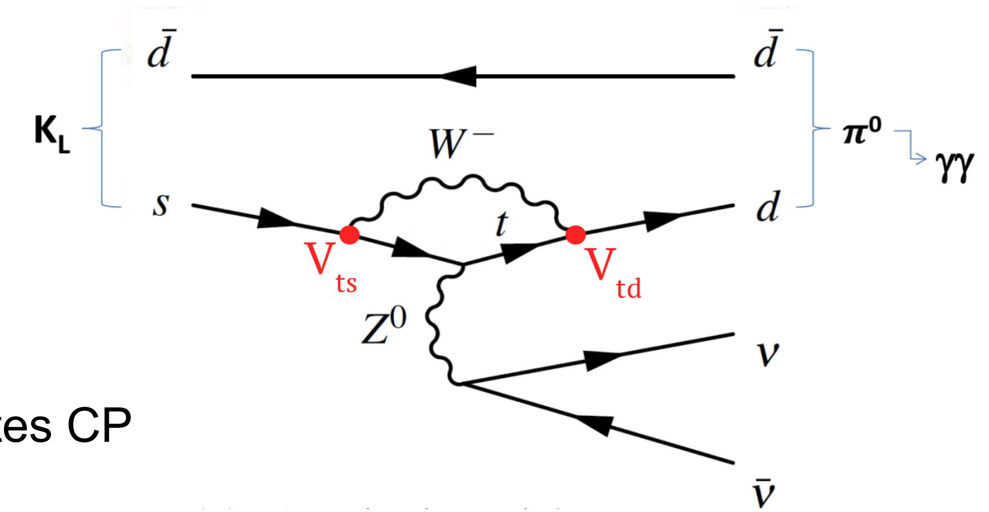
Status on the Search for $K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$ with the KOTO Experiment

Melissa A. Hutcheson
University of Michigan
On behalf of the KOTO Collaboration

$K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$

CP- CP+

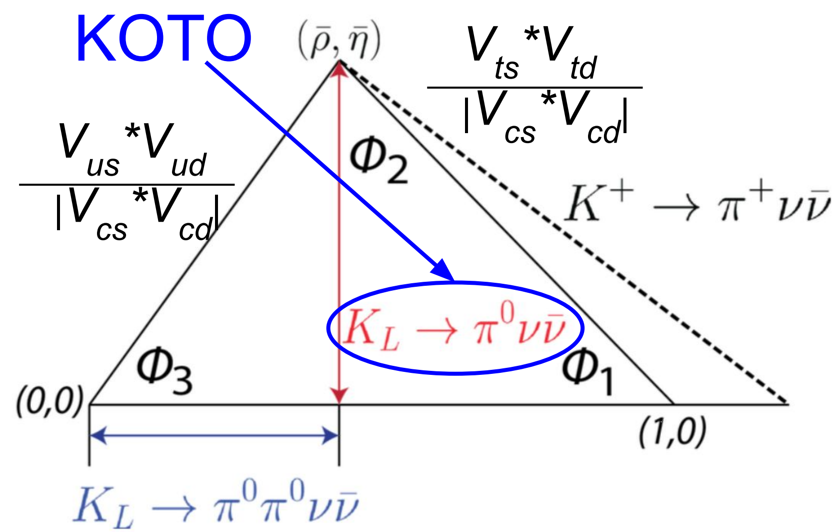


- SM predicted Branching Ratio of **(3.00 ± 0.30) x 10^{-11}**
- Clean channel, small theoretical uncertainties (~1-2%)
- 2nd order FCNC that directly violates CP

- Origin of CP violation comes from **CKM matrix**
- $K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$ corresponds to the height of the Unitary Triangle

Weak eigenstates CKM Mass eigenstates

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



$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

CP-   CP+

- SM predicted Branching Ratio of **$(3.00 \pm 0.30) \times 10^{-11}$**
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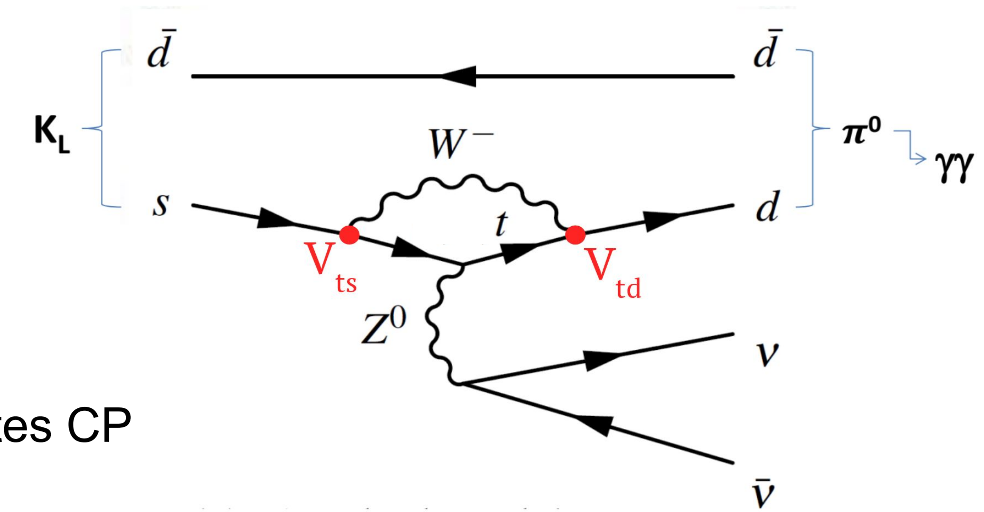
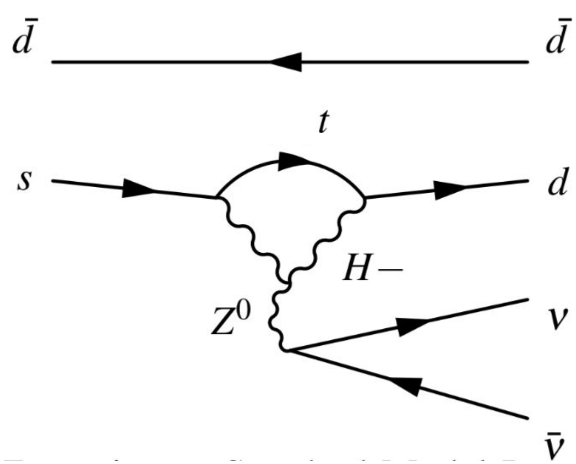
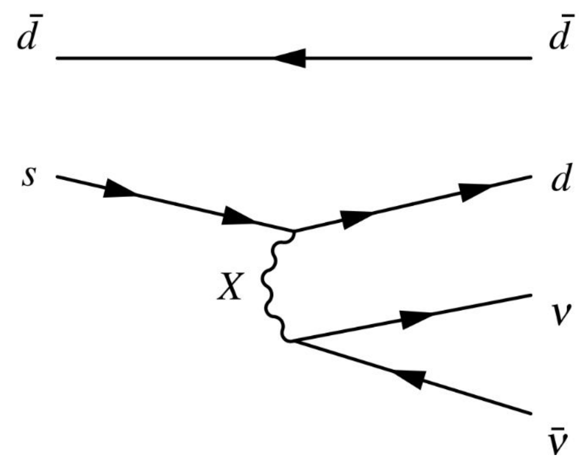


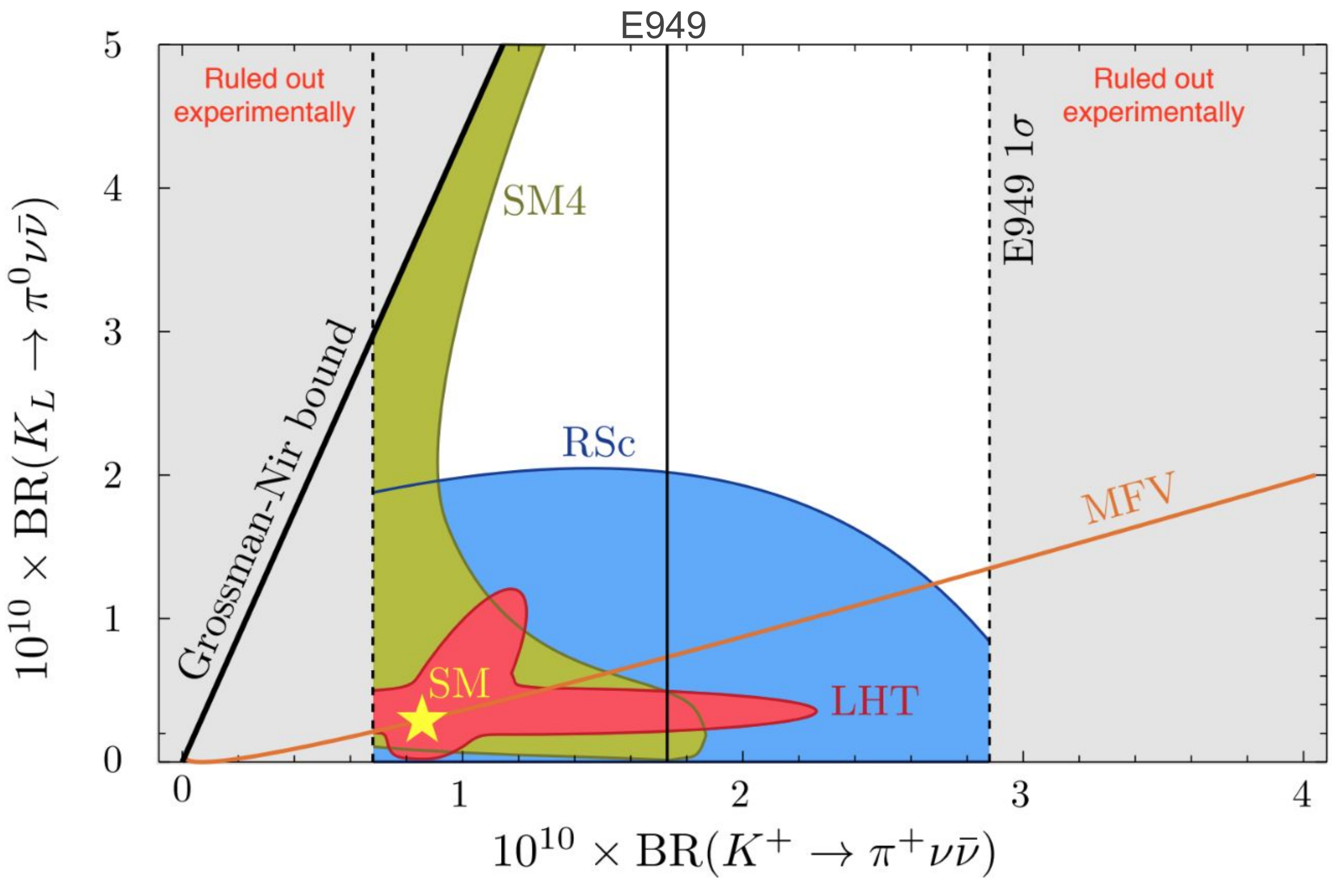
- Good probe to search for **new physics** BSM





$K^+ \to \pi^+ \nu\bar{\nu}$ & Grossman-Nir Bound

- Charged decay equally as important (NA62) → SM BR = $(9.11 \pm 0.72) \times 10^{-11}$
- Set indirect limit on $K_L^0 \to \pi^0 \nu\bar{\nu}$
  - → Grossman-Nir bound
- $BR(K_L^0 \to \pi^0 \nu\bar{\nu}) < 4.4 \times BR(K^+ \to \pi^+ \nu\bar{\nu})$ → $BR(K_L^0 \to \pi^0 \nu\bar{\nu}) < 1.5 \times 10^{-9}$



LHT: Littlest Higgs (T-parity)
MFV: Minimum Flavor Violation
RSc: Randall-Sundrum

E949 (2009):
BR = $(1.7 \pm 1.1) \times 10^{-10}$
BR < 3.4×10^{-10} @ 90% CL

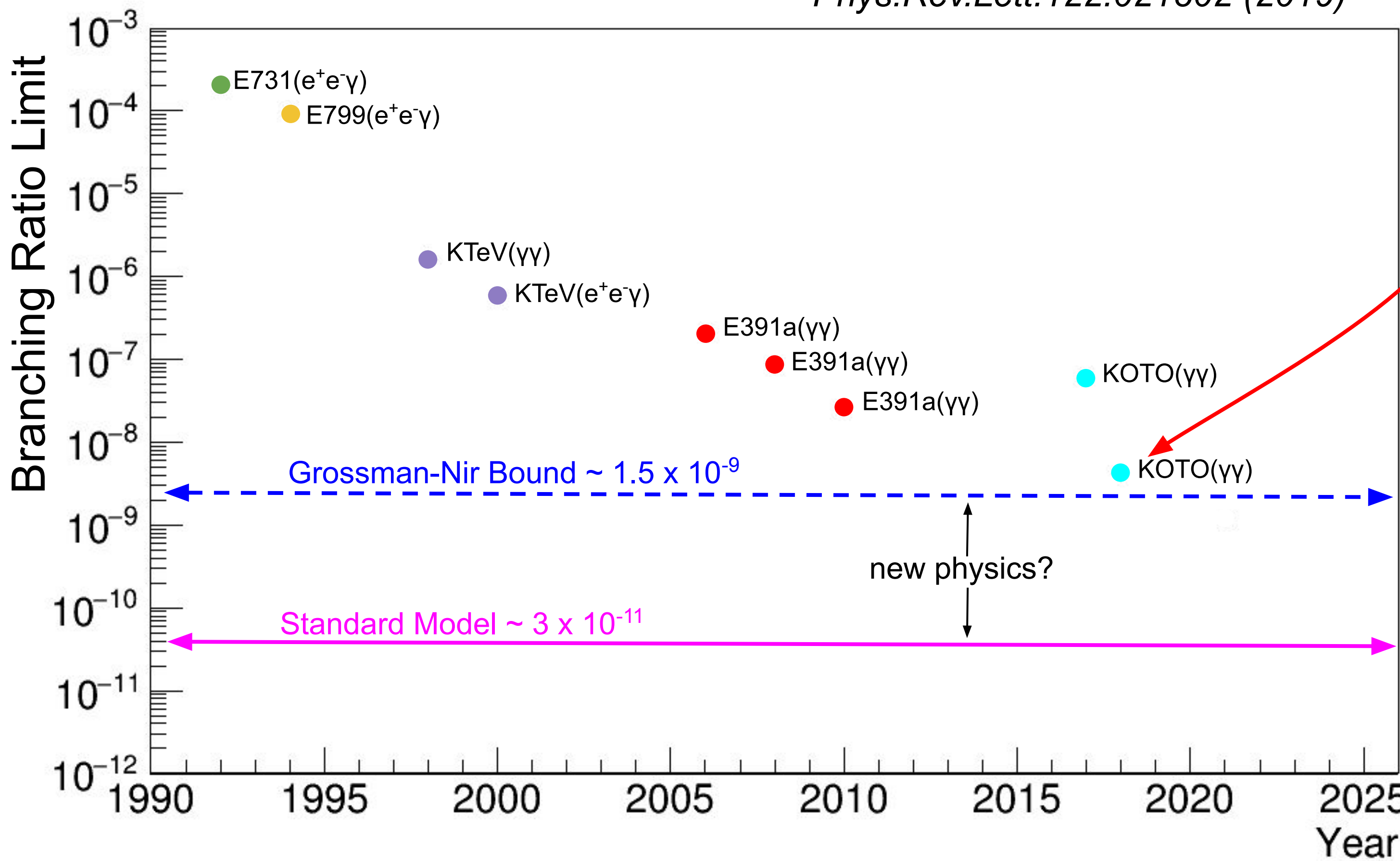
NA62 (2018):
BR < 11×10^{-10} @ 90% CL

$K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$ Search History

- First limits on BR set in early 90s
- Best experimental limit set by KOTO in 2018

