Search for Rare Kaon Decays at JPARC KOTO Experiment

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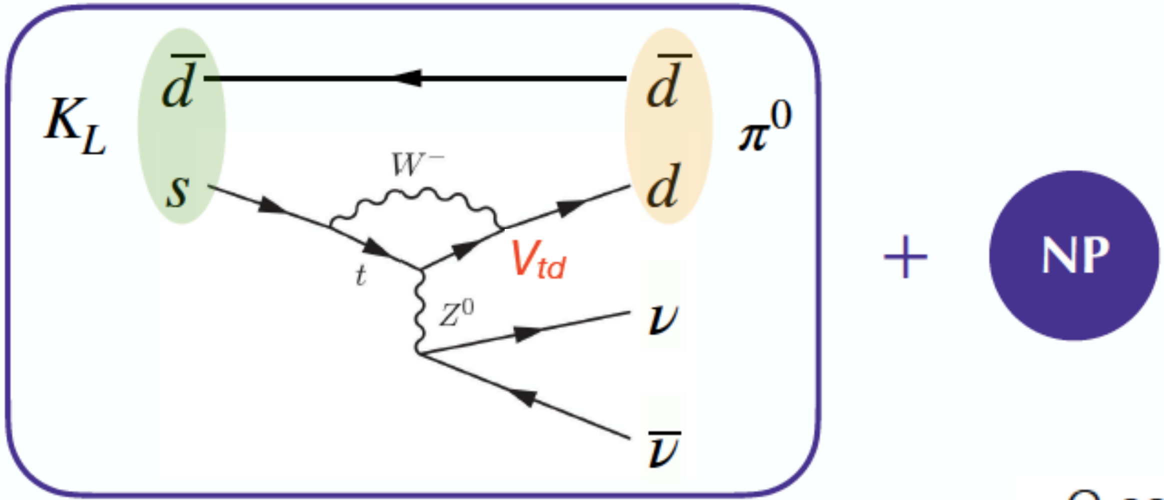
Search for $K_L \to \pi^0 \nu \bar{\nu}$

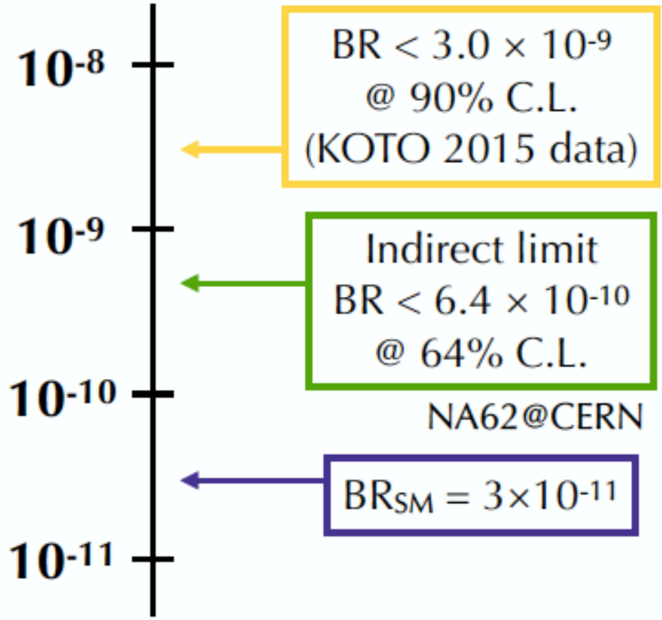
$K_L \to \pi^0 \nu \bar{\nu}$ decay in the Standard Model

- 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

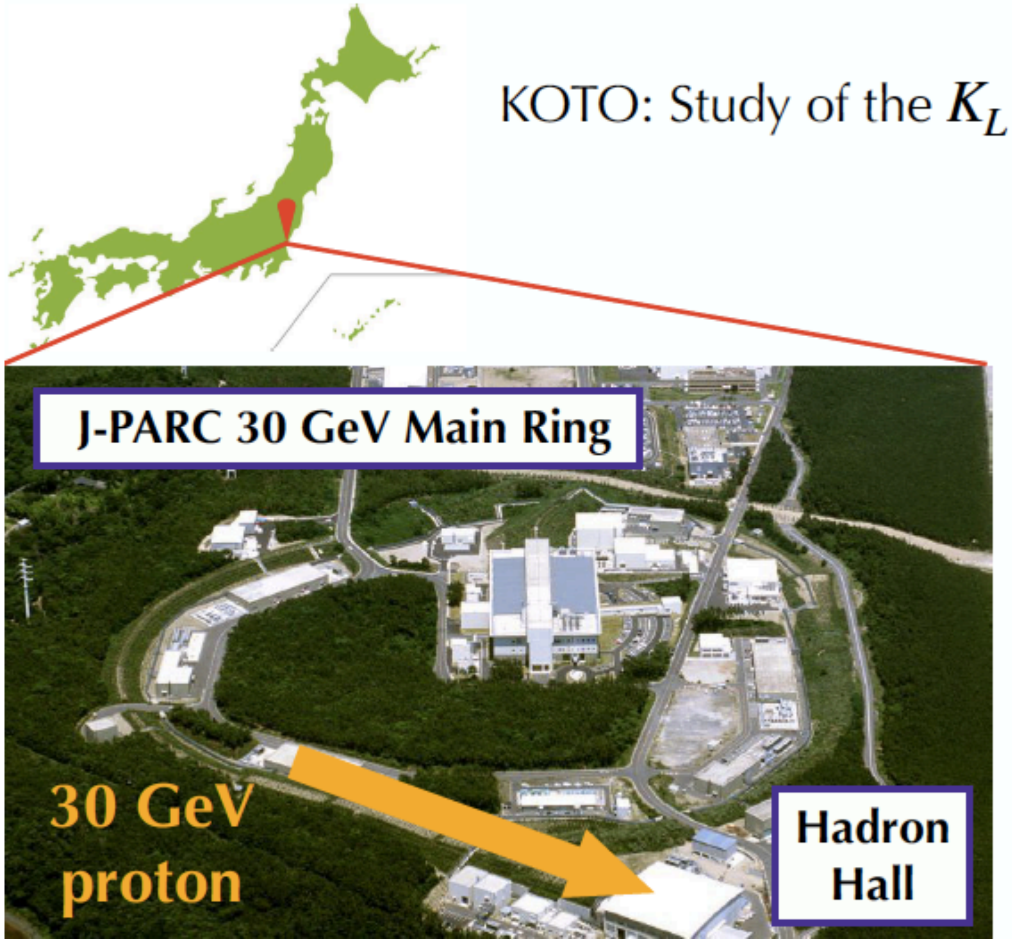


Experimental uppper limit on $BR(K_L \to \pi^0 \nu \bar{\nu})$



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

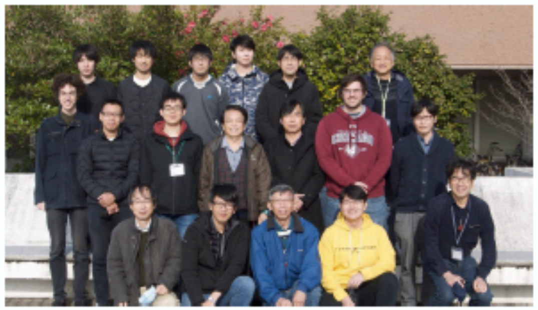
KOTO Experiment @ J-PARC

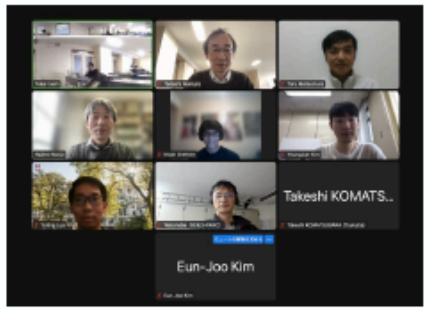


KOTO: Study of the $K_L \to \pi^0 \nu \bar{\nu}$ decay at J-PARC in Ibaraki, Japan

KOTO collaboration

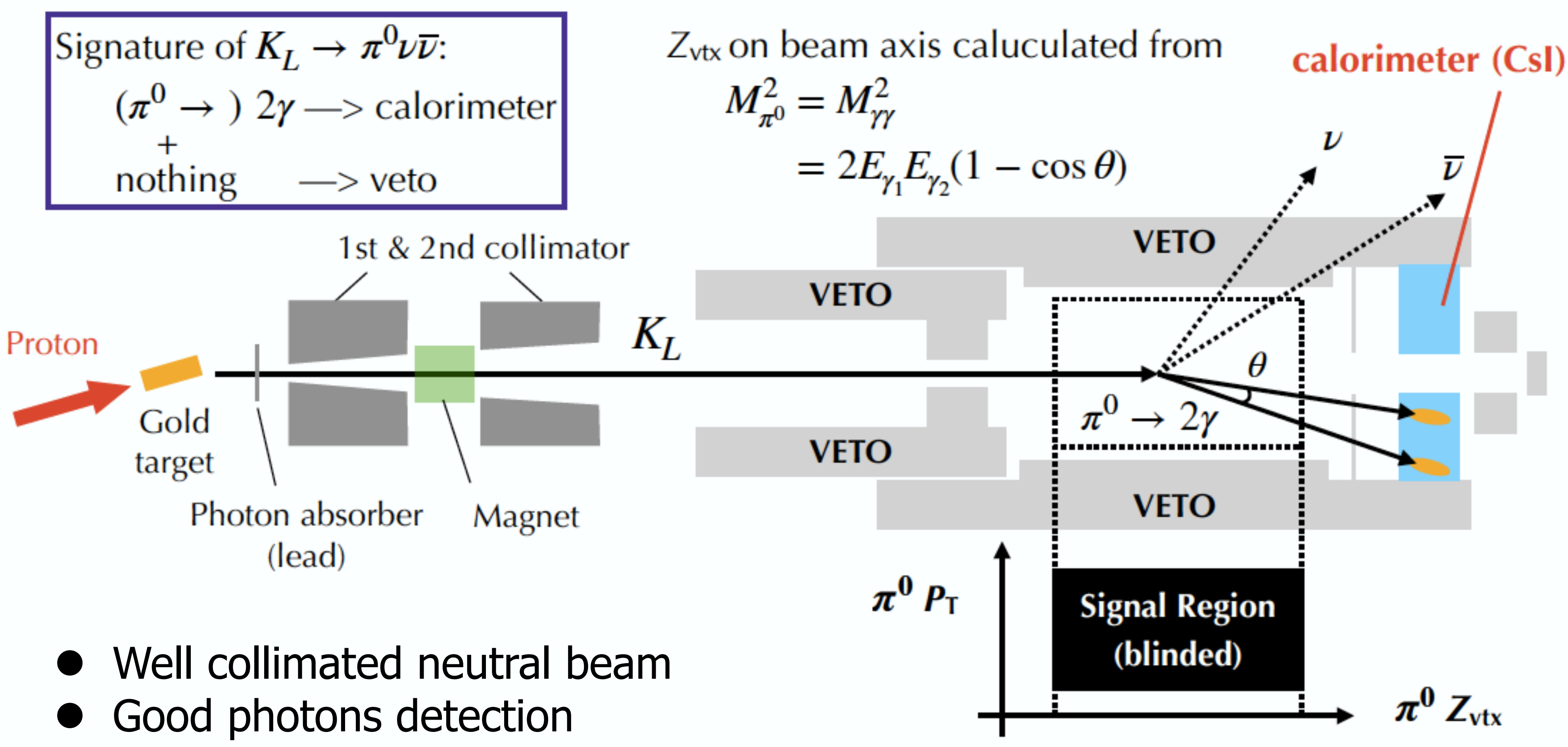
Japan Korea Taiwan U.S.





