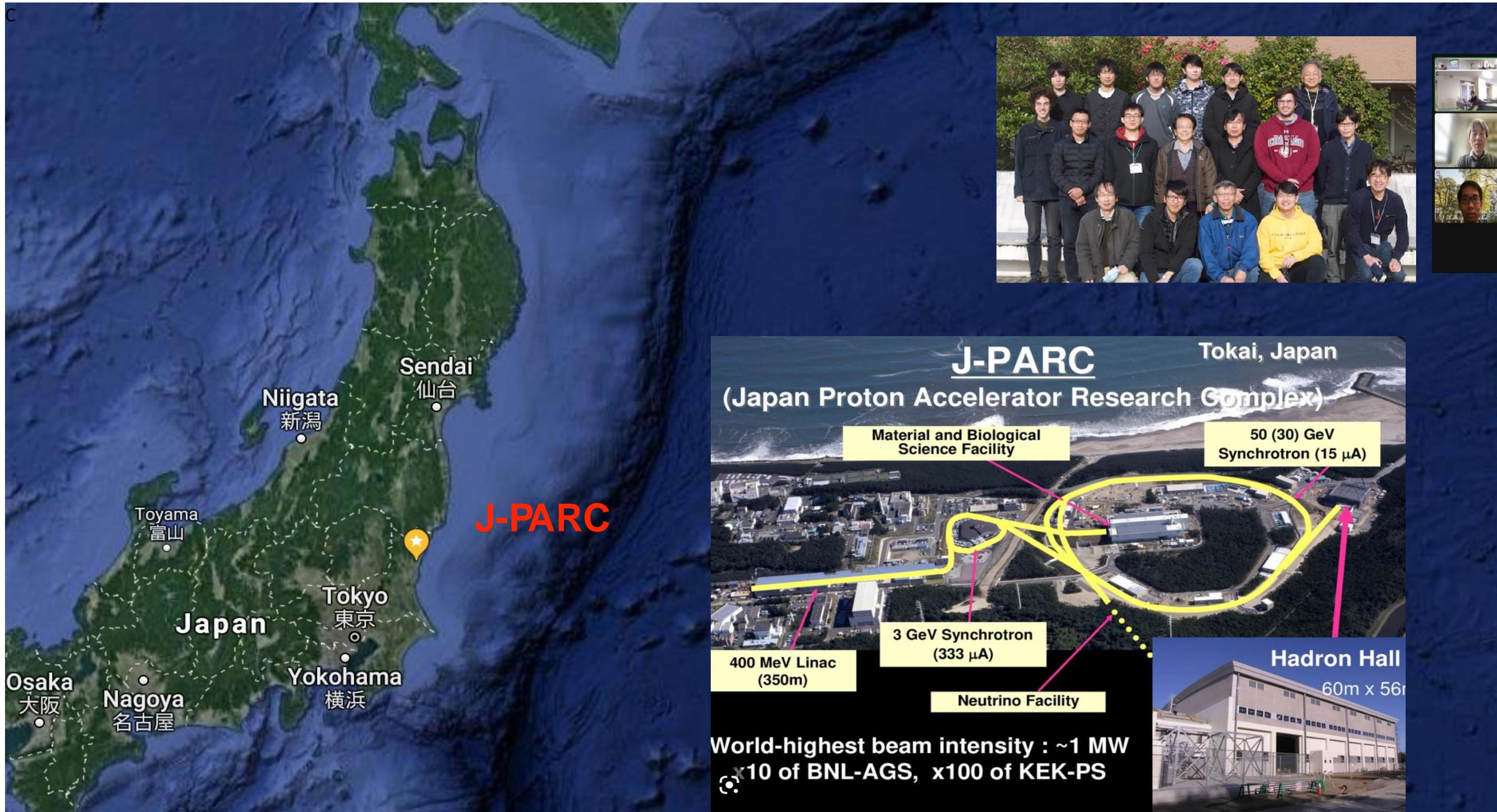


KOTO & KOTO-II

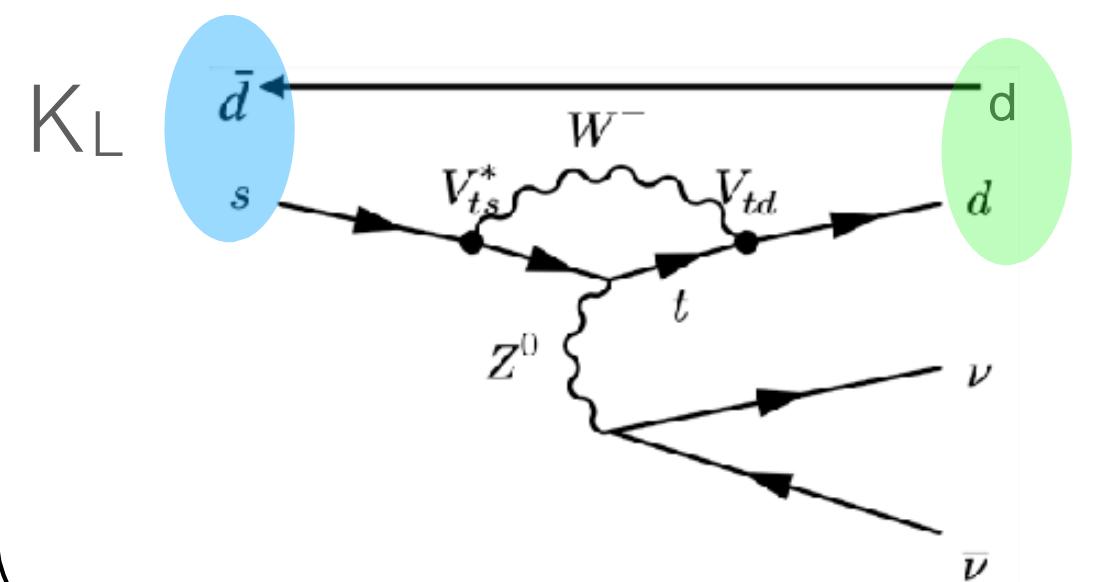
Y Wah (University of Chicago)
30 March 2023

KOTO experiment



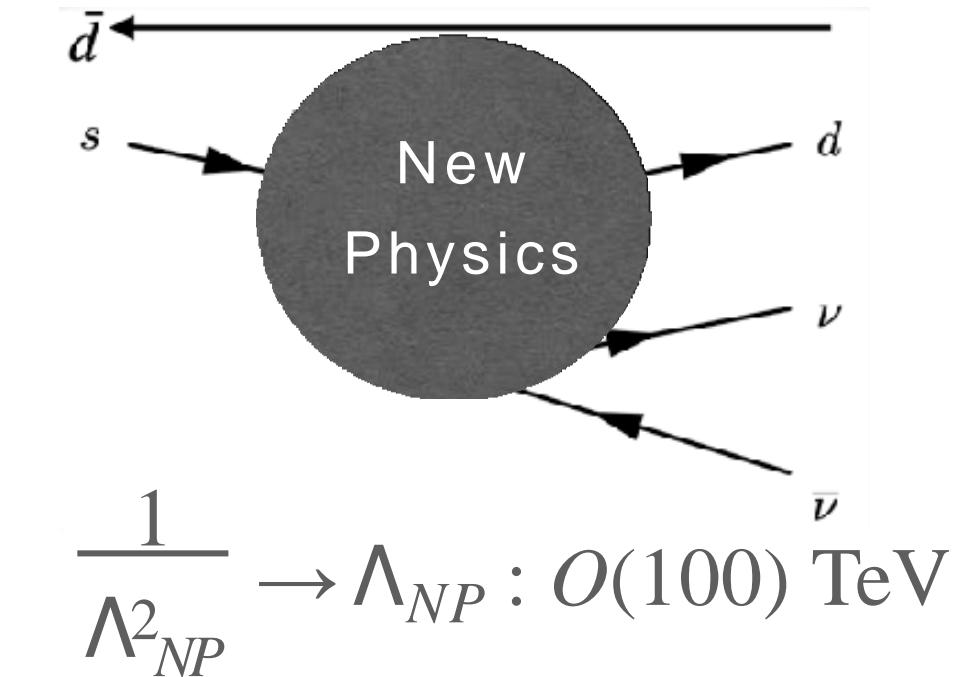
Physics on $K_L \rightarrow \pi^0 \nu \bar{\nu}$

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



- Very rare CP violating process
- $\text{BR}(\text{SM}) = 3.0 \times 10^{-11}$
- $\sim 2\%$ theoretical uncertainty

New Physics Contribution??



$\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu})$

Direct limit (KOTO 2015)
 $B_{K_L \rightarrow \pi^0 \nu \bar{\nu}} < 3.0 \times 10^{-9}$ (90 % CL)

Indirect limit
 $B_{K_L \rightarrow \pi^0 \nu \bar{\nu}} < 6.4 \times 10^{-10}$ (68 % CL)

SM

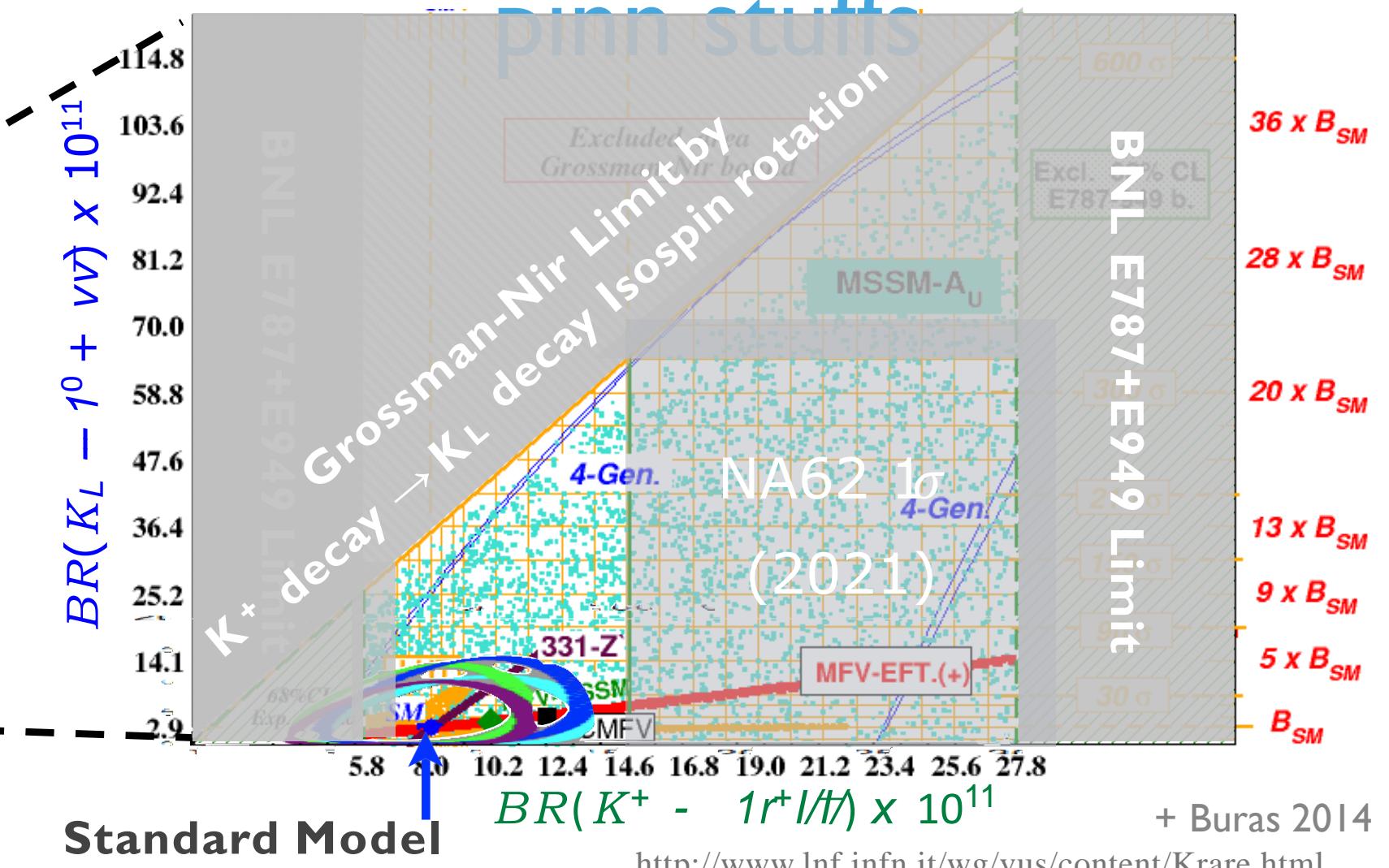
10^{-8}

10^{-9}

10^{-10}

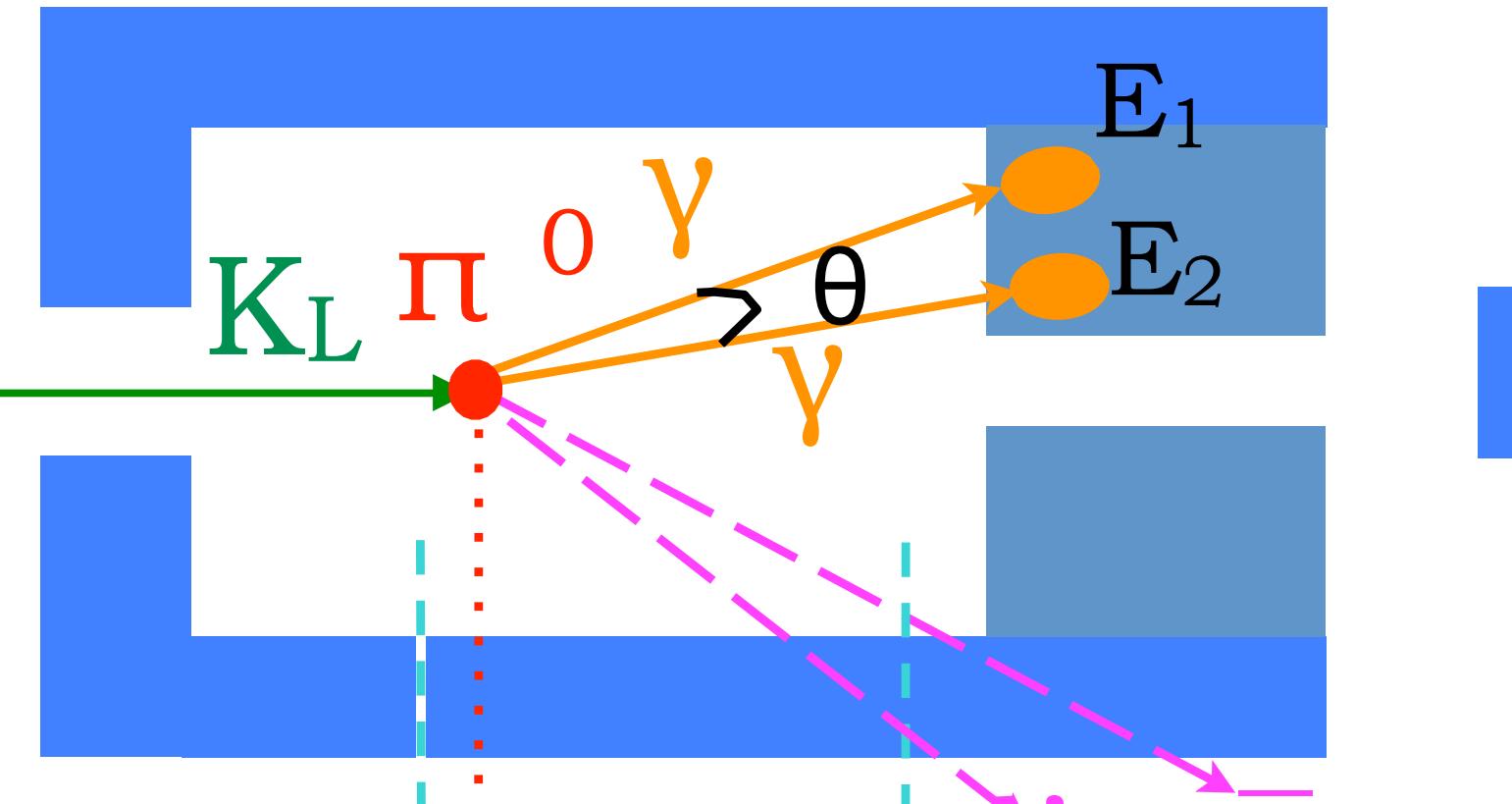
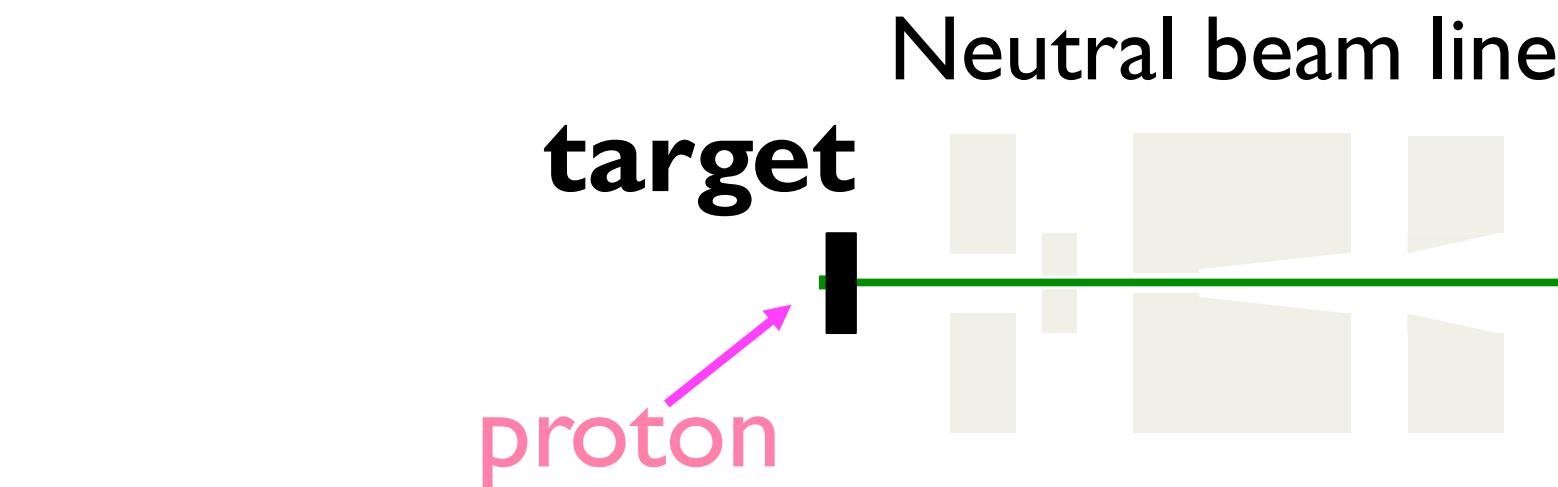
10^{-11}

New Physics?



