Kaon Physics: Some past, present, and future

Y. Wah May 20th 2023 Melfest

In the early fifties, Murray Gell-Mann recalled [3] that "...Although the presence of Enrico (Fermi) in the back row was terrifying, nothing went seriously wrong. One day, in the course of explaining the strangeness idea, I discussed the neutral meson K^0 and $\overline{K^0}$, which are antiparticle of each other. Enrico objected that nothing new was involved, since one could take, instead of the K^0 and $\overline{K^0}$ fields, their sum and difference, which would then describe two neutral spin zero particle, each its own antiparticle ... I was able to answer Enrico by saying that in certain decays of this neutral strange particle, the sum and difference would indeed be the relevant fields, but that in the production process a single K^0 could accompany a lambda hyperon, which a $\overline{K^0}$ could not. Later (with A. Pais, 1955 [4]), when I wrote up the neutral K particle situation, I thanked Fermi for his question...". K_1 and K_2 are the admixtures of K^0 and $\overline{K^0}$ with even and odd respectively, under the CP transformation.

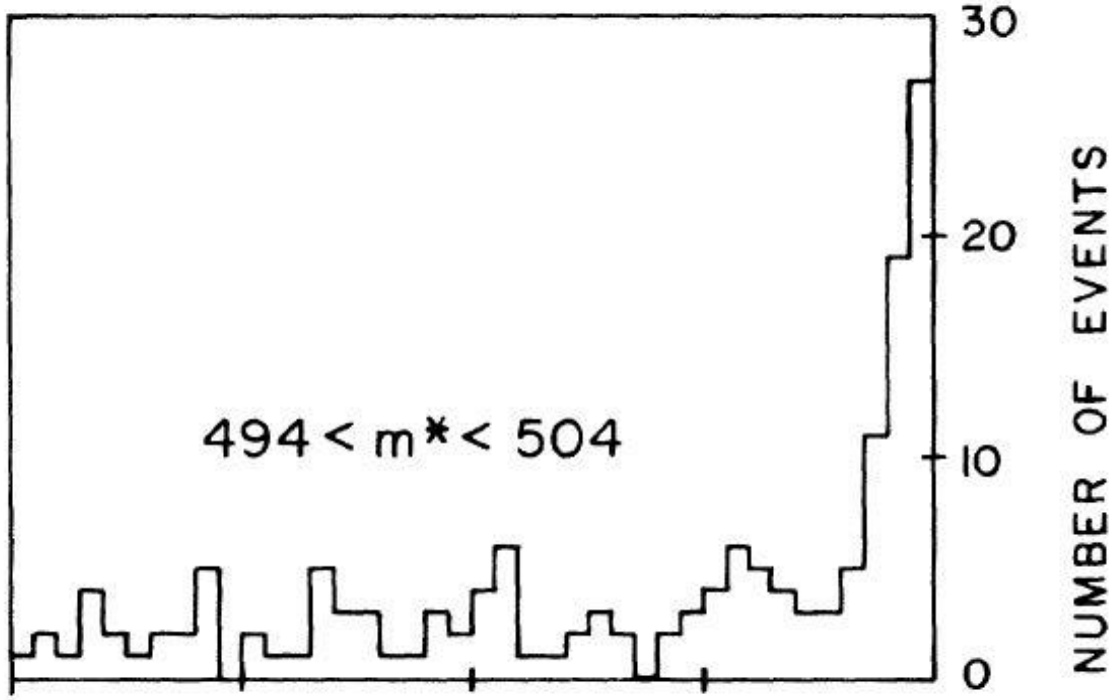
[3] J. Cronin, *Fermi Remembered*, University of Chicago Press ISBN 10:022610088X (2013)

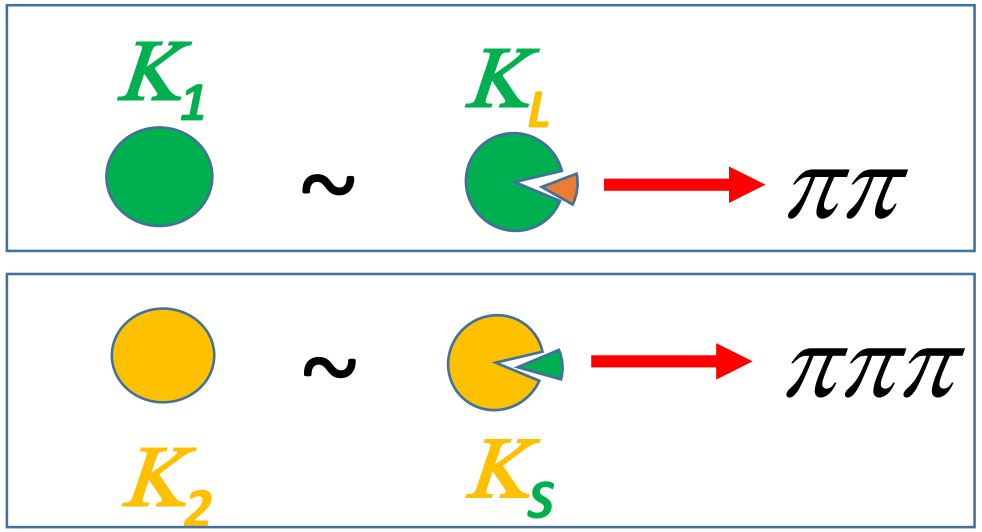
Odd CP (-1) $K^0 + \overline{K^0}$ ~ K_1 *Long lived* $\not\rightarrow \pi\pi$

Even CP (+1) $K^0 - \overline{K^0}$ ~ K_2 *Short lived* $\rightarrow \pi\pi$

1964: Observed long lived kaon decays to 2 pions (~50 events)

1964+1 month : Theory re-classification





$$|\psi(t)\rangle = A(t)|K^0\rangle + B|\overline{K}^0\rangle$$

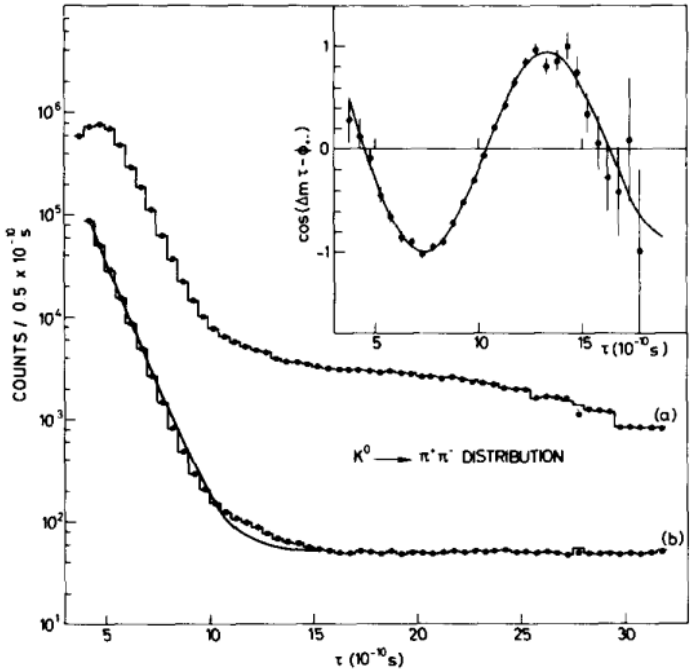
$$\psi(t) = \begin{pmatrix} A(t) \\ B(t) \end{pmatrix}$$

$$i\frac{d}{dt}\psi(t) = H\psi(t)$$

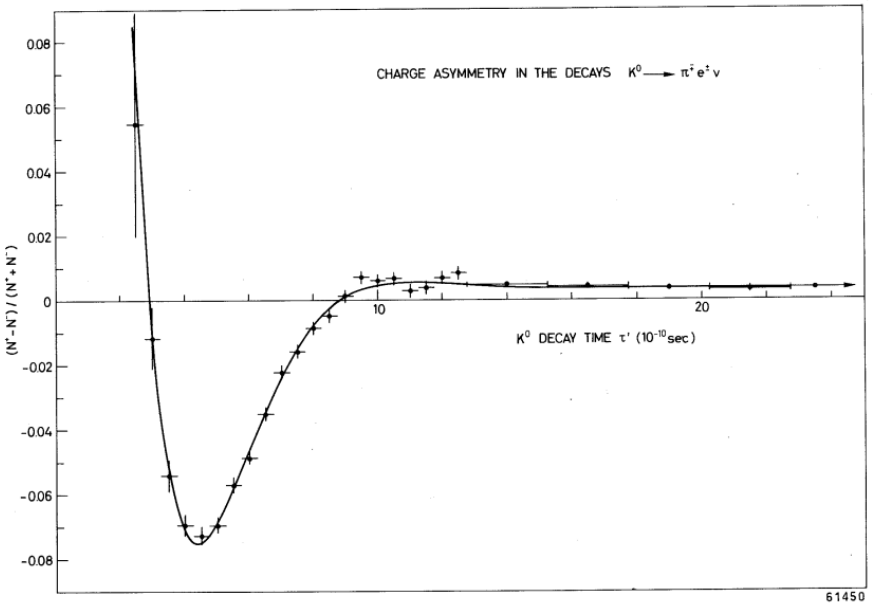
$$H = \begin{pmatrix} M - i\Gamma/2 & M_{12} - i\Gamma_{12}/2 \\ M_{12}^* - i\Gamma_{12}^*/2 & M - i\Gamma/2 \end{pmatrix}$$

CP: $M_{12} = M_{12}^*, \quad \Gamma_{12} = \Gamma_{12}^*$

~~CP~~: $\epsilon \simeq \frac{e^{i\pi/4}}{2\sqrt{2}} \frac{\mathrm{Im}\, M_{12}}{\mathrm{Re}\, M_{12}} \simeq \frac{e^{i\pi/4}\, \mathrm{Im}\, M_{12}}{\sqrt{2}\Delta M}$



CP violation in the 'mixing'
Pure ΔS = 2 effect



Superweak theories:

1. The CP violation would be the same for different decay modes such as $\pi^+\pi^-$ and $\pi^0\pi^0$ since it was determined entirely by the mixing ϵ. In a standard notation, this says ϵ' vanishes.
2. Assuming CPT invariance the phase of ϵ is given exactly by

$$\theta_\epsilon = \tan^{-1}(2\Delta M/\Delta\Gamma) \approx 43.5^\circ,$$

   where $\Delta M = M_L - M_S$ and $\Delta\Gamma = \Gamma_S - \Gamma_L \approx \Gamma_S$. This is referred to as the superweak phase.
3. It would be very unlikely that CP violation would be discovered outside the K^0 system.

Lincoln Wolfenstein " The Superweak theory 35 years later" (1999).

ε'/ε

$$K_L = K_1 + \varepsilon K_2$$

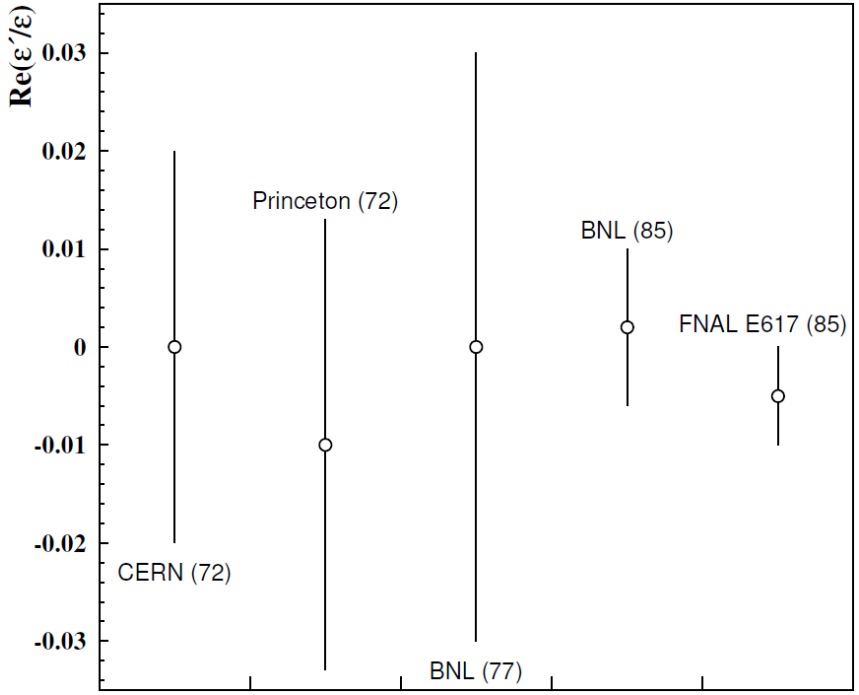
$\pi\,\pi$

ε' ?

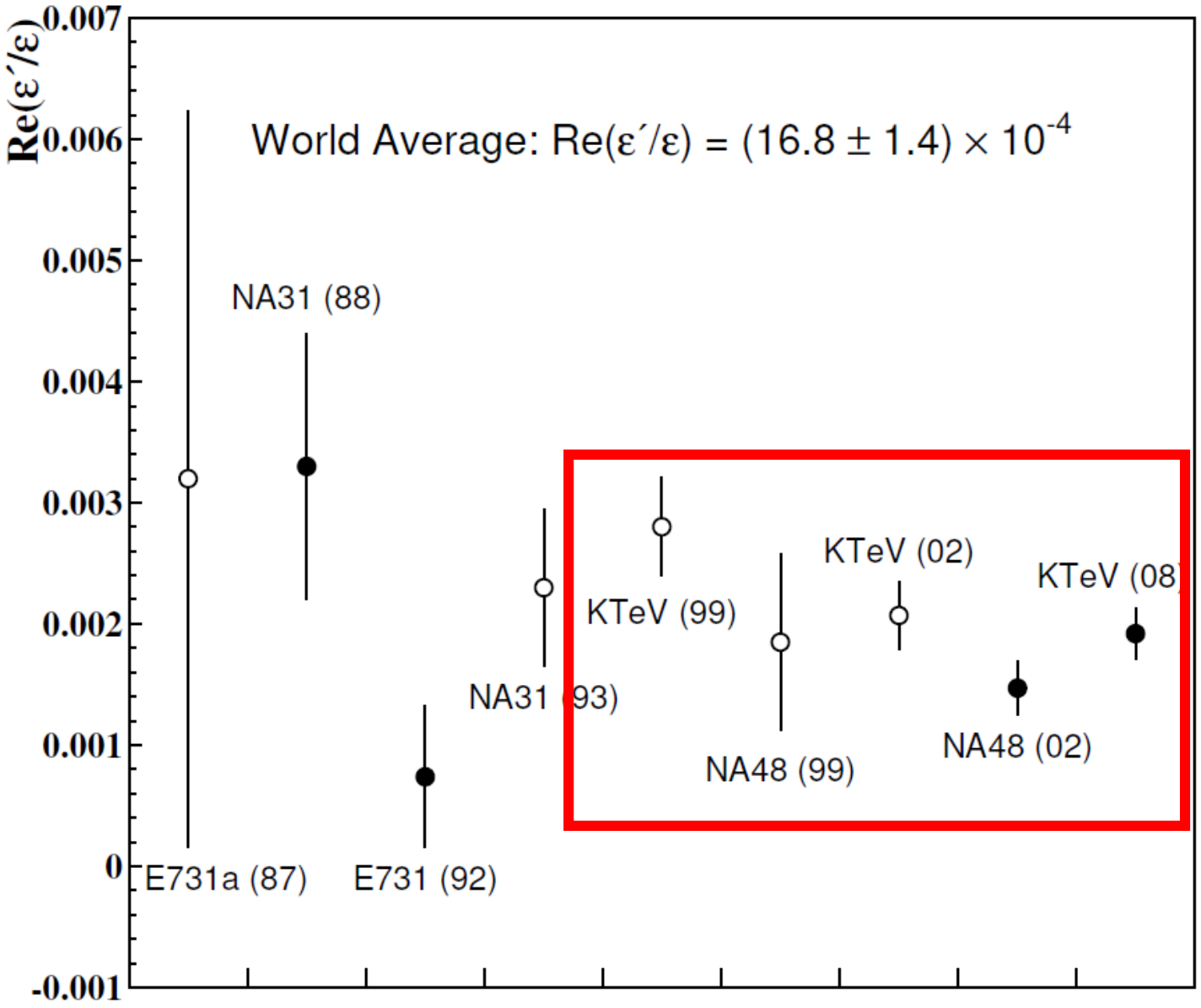
($\Delta S=1$ effect)

Note: $BR(K_L \to \pi^+\pi^-) \sim 2 \times 10^{-3}$

$$R = \frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)} \sim 1 + 6\mathrm{Re}(\epsilon'/\epsilon).$$

