KOTO:
Search for Rare Neutral-Kaon Decays at J-PARC

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on behalf of the KOTO collaboration
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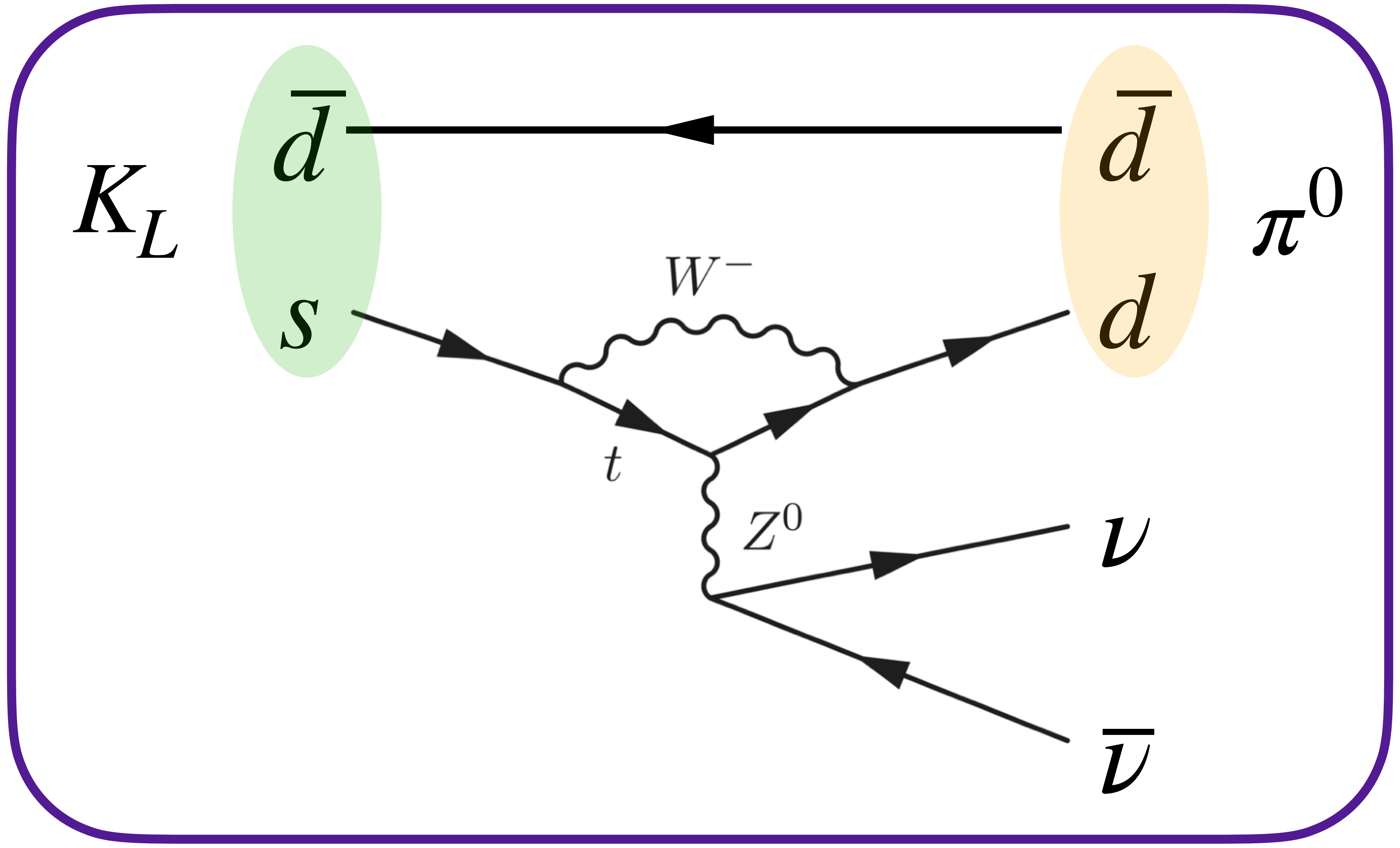
Search for $K_L \to \pi^0 \nu \bar{\nu}$

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

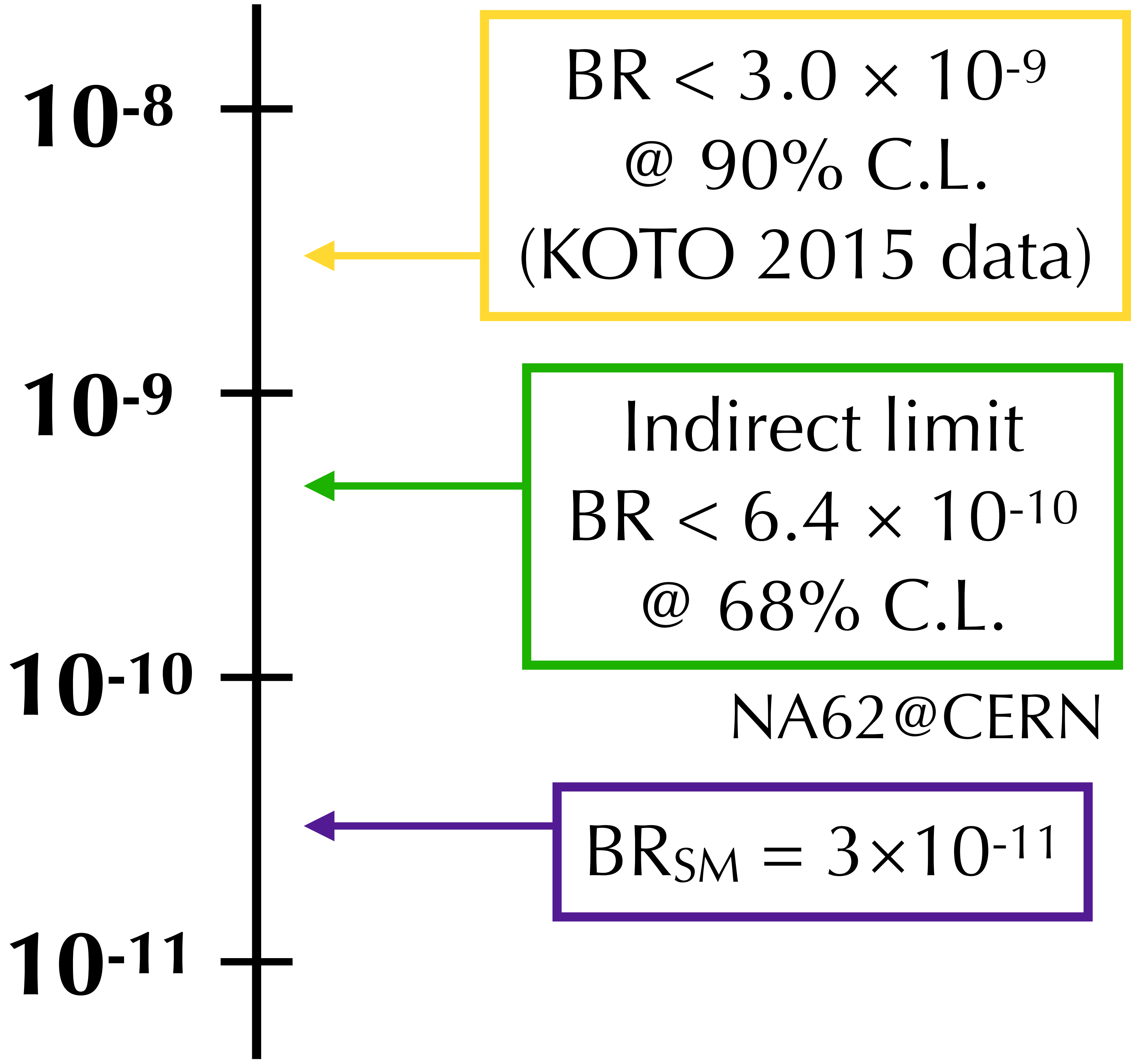
- Direct CP-violating process
- Highly suppressed: $BR(K_L \to \pi^0 \nu \bar{\nu})_{SM} = 3 \times 10^{-11}$
- Well known: ~2% theoretical uncertainties

