Chieh Lin (National Changhua University of Education)

KOTO/KOTO-II Prospect

2024 Taiwan Instrumentation And Detector Consortium (TIDC)

Messages in this talk

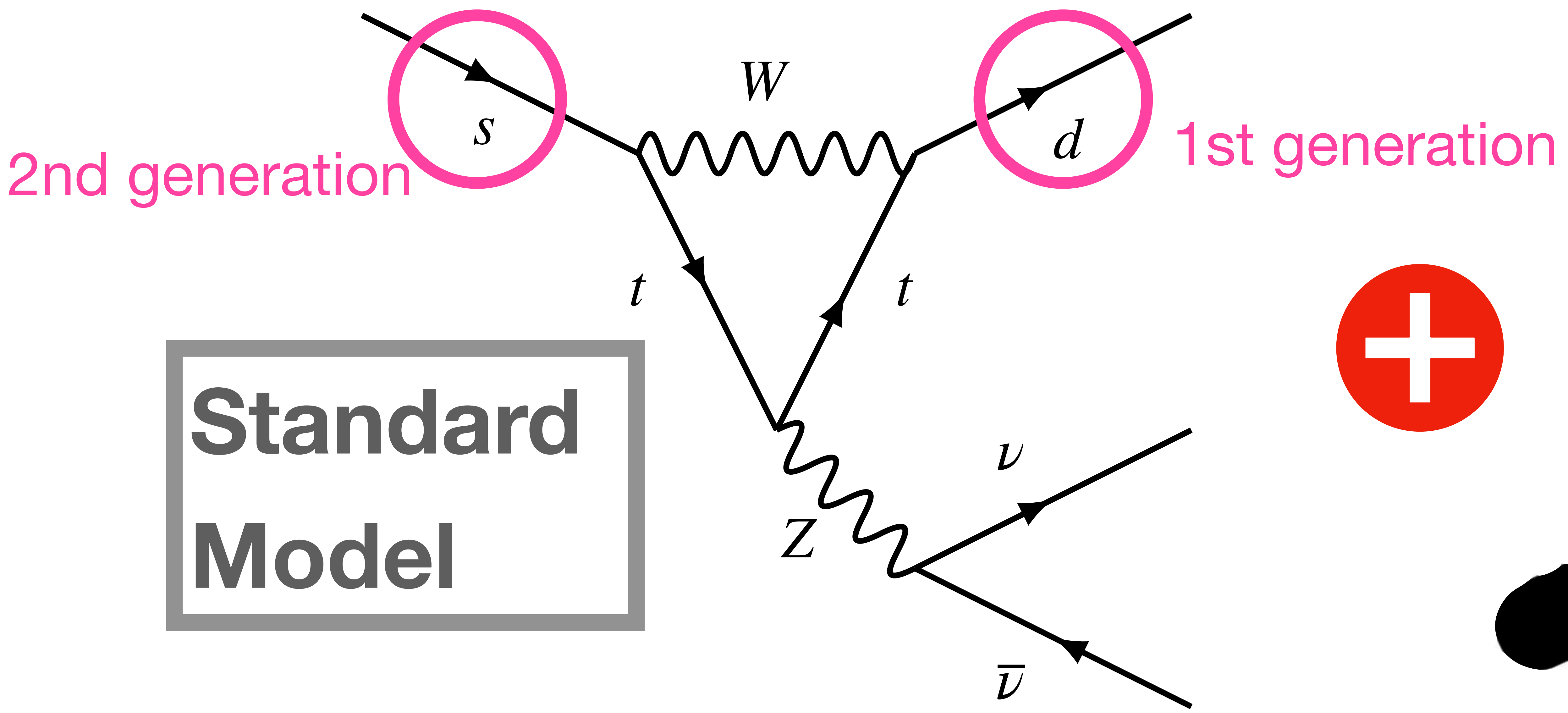
- Rare kaon decays provide a unique probe of testing new physics at very high energy regime where colliders cannot explore.
- Besides the golden mode $K_L^0 \to \pi^0 \nu \bar{\nu}$, the light new physics scenarios can also be tested at KOTO/KOTO-II.