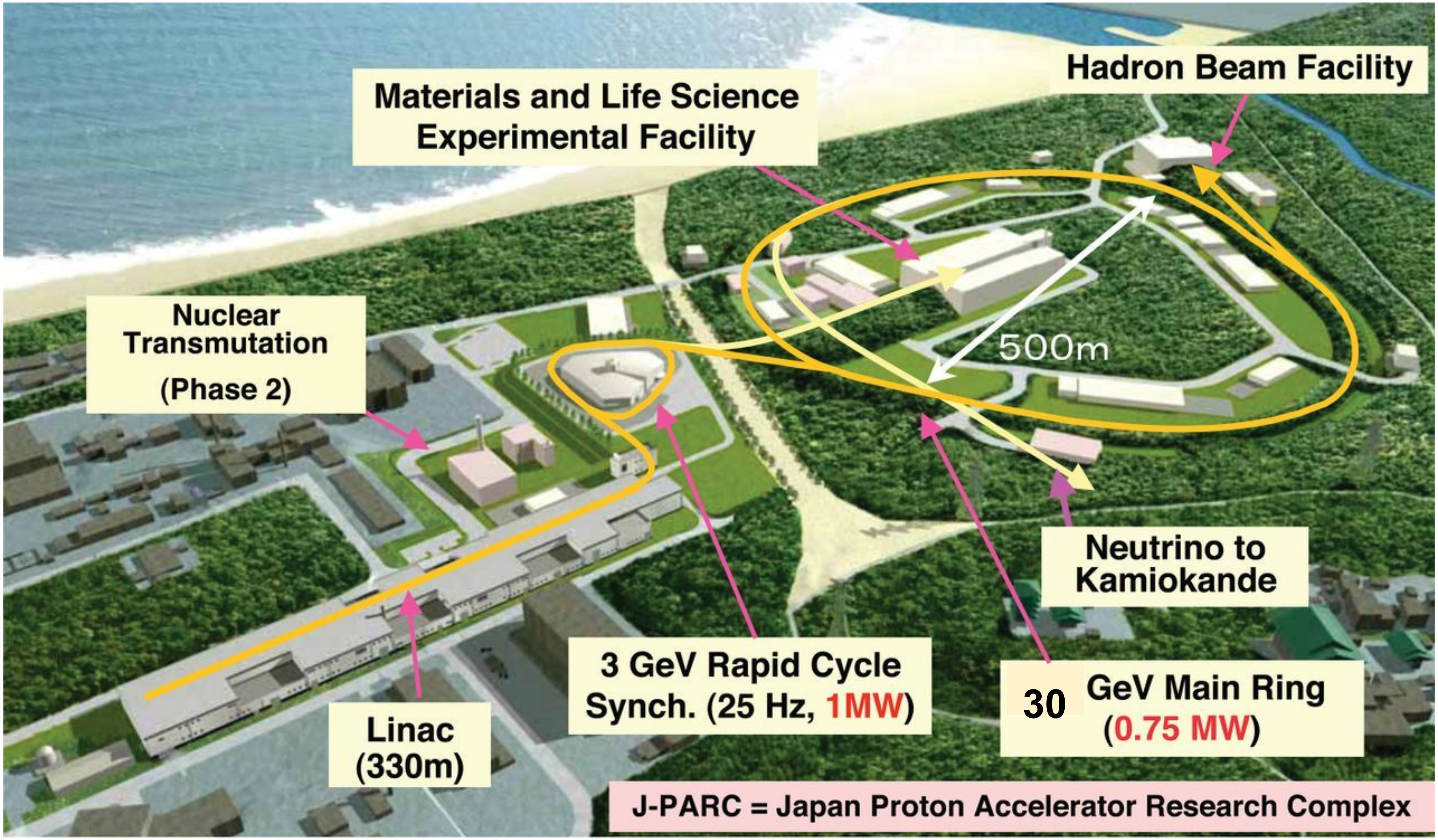
$BR(K_L^0 \rightarrow \pi^0 \nu\bar{\nu}) < 3.0 \times 10^{-9}$ (@ 90% CL)

Phys.Rev.Lett.122.021802 (2019)



Experimental Setup

- Located in Tokai, Japan at J-PARC
- 30 GeV protons → stationary gold target



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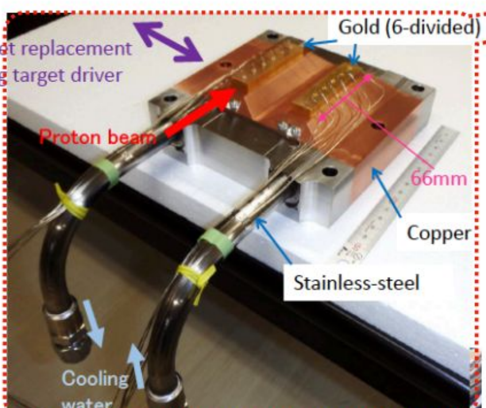
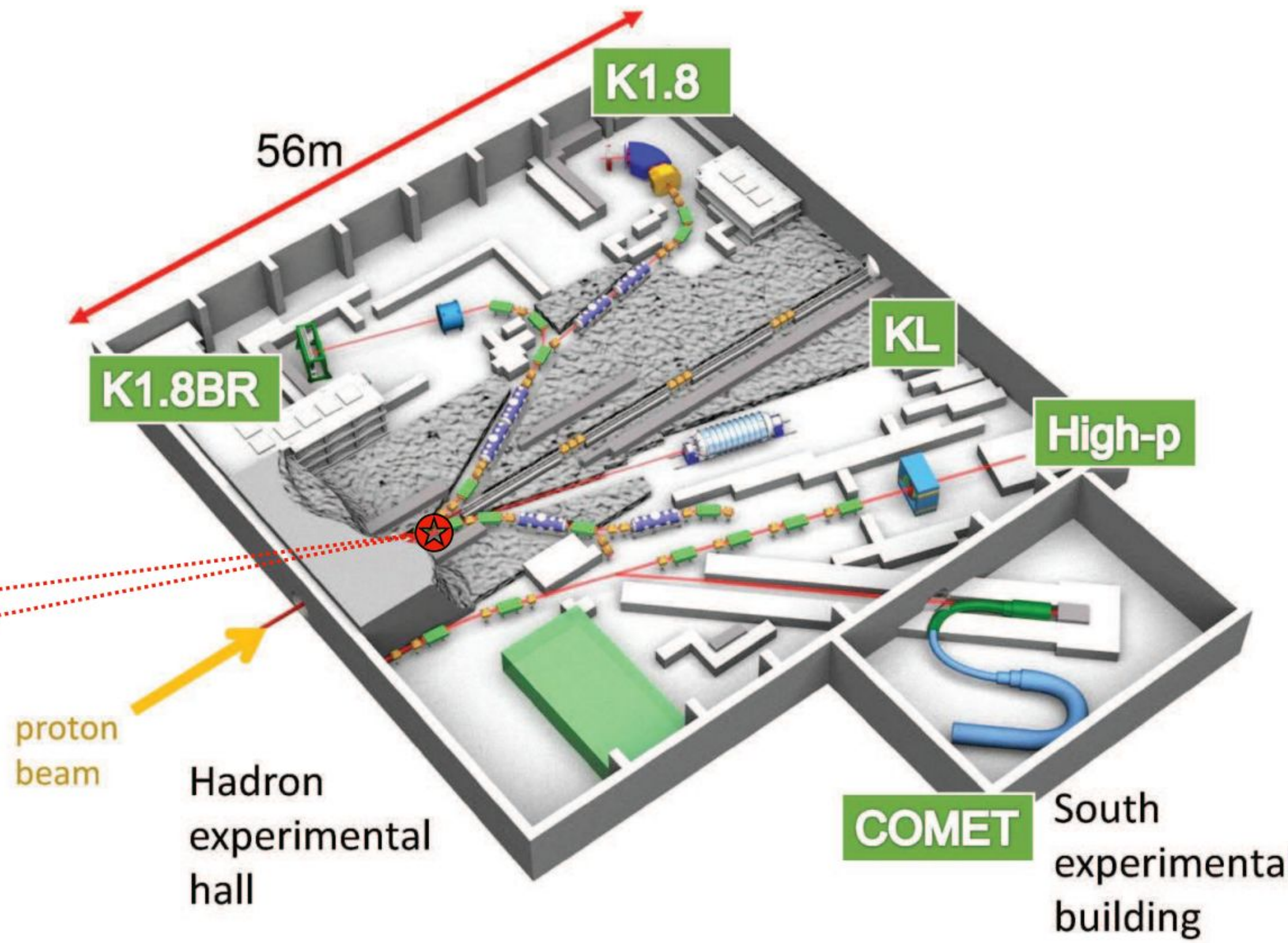
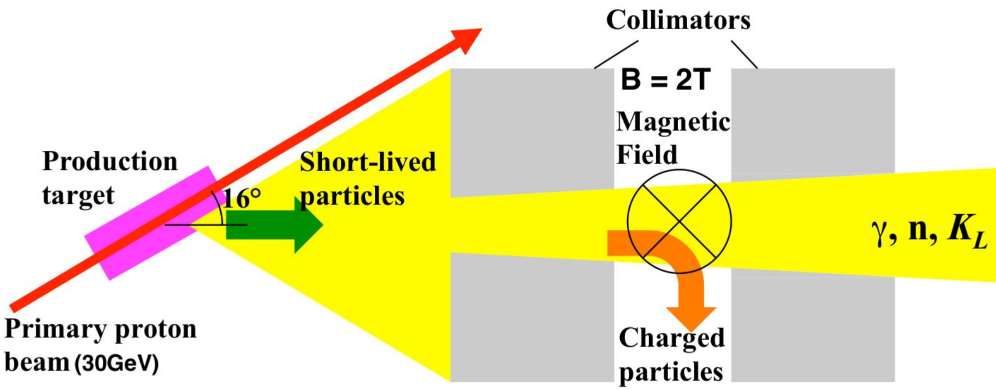
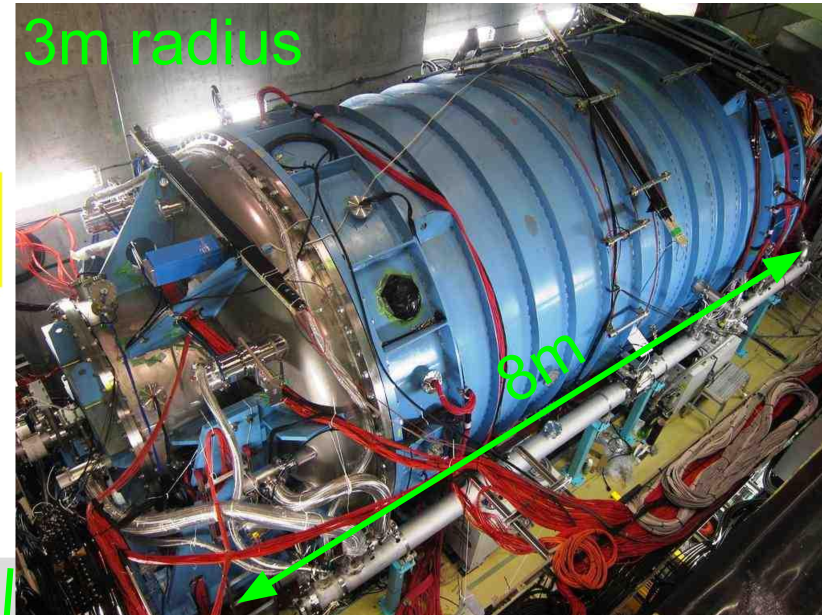


