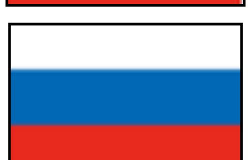
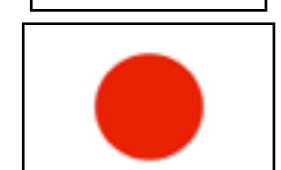
Status of the KOTO experiment (search for $K_L \text{—>} \pi^0 \nu \bar{\nu}$)

Brian Beckford
University of Michigan

KOTO Experiment

The experiment brings together over 50 collaborators from 16 different institutions

Contents

Motivation

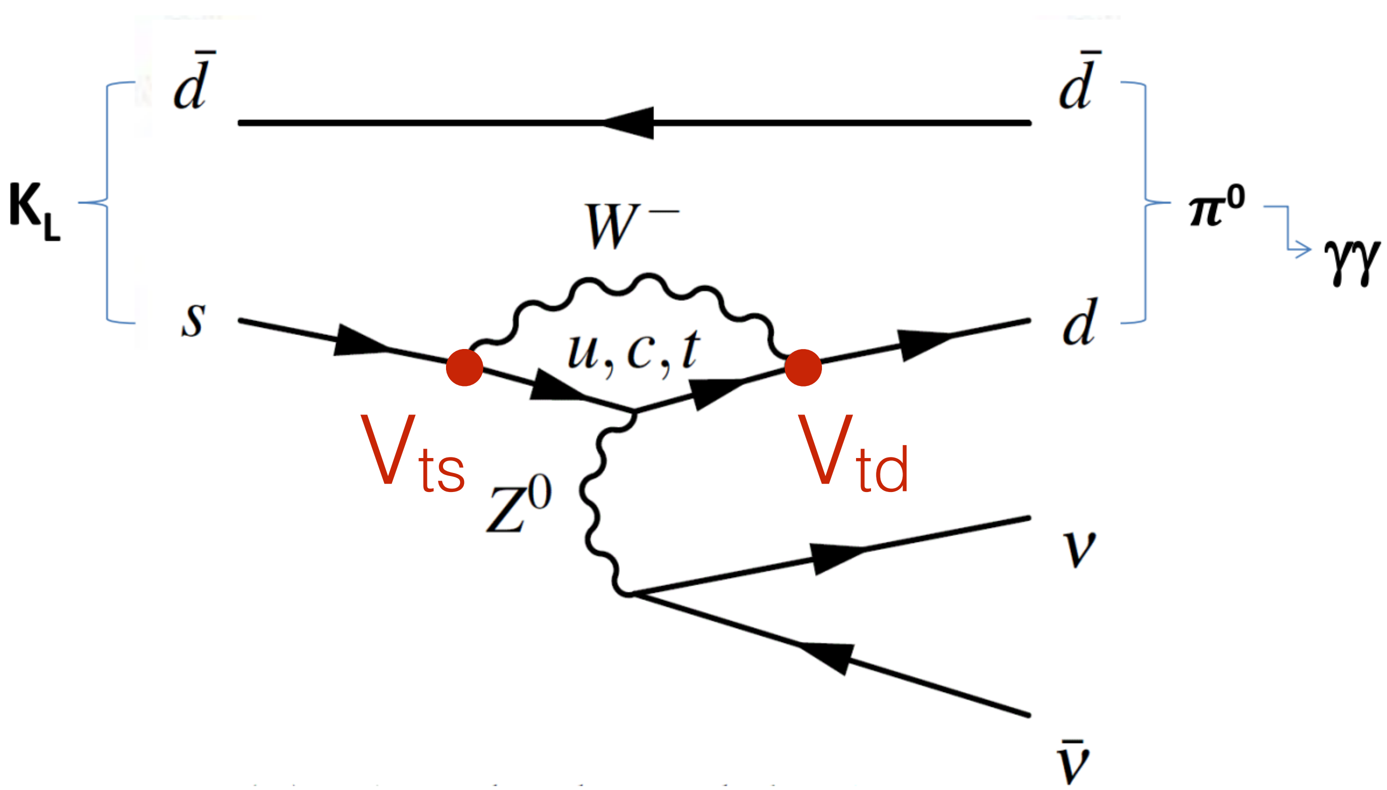
$K_L \to \pi^0 \nu\nu$ rare decay: Why is this important?

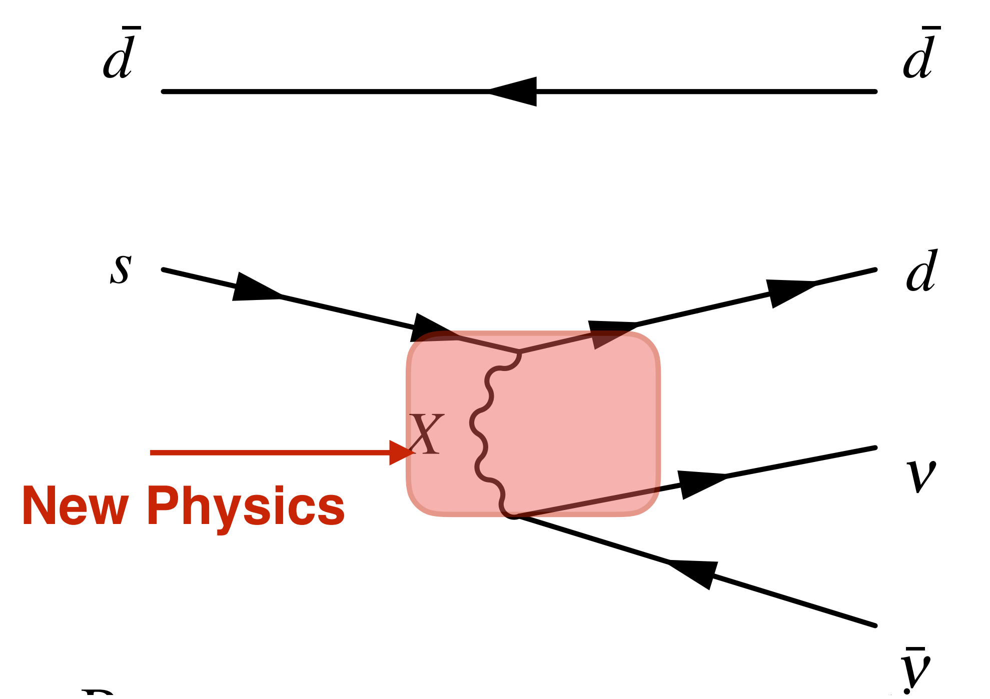
CP

CP

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

- Directly breaks CPV
- Permits probing for New Physics (NP) beyond the standard model
- Process occurs via a flavor changing neutral current (FCNC)
- Validate Standard Model or discover new physics





$K_L \longrightarrow \pi\nu\nu$

Small theoretical uncertainty ~2%

BR is proportional to CKM height

$$A(K_L \to \pi^0\nu\bar{\nu}) \propto A(K^0 \to \pi^0\nu\bar{\nu}) - A(\overline{K}^0 \to \pi^0\nu\bar{\nu})$$
$$\propto V_{td} - V_{td}^*$$
$$\propto \mathrm{Im}V_{td}$$
$$\propto \eta,$$

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

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

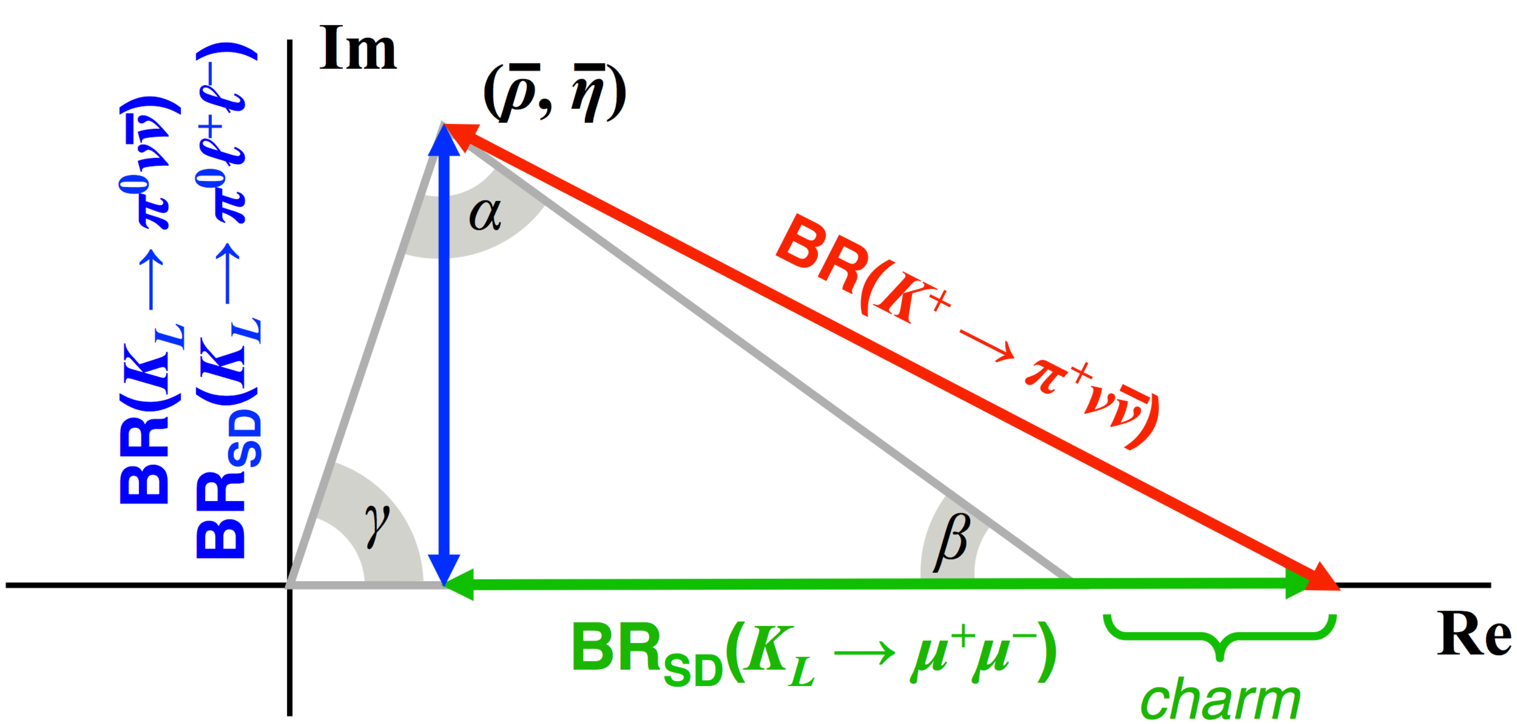
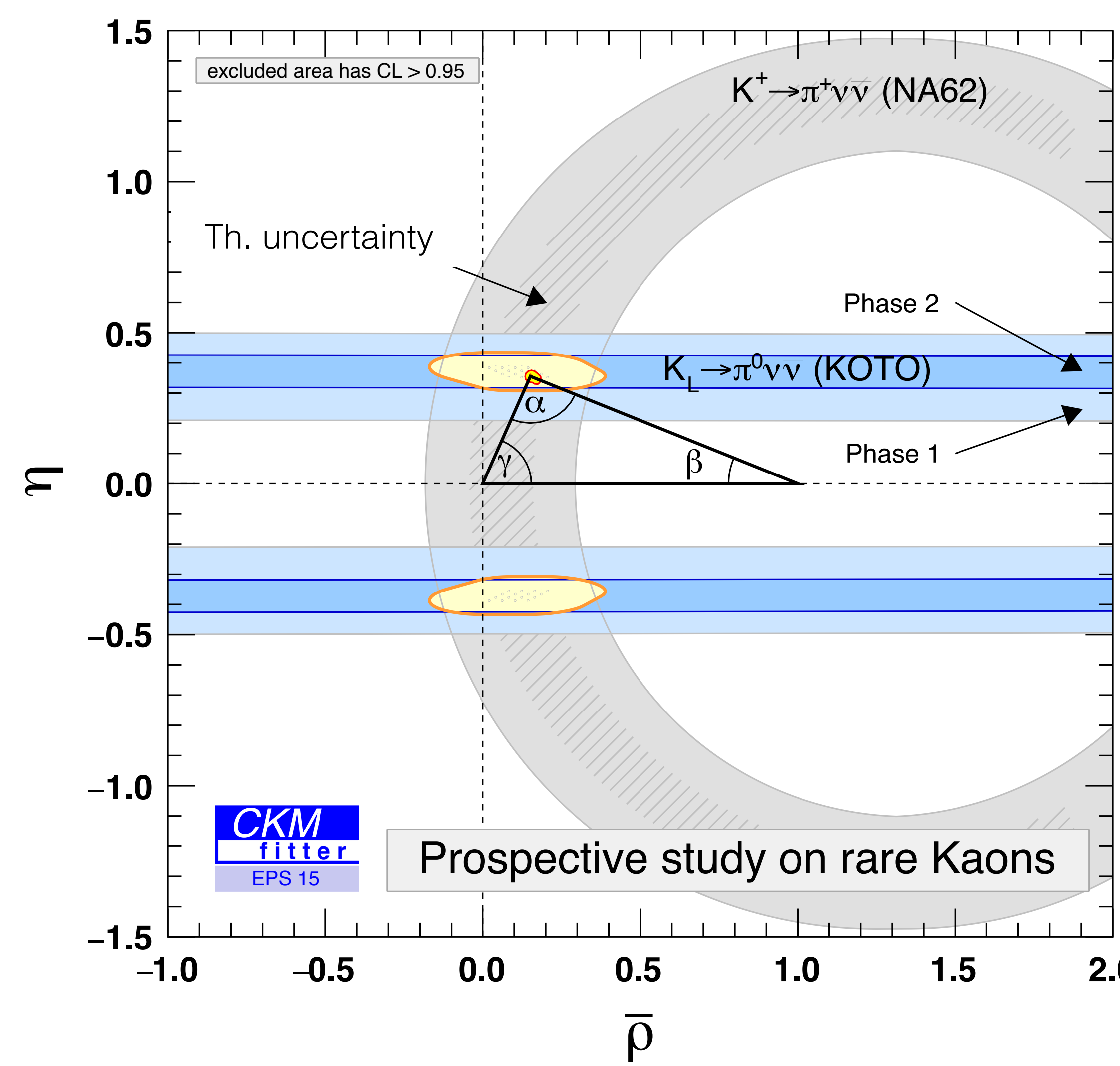


Fig. Unitary triangle

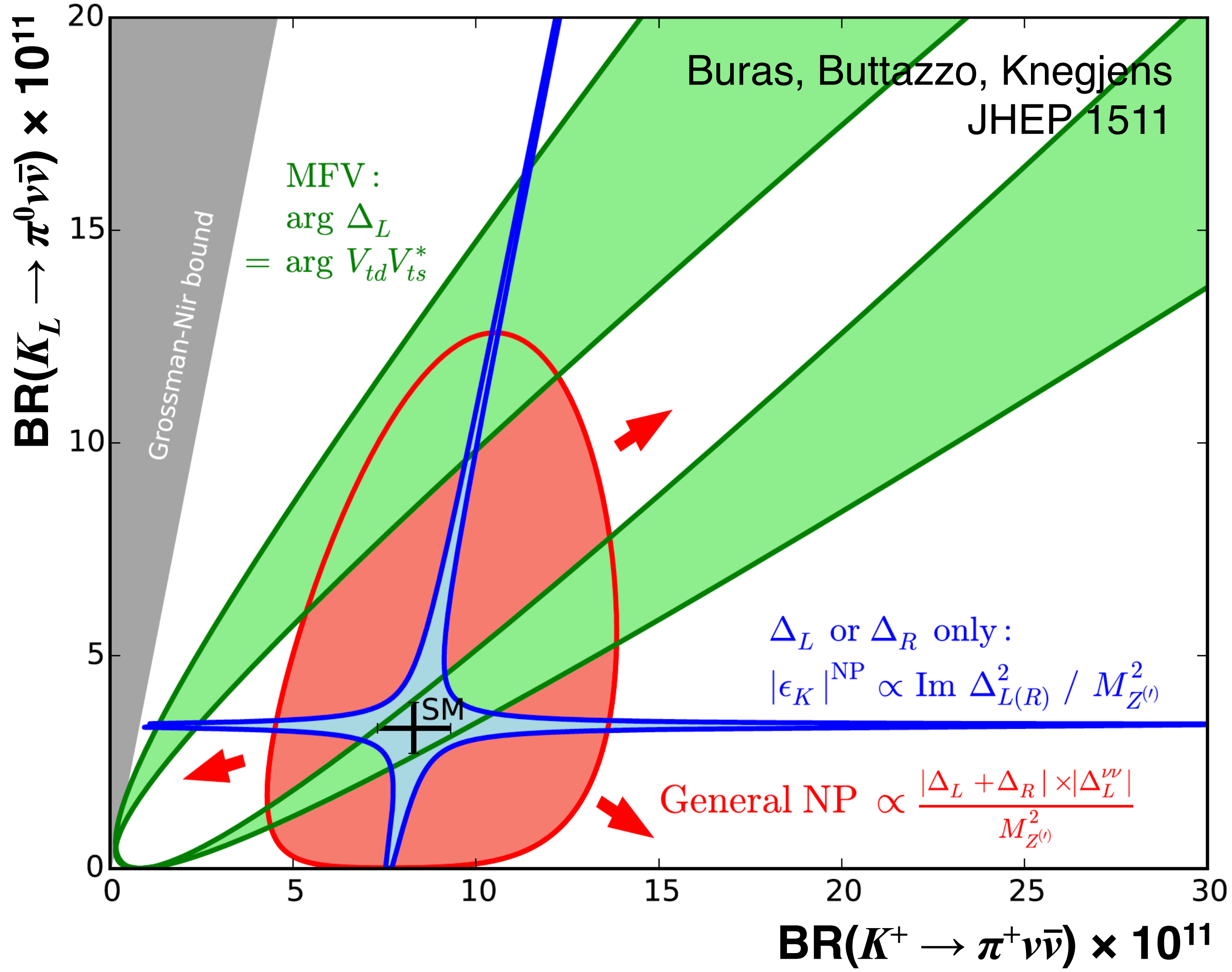


Non agreement between B and K decays indicates new physics

New physics via K_L—>πνν decays

Strong correlations seen in two-branch structure between Beyond Standard Model (BSM) predictions with left-hand/right-hand exclusive FCNC

No correlations in the K—>πνν plane for models with this constraint



- Models with CKM-like flavor structure
  - –Models with MFV
- Models with new flavor-violating interactions in which either LH or RH currents dominate
  - –Z/Z' models with pure LH/RH couplings
  - –Little Higgs with T parity
- Models without above constraints
  - –Randall-Sundrum

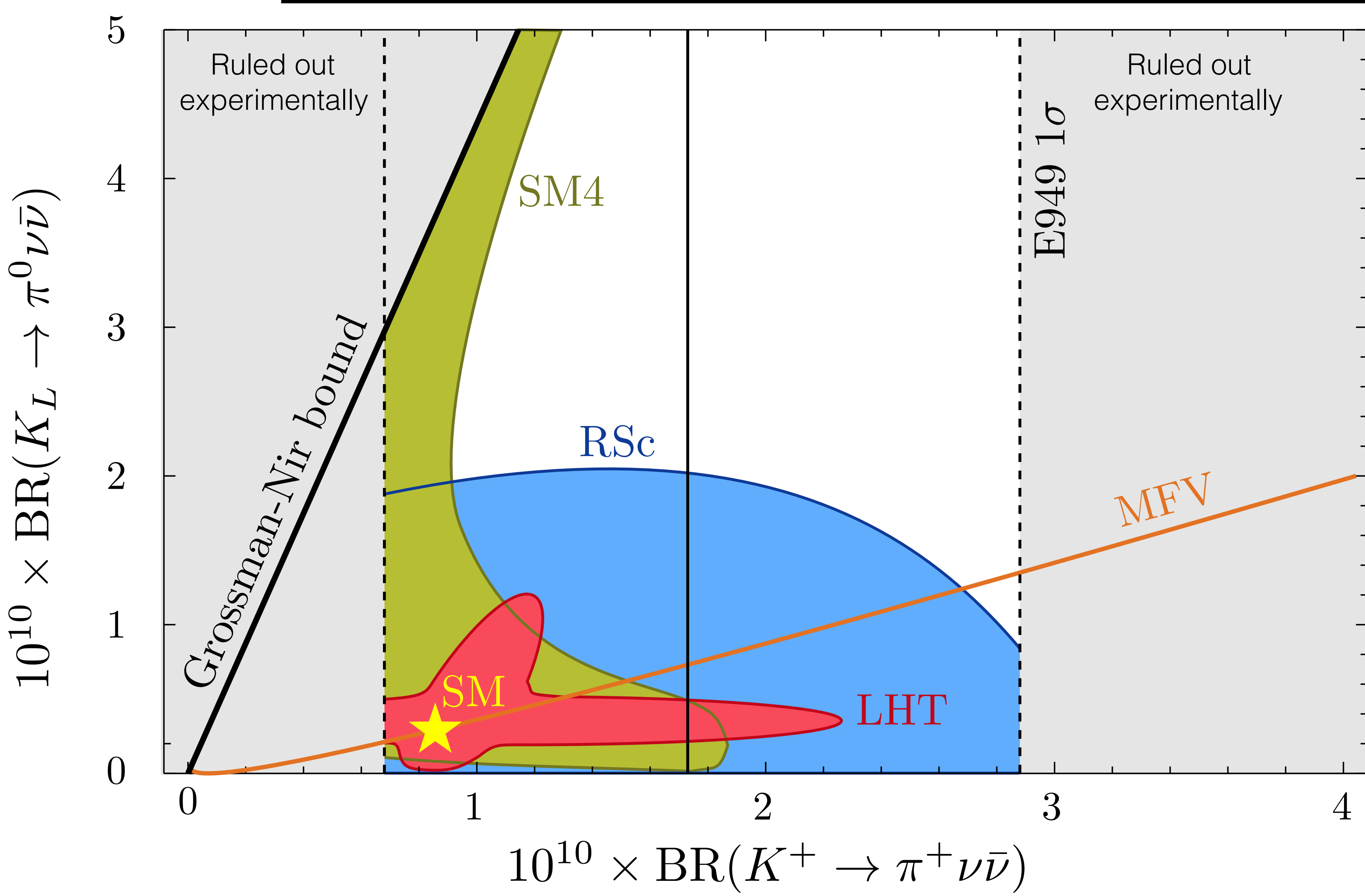
Fig. Predicted correlations between BR(K_L—>$\pi^0\nu\nu$) and BR(K_L—>$\pi^+\nu\nu$) for various BSM.

Model predictions and measurements

BNL: E949 observed 2 clean events for $K^+ \longrightarrow \pi^+ \nu\nu$~ BR ($1.73 \times 10^{-10}$)

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.



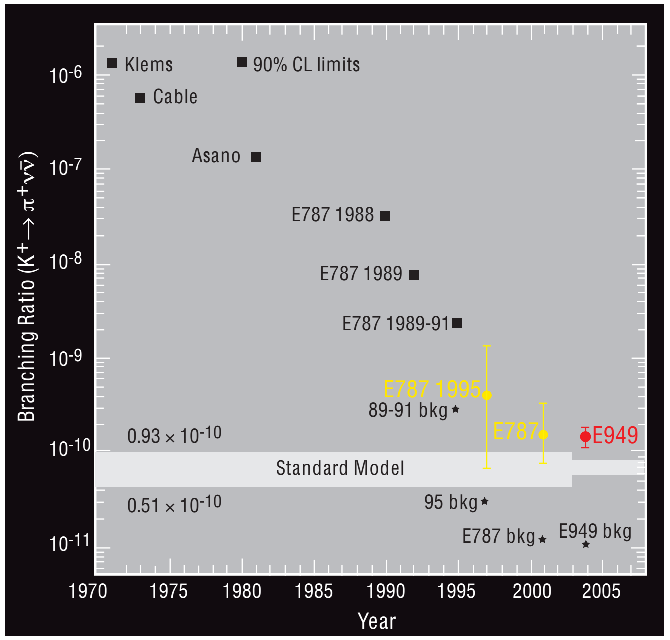


Fig. History $K_L \longrightarrow \pi^+ \nu\nu$ search

LHT: Littlest Higgs (T-parity)

MFV:Minimum Flavor Violation

RSc: Randall-Sundrum

Fig. Predicted correlations between BR($K_L \longrightarrow \pi^0 \nu\nu$) and BR($K_L \longrightarrow \pi^+ \nu\nu$) for various BSM.

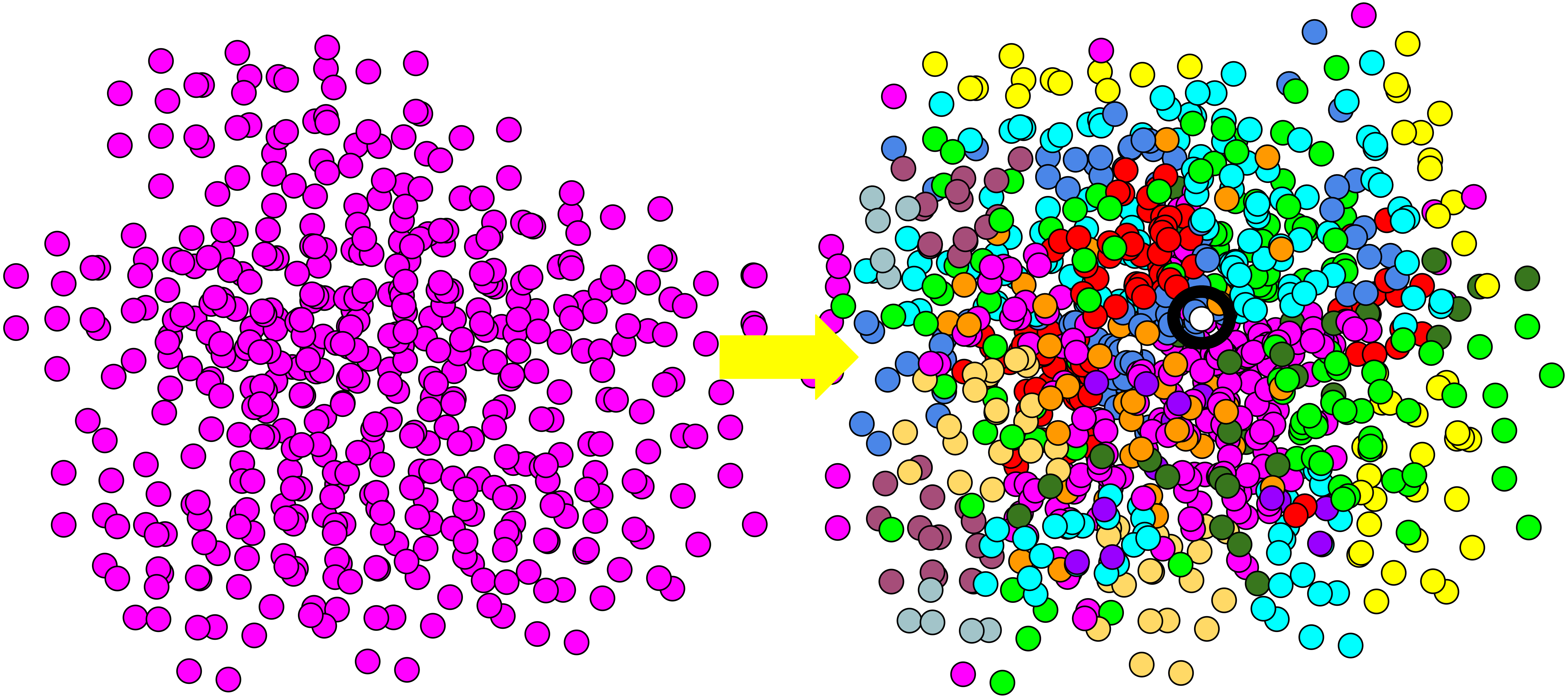
Goals of KOTO

Measure branching ratio BR($K_L \longrightarrow \pi^0 \nu\nu$) with less than 10% uncertainty

- KOTO Step 1:
  - Make first observation of signal event ($\sim 10^{-12}$ sensitivity)
  - Search for new physics with BR higher than SM predictions

- KOTO Step 2:
  - Measure roughly 100 events ($\sim 10^{-13}$ sensitivity)

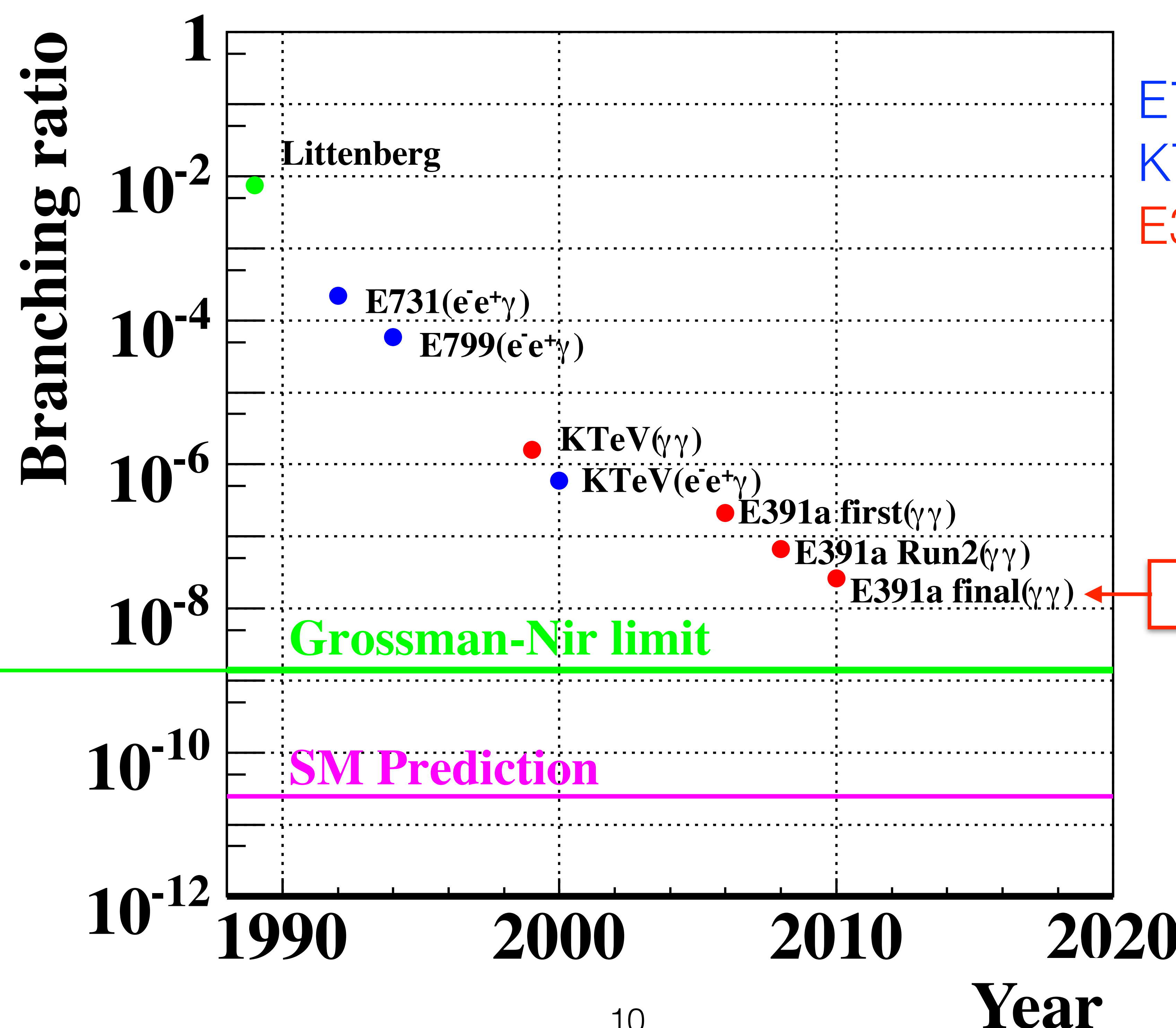
Measuring $K_L \rightarrow \pi^0 \nu\nu$



~30 billion kaons

Brief history of search

Improvements in detectors and data processing were instrumental in advancement
E391a was impeded by limited veto capabilities and lower beam power (~12GeV)



GN = 1.5×10^{-9}

E731: FNAL
KTeV: FNAL/KEK
E391a: KEK

E391a < 2.6×10^{-8}

Precursor to KOTO

Dedicated pilot search was the KEK E391a collaboration

- Indirect branching ratio limit ($K_L \longrightarrow \pi^0 \nu\nu$) <1.5 x 10^{-9} set by BNL E787/949 using isospin symmetry
- Set upper limit BR($K_L \longrightarrow \pi^0 \nu\nu$) < 2.6 x 10^{-8} (90% confidence)
- Limits of the detector were identified motivating next steps
- Having only upper limits determined drives the experiment and indicates there is still more to be explored

KOTO detector is specifically designed to measure the CP-violating $K_L \longrightarrow \pi^0 \nu\nu$ rare decay

J-PARC facility

“K^0 at TOkai”

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

J-PARC facility

J-PARC (Japan Proton Accelerator Research Complex)

- Various research projects
  - roughly 20 hrs of travel from Ann Arbor

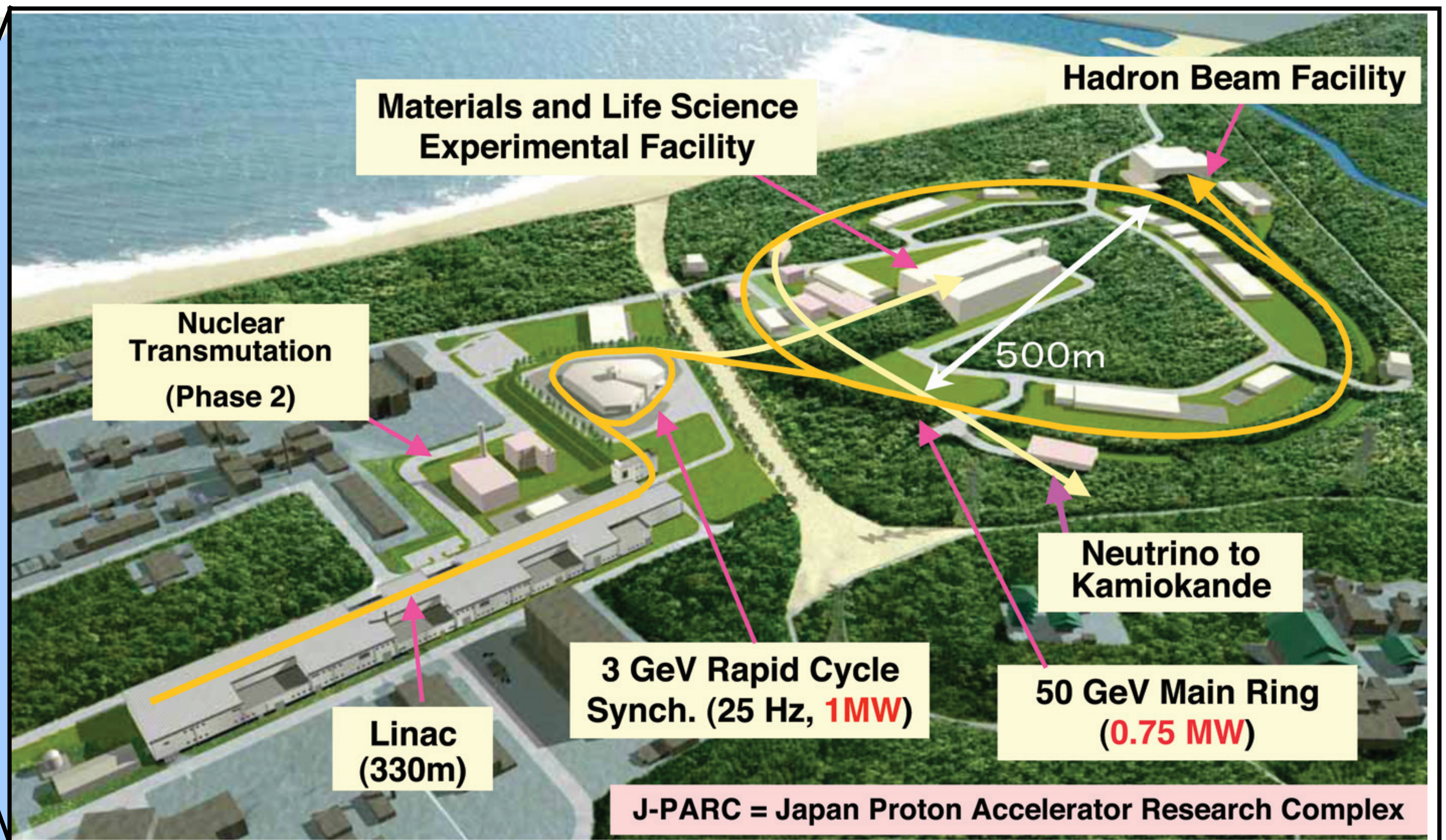


Fig. View of the J-PARC facility

Experimental hall

Hadron Experimental Facility (HEF)

- Intense 30 GeV proton beam with around 50% duty factor
- Secondary neutral beam is extracted (16°) and directed to KOTO detector