→ Good probe to search for New Physics

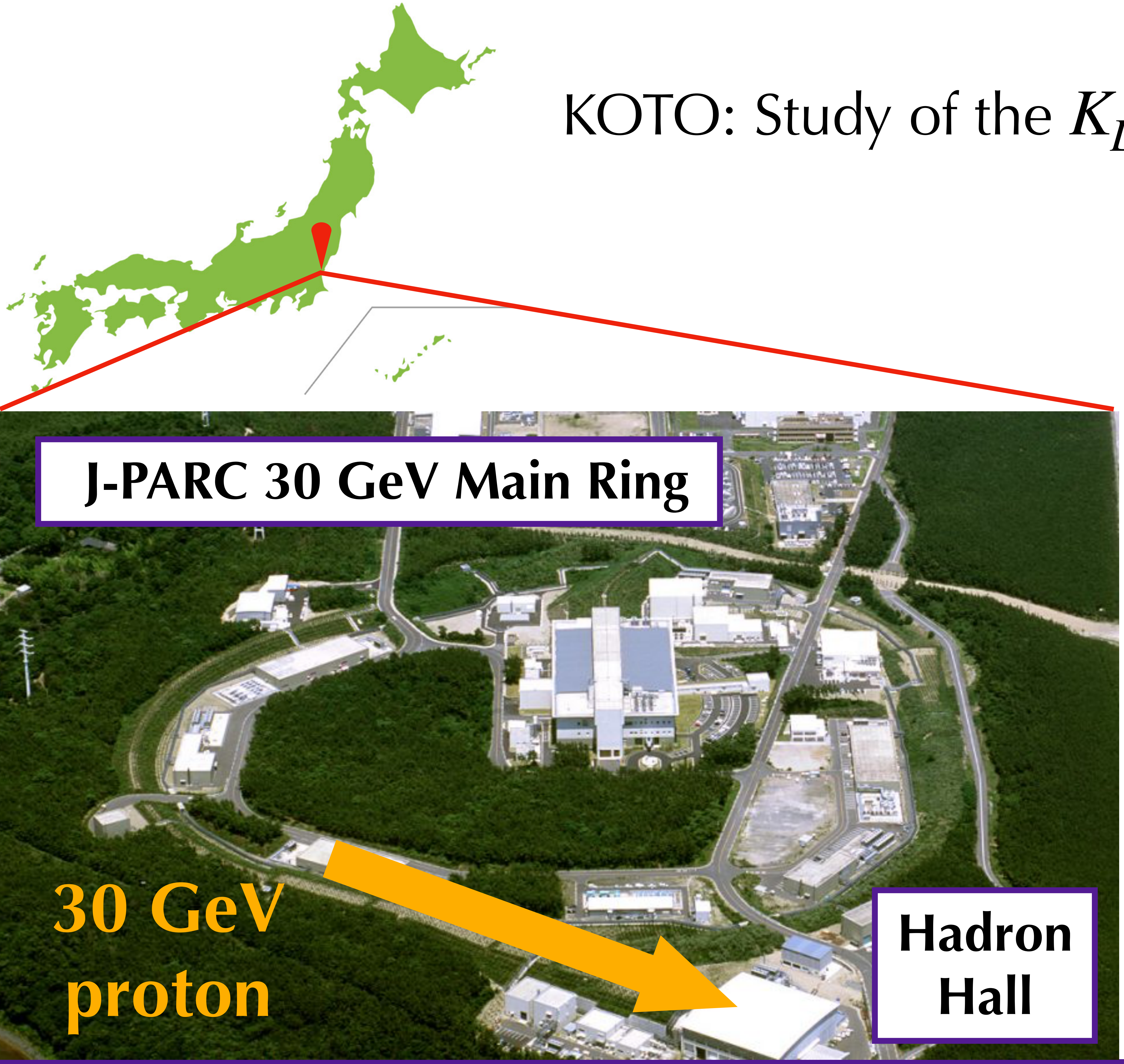


\+ NP

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

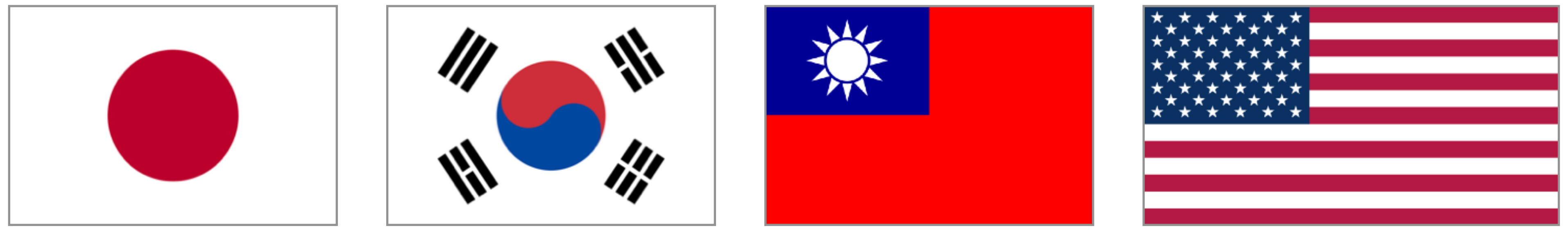


KOTO Experiment @ J-PARC

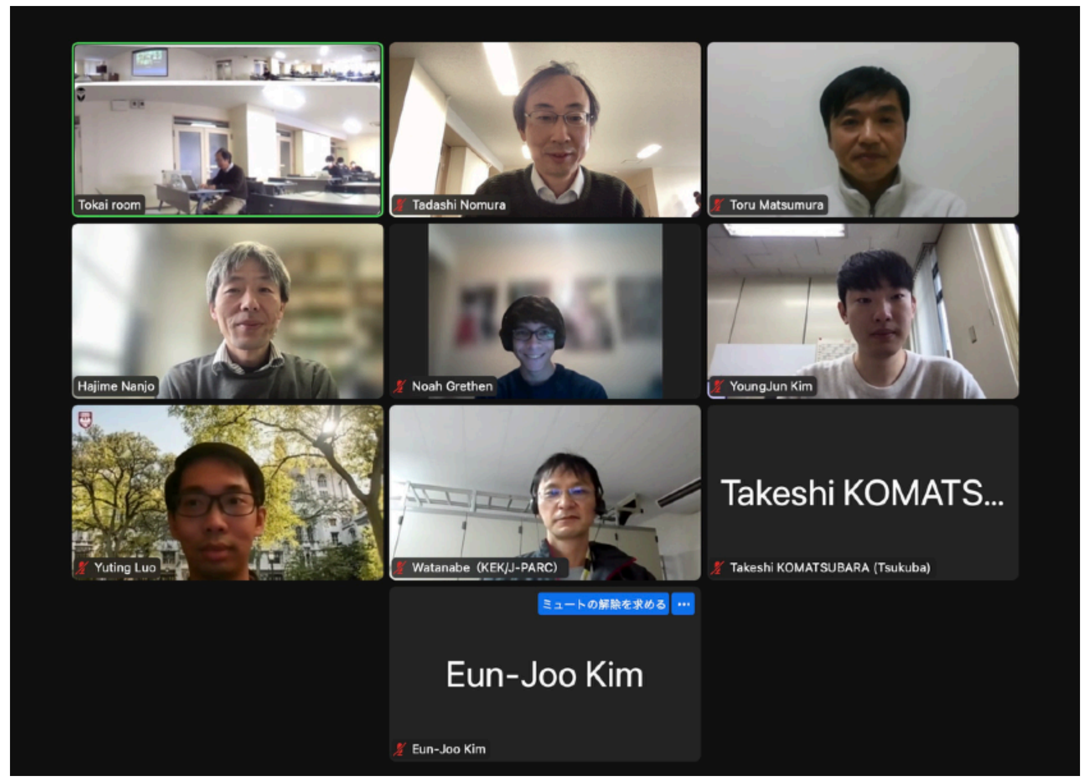


KOTO: Study of the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay at J-PARC in Ibaraki, Japan

KOTO collaboration



Japan Korea Taiwan U.S.



Collaboration Meeting
(Dec. 2022)

Experimental Principle

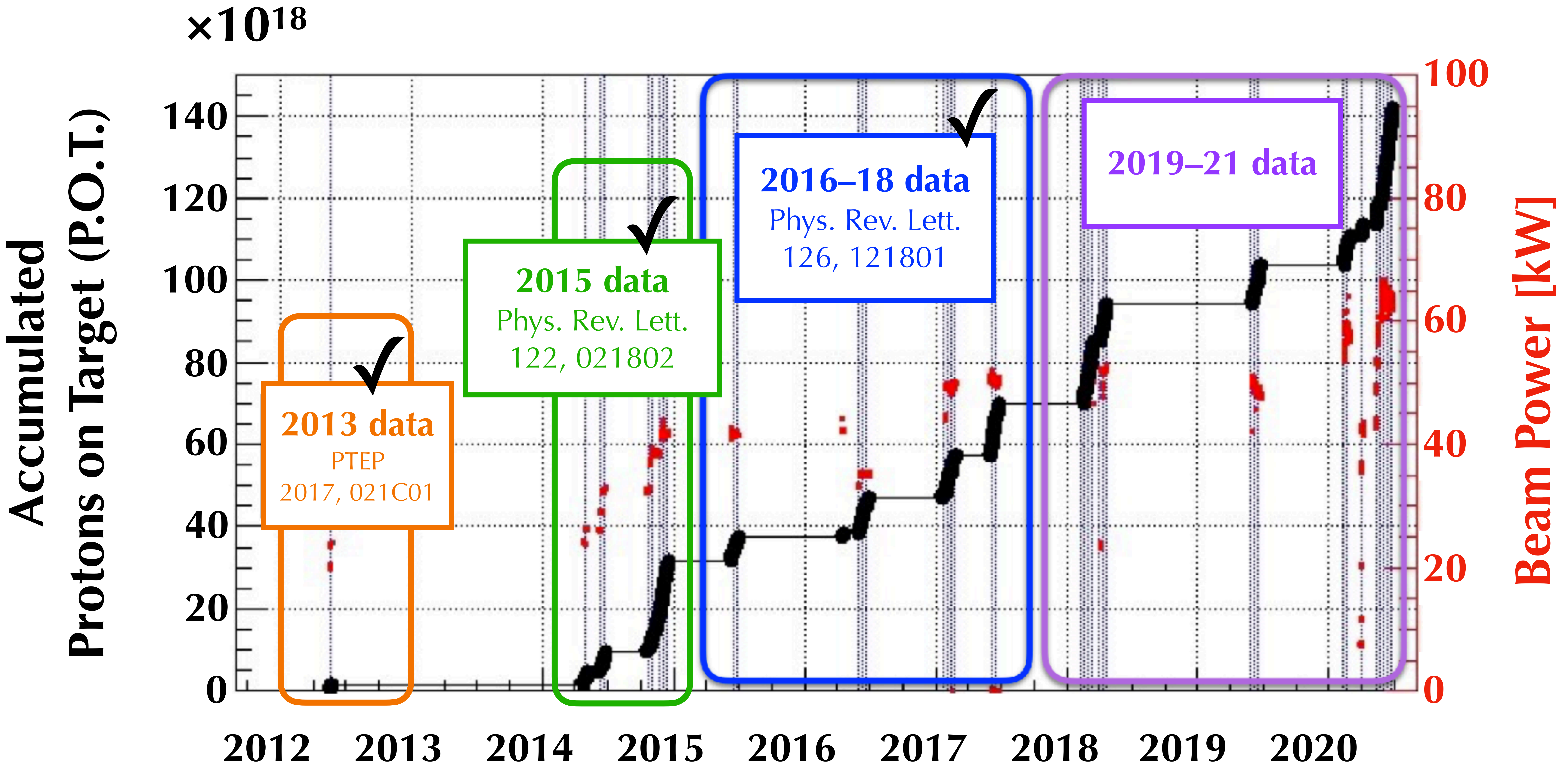
Signature of $K_L \to \pi^0 \nu \bar{\nu}$:

$(\pi^0 \to)\ 2\gamma$ —> calorimeter
\+
nothing —> veto

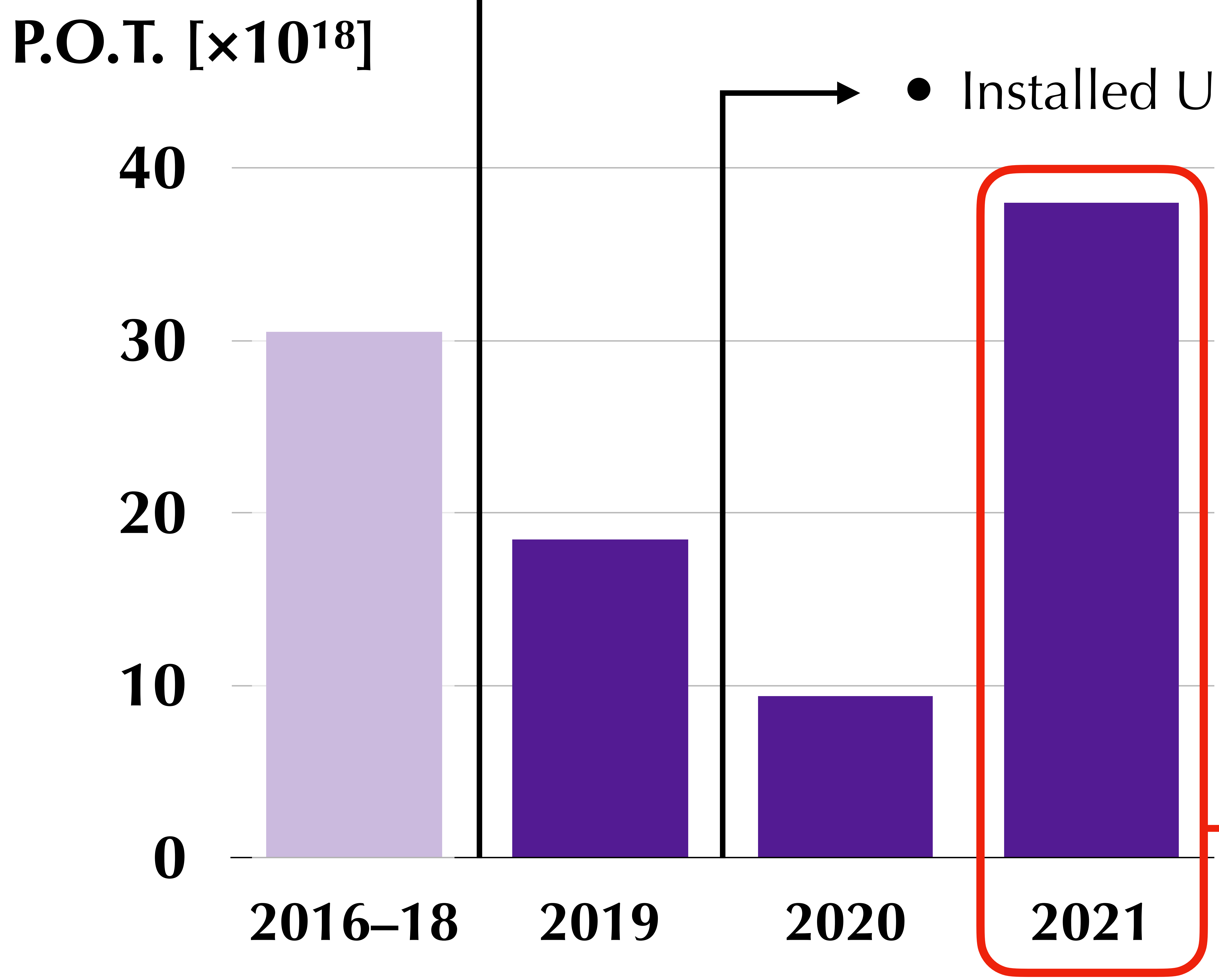
Z_{vtx} on beam axis caluculated from

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

History of Data Taking

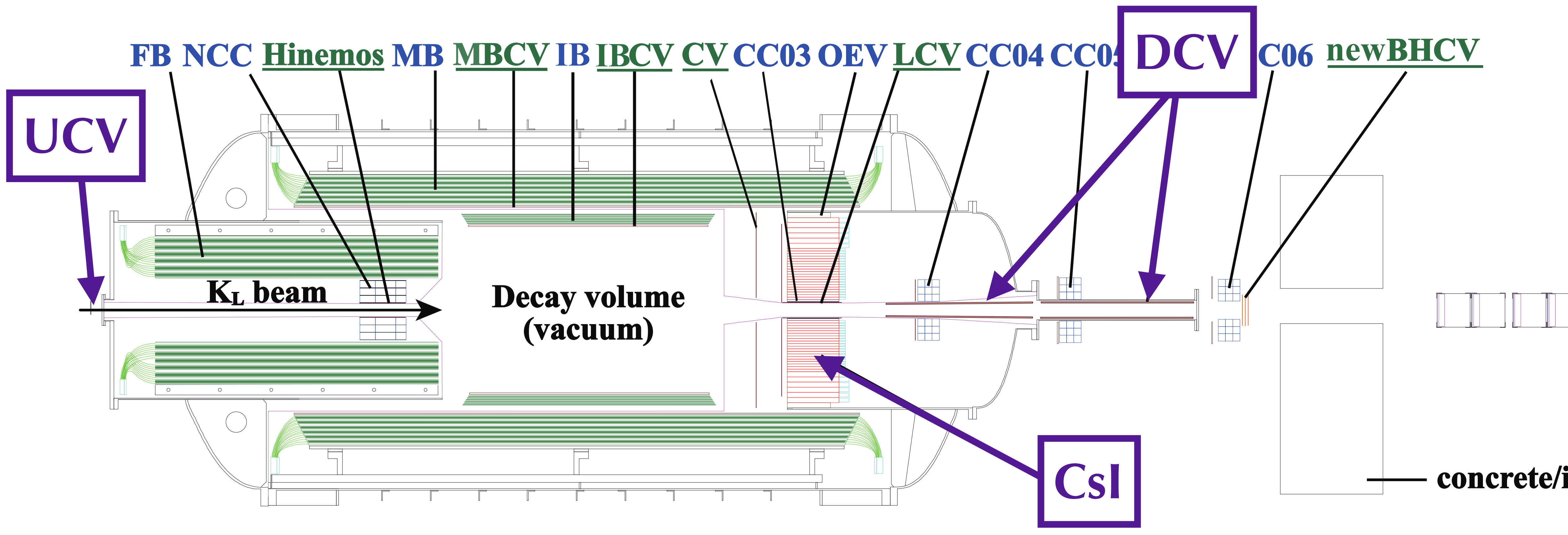


Data Collected in 2019–2021



- Upgraded the calorimeter (CsI)
- Installed Downstream Charged Veto (DCV)
- Installed Upstream Charged Veto (UCV)

Detector upgrade for BG rejection



Our current focus in analysis

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
- $BR(K_L \to \pi^0 \nu\bar{\nu}) < 4.9 \times 10^{-9}$ (90% C.L.)

