大阪大学
OSAKA UNIVERSITY

Search for new physics via rare K_L decays

Nobuhiro Shimizu for the KOTO collaboration

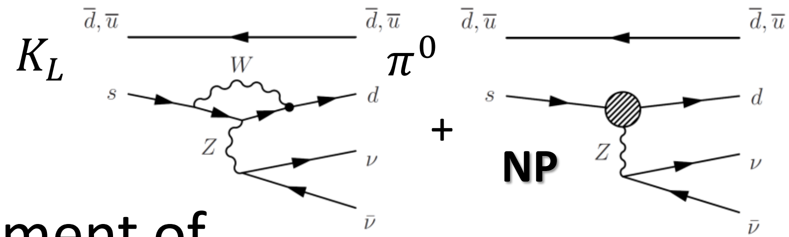
Seminar at Chiba university August 31st, 2020

Outline

- Introduction
  - $K_L \to \pi^0 \nu \bar{\nu}$
- CsI calorimeter upgrade to reduce neutron background
- Charged kaon background
- Search for $\boldsymbol{K_L \to \pi^0 \gamma}$ decay

KOTO experiment

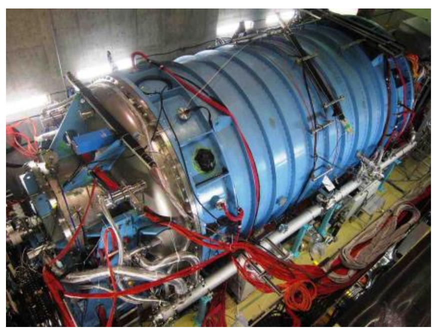
Introduction

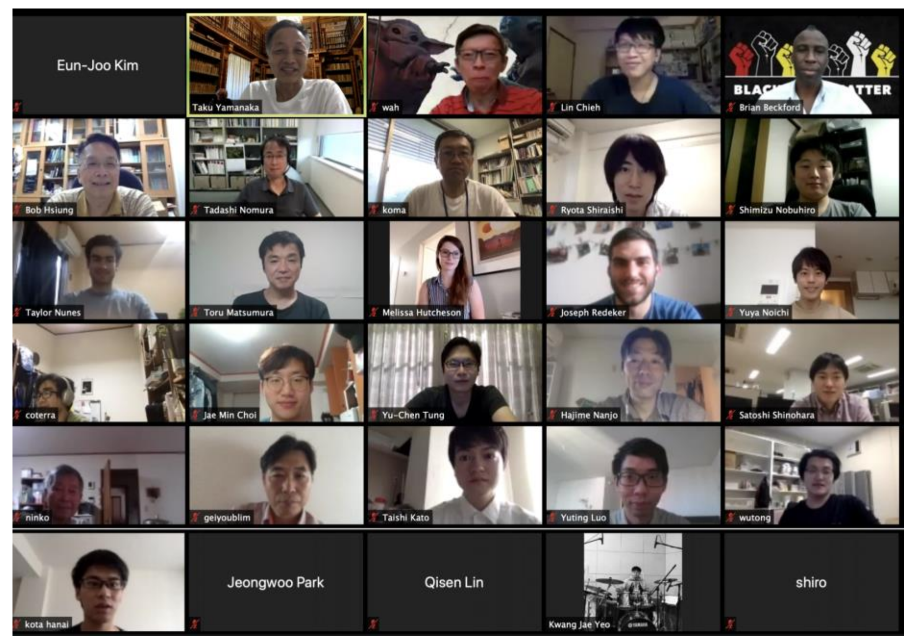


- Search for New Physics via measurement of $K_L \to \pi^0 \nu \bar{\nu}$ decay

  Very rare and theoretically clean decay:
  $\mathcal{B}_{\mathrm{SM}}(K_L \to \pi^0 \nu \bar{\nu}) = (3.0 \pm 0.3) \times 10^{-11}$ JHEP **11** 033 (2015)

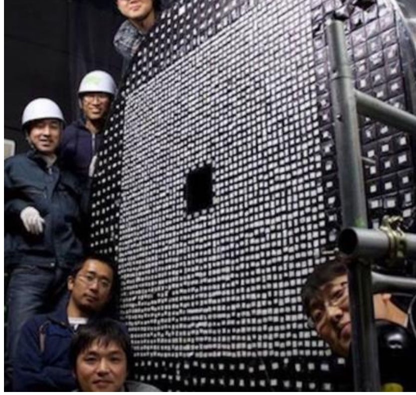
- KOTO experiment

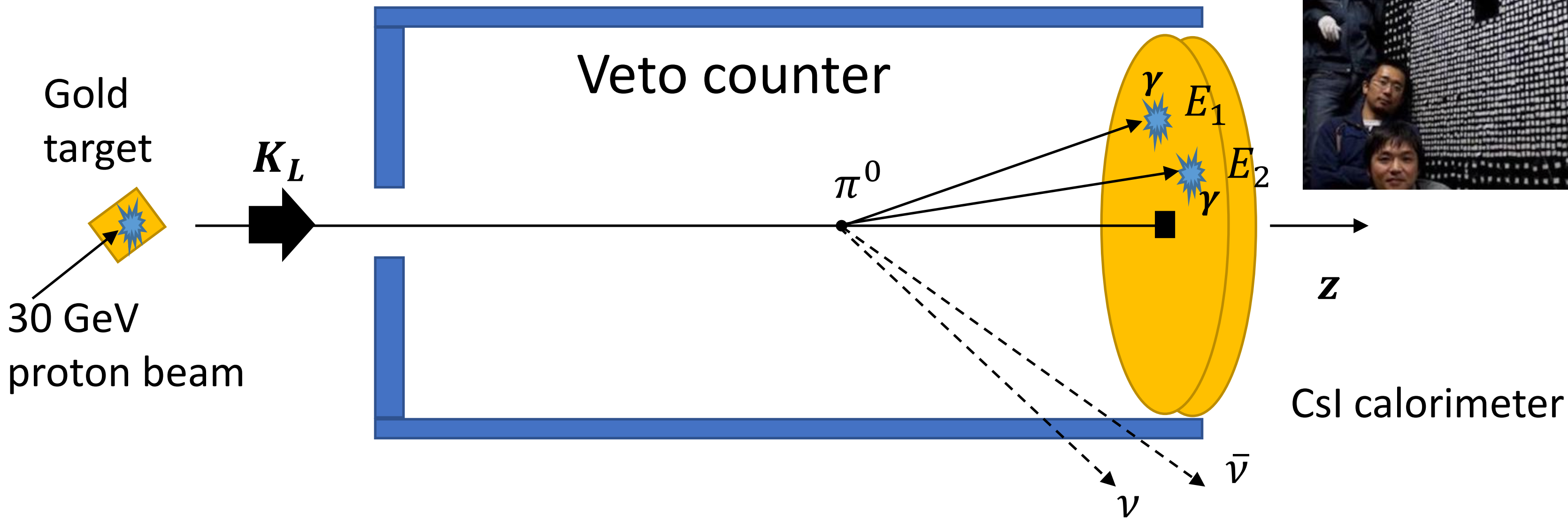




Online collaboration meeting in July

Experimental principle



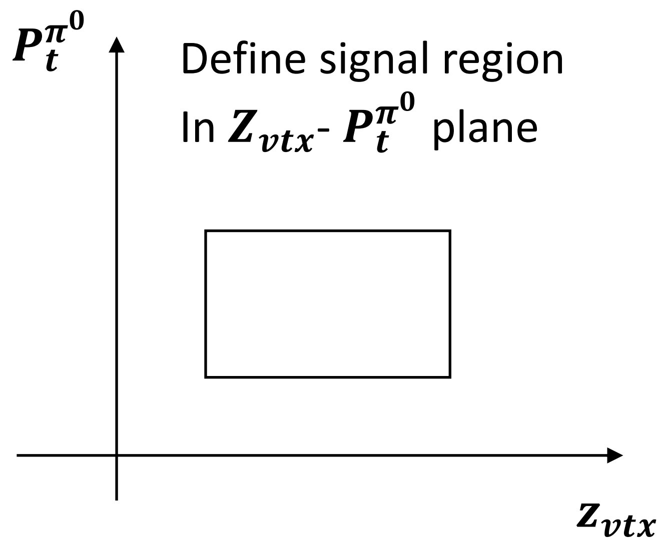


- **☐** Signature of $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay
  - Measure energy and hit position of two γ's by the CsI calorimeter
  - Neutrinos are not measured
    → Require no signal in the hermetic veto counters

Signature of signal → $2\gamma + nothing$

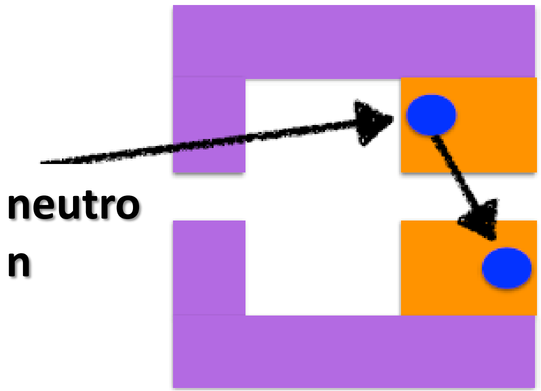
  - Calculate decay z-position assuming

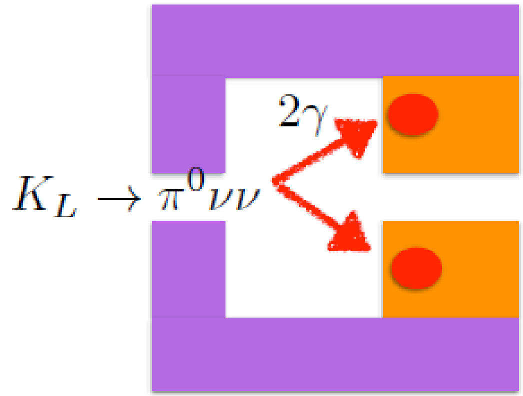
$$M_{\pi^0}^2 = M_{\gamma\gamma}^2 = 2E_1E_2(1 - \cos\theta_{\gamma\gamma})$$



CsI calorimeter upgrade

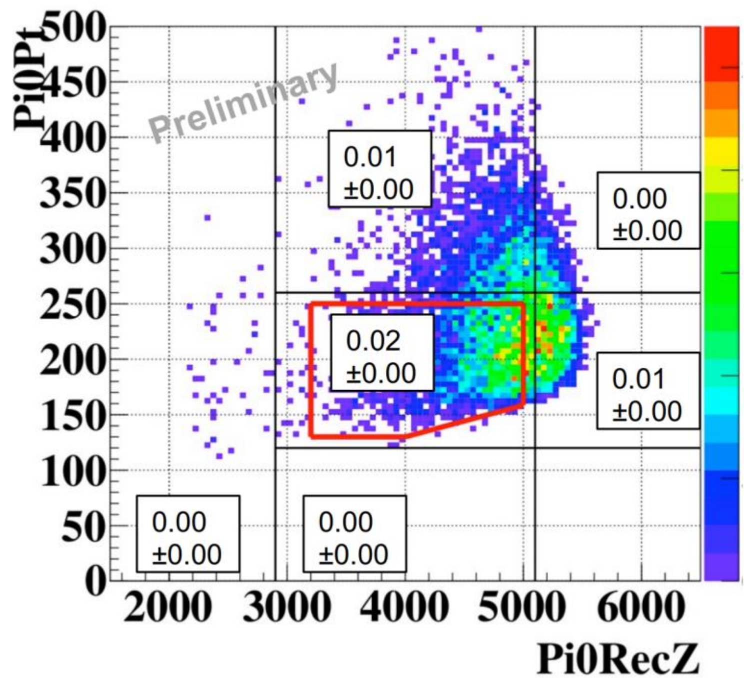
Neutron background





Run	SES	# of Hadron Cluster BG
2015	1.3×10^{-9}	0.24
2016-18	6.9×10^{-10}	0.02
	3×10^{-11} SM sensitivity	0.5

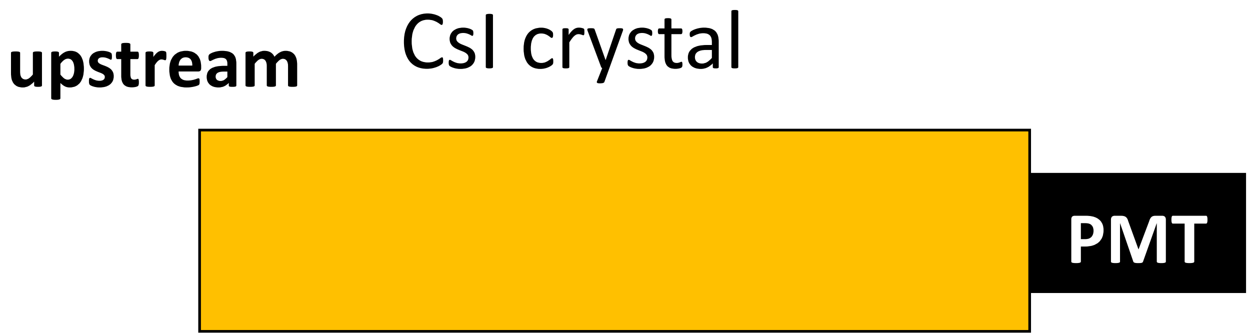
S.Shinohara Kaon2019



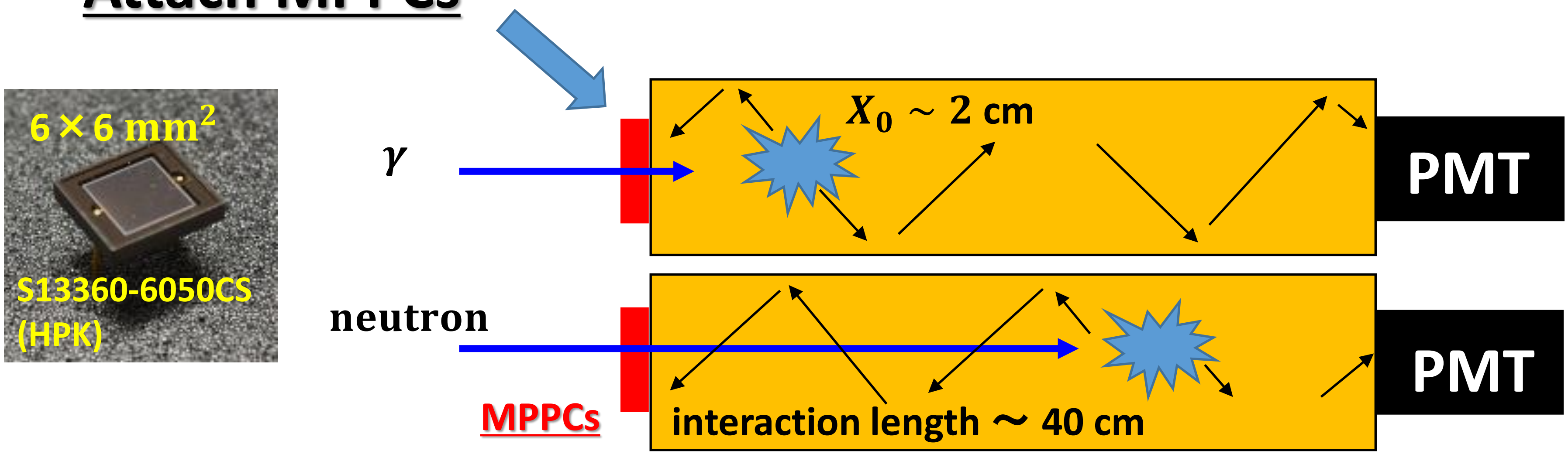
To achieve SM sensitivity, we need to suppress neutrons by a factor of ten

