

# KOTO – Search for Direct $CP$ violating $K_L$ to $\pi^0 \nu \bar{\nu}$ decays

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Amphi Dirac, IP2i, Lyon University

21<sup>st</sup> FPCP 2023

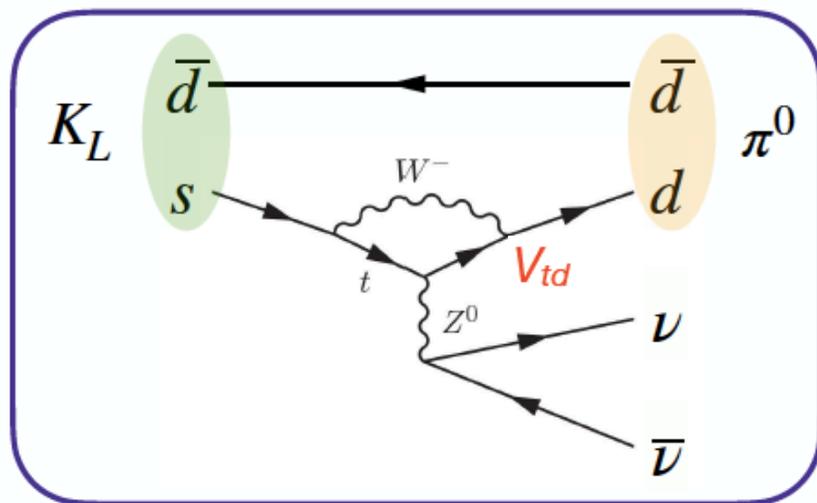


# Search for $K_L \rightarrow \pi^0 \nu \bar{\nu}$

$K_L \rightarrow \pi^0 \nu \bar{\nu}$  decay in the Standard Model

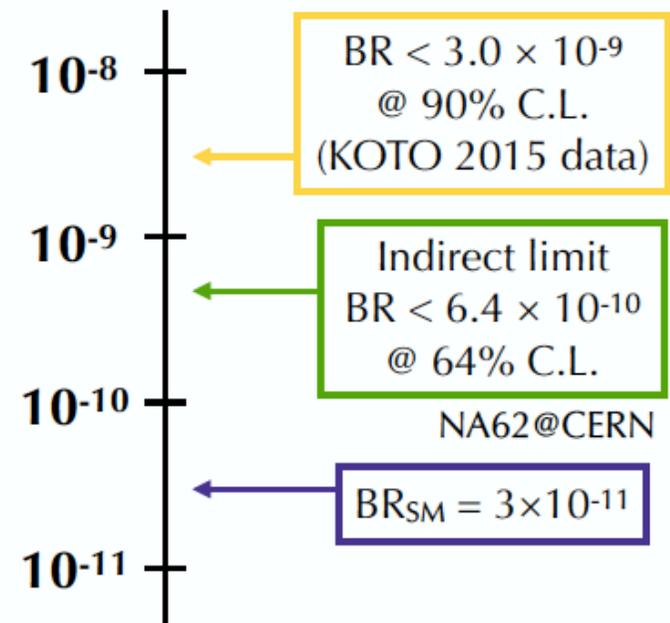
- Direct CP-violating process
- Highly suppressed:  $BR(K_L \rightarrow \pi^0 \nu \bar{\nu})_{SM} = 3 \times 10^{-11}$
- Well known:  $\sim 2\%$  theoretical uncertainties

→ Good probe to search for New Physics



+ NP

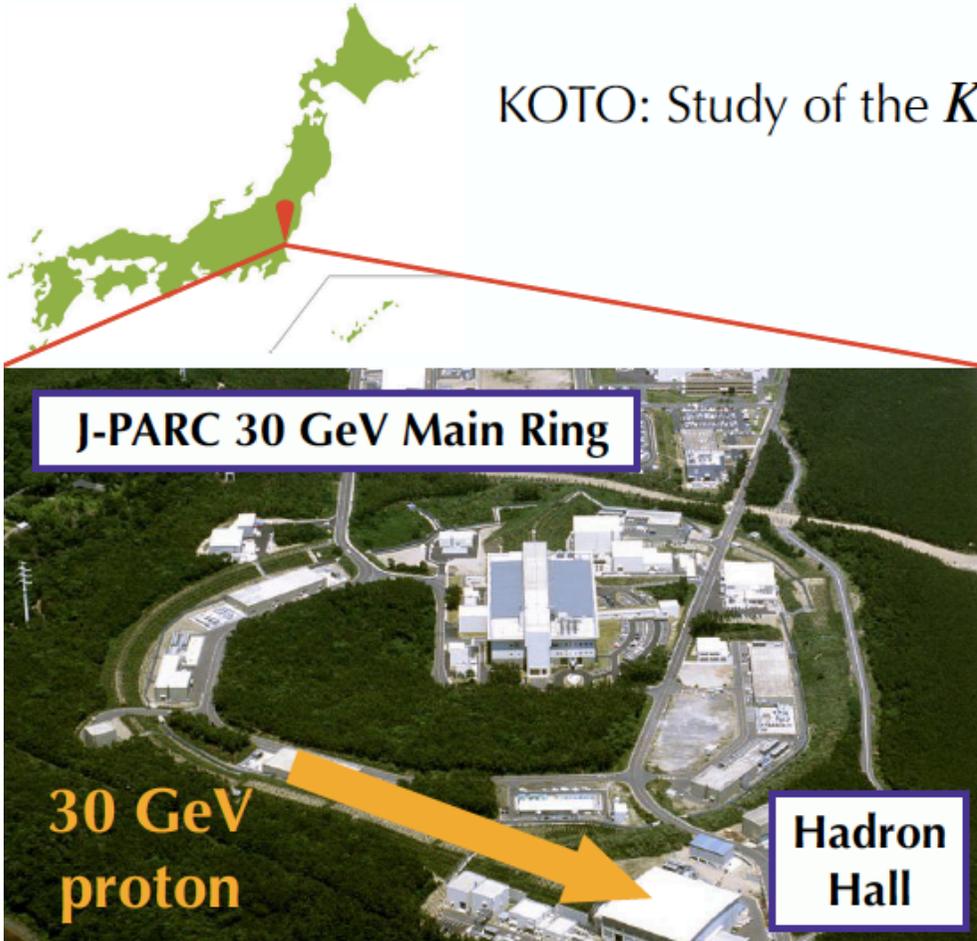
Experimental upper limit  
on  $BR(K_L \rightarrow \pi^0 \nu \bar{\nu})$



Grossman-Nir bound: indirect limit  
from relation to  $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ ;  
Calc'd from NA62 results (2021)  
with  $1\sigma$  region

# KOTO Experiment @ J-PARC

KOTO: Study of the  $K_L \rightarrow \pi^0 \nu \bar{\nu}$  decay at J-PARC in Ibaraki, Japan



KOTO collaboration



Japan



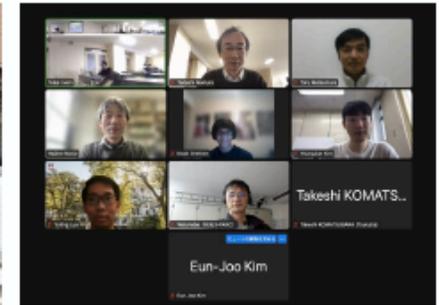
Korea



Taiwan



U.S.



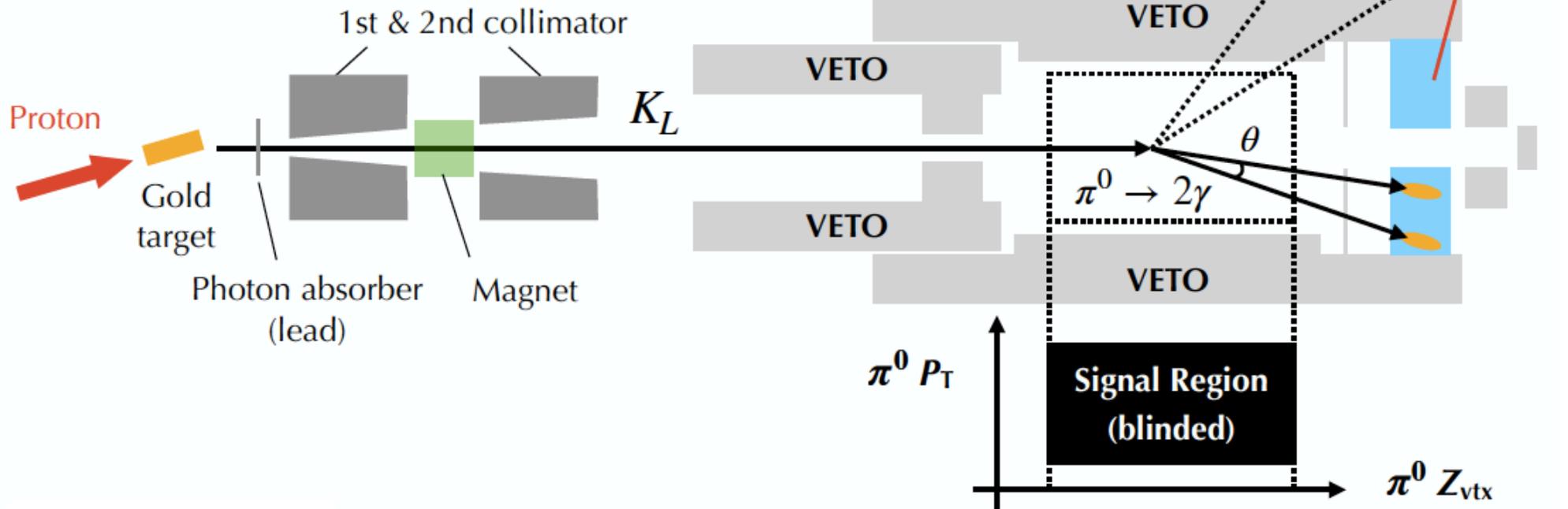
Collaboration Meeting  
(Dec. 2022)

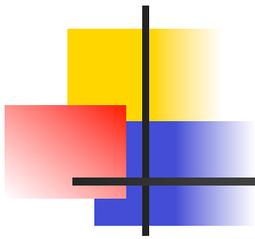
# Experimental Principle

Signature of  $K_L \rightarrow \pi^0 \nu \bar{\nu}$ :  
 $(\pi^0 \rightarrow) 2\gamma \rightarrow$  calorimeter  
 +  
 nothing  $\rightarrow$  veto

$Z_{\text{vtx}}$  on beam axis calculated from

$$M_{\pi^0}^2 = M_{\gamma\gamma}^2 = 2E_{\gamma_1}E_{\gamma_2}(1 - \cos\theta)$$

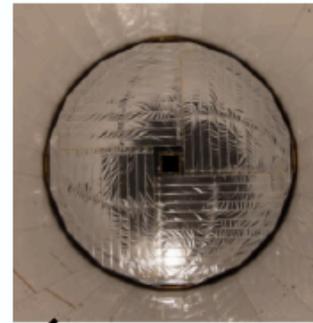
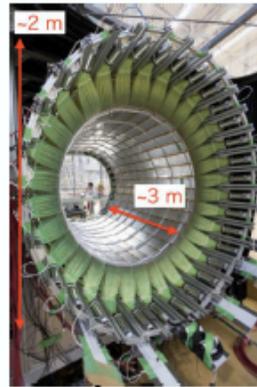
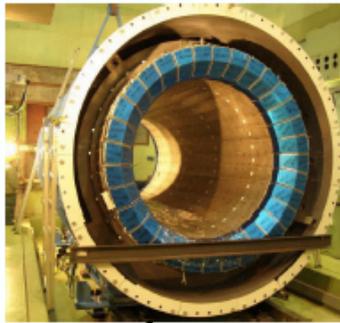
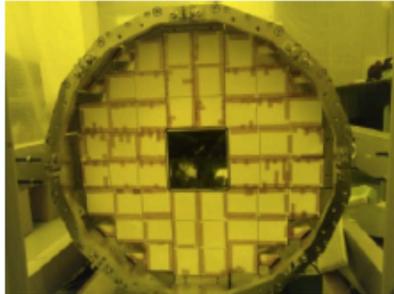