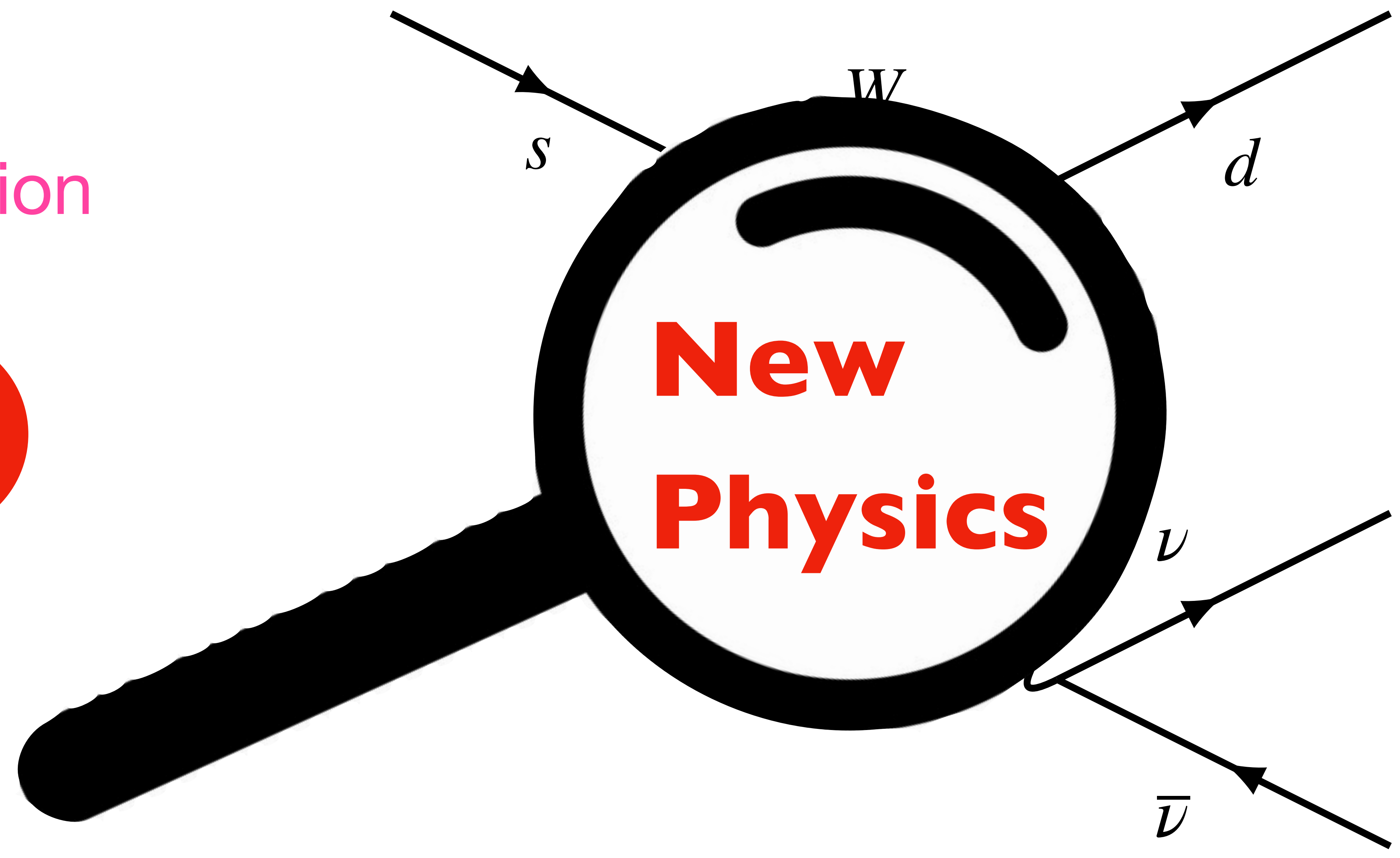
Search for new physics via rare kaon decays

Kaon: particle contains s-quark.

CP- CP+

$$K_L^0 \to \pi^0 \nu \overline{\nu}$$





$$\mathscr{B}(K_L^0 \to \pi^0 \nu \overline{\nu})_{SM} = 3 \times 10^{-11}$$

(< 2% error only)

Rare & Precisely-predicted

$$\frac{1}{\Lambda_{NP}^2} \to \Lambda_{NP} \sim \mathcal{O}(100) \text{ (TeV)}$$

Further study the energy regime where colliders cannot explore now.