Idea of the CsI calorimeter upgrade

Previous



Attach MPPCs



Measure the depth with the time difference $\Delta T\equiv T_{MPPC}-T_{PMT}$

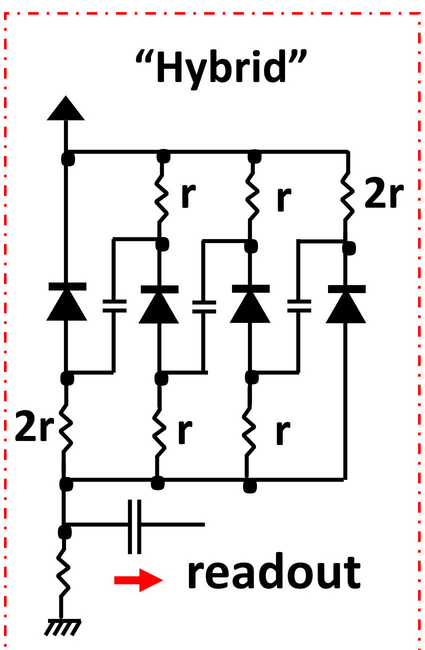
→ Small ΔT implies γ

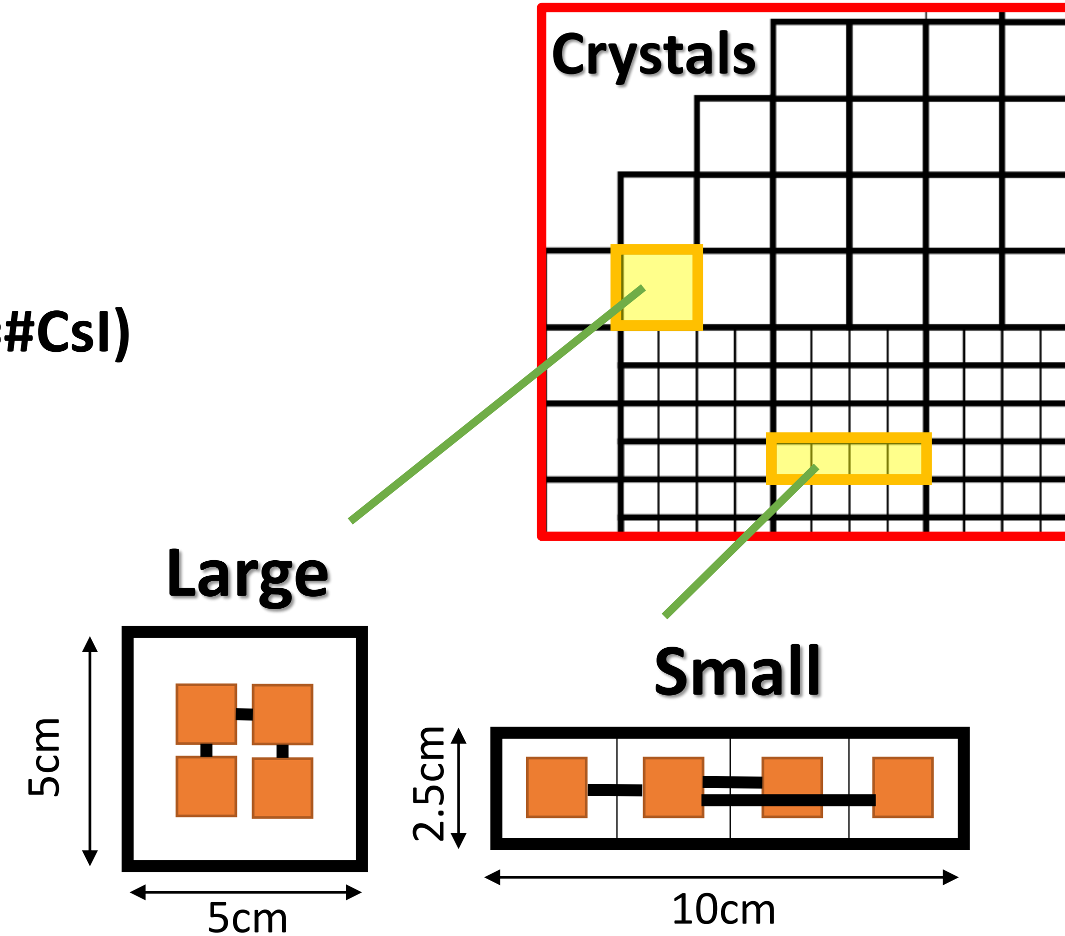
Bias circuit

- MPPC readout
  - # of MPPCs: **4080 (>#PMT=#CsI)**

To reduce # of channels..
<u>4 MPPCs</u> are connected

- Bias connection

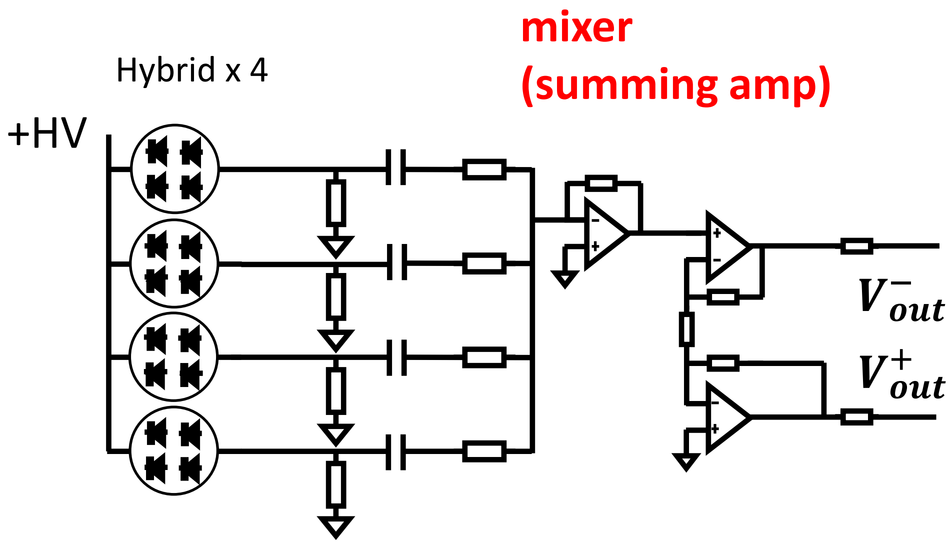


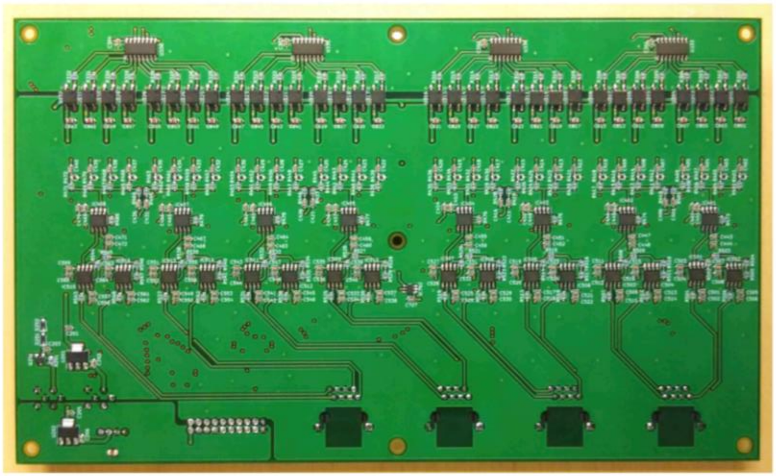


"Hybrid" bias connection

- adopted by MEG II upgrade
- AC line: series, to read out signals
- DC line: parallel, to apply bias voltage

Segmentation of readout





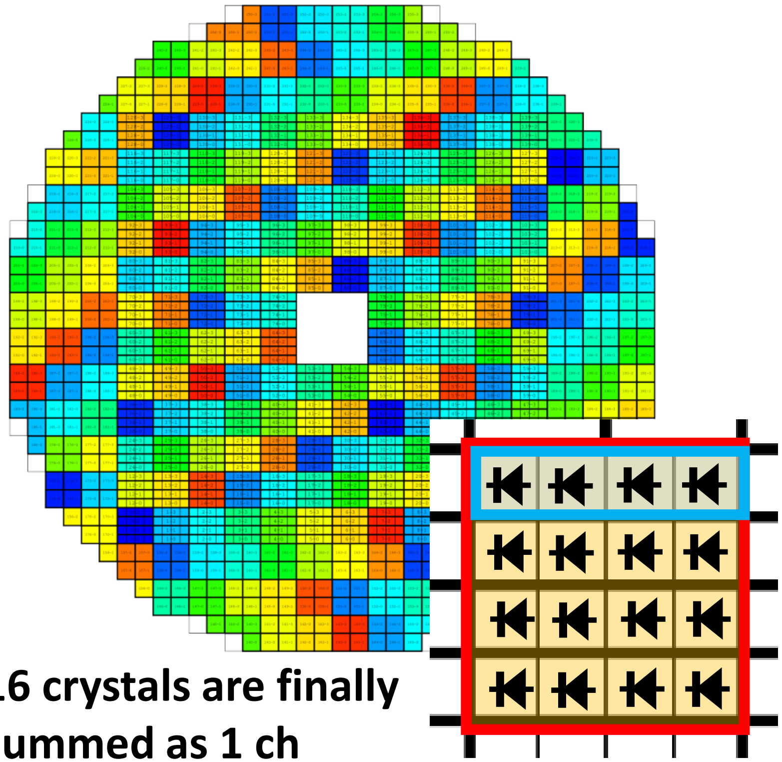
4080 MPPCs

Integrate 4 MPPCs at bias (hybrid)

1020

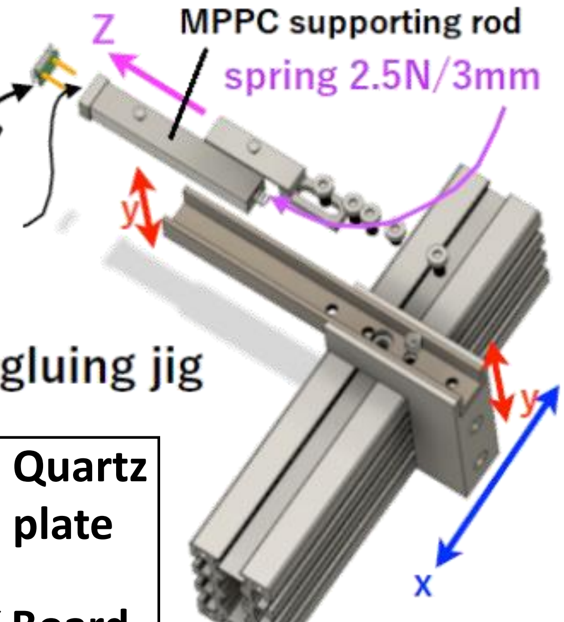
Sum 4 hybrids at amplifier

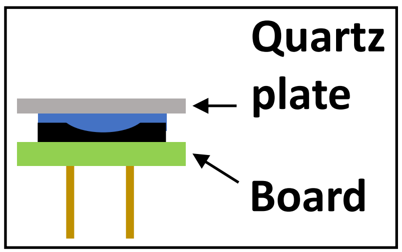
256 channels

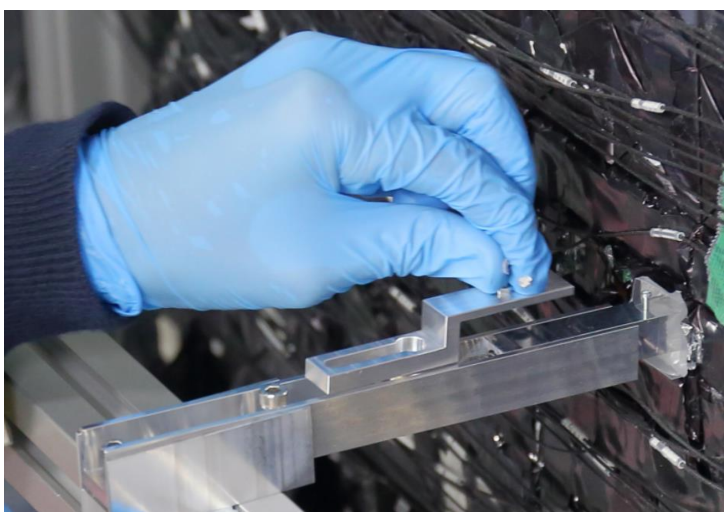


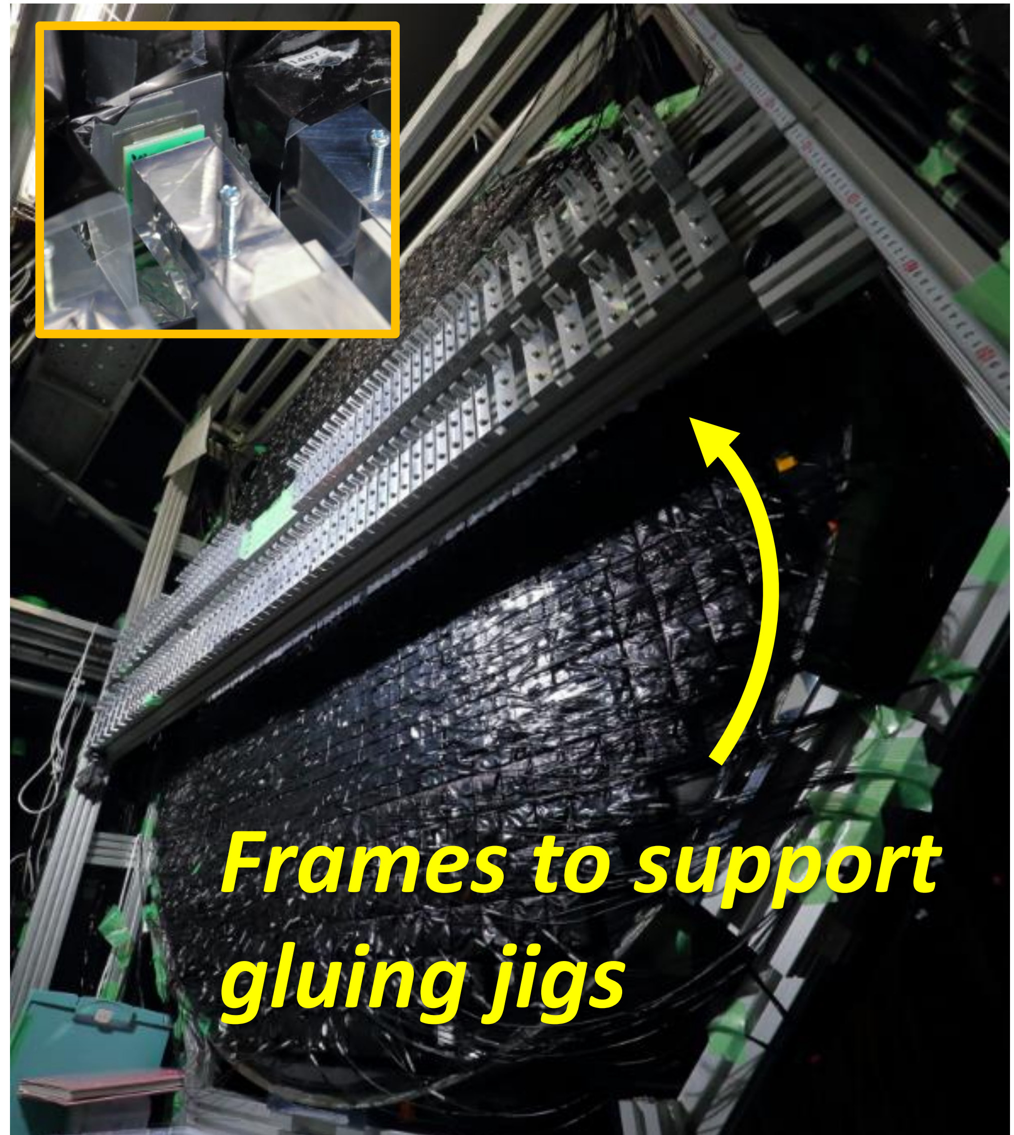
16 crystals are finally summed as 1 ch

MPPC installation (2018 autumn)



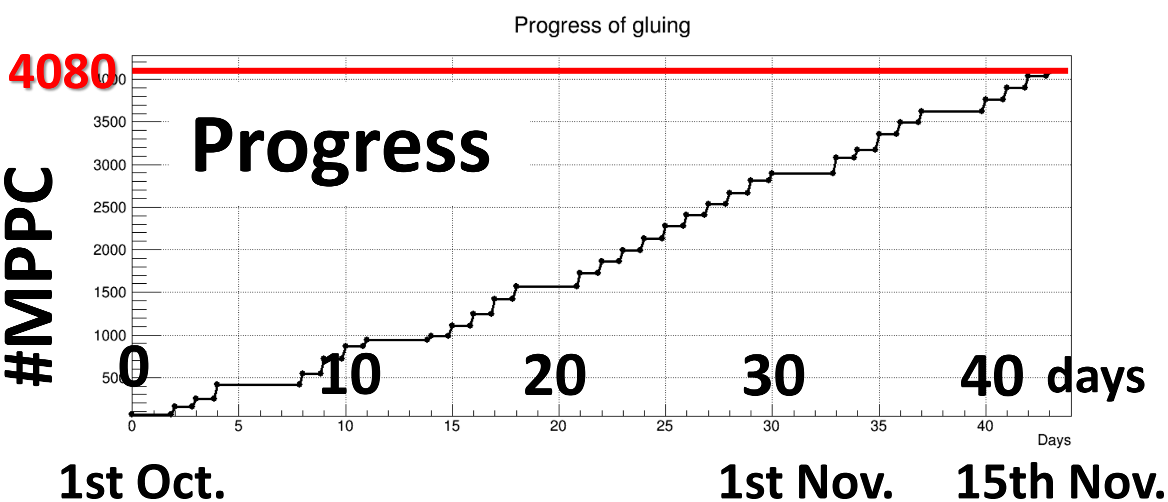






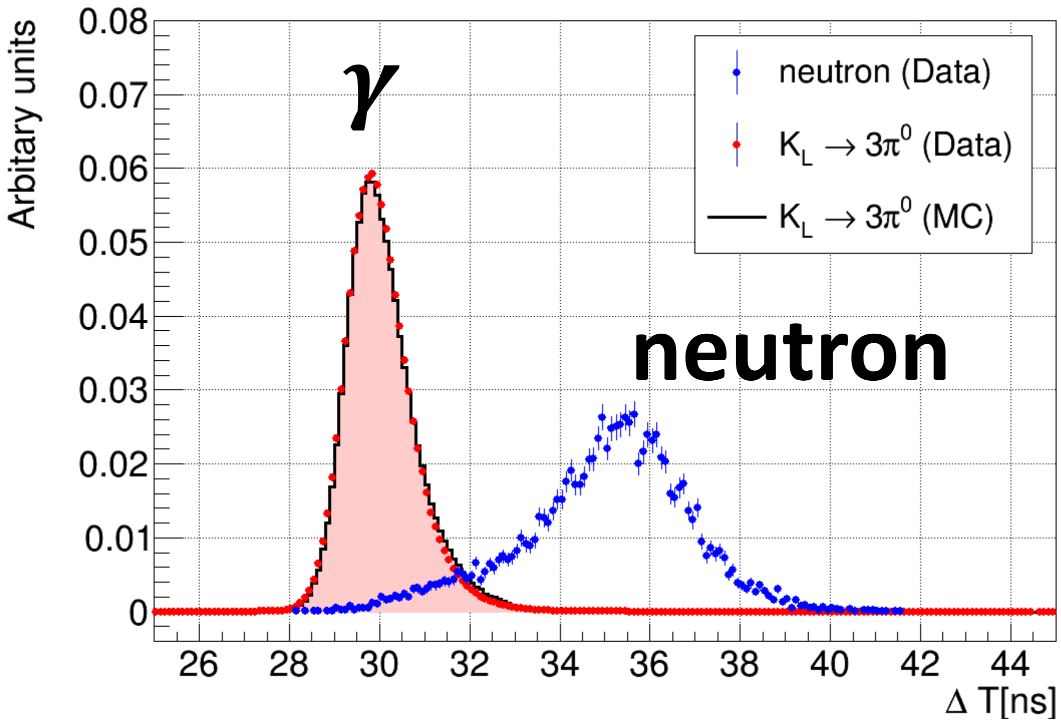
MPPC installation (2018 autumn)