Signature:

$K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay

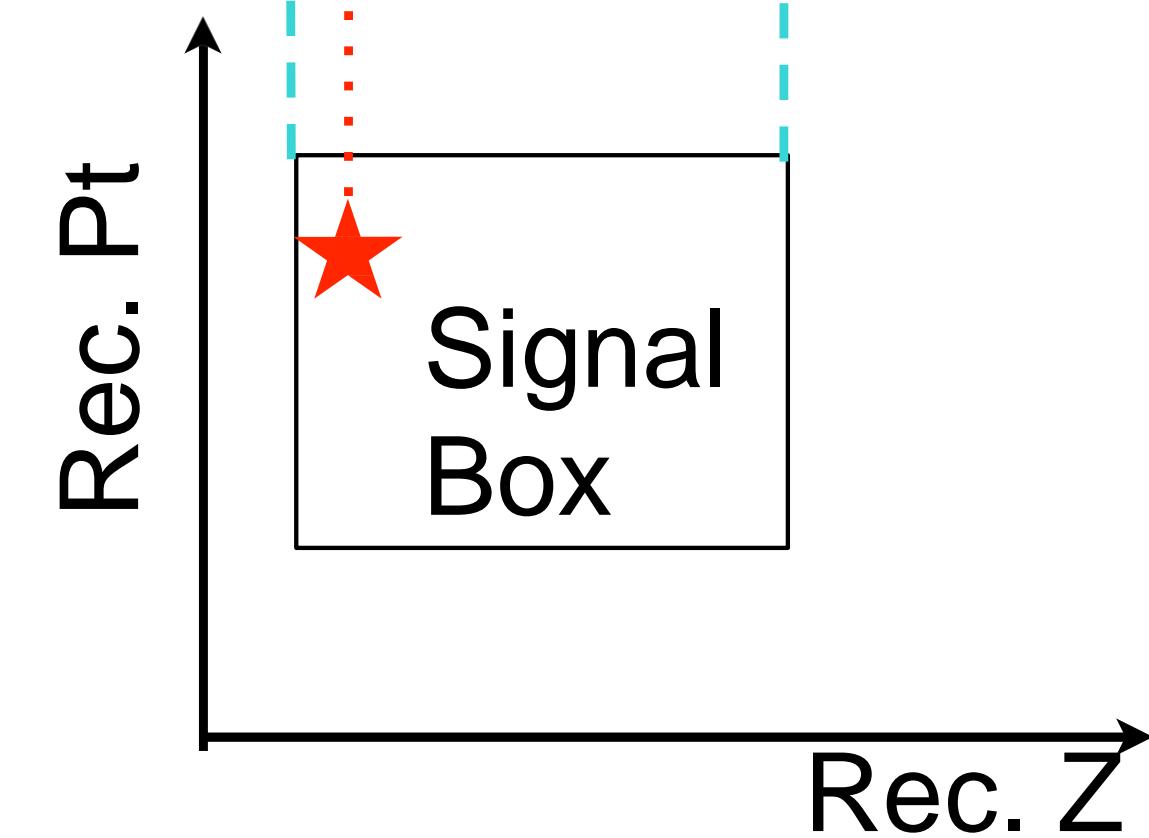


“ $2\gamma + \text{Nothing}$ ”

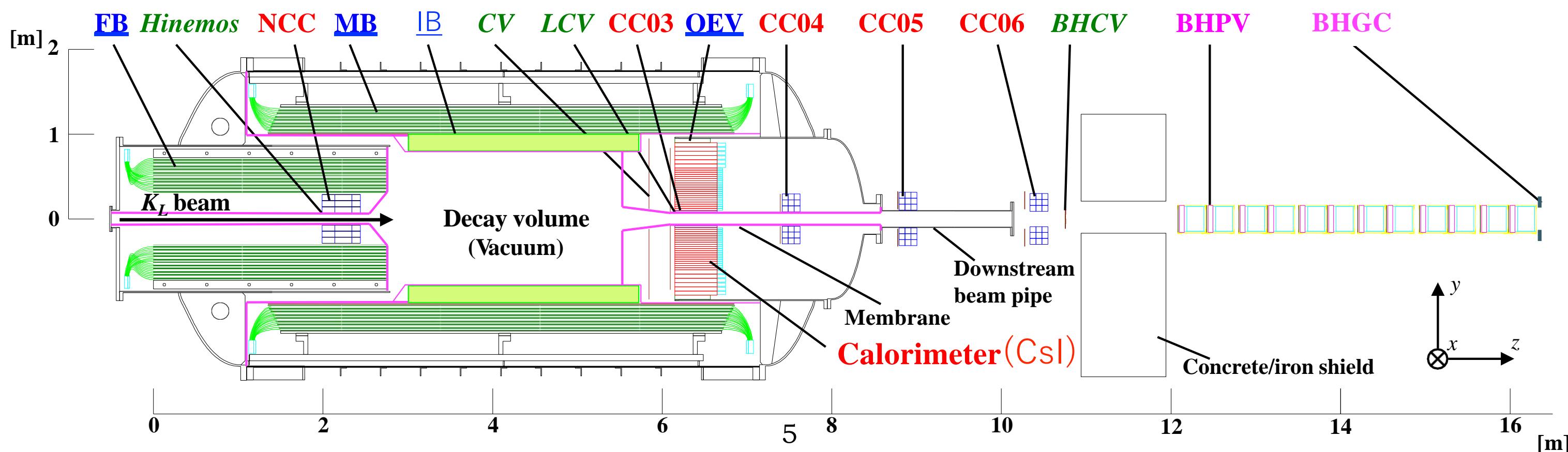
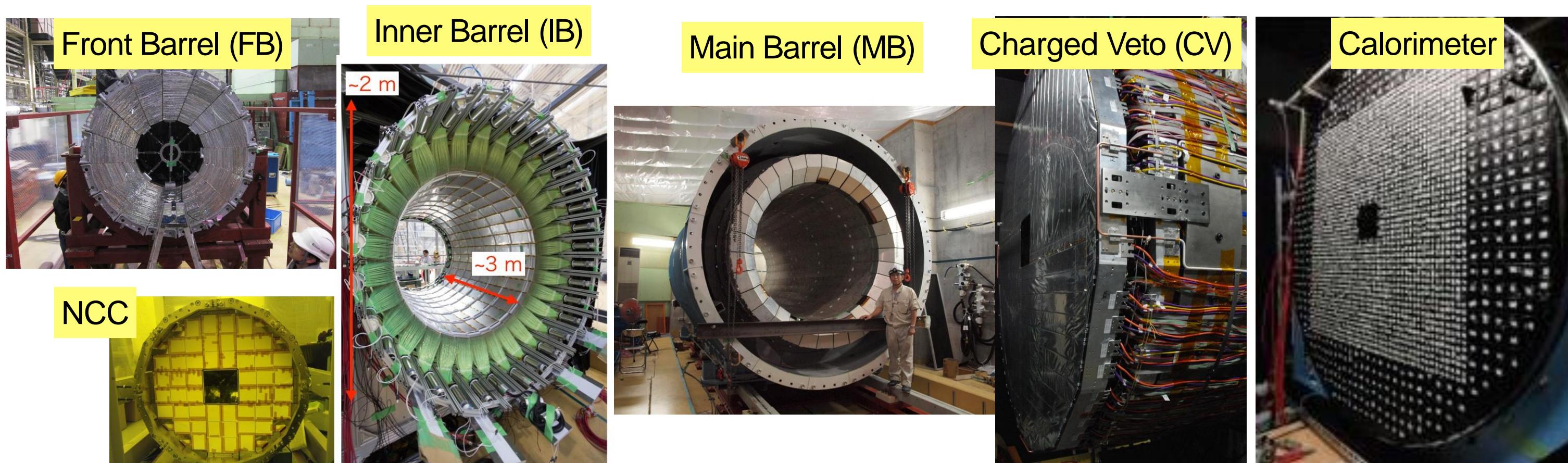
Assuming 2γ from π^0 ,
Calculate z vertex.

$$M^2(\pi^0) = 2E_1 E_2 (1 - \cos\theta)$$

Calculate π^0 Pt (large Pt for signal)

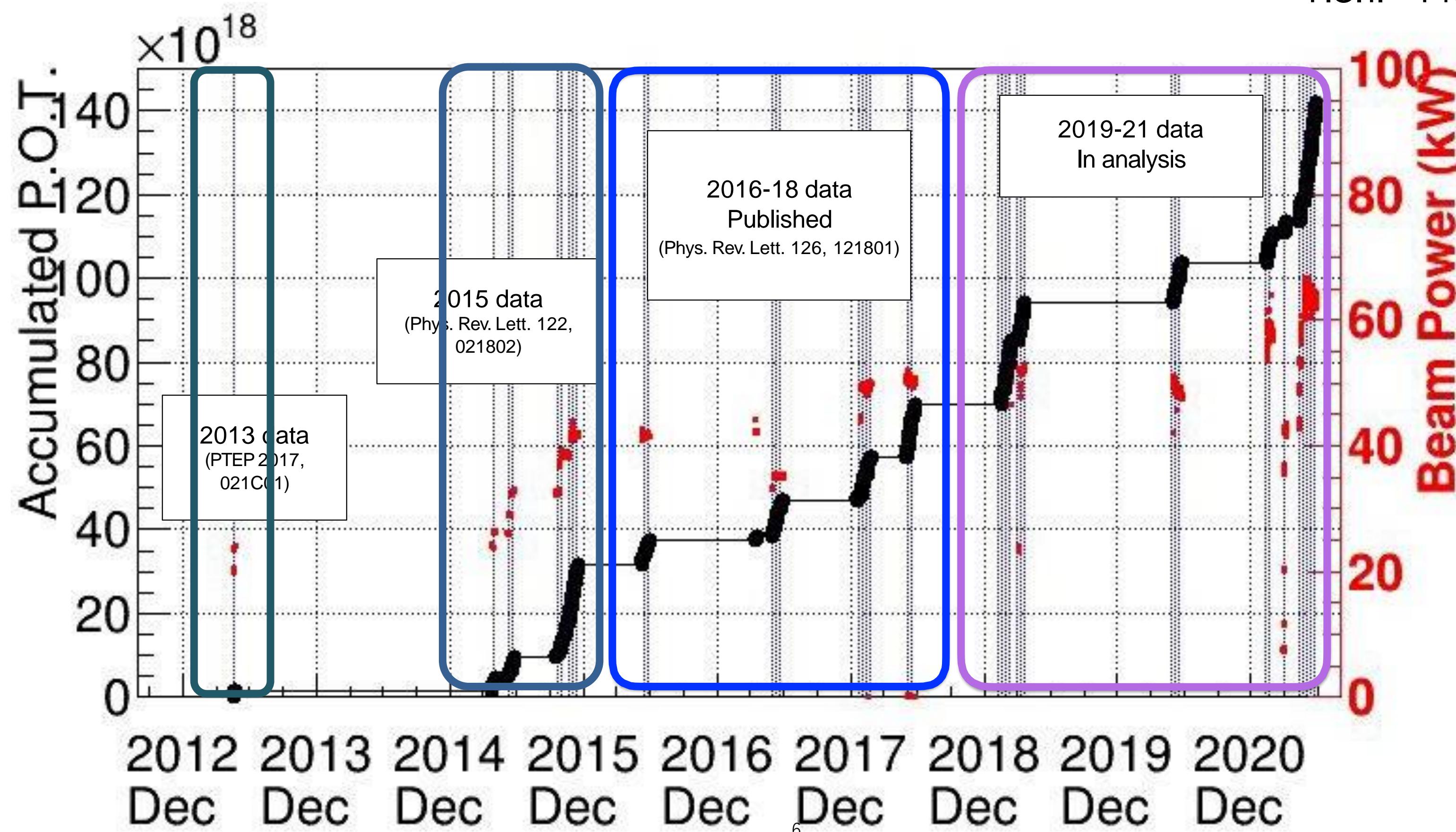


KOTO detector

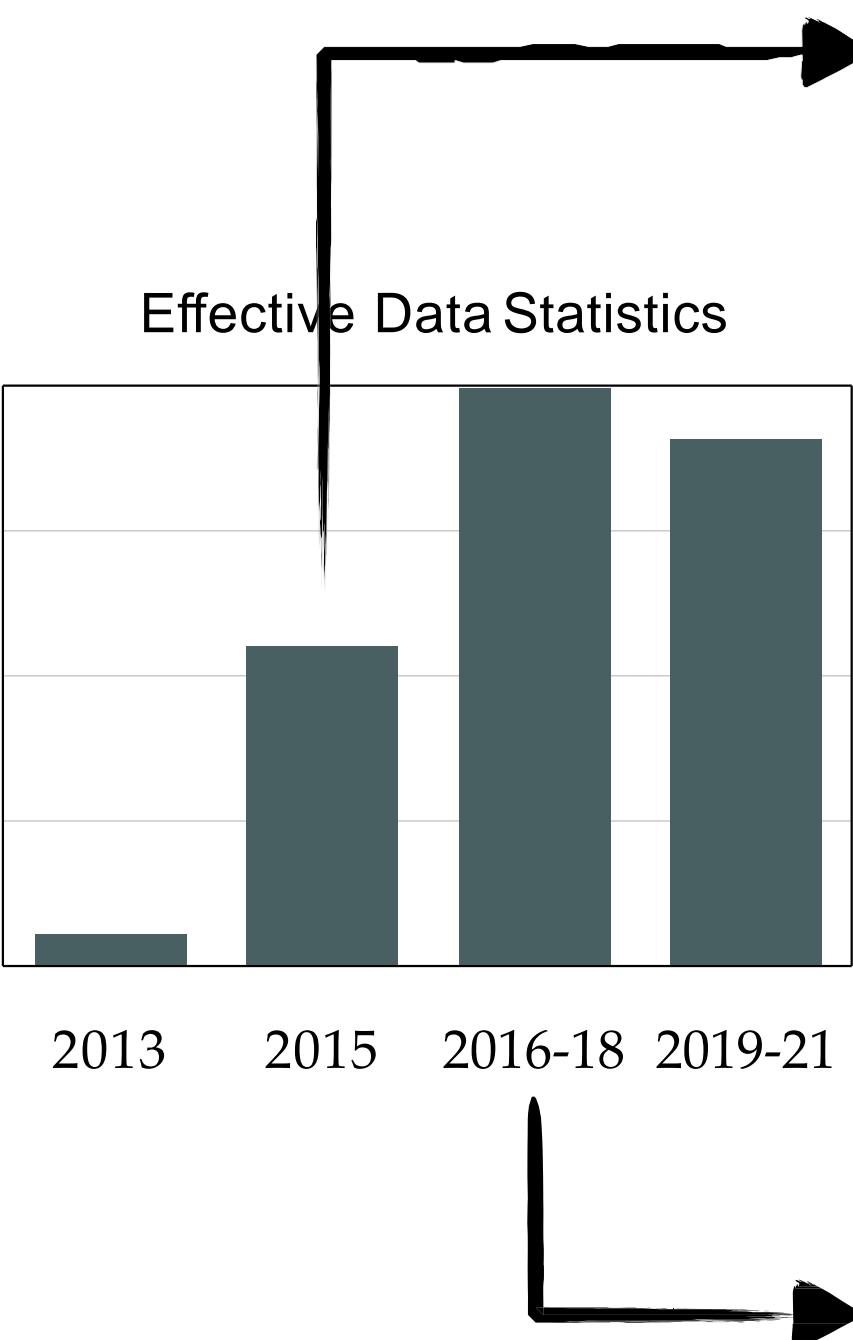


Data accumulation history

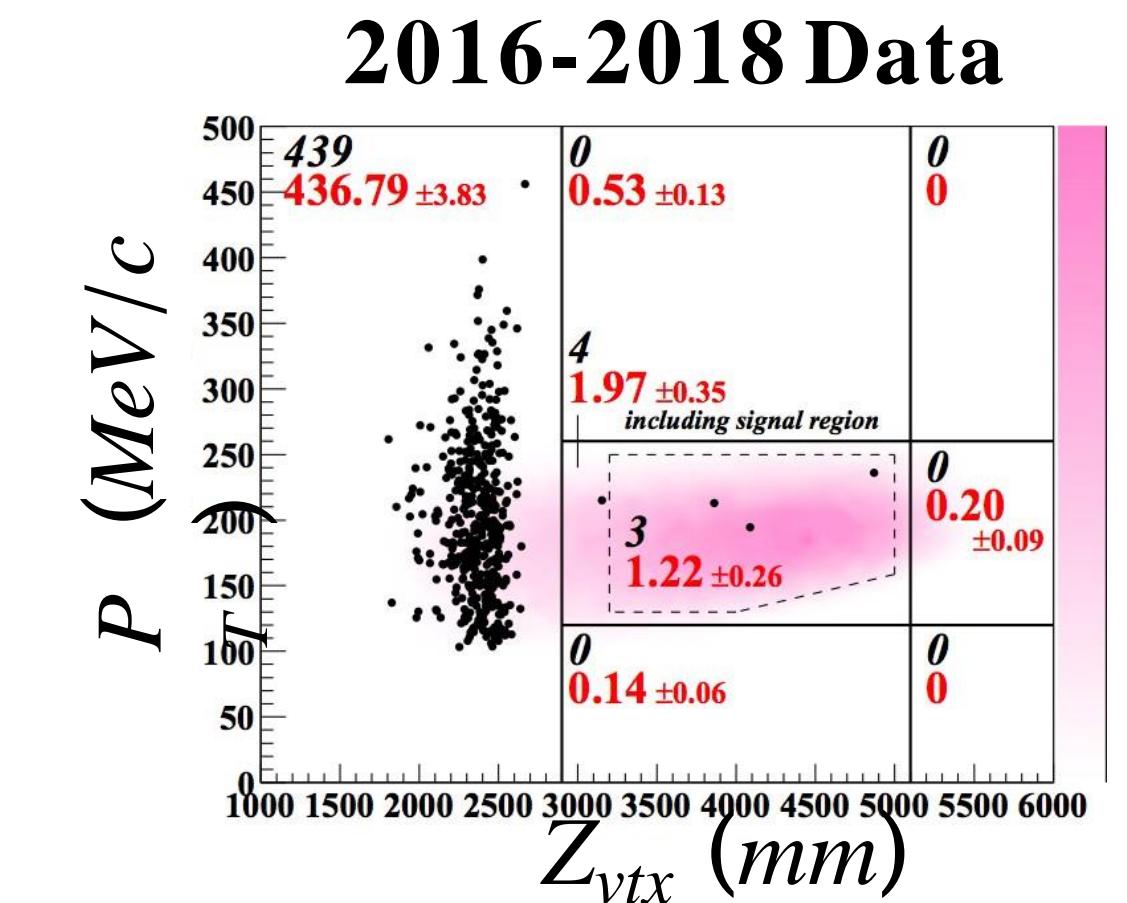
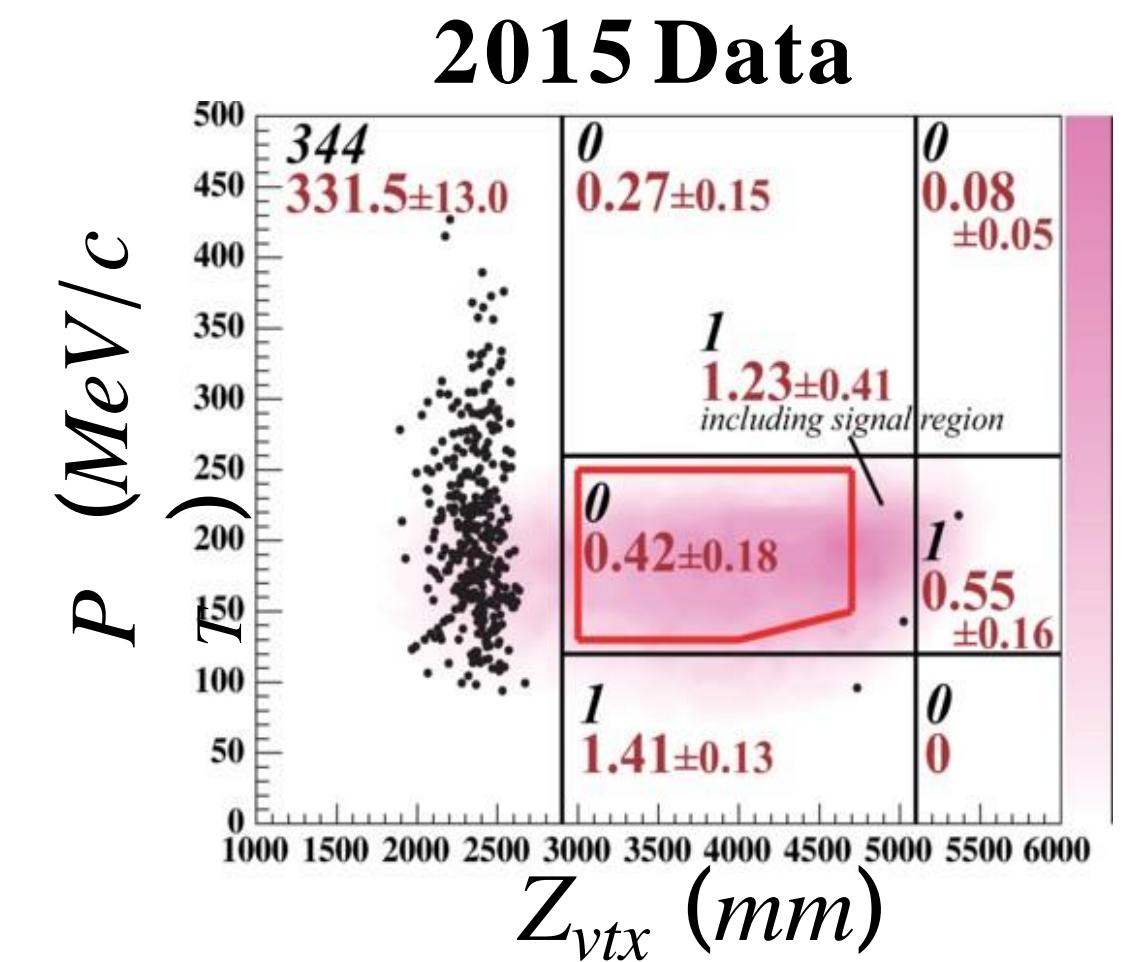
P.O.T. = Protons On Target