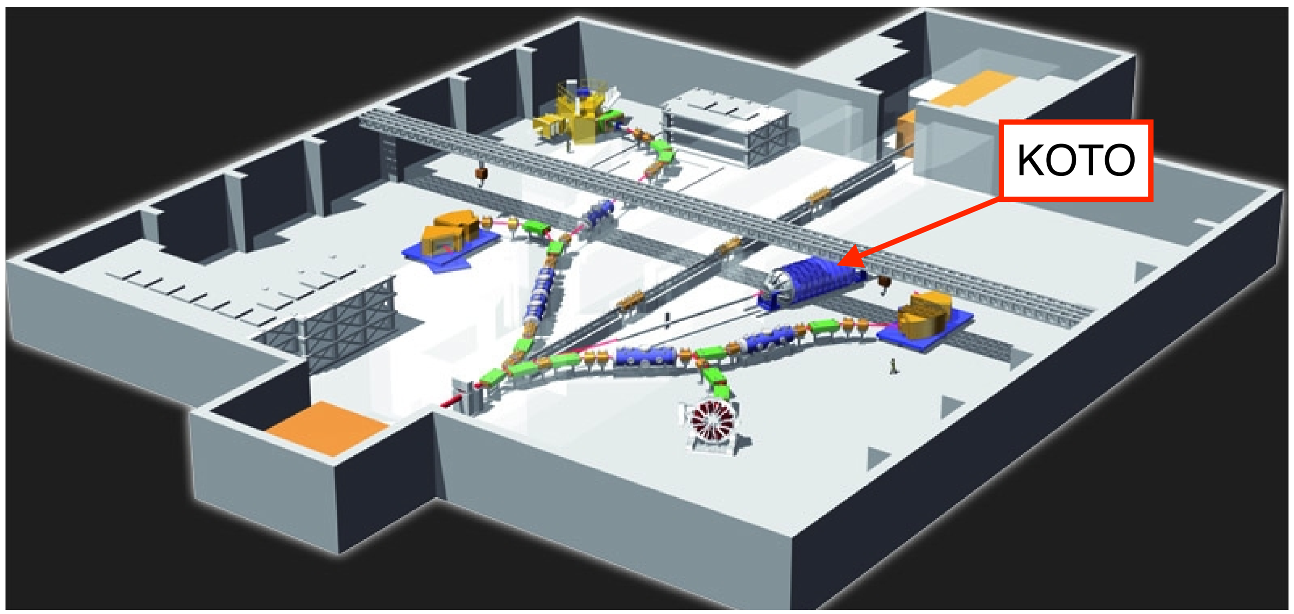


Fig. 3D view of Hadron Experimental Facility

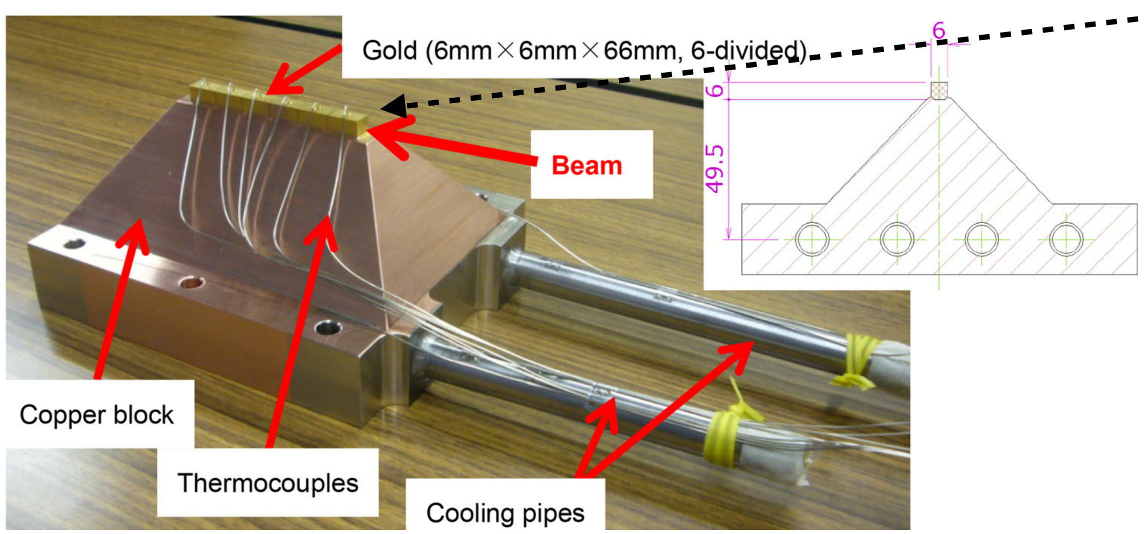


Fig. Target used for KOTO physics experiment

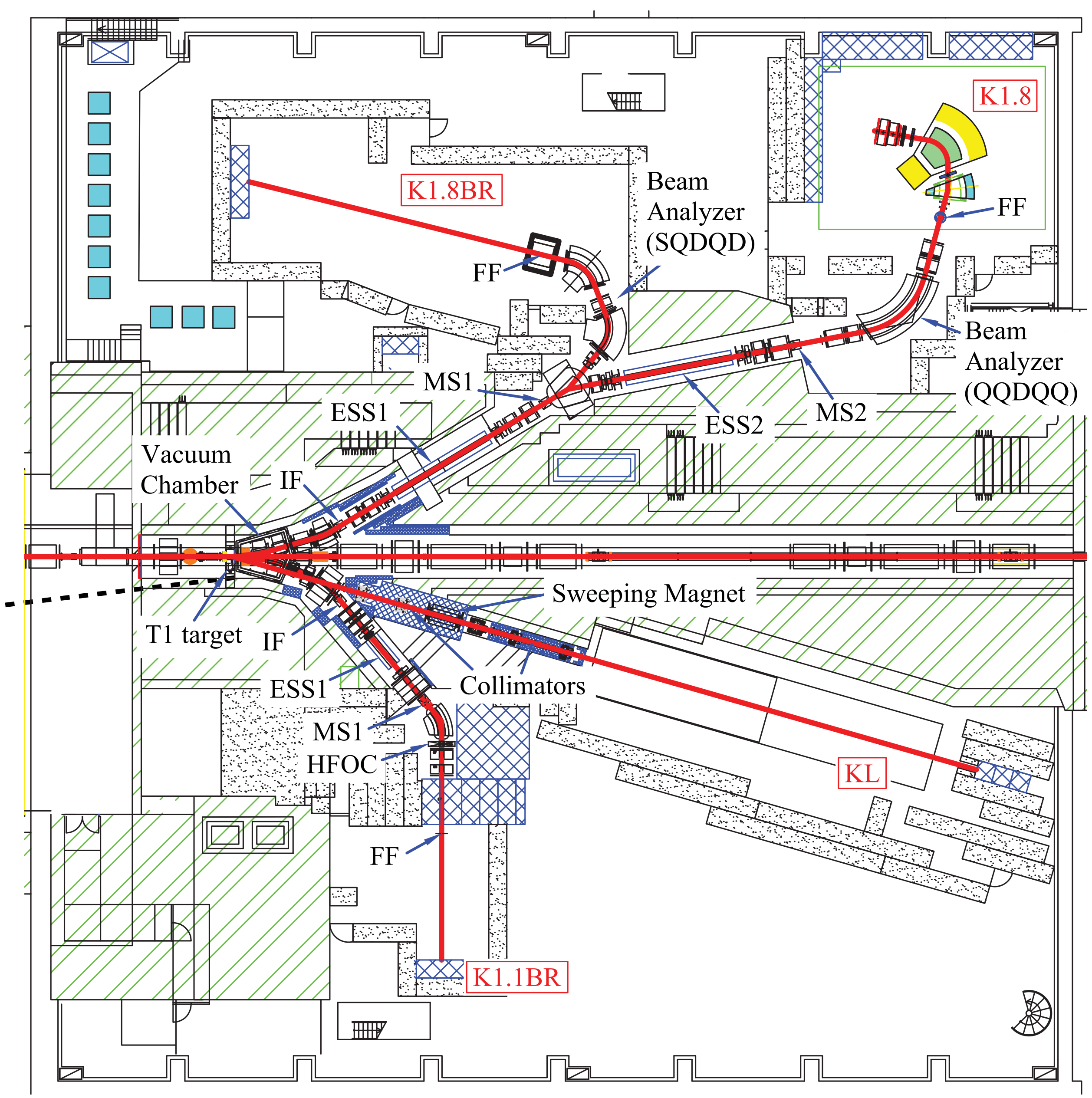


Fig. Layout inside Hadron Experimental Facility

KOTO neutral beam

Highly collimated neutral "pencil" beam

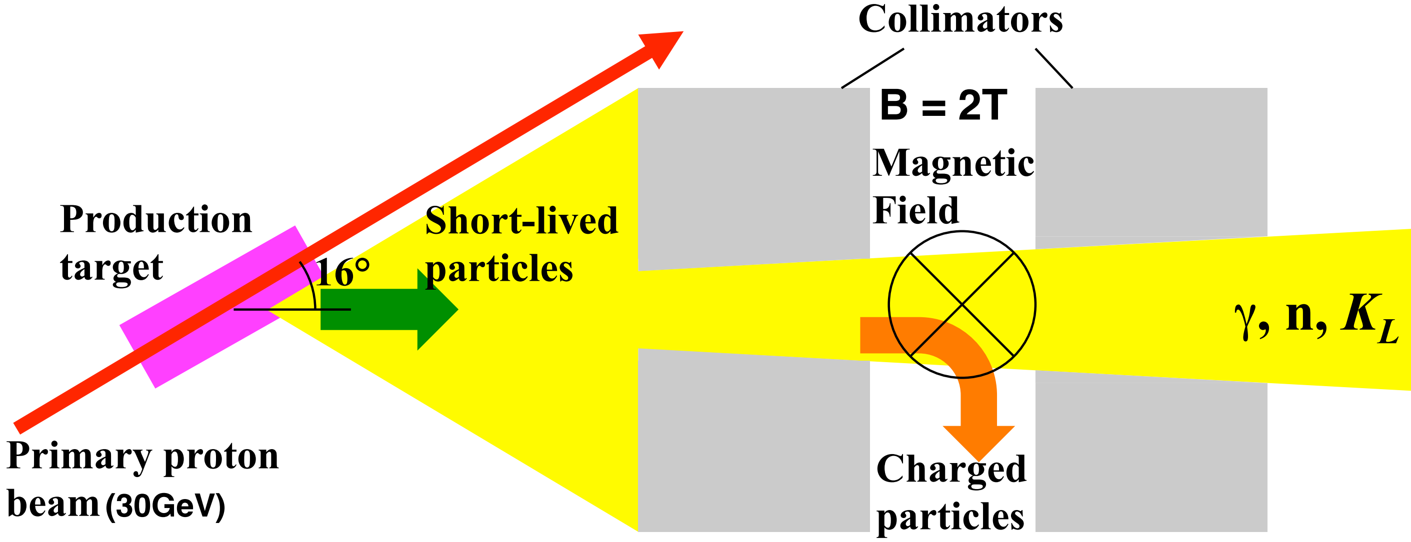


Fig. Depiction of neutral beam line production

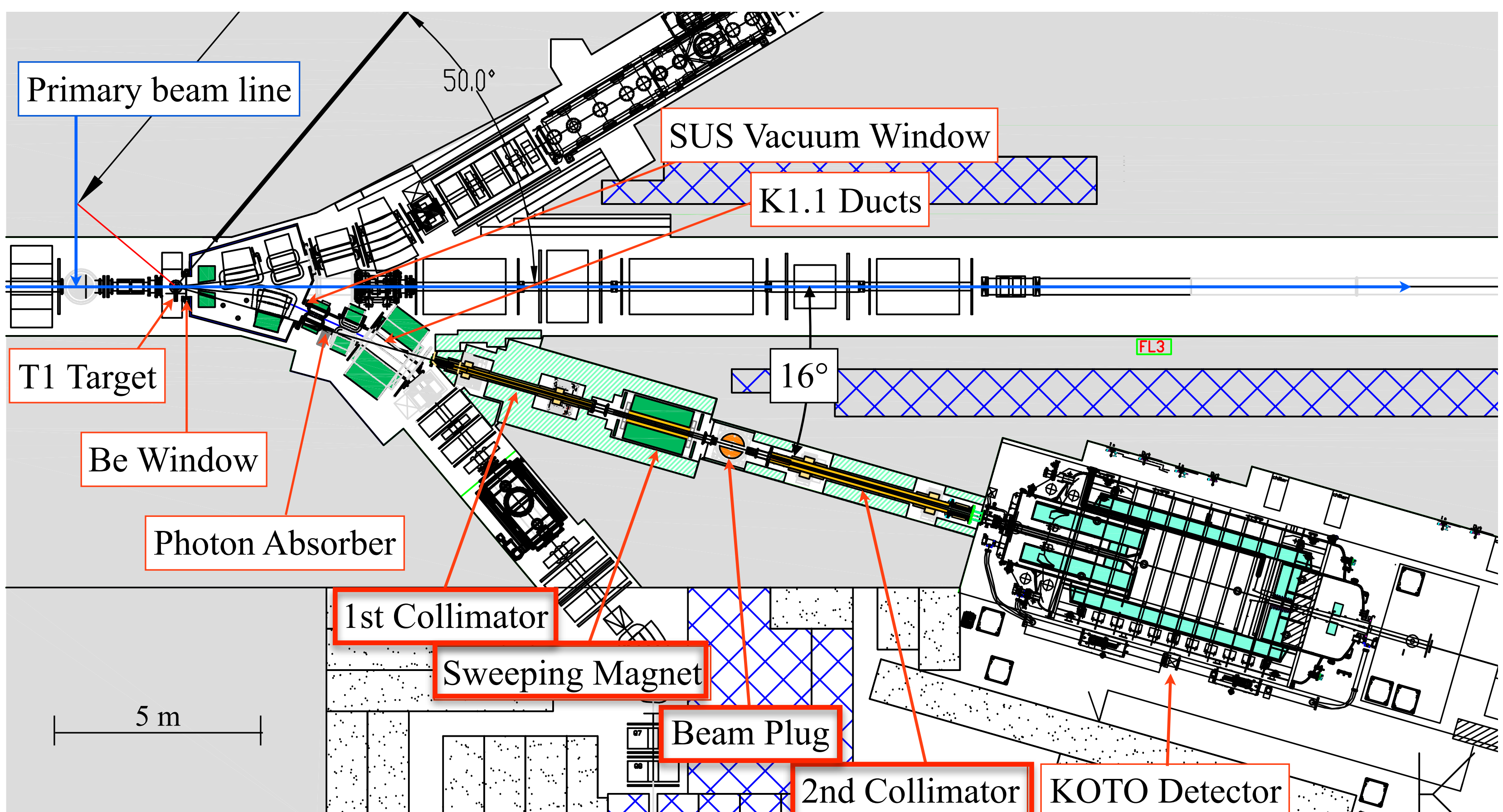


Fig. Layout inside Hadron Hall

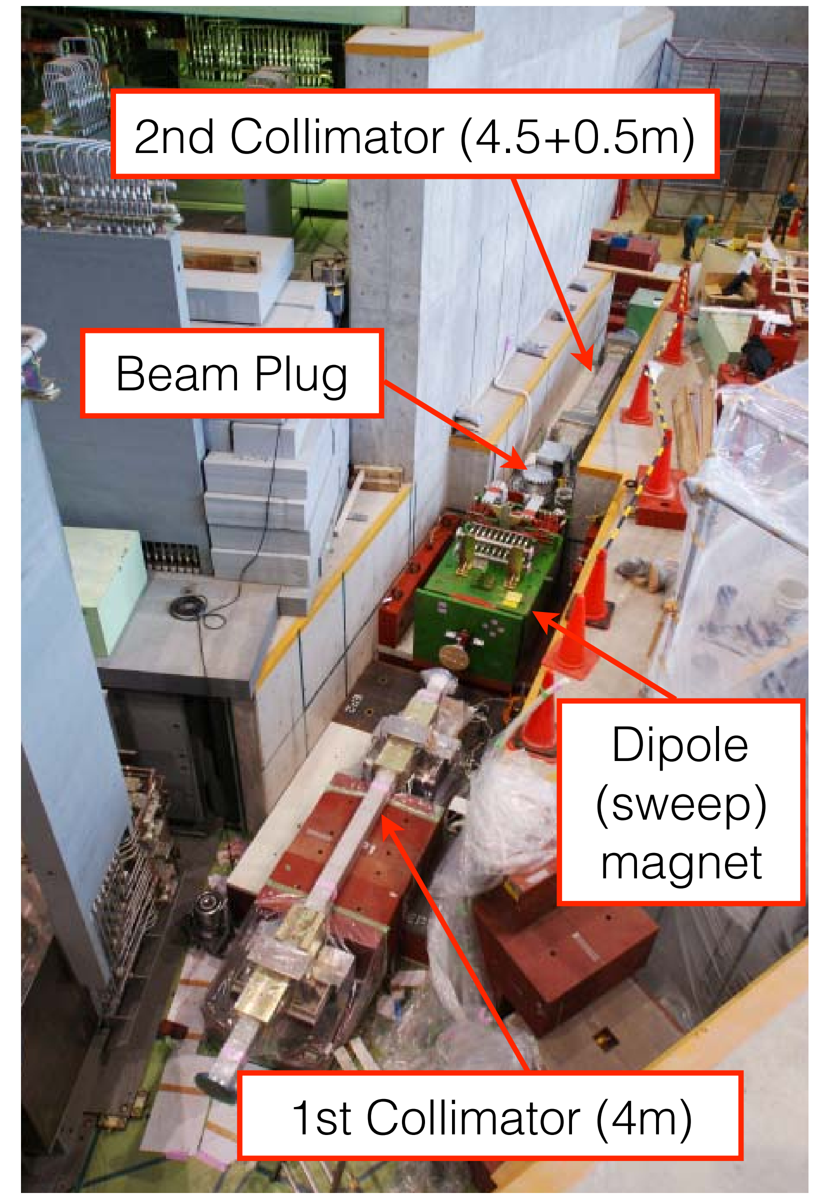


Fig. Secondary beam line

target to detector distance = 21.5 m

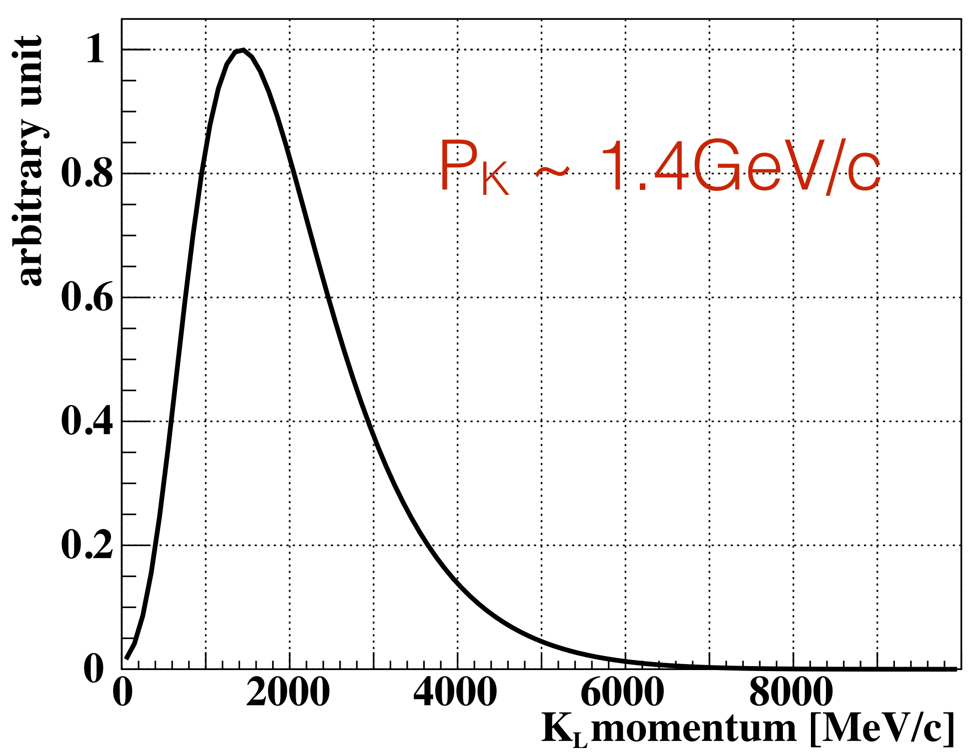
Experimental method

Principle

- Signature is a pair of photons from the pion decay and a finite transverse momentum
  - **2γ and nothing else -** Detect energy and position of photons from pion decay with an electromagnetic calorimeter, and reconstruct vertex position and momentum

Major Obstacles

- Background contribution from $K_L \rightarrow 2\pi^0$ with non-detected photons, other decay channels, and neutron interactions mimicking signals



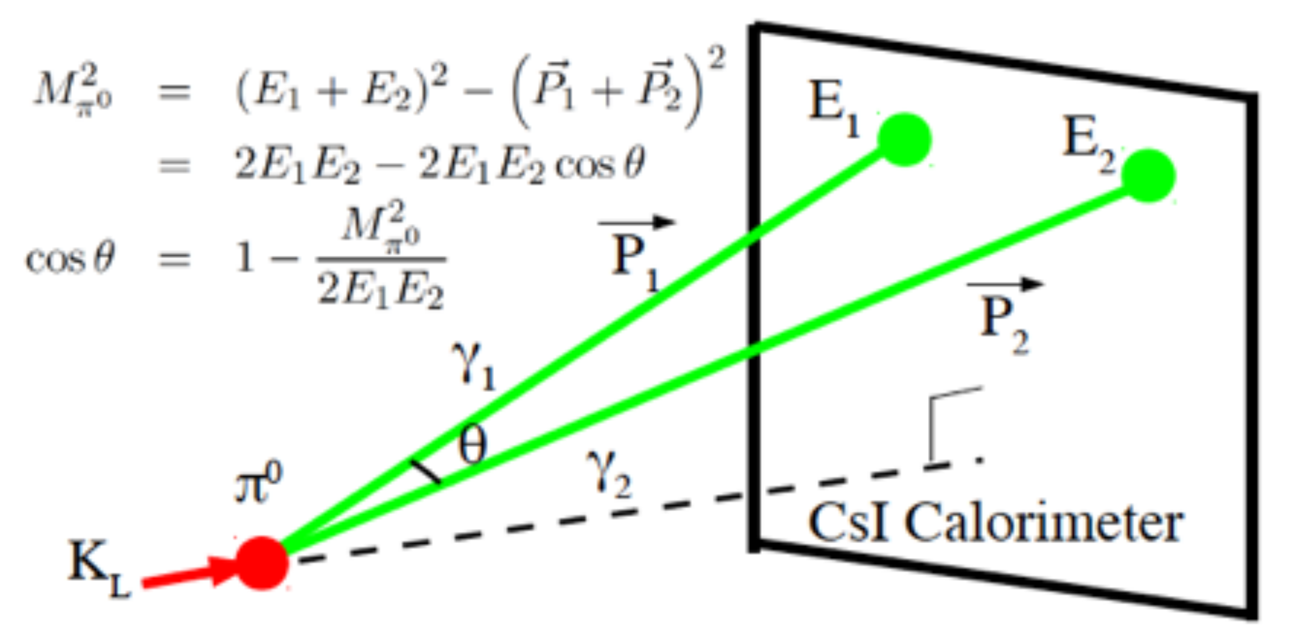
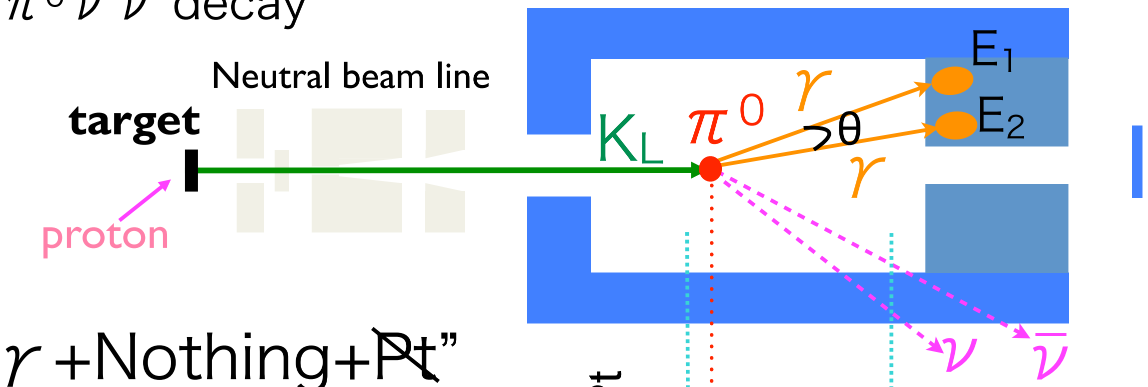


Fig. Reconstruction method

Experimental method

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

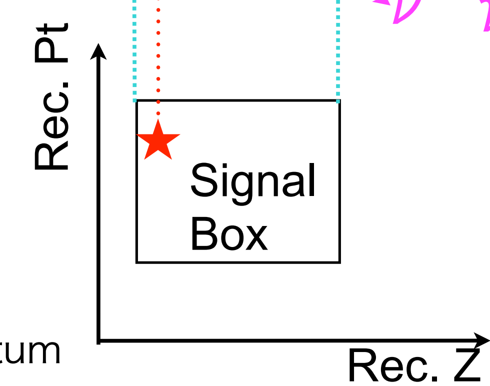


"2γ+Nothing+~~Pt~~"

Assuming 2γ from π^0,
Calculate z vertex.

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

Calculate π^0 transverse momentum



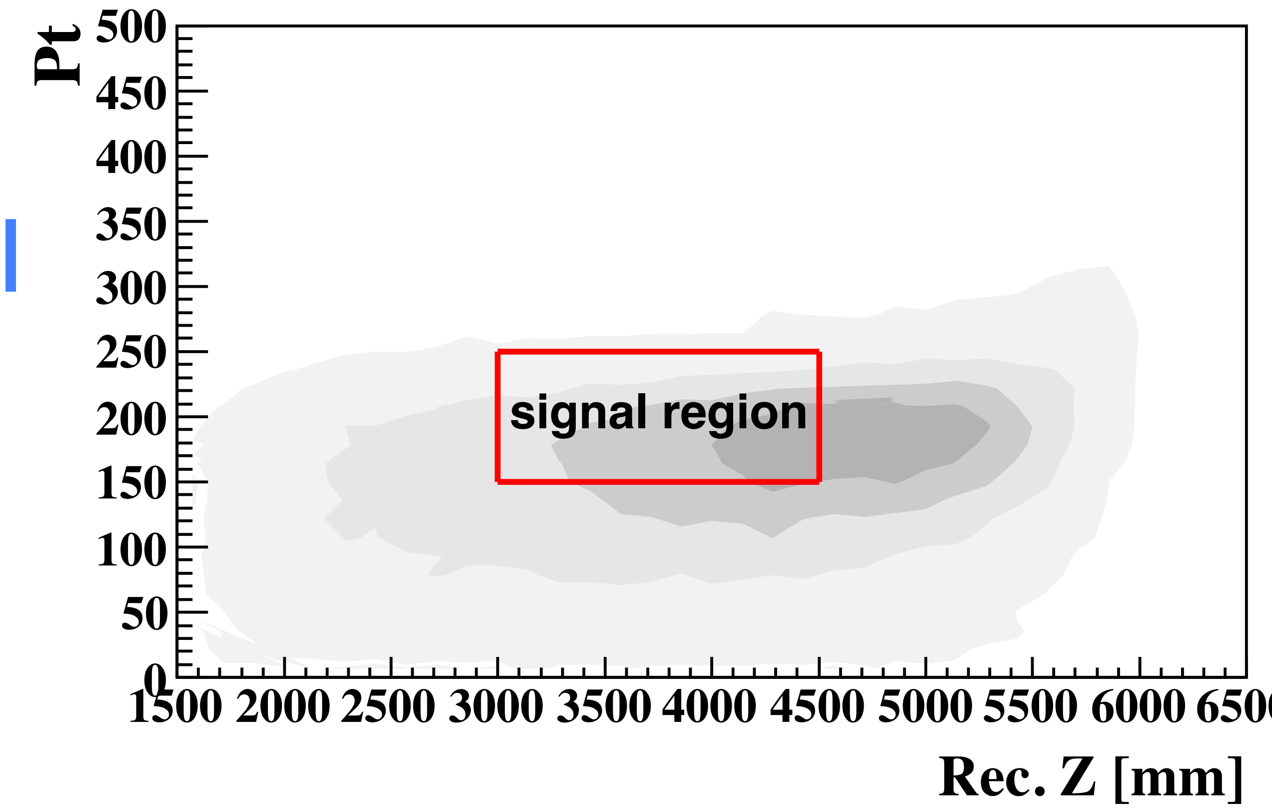


Fig. Monte Carlo sample of signal distribution

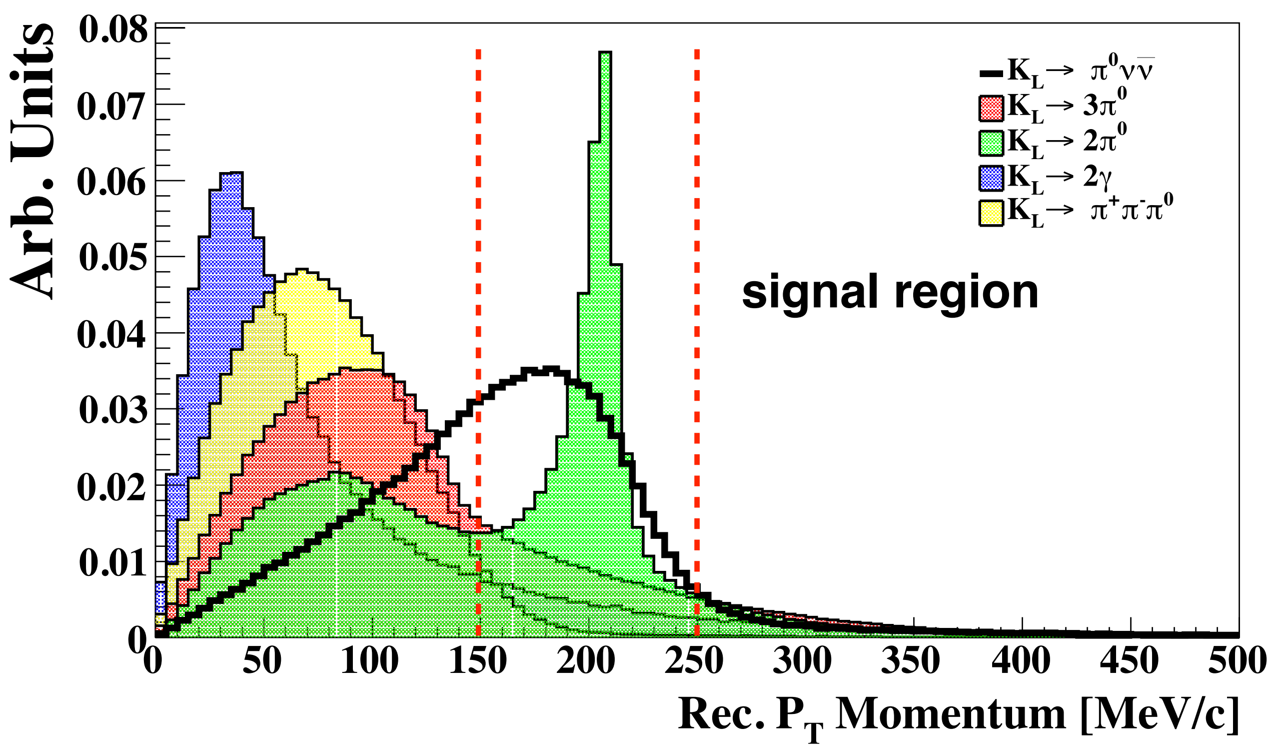


Fig. Monte Carlo of signal and background distributions

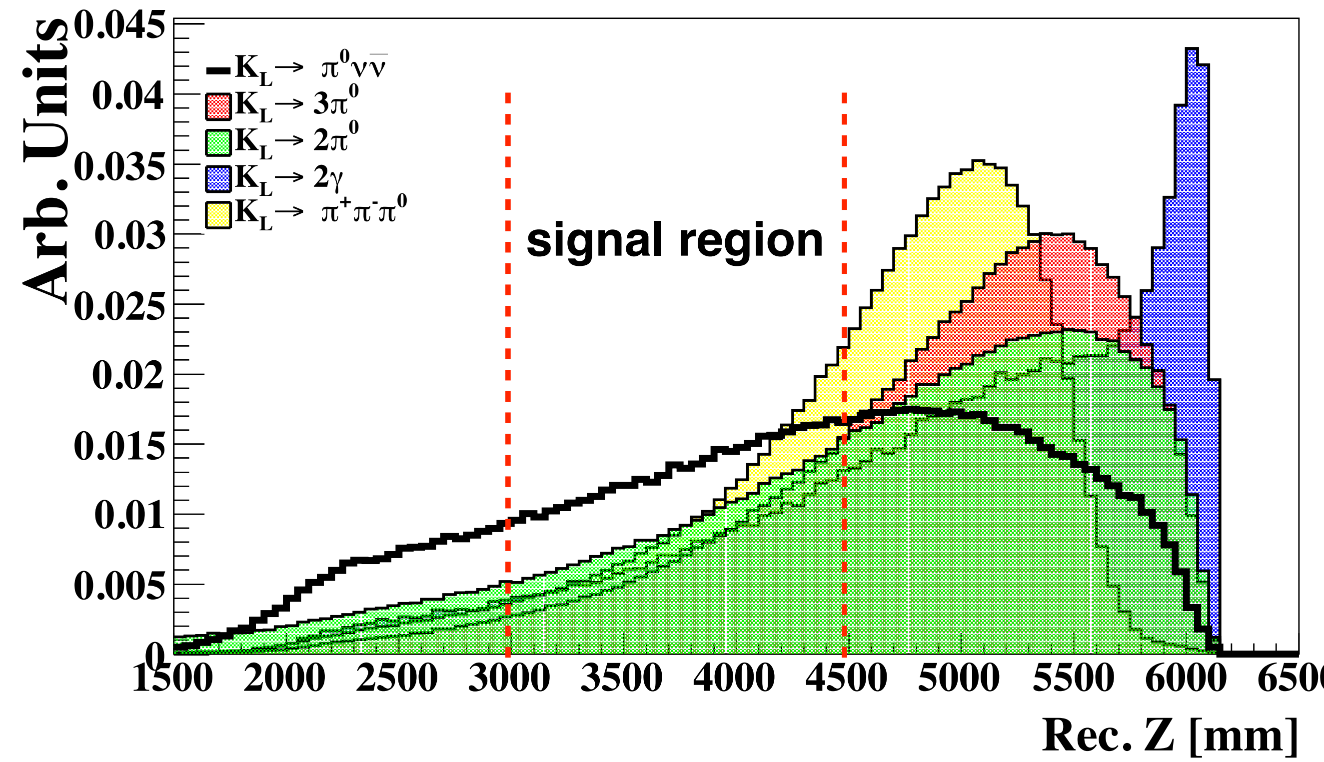


Fig. Monte Carlo of signal and background distributions

Hermetic detector

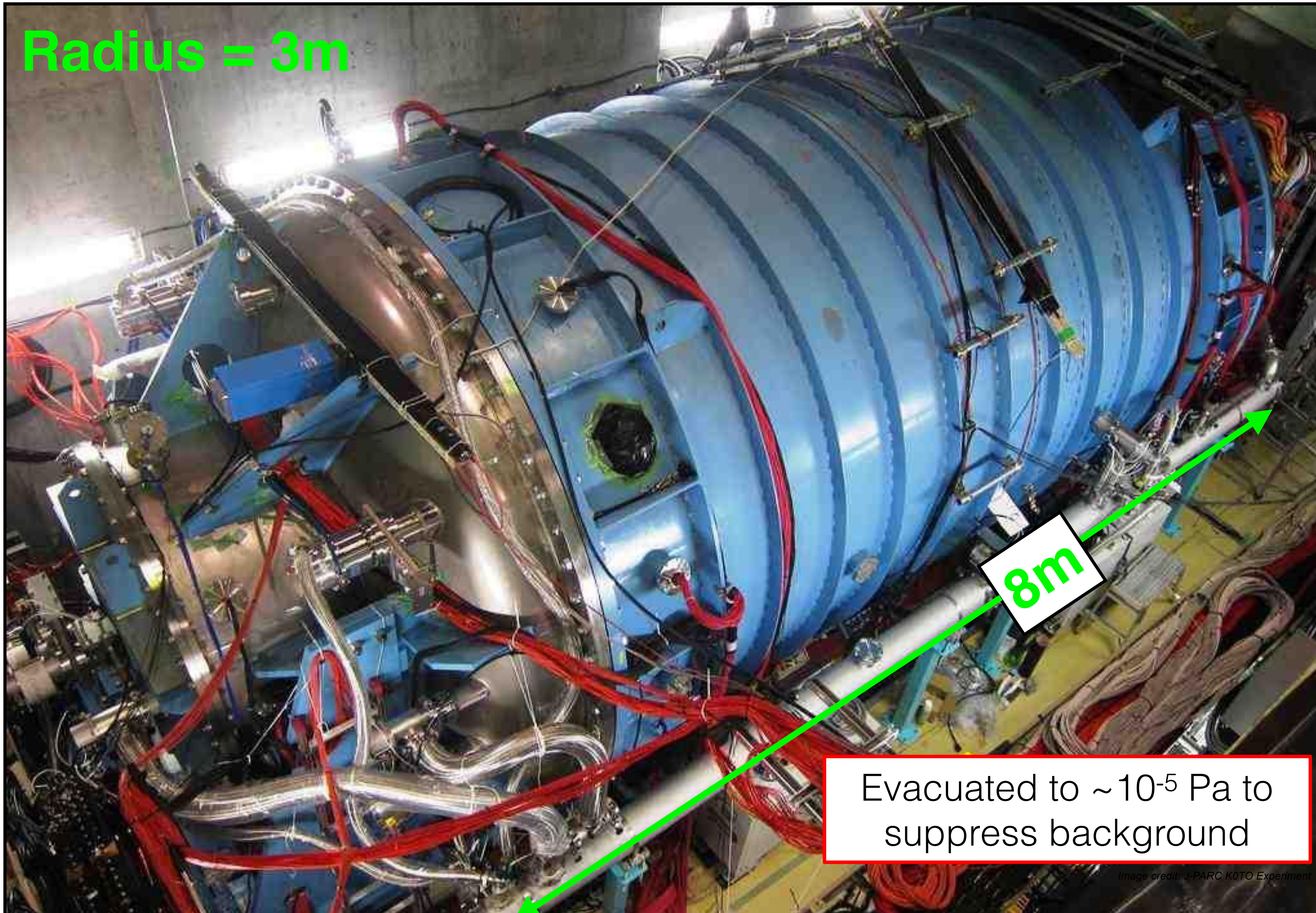


Fig. Outer vacuum container houses all main KOTO detectors

KOTO detectors

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)