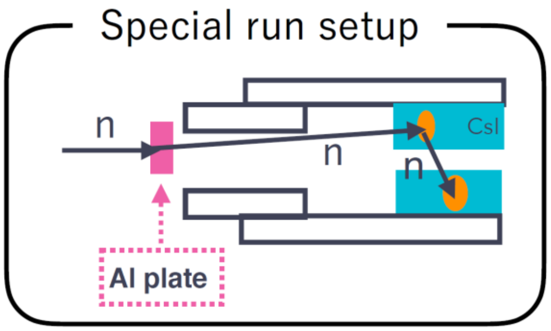
- ☐ Glue MPPCs on two rows in a day
- ☐ Spent 45 days to finish all
- ☐ Installation finished as scheduled



Time lapse movie

ΔT distribution of the control samples





$$\mathbf{max}\Delta T \equiv \max\{\Delta T_1, \Delta T_2\}$$

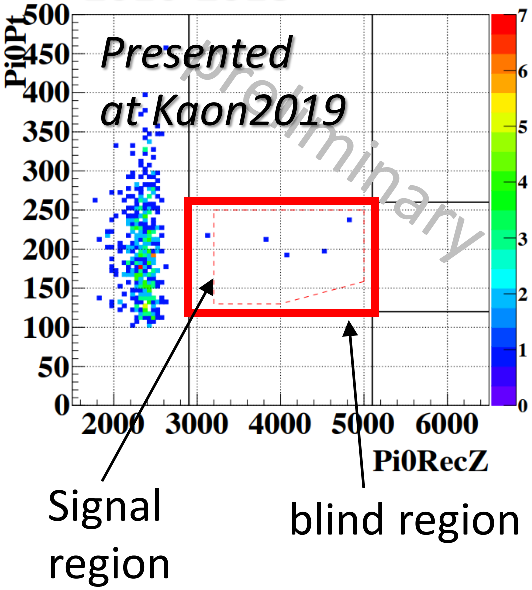
- ✓ Use the larger ΔT out of two clusters (**max**ΔT)
- ✓ $K_L \to 3\pi^0$ MC well reproduces the distribution of data

Retaining 90% of γ from $K_L \to \pi^0 \nu \bar{\nu}$ decay,
neutron contribution can be suppressed down to 1/60 !

Analysis of 2016-2018 data and charged kaon background

Post-unblind studies of 2016-2018 analysis

Data taken during 2016-2018



Expected # of BGs in the signal region

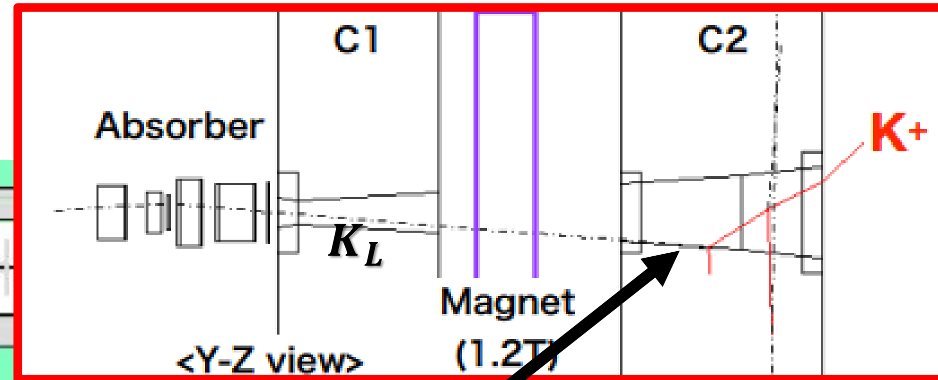
	source		#BG (90% C.L.)	#BG (68% C.L.)
U	KL	$K_L \to 2\pi^0$	<0.09	<0.05
		$K_L \to \pi^+\pi^-\pi^0$	<0.02	<0.01
U		$K_L \to 3\pi^0$ (overlapped pulse)	0.01±0.01	0.01±0.01
		Ke3 (overlapped pulse)	<0.09	<0.05
		$K_L \to 2\gamma$	0.001±0.001	0.001±0.001
N		Ke3 (π^0 production)	<0.04	<0.02
N		Ke3 (π^+ beta decay)	<0.01	<0.01
N		radiative Ke3	<0.046	<0.023
N		Ke4	<0.04	<0.02
N		$K_L \to ee\gamma$	<0.09	<0.05
N		$K_L \to \pi^+\pi^-$	<0.03	<0.02
N		$K_L \to 2\gamma$ (core-like)	<0.11	<0.06
N		$K_L \to 2\gamma$ (halo-K)	<0.19	<0.10

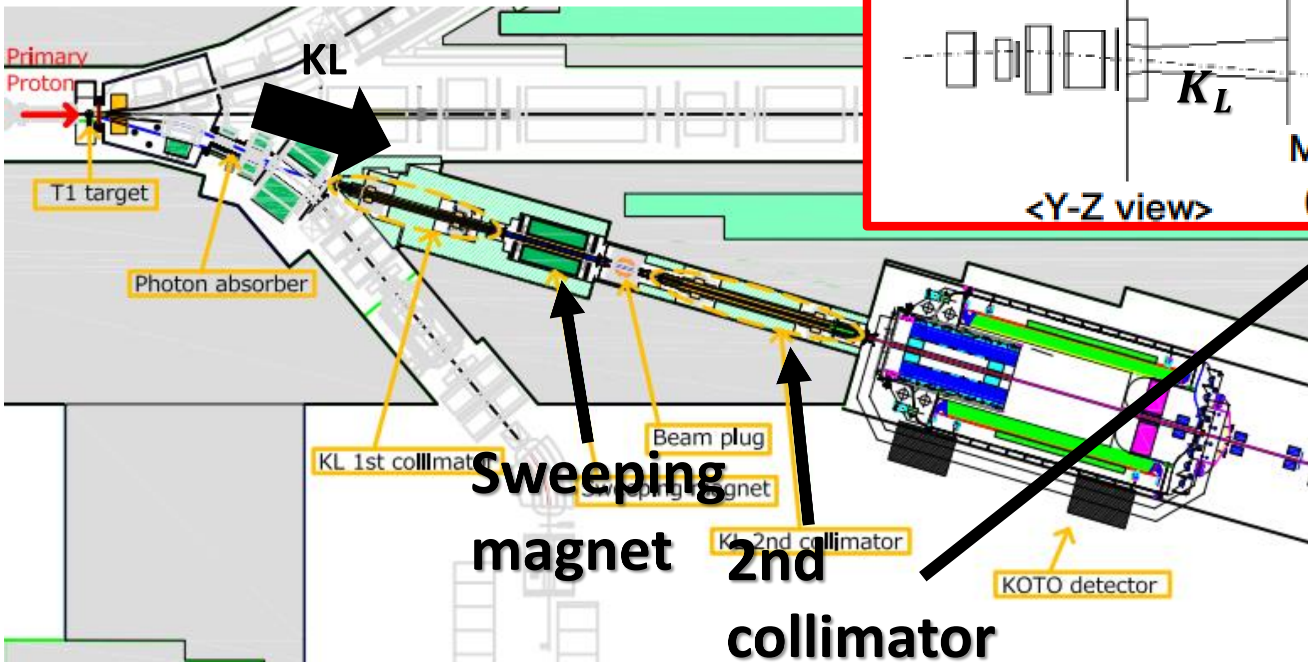
	source		#BG (90% C.L.)	#BG (68% C.L.)
N	K+/-	$K^\pm \to \pi^0\pi^\pm$	0.03±0.03	0.03±0.03
N		$K^\pm \to \pi^0 e^\pm \nu$	0.30±0.09	0.30±0.09
N		$K^\pm \to \pi^0 \mu^\pm \nu$	<0.07	<0.04
	Neutron	Upstream π^0	0.001±0.001	0.001±0.001
		Hadron cluster	0.02 ±0.00	0.02 ±0.00
		CV-pi0	<0.10	<0.05
		CV-eta	0.03±0.01	0.03±0.01
	Total	central value	0.39±0.10	0.39±0.10

U: Updated from Kaon2019
N: New

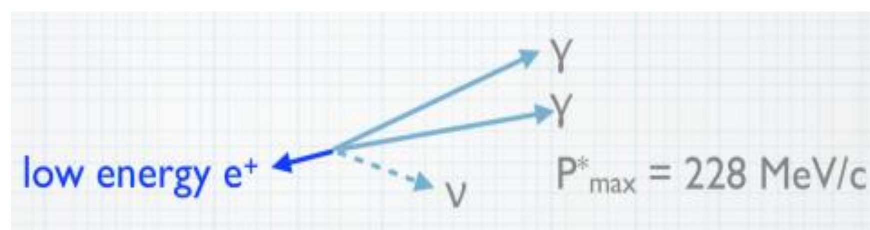
- Adopted blind analysis technique and opened the blind region (2019).
  - $\mathrm{SES} = \frac{1}{N_{K_L}\epsilon_{sig}} = 7.1 \times 10^{-10}$ or 0.04 SM events expected.
- We found four candidate events in the signal region and carefully checked our analysis.
  - New concern: K^+ background was not negligible, but **uncertain remained**.

Charged kaon?



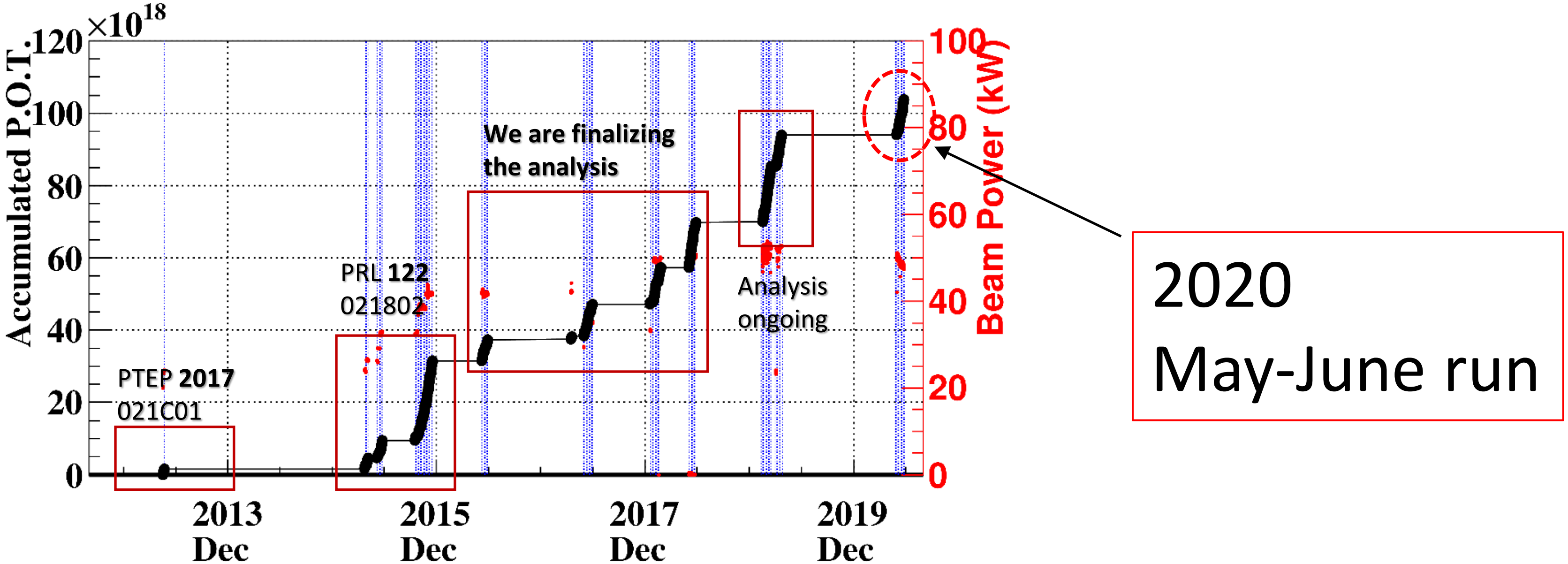


- K_L interacts with the inner wall of collimator and produces $K^{\pm}$
- Geant3-based beamline simulation predicts $K^{\pm}/K_L \sim 1.6 \times 10^{-6}$ at the entrance of the decay volume
- $K^{\pm} \rightarrow \pi^0 e^{\pm} \nu$ (BR=5%) can generate a π^0 with large P_t



\# of BG from $K^{\pm}$ decays
= $(0.33 \pm 0.09) \times$ **uncertainty of simulation**

Data collection to measure $K^{\pm}$ flux

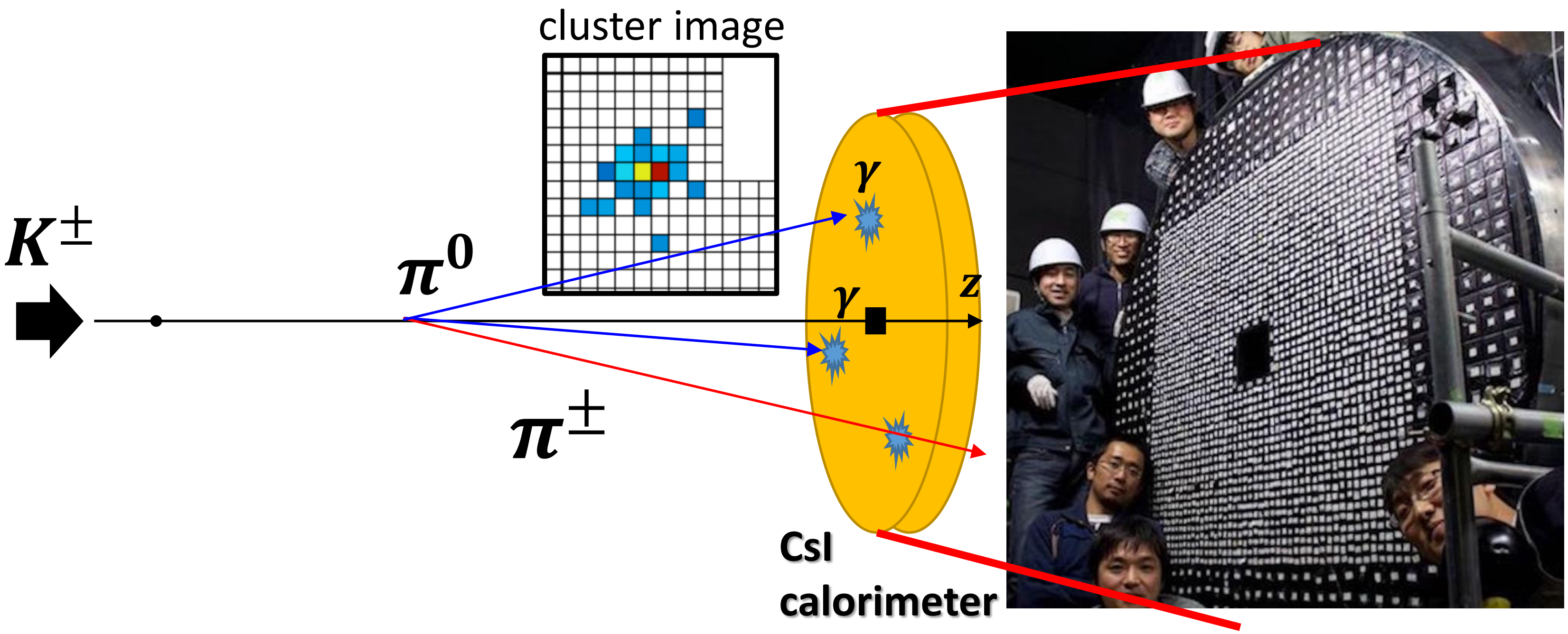


- 2020 May-June run
  → Measure $K^{\pm}$ flux with $K^{\pm} \to \pi^{+}\pi^{0}$ decay

  ✓ Develop a new trigger scheme
  ✓ Install a prototype charged veto counter in the upstream (UCV)
  ✓ Study selection criteria to purify $K^{\pm} \to \pi^{+}\pi^{0}$ events

