Status and future prospects for rare kaon decay measurements at KOTO(-II)

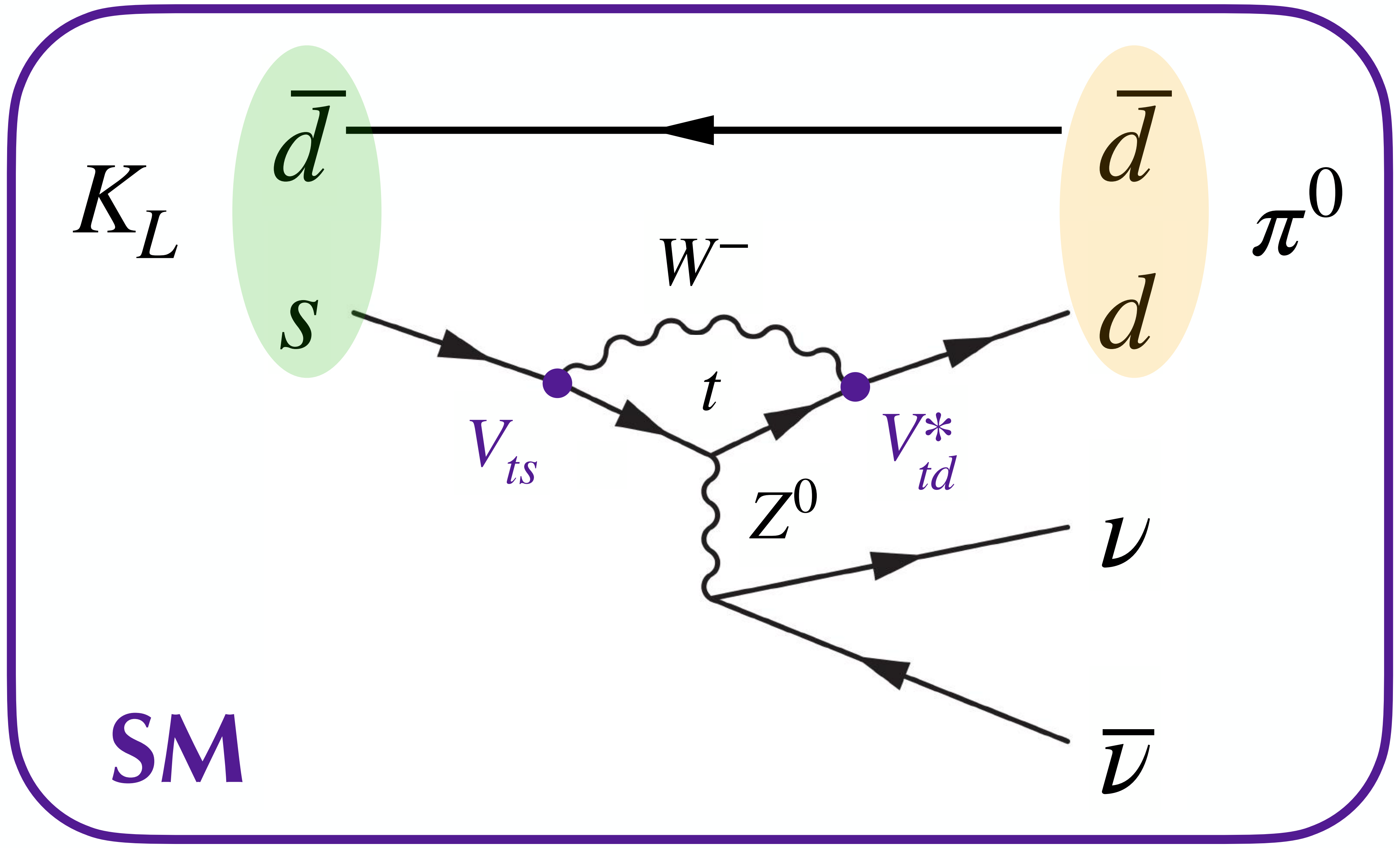
Ryota Shiraishi (KEK)
on behalf of the KOTO collaboration

d s ν ν KOTO

$K_L \to \pi^0 \nu \bar{\nu}$ search

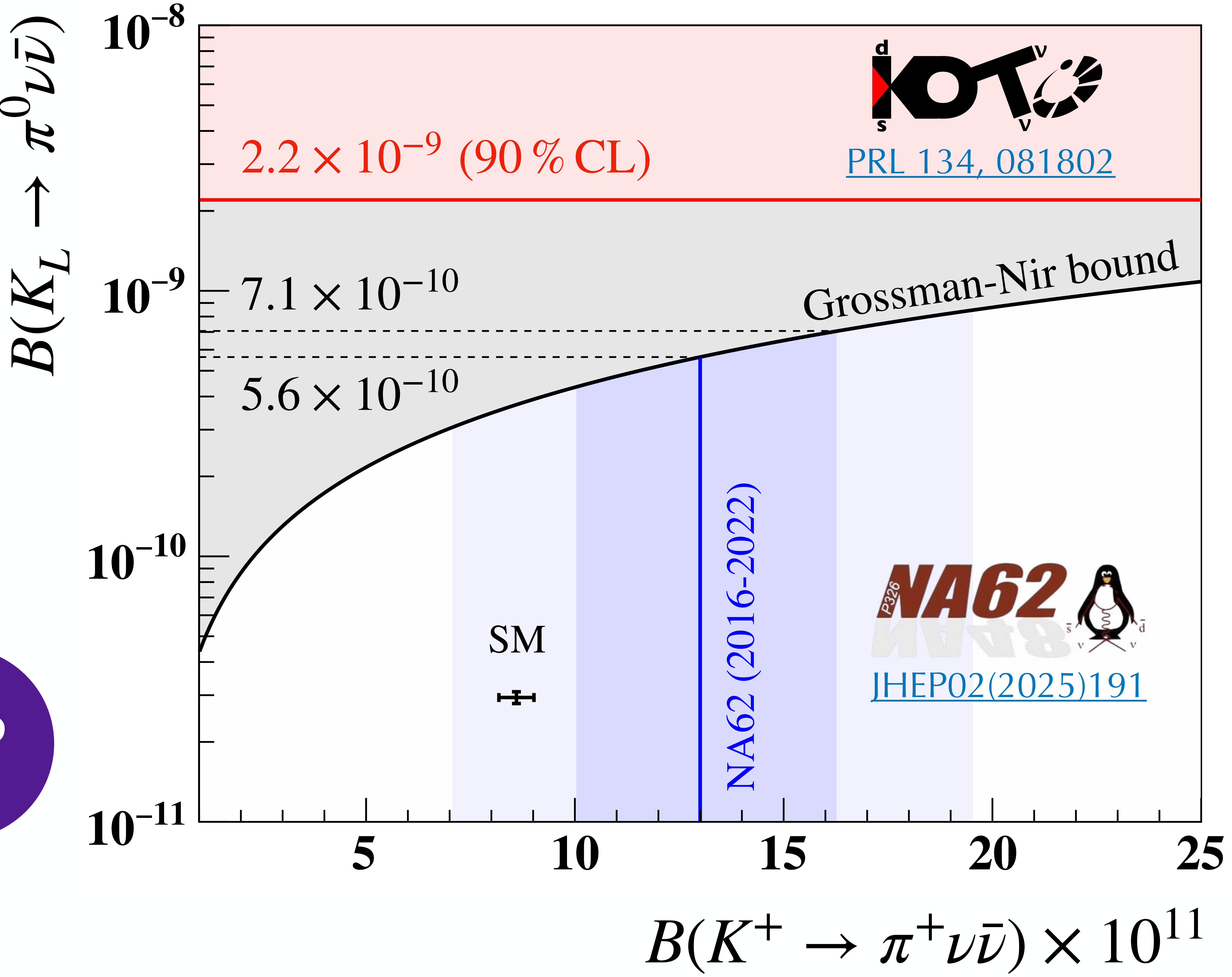
- Direct CP-violating process
- Rare: $B(K_L \to \pi^0 \nu \bar{\nu})_{\text{SM}} = 3 \times 10^{-11}$
- Well known: <2% theoretical uncertainties

  → Good probe to search for New Physics



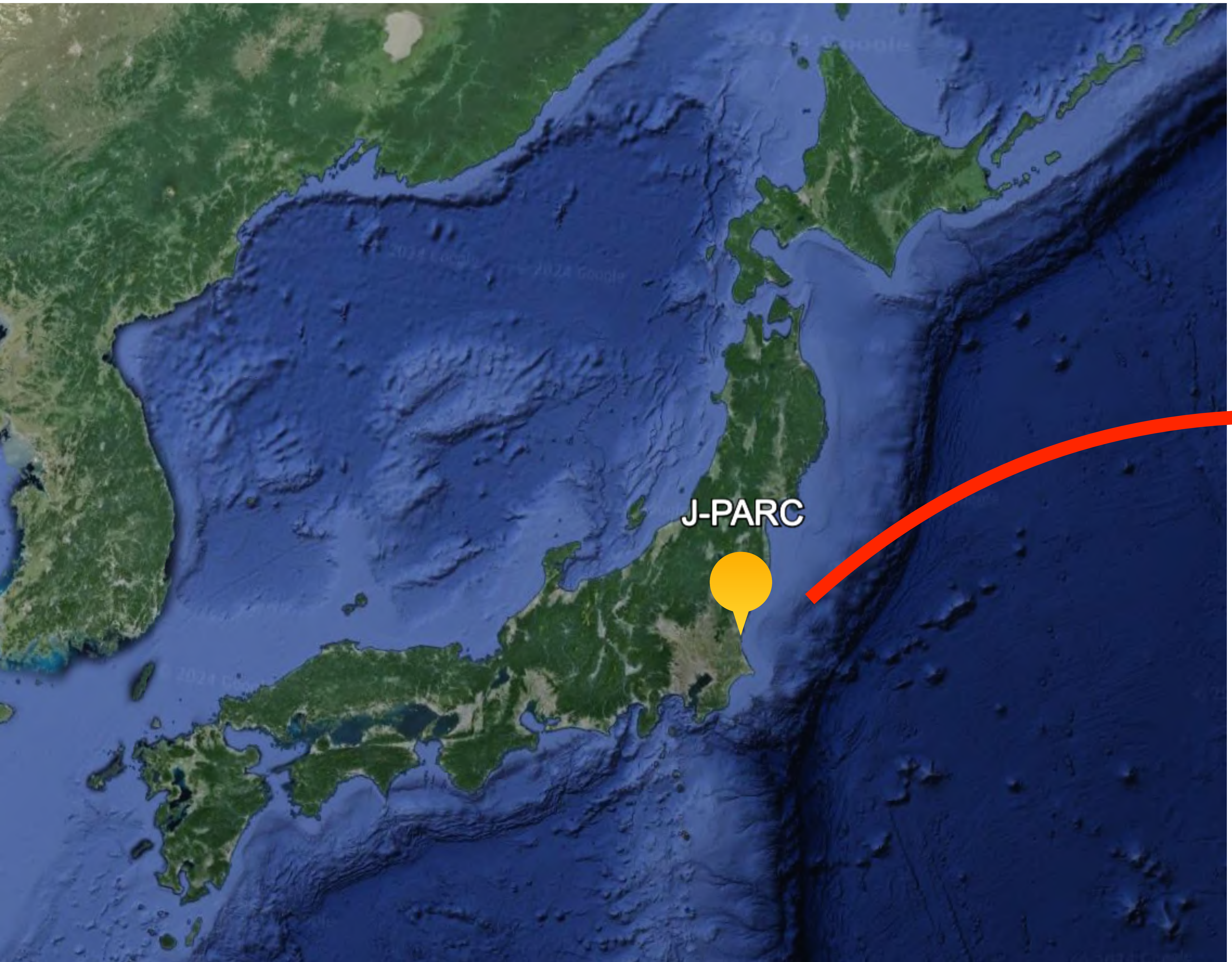
+ NP

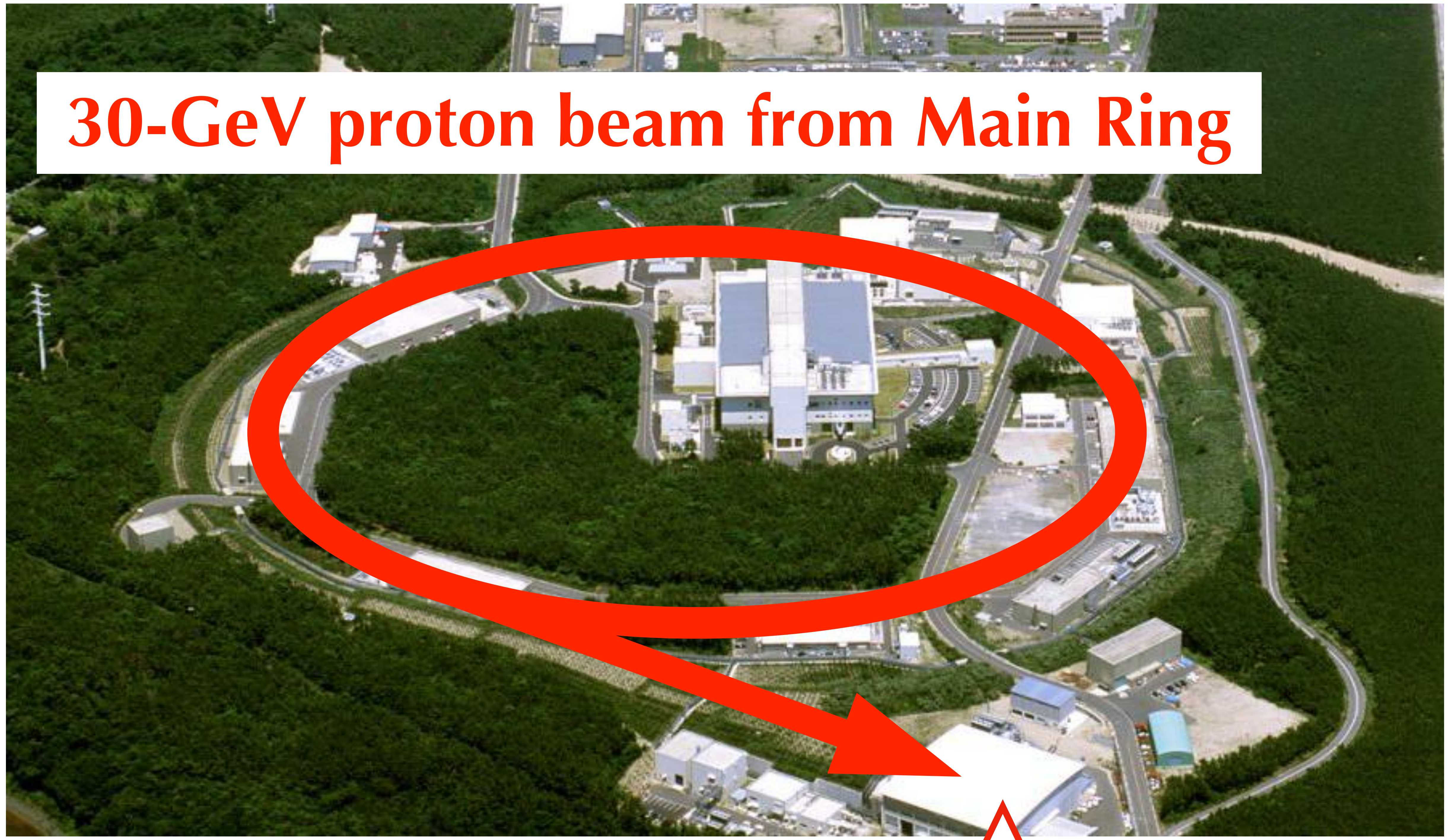
Global status of the $K \to \pi \nu \bar{\nu}$ search



J-PARC KOTO experiment

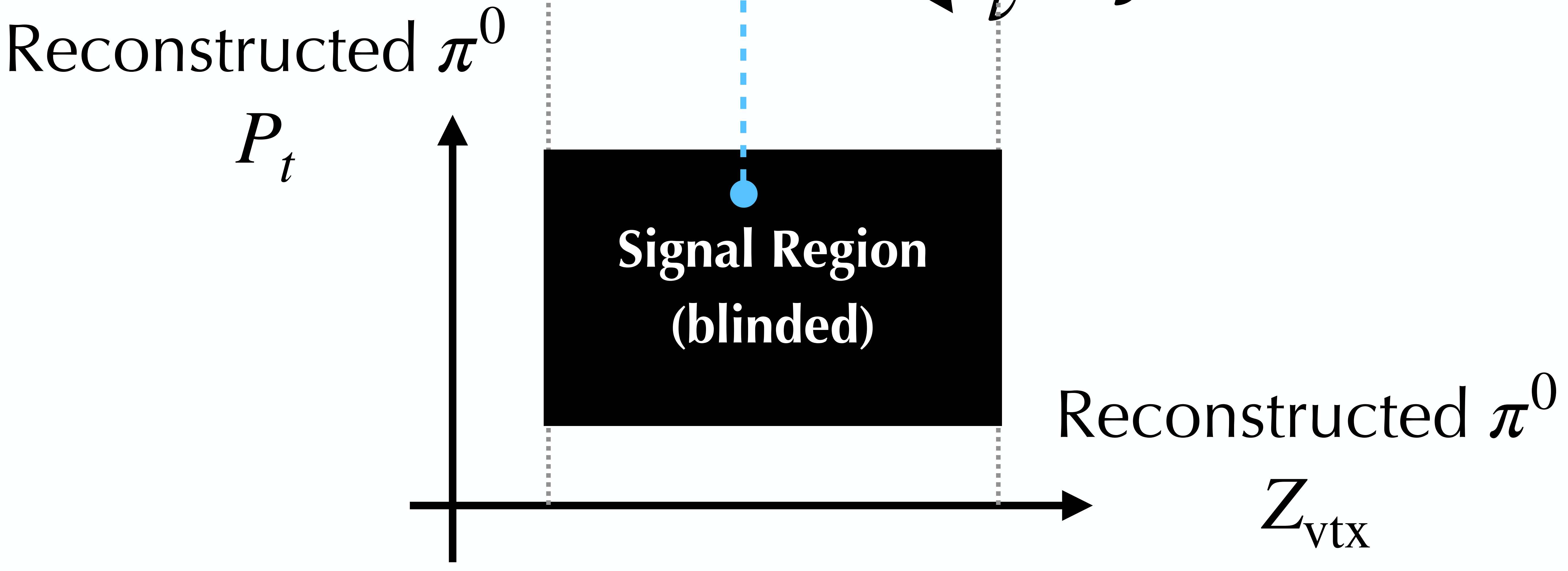
- KOTO (= K⁰ at TOkai) aims to search for new physics via the $K_L \to \pi^0 \nu \bar{\nu}$ decay
- KOTO collaboration: ~40 members from Japan, Korea, Taiwan, US