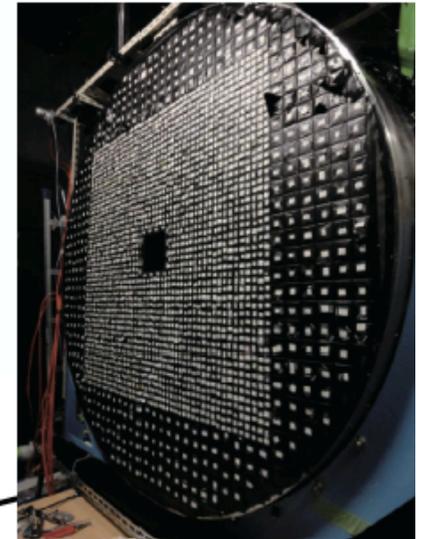
# KOTO Detector



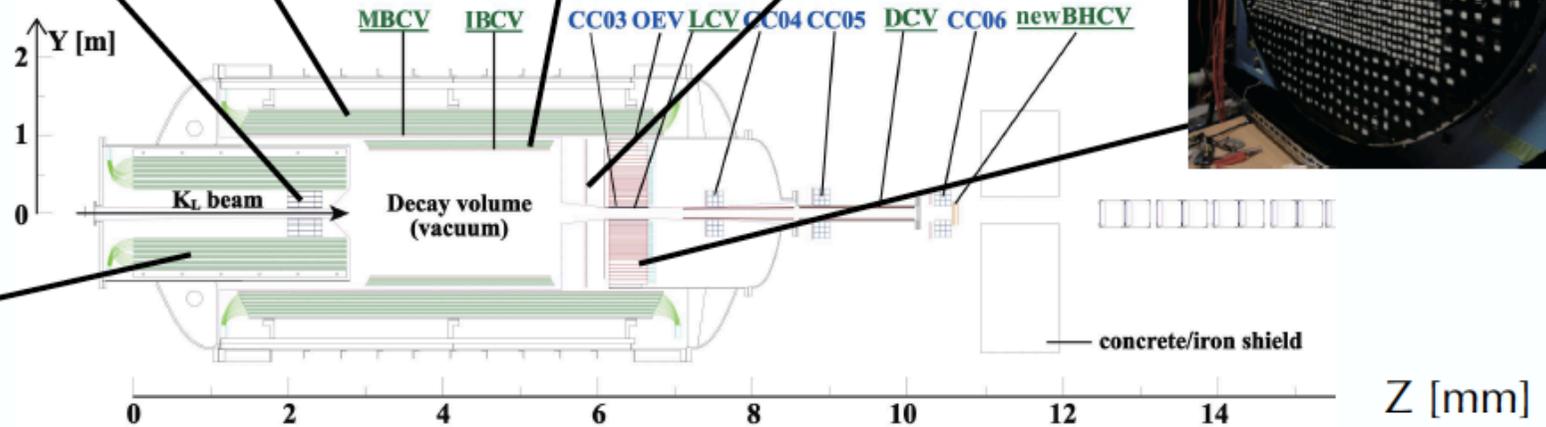
Neutron Collar Counter (NCC)    Main Barrel (MB)    Inner Barrel (IB)    Charged Veto (CV)



Calorimeter (CsI)



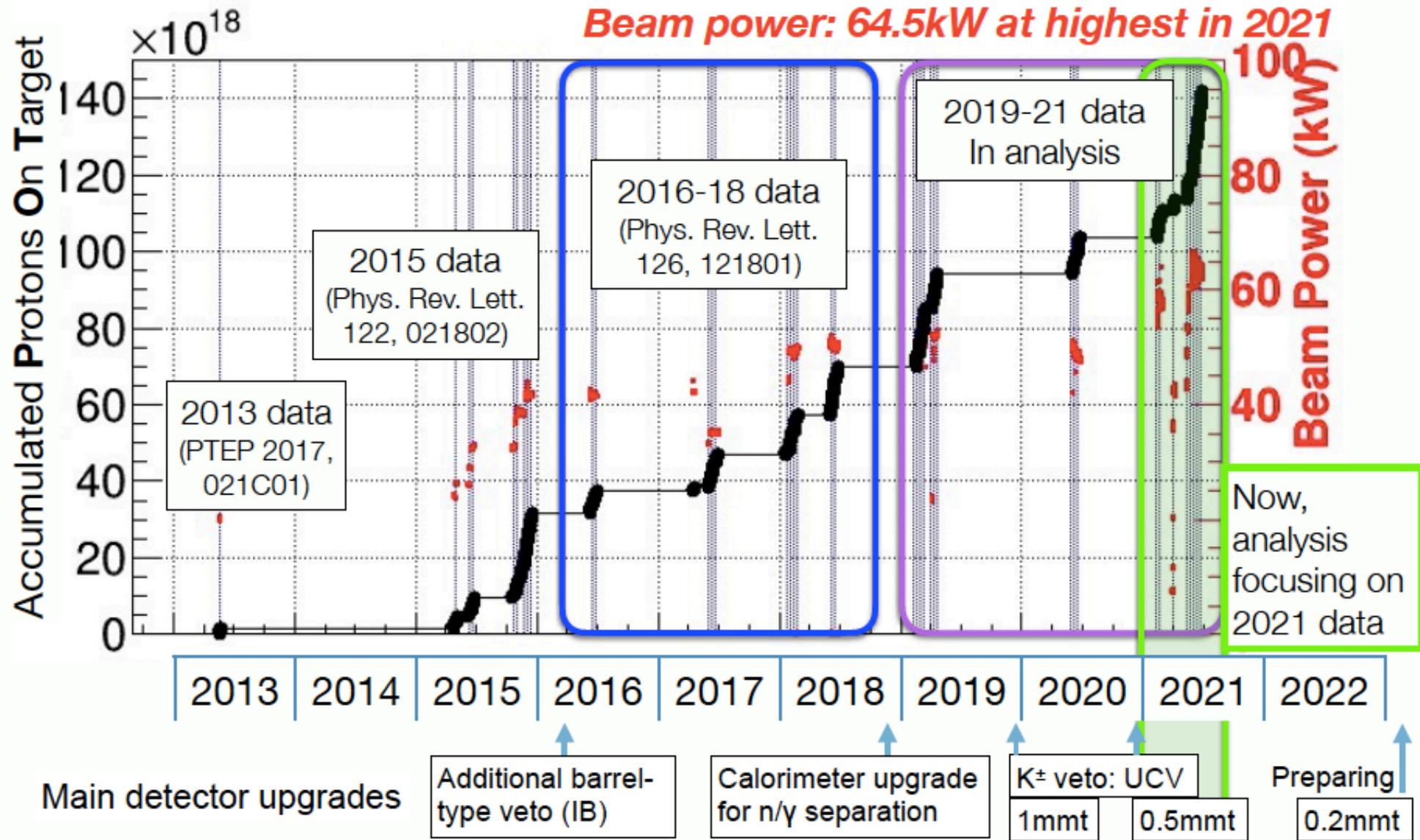
Front Barrel (FB)



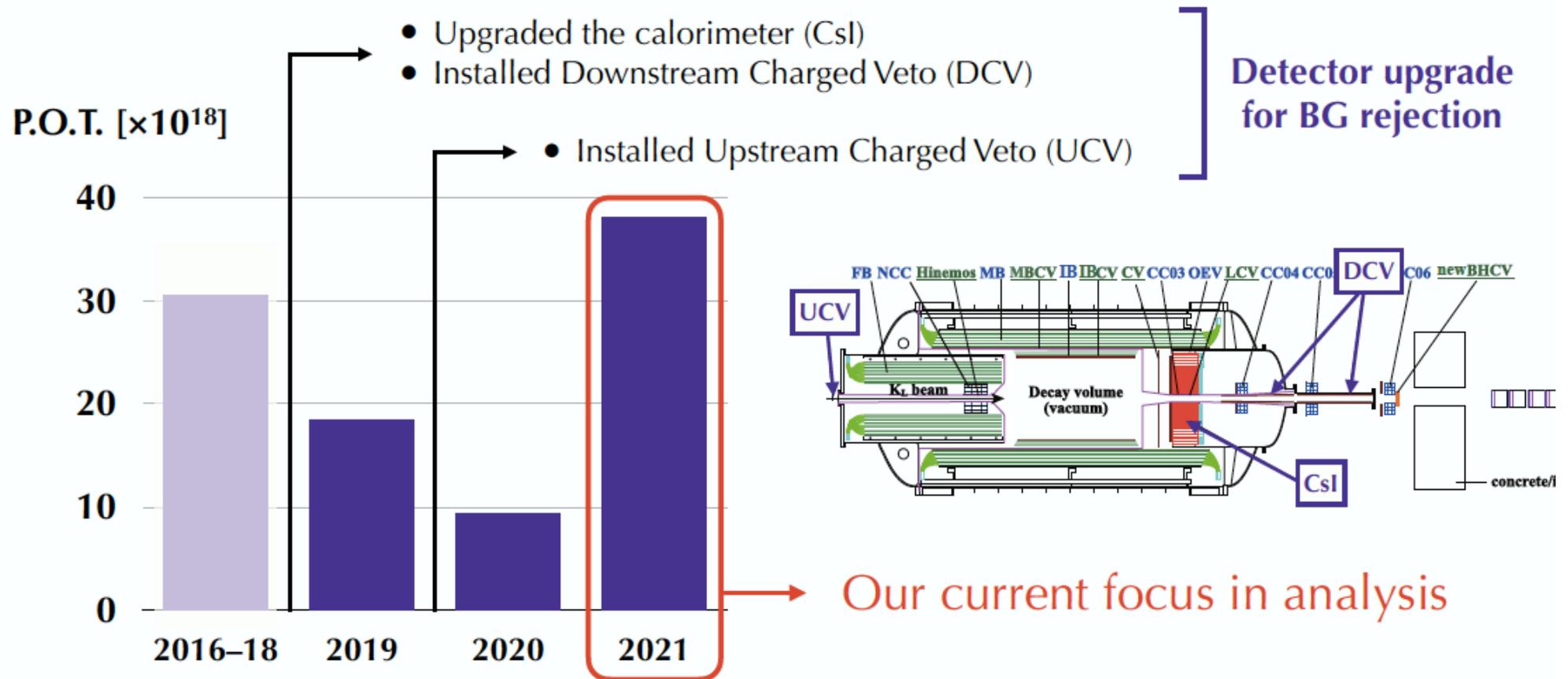
- CsI calorimeter to measure  $2\gamma$
- Hermetic veto to ensure nothing else

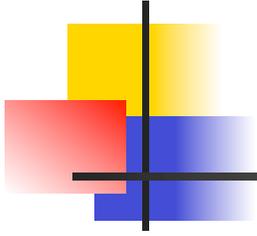


# Run history



# Data Collected in 2019–2021





# Analysis Status

# Results of the 2016–18 Data Analysis



- Single Event Sensitivity:

$$SES = \frac{1}{N_{K_L} \times A_{signal}} = 7.2 \times 10^{-10}$$

- 3 events observed ==> consistent to #BG
- $BR(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 4.9 \times 10^{-9}$  (90% C.L.)