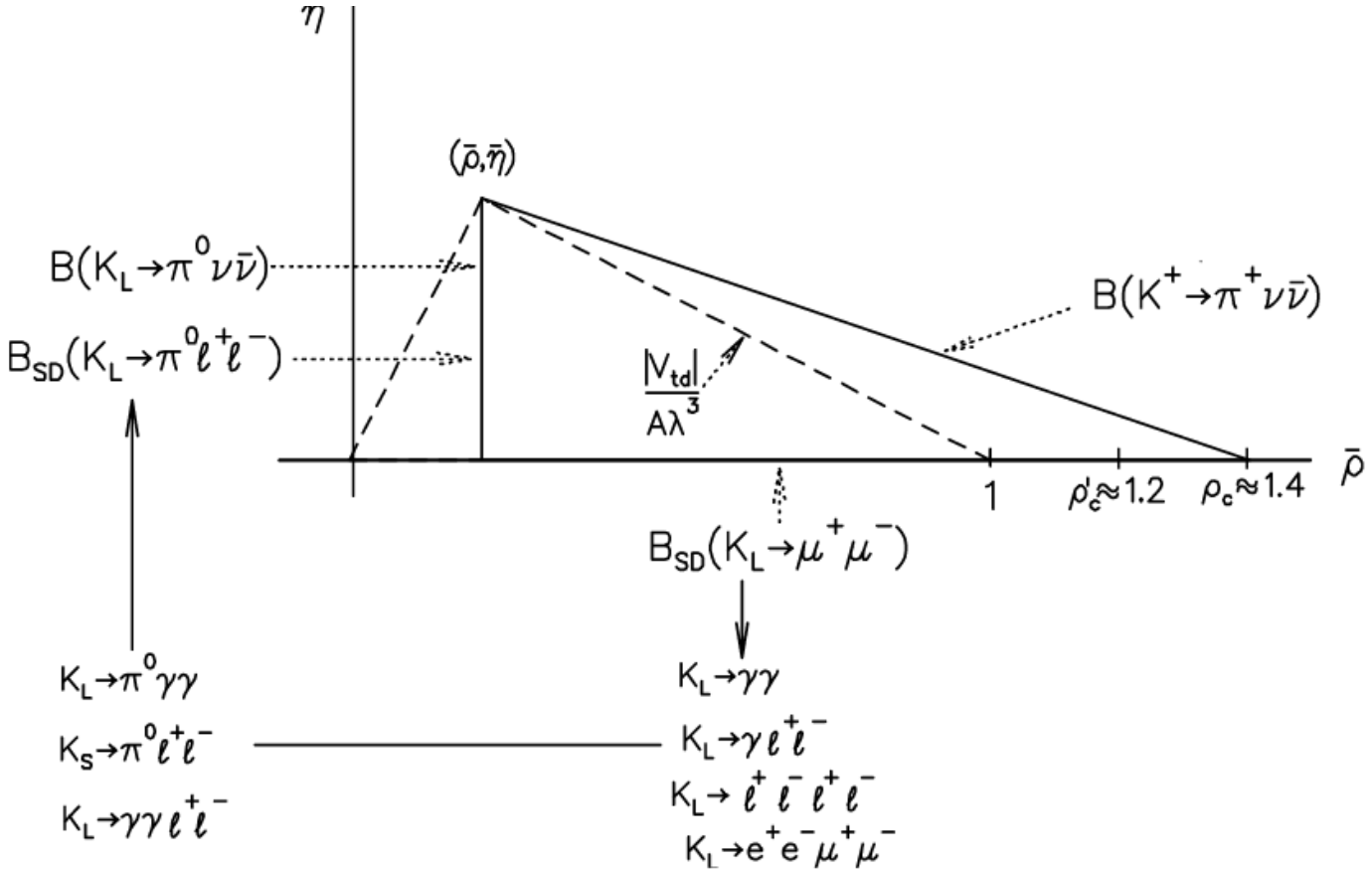


First observation of direct CP violation



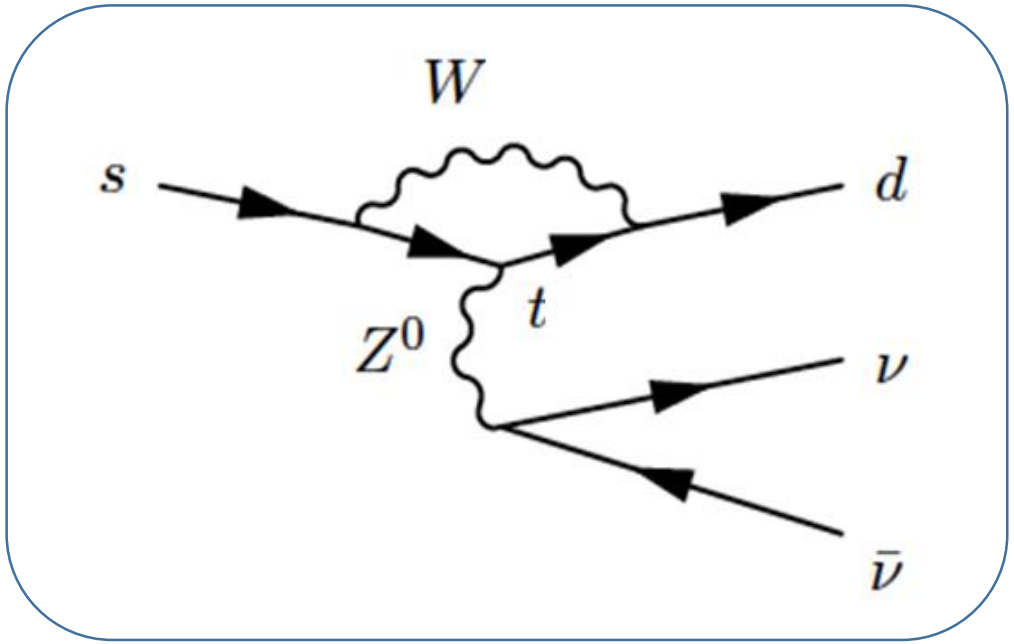
CKM and the Golden mode: $K_L \to \pi^0 \nu\nu$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = V_{\mathrm{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



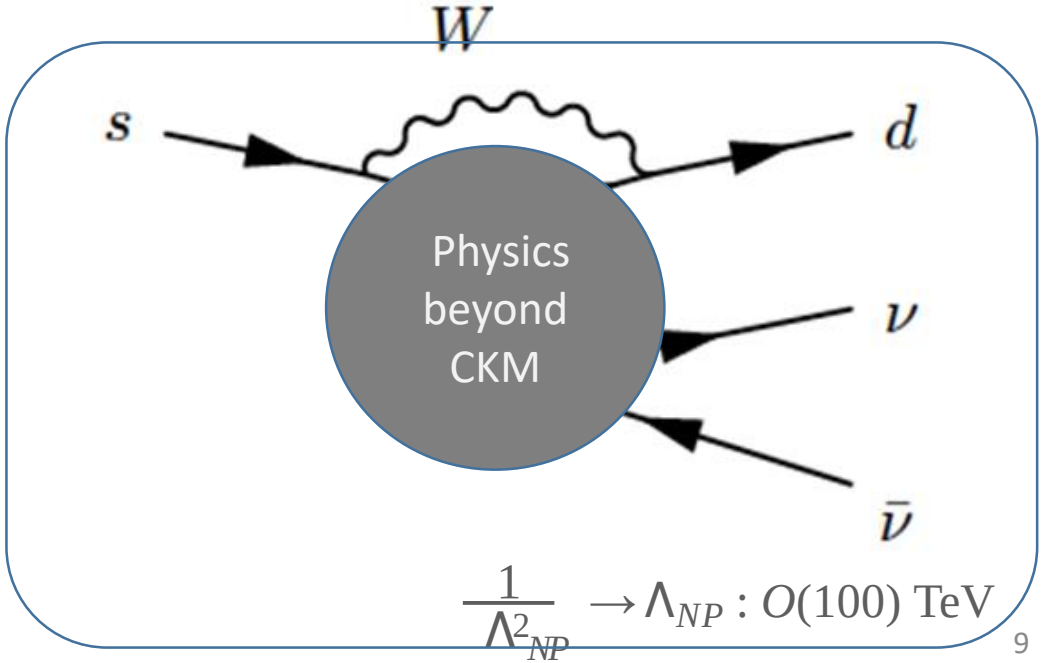
$$K_L \to \pi^0 \nu\nu$$

$$A(K_2 \to \pi^0 \nu\bar{\nu}) \propto V_{td}^* V_{ts} - V_{ts}^* V_{td} \propto 2i\eta$$



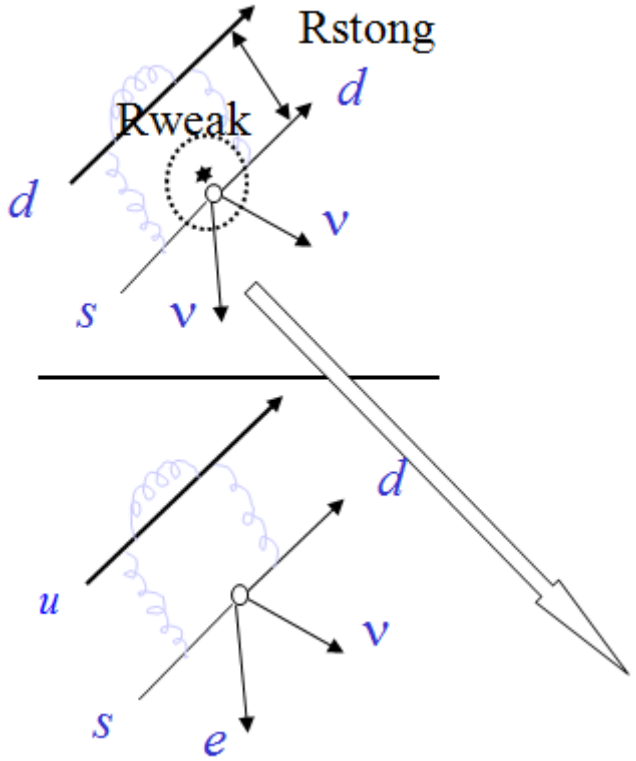
Strong suppression from CKM, ~10^{-11} for K_L

***Small** theoretical uncertainties ~ 1%*



?

Small Theoretical Uncertainty:



- The hadronic matrix element is substitute with known measurement.
- Uncertainty in the Standard Model prediction almost entirely comes from the CKM parameters, the top and W mass.

$$Br(K_L^0 \to \pi^0 \nu\bar{\nu}) = 6.87 \times 10^{-4} \times Br(K^+ \to \pi^0 e^+ \nu) \times A^4 \lambda^8 \eta^2 X^2(x_t)$$

$$\sim 3.00 \times 10^{-11}$$

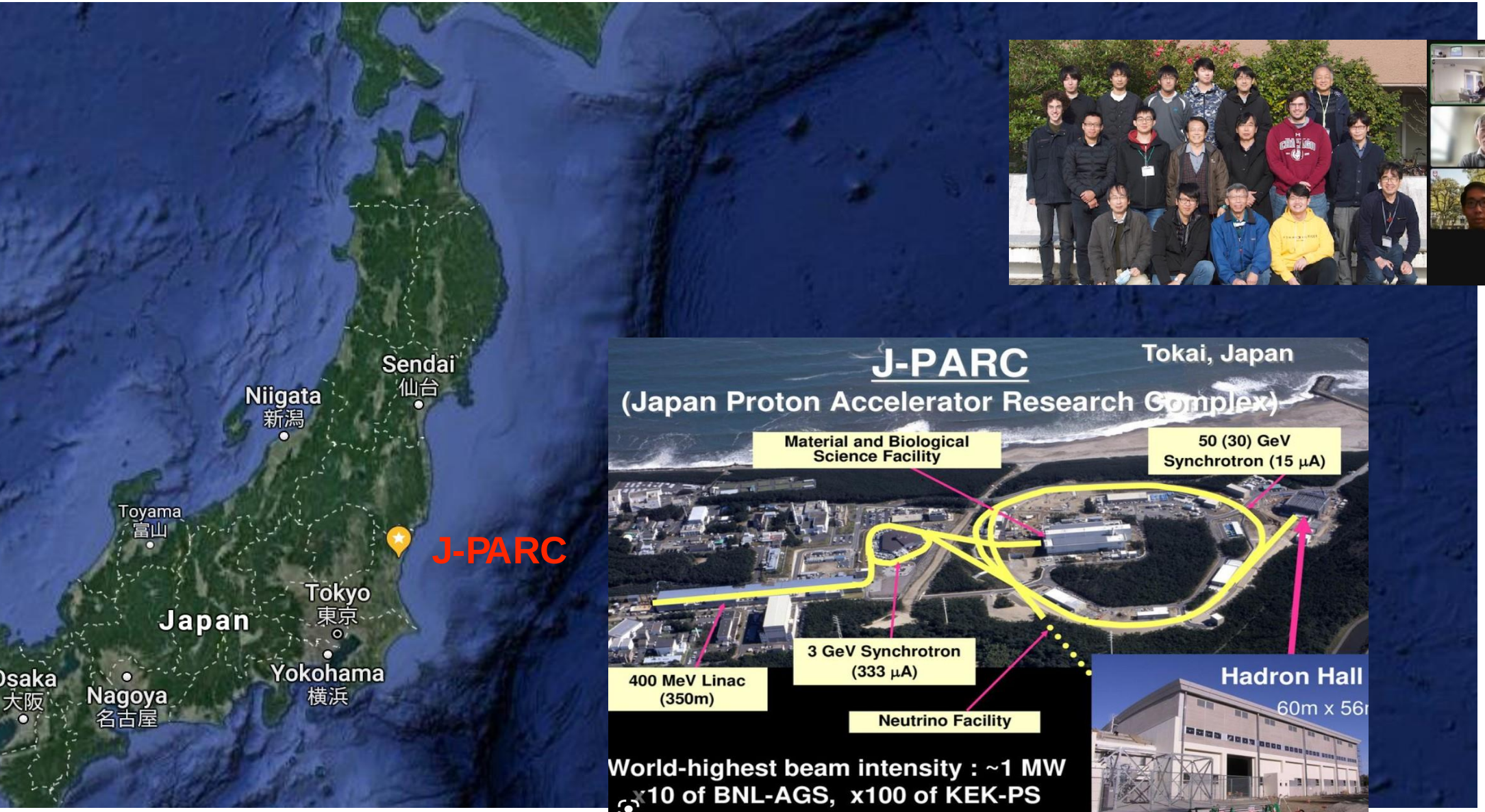
The experimental signature is kinematically limited:

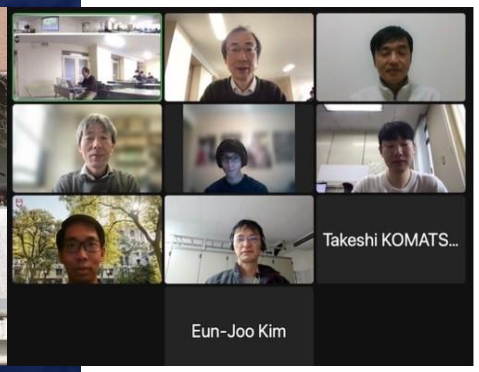
Nothing comes in, two photons go out
Tiny branching ratio

Typical comments:

Impossible …
Moths flying into fire ….
Really?…..

KOTO experiment





Japan
USA
Korea
Taiwan

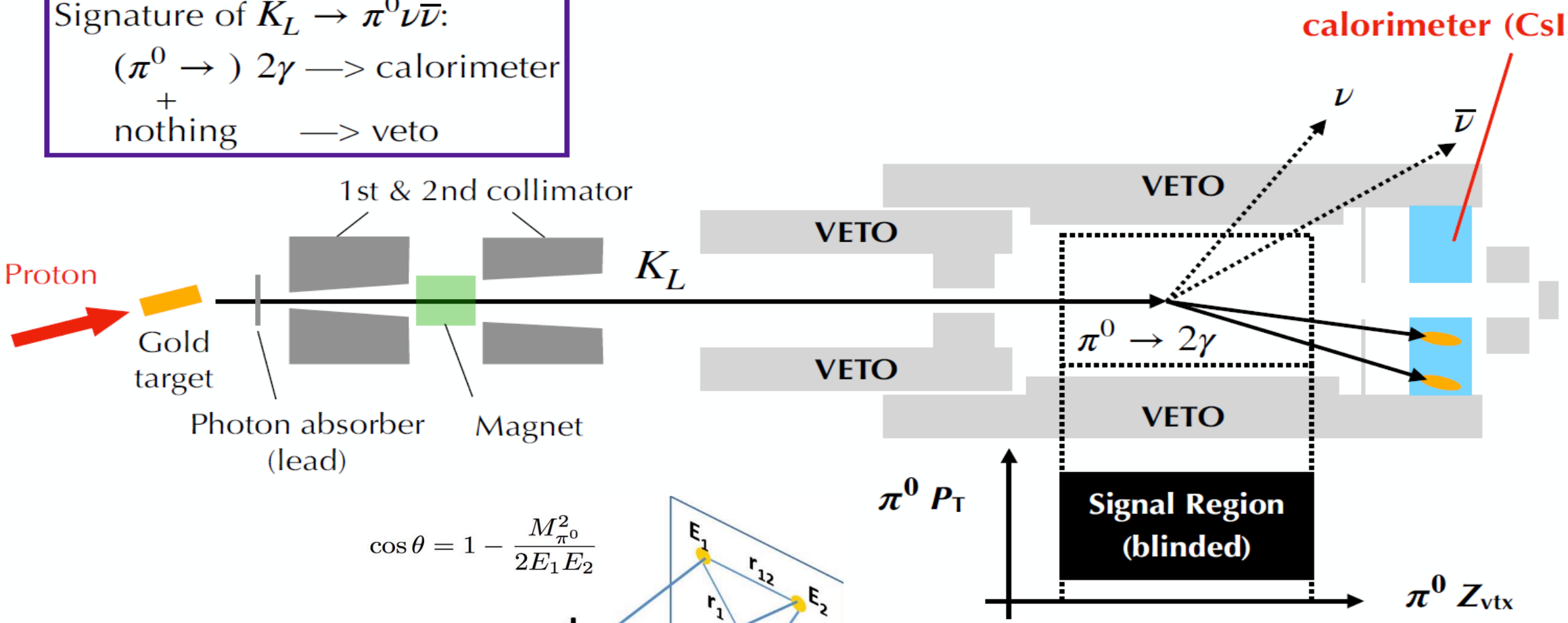
Experimental Principle

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

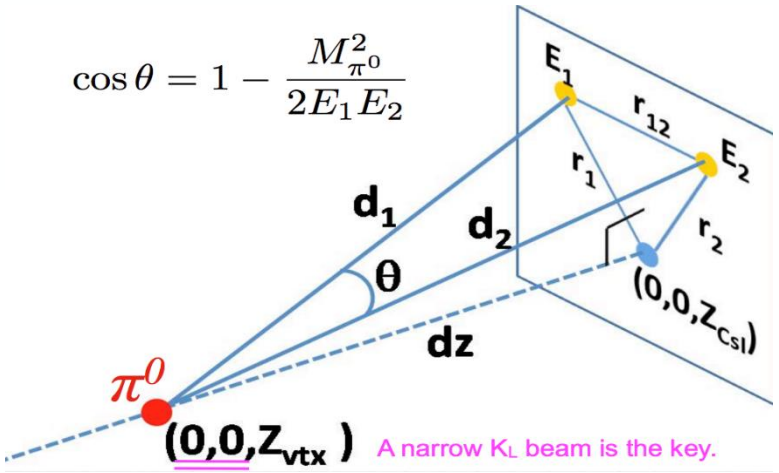
$(\pi^0 \to)\ 2\gamma$ —> calorimeter

+

nothing —> veto

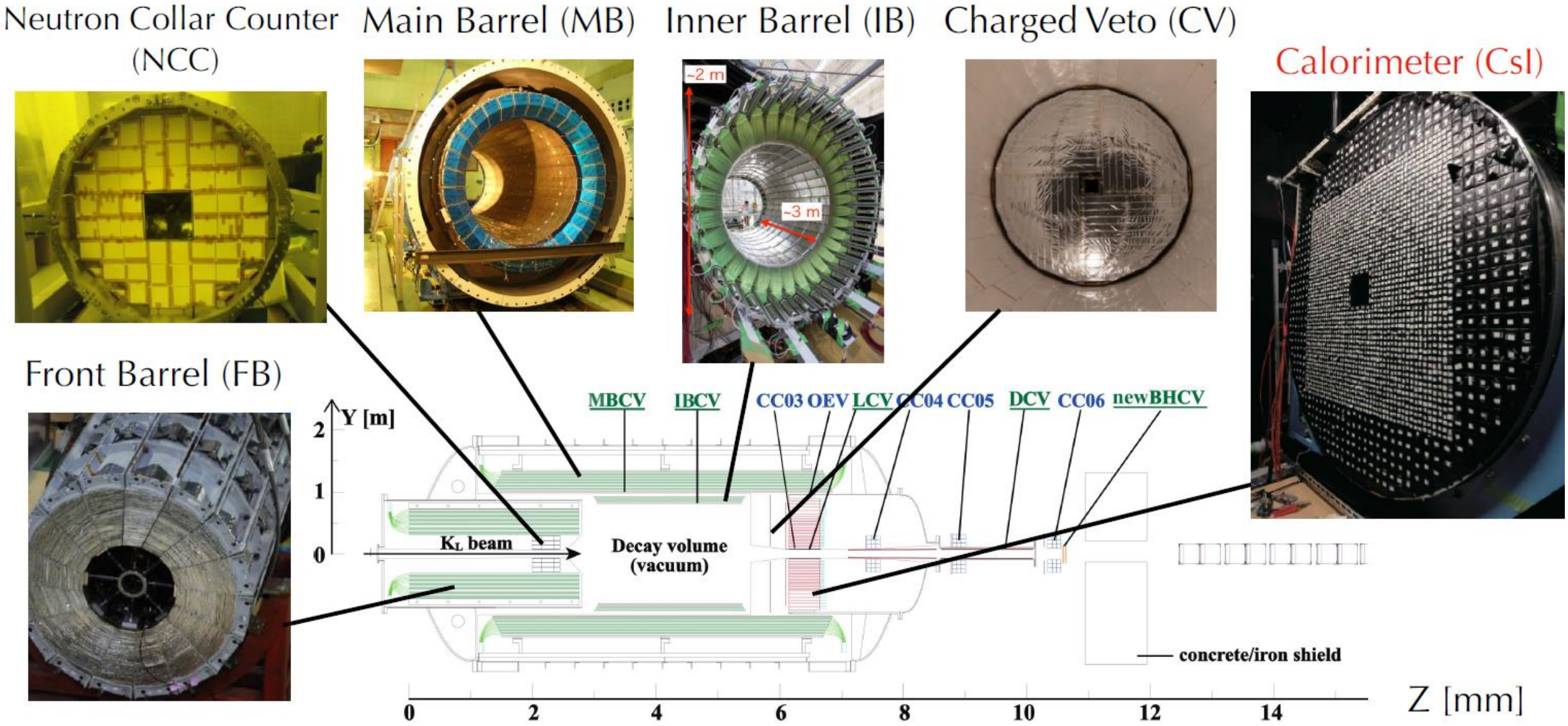


$$\cos\theta = 1 - \frac{M_{\pi^0}^2}{2E_1E_2}$$



A narrow K_L beam is the key.