Recent Results

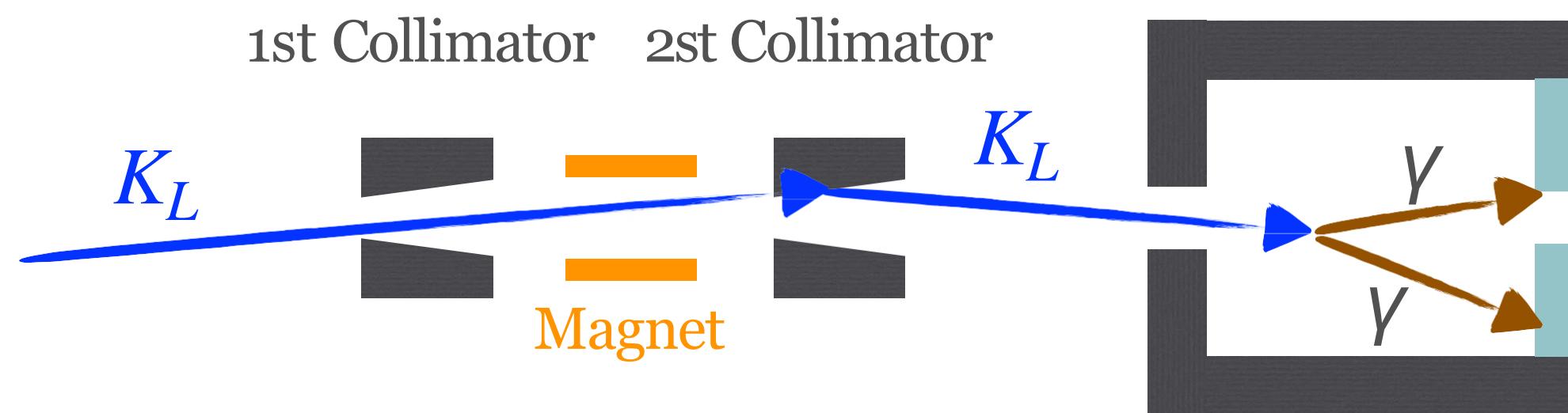


- 2015 data[PRL.122.021802]:
 - No event was observed with 0.42 predicted BGs.
 - $S.E.S. = 1.30 \times 10^{-9}$
 - $BR(K_L \rightarrow \pi^0 W) < 3.0 \times 10^{-9} \text{ at } 90\% \text{ C.L.}$
 - The world's best limit.
- 2016-2018 data[PRL.126.121801]:
 - $S.E.S. = 7.20 \times 10^{-10}$
 - Observed 3 events with 1.22 predicted BG.
 - 1.22 BG events included newly found BGs.
 - $BR(K_L \rightarrow \pi^0 W) < 4.9 \times 10^{-9} \text{ at } 90\% \text{ C.L.}$

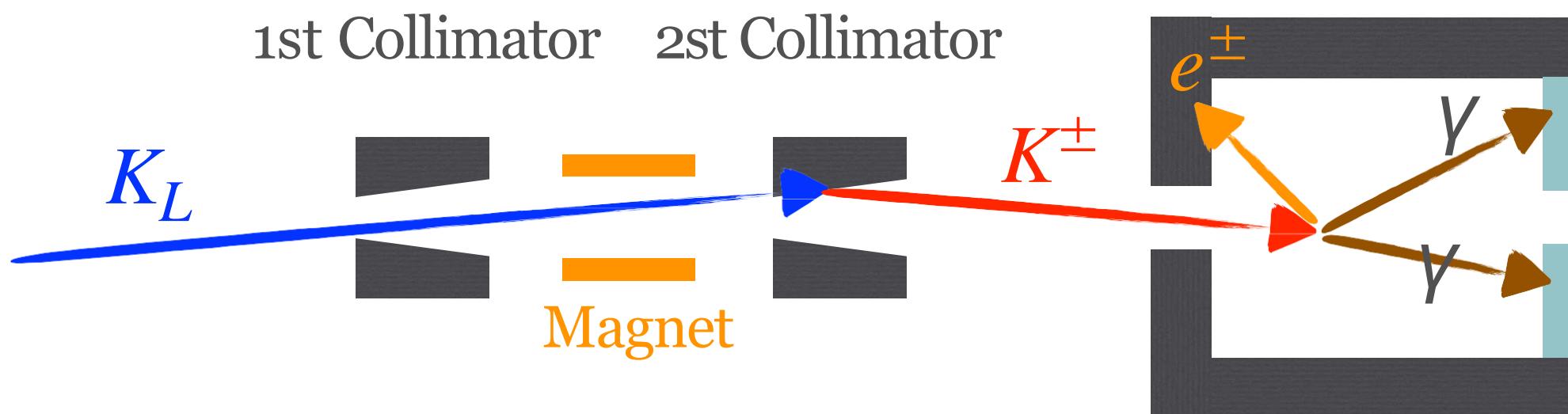


New BG Sources

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



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



BG Table

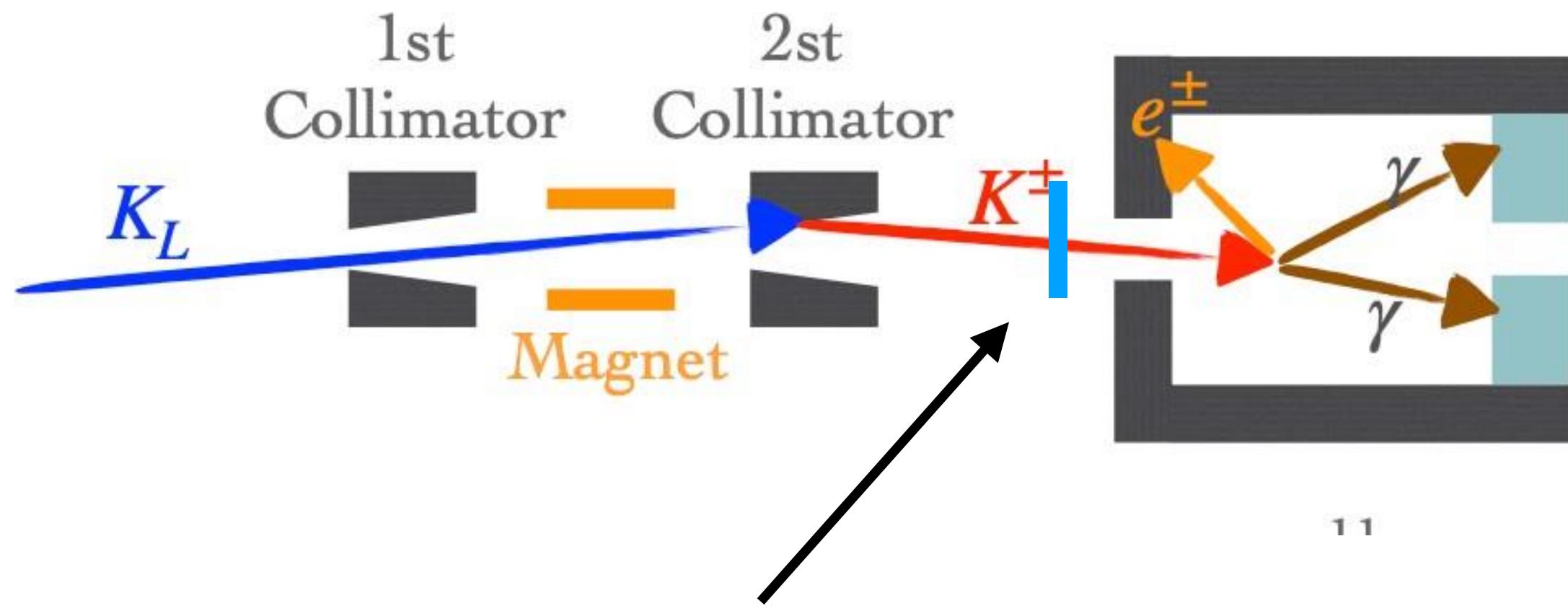
of 2016-2018 data

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

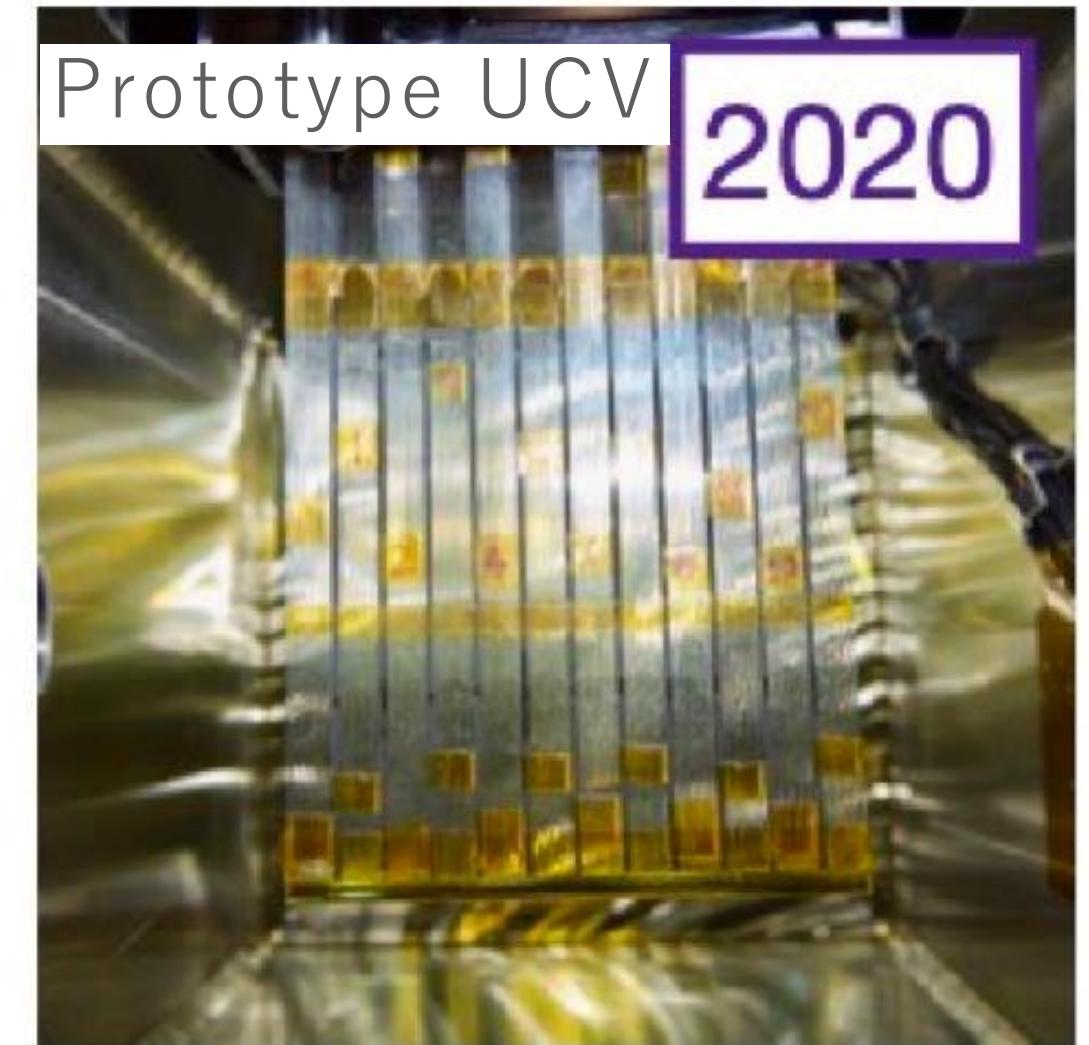
^a Background sources studied after looking inside the blind region.

K^\pm BG

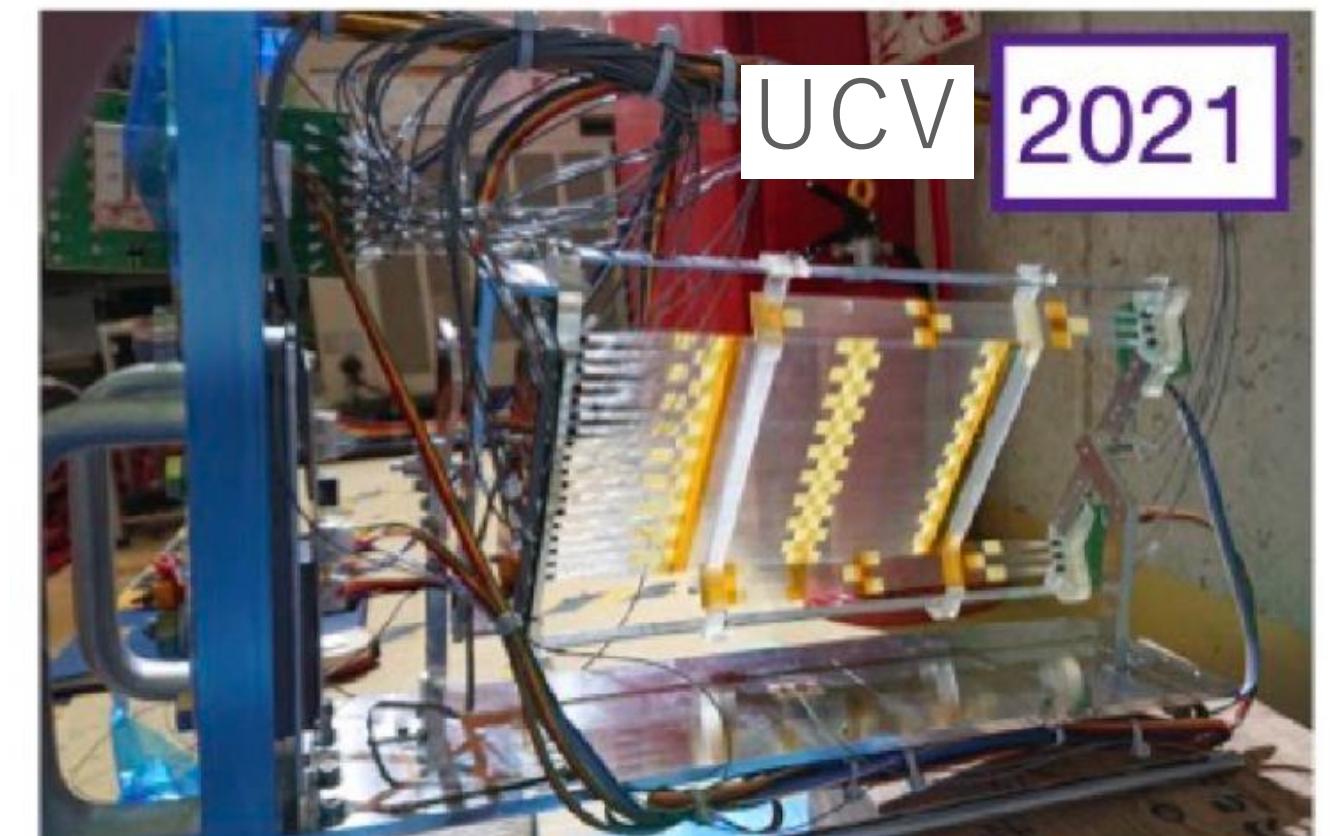
K^\pm BG ($K^\pm \rightarrow \pi^0 e^\pm \nu$)



- Installed Upstream Charged Veto(UCV) for K^\pm detection
- A plane of square scintillation fibers read by MPPC



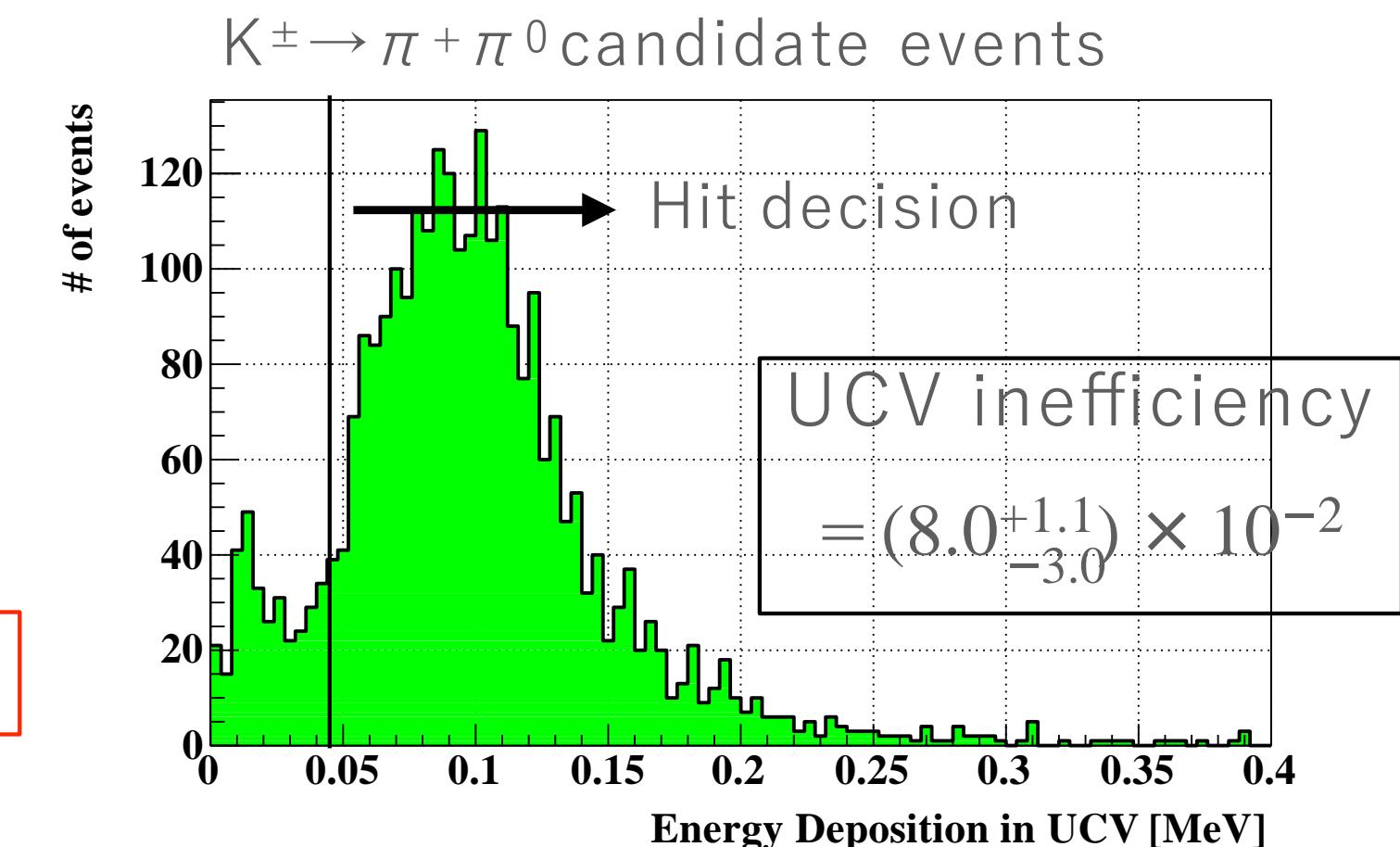
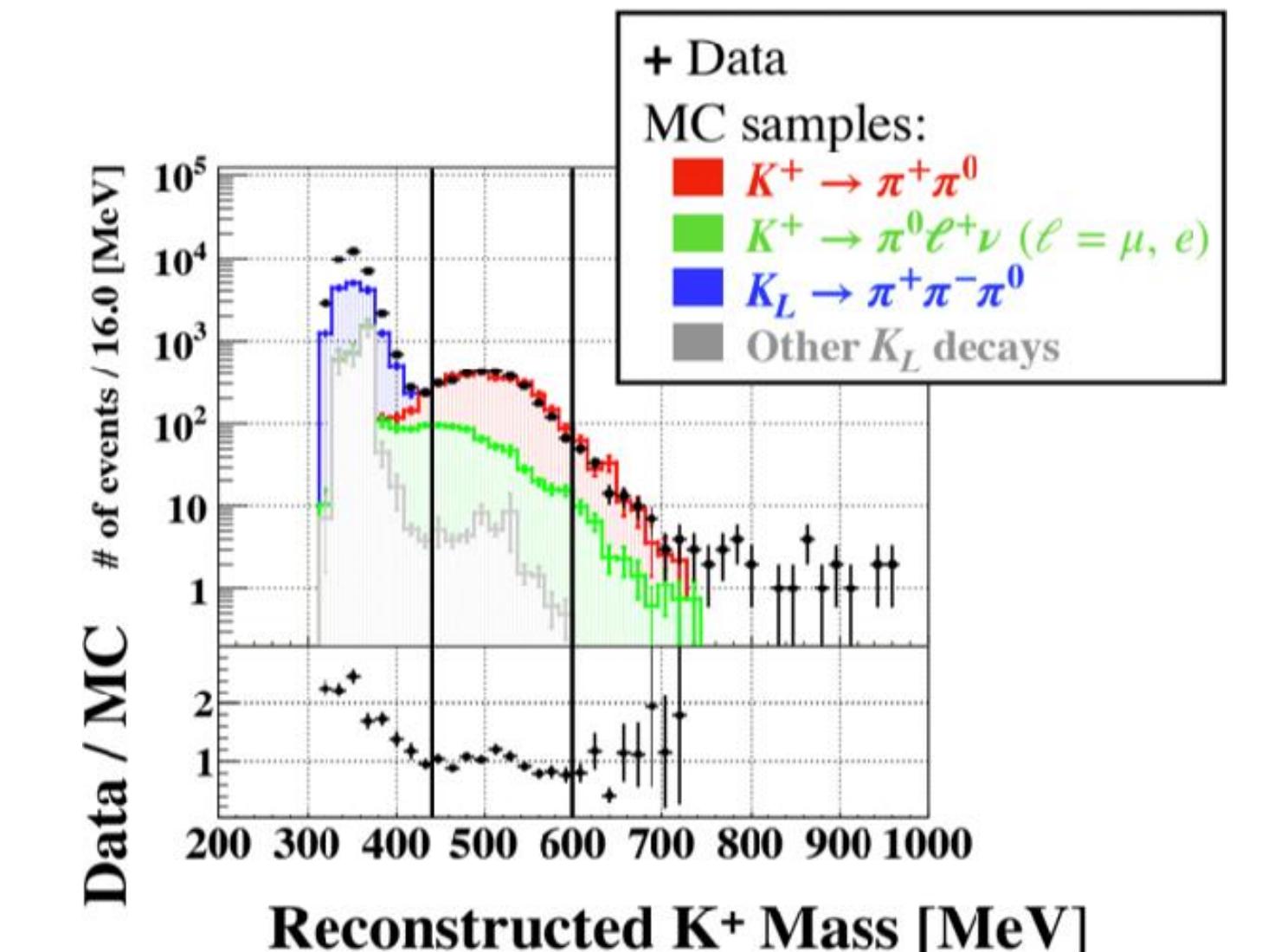
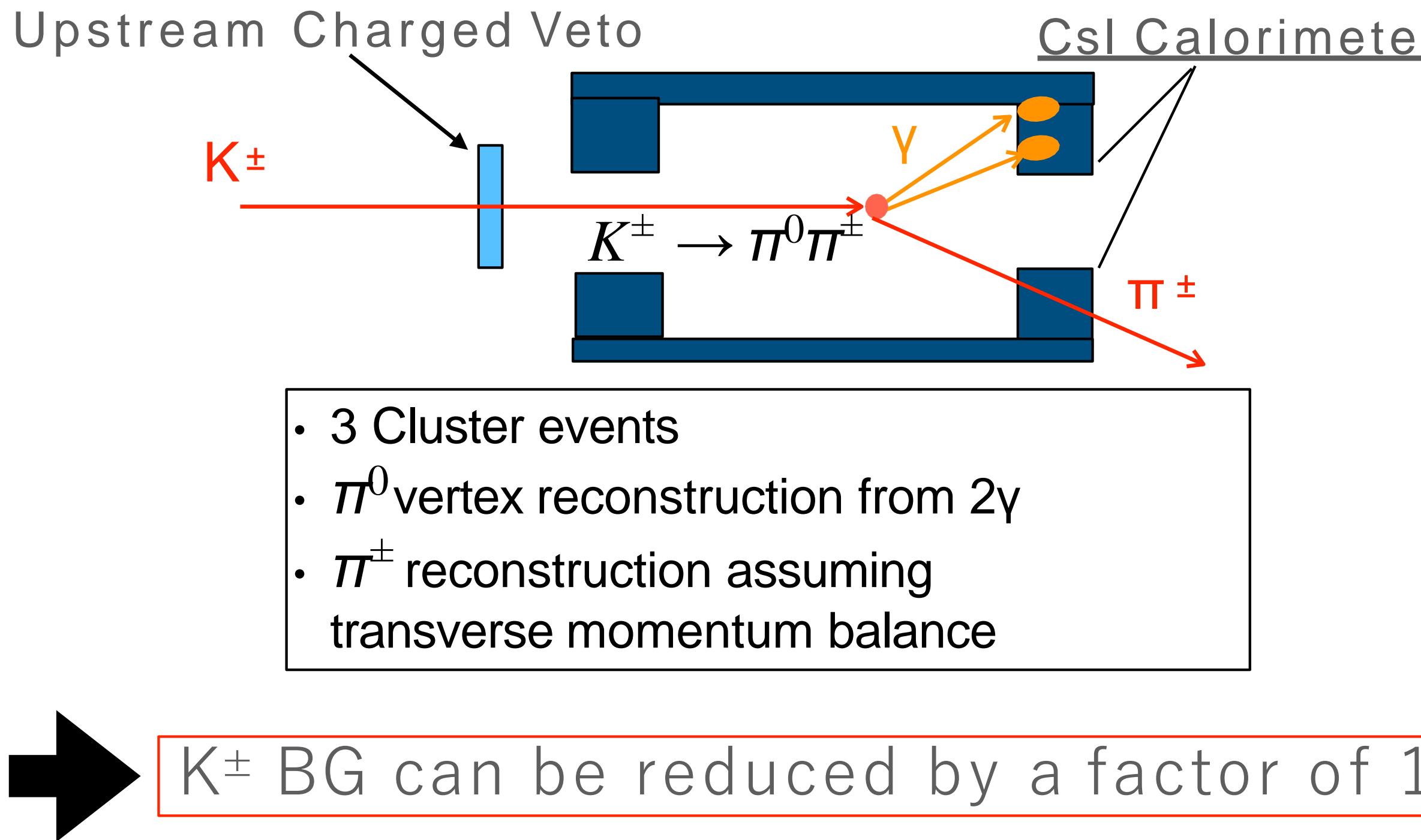
1mm-square fibers