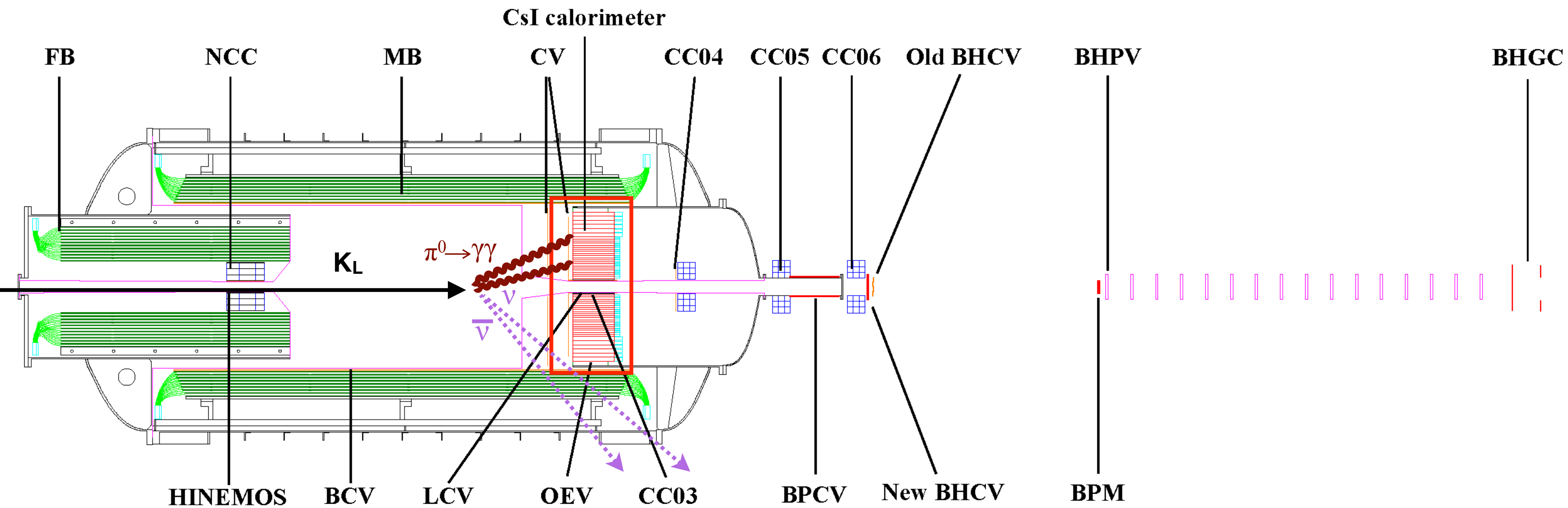


Fig. KOTO detector components

KOTO detectors

Cesium Iodide Calorimeter (CsI)

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

Hermetic veto detectors

- ~1000 channels

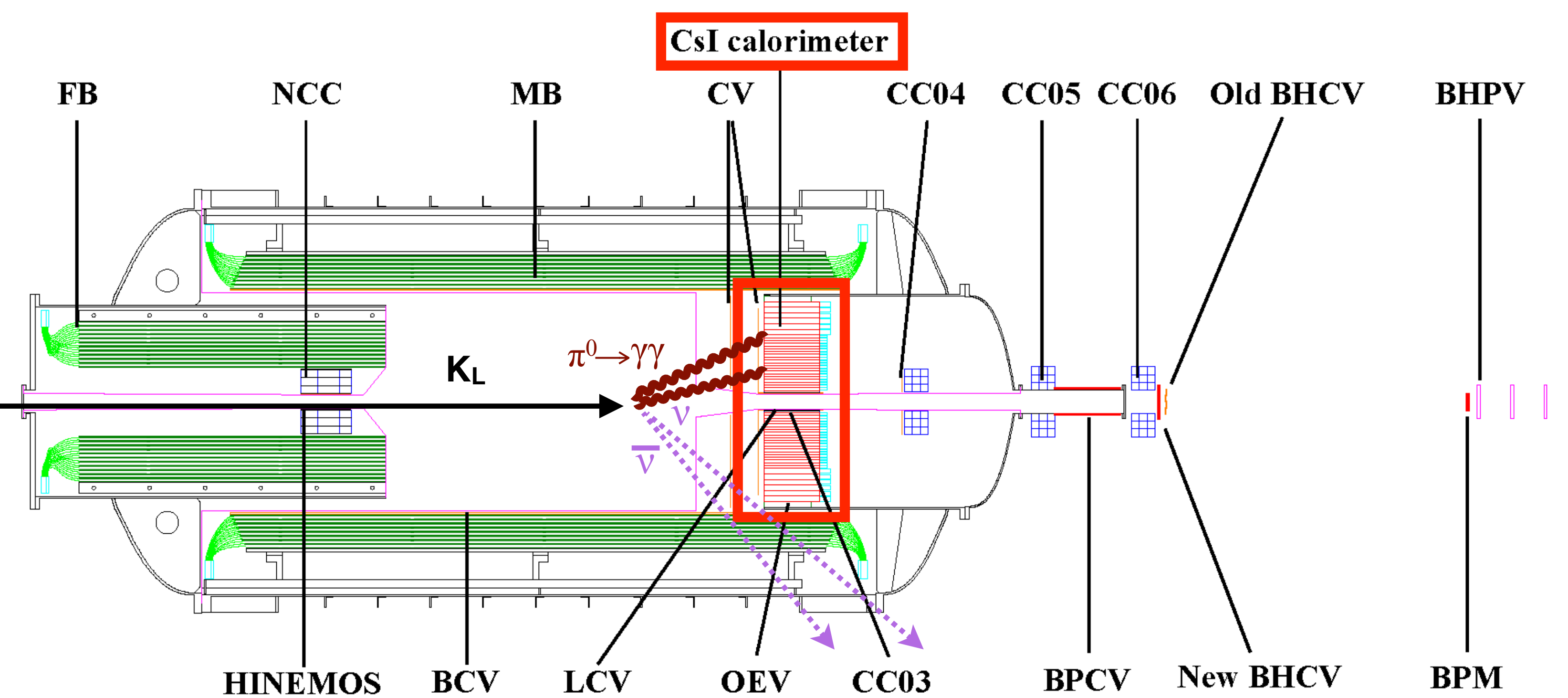


Fig. KOTO detector components

Cesium Iodide (CsI) Photon Detector

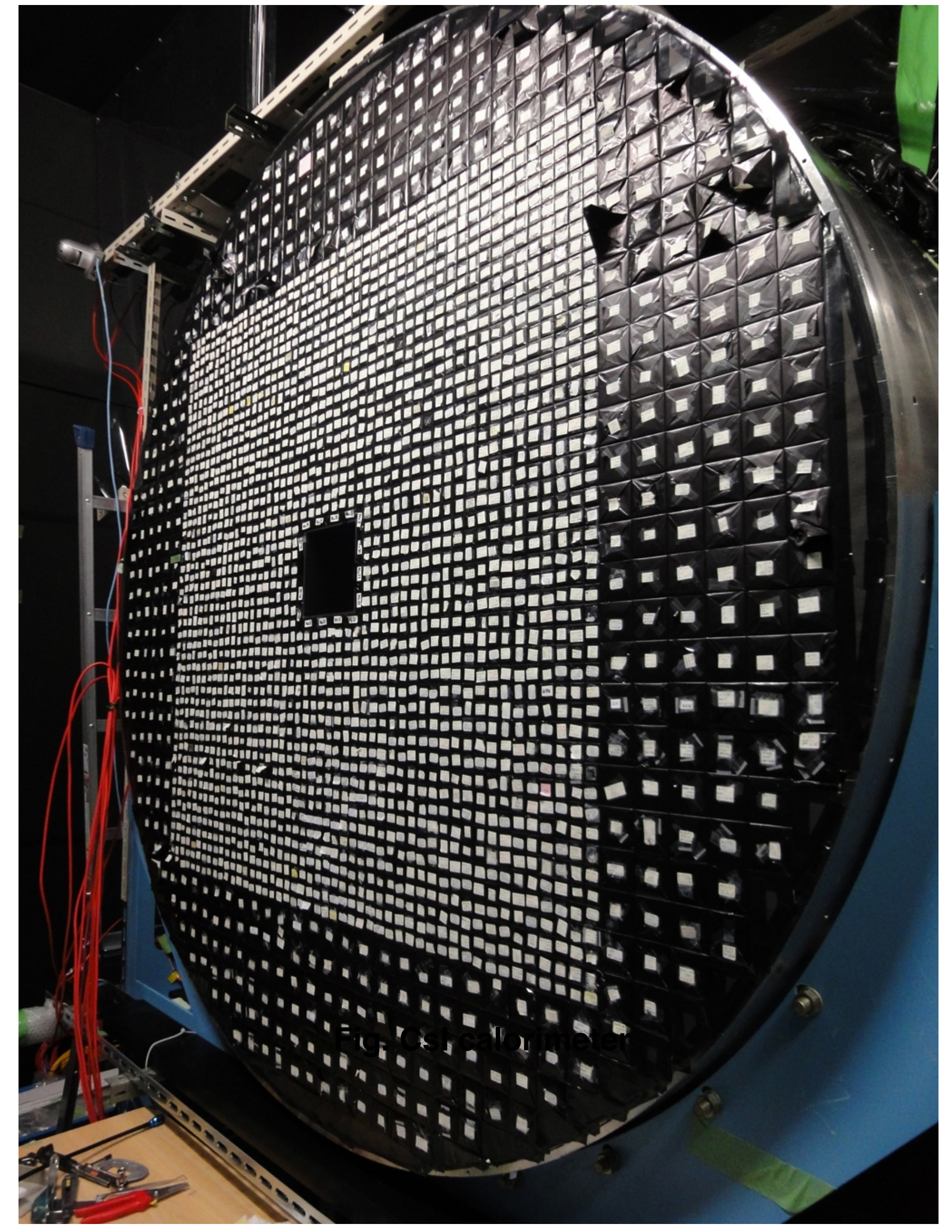


Fig. CsI detector

- 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

KOTO detectors

Neutron Collar Counter (NCC)

- NCC is used to suppress and estimate neutron background
- Measure flux and spectrum of halo neutrons
- Undoped CsI crystals (X_0=1.9 cm) read out by wavelength shifting fibers arranged in 3 optically separated regions

Background reduction is crucial!

Neutron Collar Counter (NCC)

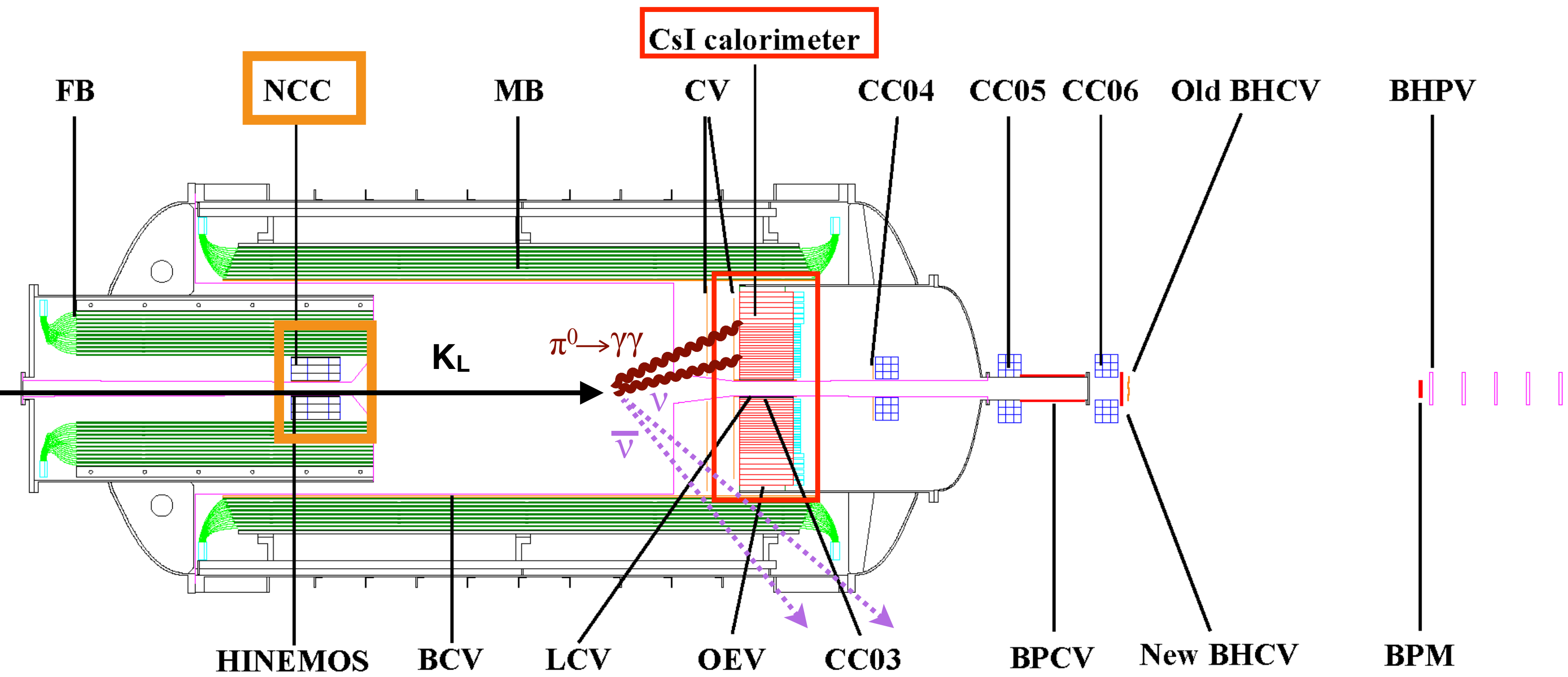


Fig. KOTO detector components

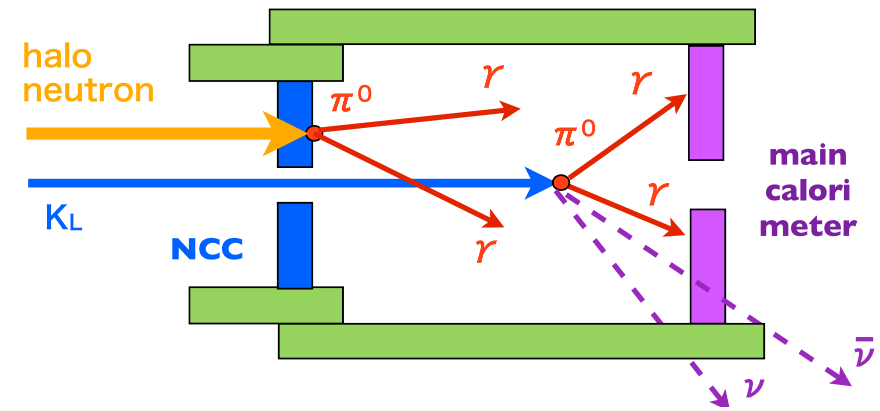


Fig. $K_L \rightarrow \pi^0\nu\nu$ and halo neutron events

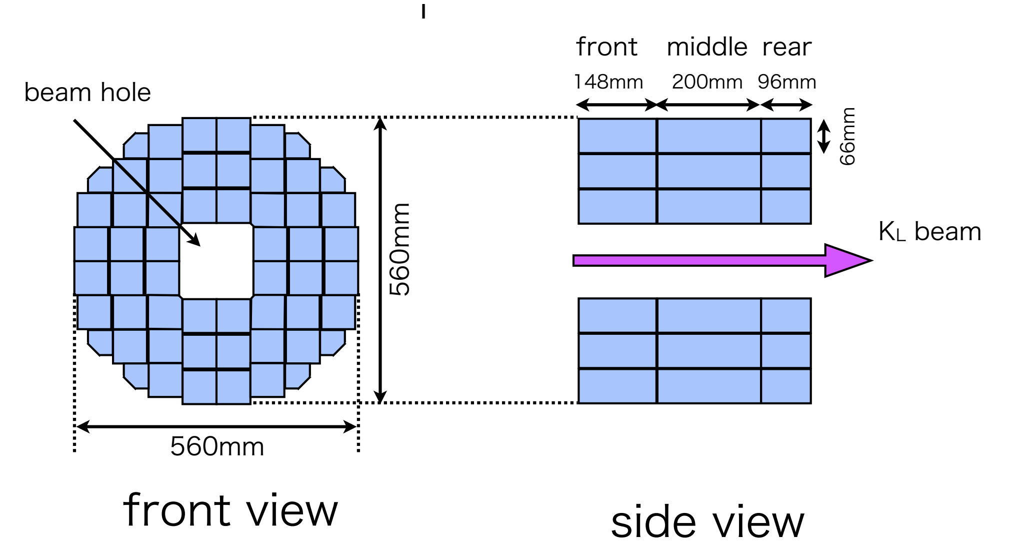
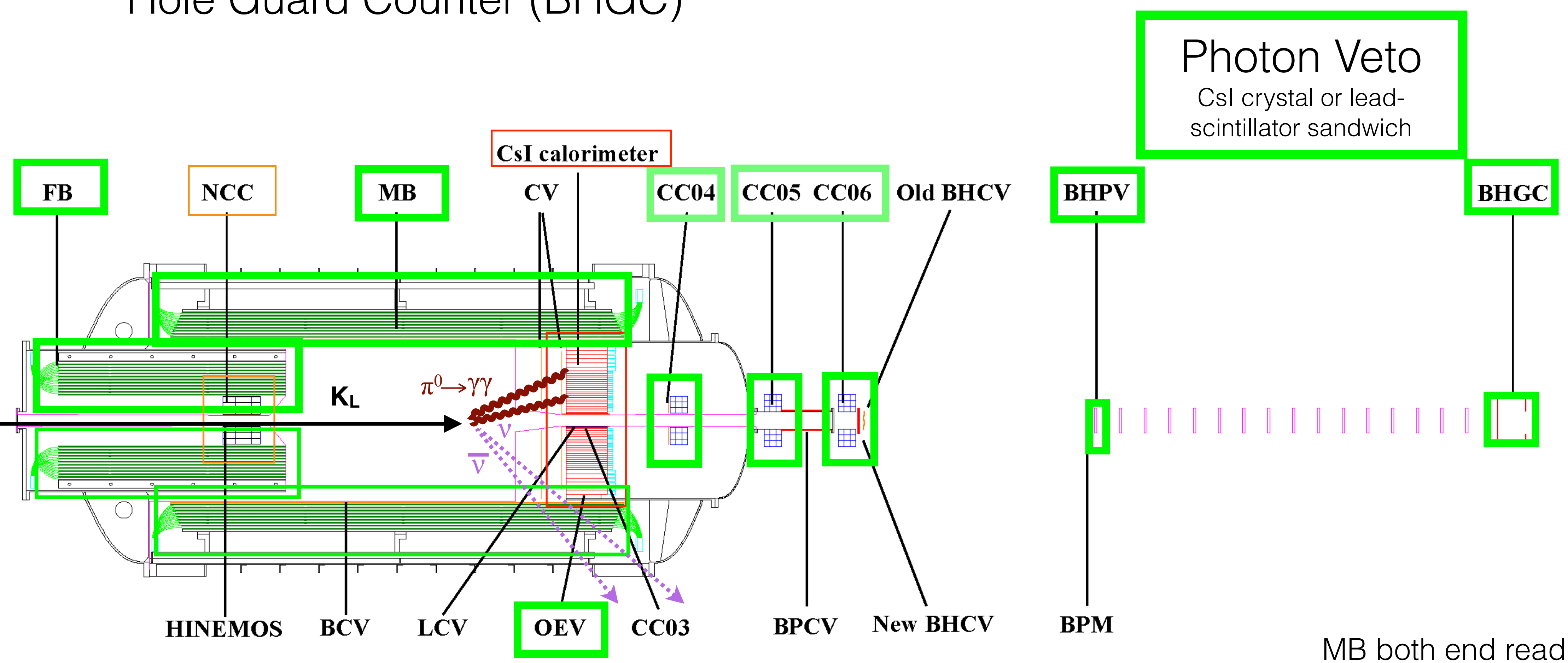


Fig. Front and side view of the NCC

KOTO detectors

Photon Veto

- Used to diminish background from other K_L decays ($K_L \longrightarrow 3\pi^0$, $2\pi^0$, $\pi^+\pi^-\pi^0$), and π^0 from halo neutron
- Upstream and decay region: Main (MB) and Front Barrel (FB), and Outer Edge Veto (OEV)
- Downstream: Collar Counters (CC04-CC06), Beam Hole Photon Veto (BHPV), and Beam Hole Guard Counter (BHGC)



MB both end read out (~128 channels)
FB single end read out (~32 channels)

Fig. KOTO detector components

KOTO detectors

Charged Veto

- Used to suppress background from other K_L decays ($K_L \longrightarrow \pi^+\pi^-\pi^0$, $\pi^\pm e^\pm \nu$),
- Upstream and decay region: Barrel Charged Veto (BCV), Charged Veto (CV), Liner Charged Veto (LCV)
- Downstream: Collar counters (CC04-CC06), Beam Hole Charged Veto (BHCV), and Beam Pipe Charged Veto (BPCV)

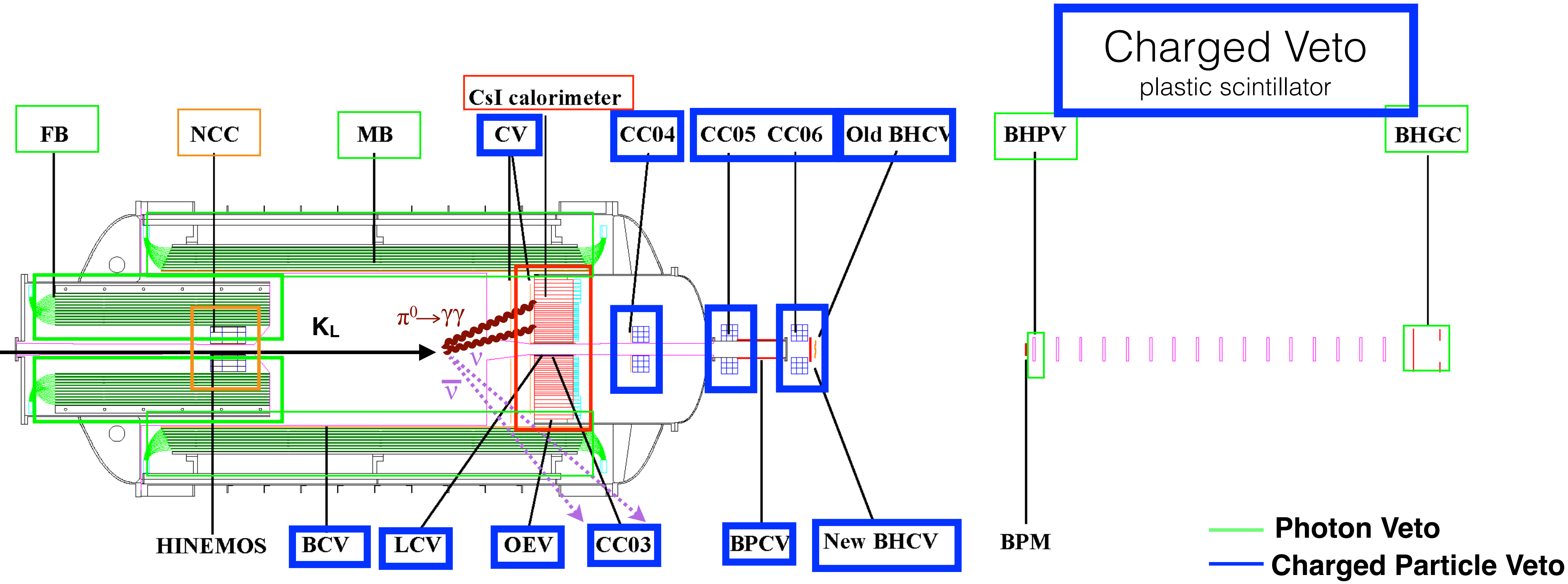
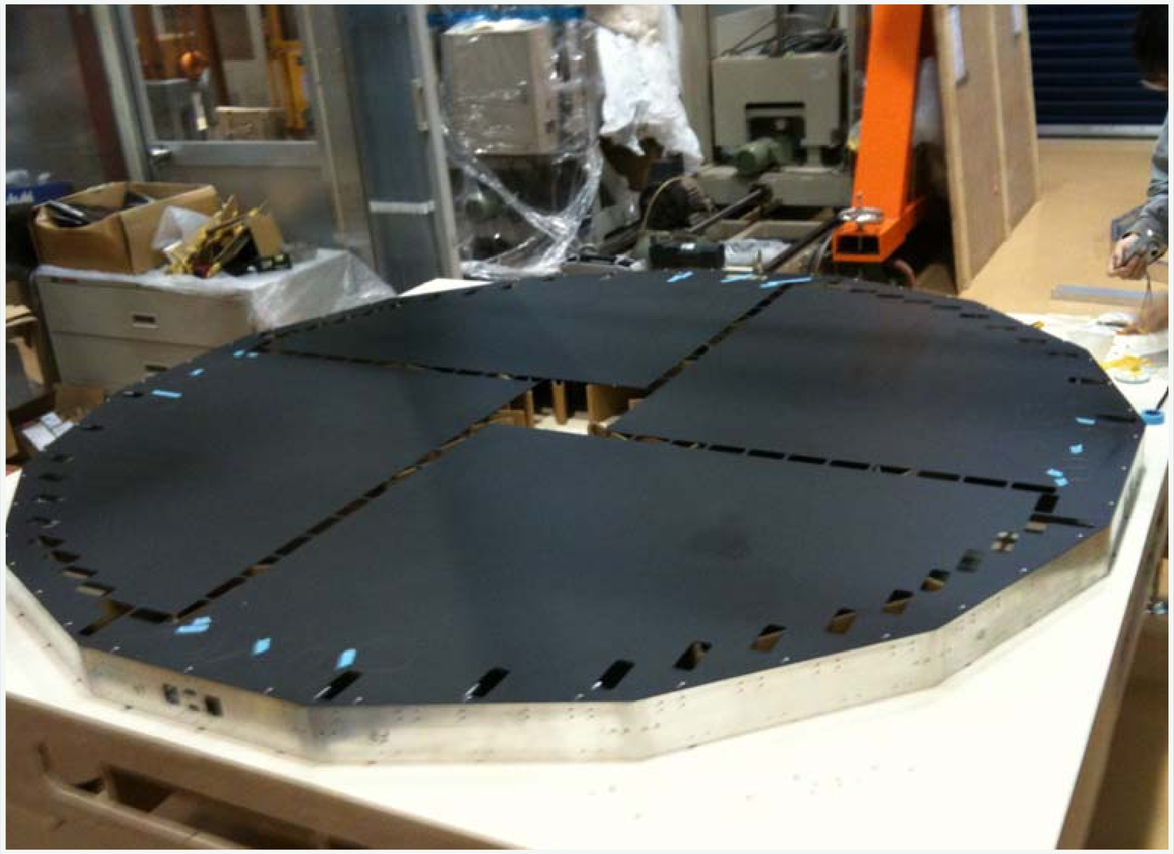


Fig. KOTO detector components

KOTO detectors

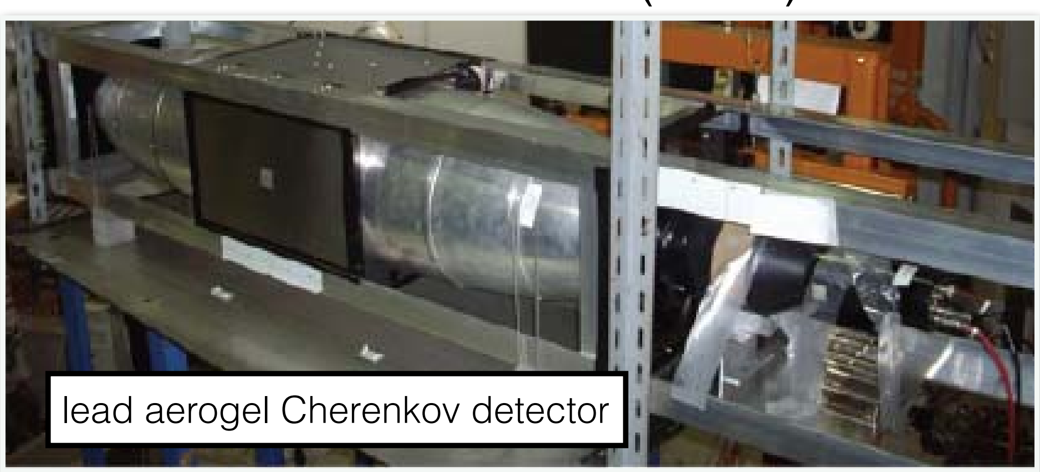
Charged Veto (CV)

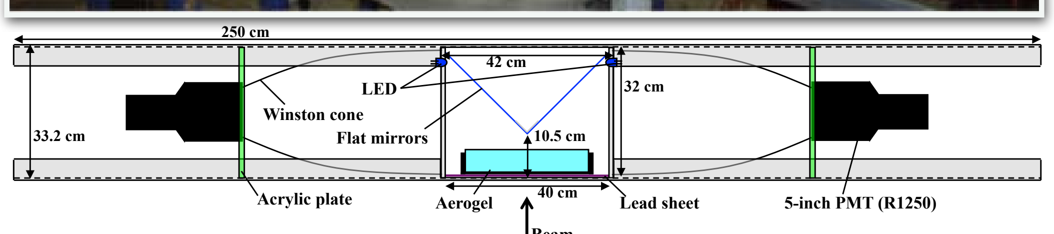


Charged Veto (CV)

- 0.8mm CFRP reinforced
- MPPC scintillator fiber both end read out
- 8-10 p.e/100KeV
- inefficiency < 10^{-3}

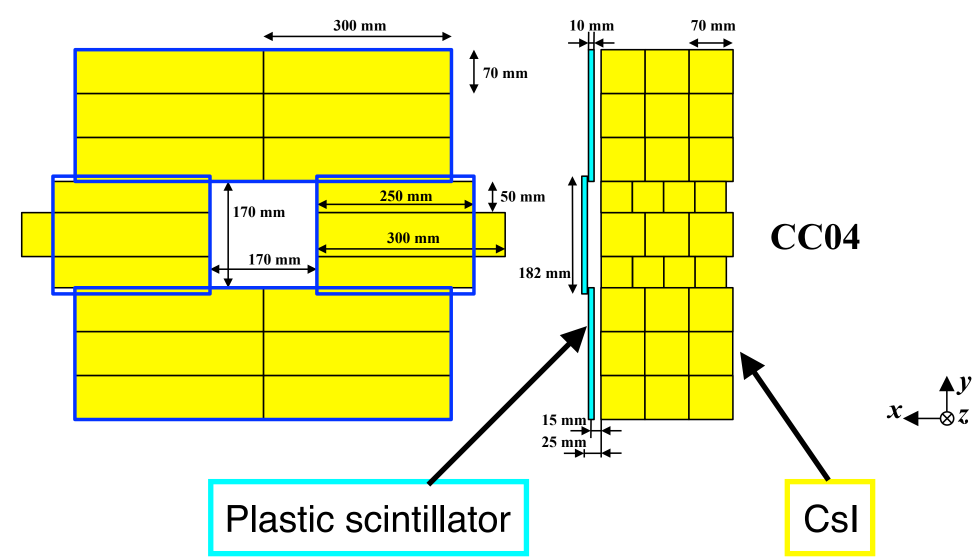
Beam Hole Photon Veto (BHPV)





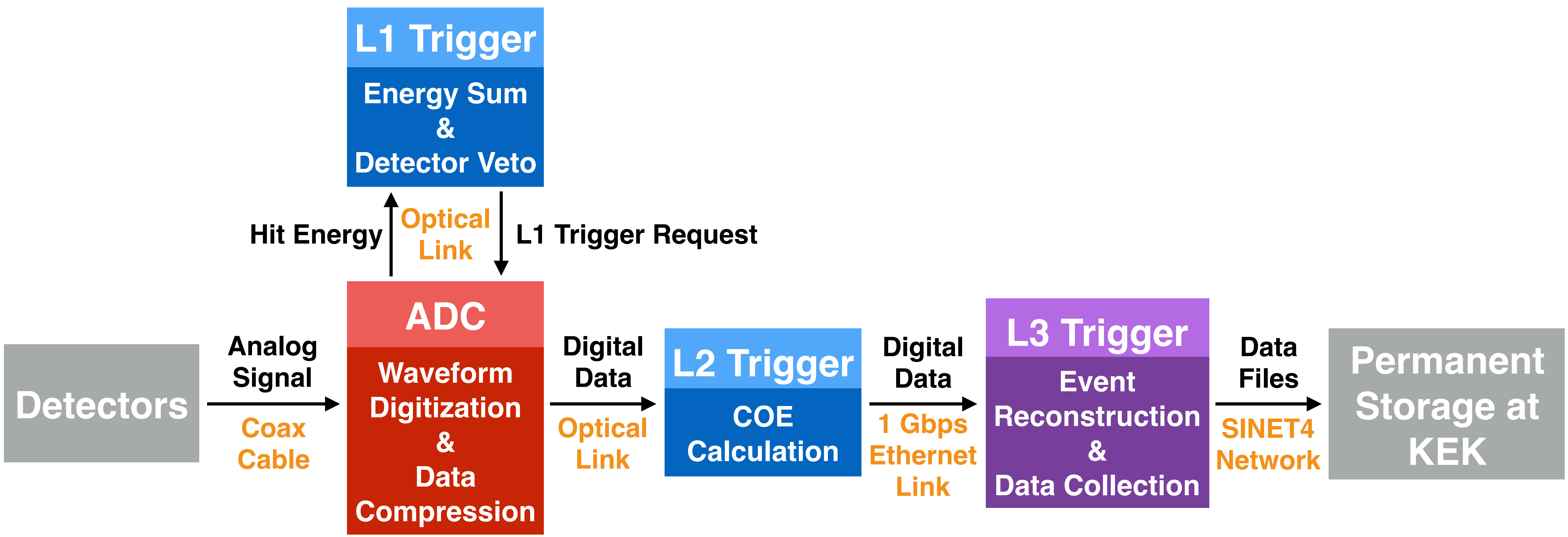
Neutron Collar Counter (NCC)

Collar Counter (CC04)



