Present status of the search for the $K_L \longrightarrow \pi^0 \nu\bar{\nu}$ decay with the KOTO detector at J-PARC

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On behalf of the KOTO collaboration

APS DPF Meeting, August 3, 2017

KOTO Experiment

The experiment brings together over 50 collaborators from 16 different institutions

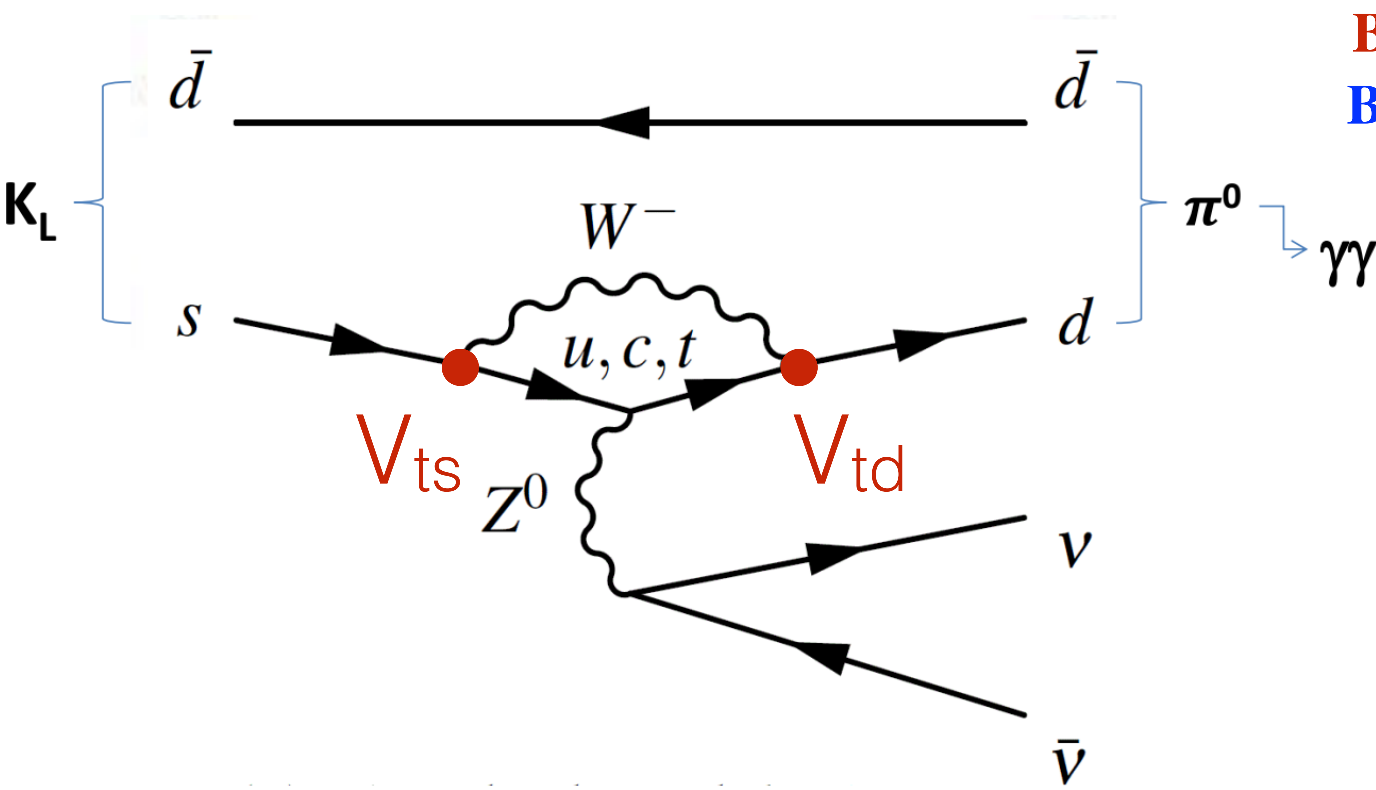
Motivation

$K_L \to \pi^0 \nu\nu$ ultra rare decay: Why is this important?

CP- CP+

$K_L \longrightarrow \pi^0 \nu\nu$

- The decay process proceeds via a flavor changing neutral current (FCNC)
- This process directly breaks CP
- Studying this decay is an excellent probe for New Physics (NP) beyond the Standard Model
- Results form this measurement will place tighter constraints or point to new physics



BR ($K^+ \longrightarrow \pi^+ \nu\nu$) = (9.11 ± 0.72) x 10^{-11} (Buras …et. al 2015)

BR ($K_L \longrightarrow \pi^0 \nu\nu$) = (3.00 ± 0.30) x 10^{-11} (Buras …et. al 2015)

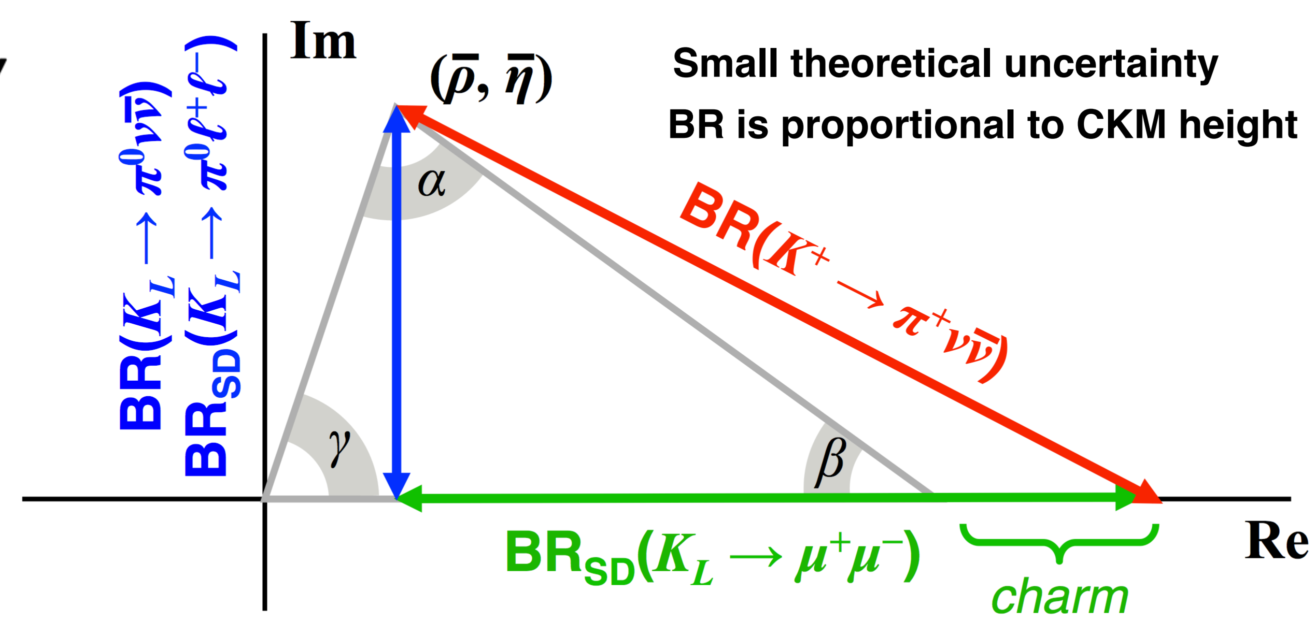


Fig. Unitarity triangle

Model predictions and measurements

BNL: E949 observed 2 clean events for K⁺—>π⁺νν~ BR (17.3 x10⁻¹¹)

Phys. Rev. Lett. 101, 191802 – Published 7 November 2008

> Three events for the decay $K^+ \to \pi^+ \nu\bar{\nu}$ have been observed in the pion momentum region below the $K^+ \to \pi^+\pi^0$ peak, $140 < P_\pi < 199$ MeV/c, with an estimated background of $0.93 \pm 0.17(\text{stat.})^{+0.32}_{-0.24}(\text{syst.})$ events. Combining this observation with previously reported results yields a branching ratio of $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ consistent with the standard model prediction.

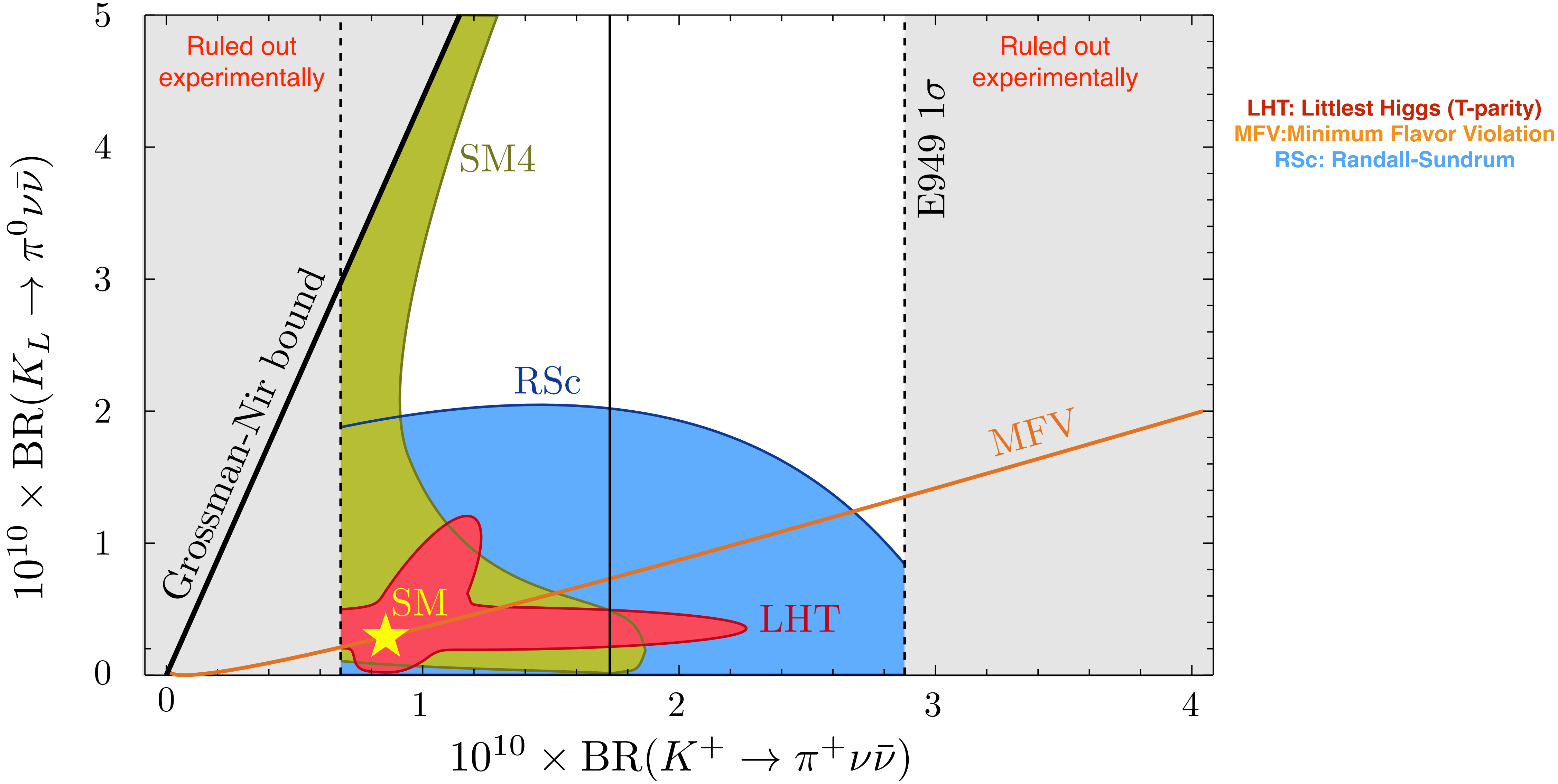


Fig. Predicted correlations between BR(K_L—>π⁰νν) and BR(K_L—>π⁺νν) for various BSM.

Goals of KOTO

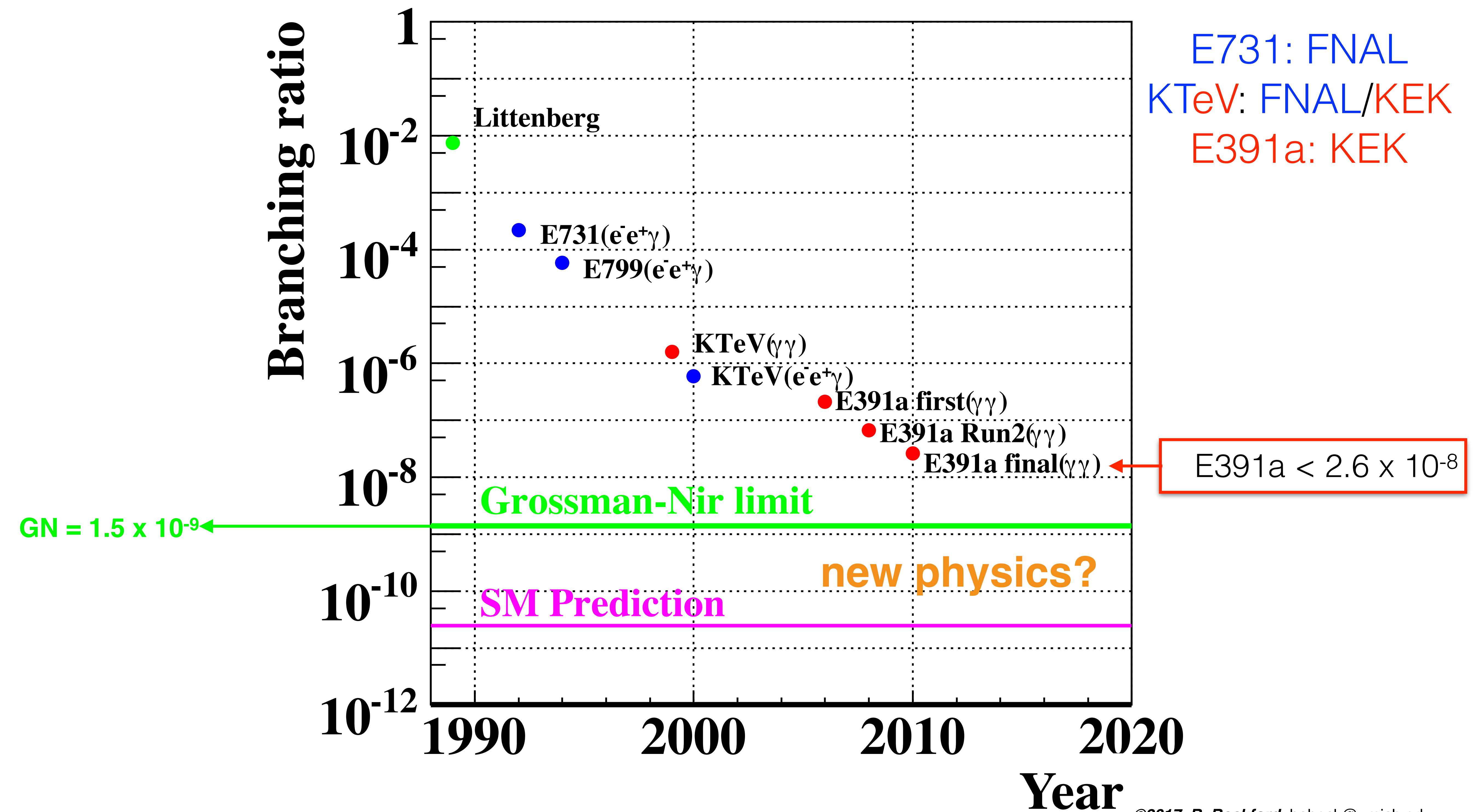
The KOTO experiment plans to report the first measurement of the branching ratio Br($K_L \rightarrow \pi^0 \nu\nu$) with less than 10% uncertainty