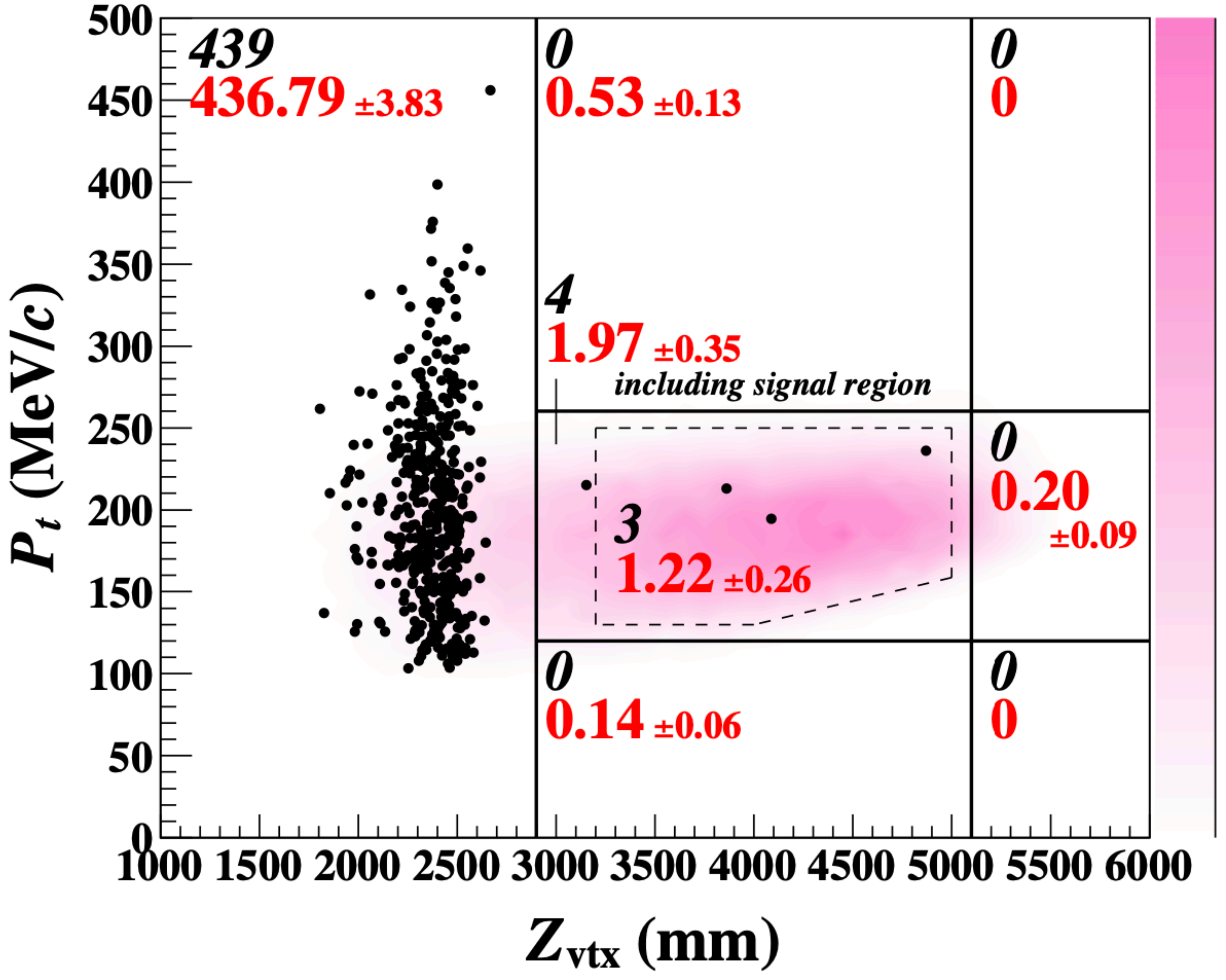
Background Table

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

Total #BG = 1.22 ± 0.26

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

Black: Observed, Red: Expected



$K^{\pm}$ 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

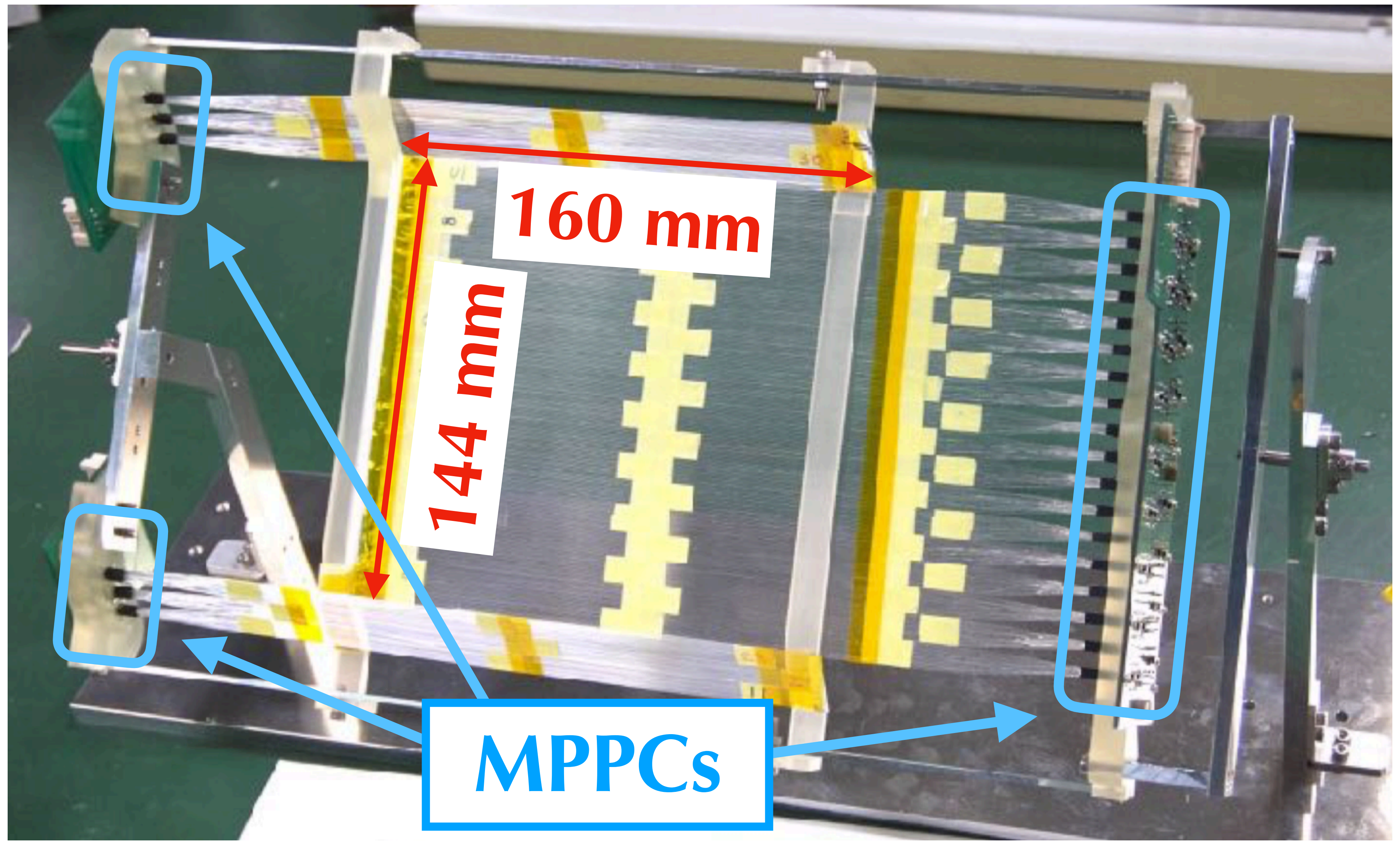
→ Could miss e^{+} and fail to veto this kind of event

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° to reduce inefficiency

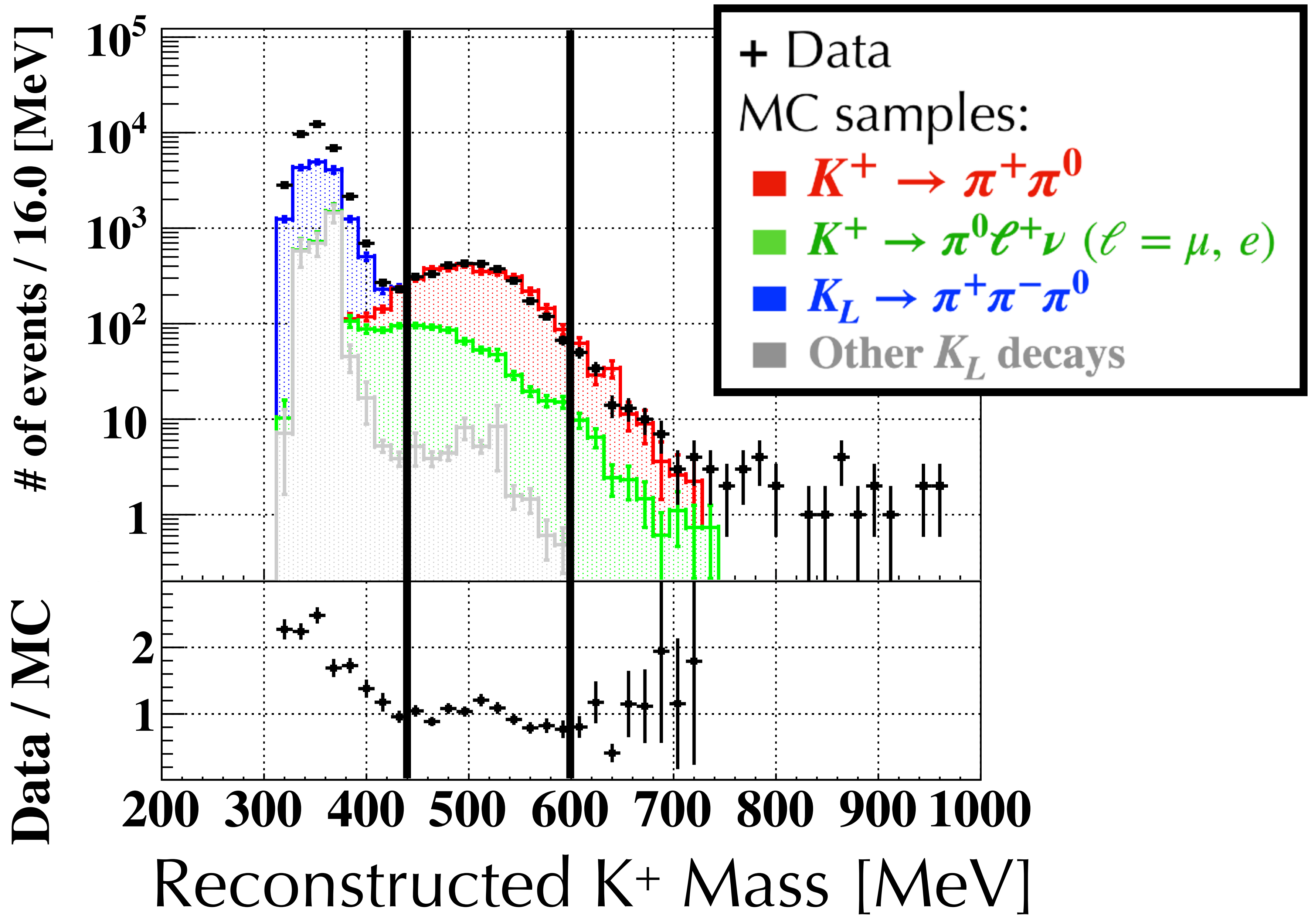
(Prototype was tested in 2020)