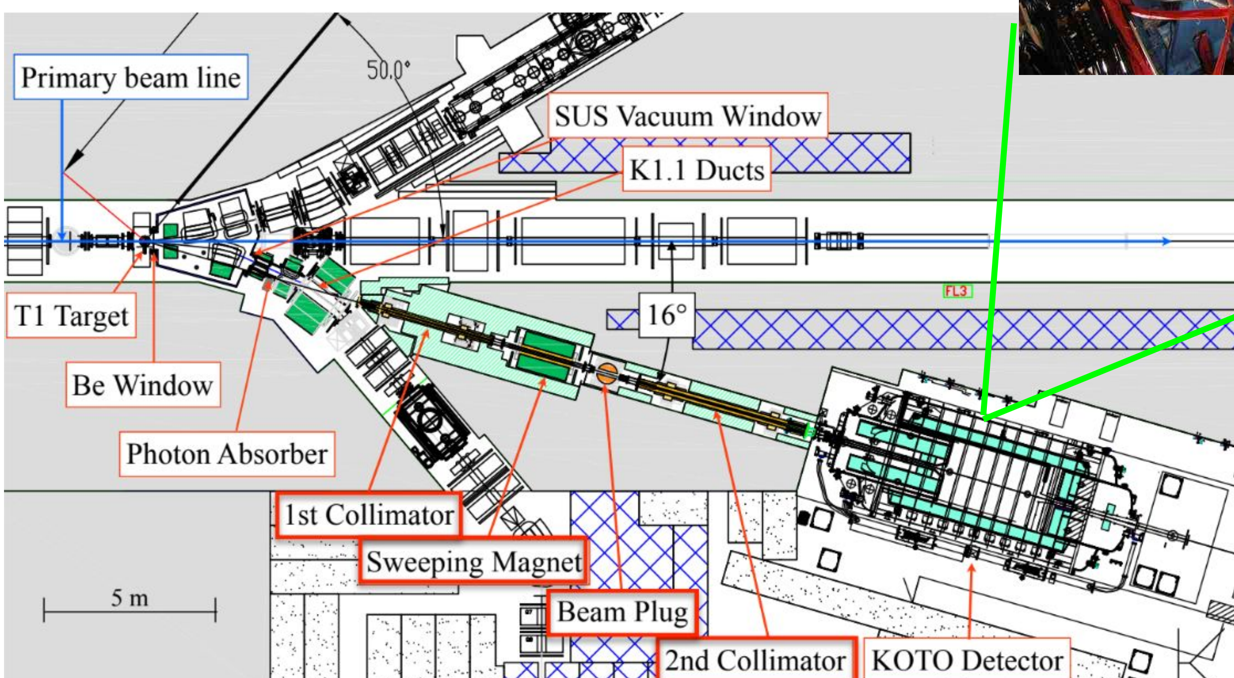


Experimental Setup





Highly collimated "pencil" beam of K_L, n, γ

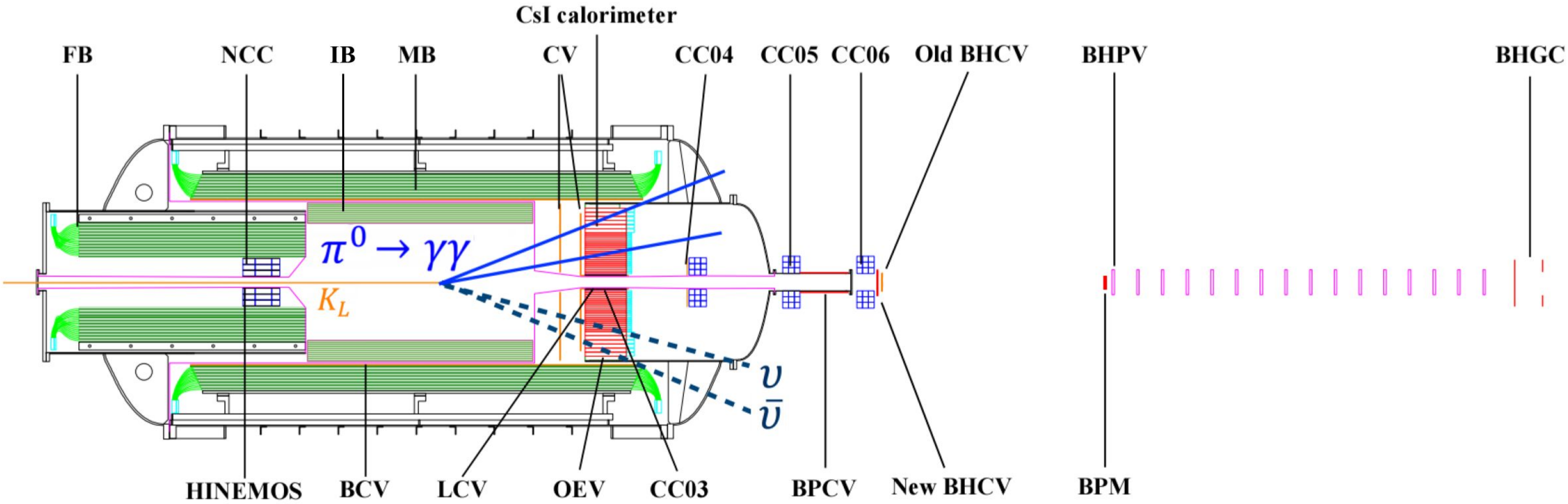


Evacuated to ~10^{-5} Pa to suppress background

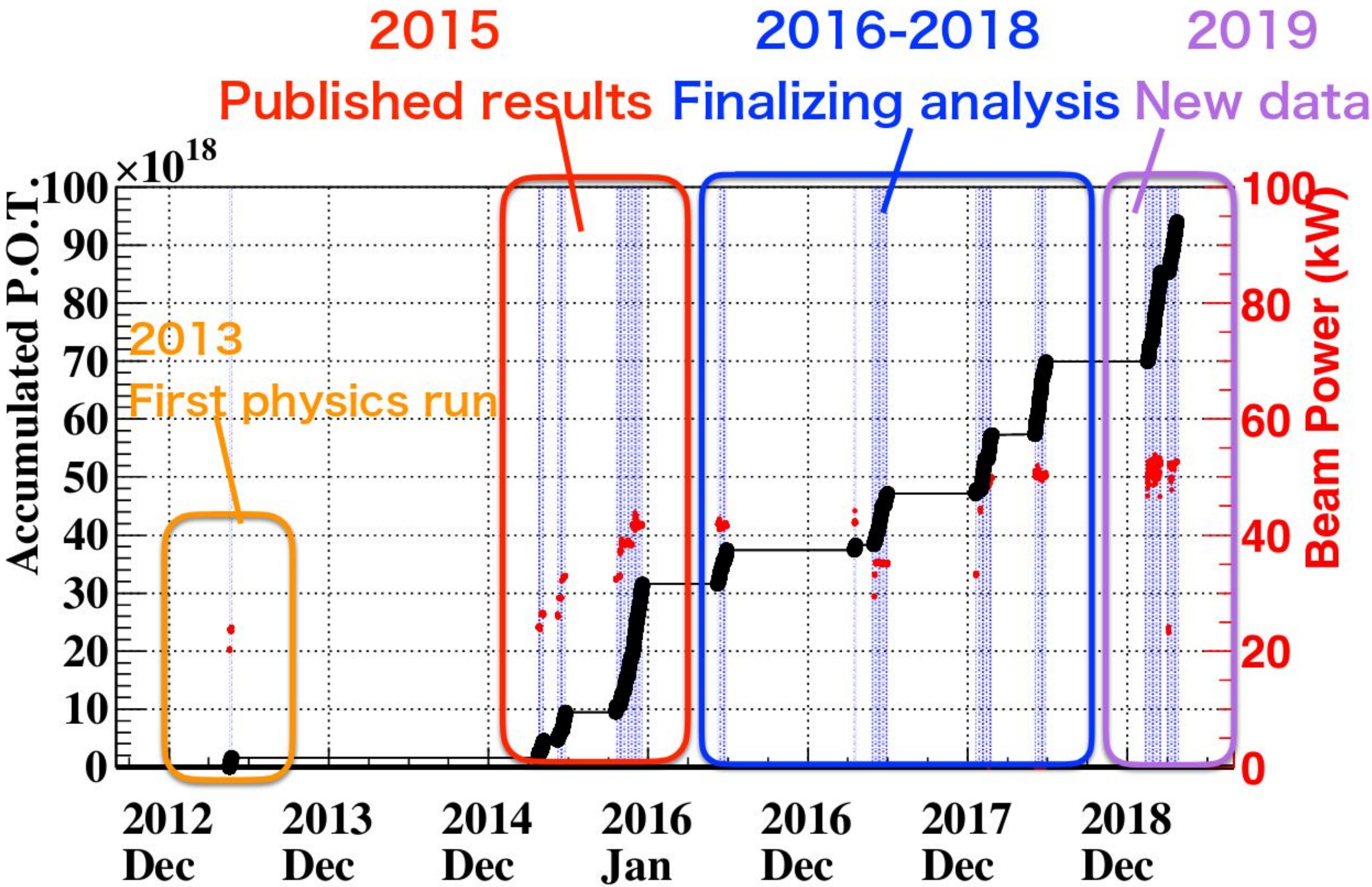
Distance from target to detector = 21.5m

Experimental Strategy

- CsI calorimeter observes 2γ from signal decay
- Difficulty → no charged particles and high efficiency required to detect all other particles
- Observe 2γ with large transverse momentum (P_t) and no other particles seen



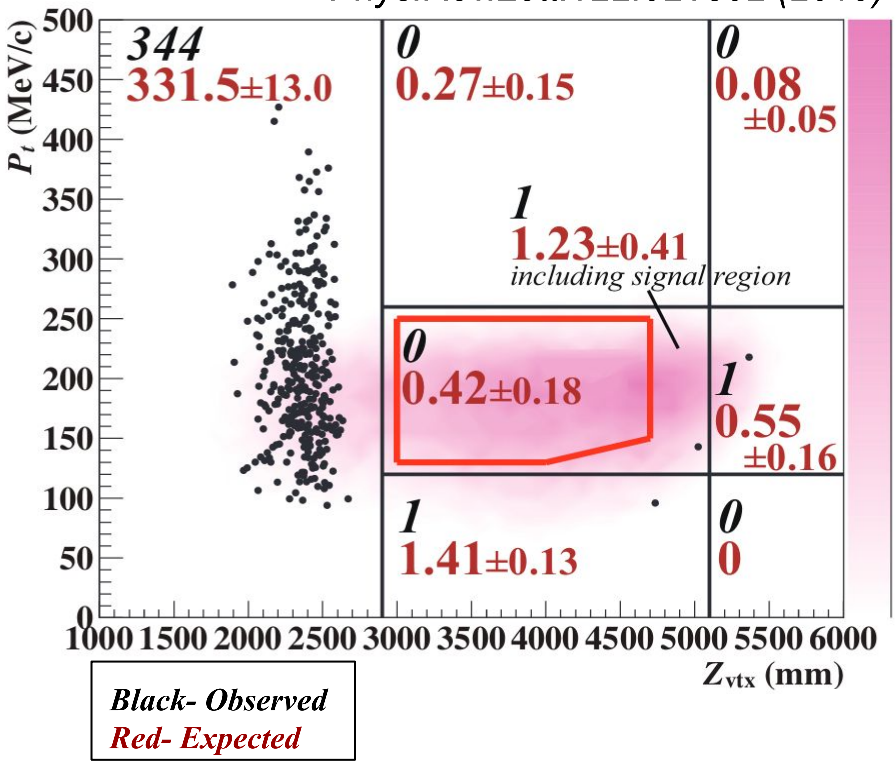
KOTO Status


2015
Published results
2016-2018
Finalizing analysis
2019
New data
2013
First physics run
Accumulated P.O.T.
×10^18
100
90
80
70
60
50
40
30
20
10
0
Beam Power (kW)
100
80
60
40
20
0
2012 Dec
2013 Dec
2014 Dec
2016 Jan
2016 Dec
2017 Dec
2018 Dec

Results of 2015 data

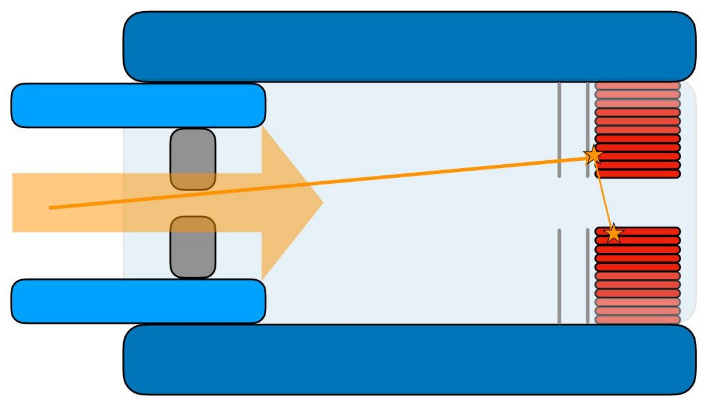
BR($K_L^0 \to \pi^0 \nu\bar{\nu}$) < 3.0 x 10^{-9} (@ 90% CL)

Phys.Rev.Lett.122.021802 (2019)



Background source	Expected no. events
K_L Decays	
$K_L \to \pi^+\pi^-\pi^0$	0.05 ± 0.02
$K_L \to 2\pi^0$	0.02 ± 0.02
Other K_L decays	0.03 ± 0.01
Neutron induced	
Hadron cluster on CsI	0.24 ± 0.17
Upstream π^0 from NCC	0.04 ± 0.03
CV η	0.04 ± 0.02
Total background	**0.42 ± 0.18**

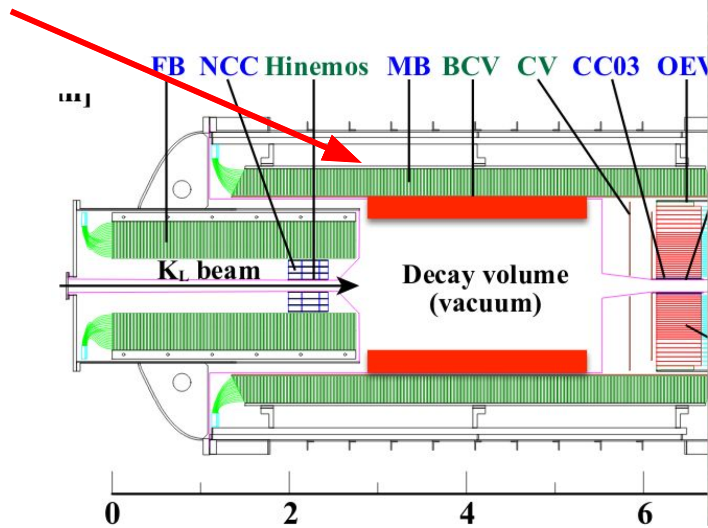
Largest background from neutrons hitting CsI

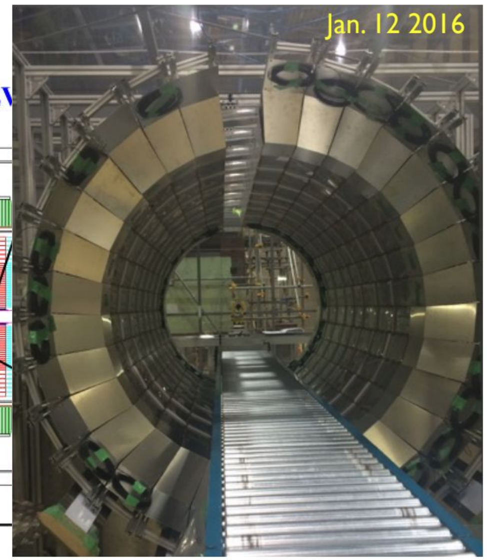


Improved previous limit (E391a) ~1 order of magnitude!

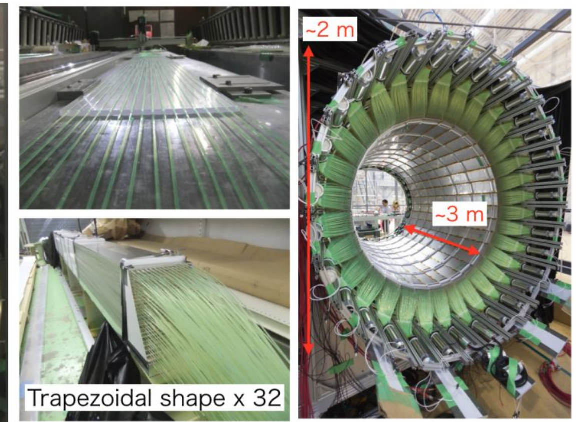
2016-2018 Improvements

- Inner Barrel (IB) installed to reduce $K_L \rightarrow 2\pi^0$ background
  - Estimated suppression x1/3





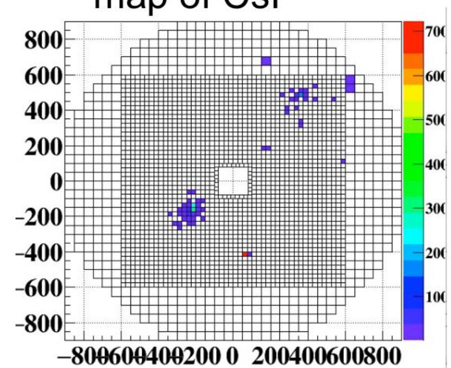
Inner Barrel



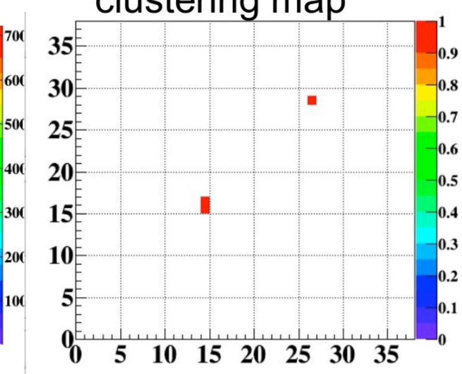
25 layers of 5mm Scintillator and 24 layers of 1mm lead plates Additional 5 radiation lengths (X_0)

- Upgraded Data Acquisition System
  - Cluster finding in trigger → to improve DAQ efficiency

