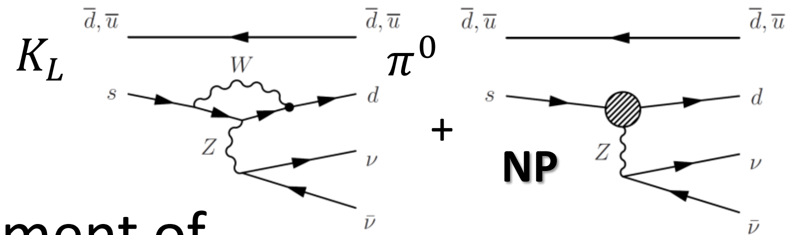
Search for New Physics via the $K_L \to \pi^0 \nu \bar{\nu}$ decay at the J-PARC KOTO experiment

Nobuhiro Shimizu (Osaka) July 28th

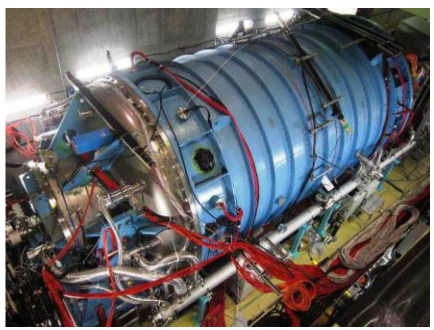
Introduction

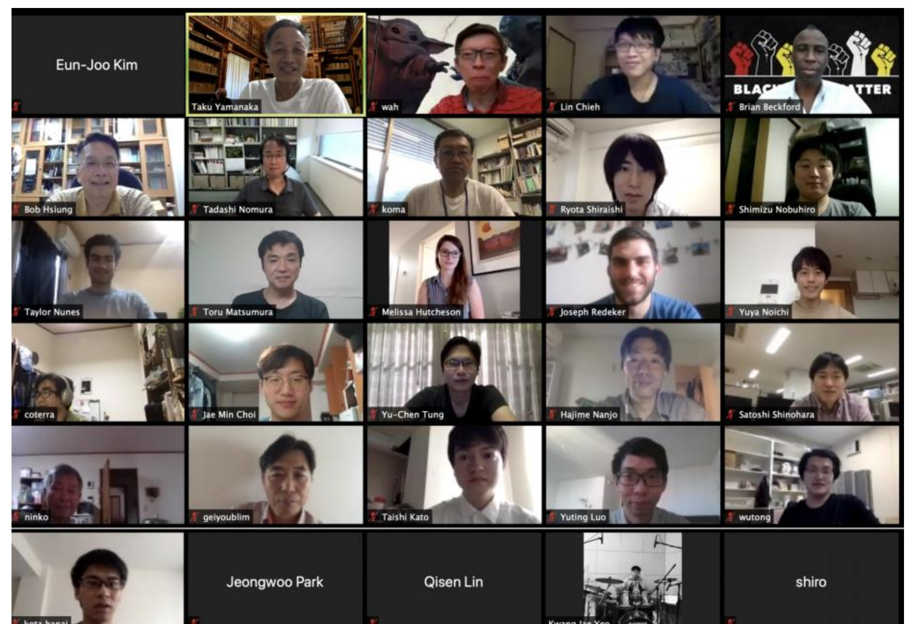


- Search for New Physics via measurement of $K_L \to \pi^0 \nu \bar{\nu}$ decay

  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)

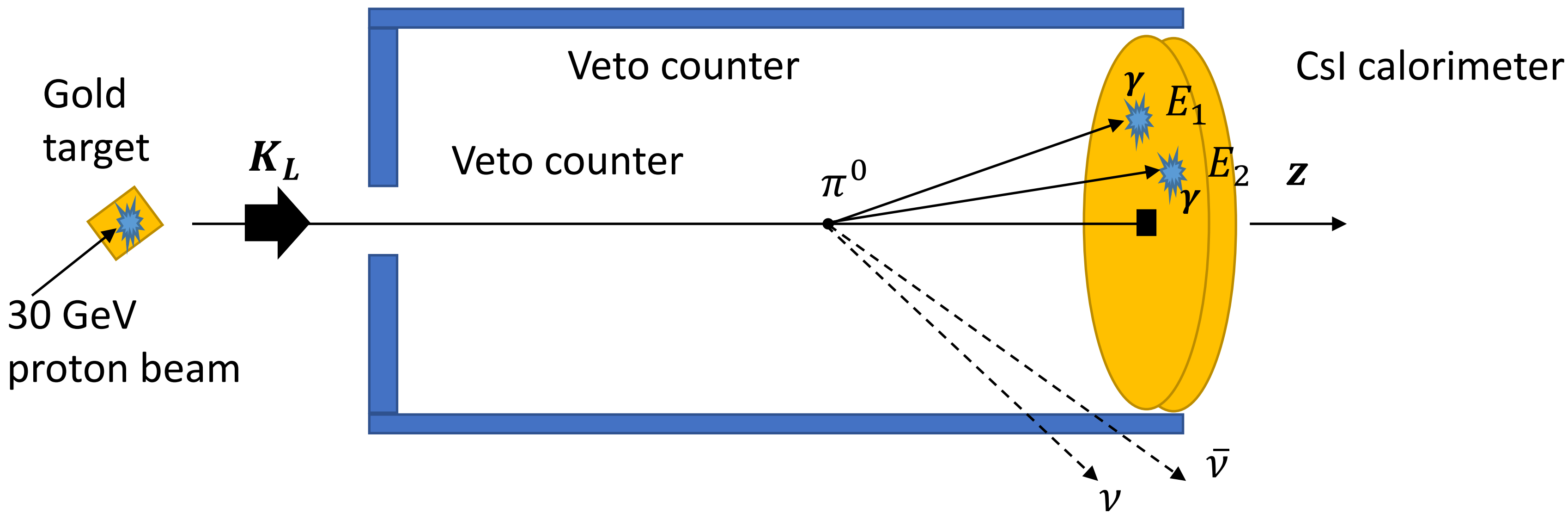
- KOTO experiment





Online collaboration meeting in July

Experimental principle

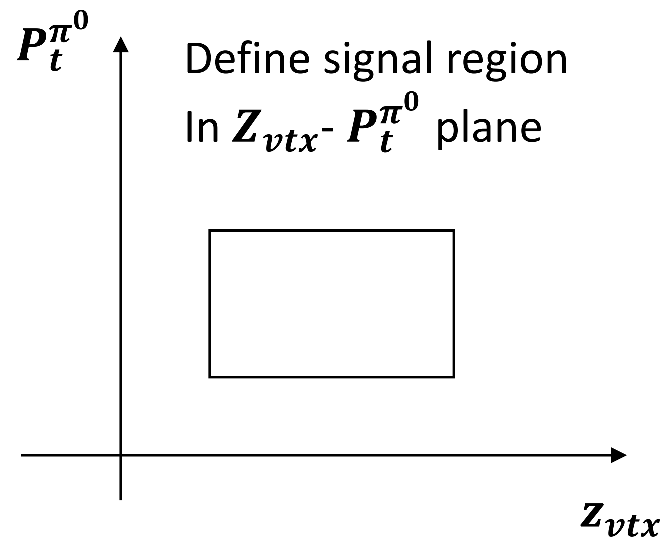


- Signature of $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay
  - Measure energy and hit position of two γ's by the CsI calorimeter
  - Neutrinos are not measured
    → Require no signal in the hermetic veto counters