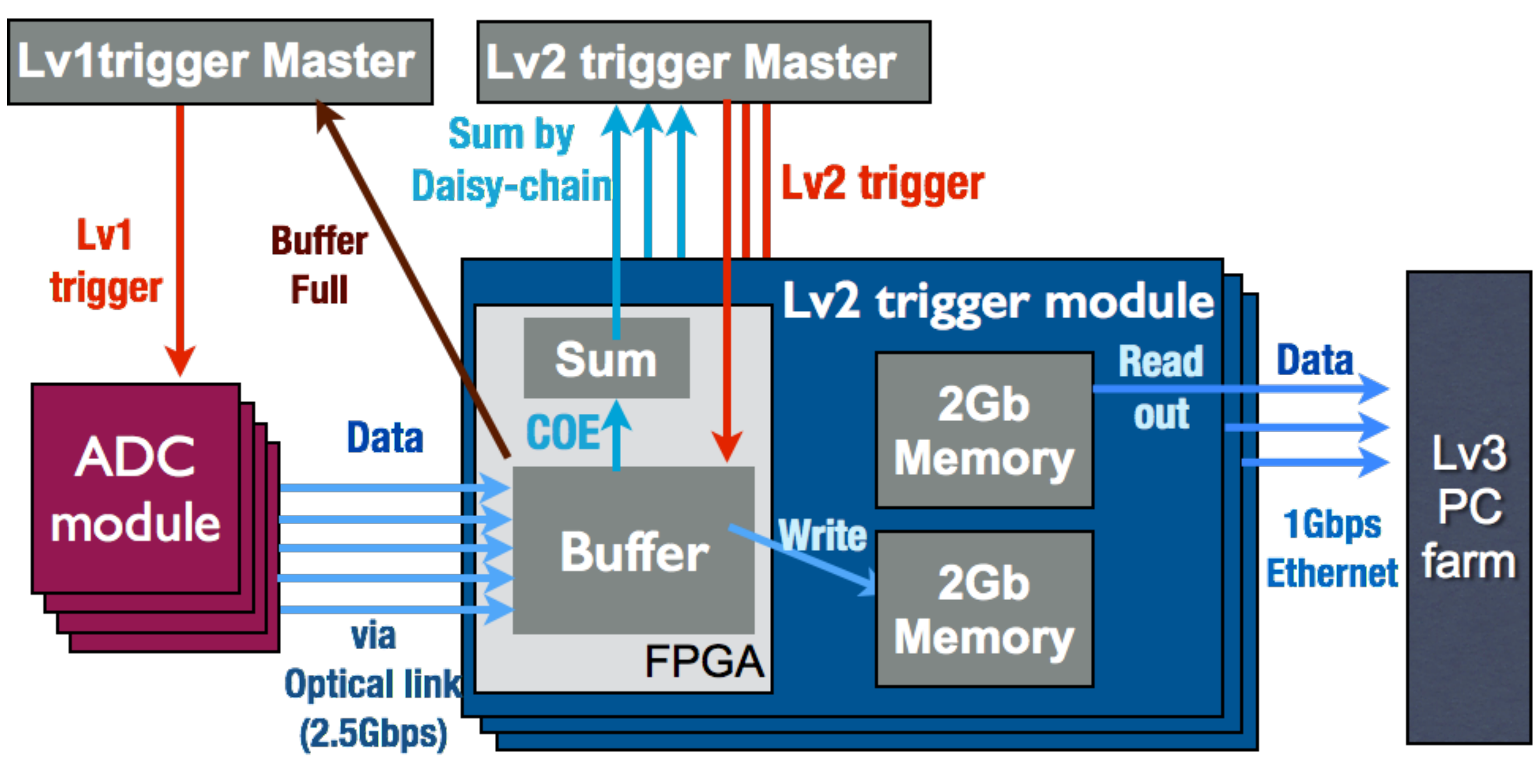
DAQ trigger levels

General schematic of data acquisition flowchart

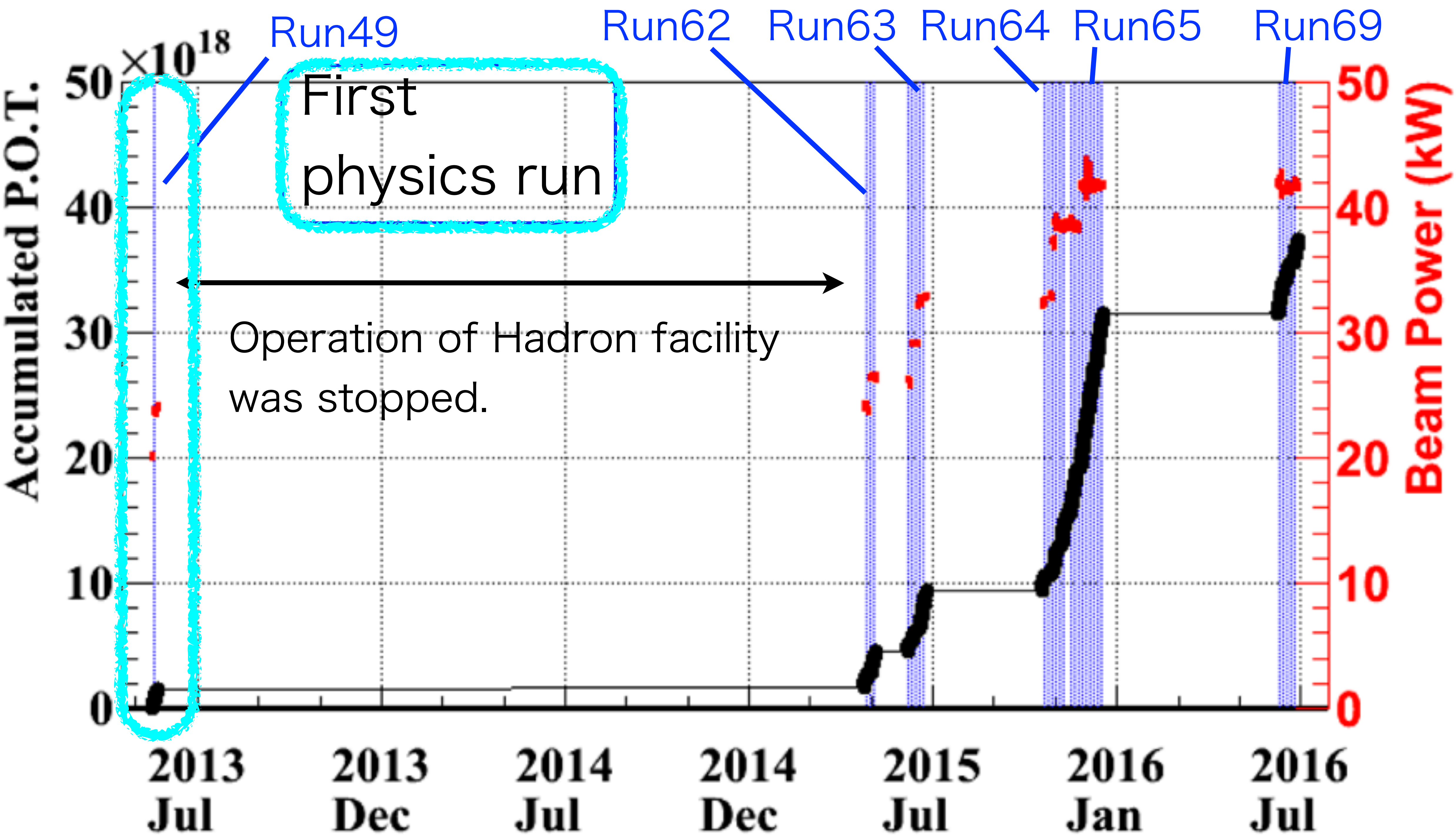


DAQ trigger levels

- **Level 1 Request** = number of triggers that meet Level 1 requirement (CsI E > E threshold [MeV] + no Veto)
- **Level 1 Accept** = number of triggers that are passed to L2 when L2 buffer is not full
- **Level 2 Accept** = number of triggers that meet Level 2 COE (>165 mm) requirement
- **Level 3** = number of events built and stored



Chronicle of KOTO runs



Results from 2013 run were accepted for publication

PTEP

Prog. Theor. Exp. Phys. **2015**, 00000 (11 pages)
DOI: 10.1093/ptep/0000000000

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
J. K. Ahn[1], K. Y. Baek[2], S. Banno[3], B. Beckford[4], B. Brubaker[5,18], T. Cai[5,19], M. Campbell[4], C. Carruth[4,20], S. H. Chen[6], S. Chu[5], J. Comfort[7], Y. T. Duh[6], T. Furukawa[8], H. Haraguchi[3], T. Hineno[9], Y. B. Hsiung[6], M. Hutcheson[4], T. Inagaki[10], M. Isoe[3], E. Iwai[3,21], T. Kamibayashi[11], I. Kamiji[9], N. Kawasaki[9], E. J. Kim[12], Y. J. Kim[13], J. W. Ko[13], T. K. Komatsubara[10,22], A. S. Kurilin[14,23], G. H. Lee[12], H. S. Lee[15], J. W. Lee[3,24] S. K. Lee[12], G. Y. Lim[10,22], C. Lin[6], J. Ma[5],

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 ($K_L \to \pi^0 \nu\nu$)

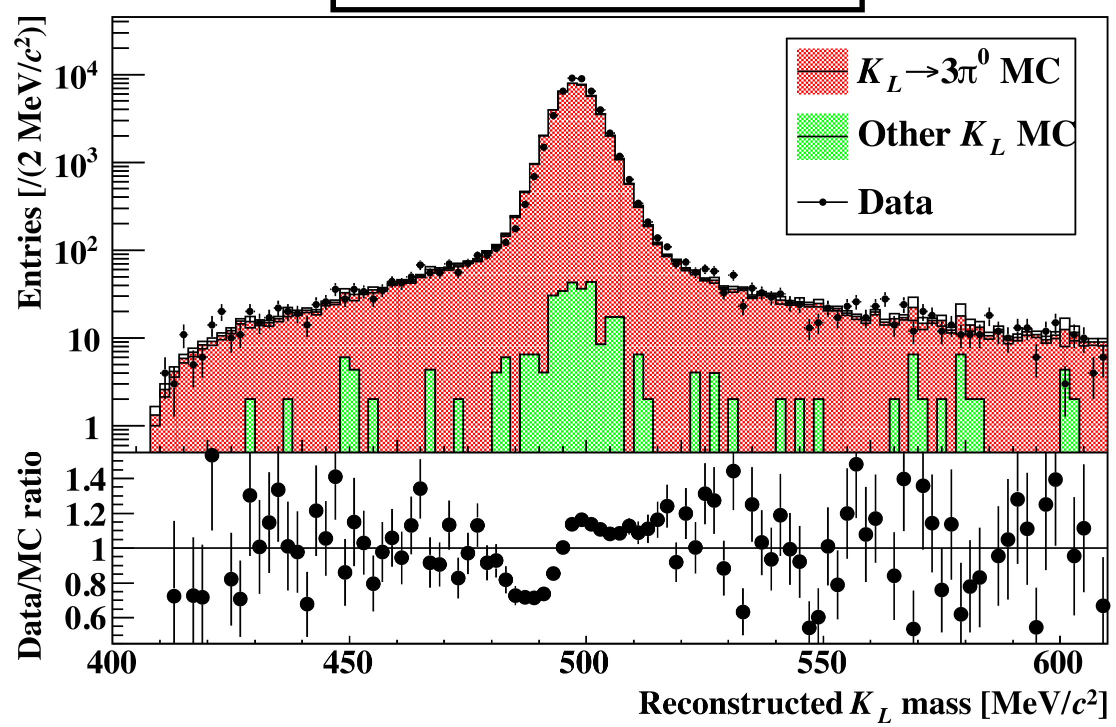
First Search: Upper limit on BR ($K_L \to \pi^0 X^0$)

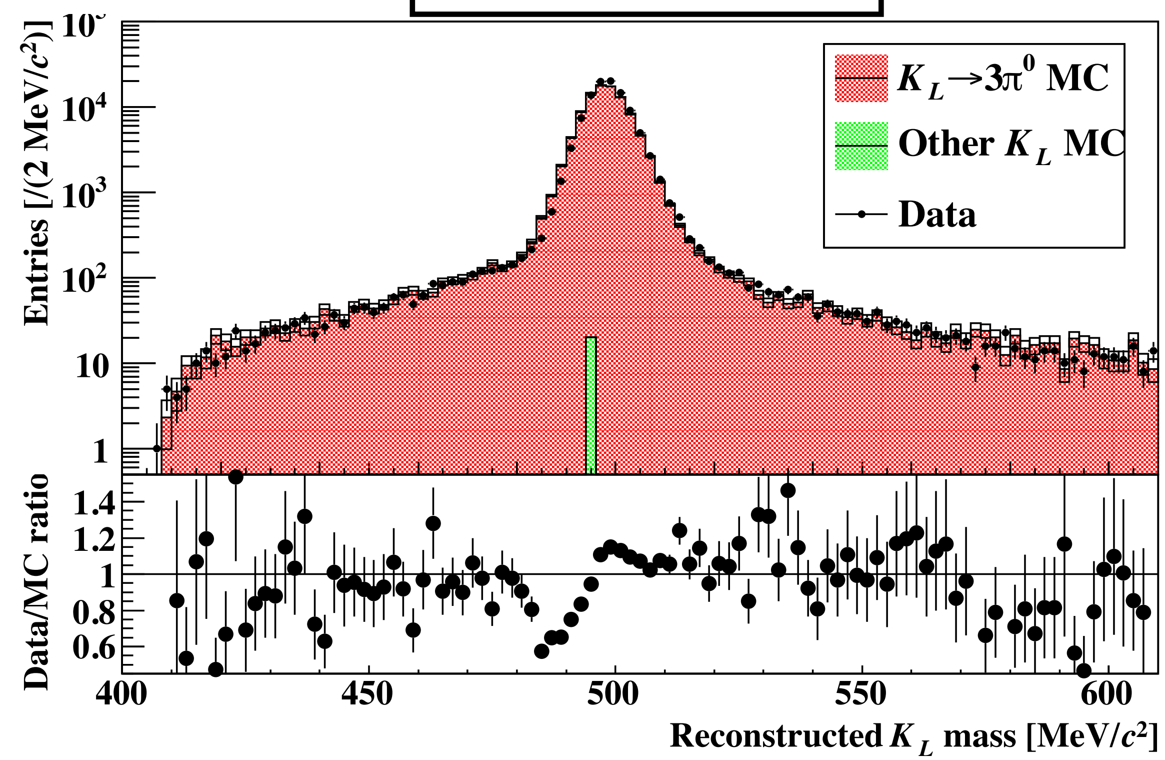
Distributions of reconstructed events

before veto cuts

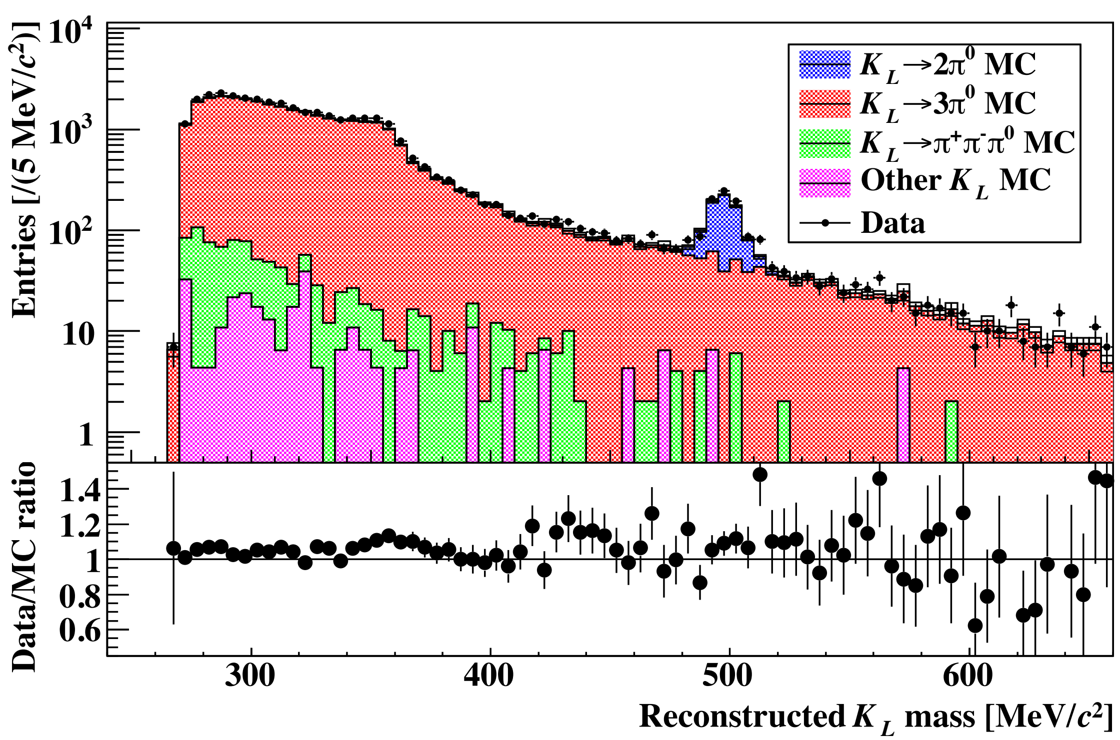
after veto cuts

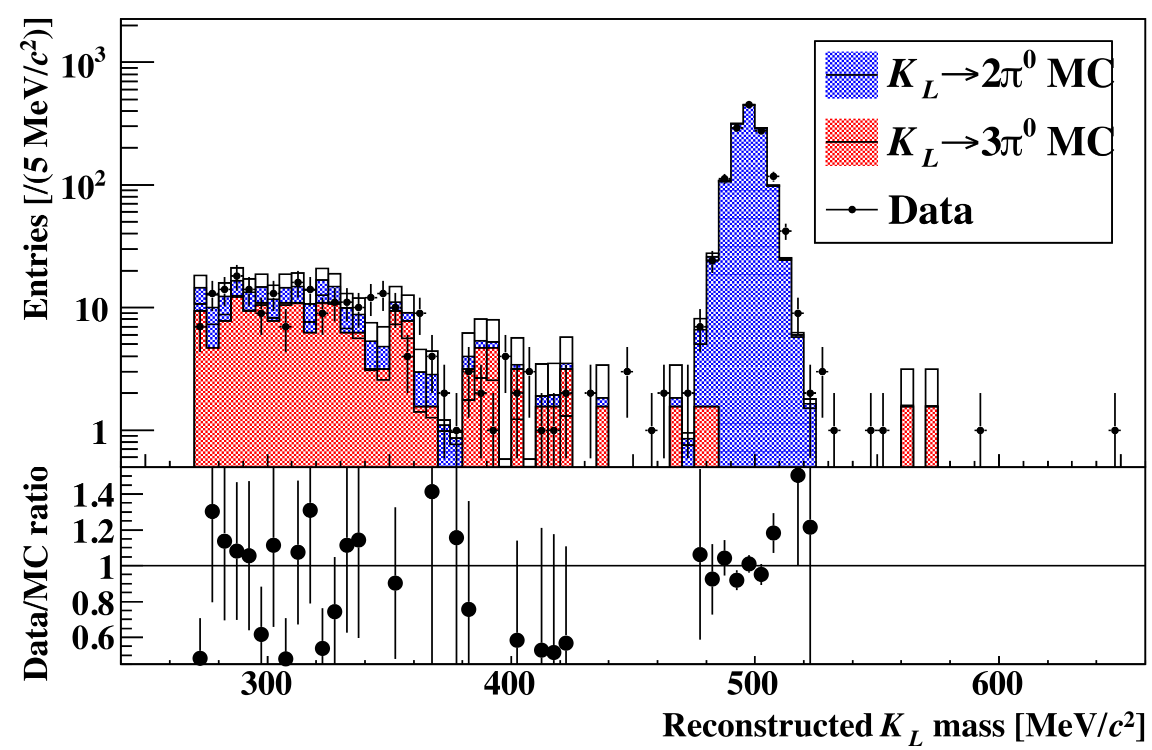
$K_L \longrightarrow 3\pi^0$





$K_L \longrightarrow 2\pi^0$





First run takeaways

Table 1 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 neutron ~70%

background source

1. Halo neutrons hitting NCC (π^0)

2. Halo neutrons hitting CsI

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

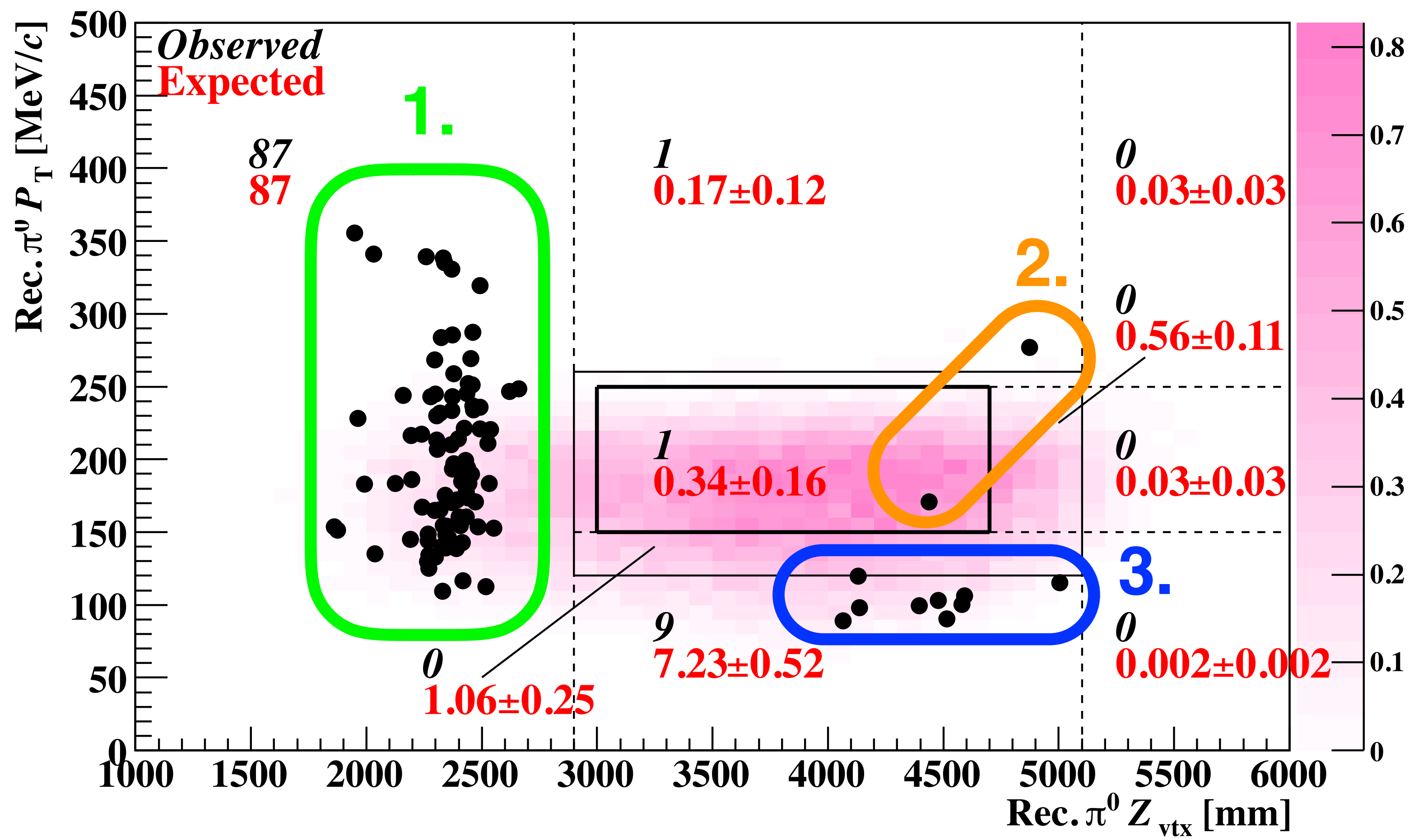


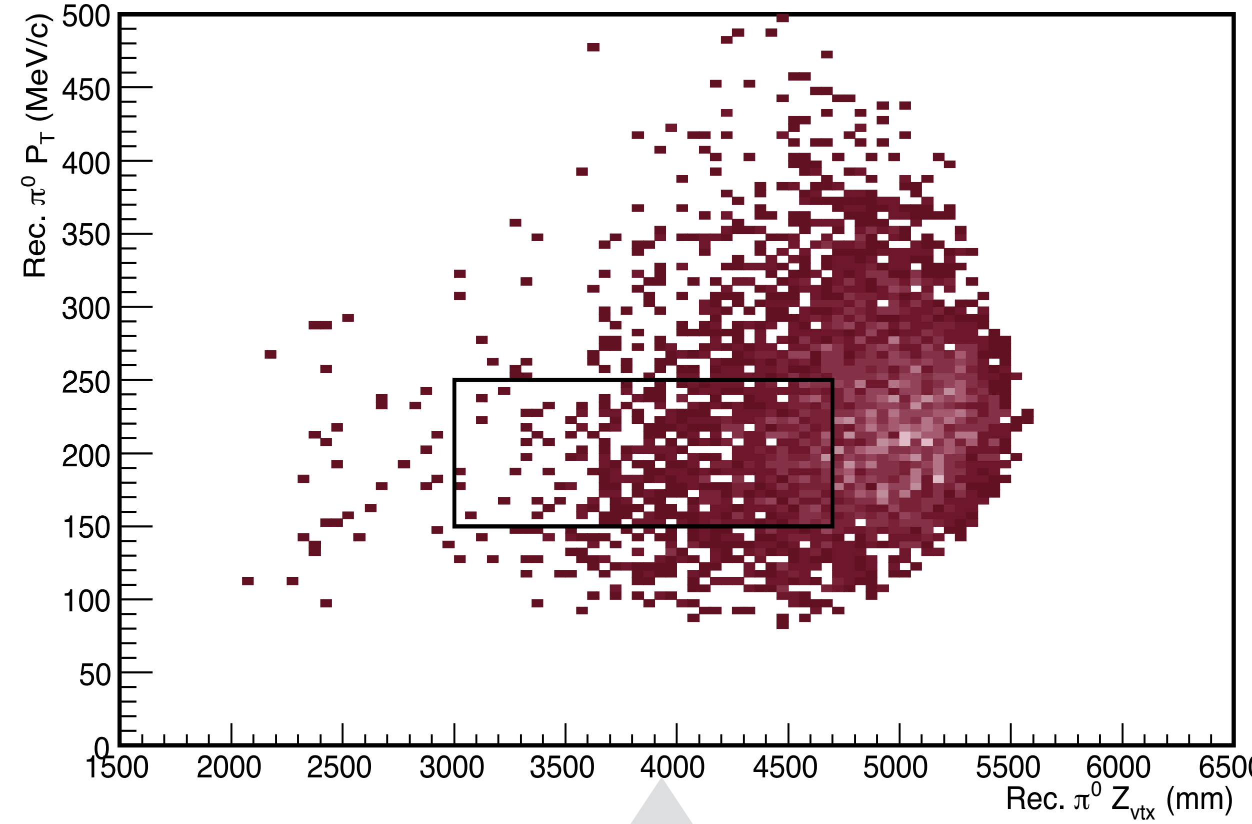
Fig. Reconstructed π^0 Pt vs. decay vertex postion

Updates to reduce region 1

Specific experimental runs to study neutron induced events

Studied using a 10 mm Al target placed on the beam line

Fig. Neutron sample from Al run



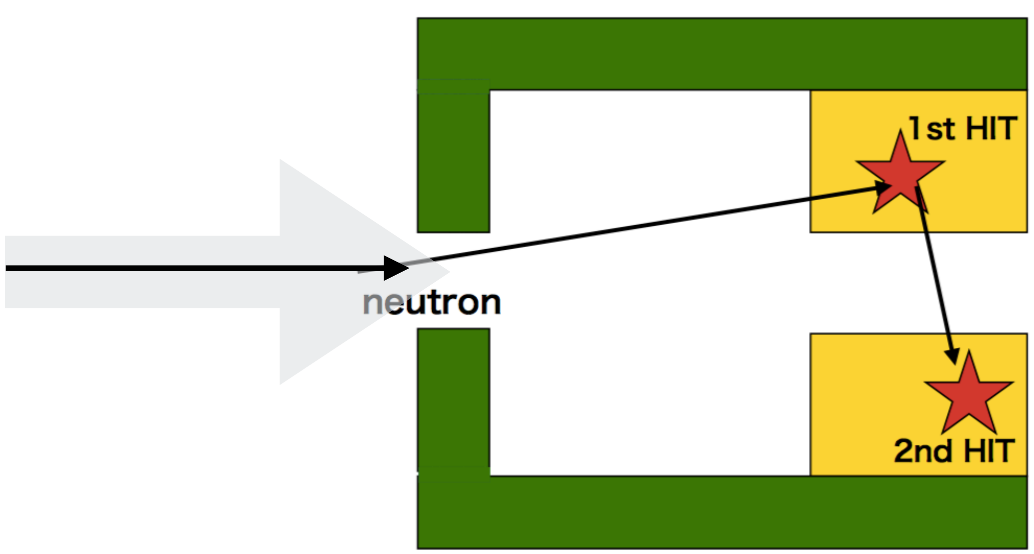


Fig. Depiction of halo neutron event

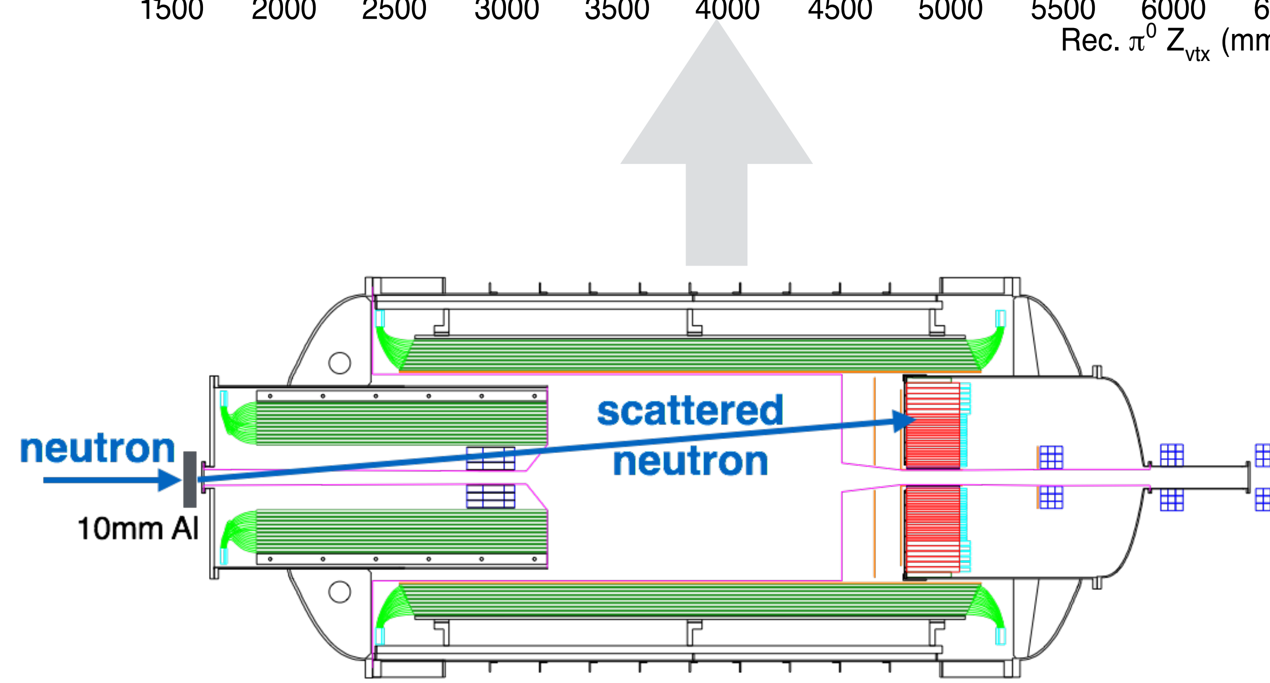


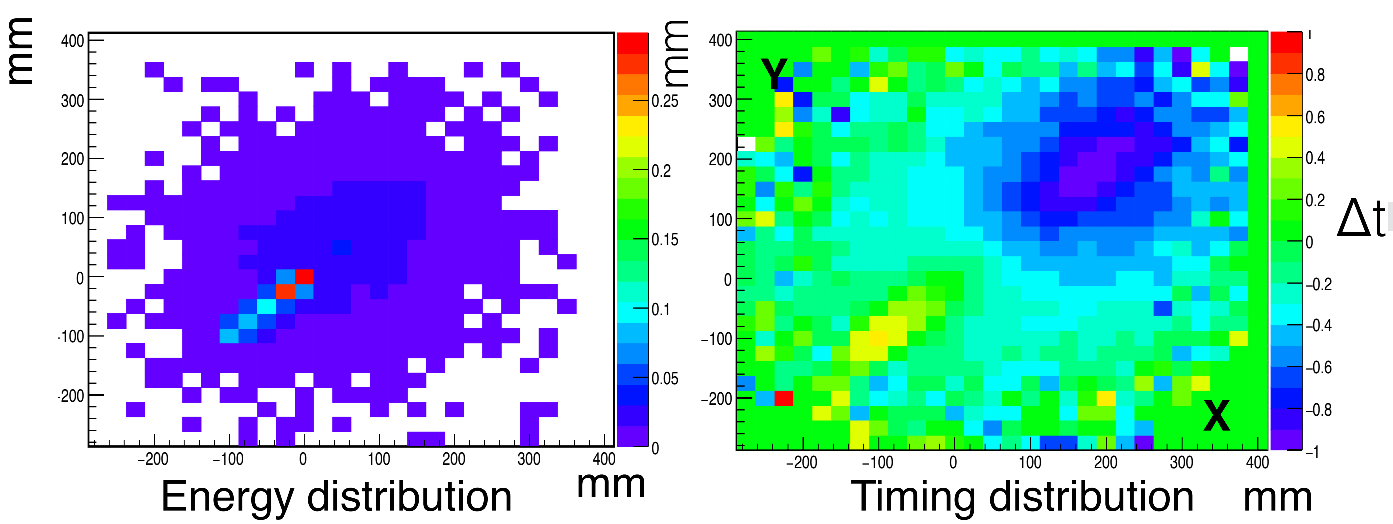
Fig. Depiction of special Al run

Updates to reduce region 1

Neutron induced events

- Analysis on neutron sample generated by using a 10mm Al target
  - Neural Networks (NN) cuts to select between hadronic and photon cluster based on cluster shape dynamics (Cluster Shape Discrimination)
  - Shape χ^2 compares observed energy deposit with the expected. The sum is taken over 27 x 27 crystals around cluster center
  - Pulse shape likelihood cut uses waveform information, hadronic showers tend to have a longer tail

hadronic and photon cluster identification performed using energy and timing information



Ex. inputs: energy X^2, E_{diff}, timing X^2

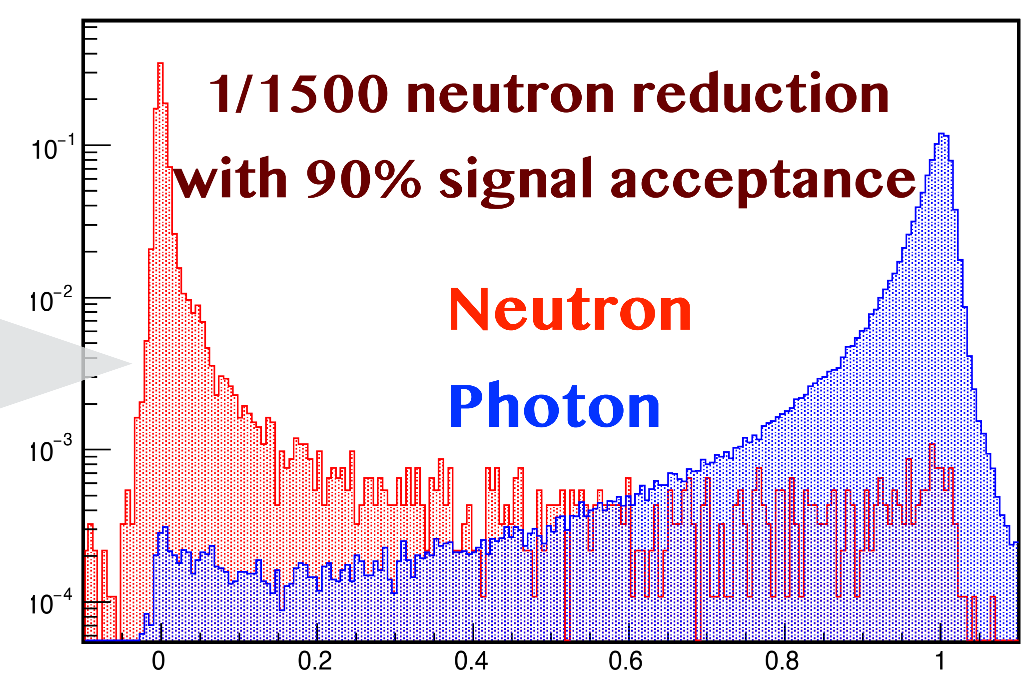


Fig. Neural Net outcome of cluster shape cut

Updates to reduce region 1

Neutron induced events

- Analysis on neutron sample generated by using a 10mm Al target
  - Neural Networks (NN) cuts to select between hadronic and photon cluster based on cluster shape dynamics (Cluster Shape Discrimination)
  - Shape χ^2 compares observed energy deposit with the expected. The sum is taken over 27 x 27 crystals around cluster center
  - Pulse shape likelihood cut uses waveform information, hadronic showers tend to have a longer tail