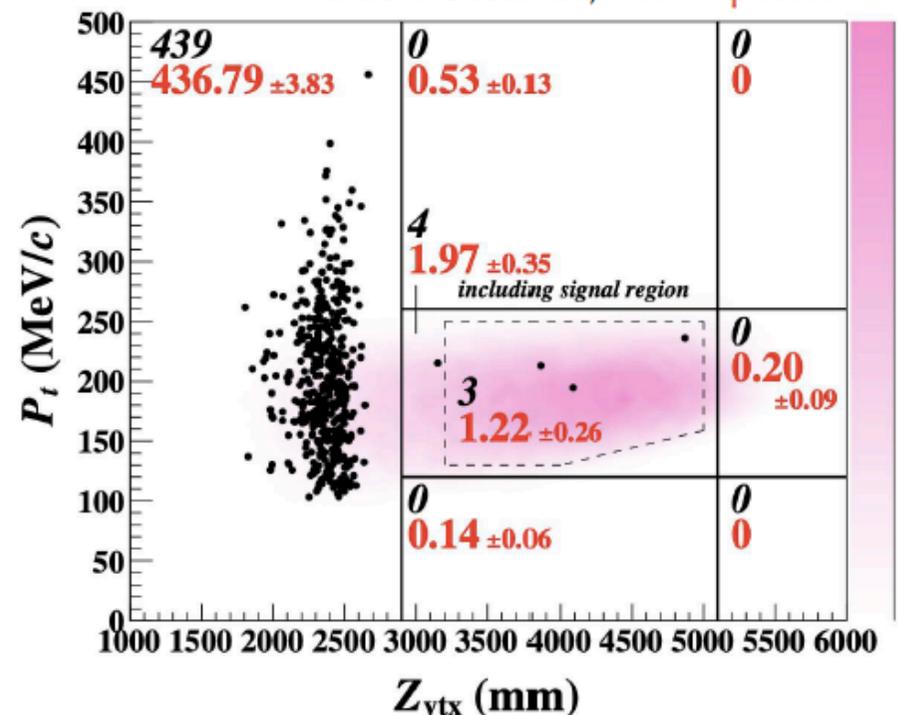
Phys. Rev. Lett. 126, 121801  
(Published in March 2021)

Black: Observed, Red: Expected

Background Table

Source		Number of events
$K_L$	$K_L \rightarrow 3\pi^0$	$0.01 \pm 0.01$
	$K_L \rightarrow 2\gamma$ (beam halo)	$0.26 \pm 0.07^a$
	Other $K_L$ decays	$0.005 \pm 0.005$
$K^\pm$		$0.87 \pm 0.25^a$
Neutron	Hadron cluster	$0.017 \pm 0.002$
	CV $\eta$	$0.03 \pm 0.01$
	Upstream $\pi^0$	$0.03 \pm 0.03$
Total		$1.22 \pm 0.26$

Total #BG =  $1.22 \pm 0.26$



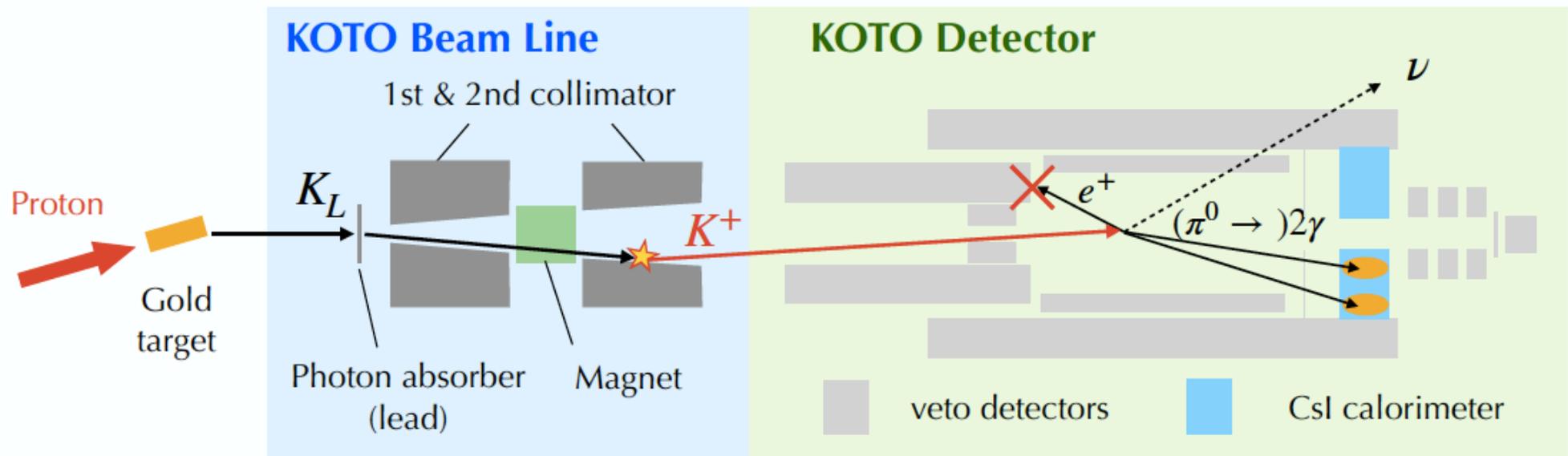
# $K^\pm$ Background

$K^+(K^-)$  that contaminates the  $K_L$  beam is the source of background.

Main contribution:  $K^+ \rightarrow \pi^0 e^+ \nu$  (BR=5%)

- $e^+$  going backward tends to have low energy
- Some dead material

➔ Could miss  $e^+$  and fail to veto this kind of event

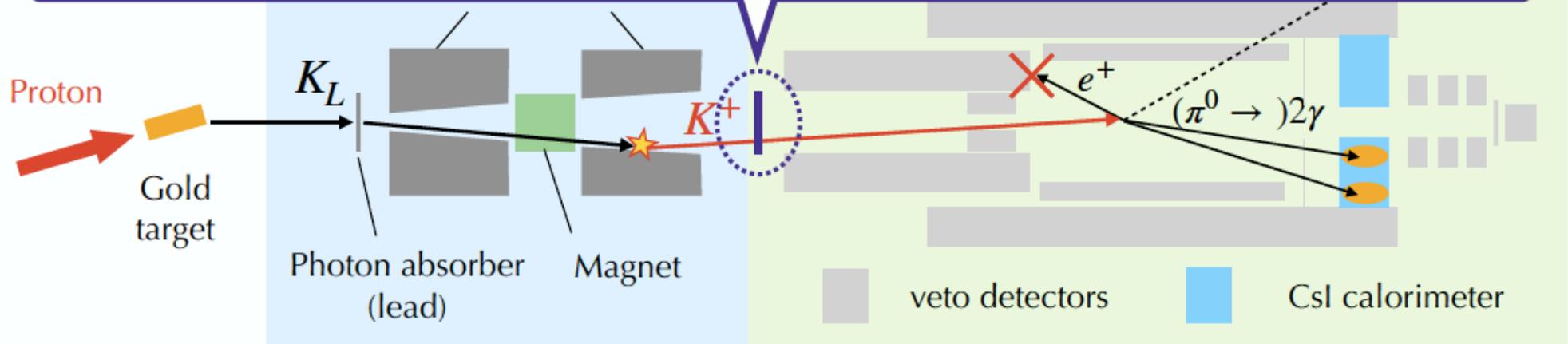
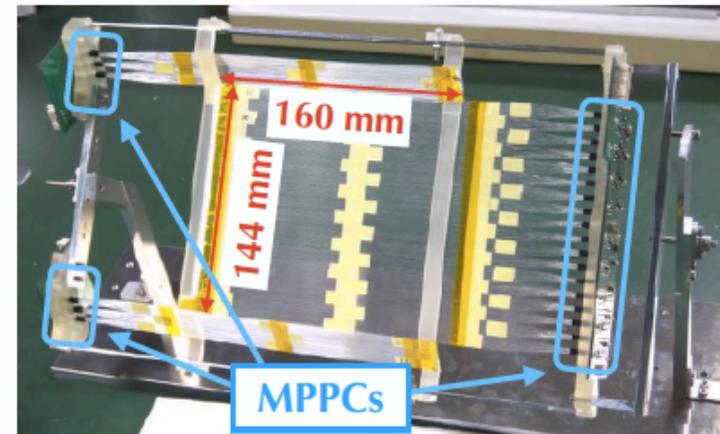


# Upstream Charged Veto (UCV)

Installed **Upstream Charged Veto (UCV)** in 2021

- 0.5-mm-square scintillating fibers
- Readout by silicon photo-sensors (MPPC)
- Detector is tilted by  $25^\circ$  to reduce inefficiency

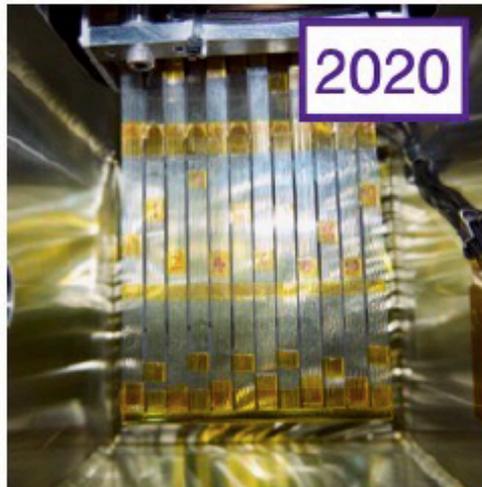
(Prototype was tested in 2020)



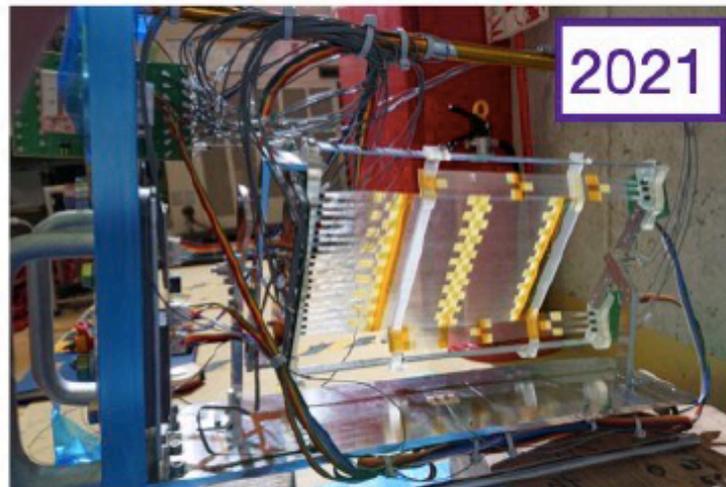
# Upstream Charged Veto (UCV) since 2020

To reject  $K^\pm$  backgrounds, found in 2016-18 data analysis

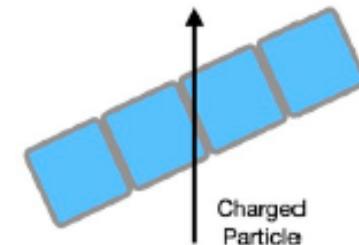
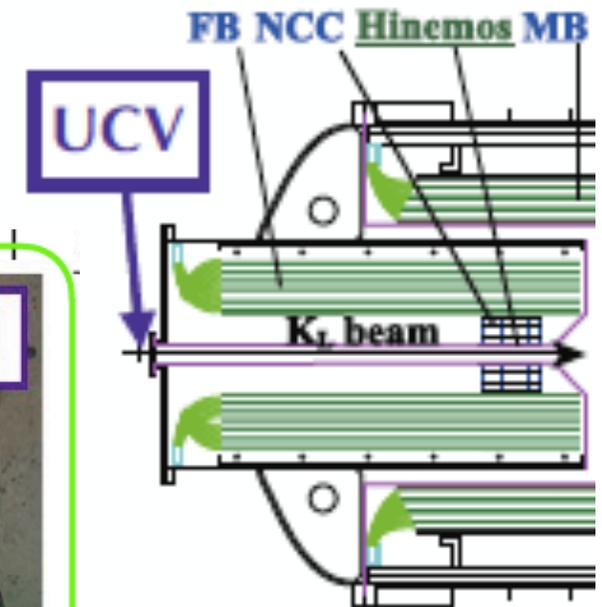
- For  $K^\pm$  detection in the beam at the entrance of the KOTO detector



A plane of 1mm-square scintillation fibers, read by MPPC



A plane of 0.5mm-square fibers  
• Tilted 25 degree to reduce inefficiency due to fibers' clad