Signature of signal → $2\gamma + nothing$

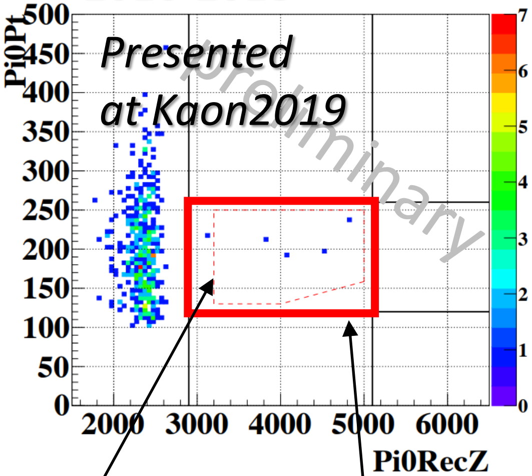
  - Calculate decay z-position assuming

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



Post-unblind studies of 2016-2018 analysis

Data taken during 2016-2018



Signal region

blind region

Expected # of BGs in the signal region

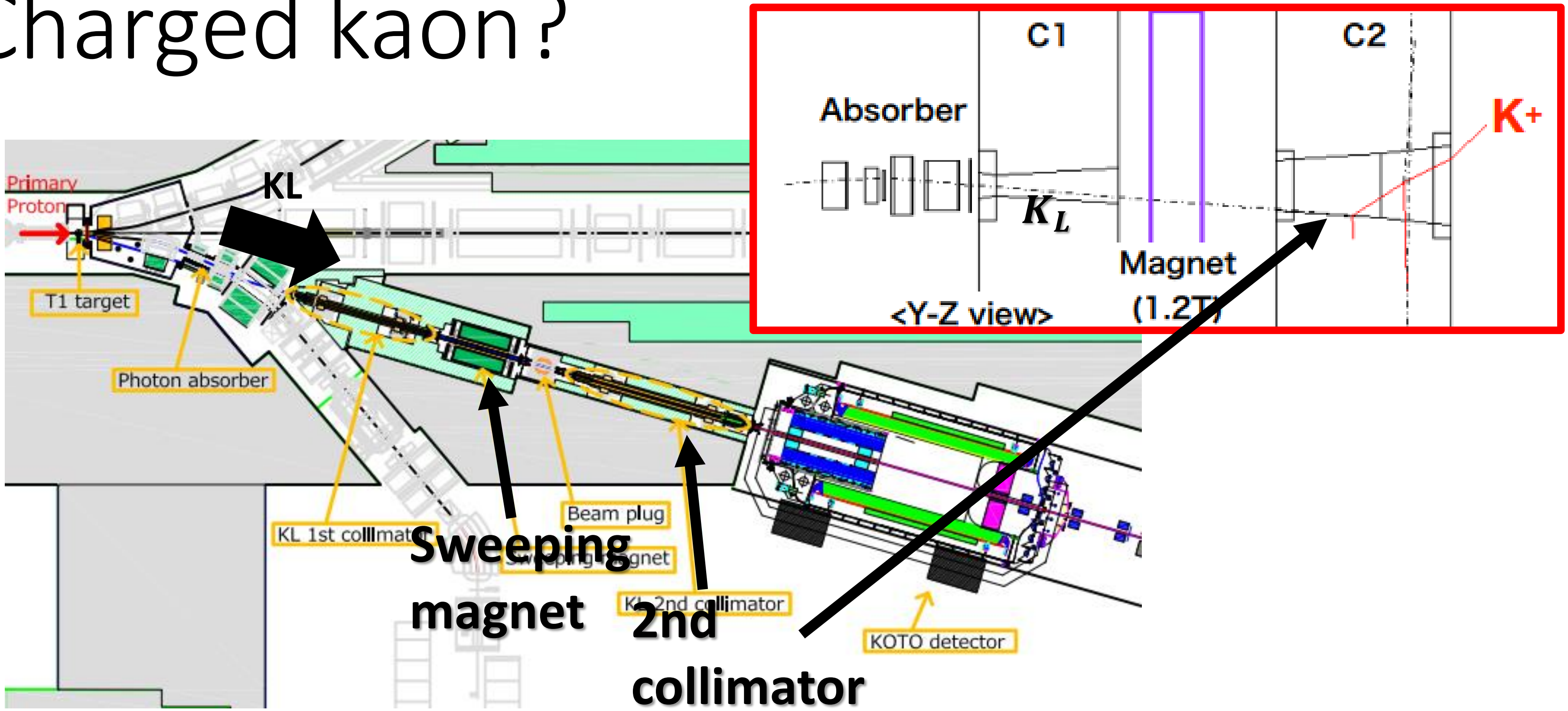
	source		#BG (90% C.L.)	#BG (68% C.L.)
U	KL	$K_L \to 2\pi^0$	<0.09	<0.05
		$K_L \to \pi^+\pi^-\pi^0$	<0.02	<0.01
U		$K_L \to 3\pi^0$ (overlapped pulse)	0.01±0.01	0.01±0.01
		Ke3 (overlapped pulse)	<0.09	<0.05
		$K_L \to 2\gamma$	0.001±0.001	0.001±0.001
N		Ke3 (π^0 production)	<0.04	<0.02
N		Ke3 (π^+ beta 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
		$K_L \to 2\gamma$ (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

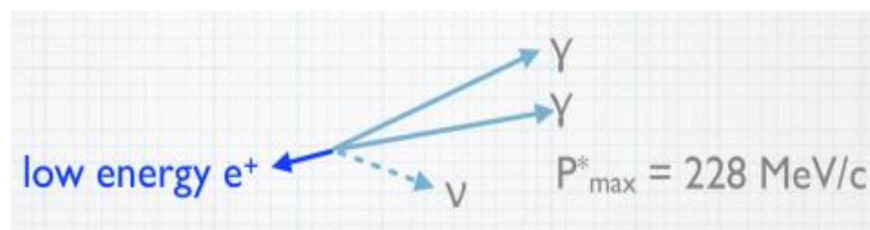
U: Updated from Kaon2019
N: New

- Adopted blind analysis technique and opened the blind region in the summer of 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.
  - One event was due to mistake of the application of cuts (N_{obs}: 4 → 3)
  - New concern: K^+, dominant contribution but syst. uncertainty remained.

Charged kaon?

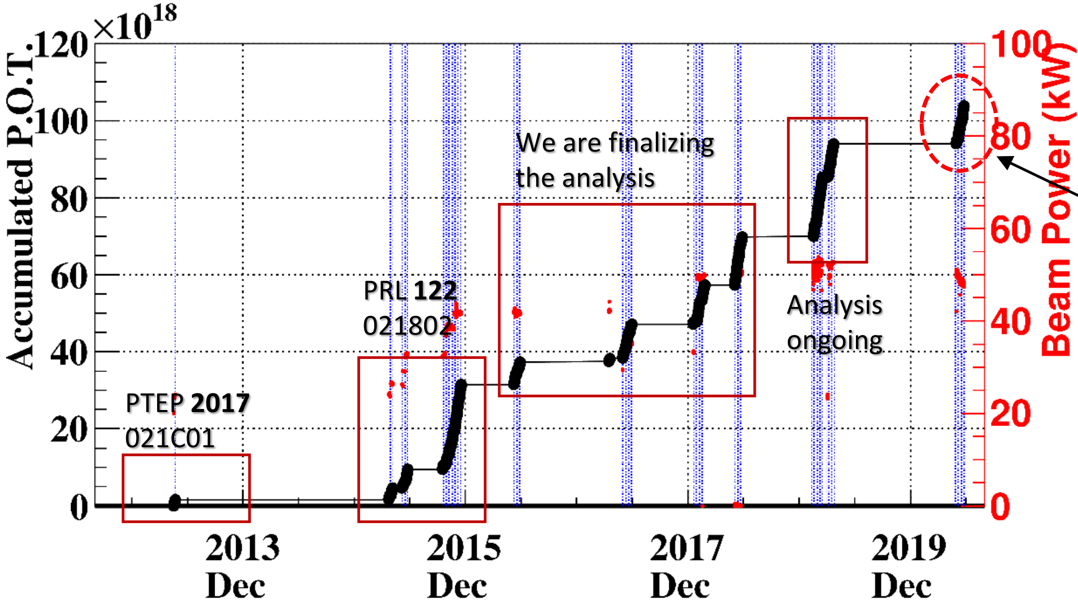


- K_L interacts with the inner wall of collimator and produces $K^{\pm}$
- Geant3-based beamline simulation predicts $K^{\pm}/K_L \sim 1.6 \times 10^{-6}$ at the entrance of the decay volume
- $K^{\pm} \rightarrow \pi^0 e^{\pm} \nu$ (BR=5%) can generate a π^0 with large P_t



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

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

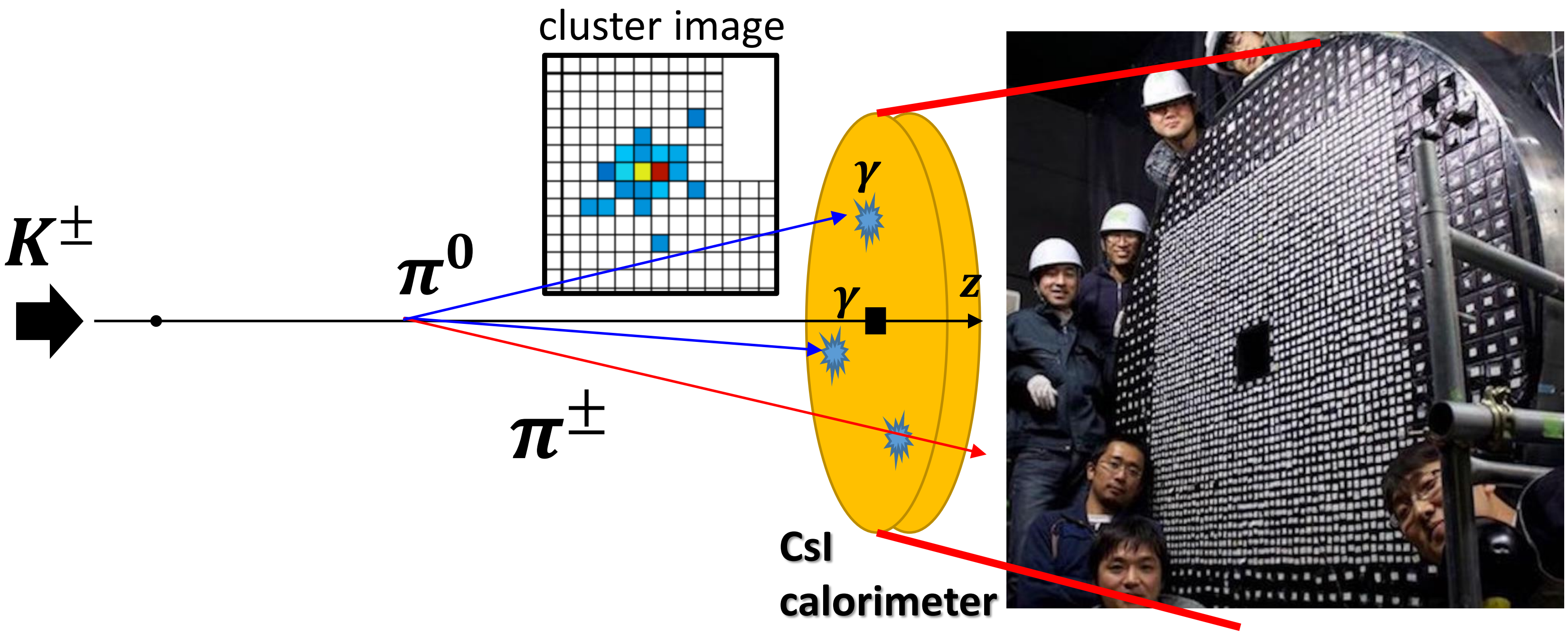


2020
May-June run

- 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

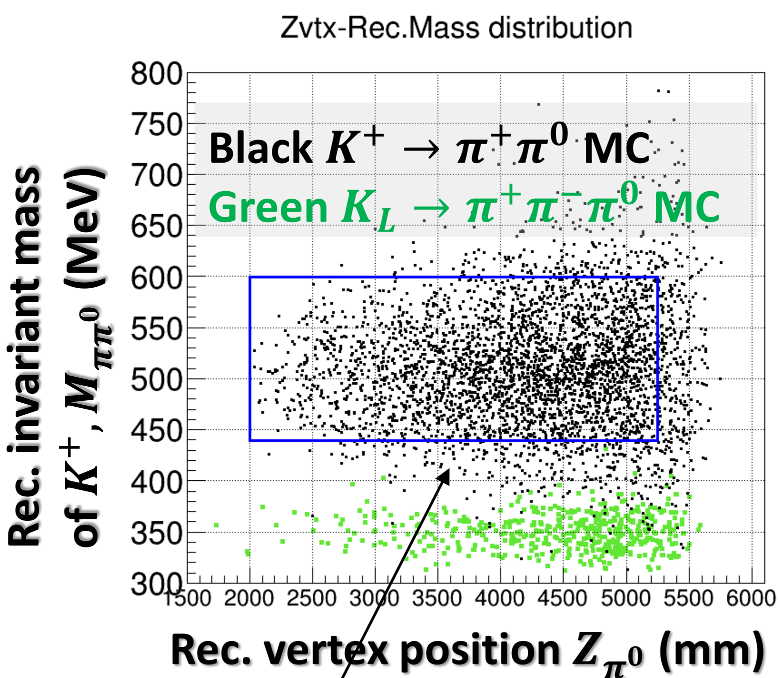
Measurement of $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}$ decay