- KOTO Step 1:
  - Make first observation of signal event (~10^{-12} sensitivity)
  - Search for new physics with BR higher than SM predictions
- KOTO Step 2:
  - Measure roughly 100 events (~10^{-13} sensitivity)

Brief history of search before KOTO

Advance in study enabled by detector R&D, computing, and accelerator technology

E391a experiment was impeded by limited veto capabilities and low beam power (~12GeV)



J-PARC facility

Experiment based at J-PARC (Japan Proton Accelerator Research Complex) in Tokai-mura

Hadron Experimental Facility (HEF)

- Intense 30 GeV proton beam with a 50% duty factor
- Secondary neutral beam is extracted (16^{o}) and directed to KOTO detector

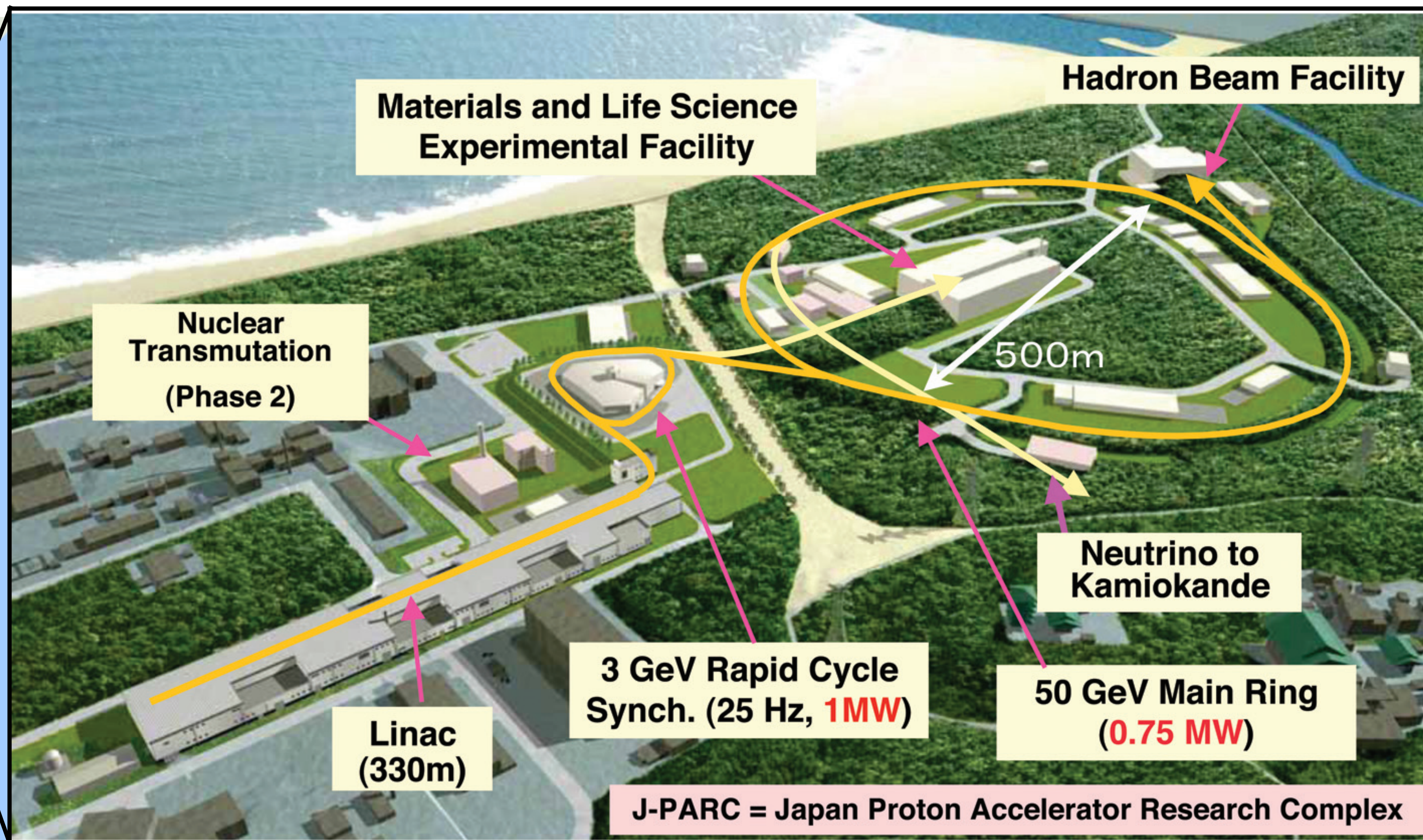


Fig. View of the J-PARC facility

KOTO detector

Two sub-system design:

- Cesium Iodide Calorimeter (CsI)
  - Main detector of the KOTO experiment
- Hermetic veto detectors
  - ~1000 channels

Background reduction is crucial!

Decay Mode	Branching Ratio
$K_L^0 \to \pi^\pm e^\mp \nu_e$	0.4055 ± 0.0011
$K_L^0 \to \pi^\pm \mu^\mp \nu_\mu$	0.2704 ± 0.0007
$K_L^0 \to 3\pi^0$	0.1952 ± 0.0012
$K_L^0 \to \pi^+\pi^-\pi^0$	0.1254 ± 0.0005
$K_L^0 \to 2\pi^0$	$(0.864 \pm 0.006) \times 10^{-3}$
$K_L^0 \to 2\gamma$	$(0.547 \pm 0.004) \times 10^{-3}$
$K_L^0 \to \pi^0\nu\bar{\nu}$	$(2.49 \pm 0.39 \pm 0.06) \times 10^{-11}$

Table. Branching ratios of various Kaon decays (PDG)