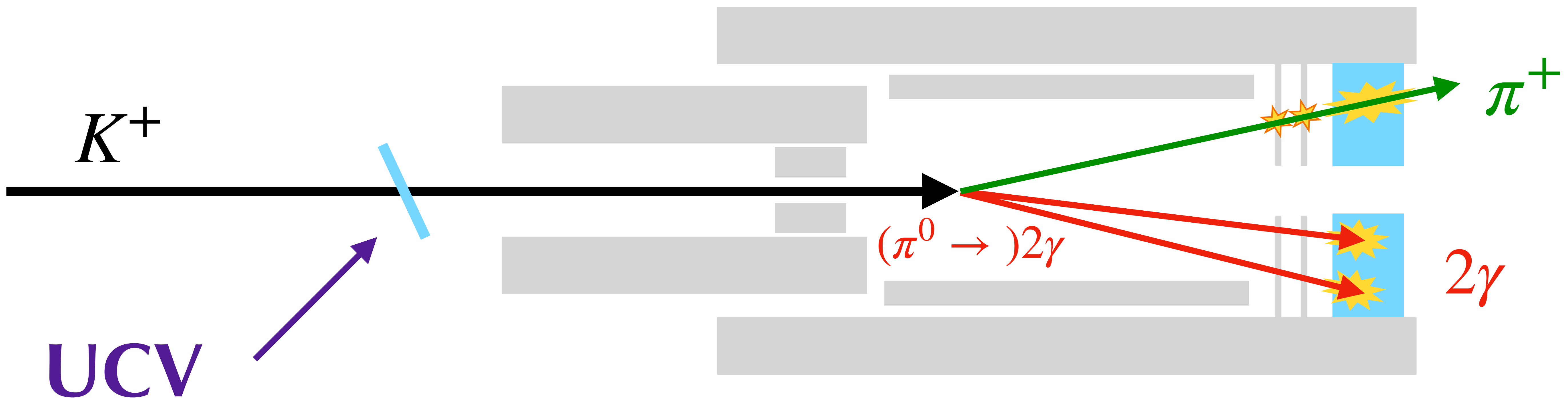


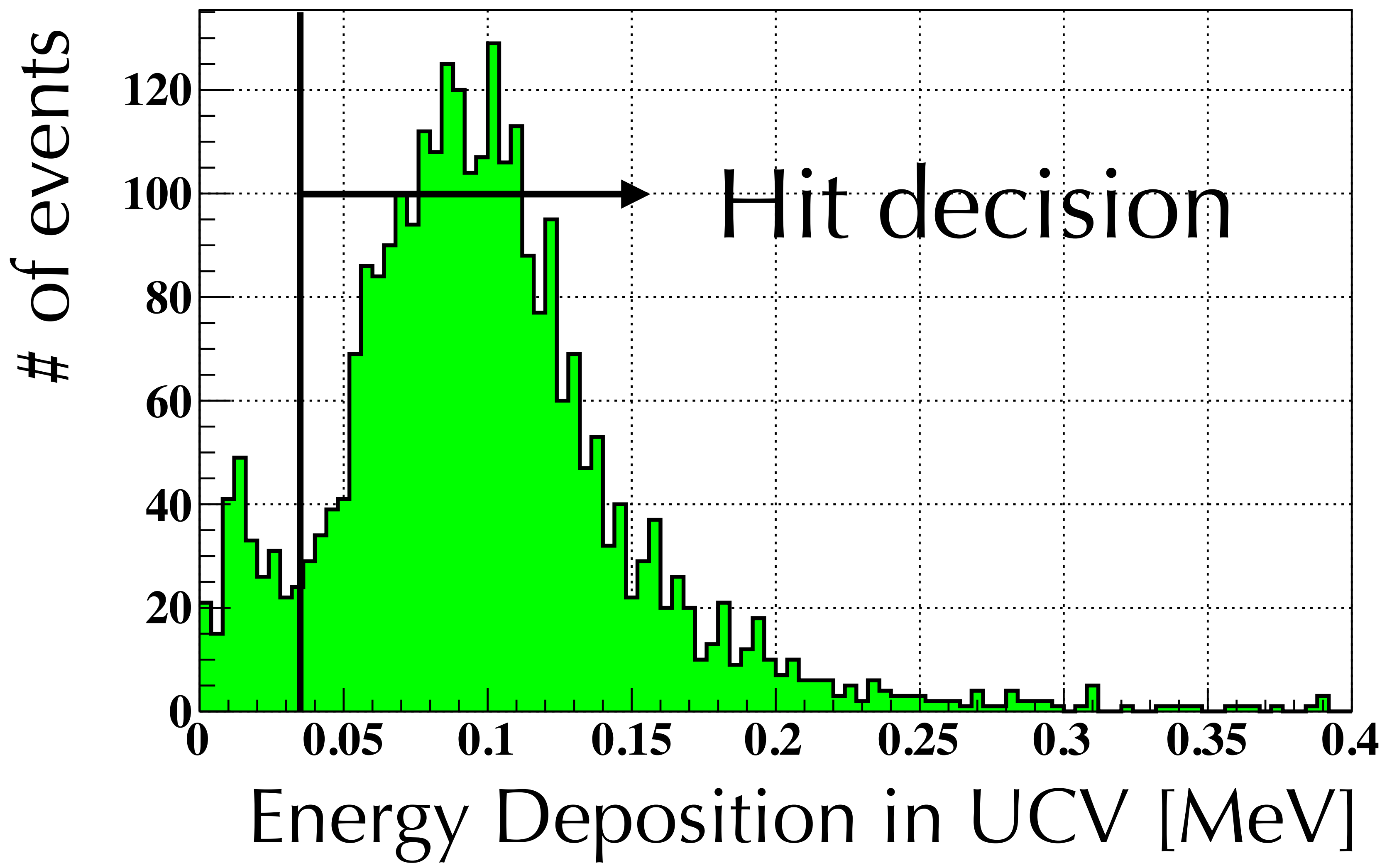
Reduction of the K^+ Background

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

> 3 clusters in calorimeter w/ no energy deposition in veto detectors
> - π^0 reconstruction from 2γ
> - π^+ reconstruction assuming p_T balance between π^+ and π^0







<u>==> ×1/13 BG reduction</u>

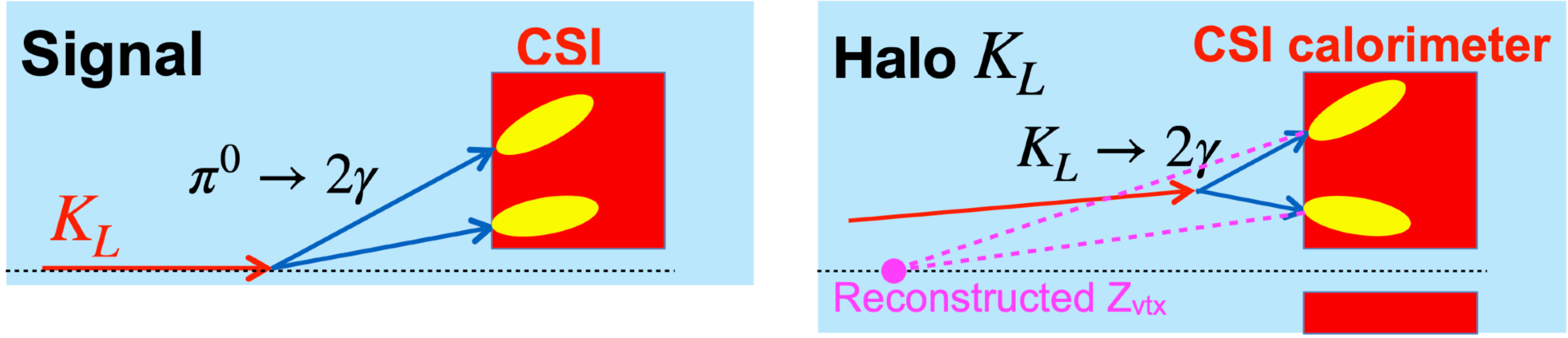
Halo $K_L \rightarrow 2\gamma$ Background

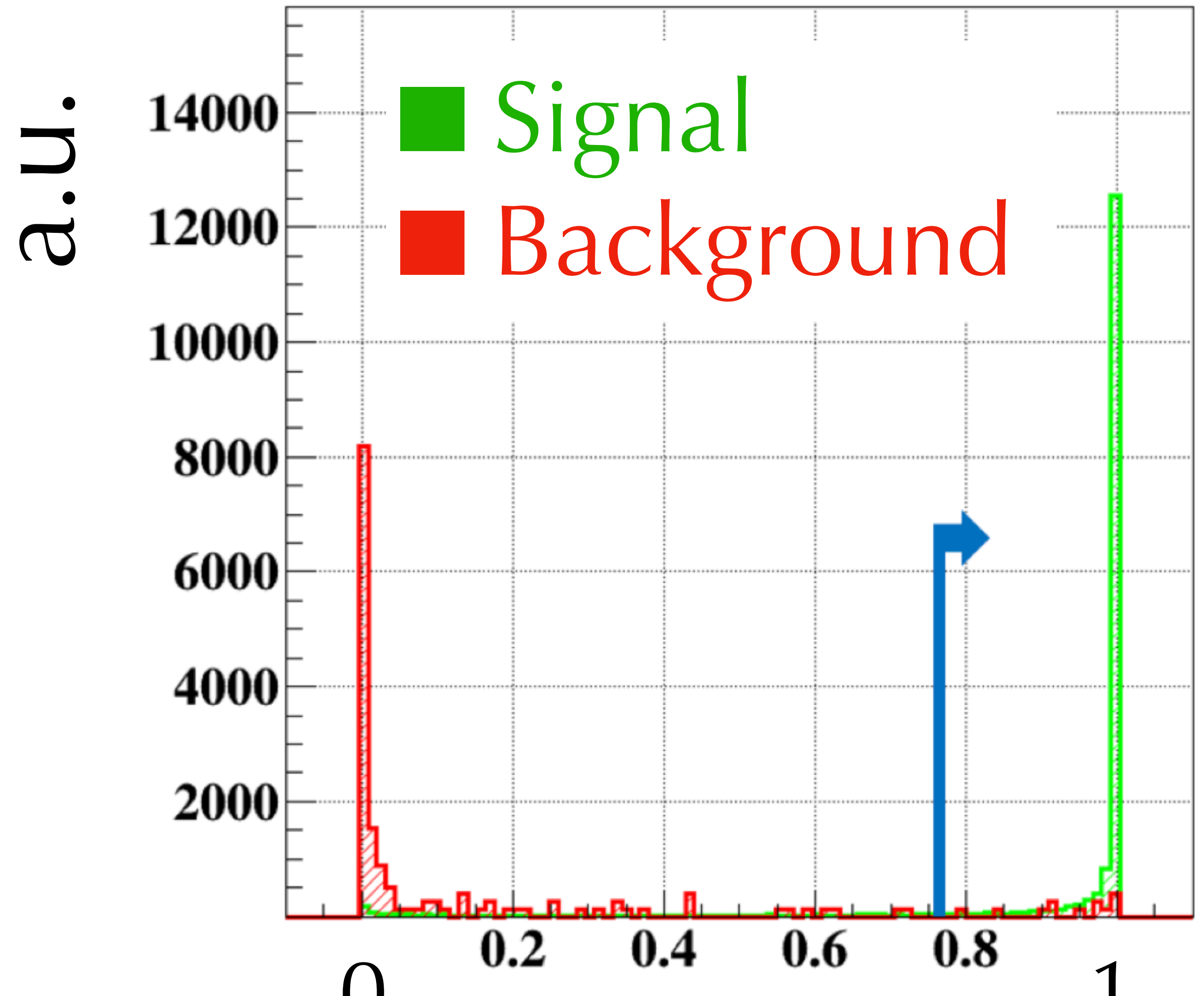
Halo (scattered) K_L decays into 2γ with a finite transverse momentum.

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

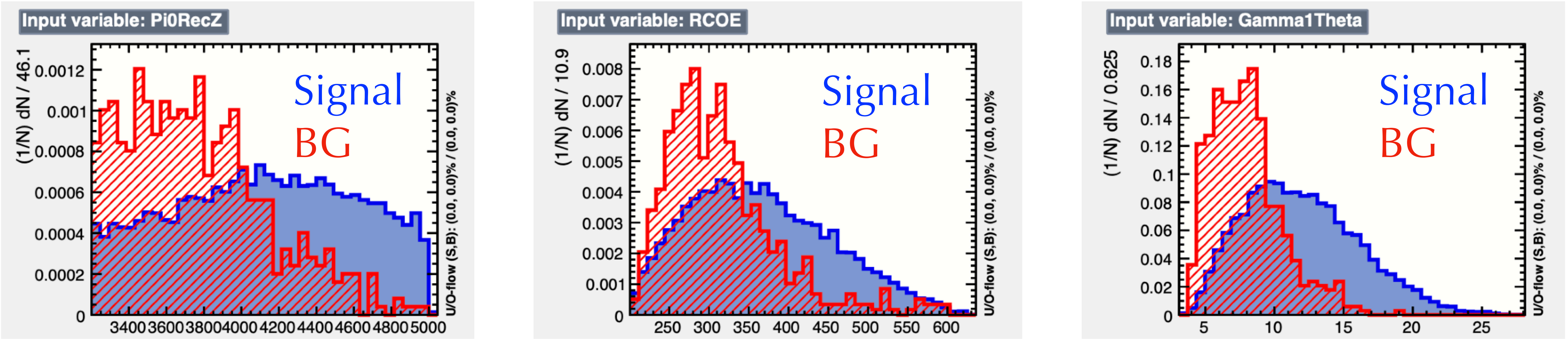
Reduction of the Halo $K_L \to 2\gamma$ Background