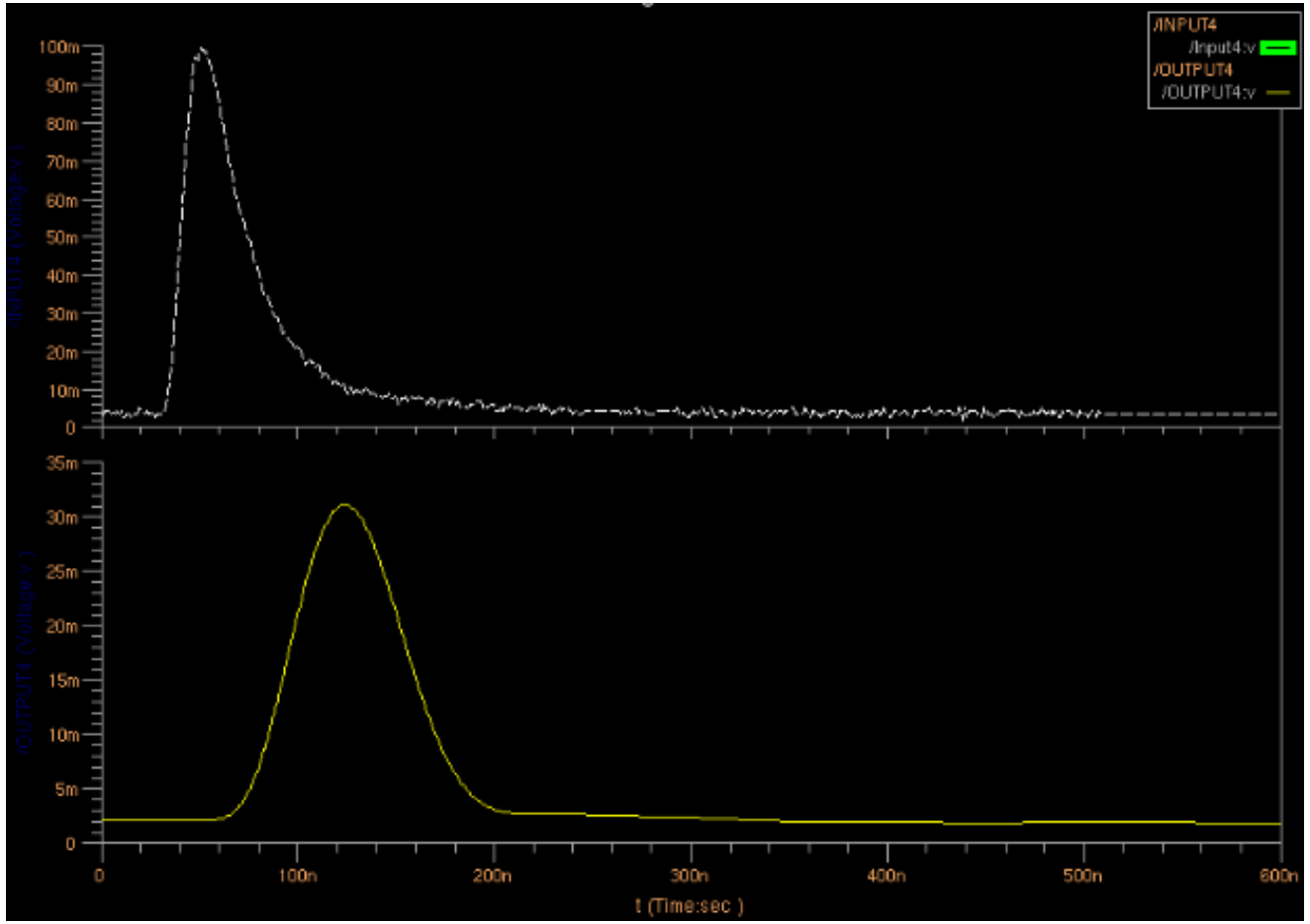
KOTO Detector



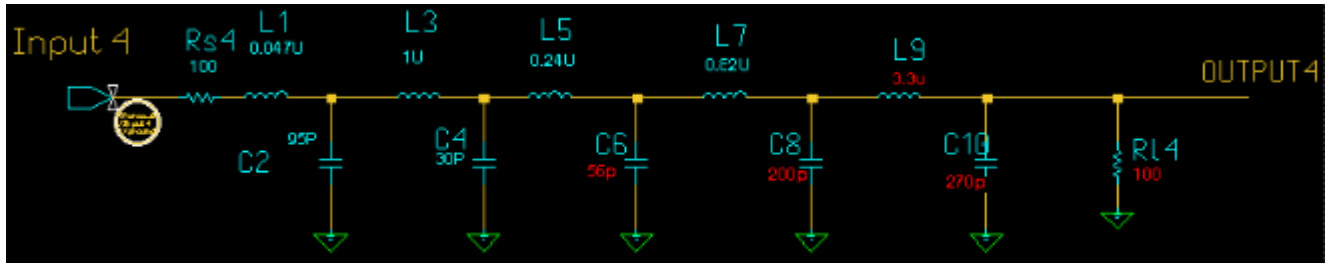
Pipeline Digitization and Trigger

CsI pulse (top)
Filtered pulse (bottom)

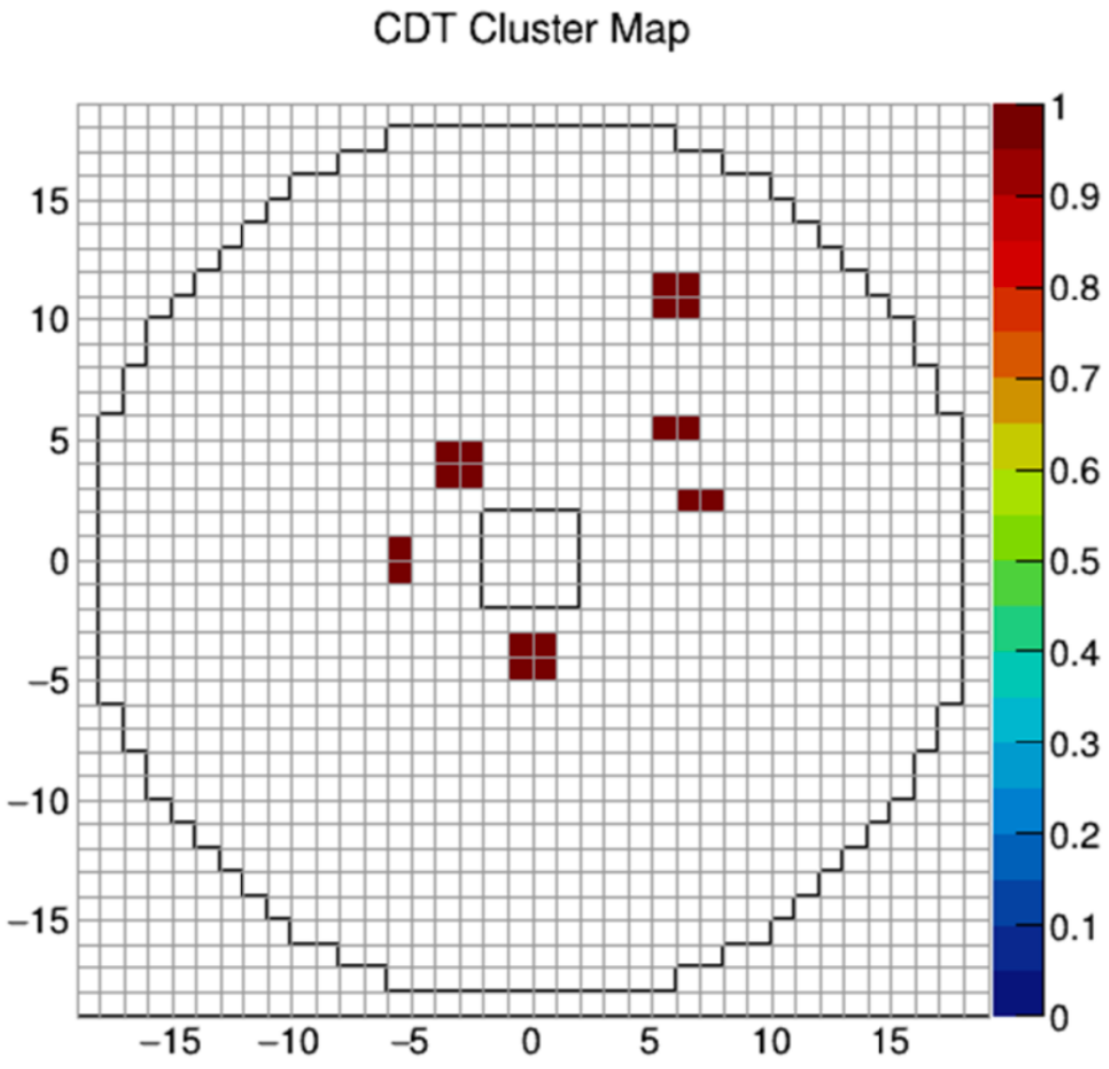
125MHz/500MHz digitization
"Noise" ~ *0.1MeV*

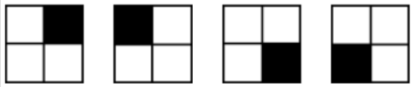


Gaussian Filter circuit:



The Photon Cluster Processor



Hit Block Patterns	Pattern Values
	0 - No corner
	+1 - One convex corner
	-1 - One concave corner
	+2 - Two convex corners
	0 - No corner

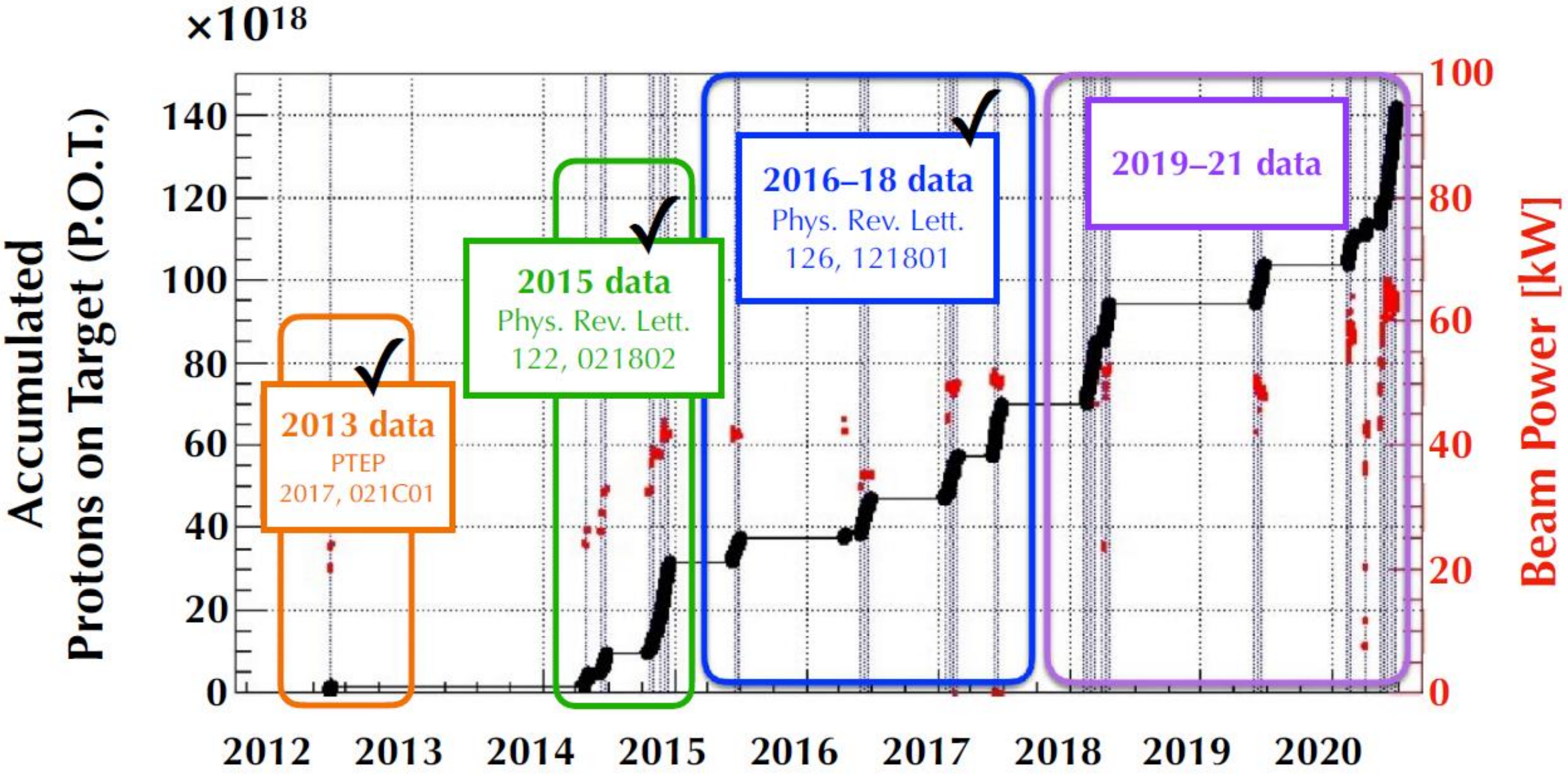
Counting total (+ and -) corners on CsI blocks

4 corners for a complete cluster

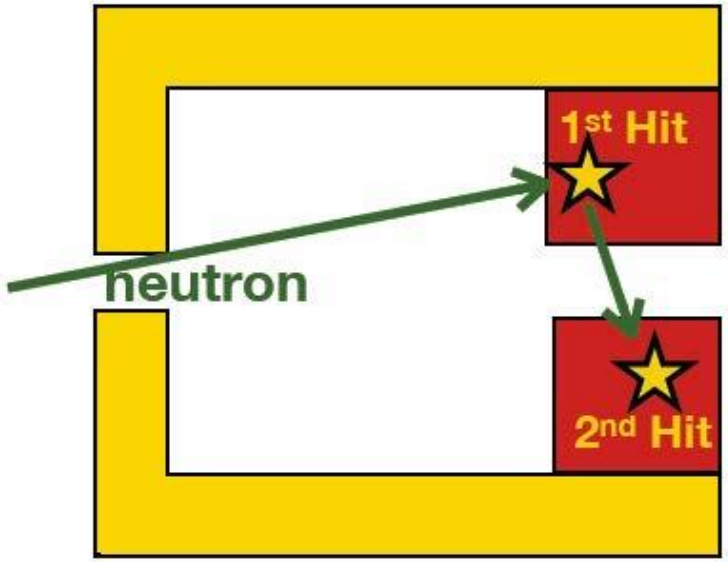
Number of clusters = Total number of corners/4

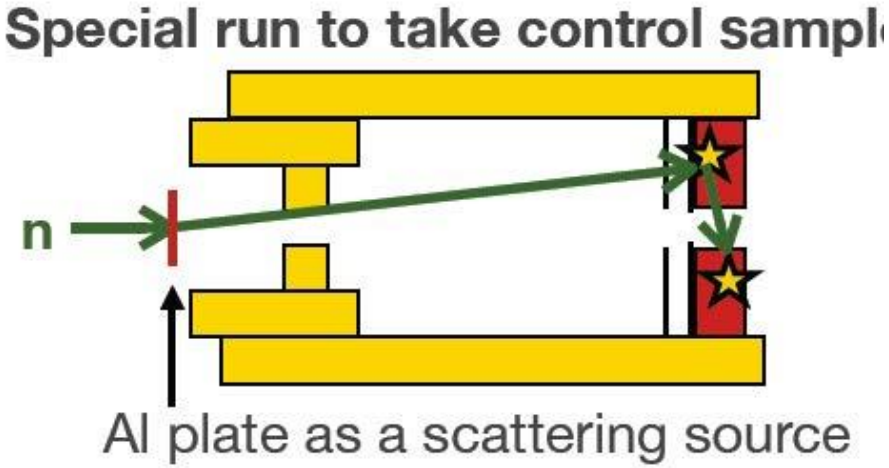
Pipeline calculation < 20 clocks (~160 nsec for KOTO)