Energy deposit map of CsI

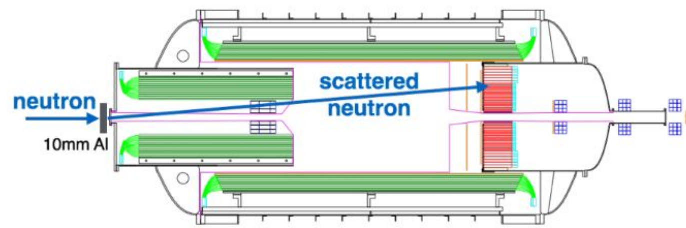


online clustering map



2016-2018 Improvements

- Specific runs to study neutron induced events
  - Scatter neutrons off of Aluminum plate
  - Implemented in 2015



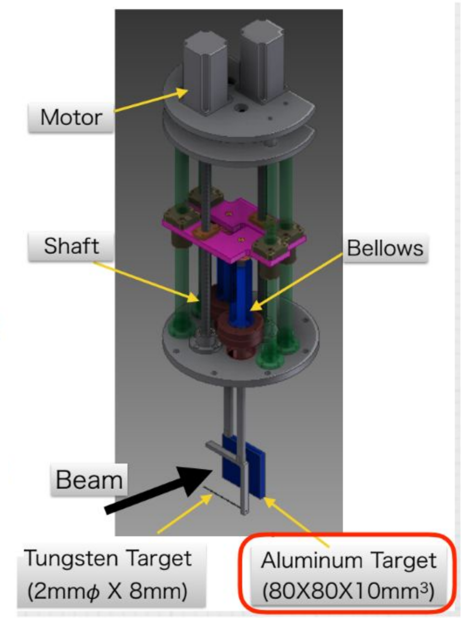
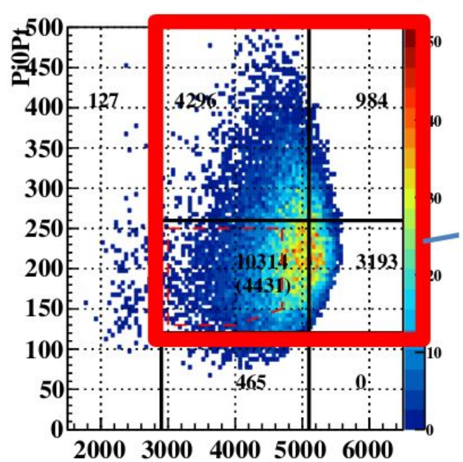


Fig. Movable Al target

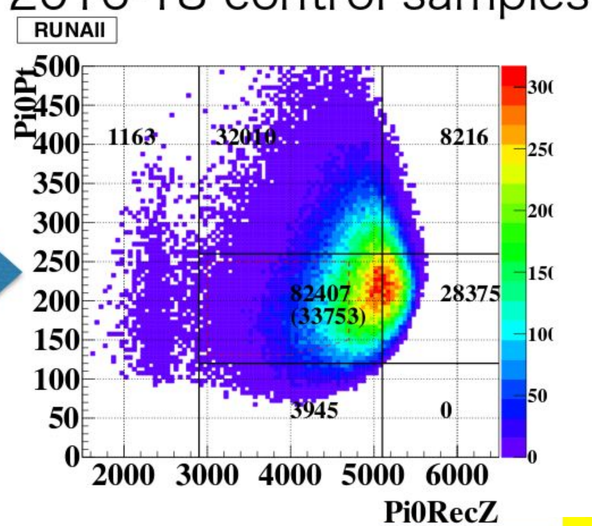
- Collect 8x larger sample of runs to study neutrons to improve n/γ discrimination

2015 control sample



×8

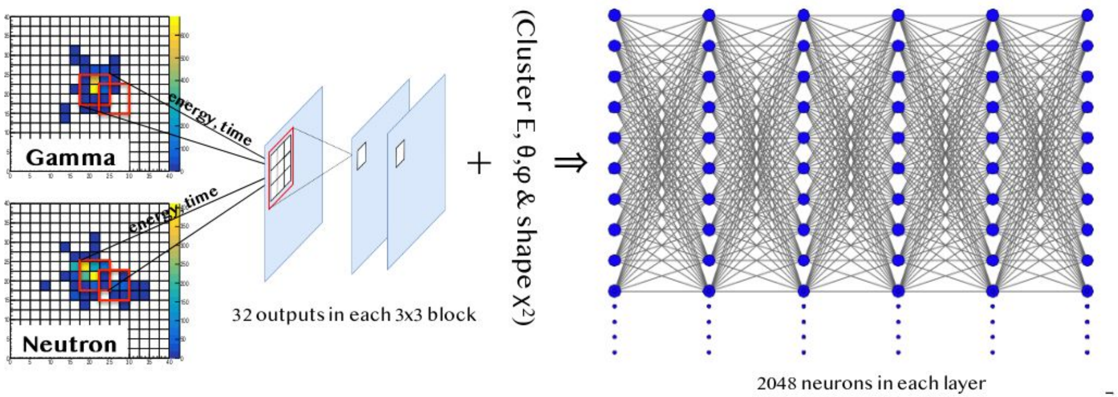
2016-18 control samples

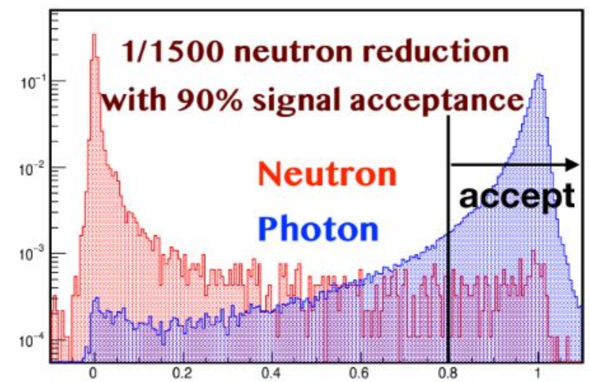


2016-2018 Improvements

- New cuts developed to reduce neutron background
  - Deep learning: convolutional neural network with cluster based inputs (energy, time)
  - (1/1500) BG reduction with 90% signal acceptance

1.8x Improvement

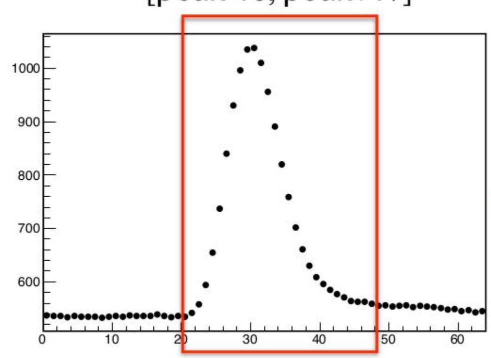




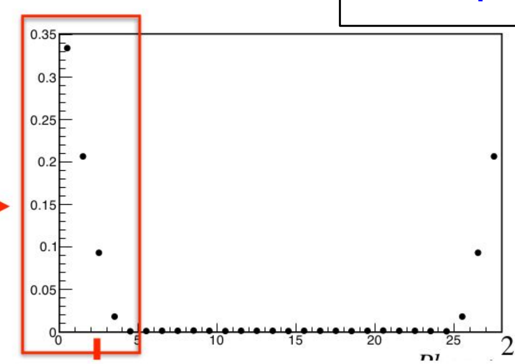
Neural Net outcome of shape cut

  - Pulse shape discrimination of n/γ by Fourier transform

2x Improvement



$$X_k = \sum_{n=0}^{N-1} x_n e^{-\frac{2\pi i}{N}kn}$$



Analysis

1) Signal reconstruction
2) Normalization
3) Background estimation and reduction

- Three variables needed to calculate BR
  - Number of signal events
  - Number of K_L^0s generated
  - Signal acceptance

$$BR(K_L^0 \to \pi^0 \nu \bar{\nu}) = \frac{N_{\mathrm{signal}}}{N_{K_L^0} \times A_{\mathrm{signal}}}$$

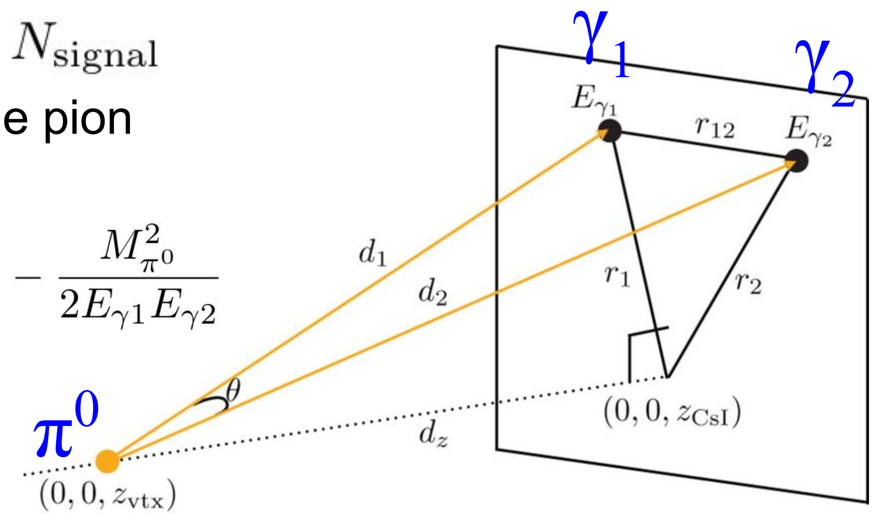
- Single Event Sensitivity

$$SES = \frac{1}{N_{K_L^0} \times A_{\mathrm{signal}}}$$

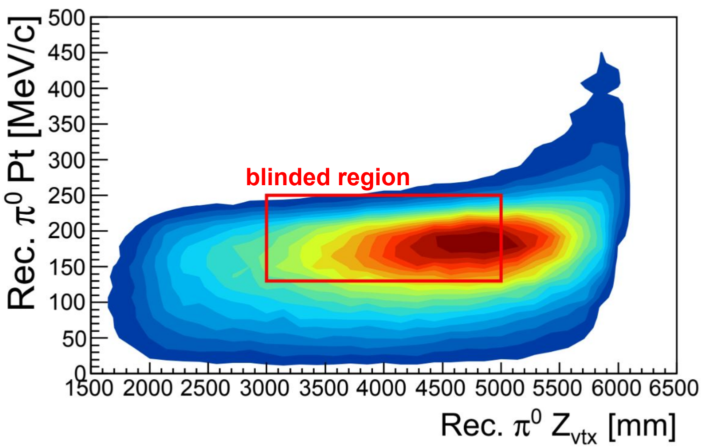
Signal Reconstruction

- Identify $K_L^0 \to \pi^0 \nu \bar{\nu}$ events to calculate N_{signal}
  - → reconstruct decay vertex of the pion
- 2 clusters hit on CsI
  - Position
  - Energy
- Constraints
  - π^0 mass
  - Decay position on beamline

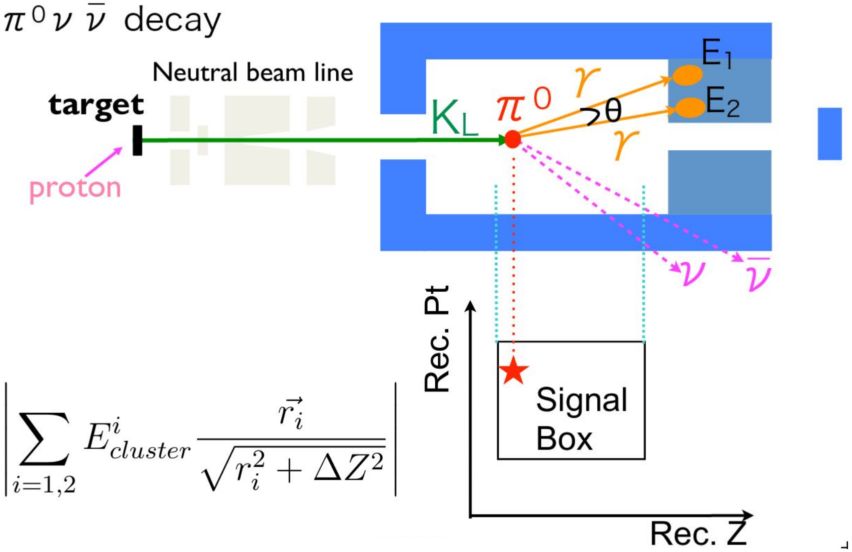
$$\cos\theta = 1 - \frac{M_{\pi^0}^2}{2E_{\gamma 1}E_{\gamma 2}}$$



- Reconstruct decay vertex (Z position) and transverse momentum (P_t)
  - Monte Carlo sample of $K_L^0 \to \pi^0 \nu \bar{\nu}$



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

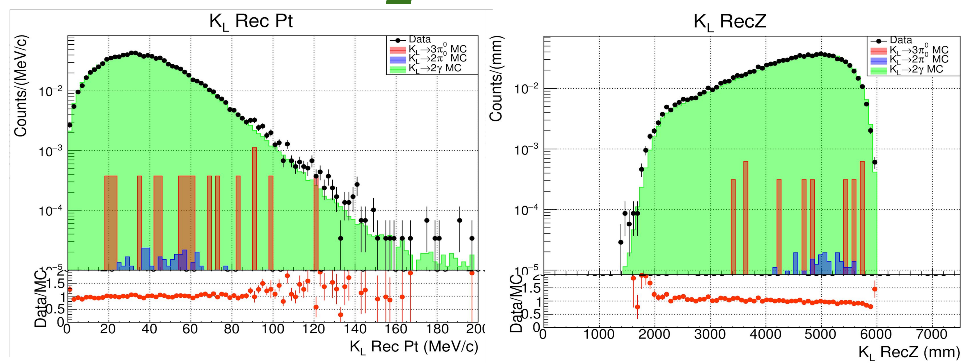


$$P_T^{\pi^0} = \left| \sum_{i=1,2} E_{cluster}^i \frac{\vec{r_i}}{\sqrt{r_i^2 + \Delta Z^2}} \right|$$

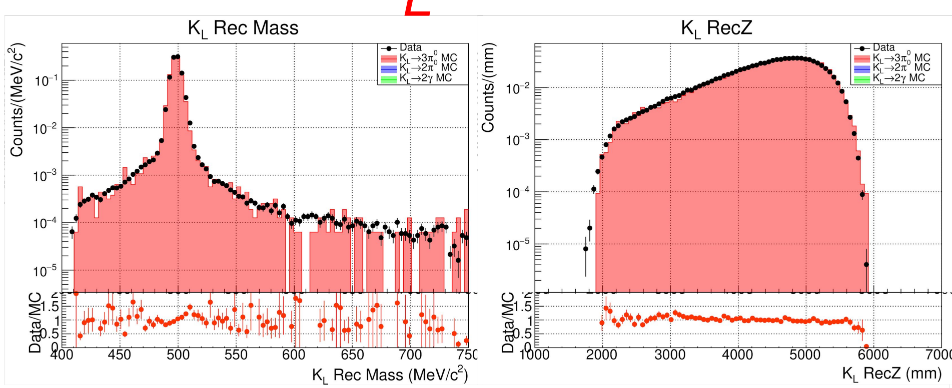
Normalization

- Calculate the number of K_L^0s at the beam exit, $N_{K_L^0}$
- Normalization modes also used for
  - Measure kaon mass ($3\pi^0$)
  - Measure z vertex of kaon
  - Also used for data checking and evaluating kinematic and veto cut efficiencies
  - Evaluate MC reproducibility of data
- Signal acceptance, A_{signal}
  - Geometric acceptance of detectors
  - Kinematic and veto efficiencies of cuts