- Likelihood ratio based on shower shape consistency

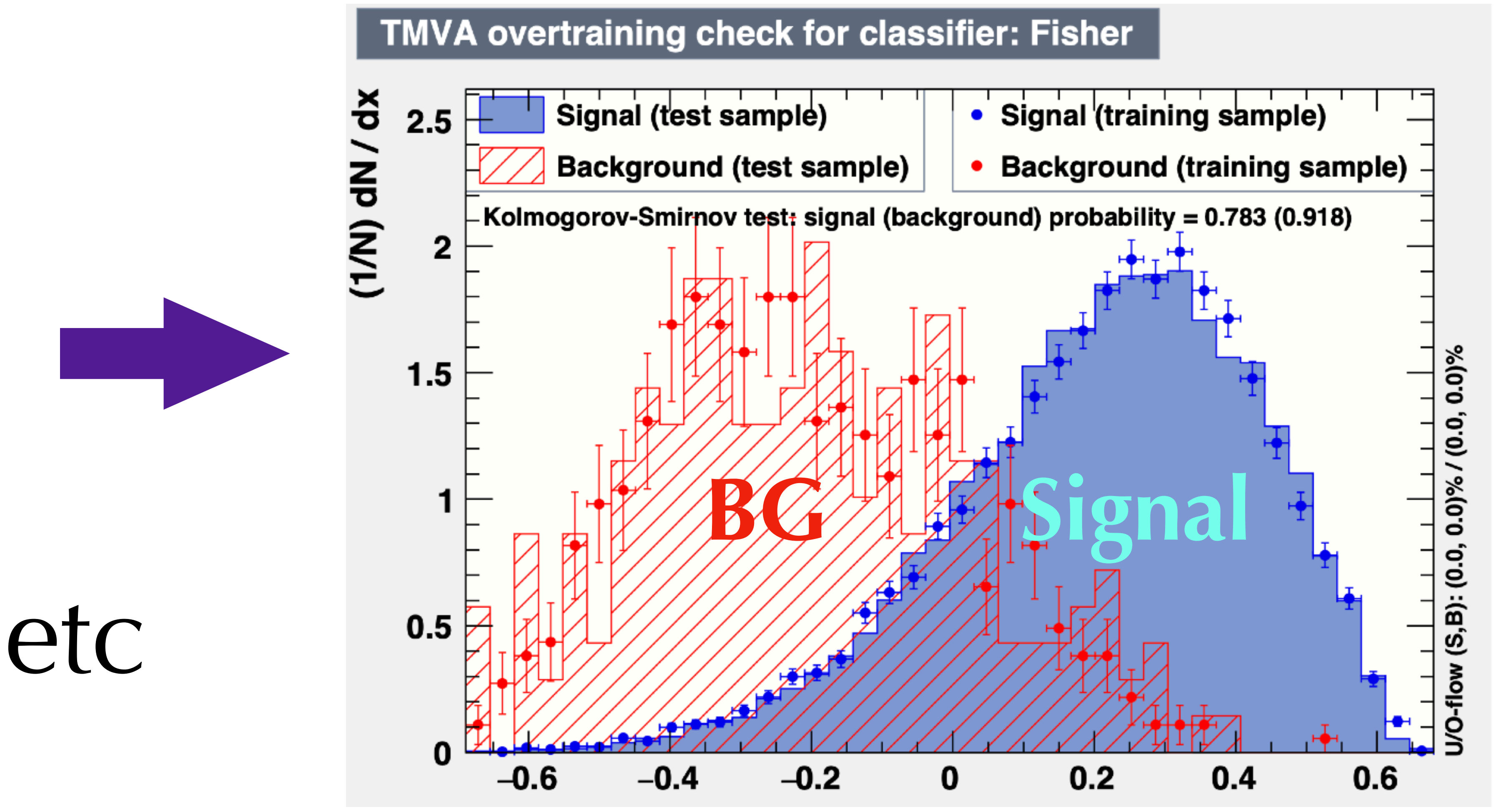




- Multivariate analysis using Fisher Discriminant



Reconstructed Z   RCOE $\theta_{\gamma 1}$, etc



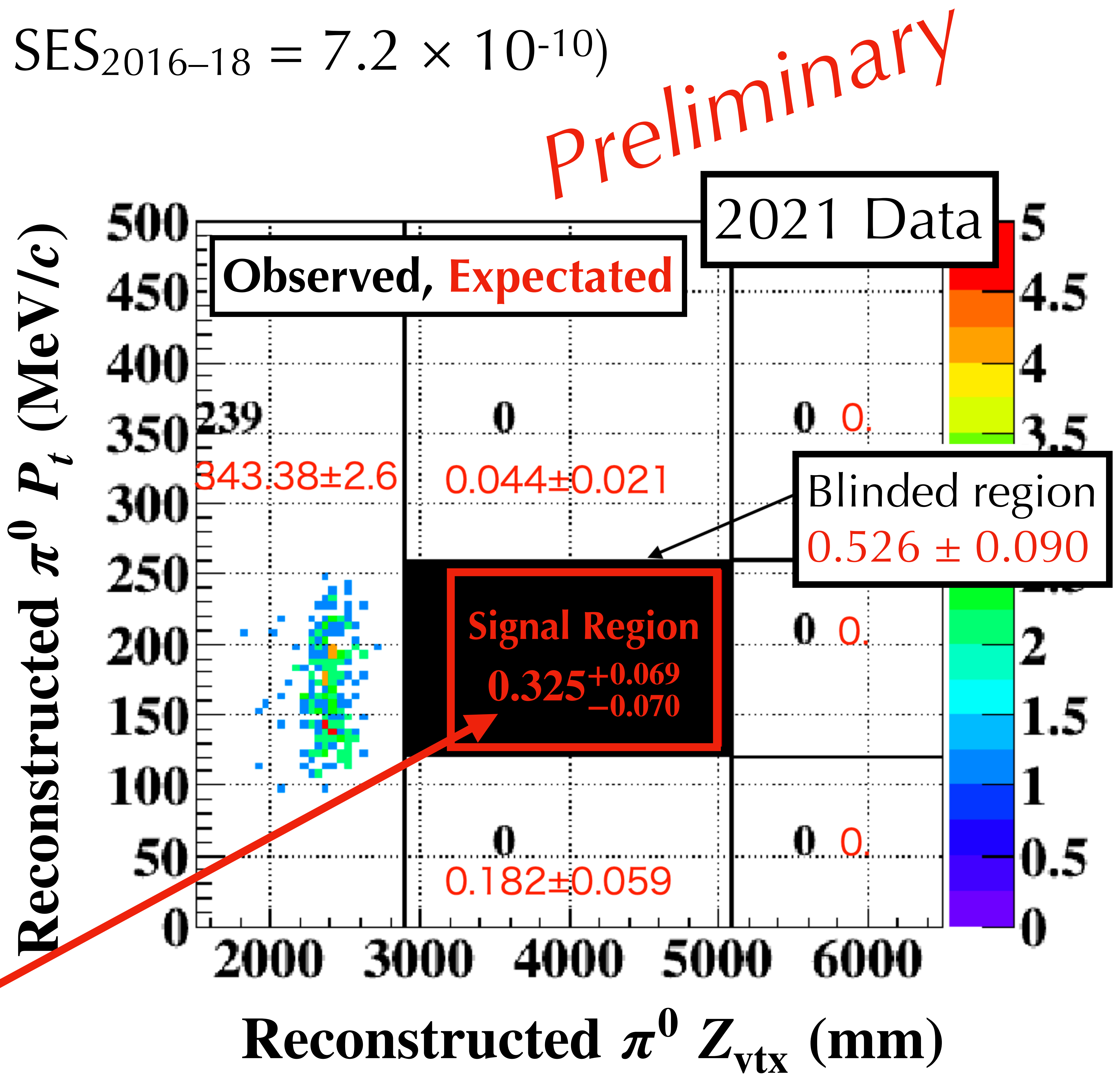
Fisher response

<u>==> ×1/10 BG reduction (with 94% signal acceptance)</u>

Summary of the Background Estimation

- 2021 data analysis
  Single Event Sensitivity (SES) = 7.9×10^{-10} (Cf. $SES_{2016-18} = 7.2 \times 10^{-10}$)

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



Issue on the $K_L \to 2\pi^0$ Background

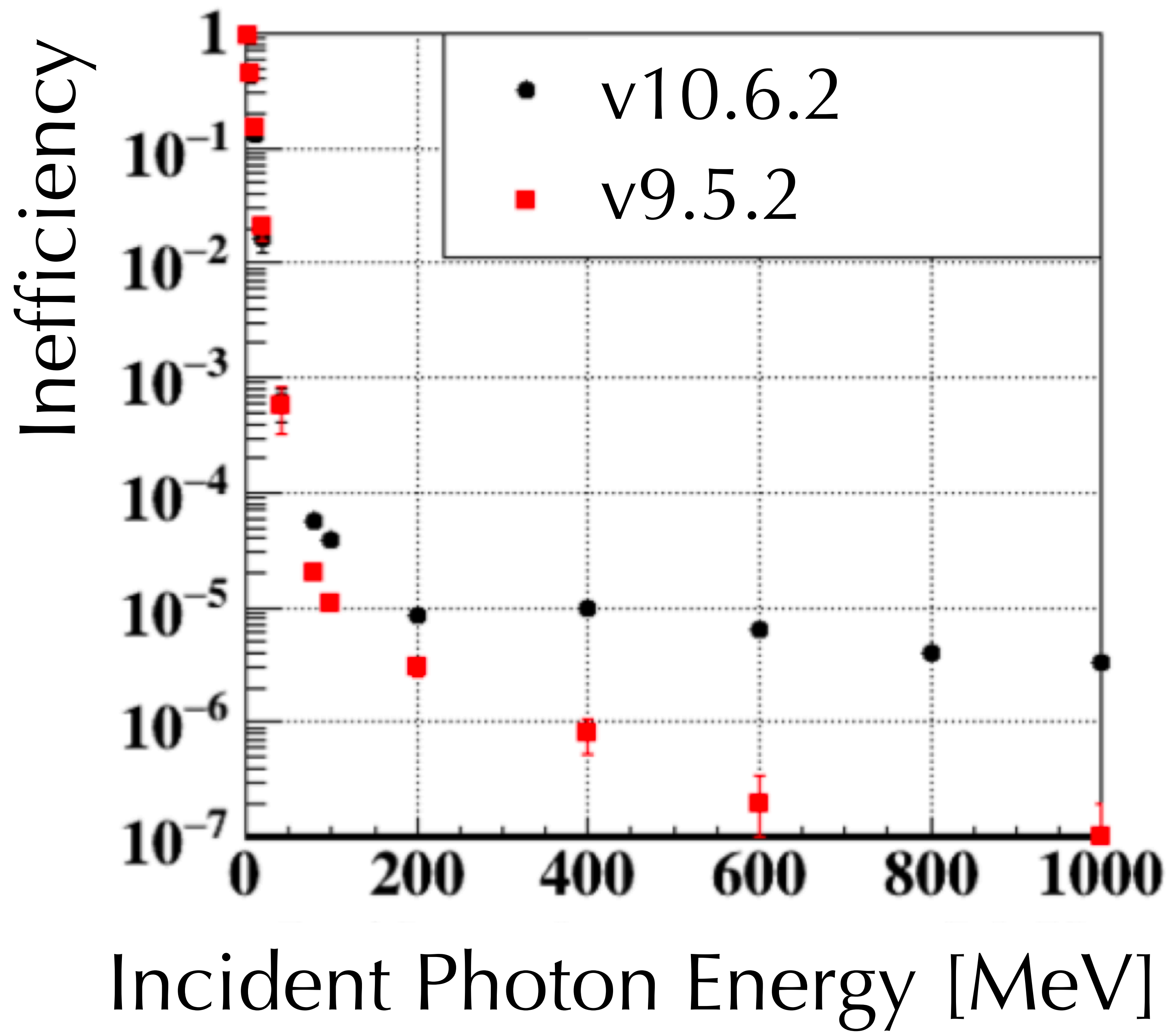
We estimated #BG from the $K_L \to 2\pi^0$ decay in simulation-based evaluation.