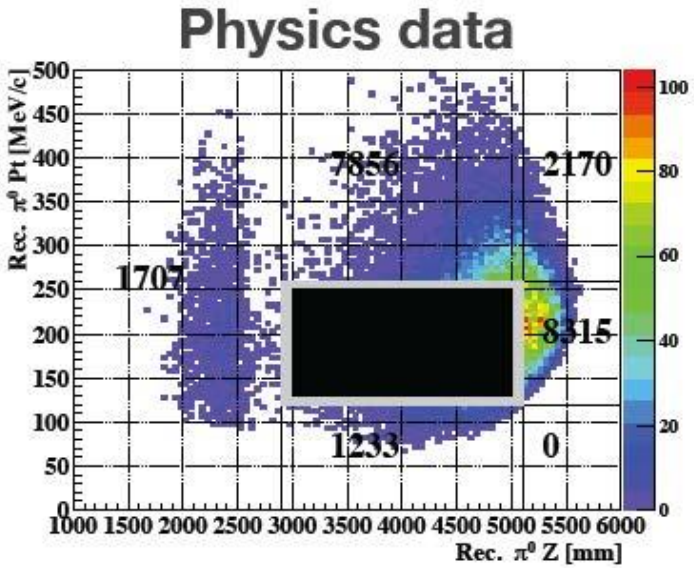
Data Taking History

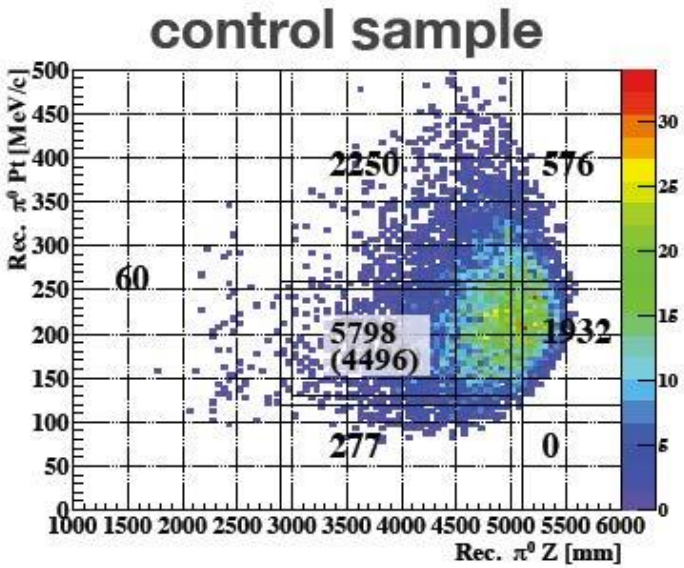


First look at data: surprise to say the least

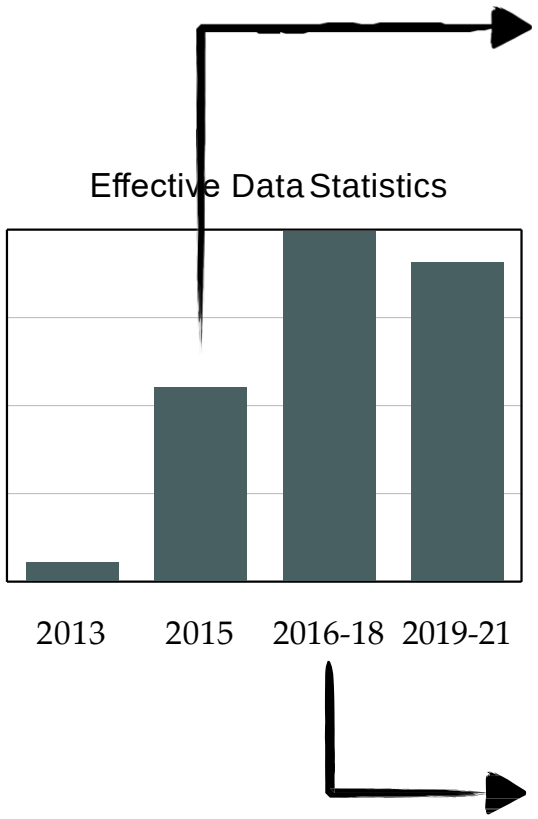




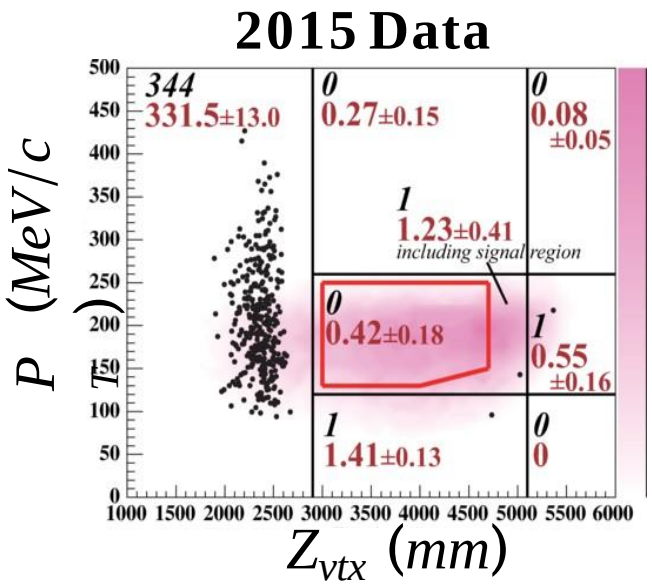




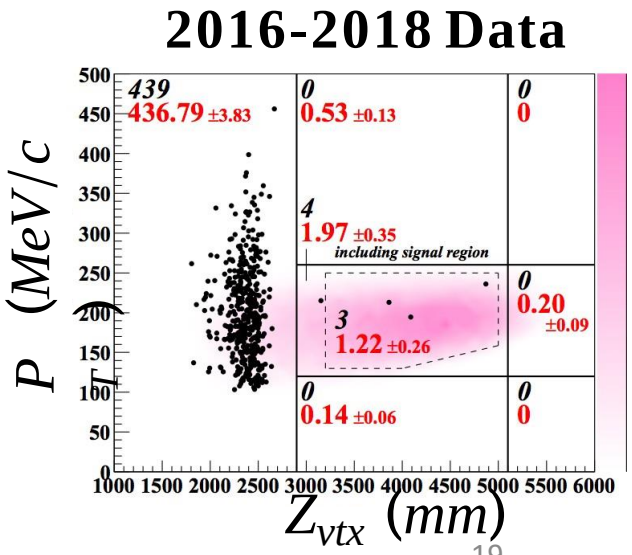
Recent Results



- 2015 data[PRL.122.021802]:
  - No event was observed with 0.42 predicted BGs.
  - $S.E.S. = 1.30 \times 10^{-9}$
  - $BR(K_L \to \pi^0 w^-) < 3.0 \times 10^{-9}$ at 90% C.L.
    - The world's best limit.

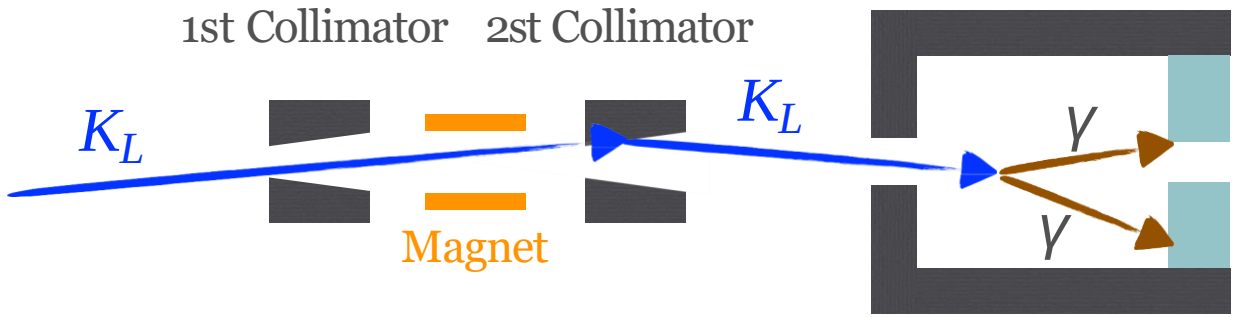


- 2016-2018 data[PRL.126.121801]:
  - $S.E.S. = 7.20 \times 10^{-10}$
  - Observed 3 events with 1.22 predicted BG.
    - 1.22 BG events included newly found BGs.
  - $BR(K_L \to \pi^0 w^-) < 4.9 \times 10^{-9}$ at 90% C.L.

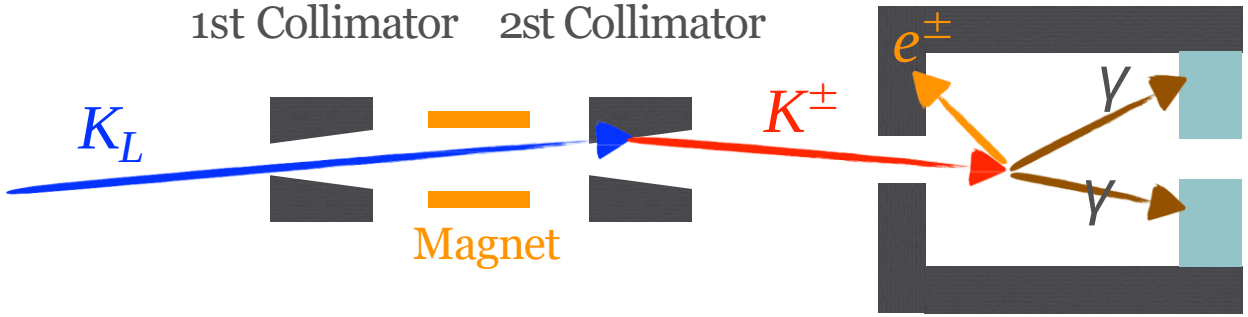


New BG Sources

Beam halo K_LBG ($K_L \rightarrow \gamma\gamma$)



$K^{\pm}$BG ($K^{\pm} \rightarrow \pi^0 e^{\pm} \nu$)



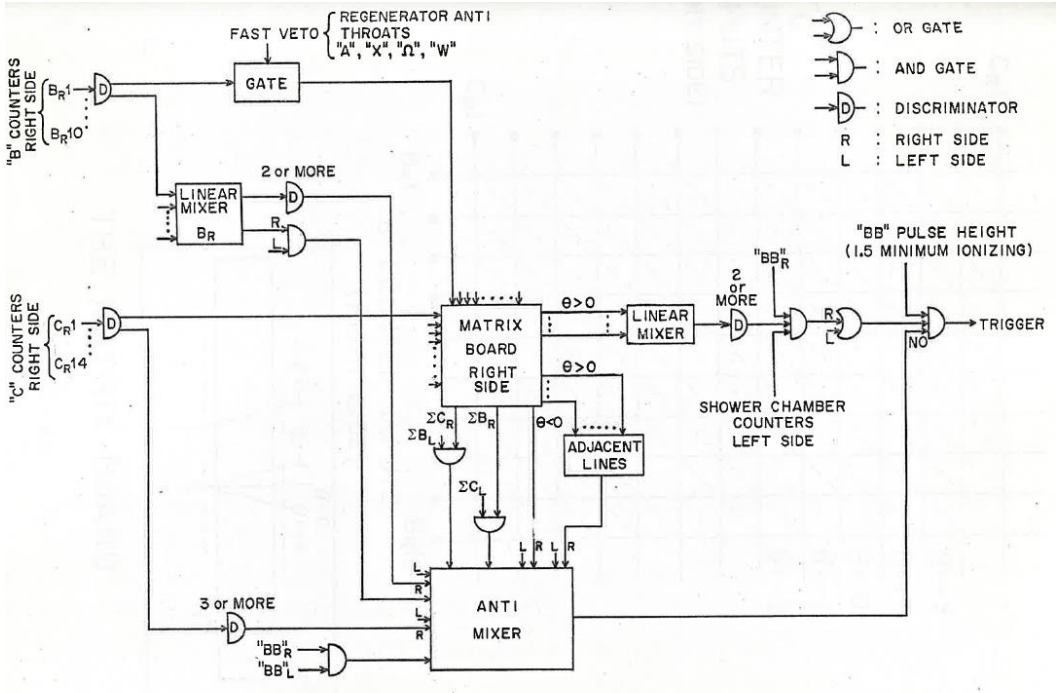
BG Table

of 2016-2018 data

source		Number of events
K_L	$K_L \rightarrow 3\pi^0$	0.01 ± 0.01
	$K_L \rightarrow 2\gamma$ (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

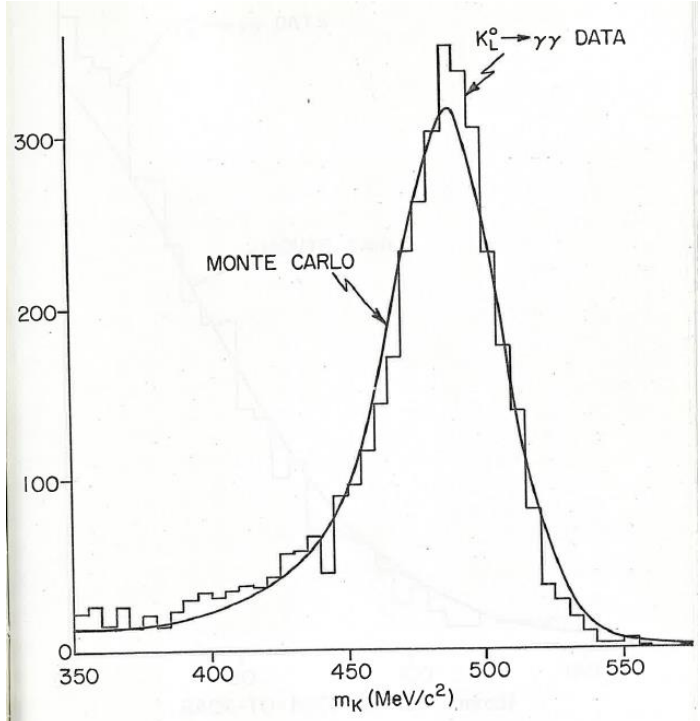
[a] Background sources studied after looking inside the blind region.

Mel's Measurement of $K_L \rightarrow \gamma\gamma$



TRIGGER LOGIC (showing circuitry for the right side of the spectrometer)

FIG. II-9



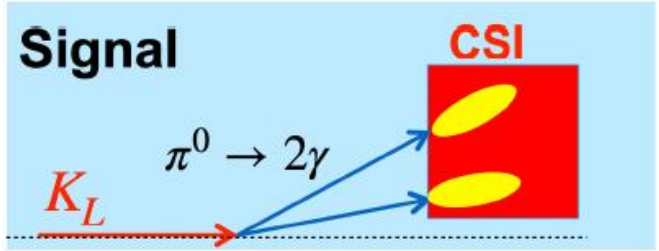
$K^0 \rightarrow \gamma\gamma$ MASS SPECTRUM

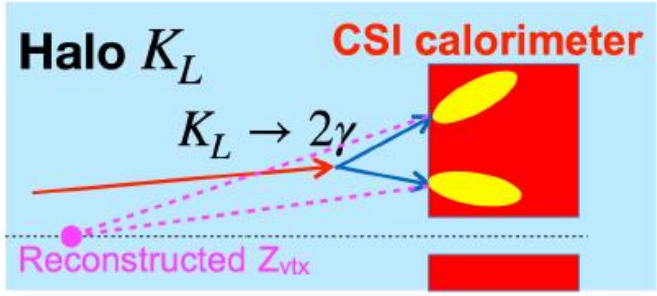
FIG. IV-4

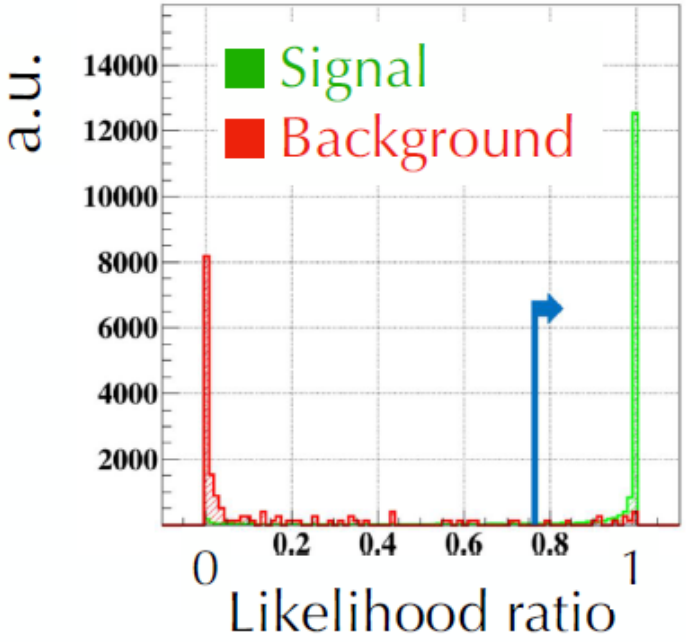
Mel's PhD thesis measurement is KOTO #1 background

Reduction of the halo $K_L \rightarrow \gamma\gamma$ Background

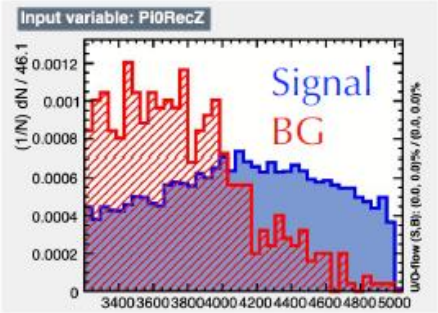
- Likelihood ratio based on shower shape consistency



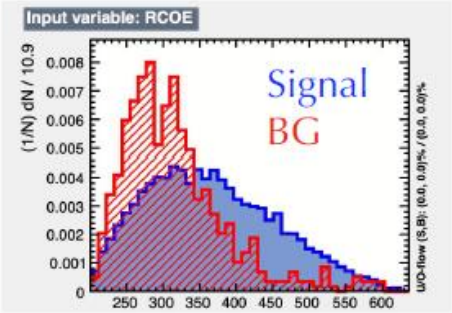




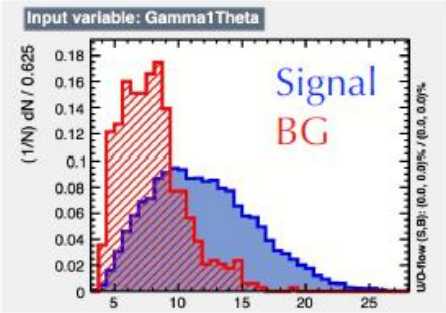
- Multivariate analysis using Fisher Discriminant