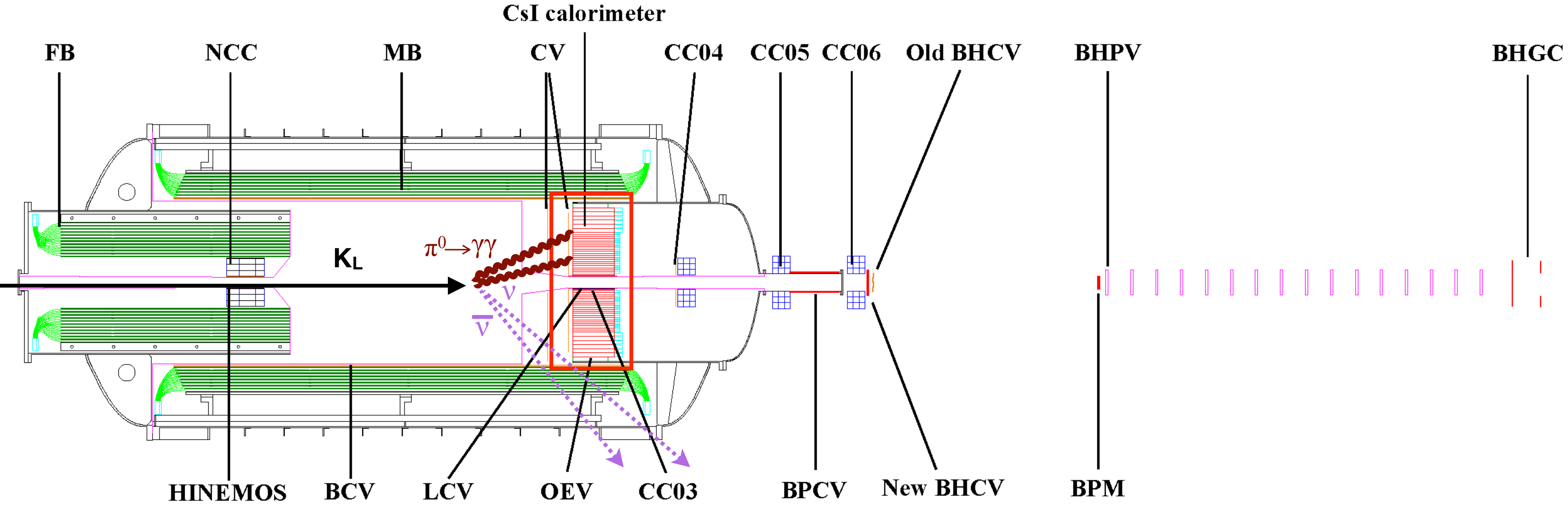


Fig. KOTO detector components

Experimental method

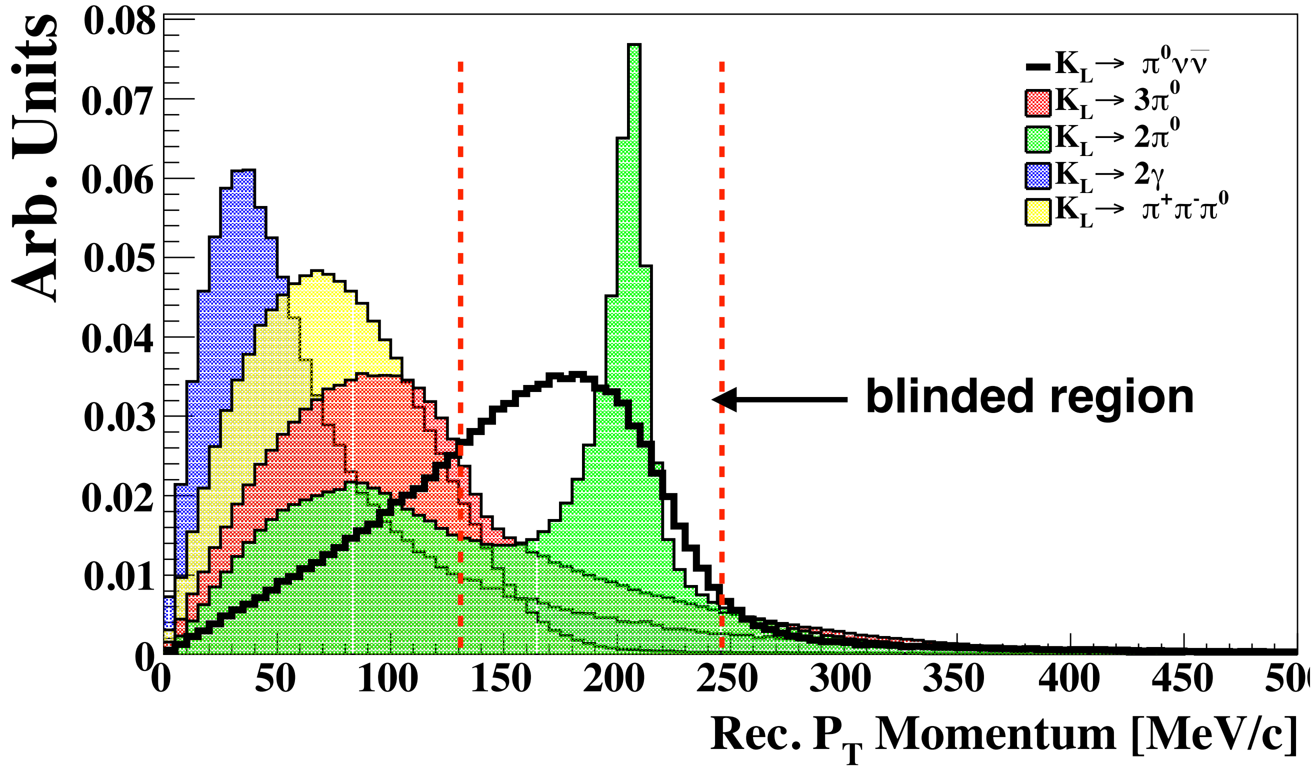


Fig. Monte Carlo of signal and background distributions

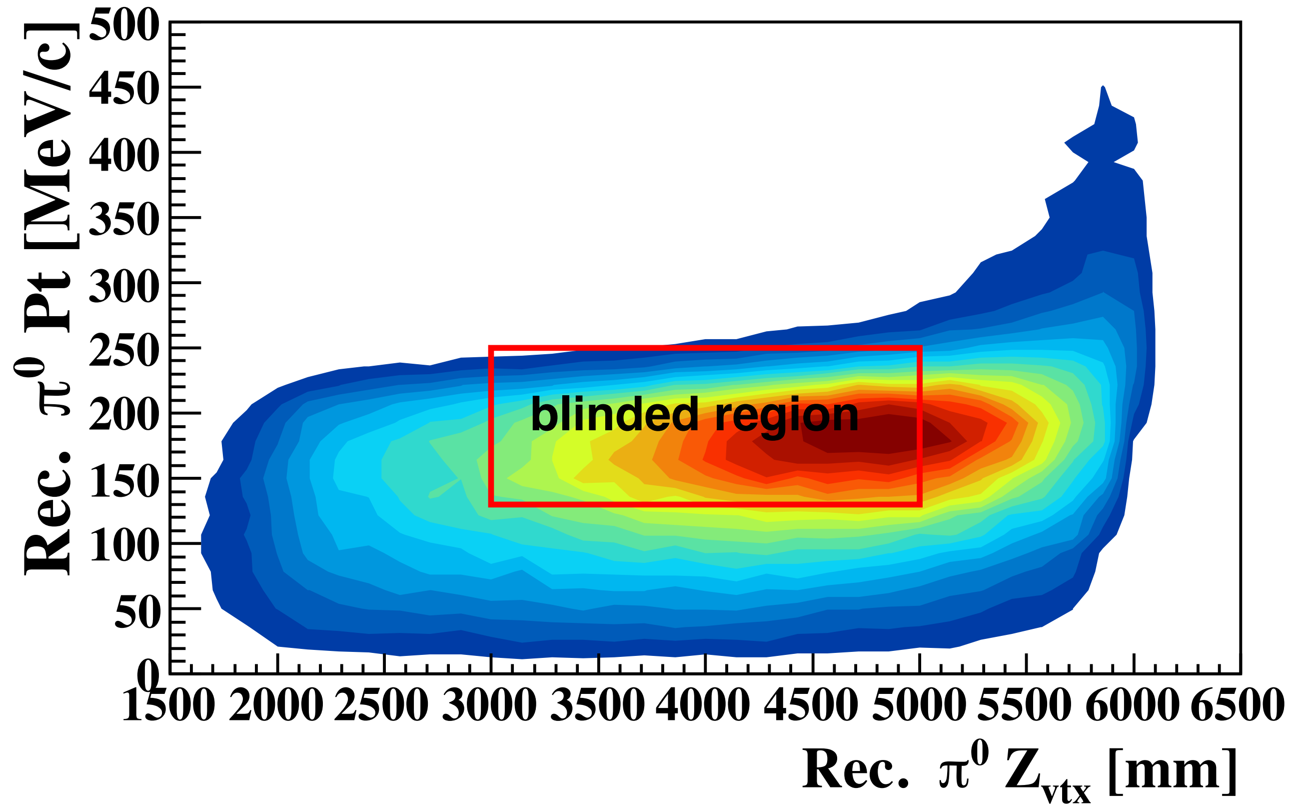
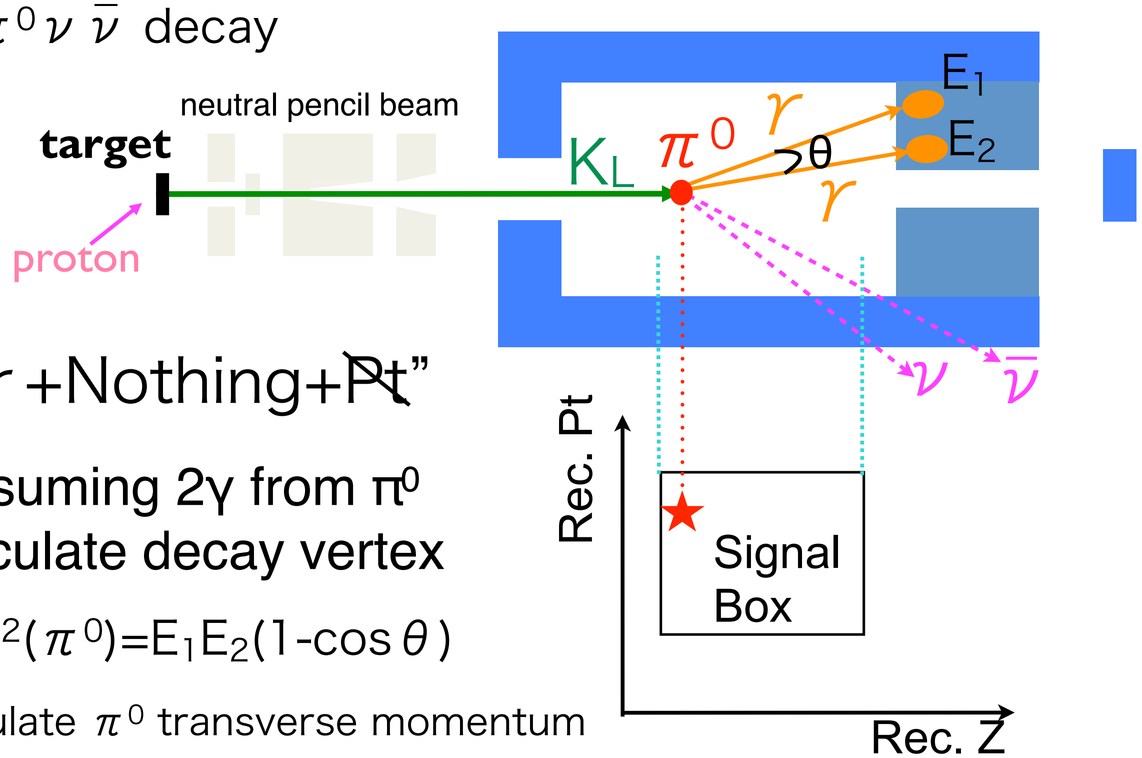


Fig. Monte Carlo sample of signal distribution

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



"2γ+Nothing+$\cancel{\text{Pt}}$"

Assuming 2γ from π^0
Calculate decay vertex

$M^2(\pi^0)=E_1E_2(1-\cos\theta)$

Calculate π^0 transverse momentum

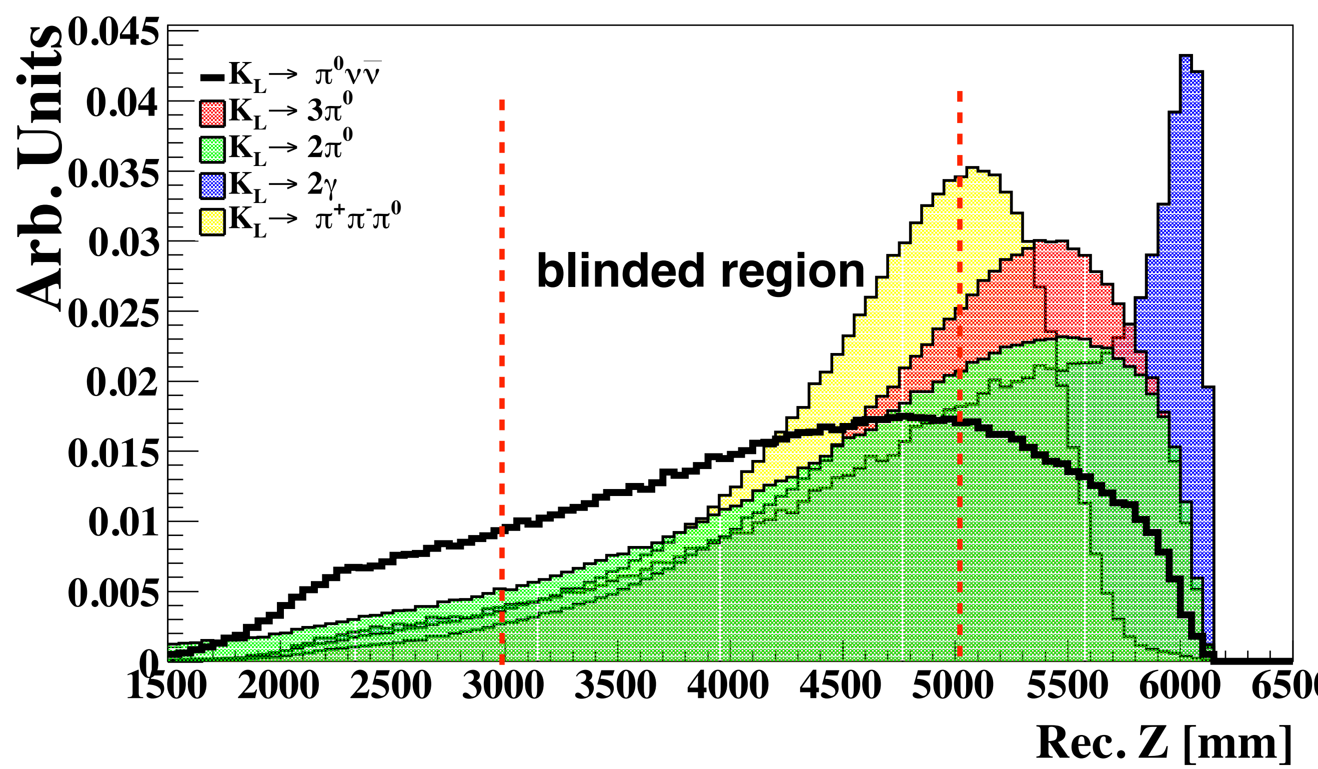
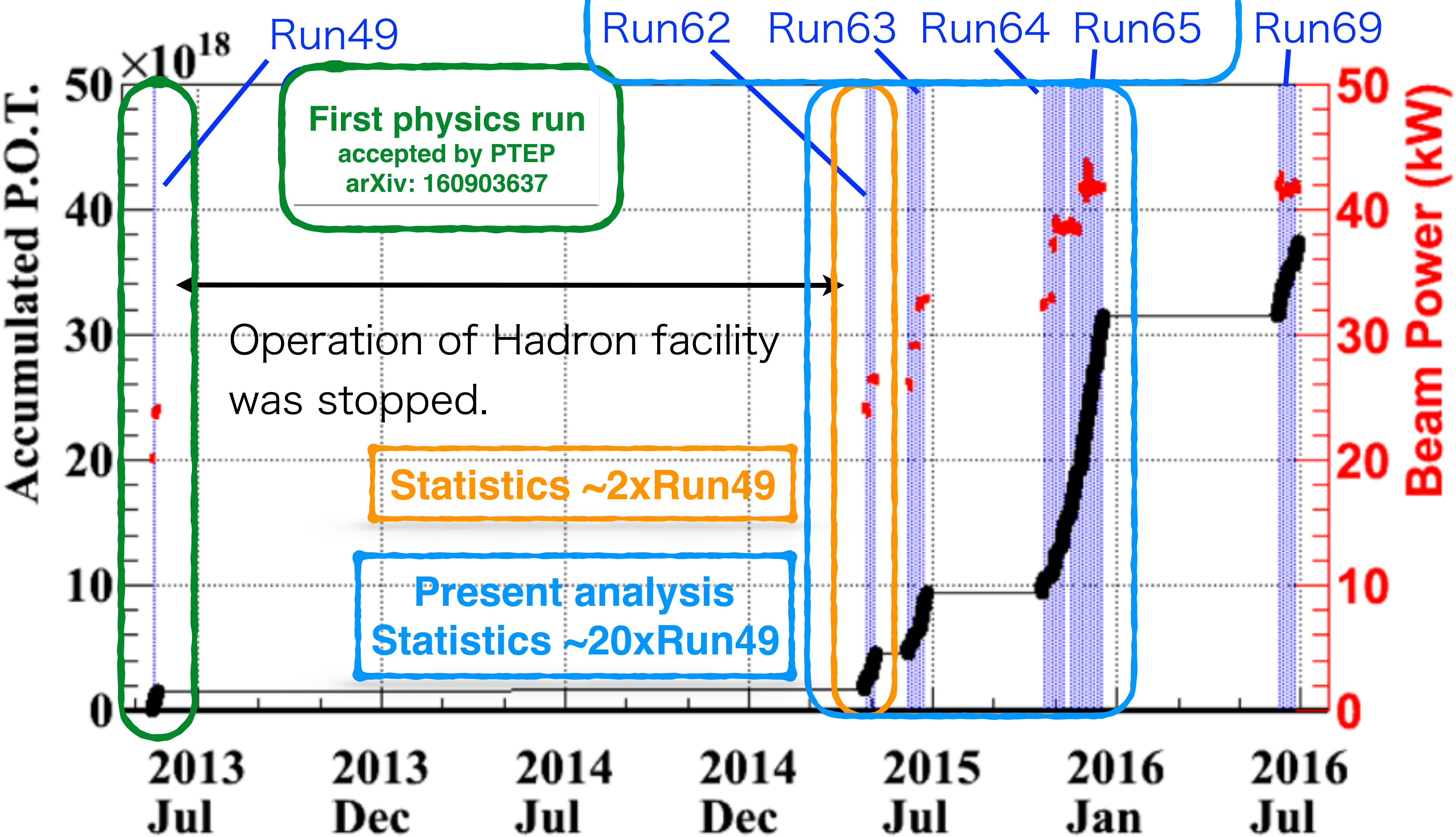


Fig. Monte Carlo of signal and background distributions

Chronicle of KOTO runs



Results from 2013 run49 accepted for publication

PTEP

Prog. Theor. Exp. Phys. **2017**, 021C01 (11 pages)
DOI: 10.1093/ptep/ptx001

A new search for the $K_L \to \pi^0 \nu\bar{\nu}$ and $K_L \to \pi^0 X^0$ decays

J-PARC KOTO collaboration
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We searched for the CP-violating rare decay of neutral kaon, $K_L \to \pi^0 \nu\bar{\nu}$, in data from the first 100 hours of physics running in 2013 of the J-PARC KOTO experiment. One candidate event was observed while 0.34 ± 0.16 background events were expected. We set an upper limit of 5.1×10^{-8} for the branching fraction at the 90% confidence level (C.L.). An upper limit of 3.7×10^{-8} at the 90% C.L. for the $K_L \to \pi^0 X^0$ decay was also set for the first time, where X^0 is an invisible particle with a mass of 135 MeV$/c^2$.

Results: Upper limit on BR ($K_L \text{—>} \pi^0 \nu\nu$)

First Search: Upper limit on BR ($K_L \text{—>} \pi^0 X^0$)

First run takeaways

Summary of background estimation in the signal region

background source	number of events
$K_L \to 2\pi^0$	0.047 ± 0.033
$K_L \to \pi^+\pi^-\pi^0$	0.002 ± 0.002
$K_L \to 2\gamma$	0.030 ± 0.018
pileup of accidental hits	0.014 ± 0.014
other K_L background	0.010 ± 0.005
halo neutrons hitting NCC	0.056 ± 0.056
halo neutrons hitting the calorimeter	0.18 ± 0.15
total	0.34 ± 0.16