- Measure $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}$ 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 $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}$ decay

MC simulation



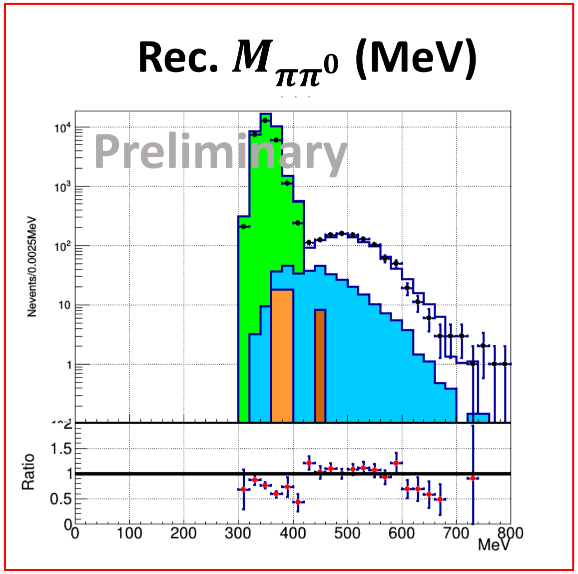
Signal region

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

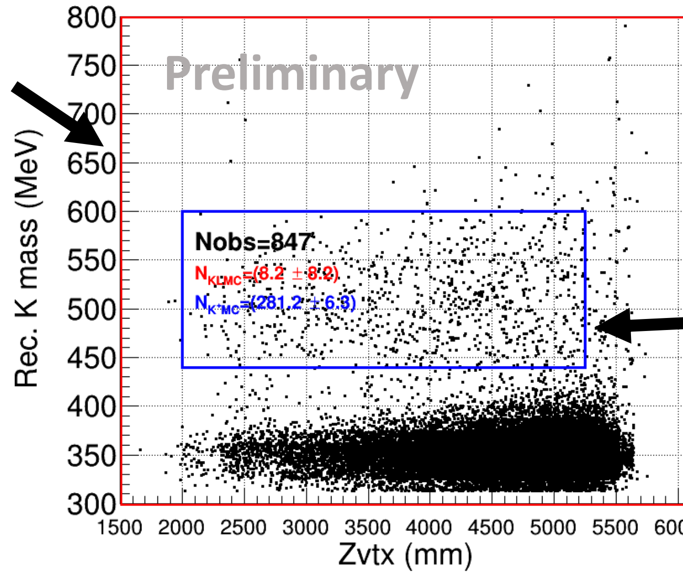
Measured $K^{\pm}$ flux

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

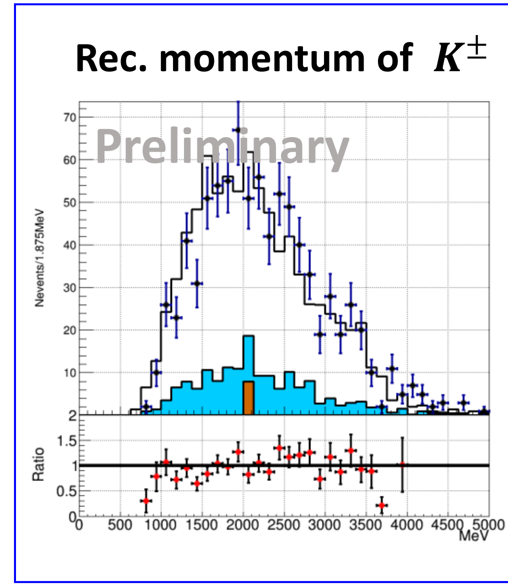
Projected mass distribution



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

$$\rightarrow \mathcal{R}^{meas.}_{K^{\pm}} / \mathcal{R}^{MC}_{K^{\pm}} = 3.0 \pm 0.1$$

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
	Ke3 (π^0 production)	<0.04	<0.02
	Ke3 (π^+ beta decay)	<0.01	<0.01
	radiative Ke3	<0.046	<0.023
	Ke4	<0.04	<0.02
	$K_L \to ee\gamma$	<0.09	<0.05
	$K_L \to \pi^+\pi^-$	<0.03	<0.02
	$K_L \to 2\gamma$ (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) × <u>uncertainties of simulation</u>

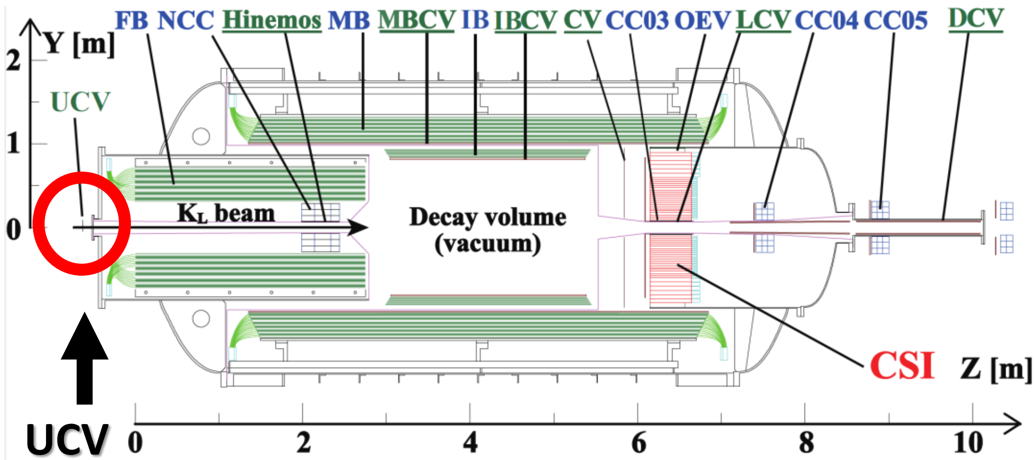
Prediction by MC simulation

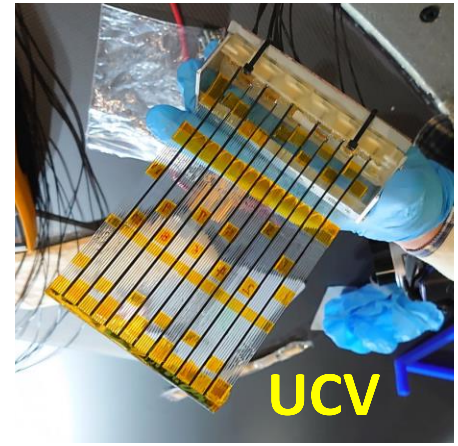
Uncertainty of flux → x 3.0

Uncertainty of the estimation of acceptance → ongoing using K^+ control sample

- ☐ BG table was updated based on the result of the $K^\pm$ flux.
- ☐ Tentative total BG estimation → 1.05 ± 0.28

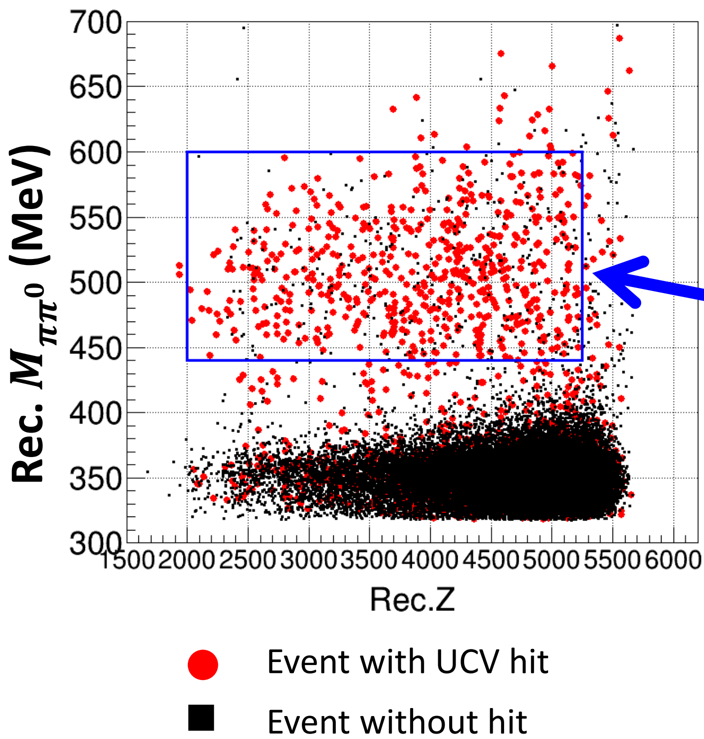
To veto $K^{\pm}$ (upstream charged veto, UCV)