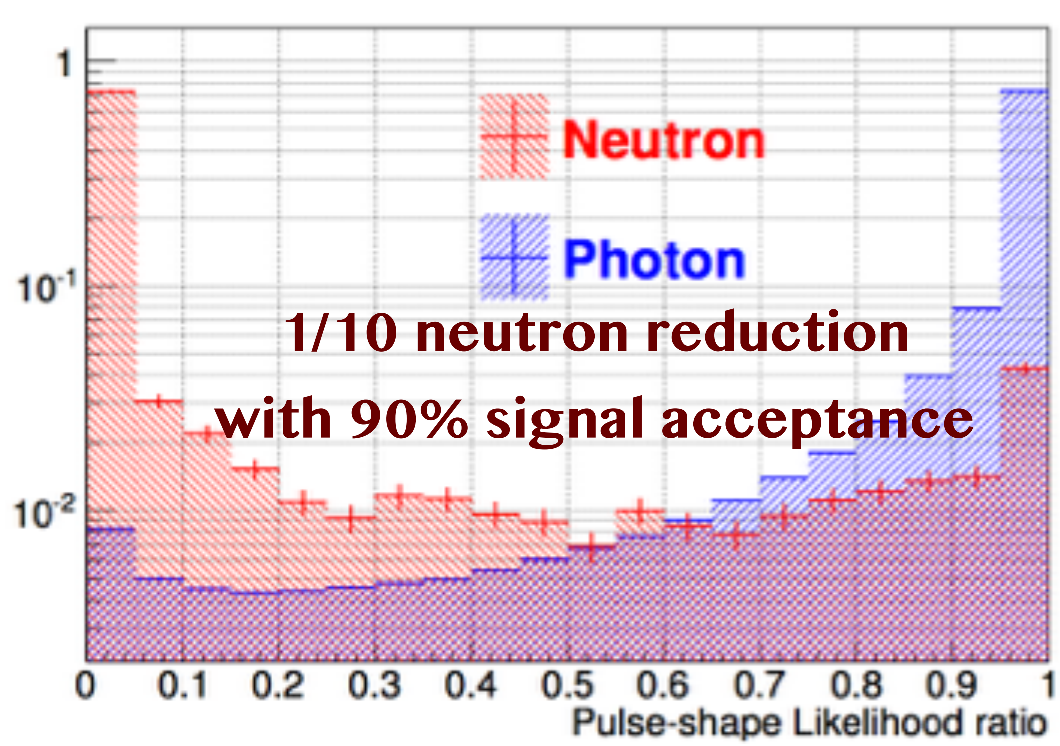


Fig. Pulse shape likelihood ratio

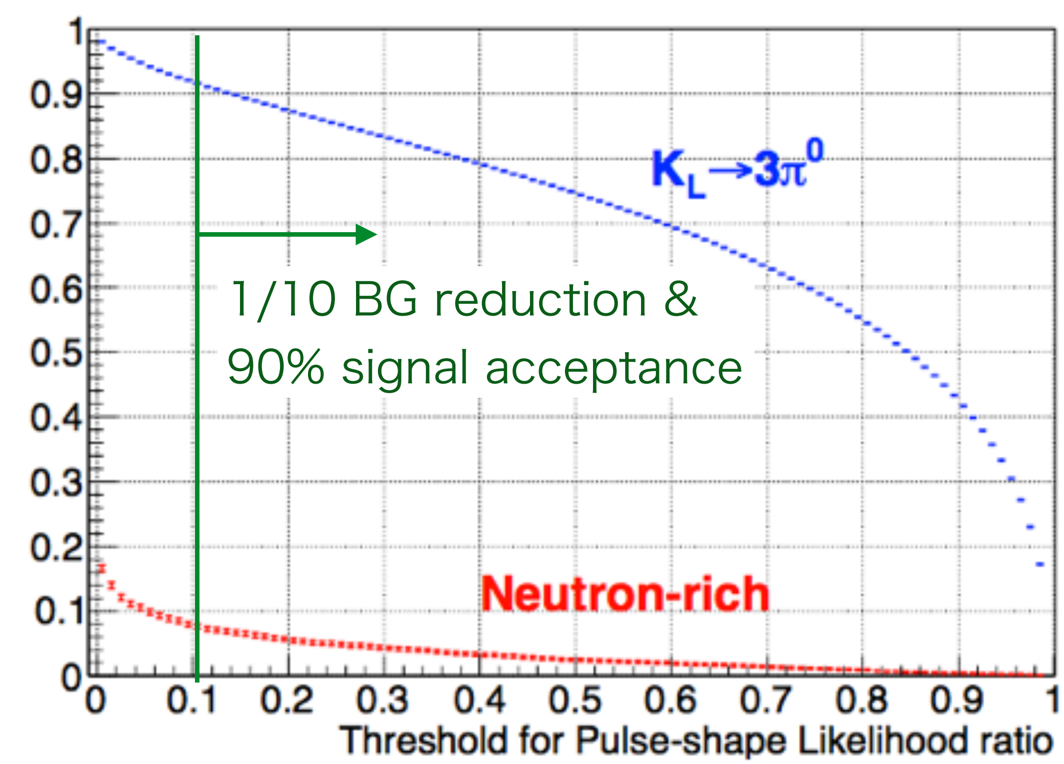


Fig. Pulse shape likelihood ratio

Updates to reduce region 2

Reduction of produced halo neutrons

- Improved aligned surfaces of collimators
  - Beam profile monitor
- Vacuum window replaced (thinner)
  - 125 μm —>12.5 μm reduce neutron interactions

Fig. Beam Profile Monitor

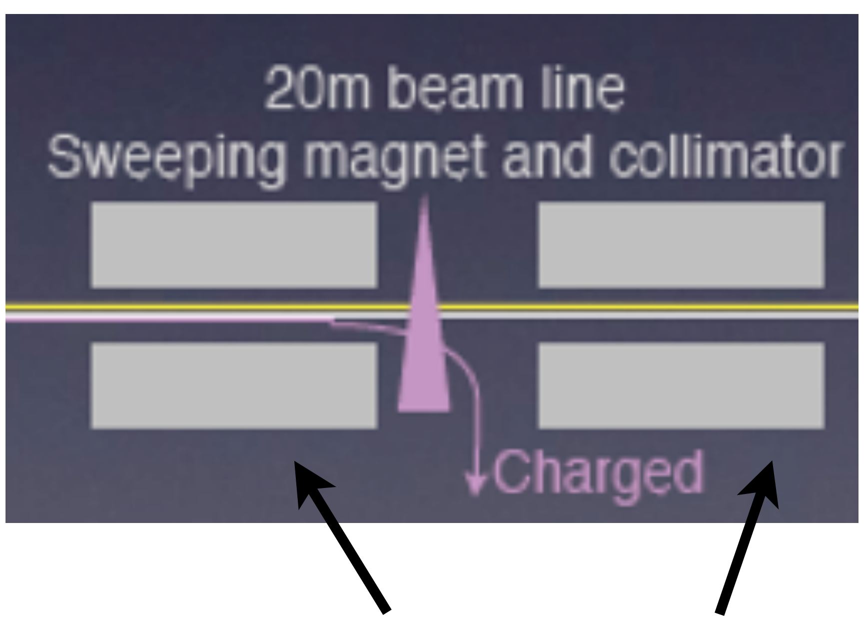


Fig. Movable collimators aligned with BPM

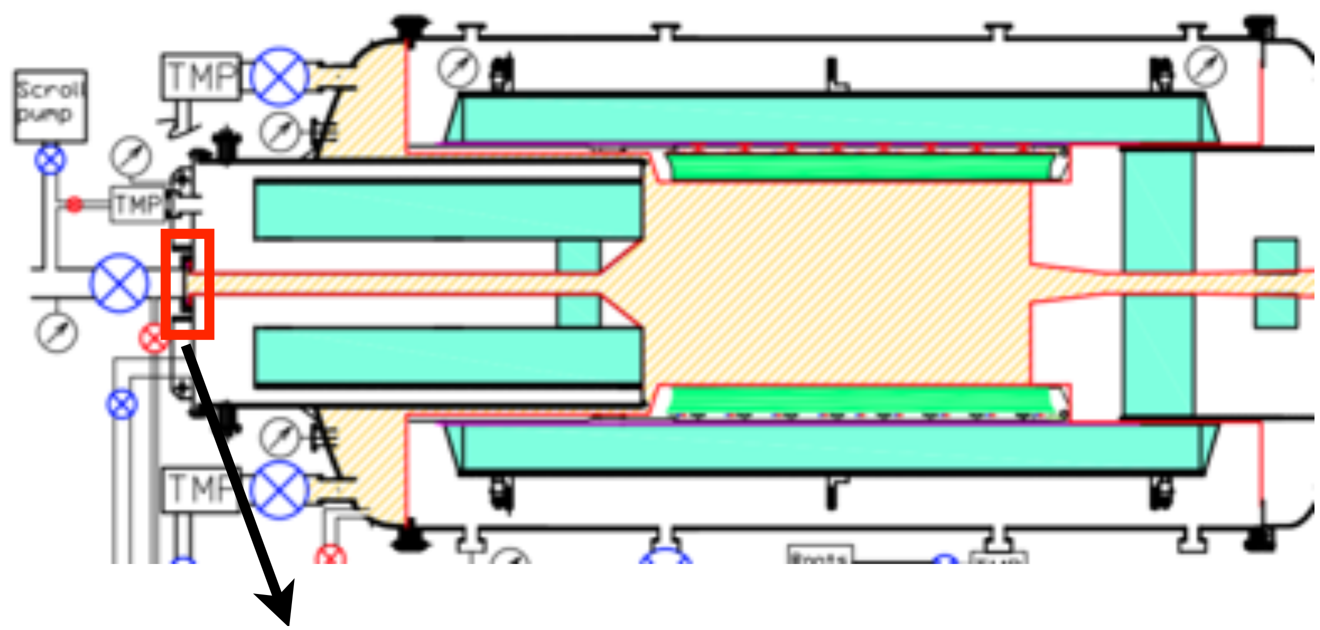


Fig. Polymide vacuum window

Updates to reduce region 3

Upgrade of Beam Hole Charge Veto (BHCV)

- Suppress $K_L \to \pi^+\pi^-\pi^0$
- Previous design: plastic scintillator
- Now: 3 layers of wire chambers reduced count rate by 65%
- Acceptance loss reduced by ~40% due to an achieved 99% efficiency in all layers

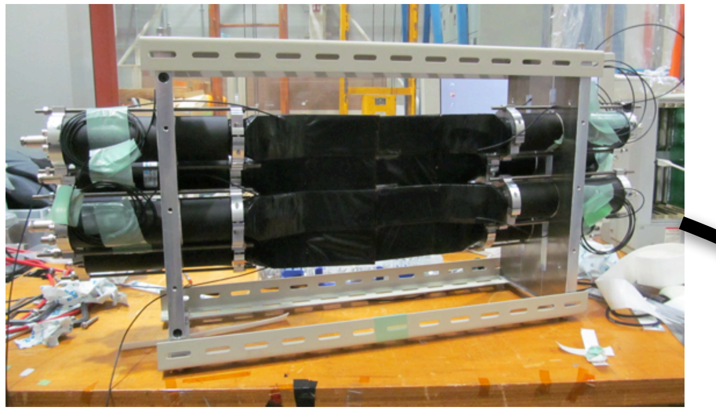


Fig. BHCV

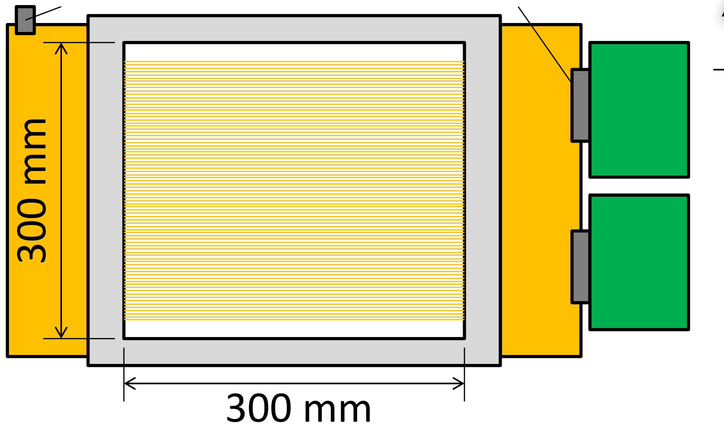
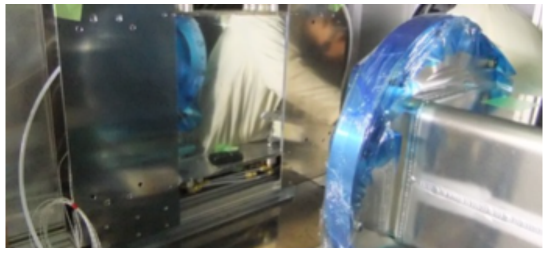


Fig. new BHCV

In-beam Charged Veto
(Wire chamber CF_4+C_5H_{12} gas)



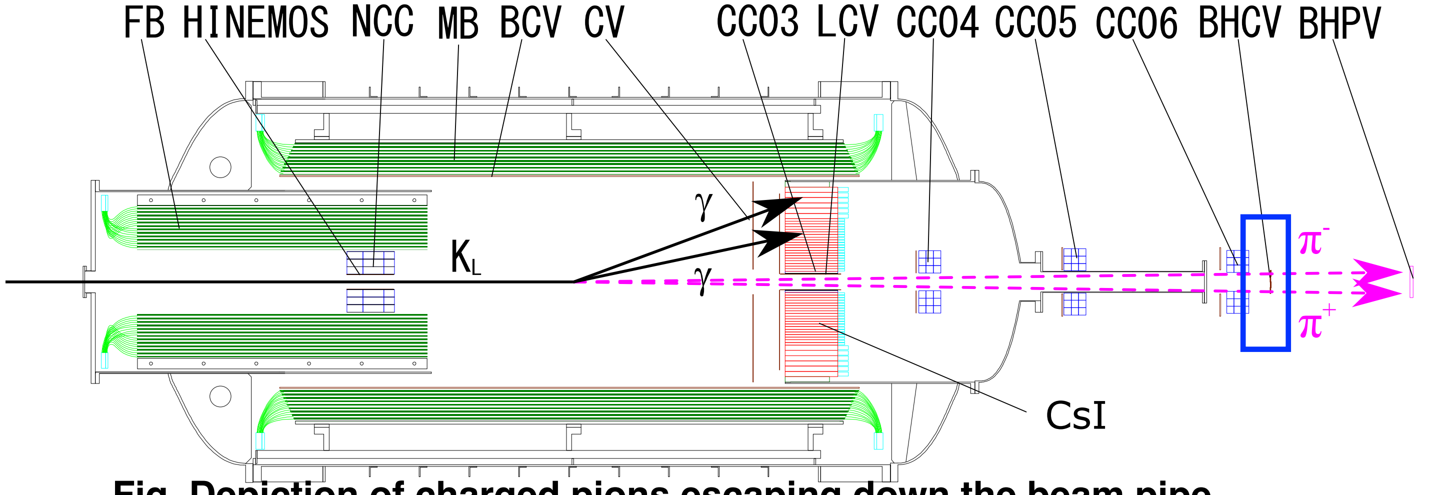


Fig. Depiction of charged pions escaping down the beam pipe

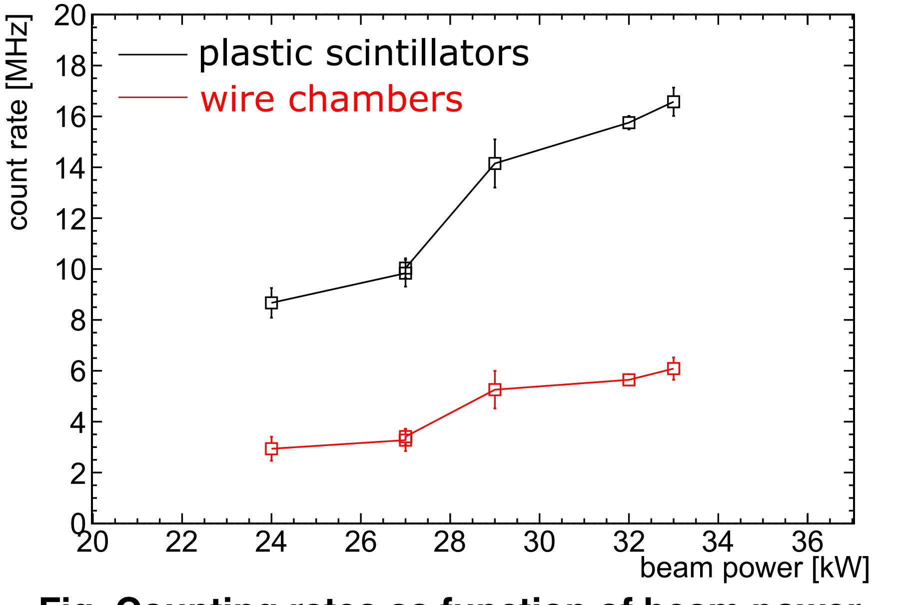


Fig. Counting rates as function of beam power

Updates to reduce region 3

Beam Pipe Charged Veto (BPCV)

- BPCV ~ 10% BG reduction

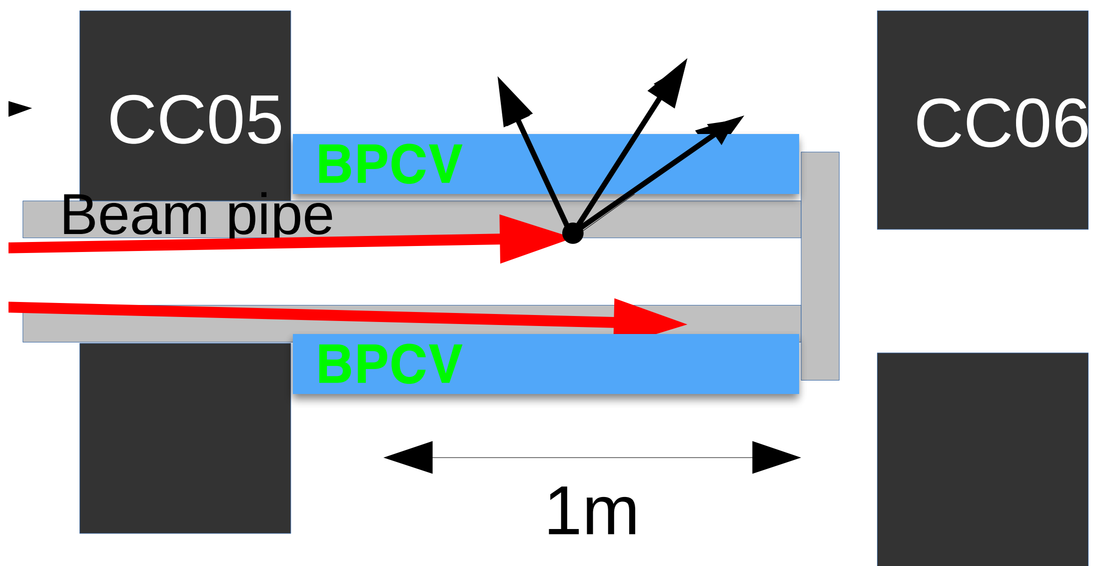


Fig. Depiction of BPCV placement

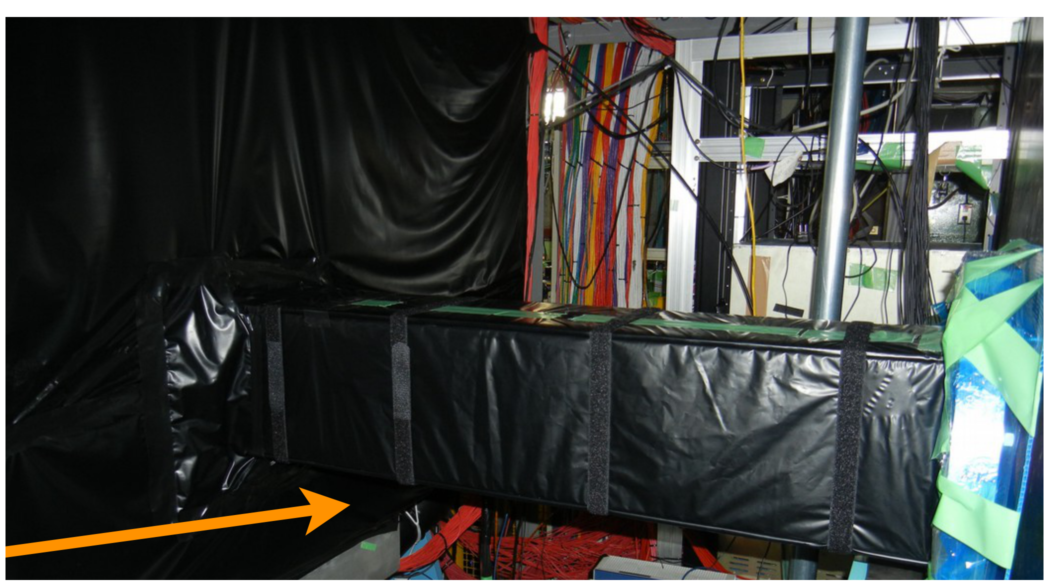


Fig. BPCV detector

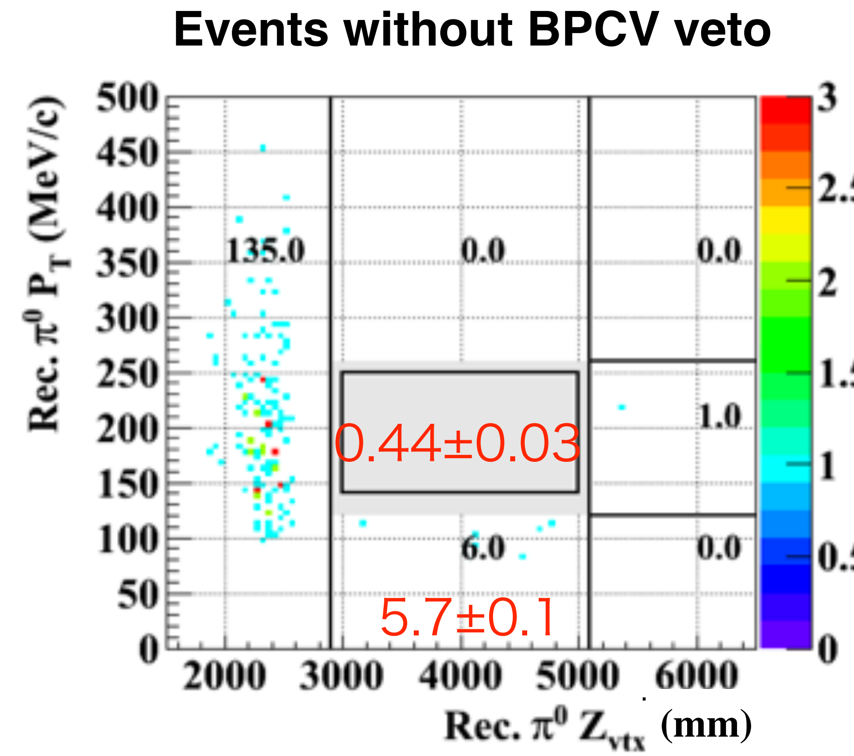


Fig. Reconstructed Pt vs. decay vertex postion

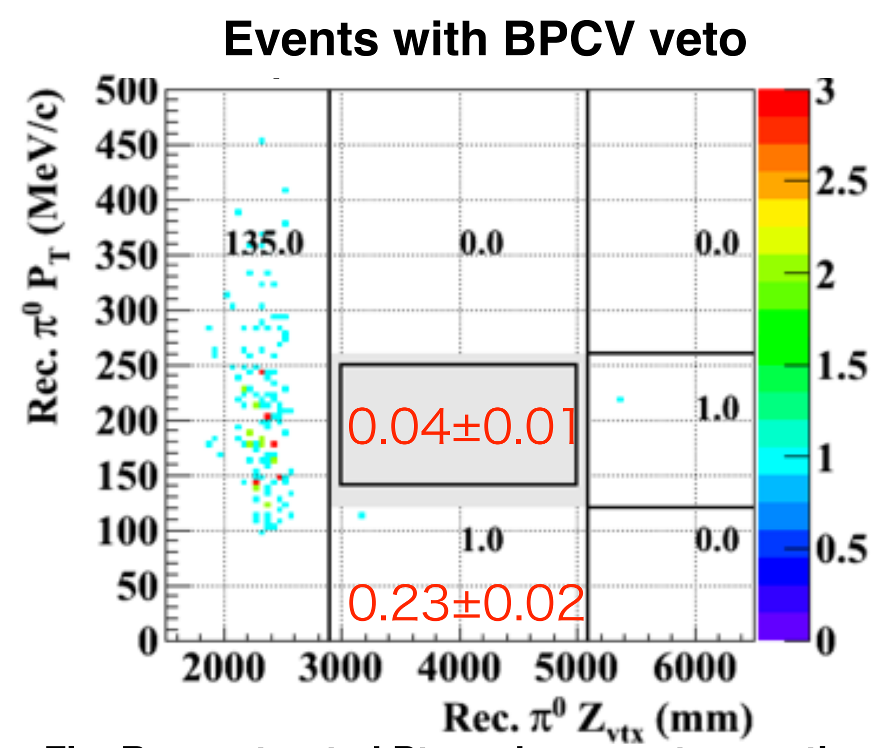


Fig. Reconstructed Pt vs. decay vertex postion

Other improvements

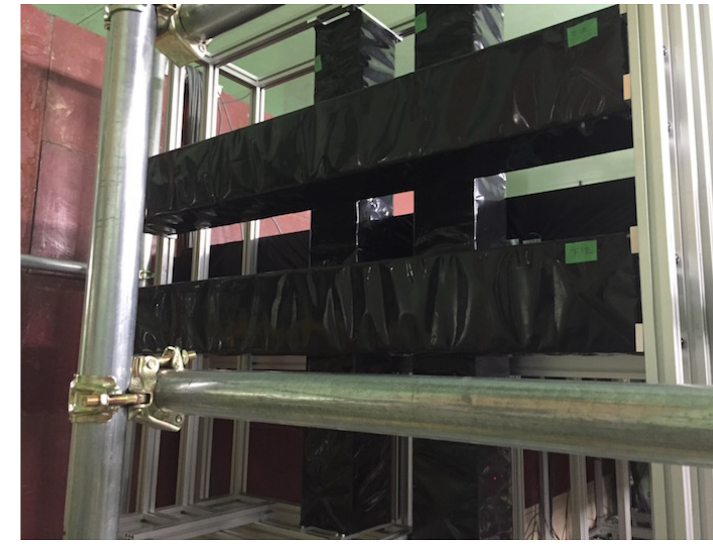
With expected higher beam power, upgrades are essential

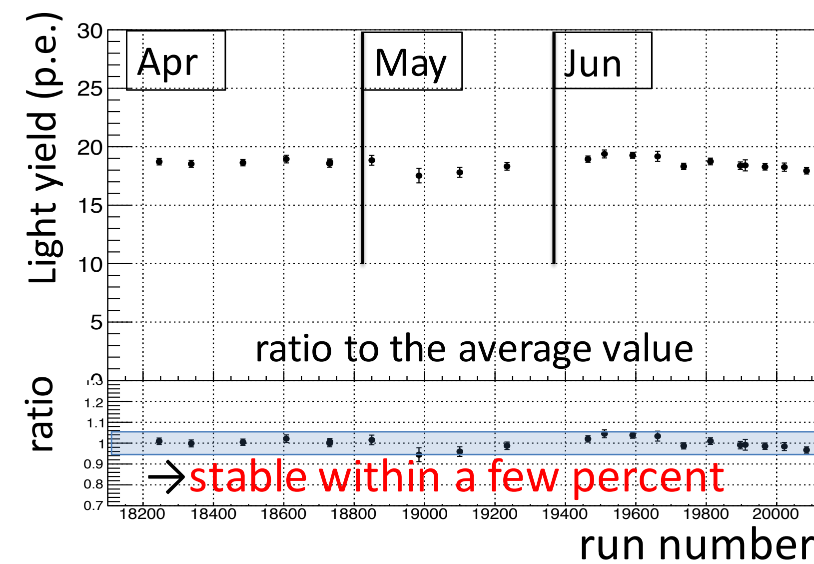
- Additional veto detector(s)
- New barrel detector
- DAQ improvements
- Both-end read out of CsI

Other improvements

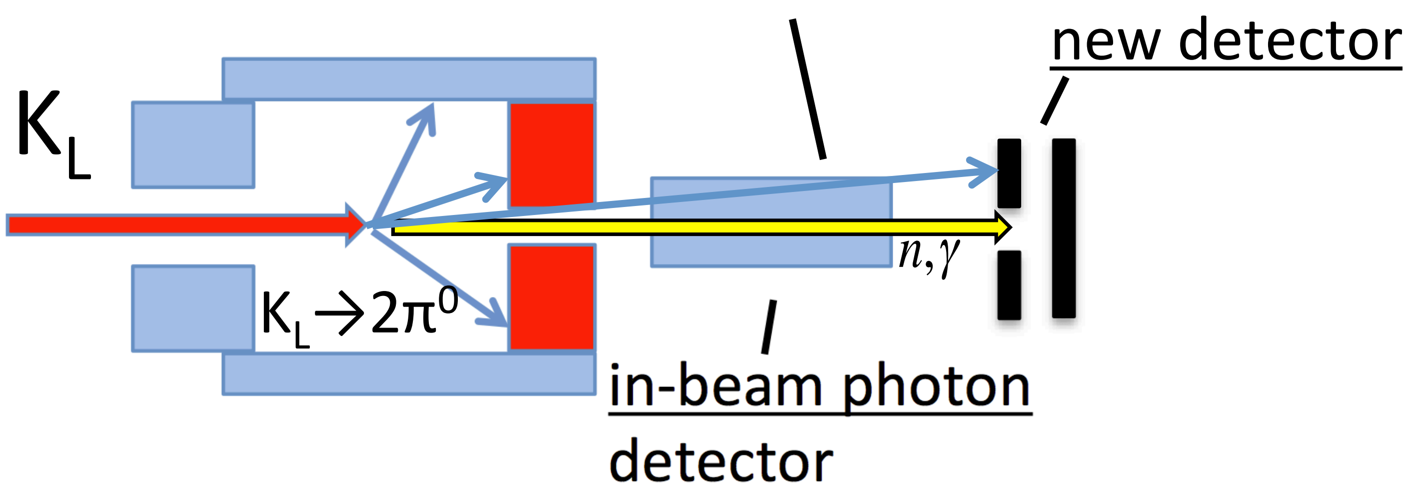
Beam Hole Guard Counter (BHGC)

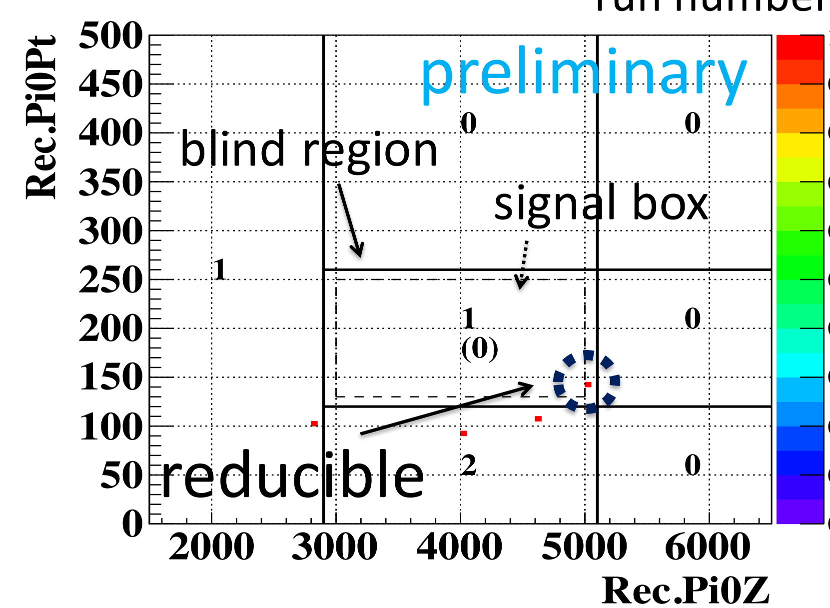
- In-beam photon counter was added to tag photons that escape through the beam hole
- Lead plate in front of acrylic Cherenkov detector
- Estimated 90% rejection of 1 GeV photons





The detection gap due to shorter path





Inner Barrel

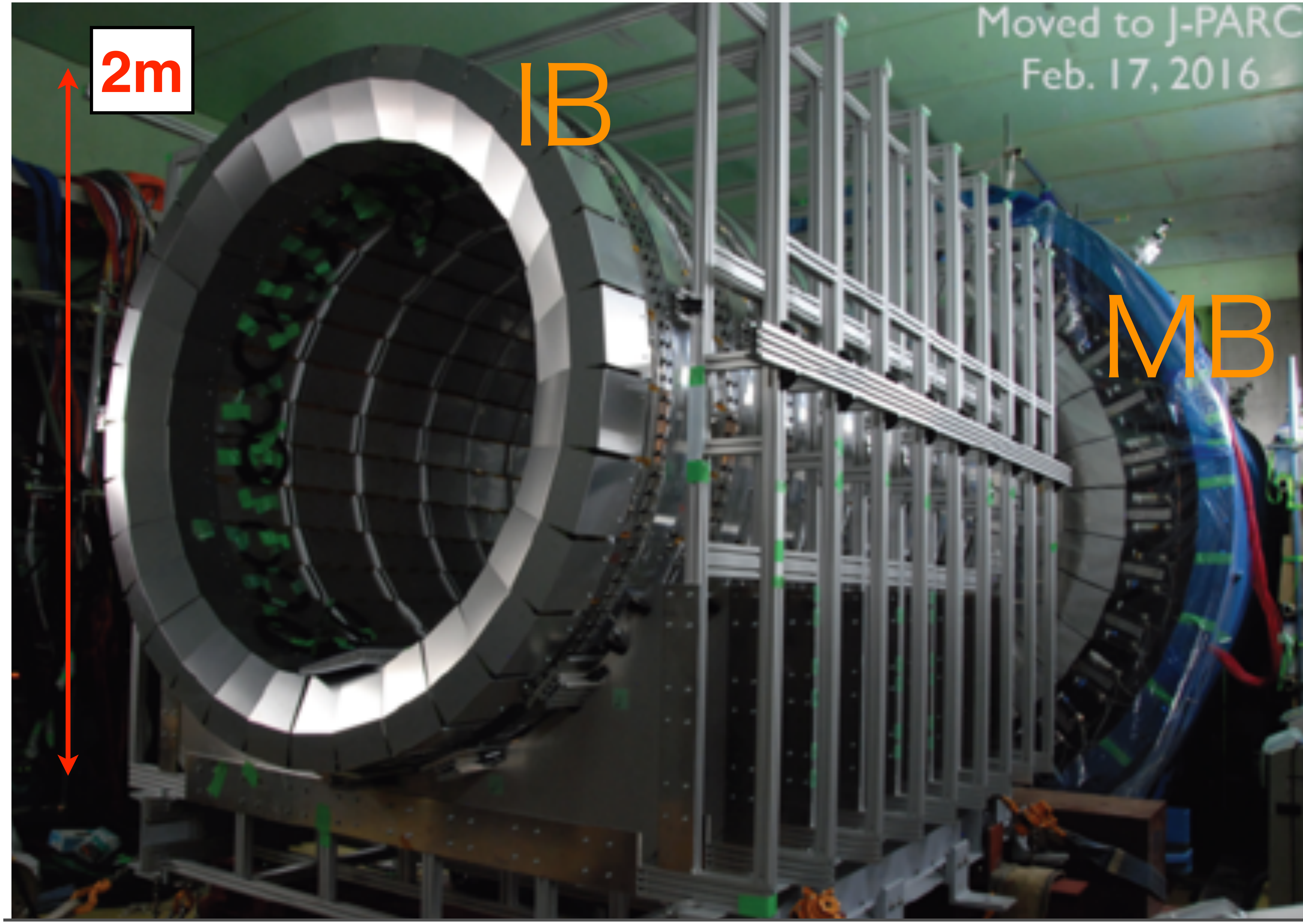


Fig. Inner barrel prior to being inserted into main barrel detector

Inner Barrel

New barrel photon veto (IB)