- Expected/observed ~ 0.34/1
- Major contribution from neutrons ~70%

Background sources

1. Halo neutrons hitting NCC (π^0)

2. Halo neutrons hitting CsI

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

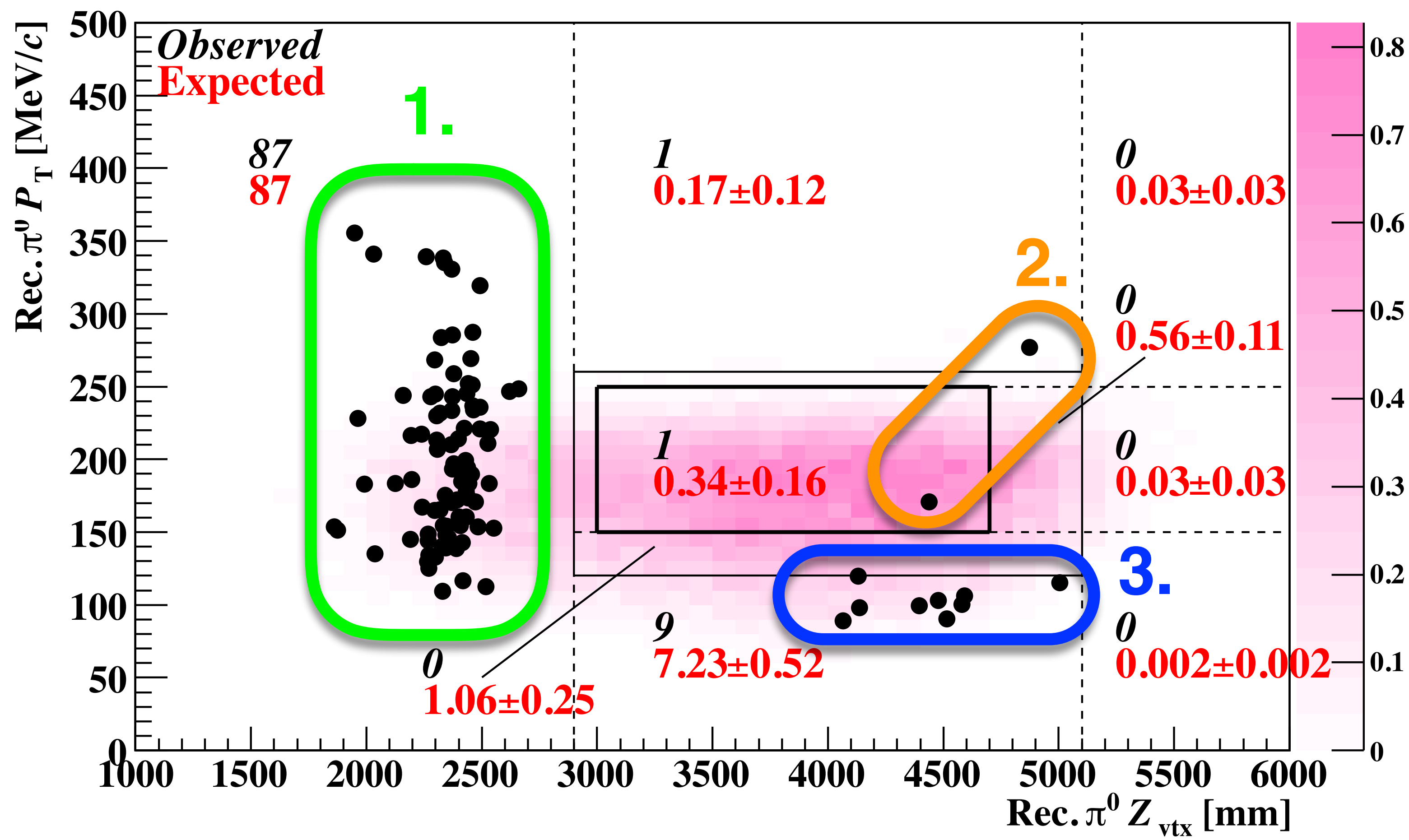


Fig. Reconstructed π^0 Pt vs. decay vertex postion

Updates to reduce BG sources

Reduction of background sources

- Source 1:
  - Improved surface alignment of collimators
  - Thinner vacuum window: 125 µm —>12.5 µm
- Source 2:
  - Specific experimental runs to study neutron induced events using an aluminum target
    - Neural Networks cut (Cluster Shape Discrimination) = 1/1500 reduction of original
    - Pulse-shape-likelihood cut =1/10 reduction of original
- Source 3:
  - Added downstream detectors to identify particles escaping down beam pipe
    - Beam pipe charge veto = reduction by a factor of 10
    - New BHCV ~ reduced counting rate ~65% and accidental loss ~40%

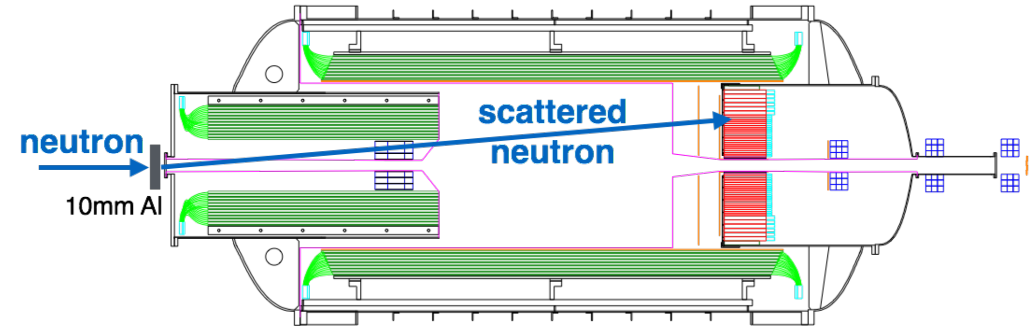


Fig. Depiction of special Al run

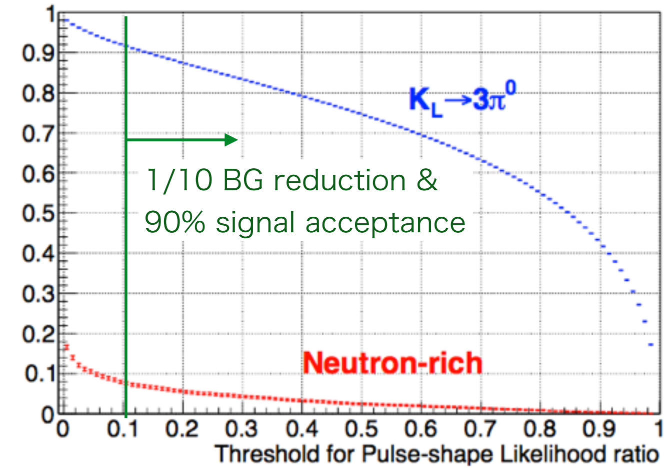


Fig. Pulse-shape-likelihood ratio

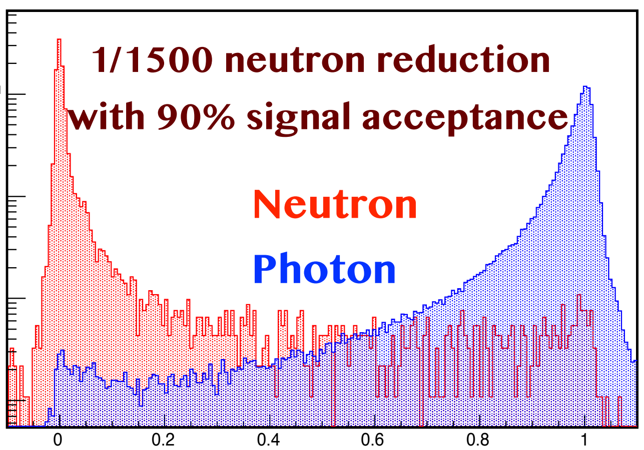


Fig. Neural Net outcome of cluster shape cut

Events without BPCV veto

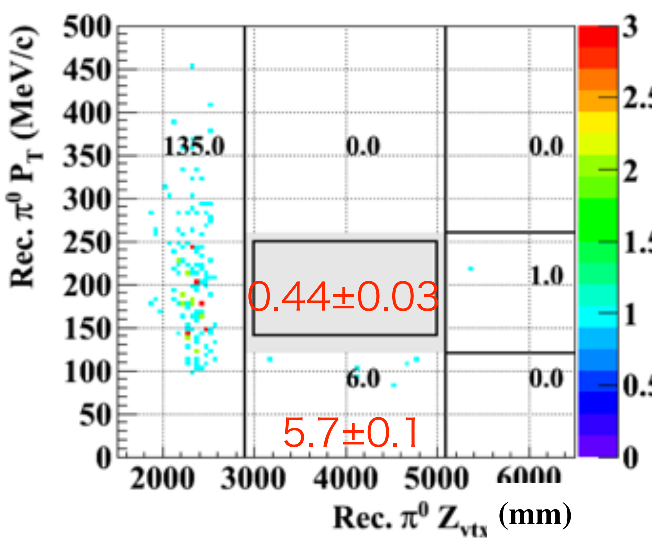


Fig. Reconstructed Pt vs. decay vertex postion

Events with BPCV veto

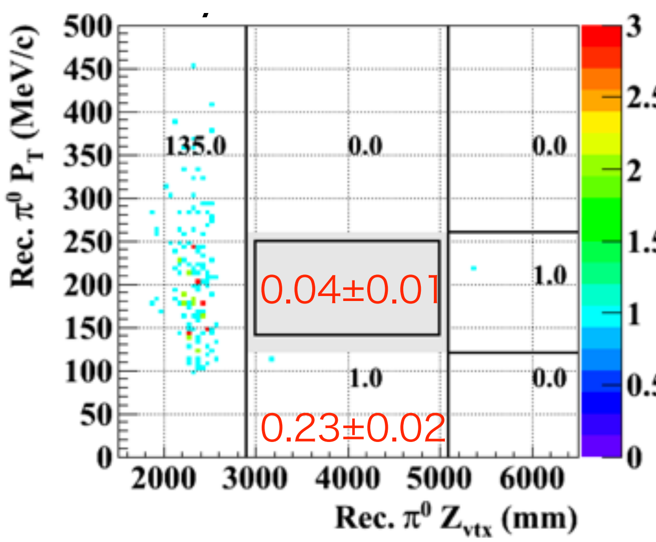


Fig. Reconstructed Pt vs. decay vertex position

Preliminary results of Run62

Single Event Sensitivity (SES) is a measure of signal ($K_L \longrightarrow \pi^0 \nu\nu$) sensitivity

Increased (SES) attributed to:

- Measured K_L flux and a wider signal region due to improved BG reduction methods and upgrades to detectors

$$SES = \frac{1}{K_{yield} \cdot Acceptance_{signal}}$$

Estimated background events in Run 62	
Source	**Number of Events**
KL—>2π⁰	0.04±0.03
KL—>π⁺π⁻π⁰	0.04±0.01
Halo neutrons hitting NCC	0.04±0.04
Halo neutrons hitting CsI	0.05±0.02
Total	**0.17±0.05**
Single Event Sensitivity	**5.8 x 10⁻⁹**