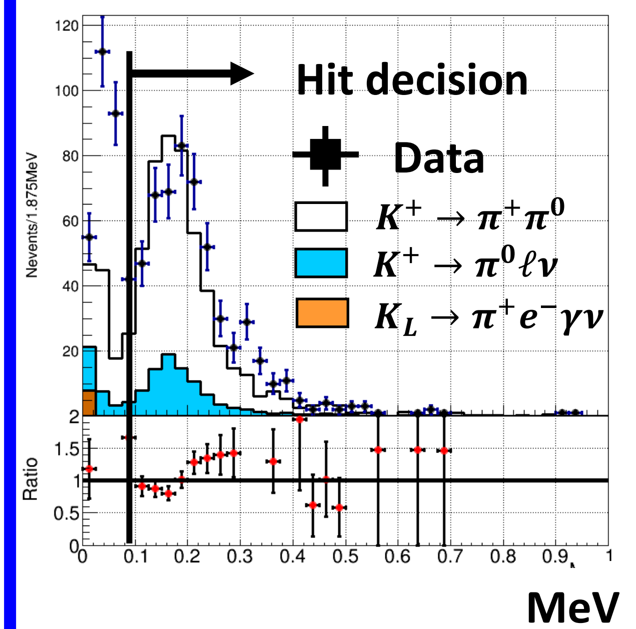


- ☐ A new detector installed before 2020 May-June run
- ☐ Purpose
  - ◆ To confirm the existence of $K^{\pm}$
  - ◆ **To veto $K^{\pm}$**
- ☐ Basic design
  - ◆ 1-mm-thick plastic scintillation plate (composed of 1mm☐ plastic scintillation fibers)
  - ◆ Use 6mm☐ MPPCs (Si-photo sensor) to detect scintillation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

Veto functionality of the prototype UCV



Distribution in the signal region



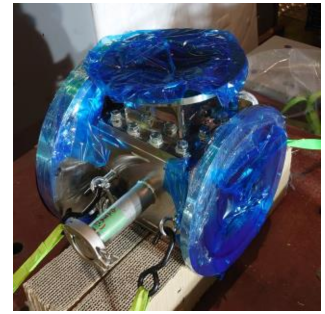
- The selected events have on-time and MIP like energy deposit in UCV.
- 30% inefficiency exists but can be explained by
  ① limited coverage of K^+ halo
  ② limited sensitive region of scintillation fiber
  ③ noise fluctuation

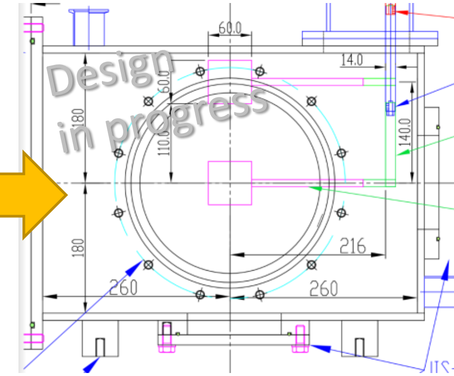
Development of new UCV

☐ To reduce inefficiency

① Limited coverage of $K^{\pm}$ halo

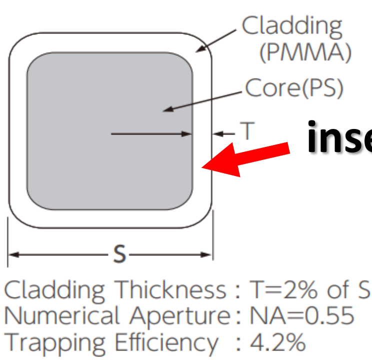
→ Enlarge the chamber





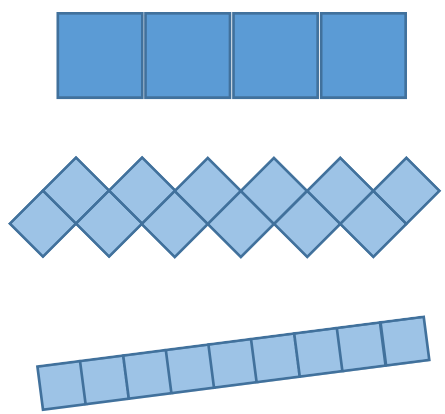
② Limited sensitive region of scintillation fiber

→ New scheme to place fibers (under consideration)



insensitive

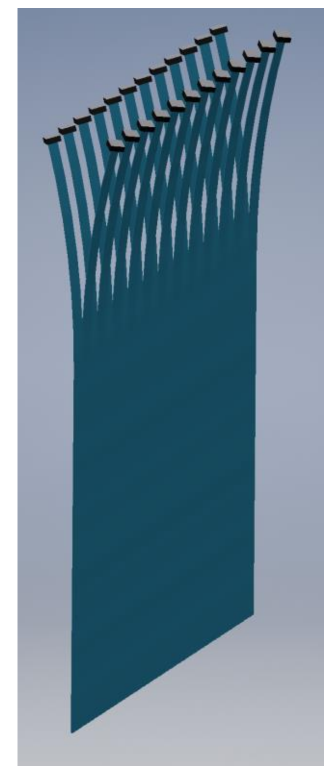
From Kuraray's brochure



Current 1mm

0.5mm Zig-zag shape

0.5mm with angle



③ Noise fluctuation

→ Keep distance between MPPC and beam core to avoid irradiation of MPPC

Summary and plan

- We collected the data to measure the incident $K^{\pm}$ flux into KOTO detector.
  - The measured $K^{\pm}$ flux was larger than MC simulation by a factor of 3.

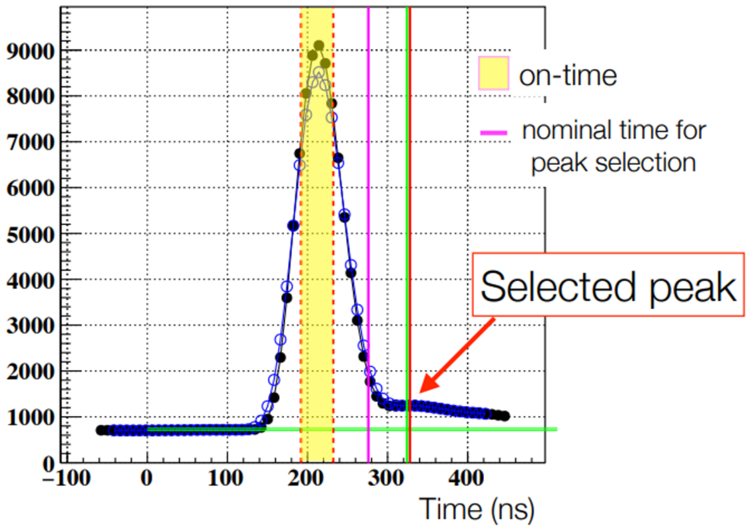
- BG table of the 2016-2018 analysis was updated by this measurement. The level of BG is not negligible.

→ After wrapping up our BG studies, we will publish paper in autumn

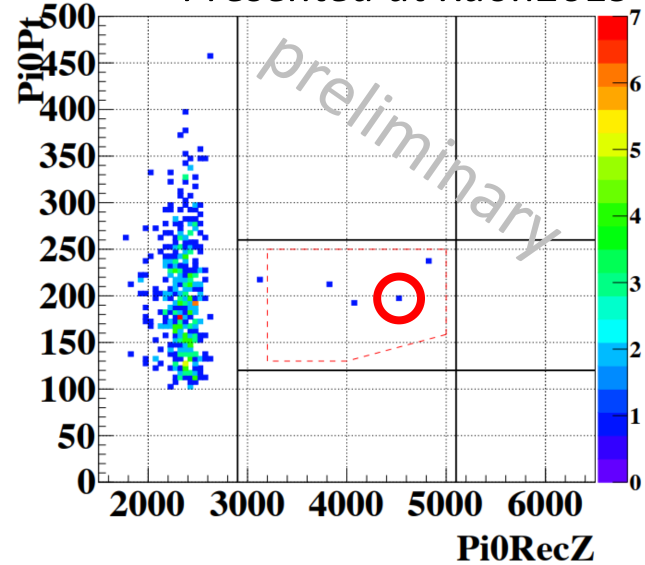
- To suppress $K^{\pm}$, UCV (upstream charged veto) is needed
  - Prototype test was done in 2020 run
  - New UCV is under development and will have more sensitivity to New Physics with new data collection

backup

An event appeared due to mis-measurement of timing

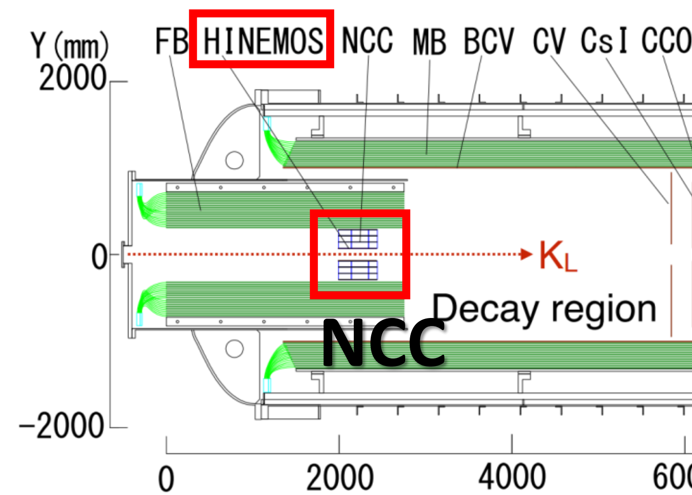


Presented at Kaon2019



☐ Mistreatment of cuts

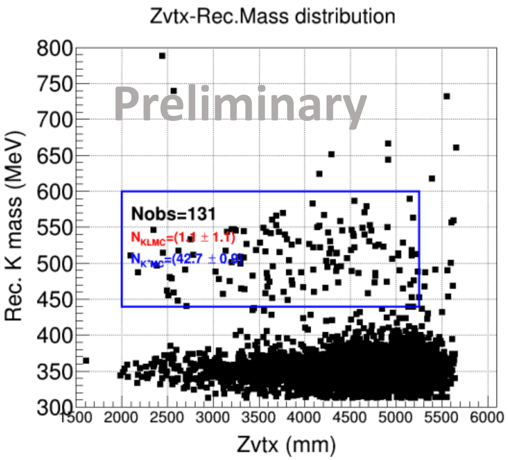
- Hinemos (inner scintillator of NCC) had a hit but the timing was mis-measured.
- The nominal time was once correctly defined with an appropriate algorithm, but was shifted due to a mistake. We just corrected it because we did not perform an additional tuning.