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

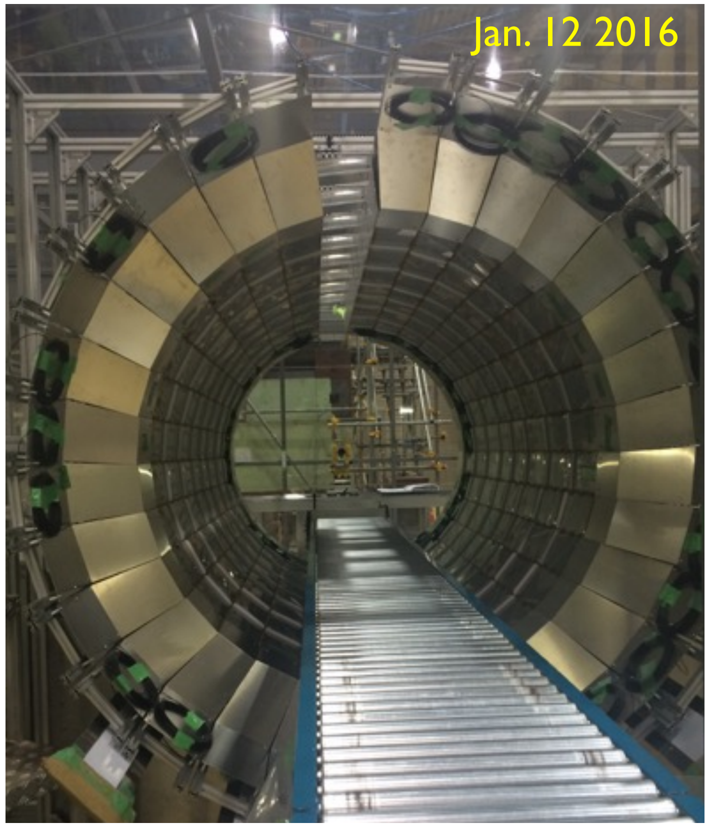


Fig. Inner Barrel

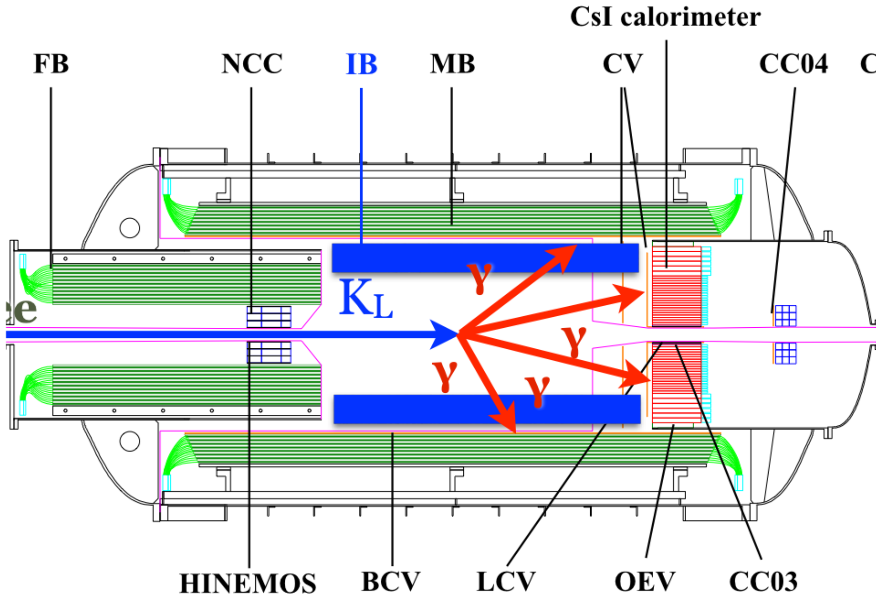
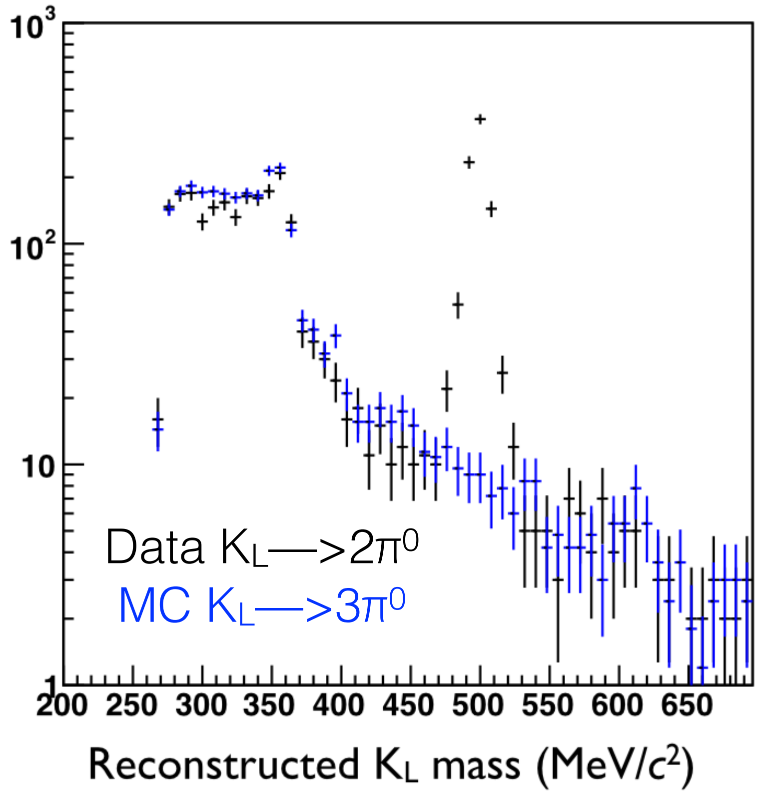


Fig. Depiction of inner barrel placement within MB



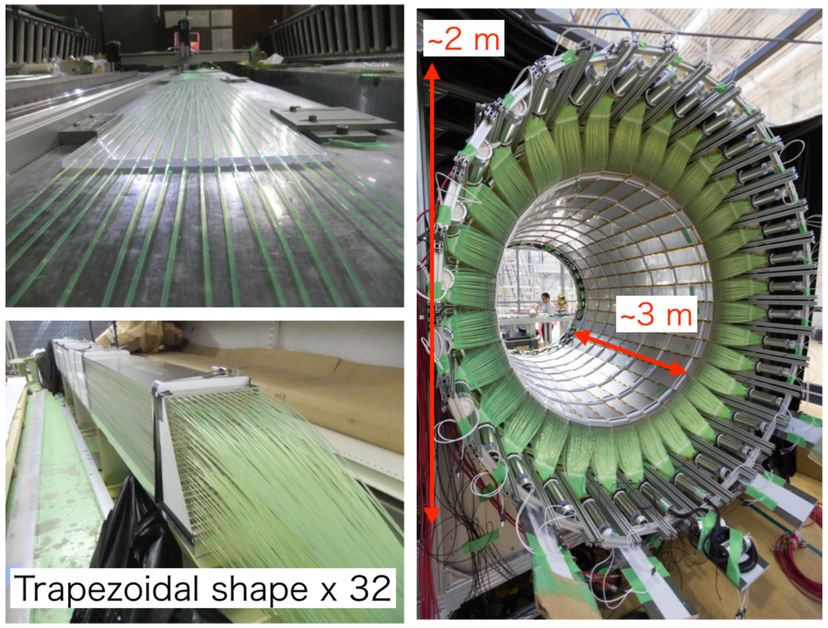


Fig. Inner Barrel

DAQ improvements

Component	2013	Summer 2015	Fall 2015	Summer 2016
ADC	16 Crates Uncompressed data	17 Crates Uncompressed data	17 Crates Compressed data	18 Crates Compressed data
FANOUT	16 FANOUT Module	32 FANOUT Module	32 FANOUT Module	32 FANOUT Module
MACTRIS	Clock to two trigger boards	Clock to three trigger boards	Clock to three trigger boards	Clock provided to four trigger boards
L2	Firmware design by schematic only	Firmware design using Verilog with compression	Firmware design using Verilog with compression	Firmware design using Verilog with compression
L3	**Mandolin** Ethernet switch for event building	**Banjo** cluster (2 node type) Infiniband for event matching and building	**Banjo** Infiniband for event matching and building	**Banjo** Infiniband for event matching and building

DAQ performance

Improved DAQ efficiency:

- Data acquisition system has been steadily improved to accommodate larger data sets with increasing beam power
- From 75-80% up to 90-95%

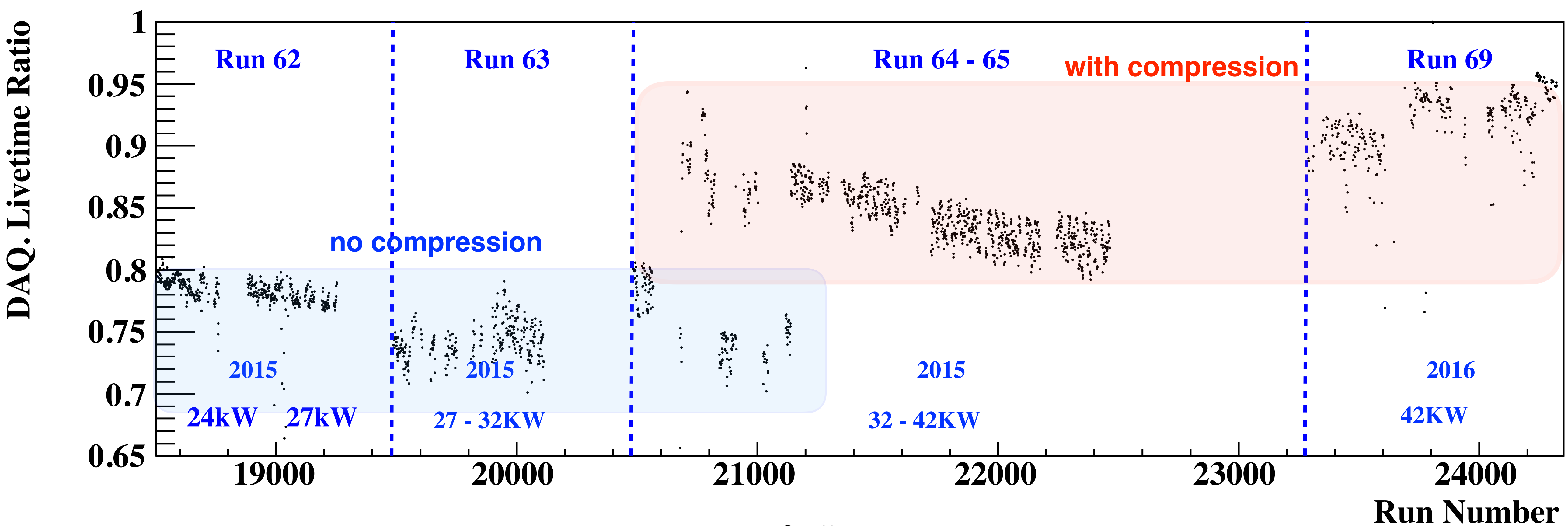
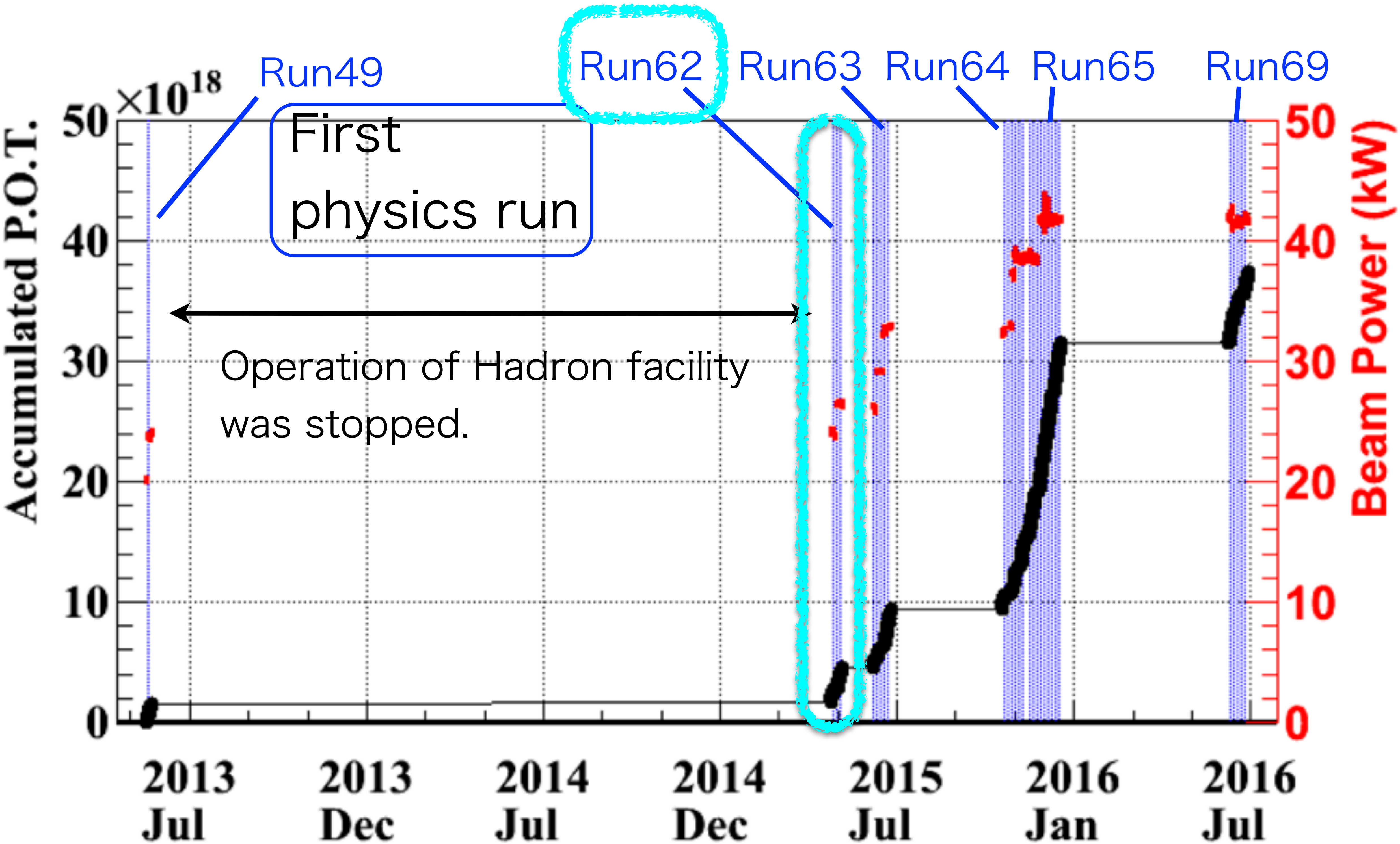


Fig. DAQ efficiency

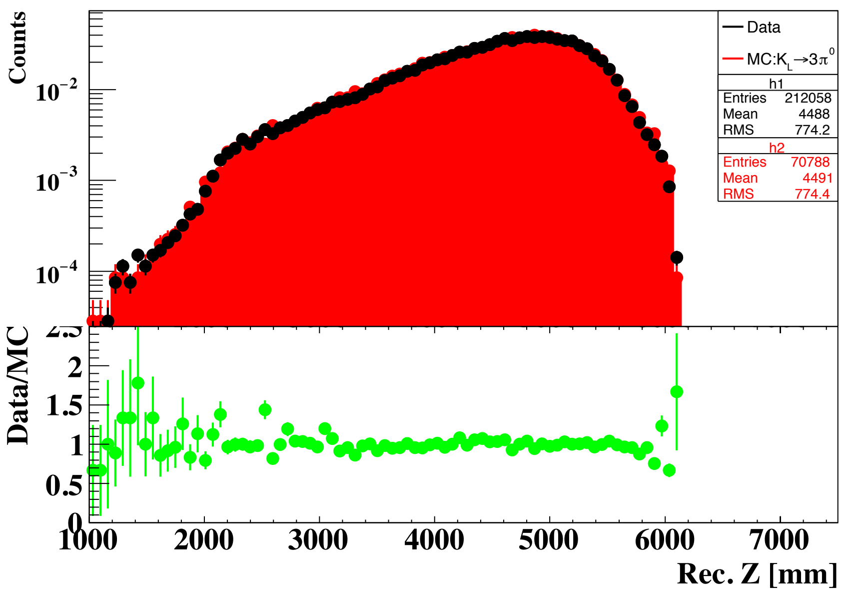
Current status



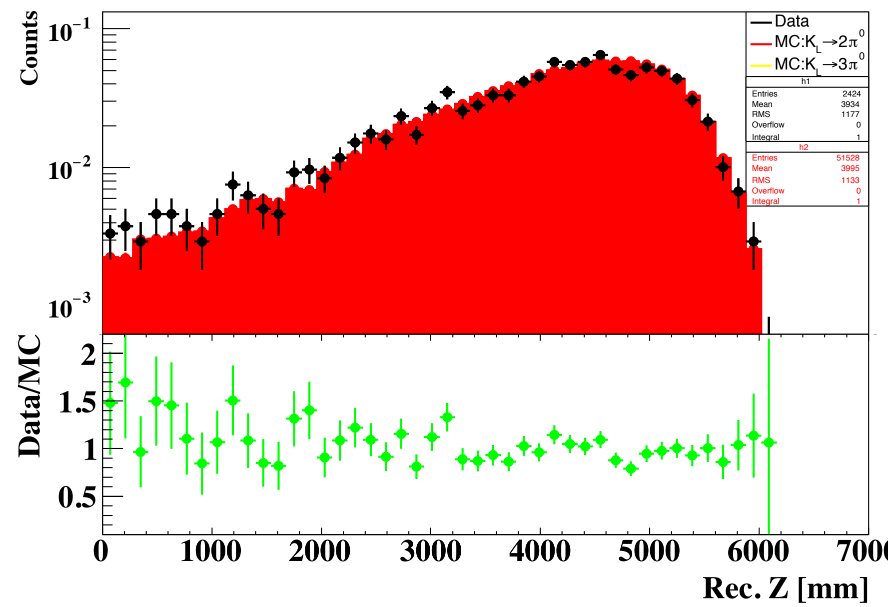
Distributions of reconstructed events

Data/MC Comparisons

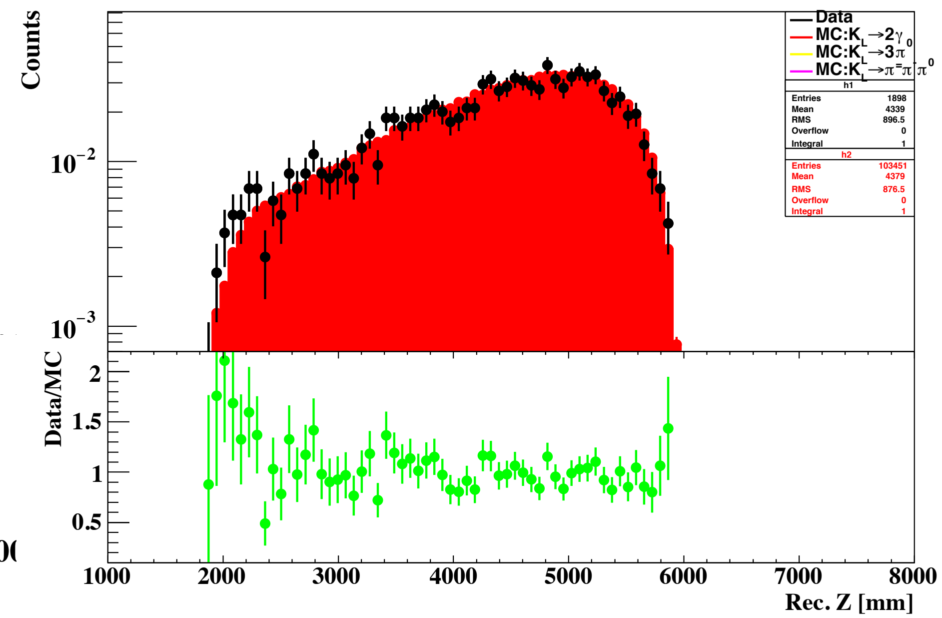
$K_L \rightarrow 3\pi^0$

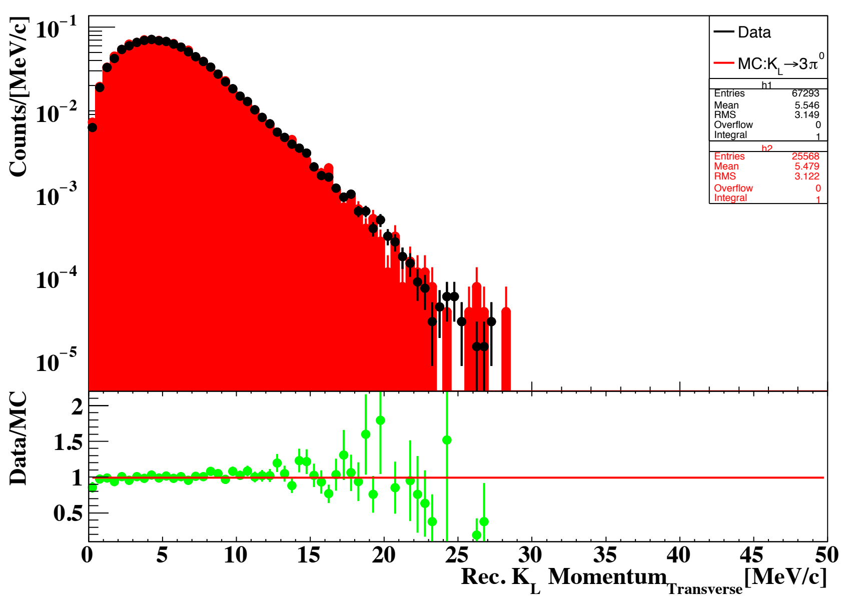


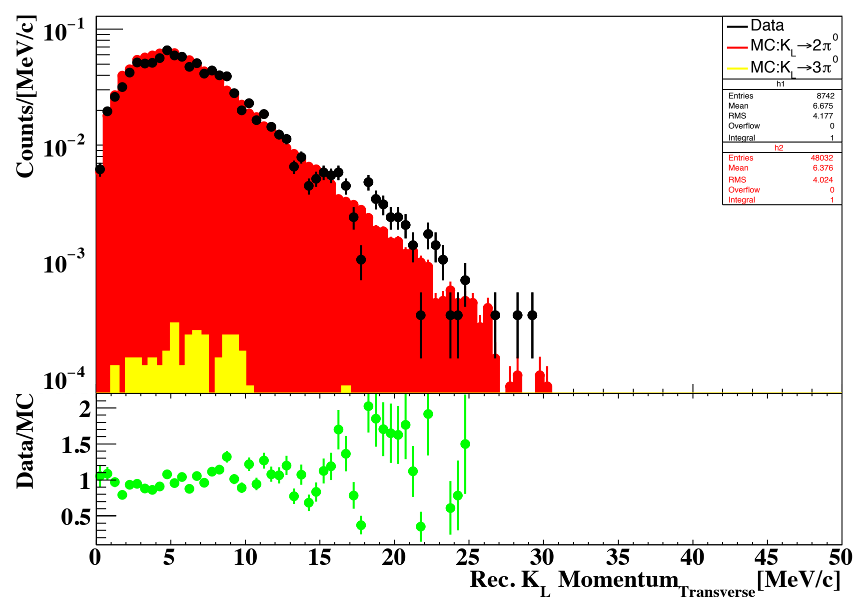
$K_L \rightarrow 2\pi^0$

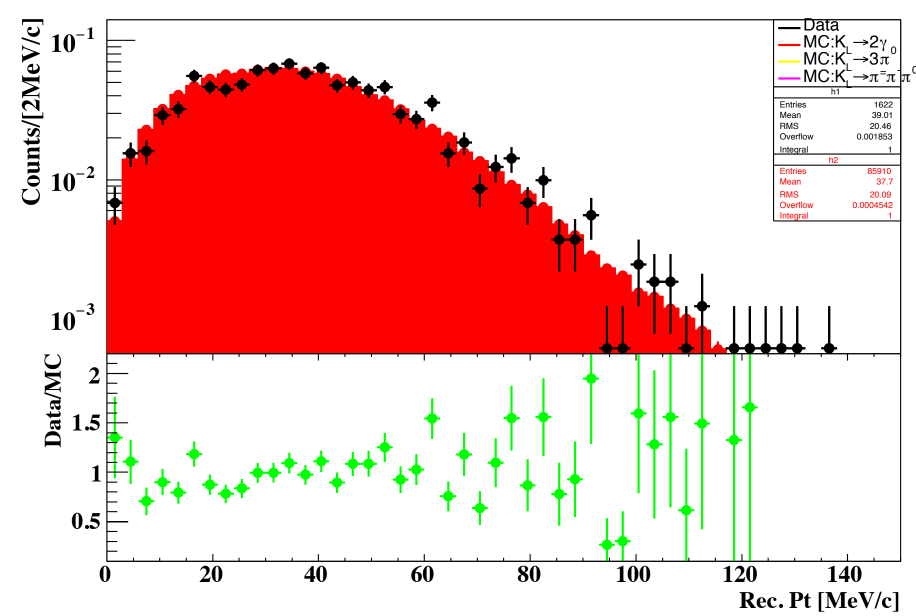


$K_L \rightarrow 2\gamma$









Data is well reproduced

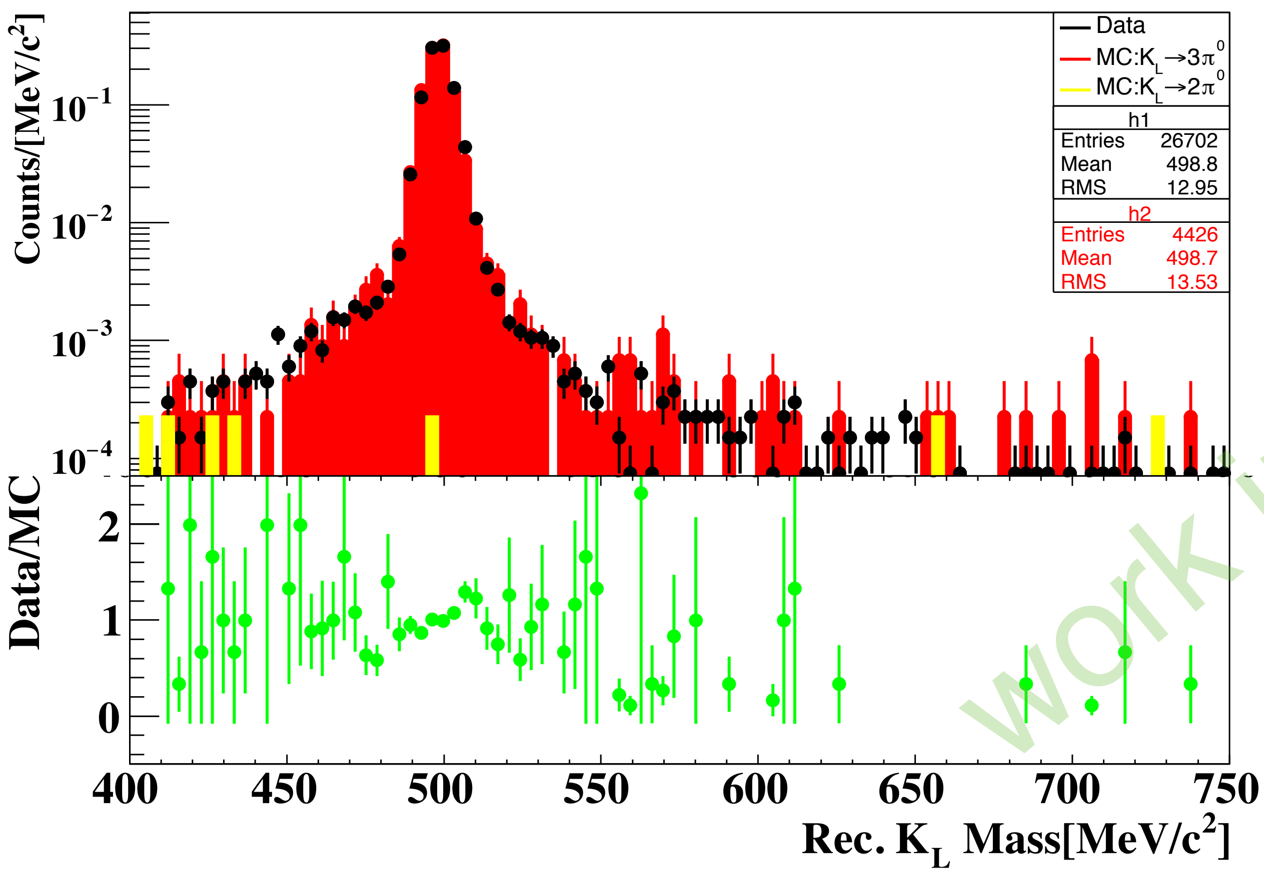
Black: Data

MC: Monte Carlo

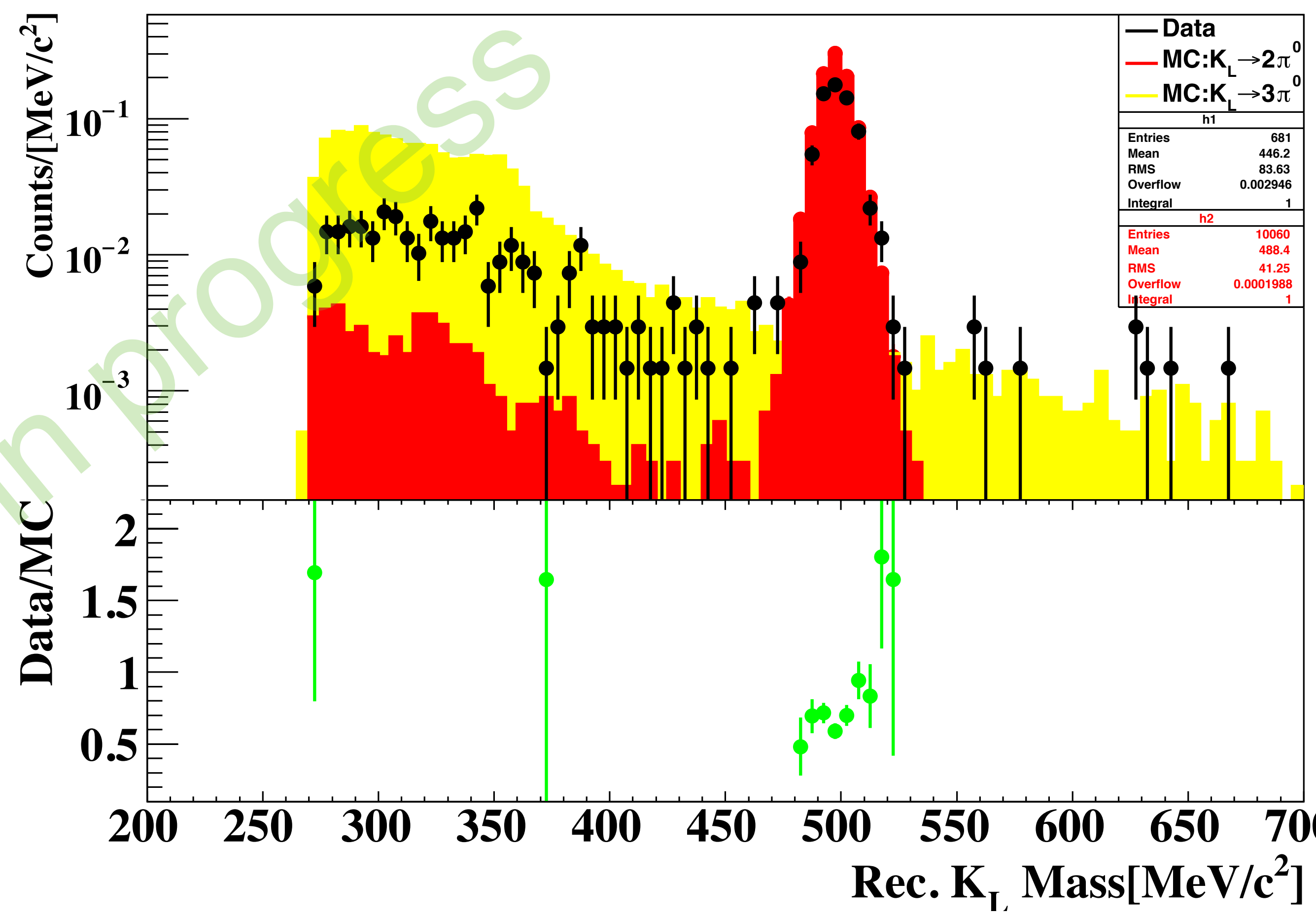
Distributions of reconstructed events

Data/MC Comparisons

K_L —> $3\pi^0$



K_L —> $2\pi^0$



Distributions are well reproduced

Preliminary results

Estimated background events in Run 62	
Source	**Number of Events**
KL—>2π^0	0.04±0.03
KL—>$\pi^+\pi^-\pi^0$	0.04±0.01
Halo neutrons hitting NCC (upstream)	0.04±0.04
Halo neutrons hitting CSI	0.05±0.02
Total	**0.17±0.05**

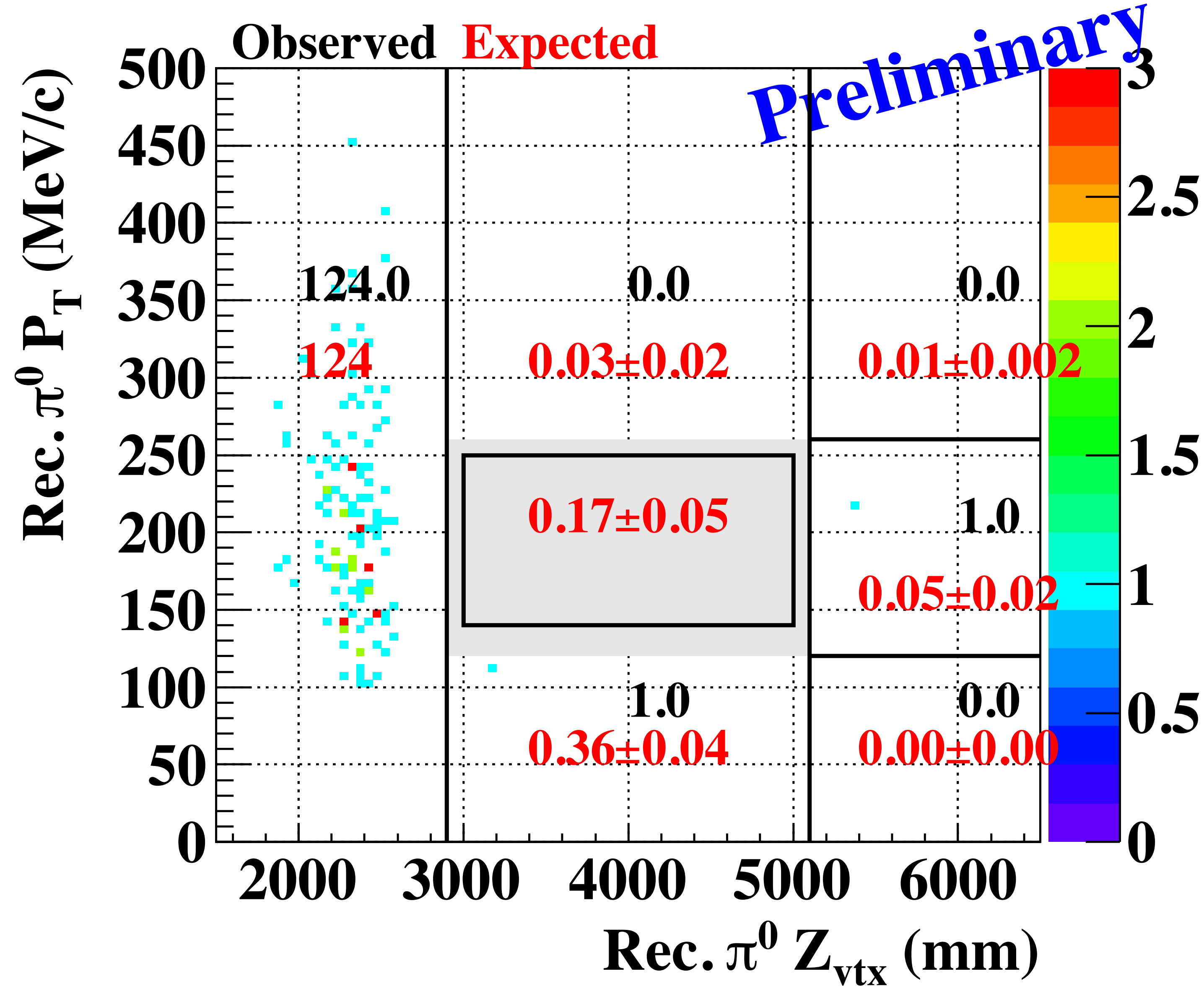
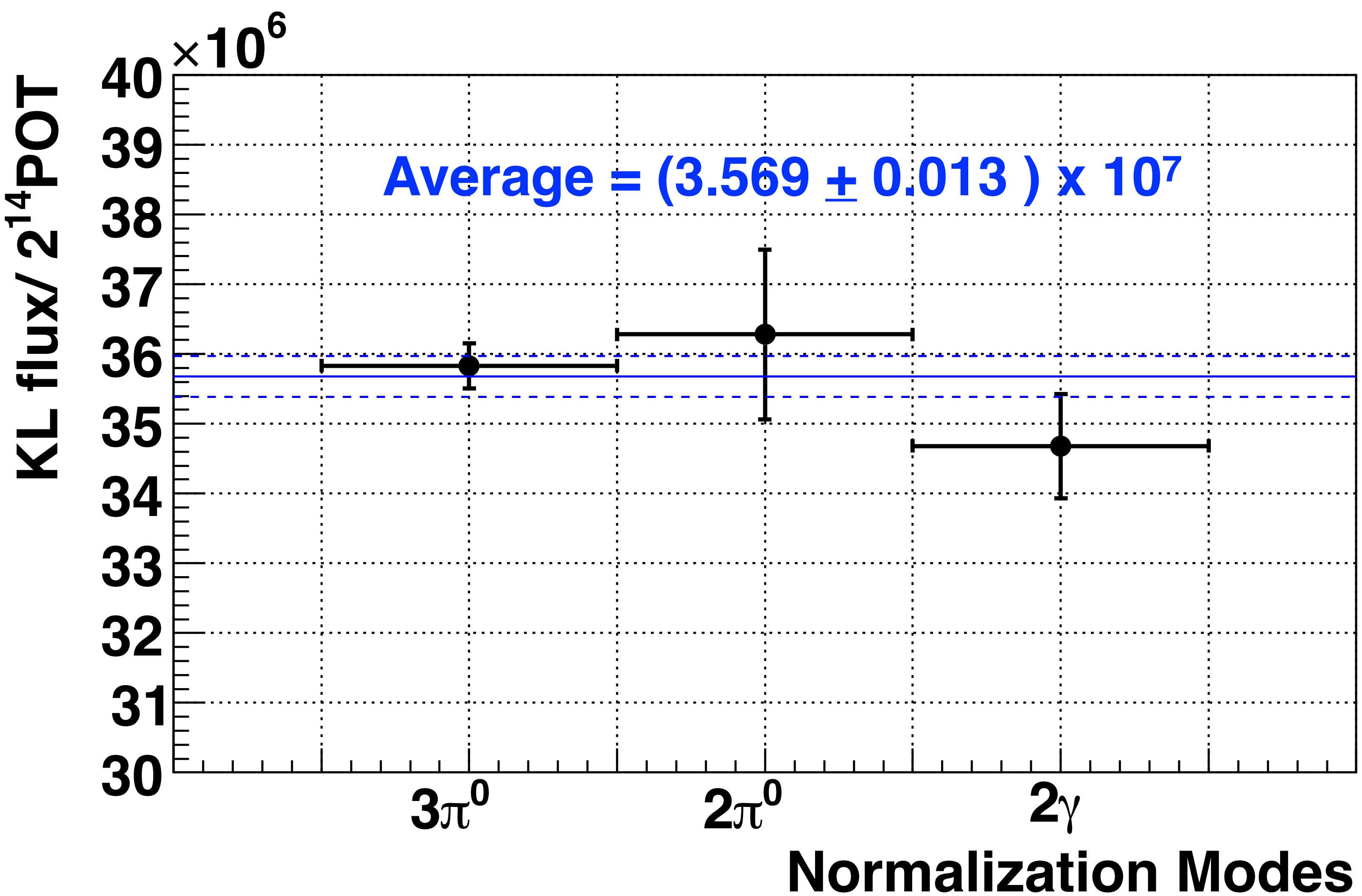