0.5 mm-square fibers tilted 25 degree

Reduction of K^\pm BG

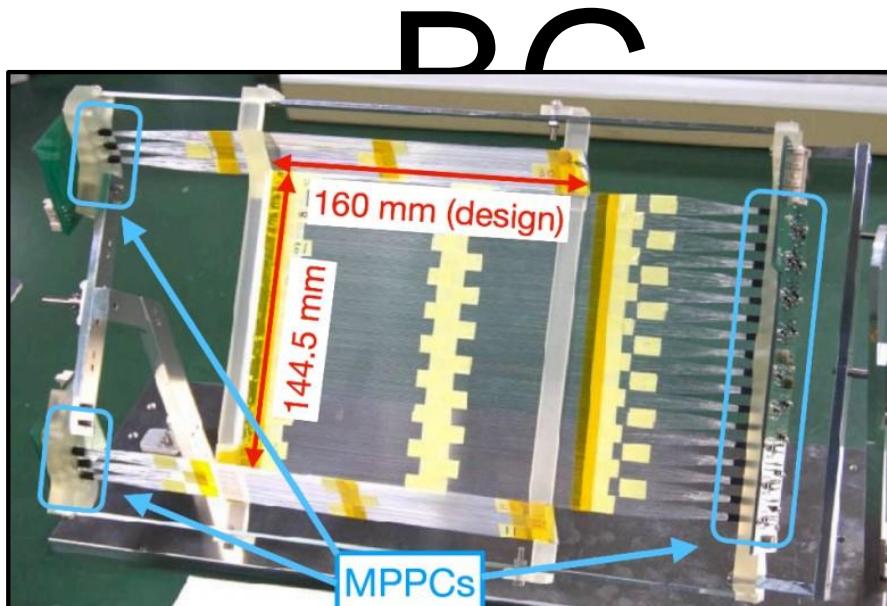
- Inefficiency of Upstream Charged Veto(UCV) was evaluated by identifying $K^\pm \rightarrow \pi^\pm \pi^0$ decay



Charged Kaon

2021

- UCV was installed.
- Scintillating fiber.
- $K^\pm BG \times 1/13$

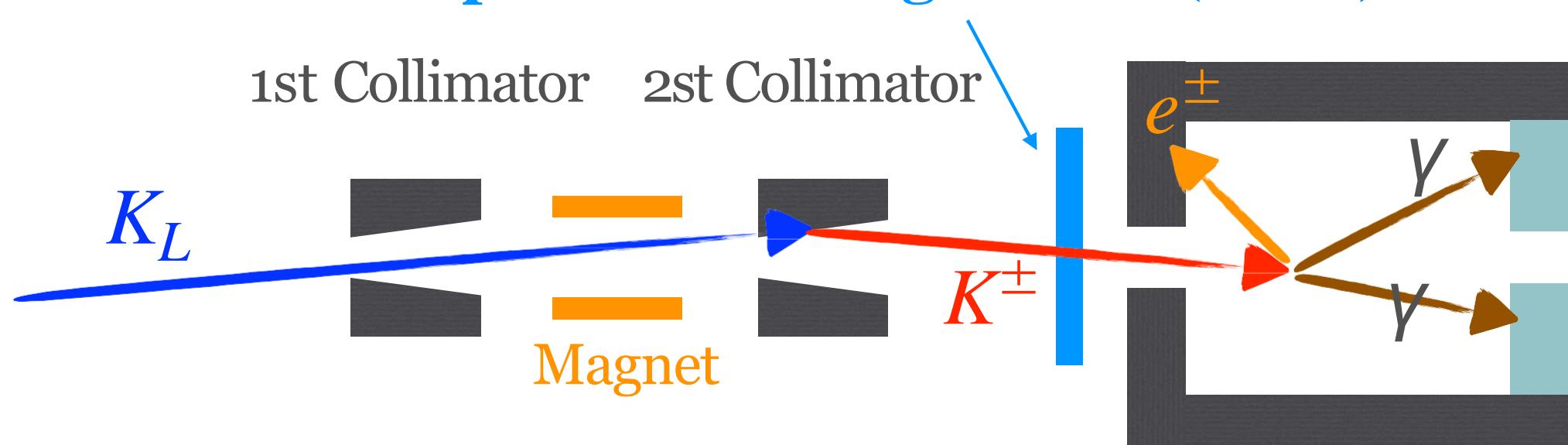


2023

- UCV will be upgraded.
- Scintillator film.
- $K^\pm BG \times 1/100$

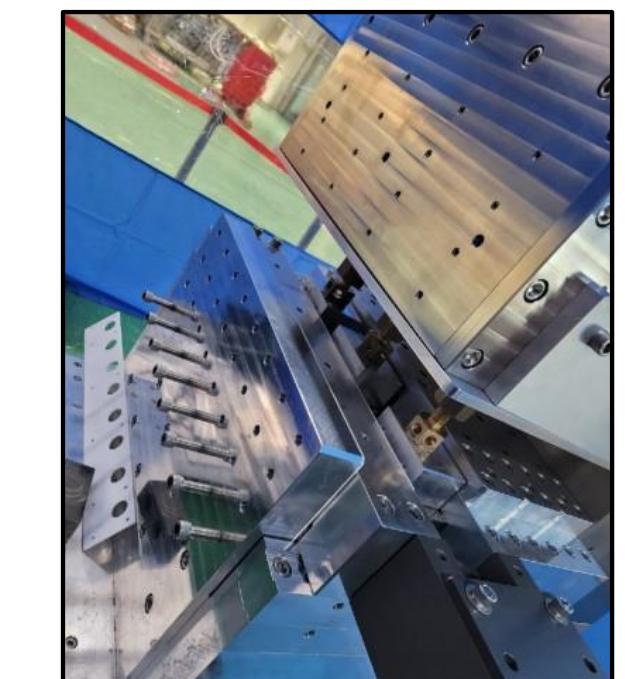


New Upstream Charged Veto (UCV)



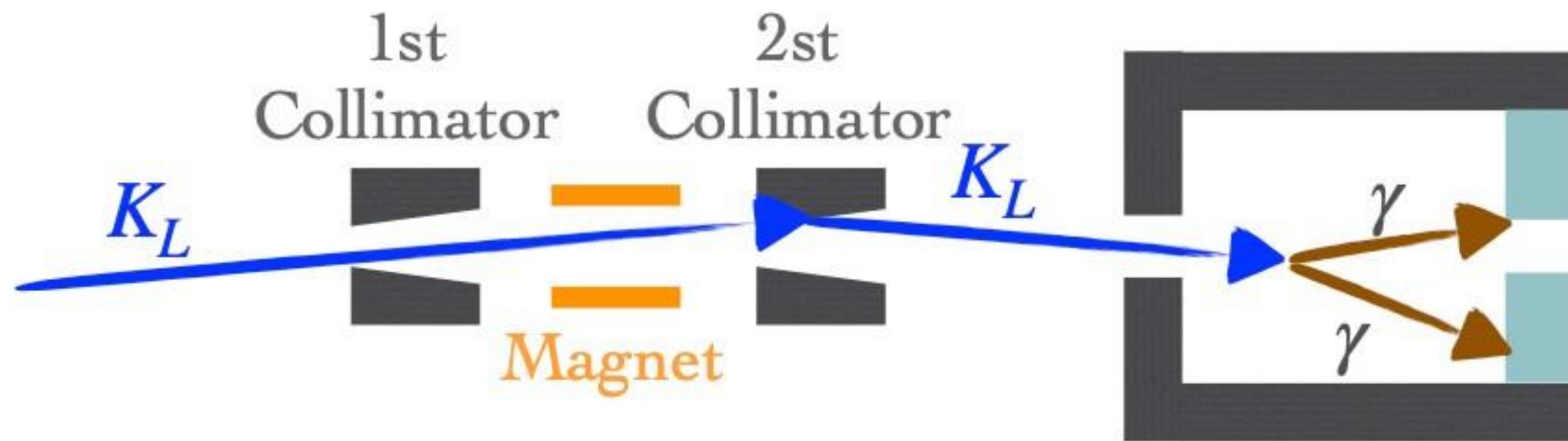
2023

- Will install a magnet after 2nd collimator.
- $K^\pm BG \times 1/10$



- Combined reduction $\sim 1/1000$ after 2023.
- $K^\pm BG \sim 0.02$ events at $BR_{EXP}(K_L \rightarrow \pi^0 W) \sim O(10^{-11})$.

