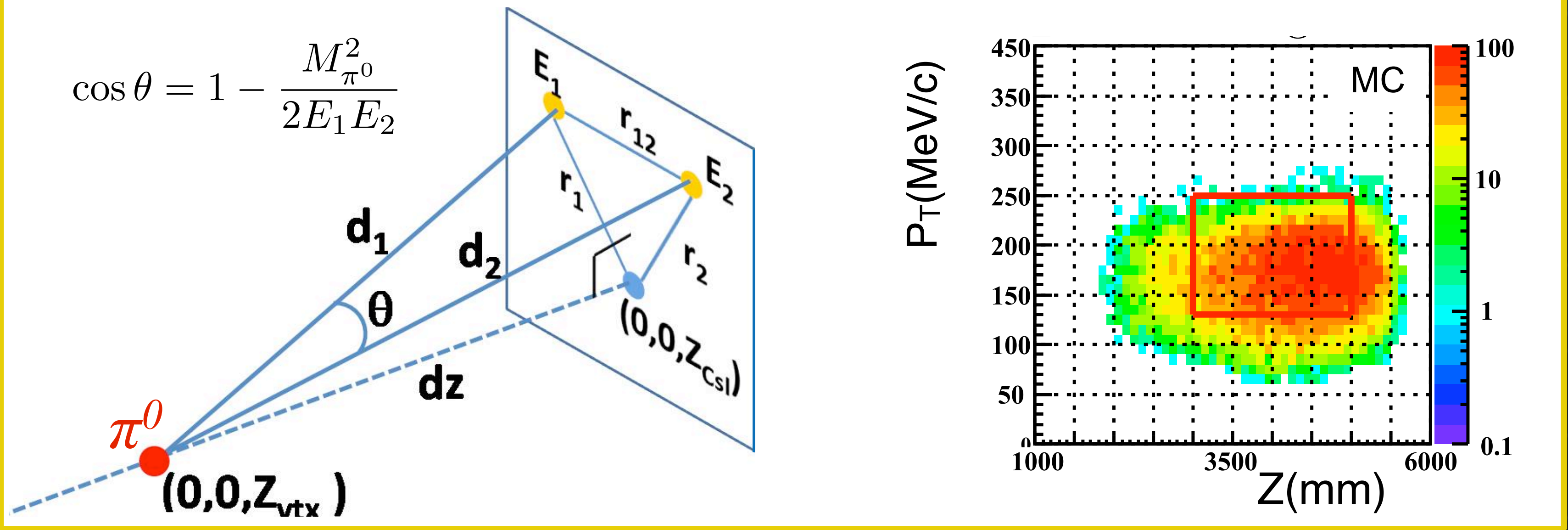
- No information of incident K_L
  - Only decaying particle is K_L in the neutral beam.
  - Momentum distribution can be obtained by using monitoring modes such as $K_L \to \pi^0\pi^0\pi^0$
- One clear π^0 and only one
  - Properly reconstruct π^0
    - $\pi^0 \to e^+e^-\gamma, \ \pi^0 \to \gamma\gamma$
  - No any other decay products
    - Hermetic veto detector



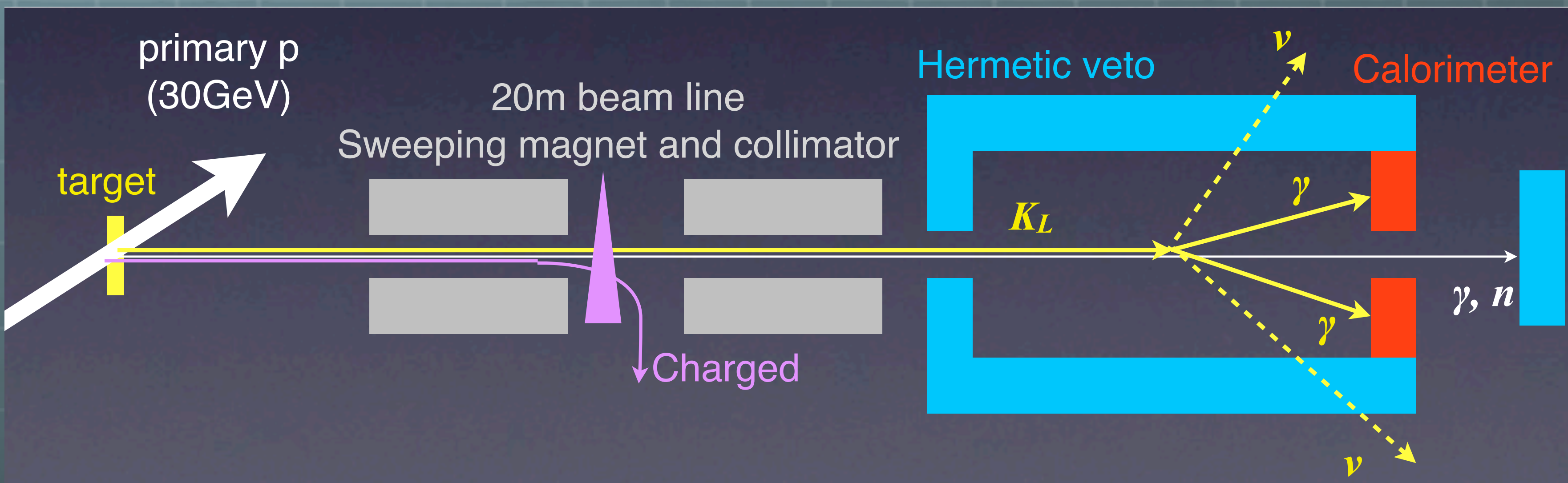
π^0 reconstruction

- EM calorimeter provides energies and incident positions of two photons
- With an assumption that π^0 decays at beam center and π^0 rest mass, we can obtain a distance between calorimeter and decaying vertex.
- Pair of neutrinos take away transverse momentum (P_T)