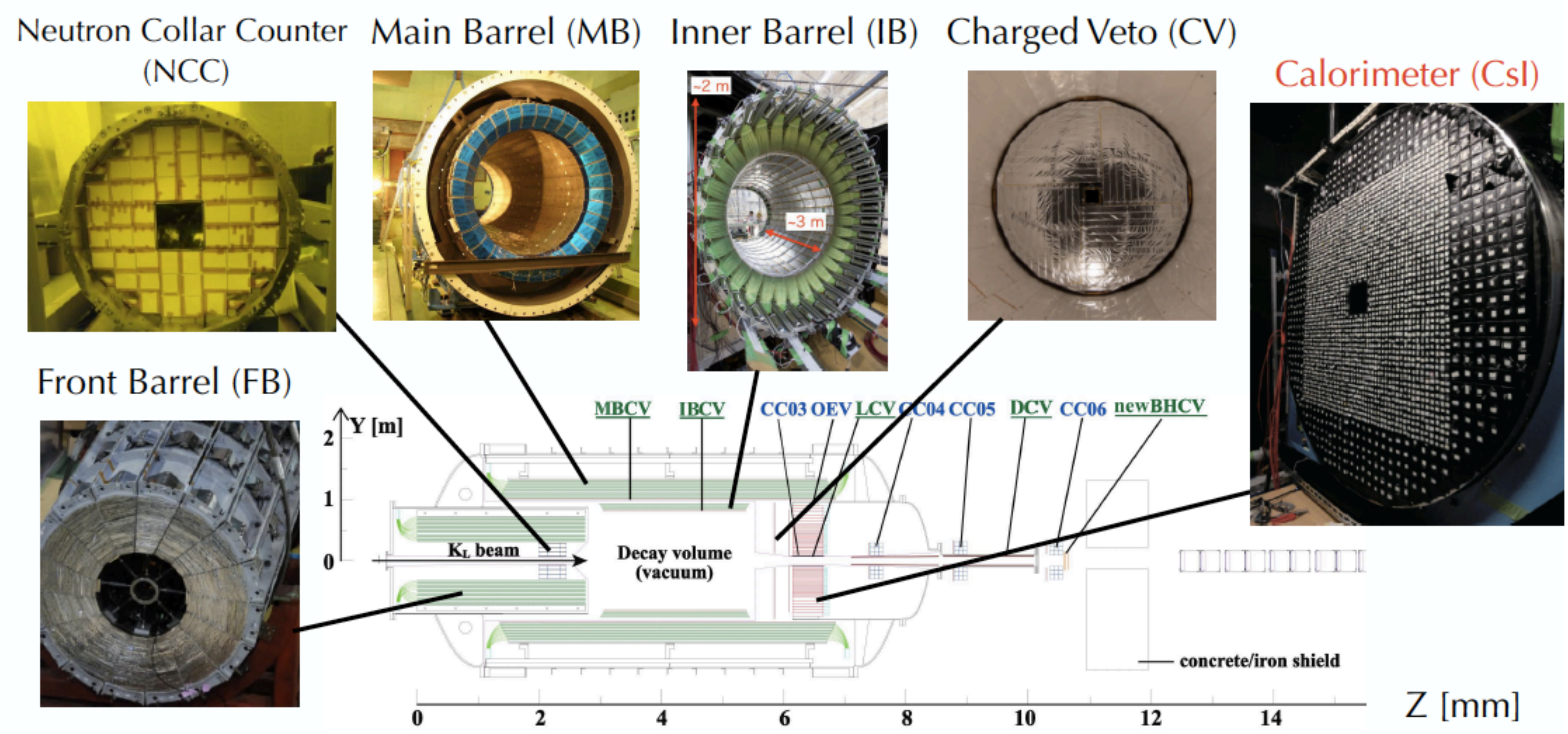
Collaboration Meeting
(Dec. 2022)

Experimental Principle



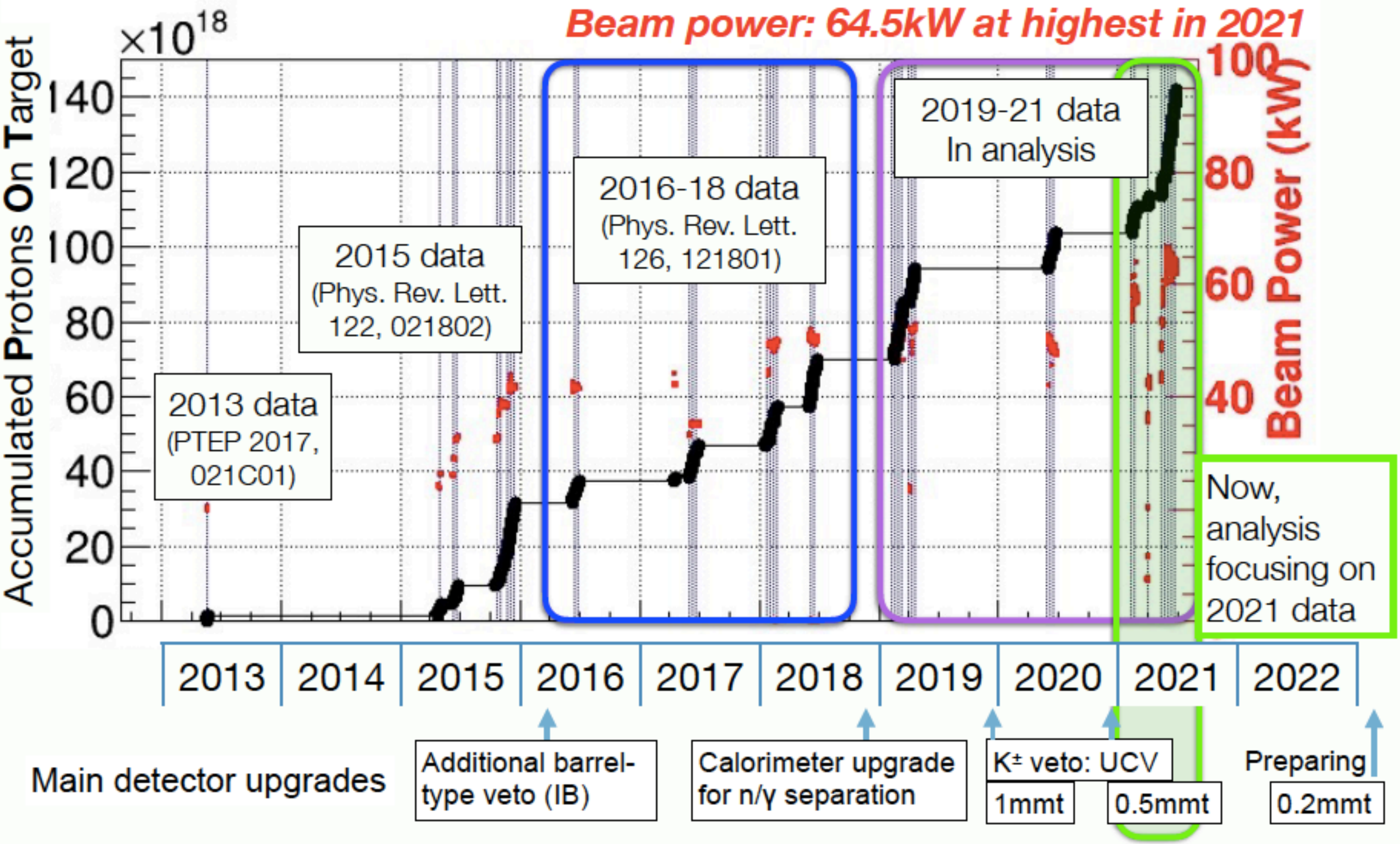
- Well collimated neutral beam
- Good photons detection
- Hermetic vetoes in decay region and in beam region after EM calorimeter

KOTO Detector



- CsI calorimeter to measure 2γ
- Hermetic veto to ensure nothing else

Run history

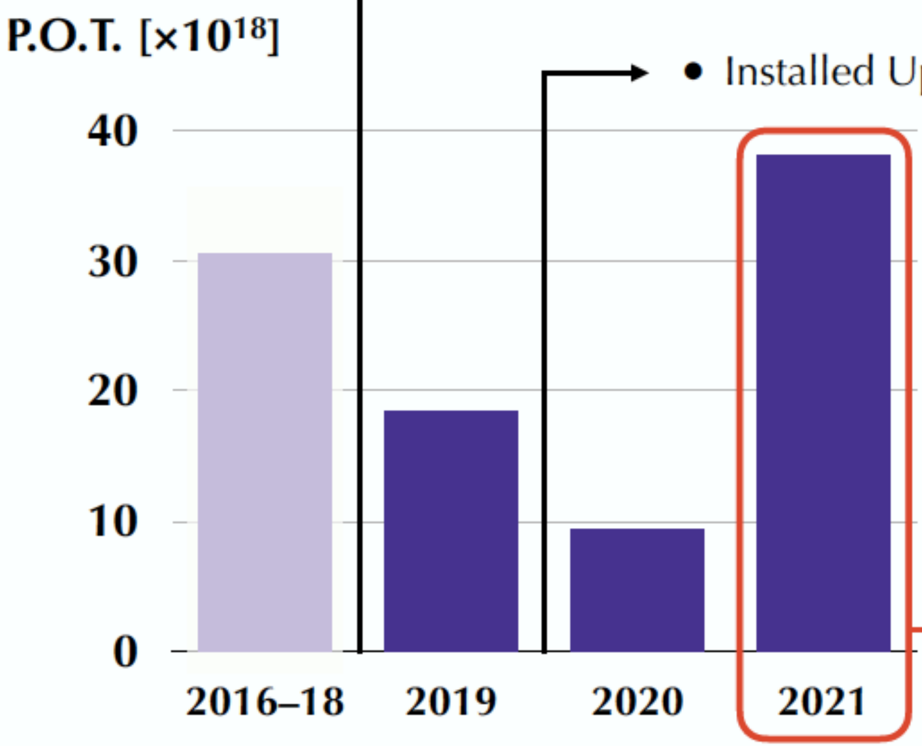


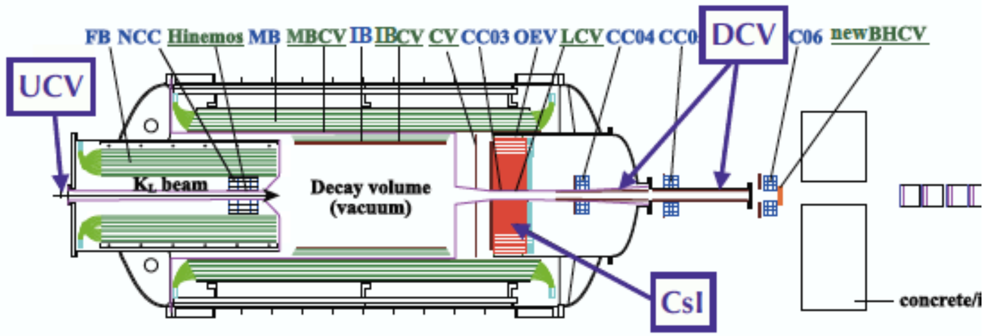
Beam power: 64.5kW at highest in 2021
×10^18
Accumulated Protons On Target
Beam Power (kW)
0
20
40
60
80
100
120
140
2013 data
(PTEP 2017, 021C01)
2015 data
(Phys. Rev. Lett. 122, 021802)
2016-18 data
(Phys. Rev. Lett. 126, 121801)
2019-21 data
In analysis
Now, analysis focusing on 2021 data
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
Main detector upgrades
Additional barrel-type veto (IB)
Calorimeter upgrade for n/γ separation
K± veto: UCV
1mmt
0.5mmt
Preparing
0.2mmt

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

Expect to complete the analysis for 2021 data this year!