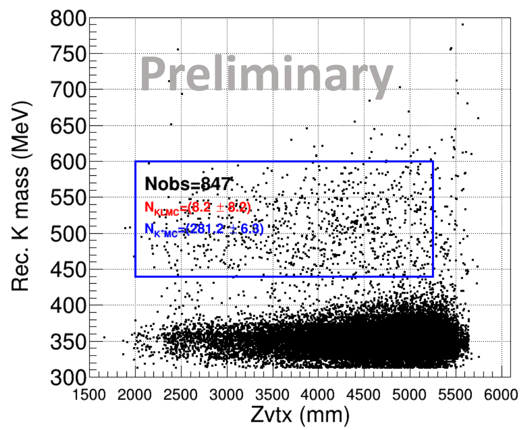
# of observed events: 4 → 3

$K^{\pm}$ production at UCV

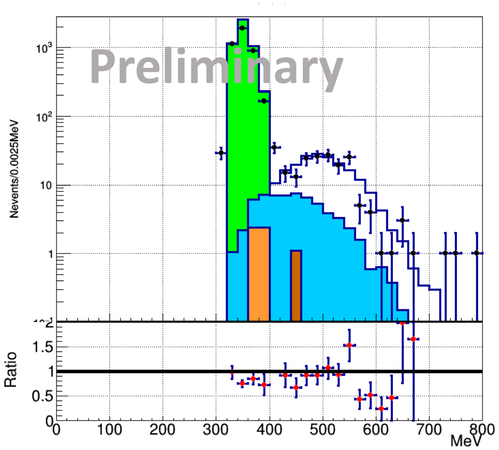
w/o UCV



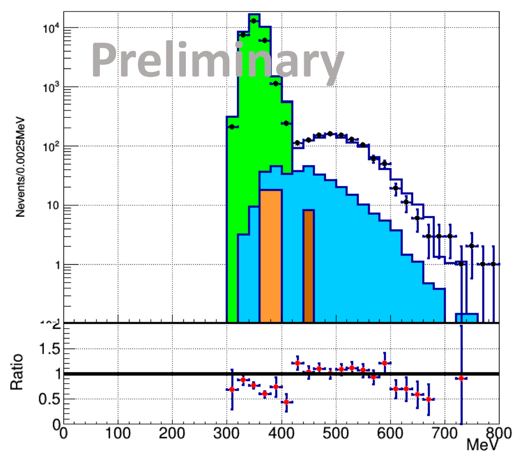
w/ UCV



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



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



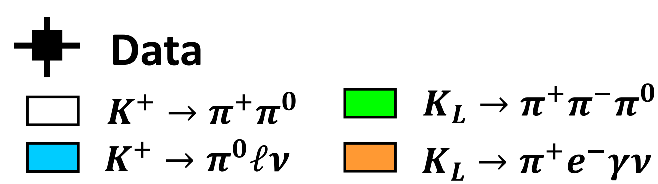
$\mathcal{R}_{K^{\pm}} = F_{K^{\pm}}/F_{K_L}$ was measured with and without inserting UCV in beam.

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

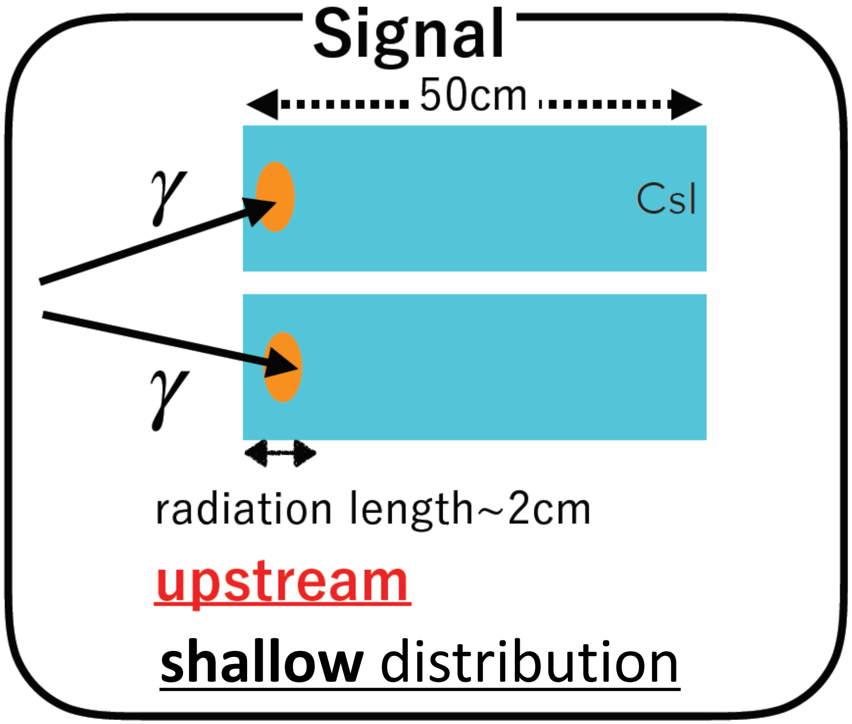
$$\mathcal{R}_{K^+}^{Meas.}/\mathcal{R}_{K^+}^{\mathrm{MC}} = 3.0 \pm 0.1 \ \ \text{w/UCV}$$
$$= 3.0 \pm 0.3 \ \ \text{w/o UCV}$$

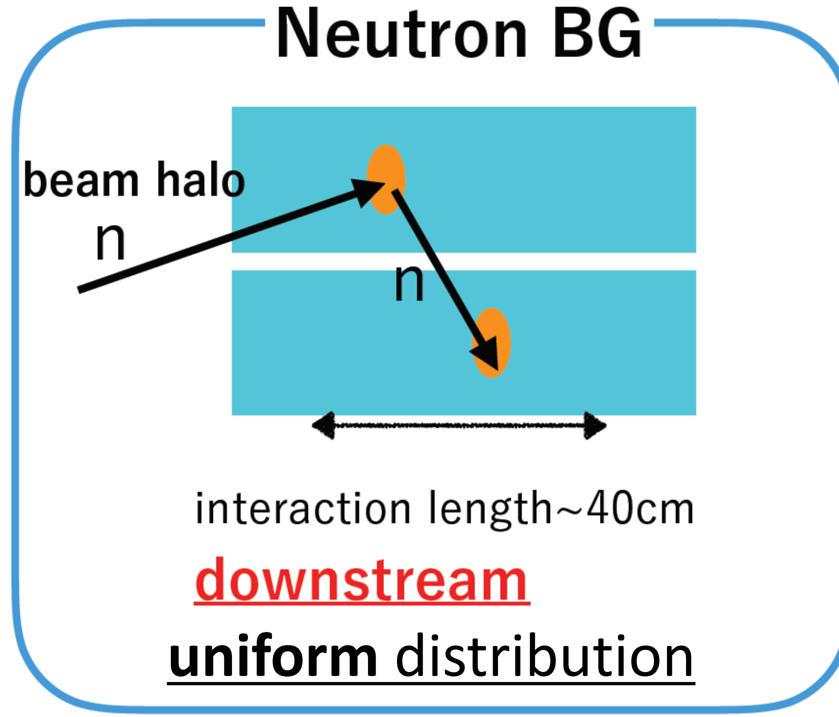
✓ We did not observe $R_{K^{\pm}}$ difference between w/UCV and w/o UCV.

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



2018 autumn CSI calorimeter upgrade 1 (hadron cluster BG)





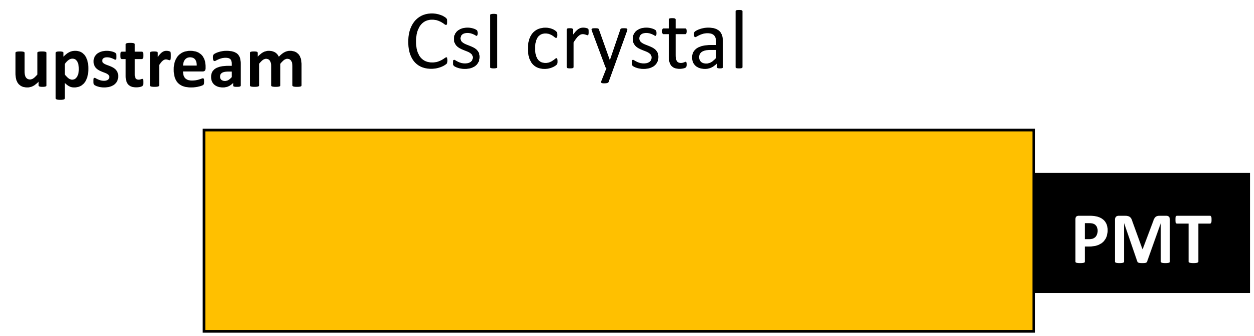
Run	SES	# of Hadron Cluster BG
2015	1.3×10^{-9}	0.24
2016-18	6.9×10^{-10}	0.02
	3×10^{-11} SM sensitivity	0.5