$$\cos\theta = 1 - \frac{M_{\pi^0}^2}{2E_1E_2}$$

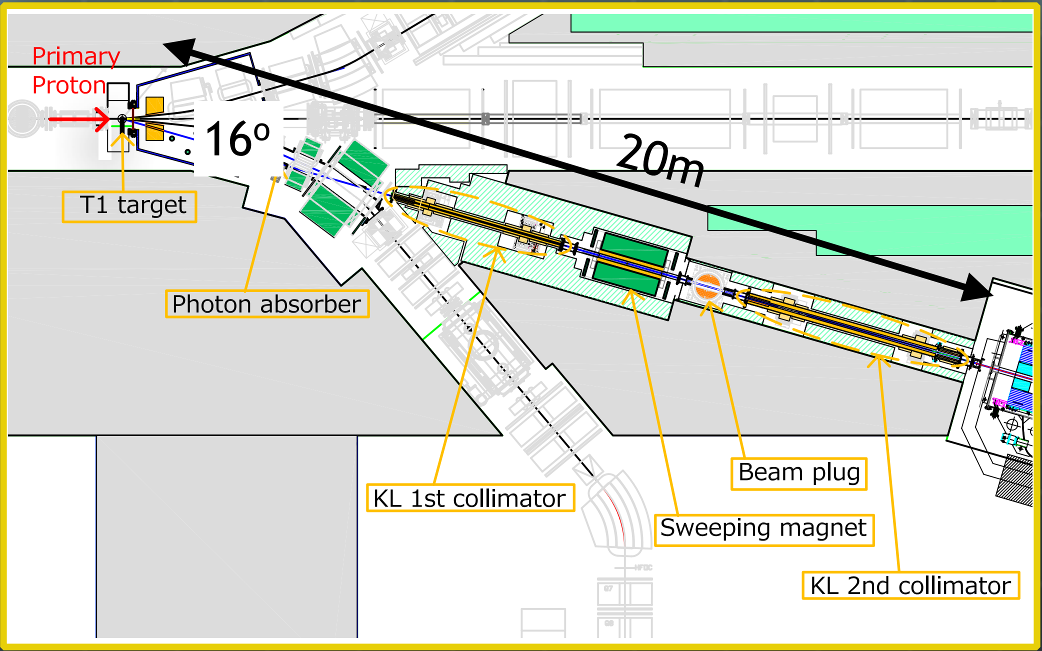


Experimental Method



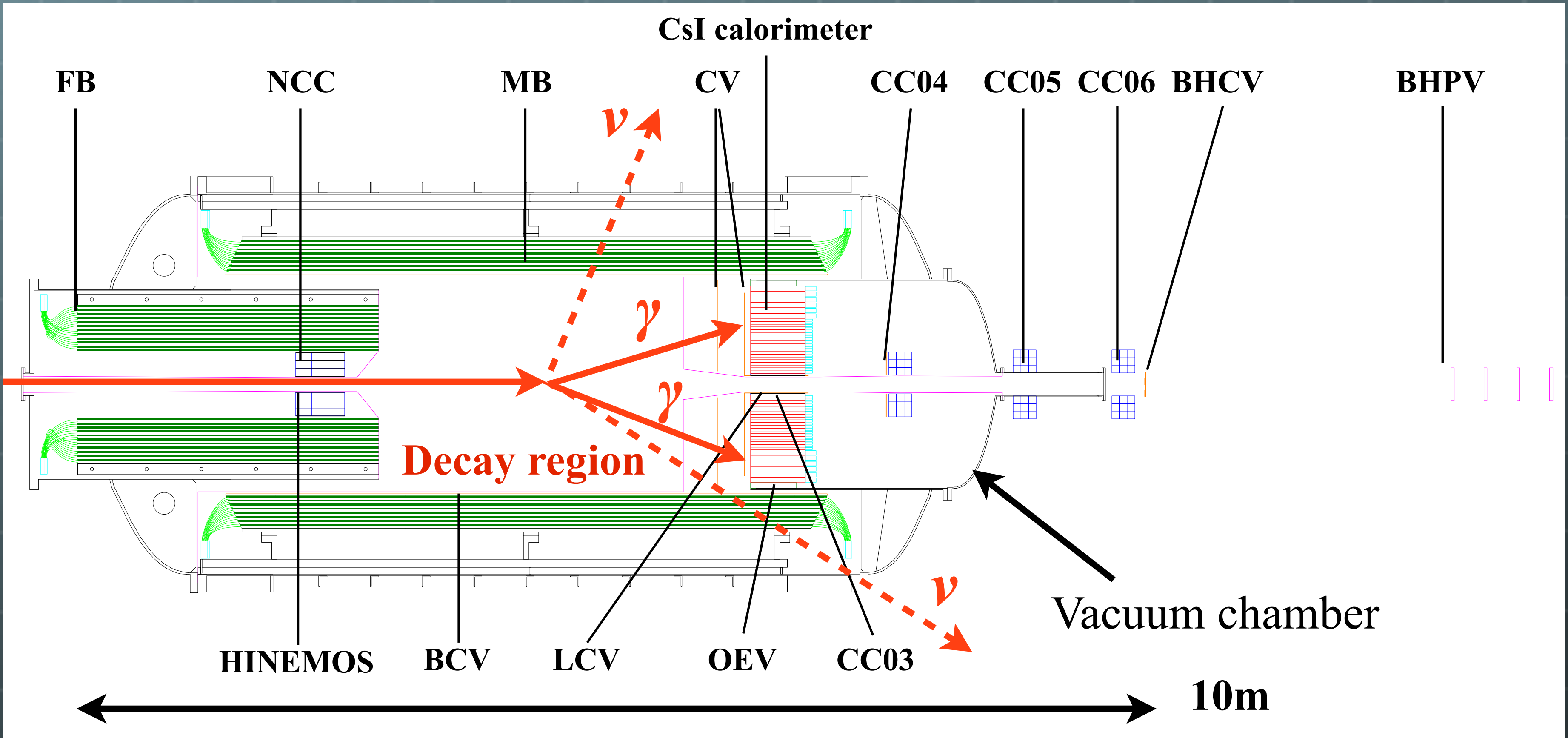
2γ+ Nothing

KL Beam Line

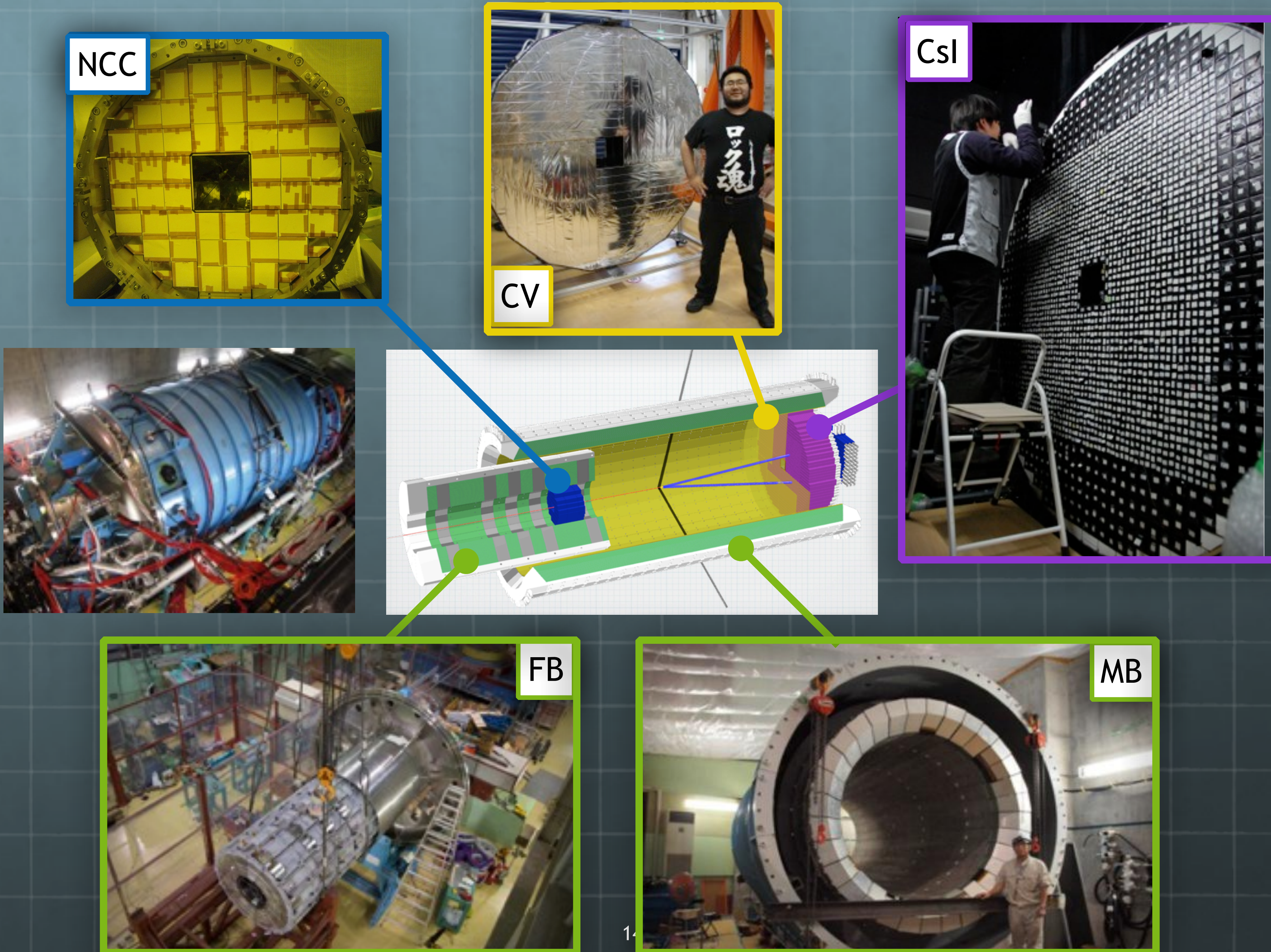


Primary
Proton
16°
20m
T1 target
Photon absorber
KL 1st collimator
Beam plug
Sweeping magnet
KL 2nd collimator

Detector



CsI calorimeter
FB
NCC
MB
CV
CC04
CC05
CC06
BHCV
BHPV
ν
γ
γ
Decay region
ν
Vacuum chamber
HINEMOS
BCV
LCV
OEV
CC03
10m