Reconstructed Z



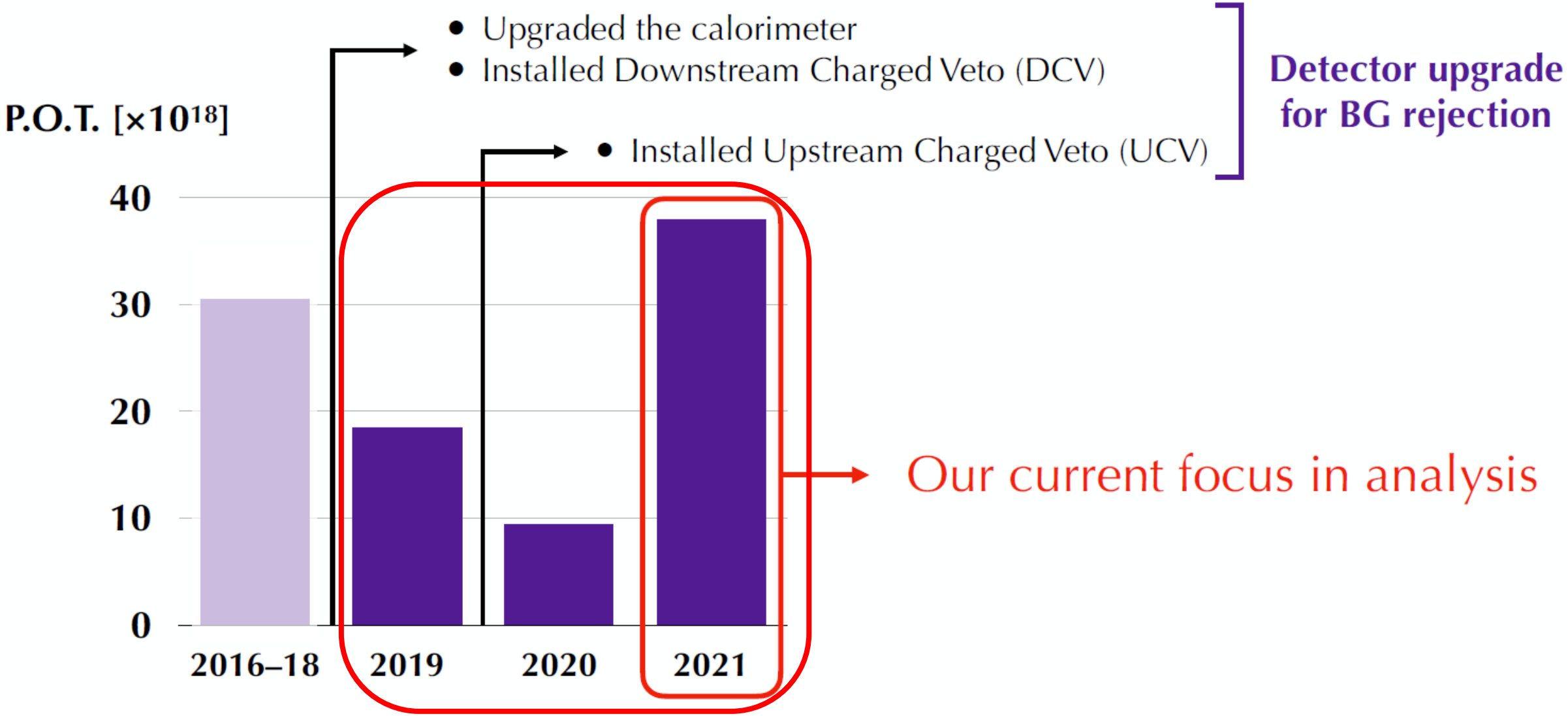
R_{COE}



$\theta_{\gamma 1}$

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

Data Collected In 2019-2021



Status of 2021 data set analysis

Currently we are focusing on the analysis of the 2021 data set

-High statistics, UCV was installed against $K^{\pm}$ BG

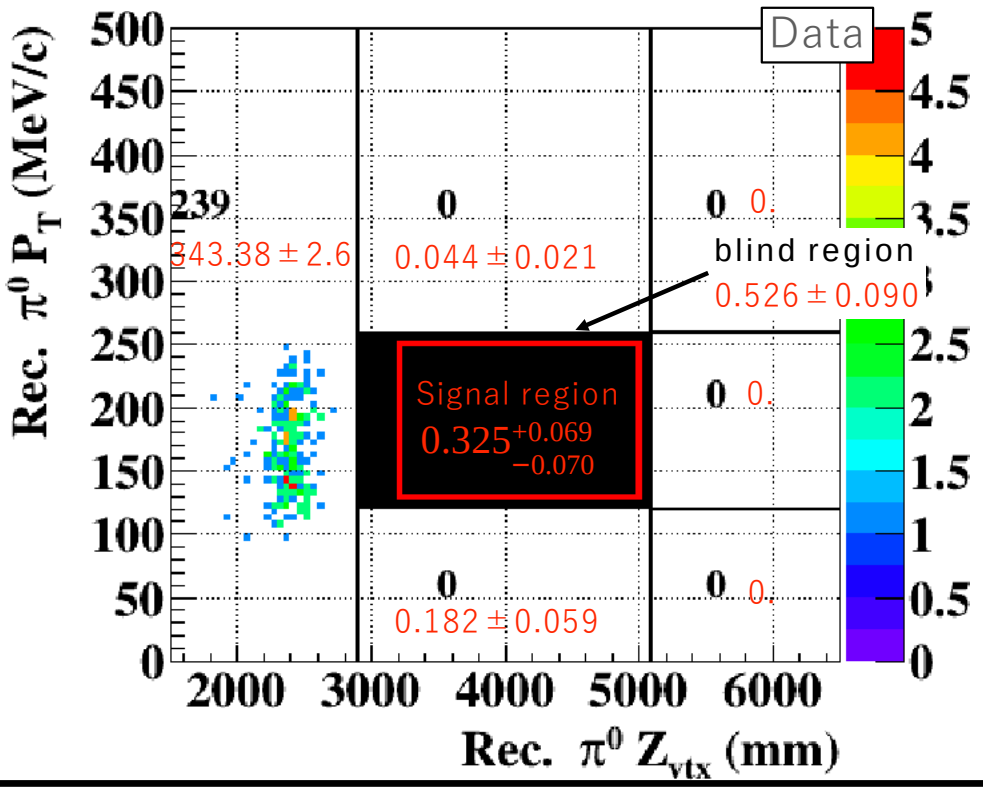
Single Event Sensitvity(S.E.S)=7.9×10^{-10}

c.f. 2016-18 analysis: 7.2×10^{-10}

source	#BG in the signal box
$K_L\to2\pi^0$	0.141 ± 0.059
K^+	$0.043^{+0.016}_{-0.022}$
Hadron cluster BG	0.042 ± 0.007
Halo $K_L\to2\gamma$	0.013 ± 0.006
Scattered $K_L\to2\gamma$	0.025 ± 0.005
η production in CV	0.023 ± 0.010
Upstream π^0	0.02 ± 0.02
$K_L\to3\pi^0$	0.019 ± 0.019
Sum	0.325 ± 0.069

BG Estimation

c.f. 2016-2018 analysis:1.23 ± 0.26

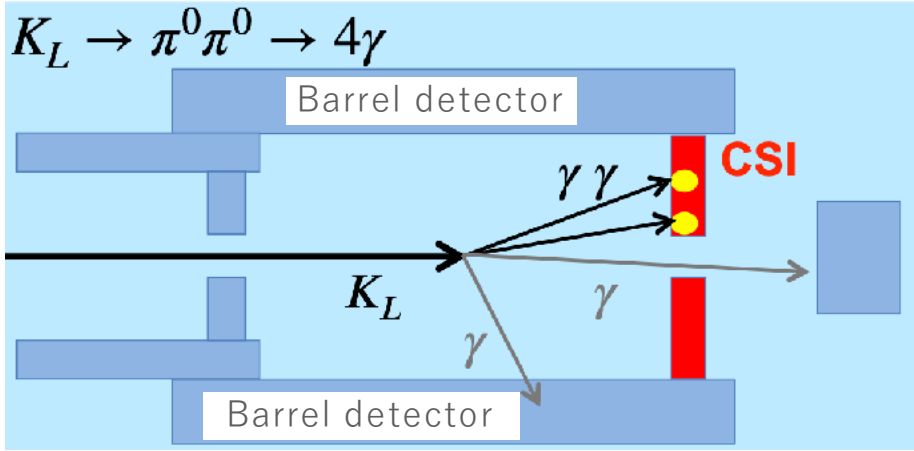


Black:Data Red:Estimation

-0.33 in the signal region

-0.53 in the blind region

Issues on $K_L \to 2\pi^0$ BG



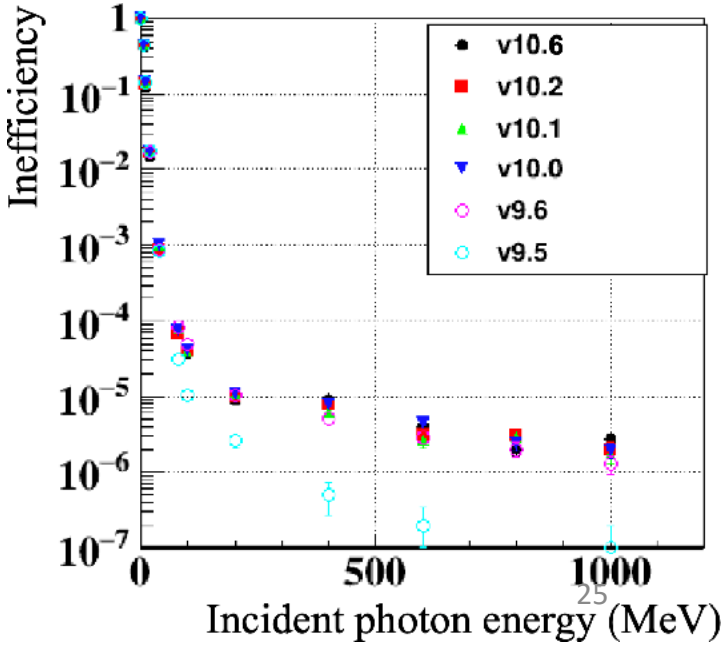
- BGL for $K_L \to 2\pi^0$ BG is increased.

$$\mathrm{BGL} = \#\mathrm{BG} \times (\mathrm{S.E.S})$$

	2016-2018 ana (Geant4 9.5.2)	2021 ana (Geant4 10.6.2)
BGL for $K_L \to 2\pi^0$	$<0.6 \times 10^{-10}$ @90% C.L.	$(1.1 \pm 0.4) \times 10^{-10}$

- Photon inefficiency of the barrel detectors depends on the GEANT4 version
  - Physics model was changed between two versions due to difficulty of code management. (Info from a GEANT4 code manager)

Simulation study
with a modeled barrel detector

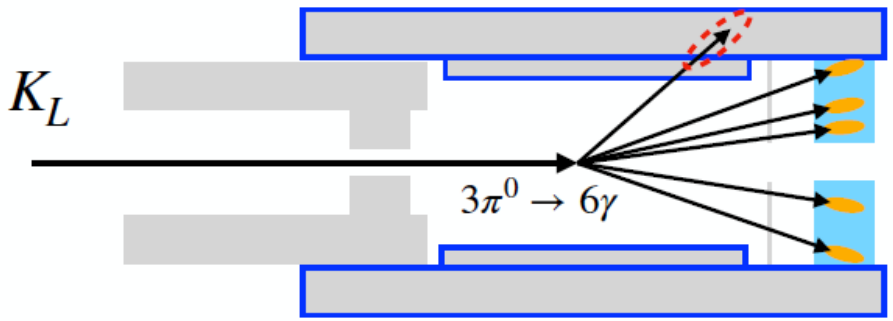


Inefficiency evaluation with 5γ data

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

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

  —> reconstruct the remaining γ (γ_6)



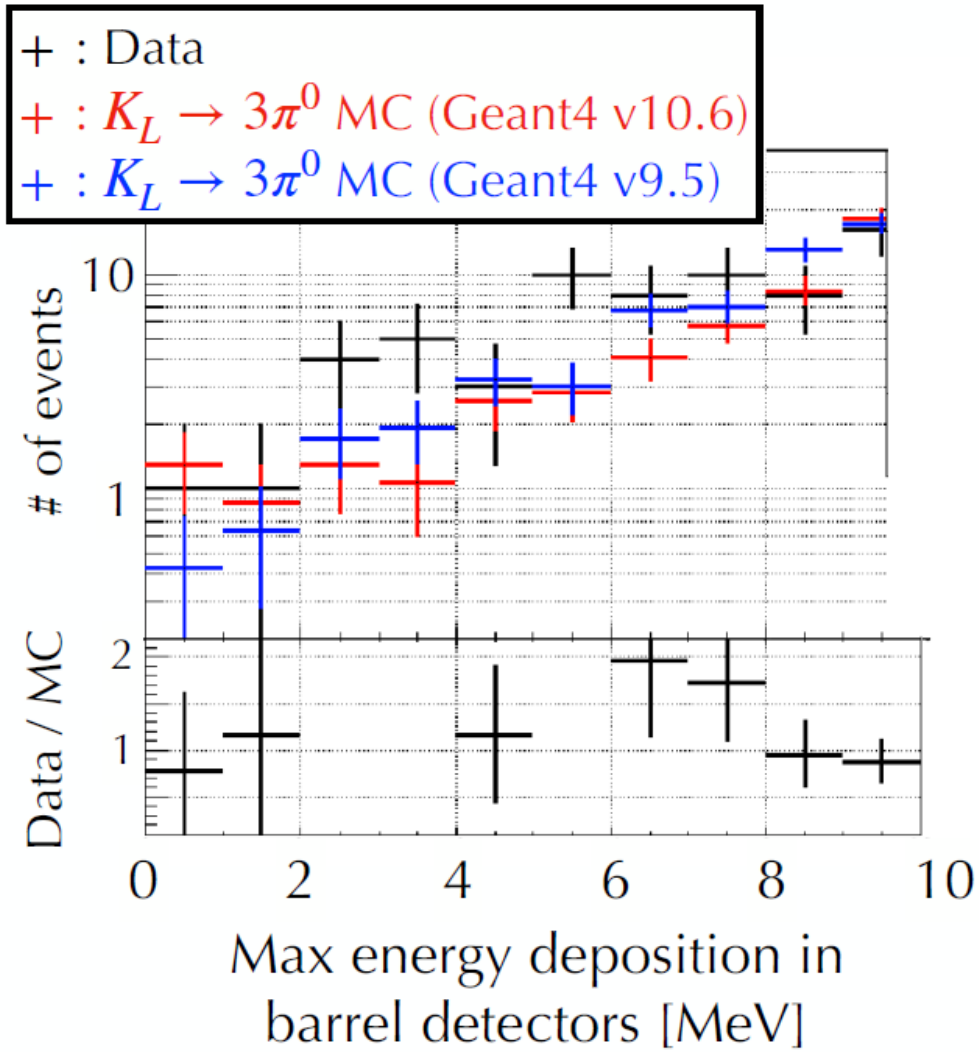
For 1 MeV threshold,

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

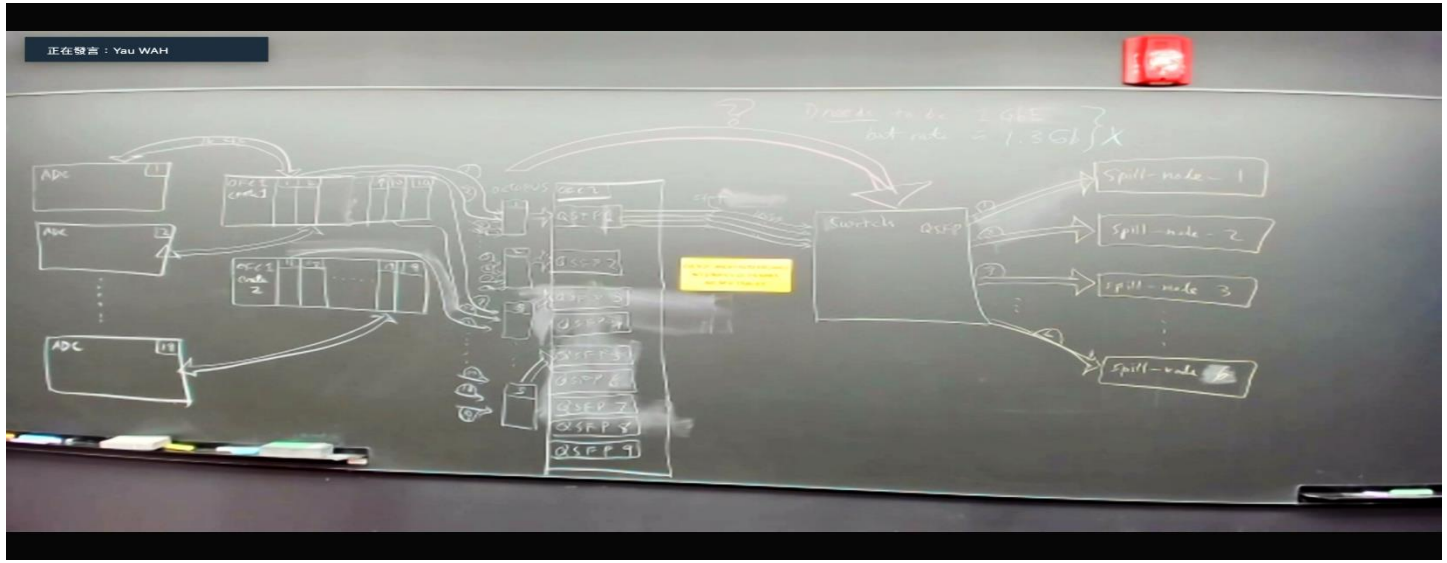
Inefficiency (MC) = $(6.2 \pm 2.5) \times 10^{-5}$ (v10.6)

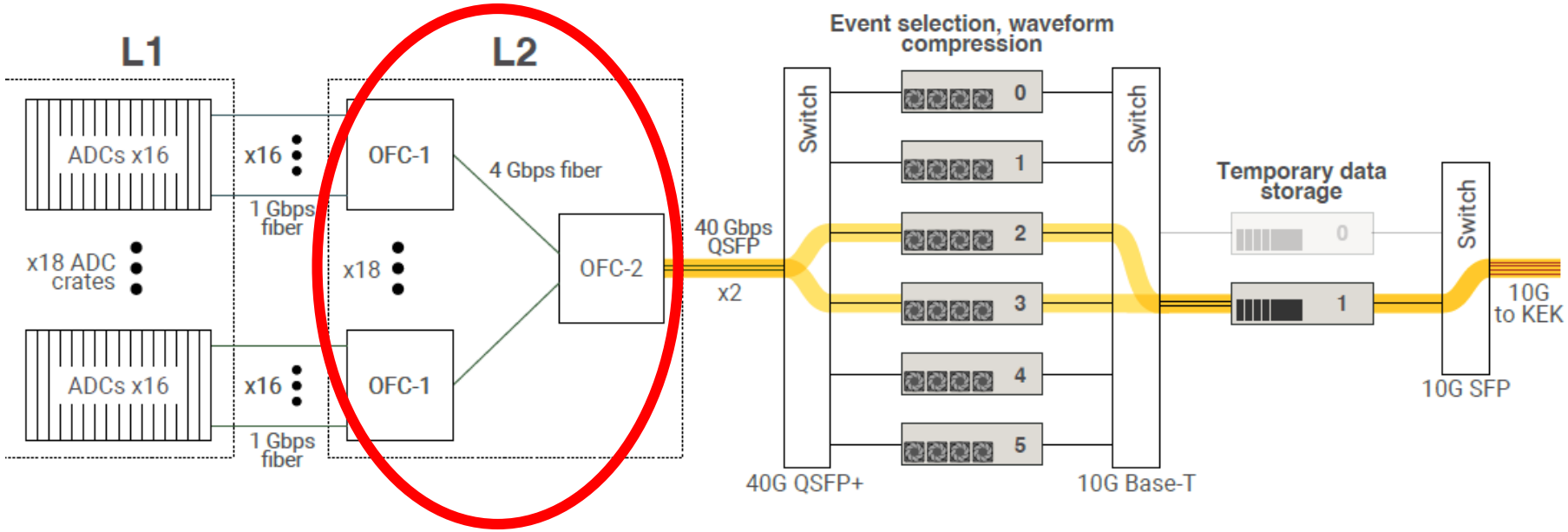
= $(2.1 \pm 1.5) \times 10^{-5}$ (v9.6)