Hadron Experimental Facility

Experimental method

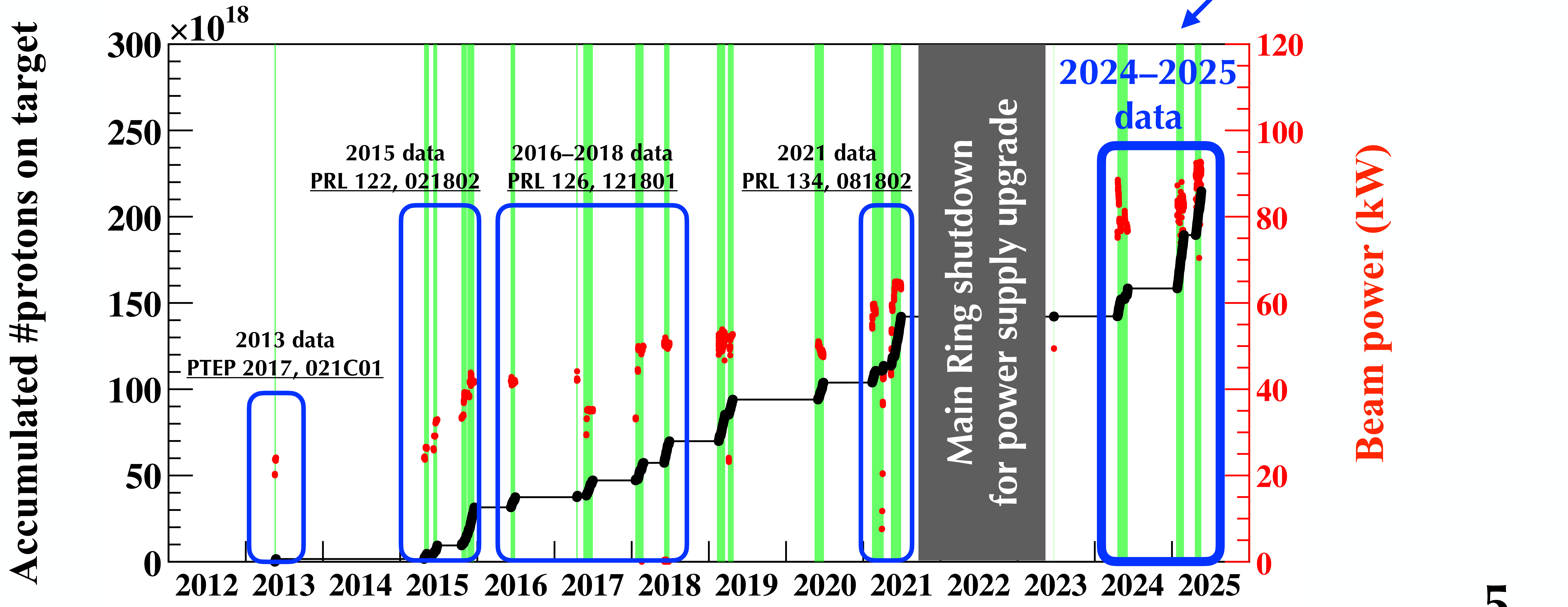


Signal identification:
$(\pi^0 \rightarrow)\ 2\gamma$ + nothing else

↑ Calorimeter ↑ Veto

KOTO data-taking history

- Beam power has been increased: 64 kW (2021) → 92 kW (2025 June)
- Data collected in 2024–2025 is around twice as much as 2021 data



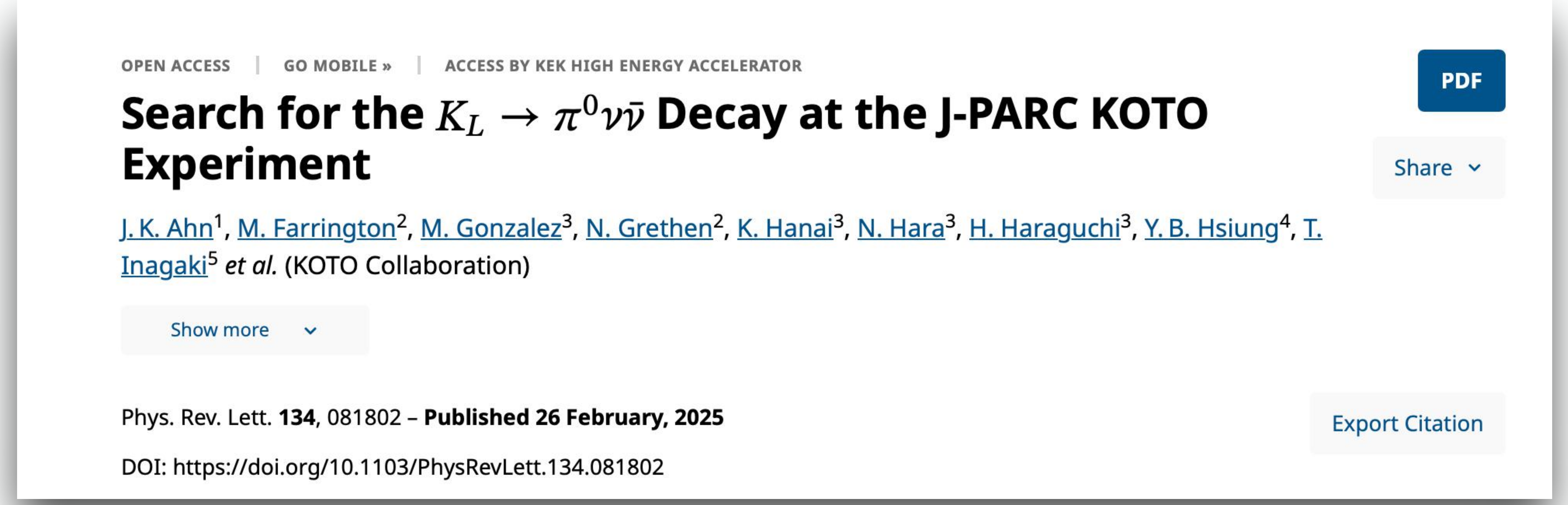
Latest results from 2021 data

- Single Event Sensitivity (SES)
  - $\mathrm{SES} = (9.33 \pm 0.06 \pm 0.84) \times 10^{-10}$
- Expected number of background events
  - $0.252 \pm 0.055^{+0.052}_{-0.067}$
- No events observed in the signal region

$\Rightarrow B(K_L \to \pi^0 \nu \bar{\nu}) < 2.2 \times 10^{-9}$ (90% C.L.)

(current best limit)

[Phys. Rev. Lett. 134, 081802]



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Search for the $K_L \to \pi^0 \nu \bar{\nu}$ Decay at the J-PARC KOTO Experiment

Share

J. K. Ahn[1], M. Farrington[2], M. Gonzalez[3], N. Grethen[2], K. Hanai[3], N. Hara[3], H. Haraguchi[3], Y. B. Hsiung[4], T. Inagaki[5] *et al.* (KOTO Collaboration)

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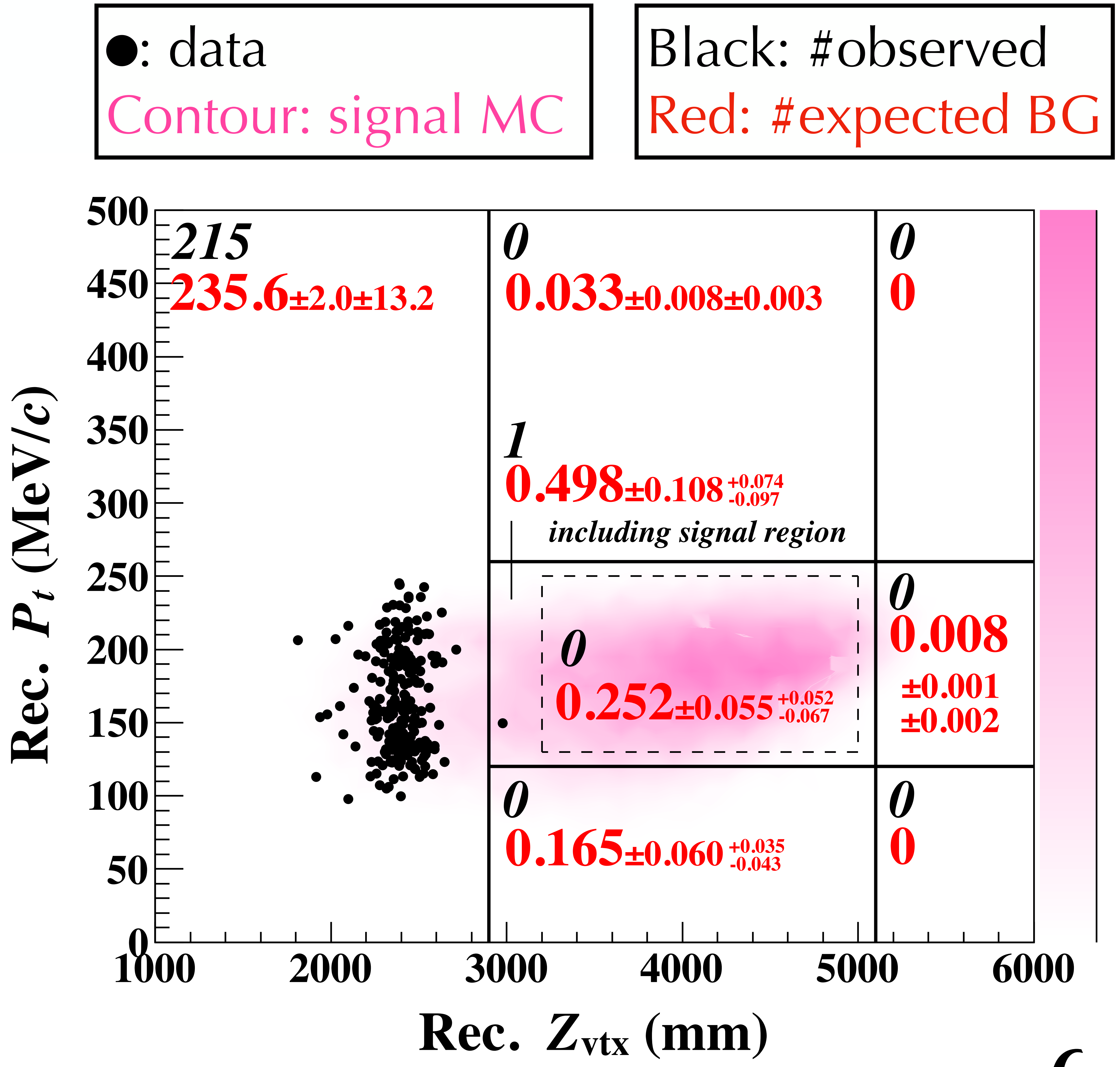
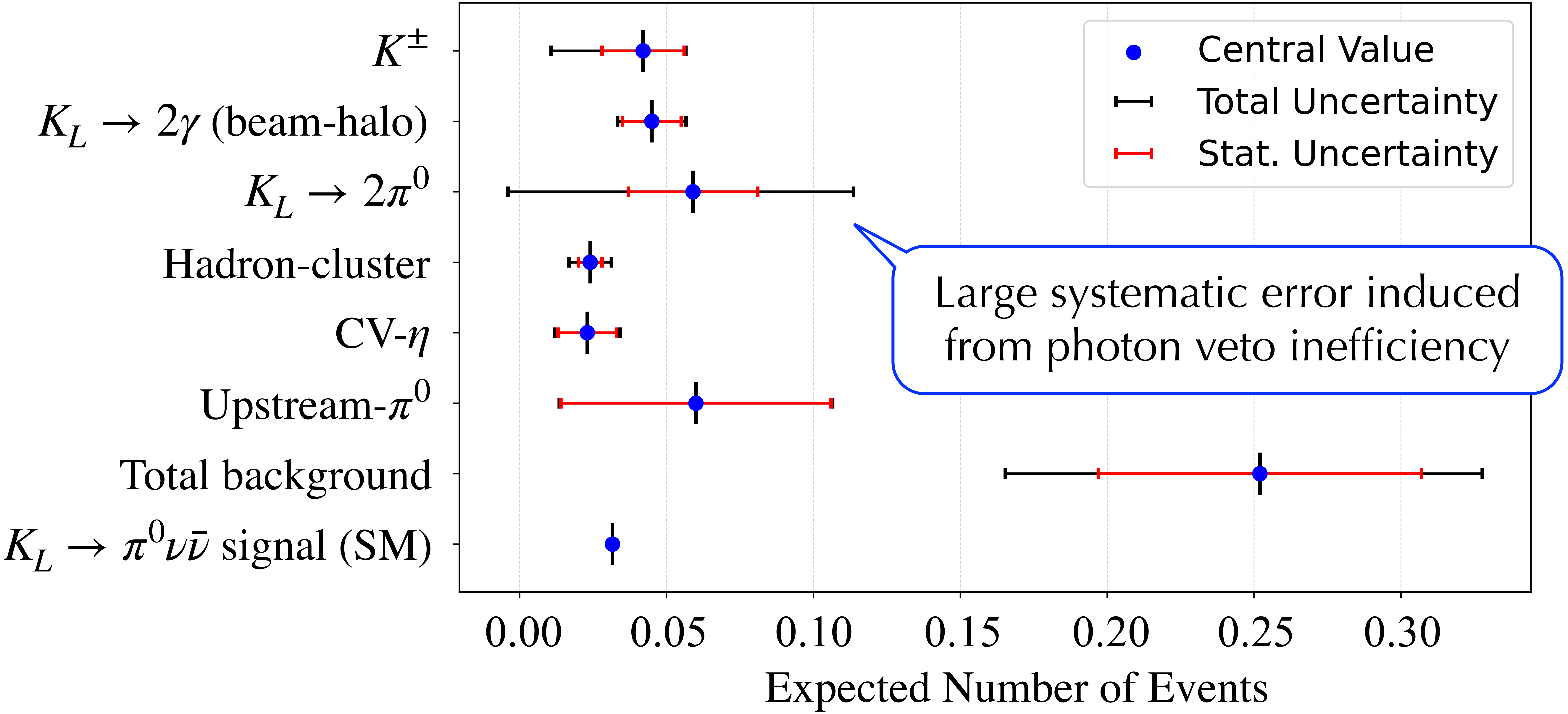


Lessons from the 2021 data analysis

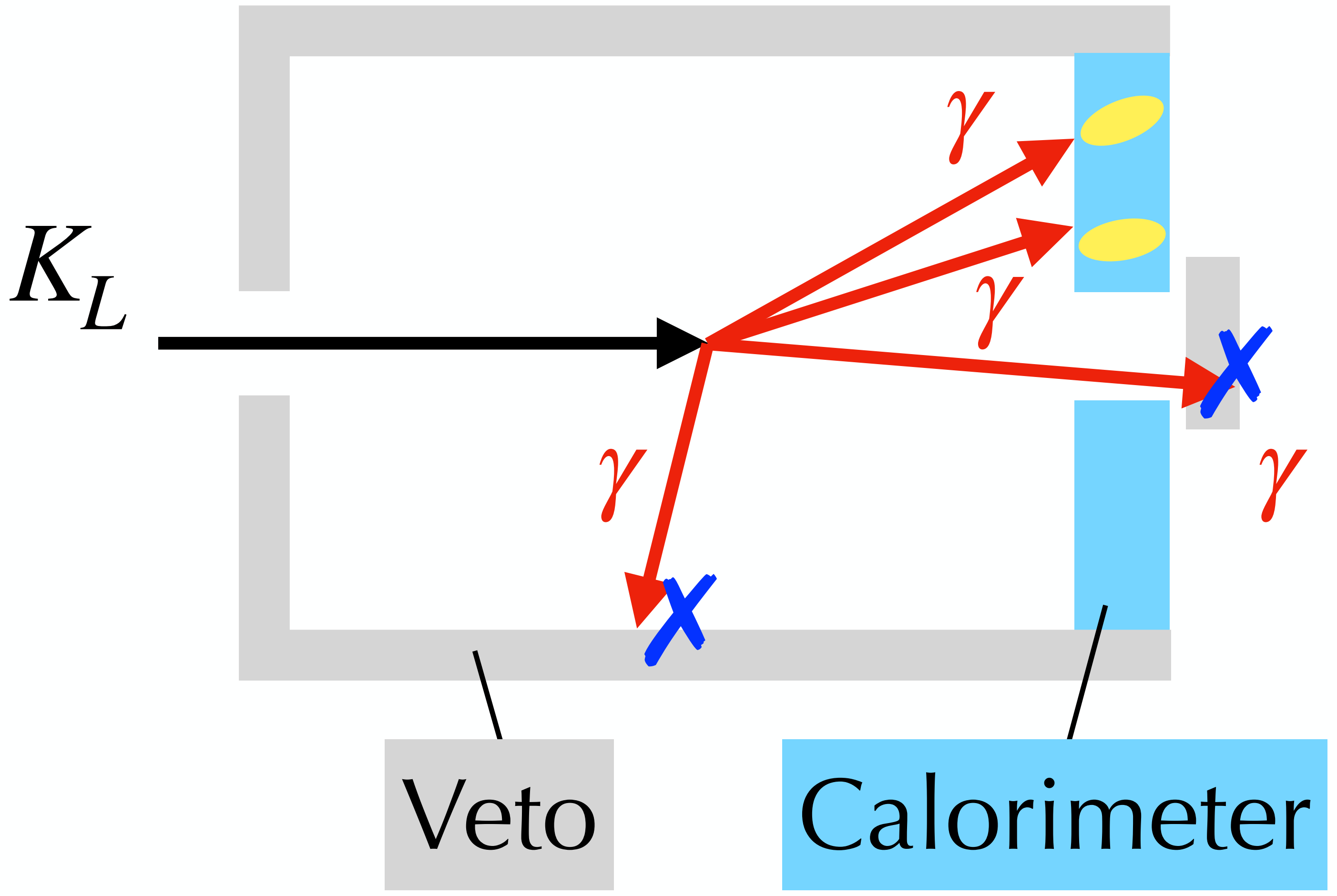
Background estimation in the 2021 data analysis



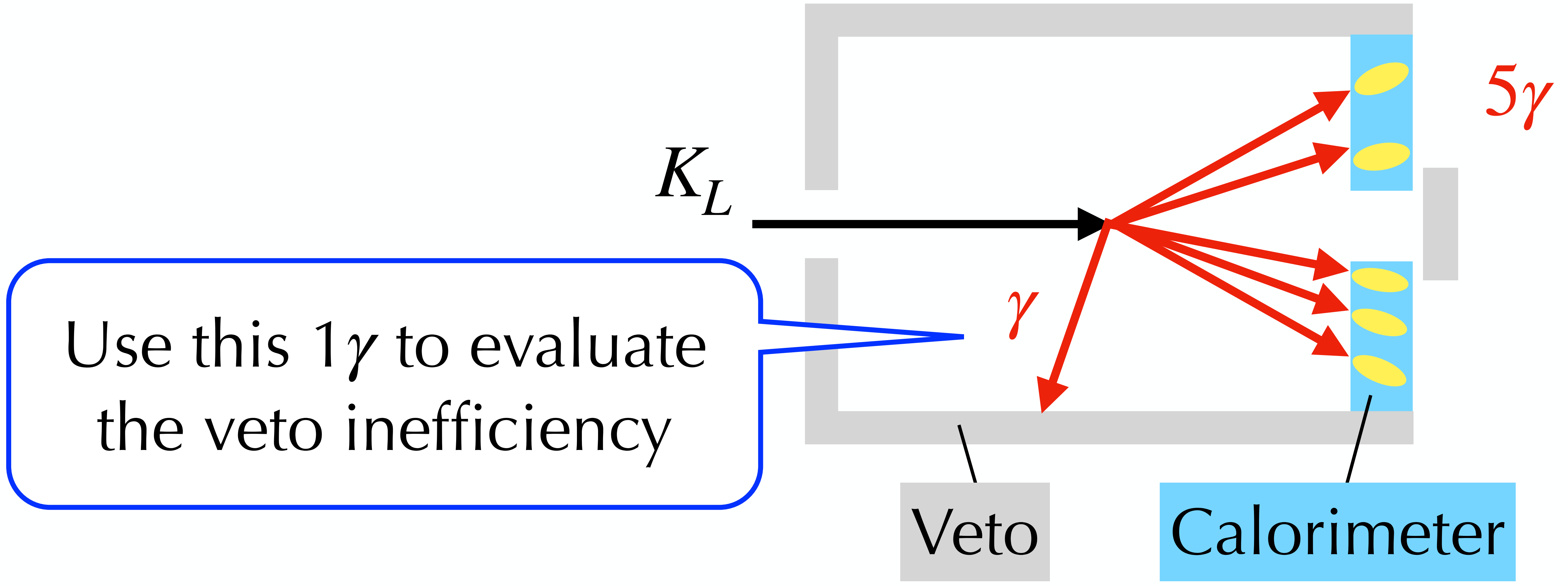
Upgrade after 2021: DAQ

- Upgraded the DAQ system to have more rate capability → added new triggers
  - 5γ trigger to collect a control sample (5γ sample) for **veto inefficiency evaluation** → aims to reduce the systematic uncertainty of $K_L \to 2\pi^0$ BG
  - New trigger to collect events for other physics targets (e.g., $K_L \to \pi^0 ee$)