NCC
CV
CsI
FB
MB
ロック魂

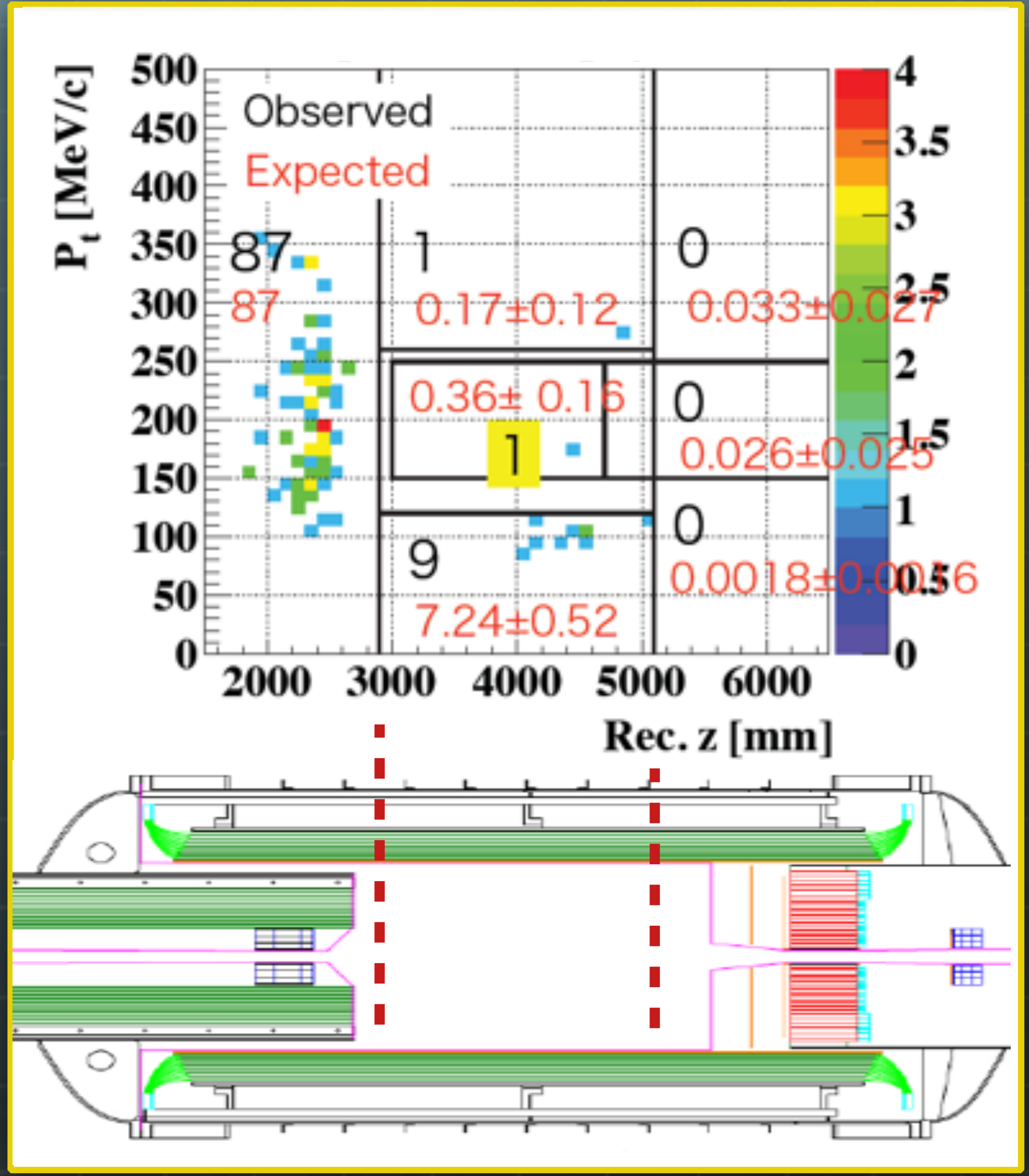
Data taking in 2013

- January : Engineering run in vacuum
  - 11 kW X 1.5 days + 15 kW X 6.5 days
- March-April: Tuning for physics run
  - 15 kW X 5 days
- May: Physics run
  - 20 kW X 1 day + 24kW X 4 days (~ 100 hours)

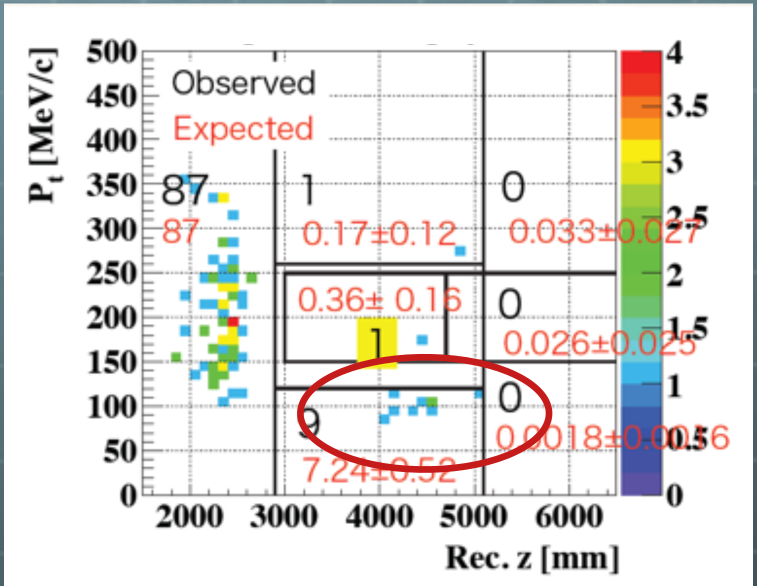
Results of May 2013

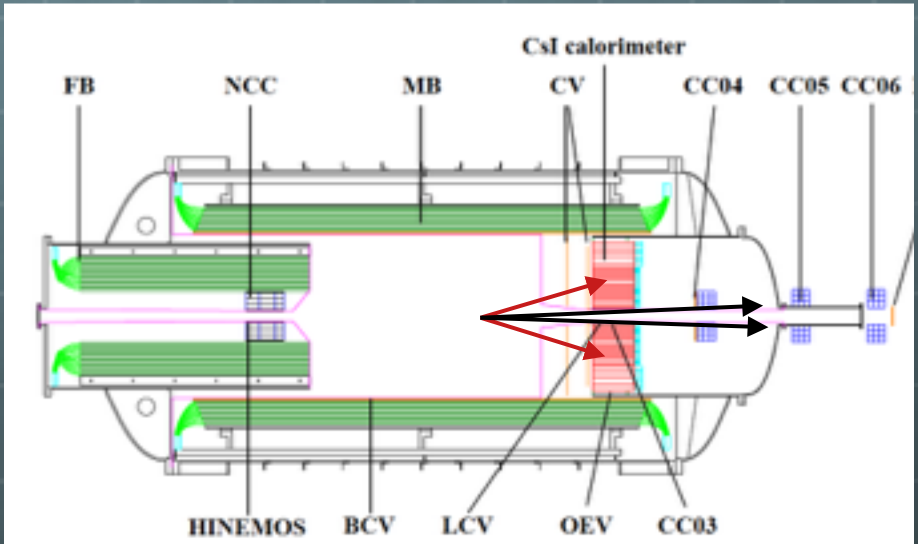
- Removed B.G. events learned from the E391a. (π^0 production at the detectors)
- We found two new sources of the B.G.
- Upgraded detector for run 2015