S.Shinohara Kaon2019

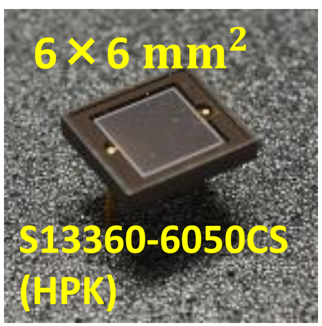
To achieve SM sensitivity, we need to suppress neutrons by a factor of ten

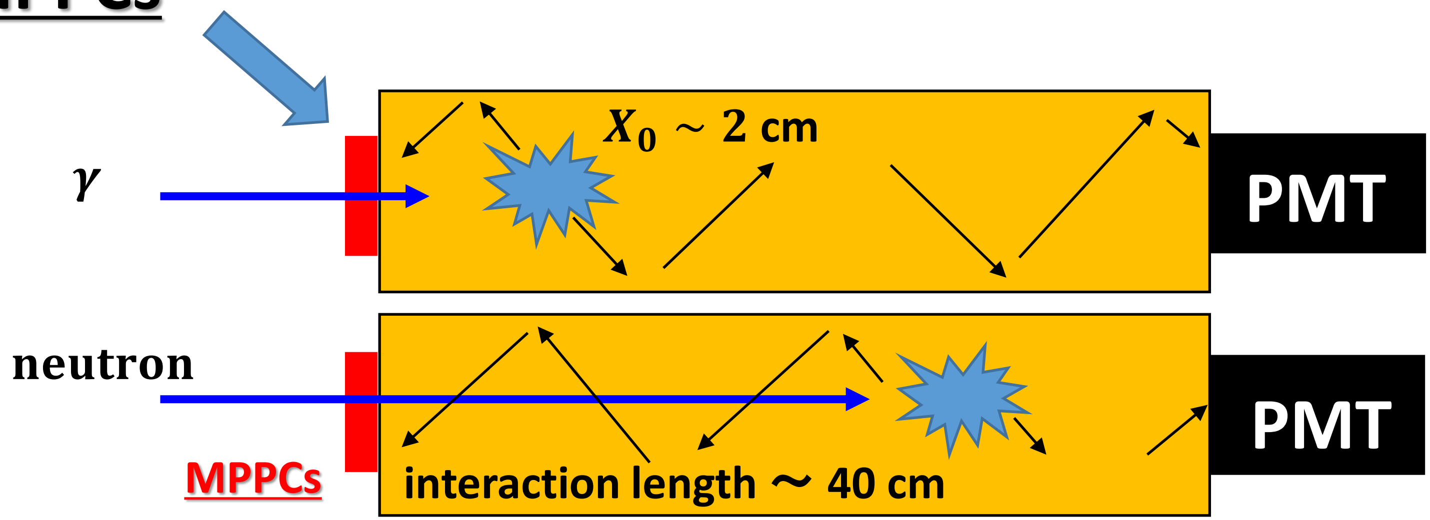
2018 autumn CSI calorimeter upgrade 2 (idea)

Previous



Attach MPPCs

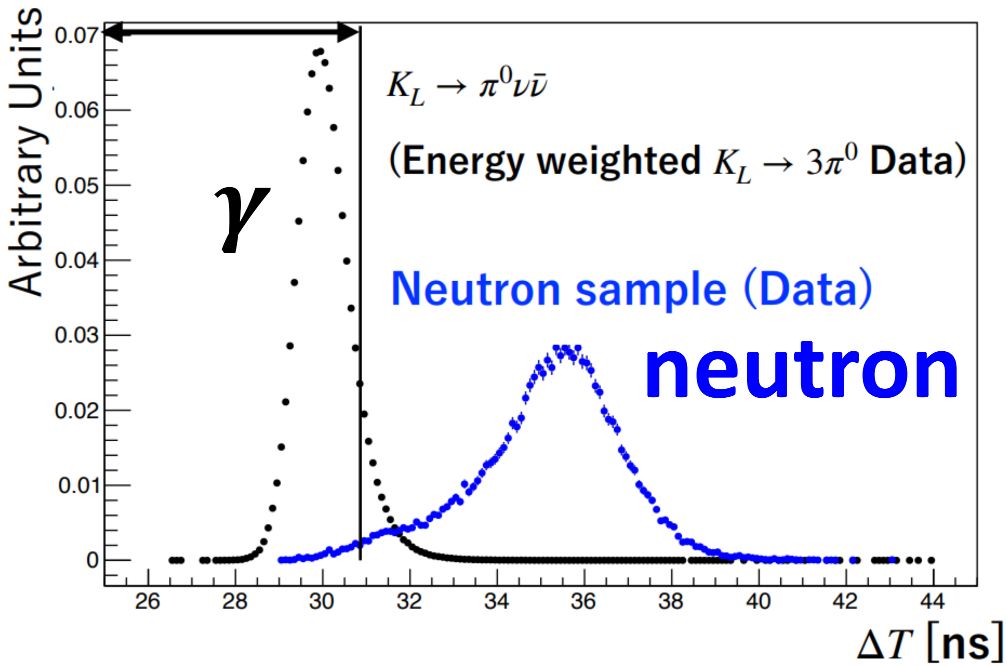


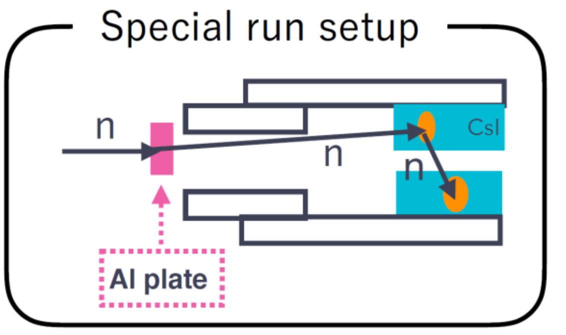


Measure the depth with the time difference $\Delta T \equiv T_{MPPC} - T_{PMT}$

→ **Small ΔT** implies γ

2018 autumn CSI calorimeter upgrade 4 (result)





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

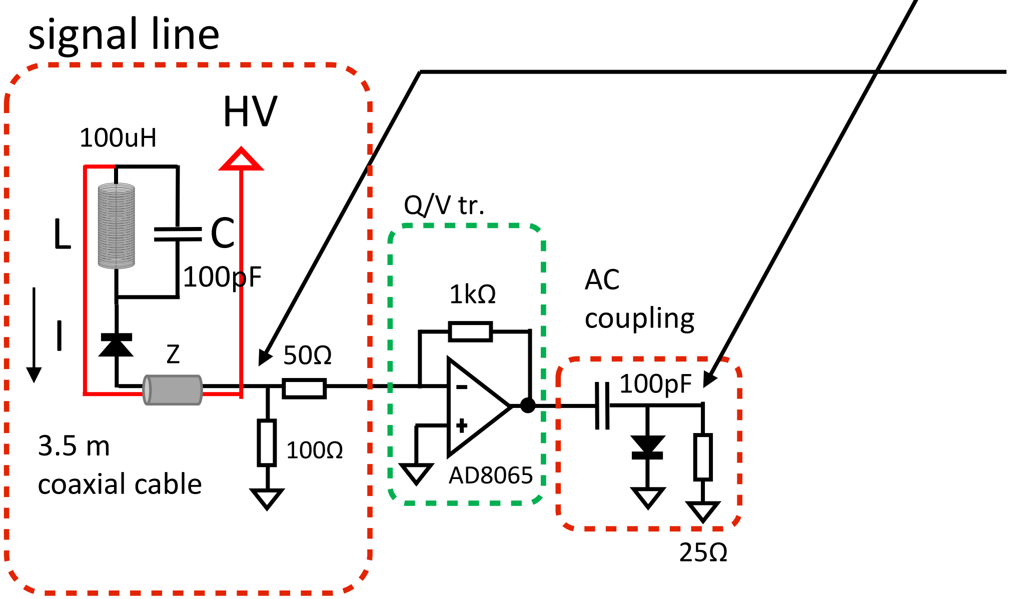
Use the larger ΔT out of two clusters (**max**ΔT)

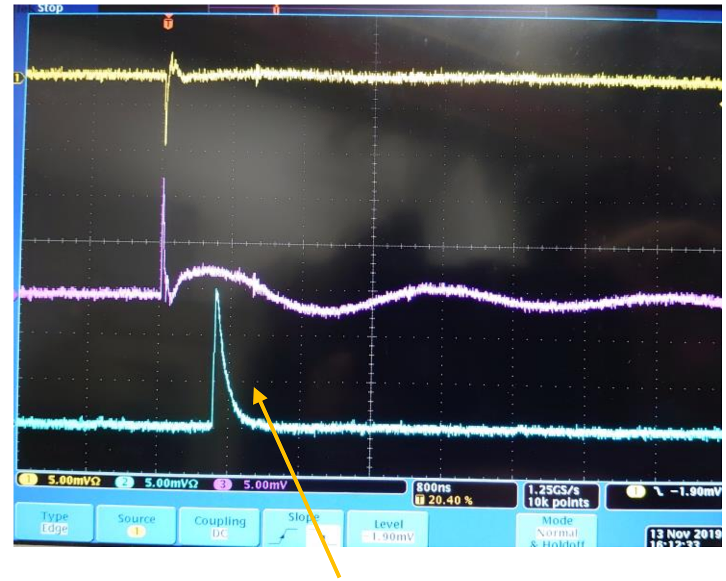
Retaining 90% of γ from $K_L \to \pi^0 \nu \bar{\nu}$ decay, neutron contribution was be able to be suppressed down to 1/60 !