work in progress

$K_L \longrightarrow 3\pi^0$

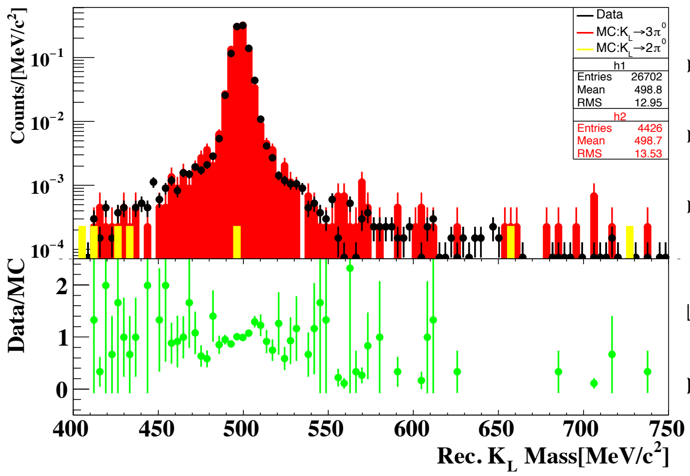


Fig. Data/MC Comparison

$K_L \longrightarrow 2\pi^0$

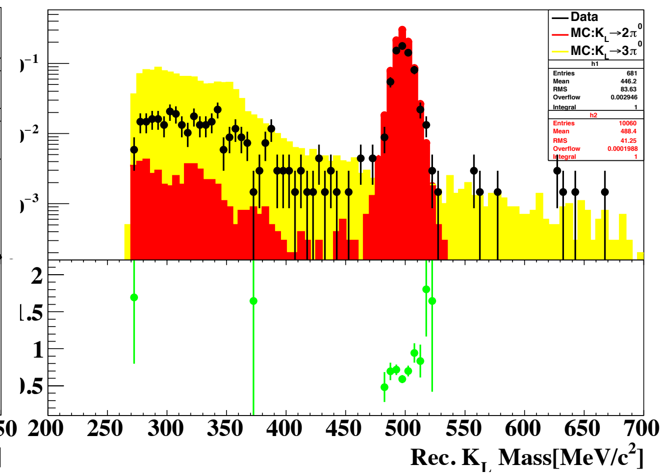


Fig. Data/MC Comparison

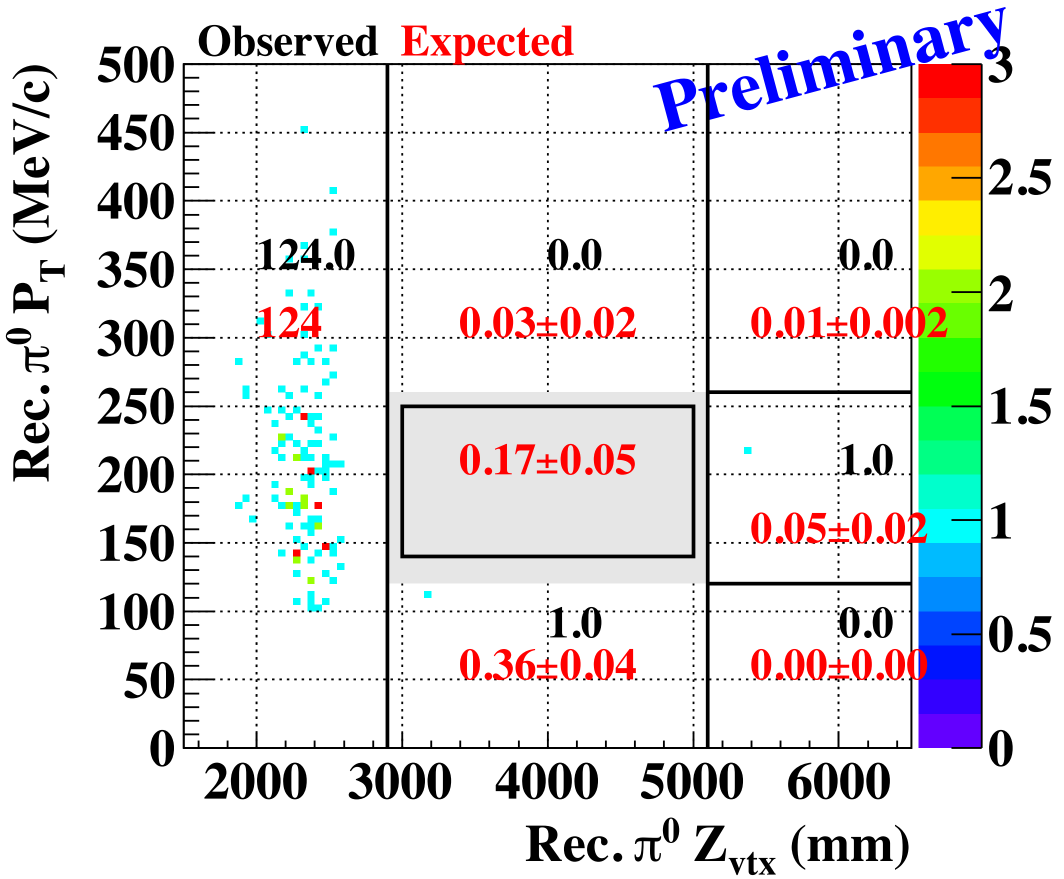


Fig. Reconstructed π⁰ Pt vs. decay vertex postion

Estimate of all 2015 data

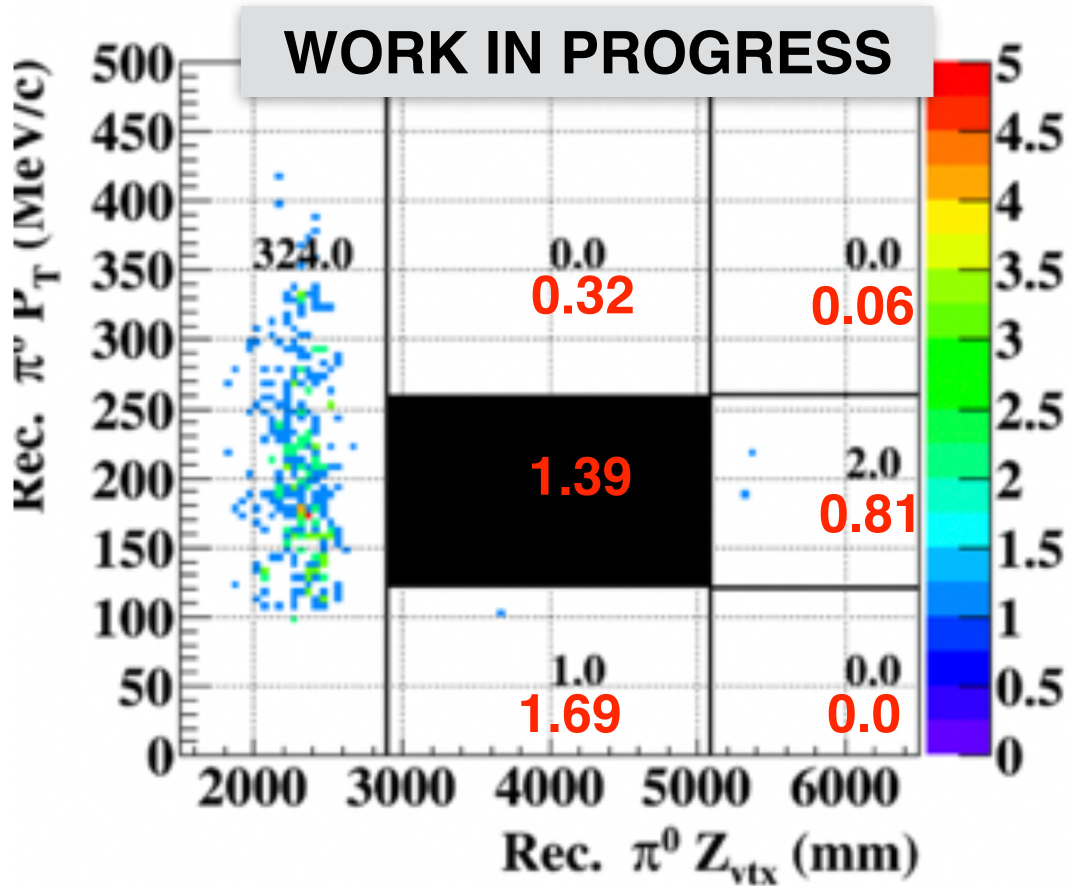


Fig. Reconstructed π^0 Pt vs. decay vertex position

Black: Observed

Red: Expected

Estimated single event sensitivity = 1.1×10^{-9}

Estimated background events		
Source	***Run 62 Number of Events***	***All 2015***
KL—>2π^0	0.04±0.03	**0.07**
KL—>$\pi^+\pi^-\pi^0$	0.04±0.01	**0.23**
Halo neutrons hitting NCC (upstream)	0.04±0.04	**0.13**
Halo neutrons hitting CsI	0.05±0.02	**0.34**
CV π^0		**0.14**
CV η		**0.48**
Total	**0.17+0.05**	**1.39**

Summary

KOTO experiment performed at J-PARC is a dedicated search for the $K_L \to \pi^0 \nu\nu$ decay

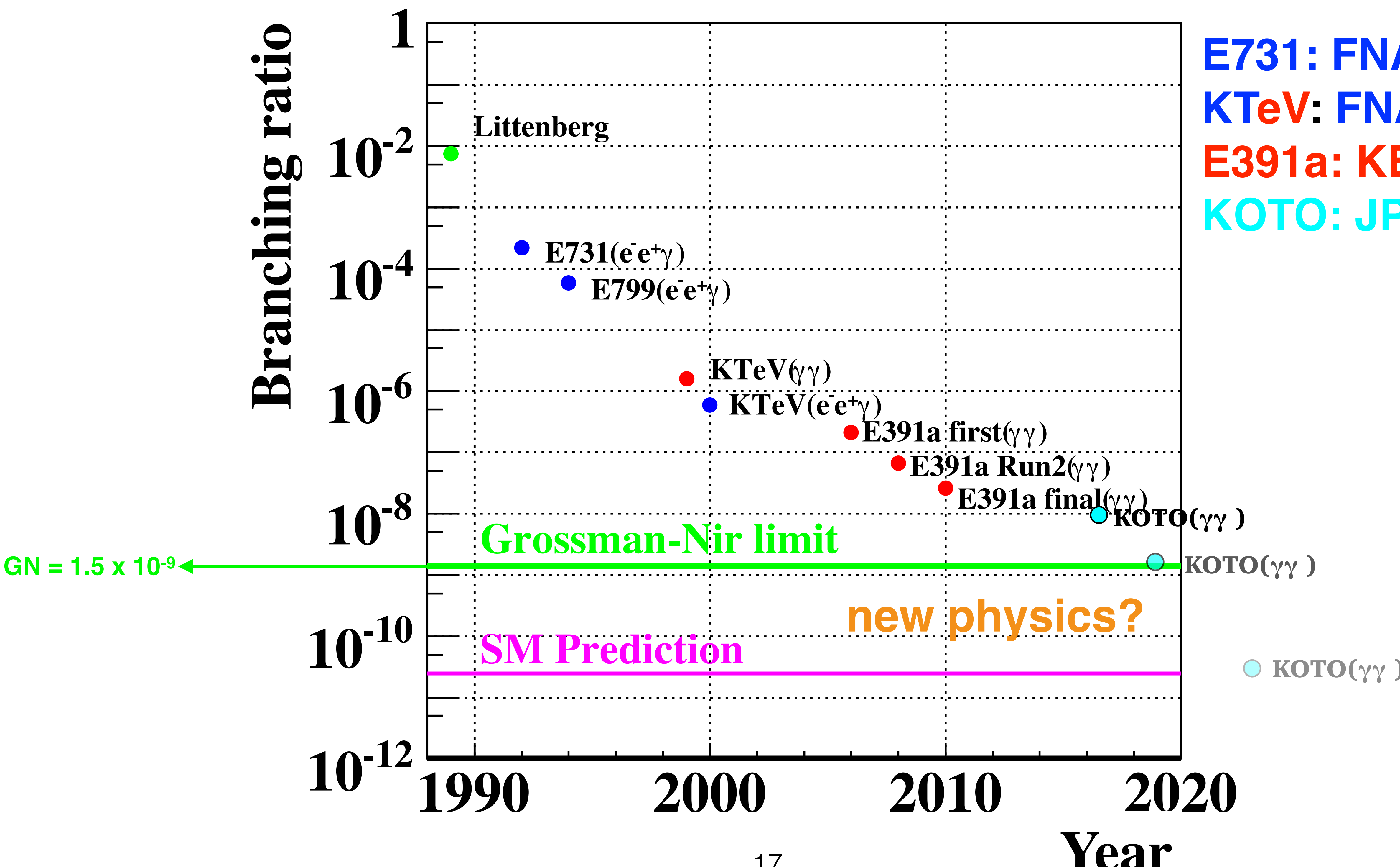
Summary of KOTO first results

- KOTO Run 49 set a BR($K_L \to \pi^0 \nu\nu$) upper limit of < 5.8×10^{-8} (90% confidence)
- KOTO Run 49 set a BR($K_L \to \pi^0 X^0$) upper limit of < 3.7×10^{-8} (90% confidence), which is the first upper limit for X^0 mass of 135 MeV/c^2

Present status

- Collected a data set (2015 runs) ~ 20 times larger than the 2013 published results
- Confirmed that major BGs observed in 2013 run are well suppressed
- Analysis is in progress:
  - Focused on continued BG estimation and suppression
  - With the current calculated flux, we estimate a SES of 5.82×10^{-9} for Run 62, twice that of Run 49, and a SES of 1.1×10^{-9} for the entire 2015 data set
- After completing analysis of all 2015 data and finalization of SES, we expect to approach Grossman-Nir limit (theoretical model independent limit ~1.5×10^{-9})

Outlook



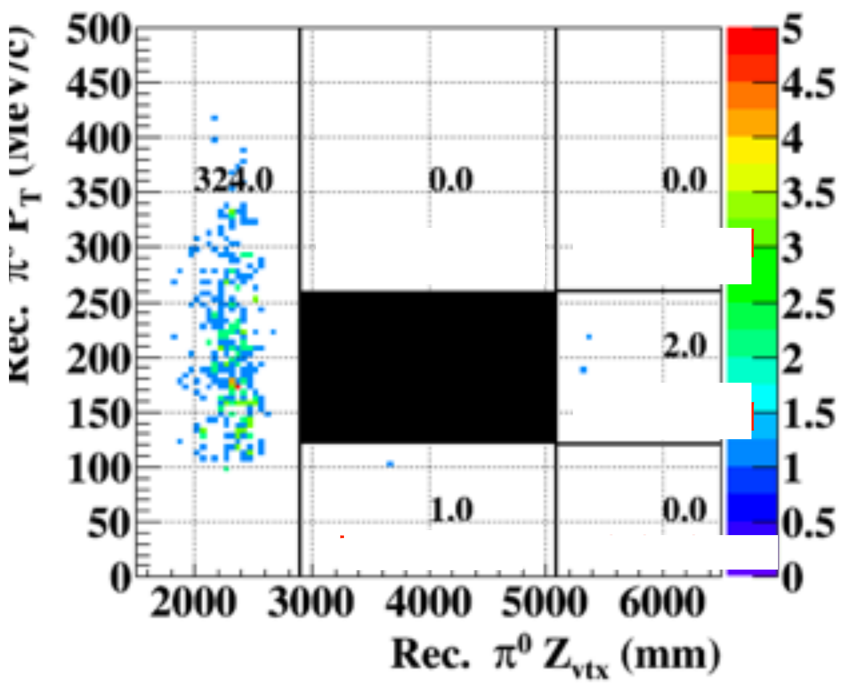
E731: FNAL
KTeV: FNAL/KEK
E391a: KEK
KOTO: JPARC

Thank You

Supplemental

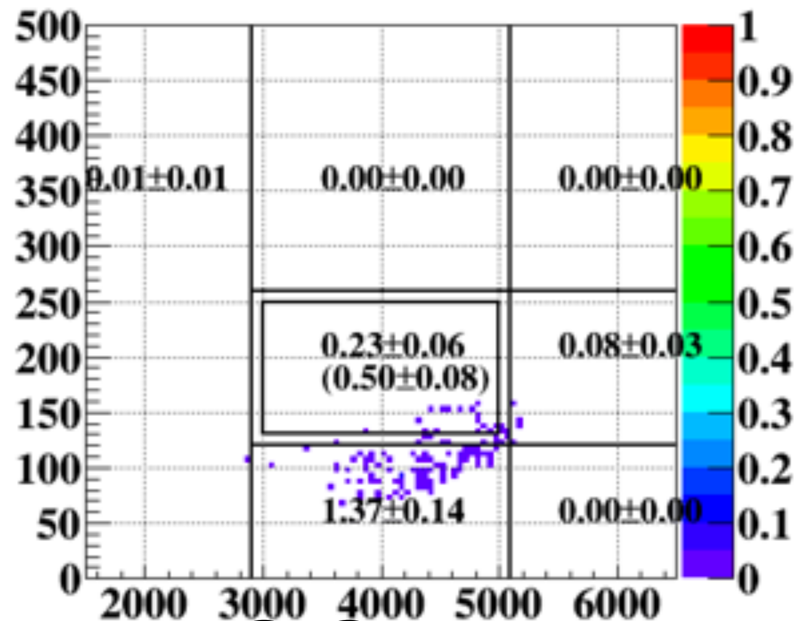
2015 Background Estimations

Data

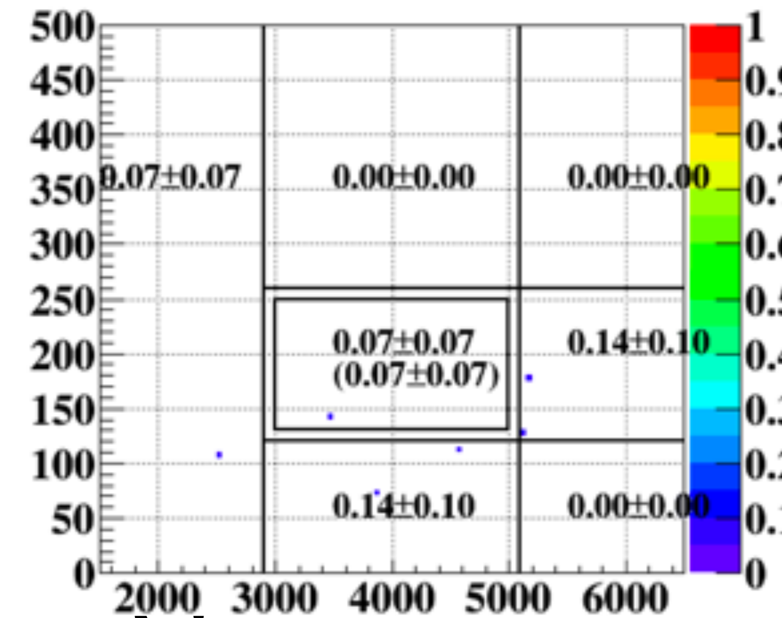


BG source	#BG
$K_L \to 2\pi^0$	0.07±0.07
$K_L \to \pi^+\pi^-\pi^0$	0.23±0.06
Upstream events	0.13±0.07
Hadron cluster	0.34±0.11
Other BG sources	Under estimation