$$S.E.S = 1.29 \times 10^{-8}$$

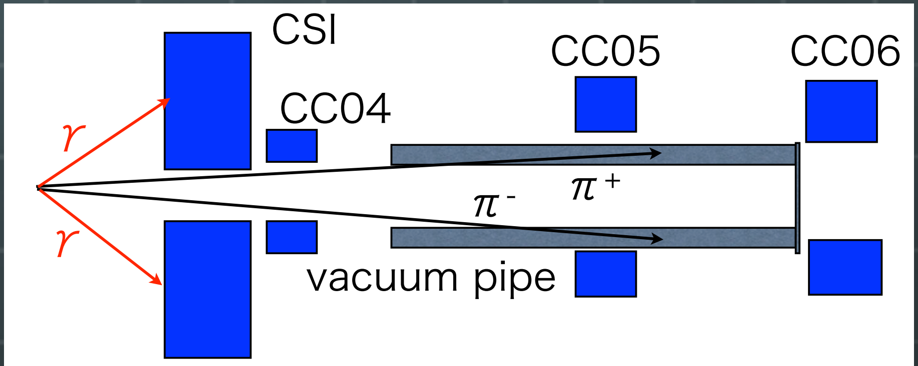


$K_L \rightarrow \pi^+\pi^-\pi^0$

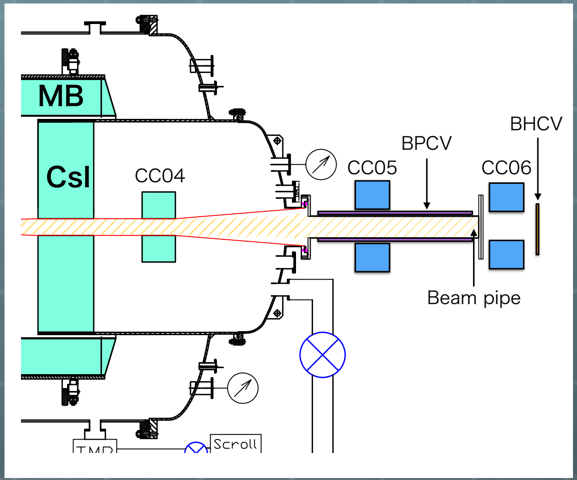


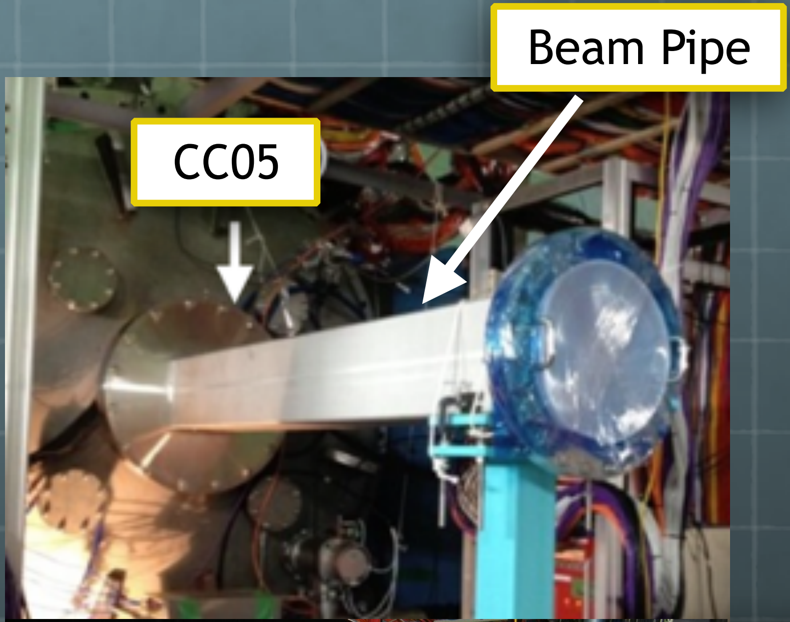


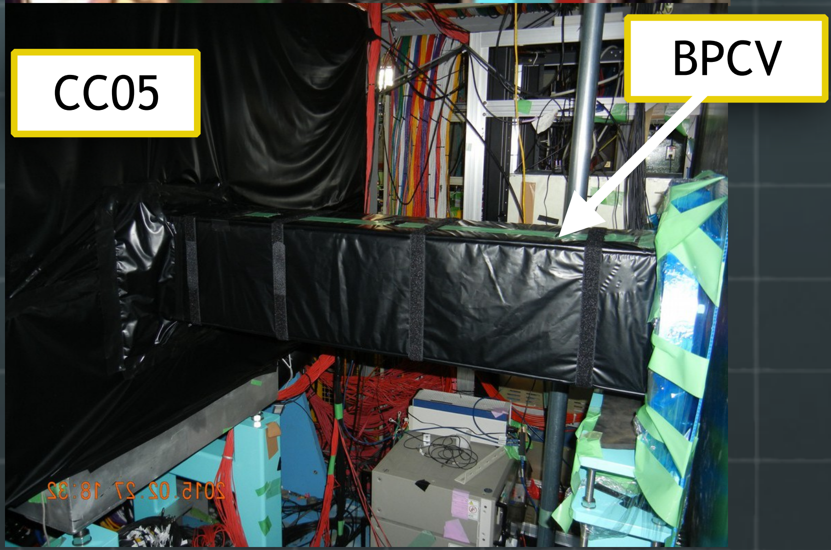
π^+ and/or π^- were not detected due to interaction inside vacuum pipe



$K_L \rightarrow \pi^+\pi^-\pi^0$



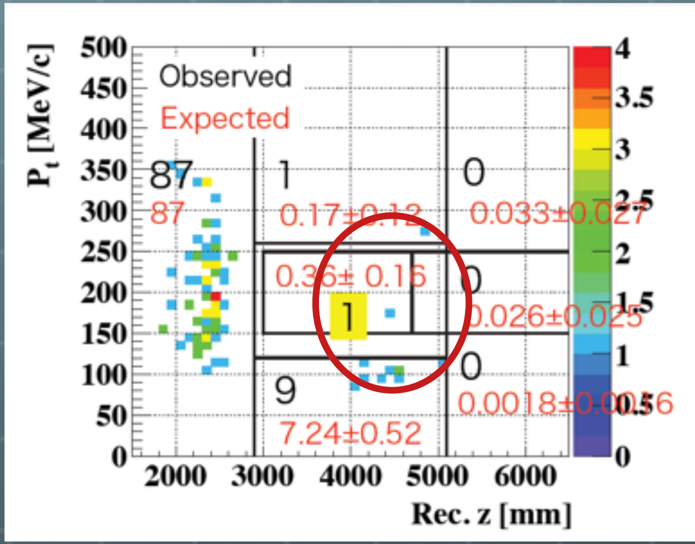


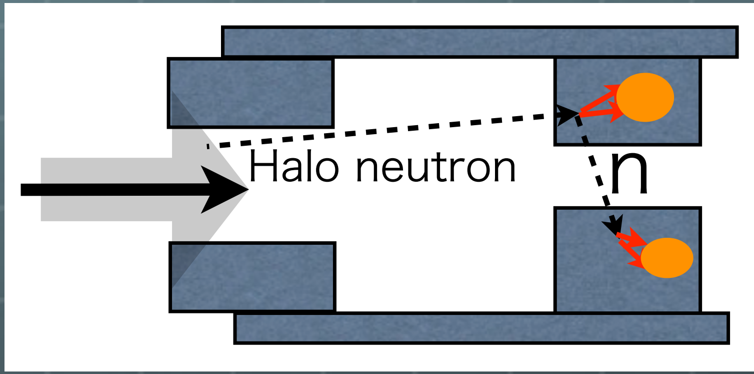


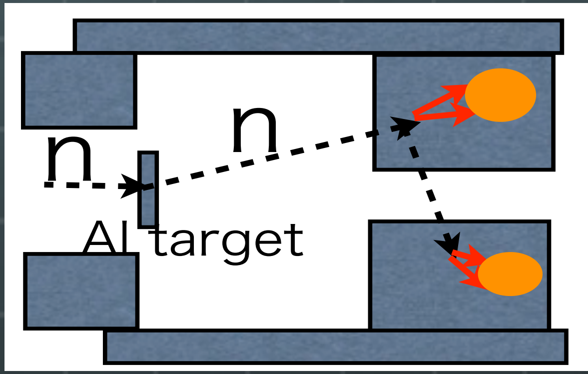
- Beam pipe with lighter material
  - Stainless Steel -> Aluminum
- Beam Pipe Charged Veto
  - 5mm-thick Plastic Scintillator
  - Wavelength shifting fiber readout