Prototype UCV used in May-June 2020 run

UCV front-end scheme 1

We decided to use an inductor to shorten the waveform





Normal MPPC signal

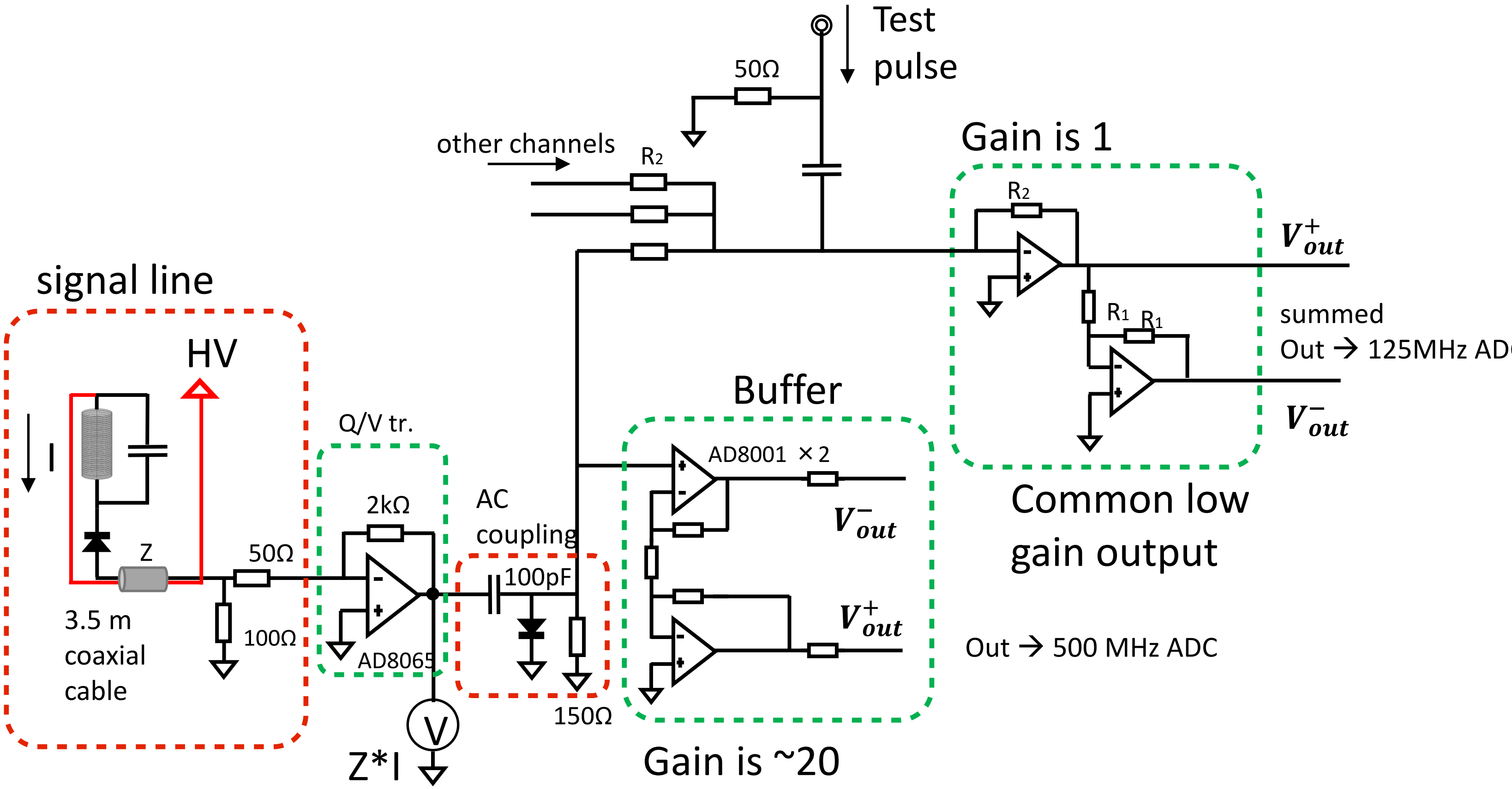
Keys of the bias circuit:

① Small resistance of inductor → avoid the loss of gain due to leak current.

② Inductor becomes high impedance for high freq. → capacitor shortens the pulse.

③ The slow oscillation frequency (1.6MHz or 630 ns) can be removed by differential circuit.

UCV front-end scheme 2

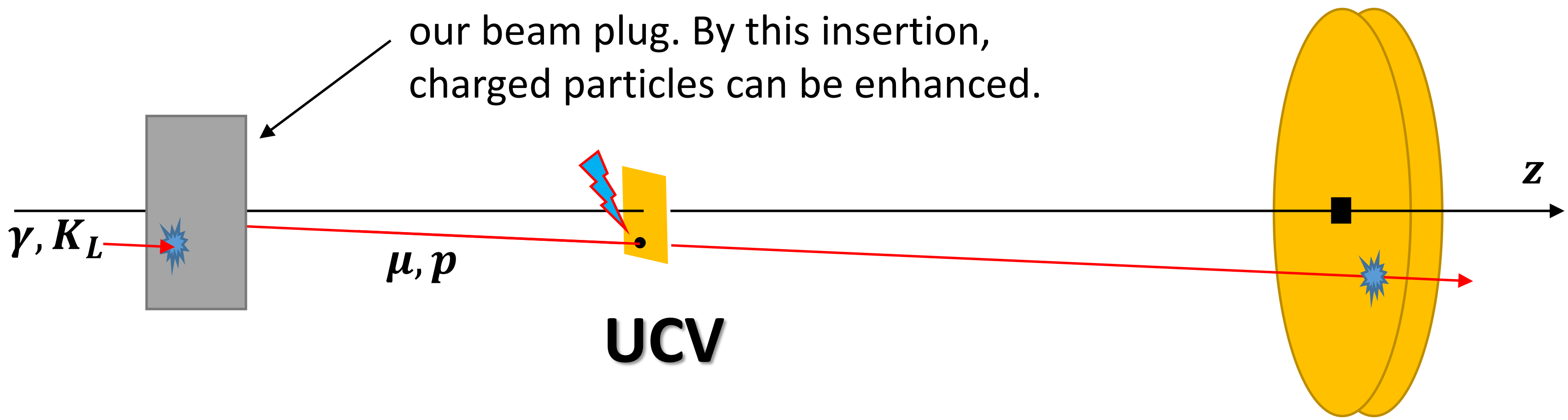


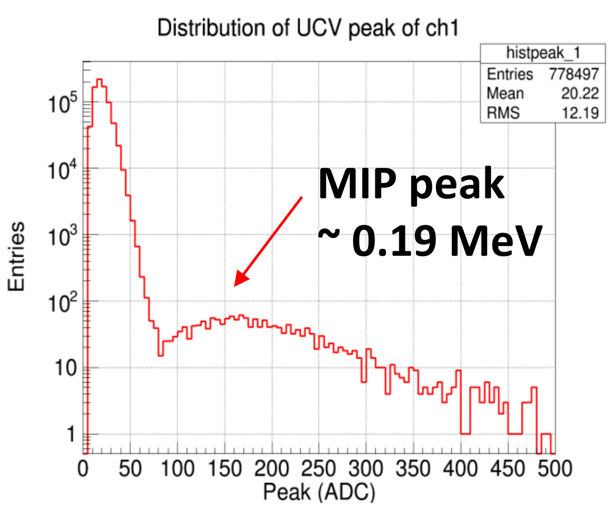
Keys of the entire front-end circuits

- Avoid using large resistor in the bias circuit to accept large leakage current do to irradiation
- Simultaneously read with two gain circuits without increasing # of channels
  - ✓High gain (x20) readout for each channel (12ch 500MHz ADCs)
  - ✓Low gain (x1) summed readout (6 MPPCs are summed, 2ch 125MHz ADCs)

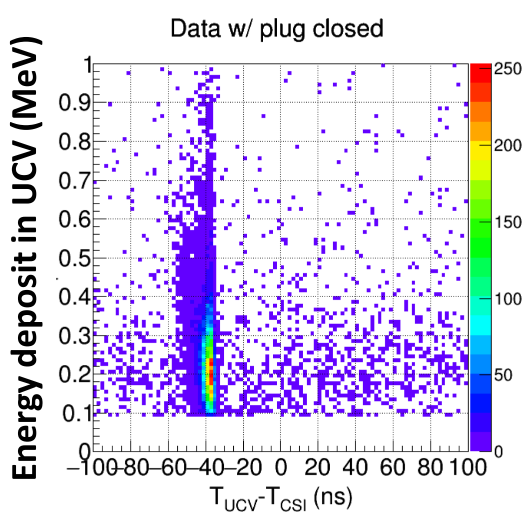
Basic performance check of UCV

Neutral particles are removed by our beam plug. By this insertion, charged particles can be enhanced.





Signal peak height (in ADC unit)



Timing difference between CSI and UCV hits (ns)
(arbitrary timing offset is included)

Collected data by inserting our beam plug. †

The events were triggered by CSI energy deposit.

MIP and clear on-time peaks could be observed.

→ UCV worked as expected.