$K_L \to 2\pi^0(\to 4\gamma)$ background with two extra photons missed

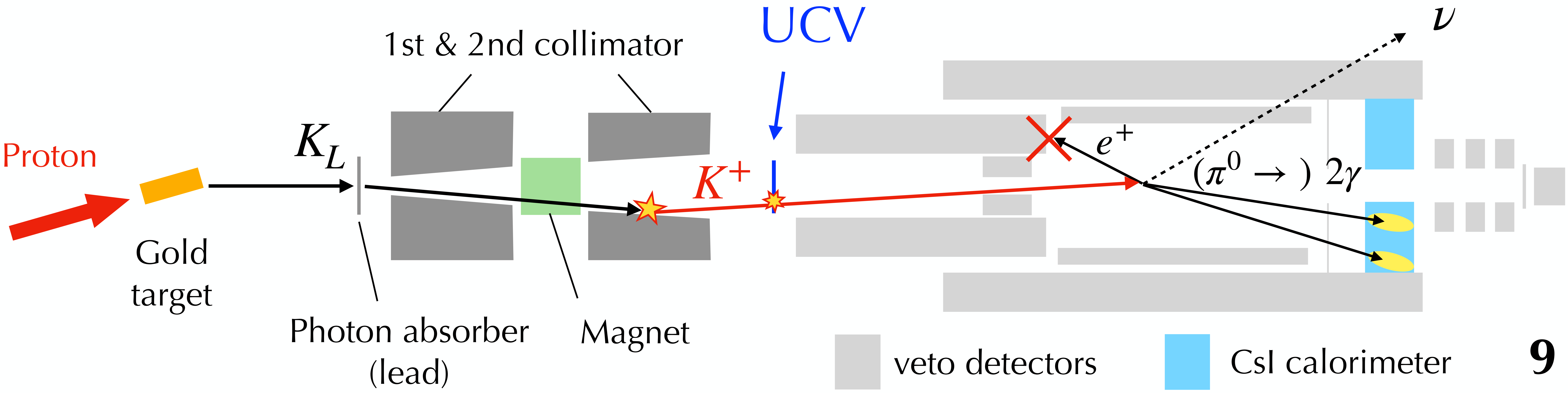


5γ-sample collection using $K_L \to 3\pi^0(\to 6\gamma)$ decays



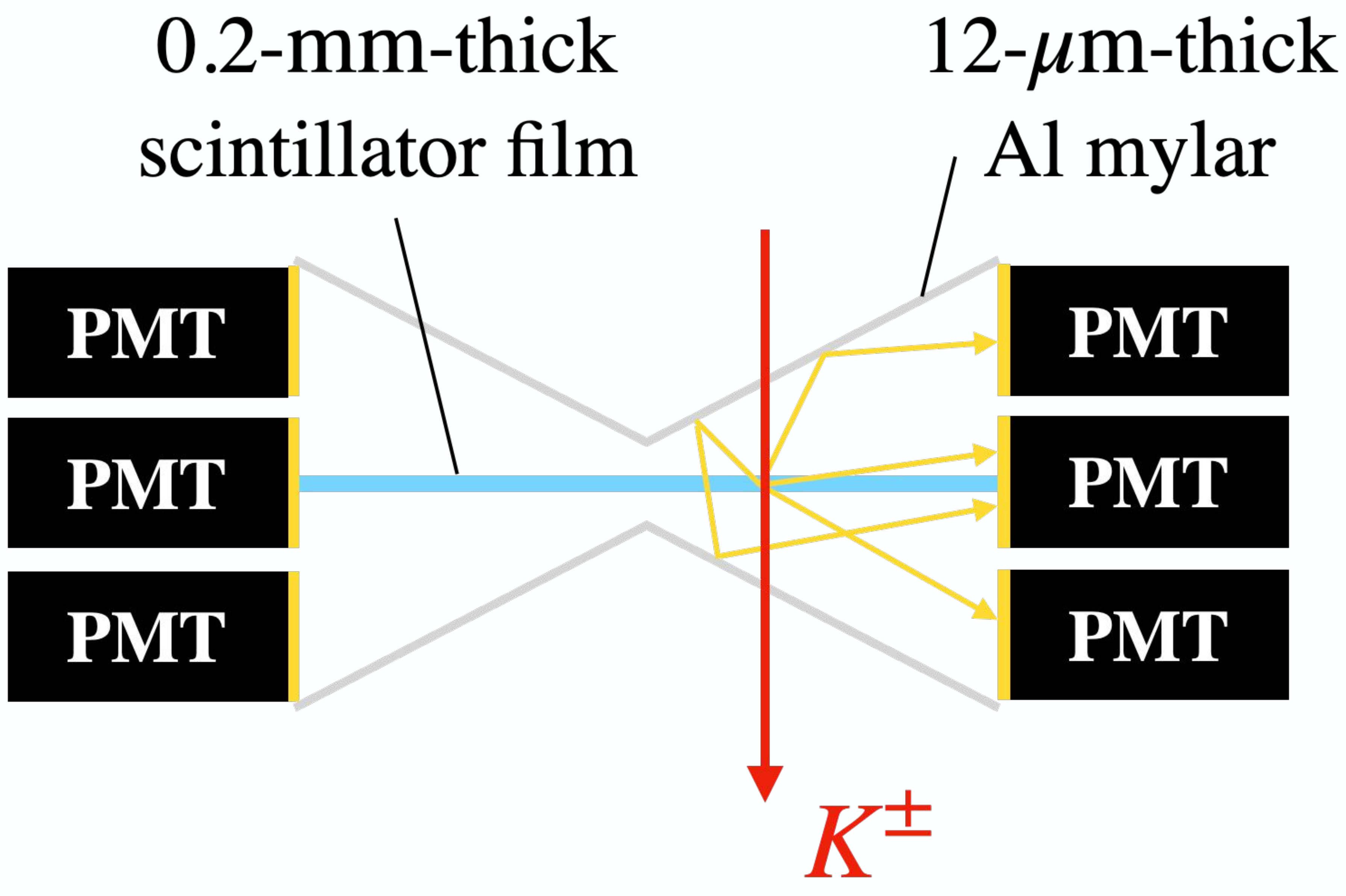
Upgrade after 2021: detector

- Installed a new charged veto counter (Upstream Charged Veto, UCV) in 2023 for further reduction of the $K^{\pm}$ background
  - Important features
    - Sensitive to charged particles to detect $K^{\pm}$ in the beam
    - Less sensitive to neutral particles (K_L, n, γ) to avoid scattering

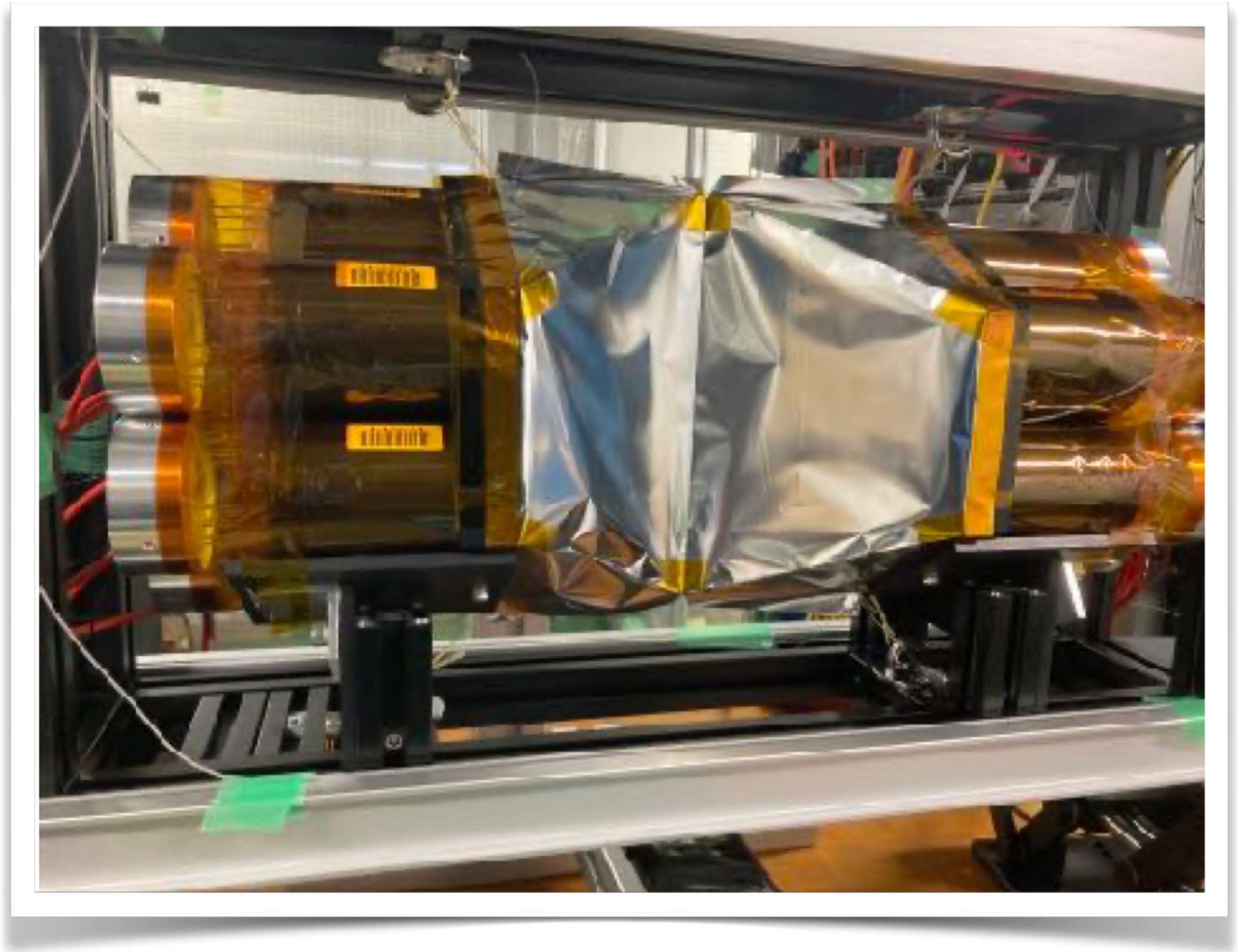


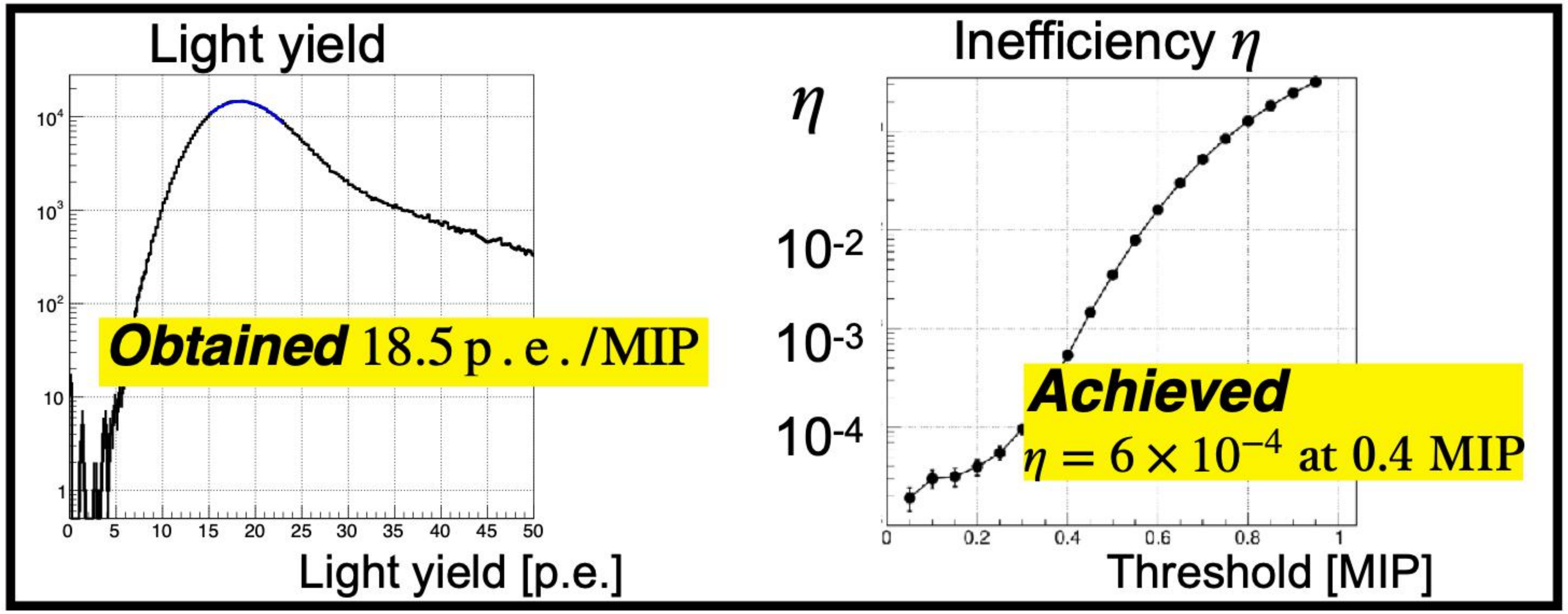
Upgrade after 2021: detector

- Upstream Charged Veto (2021)
  - Thickness: 0.5 mm (scinti. fiber), Inefficiency: 7.8%
- Upstream Charged Veto (2023–)
  - Thickness: **0.2 mm** (scinti. film), Inefficiency: **0.06%**



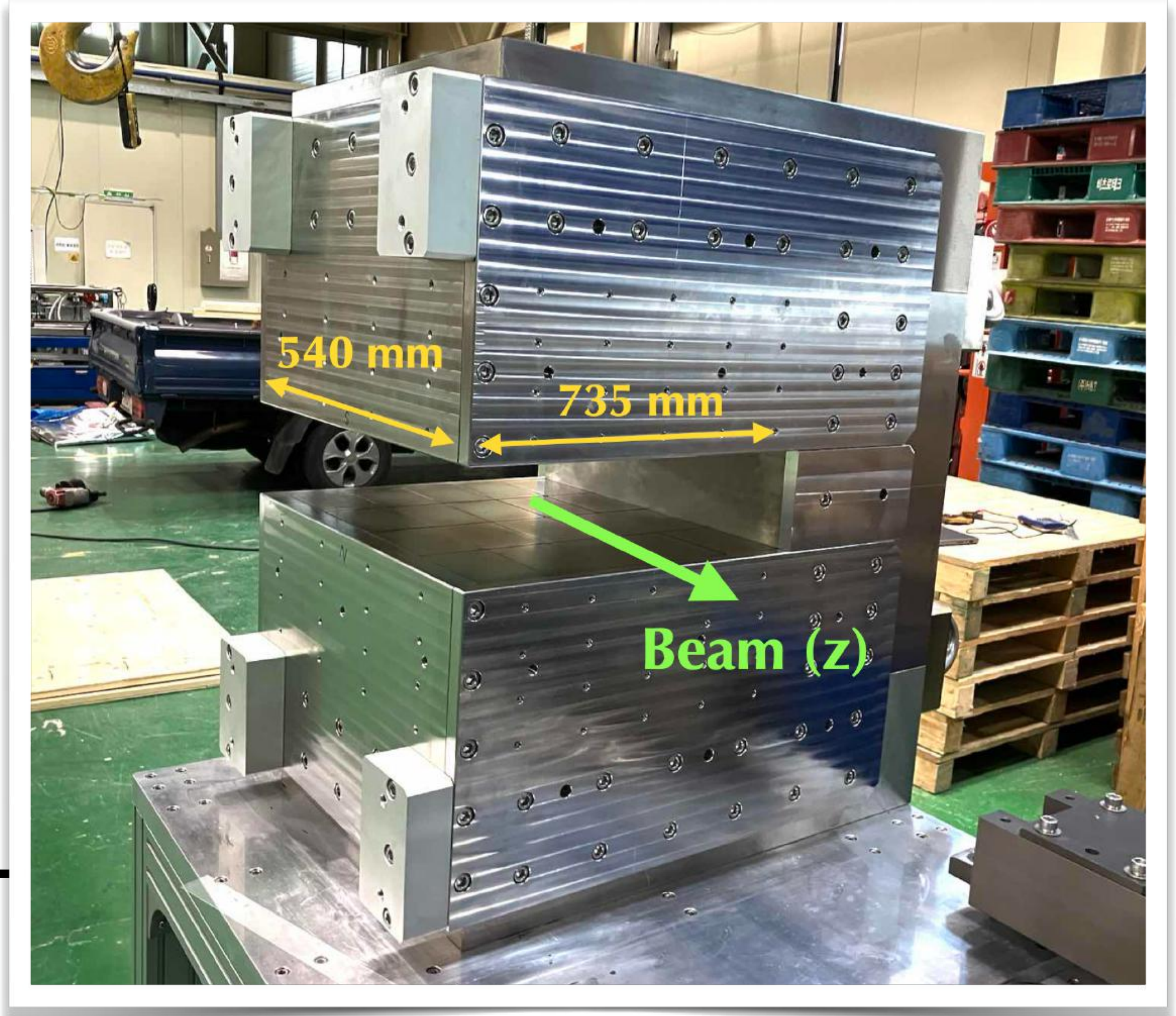
UCV (2023–)

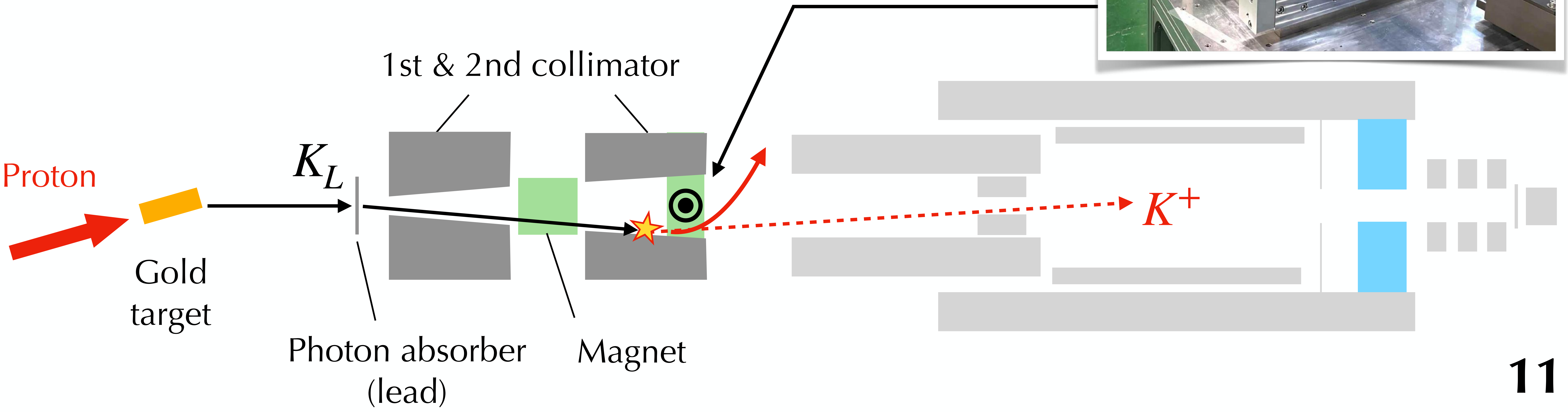




Upgrade after 2021: beam line

- Installed a permanent magnet at the downstream edge of the collimator
  - B (~0.9T) x 0.5 m on average
  - Expect 1/10 reduction of the $K^{\pm}$ background