We have successfully collected the data

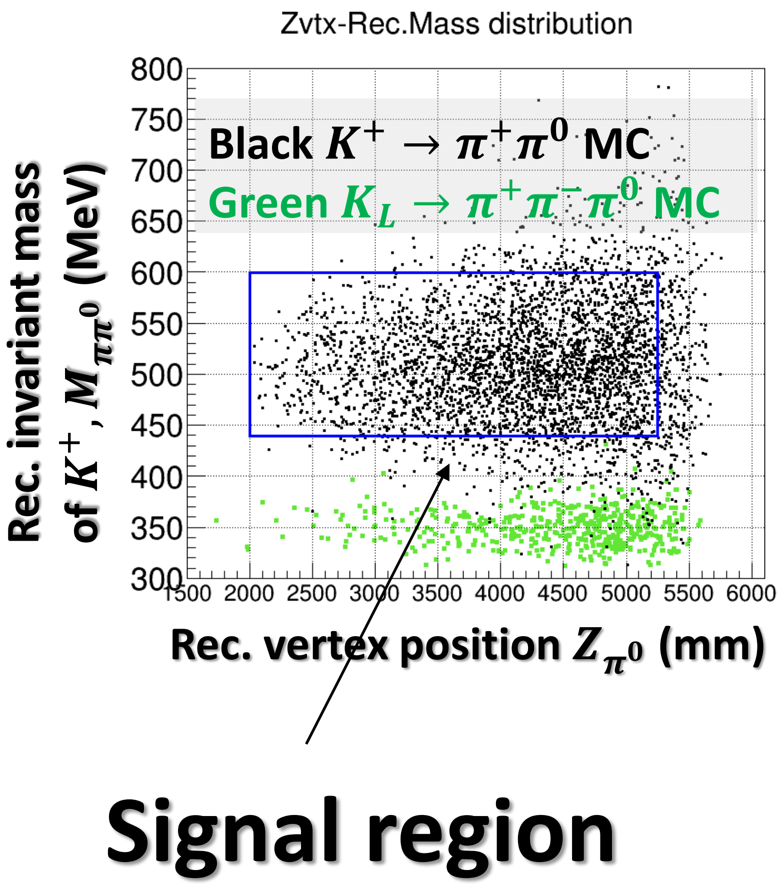
Measurement of $K^{\pm} \to \pi^{\pm}\pi^{0}$ decay



- Measure $K^{\pm} \to \pi^{\pm}\pi^{0}$ decay (BR=20%)
- Trigger three cluster events in the calorimeter
- Reconstruction
  - For two neutral hits, impose $M_{\gamma\gamma} = M_{\pi^0}$ → define $\boldsymbol{K}^{\pm}$ decay vertex
  - For a charged hit, from the hit position and assumption of Pt balance of $\pi^{\pm}$ and π^{0}
    → calculate the magnitude of the momentum
    → reconstruct four vectors of all the particles
  - Calculate $M_{\pi\pi^0}$

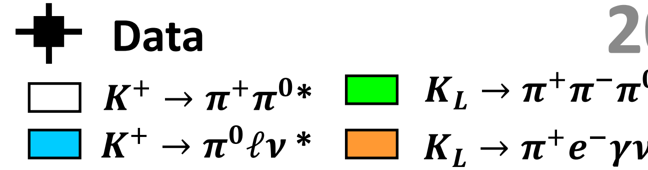
Event selection of $K^{\pm} \to \pi^{\pm}\pi^{0}$ decay

MC simulation

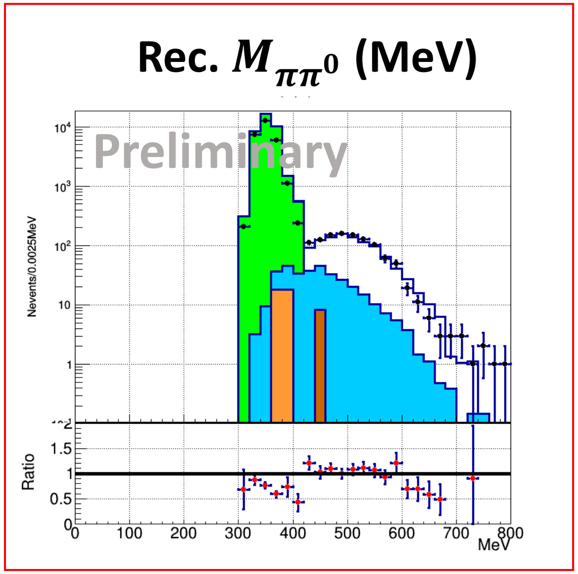


- Selection criteria
  - determined by the MC study
  - Sufficiently large acceptance $\epsilon \sim 4 \times 10^{-4}$
- Purity of $K^+ \to \pi^+\pi^0$ events
  - >> 90% by MC study
- Backgrounds
  - $K_L \to \pi^+\pi^-\pi^0$ (BR=13%) populates in low $M_{\pi\pi^0}$ region

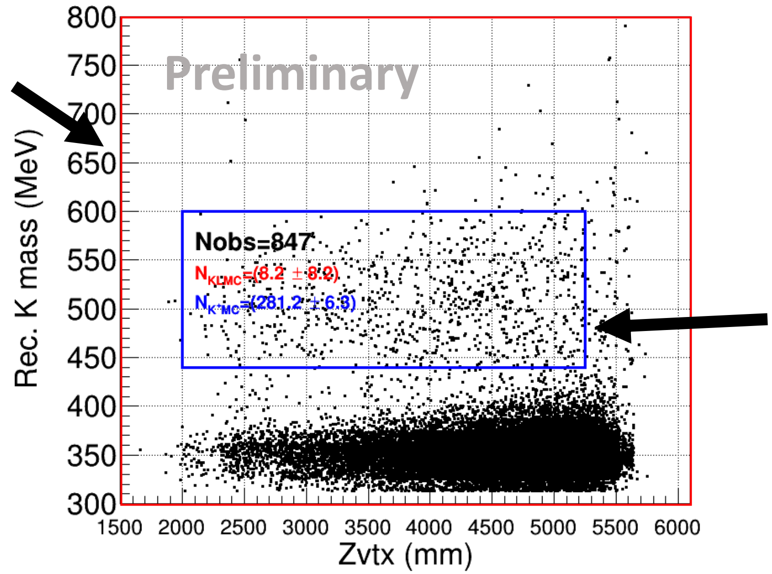
Measured $K^{\pm}$ flux



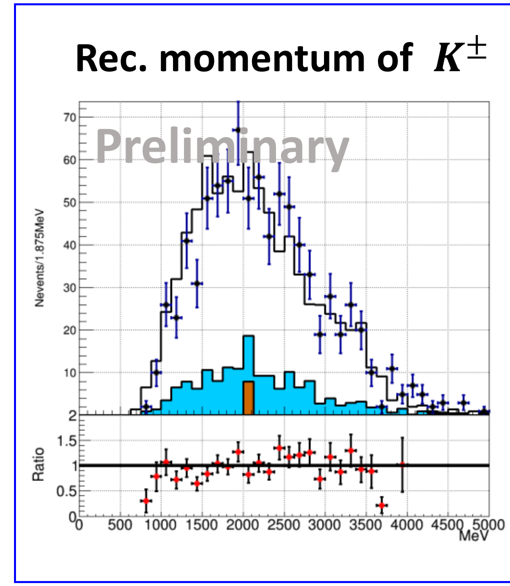
Projected mass distribution



Data in 2020 run



Distribution of events in the signal region



- The distribution of selected events are well reproduced by MC simulation of $K^{\pm}$ decays.
- $K^{\pm}$ flux ratio:

$$\mathcal{R}_{K^{\pm}} = F_{K^{\pm}}/F_{K_L}$$

Comparison between simulation
→ $\mathcal{R}^{meas.}_{K^{\pm}}/\mathcal{R}^{MC}_{K^{\pm}} = 3.0 \pm 0.1$

Measured $K^{\pm}$ flux is 3 times larger than MC.

* K^+ distribution is scaled by best fit

2016-2018 analysis BG table (updated, preliminary)

Preliminary

source		#BG (90% C.L.)	#BG (68% C.L.)
KL	$K_L \to 2\pi^0$	<0.09	<0.05
	$K_L \to \pi^+\pi^-\pi^0$	<0.02	<0.01
	$K_L \to 3\pi^0$ (overlapped pulse)	0.01±0.01	0.01±0.01
	Ke3 (overlapped pulse)	<0.09	<0.05
	$K_L \to 2\gamma$	0.001±0.001	0.001±0.001
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	$K_L \to ee\gamma$	<0.09	<0.05
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	$K_L \to 2\gamma$ (core-like)	<0.11	<0.06
	$K_L \to 2\gamma$ (halo-K)	<0.19	<0.10

source		#BG (90% C.L.)	#BG (68% C.L.)	
K+/-	$K^\pm \to \pi^0\pi^\pm$	0.09±0.09	0.09±0.09	New
	$K^\pm \to \pi^0 e^\pm \nu$	0.90±0.27	0.90±0.27	New
	$K^\pm \to \pi^0 \mu^\pm \nu$	<0.21	<0.12	
Neutron	Upstream π^0	0.001±0.001	0.001±0.001	
	Hadron cluster	0.02 ±0.00	0.02 ±0.00	
	CV-pi0	<0.10	<0.05	
	CV-eta	0.03±0.01	0.03±0.01	
Total	central value	1.05±0.28	1.05±0.28	New

\# from $K^\pm$ decays
= (0.33±0.08) × **uncertainties of simulation**

Prediction by MC simulation

Uncertainty of flux → x 3.0

- BG table was updated based on the result of the $K^\pm$ flux.
- Preliminary total BG estimation → 1.1 ± 0.3

→ The BG level is not negligible

2016-2018 analysis BG table (updated, preliminary)

Preliminary

source		#BG (90% C.L.)	#BG (68% C.L.)
KL	$K_L \to 2\pi^0$	<0.09	<0.05
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	$K^\pm \to \pi^0 e^\pm \nu$	0.90±0.27	0.90±0.27	New
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Neutron	Upstream π^0	0.001±0.001	0.001±0.001	
	Hadron cluster	0.02 ±0.00	0.02 ±0.00	
	CV-pi0	<0.10	<0.05	

After wrapping up our post-unblinded study, we plan to submit a paper in this autumn.

ion

- BG table was updated based on the result of the $K^\pm$ flux.
- Preliminary total BG estimation → 1.1 ± 0.3

→ **The BG level is not negligible**

Search for $\boldsymbol{K_L \to \pi^0 \gamma}$ decay

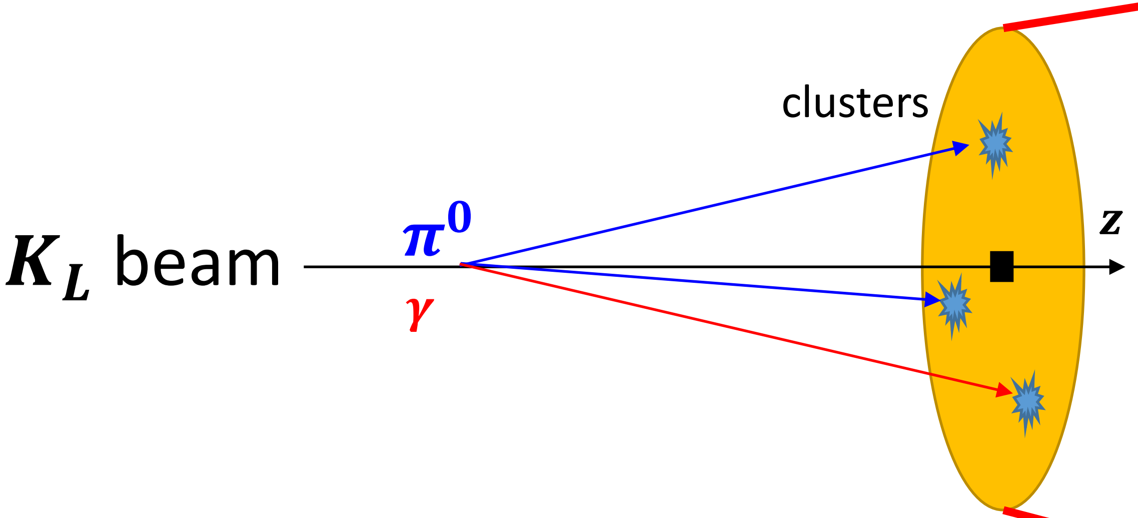
$K_L \to \pi^0\gamma$ decay?

- No measurements so far
  - ✔ $s \to d\gamma$ transition, forbidden by FCNC

- Violates an angular conservation
  - the spin of γ must be "compensated" by an orbital angular momentum, but back-to-back configuration cannot produce L_z
  - IF v > "speed of light", it's allowed. (see PRD **59** 116008)

Oppositely to say,
good test of the Lorentz invariance
in the realm of short distances

Reconstruction of $K_L \to \pi^0\gamma$



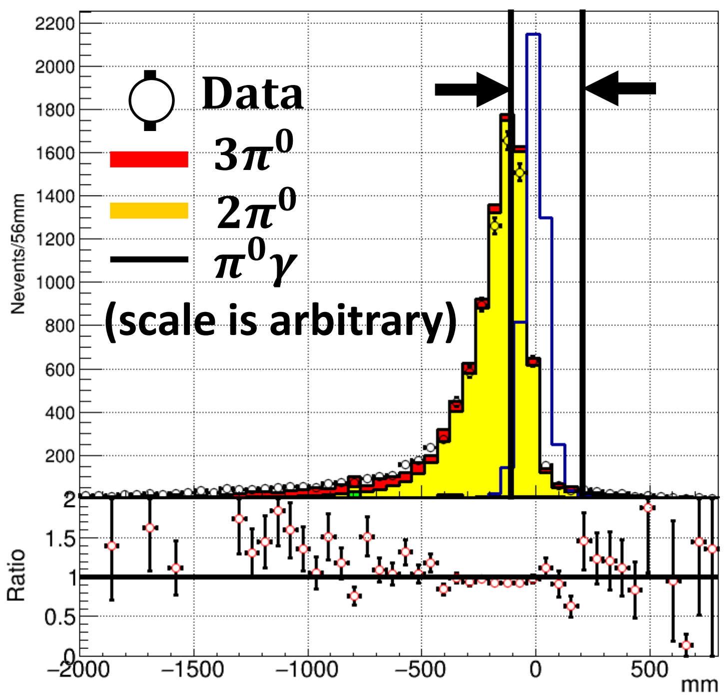
1. Find events which have exactly 3 clusters
2. Reconstruct a π^0 : $m_{\pi^0}^2 = 2E_1E_2(1-\cos\theta_{\gamma\gamma}) \rightarrow z_{vtx}^{\pi^0}$
3. Reconstruct a K_L: $m_{K_L}^2 = (p_{\gamma_1}+p_{\gamma_2}+p_{\gamma_3})^2 \rightarrow z_{vtx}^{K_L}$

   Two types of vertex position, which should be close.
4. Define $\Delta z_{vtx} = z_{vtx}^{\pi^0} - z_{vtx}^{K_L}$ to suppress various BGs

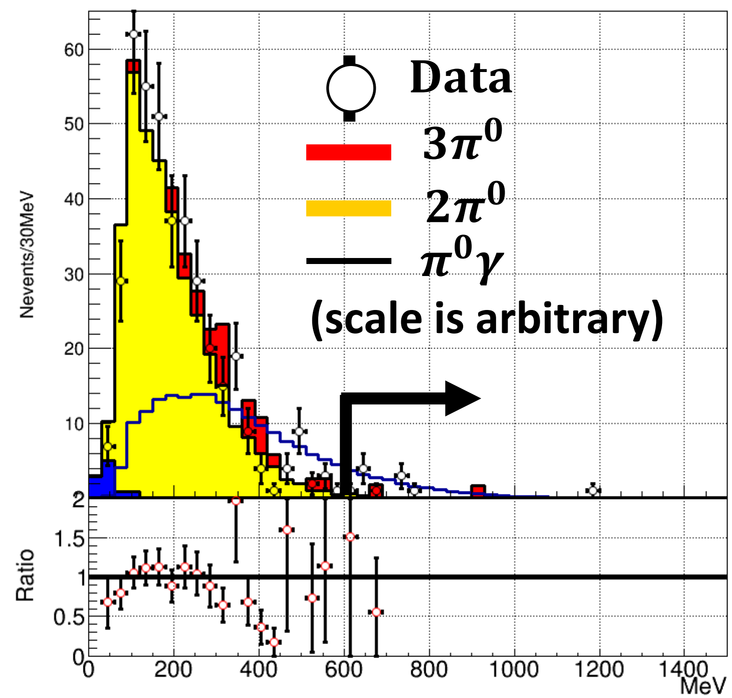
Event selection of $K_L \rightarrow \pi^0\gamma$