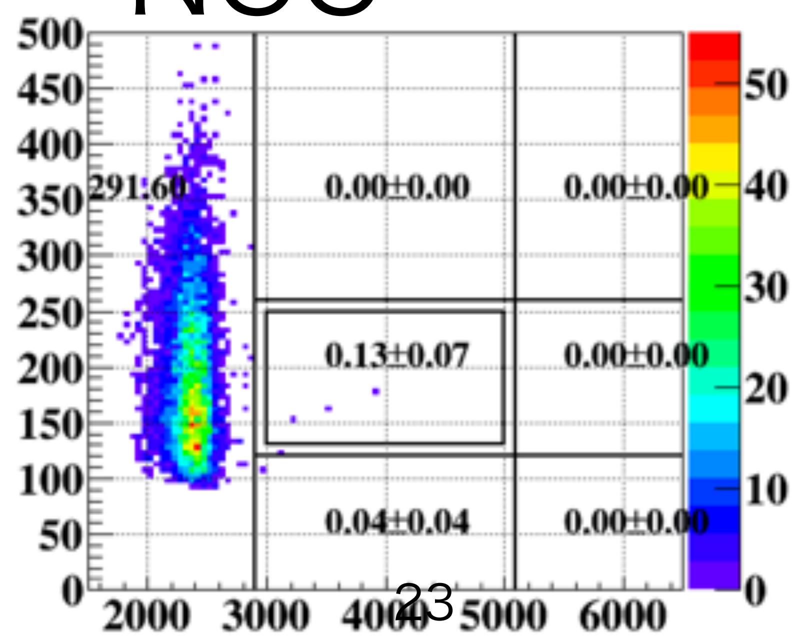
KL->pipipi0



KL->2pi0



NCC



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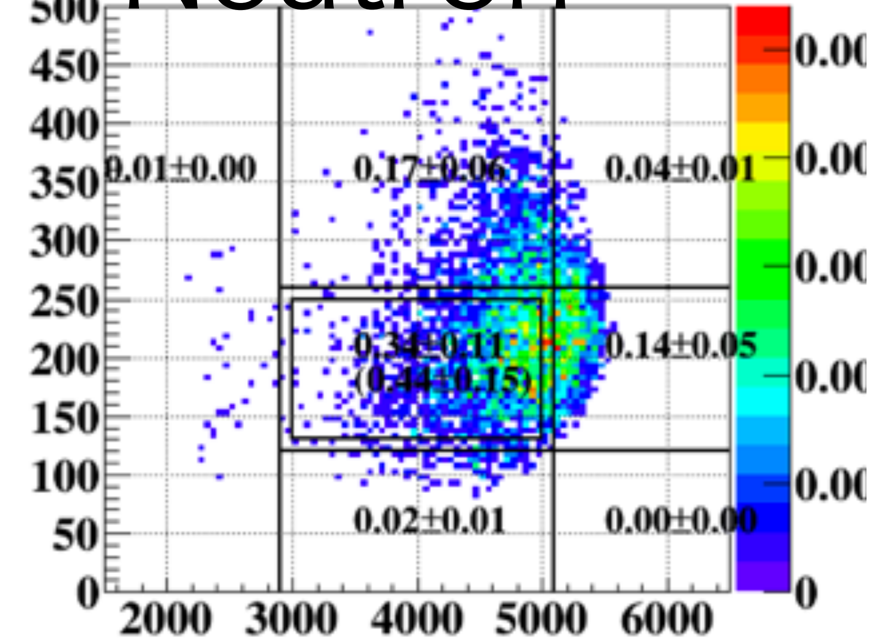
Neutron



Hermetic detector

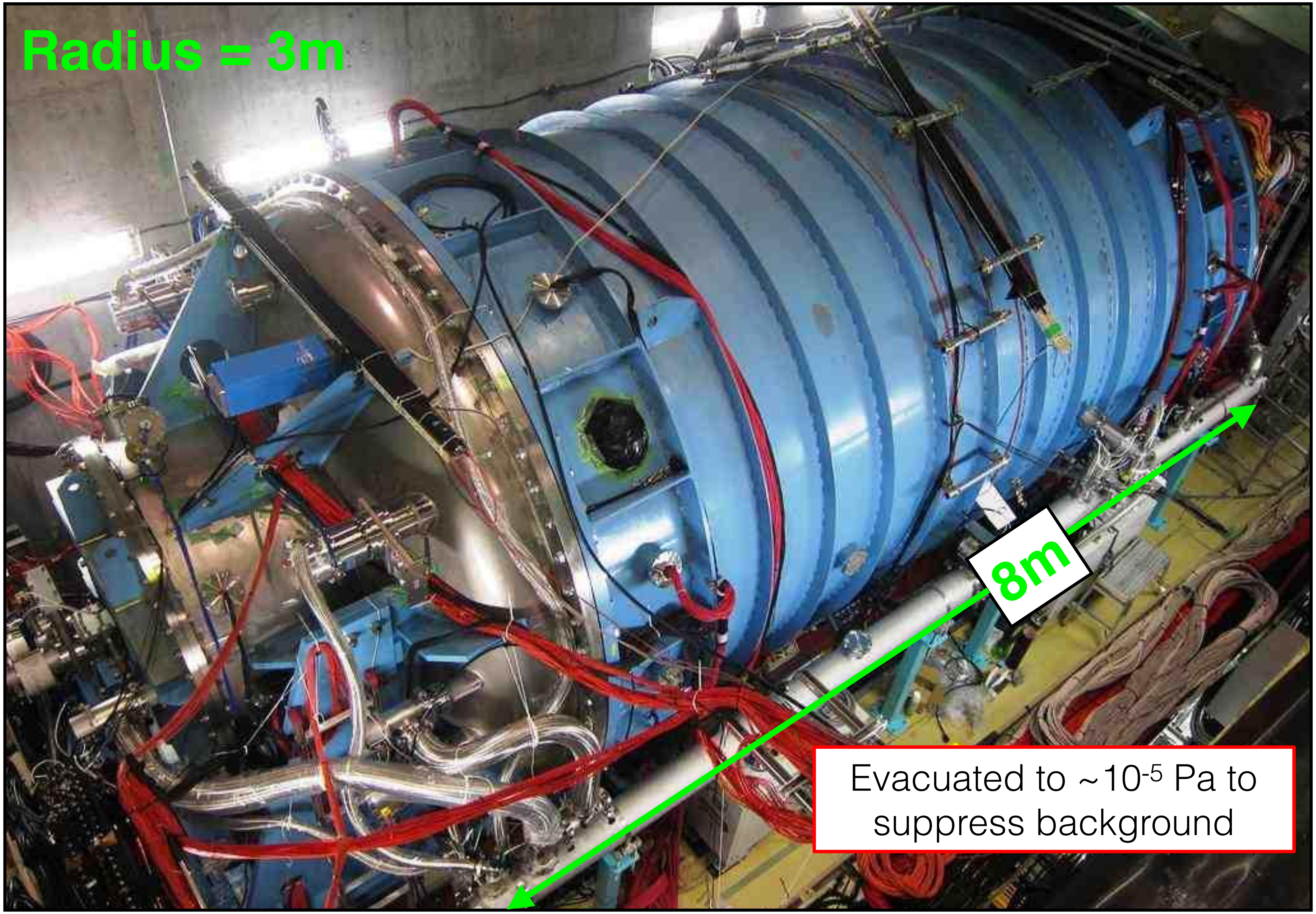


Fig. Outer vacuum container houses all main KOTO detectors

Experimental hall

Hadron Experimental Facility (HEF)

- Intense 30 GeV proton beam with ~ a 50% duty factor
- Secondary neutral beam is extracted (16^{o}) and directed to KOTO detector