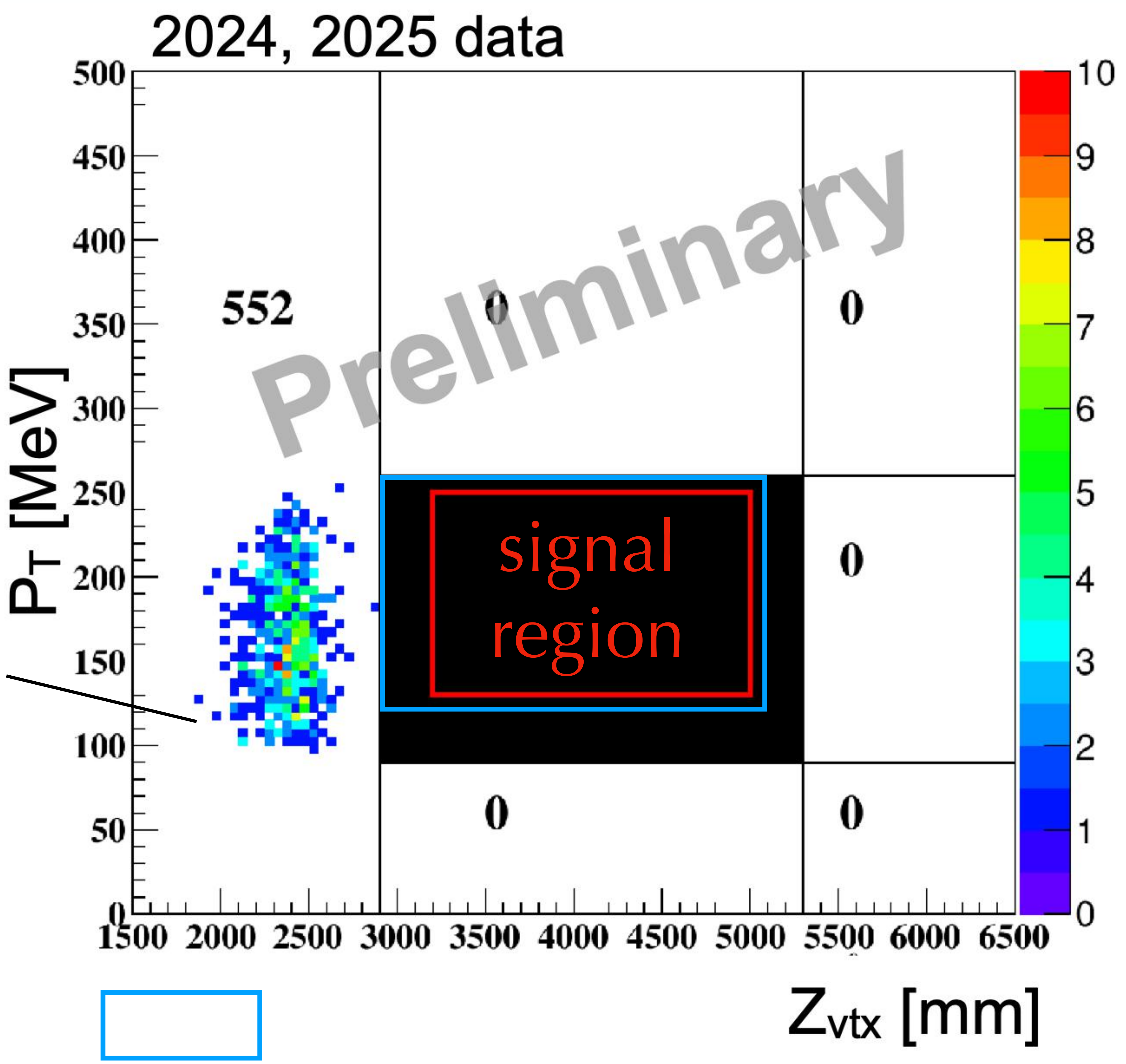


Analysis status: 2024–2025 data

- Accumulated #protons on target (POT) in 2024-25
  - $POT_{2024\text{-}25} = 6.59 \times 10^{19}$ (~2 x POT_{2021})
- No events are found outside the blind region except for the upstream π^0 events. (As expected.)
- Used a wider blind region to consider possible extension of the signal region.

- Currently checking stability of K_L yield and veto performance
- Will start sensitivity and background estimations soon

Under almost the same cut set for the 2021 data analysis



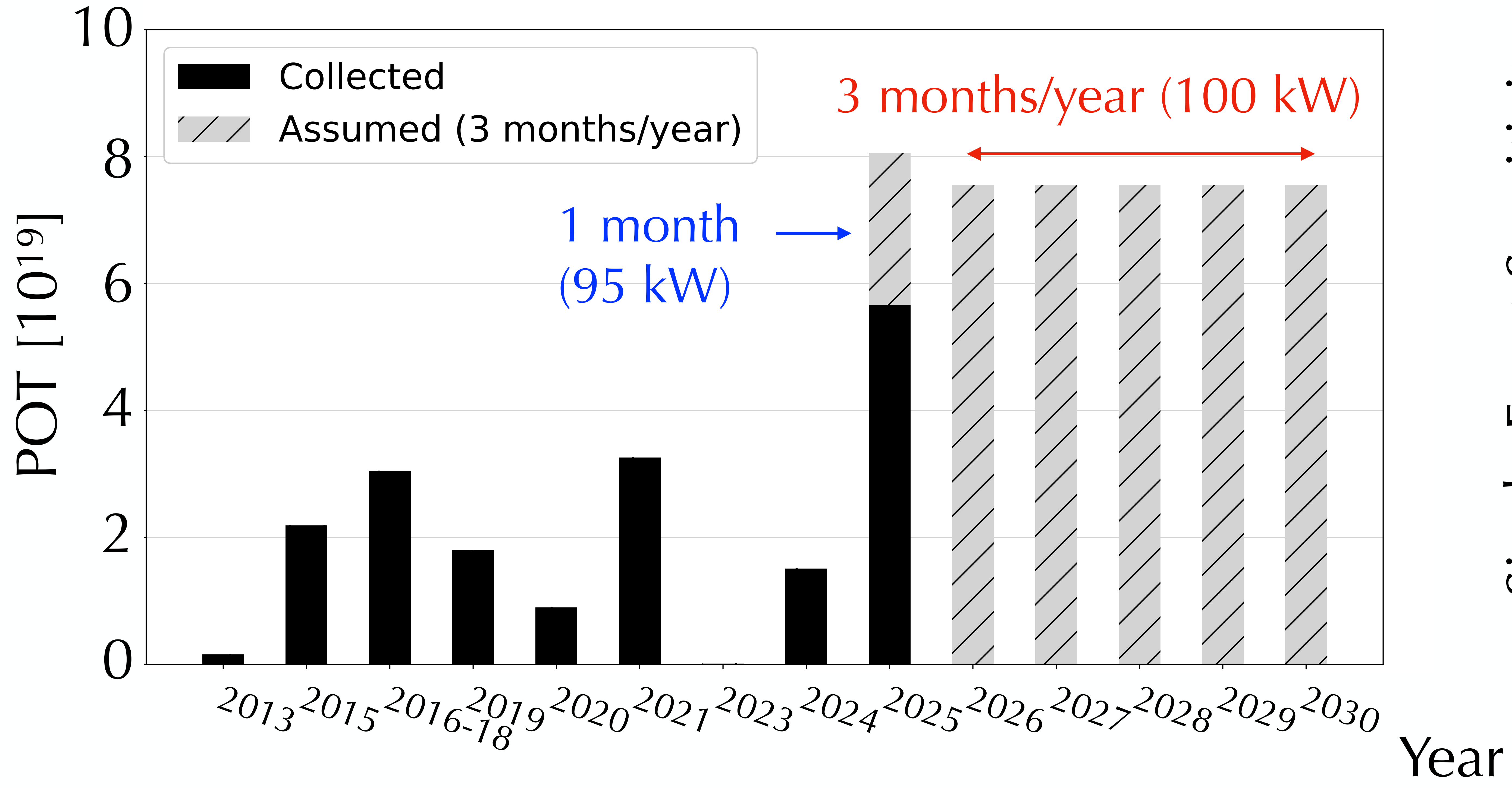
Blind region used for 2021 data

Prospect of KOTO

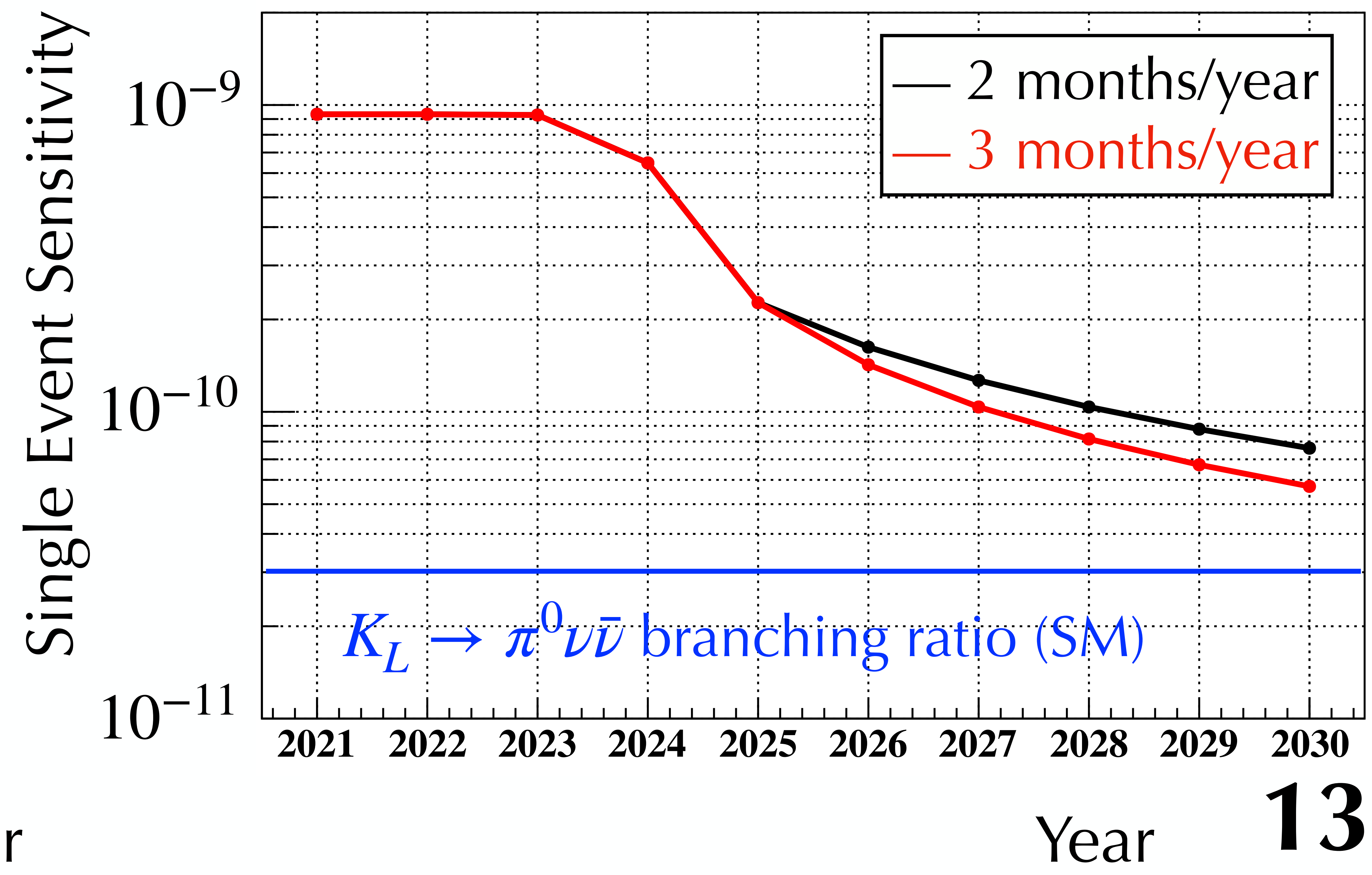
With the following assumptions, we aim to reach SES < 10^{-10} in 3-4 years

- Beam power will reach 100 kW in 2026–
- Run time: 20 days/month x 2 or 3 months/year
- 70% efficiency for physics data taking

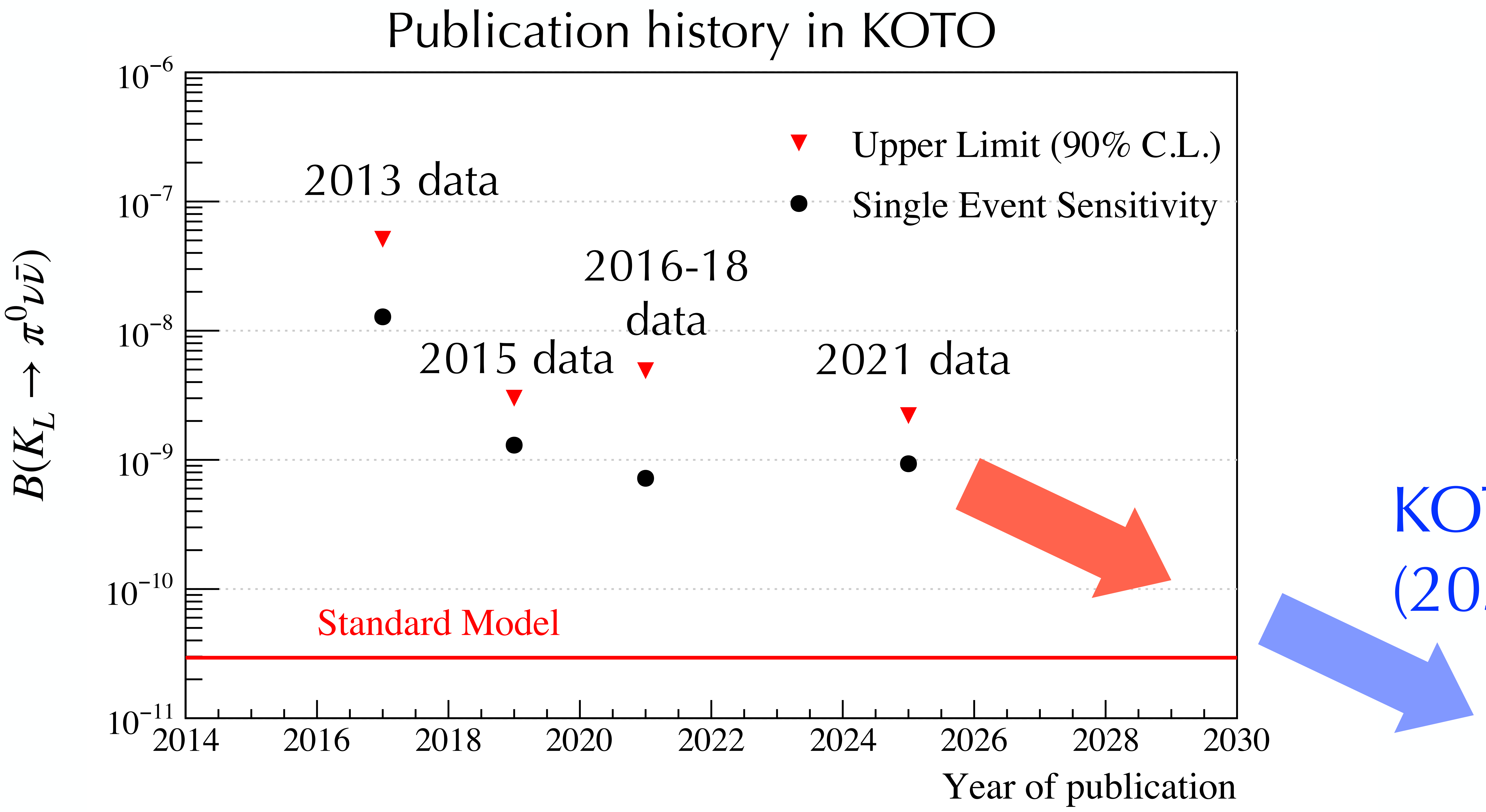
Expected #Protons On Target (POT)