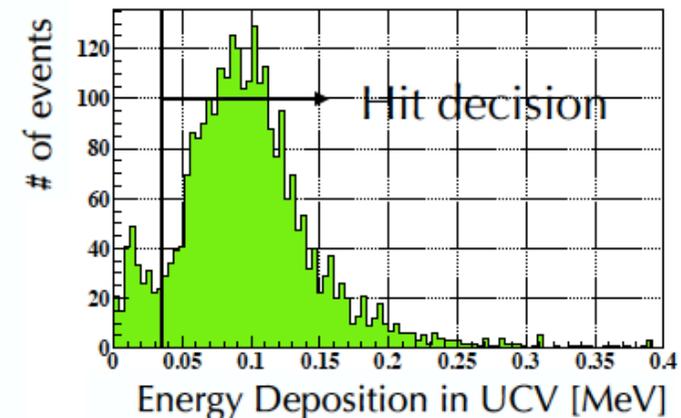
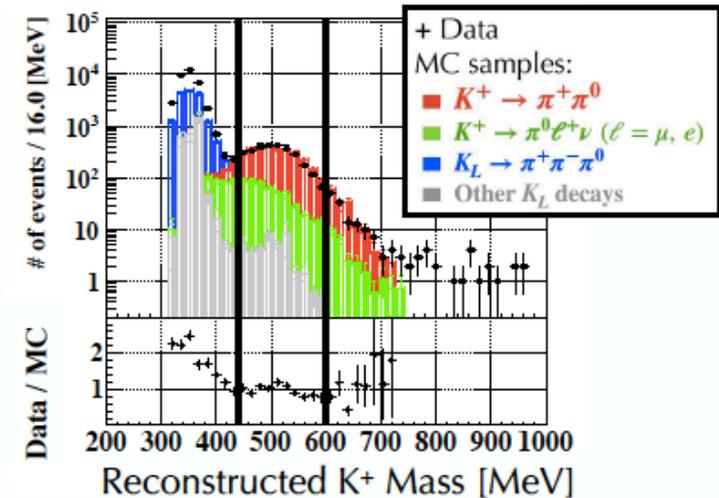
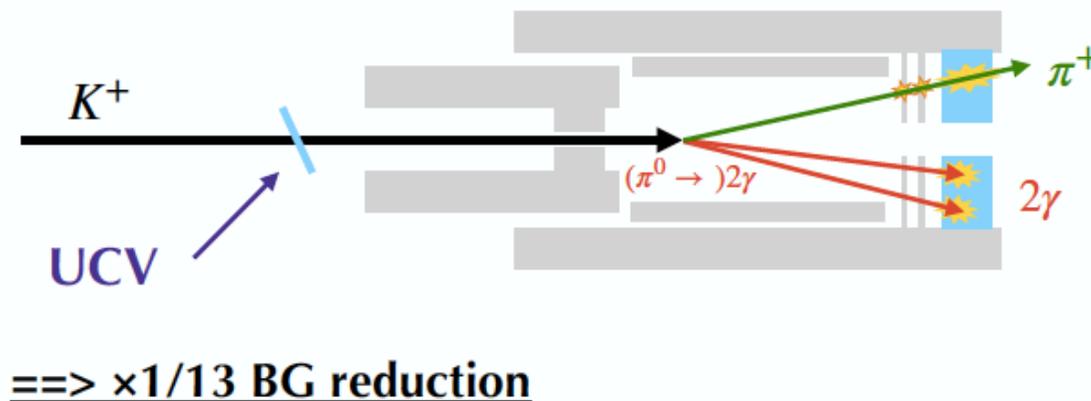


# Reduction of the $K^+$ Background

Performance evaluation using  $K^+$  sample by collecting  $K^+ \rightarrow \pi^+\pi^0$  (BR=21%) events

3 clusters in calorimeter w/ no energy deposition in veto detectors

- $\pi^0$  reconstruction from  $2\gamma$
- $\pi^+$  reconstruction assuming  $p_T$  balance between  $\pi^+$  and  $\pi^0$



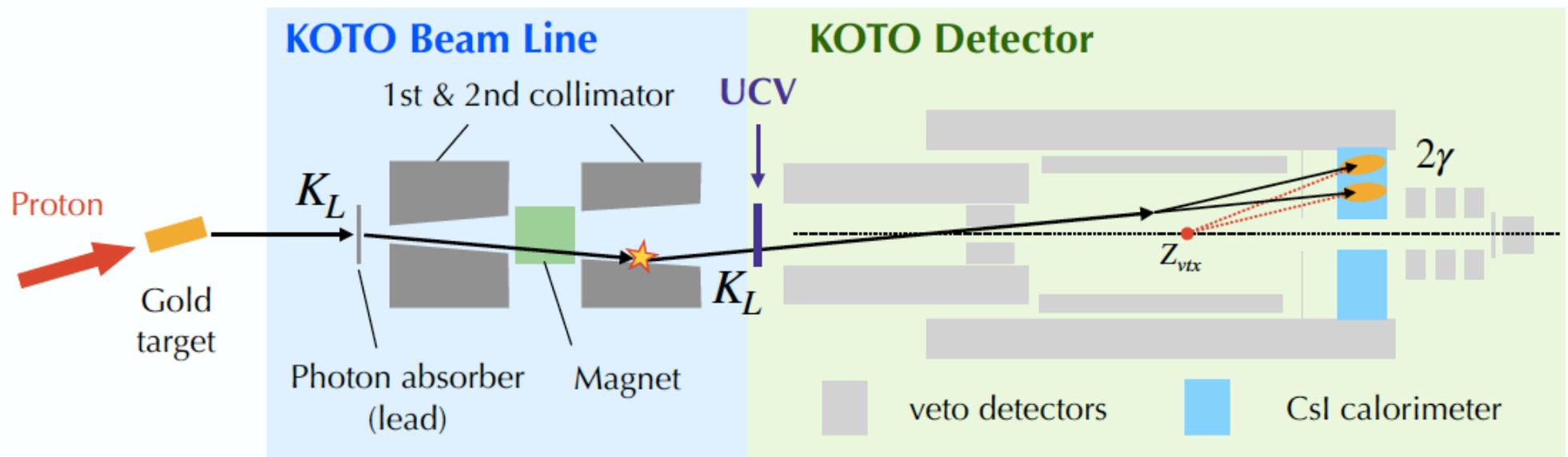
Measured the flux ratio of  $K^+$  to  $K_L$  to be  $F_{K^+}/F_{K_L} = (3.3 \pm 0.1) \times 10^{-5}$ .



# Halo $K_L \rightarrow 2\gamma$ Background

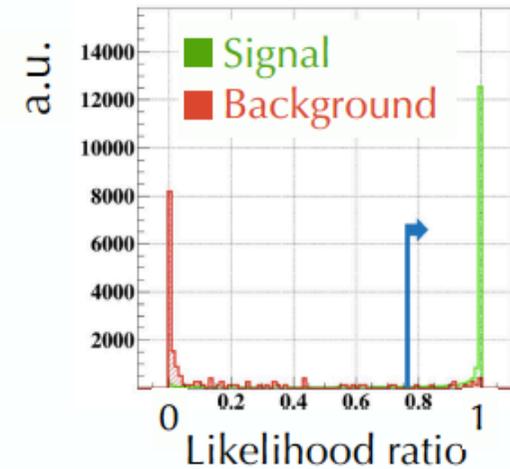
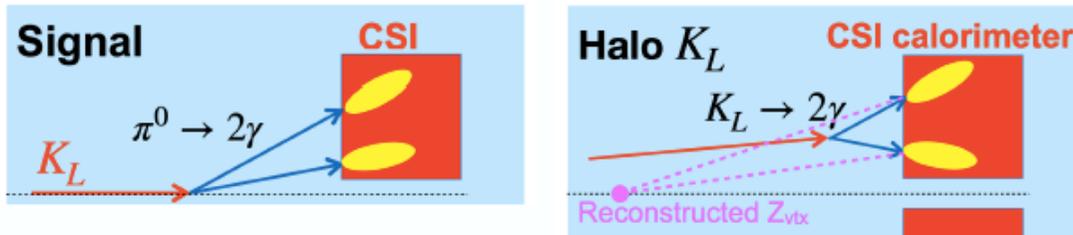
Halo (scattered)  $K_L$  decays into  $2\gamma$  with a finite transverse momentum.

- UCV that was installed to reject  $K^+$  BG also enhances the scattered component.

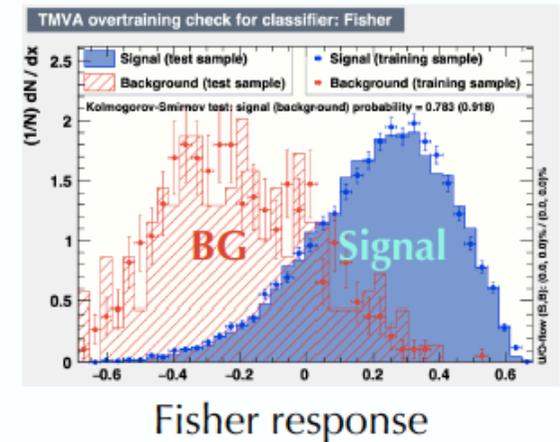
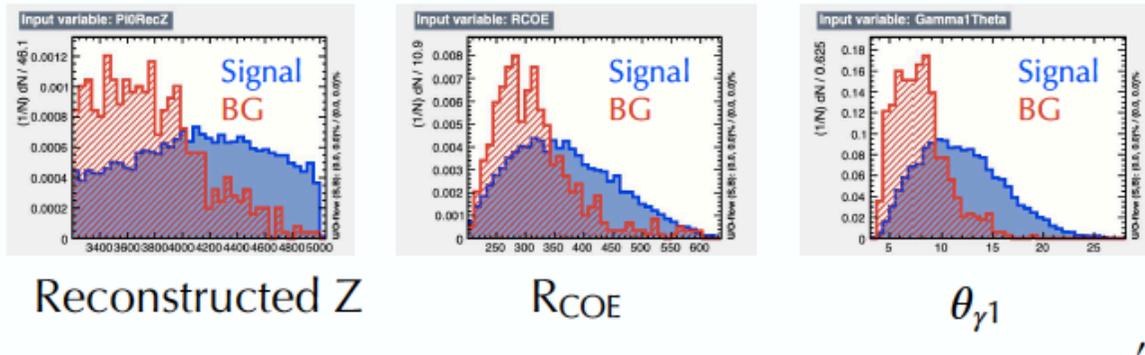


# Reduction of the Halo $K_L \rightarrow 2\gamma$ Background

- ◆ Likelihood ratio based on shower shape consistency



- ◆ Multivariate analysis using Fisher Discriminant



**==> x1/10 BG reduction (with 94% signal acceptance)**

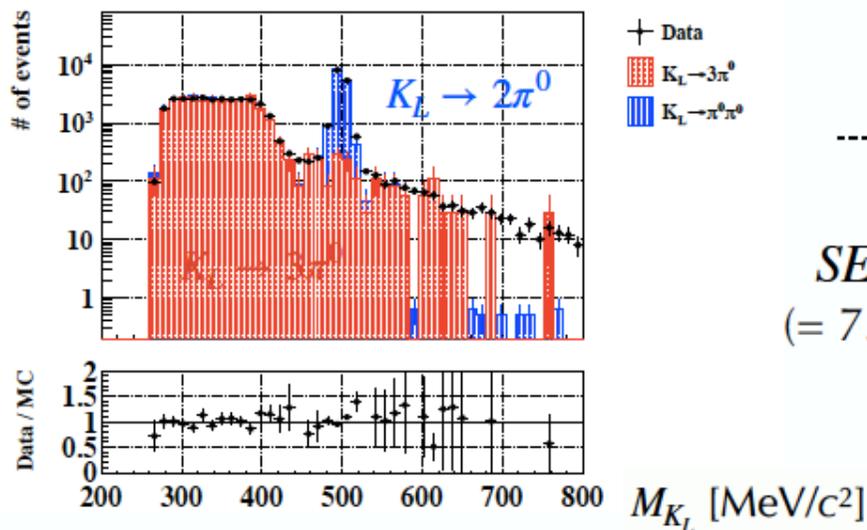


# Sensitivity

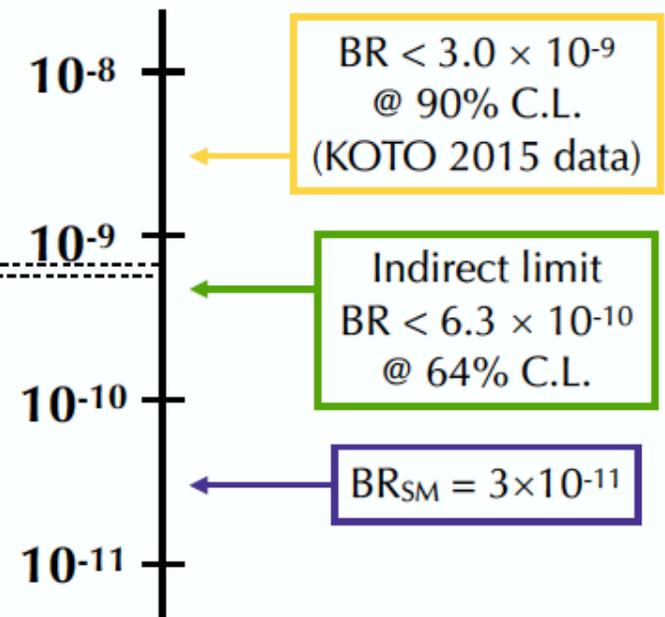
Single Event Sensitivity:

$$SES = \frac{1}{N_{K_L} \times A_{signal}} = 7.9 \times 10^{-10}$$

$\Rightarrow \sim 0.04$  SM events expected



Experimental upper limit  
on  $BR(K_L \rightarrow \pi^0\nu\bar{\nu})$

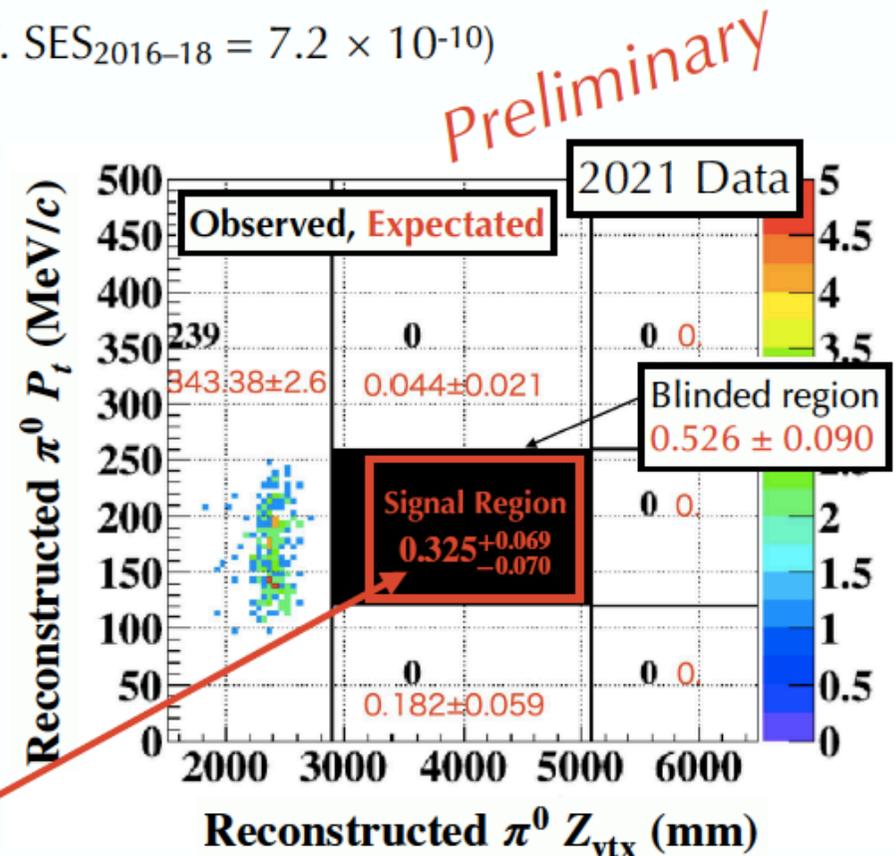


# Summary of the Background Estimation

◆ 2021 data analysis

Single Event Sensitivity (SES) =  $7.9 \times 10^{-10}$  (Cf.  $SES_{2016-18} = 7.2 \times 10^{-10}$ )

Source	#BG in Signal Region
$K_L \rightarrow 2\pi^0$	$0.141 \pm 0.059$
$K^\pm$	$0.043^{+0.016/-0.022}$
Hadron cluster	$0.042 \pm 0.007$
Halo $K_L \rightarrow 2\gamma$	$0.013 \pm 0.006$
Scattered $K_L \rightarrow 2\gamma$	$0.025 \pm 0.005$
$\eta$ production at CV	$0.023 \pm 0.010$
Upstream $\pi^0$	$0.02 \pm 0.02$
$K_L \rightarrow 3\pi^0$	$0.019 \pm 0.019$
<b>Total</b>	<b><math>0.325^{+0.069/-0.070}</math></b>



# Issue on the $K_L \rightarrow 2\pi^0$ Background

We estimated #BG from the  $K_L \rightarrow 2\pi^0$  decay in simulation-based evaluation.

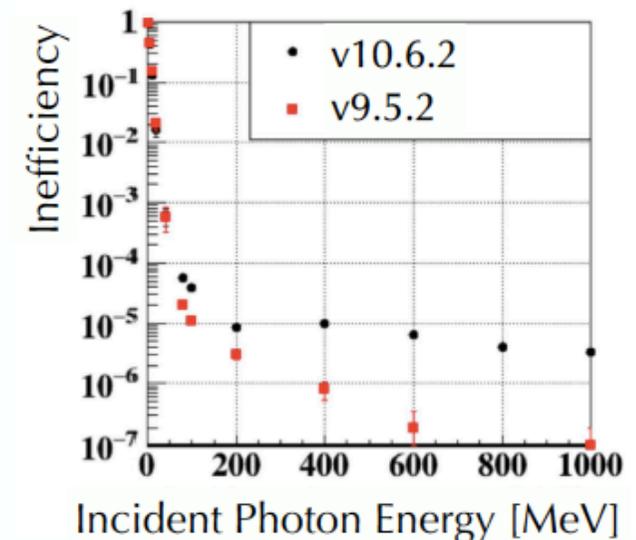
==> Background Level (BGL) was increased due to the different version of Geant4.

(We used Geant4 v9.5.2 for 2016–18, v10.6.2 for 2021.)

	#BG	BGL (= #BG × SES)
2016–2018 analysis (SES = $7.2 \times 10^{-10}$ )	< 0.08 @ 90%CL	< $0.6 \times 10^{-10}$
<b>2021 analysis</b> (SES = $7.9 \times 10^{-10}$ )	<b><math>0.14 \pm 0.06</math></b>	<b><math>1.1 \times 10^{-10}</math></b>

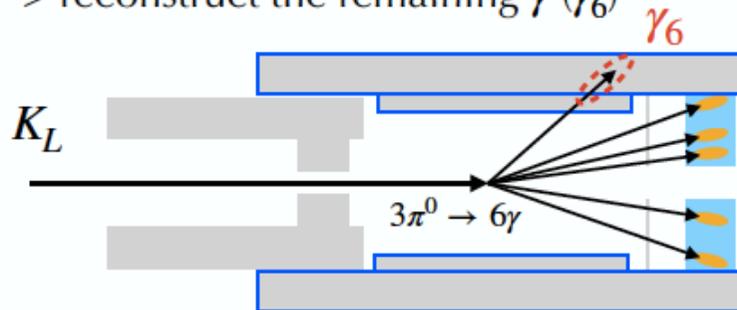
- **Photonuclear (PN) reaction** occurs in the  $K_L \rightarrow 2\pi^0$  events that remain in the signal region.
- Inefficiency of the barrel detectors depends on the version of Geant4. (No difference when turning off the PN process.)
- The physics model of PN process was changed for better code management.

Barrel detector inefficiency  
(simulation study)



# Inefficiency Evaluation with $5\gamma$ Data

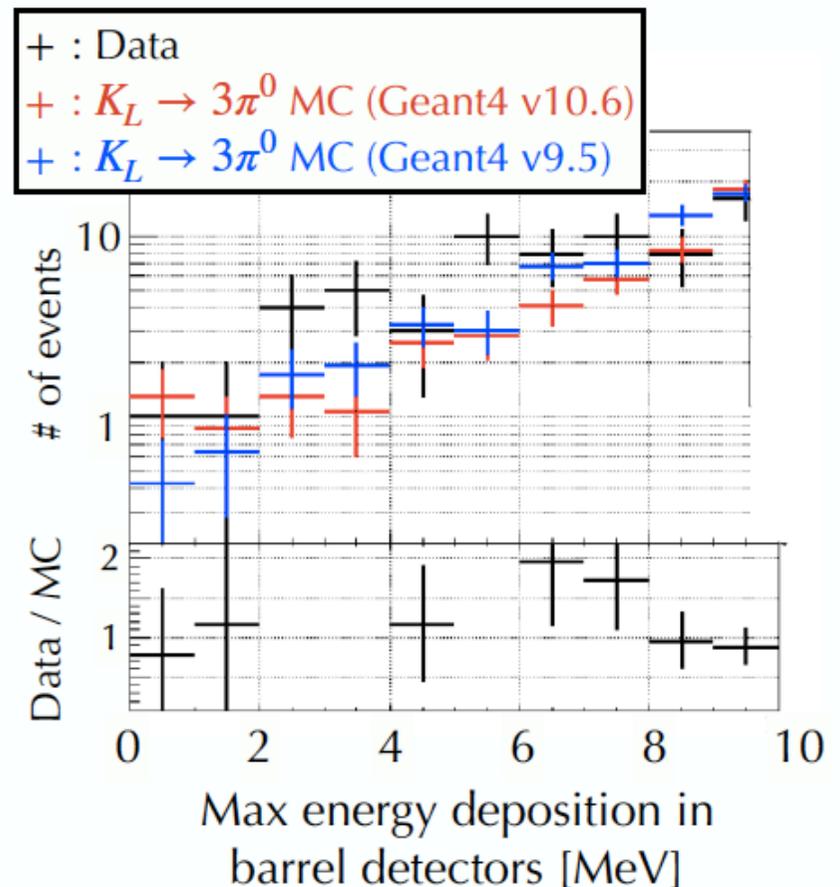
- ◆ Evaluation using  $K_L \rightarrow 3\pi^0 (\rightarrow 6\gamma)$  events  
 Target:  $5\gamma$  in the calorimeter +  $1\gamma$  in the barrel veto  
 → reconstruct the remaining  $\gamma$  ( $\gamma_6$ )



For 1 MeV threshold,

$$\begin{aligned} \text{Inefficiency (Data)} &= (4.8 \pm 4.8) \times 10^{-5} \\ \text{Inefficiency (MC)} &= (6.2 \pm 2.5) \times 10^{-5} \text{ (v10.6)} \\ &= (2.1 \pm 1.5) \times 10^{-5} \text{ (v9.6)} \end{aligned}$$

- ~100% syst. error will be accounted for in  $K_L \rightarrow 2\pi^0$  BG estimation of 2021 analysis
- Need more statistics for future analysis



# Expansion of Computing Resource

Mass production of MC samples using the **Open Science Grid (OSG)** system

- High statistics MC sample (e.g.  $K_L \rightarrow 2\pi^0$ ) for background estimation
- Training sample for deep-learning analysis

Average production rate ( $K_L \rightarrow 2\pi^0$  MC):

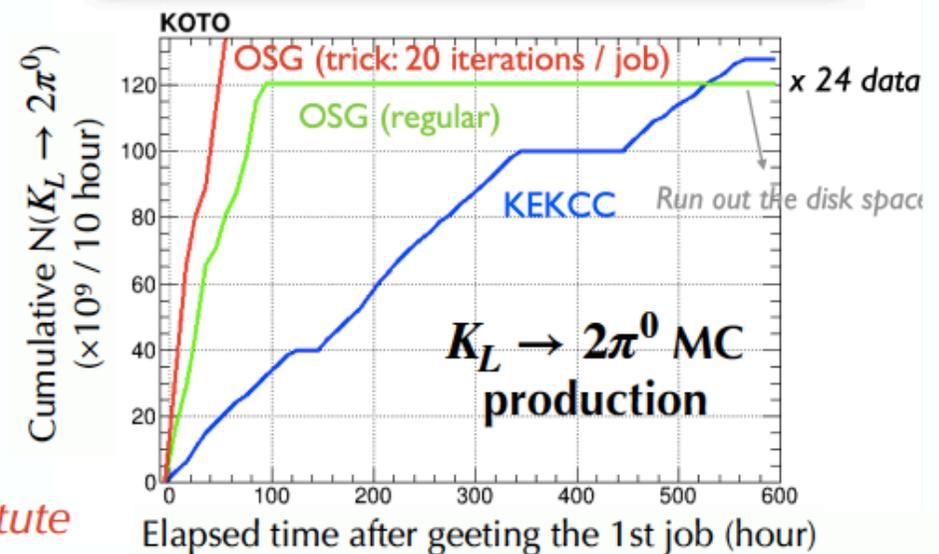
KEKCC =  $3 \times 10^9$  events / 10 hour

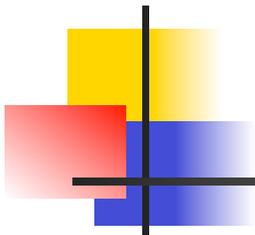
OSG =  $12 \times 10^9$  events / 10 hour (regular)

=  $24 \times 10^9$  events / 10 hour (optimized)

**==> 4–8 times faster production**

*Supported by the UChicago Computational Institute*



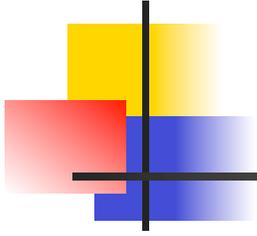


# Toward Unblinding

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We will finish the followings before opening the blinded region.