Analysis Status

Results of the 2016–18 Data Analysis

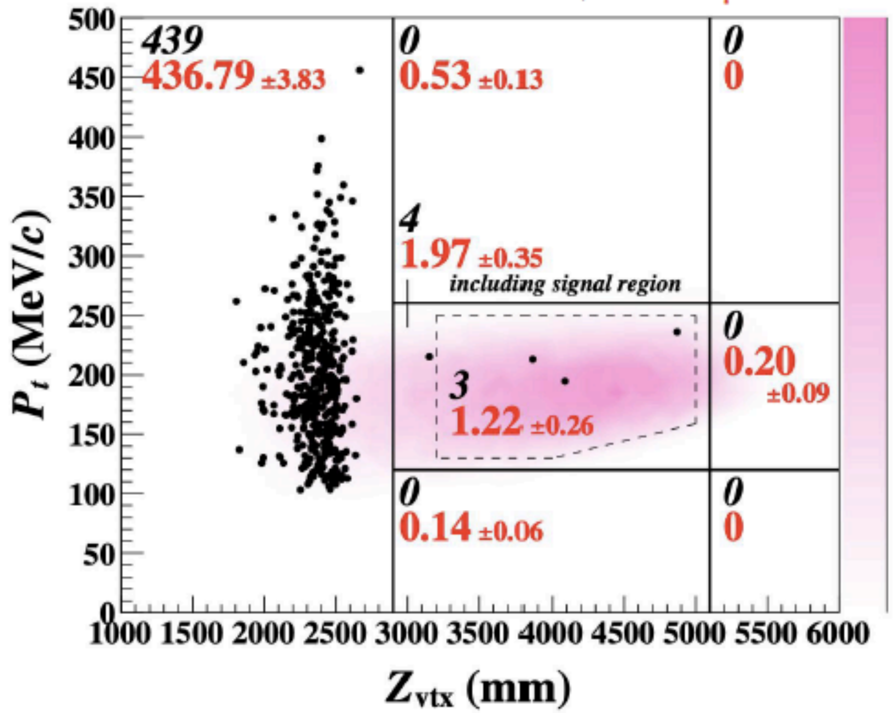
- Single Event Sensitivity:

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

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

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

Black: Observed, Red: Expected



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

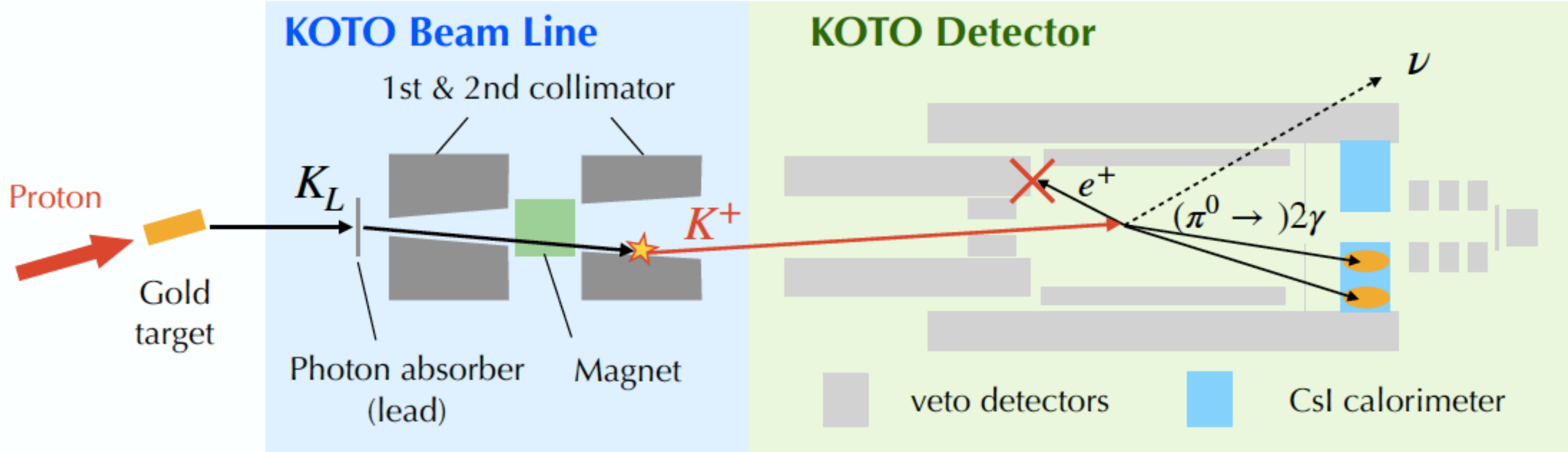
$K^{\pm}$ Background

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

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

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

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



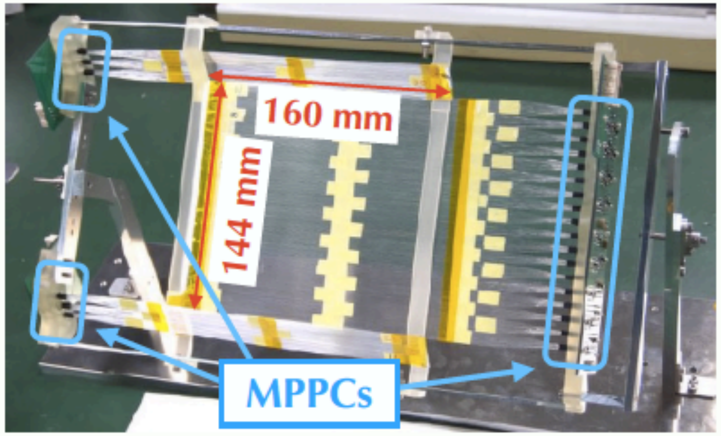
Verified in 2020 special run by a upstream charged veto (UCV) prototype!

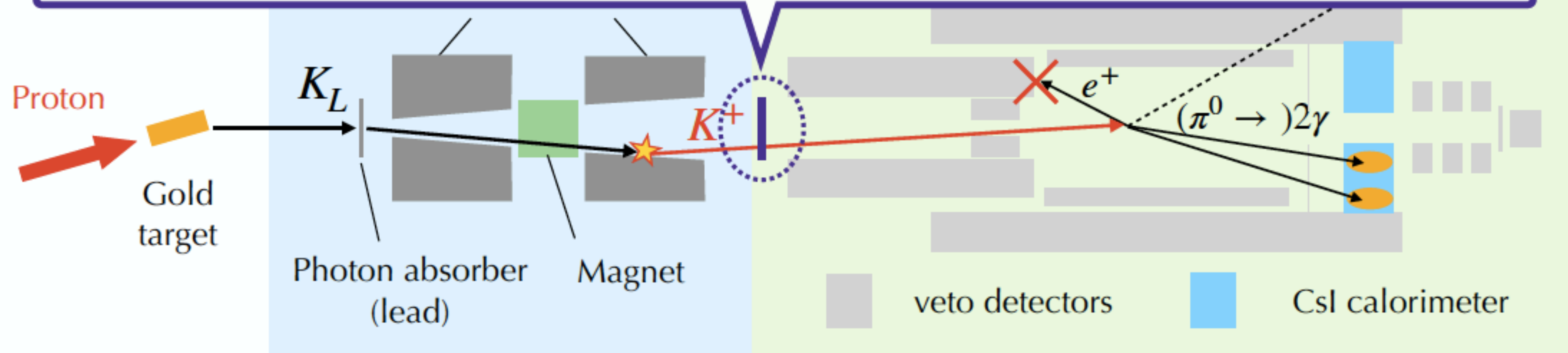
Upstream Charged Veto (UCV)

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)

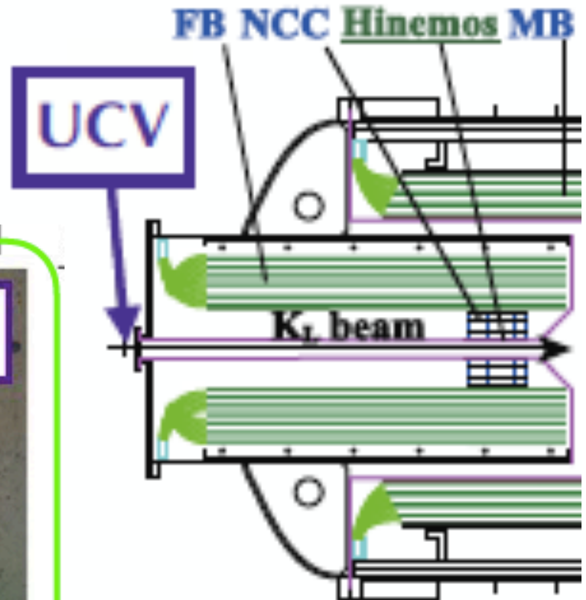


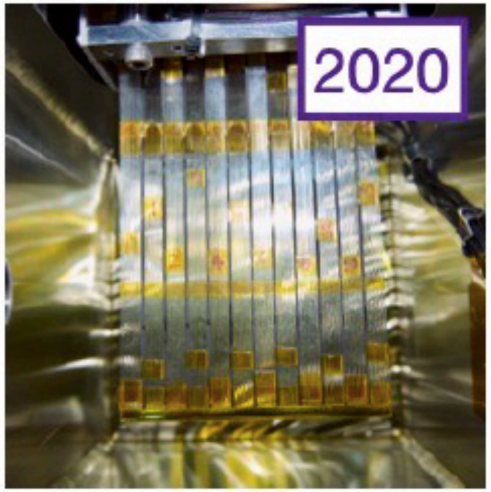


Upstream Charged Veto (UCV) since 2020

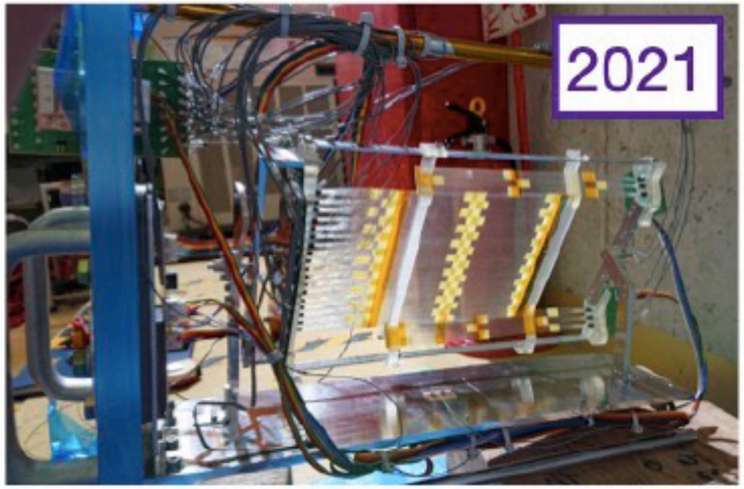
To reject K± backgrounds, found in 2016-18 data analysis

- For K± detection in the beam at the entrance of the KOTO detector



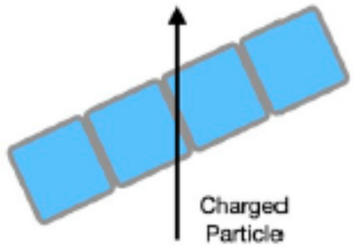


A plane of 1mm-square scintillation fibers, read by MPPC



A plane of 0.5mm-square fibers

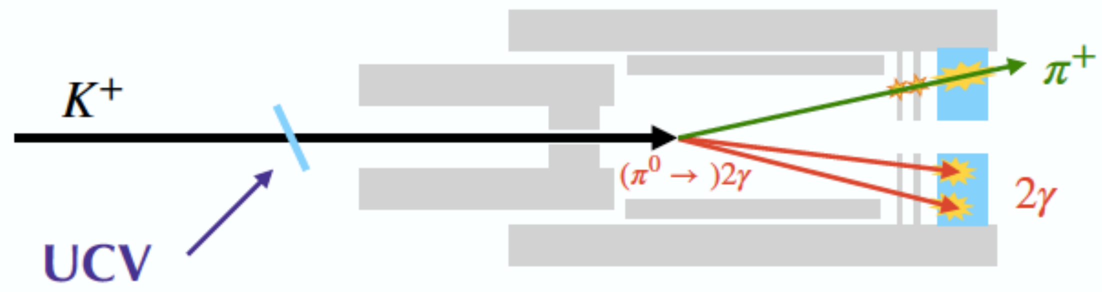
- Tilted 25 degree to reduce inefficiency due to fibers' clad