Fig. Reconstructed π^0 Pt vs. decay vertex postion

K_L flux estimation

Measured K_L yield for each normalization decay mode ($K_L \to 3\pi^0$, $2\pi^0$, 2γ):

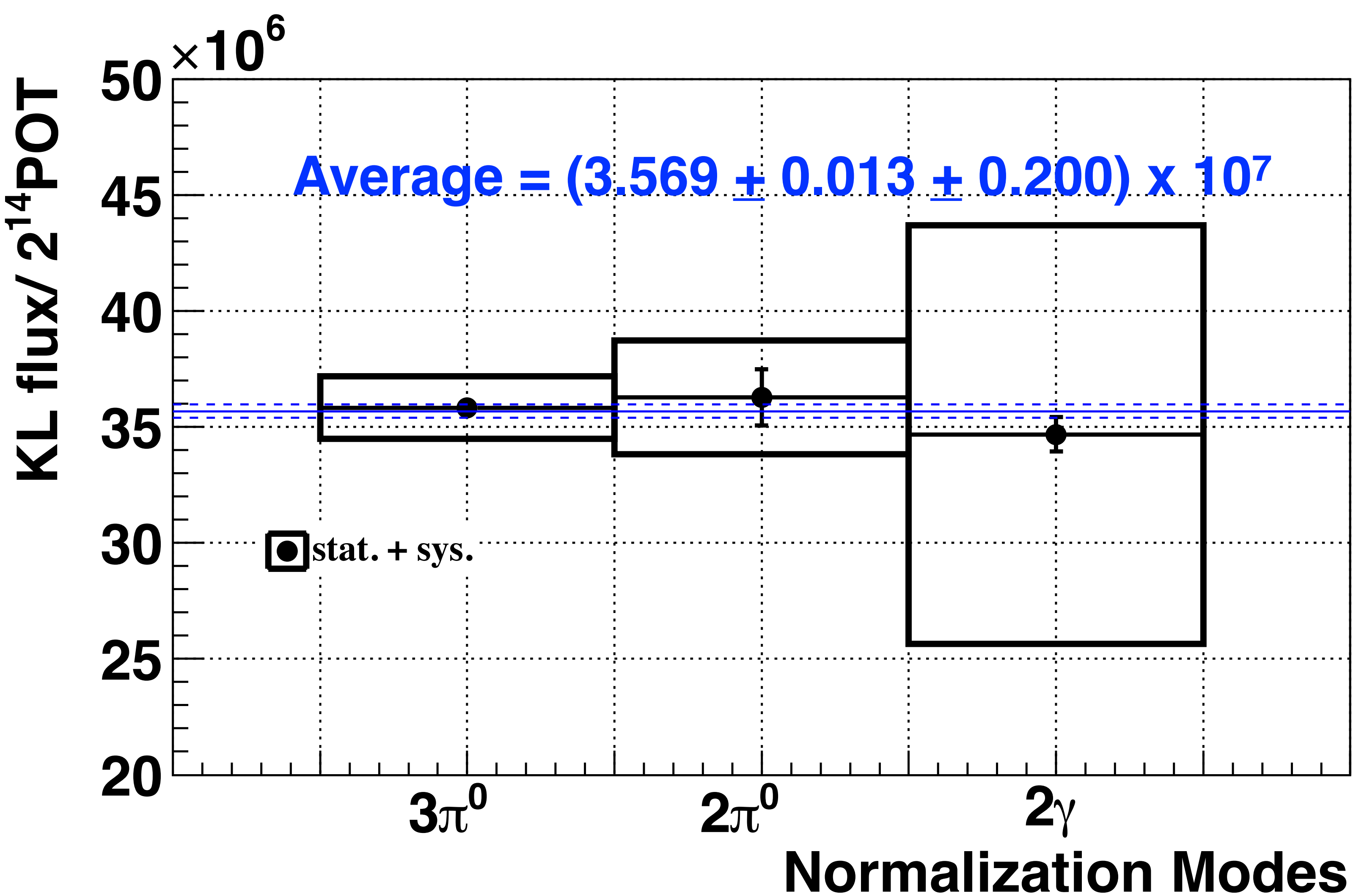
- Estimated from number of reconstructed events in data after application of selection requirements for mode, acceptance of mode, BR(mode), and Protons on Target (POT)



K_L flux estimation

Measured K_L yield for each normalization decay mode ($K_L \to 3\pi^0$, $2\pi^0$, 2γ):

- Estimated from number of reconstructed events in data after application of selection requirements for mode, acceptance of mode, BR(mode), and Protons on Target (POT)
- Systematic uncertainty estimated from single cut efficiency



Single event sensitivity

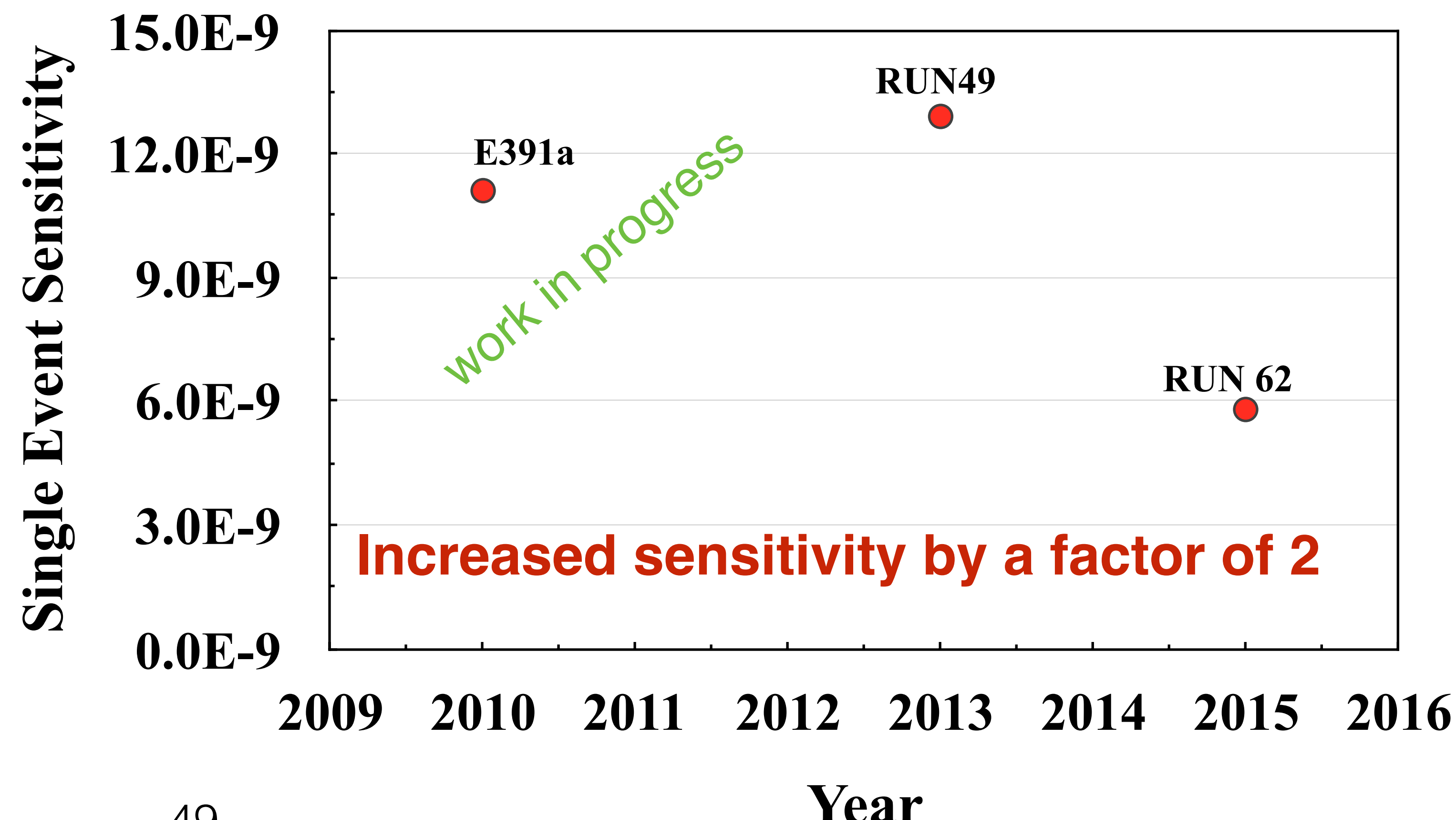
Single Event Sensitivity (SES) is a measure of signal ($K_L \rightarrow \pi^0 \nu\nu$) sensitivity and is obtained from remaining events in normalization modes after applying kinematic and veto cuts and total acceptance

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

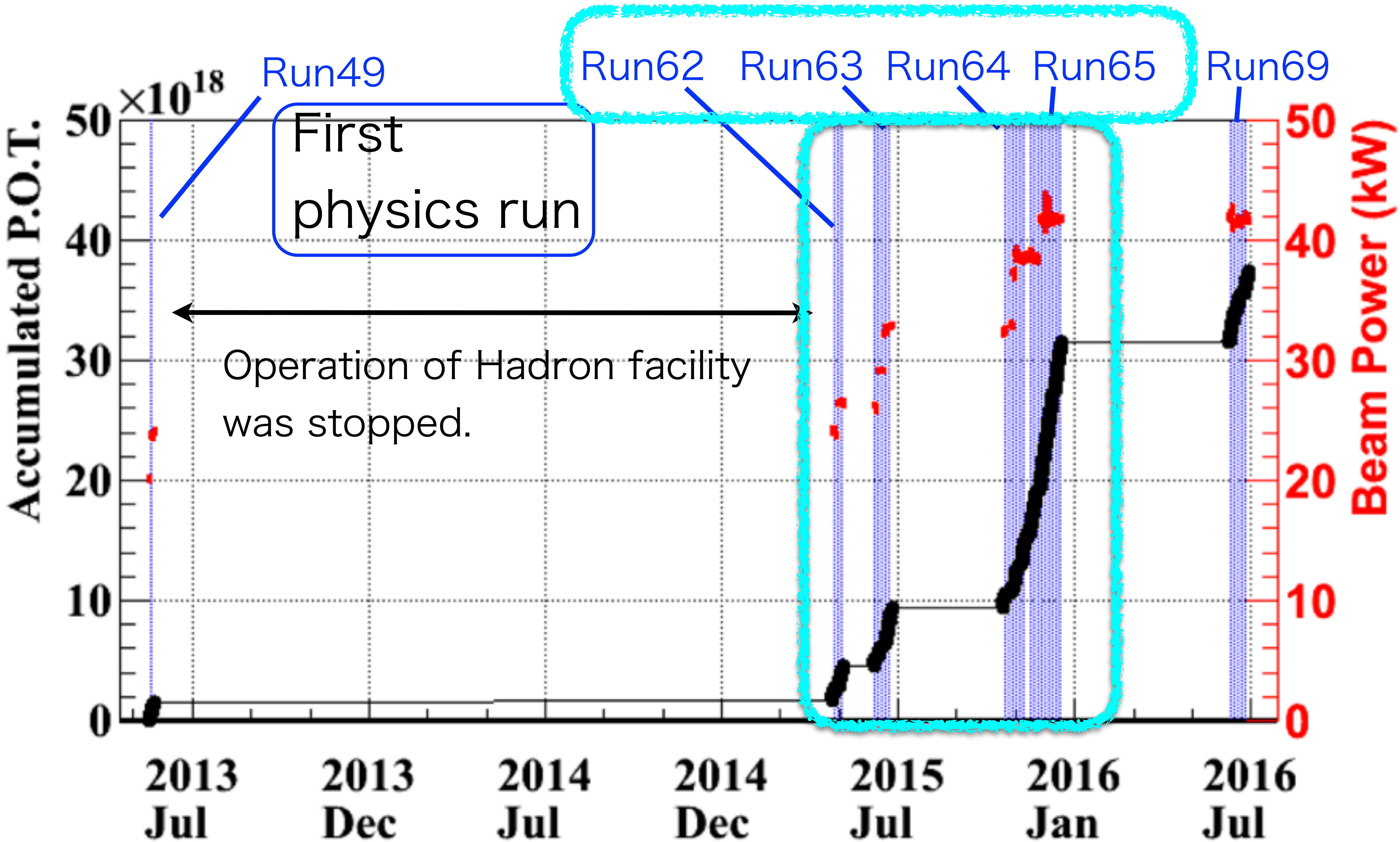
Experimental Run	SES
E391a	11.1×10^{-9}
Run49	12.9×10^{-9}
Run62	~5.9×10^{-9}

Increased Single Event Sensitivity attributed to:

- Measured K_L flux
- Wider signal box due to improved BG reduction methods and upgraded detectors
- Signal acceptance of cuts is roughly the same



Projections



Estimate of all 2015 data

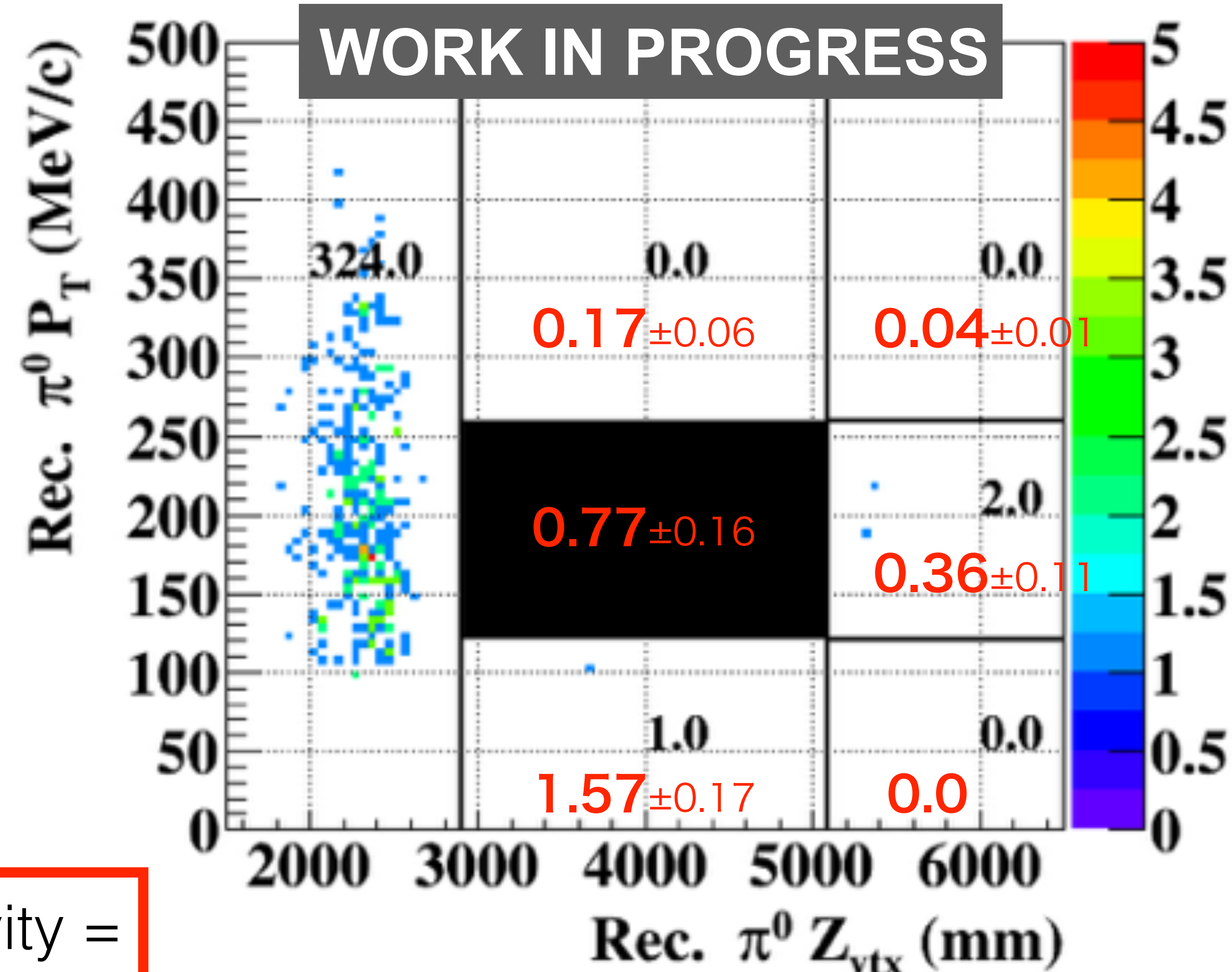


Fig. Reconstructed π⁰ Pt vs. decay vertex postion

Black: Observed
Red: Expected

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

Estimated background events		
Source	***Run 62 Number of Events***	***All 2015***
KL—>$2\pi^0$	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**
Total	**0.17+0.05**	**0.77**

Summary

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

Summary of KOTO first results

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

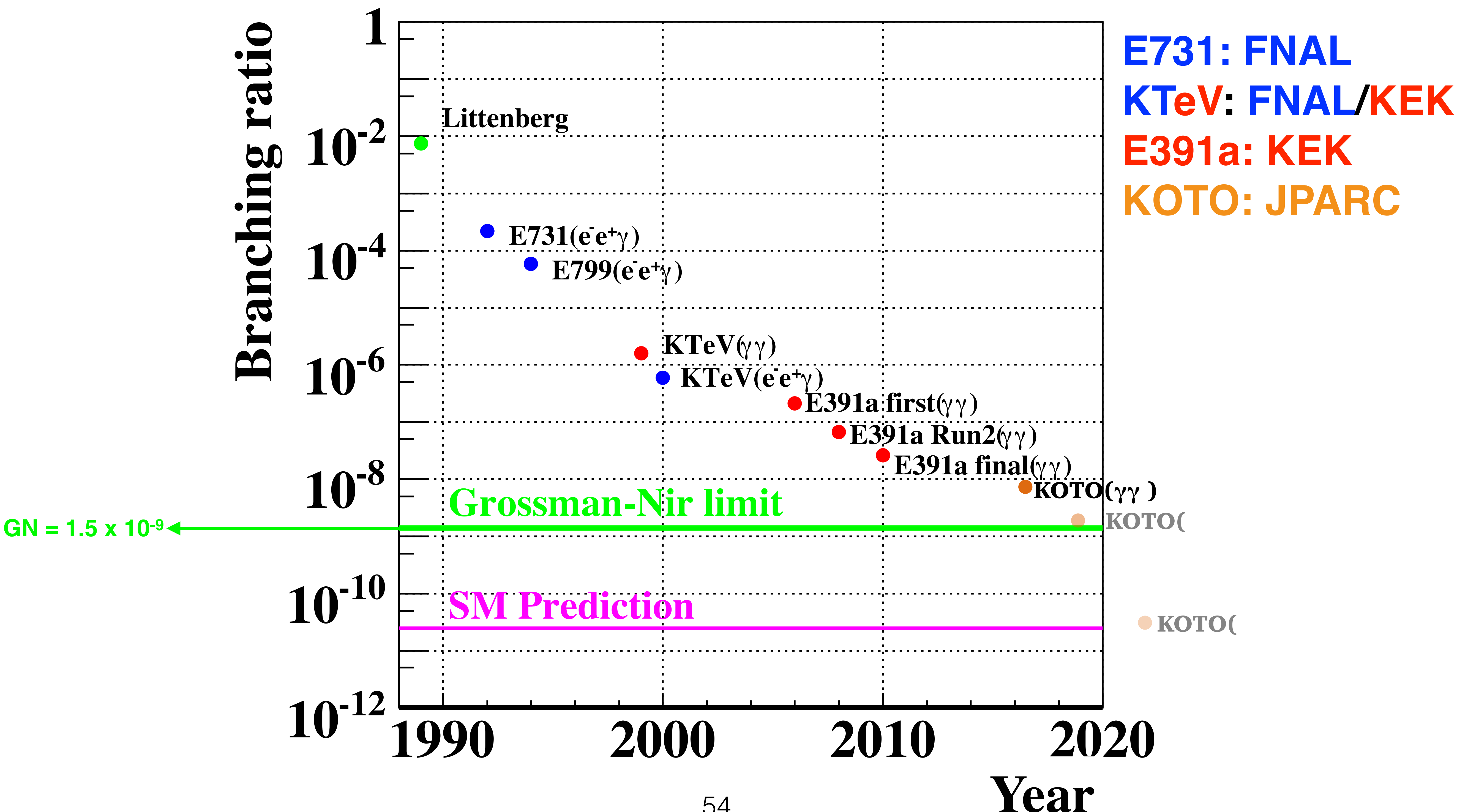
Present

- We have collected a data set (2015 runs) roughly 20 times larger than the 2013 run
- Confirmed that major BG observed 2013 run are well suppressed
- Analysis is on going:
  - Focused on continued BG estimation and suppression
  - With the current calculated flux, we estimate a SES of 5.82×10^{-9} for Run 62 and a SES of 1.1×10^{-9} for the entire 2015 data set
- After completing analysis of all 2015 data, we expect to approach Grossman-Nir limit (theoretical model independent limit $\sim 1.5 \times 10^{-9}$)

Next steps

- Overcome the background level and improve sensitivity $\sim 10^{-11}$
- Additional detector upgrades (2018)
- DAQ upgrades (2017~)
- Beam power increase 42kW—>100kW (2019)
- Explore new physics with a direct measurement
- Extension of hadron hall (KOTO Step 2)

Outlook

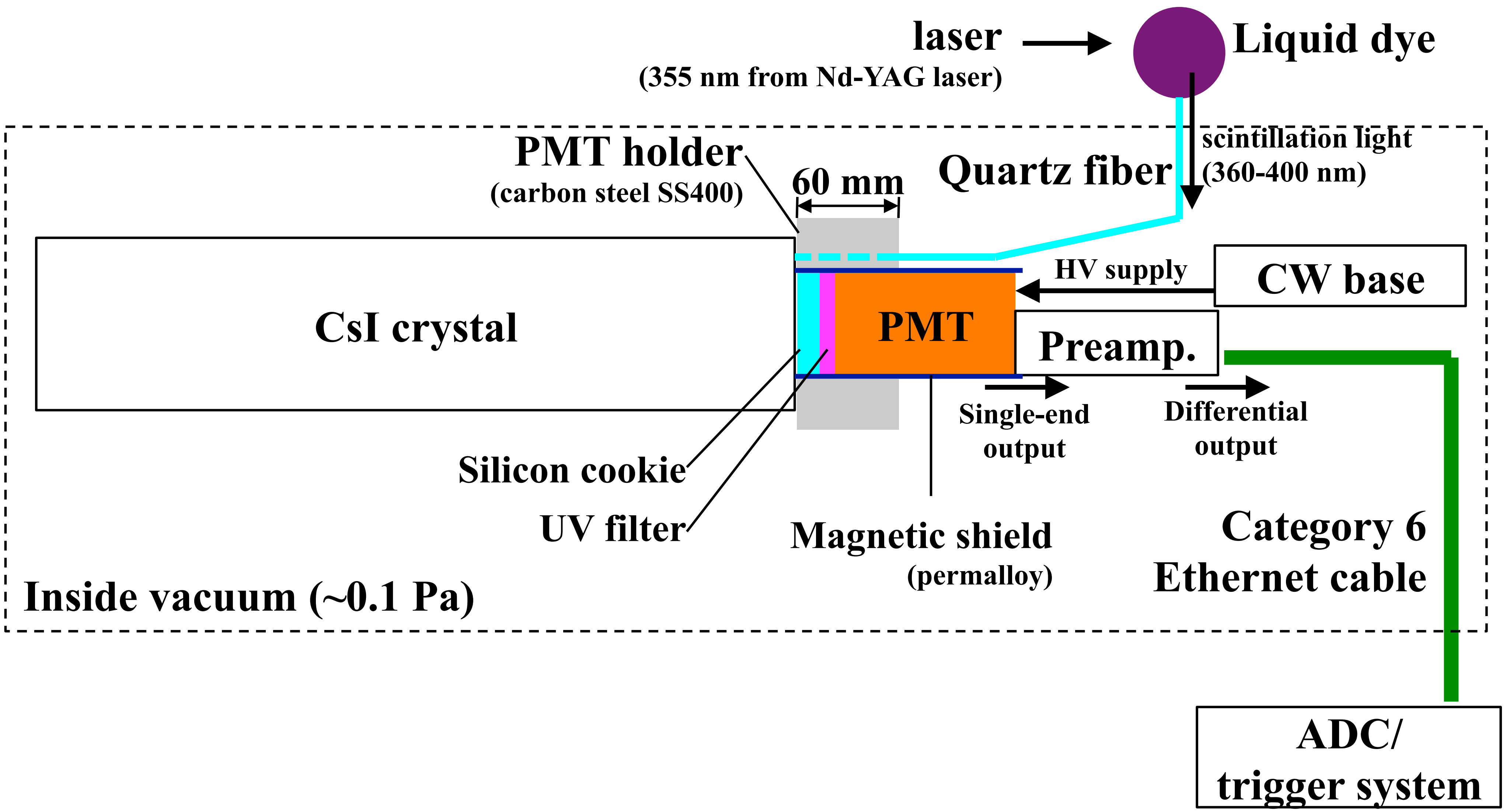


Branching ratio
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
1990
2000
2010
2020
Year
Littenberg
E731($e^-e^+\gamma$)
E799($e^-e^+\gamma$)
KTeV($\gamma\gamma$)
KTeV($e^-e^+\gamma$)
E391a first($\gamma\gamma$)
E391a Run2($\gamma\gamma$)
E391a final($\gamma\gamma$)
KOTO($\gamma\gamma$)
KOTO(
KOTO(
Grossman-Nir limit
SM Prediction
GN = 1.5×10^{-9}
E731: FNAL
KTeV: FNAL/KEK
E391a: KEK
KOTO: JPARC

Thank You

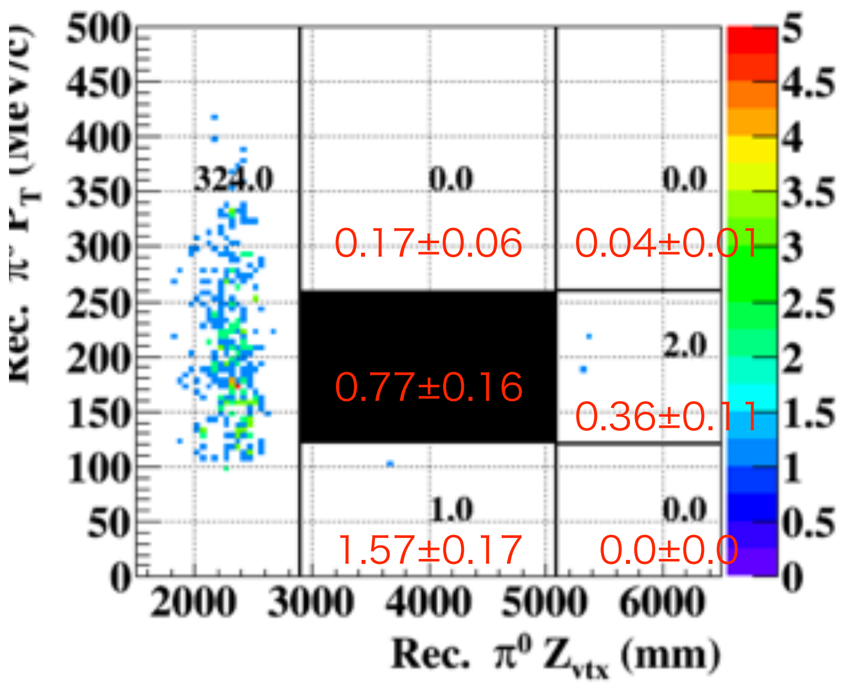
Additional Information

Output of Calorimeter system



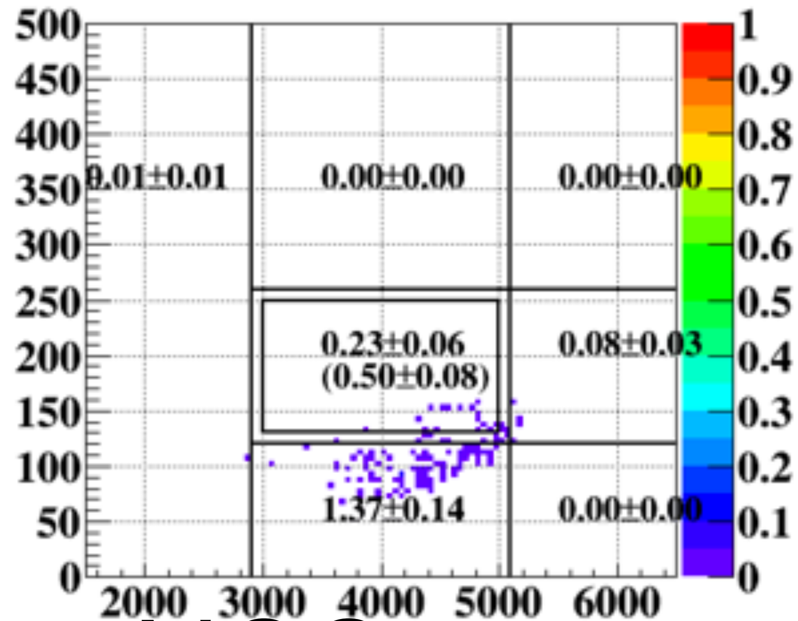
2015 Background Estimations

Data

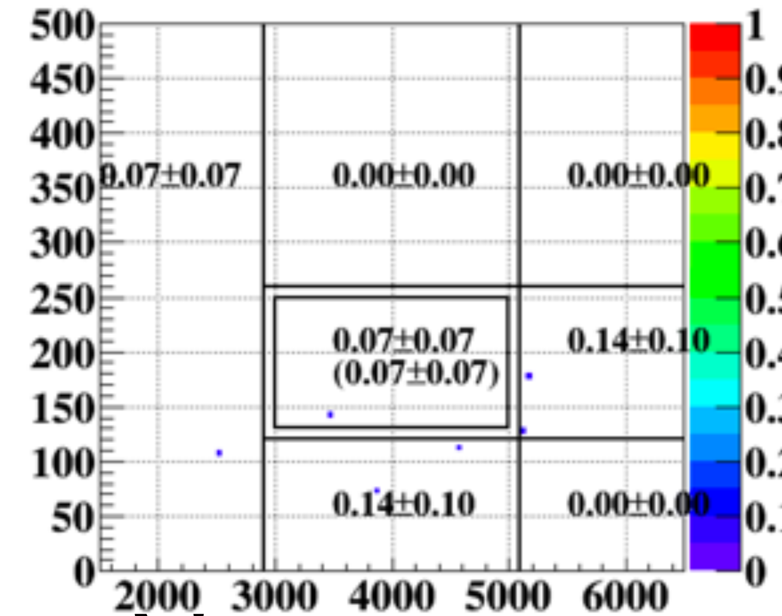


BG source	#BG
$K_L \to 2\pi^0$	0.07±0.07
$K_L \to \pi^+\pi^-\pi^0$	0.23±0.06
Upstream events	0.13±0.07
Hadron cluster	0.34±0.11
Other BG sources	Under estimation

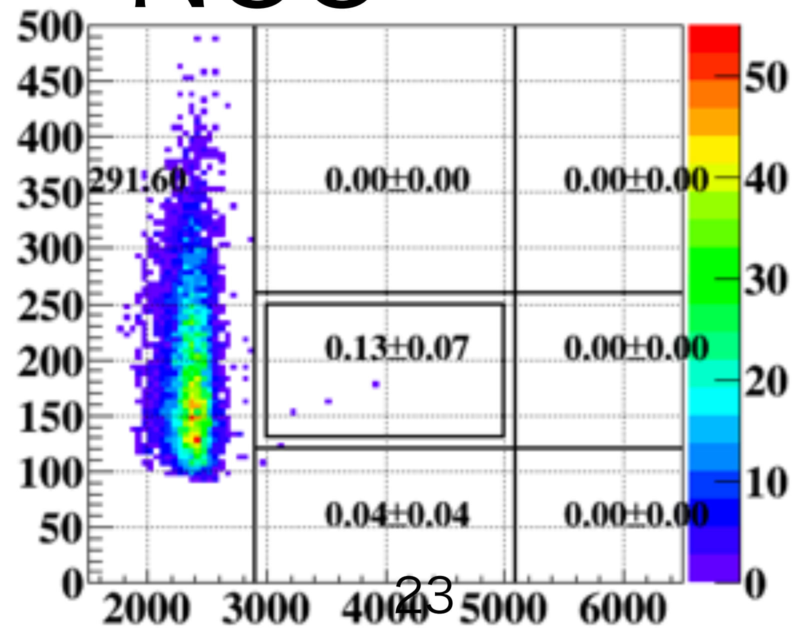
KL->pipipi0



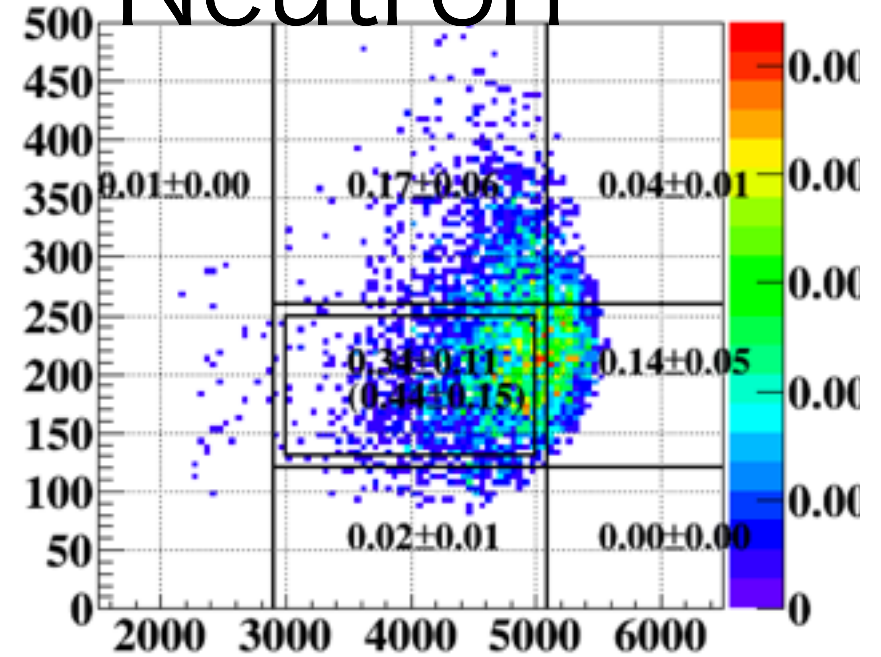
KL->2pi0



NCC



Neutron



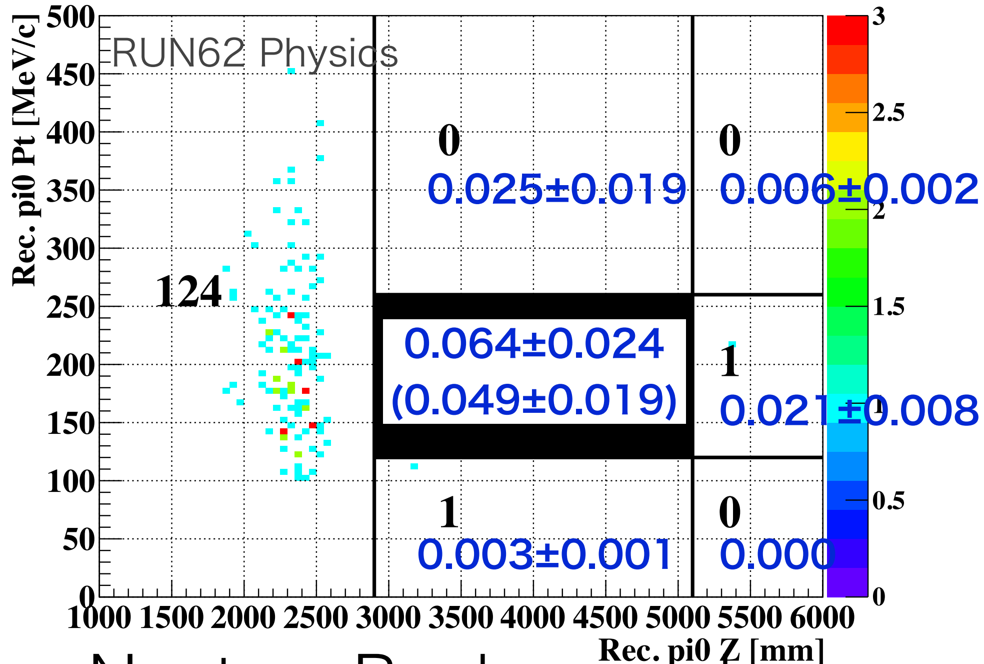
Background estimations

Estimation method

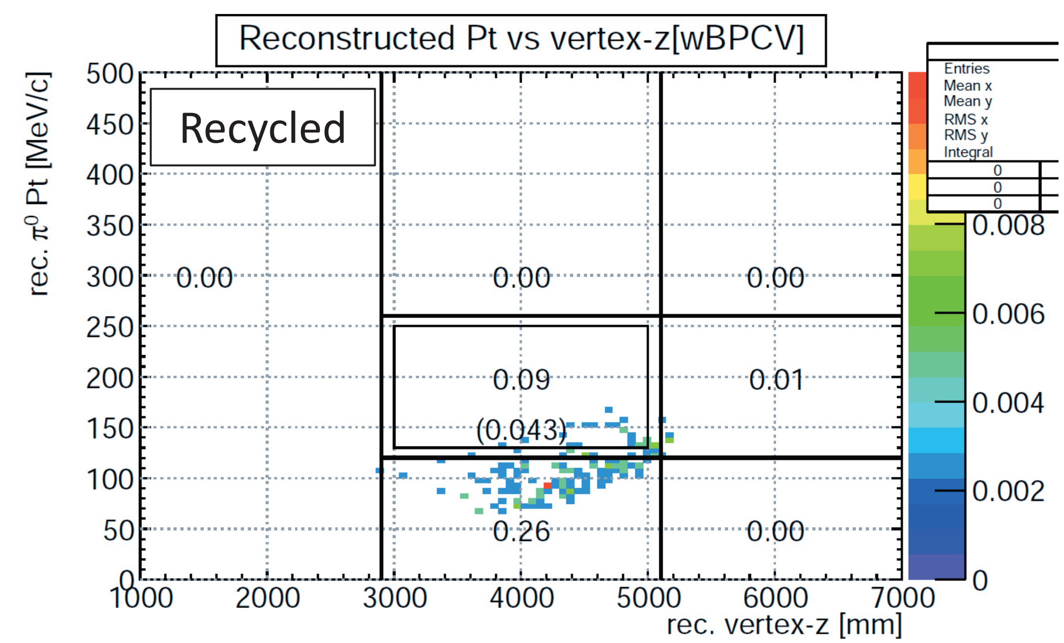
- $K_L \rightarrow 2\pi^0$ and $\pi^+\pi^-\pi^0$ estimated with MC and accidental overlay file
- NCC was estimated with MC and normalization was performed by events in NCC region
- Neutron events were estimated with the use of an aluminum target placed on the beam line