==> 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 = 7.2×10^{-10})	< 0.08 @ 90%CL	$< 0.6 \times 10^{-10}$
2021 analysis (SES = 7.9×10^{-10})	**0.14 ± 0.06**	**1.1×10^{-10}**

Barrel detector inefficiency
(simluation study)



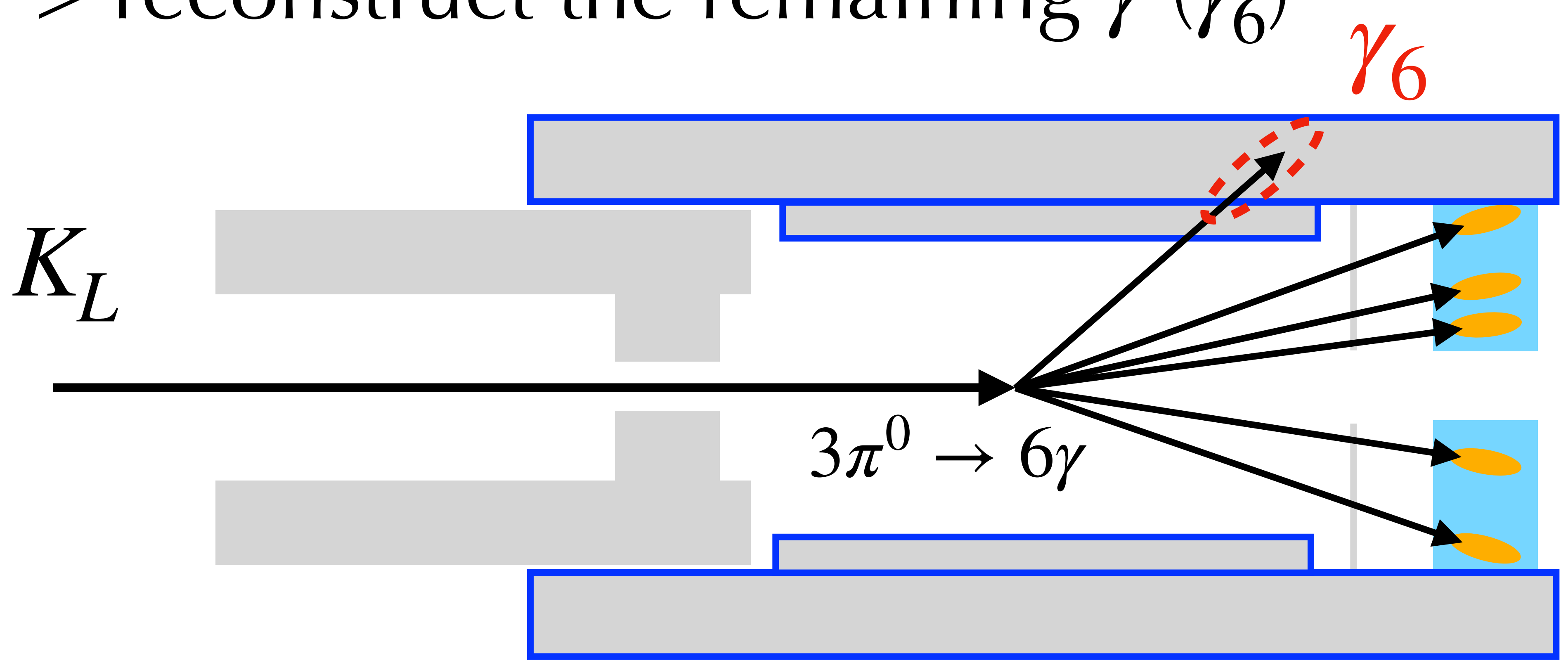
- **Photonuclear (PN) reaction** occurs in the $K_L \to 2\pi^0$ events that remain in the signal region.
- Inefficiency of the barrel detectors depends on the version of Geant4. (No difference when turning off the PN process.)
- The physics model of PN process was changed for better code management.

Inefficiency Evaluation with 5γ Data

- Evaluation using $K_L \rightarrow 3\pi^0(\rightarrow 6\gamma)$ events

  Target: 5γ in the calorimeter + 1γ in the barrel veto

  —> reconstruct the remaining γ (γ_6)



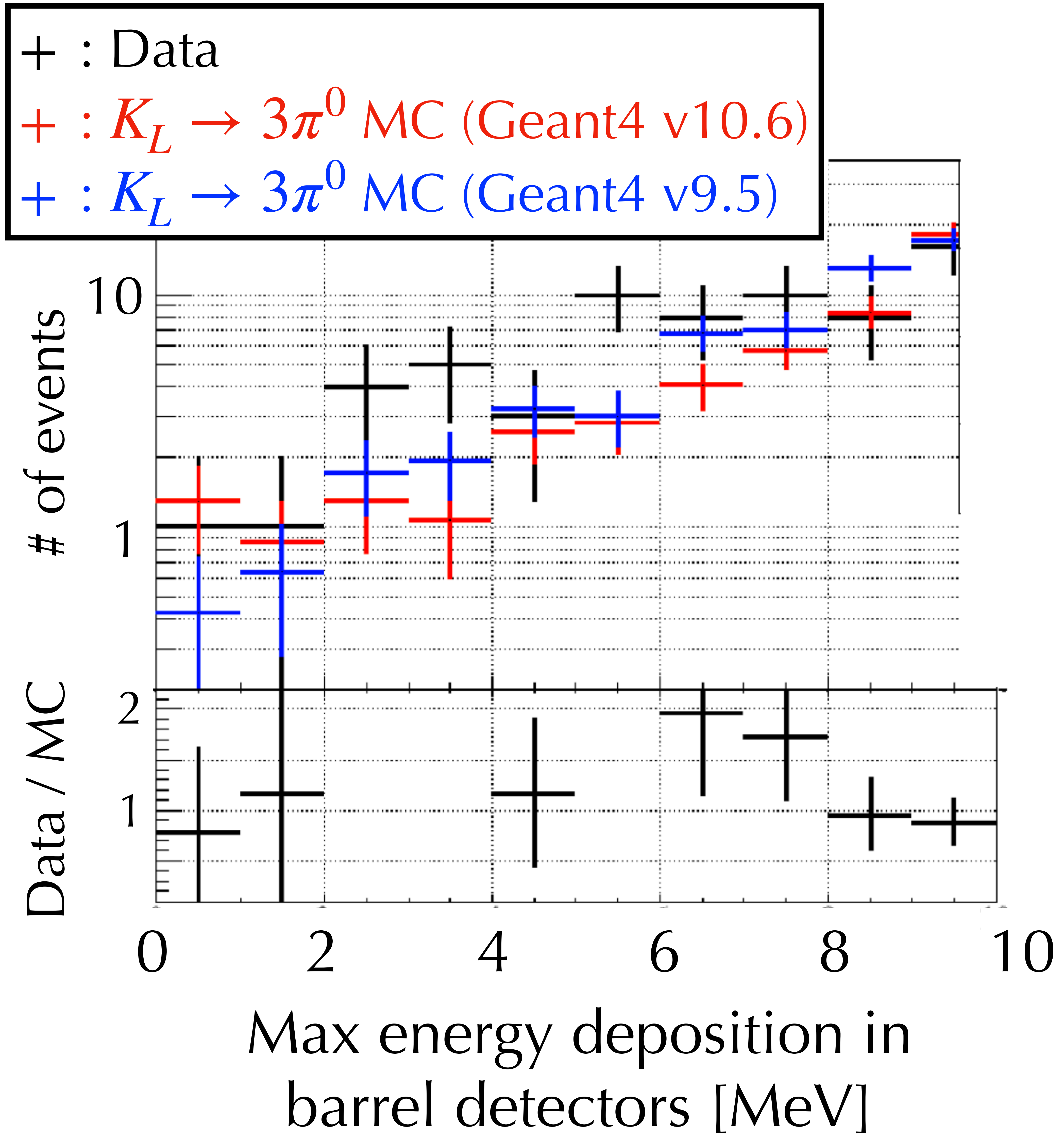
For 1 MeV threshold,

Inefficiency (Data) = $(4.8 \pm 4.8) \times 10^{-5}$

Inefficiency (MC) = $(6.2 \pm 2.5) \times 10^{-5}$ (v10.6)

= $(2.1 \pm 1.5) \times 10^{-5}$ (v9.6)