Analyzed data collected between 2016-2018 runs

Δz_{vtx}



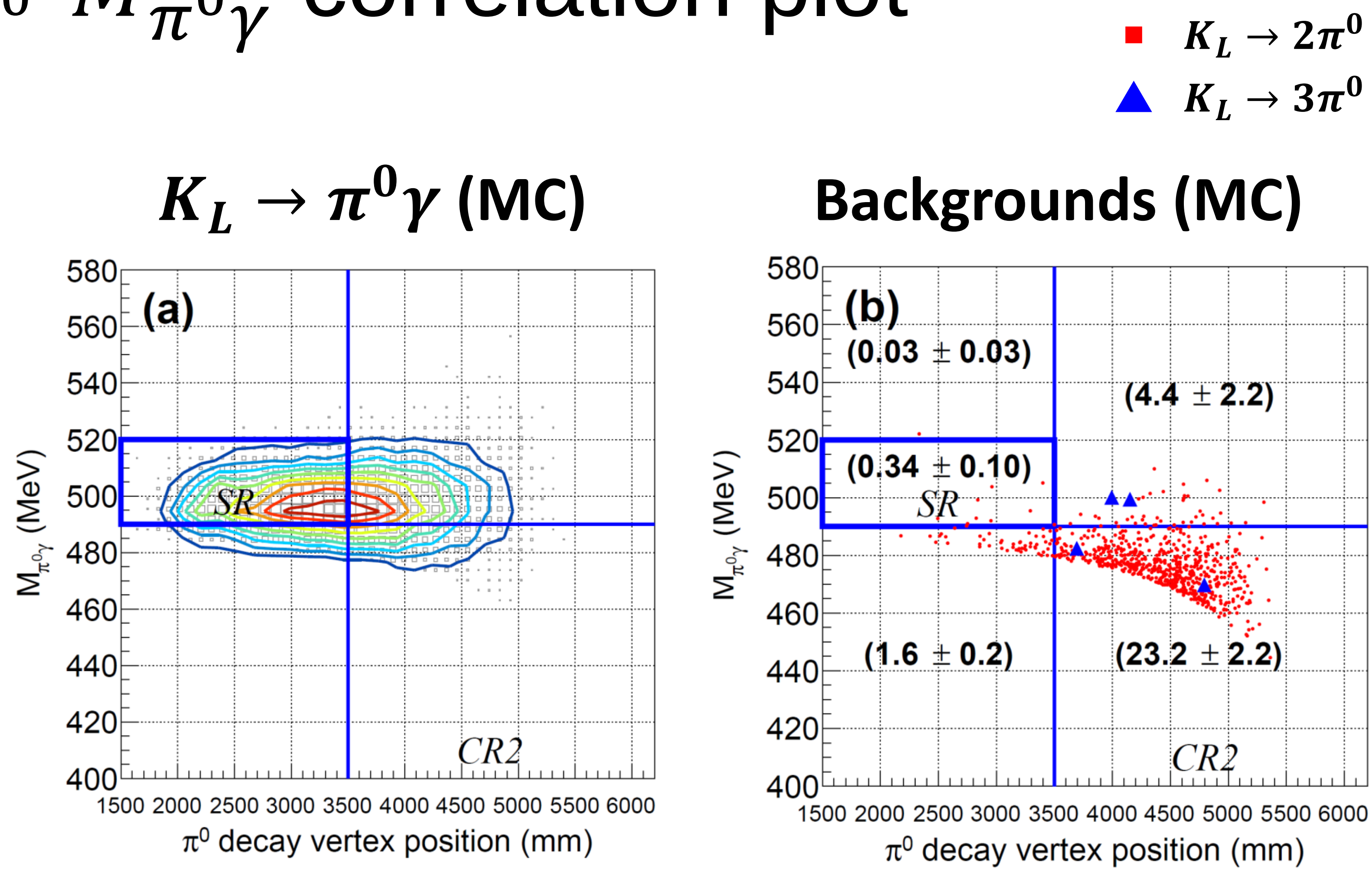
E^{γ}_{min}



The dominant background: $K_L \rightarrow\ 2\pi^0$

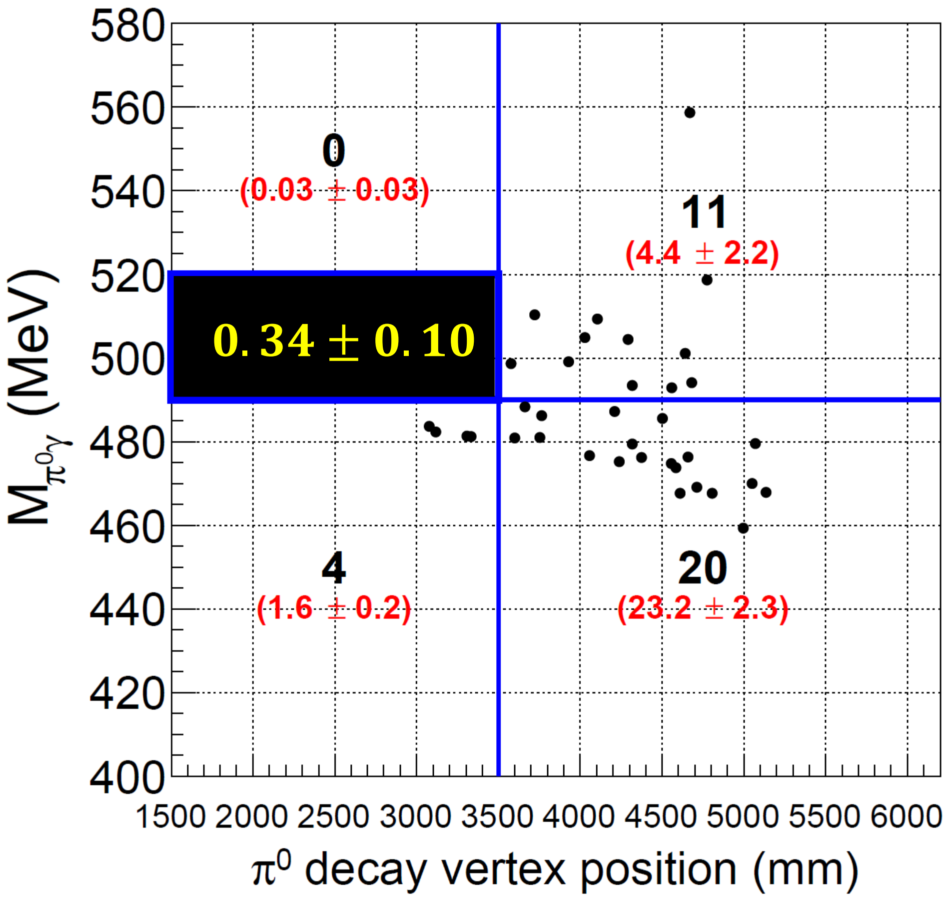
Δz_{vtx} and E^{γ}_{min} cuts suppress the contribution

Z_{π^0}-$M_{\pi^0\gamma}$ correlation plot



The signal region (SR) is defined in ($z_{vtx}^{\pi^0}, M_{\pi^0\gamma}$) plane and masked the signal region before opening the box.

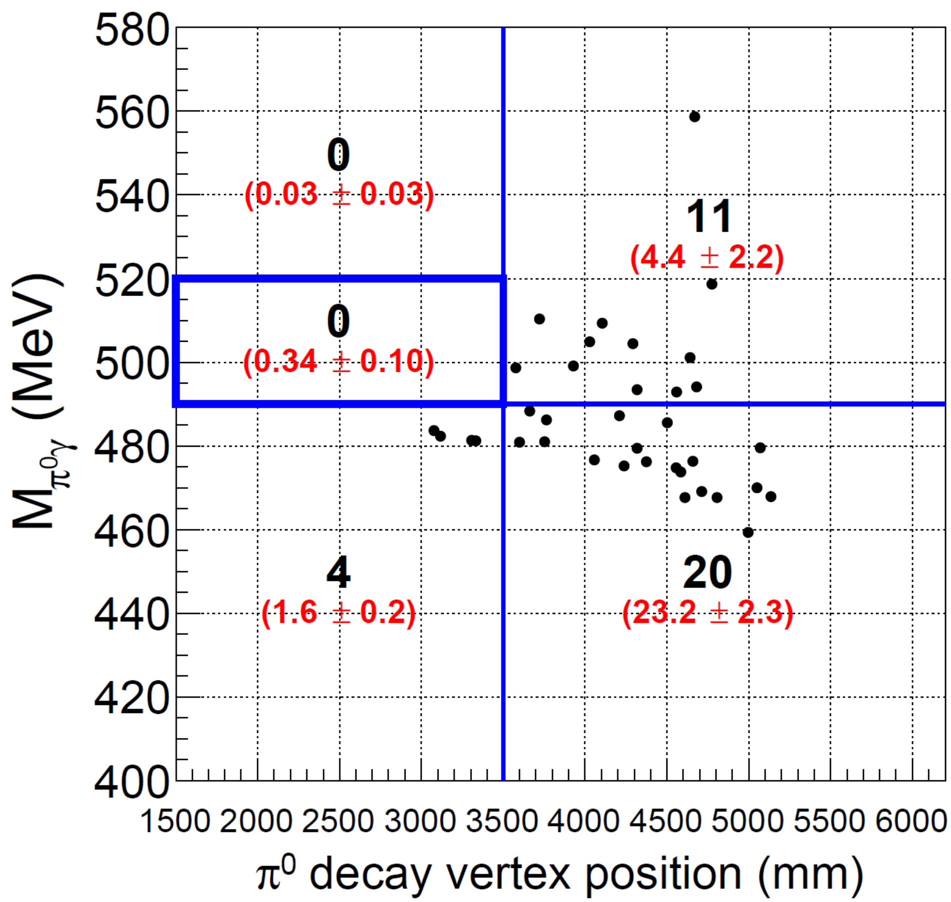
Open signal box



Single event sensitivity of signal:

$$\frac{1}{N_{K_L}\epsilon(K_L \to \pi^0\gamma)} = \left(7.1 \pm 0.3_{\mathrm{stat}} \pm 1.6_{syst}\right) \times 10^{-8}$$

Open signal box



$\mathcal{B}(K_L \to \pi^0\gamma) < 1.7 \times 10^{-7}$ at 90% C.L.

Paper is now under the referee process

Summary

- KOTO searches for New Physics
  via very rare ($BR = 3 \times 10^{-11}$) decay $K_L \to \pi^0 \nu \bar{\nu}$

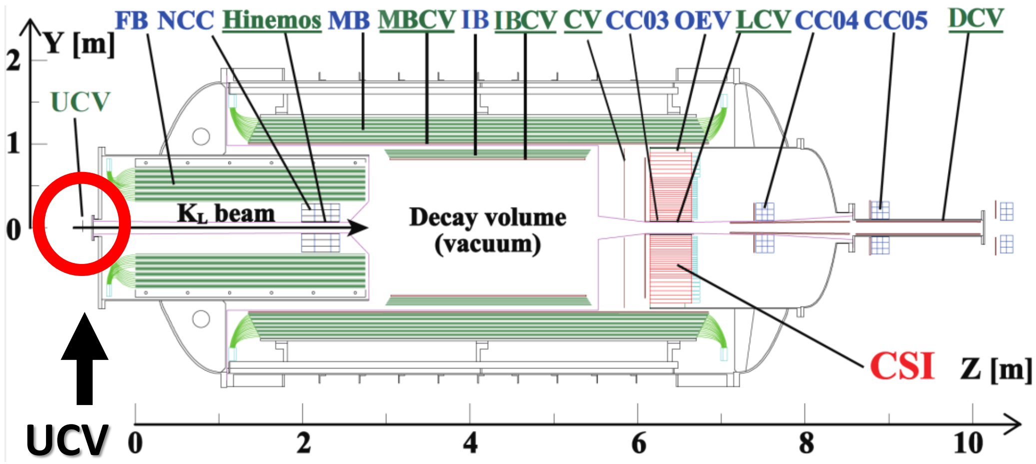
- To reduce neutron background,
  we attached >4000 MPPCs on the front surface of CsI crystal and succeeded to reduce the background by 60.

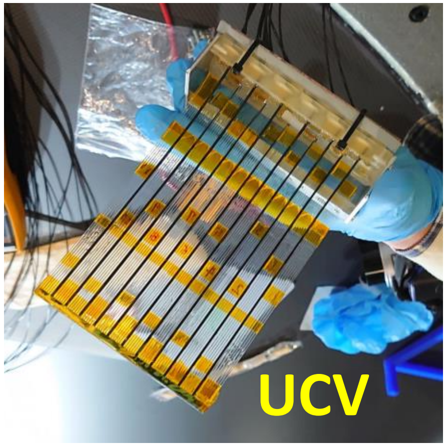
- By opening the signal region of 2016-2018 data, we found 4 candidate events.
  - After the post-unblind study, we found charged kaon incident had non-negligible contribution.
  - Using 2020 data, we measured K^+ flux to be 3 times larger than simulation

- Forbidden decay $\boldsymbol{K_L \to \pi^0 \gamma}$ was searched for using 2016-2018 data.
  We found no candidate events in the signal region and set the first upper limit $BR < 1.7 \times 10^{-7}$ at 90% C.L

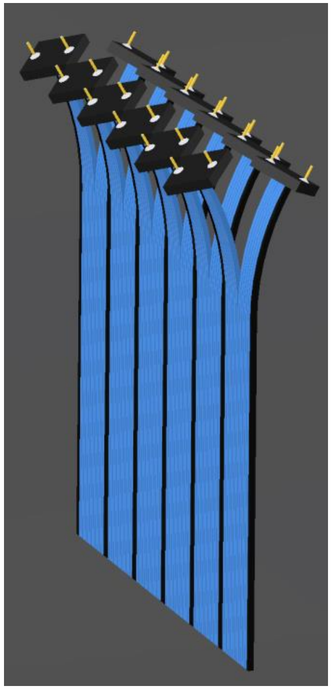
That's all

To veto $K^{\pm}$ (upstream charged veto, UCV)

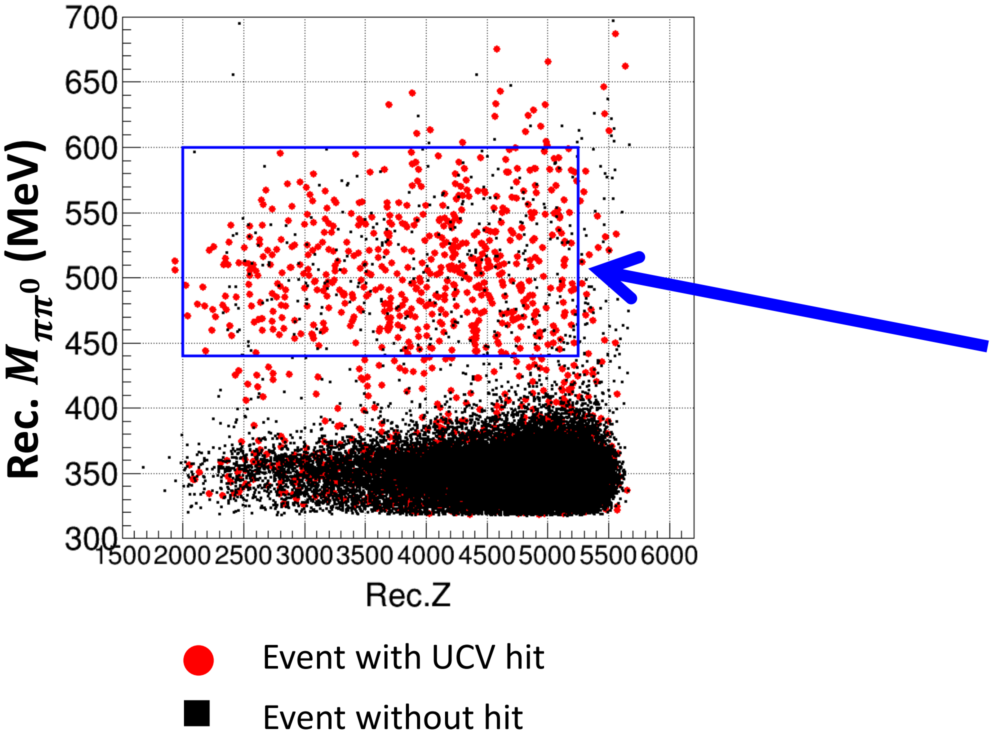




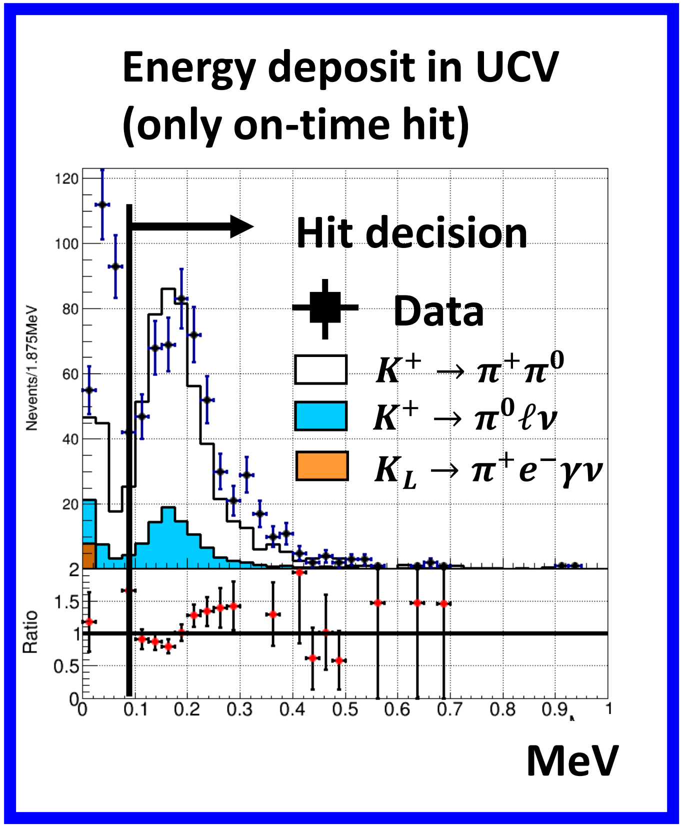
- A new detector installed before 2020 May-June run
- Purpose
  - To confirm the existence of $K^{\pm}$
  - **To veto $K^{\pm}$**
- Basic design
  - 1-mm-thick plastic scintillation plate (composed of 1mm☐ plastic scintillation fibers)
  - Use 6mm☐ MPPCs (Si-photo sensor) to detect scintillation photons



Veto functionality of the prototype UCV



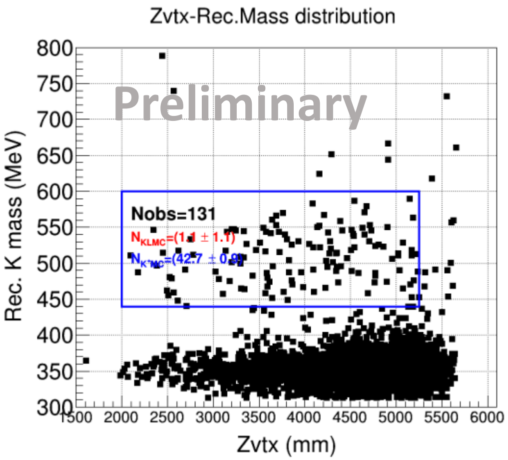
Distribution in the signal region



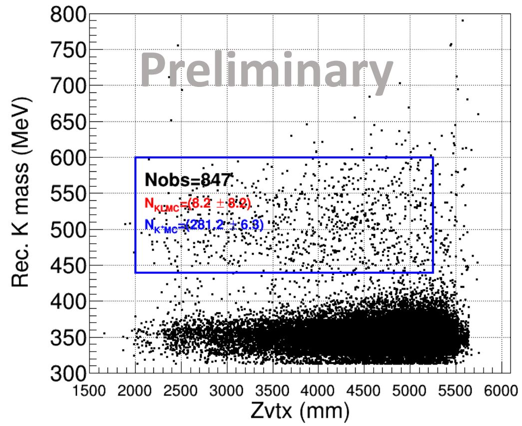
- The selected events have on-time and MIP like energy deposit in UCV.
- 30% inefficiency exists but can be explained by
  ① limited coverage of K^+ halo
  ② limited sensitive region of scintillation fiber
  ③ noise fluctuation

$K^{\pm}$ production at UCV

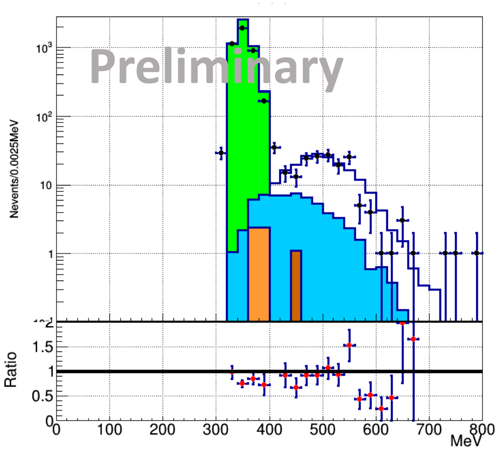
w/o UCV



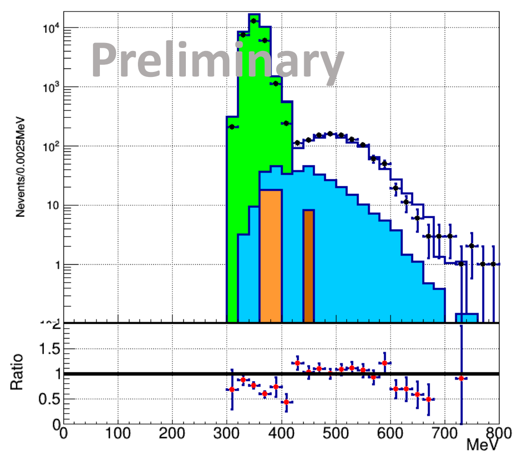
w/ UCV



Rec. $M_{\pi\pi^0}$ (MeV)



Rec. $M_{\pi\pi^0}$ (MeV)



$\mathcal{R}_{K^{\pm}} = F_{K^{\pm}}/F_{K_L}$ was measured with and without inserting UCV in beam.