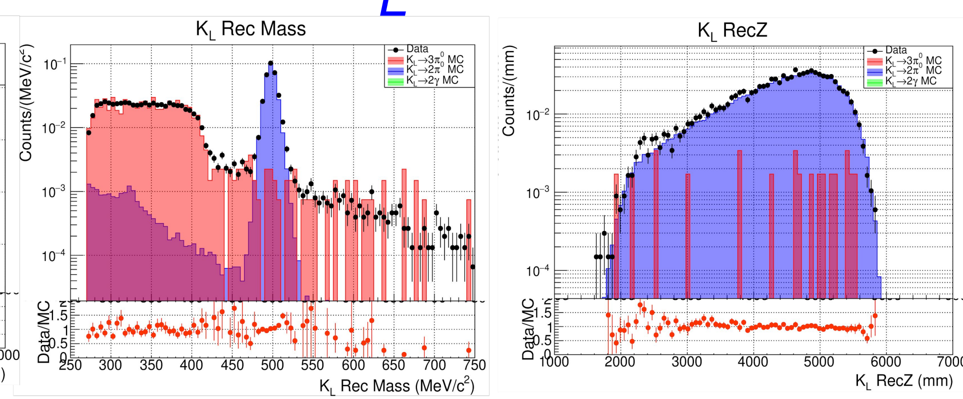
$K_L \rightarrow 2\gamma$



$K_L \rightarrow 3\pi^0$



$K_L \rightarrow 2\pi^0$

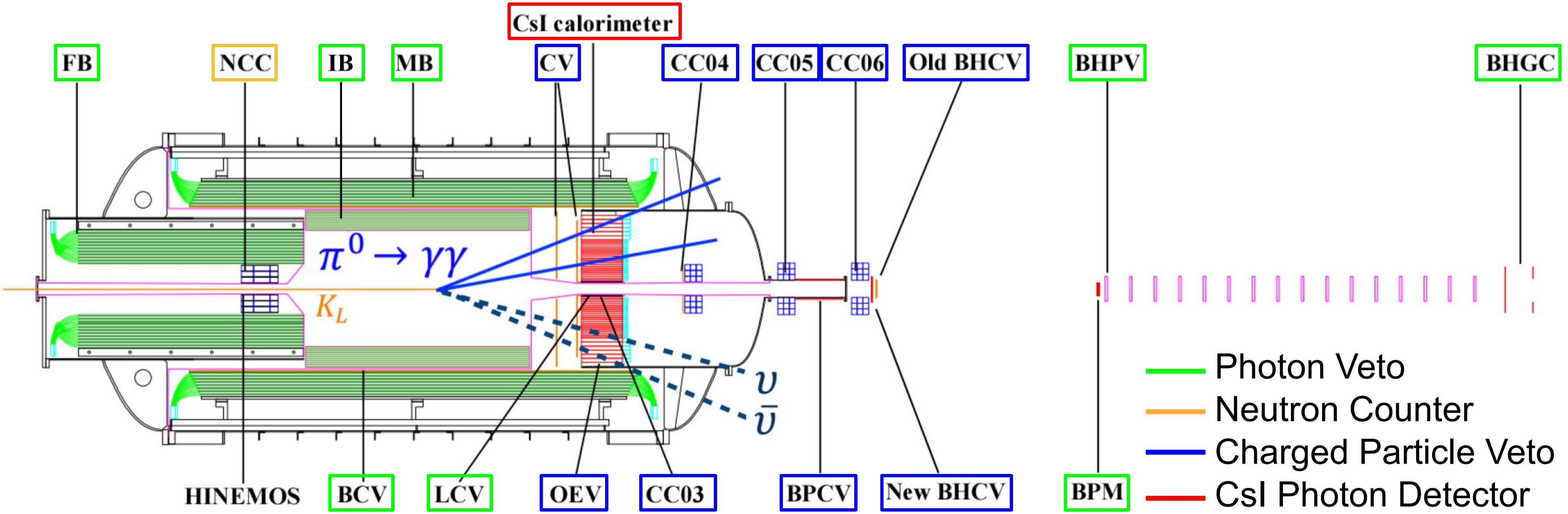


Background Analysis

- Charged vetos remove events with charged particles (~80%)
- Photon vetos must detect other K_L^0 decay modes

  $K_L^0 \rightarrow 3\pi^0$
  $K_L^0 \rightarrow 2\pi^0$
  $K_L^0 \rightarrow \pi^+\pi^-\pi^0$

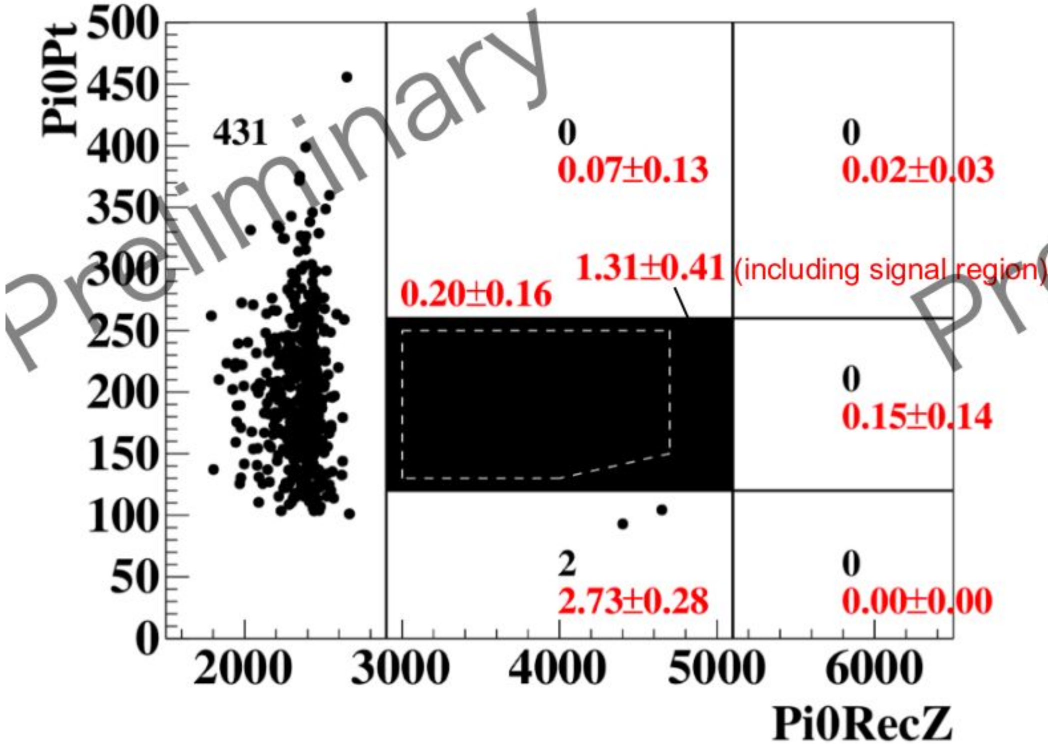
- Detailed MC studies of various background modes



2016-2018 Analysis Status

- 1.5x more data than 2015 (accumulated POT ~ 3.1 x 10^{19})
- SES improved x1.6 from SES = 1.3 x 10^{-9} in 2015
- Background is well controlled

Estimated SES = 8.2 x 10^{-10}

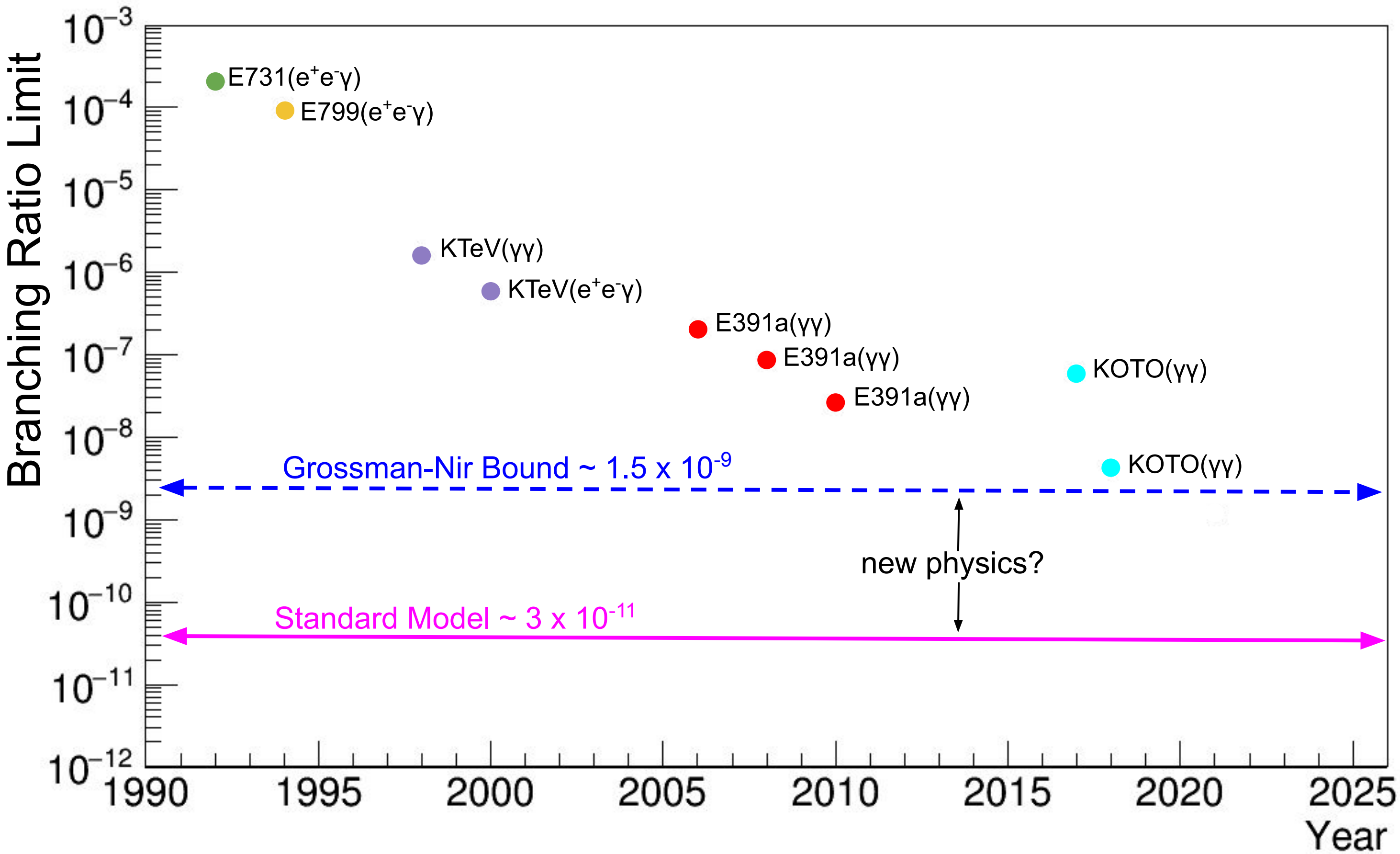


	# of BG inside signal region
$K_L \to 2\pi^0$	0.09±0.09
$K_L \to \pi^+\pi^-\pi^0$	0.02±0.02
Hadron cluster	0.07±0.13
CV-pi0	< 0.19
CV-eta	0.02±0.01
Total	**0.20±0.16**

Preliminary

Outlook

- Finalizing analysis → will present new results at Kaon 2019 conference in mid September
- Expect to push into the realm of new physics!



Thank You

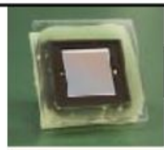
Dec ’17 collaboration meeting

Supplemental

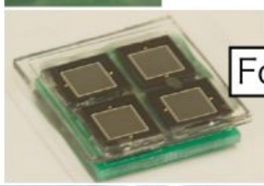
KOTO Beyond 2018

- Upgrade of detectors to further enhance background reduction
  - *MPPC dual ended readout of CsI crystals (2018) with Experimental run in 2019!*

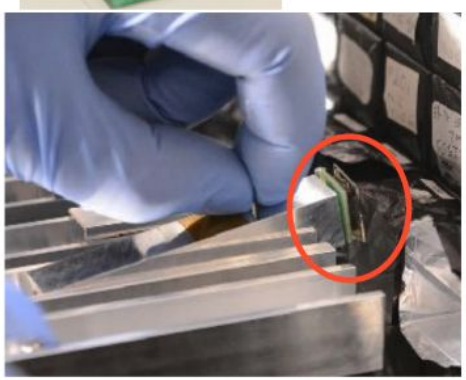
Attach 4080 MPPCs to 2800 crystals

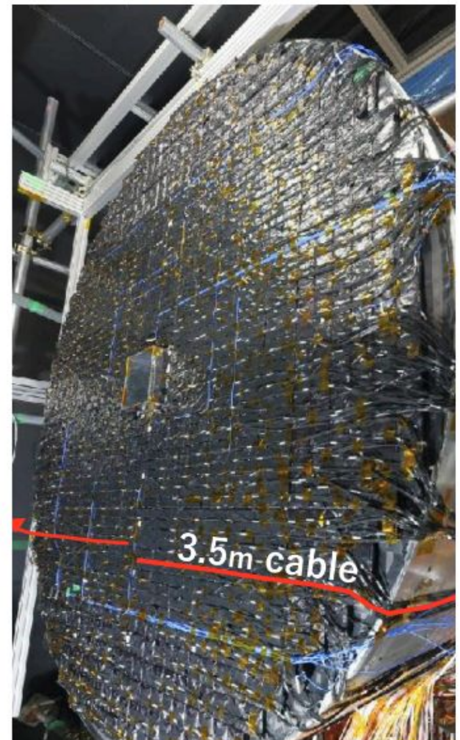


6x6 mm^2 MPPC for small crystal



Four MPPCs for large crystal





Grouping readout of 10x10cm^2 region
→ additional readout of 256 channels

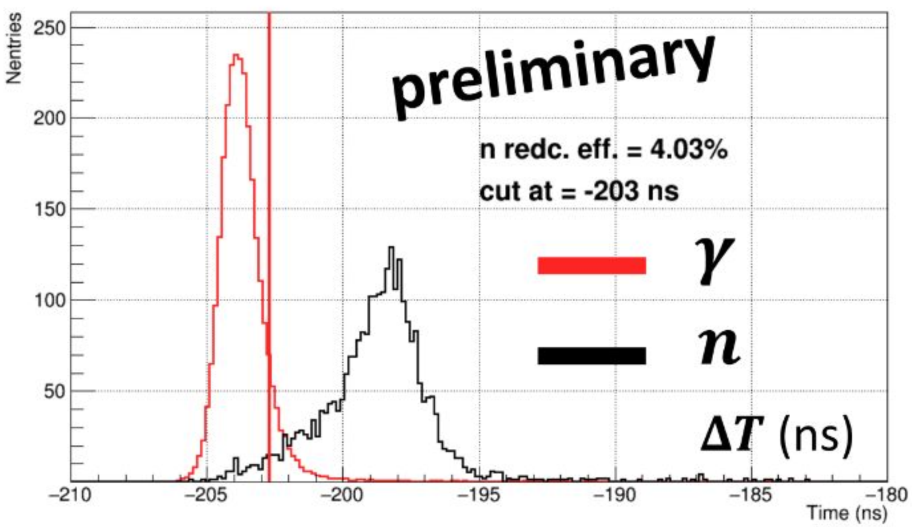
KOTO Beyond 2018

- Upgrade of detectors to further enhance background reduction
  - *MPPC dual ended readout of CsI crystals (2018) with Experimental run in 2019!*