- Estimation of systematic uncertainties of other backgrounds
- Estimation of minor backgrounds
- Optimization of event selection (multiple cuts against the hadron cluster background) to increase signal acceptance



Next Beam Time 2023-2026

# DAQ Upgrade

Beam power will be increased from 64.5 kW to 80 kW (~100 kW in the future).

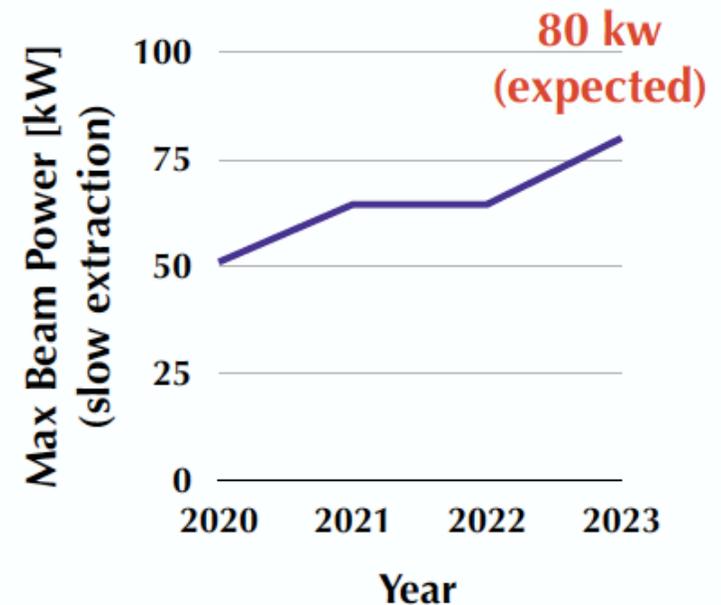


We have been upgrading our DAQ system to

- handle higher trigger rate
- introduce new triggers (e.g. 5-cluster trigger)

*Experts from UChicago are working on this project with other members from Japan (UOsaka) and Taiwan (NTU).*

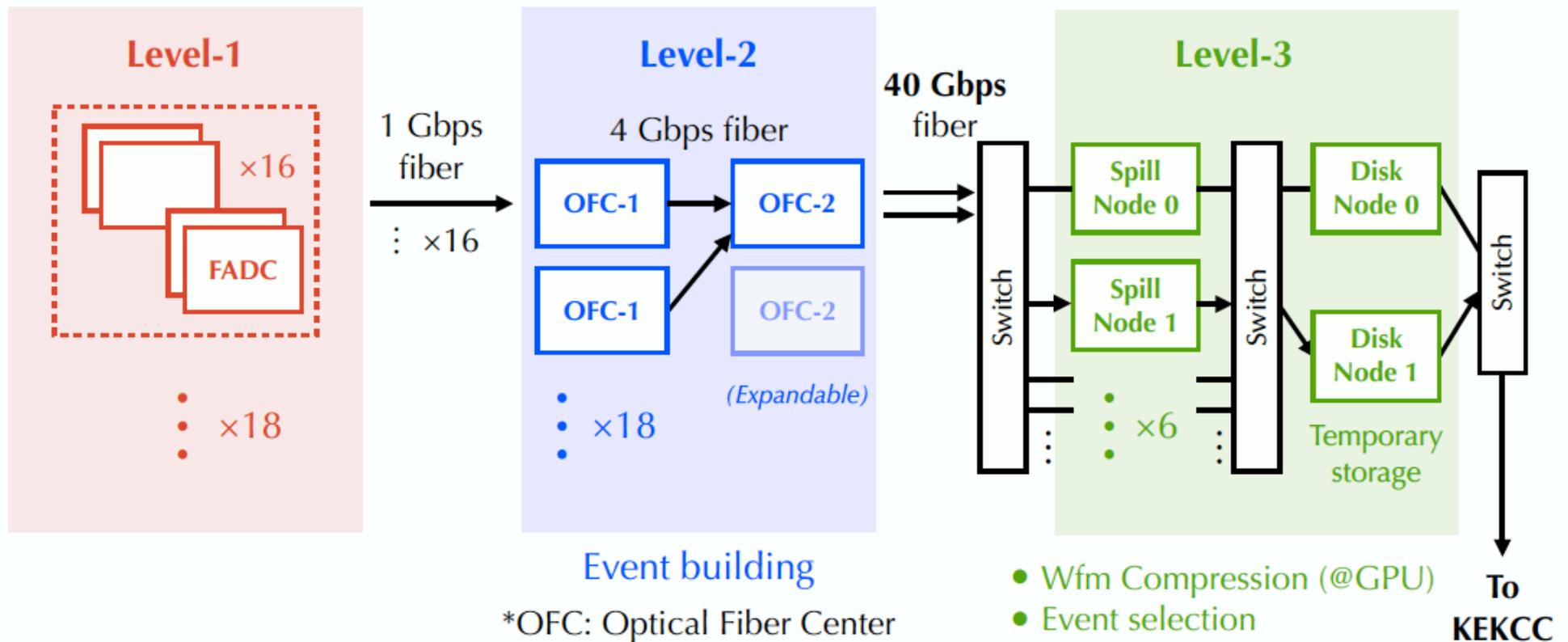
Supported by US-Japan program (2021–2023)

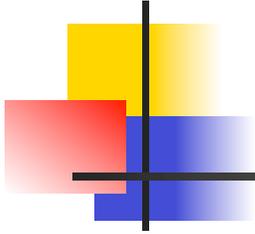


2023 run plan to start in June!

# New DAQ System

DAQ Rate:  $\sim 10$  k events/spill  $\longrightarrow$  **25–30 k events/spill**





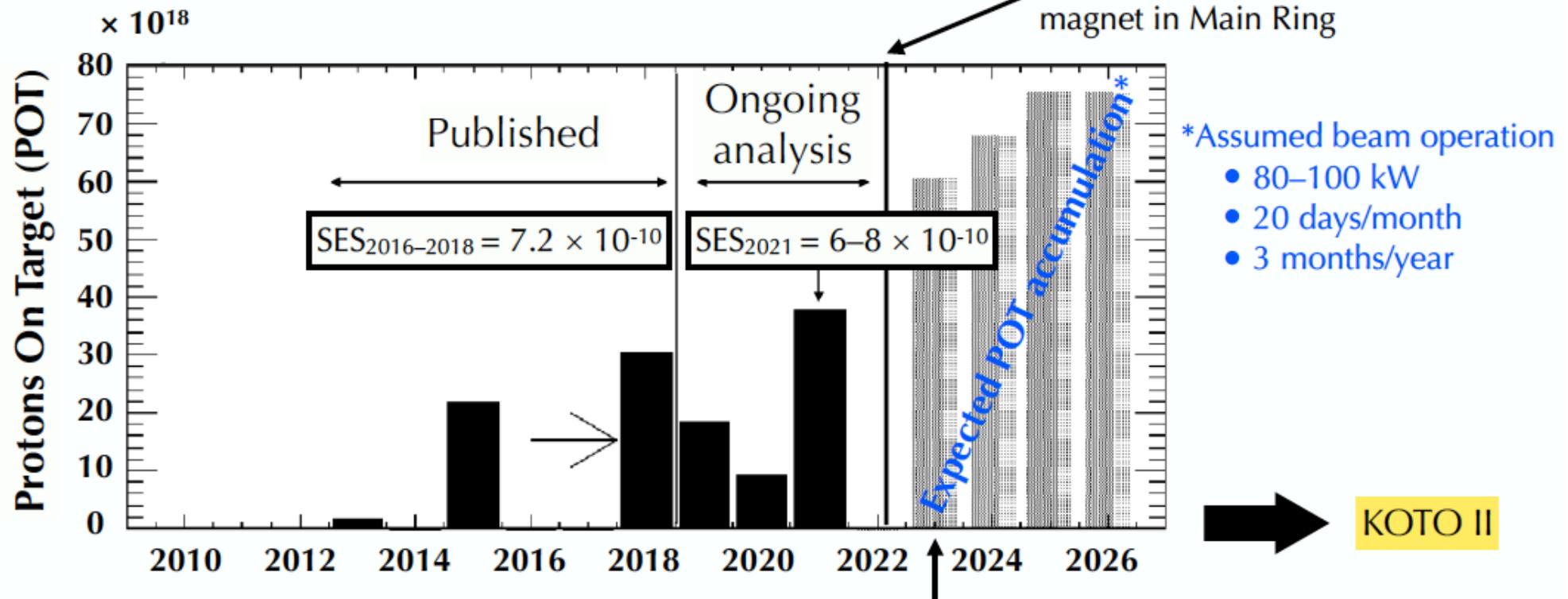
# Summary

- KOTO searches for the rare decay  $K_L \rightarrow \pi^0 \nu \bar{\nu}$  at J-PARC
- Finalizing the analysis of the 2021 data
  - Single Event Sensitivity =  $7.9 \times 10^{-10}$  (preliminary)
  - #BG(total) =  $0.325_{+0.069/-0.070}$  (preliminary)
- For the next data taking,
  - Upgrading our DAQ system to be capable of higher trigger rate for increased beam intensity (> 80 kW)

# Sensitivity Reach of KOTO

KOTO will reach sensitivity  $< 10^{-10}$  in 3–4 years

Upgrade of the power supply of magnet in Main Ring



Upgrade the DAQ system, install a new UCV (done), Install a new magnet for K<sup>+</sup> BG rejection (in Fall)

# KOTO II

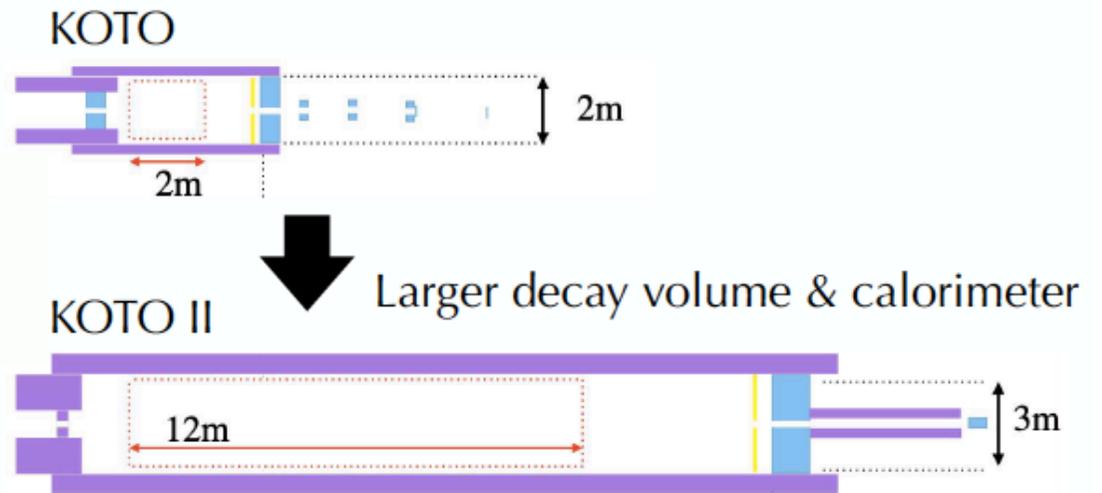
KOTO II

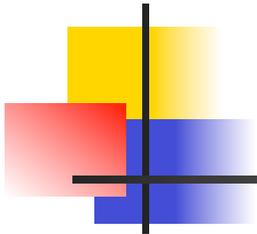
Sensitivity  $\sim O(10^{-13})$ ,  $\sim 40$  SM signals

arXiv:2110.04462

**Extended** Hadron Experimental Facility

Smaller extraction angle:  $16^\circ$ (KOTO)  $\rightarrow$   $5^\circ$ (KOTO II)  $\Rightarrow$  higher flux & momentum