1/60 additional reduction

Halo neutron events



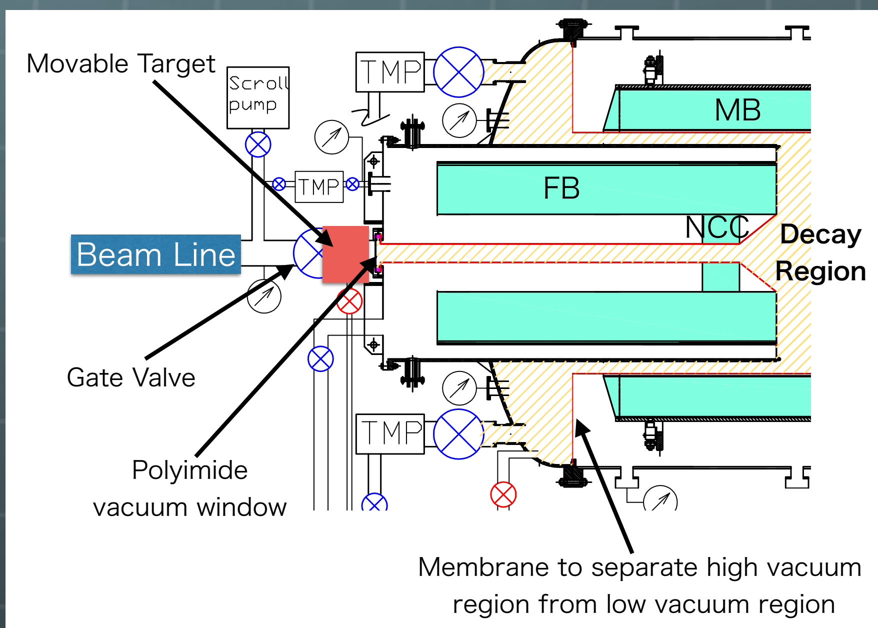


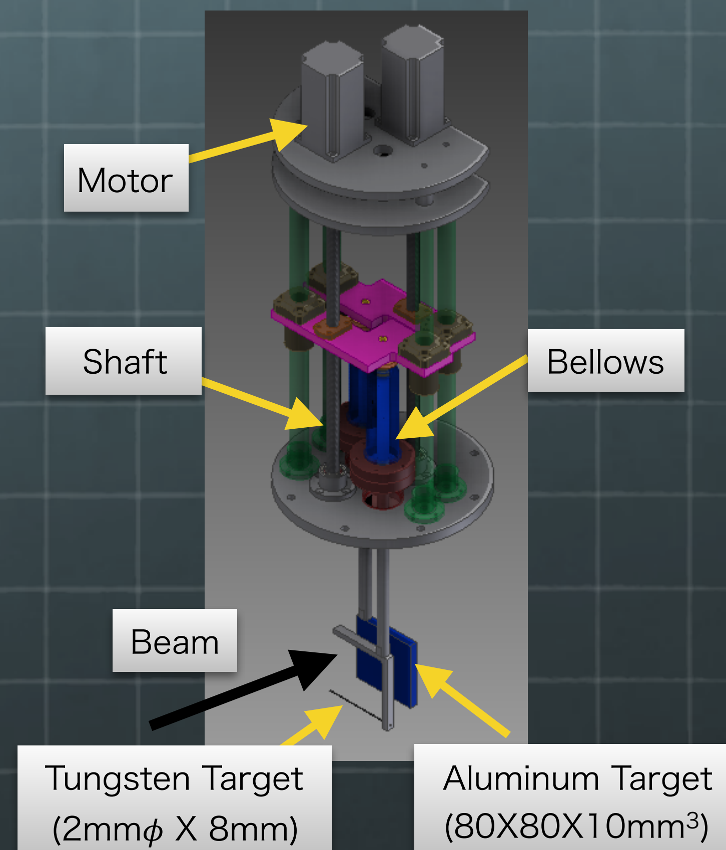


- Single neutron produce two clusters
  - Newly founded background source
  - Studied by using aluminum target data

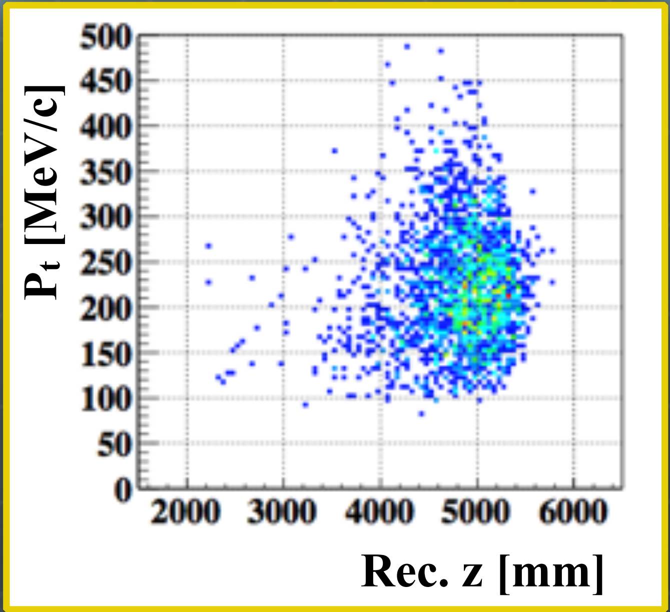
Halo neutron events

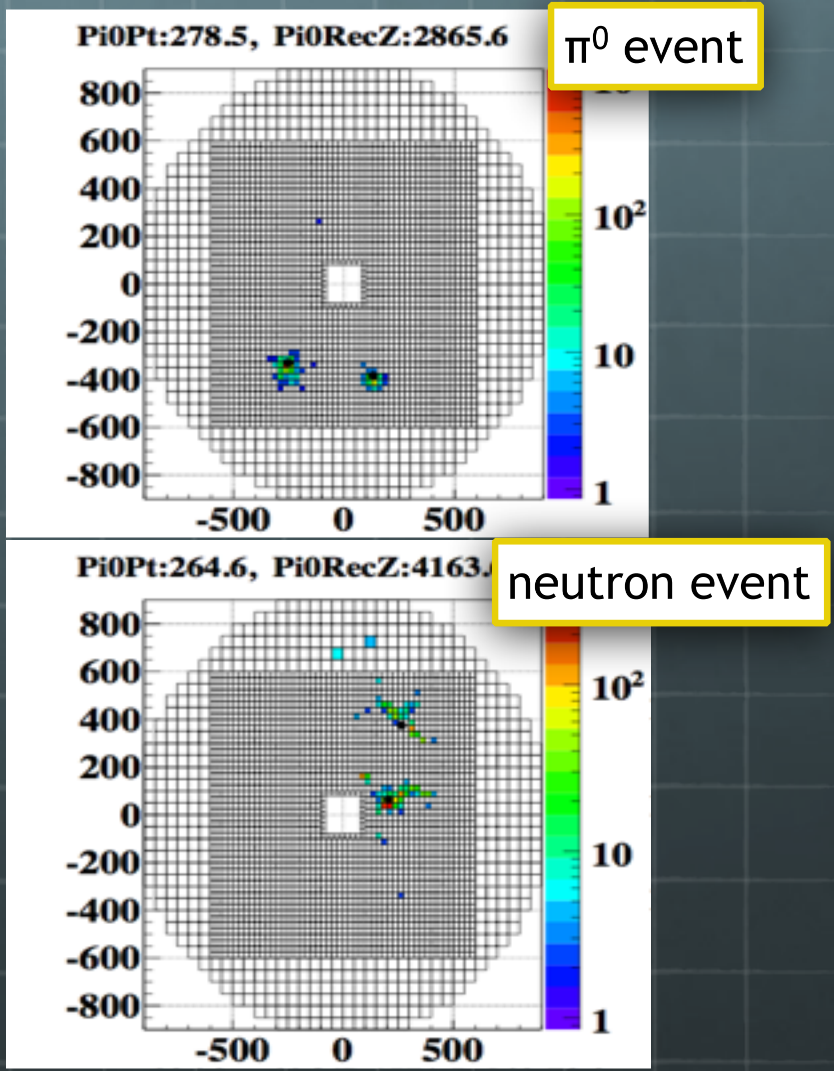
- To reduce scattering source
- To take data for enhanced neutron events