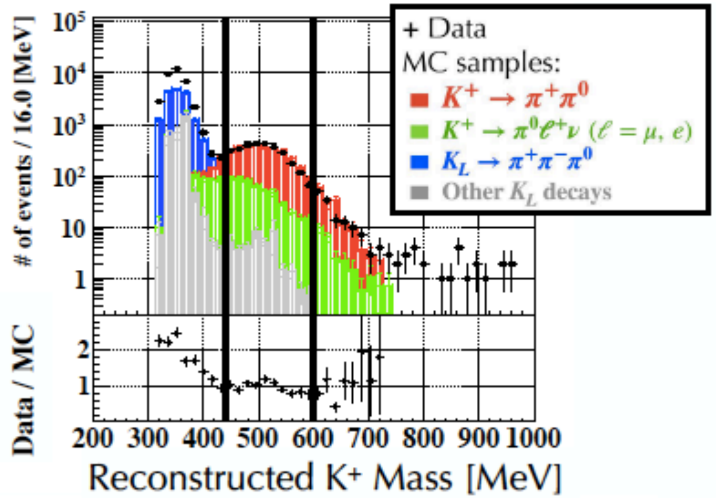


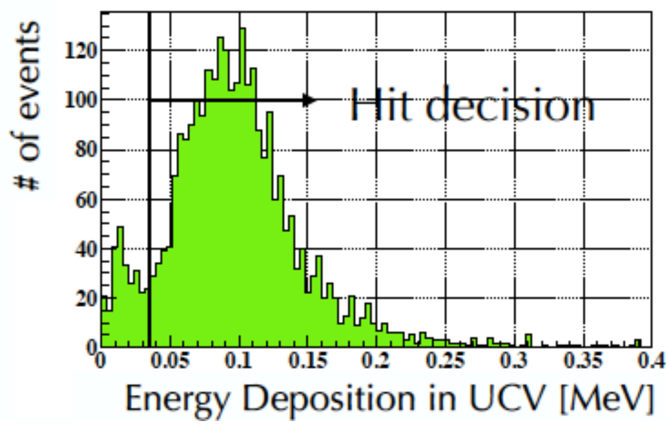
Reduction of the K^+ Background

Performance evaluation using K+ sample by collecting $K^+ \to \pi^+\pi^0$ (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







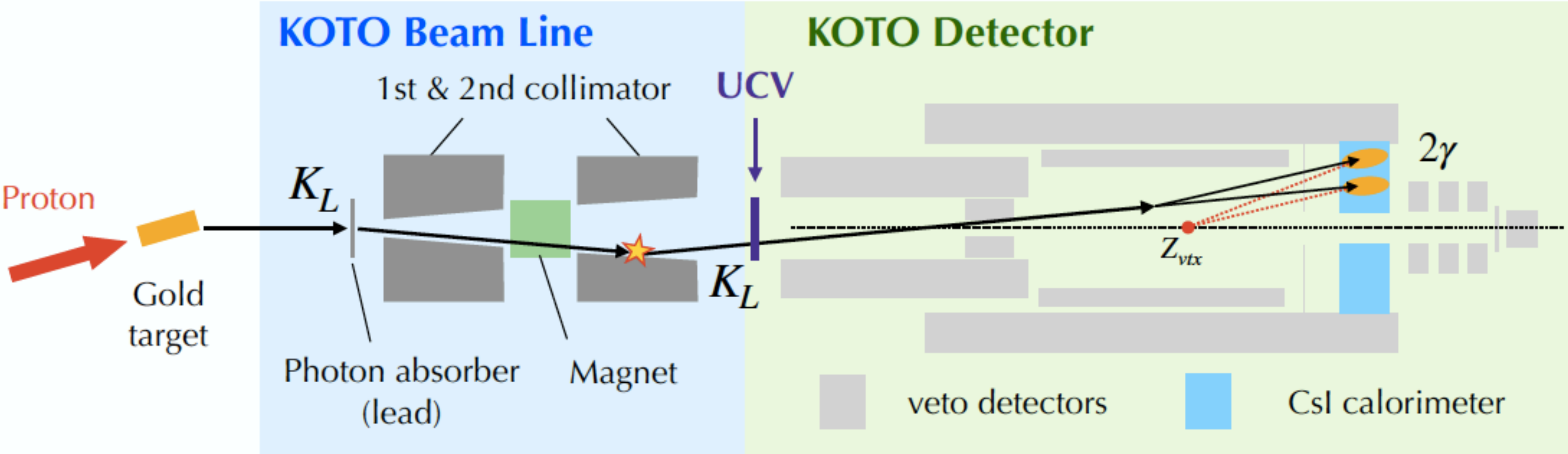
==> ×1/13 BG reduction

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 $K_L \to 2\gamma$ Background

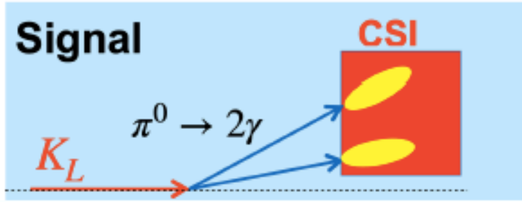
Halo (scattered) K_L decays into 2γ with a finite transverse momentum.

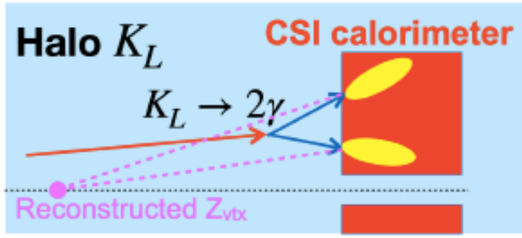
- UCV that was installed to reject K^+ BG also enhances the scattered component.

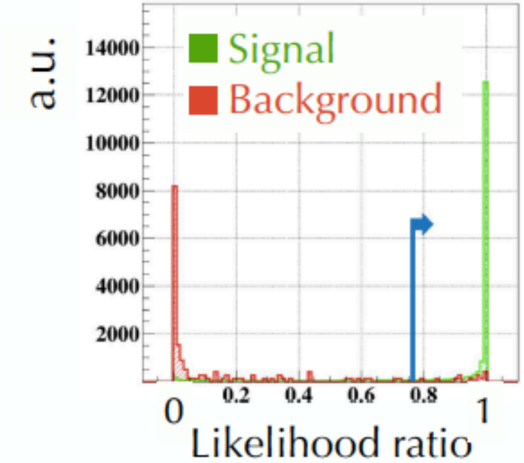


Reduction of the Halo $K_L \to 2\gamma$ Background

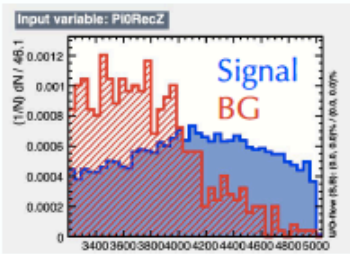
- Likelihood ratio based on shower shape consistency



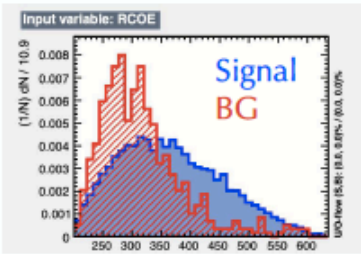




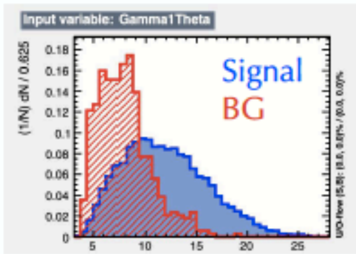
- Multivariate analysis using Fisher Discriminant



Reconstructed Z

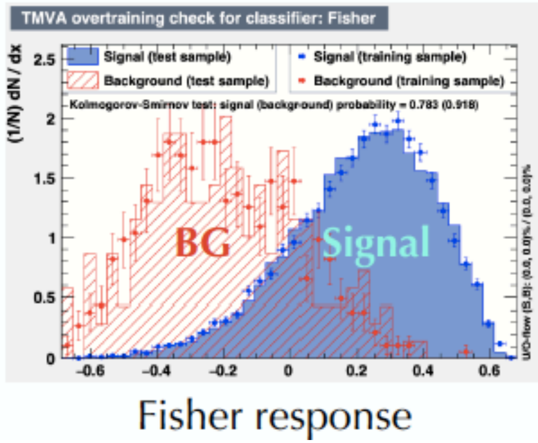


R_{COE}



$\theta_{\gamma 1}$

, etc



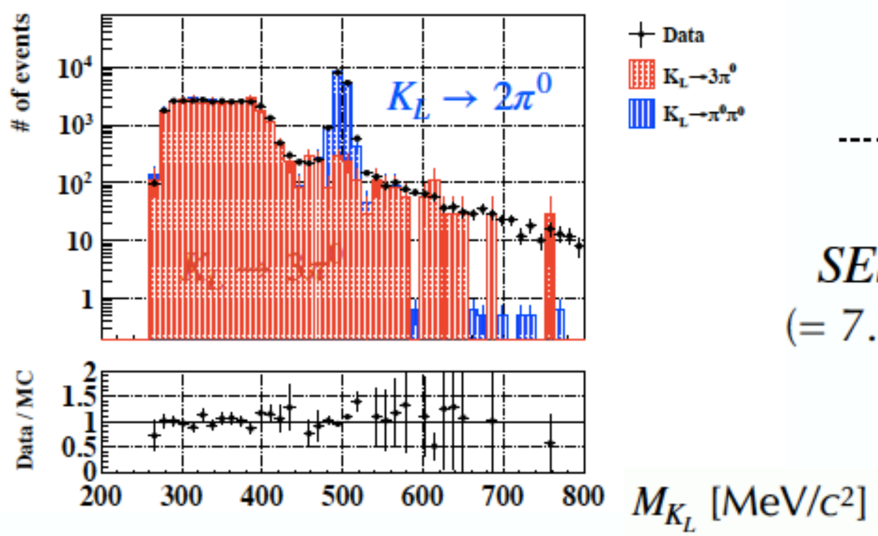
<u>**==> ×1/10 BG reduction (with 94% signal acceptance)**</u>

Sensitivity

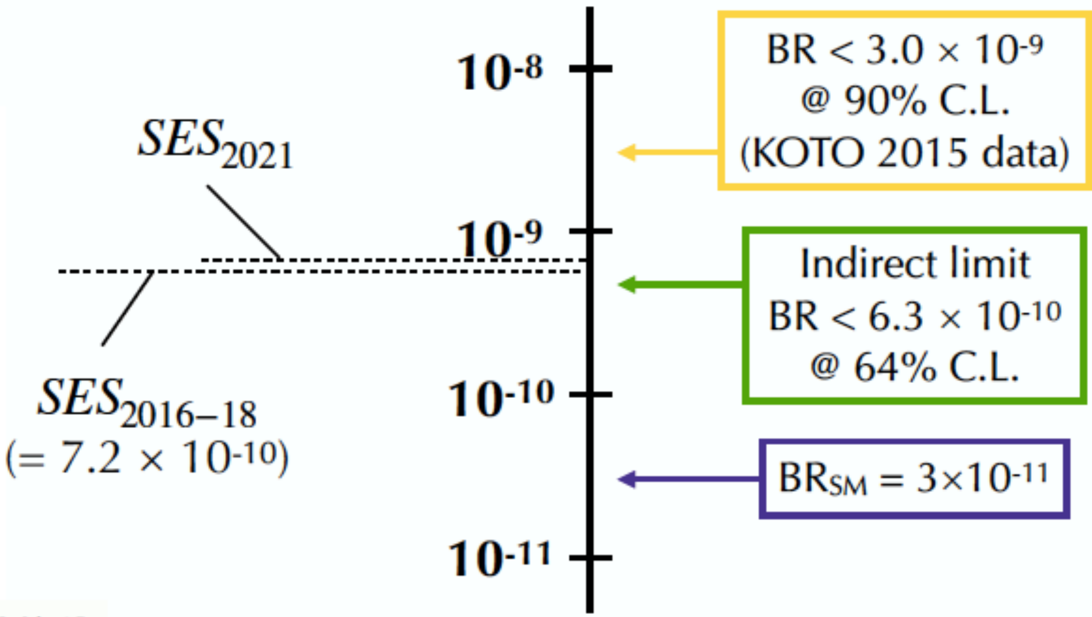
Single Event Sensitivity:

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

==> ~0.04 SM events expected



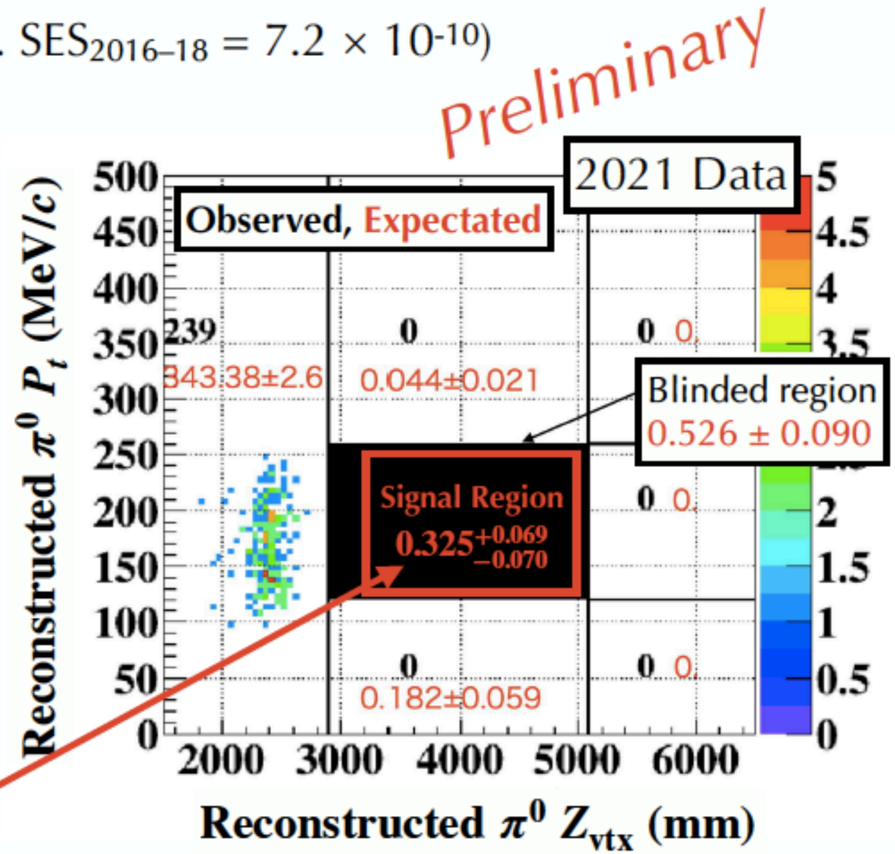
Experimental uppper limit on $BR(K_L \to \pi^0 \nu \bar{\nu})$



Summary of the Background Estimation

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

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



Shown in Kaon2022 with
limited MC statistics
➔ Try to improve!

Blind analysis

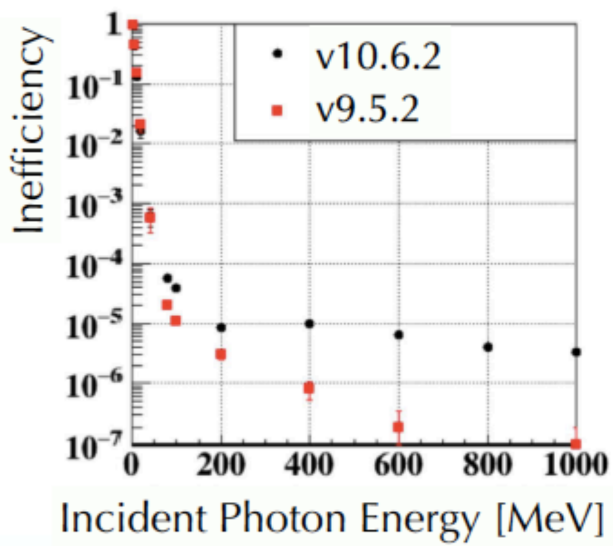
Issue on the $K_L \to 2\pi^0$ Background

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**	$\mathbf{1.1 \times 10^{-10}}$

- **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.

Barrel detector inefficiency
(simluation study)

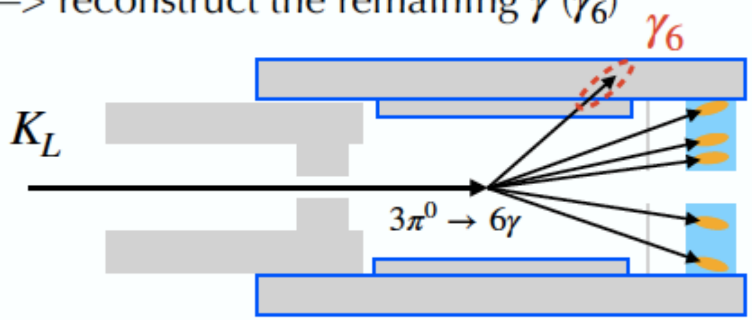


Inefficiency Evaluation with 5γ Data

- 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)



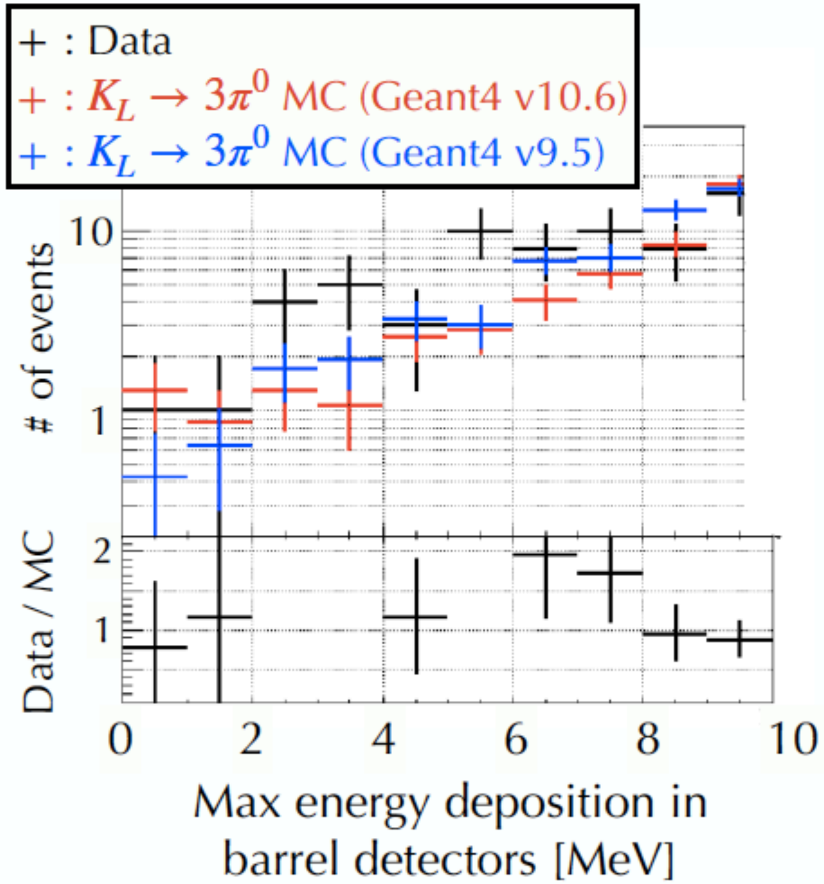
For 1 MeV threshold,

Inefficiency (Data) = (4.8 ± 4.8) × 10-5

Inefficiency (MC) = (6.2 ± 2.5) × 10-5 (v10.6)

= (2.1 ± 1.5) × 10-5 (v9.6)

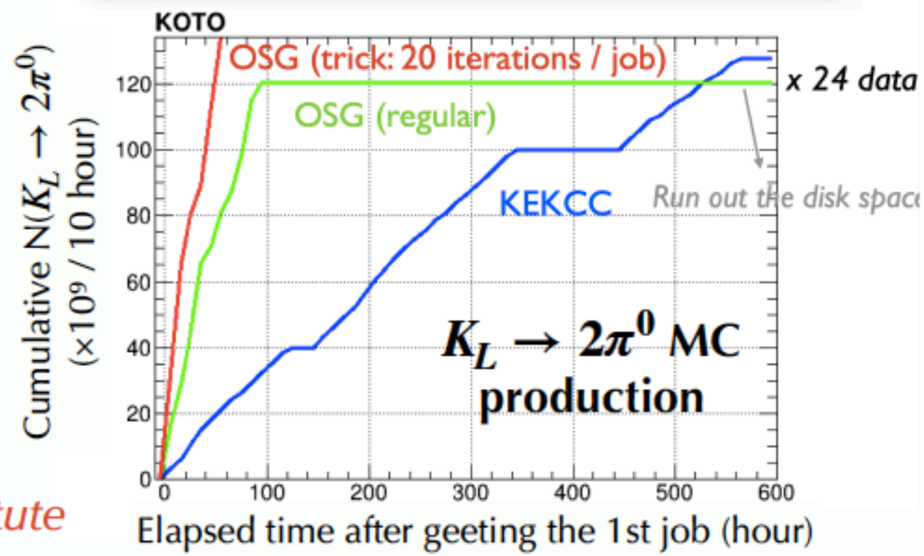
- **~100% syst. error will be accounted for in $K_L \rightarrow 2\pi^0$ BG estimation of 2021 analysis**
- **Need more statistics for future analysis**



Expansion of Computing Resource

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

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



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

KEKCC = 3×10^9 events / 10 hour
OSG = 12×10^9 events / 10 hour (regular)
= 24×10^9 events / 10 hour (optimized)

==> 4–8 times faster production

Supported by the UChicago Computational Institute

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

Based on inverse cut studies for various vetos by comparing data vs MC with much improved MC statistics (OSG resources)!

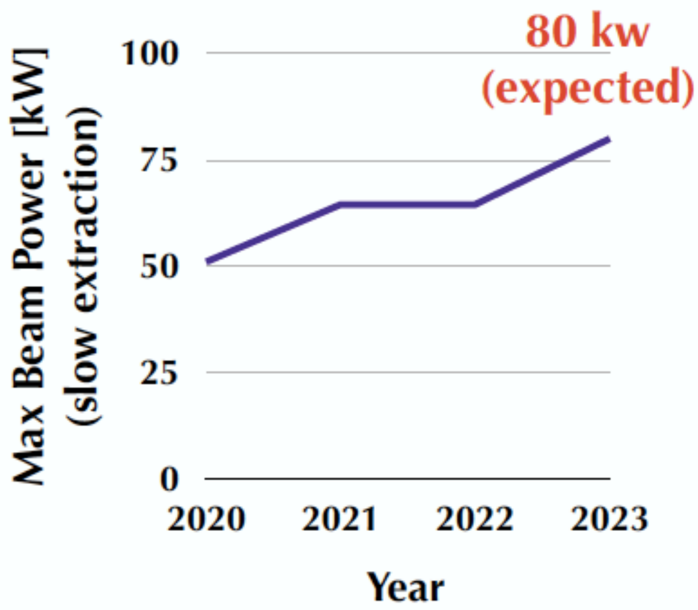
Next Beam Time 2023-2026

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)



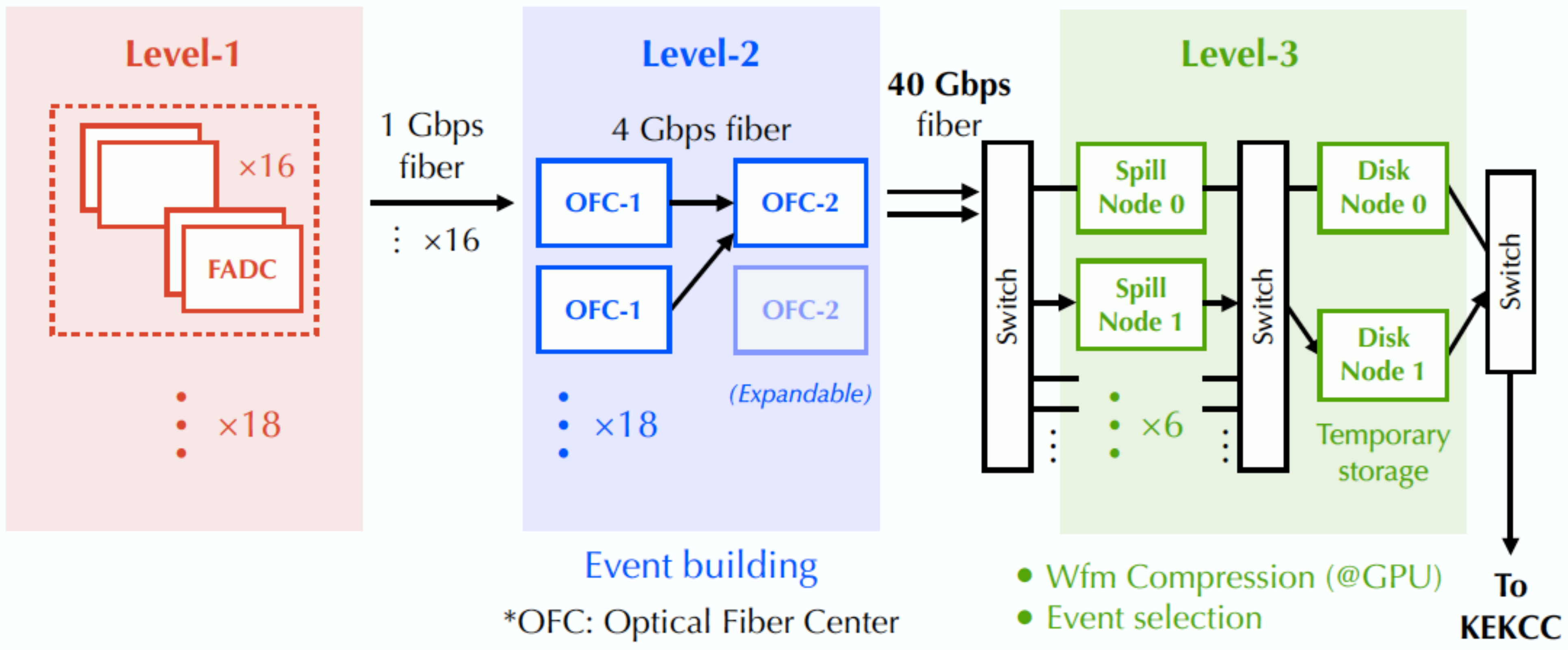
Experts from UChicago are working on this project with other members from Japan (UOsaka) and Taiwan (NTU).