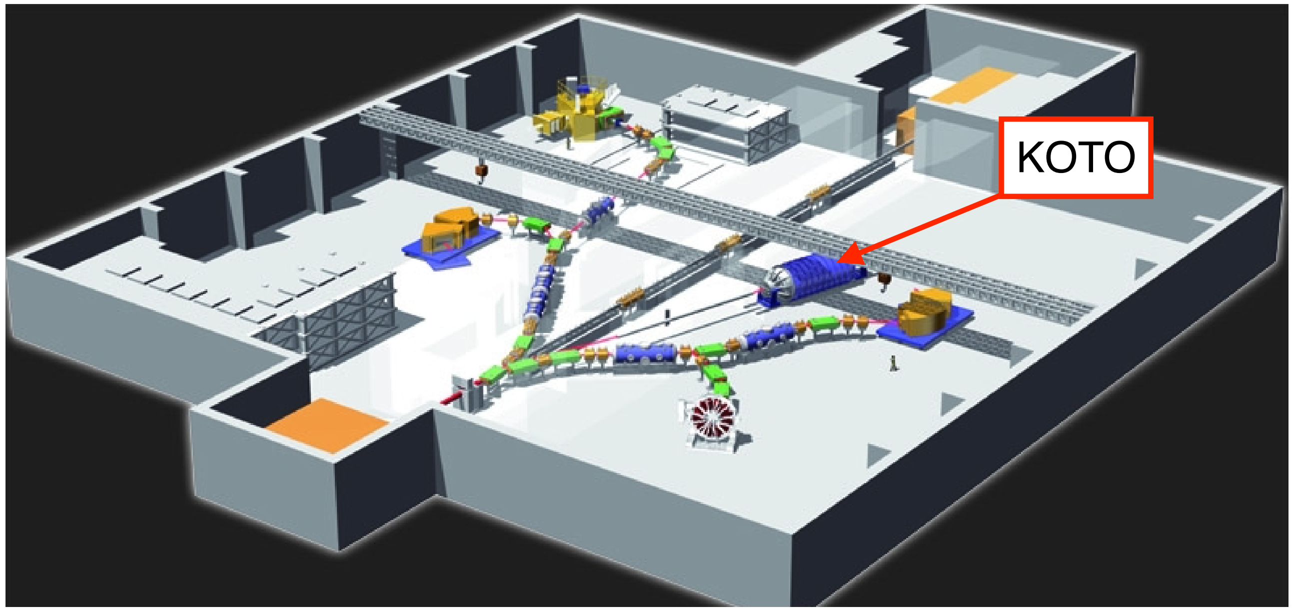


Fig. 3D view of Hadron Experimental Facility

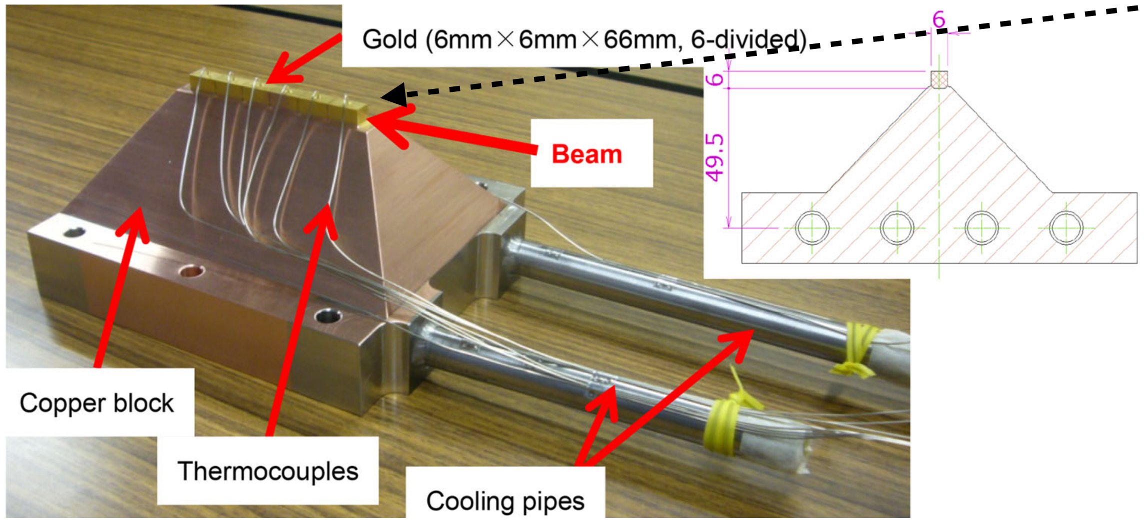


Fig. Target used for KOTO physics experiment

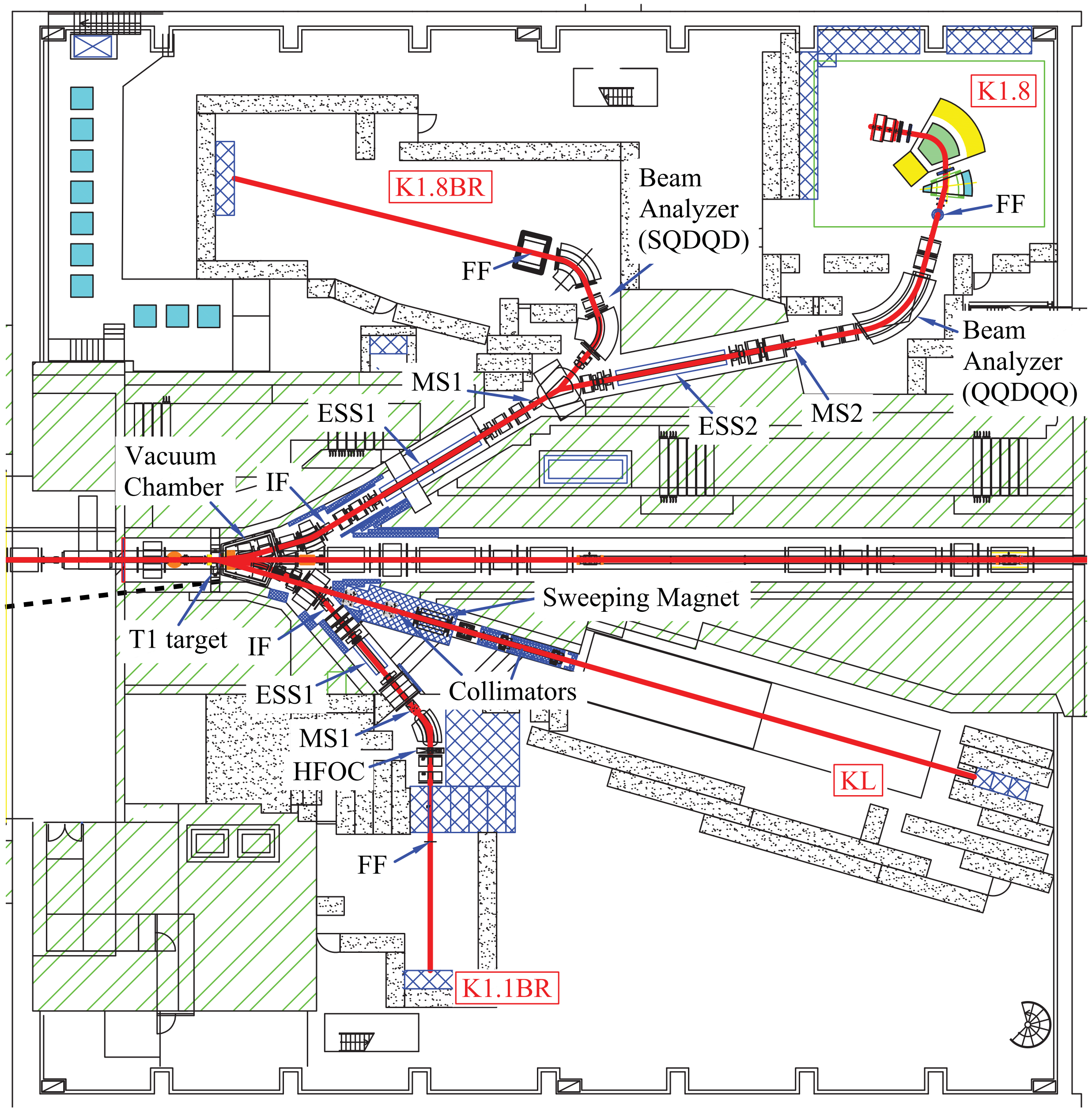


Fig. Layout inside Hadron Experimental Facility

KOTO neutral beam

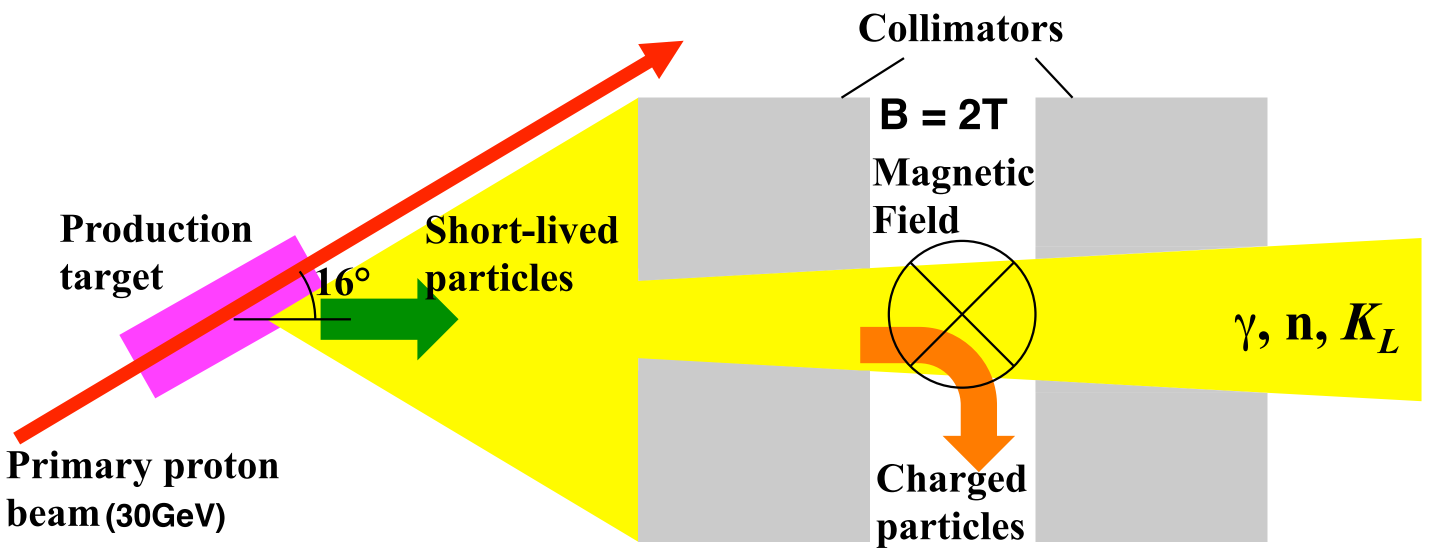


Fig. Depiction of neutral beam line production

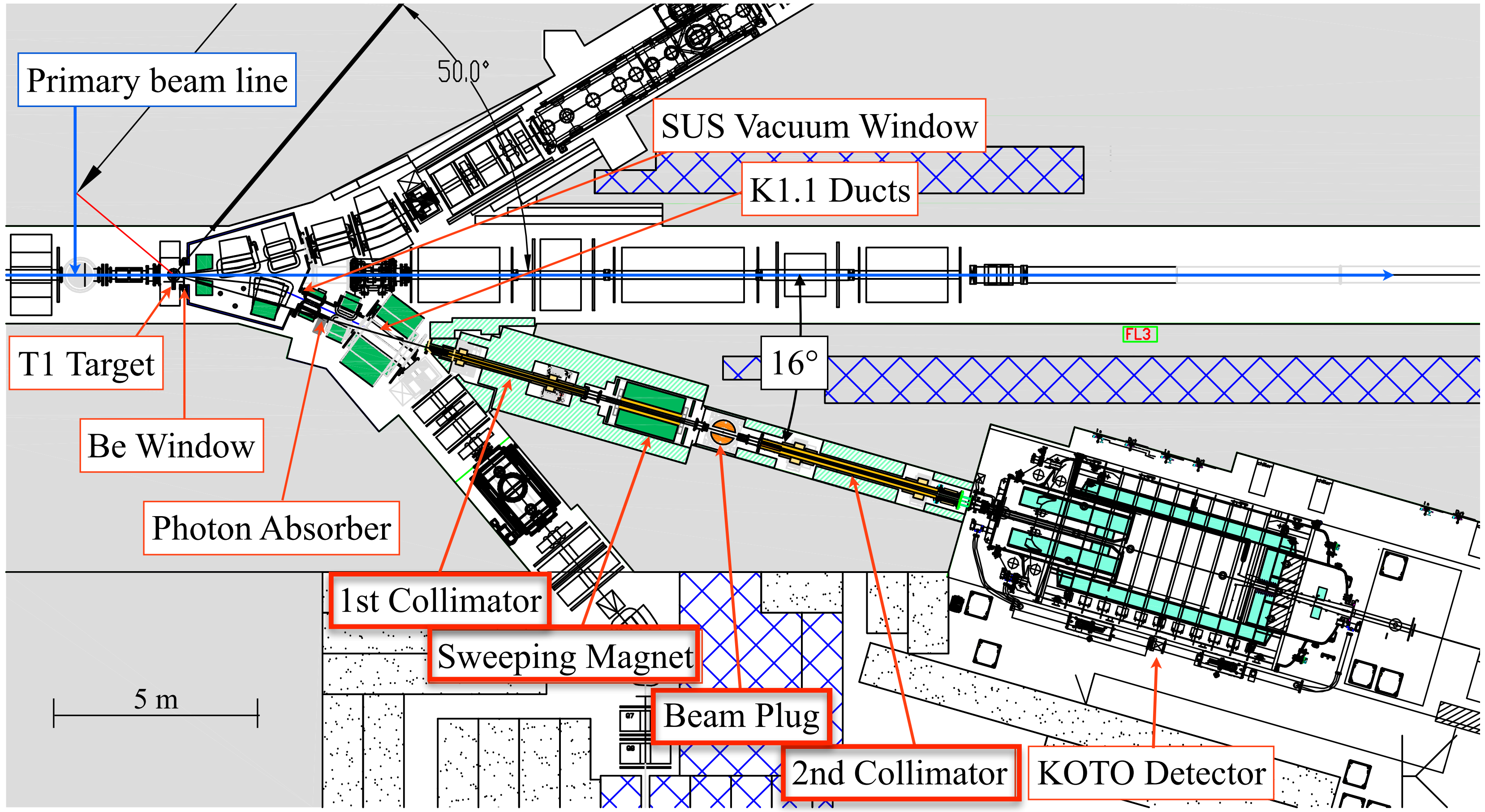


Fig. Layout inside Hadron Hall

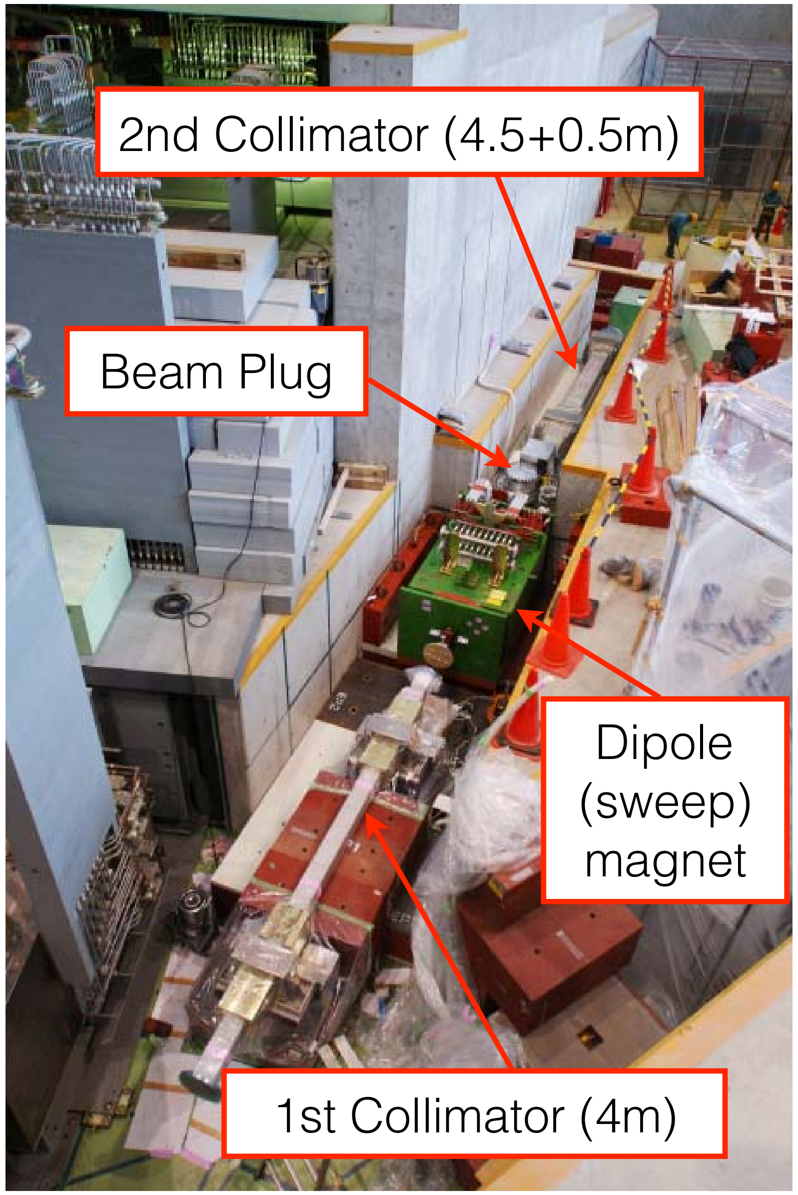


Fig. Secondary beam line

Target to detector distance = 21.5 m

KOTO detectors

Cesium Iodide Calorimeter (CsI)

Cesium Iodide (CsI) Photon Detector

- Main detector of the KOTO experiment
  - 2716 channels (undoped CsI crystals X_0= 27) read out by PMTs