Enhanced neutron events

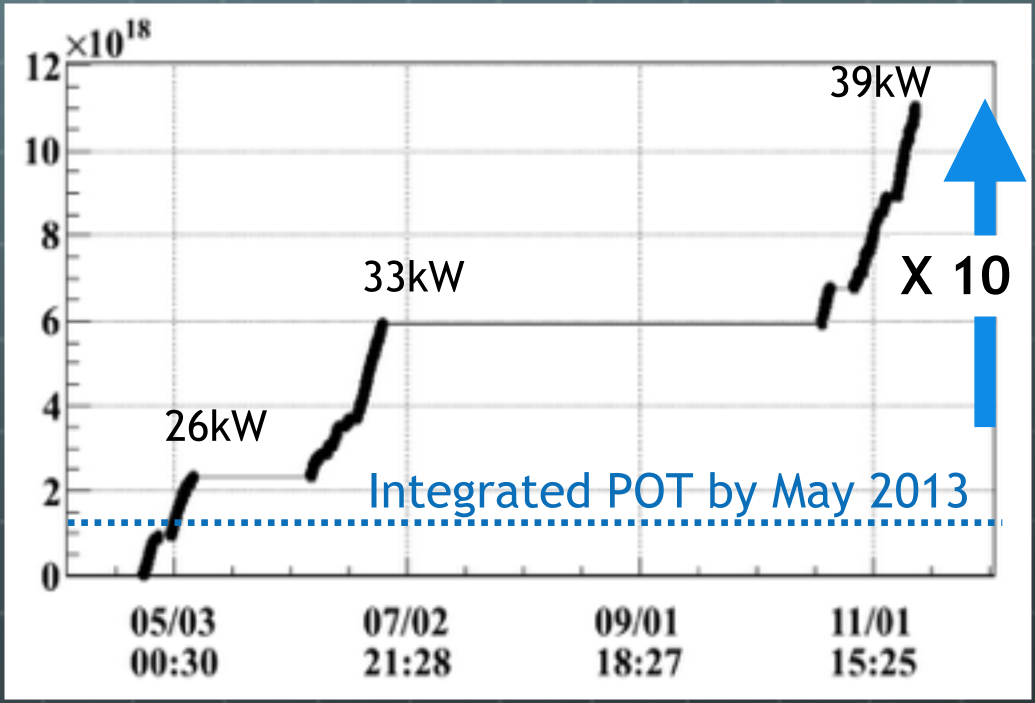




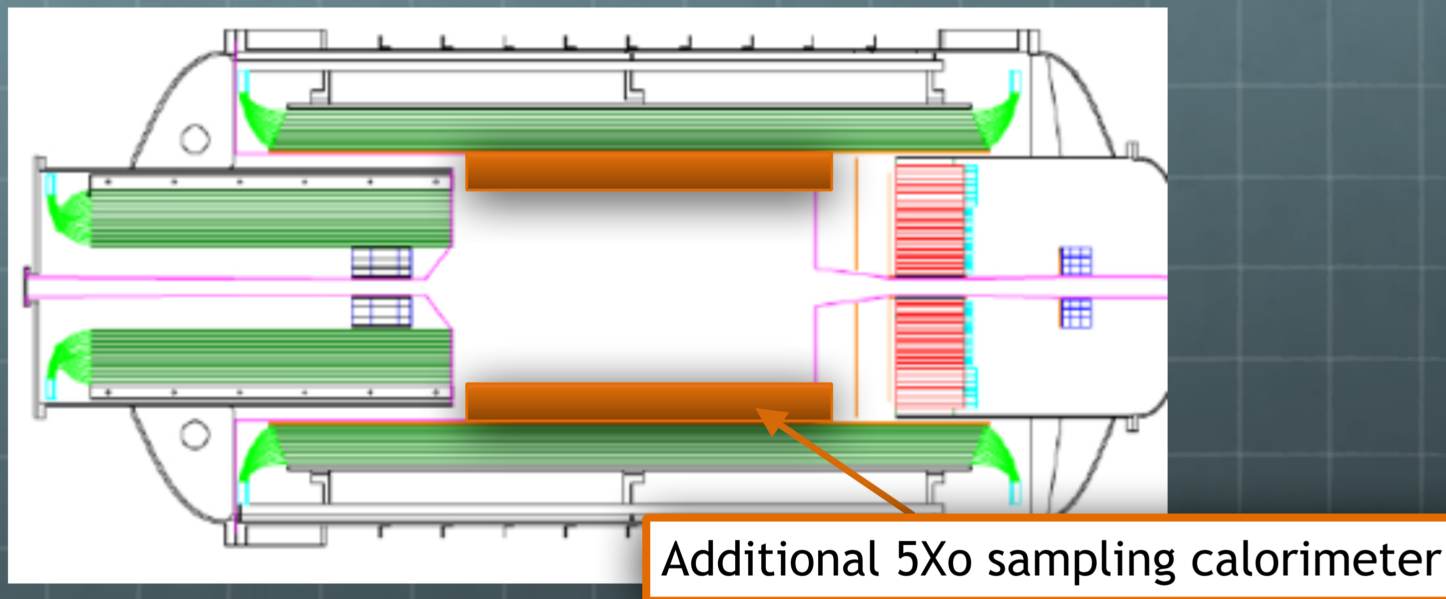
- 70-hour data taking with Al-target (>15 times more than May 2013)
- To study cluster and pulse shape in the calorimeter
- To develop a method to discriminate neutron induced events from the π^0 events

Run in 2015

- 10 times larger POT than run in May 2013
- Newly installed detectors work properly
  - Detailed performance check in undergoing
- With the data collecting in coming beam time (Oct.~ Dec.), we aim at across the Grossman-Nir limit.

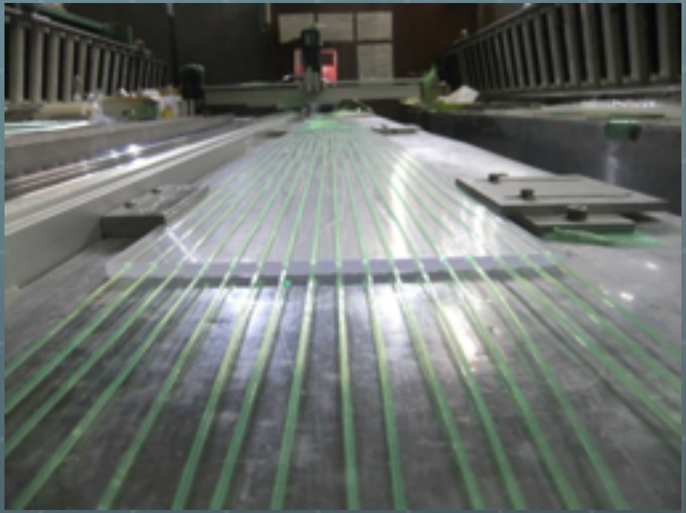


Inner Barrel



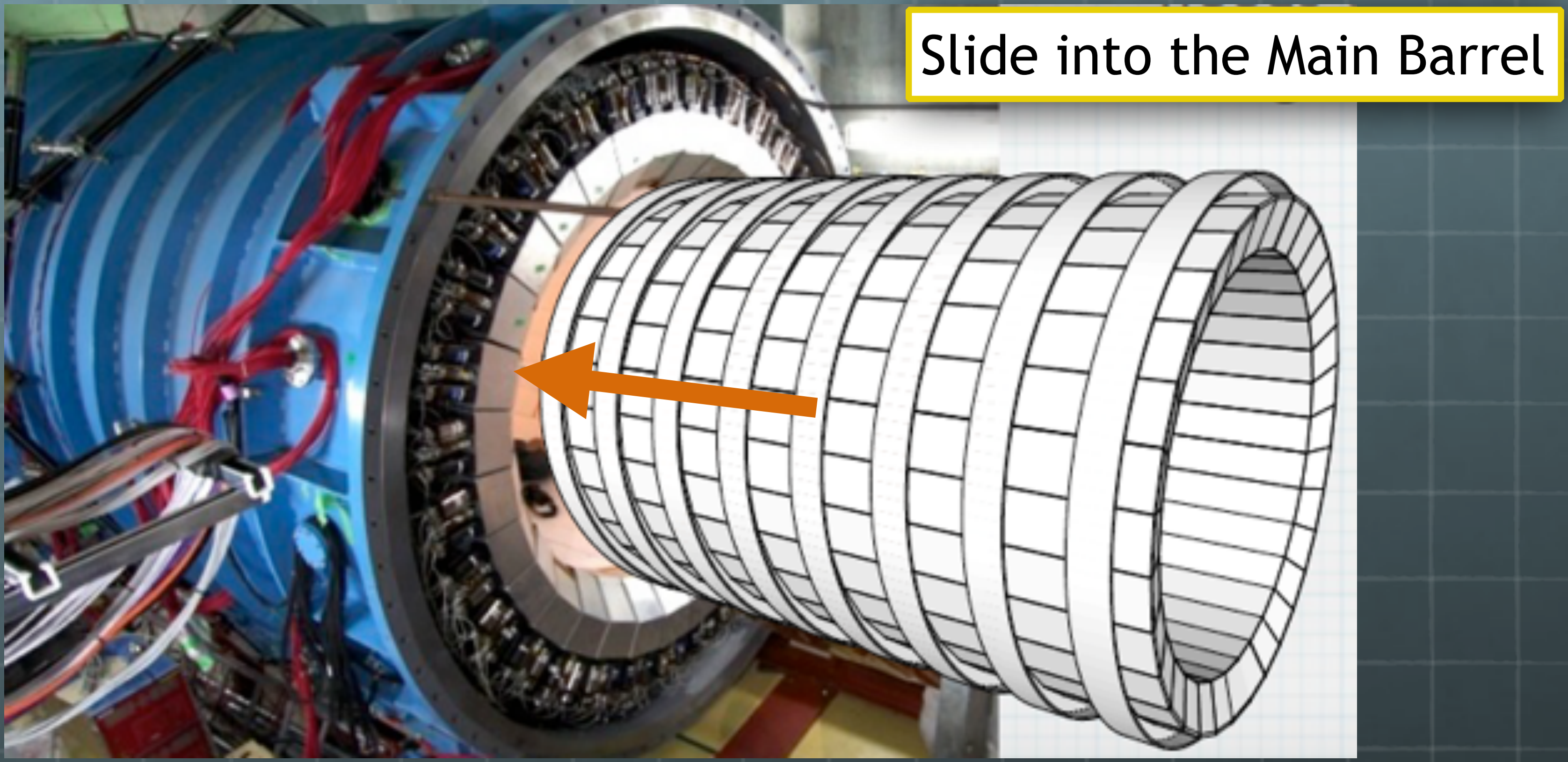
- Additional reduction for detection inefficiency due to punch-through as a factor of 50
- Increase better visible ration portion
- Reduction of background as a factor of three

Inner Barrel



- Alternation lead sheet (1mm) and plastic scintillator(5mm)
- Wave length shifting fiber read-out (BCF-92, ϕ1.5mm)