Halo $K_L \rightarrow 2\gamma$ BG

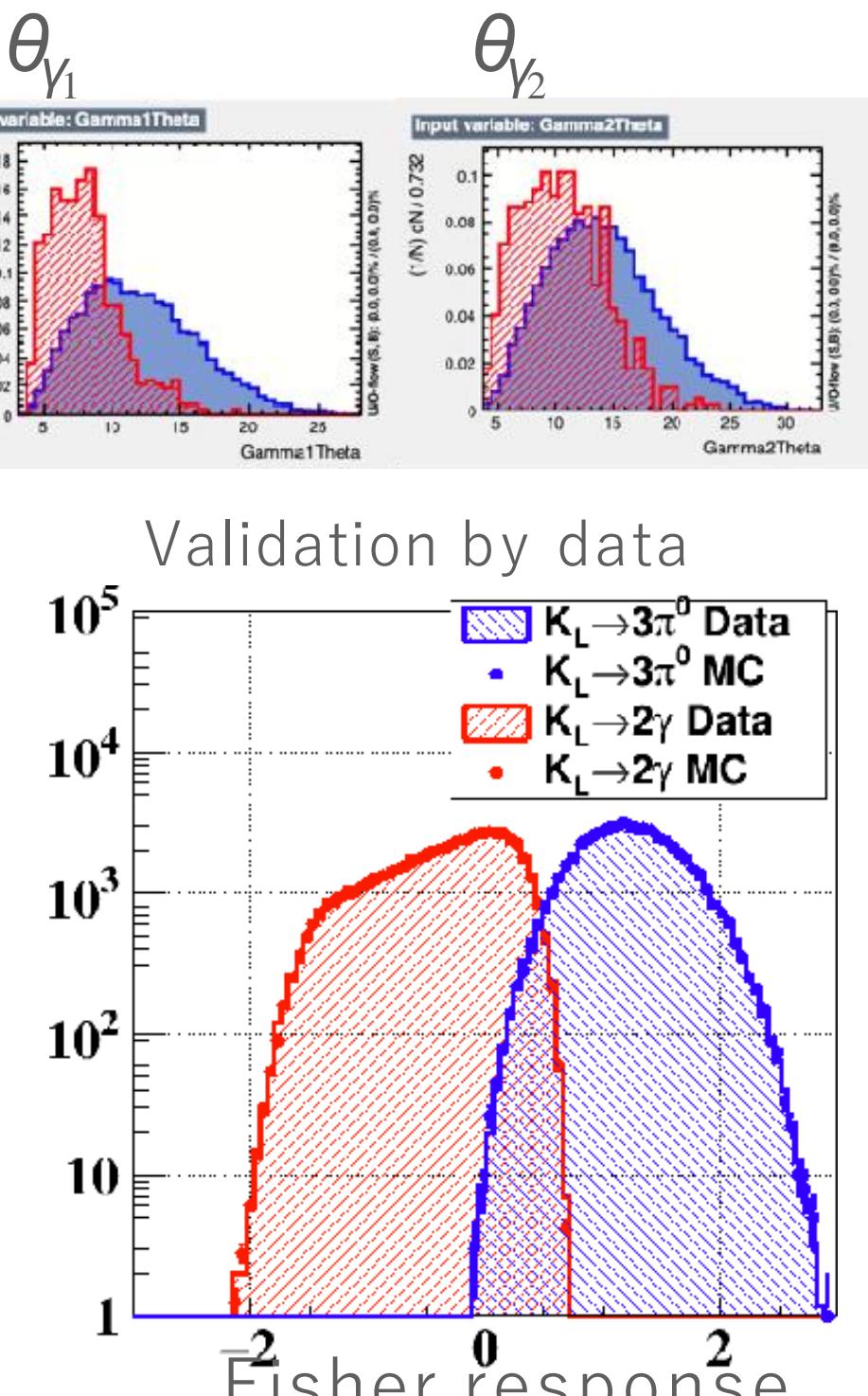
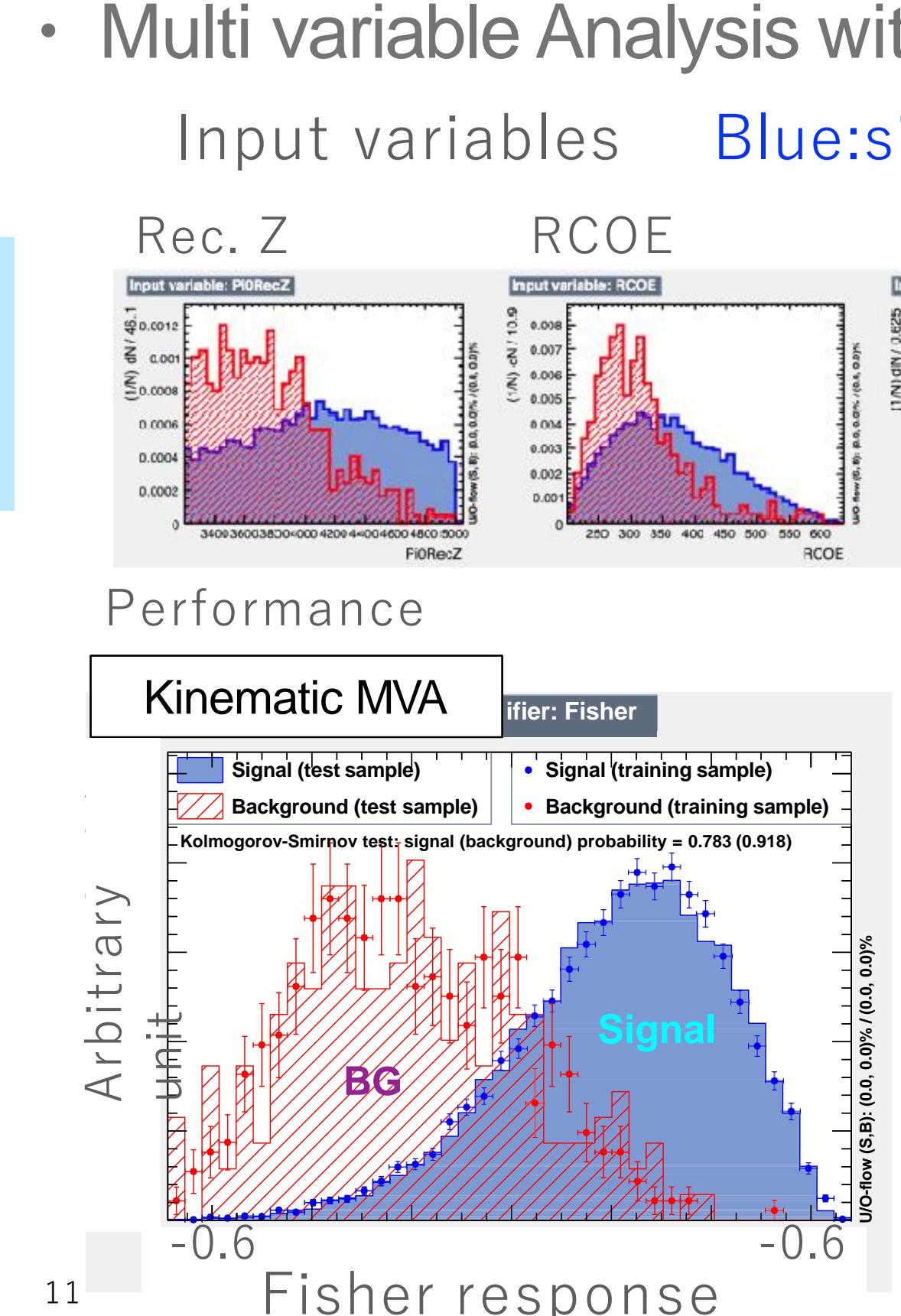
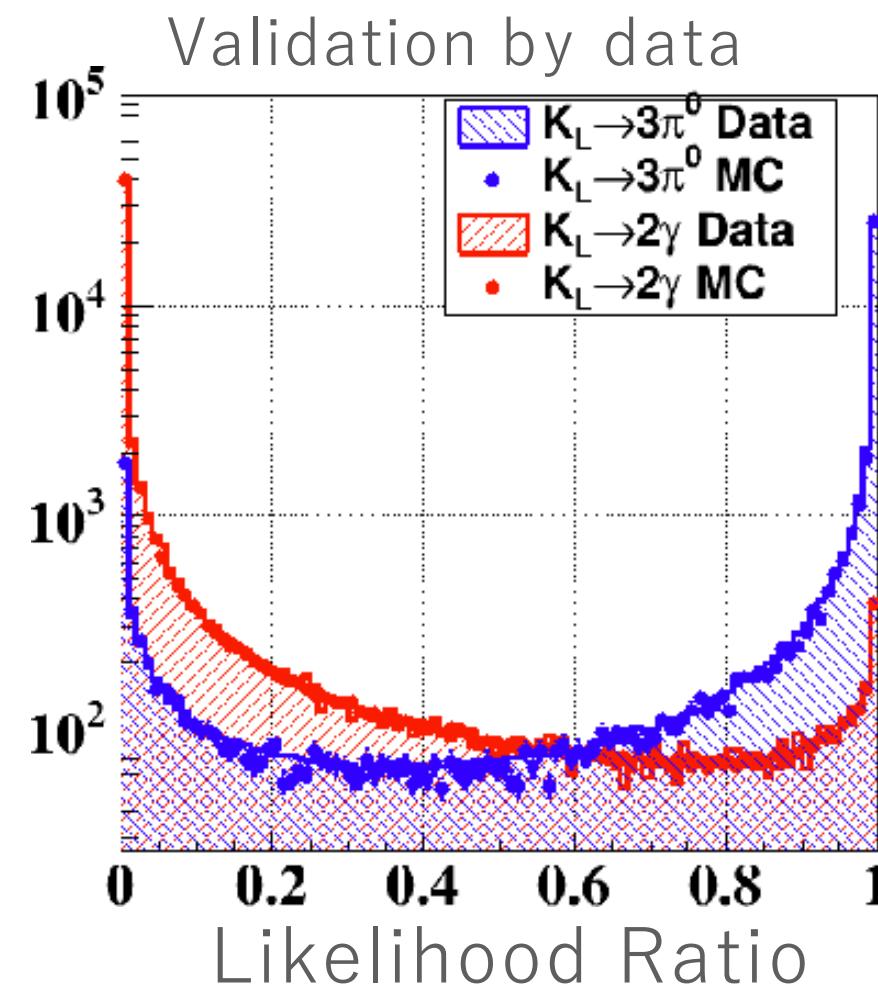
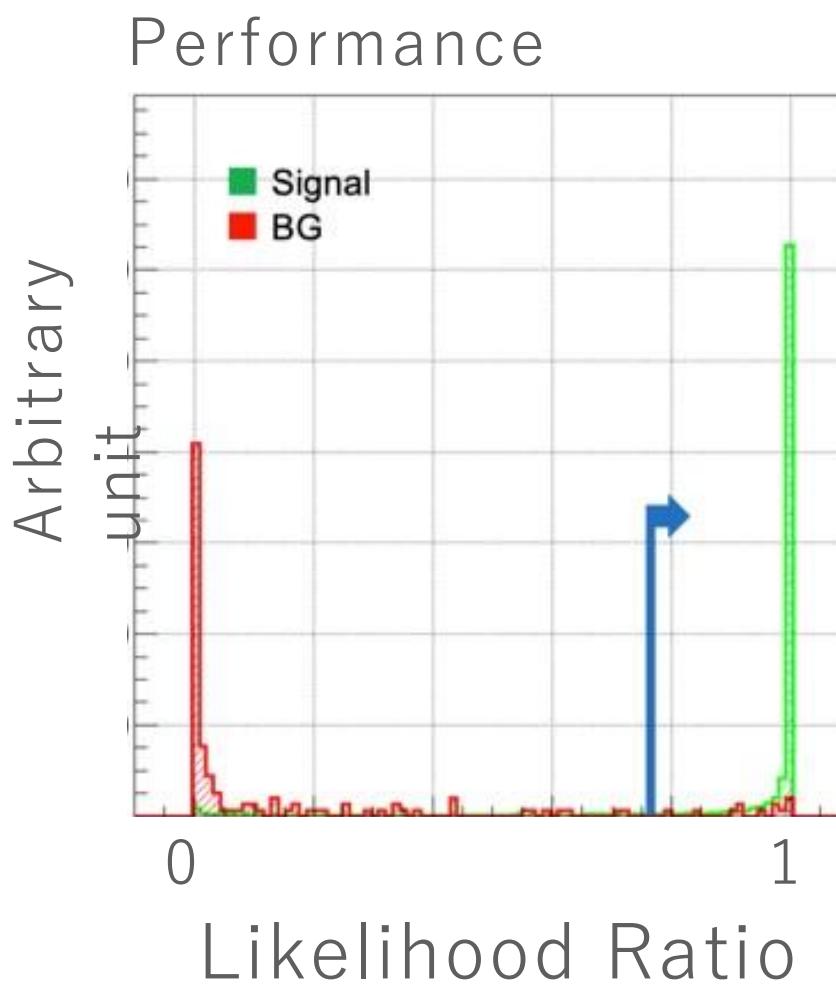
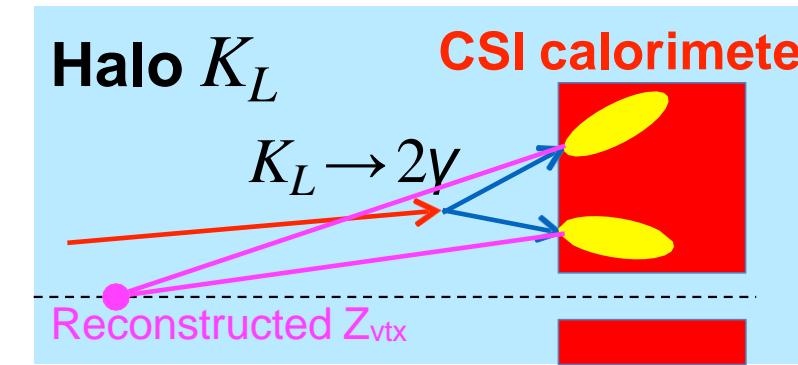
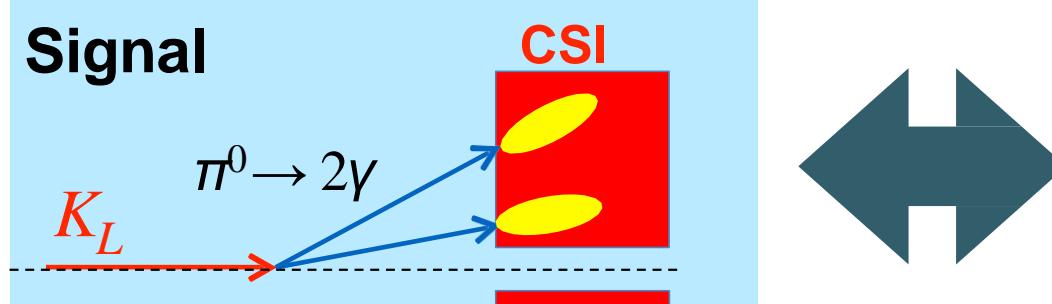


- Developed new cuts based on the difference of kinematical distributions or shower shape to reduce the Halo $K_L \rightarrow 2\gamma$ BG

New cuts against Halo $K_L \rightarrow 2\gamma$ BG

Signal efficiency : 95%
BG rejection : x0.1

- Shower shape consistency
 - Likelihood Ratio
- Multi variable Analysis with kinematical variables
 - Input variables Blue:signal Red:Halo $K_L \rightarrow 2\gamma$



Status of 2021 data set analysis

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

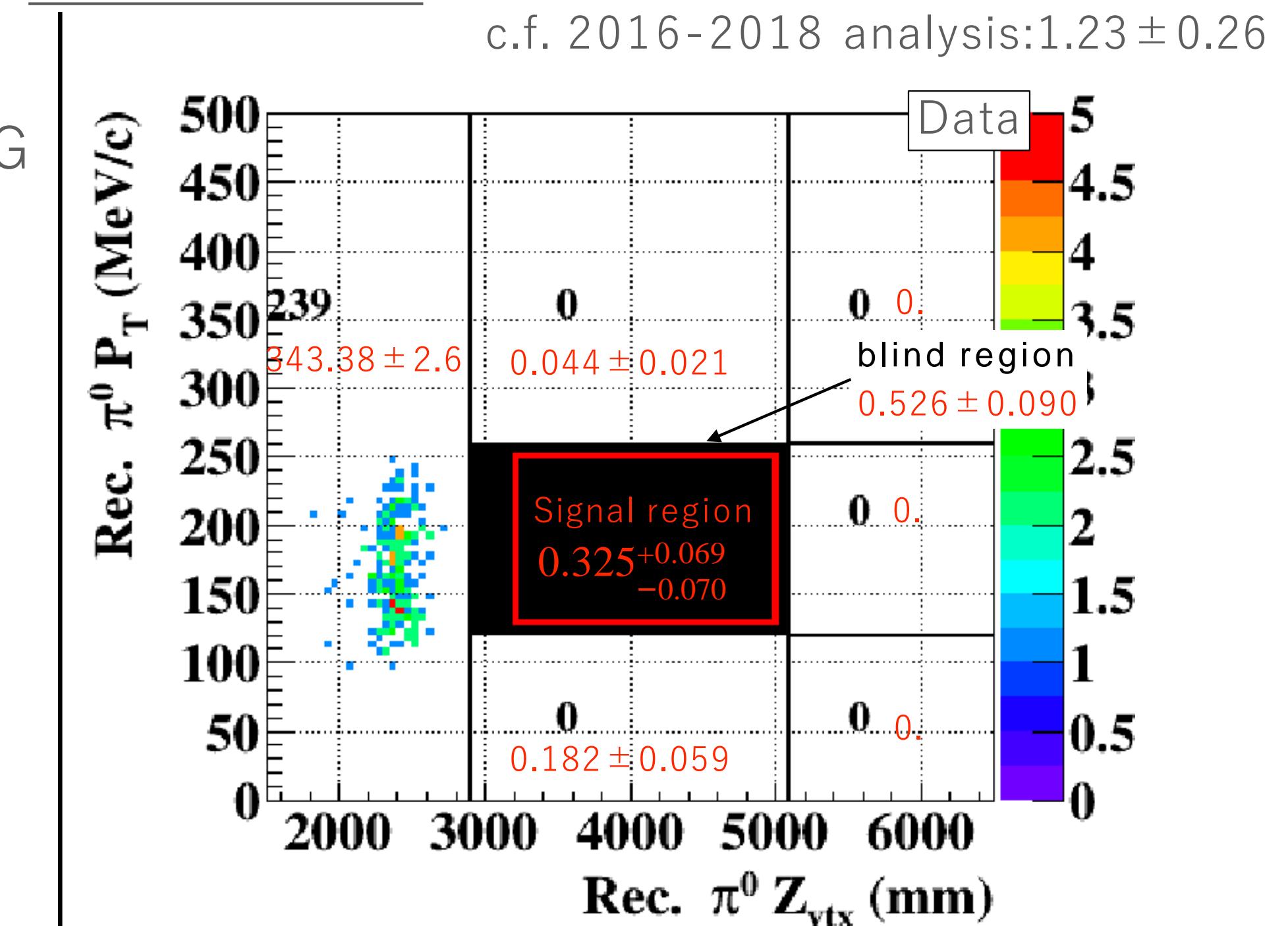
-High statistics, UCV was installed against K^\pm BG

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

c.f. 2016-18 analysis: 7.2×10^{-10}

source	#BG in the signal box
$K_L \rightarrow 2\pi^0$	0.141 ± 0.059
K^+	$0.043^{+0.016}_{-0.022}$
Hadron cluster BG	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 in CV	0.023 ± 0.010
Upstream π^0	0.02 ± 0.02
$K_L \rightarrow 3\pi^0$	0.019 ± 0.019
Sum	$0.325^{+0.069}_{-0.070}$

BG Estimation



Black:Data

Red:Estimation

-0.33 in the signal region

-0.53 in the blind region

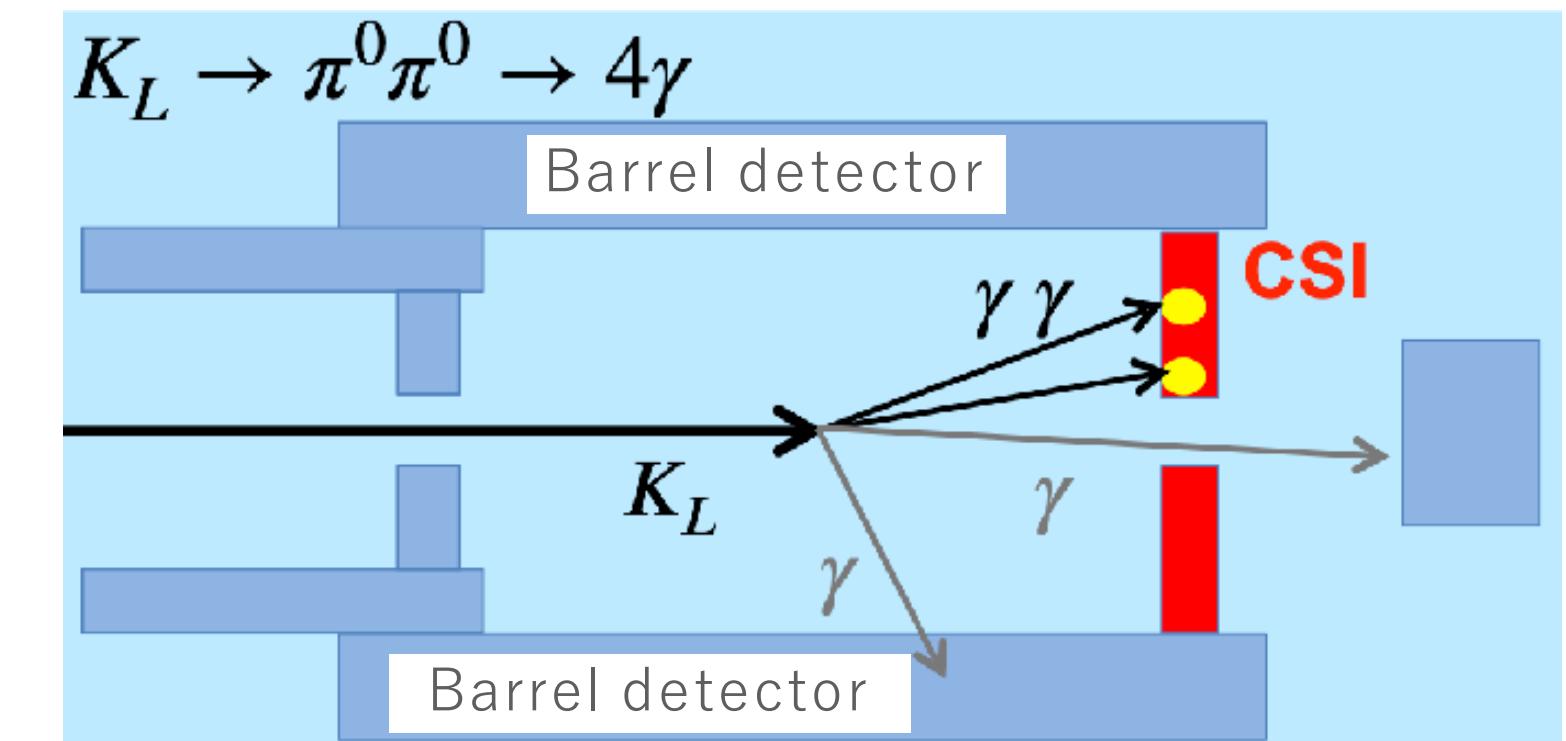
Issues on $K_L \rightarrow 2\pi^0$ BG

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

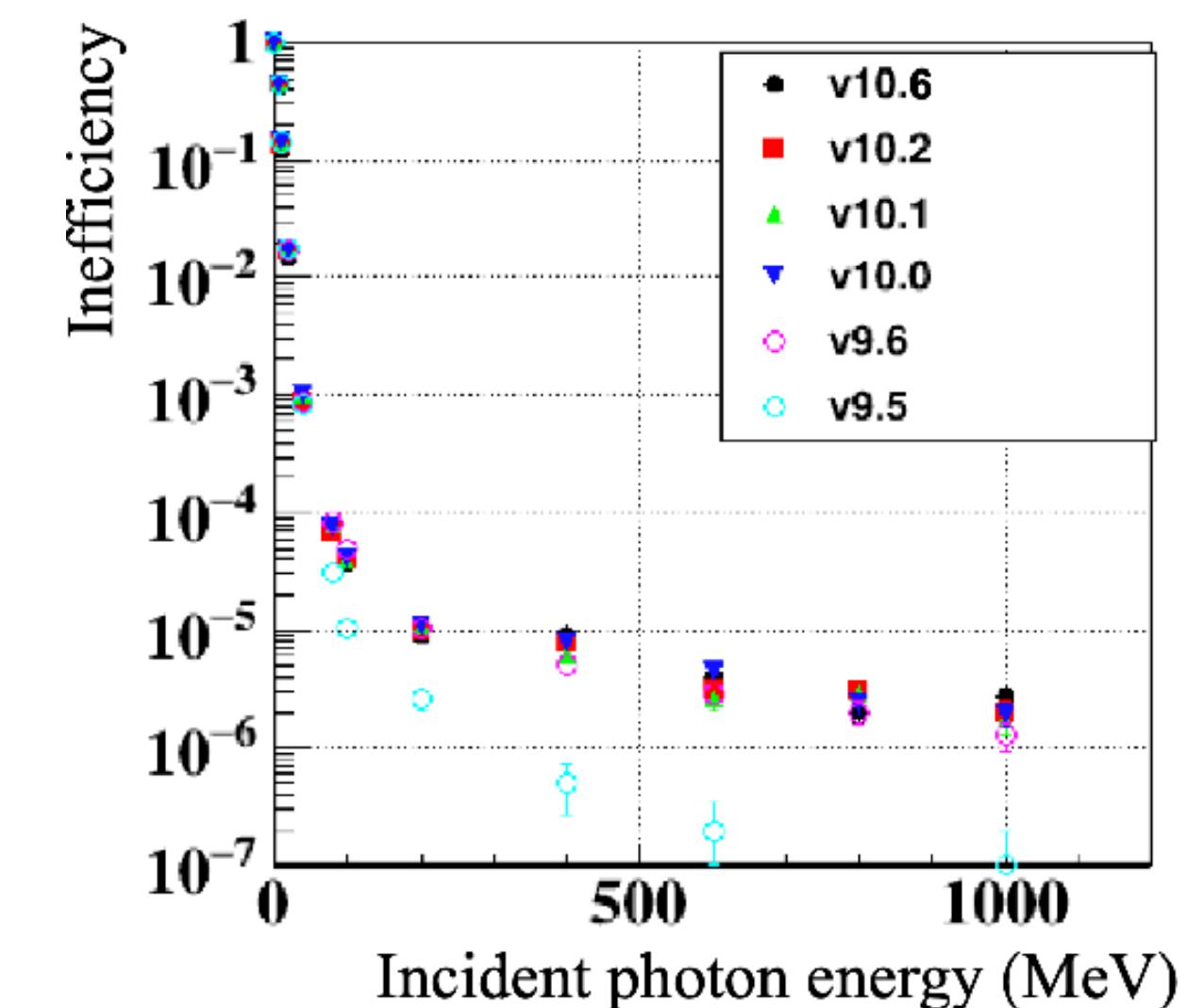
$$\text{BGL} = \#\text{BG} \times (\text{S.E.S})$$

	2016-2018 ana (Geant4 9.5.2)	2021 ana (Geant4 10.6.2)
BGL for $K_L \rightarrow 2\pi^0$	$<0.6 \times 10^{-10}$ @ 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