- **~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**



Toward Unblinding

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

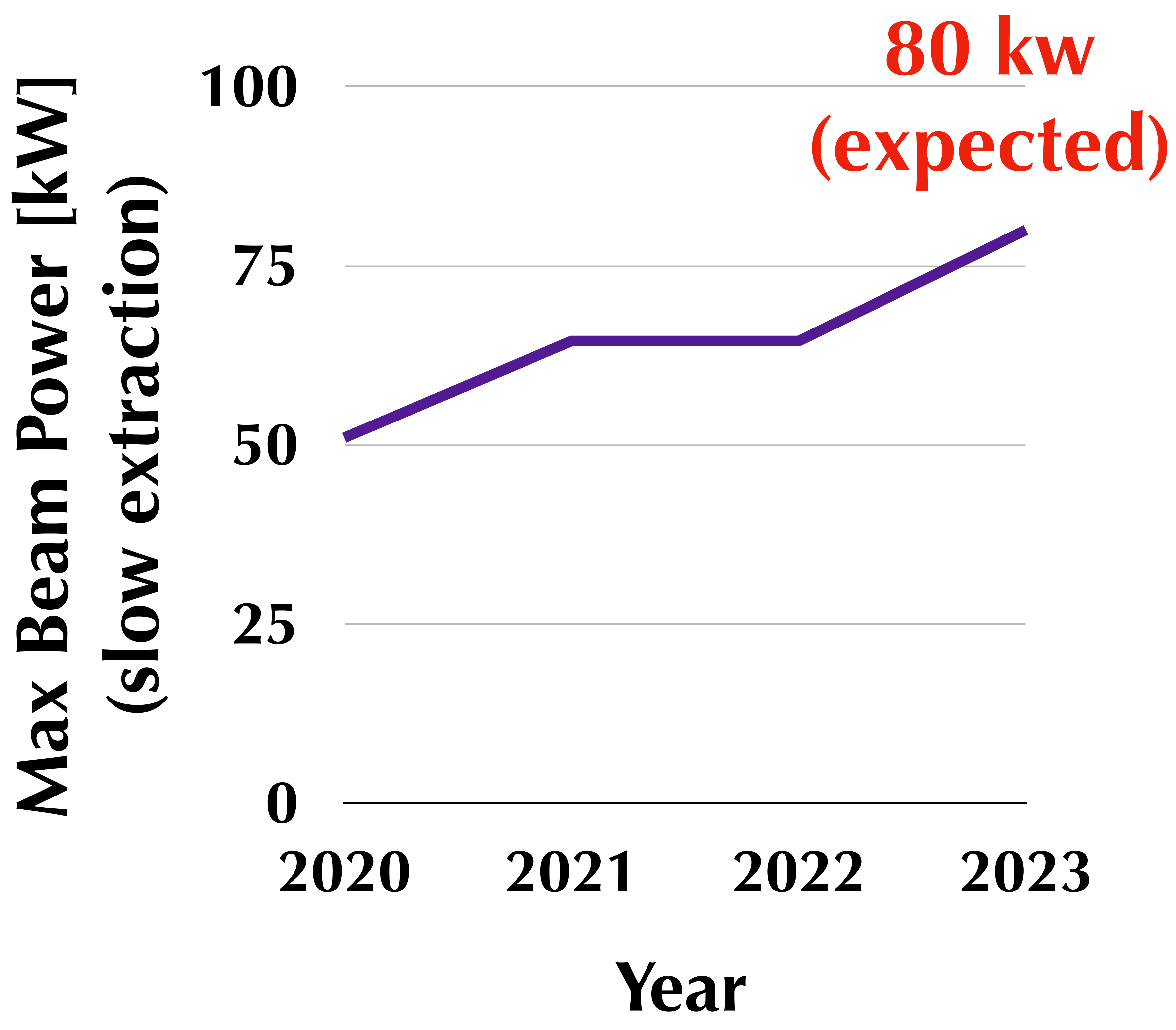
Toward the Next Beam Time

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

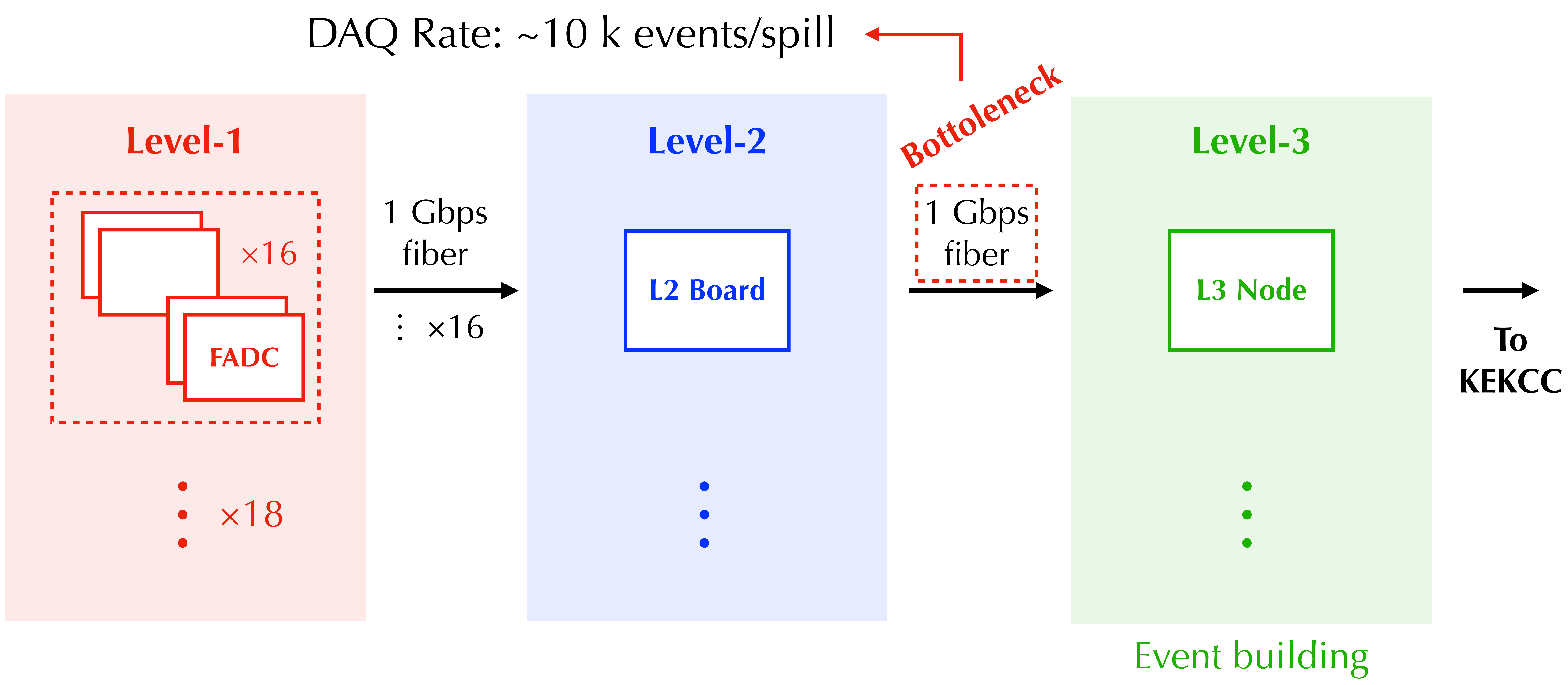
- handle higher trigger rate
- introduce new triggers (e.g. 5-cluster trigger)



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

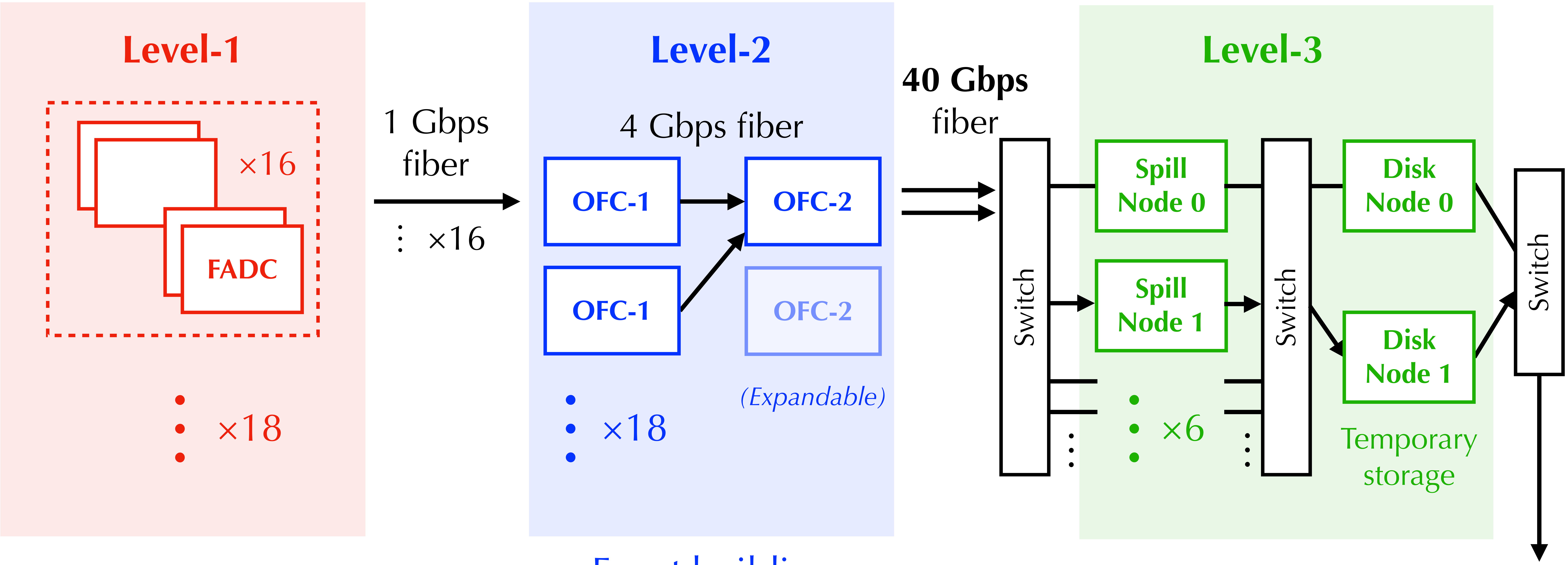
Supported by US-Japan program (2021–2023)

Old DAQ System



New DAQ System

DAQ Rate: ~10 k events/spill —> **25–30 k events/spill**



Event building

*OFC: Optical Fiber Center

- Wfm Compression (@GPU)
- Event selection

To KEKCC

Summary

- KOTO searches for the rare decay $K_L \to \pi^0 \nu \bar{\nu}$ at J-PARC
- Finalizing the analysis of the 2021 data
    - Single Event Sensitivity = 7.9×10^{-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)