Supported by US-Japan program (2021–2023)

2023 June run with beam power 30 kW and 50kW, but had been cut short due to an accident of a PS fire near Hadron Hall.

New DAQ System

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

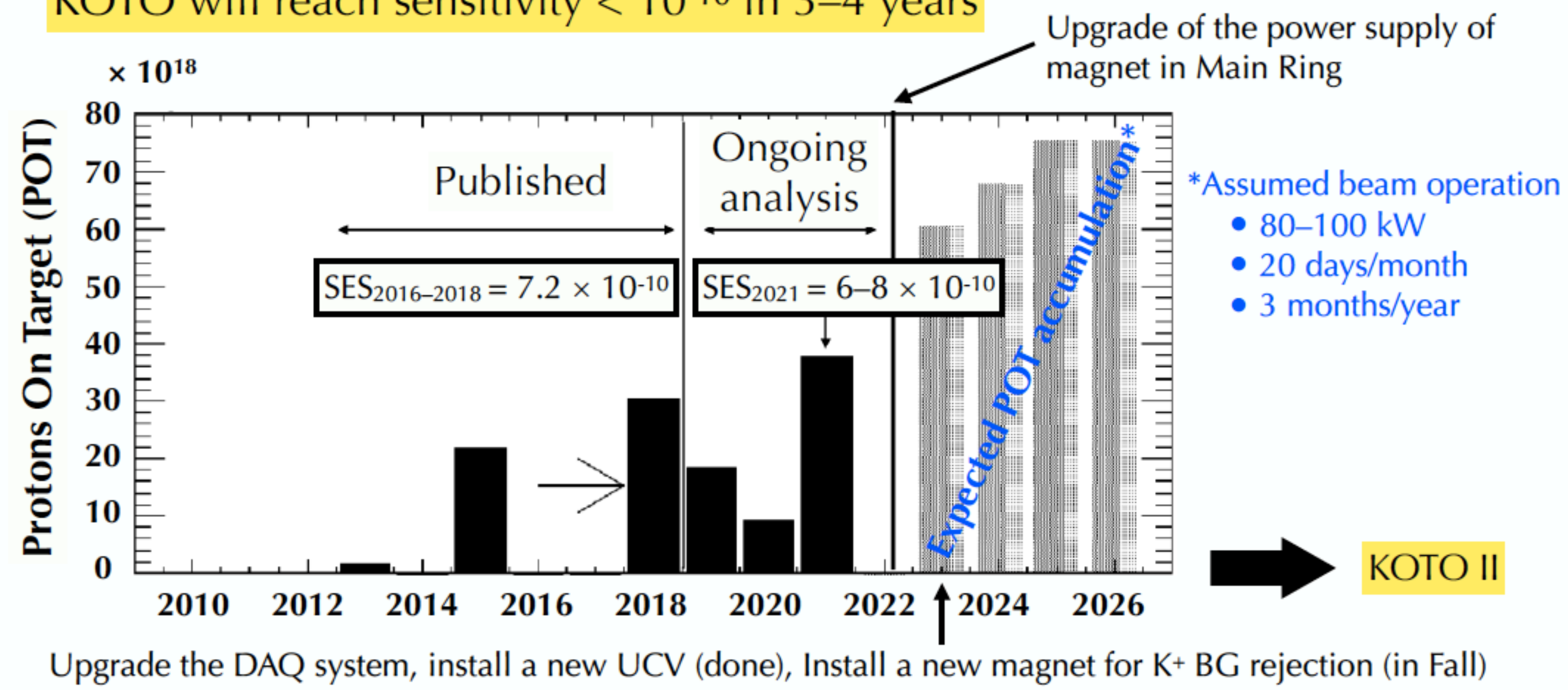


Summary

- 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)

Sensitivity Reach of KOTO

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

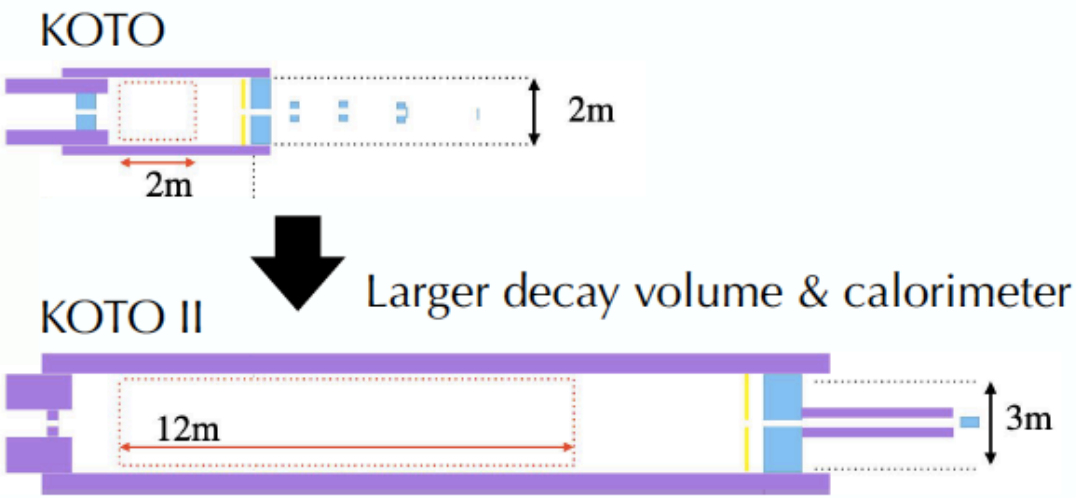


KOTO II

KOTO II
Sensitivity~$O(10^{-13})$, ~40 SM signals

arXiv:2110.04462

Extended Hadron Experimental Facility
Smaller extraction angle: 16°(KOTO) —> 5°(KOTO II) => higher flux & momentum

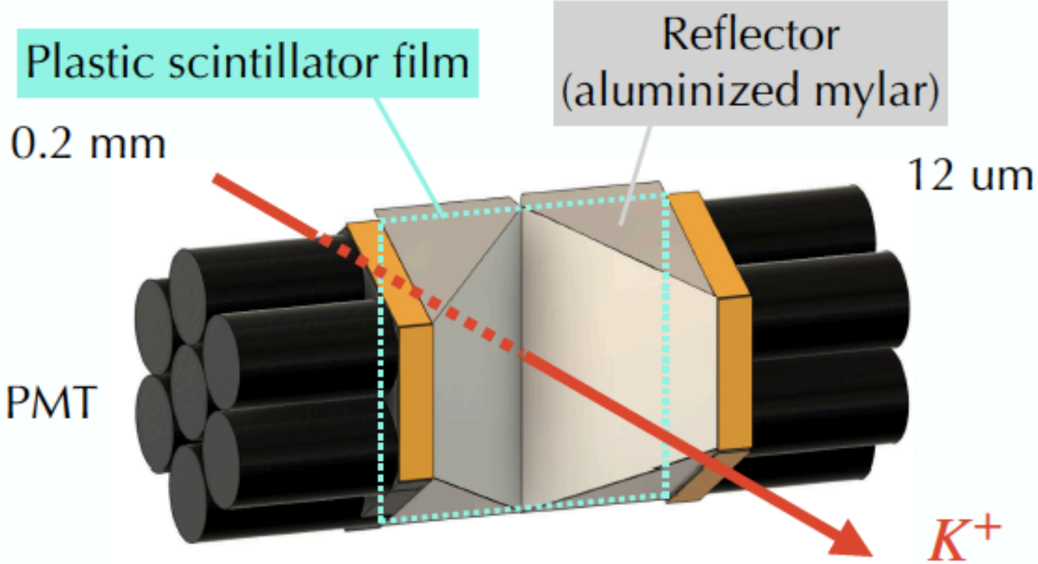


Backup

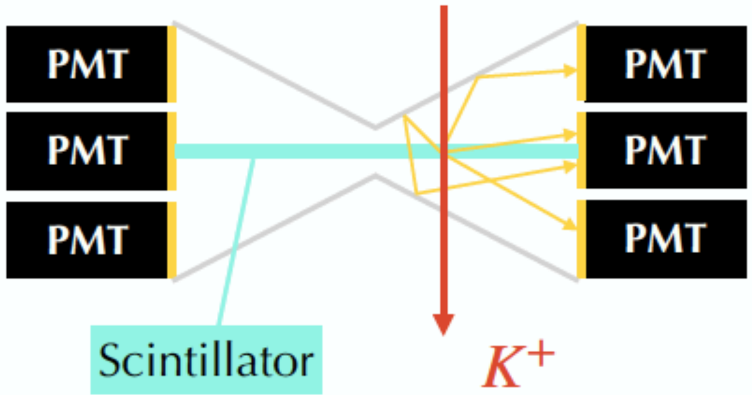
New Upstream Charged Veto (UCV)

Installed a new upstream charged veto detector with better performance

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



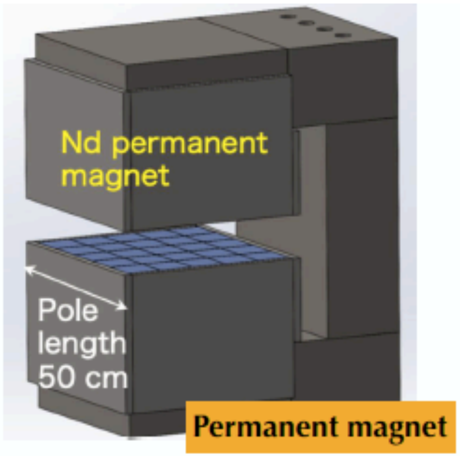
- Collect photons that are **not trapped** inside the scintillator
- ~20 p.e./MIP (result at e^- beam test)