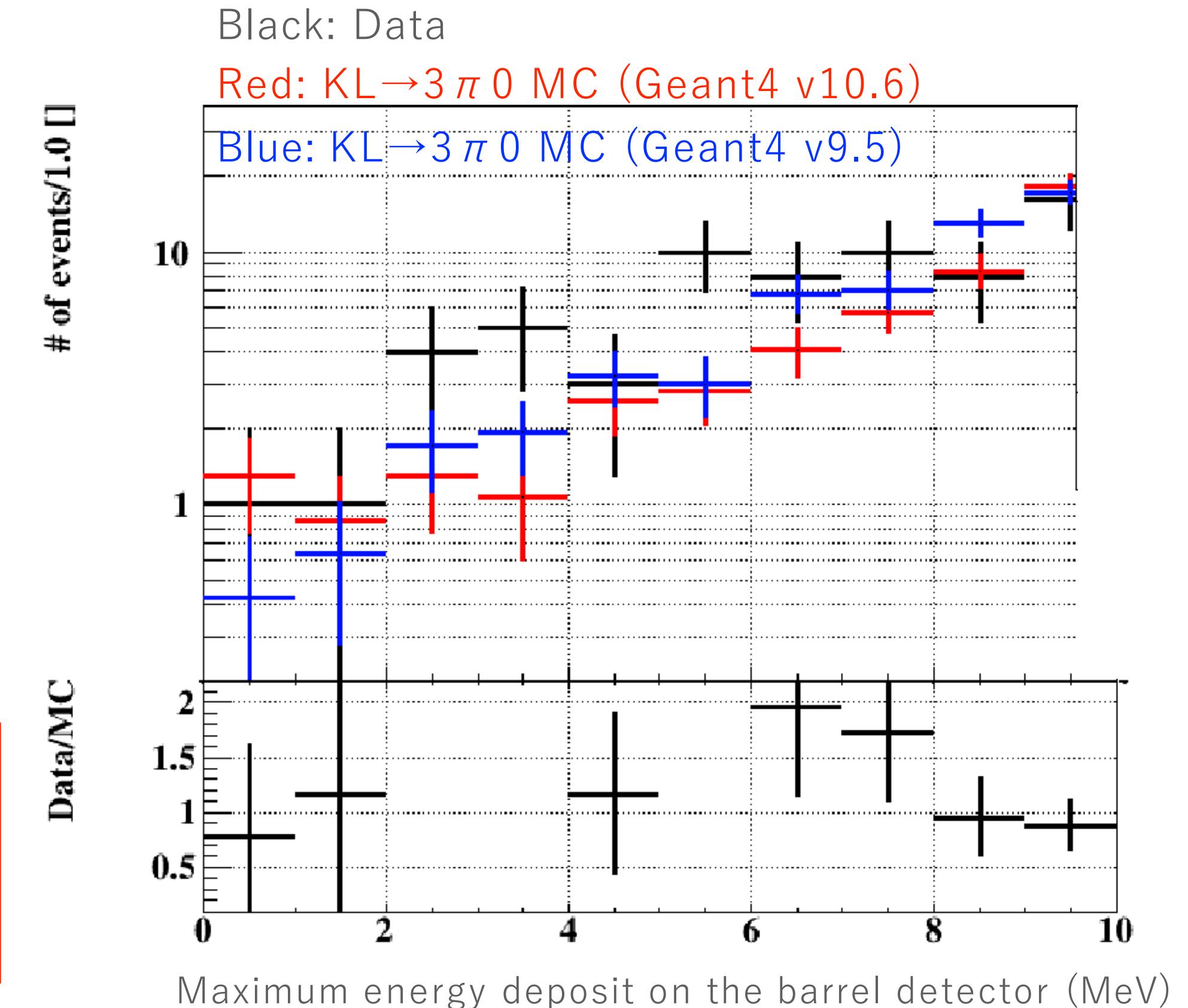


Inefficiency evaluation with 5 γ data 6 th γ with high energy into barrel detector

Reconstructed $E_{\gamma_6} > 200\text{MeV}$
Destination: Barrel detector

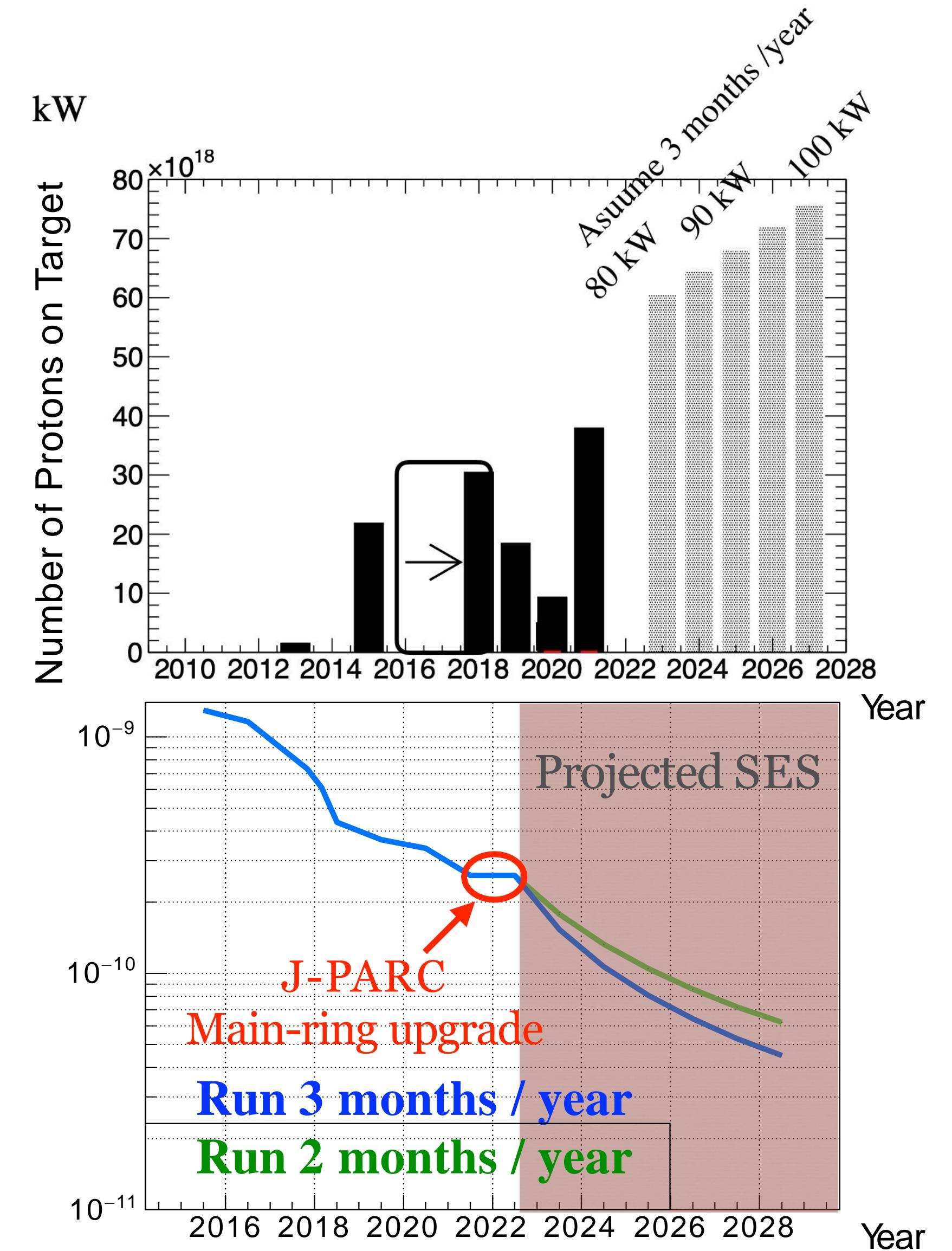
- For 1 MeV threshold
 - $\text{Ineffi}_{\text{Data}} = (4.8 \pm 4.8) \times 10^{-5}$
 - $\text{Ineffi}_{\text{MC}} = (6.2 \pm 2.5) \times 10^{-5}$ (for v10.6)
 $= (2.1 \pm 1.5) \times 10^{-5}$ (for v9.5)
 - Purity $\approx 100\%$

-Need more statistics to distinguish the version difference.
-The systematic uncertainties will be accounted to be $\sim 100\%$.



Prospects

- **2021-2022 Accelerator Shutdown**
 - Main-ring power supply upgrade.
 - Beam power $64\text{kW} \rightarrow 80\text{-}100\text{kW}$.
- **Will resume data-taking from May, 2023**
- **By 2027, with 2-3 month run per year**
 - Expect to collect $\times 11$ more data.
 - S.E.S. can reach below $O(10^{-10})$.



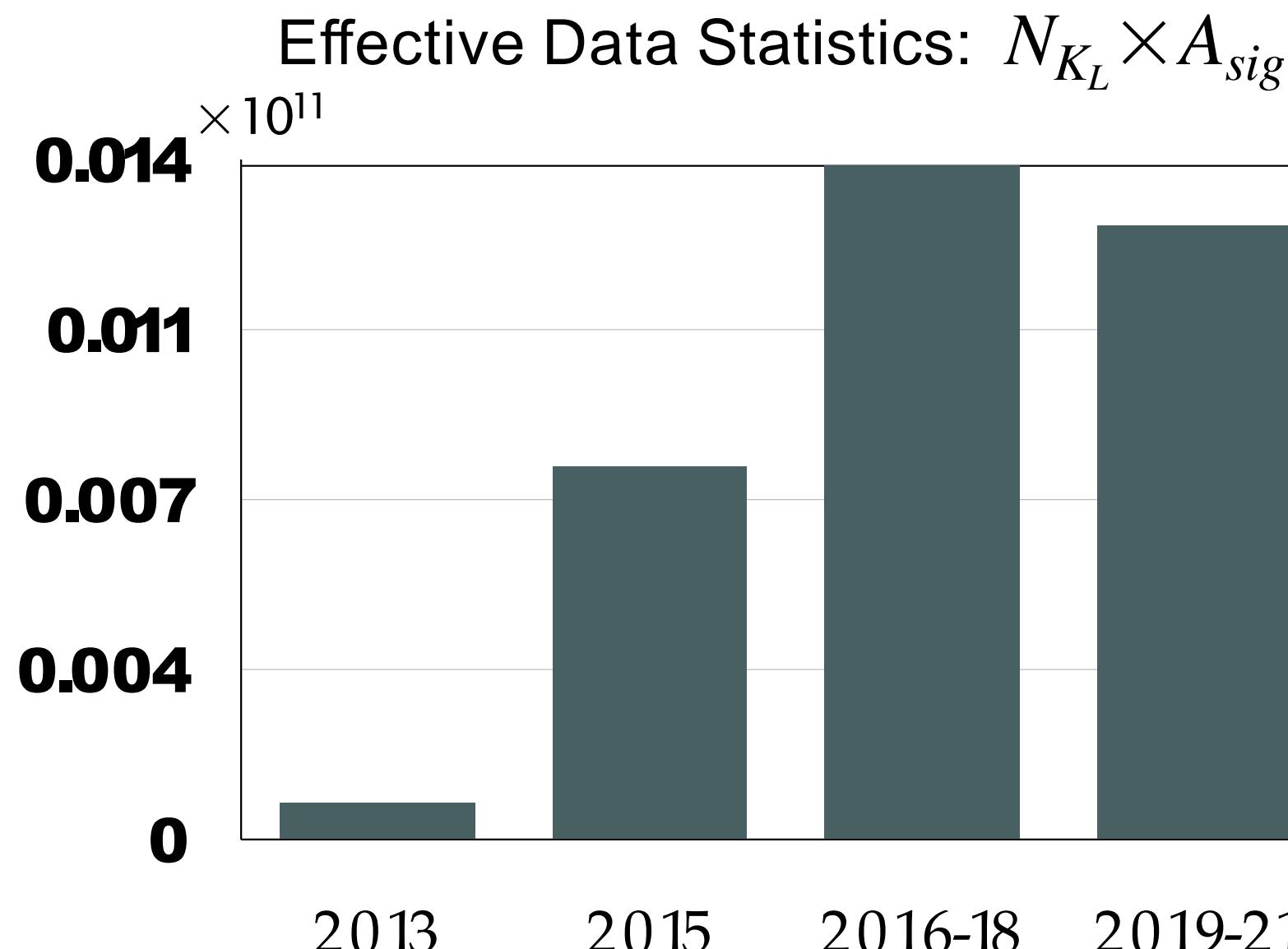
Run History and Results

2013 data: 100h run, interrupted by radiation accident. [PTEP.2017.021C01]

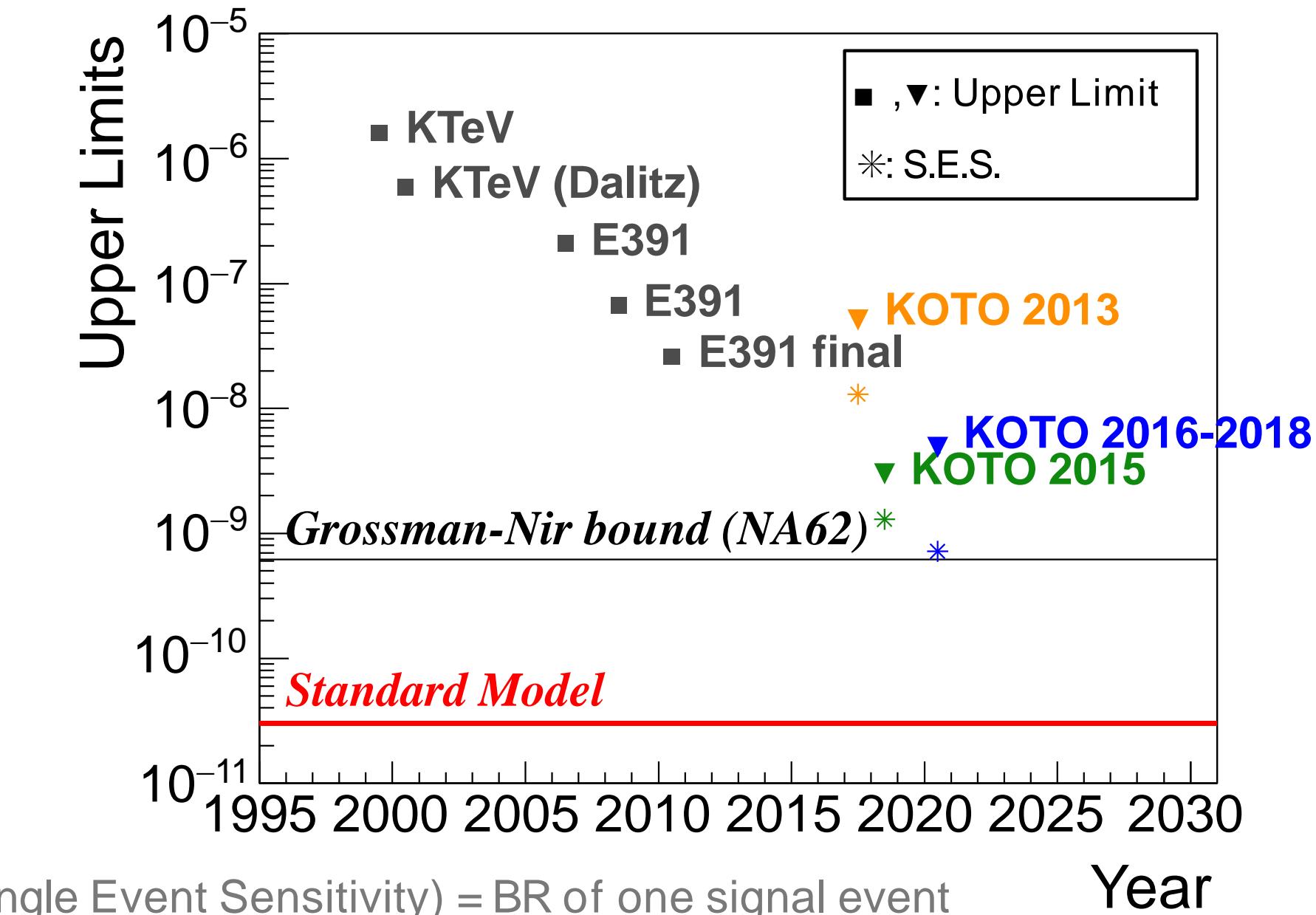
2015 data: set the current best limit on $B(K_L \rightarrow \pi^0 \nu \bar{\nu})$. [PRL.122.021802]

2016-2018 data: recent results with new background sources. [PRL.126.121801]

2019-2021: analysis in progress.

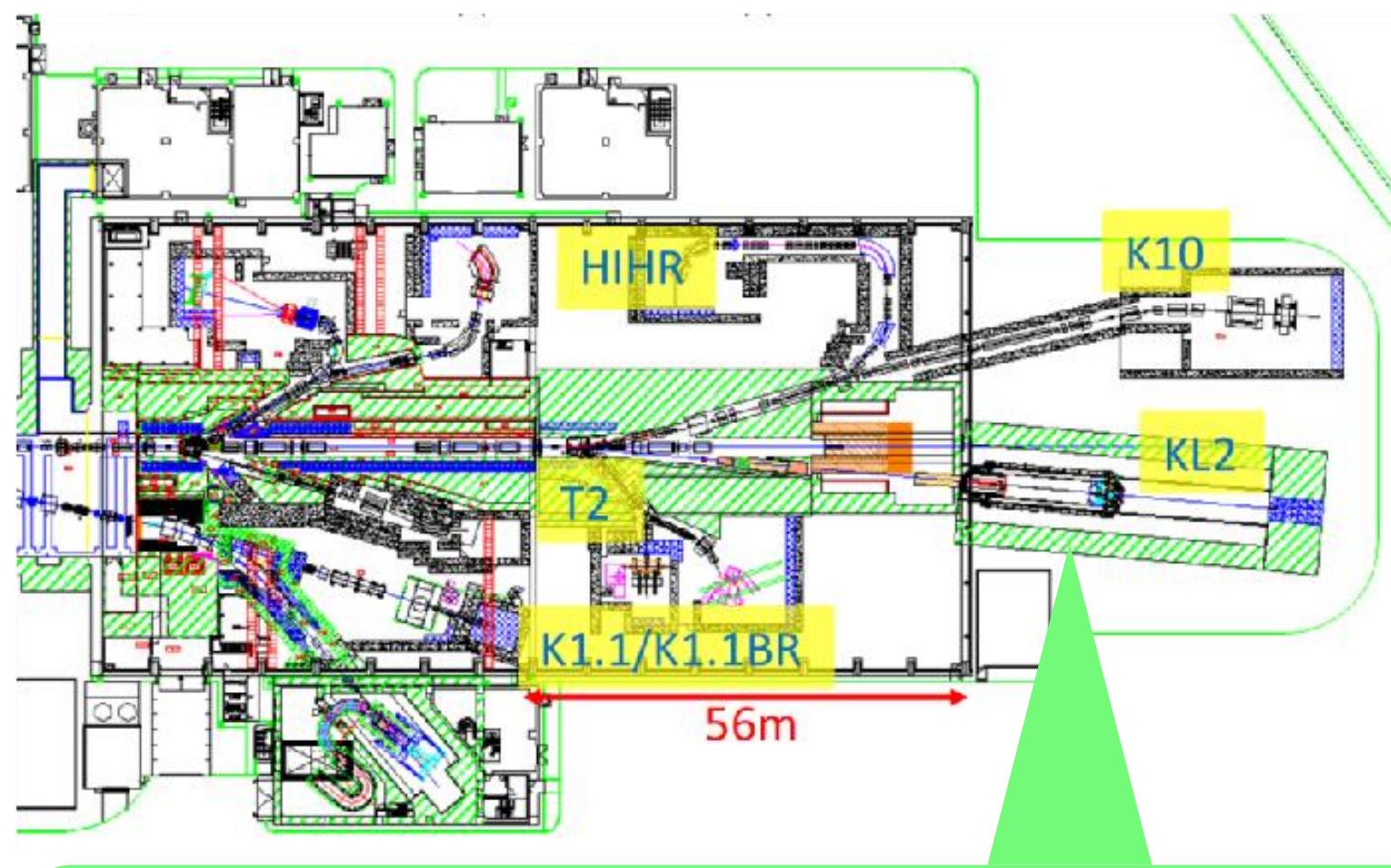


First limit: 1992, SES $\sim 1.0 \times 10^{-4}$



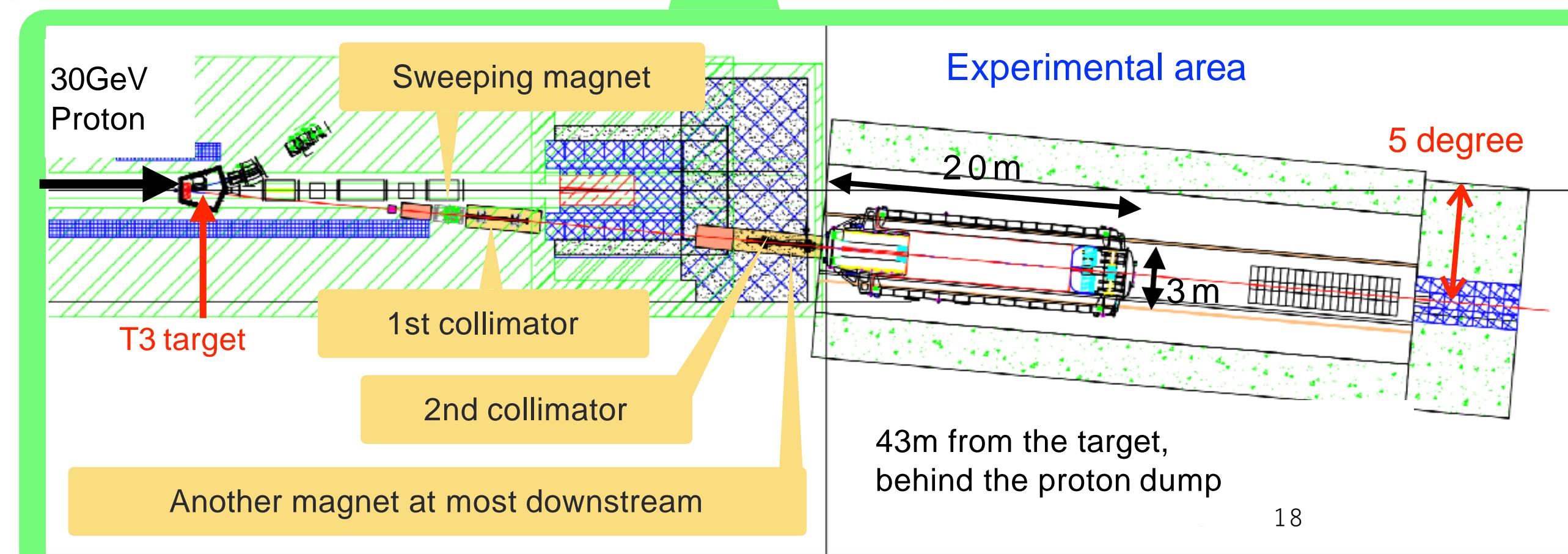
KOTO-II

KOTO I with extension of hadron experimental facility



Measure branching ratio of the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay with
-Higher intensity K_L beam
-Larger detector