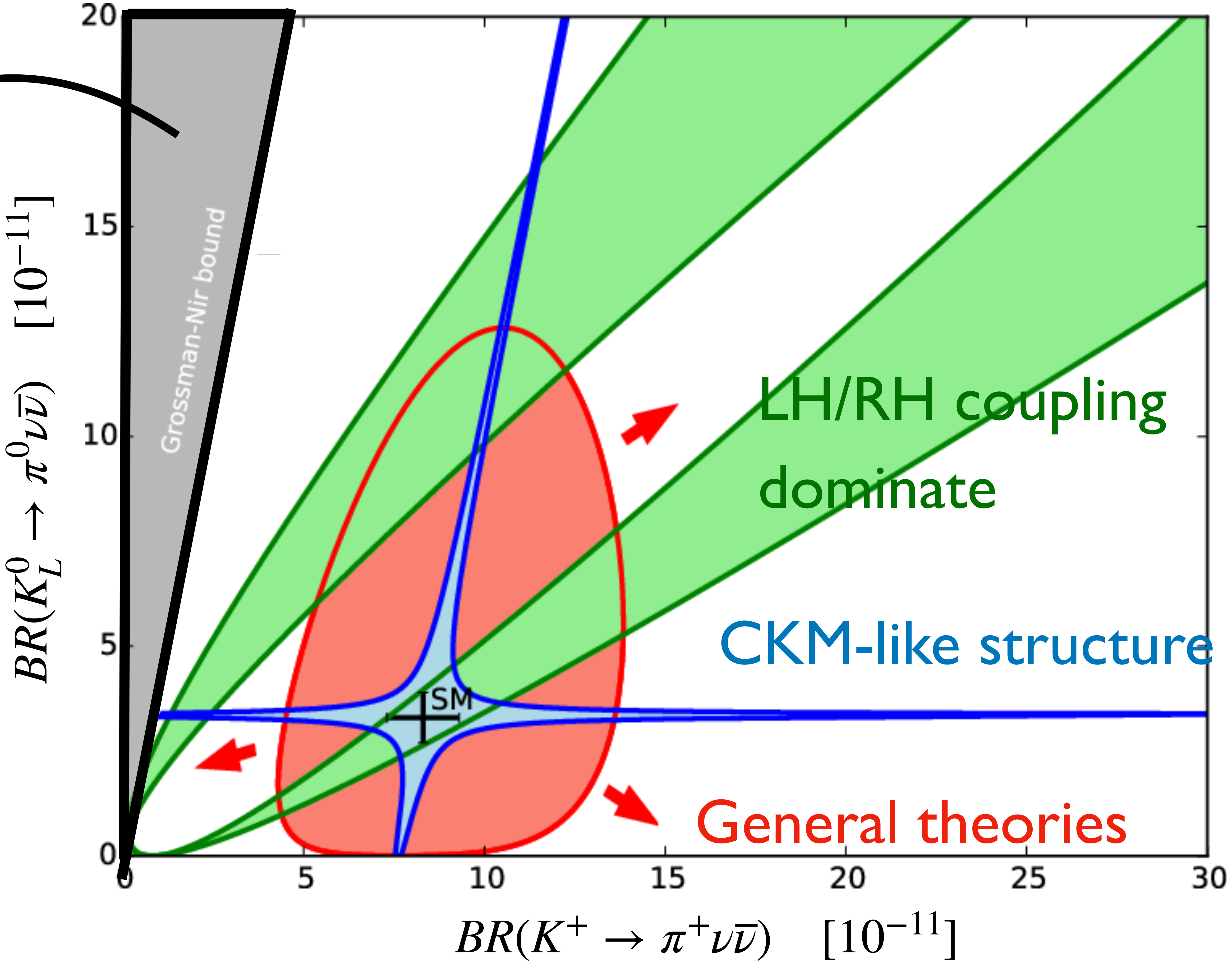
New physics scenario via $K \to \pi\nu\bar{\nu}$

Grossman-Nir (GN) bound

Model-independent constraint

(Weak isospin rotation with $\Delta I = 1/2$)

$B(K_L^0 \to \pi^0\nu\bar{\nu}) \leq 4.3 \times B(K^+ \to \pi^+\nu\bar{\nu})$



New physics scenario via $K \to \pi\nu\bar{\nu}$

Experimental result of $B(K^+ \to \pi^+\nu\bar{\nu})$

$(10.6^{+4.0}_{-3.5} \pm 0.9) \times 10^{-11}$ (68% C.L.)