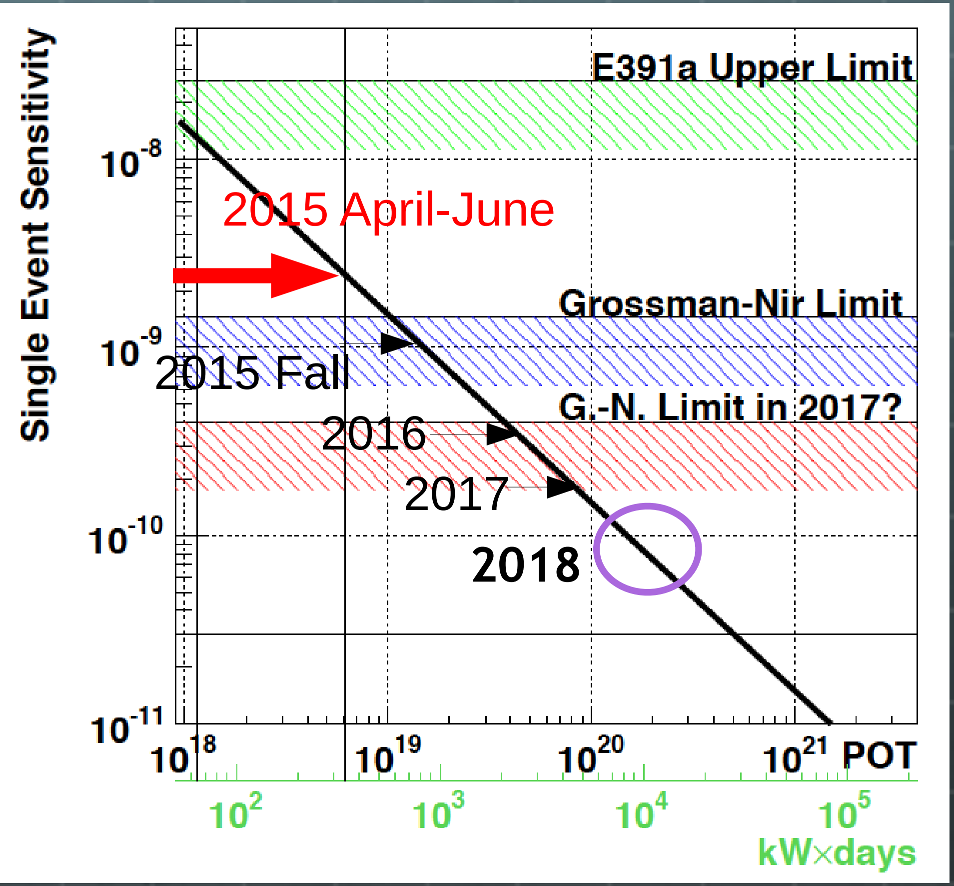
Inner Barrel



- Fabrication of the 32 modules is undergoing
- Assembling of the modules is preparing to start this month
- Installation will be done in middle of next January

3 years from now

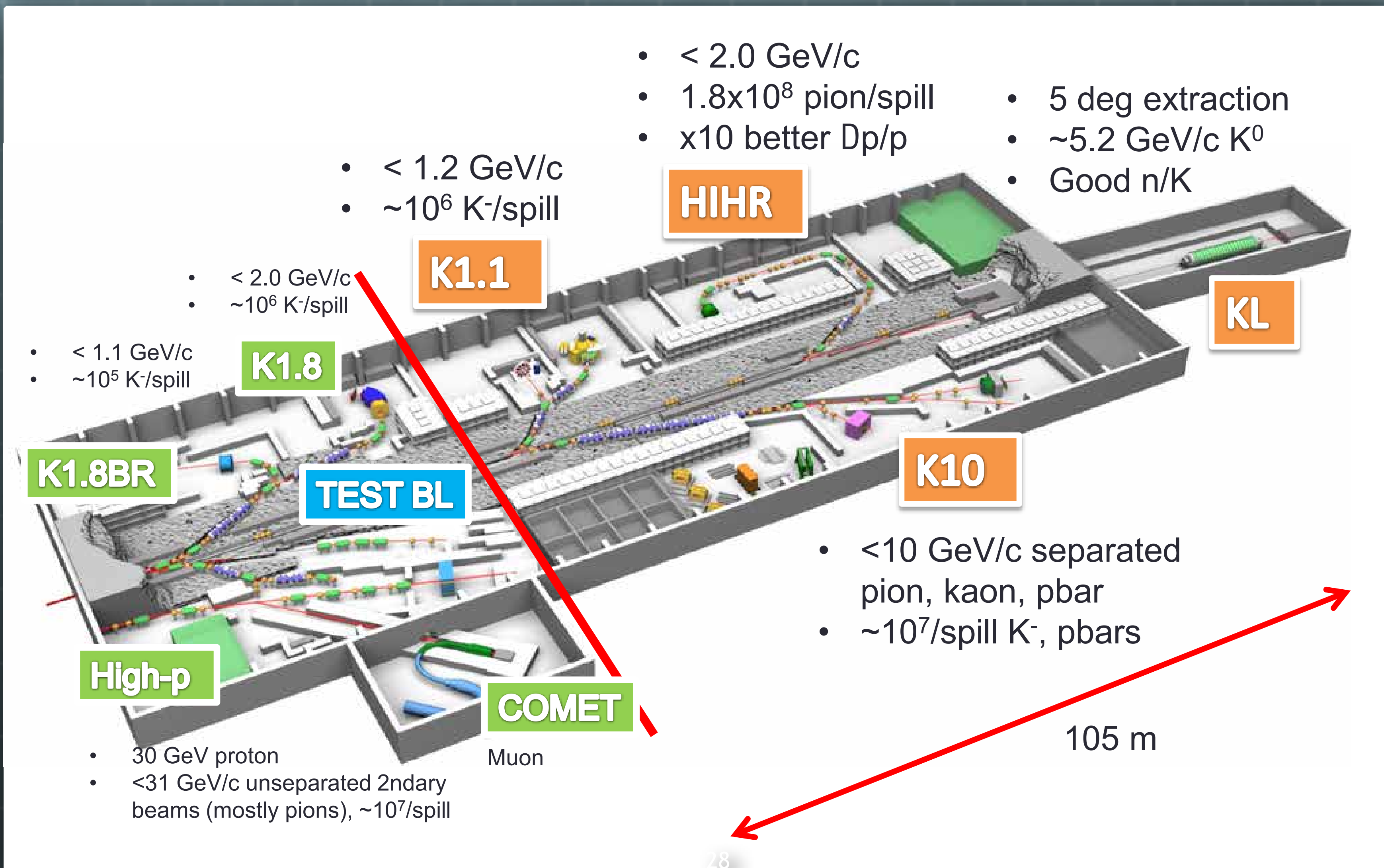
- Up-graded detector System
- Higher beam intensity of J-PARC



In near future

- To perform precise measurement of the branching ratio (KOTO II)
- It is worth to design an experiment to determine branching ratio with comparable uncertainty to that of the theoretical calculation
- For the experiment
  - Correct understanding all background sources
  - Higher beam intensity
  - Larger detector acceptance

Hadron Hall Extension

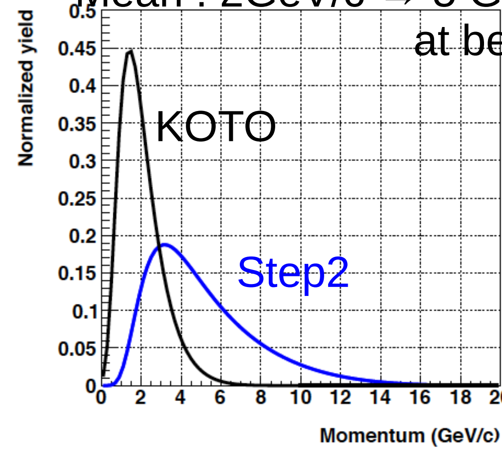


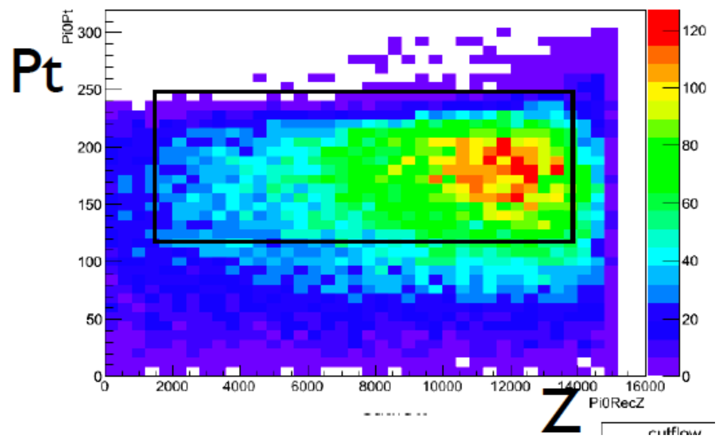
One solution

Study in 2014	KOTO
5 deg extraction	16deg
36m beamline	20m
8usr solid angle	7.8usr
4m-diamter calorimeter	2m
20m decay volume	3.3m
~100kW x 3e7 sec	