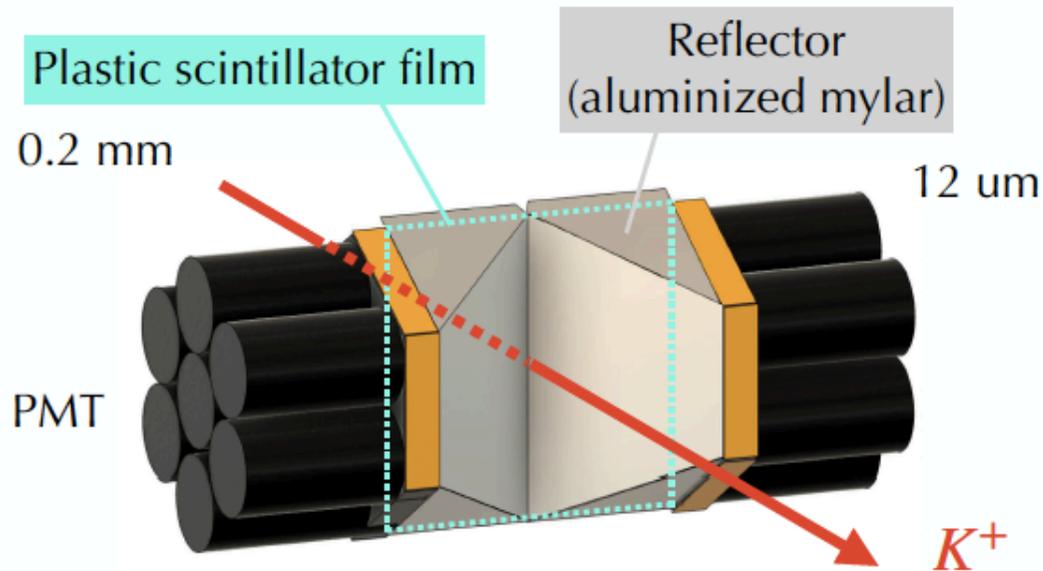


# Backup

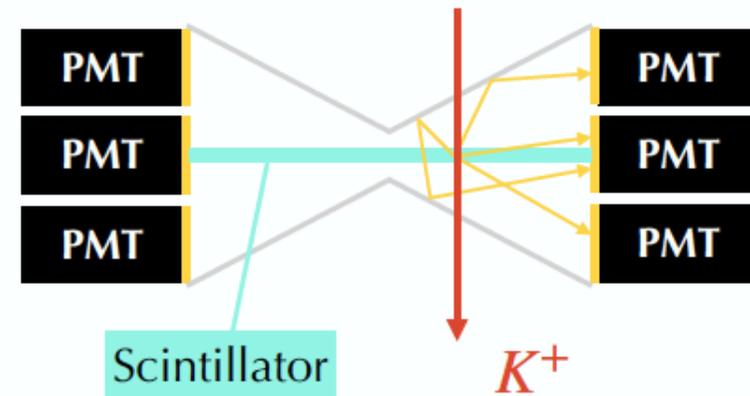
# New Upstream Charged Veto (UCV)

Installed a new upstream charged veto detector with better performance

- Inefficiency  $\sim O(10^{-4})$  (result at  $e^-$  beam test)
- Thinner material (0.2 mm thick film) in beam ( $\rightarrow$  suppress scattering of beam particles)
- PMT readout for better radiation hardness



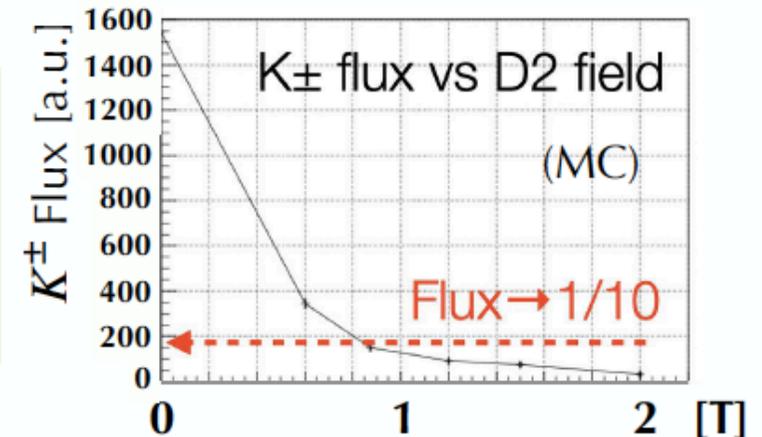
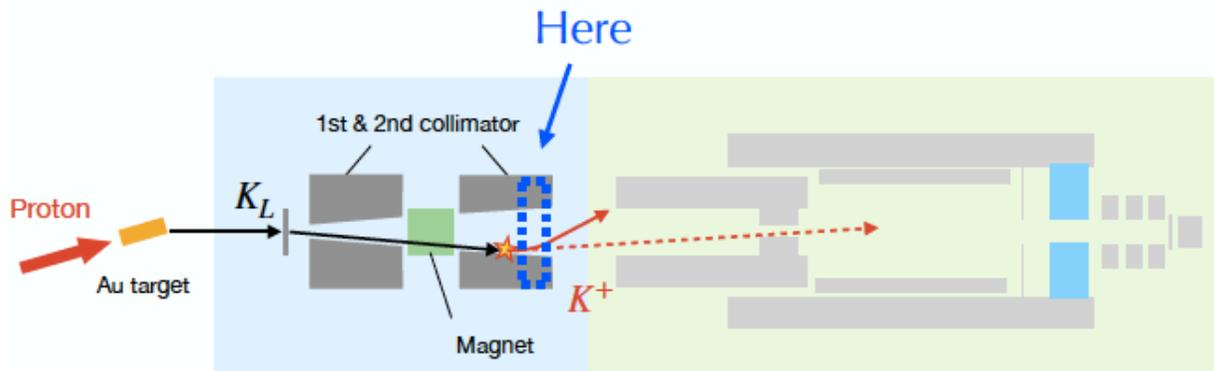
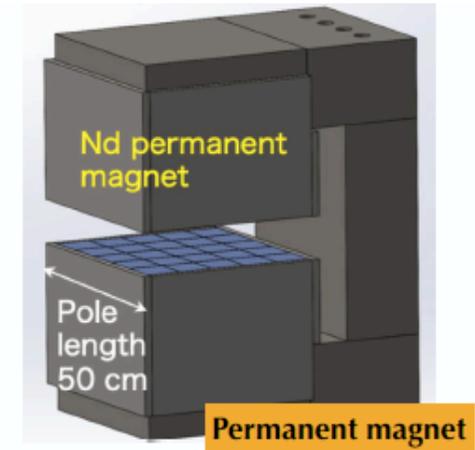
- Collect photons that are **not trapped** inside the scintillator
- $\sim 20$  p.e./MIP (result at  $e^-$  beam test)



# New Magnet

Plan to add a new magnet at the downstream end of the collimator.  
(0.5 m, 0.9 T dipole magnet)  
—> Will reduce the  $K^\pm$  flux by 1/10.

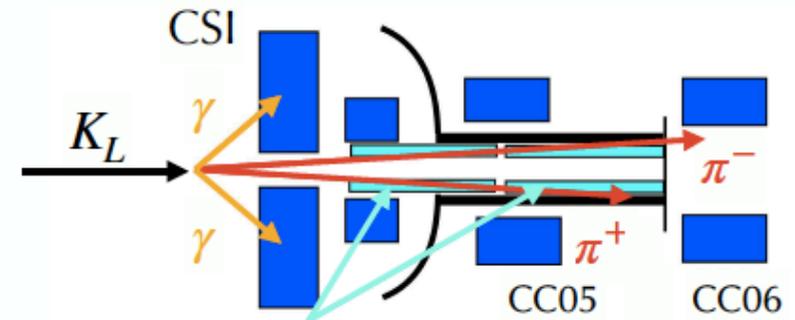
Will be installed this Autumn.



# Downstream Charged Veto (DCV)

Downstream Charged Veto (DCV) (2019–)

- Reject the  $K_L \rightarrow \pi^+\pi^-\pi^0$  BG ( $< 0.07$  @90%CL)  
 $\implies$  acceptance recovery by extending the signal region

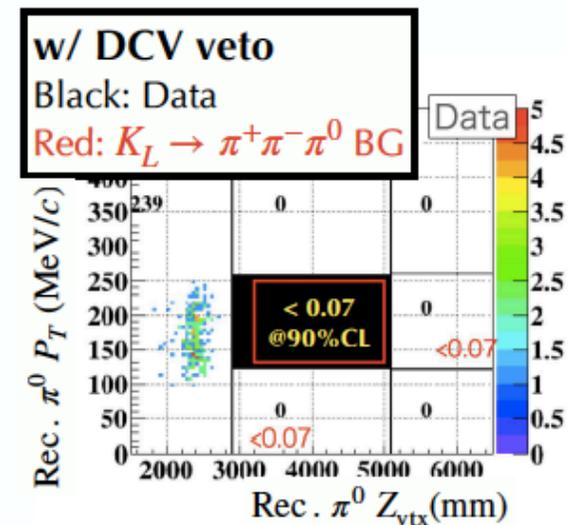
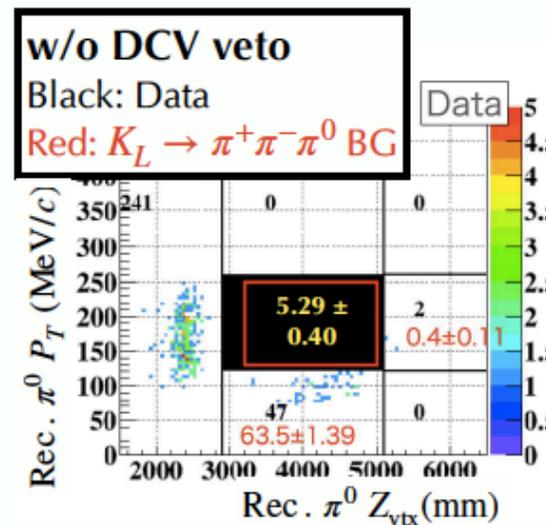


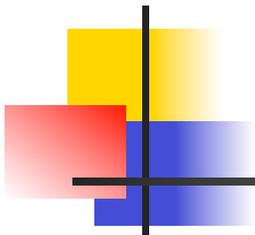
Plastic scintillator plates inside the beam pipe

2016–18 signal region



2021 signal region





# New Level-2

Optical Fiber Center (OFC) is designed to transfer data between ADC and PC.

	OFC-I	OFC-II
<b>Upstream</b>	16 x ADC data	18 x OFC-I data
<b>Downstream</b>	OFC-II	PC (ethernet protocol)
<b>Input/Output</b>	18 x 4 Gbps (18 SFP)	36 x 10 Gbps (9 QSFP)
<b>FPGA type</b>	Arria V	Stratix X
<b>Memory buffer</b>	~50 events	~20 events