◆ To confirm whether UCV produces $K^{\pm}$.

$$\mathcal{R}_{K^+}^{Meas.}/\mathcal{R}_{K^+}^{\mathrm{MC}} = 3.0 \pm 0.1 \ \text{w/UCV}$$
$$= 3.0 \pm 0.3 \ \text{w/o UCV}$$

✓ We did not observe $R_{K^{\pm}}$ difference between w/UCV and w/o UCV.

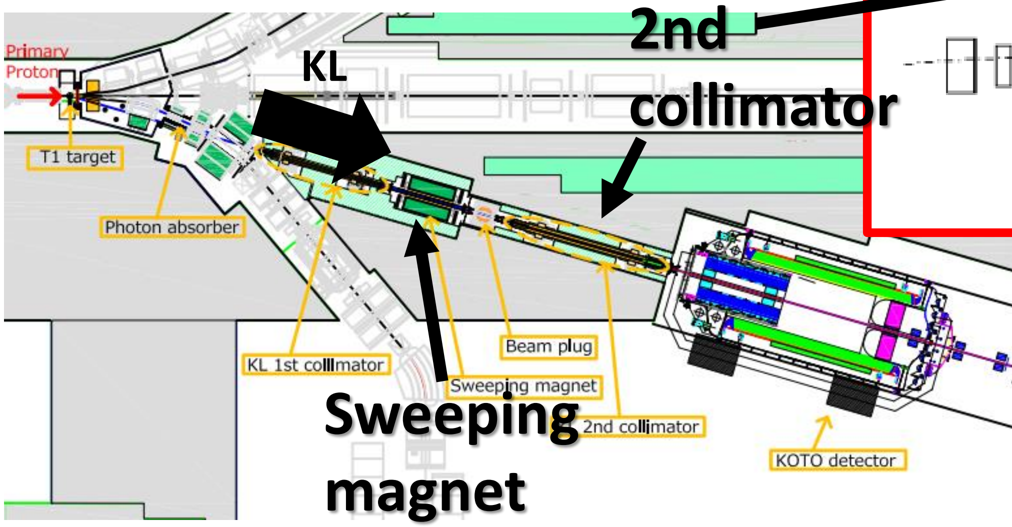
→ Level of UCV-induced $K^{\pm}$ was not significant compared to beamline originated $K^{\pm}$.

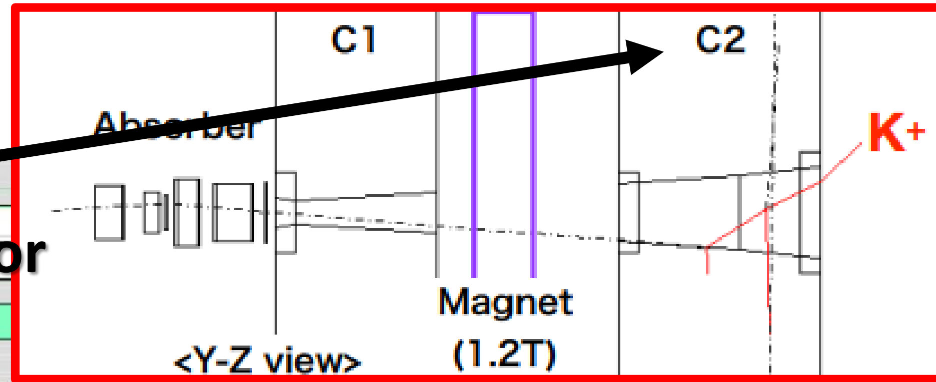
Data

$K^+ \to \pi^+\pi^0$ | $K_L \to \pi^+\pi^-\pi^0$

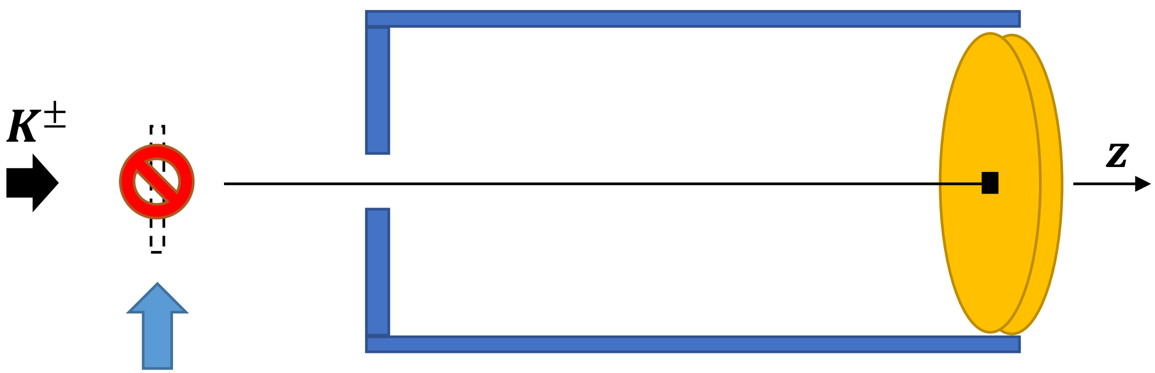
$K^+ \to \pi^0\ell\nu$ | $K_L \to \pi^+e^-\gamma\nu$

Charged kaon BG





- K_L interacts inner wall of the 2nd collimator and produces $K^{\pm}$
- Currently, the dominant contribution comes from $K^{\pm}$ decays



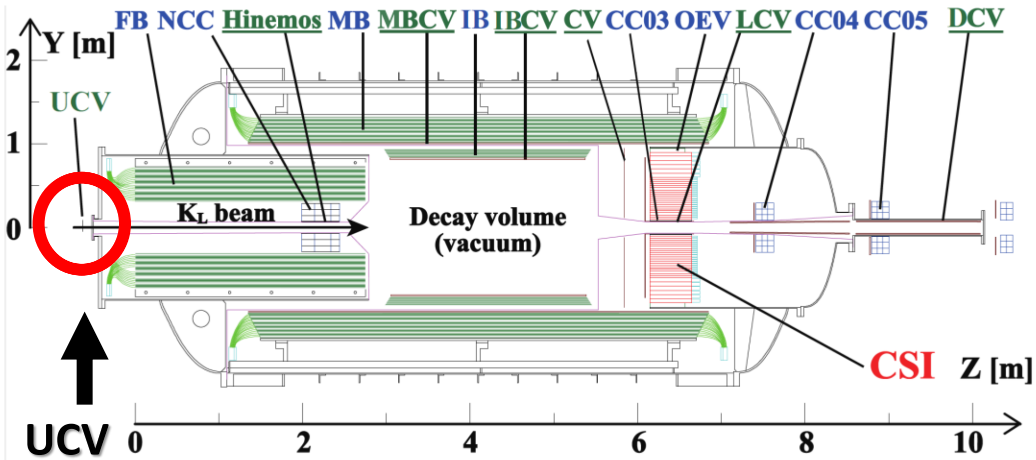
We need to block the incident of $K^{\pm}$ in front of KOTO detector

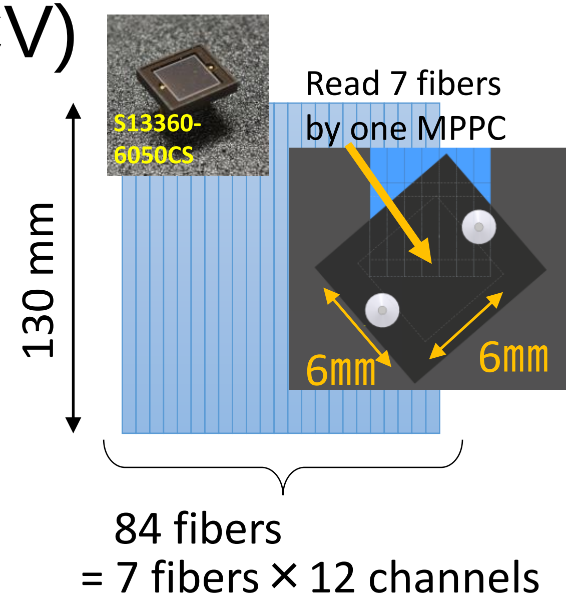
Summary of inefficiency

Source	Estimated inef. of prototype (%)	Possible goal with fiber option (%)	Possible goal with plate option (%)
Limited coverage	8	0	0
Gap and insensitive region	7	0.3	0
Noise and photo-statistics	11	(3.5+2)%	>5%
Low light yield of black fiber	2	—	—
Inactive interaction	0.5%	0.5%	Not yet considered
Masking	Included in noise	Negligible	Need to consider
Total	28	6%	

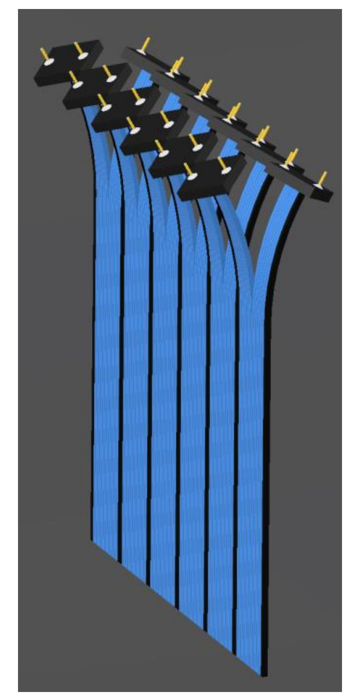
For the estimation of each category, please see backup

Prototype upstream charged veto (UCV)

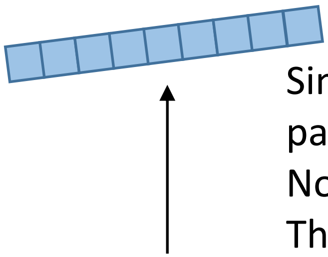




- A new detector installed Dec. 2019.
- Purpose
  - To confirm the existence of K^+
  - **To veto K^+**
- Basic design
  - 1-mm-thick plastic scintillation plate (composed of 1mm□ plastic scintillation fibers)
  - Use 6mm□ MPPCs to detect scintillation photons
  - A unique front-end readout to accept high hit rates and the severe irradiation environment†



Study of the tilting angle



Simulate interaction of the charged particles, generated based on Nomura-san's beamline simulation. The particles were required to enter NCC hole.

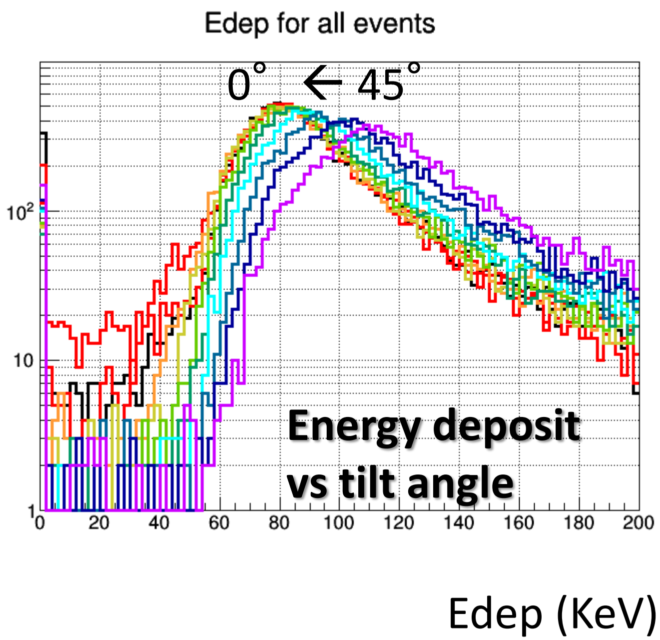
Configuration and hit definition

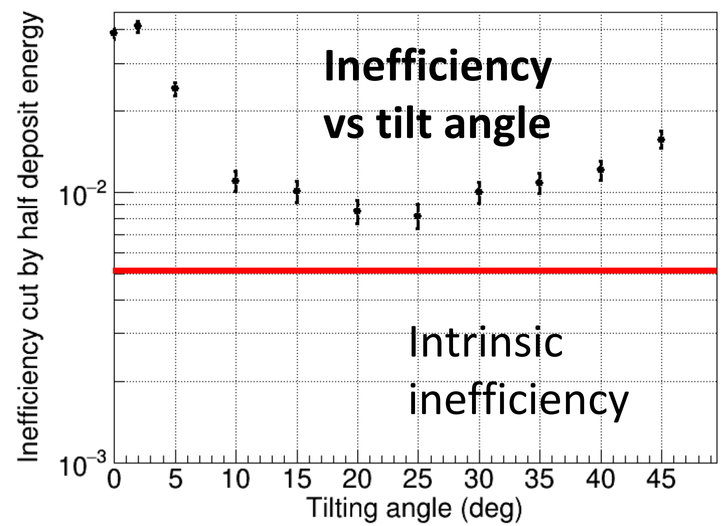
0.5-mm-thick fibers

Gap due to cladding is 4%.

Plate is rotated around y axis by θ (0, 2, 5, …,45 degrees).