JHEP 06 (2021) 093

Agrees with SM $(9.11 \pm 0.72) \times 10^{-11}$

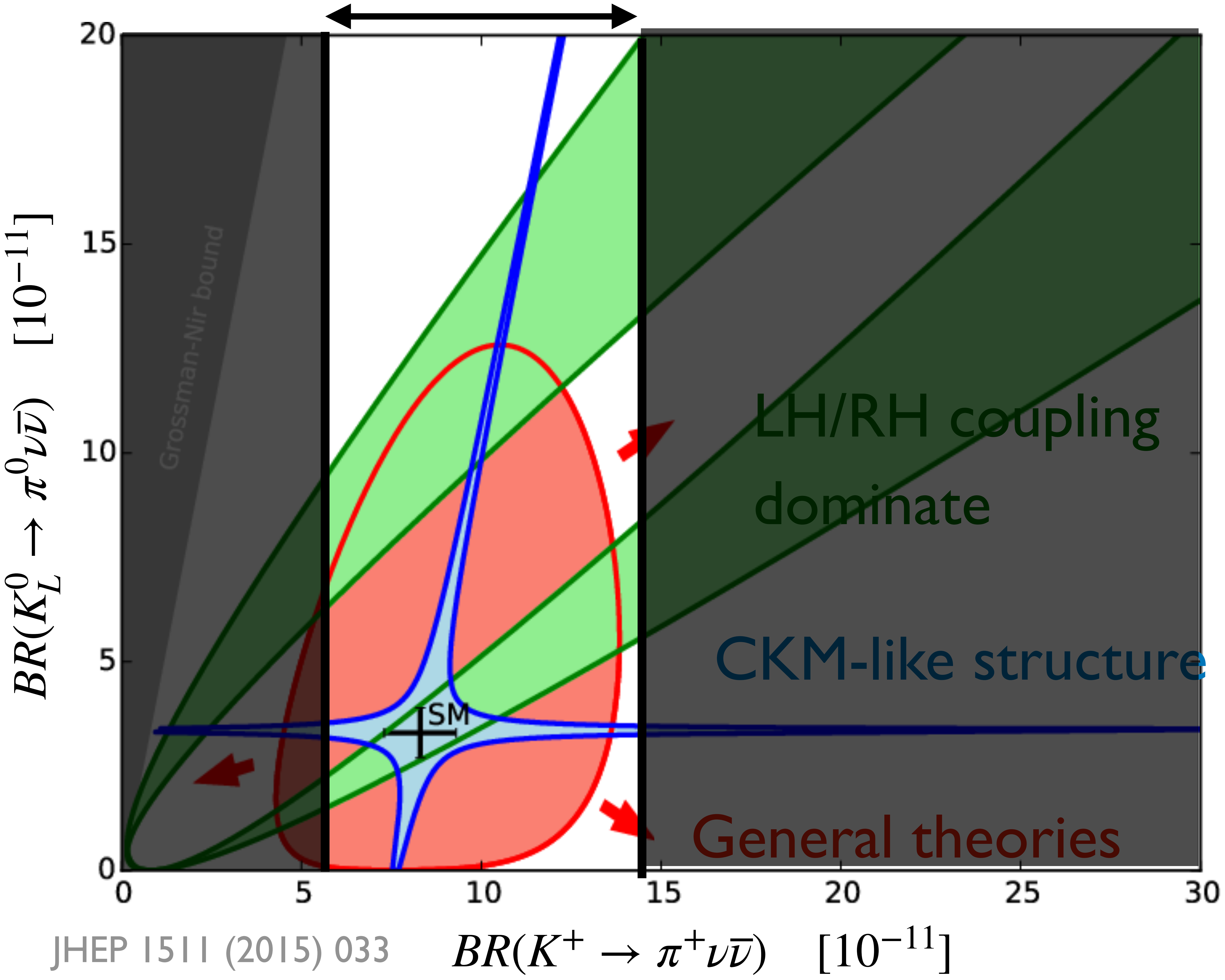
JHEP 1511 (2015) 033

Grossmain-Nir (GN) bound

$B(K_L^0 \to \pi^0\nu\bar{\nu}) \leq 4.3 \times B(K^+ \to \pi^+\nu\bar{\nu})$

$\leq 6.3 \times 10^{-10}$ (68% C.L.)