Hermetic veto detectors

- ~1000 channels

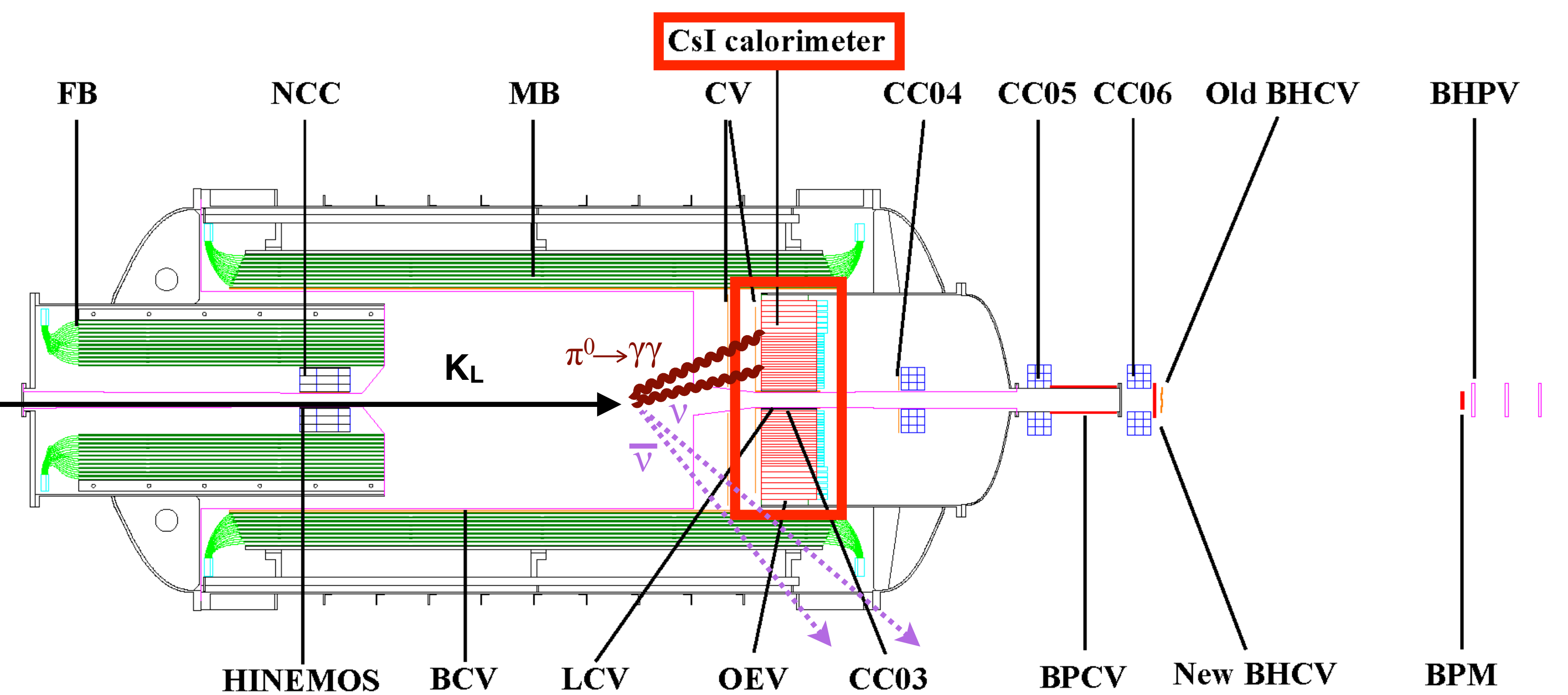


Fig. KOTO detector components

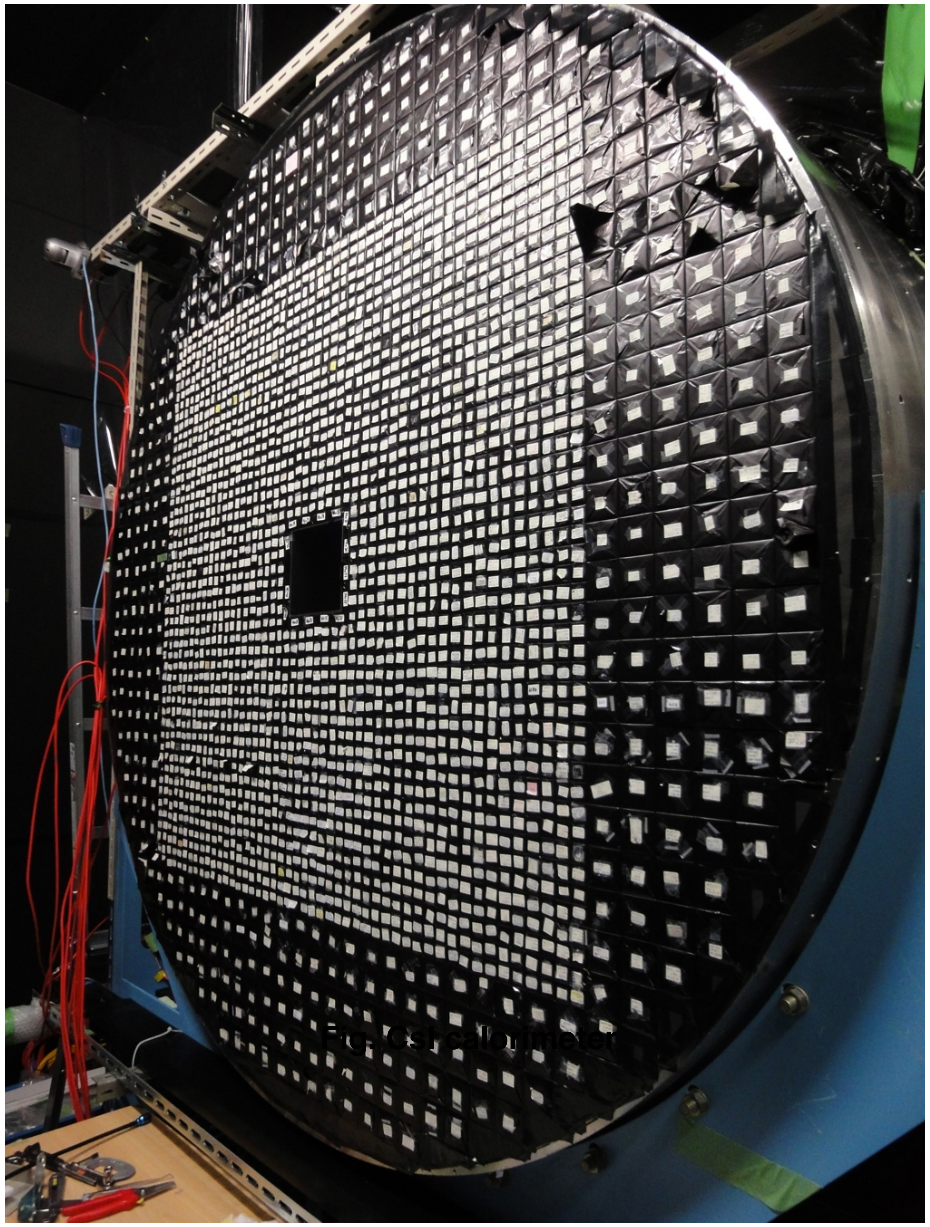


Fig. CsI detector

- Energy resolution (σ_E/E) = 0.99 %/$E_{GeV}^{1/2}$
- Timing resolution (σ_t/E) = 0.13 /$E_{GeV}^{1/2}$ ns
- Position resolution (σ_d/E) = ~2.5 /$E_{GeV}^{1/2}$ mm

Inner Barrel

New barrel photon veto (IB)

- Aimed at reducing $K_L \rightarrow 2\pi^0$ background
- Is a sampling calorimeter (25 layers of 5 mm scintillators and 24 layers of 1 mm lead plates)
- Gained added another 5 X_0 to the MB 13 X_0 to decrease inefficiency of 4 gamma veto
- MC estimated suppression of $K_L \rightarrow 2\pi^0$ of 1/3

Fig. Inner Barrel

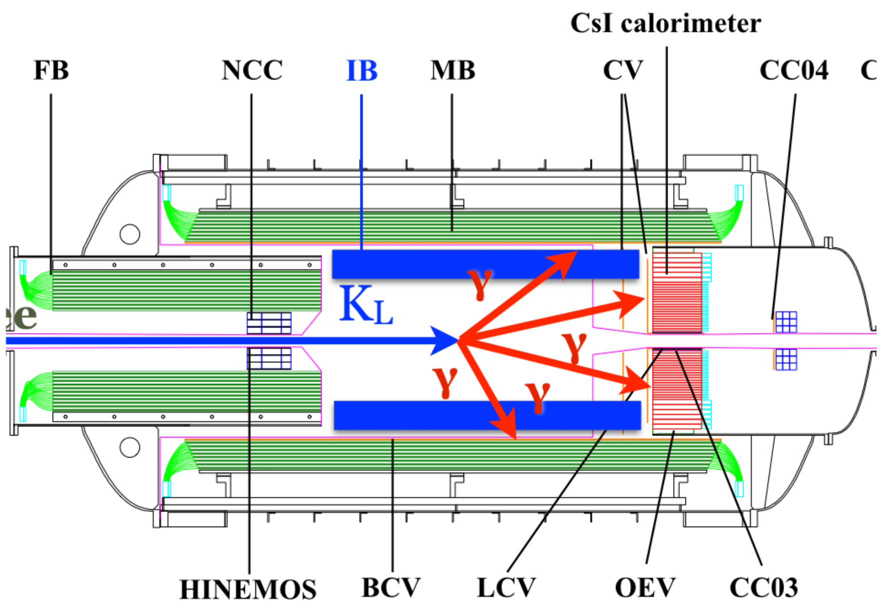
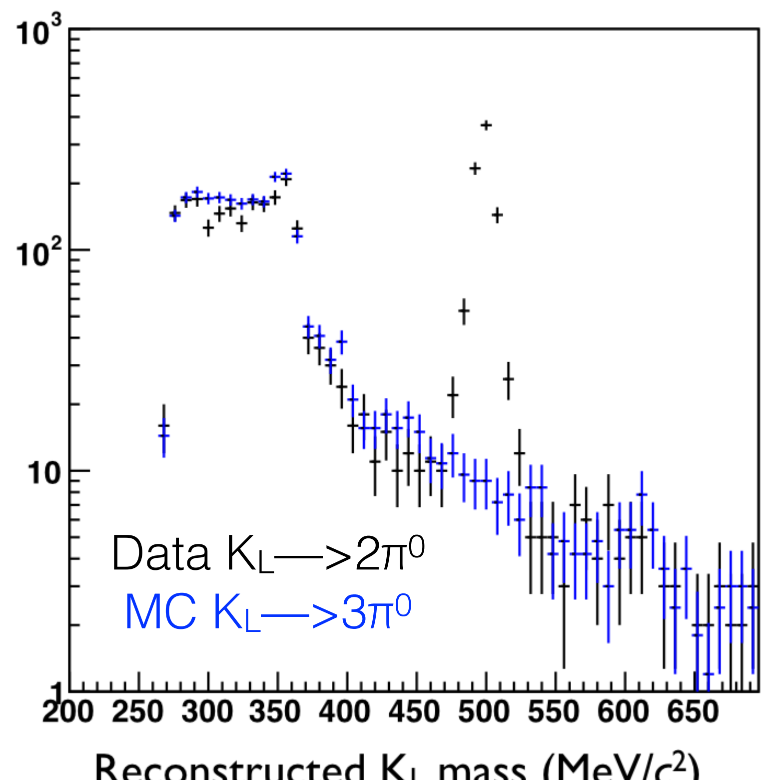


Fig. Depiction of inner barrel placement within MB



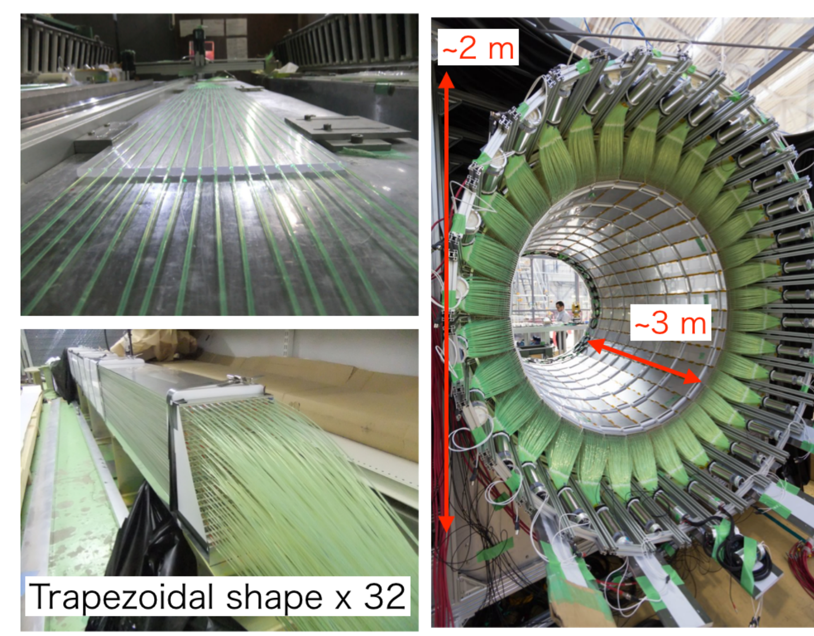
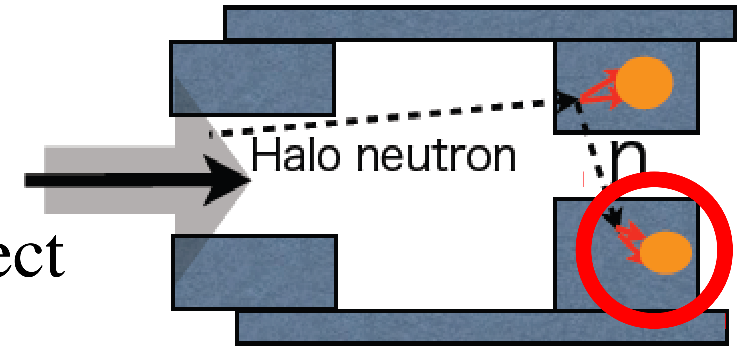


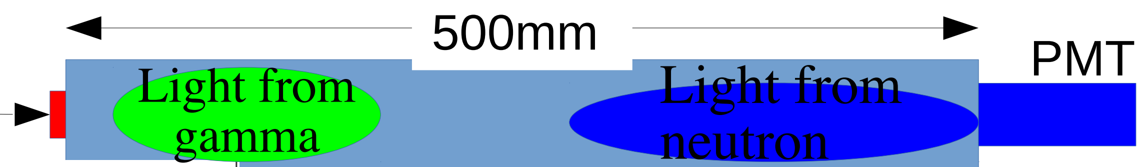
Fig. Inner Barrel

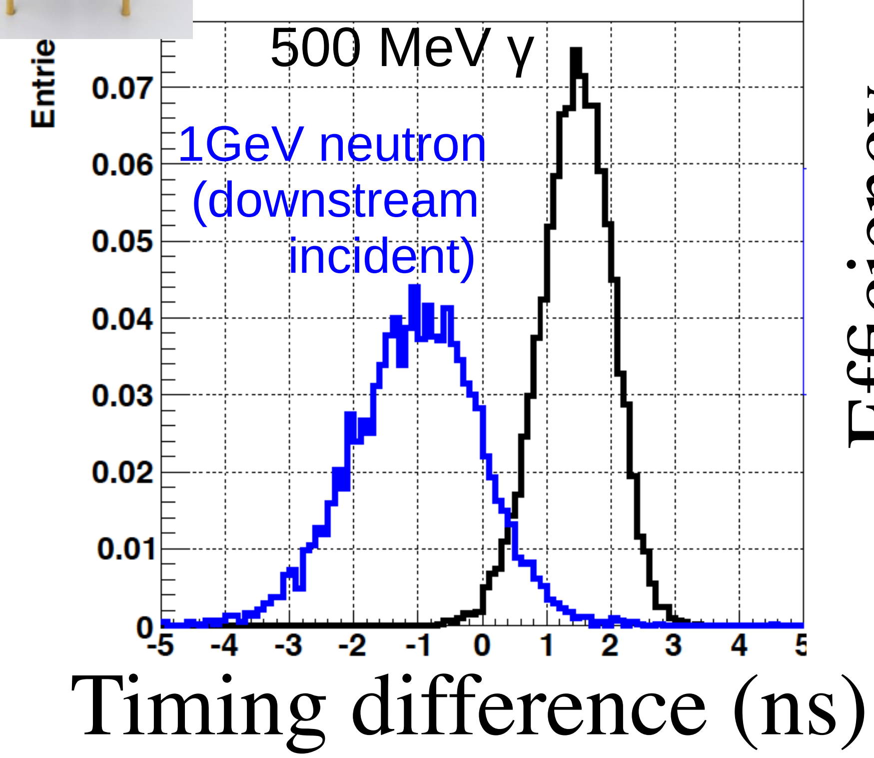
Next steps

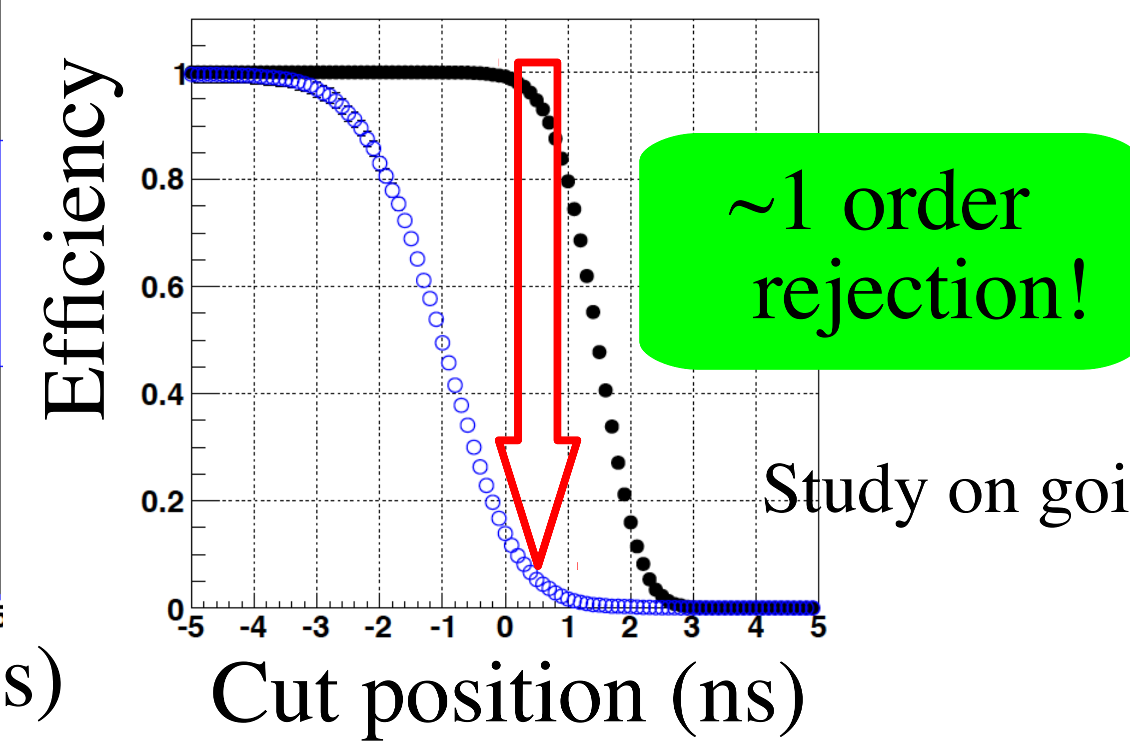
New photo sensor upstream



- Both-end readout of CsI crystal → new project
  - Longitudinal position with timing difference
- New 6mm□ MPPC with Silicone window
  - Low mass, UV sensitive → ~20% photo detection for 310nm







Study on going