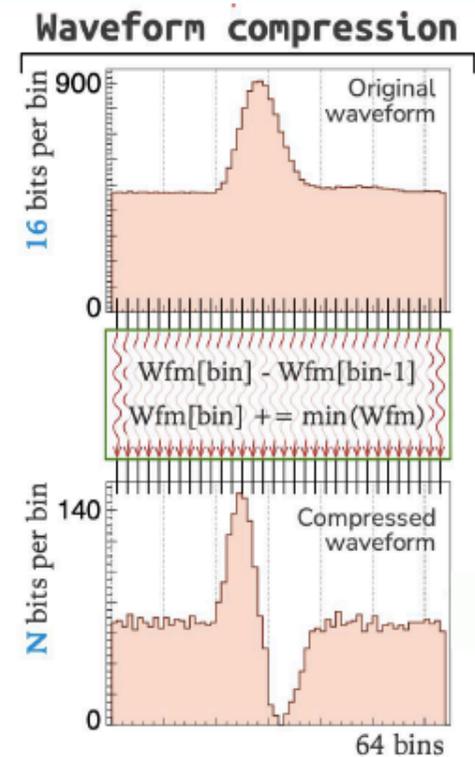
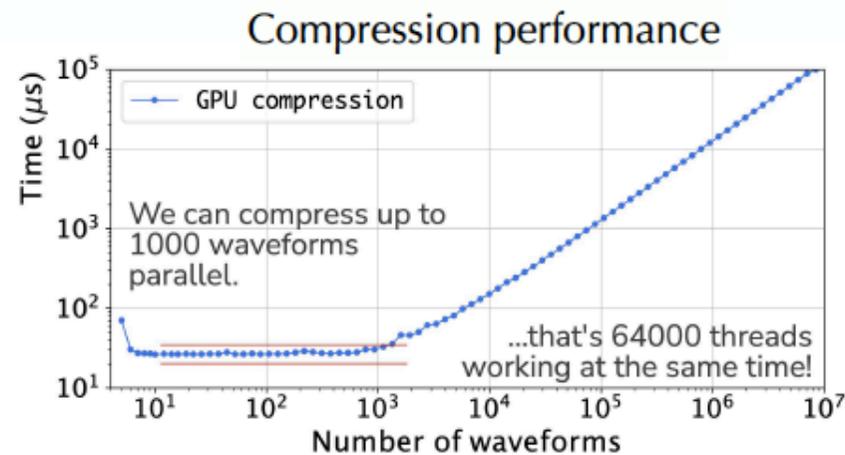
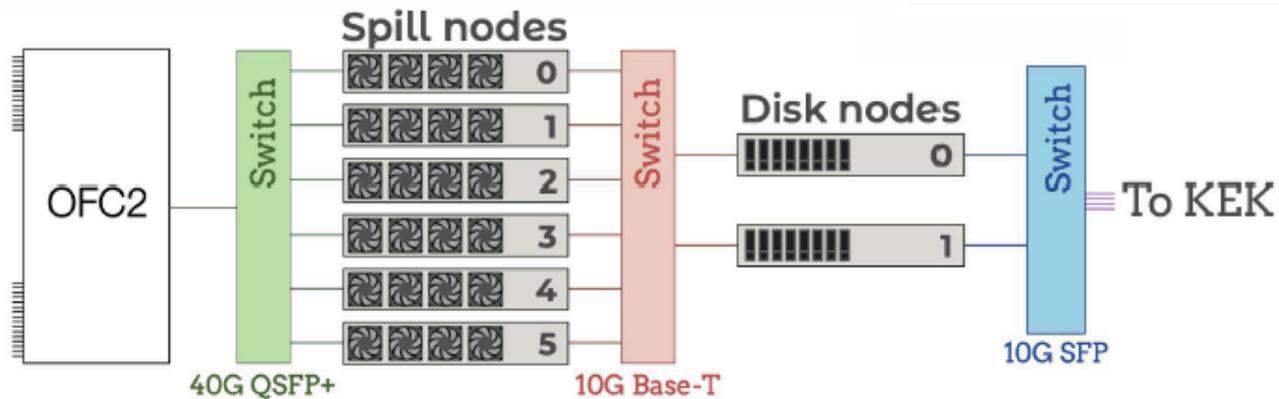
**OFC-I**



**OFC-II**

\* Memory can be read / written simultaneously.

# New Level-3



# Future Data Collection of $5\gamma$ Sample

Trigger rate (per spill) (in case of 64kW beam)

Trigger ingredient	Et	Veto	$N_{\text{cluster}=5}$	Csl fiducial	Center of Energy in Csl	Prescale factor	Final rate
2021 Run	500K	→ 16K	-	-	-	1/30	→ 500
Future run	500K	→ 16K	→ 4K	→ 3.3K	→ 1.5K	1	→ 1.5K

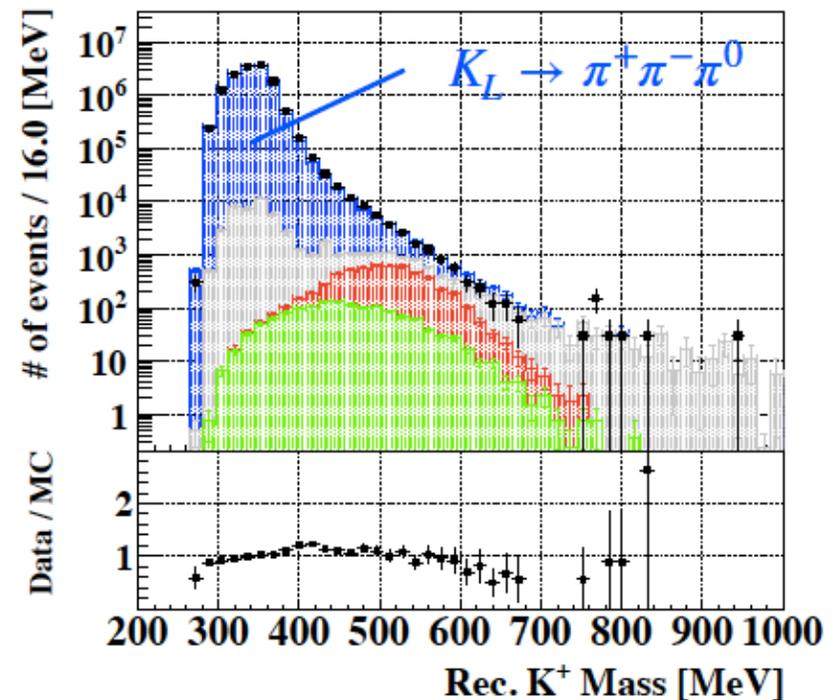
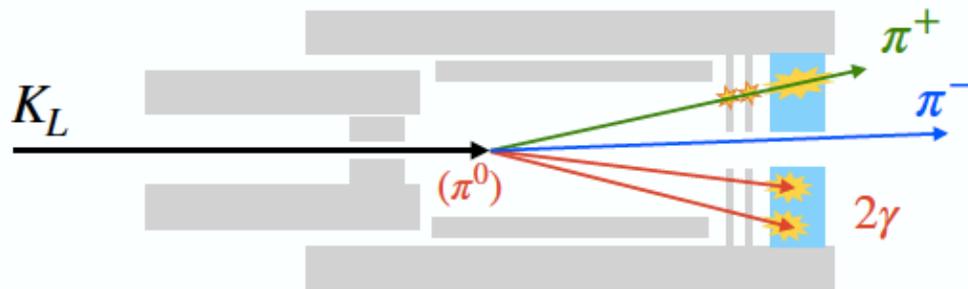
We collect 30 times more data by removing prescale factor

- Csl fiducial: Reject events with hits in the inner most region of the calorimeter
  - COE: Center of energy on the Csl calorimeter
- ==> These event selections will be implemented in the new DAQ system

# $K_L$ Flux Measurement

$K_L$  flux was measured under loose cut selection.

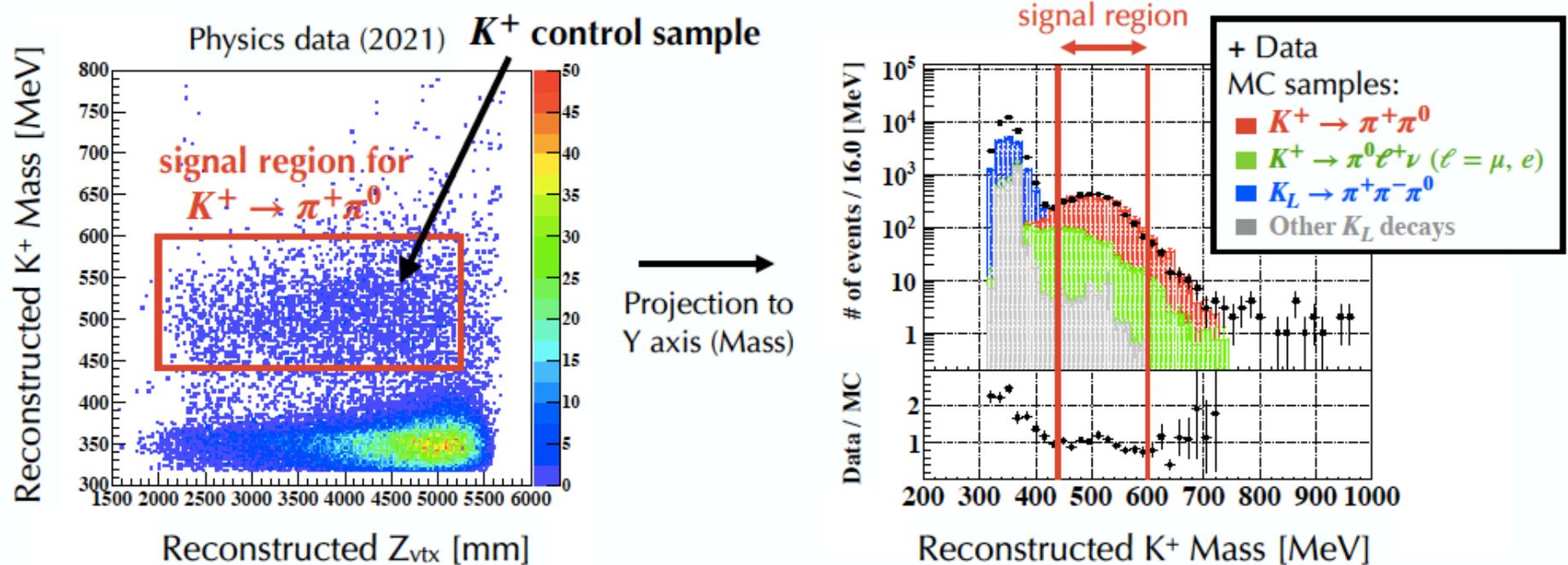
- Flux =  $3.8 \times 10^7 K_L / (2 \times 10^{14} \text{ POT})$
- Purity of  $K_L \rightarrow \pi^+ \pi^- \pi^0$  events > 99%



# $K^+$ Flux Measurement

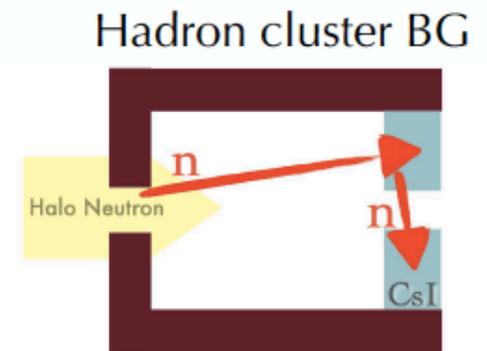
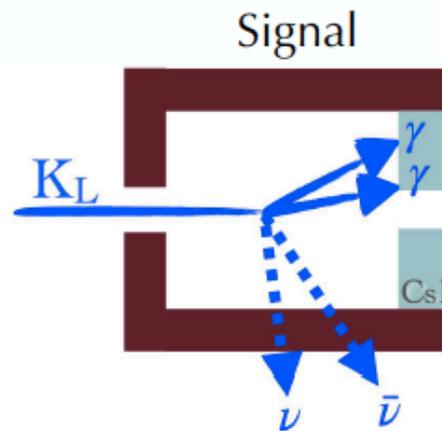
Measured the flux ratio of  $K^+$  to  $K_L$  to be  $F_{K^+}/F_{K_L} = (3.3 \pm 0.1) \times 10^{-5}$ .

- $K_L$  flux was measured under loose selection where  $K_L \rightarrow \pi^+\pi^-\pi^0$  is dominant
- There is 1.4% of  $K_L$  contamination in the  $K^+$  sample

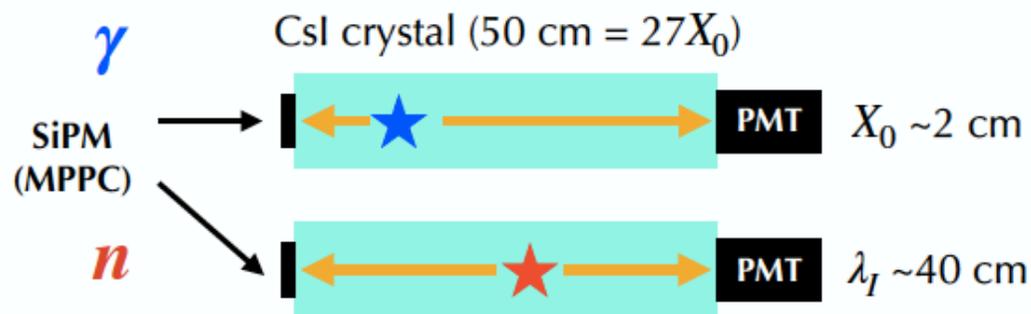


# Upgrade of the Calorimeter

- ◆ Hadron cluster background  
Halo neutron hits the calorimeter, which makes another cluster



- ◆ Both-end readout  
=>  $\gamma/n$  separation by  $\Delta T$  between front-side(SiPM) & rear-side(PMT)



Front view  
(~4000 MPPCs in total)