Run 62 background

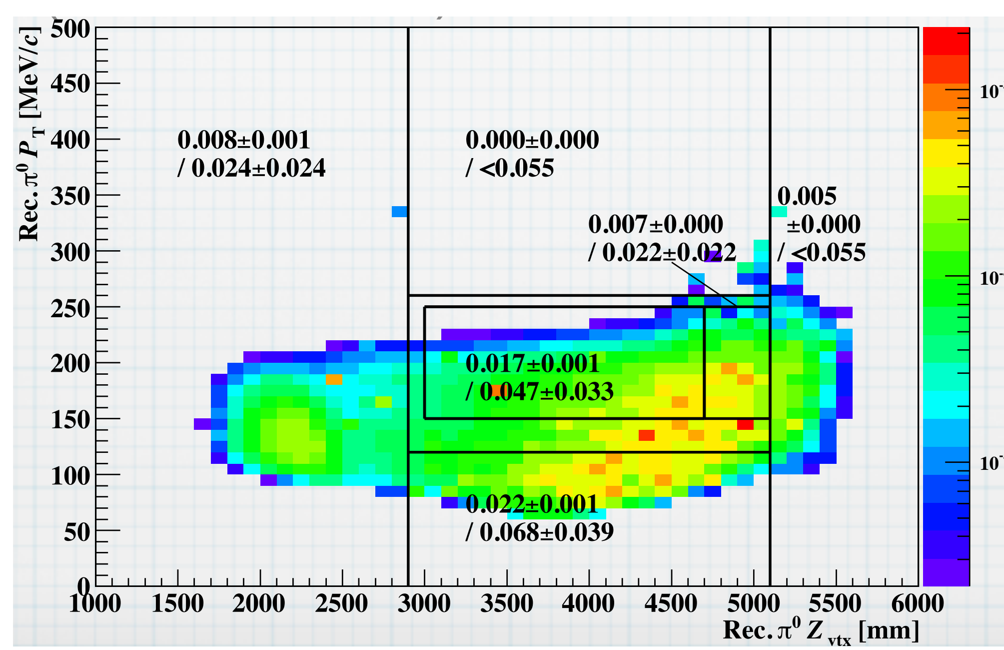
observed
(MC events in signal box)



Neutron Background



K_L—>$\pi^+\pi^-\pi^0$ Background



ALL MC
observed
(events in signal box)

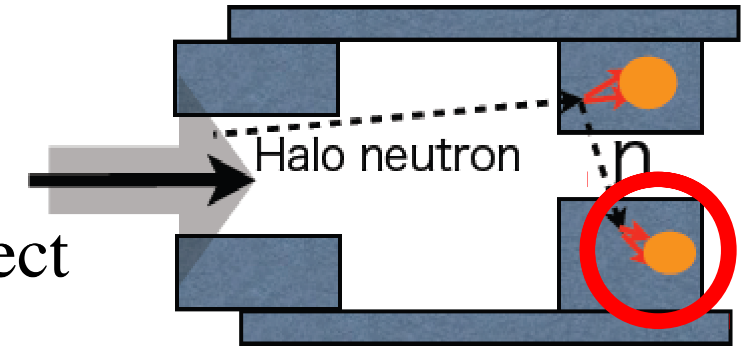
K_L—>$2\pi^0$ Background

Next steps

Neutron shower reduction:

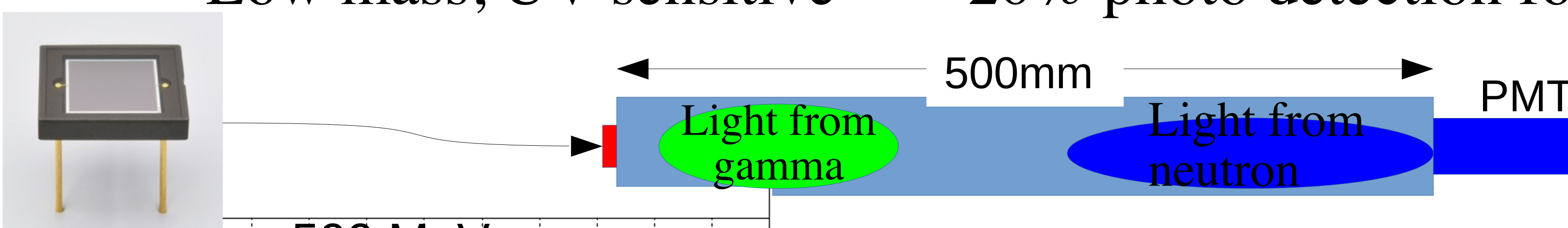
- Adding a two-sided read out to the CsI crystals
- crystals:
  - interaction length ~38 cm
  - radiation length (X_0) ~1.9cm

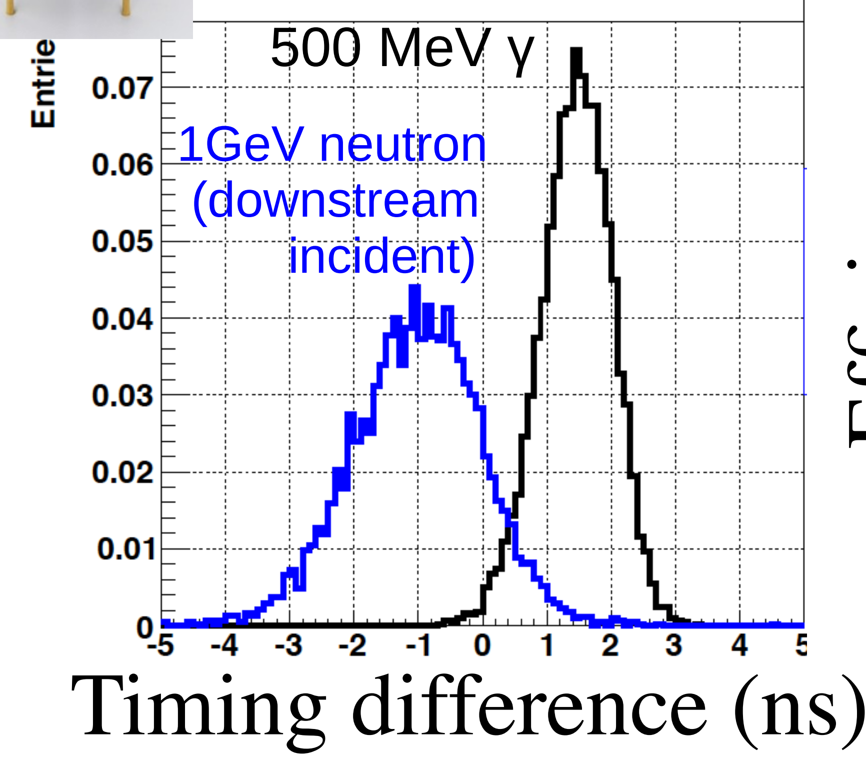
Next steps

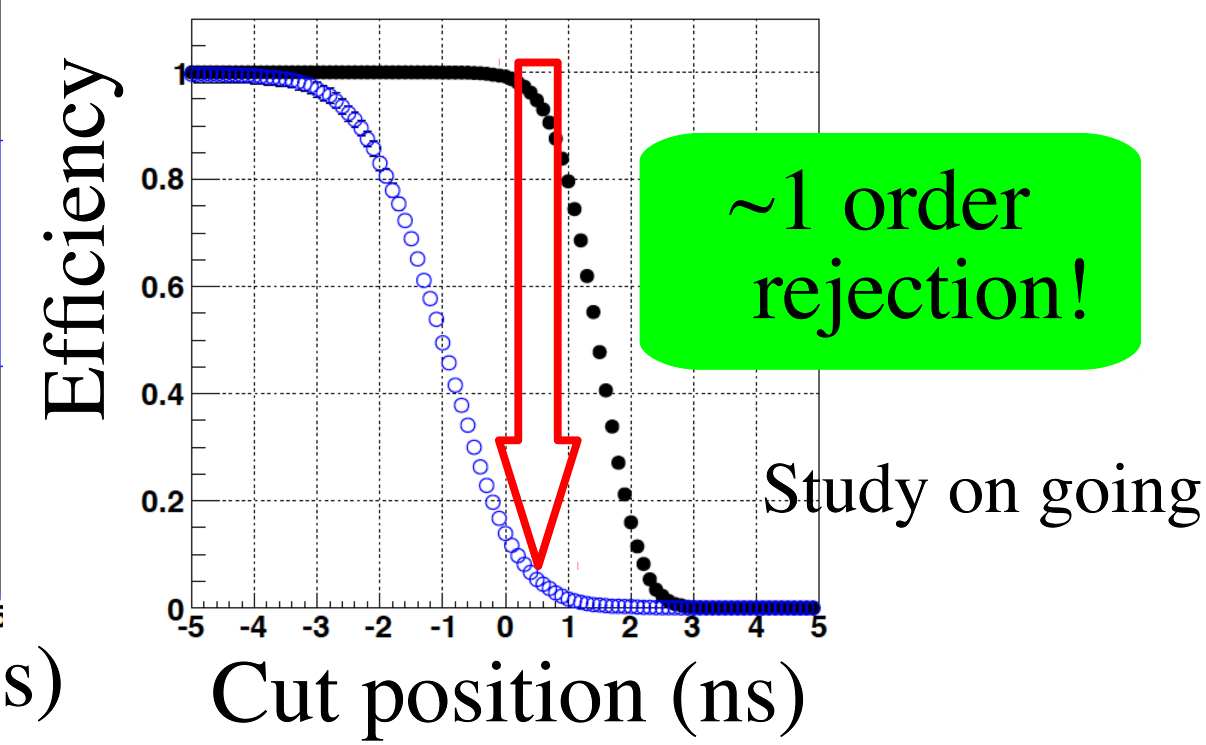


New photo sensor upstream

- 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







Event reconstruction

Physics Trigger:

- CsI, MB, CV, NCC, and CC03 veto detectors

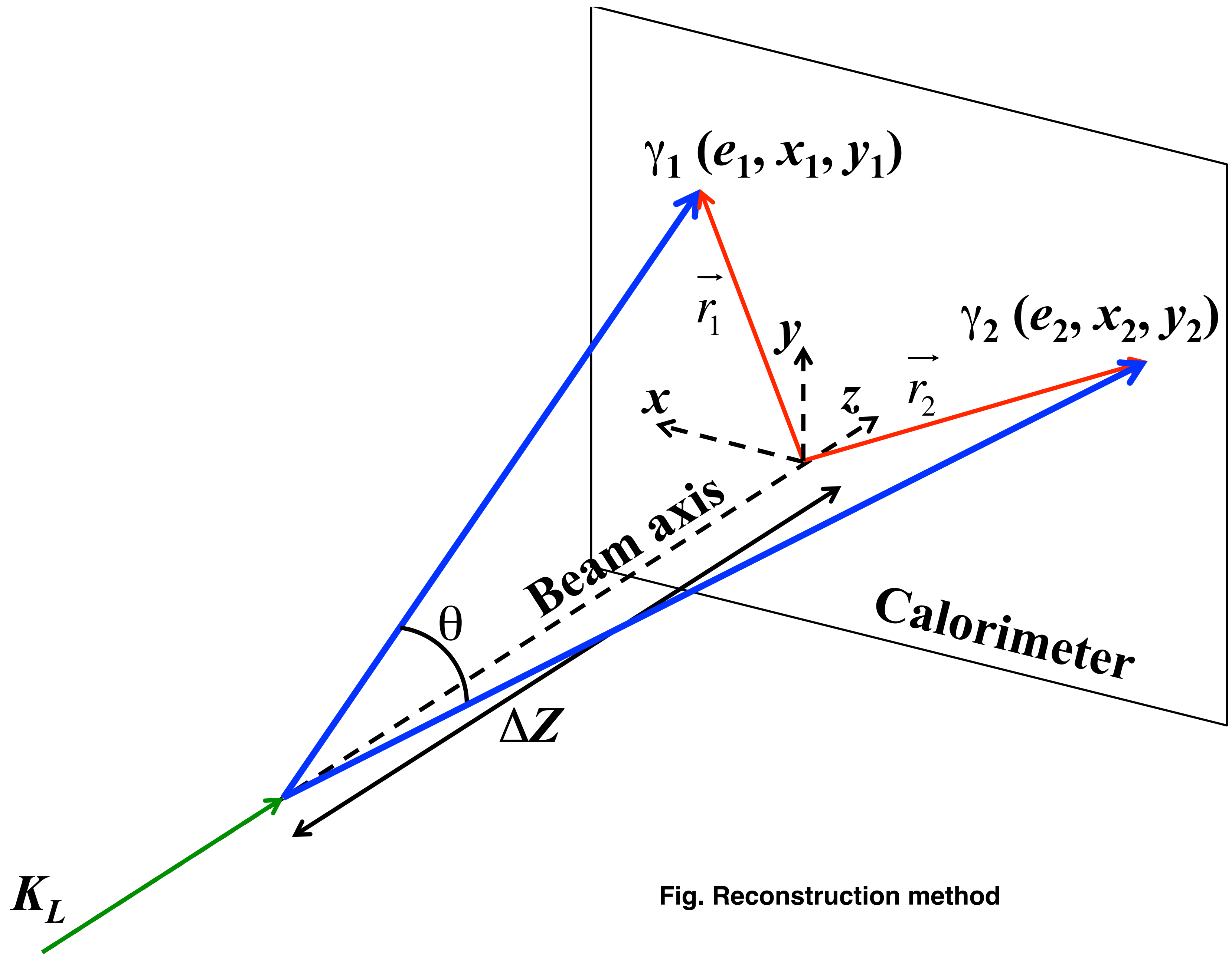


Fig. Reconstruction method

Flux calculation

Acceptance calculated as:

- A_{mode} = (# $Reconstructed_{mode}$ / # $Simulated_{mode}$)

K_L yield found as:

- #K_L = # of. Rec. K_L $(_{data})$ / ($Acceptance_{mode}$ x BR_{mode})

Flux calculated as:

- #K_L/POT = K_L yield / (POT_{runs} * $POT_{norm\ factor}$)

$POT_{runs} = 2.61 \times 10^{16}$, $POT_{norm\ factor} = 2.00 \times 10^{14}$

K_L flux estimation

Mode	N (Data Rec.)	Acceptance (MC)	Acceptance (MC) x BR (mode)	Yield= Ndata/ (AxBR)
$Kl \rightarrow 3\pi^0$	44365 ± 210	$(4.866 \pm 0.022) \times 10^{-5}$	$(9.499 \pm 0.072) \times 10^{-6}$	$(4.645 \pm 0.042) \times 10^{9}$
$Kl \rightarrow 2\pi^0$	1032 ± 32	$(2.526 \pm 0.003) \times 10^{-4}$	$(2.183 \pm 0.080) \times 10^{-7}$	$(4.709 \pm 0.159) \times 10^{9}$
$Kl \rightarrow 2\gamma$	3113 ± 56	$(1.259 \pm 0.005) \times 10^{-3}$	$(6.887 \pm 0.080) \times 10^{7}$	$(4.521 \pm 0.097) \times 10^{9}$

FLUX

Mode	Chen (Run62-24kW)/2E14 POT	Lin (Run62-24kW)/2E14 POT	Beckford (Run62-24kW)/2E14 POT
$Kl \rightarrow 3\pi^0$	$(3.582 \pm 0.021) \times 10^{7}$	$(3.57 \pm 0.020) \times 10^{7}$	$(3.583 \pm 0.032) \times 10^{7}$
$Kl \rightarrow 2\pi^0$	$(3.613 \pm 0.113) \times 10^{7}$	$(3.61 \pm 0.113) \times 10^{7}$	$(3.628 \pm 0.122) \times 10^{7}$
$Kl \rightarrow 2\gamma$	$(3.464 \pm 0.064) \times 10^{7}$	$(3.46 \pm 0.064) \times 10^{7}$	$(3.468 \pm 0.074) \times 10^{7}$
Average(old)	$(3.549 \pm 0.062) \times 10^{7}$	$(3.55 \pm 0.045) \times 10^{7}$	$(3.568 \pm 0.045) \times 10^{7}$

Single event sensitivity

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

Where:

$$K_{yield} = \frac{K_{flux}}{2 * 10^{14} POT} * POT_{run}$$

$$Acceptance_{signal} = Accidental_{loss} * \epsilon_{Vetos} * \epsilon_{kinematics}$$

Experimental run	Kl Flux (Run62)	POT	Accidental Loss	Eff. veto	Eff. kinematics
Run 62	$(3.56 \pm 0.013) \times 10^7$	2.05×10^7	0.511	0.645	1.44×10^{-3}

Systematic Uncertainties

Partial acceptance

Partial Acceptance for i_{th} cut or veto is:

- Partial Acceptance: PA^i = # of events with all cuts including cut {i}) / # of events excluding cut {i}

Fractional Difference is calculated as:

$$FD^i = \frac{PA^i_{data} - PA^i_{data}}{PA^i_{data}}$$

Systematic Error is calculated as:

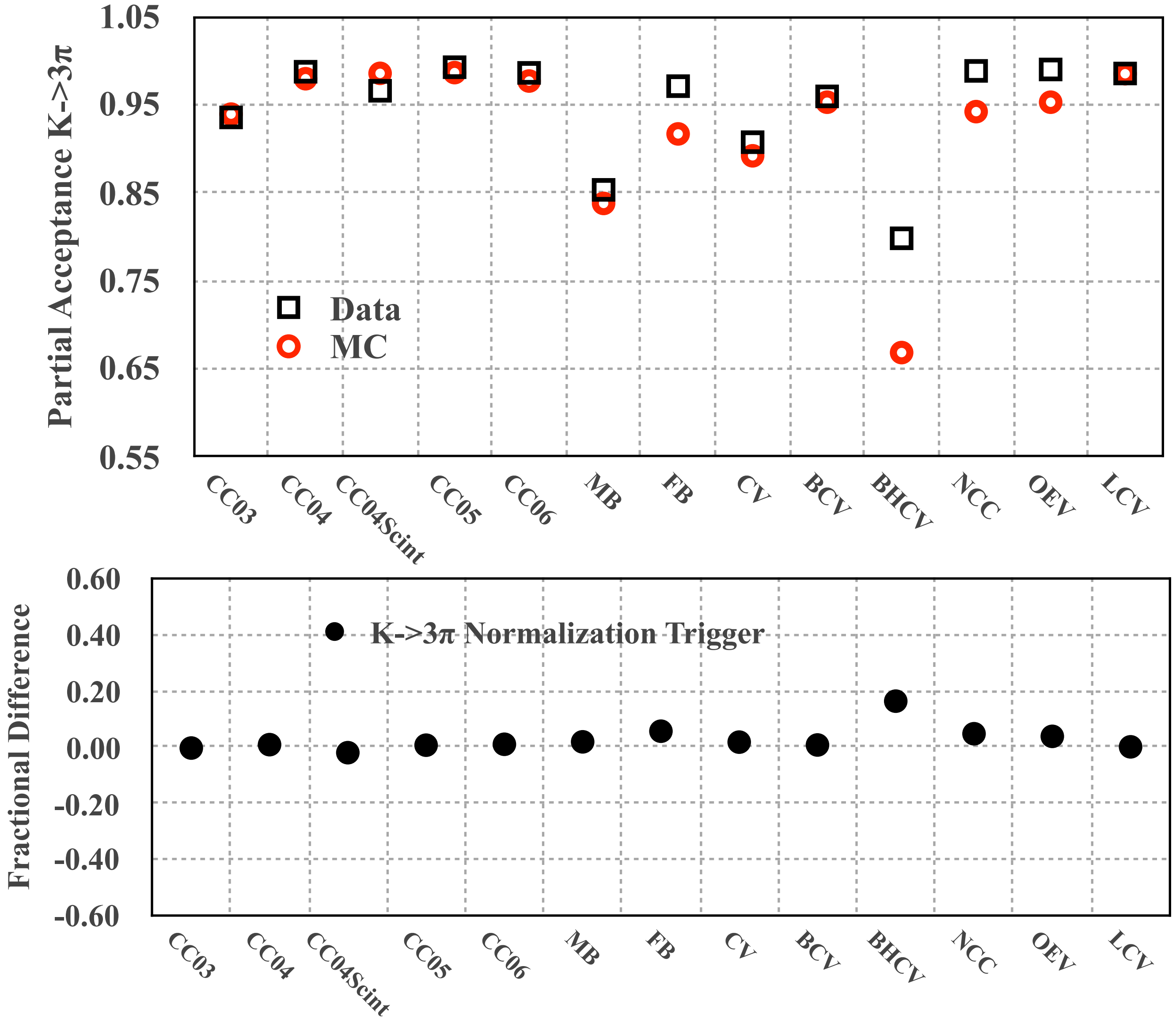
$$\sigma = \sqrt{\frac{\sum(FD^i/PA^i_{data})^2}{\sum(1/PA^i_{data})^2}}$$

Partial acceptance

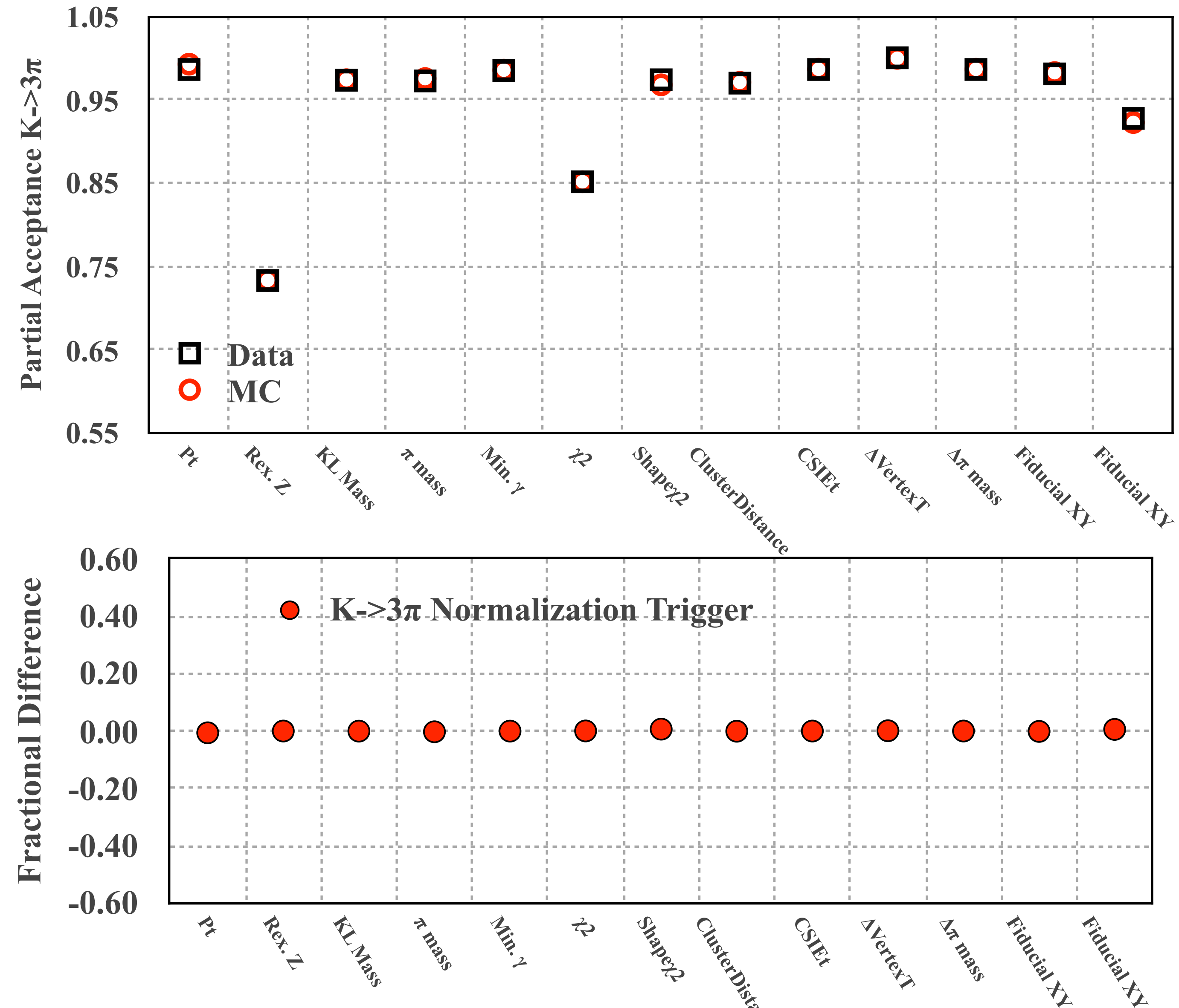
Systematic Errors KL—>3π^0 (24kW):

- Kinematic cuts: Beckford (**0.3%**)
- Vetos: Beckford (**2.6%**)

Veto



Kinematic

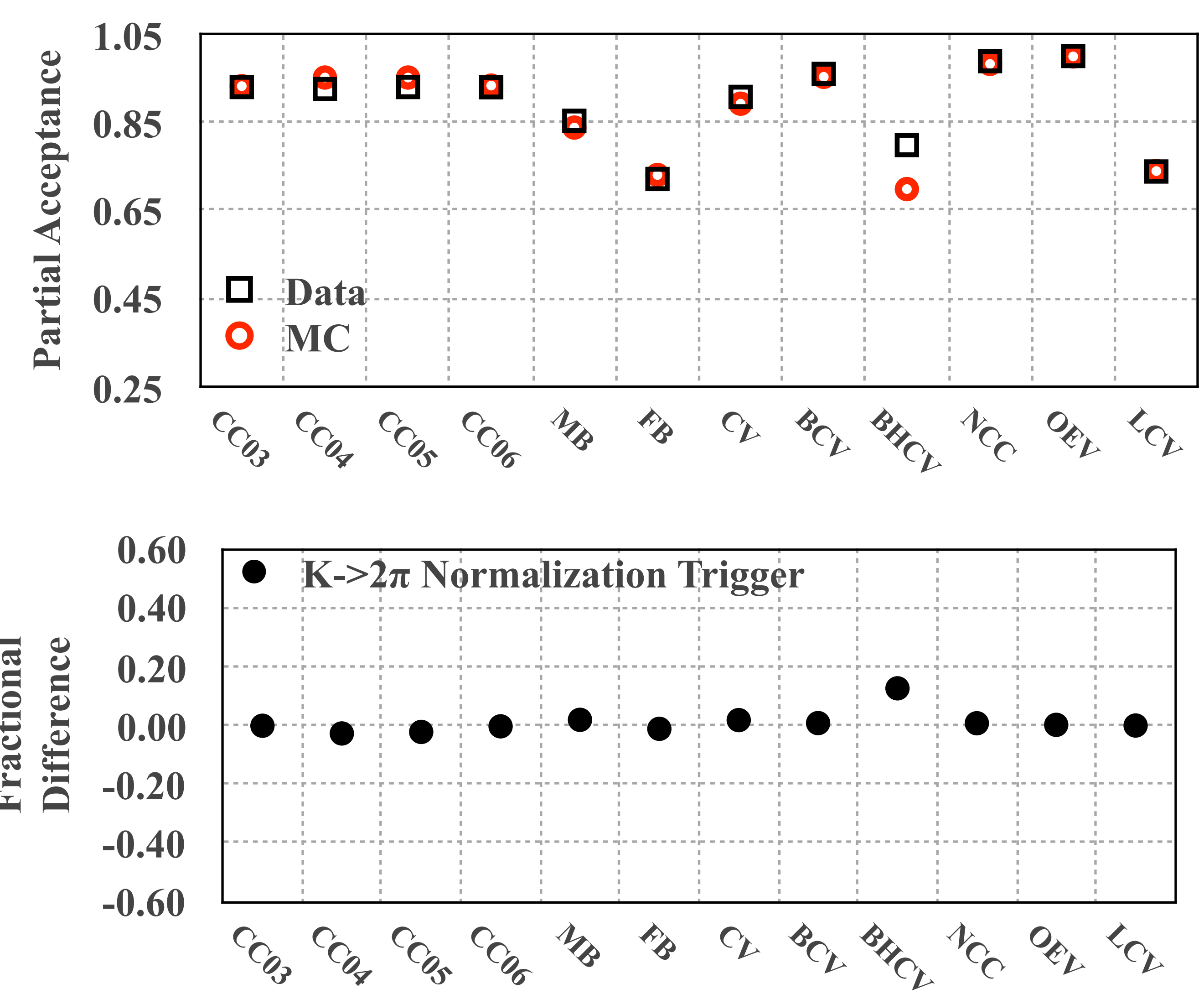


Partial acceptance

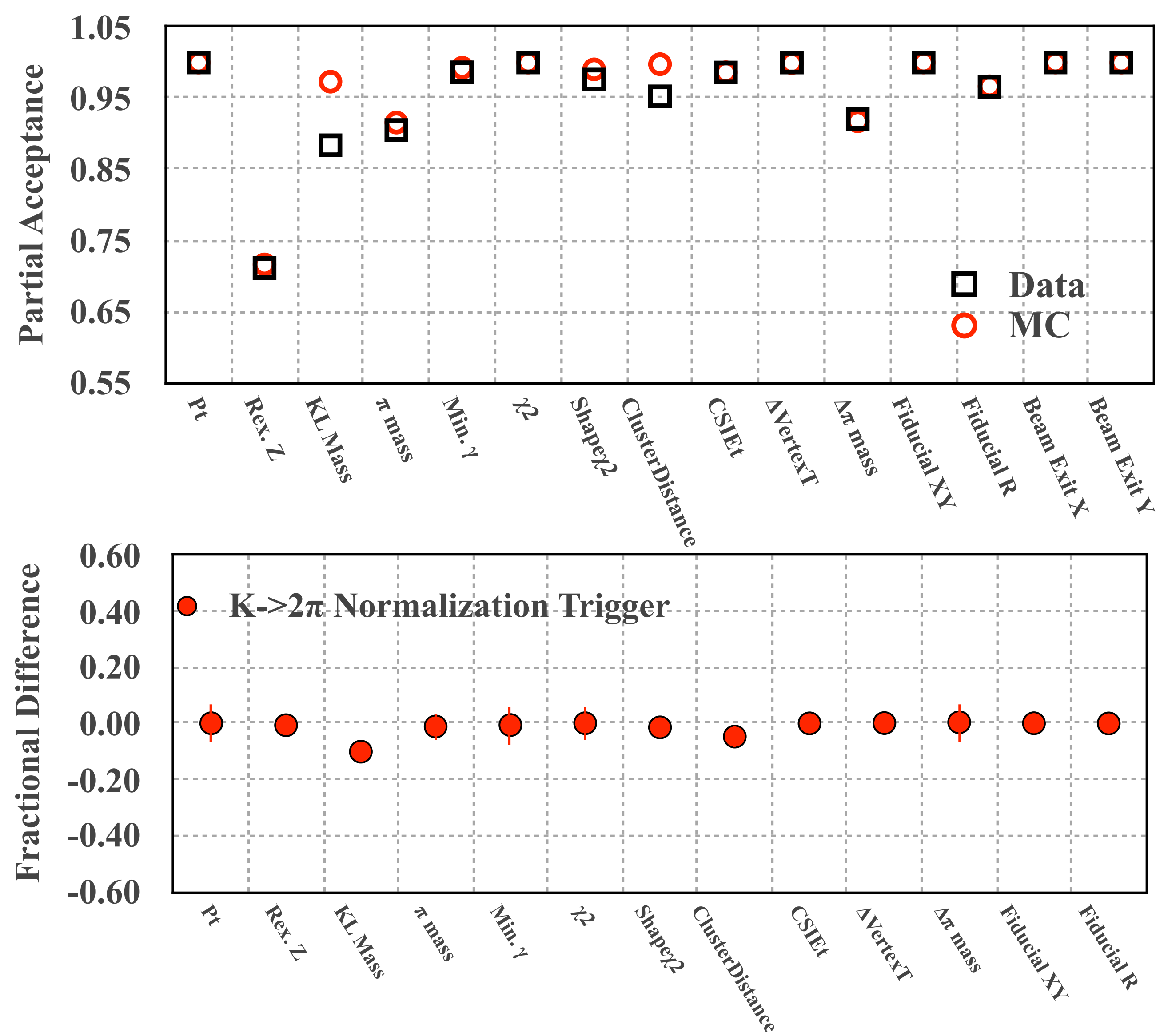
Systematic Errors KL—>$2\pi^0$ (24kW):

- Kinematic cuts: Beckford (**3.3%**)
- Vetos: Beckford (**4.2%**)

Veto



Kinematic

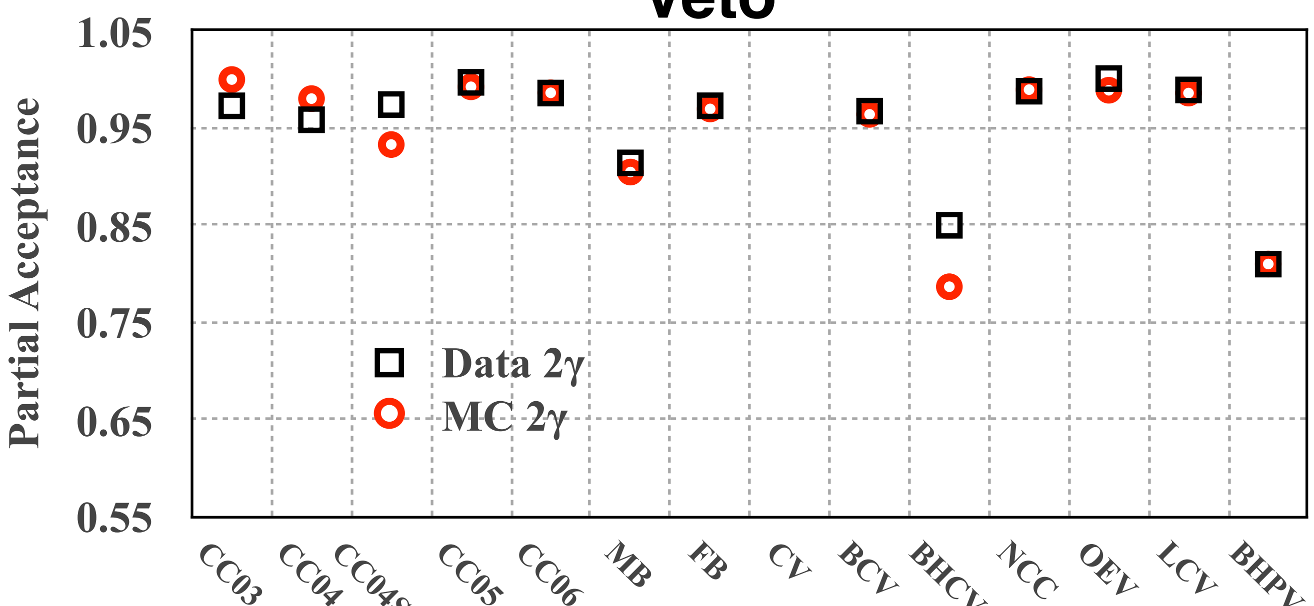


Partial acceptance

Systematic Errors KL—>2γ (24kW):

- Kinematic cuts: Beckford (**1.39%**)
- Vetos: Beckford (**25.9%**)

Veto



Kinematic