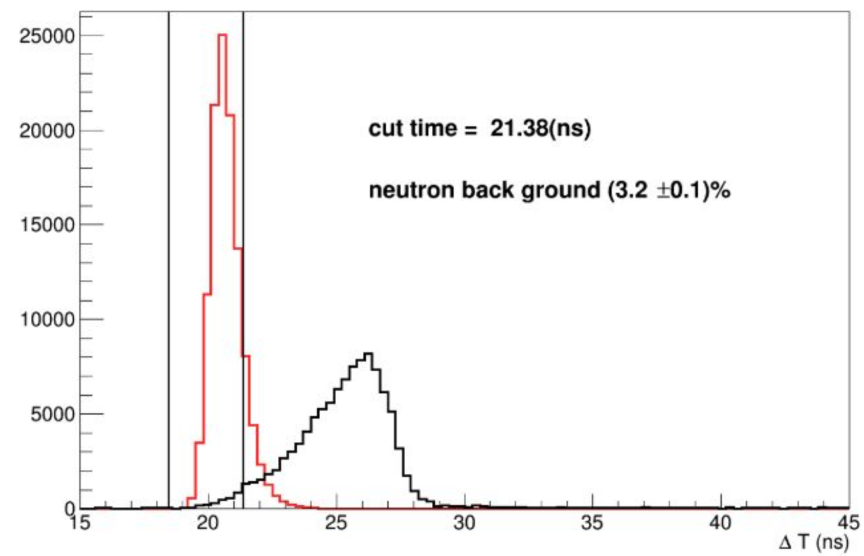
$$\Delta T \equiv T_{MPPC} - T_{PMT}$$

large ΔT ⇔ deep E deposit

ΔT distribution (**Data**)

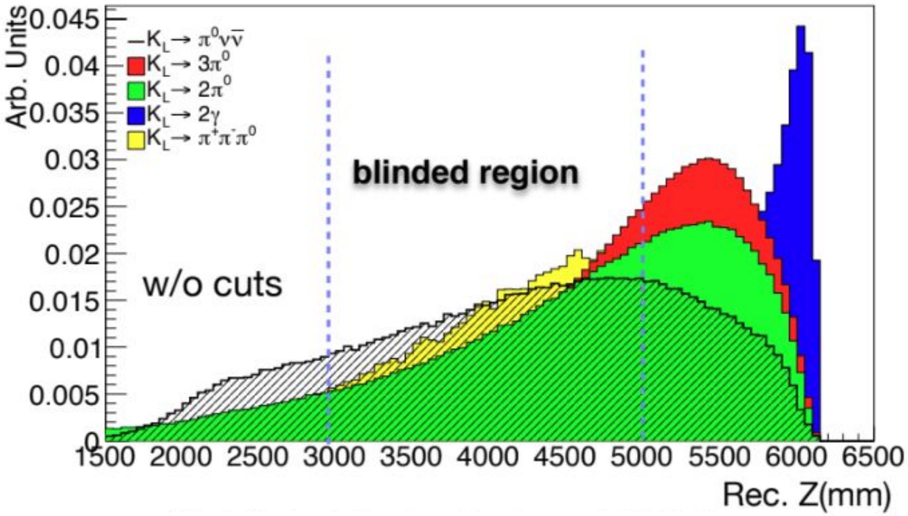


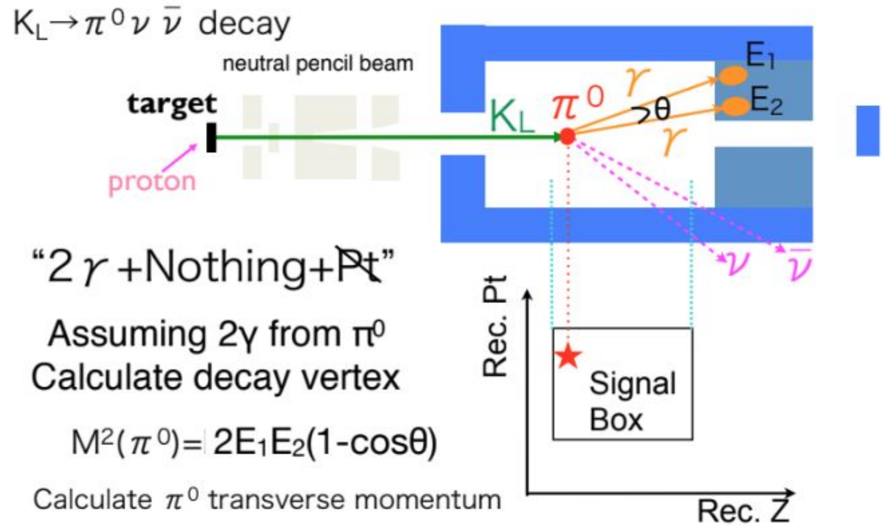
ΔT distribution (MC)