Hits defined by Edep > 40 KeV/cosθ

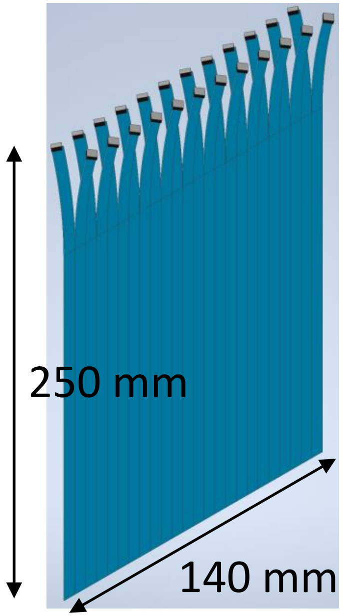




- (As is expected) the mean energy deposit increases as tilting angle increases.
- If plate is rotated by ~20 degrees, the inefficiency is reduced from 3.5% → 0.3%

→ Design target is > 20 degrees

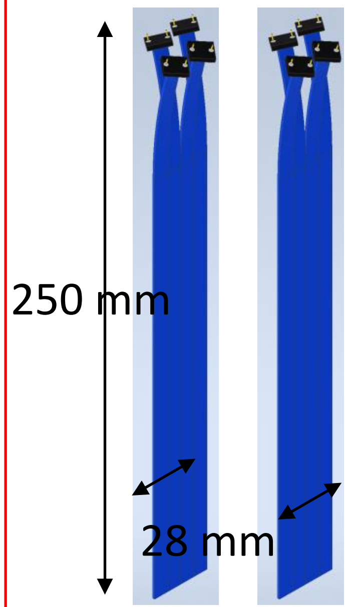
Mechanics (UCV design)



Core UCV
0.5-mm-thick fiber
3mm MPPC × **20**

14 fibers are read by a MPPC
→ 7mm x 20 = 140 mm

20 MPPCs are separately amplified



Halo catcher (two modules)
1-mm-thick fiber
6mm MPPC × **8**

7 fibers are read by a MPPC
→ 7mm x 14 = 28 mm
(per module)

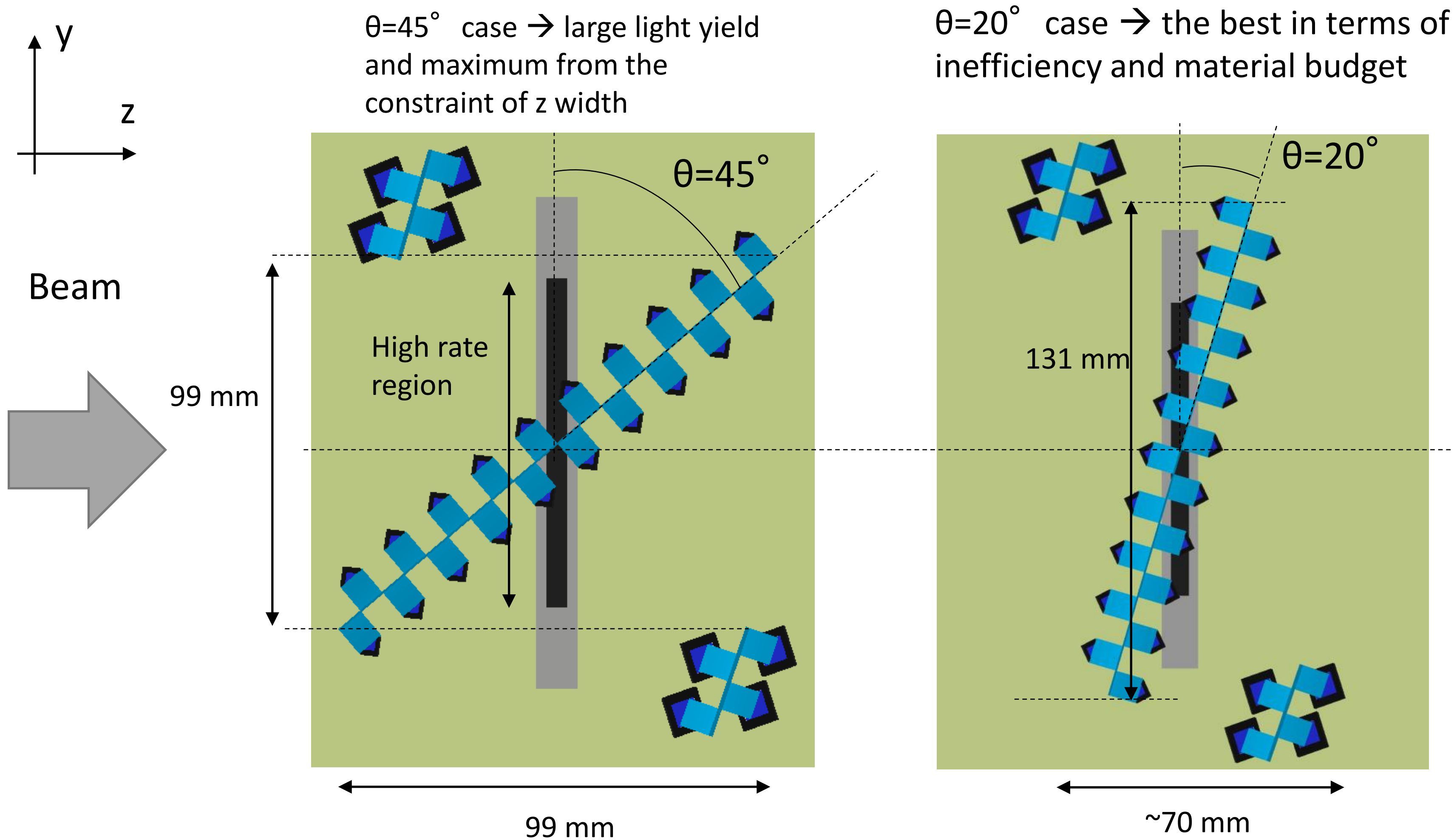
2 MPPCs are summed at bias circuit. In total, 4 channels are separately amplified.

Core region is read by thin 0.5 mm fiber with high granularity.
Halo region is read by thick 1 mm fiber with modest granularity.

In total, 24 (= 20 from core and 4 from halo) signals come out.
In the future upgrade, we may separately read 24 channels, but in the next beam time, we will reduce them by a factor of **two** at summing amplifiers placed outside of the vacuum chamber.

The important key of this two module scheme is that we can adjust the tilting angle of core UCV (see next page)

Mechanics (UCV entire view)



θ is important parameter, which determines material budget, inefficiency and light yield.

θ is not completely fixed yet and will be finally determined based the result of beam test.

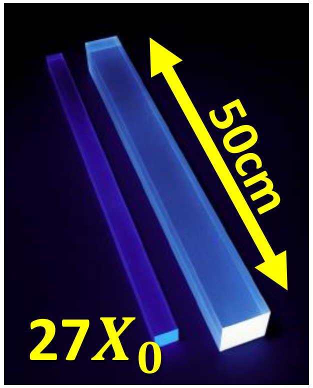
CsI calorimeter of the KOTO detector

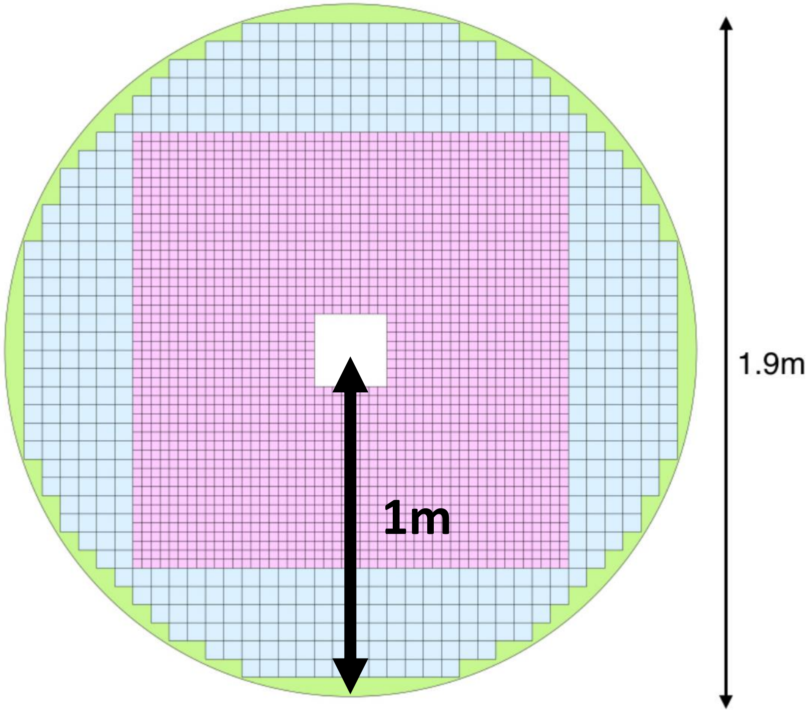
- CsI crystal
  - undoped CsI ($\lambda \sim 300$ nm)

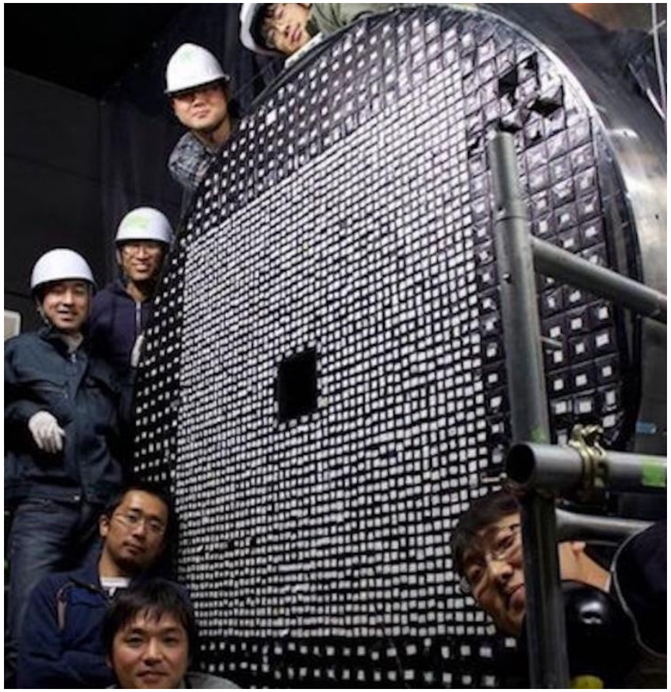
    #crystal = 2716

    2240 *small* ($25 \times 25\ \mathrm{mm}^2$)

    476 *large* ($50 \times 50\ \mathrm{mm}^2$)







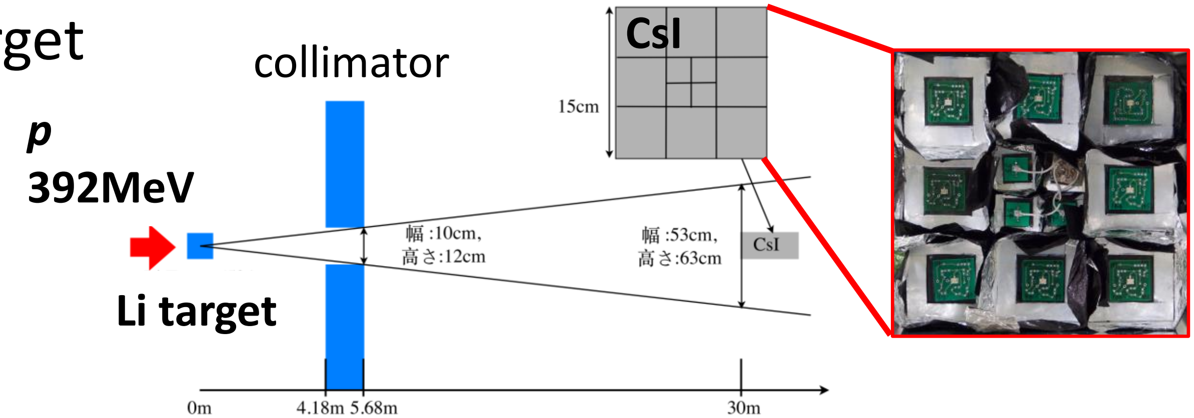
Performance tests (γ/n separation)

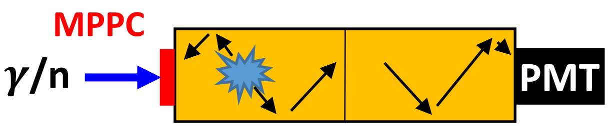
Beam test at RCNP-Osaka cyclotron

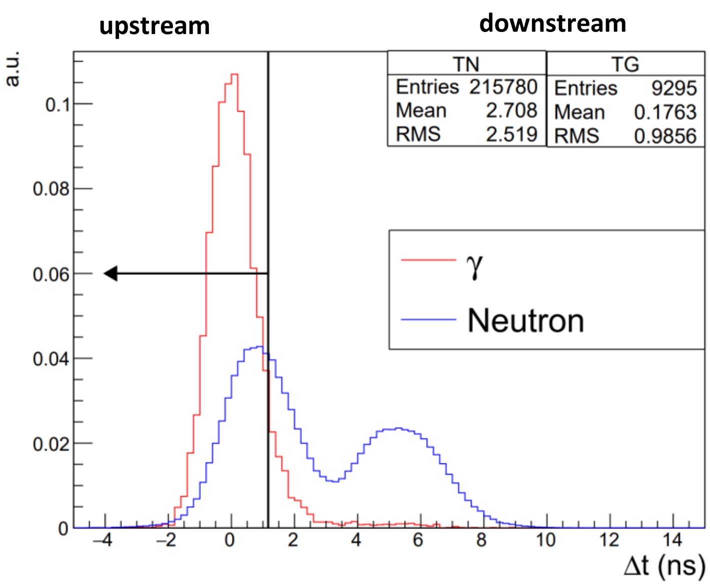
- γ/n beam from Li target

γ: **continuous beam up to 392 MeV**

n: **392 MeV**







Distribution

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

Retain 90% of γ while suppressing n to 34%

Rejection of neutron BG

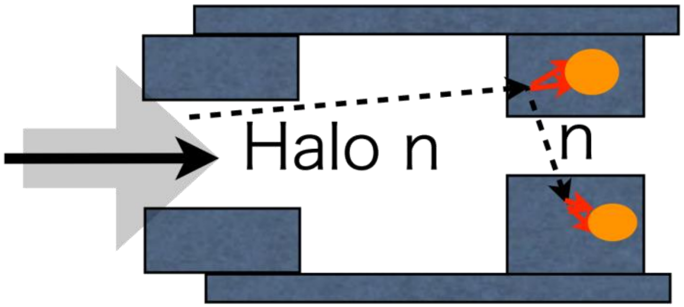
☐ Halo-neutron BG

* Prog. Theor. Exp. Phys. (2017) 021C01

Result of 4 days run: $\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu}) < 5.1 \times 10^{-8}$ (90% C.L.)*

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

The largest contribution from BG



- We need 3 more magnitudes of suppression

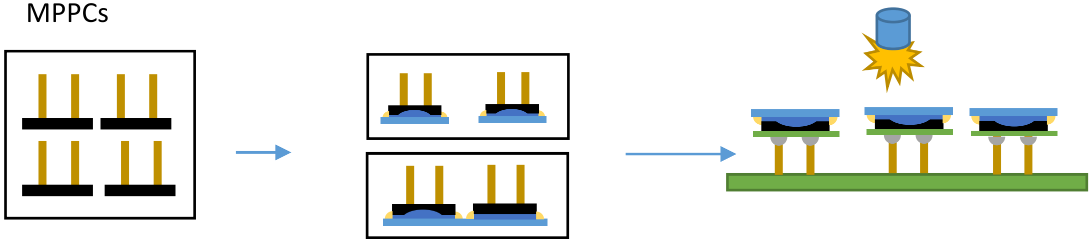
two-dimensional shower envelope → 1/10 ✓done

Pulse shape likelihood → 1/10 ✓done

measure shower development (in z)

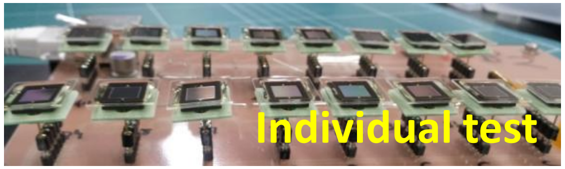
in the calorimeter → O(1/10)

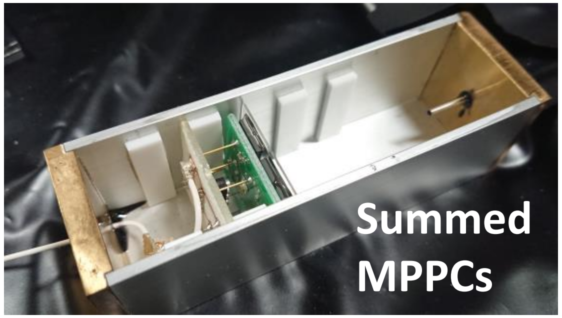
Quality assurance of MPPCs

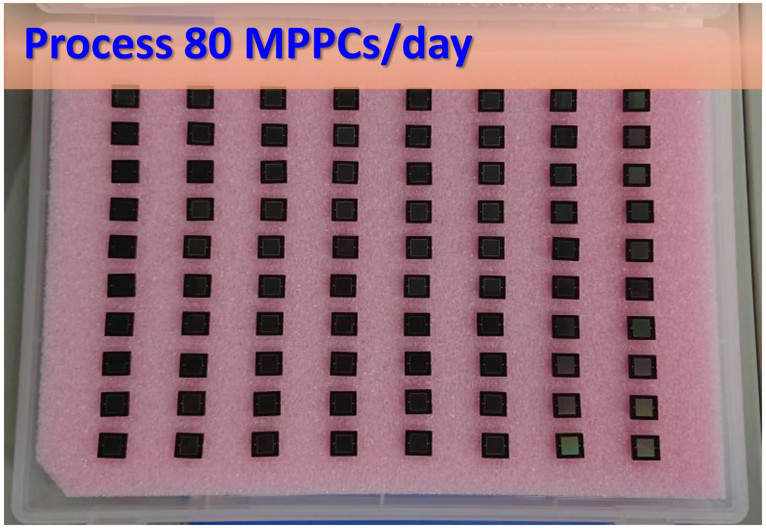


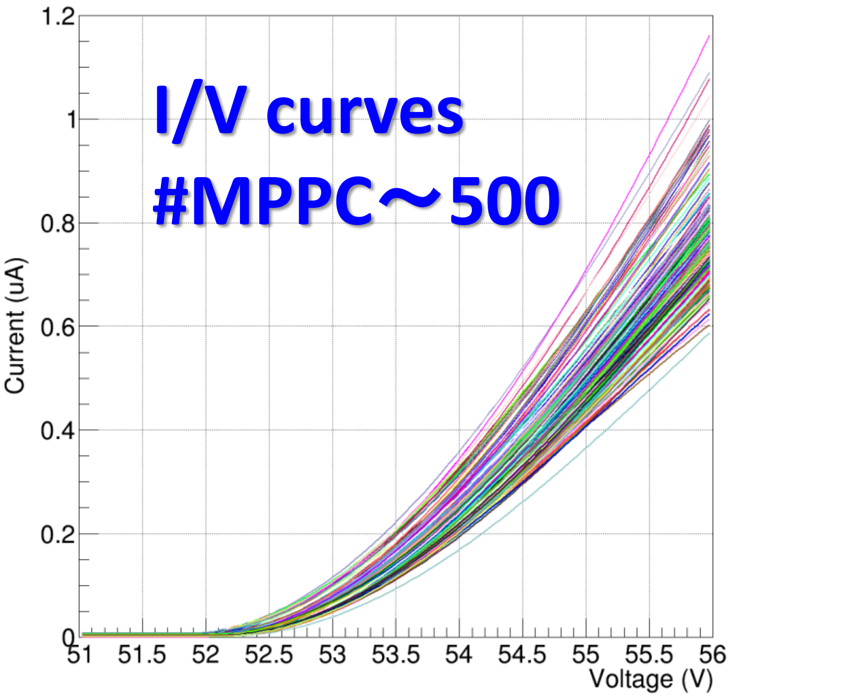
Quartz gluing
Soldering
temperature test