Expected sensitivity



Next step

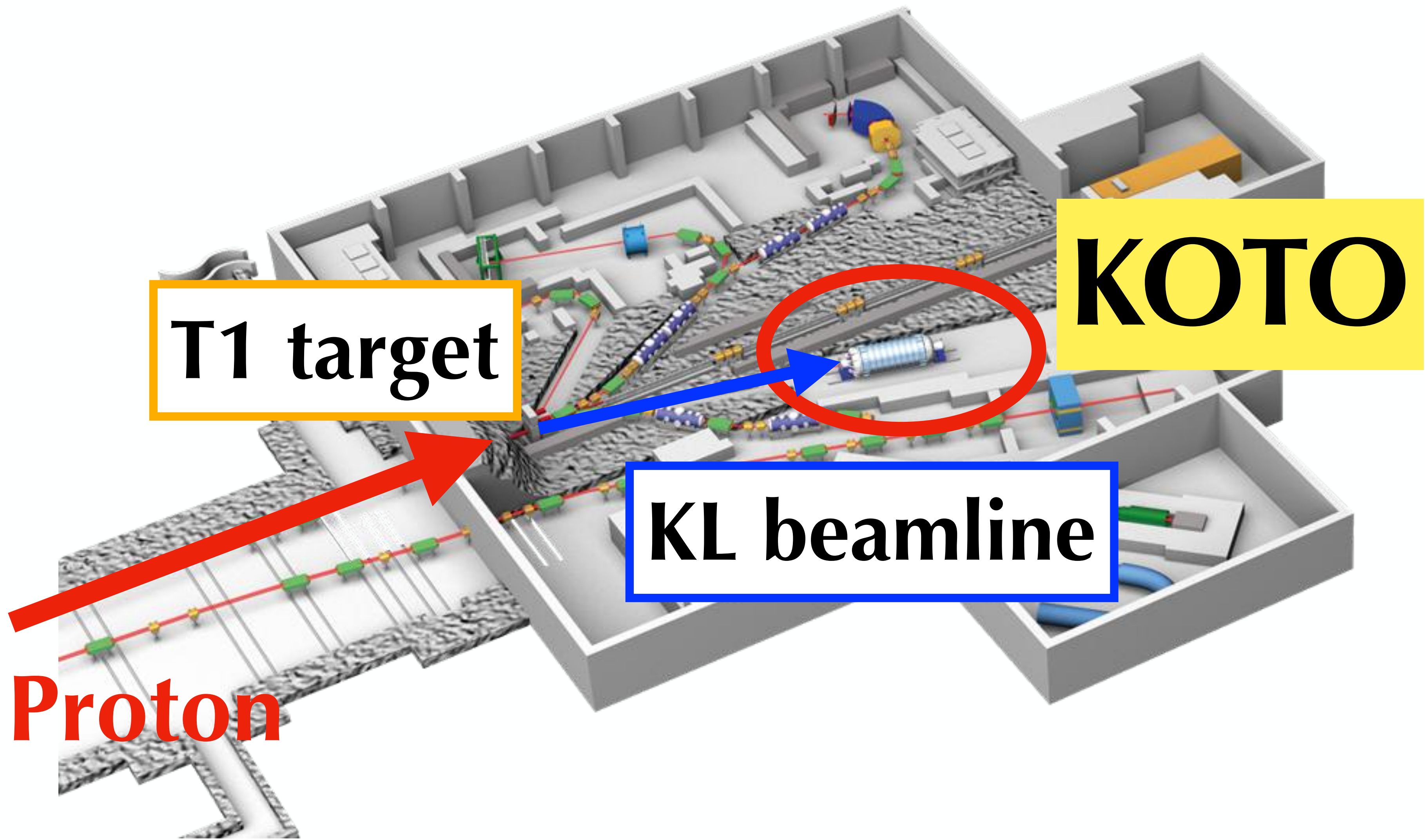


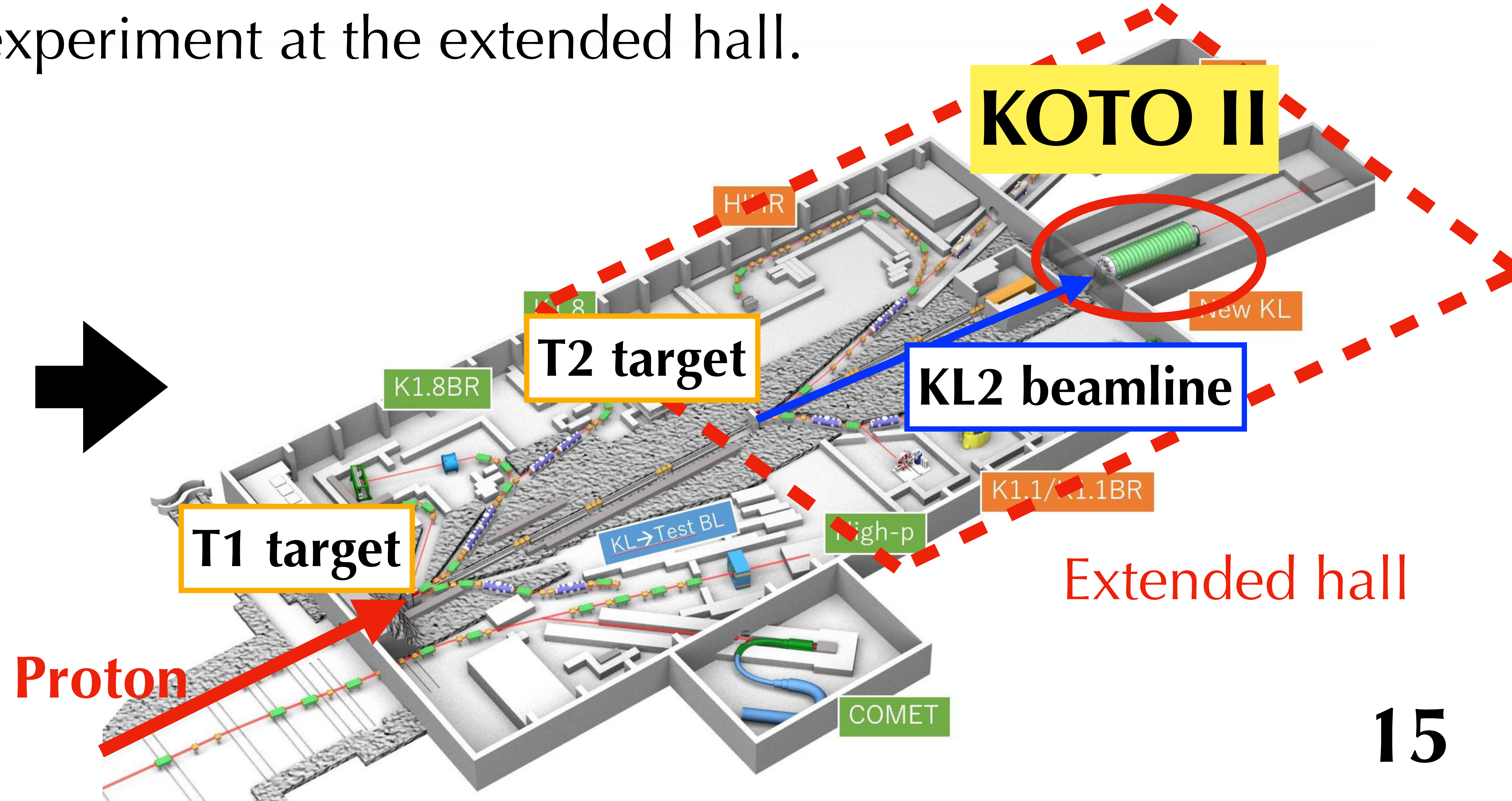
KOTO II
(2030s–)

Hadron Experimental Facility extension (HEF-ex)

- Double the area for hadron/nuclear and particle physics experiments.
  (HEF-ex white paper [arXiv:2110.04462])
- Supported by the KEK Project Implementation Plan 2022 as a **1st priority project** for budget request.
- We are planning the **KOTO II** experiment at the extended hall.

Current hadron hall



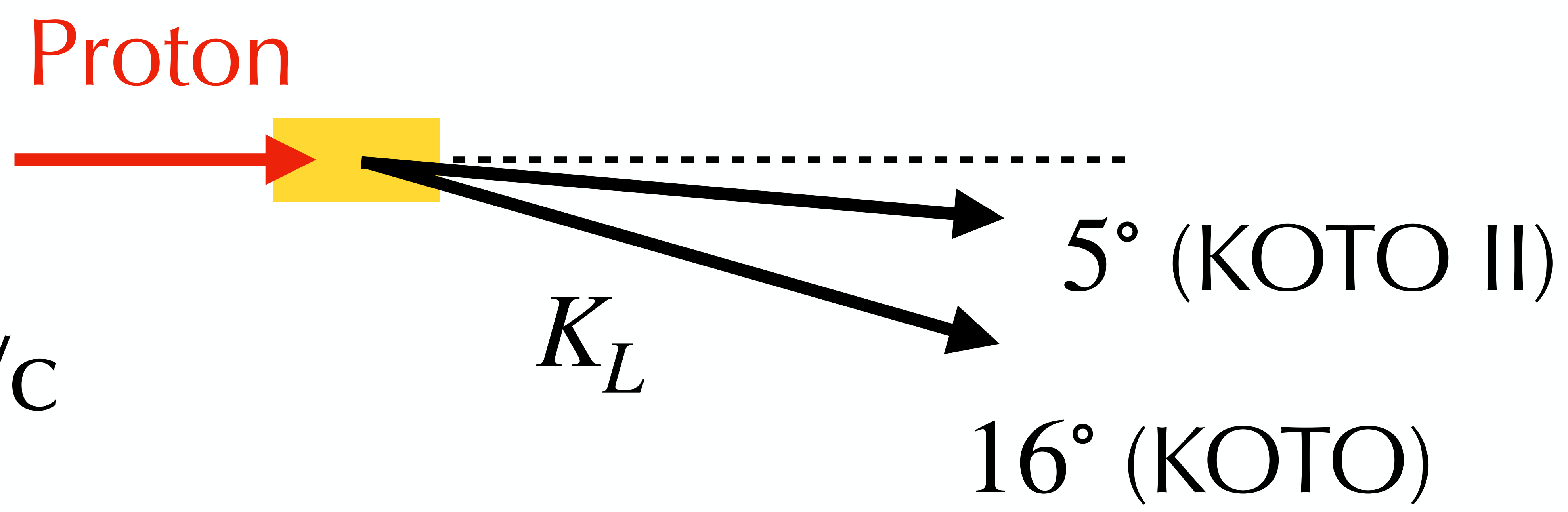


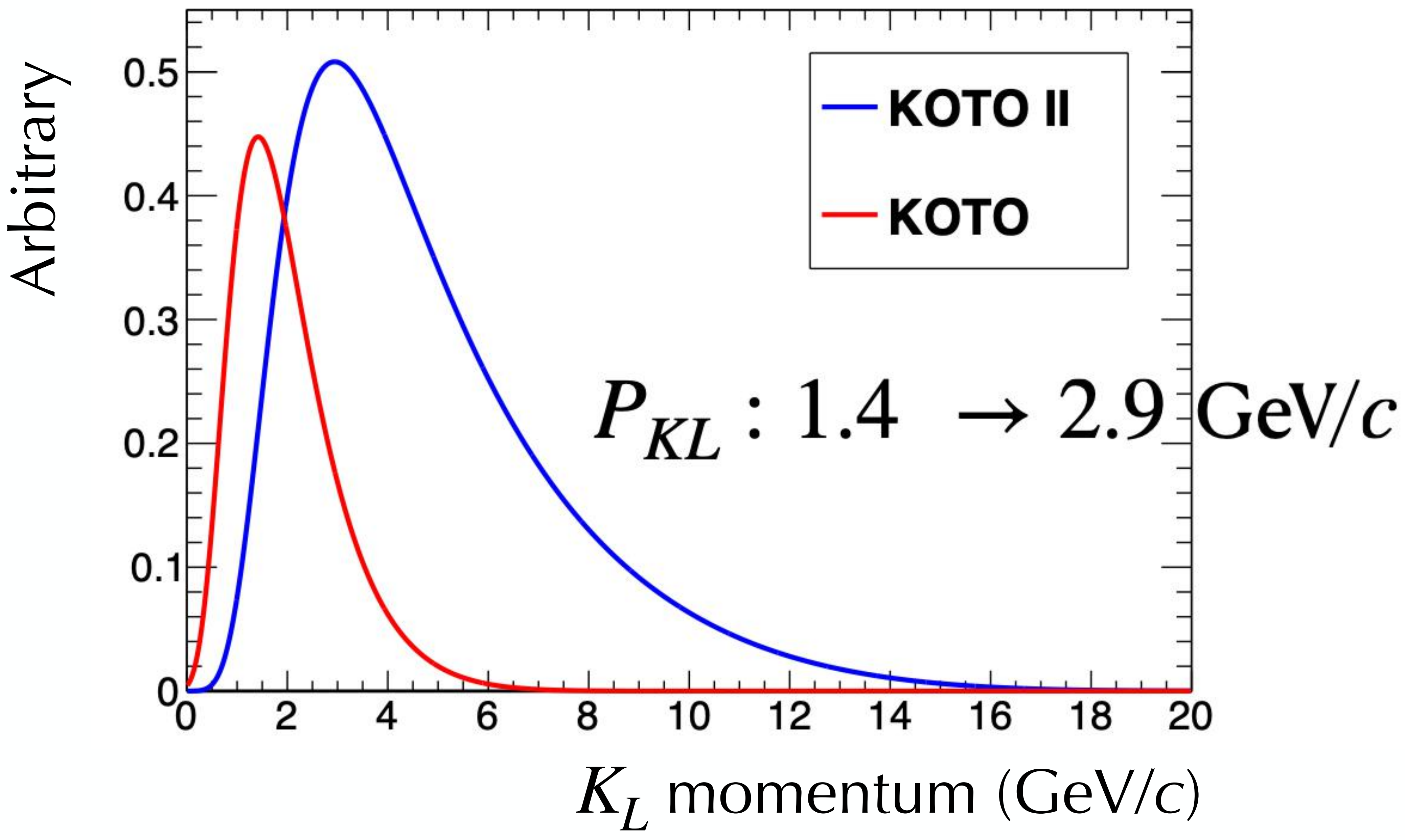
KOTO II experiment

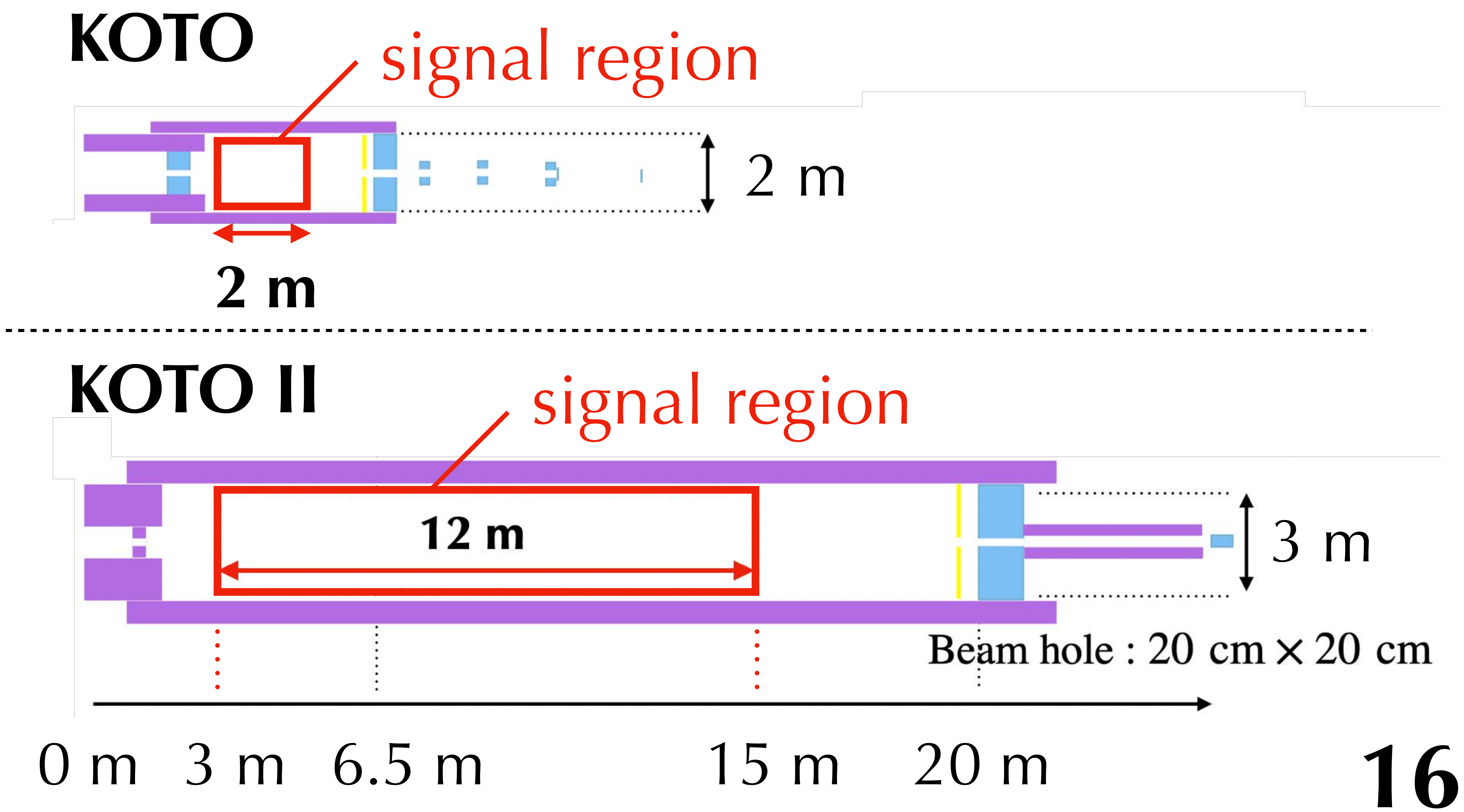
What's new?

- Extraction angle: 16° → 5°
- Peak K_L momentum: 1.4 GeV/c → 2.9 GeV/c
- Decay volume (signal region): 2 m → 12 m

==> <u>More signal acceptance</u>

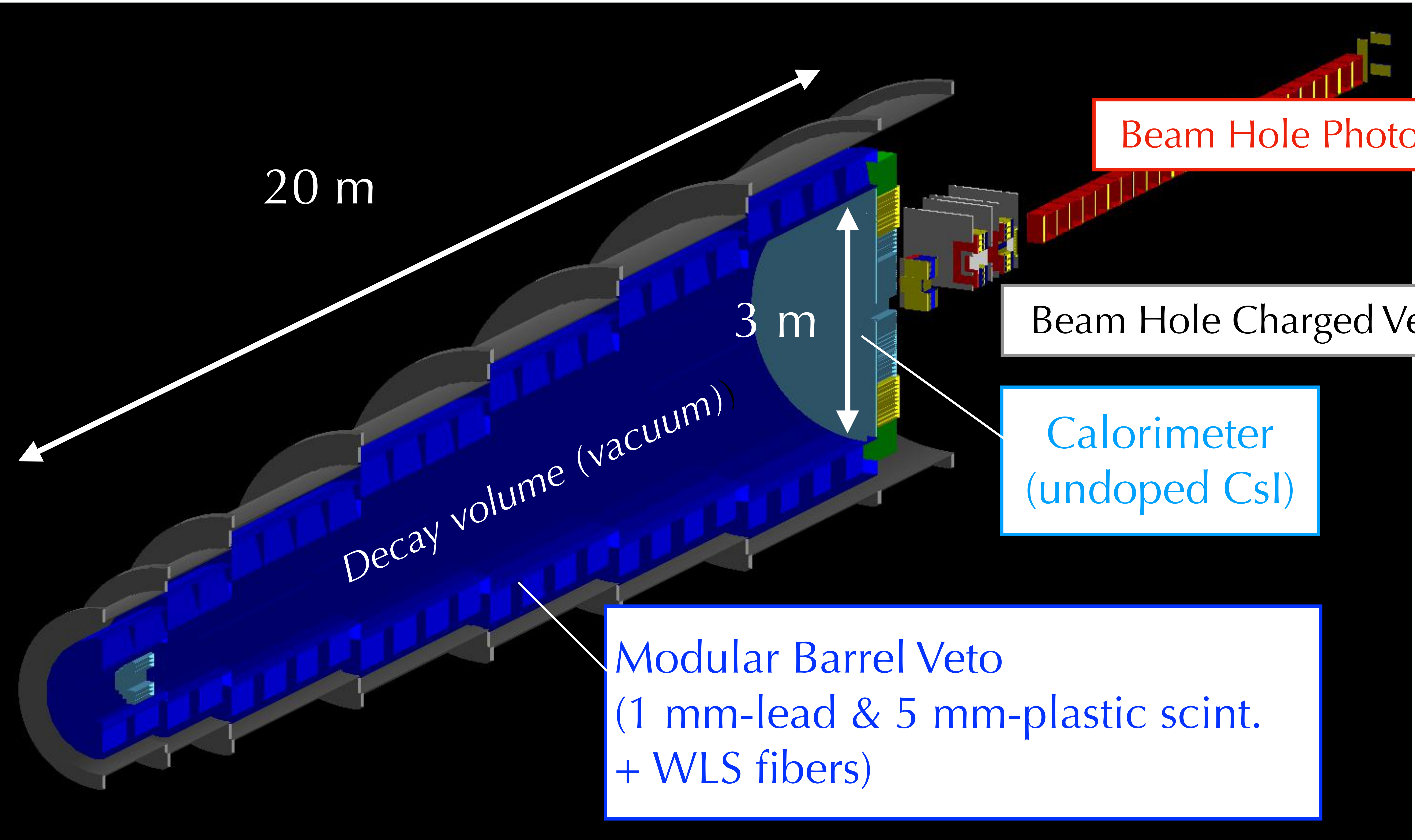




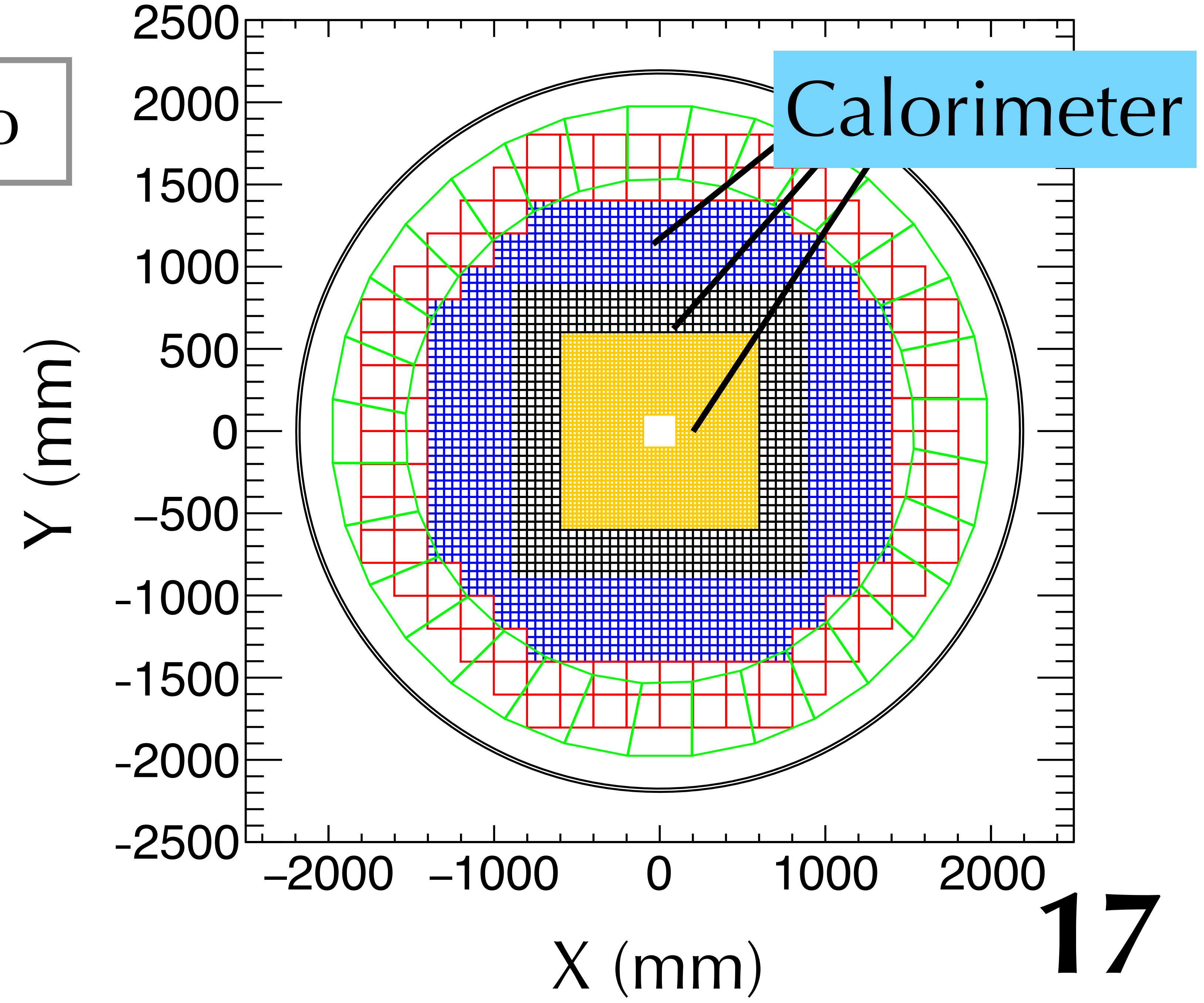


KOTO II detector (base design)