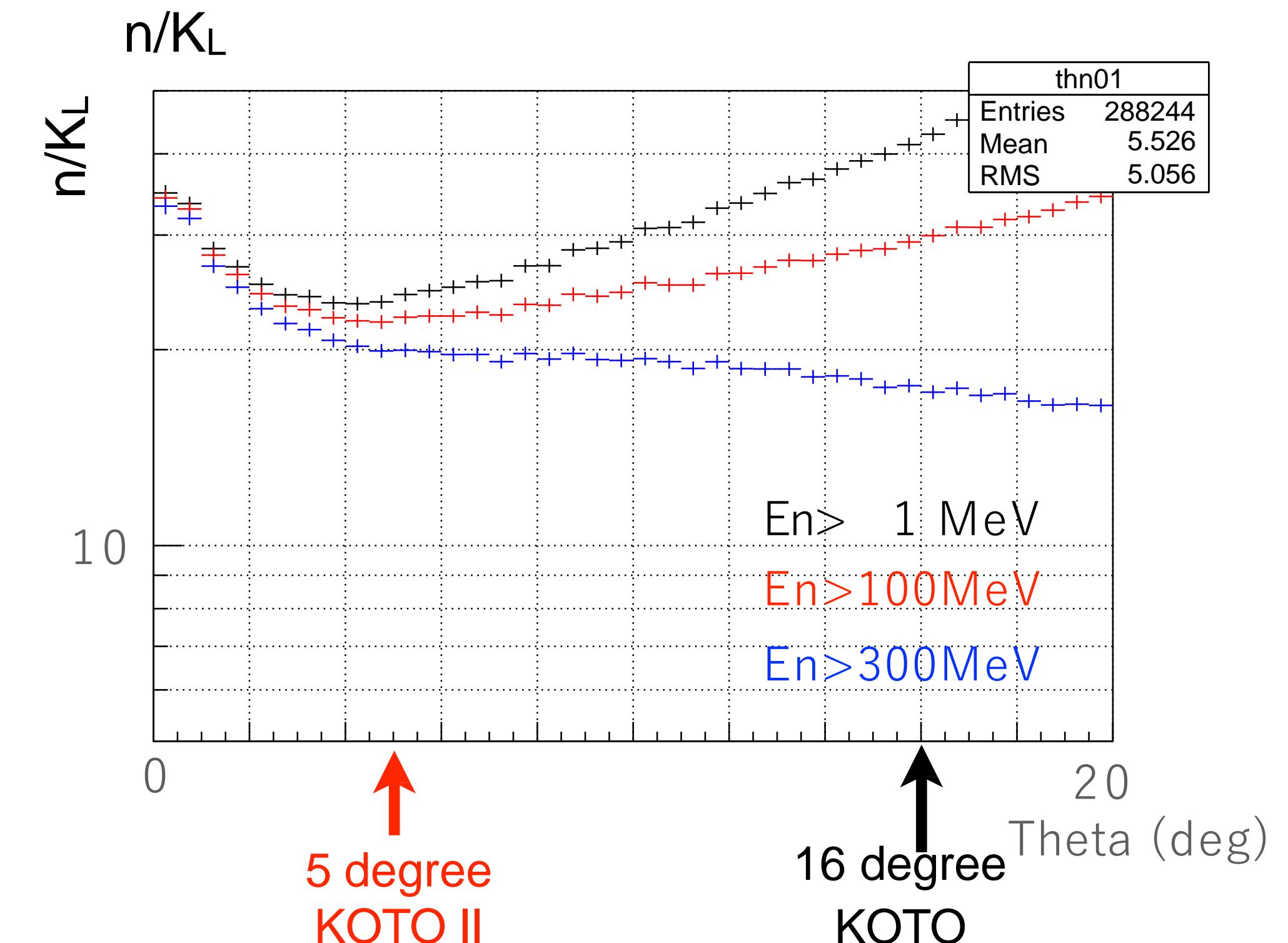
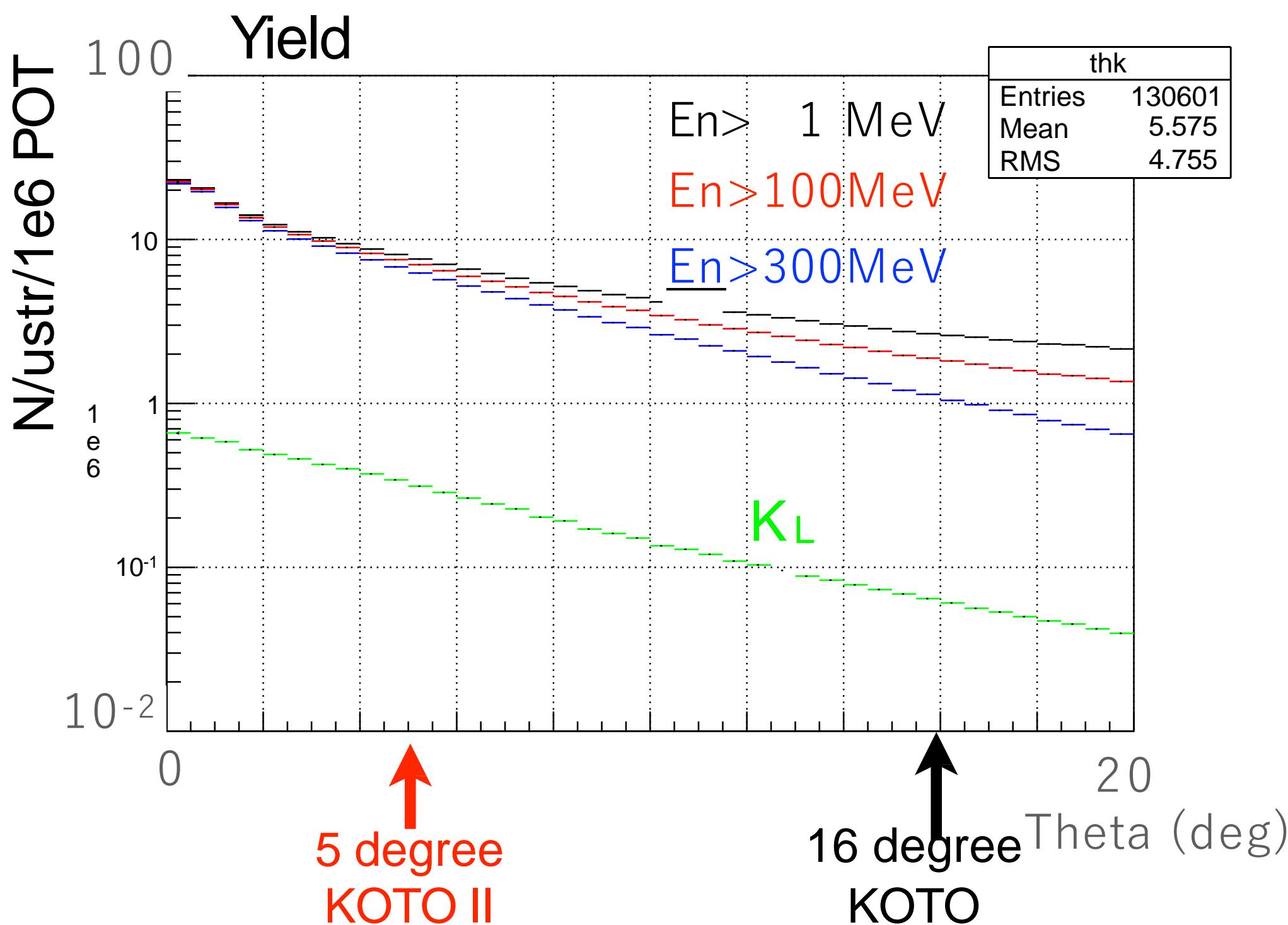
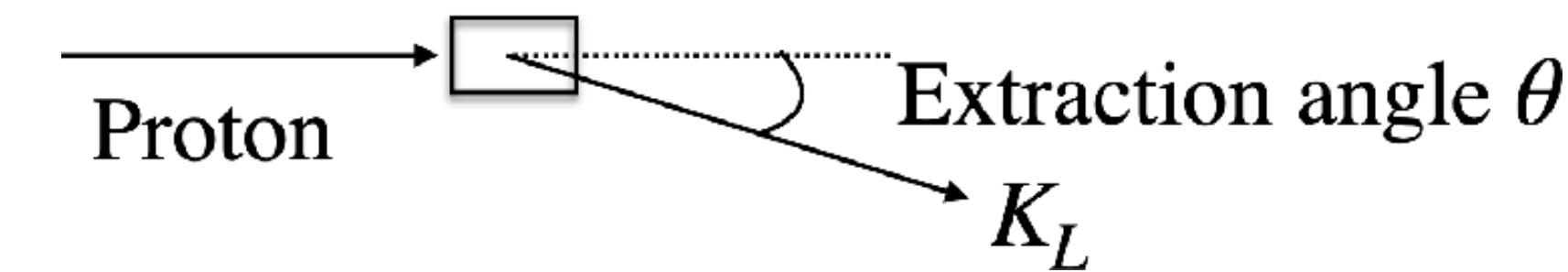
- ~50 SM events for 3×10^7 s run time with 100kW beam
- Signal-to-background ratio ~ 0.4



- $\text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \simeq \text{SM}$
 $\rightarrow \sim 5\sigma$ discovery
- $|\text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu}) - \text{SM}|/\text{SM} > 40\%$
 \rightarrow Indication of new physics

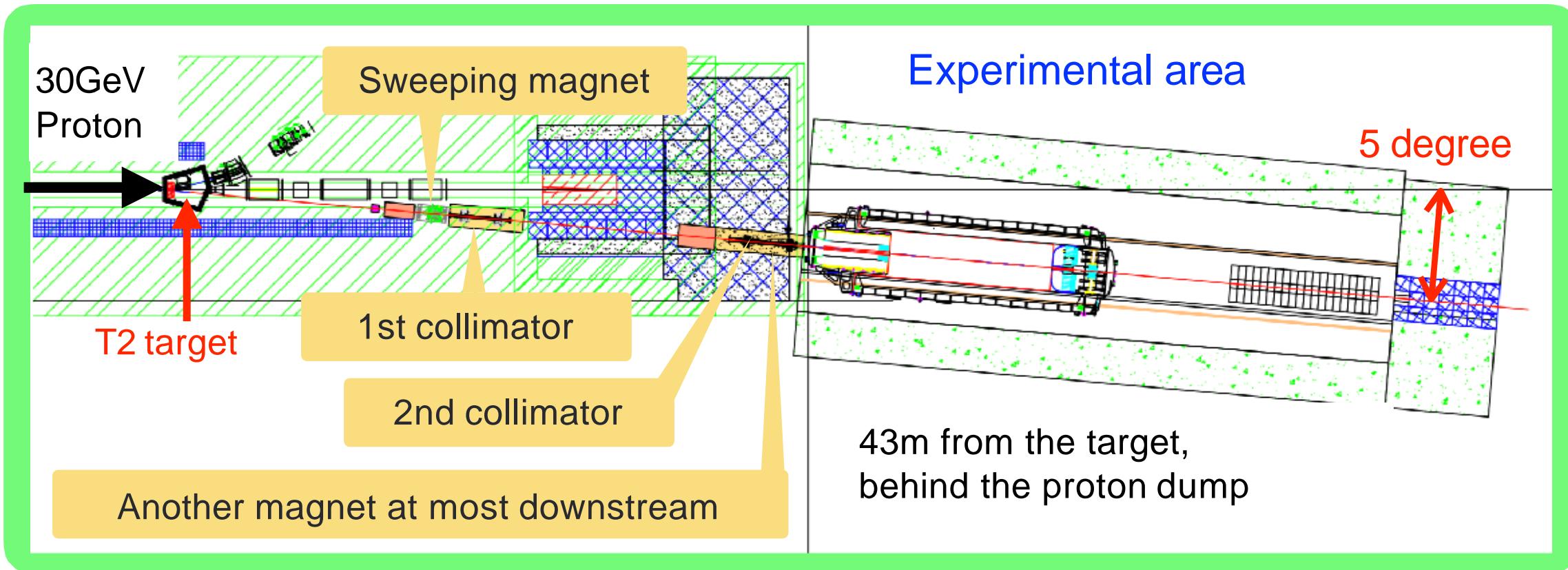
A new KL beam line

KL yield dependence on extraction angle

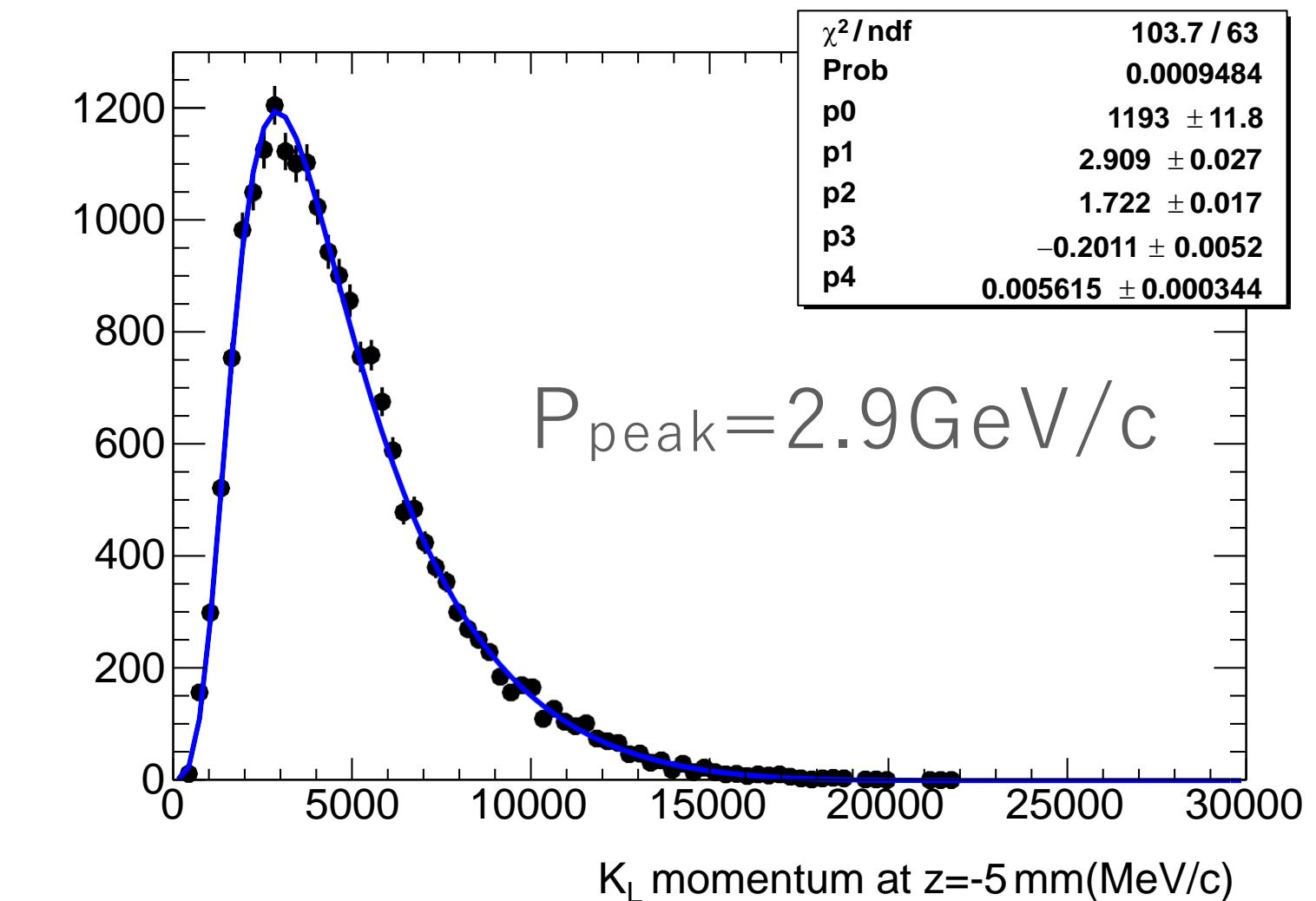


A new KL beam line

Basic design



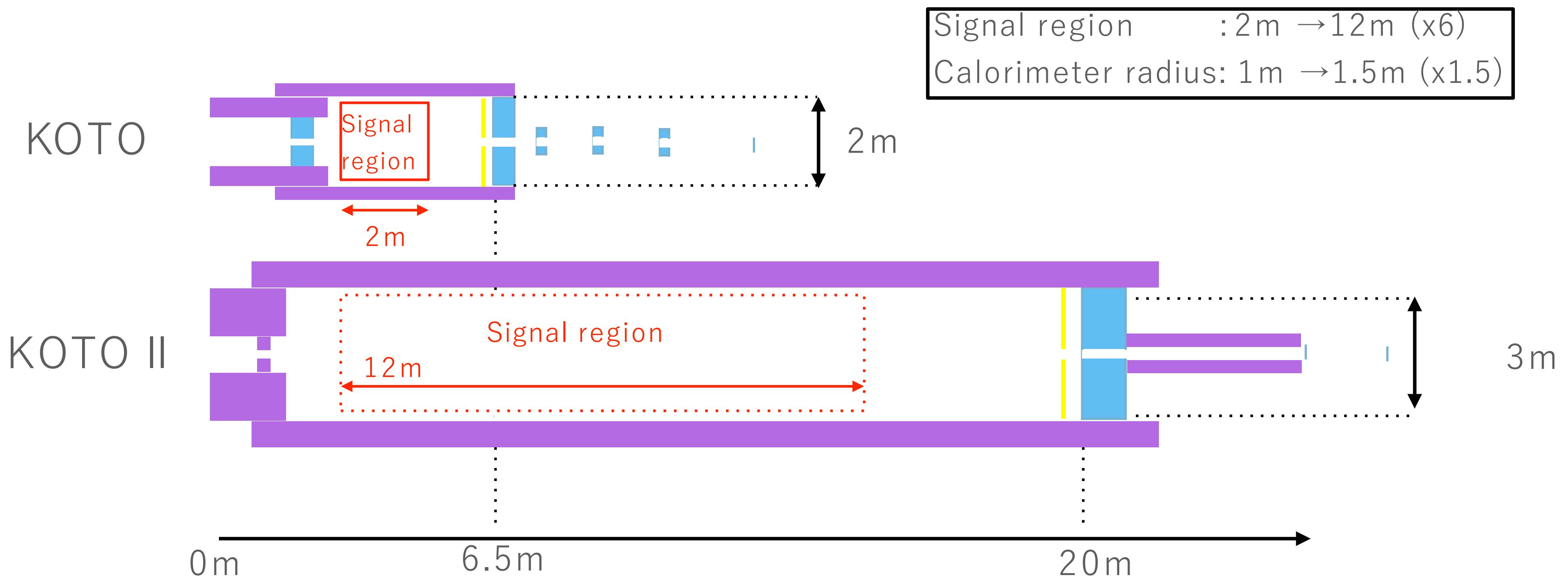
- 5 degree production
- The beam line length is 43m.
- KOTO II area is located behind the beam dump.