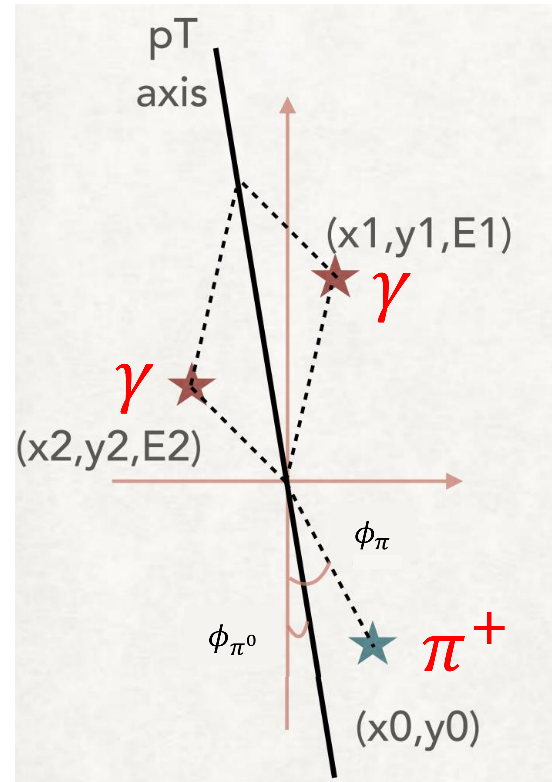
$K^{\pm}$ study

Reconstruction of $K^+ \rightarrow \pi^+\pi^0$

1. Repeat following procedure 2-6 for all the combinations
2. Reconstruct a π^0 from two γ's
   - ✓ Determine Z position of vertex assuming a π^0 decays on z-axis.
   - ✓ Polar angles of three momenta are determined.
   - ✓ Energies of γ clusters are reliable, so two four-vectors p_{γ_1} and p_{γ_2} are also determined
3. Calculate p_t of π^0 (← magnitude)
4. Assuming the transverse momentum of K^+ is zero, momentum conservation in the transverse plane gives

   $$|\vec{p}_\pi| = \frac{p_t^{\pi^0}}{\sin\theta_\pi}$$ → p_π is determined
5. Calculate *shape*-χ^2 of three clusters.
6. Sort all the combinations with respect to smallness of $\chi^2_{\gamma_1} + \chi^2_{\gamma_2}$. Choose the smallest.
7. For momenta of all the particles are now on ready
8. Calculate the invariant mass of K^+ as:

   $$M_{\pi^0\pi} = \sqrt{(p_{\gamma_1} + p_{\gamma_2} + p_\pi)^2}$$



KOTO CSI calorimeter cannot directly measure momentum of π^+, but can measure hit position.

shape-χ^2 represents how the cluster's 2D energy deposit is likely to be that of γ. If a cluster is made by π^+, this becomes large.

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

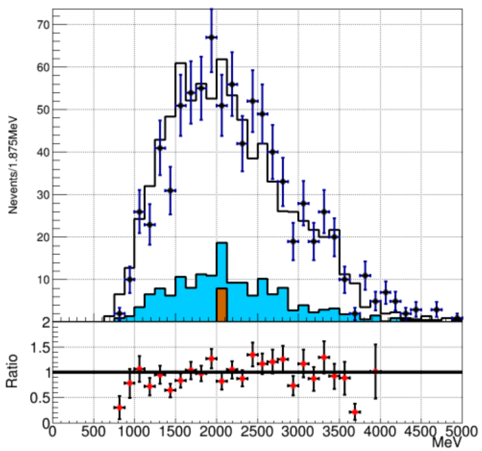
1. Require exactly three clusters in the CSI calorimeter
2. Requirement of the simultaneity of three hits
3. Consistency of γ-candidate cluster's 2D energy deposition properties in each CSI crystal between observed and that of γ-MC.
4. Veto cuts
   - ◆Almost the same as $K_L \rightarrow \pi^0 \nu\bar{\nu}$ analysis except for CV

     Require CV hit (more than 0.3 MeV = 60 % of MIP energy deposit)
5. CV hit count

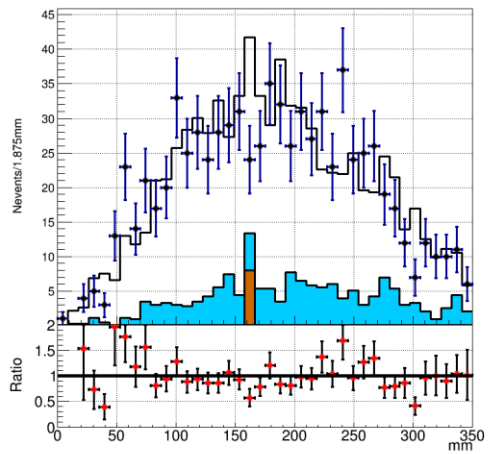
   For both rear and front CV planes, there are only one hit in each plane.
6. Consistency of CV hit module ID and the $\pi^{\pm}$ cluster position
7. The $\pi^{\pm}$ cluster energy deposit should be MIP-like
8. Accoplanarity angle of $\pi^{\pm}$ and π^{0} must be back-to-back
9. Draw 2D correlation plot of $(Z_{\pi^0}, M_{\pi^0\pi})$

Distributions of K^+ candidates collected in run85

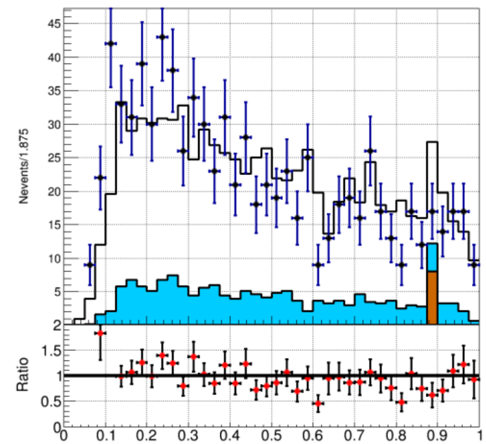
P_{K^+}



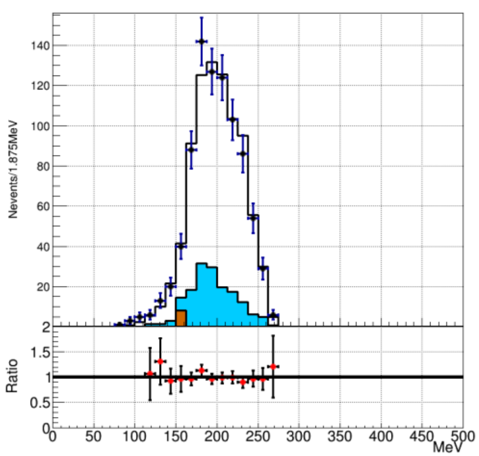
R_{coe}



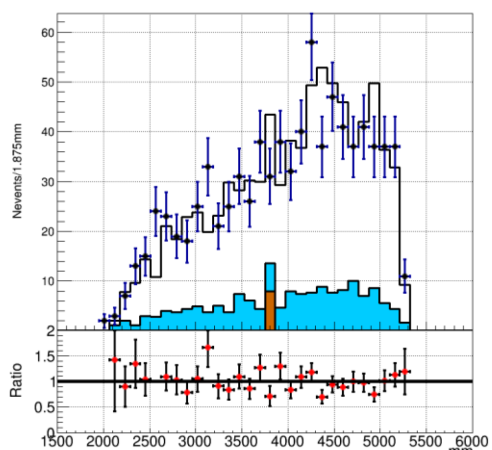
$E_{\gamma_0}/E_{\gamma_1}$

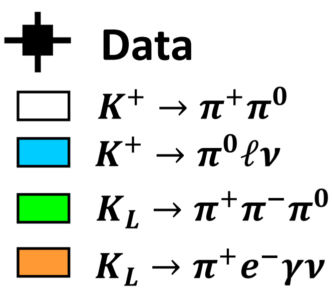


$P_t(\pi^0)$

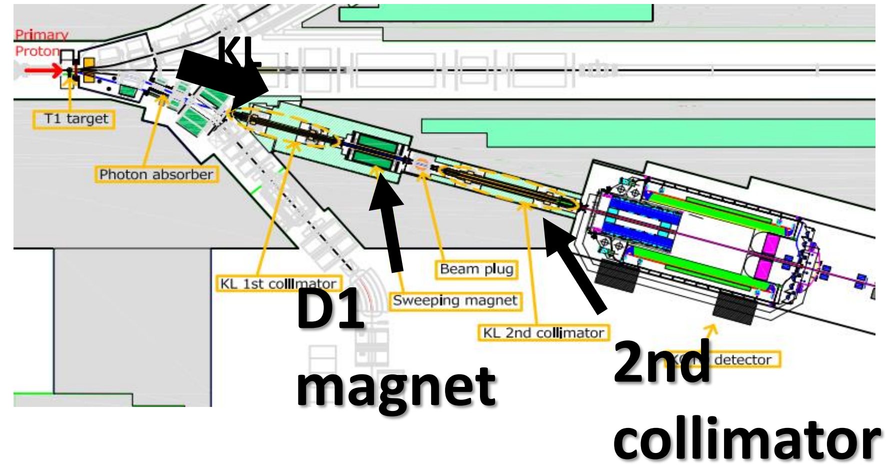


$Z_{vtx}(\pi^0)$





Data collection of K^+ control sample for the acceptance estimation

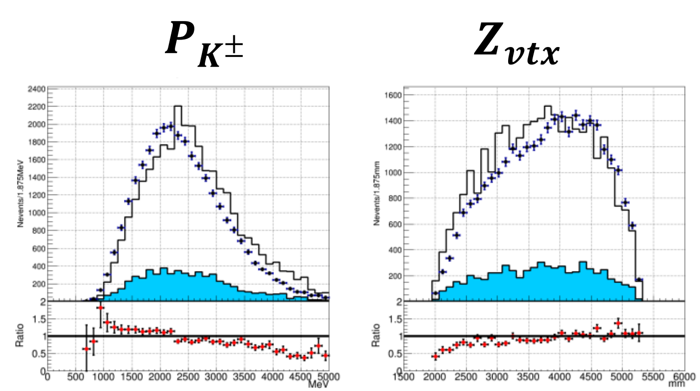


- Sweeping magnet in the beamline
  - D1 magnet is placed upstream of the 2nd collimator
  - By turning off D1, $K^{\pm}$ contribution can be enhanced by 4000

- K^+ control sample
  - 5 hours data

    Corresponds to 7×10^8 K^+ incidents measured by $K^+ \to \pi^+\pi^0$ decay (3 cluster events)
  - Directly evaluate K^+ BG contribution for $K_L \to \pi^0\nu\bar{\nu}$ by data-driven approach (2 cluster events)

→ ***Analysis is ongoing***



Data

$K^+ \to \pi^+\pi^0$

$K^+ \to \pi^0\ell\nu$

Distributions obtained by $K^+ \to \pi^+\pi^0$ analysis