3D cutaway view of the KOTO II detector



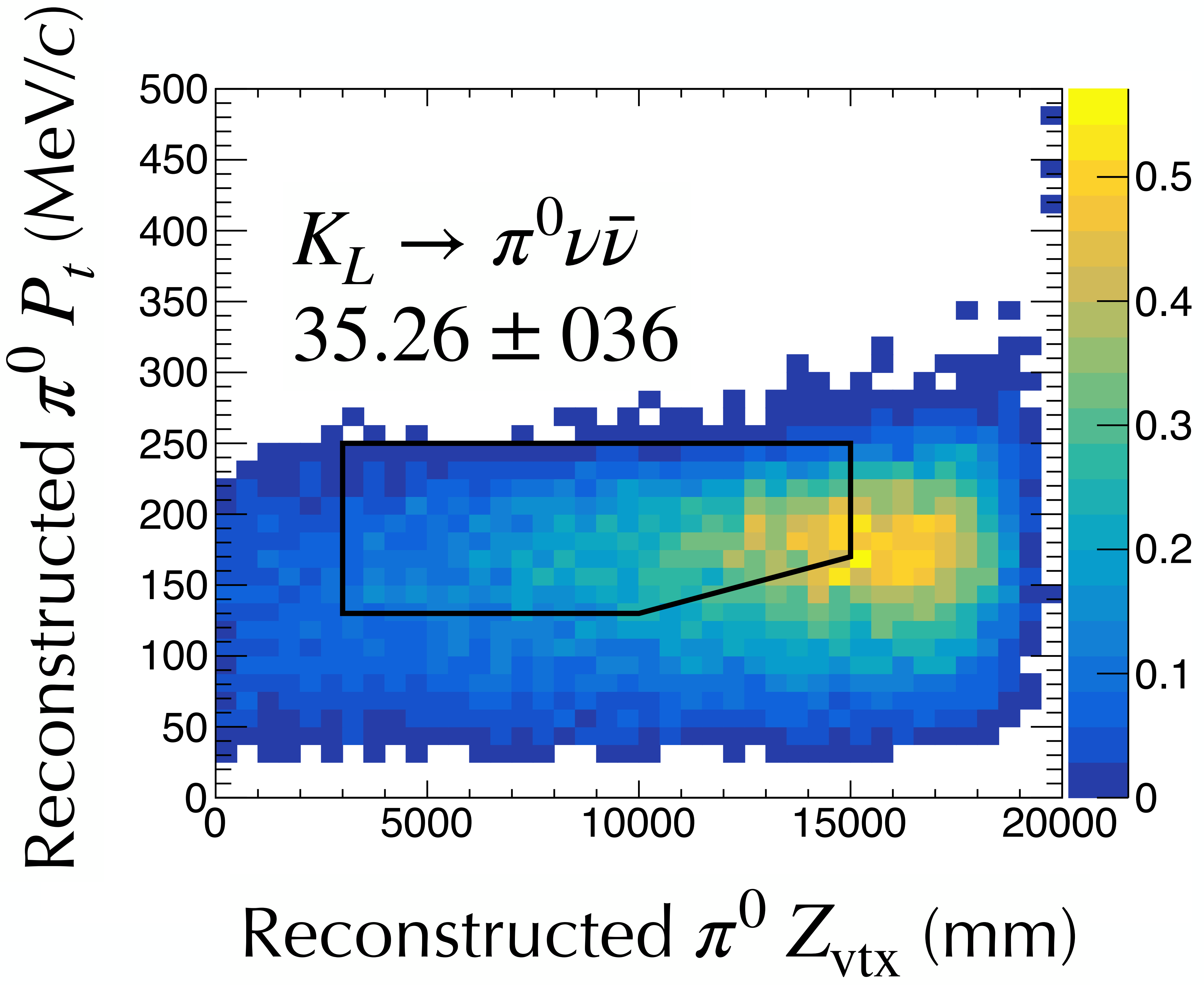
Calorimeter
1.9 m ϕ (KOTO)
→ 3 m ϕ (KOTO II)



Signal yield and sensitivity

- With 5 years ($3\text{x}10^7$ s running time) of data-taking at 100 kW beam power, we expect
  - SES = 8.5×10^{-13}
  - 35 signal and 40 background events
  - 5.6σ discovery
  - $\Delta\mathscr{B}/\mathscr{B}$ = 25%

- 40% deviation from SM
  → 90%-CL indication of NP



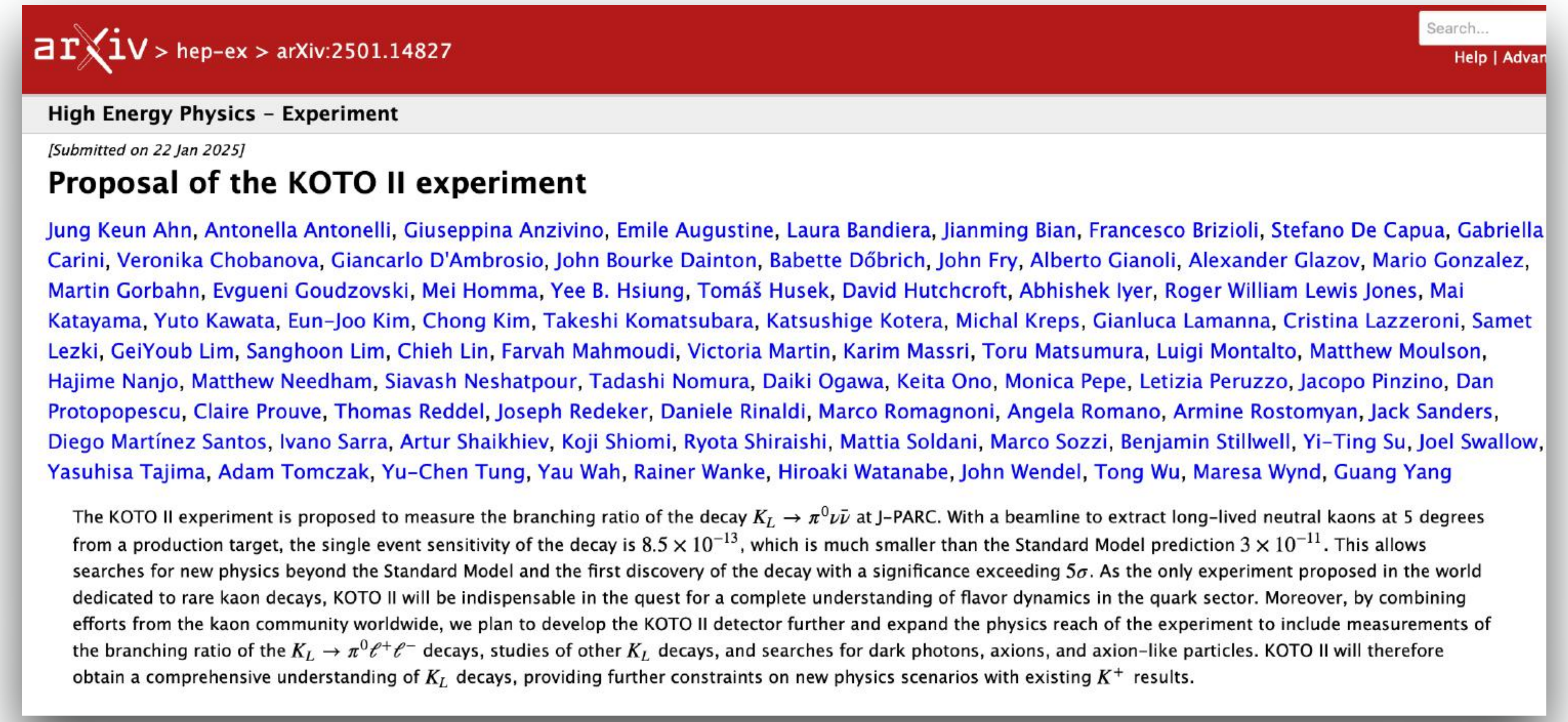
KOTO II status & prospect

- Proposal was submitted by 82 members from 11 countries in Jan. 2025
  - Scientific approval (stage-1 status) was granted by J-PARC PAC
- KOTO II collaboration was formed this summer (KEK as a host)

- Next steps toward full approval (stage-2):
  - Strategy for KL2 beam line construction
  - Realistic detector design

- Detailed information and recent studies can be found in talks at KAON2025 & KOTO II workshop

KOTO II proposal [arXiv:2501.14827]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High Energy Physics – Experiment

[Submitted on 22 Jan 2025]

Proposal of the KOTO II experiment

Jung Keun Ahn, Antonella Antonelli, Giuseppina Anzivino, Emile Augustine, Laura Bandiera, Jianming Bian, Francesco Brizioli, Stefano De Capua, Gabriella Carini, Veronika Chobanova, Giancarlo D'Ambrosio, John Bourke Dainton, Babette Dőbrich, John Fry, Alberto Gianoli, Alexander Glazov, Mario Gonzalez, Martin Gorbahn, Evgueni Goudzovski, Mei Homma, Yee B. Hsiung, Tomáš Husek, David Hutchcroft, Abhishek Iyer, Roger William Lewis Jones, Mai Katayama, Yuto Kawata, Eun-Joo Kim, Chong Kim, Takeshi Komatsubara, Katsushige Kotera, Michal Kreps, Gianluca Lamanna, Cristina Lazzeroni, Samet Lezki, GeiYoub Lim, Sanghoon Lim, Chieh Lin, Farvah Mahmoudi, Victoria Martin, Karim Massri, Toru Matsumura, Luigi Montalto, Matthew Moulson, Hajime Nanjo, Matthew Needham, Siavash Neshatpour, Tadashi Nomura, Daiki Ogawa, Keita Ono, Monica Pepe, Letizia Peruzzo, Jacopo Pinzino, Dan Protopopescu, Claire Prouve, Thomas Reddel, Joseph Redeker, Daniele Rinaldi, Marco Romagnoni, Angela Romano, Armine Rostomyan, Jack Sanders, Diego Martínez Santos, Ivano Sarra, Artur Shaikhiev, Koji Shiomi, Ryota Shiraishi, Mattia Soldani, Marco Sozzi, Benjamin Stillwell, Yi-Ting Su, Joel Swallow, Yasuhisa Tajima, Adam Tomczak, Yu-Chen Tung, Yau Wah, Rainer Wanke, Hiroaki Watanabe, John Wendel, Tong Wu, Maresa Wynd, Guang Yang

The KOTO II experiment is proposed to measure the branching ratio of the decay $K_L \to \pi^0 \nu \bar{\nu}$ at J-PARC. With a beamline to extract long-lived neutral kaons at 5 degrees from a production target, the single event sensitivity of the decay is 8.5×10^{-13}, which is much smaller than the Standard Model prediction 3×10^{-11}. This allows searches for new physics beyond the Standard Model and the first discovery of the decay with a significance exceeding 5σ. As the only experiment proposed in the world dedicated to rare kaon decays, KOTO II will be indispensable in the quest for a complete understanding of flavor dynamics in the quark sector. Moreover, by combining efforts from the kaon community worldwide, we plan to develop the KOTO II detector further and expand the physics reach of the experiment to include measurements of the branching ratio of the $K_L \to \pi^0 \ell^+ \ell^-$ decays, studies of other K_L decays, and searches for dark photons, axions, and axion-like particles. KOTO II will therefore obtain a comprehensive understanding of K_L decays, providing further constraints on new physics scenarios with existing K^+ results.

Summary

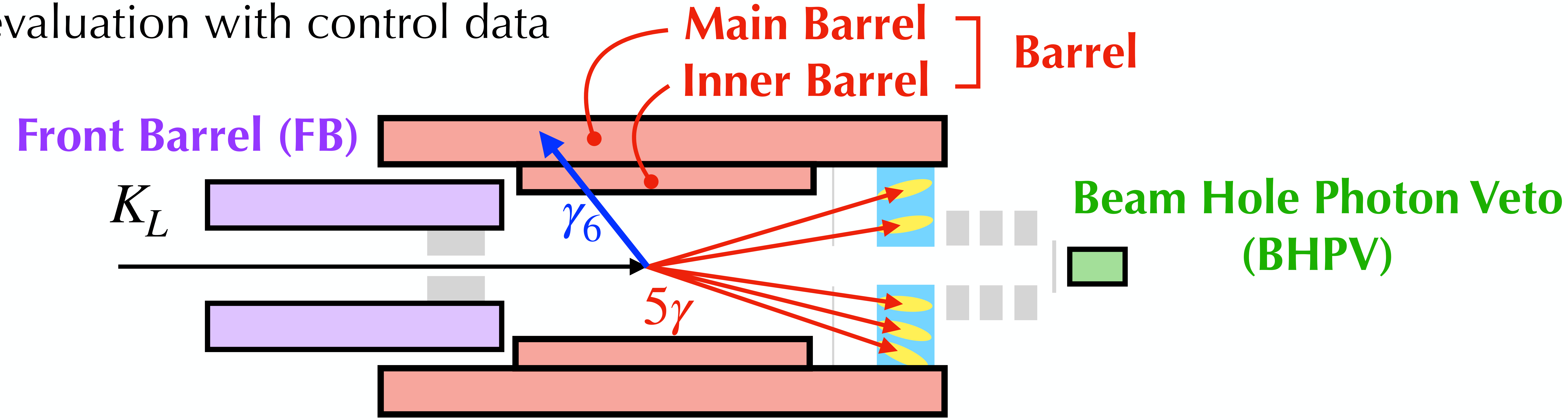
- KOTO
  - Upgrades of detector/beamline/DAQ were done after 2021 data-taking
  - Twice more data has been collected in 2024-25 compared to 2021 data
  - Analysis of the 2024-25 data is ongoing
  - KOTO will reach SES below 10^{-10} in 3-4 years

- KOTO II
  - Submitted a proposal and formed the KOTO II collaboration
  - Aim to discover $K_L \to \pi^0 \nu \bar{\nu}$ with $> 5\sigma$
  - Will measure $B(K_L \to \pi^0 \nu \bar{\nu})$ with 25% precision

Backup

Background: $K_L \to 2\pi^0$

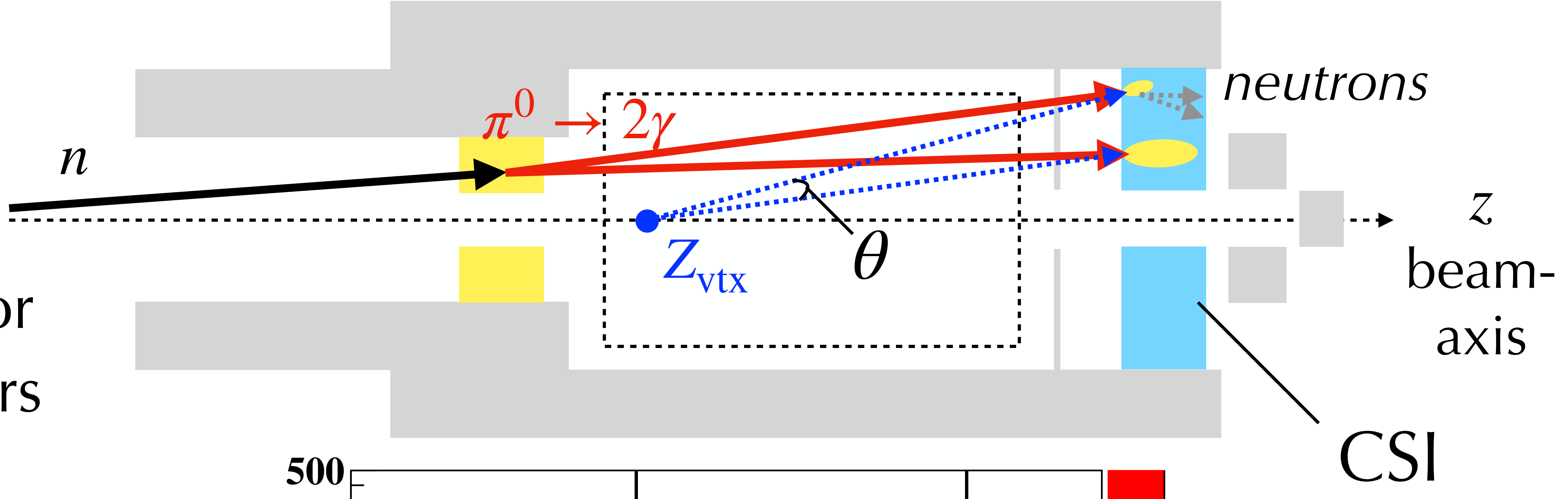
- Inefficiency evaluation with control data



Summary of inefficiency evaluation with $K_L \to 3\pi^0$ events

Veto Detector	FB	Barrel for high $E\gamma_6$	Barrel for low $E\gamma_6$	BHPV
Correction Factor (= Ineff.(Data) / Ineff.(MC))	1.42 ± 0.13	$0.77^{+0.85}_{-0.77}$	1.10 ± 0.10	$1.50^{+0.42}_{-0.51}$