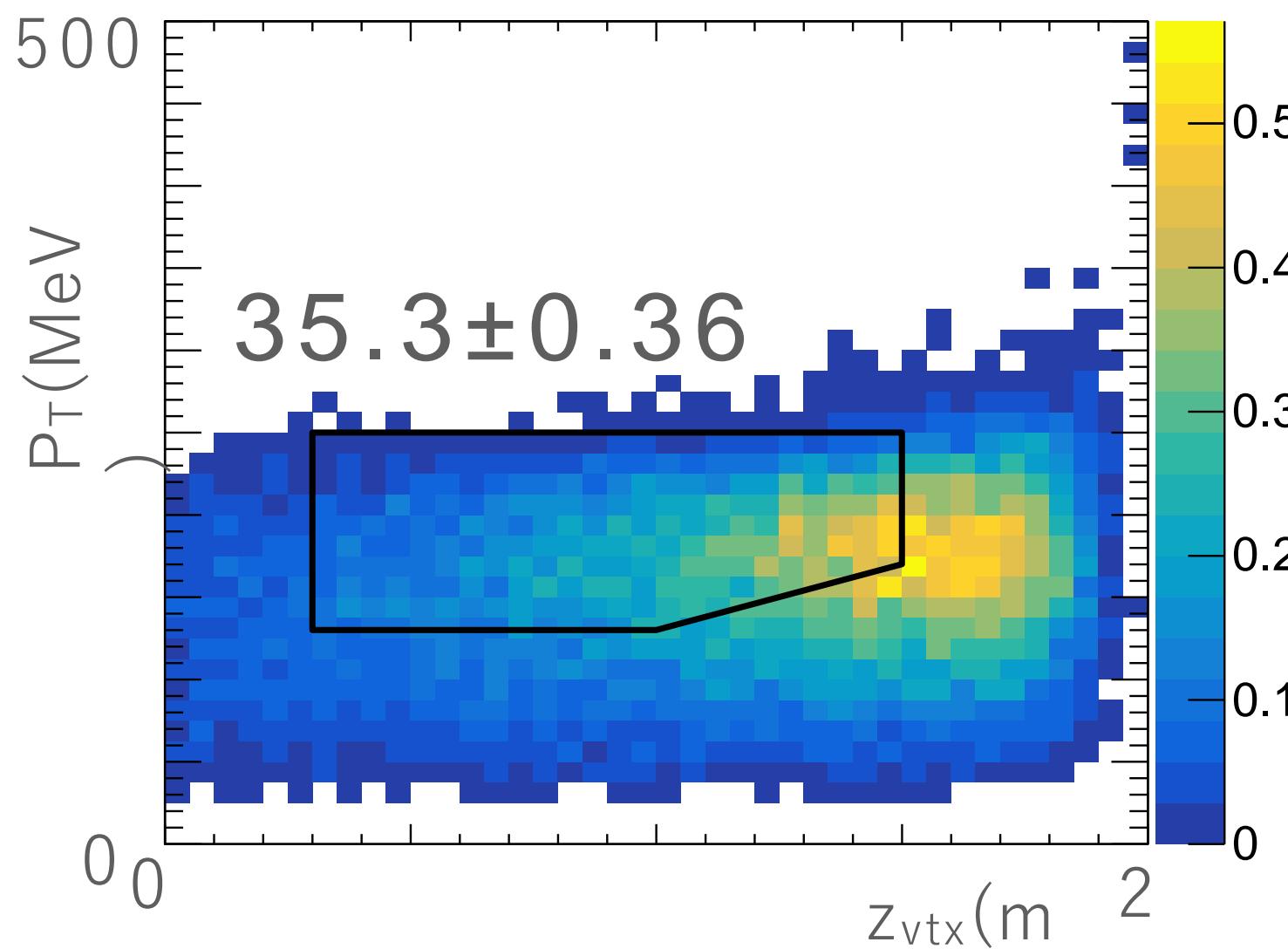
	KOTO	KOTO II	Gain for K_L yield
Production Angle	16 degree	5 degree	x5
Beam line Length	20m	43m	x0.8
Solid angle	$7.8 \mu \text{sr}$	$4.8 \mu \text{sr}$	x0.6

$N(K_L) = 4.8 \times 10^7 / \text{spill} @ 100 \text{kW beam on T2 Target}$
→ x 2.6 higher than KOTO (per POT)

Detector for KOTO II



Signal acceptance

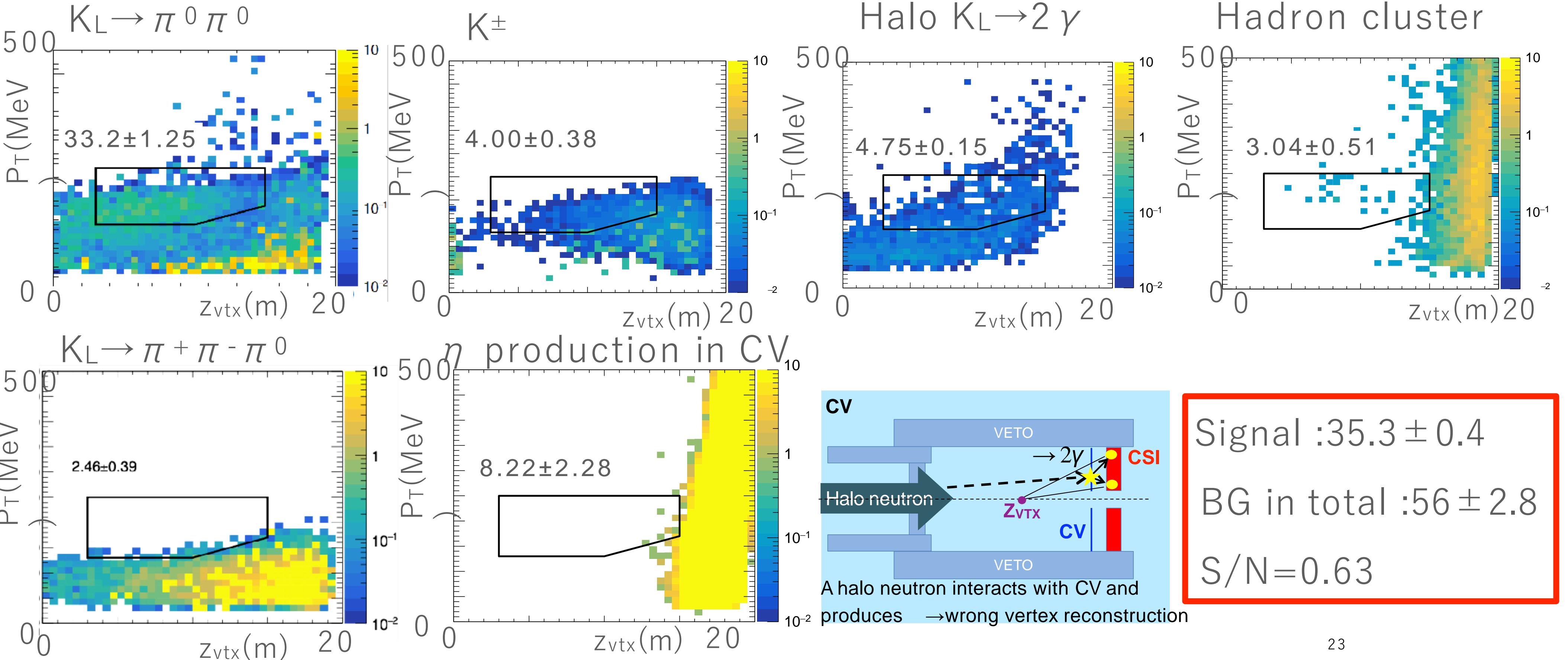


- Beam power: 100kW at T2 target
- KL yield: $4.8 \times 10^7/\text{spill} \rightarrow \times 2.6$ from KOTO (per POT)
- Data taking : 3 Snowmass years (3×10^7 s)

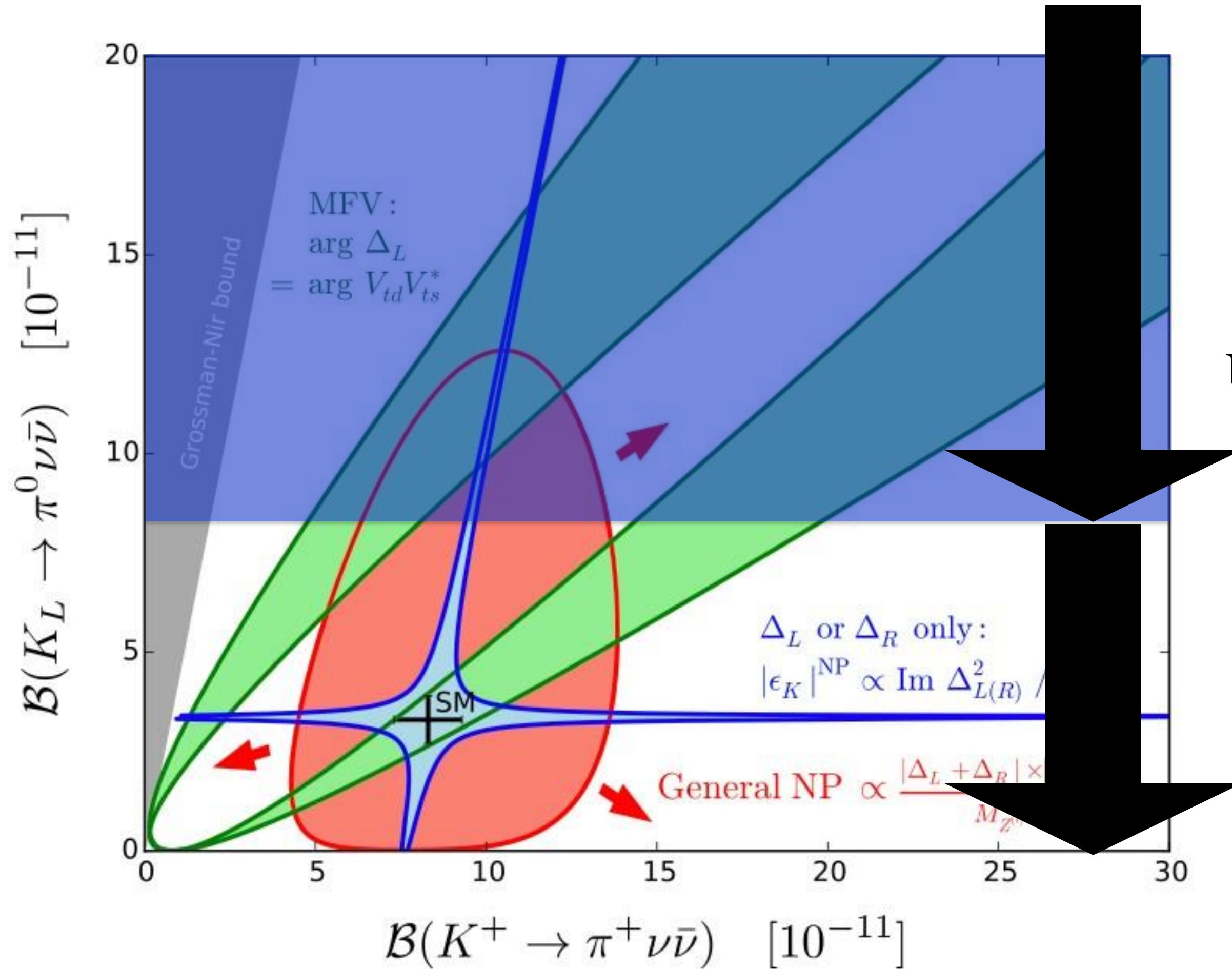
	Decay Probability	Geometrical Acceptance	Cut efficiency	1- Accidental loss	1-Backsplash loss
KOTO II Efficiency	10%	24%	26%	61%	91%
KOTO Efficiency Improvement factor	3.3%	26%	3%	36%	50%
	3	0.9	8.7	1.7	1.8

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

BG estimation



Prospects for KOTO to KOTO II



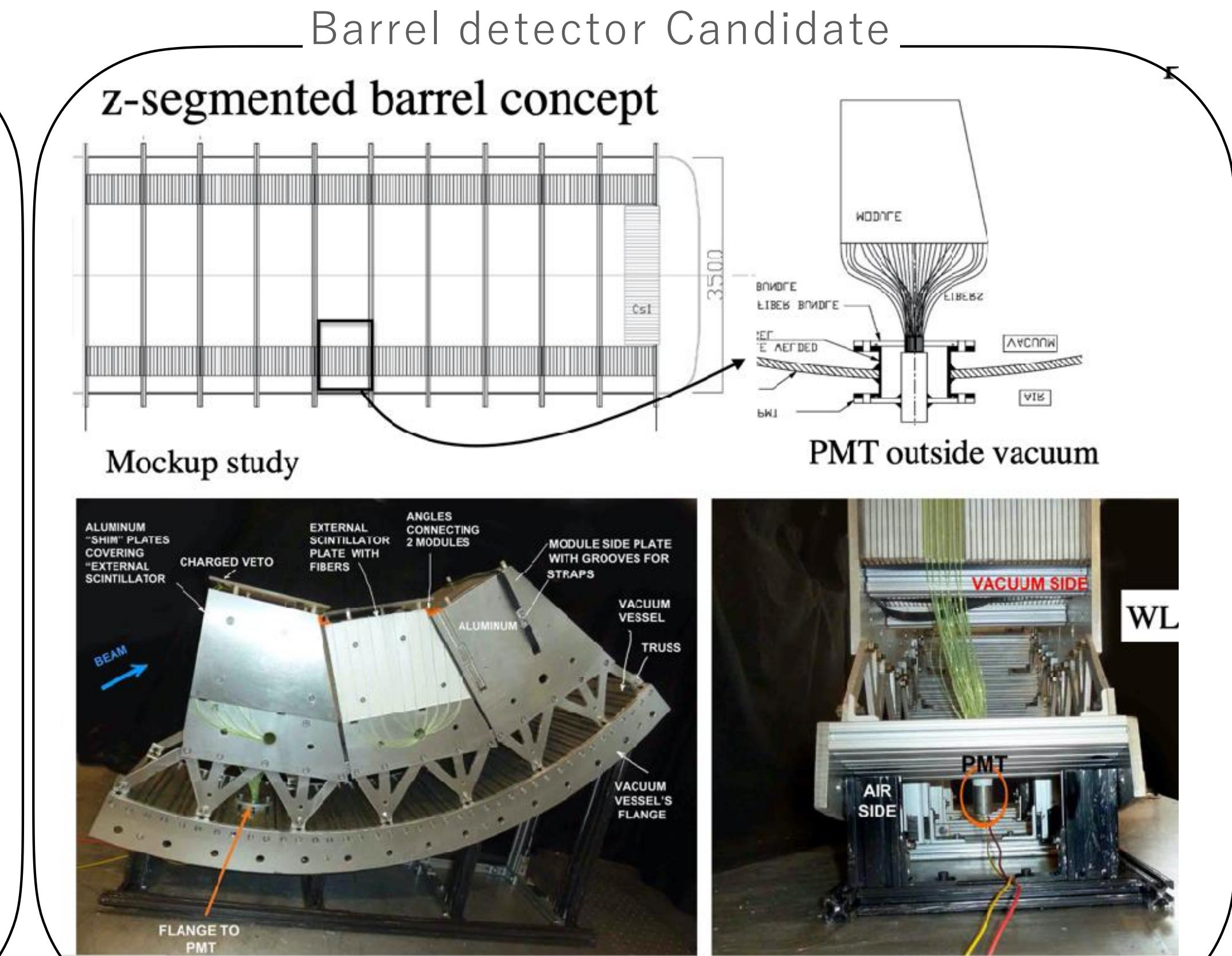
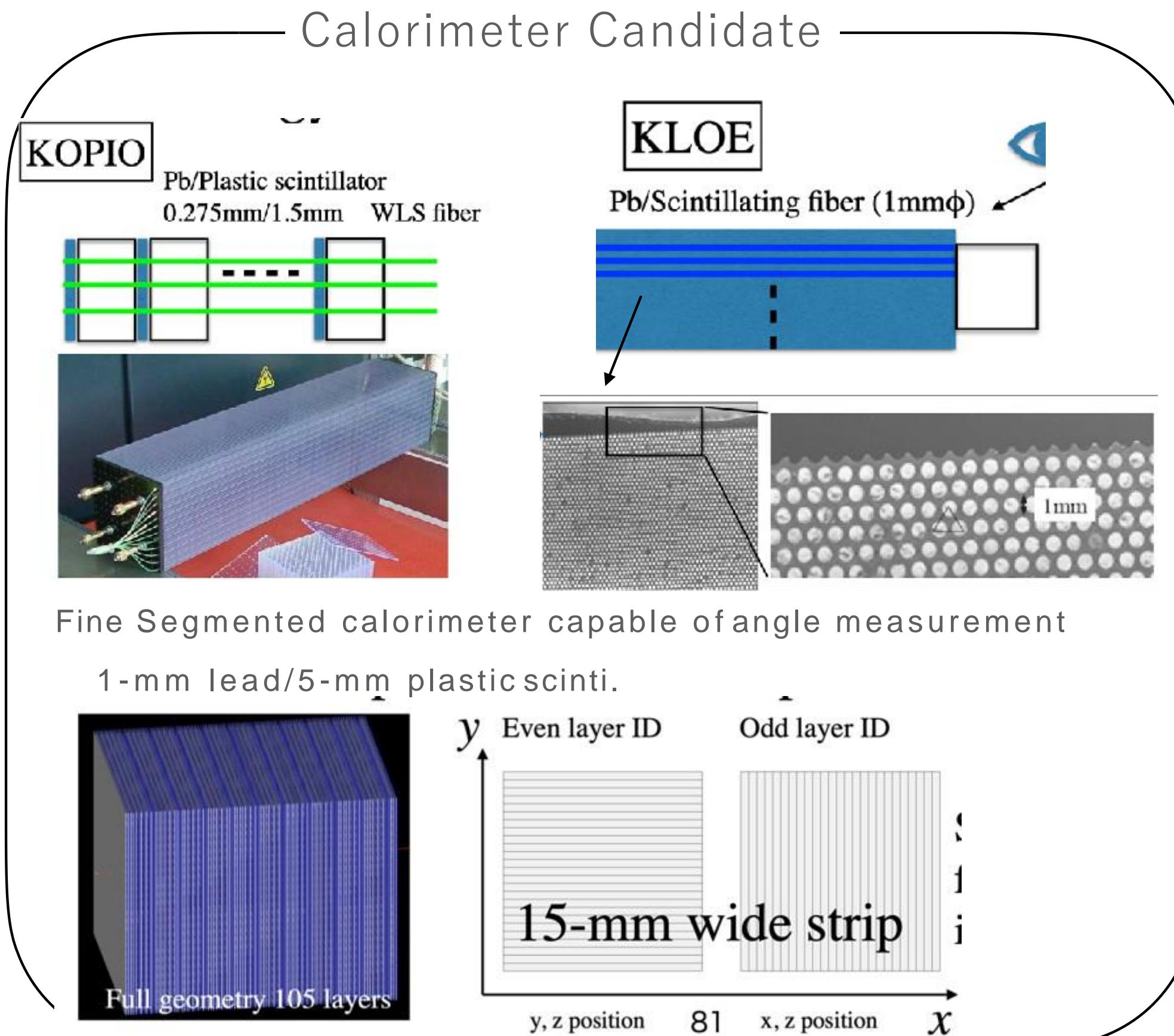
KOTO will reach
 $O(10^{-11})$ sensitivity

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

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

Toward KOTO II

- Detector R&D for the KOTO II experiment is also on going.



Summary

- The $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay is sensitive to New Physics.
- KOTO
 - Currently finalizing the 2021 data analysis;
 - Will reach S.E.S below 10^{-10} in 3-4 years data taking.
- KOTO II
 - Have the potential of 5σ discovery if $\text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu})$ is same as the SM prediction.
 - Detector R&D for KOTO II is on going.