- **~100% syst. error on $K_L \to 2\pi^0$ BG will be accounted for 2021 data analysis**
- **Need more statistics for future analysis**

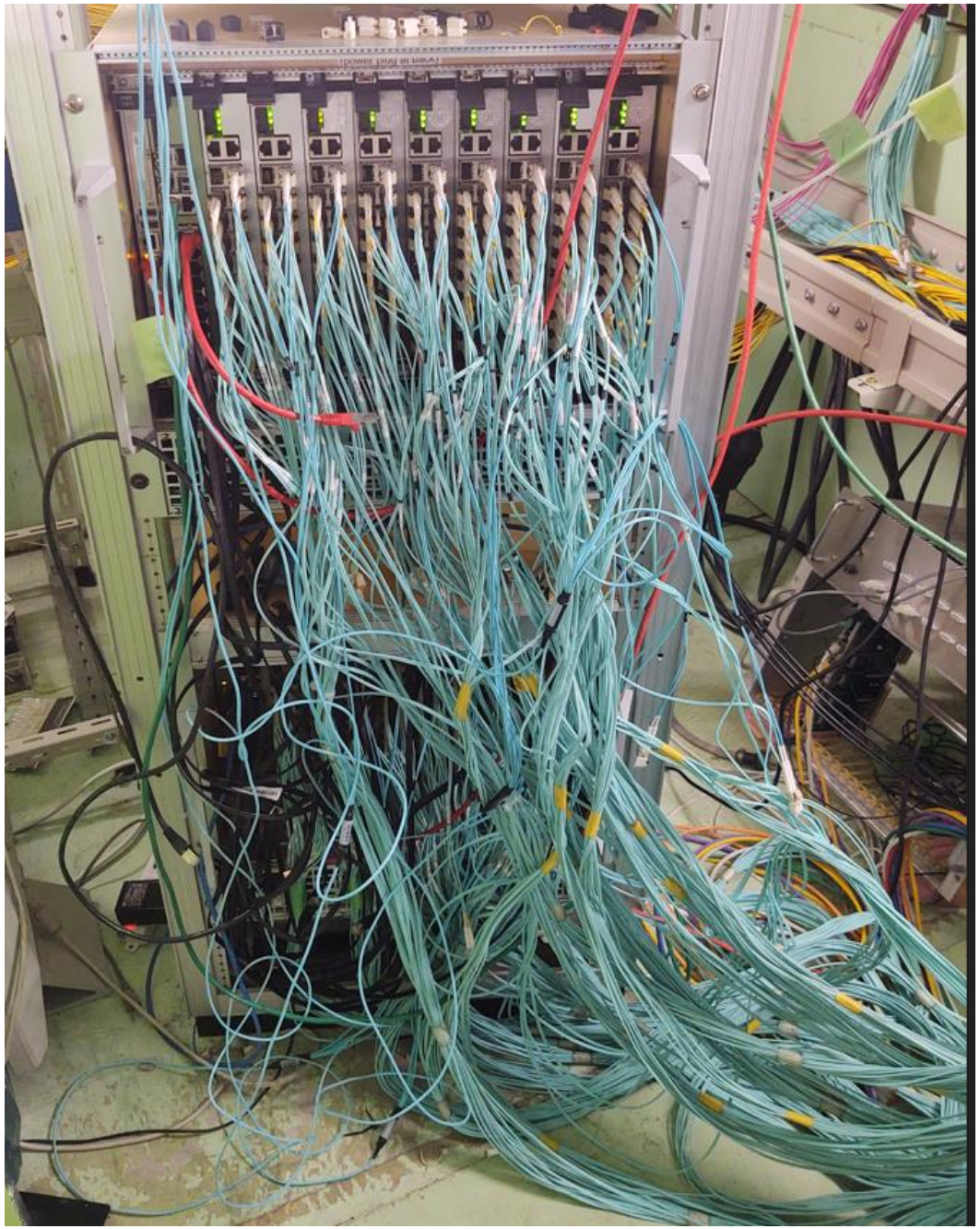


DAQ upgrade


正在發言：Yau WAH
ADC
Switch
QSFP
Spill-node 1
Spill-node 2
Spill-node 3

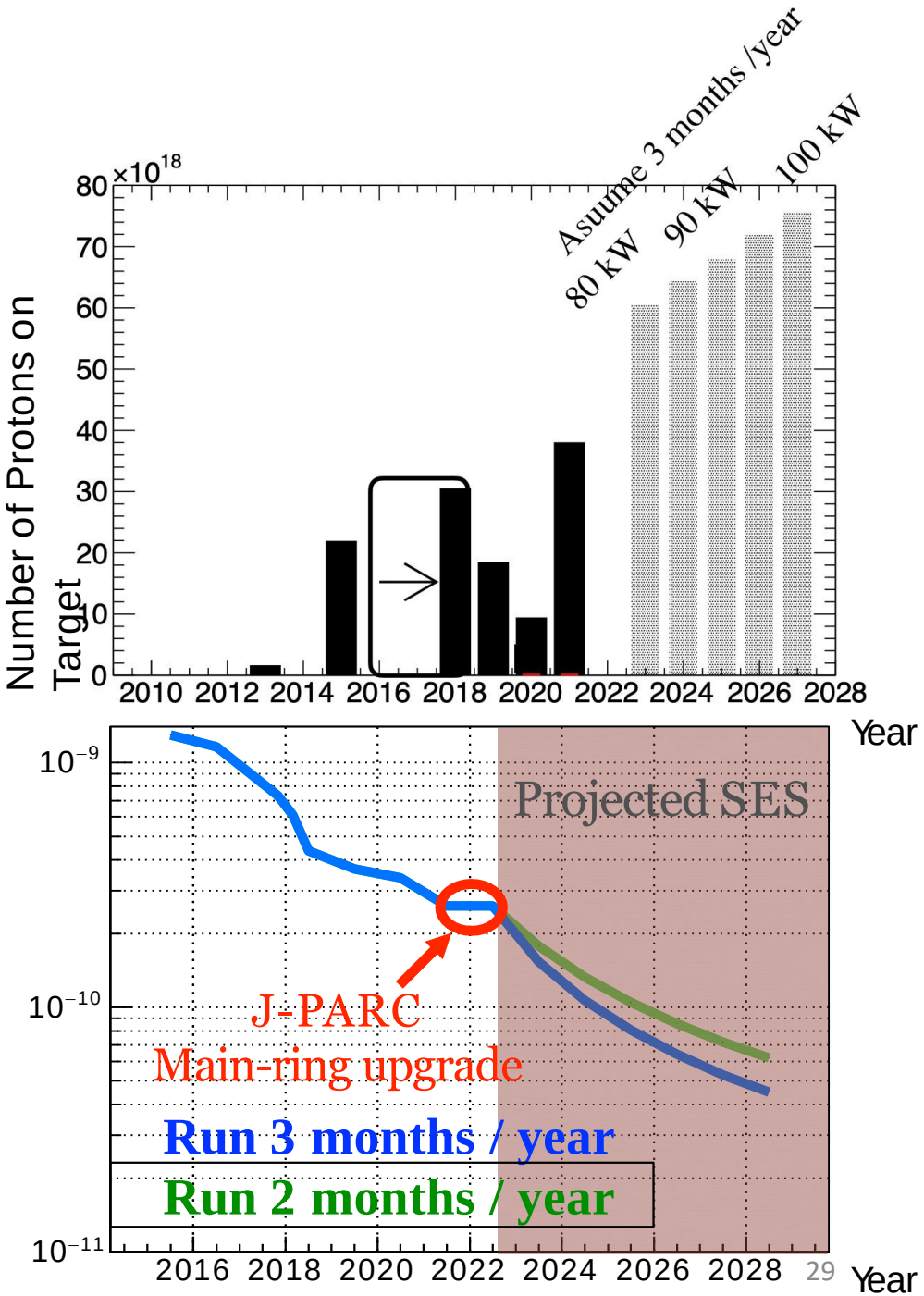

L1
L2
ADCs x16
x16
1 Gbps fiber
x18 ADC crates
ADCs x16
x16
1 Gbps fiber
OFC-1
x18
OFC-1
4 Gbps fiber
OFC-2
40 Gbps QSFP
x2
Switch
40G QSFP+
Event selection, waveform compression
0
1
2
3
4
5
Switch
10G Base-T
Temporary data storage
0
1
Switch
10G SFP
10G to KEK

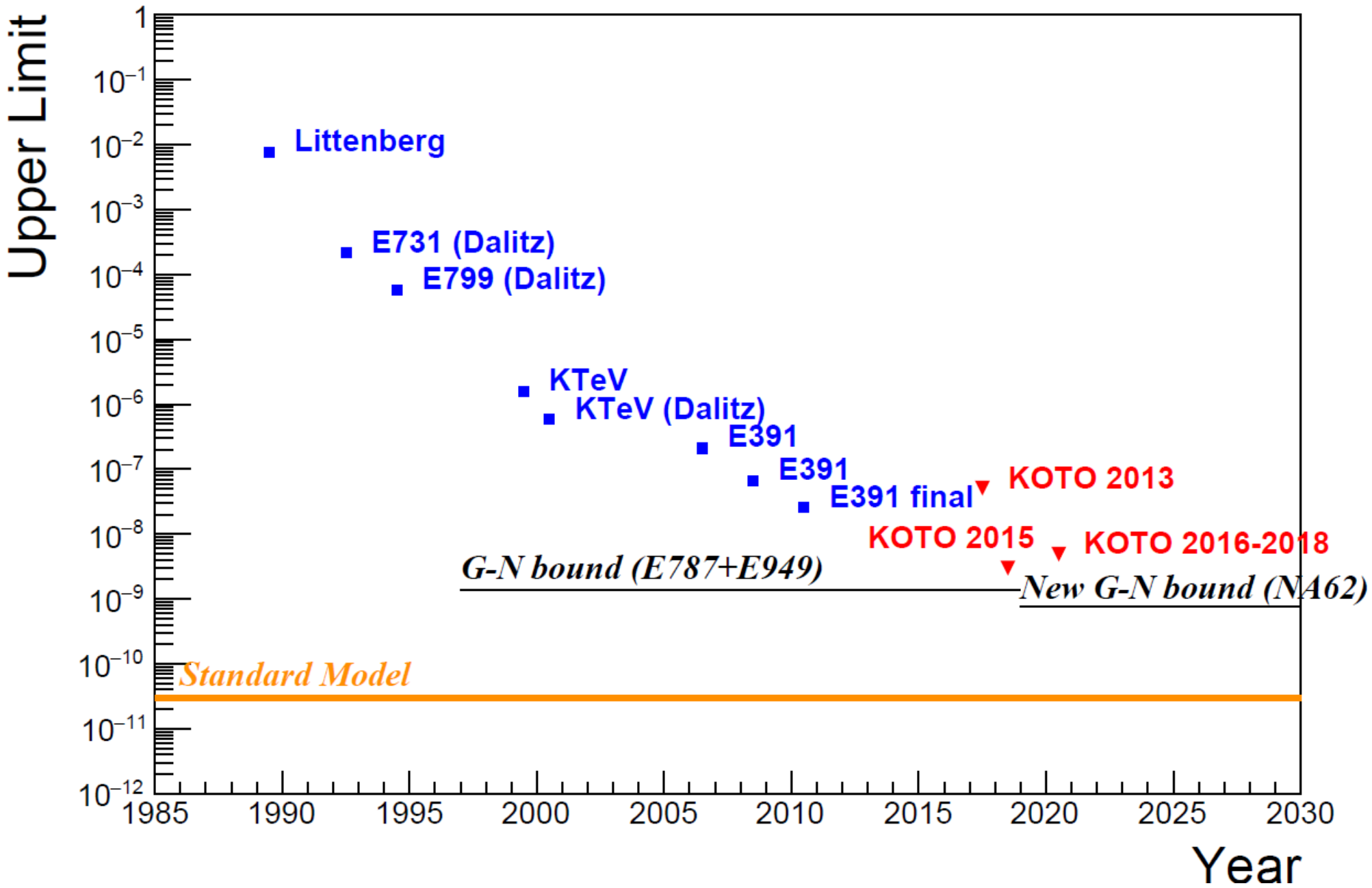
In Real:



Prospects:

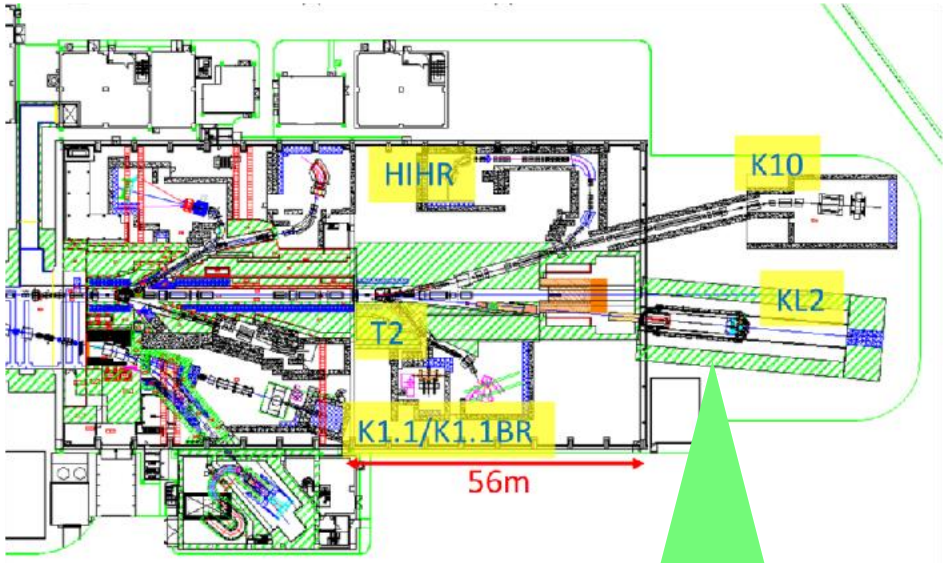
- **2021-2022Accelerator Shutdown**
  - Main-ring power supply upgrade.
    - Beam power 64kW → 80-100kW.
- **Will take data-taking in May/June 2023**
- **By 2027, with 2-3 month run per year**
  - Expect to collect ×11 more data.
  - S.E.S. can reach below O(10^{-10}).




Upper Limit
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
Year
Littenberg
E731 (Dalitz)
E799 (Dalitz)
KTeV
KTeV (Dalitz)
E391
E391
E391 final
KOTO 2013
KOTO 2015
KOTO 2016-2018
G-N bound (E787+E949)
New G-N bound (NA62)
Standard Model