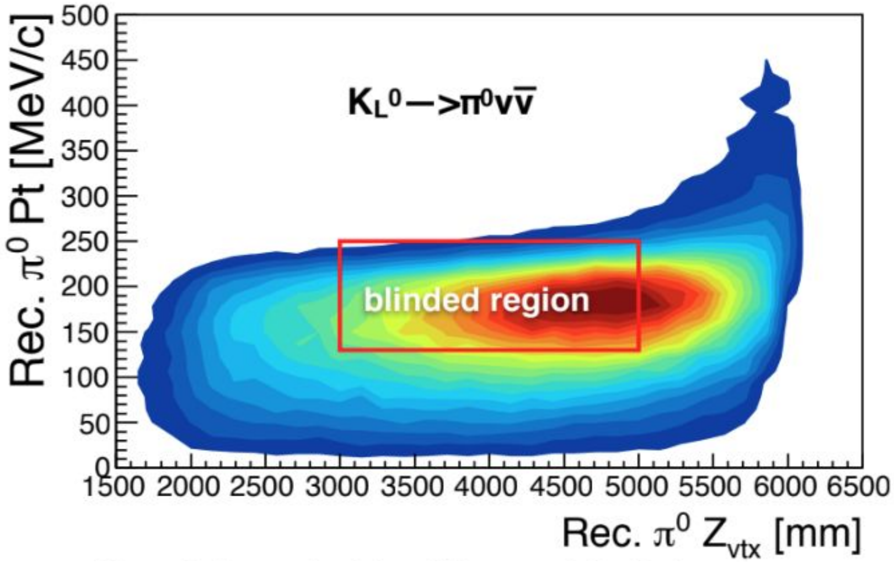


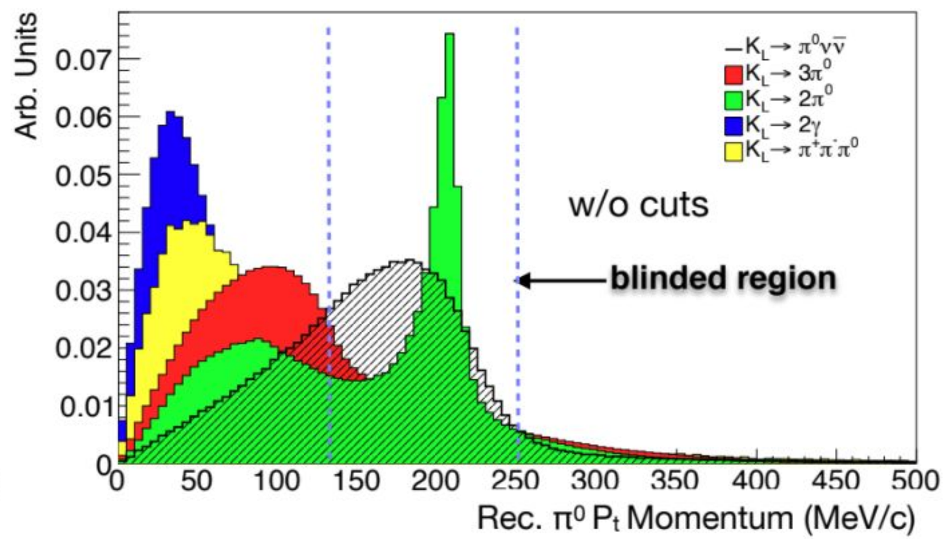
1/35 neutron reduction
90% γ efficiency

Signal Distribution

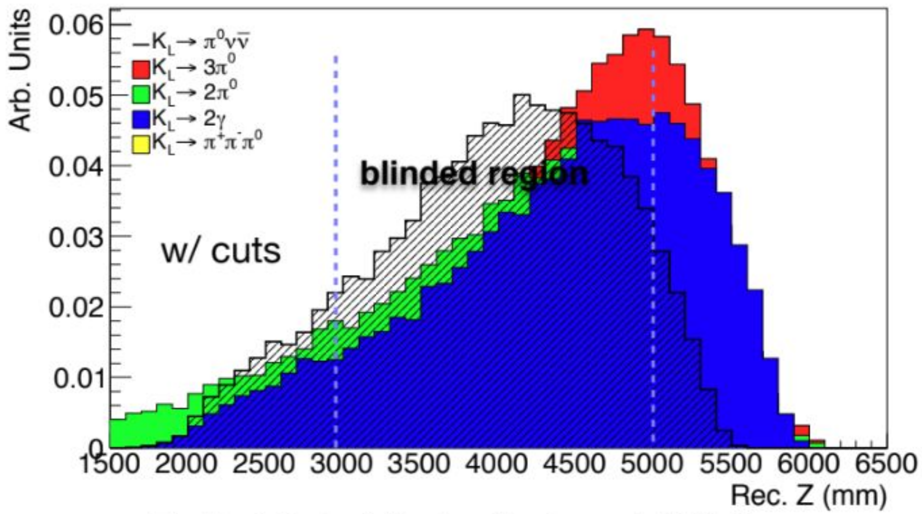


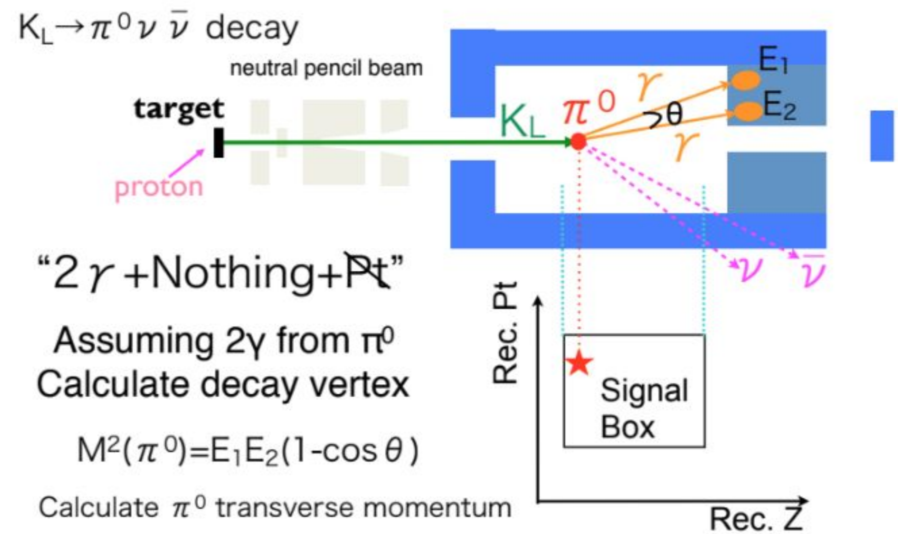


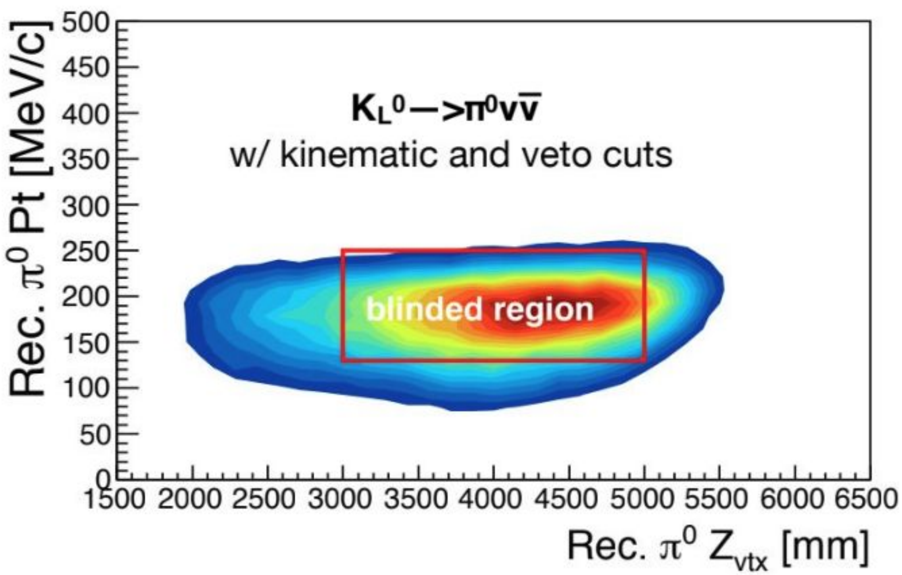


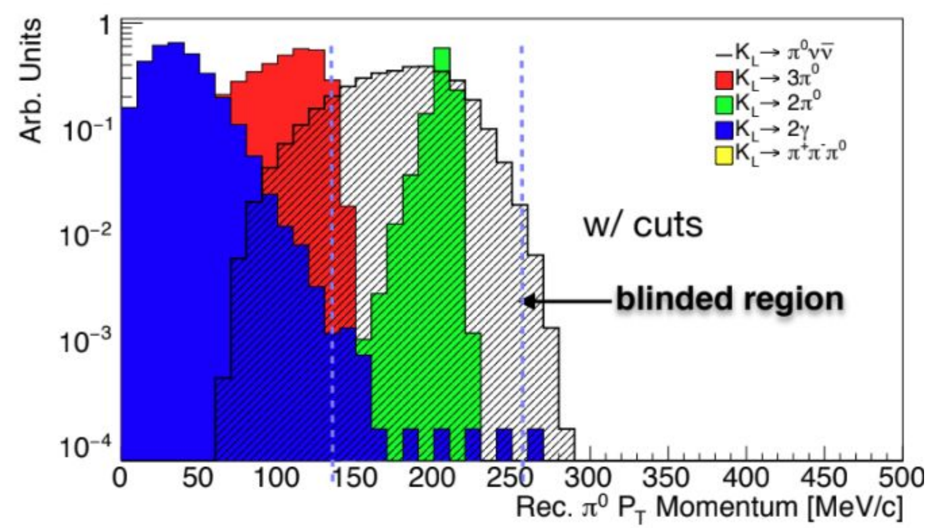


Signal Distribution





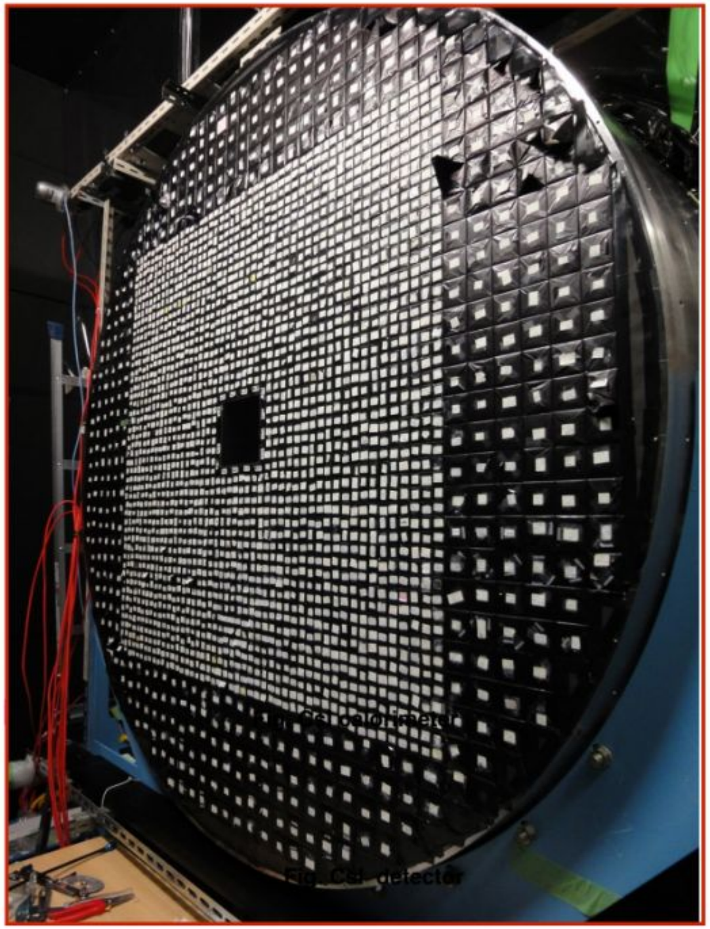




KOTO Detectors

- Cesium Iodide (CsI) calorimeter
- Main detector for KOTO
- 2716 channels read out by PMTs
  - 2.5 cm x 2.5 cm small crystals
  - 5 cm x 5 cm large crystals
- Timing and energy information for each crystal
- Hermetic veto detectors around decay Volume
  - ~1000 channels

Cesium Iodide (CsI) Photon Detector



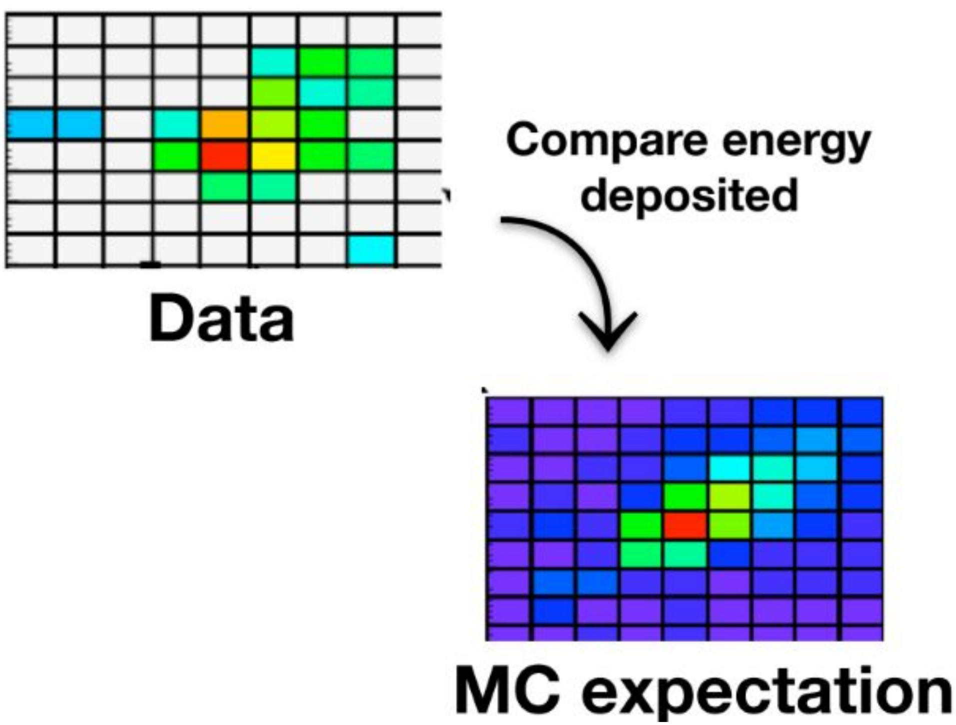
CsI calorimeter

- 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

Discrimination methods

Shape χ^2 (first run) compares observed energy deposited with the expected energy derived from MC. The sum is taken over 27 x 27 crystals around the cluster center.

- (1/300) BG reduction with 80% signal acceptance



$$\chi^2 = \frac{1}{N}\sum_{i}^{\text{in } 27\times 27 \text{ region}} \left(\frac{e_i/E_{inc}-\mu}{\sigma}\right)^2$$

E_{inc} : measured photon energy

e_i : measured deposit energy in ith crystal in a cluster

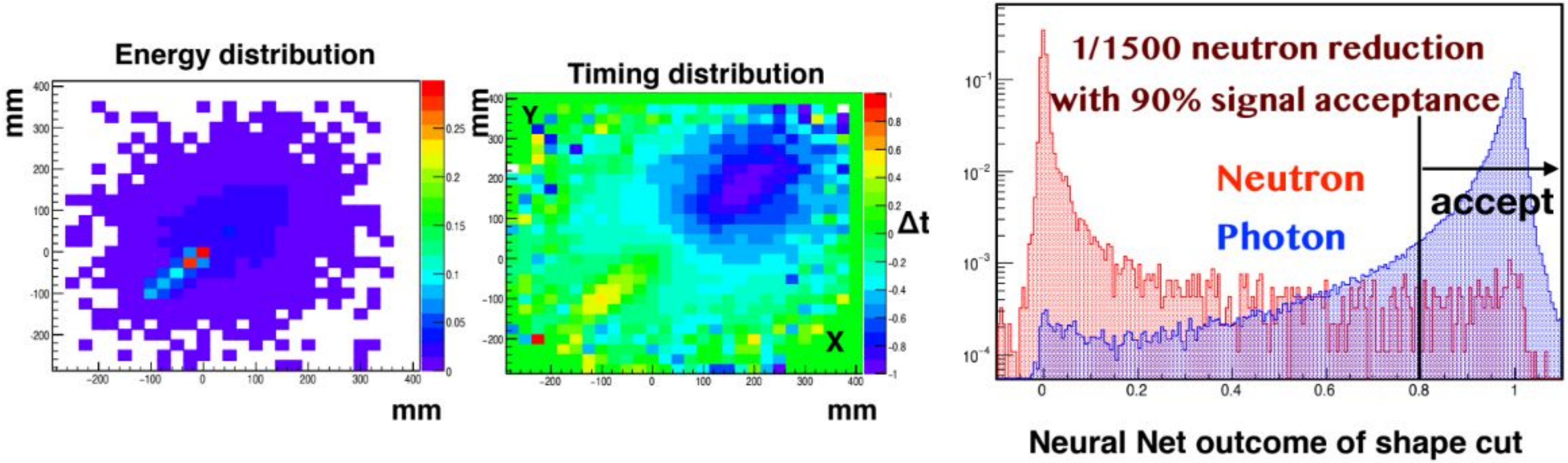
μ : expected mean e/E

σ : expected RMS of e/E

Discrimination methods

Cluster Shape Discrimination (CSD) uses energy and timing information from the CsI as inputs into a Neural Net

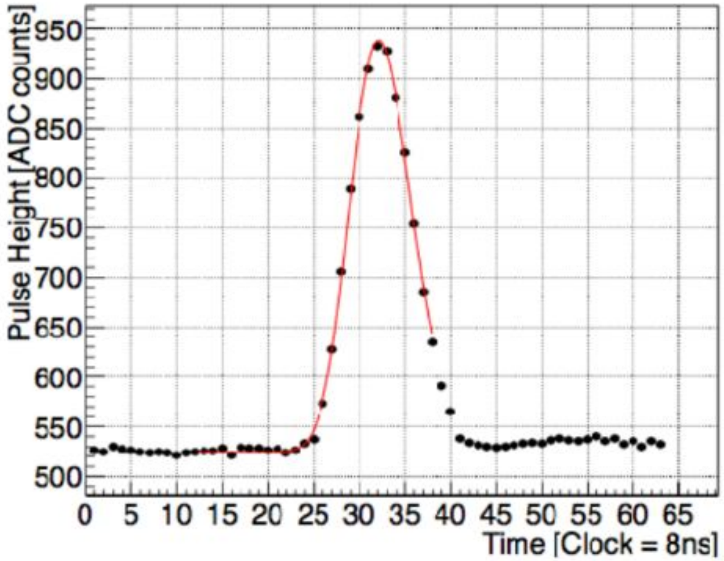
- (1/1500) BG reduction with 90% signal acceptance
- Main inputs: Energy χ^2, Cluster $E_{difference}$, timing χ^2, Cluster COE, Cluster RMS, crystal energy probability…



Discrimination methods

Pulse Shape Discrimination (PSD) cut uses waveform information to discriminate photon and hadronic showers

- Fitted waveforms with asymmetric Gaussian, obtained templates, and calculated likelihood ratio from fit parameters taken from control and photon samples
- Difference in the tail of hadronic showers corresponds to a larger **(a)**



Fitted waveform with asymmetric Gaussian

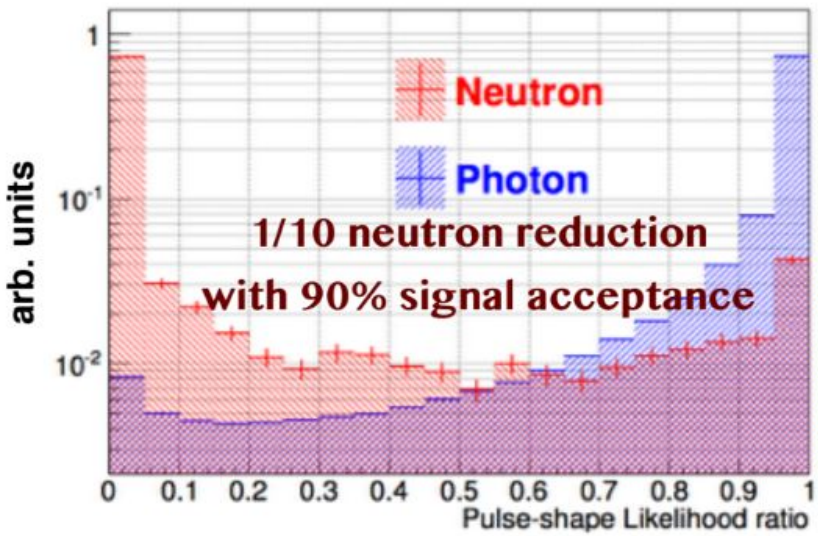
$$A(t) = |A| exp\left(-\frac{(t-t_0)^2}{2\sigma(t)^2}\right)$$

$$\sigma(t) = \sigma_0 + a(t-t_0)$$

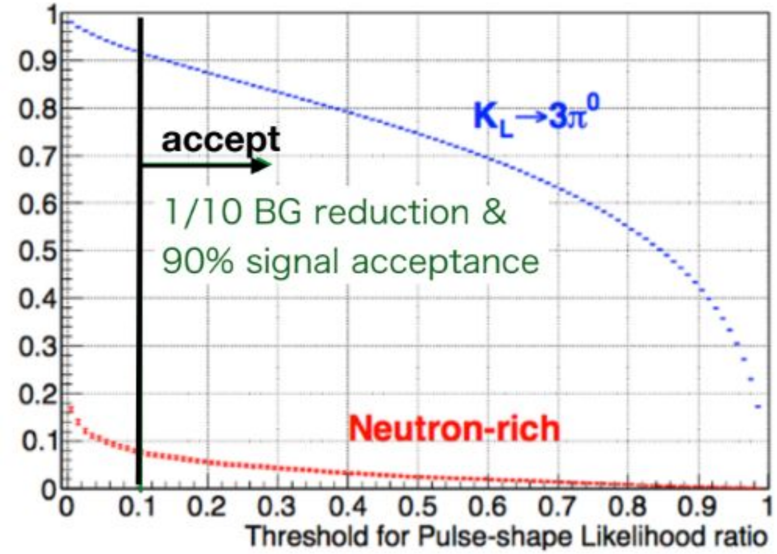
Discrimination methods

Pulse Shape Discrimination (PSD) cut uses waveform information to discriminate photon and hadronic showers

- Fitted waveforms with asymmetric Gaussian, obtained templates, and calculated likelihood ratio from fit parameters taken from control and photon samples
- Difference in the tail of hadronic showers corresponds to a larger (a)
- (1/10) BG reduction with 90% signal acceptance



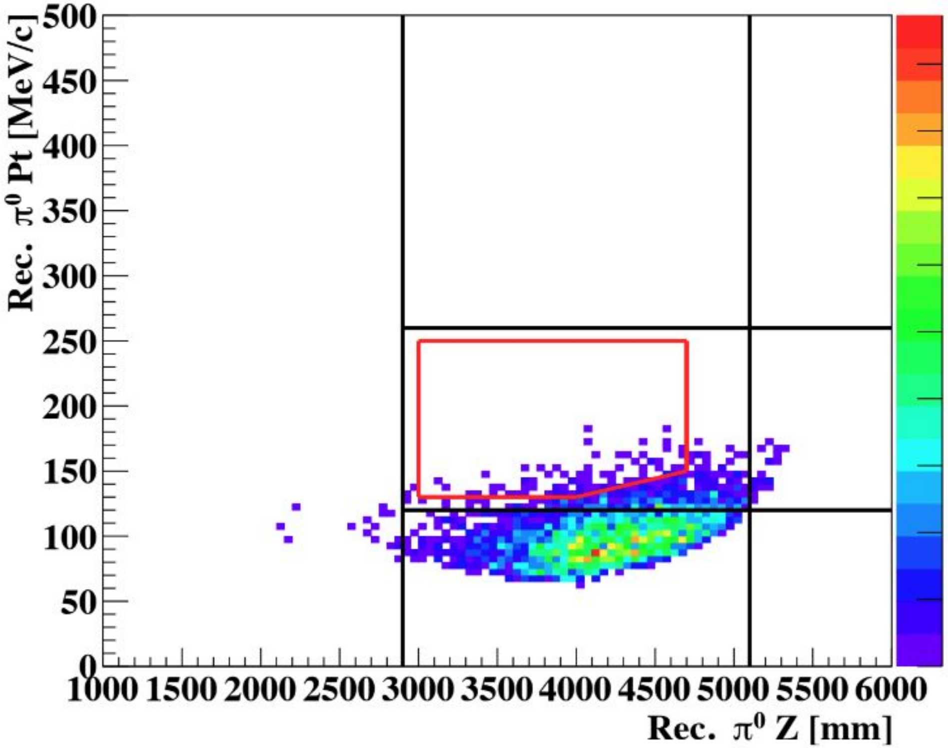
Pulse-shape-likelihood ratio



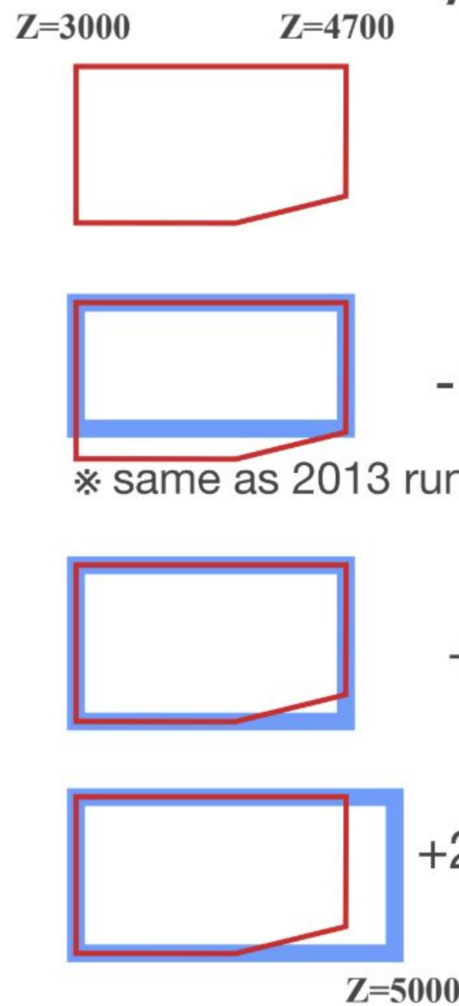
Pulse-shape-likelihood ratio

Signal Region

$K_L \to \pi^+\pi^-\pi^0$ MC (Loose cut condition)