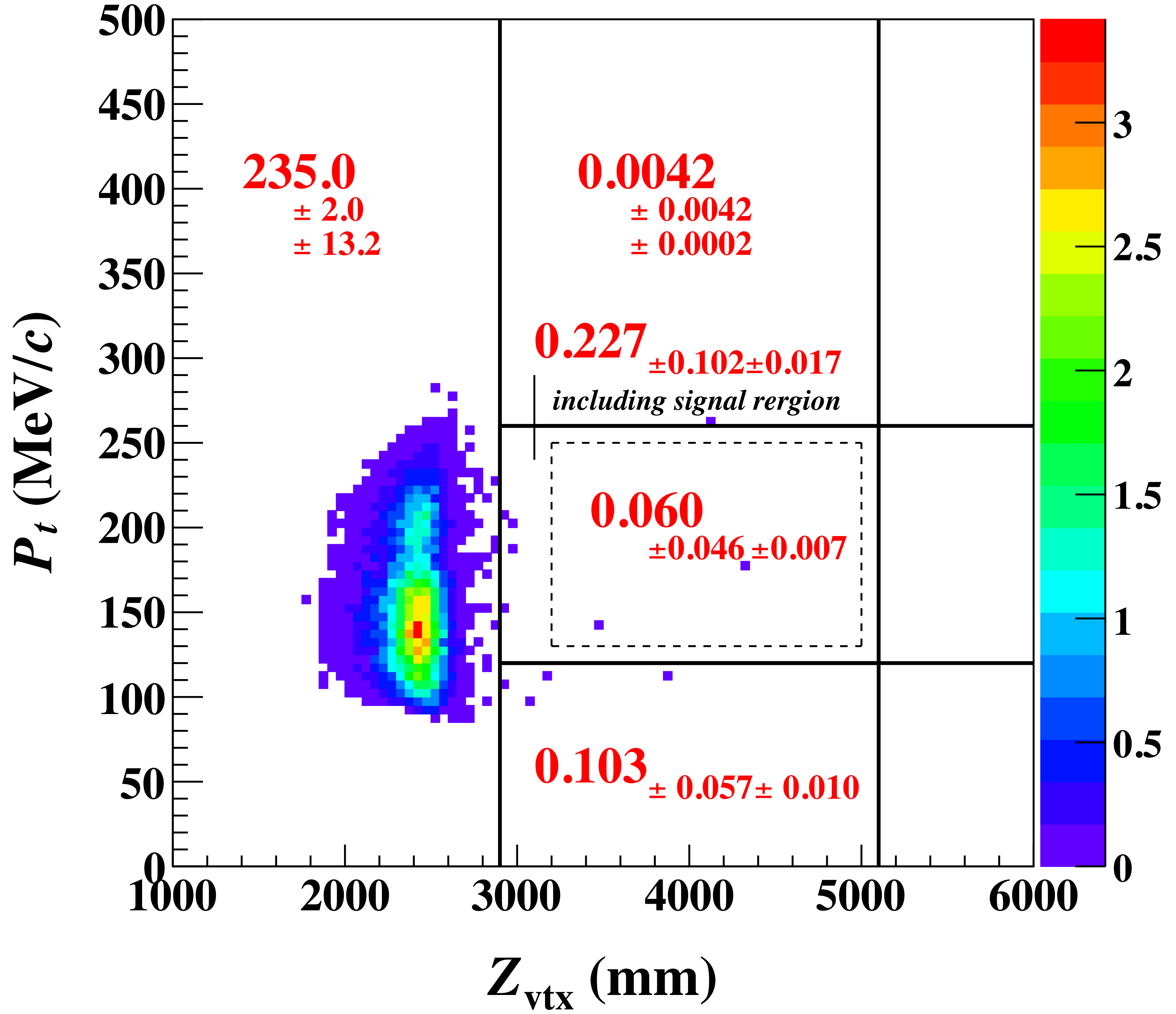
Background Estimation: Upstream-π^0



Background mechanism

- Halo neutron hits the upstream veto detector
  $\to$ A produced $\pi^0(\to 2\gamma)$ makes two clusters
- Photonuclear reaction in CSI causes energy mis-measurement of incident photons
  $\to$ Reconstructed Z_{vtx} shifts downstream

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



Number of background events
$= 0.060 \pm 0.046 \pm 0.007$

KOTO II: signal acceptance improvement

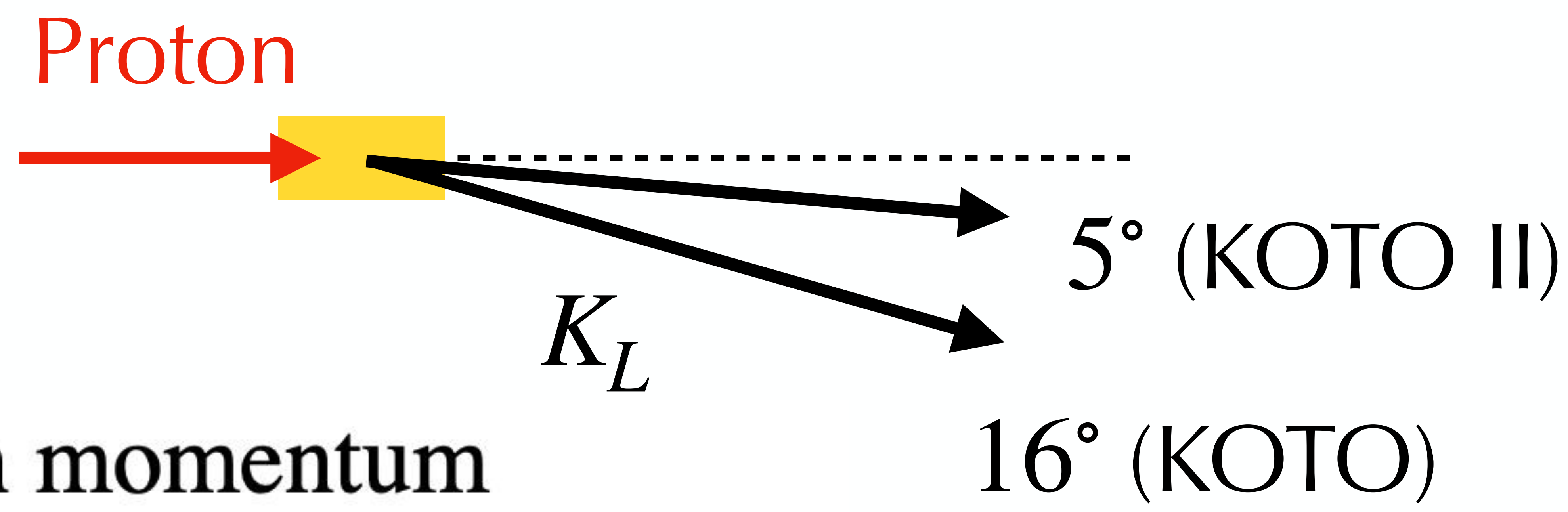
	KOTO II	KOTO	Improvement factor
Number of K_L/POT	$\times$ 2.6		2.6
P_{decay}	9.9%	3.3%	3.0
A_{geom}	24%	26%	0.9
A_{cut}	26%	11%	2.4
1-accidental loss	61%	29%	2.1
1-backsplash loss	91%	56%	1.6
Total			58

KOTO II: beam condition & running time

Assumed beam conditions and running time

Beam power	100 kW	(at 1-interaction-length T2 target)
		$(1.1 \times 10^7 K_L / 2 \times 10^{13}$ POT)
Repetition cycle	4.2 s	
Spill length	2 s	
Running time	3×10^7 s	

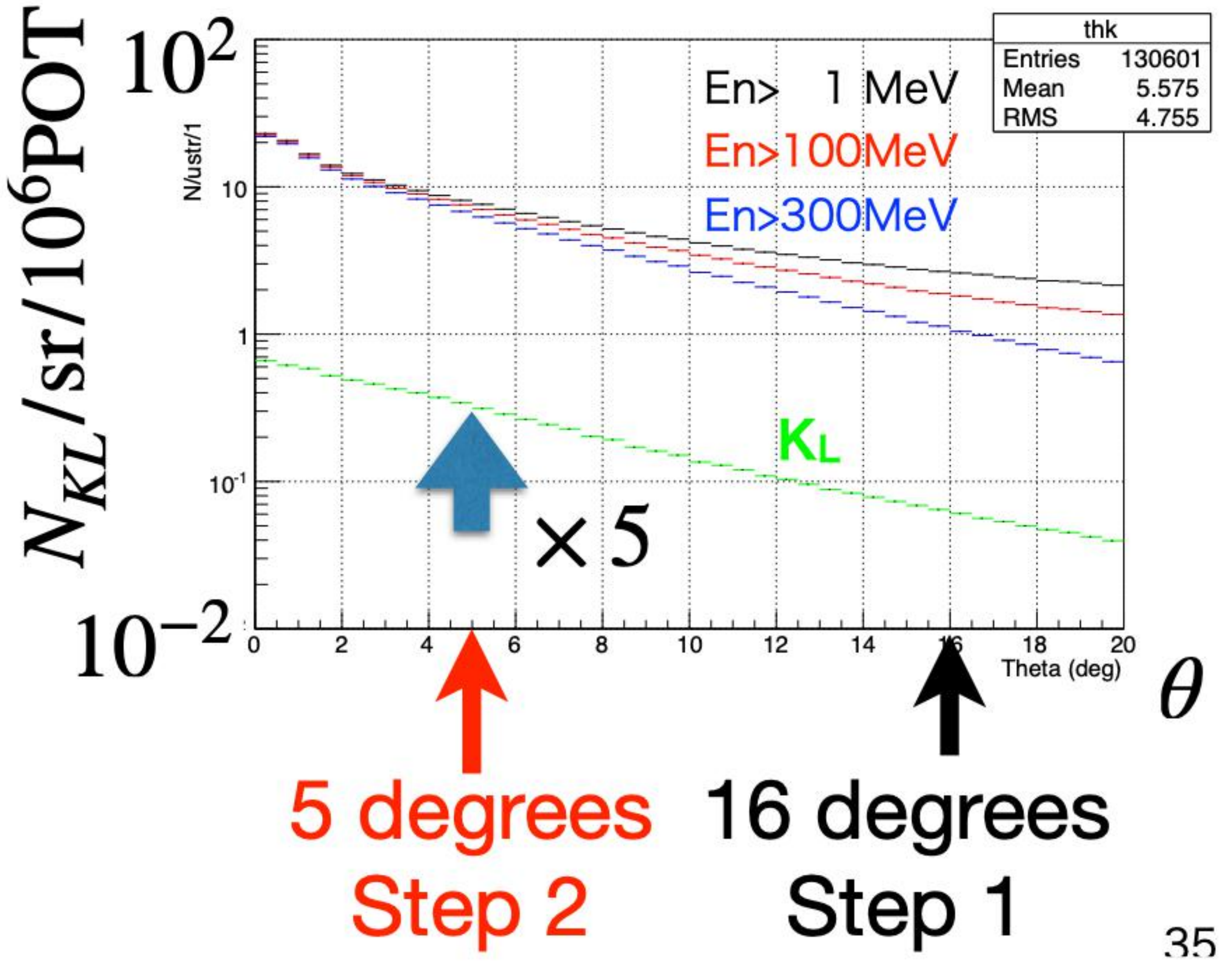
KOTO II: extraction angle

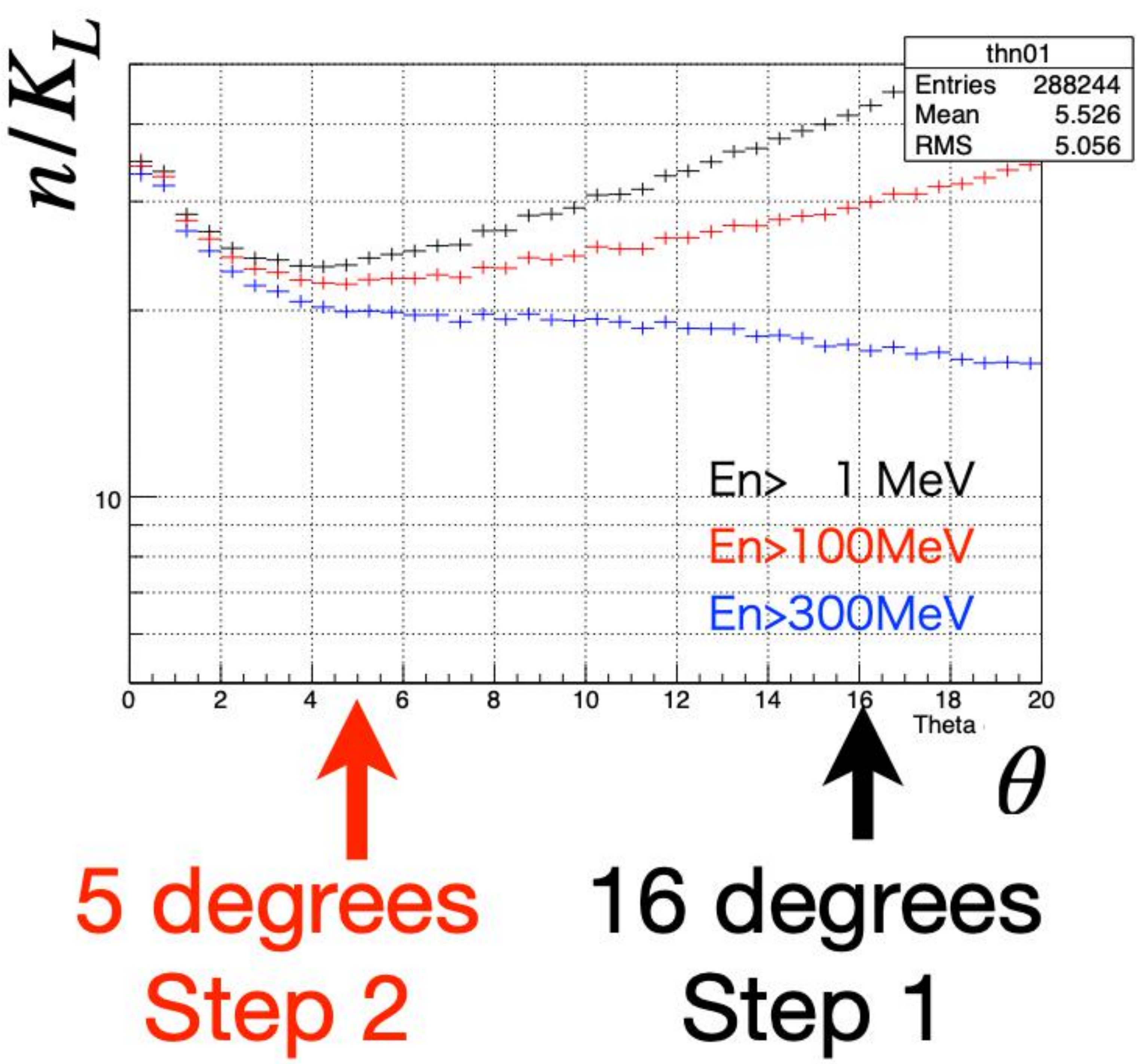


Small extraction angle $\theta \rightarrow$ High flux, High momentum

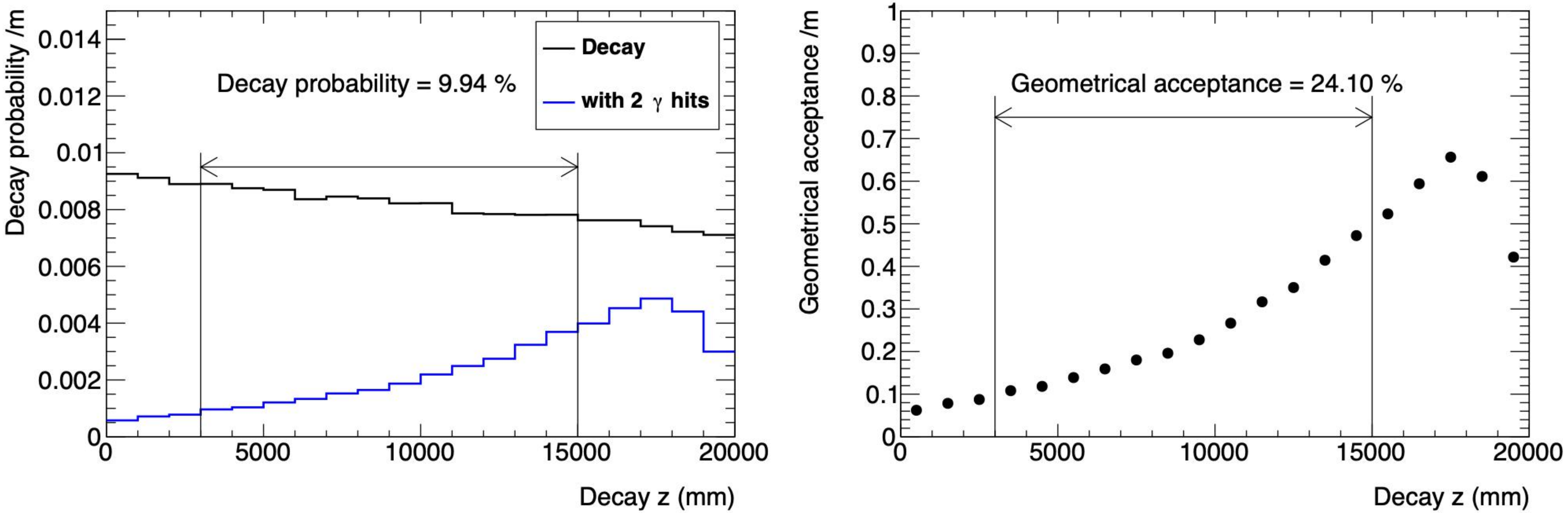
$\rightleftarrows$ neutron background

$\rightarrow$ 5° is optimal





KOTO II: decay volume



KOTO II: signal yield

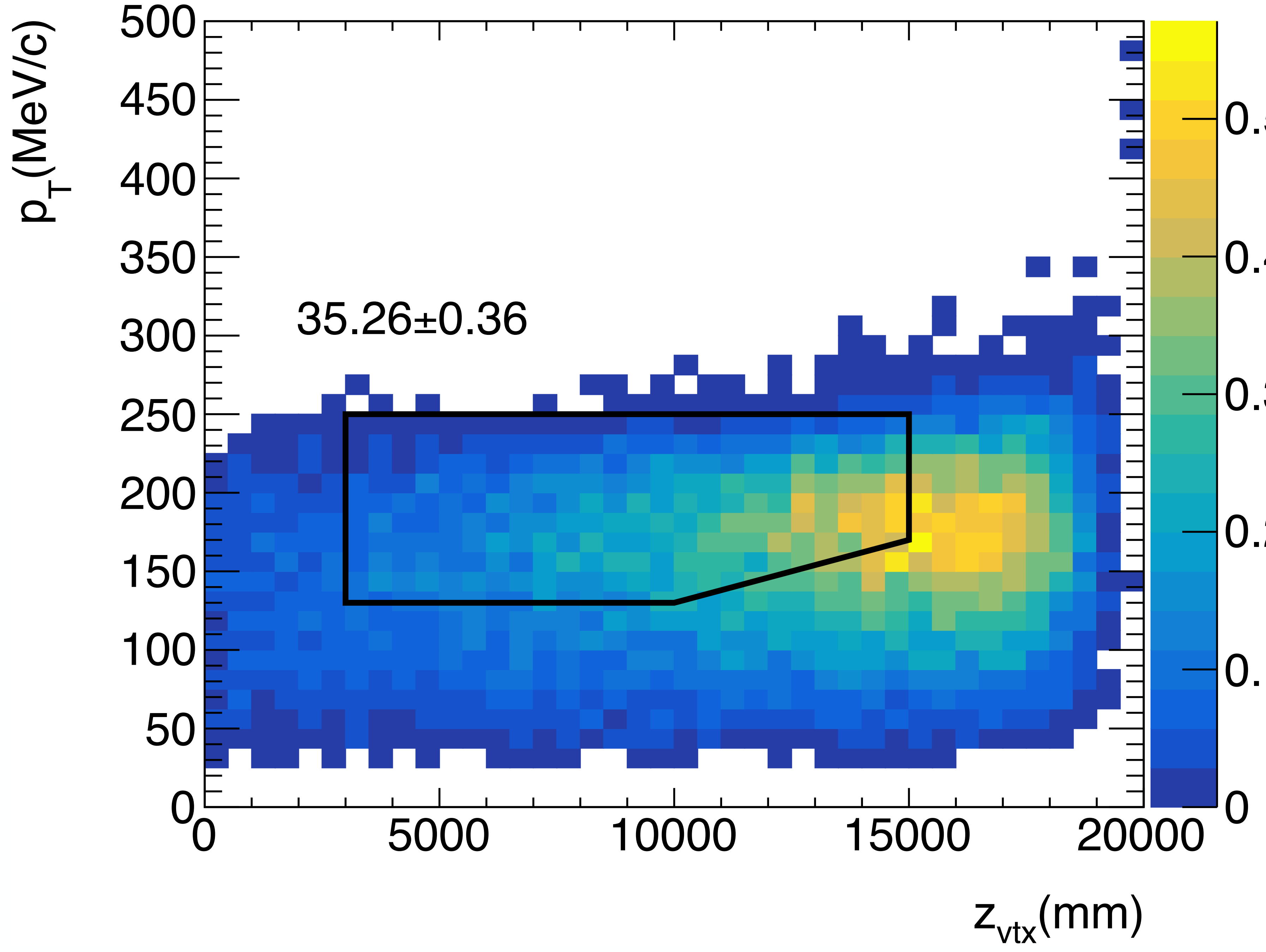
$$S = \frac{(\text{beam power}) \times (\text{running time})}{(\text{beam energy})} \times (\text{number of } K_L/\text{POT})$$

$$\times P_{\text{decay}} \times A_{\text{geom}} \times A_{\text{cut}} \times (\text{1-accidental loss}) \times (\text{1-backsplash loss}) \times \mathcal{B}_{K_L \to \pi^0 \nu \overline{\nu}}$$

$$= \frac{(100\ \text{kW}) \times (3 \times 10^7\ \text{s})}{(30\ \text{GeV})} \times \frac{(1.1 \times 10^7 K_L)}{(2 \times 10^{13}\ \text{POT})}$$

$$\times 9.9\% \times 24\% \times 26\% \times (1 - 39\%) \times 91\% \times (3 \times 10^{-11})$$