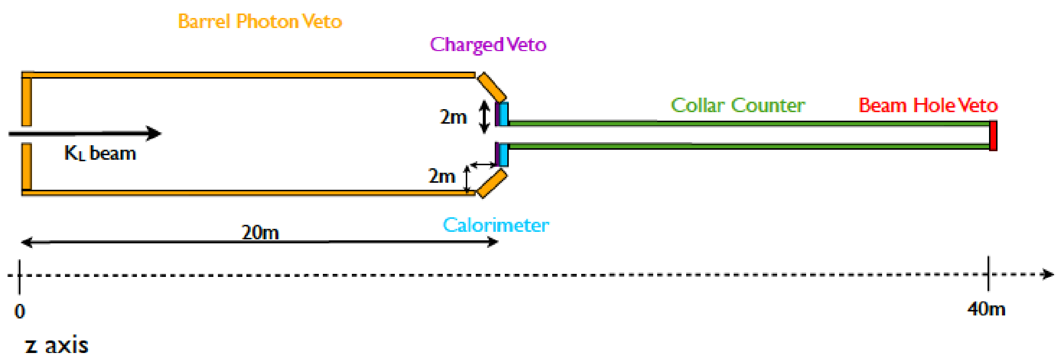
~350 signal with S/N ~3 (K decay)
ΔBR/BR ~6%

Peak :1.4 GeV/c → 3GeV/c
Mean : 2GeV/c → 5 GeV/c
at beam exit





beam power	109kW
proton energy	30GeV
proton intensity	7.5×10^{13}/spill
Spill length / Beam repetition	0.7s/3.3s
Target	Ni(1λ)
Absorber	Pb(7cm)
Extraction angle	5°



100 events/10^7s ?

- # of events = Branching ratio*# of K-decay*Acceptance
- For Br=3X10-11, Acceptance = 0.1
  - Needed K-decay for 100 events :3.3X10^{14} (33MHz)
  - Event definition time as 10ns
  - Accidental coincidence = 0.33
  - Increasing of instantaneous rate as 3 : Always two decay inside detector
  - Accidental hits have longer decay region (factor of 5 ?)
- Totally new approach is needed

Summary

- Measurement of the $K_L \rightarrow \pi^0 \nu\nu$ decay will enable us to find new physics effect.
- KOTO is aiming for the first event.
- High statistics experiment is needed even though lots of difficulties.
  - large number of KAONS - High intensity beam
  - large acceptance and enough background suppression.
  - Fully understand accidental activities.
- We started hadron hall extension
  - KOTO-II will be performed

10 April 1997

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 398 (1997) 163–168

$K_L \to \pi^0 \nu\bar{\nu}$ beyond the Standard Model ⋆

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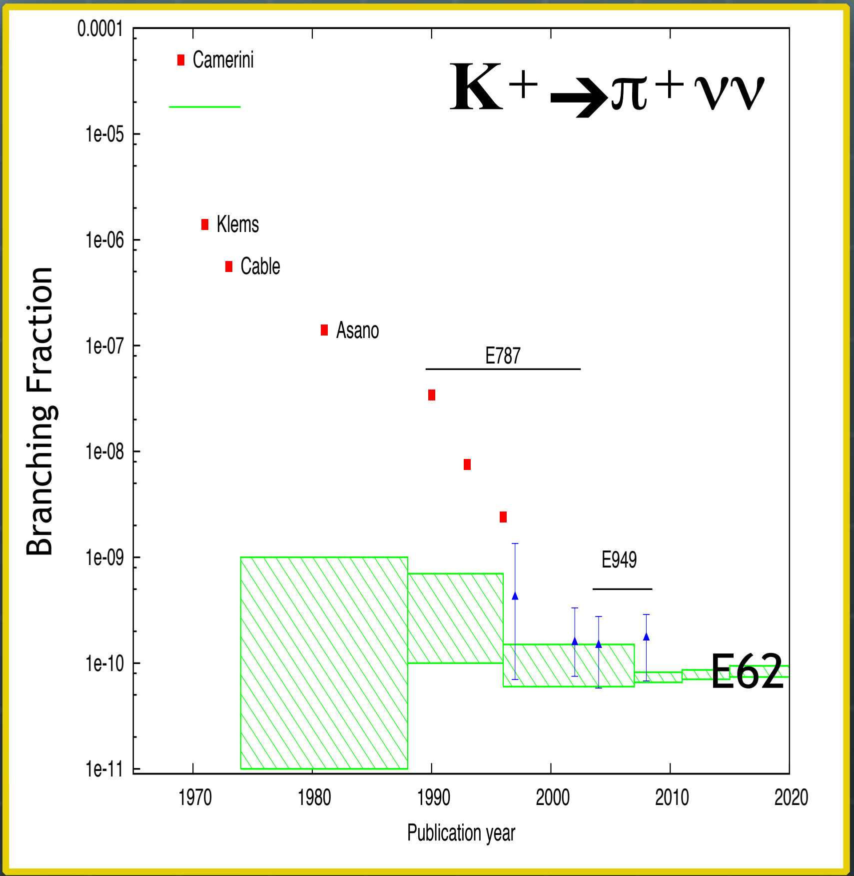
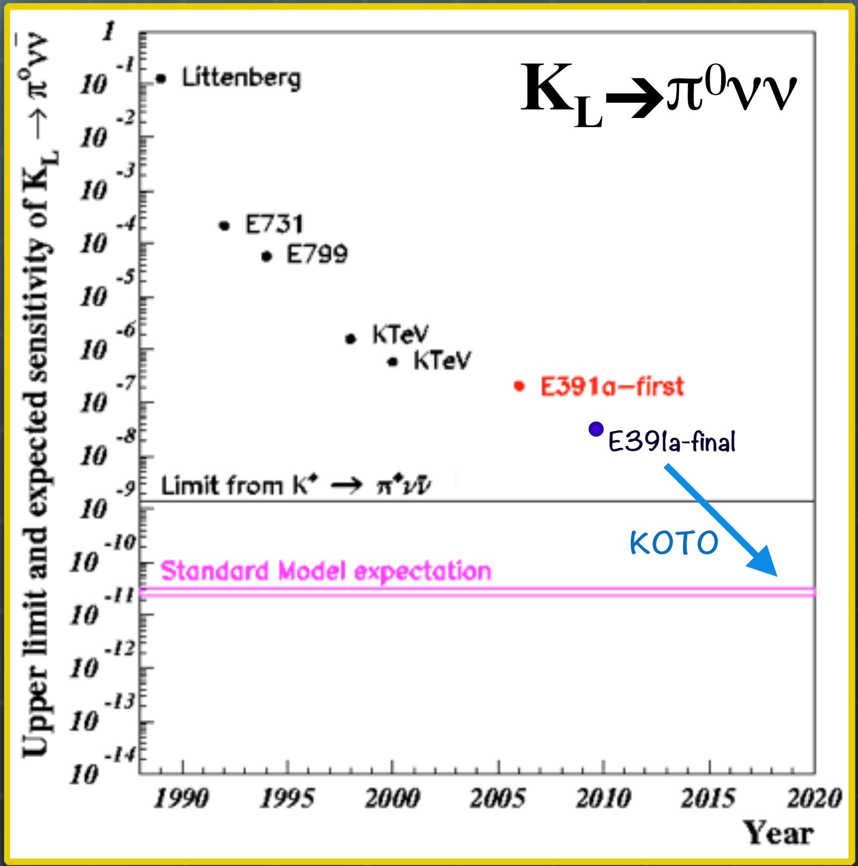
Received 29 January 1997
Editor: M. Dine

Abstract

We analyze the decay $K_L \to \pi^0 \nu\bar{\nu}$ in a model independent way. If lepton flavor is conserved the final state is (to a good approximation) purely CP even. In that case this decay mode goes mainly through CP violating interference between mixing and decay. Consequently, a theoretically clean relation between the measured rate and electroweak parameters holds in any given model. Specifically, $\Gamma(K_L \to \pi^0 \nu\bar{\nu})/\Gamma(K^+ \to \pi^+ \nu\bar{\nu}) = \sin^2\theta$ (up to known isospin corrections), where θ is the relative CP violating phase between the $K - \bar{K}$ mixing amplitude and the $s \to d\nu\bar{\nu}$ decay amplitude. The experimental bound on $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$ provides a model independent upper bound: $\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) < 1.1 \times 10^{-8}$. In models with lepton flavor violation, the final state is not necessarily a CP eigenstate. Then CP conserving contributions can dominate the decay rate.

Experimental Status





Still far from the goal …