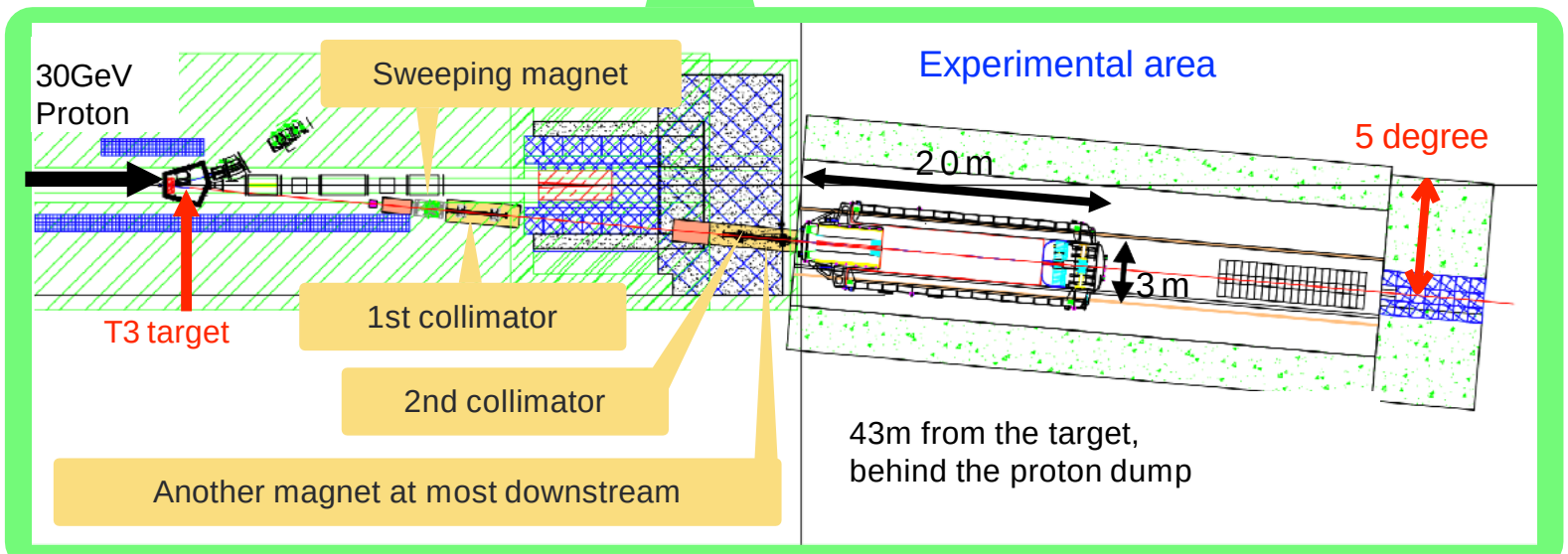
Future: KOTO-II

KOTO II



Measure branching ratio of the $K_L \rightarrow \pi^0 \nu\nu$ decay with

-Higher intensity K_L beam
-Larger detector

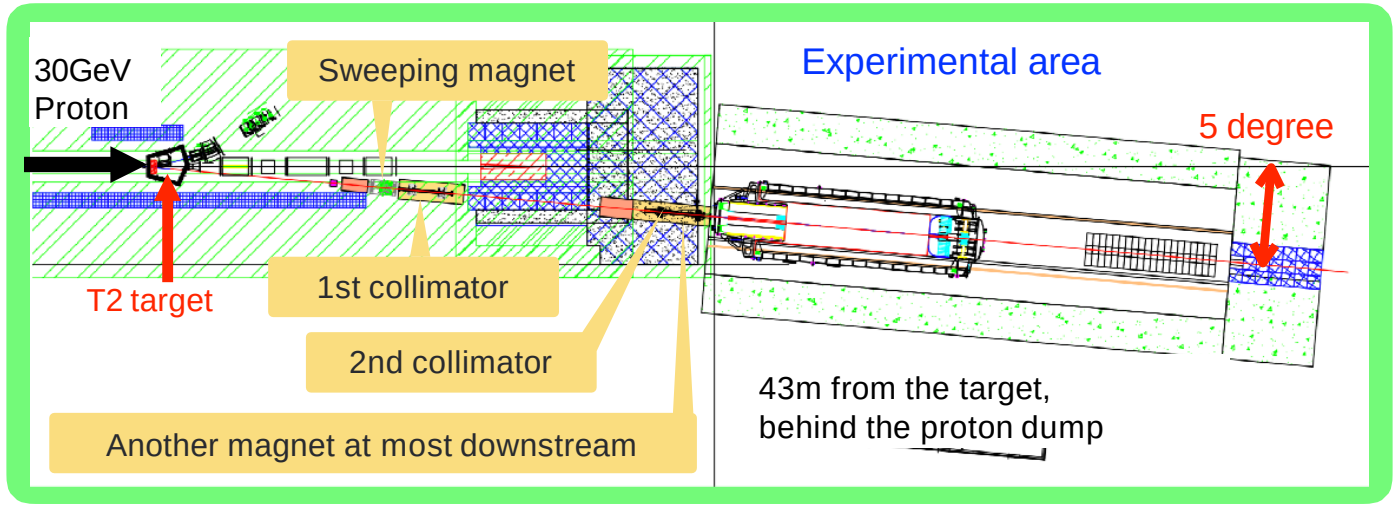


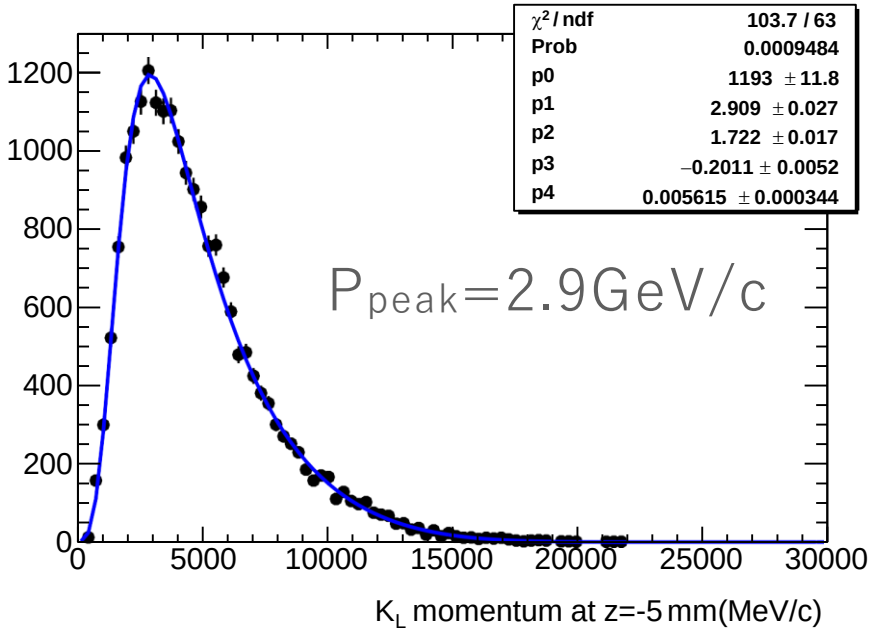
~50 SM events for 3×10^7 s run time with 100kW beam

Signal-to-background ratio ~ 0.4

A new K_L beam line

Basic design

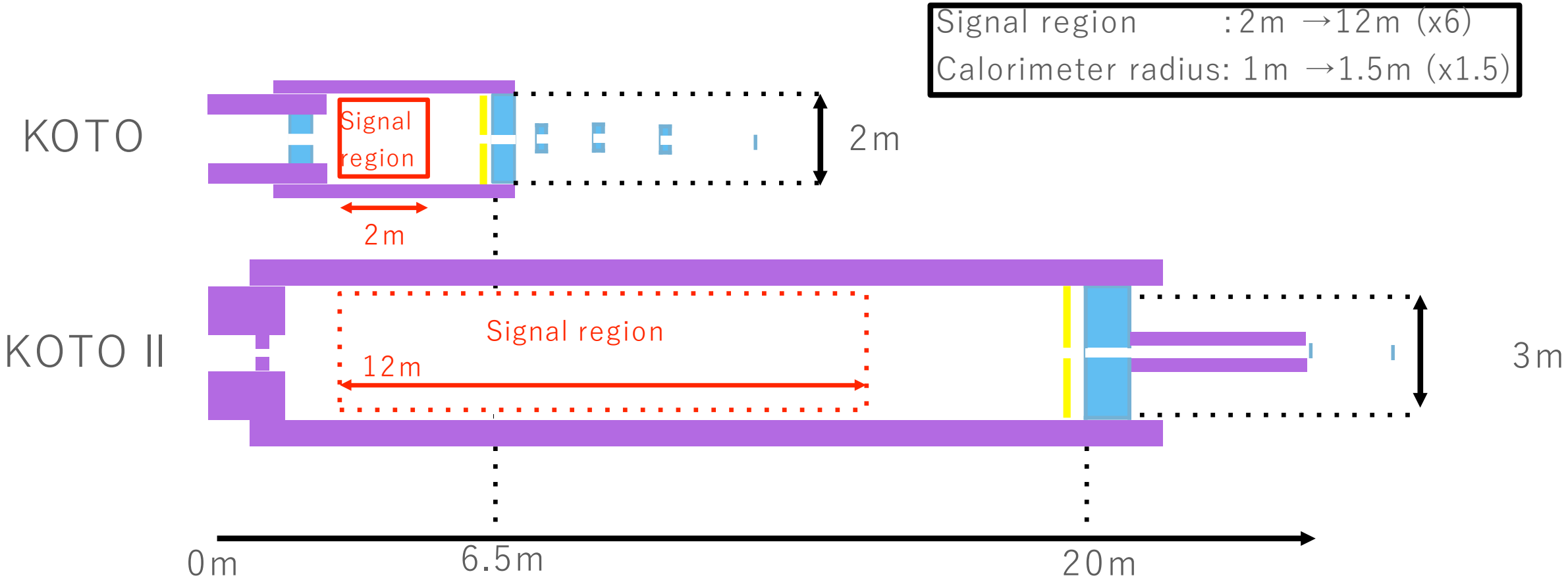




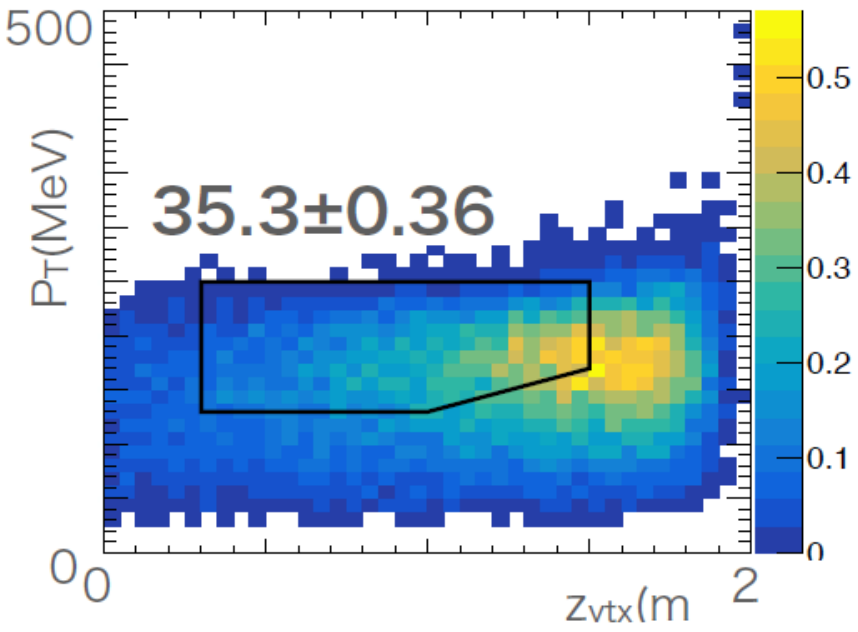
- 5 degree production
- Beam line length: 43m.
- $N(K_L) = 4.8 \times 10^7$/spill @ 100kW beam on T2 Target→x 2.6 higher than KOTO (per POT)

	KOTO	KOTO II	Gain for K_L yield
Production Angle	16 degree	5 degree	x5
Beam line Length	20m	43m	x0.8
Solid angle	7.8 μsr	4.8 μsr	x0.6

Detector for KOTO II



Signal acceptance

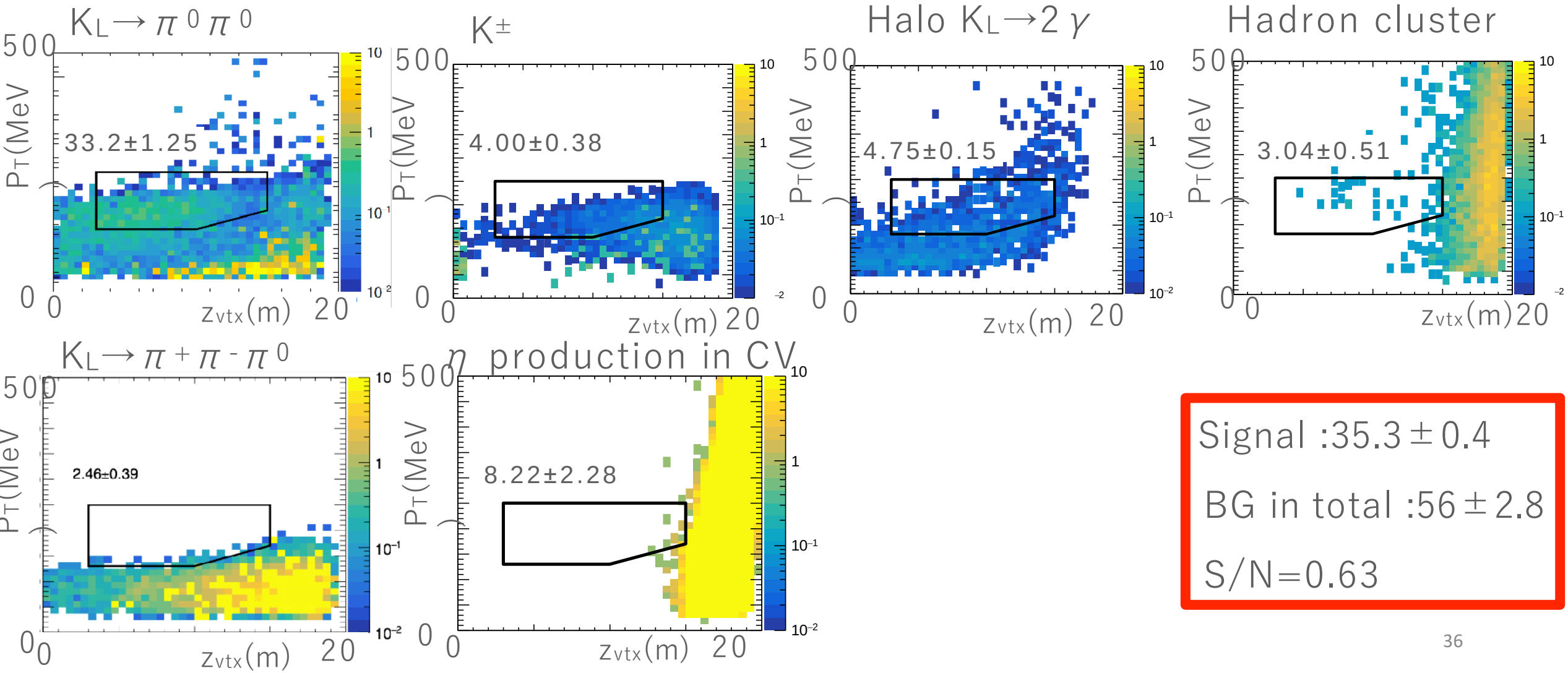


- Beam power: 100kW at T2 target
- KL yield: 4.8×10^7/spill → ×2.6 from KOTO (per POT)
- Data taking : 3 Snowmass years (3×10^7s)

	Decay Probability	Geometrical Acceptance	Cut efficiency	1- Accidental loss	1-Backsplash loss
KOTO II Efficiency	10%	24%	26%	61%	91%
KOTO Efficiency	3.3%	26%	3%	36%	50%
Improvement factor	3	0.9	8.7	1.7	1.8

(Product of improvement factor on efficiency) × (Increase of KL yield)=190

BG estimation

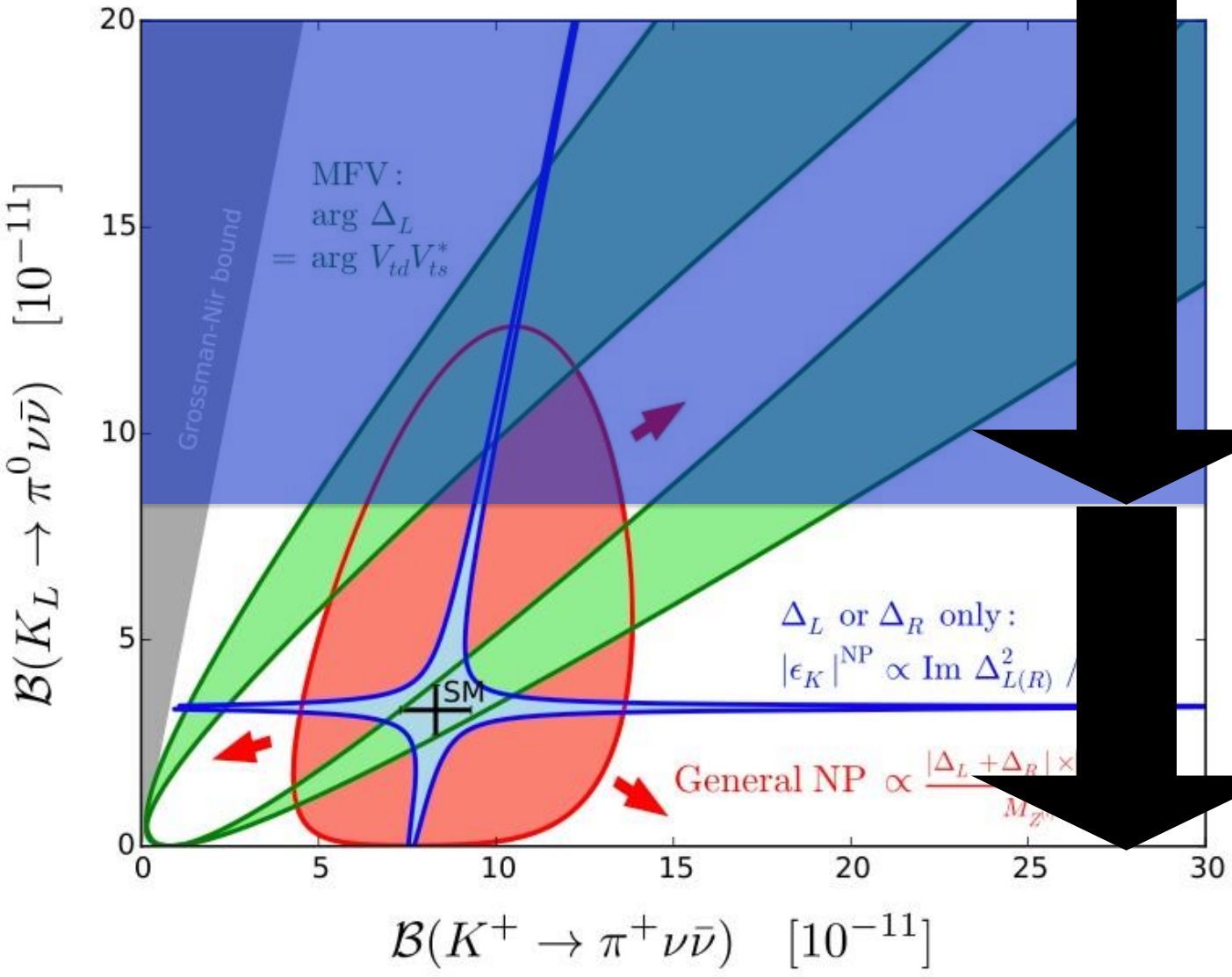


Signal :35.3 ± 0.4

BG in total :56 ± 2.8

S/N=0.63

KOTO & KOTO II

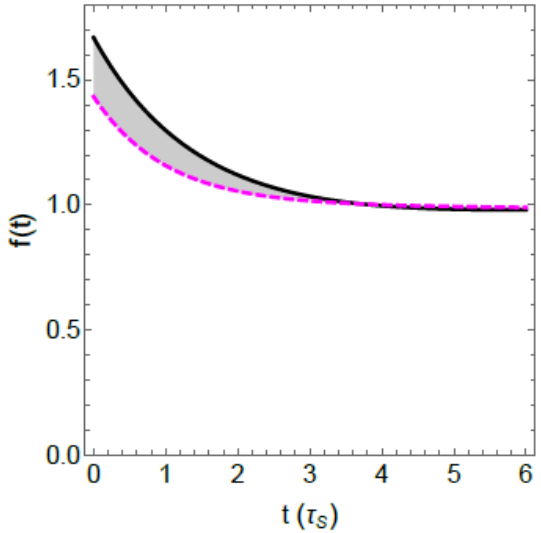


KOTO will reach
$O(10^{-11})$ sensitivity

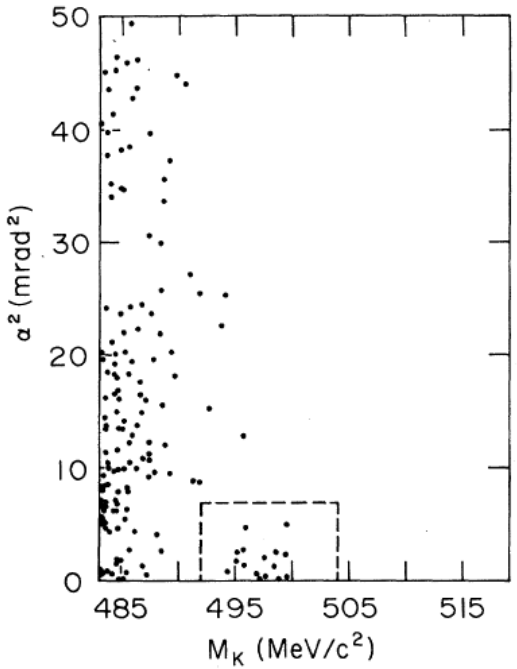
Upper limits or a few events
with # of backgrounds ~ 0
Saturation of sensitivity