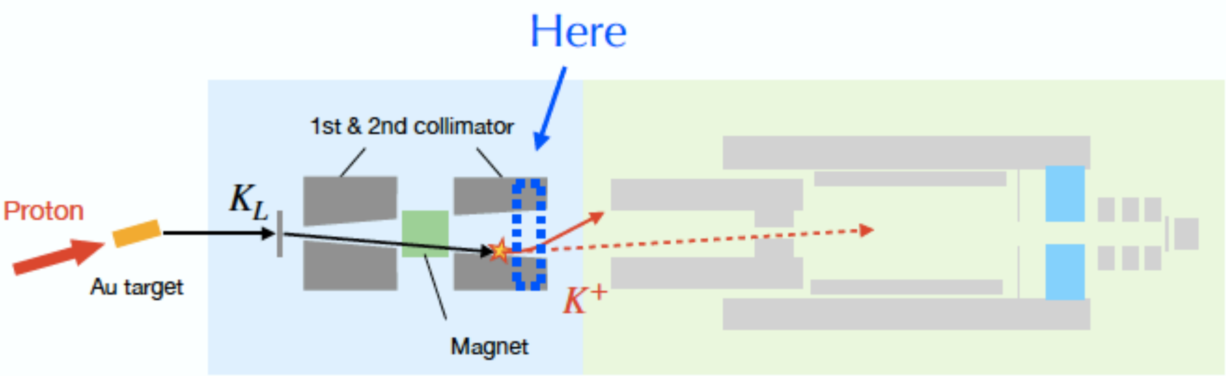


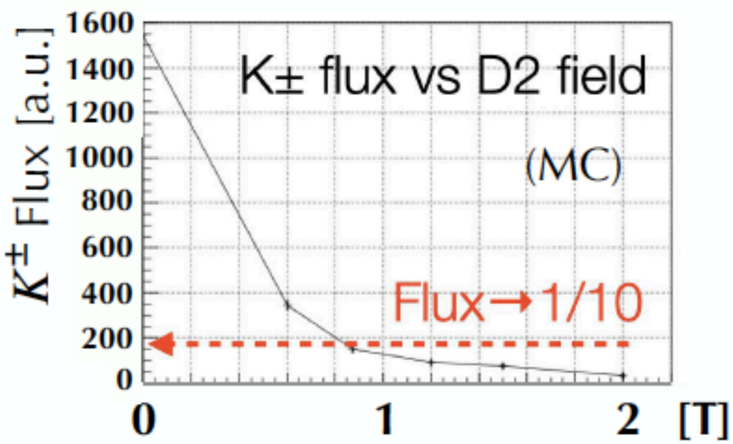
New Magnet

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.



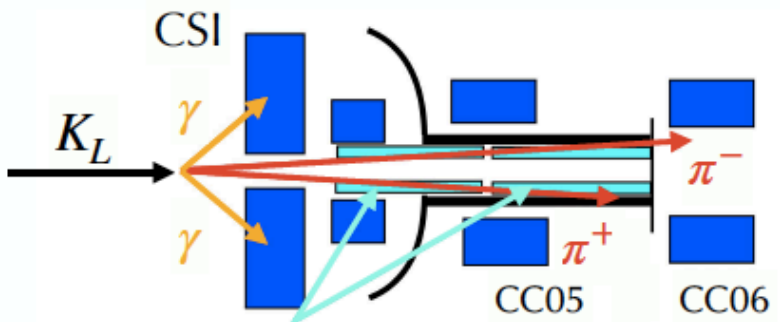




Downstream Charged Veto (DCV)

Downstream Charged Veto (DCV) (2019–)

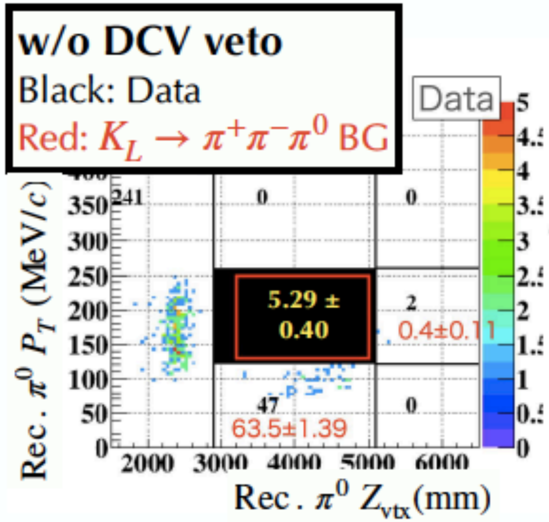
- Reject the $K_L \to \pi^+\pi^-\pi^0$ BG (< 0.07 @90%CL)
  ==> acceptance recovery by extending the signal region

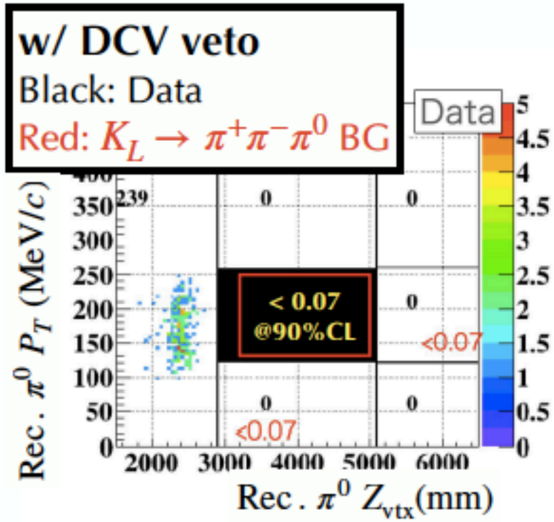


Plastic scintillator plates inside the beam pipe

2016–18 signal region

2021 signal region





New Level-2

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

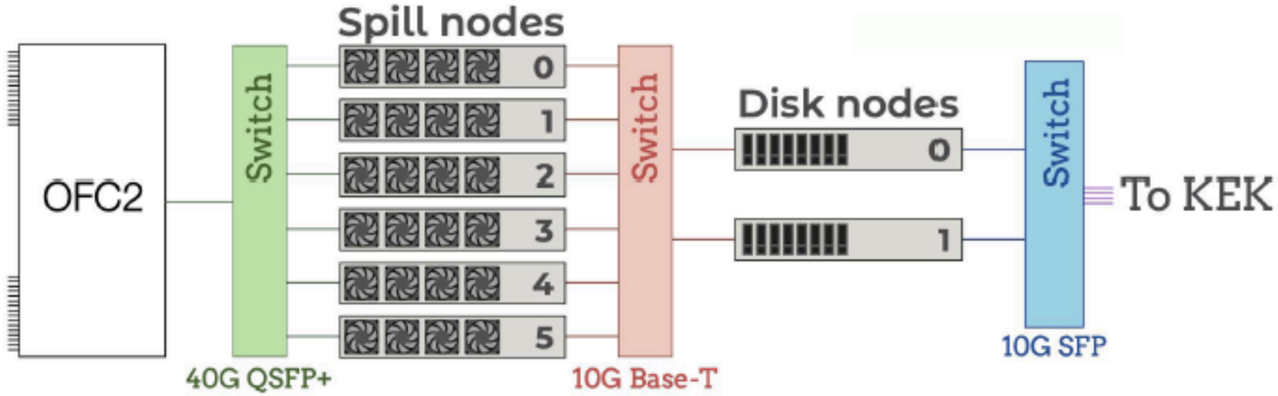
	OFC-I	OFC-II
Upstream	16 x ADC data	18 x OFC-I data
Downstream	OFC-II	PC (ethernet protocol)
Input/Ouput	18 x 4 Gbps (18 SFP)	36 x 10 Gbps (9 QSFP)
FPGA type	Arria V	Stratix X
Memory buffer	~50 events	~20 events

* *Memory can be read / written simultaneously.*

OFC-I

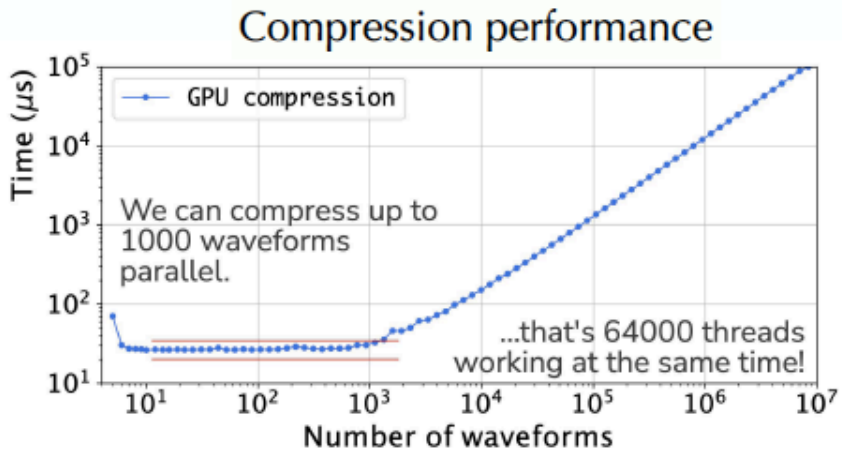
OFC-II

New Level-3

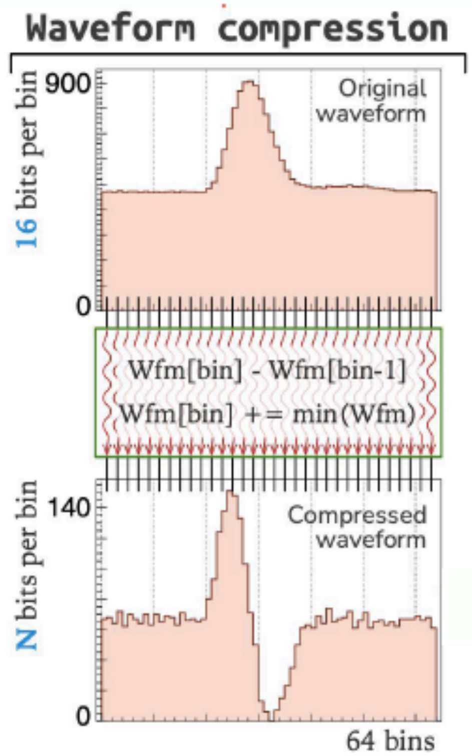


Spill nodes
OFC2
Switch
0
1
2
3
4
5
Switch
Disk nodes
0
1
Switch
To KEK
40G QSFP+
10G Base-T
10G SFP

PC- farm



Compression performance
GPU compression
Time (µs)
We can compress up to
1000 waveforms
parallel.
...that's 64000 threads
working at the same time!
Number of waveforms



Waveform compression
16 bits per bin
900
0
Original
waveform
Wfm[bin] - Wfm[bin-1]
Wfm[bin] += min(Wfm)
N bits per bin
140
0
Compressed
waveform
64 bins

Future Data Collection of 5γ Sample

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

Trigger ingredient	Et	Veto	$N_{cluster}$=5	CsI fiducial	Center of Energy in CsI	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

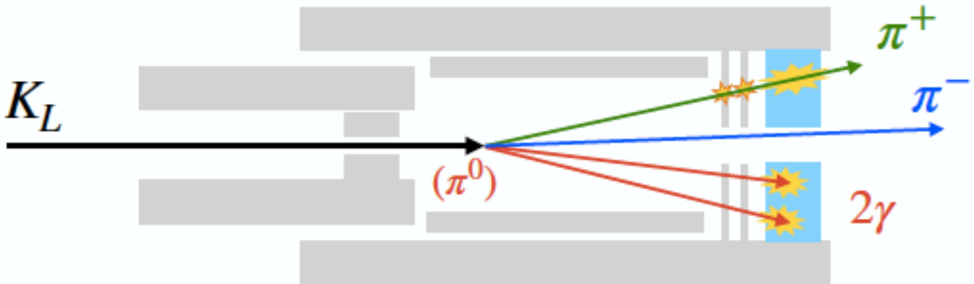
- CsI fiducial: Reject events with hits in the inner most region of the calorimeter
- COE: Center of energy on the CsI calorimeter

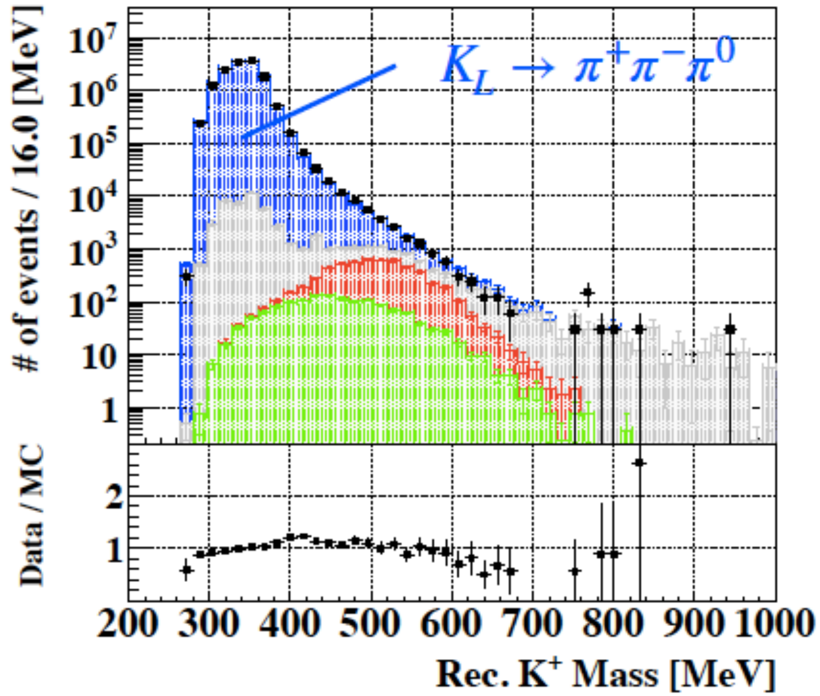
==> These event selections will be implemented in the new DAQ system

K_L Flux Measurement

K_L flux was measured under loose cut selection.