I/V inspection
LED test







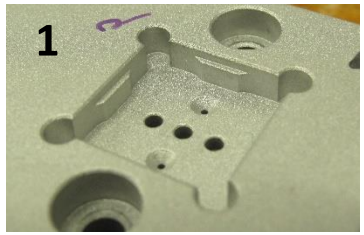


Inspect all of MPPCs (#~4000) before installation
→ Start gluing on CsI in this summer

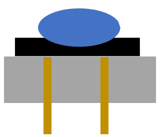
Fabrication of MPPCs

1

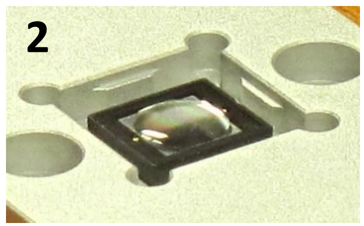
Insert MPPC on jig



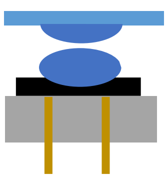
2



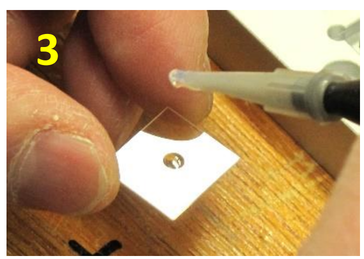
Drop glue



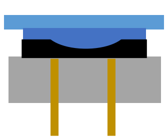
3



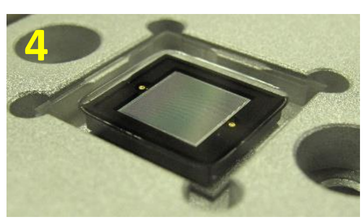
Drop glue on quartz



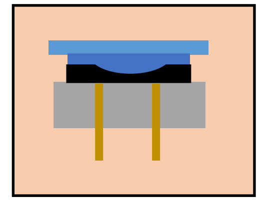
4



wait for cure keeping the quartz floated

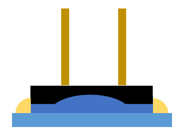


5

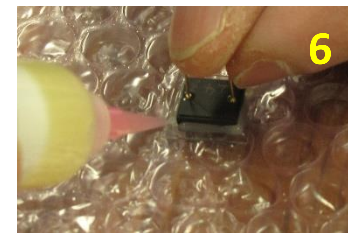


Put MPPCs into oven and wait 24 h (keeping 45 deg)

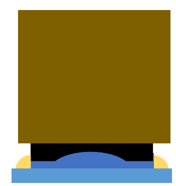
6



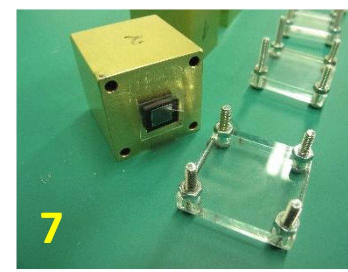
dispense epoxy glue (araldite 2011)



7

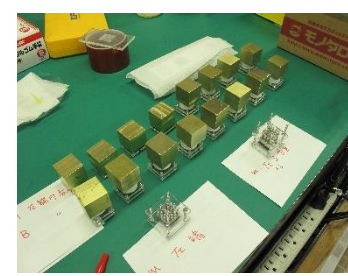


apply weight

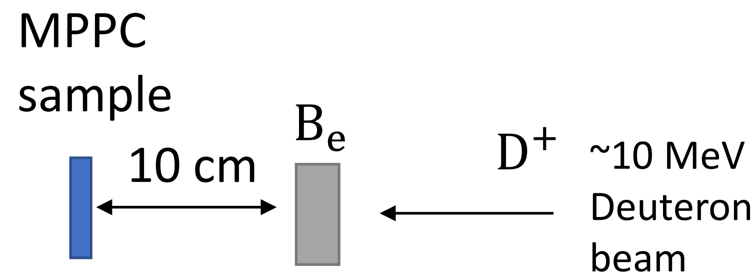


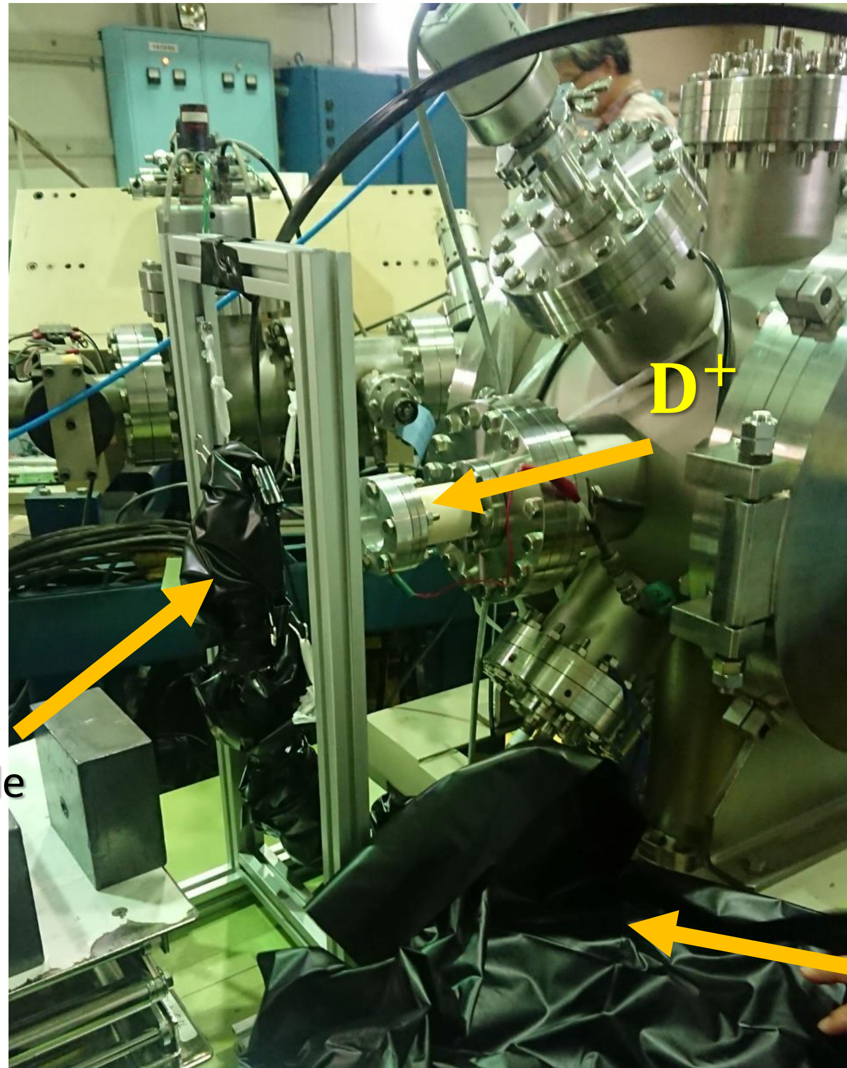
8

wait 24 h for cure



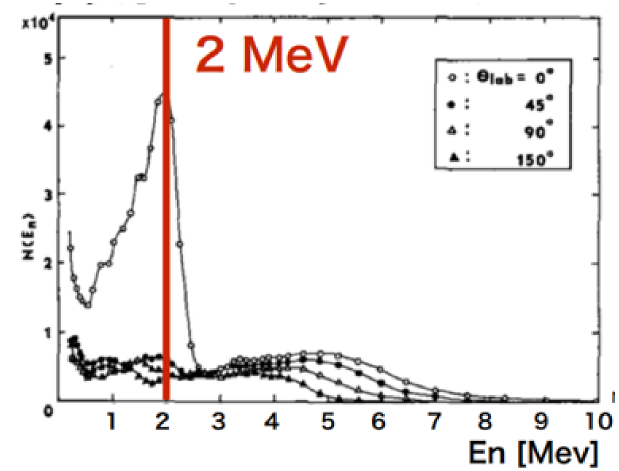
Setup





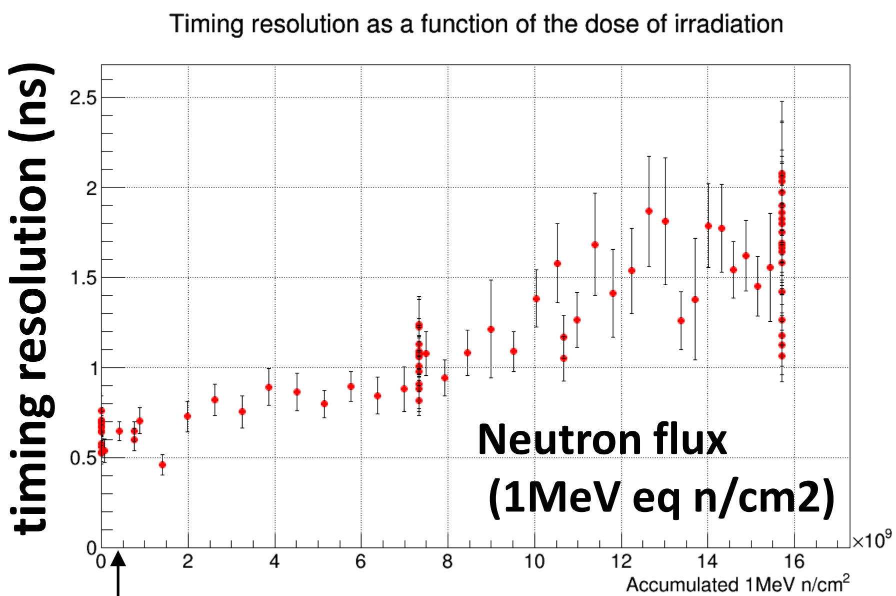
Our sample

Neutron energy spectrum



LED attached with fiber is under this sheet

Effect of the irradiation on the timing resolution

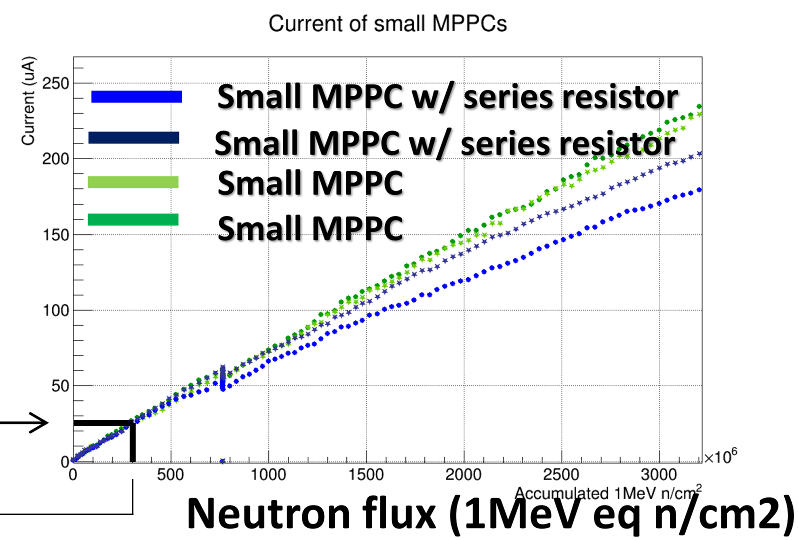


From the smoothed waveform, peak and CFT were calculated.

The fitted sigma divided by $\sqrt{2}$ was used to define the timing resolution of MPPC.

For the innermost layer of MPPC, we are around here.

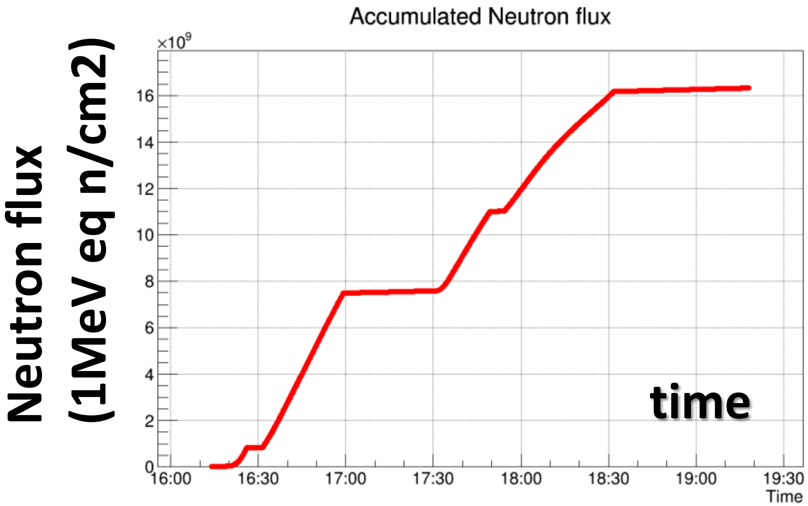
Current of the innermost layer is ~25uA now



Future study

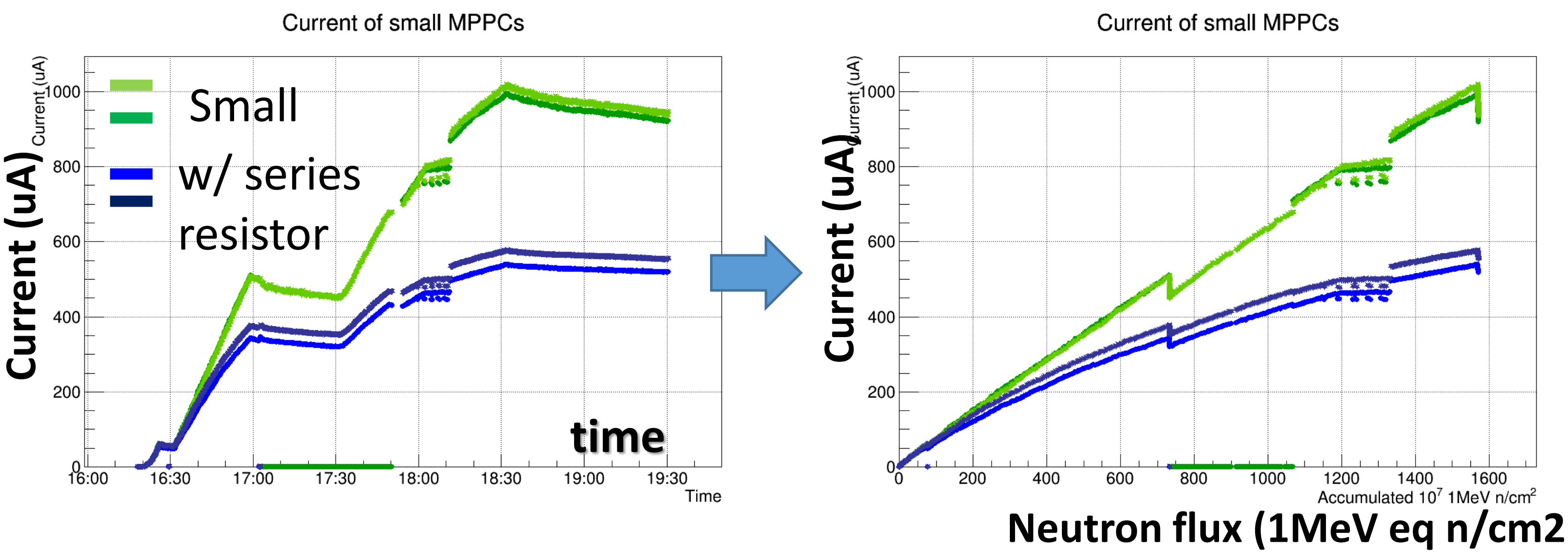
The timing resolution may be recovered by increasing the bias voltage.
This degradation may come from the decrease of gain.

Linearity of the dark current as a function of dose



Beam current is simultaneously monitored and we can convert the absolute neutron flux based on the previous experiment.

X axis is converted to the accumulated neutron flux.



Systematic uncertainty of S.E.S

$$\mathcal{B}(K_L \to \pi^0\gamma) = \frac{N^{obs(SR)}}{N_{2\pi^0}^{obs(CR2)}} \cdot \frac{\epsilon_{2\pi^0}^{CR2}}{\epsilon_{\pi^0\gamma}^{SR}} \cdot \mathcal{B}(K_L \to 2\pi^0)$$

preliminary

Source	σ_ϵ/ϵ (in %)	Comment
$\mathcal{B}(K_L \to 2\pi^0)$	**0.6**	From PDG
Geometry	**1.5**	Estimated by varying beam E (+1%) and position (x,y=1mm) for signal
Veto cuts	**17**	By comparing data and MC in CR2 with $\boldsymbol{\Delta Z_{vtx}}$ cut
Online veto	**6.4**	From the detector bits in the minimum bias data
Kinematic cuts	**12**	100% error of $\lvert 1\text{-}\epsilon_{Data}^{2\pi^0}/\epsilon_{MC}^{2\pi^0} \rvert$
Clustering	**1.0**	Compare five and six cluster events
CSD cuts	**1.5**	Use five cluster events
Reconstruction	**0.3**	By comparing $N_{rec\ 3\pi^0}^{obs\ 6cls}$ and $N_{rec\ 2\pi^0}^{obs\ 6cls}$
Trigger	**1.8**	Difference of CDT efficiency from unity
Statistics	**4.4**	Statistics of normalization
Total	**22**	

Syst. uncertainty due to ϵ^{veto}

$\epsilon^{veto} = \dfrac{N_{all}}{N_{all\,wo/\,ith\,veto}}$ is compared between data and MC: $R = \epsilon^{DT}_{CR2}/\epsilon^{MC}_{CR2}$

$$\frac{\sigma_{\epsilon^{veto}}}{\epsilon^{veto}} = \sqrt{\sum_{i:all\,detectors} (R_i - 1)^2} = 17\%$$

Inefficiency of veto detector is well understood by MC.