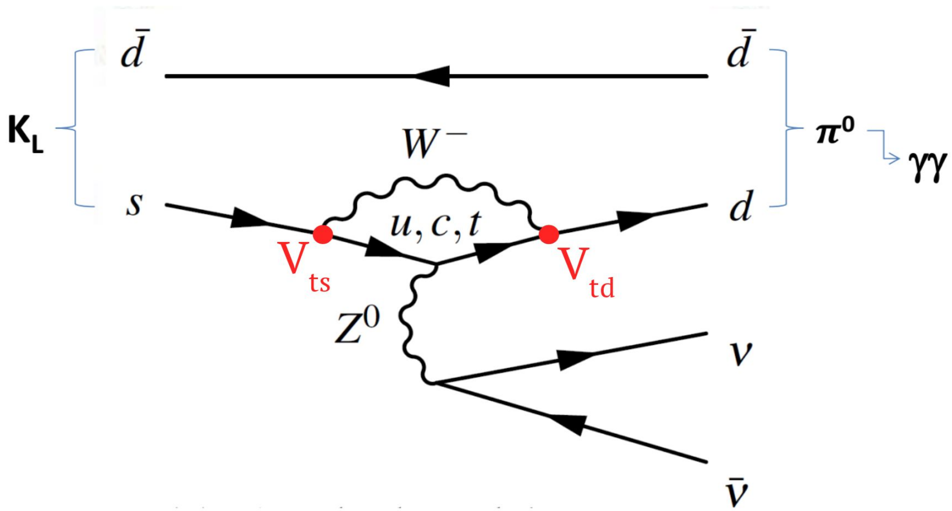


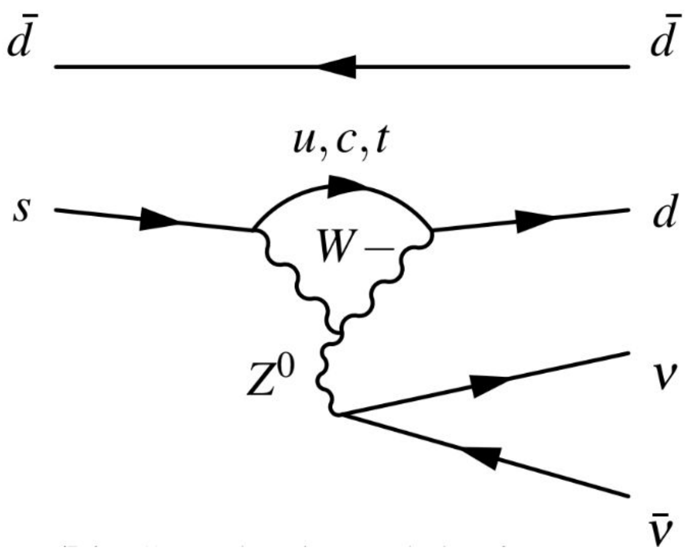
Slope to suppress $K_L \to \pi^+\pi^-\pi^0$ BG

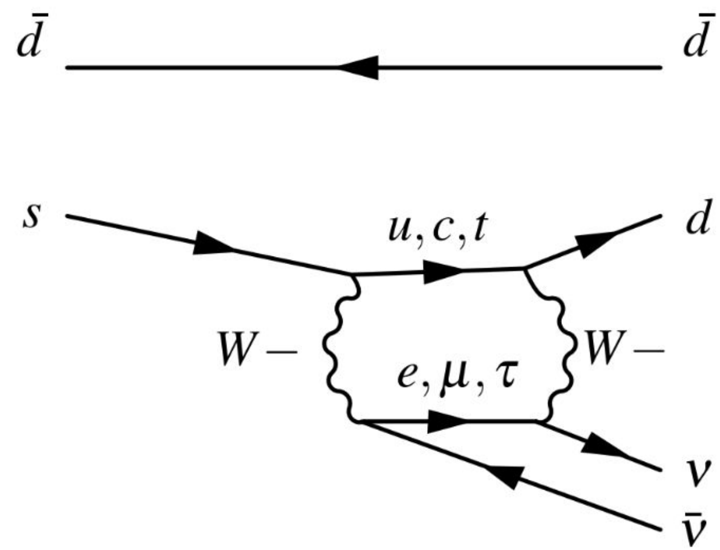


	A_{sig}	N_{BG}
Nominal		**0.40**
※ same as 2013 run	-15%	-0.04
	+3%	+0.04
Z=5000	+23%	+0.30

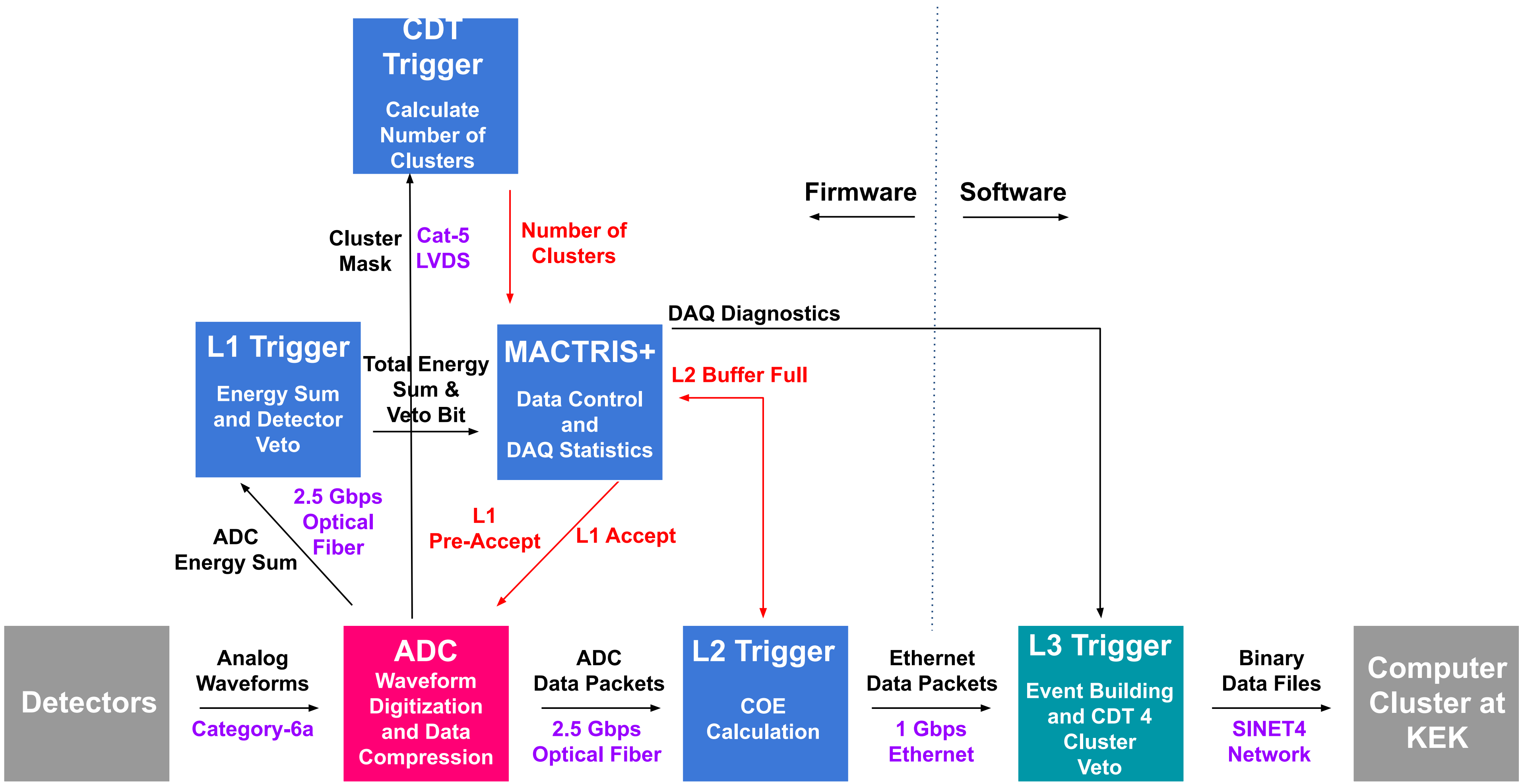
$K_L^0 \to \pi^0 \nu\bar{\nu}$ Feynman Diagrams





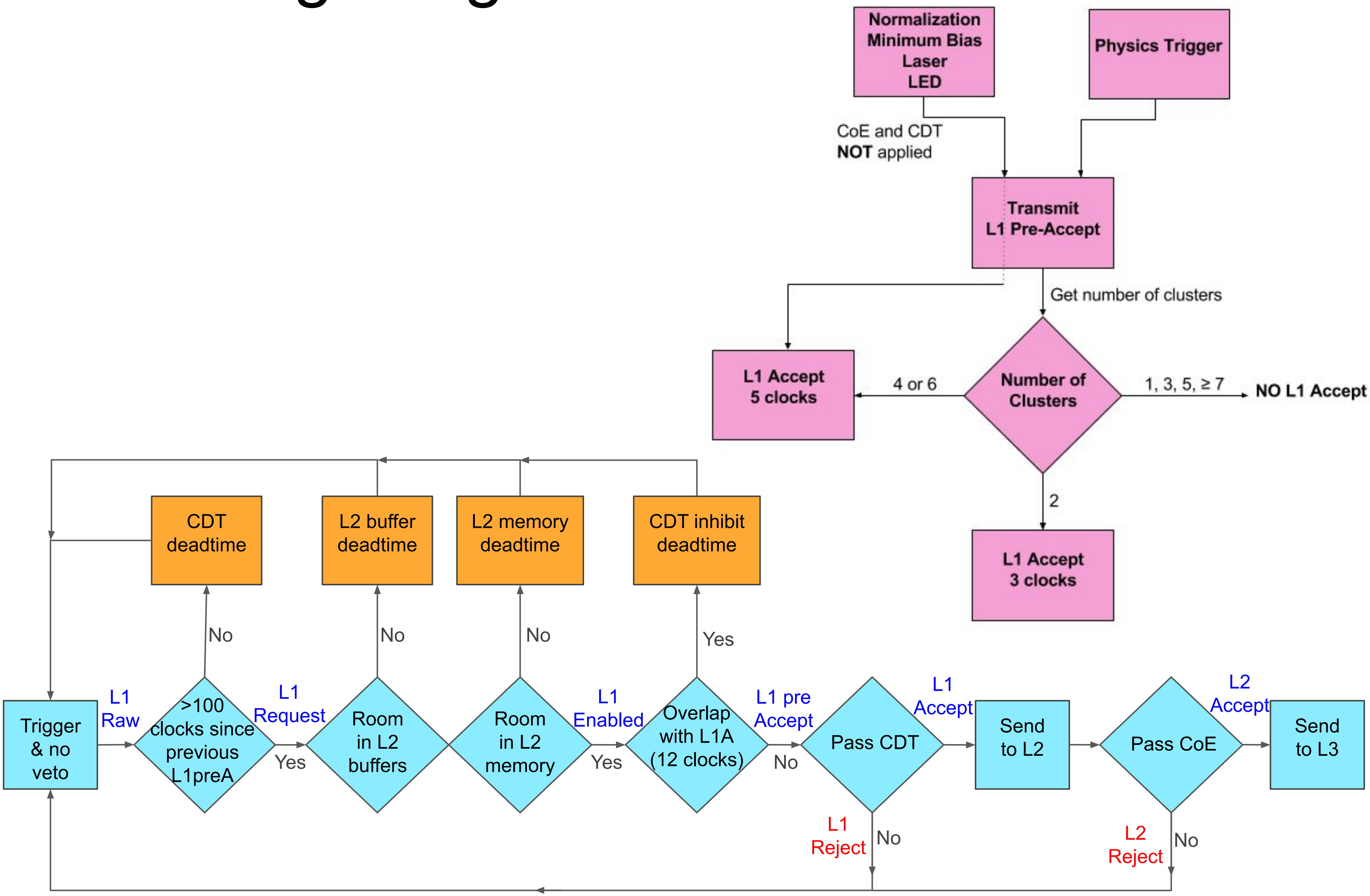


DAQ



CDT Trigger
Calculate Number of Clusters
Firmware
Software
Cluster Mask
Cat-5 LVDS
Number of Clusters
DAQ Diagnostics
L1 Trigger
Energy Sum and Detector Veto
Total Energy Sum & Veto Bit
MACTRIS+
Data Control and DAQ Statistics
L2 Buffer Full
2.5 Gbps Optical Fiber
ADC Energy Sum
L1 Pre-Accept
L1 Accept
Detectors
Analog Waveforms
Category-6a
ADC
Waveform Digitization and Data Compression
ADC Data Packets
2.5 Gbps Optical Fiber
L2 Trigger
COE Calculation
Ethernet Data Packets
1 Gbps Ethernet
L3 Trigger
Event Building and CDT 4 Cluster Veto
Binary Data Files
SINET4 Network
Computer Cluster at KEK

DAQ Logic Signal Flow



2013 Data Analysis

- 2013 data analysis revealed largest contribution to background is neutrons hitting detector material

$BR(K_L^0 \to \pi^0 \nu\bar{\nu}) < 5.1 \times 10^{-8}$ @ 90% CL

- New detector changes to reduce neutron background
  - Improved surface alignment of collimators; BPM (Beam Profile Monitor)
  - Vacuum window replaced
  - Specific experimental runs with aluminum target to study neutron background

- Beam Hole Charge Veto
  - Suppress $\pi^+\pi^-\pi^0$

- Beam Hole Guard Counter
  - Tag photons escaping near edge of beam hole