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

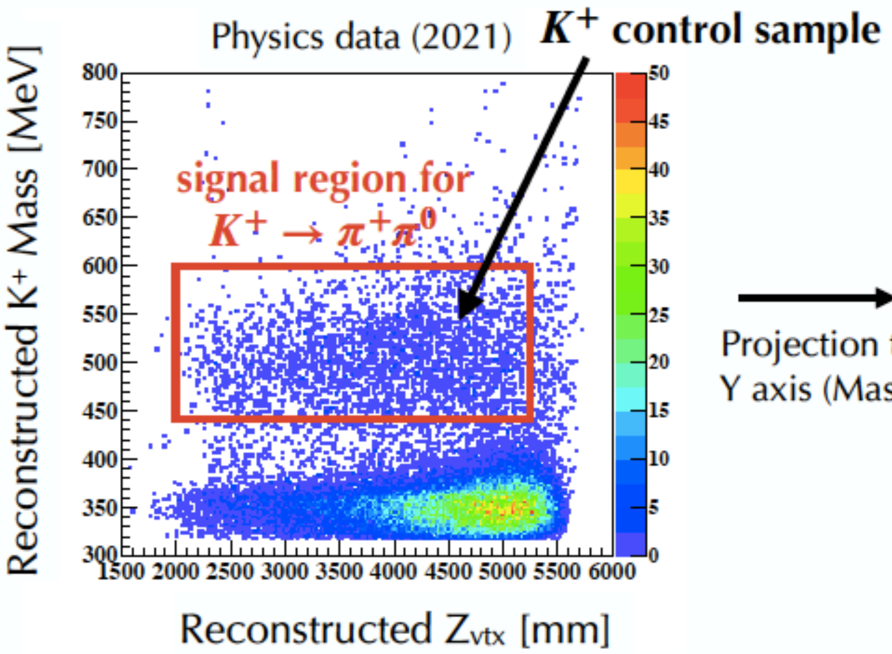




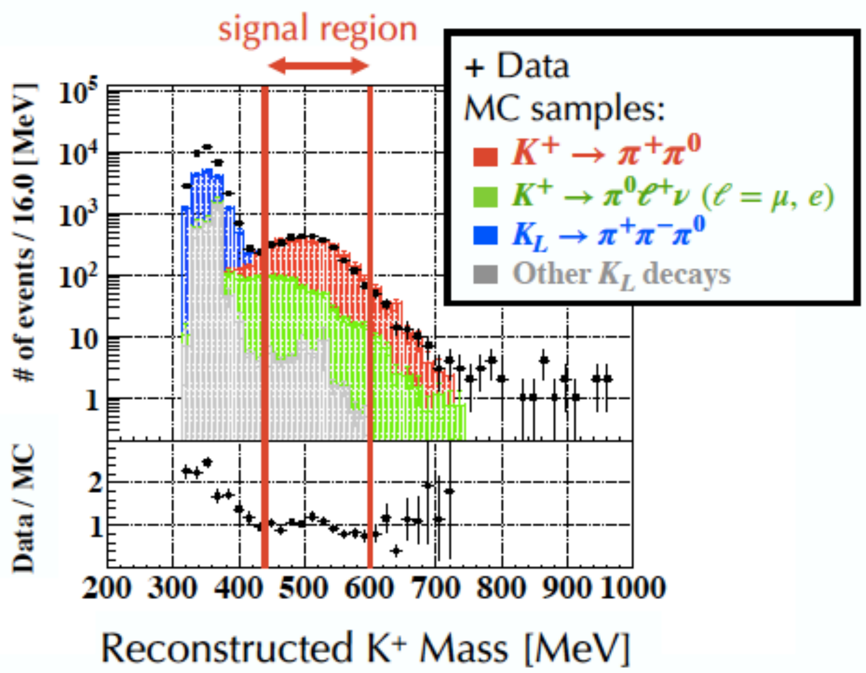
K^+ Flux Measurement

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



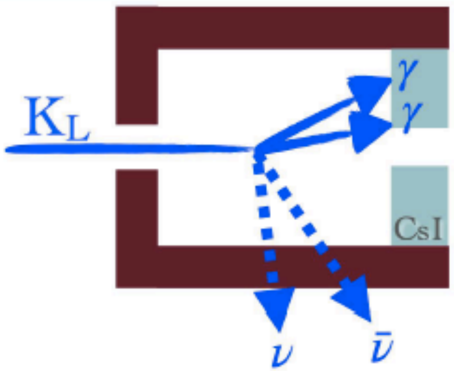
Projection to Y axis (Mass)



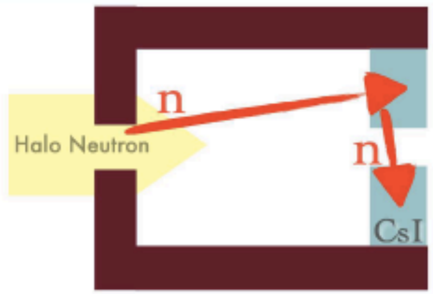
Upgrade of the Calorimeter

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

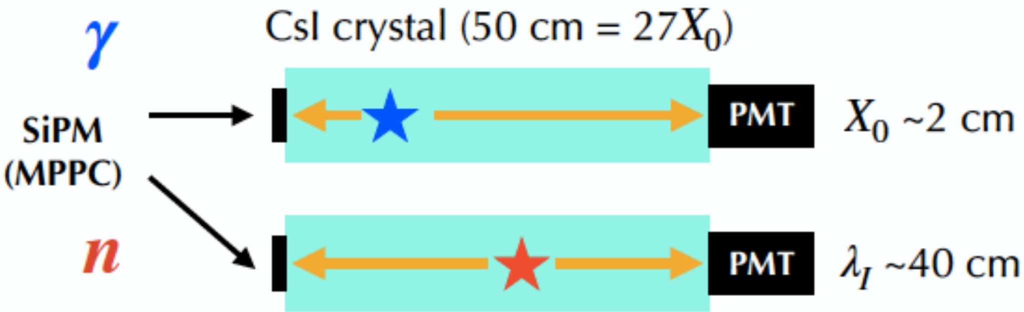
Signal



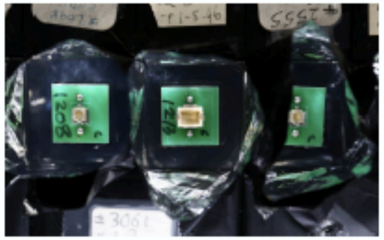
Hadron cluster BG

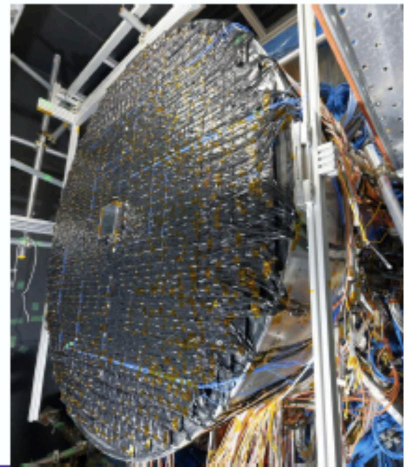


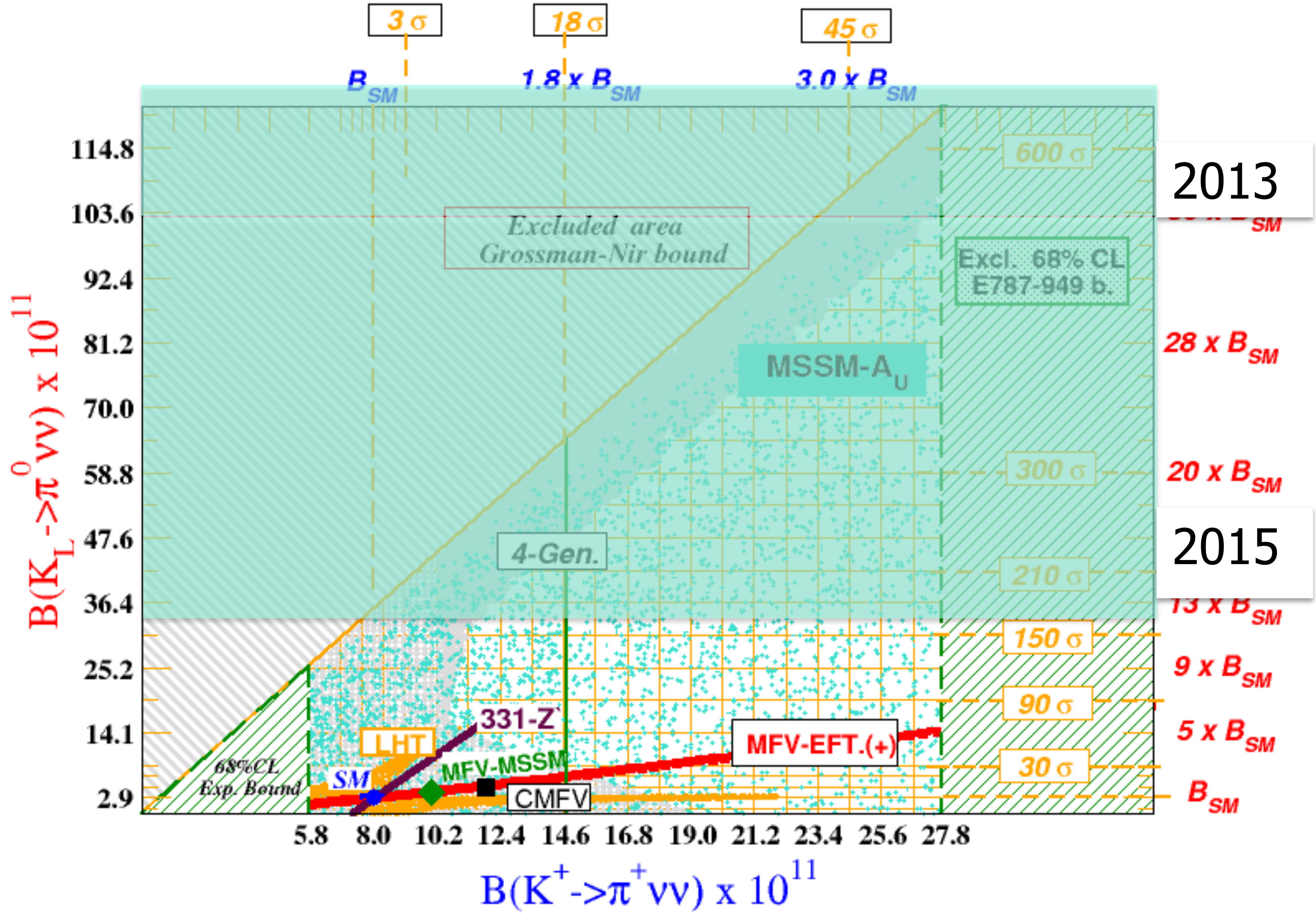
- Both-end readout
  ==> γ/n separation by ΔT between front-side(SiPM) & rear-side(PMT)



Front view
(~4000 MPPCs in total)







http://www.lnf.infn.it/wg/vus/content/Krare.html