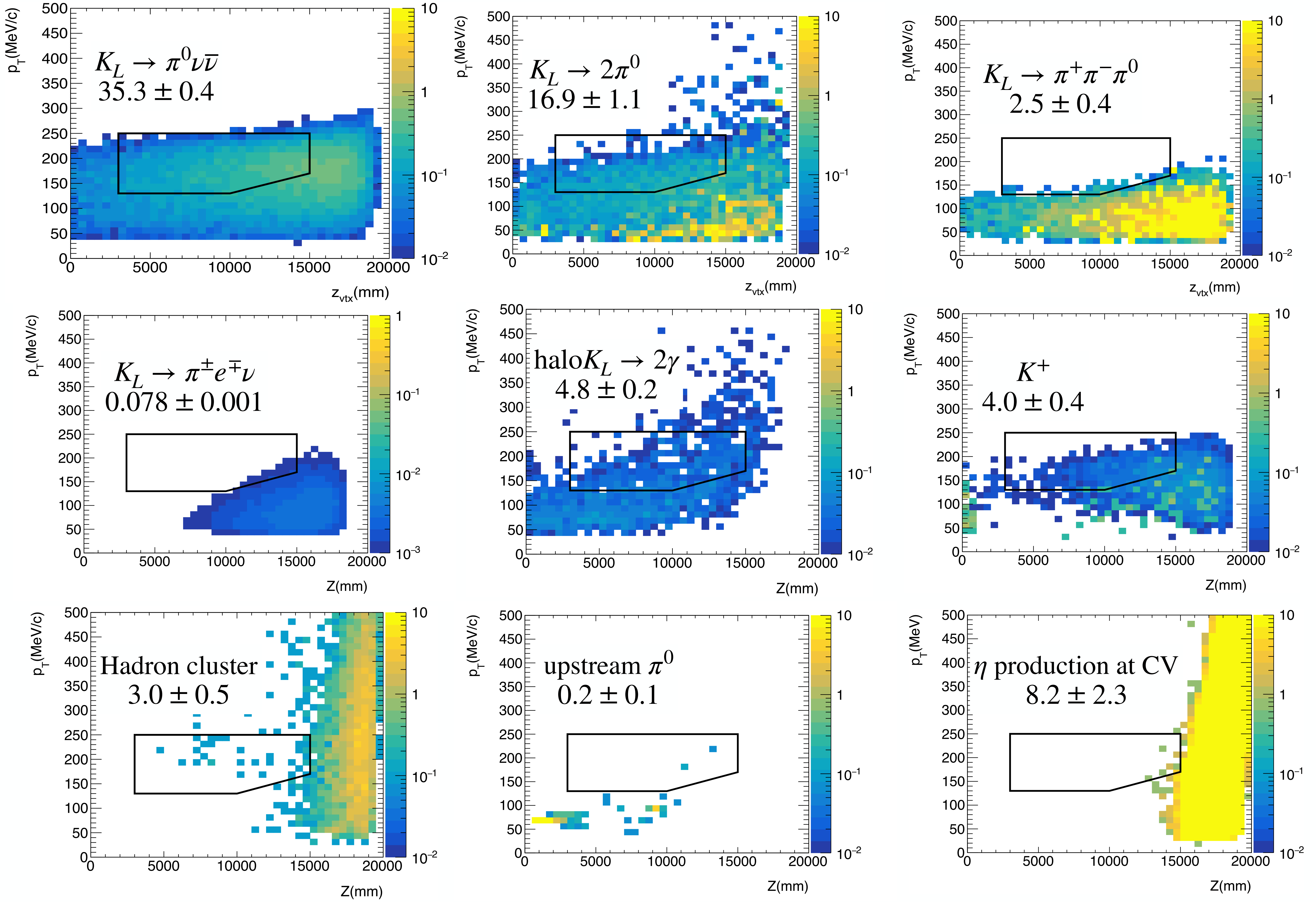
$$= 35.$$



KOTO II: background

Background summary

Background	Number	
$K_L \to \pi^0\pi^0$	16.9	± 1.1
$K_L \to \pi^+\pi^-\pi^0$	2.5	± 0.4
$K_L \to \pi^\pm e^\mp \nu$	0.08	± 0.0006
halo $K_L \to 2\gamma$	4.8	± 0.2
$K^\pm \to \pi^0 e^\pm \nu$	4.0	± 0.4
hadron cluster	3.0	± 0.5
π^0 at upstream	0.2	± 0.1
η at downstream	8.2	± 2.3
Total	40	± 2.7

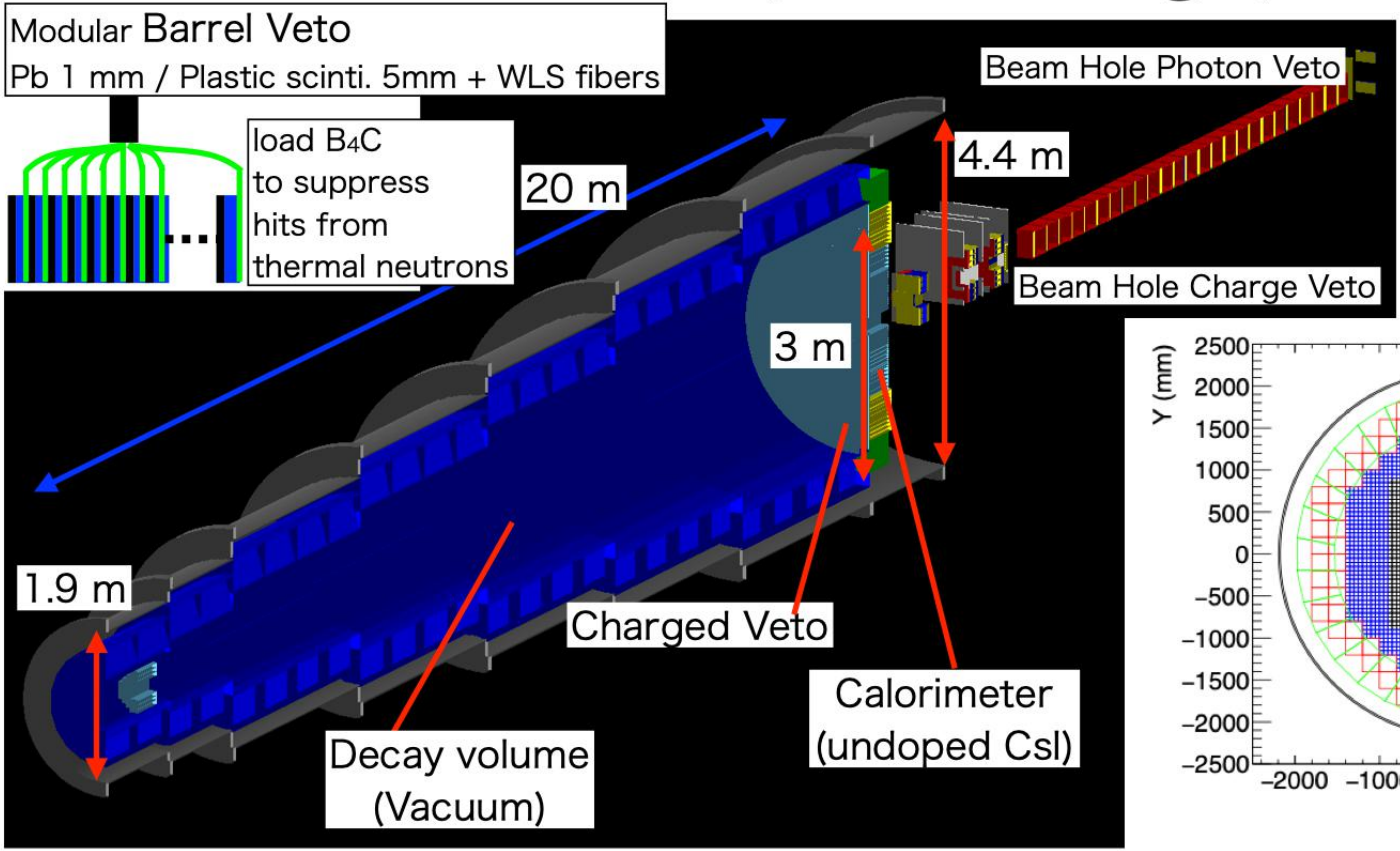


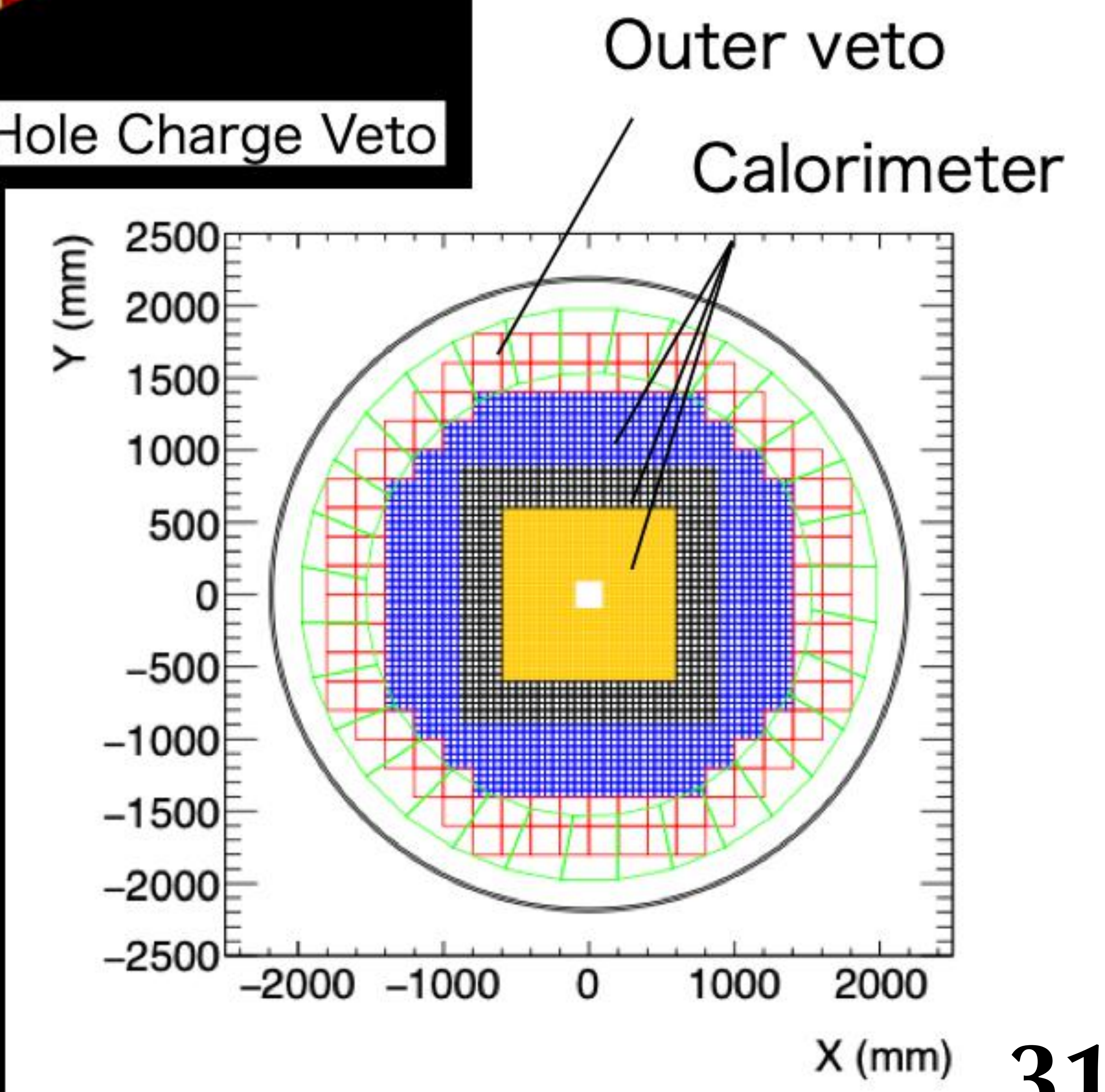
KOTO II: sensitivity and physics impact

	Formula	Value
Signal (branching fraction : 3×10^{-11})	S	35.3 ± 0.4
Background	B	40 ± 2.7
Single event sensitivity	$(3 \times 10^{-11})/S$	8.5×10^{-13}
Signal-to-background ratio	S/B	0.89
Significance of the observation	$S/\sqrt{B}$	5.6σ
90%-C.L. excess / deficit	$1.64 \times \sqrt{S+B}$	14 events
	$1.64 \times \sqrt{S+B}/S$	40% of SM
Precision on branching fraction	$\sqrt{S+B}/S$	25%
Precision on CKM parameter η	$0.5 \times \sqrt{S+B}/S$	12%

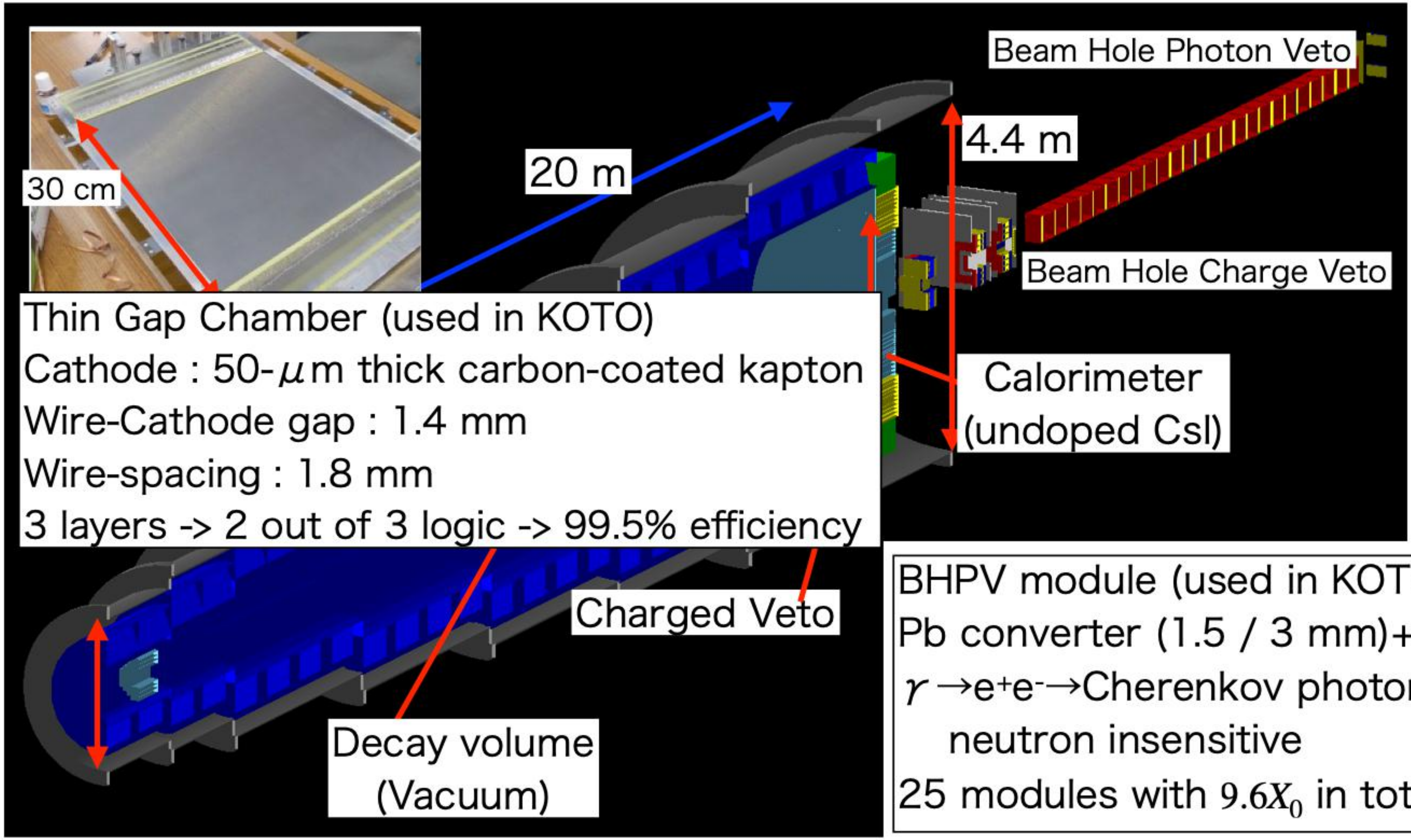
* A running time of 3×10^{7} s is assumed in the calculation.

KOTO II detector (base design)





KOTO II detector (base design)



Thin Gap Chamber (used in KOTO)
Cathode : 50-μm thick carbon-coated kapton
Wire-Cathode gap : 1.4 mm
Wire-spacing : 1.8 mm
3 layers -> 2 out of 3 logic -> 99.5% efficiency

BHPV module (used in KOTO)
Pb converter (1.5 / 3 mm)+Aerogel
$\gamma \rightarrow e^+e^- \rightarrow$ Cherenkov photon
neutron insensitive
25 modules with $9.6X_0$ in total