KOTO II aims at measurements
of $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$
~40 events in SM sensitivity
$O(10^{-13})$ sensitivity

$K \to \mu^+\mu^-$ as a third kaon golden mode



Clean SM prediction



Mel's 1977 measurement of $K_L \to \mu^+ \mu^-$

First clean measurement with 16 events

Mel and Kaon:

η_{00}/η_{+-}	*Early work on Direct CPV*
$K_L \rightarrow \gamma\gamma$	*KOTO #1 background*
$K_{L,S} \rightarrow \mu^+\mu^-$	*Third Kaon Golden Mode*

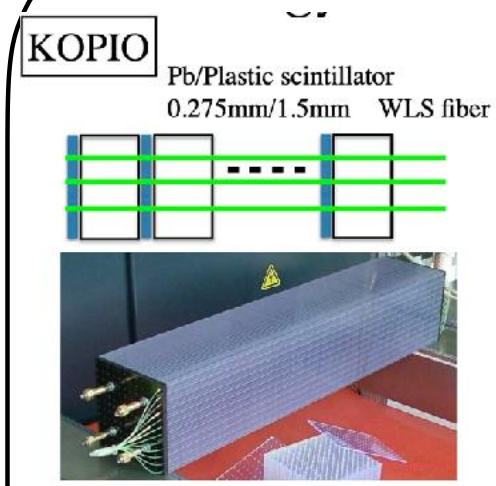
Backups:

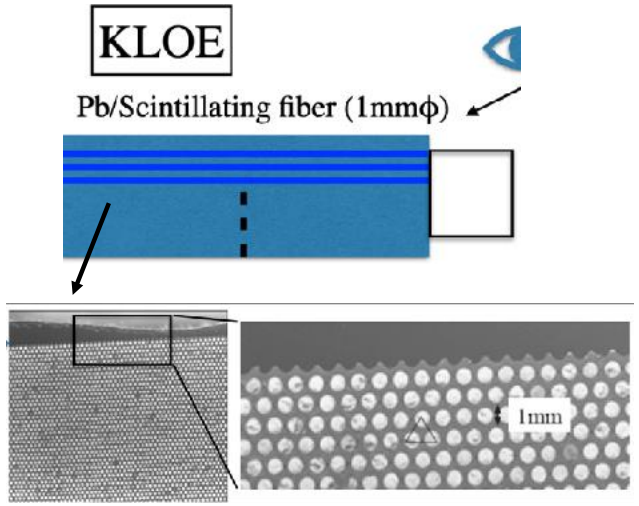
Summary

- The $K_L \to \pi^0 \nu \nu$ decay is sensitive to New Physics.
- KOTO
  - Finalizing the 2021 data analysis
    - Will open the signal box after optimization of the selection criteria and evaluation of the systematic uncertainties on the BG events.
  - Will reach the S.E.S below 10^{-10} in 4 years data taking.
- KOTO II
  - Have the potential of 5 σ discovery if $Br(K_L \to \pi^0 \nu \nu)$ is the same as the SM prediction.
  - Detector R&D for KOTO II is on going.

Toward KOTO II

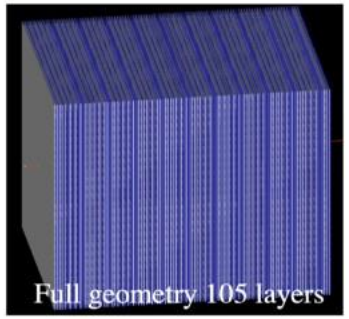
Calorimeter Candidate

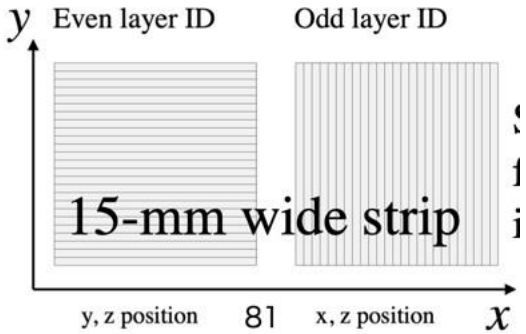




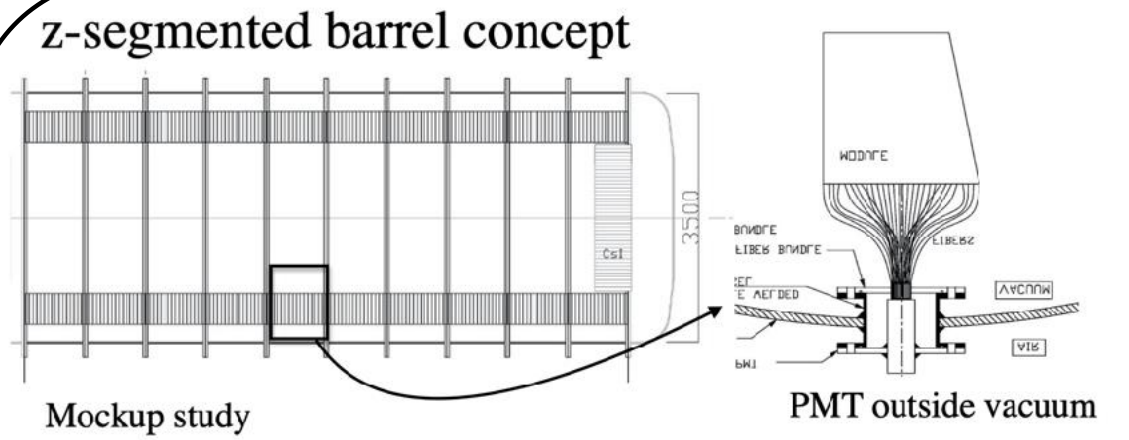
Fine Segmented calorimeter capable of angle measurement

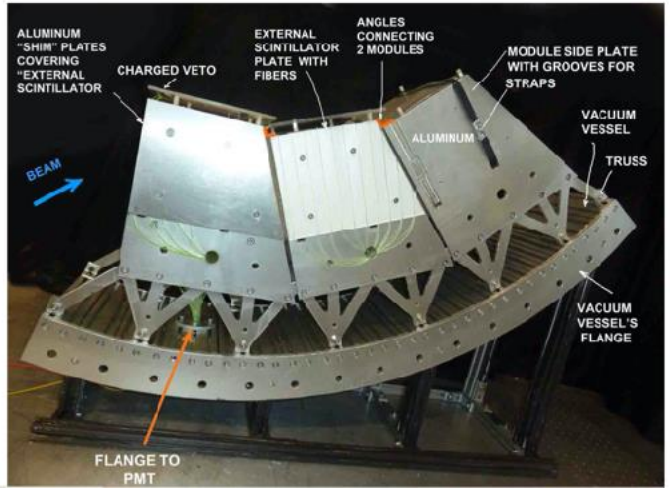
1-mm lead/5-mm plastic scinti.

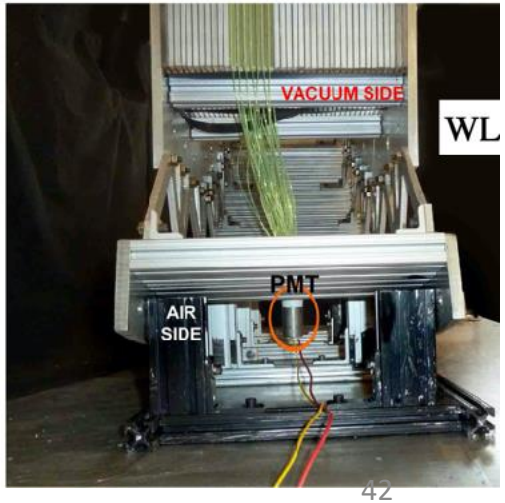




Barrel detector Candidate

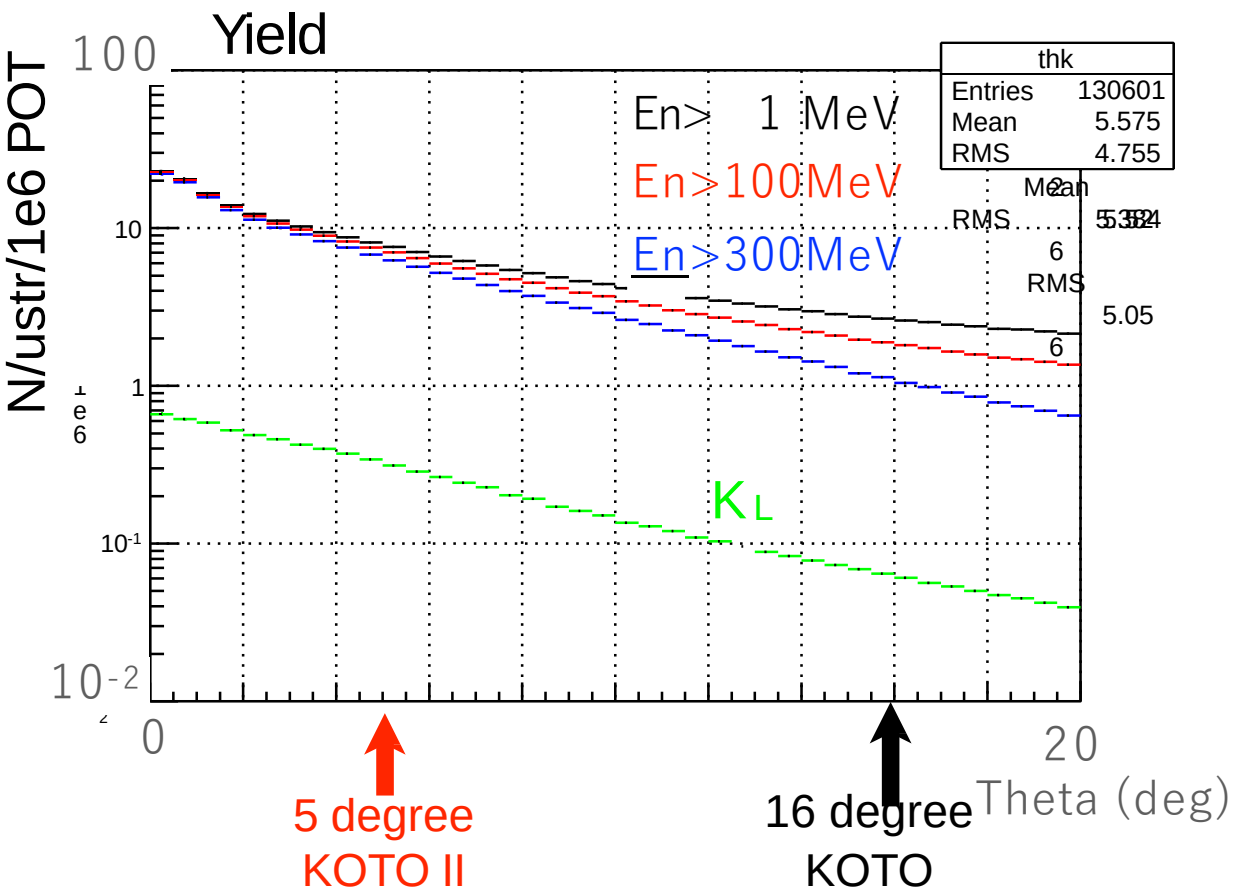


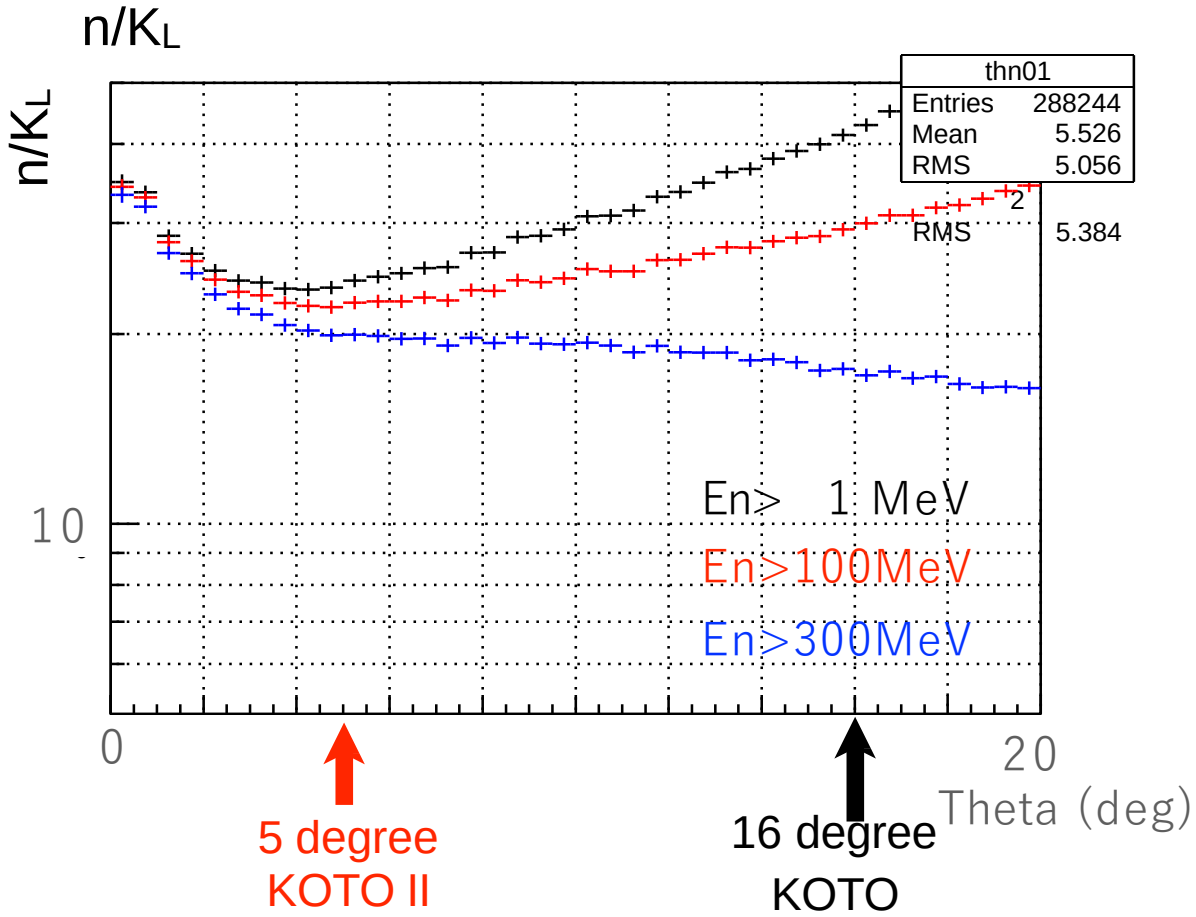




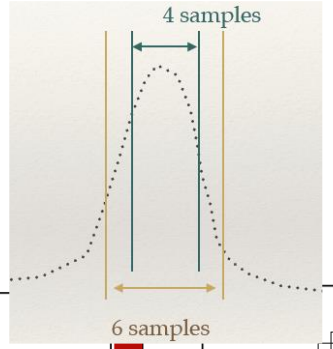
A new KL beam line

KL yield dependence on extraction angle



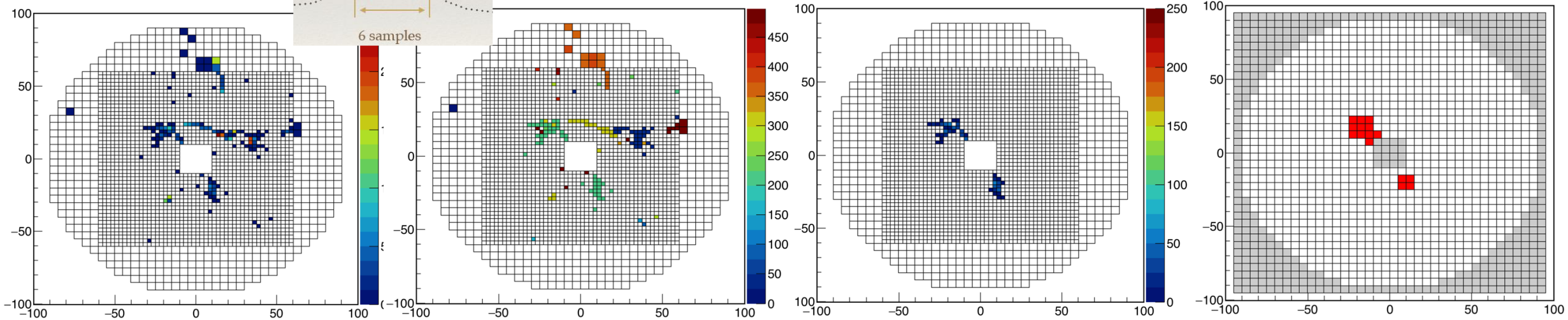


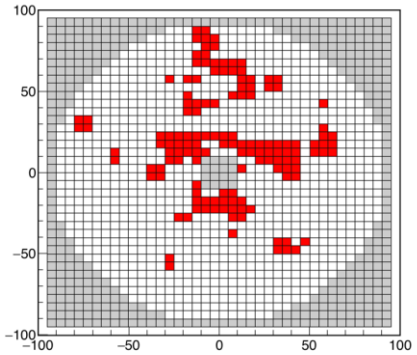
Photon cluster trigger:



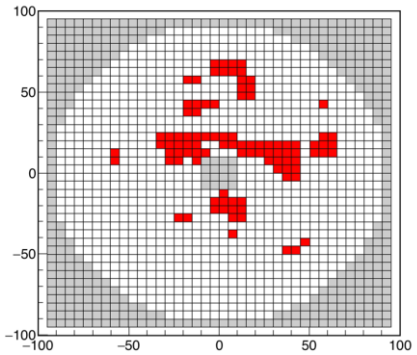
Small block: >22MeV
Large block: >44MeV

Turns counting parallel algorithm

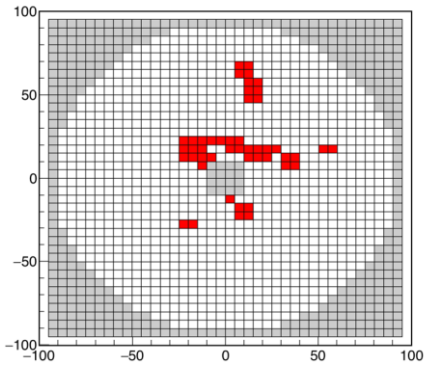




15 clusters



3MeV: 11 clusters



22MeV: 5 clusters

> 99% efficient

Blind Analysis:

1. Blind off signal region
2. Do we understand all features outside the box?
3. Open the box when we do