1-σ window by NA62 (2021)



JHEP 1511 (2015) 033

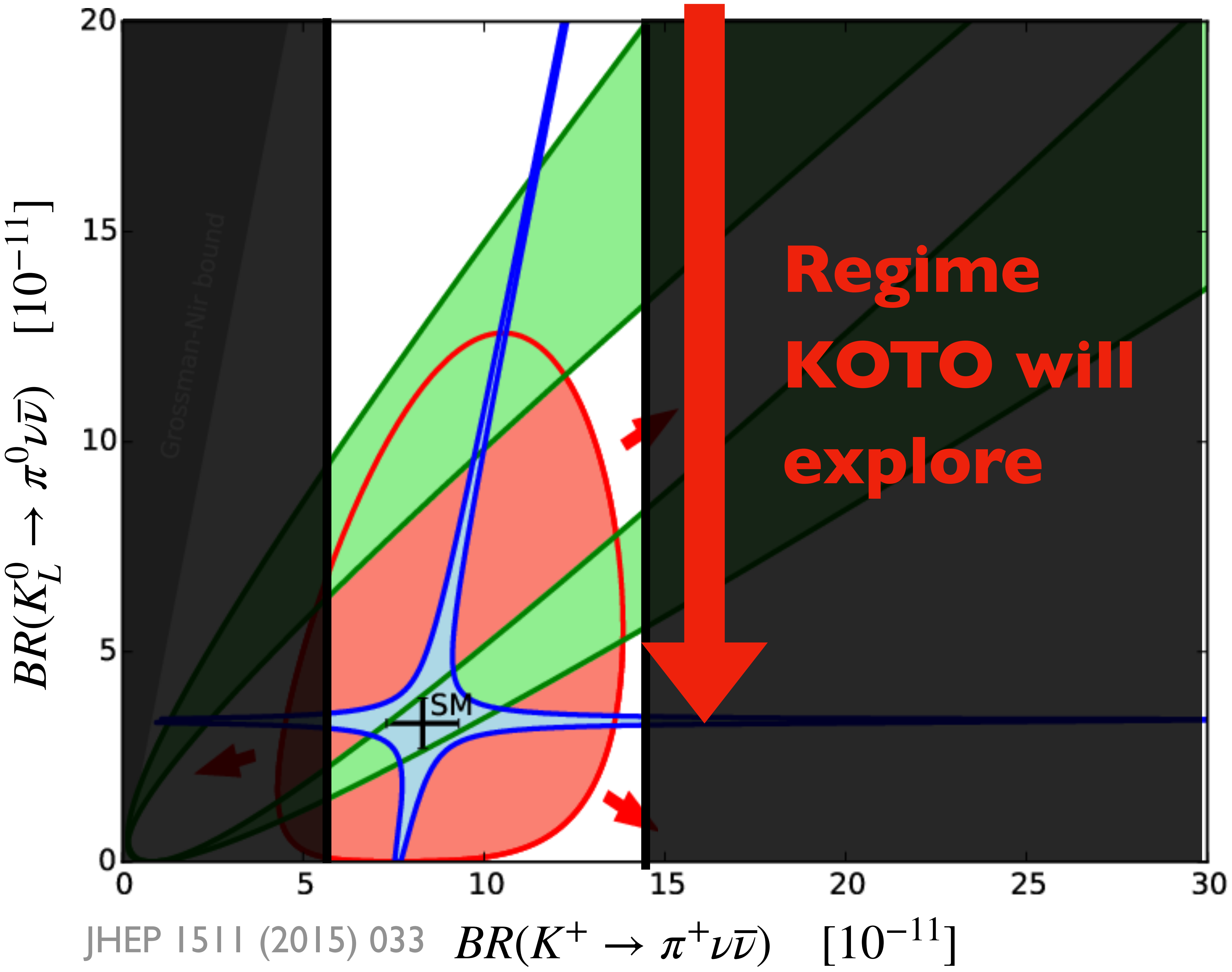
New physics scenario via $K \to \pi\nu\bar{\nu}$

Experimental result of $B(K_L^0 \to \pi^0\nu\bar{\nu})$

$< 2.2 \times 10^{-9}$ (90% C.L.)

arXiv:2411.11237 [hep-ex]

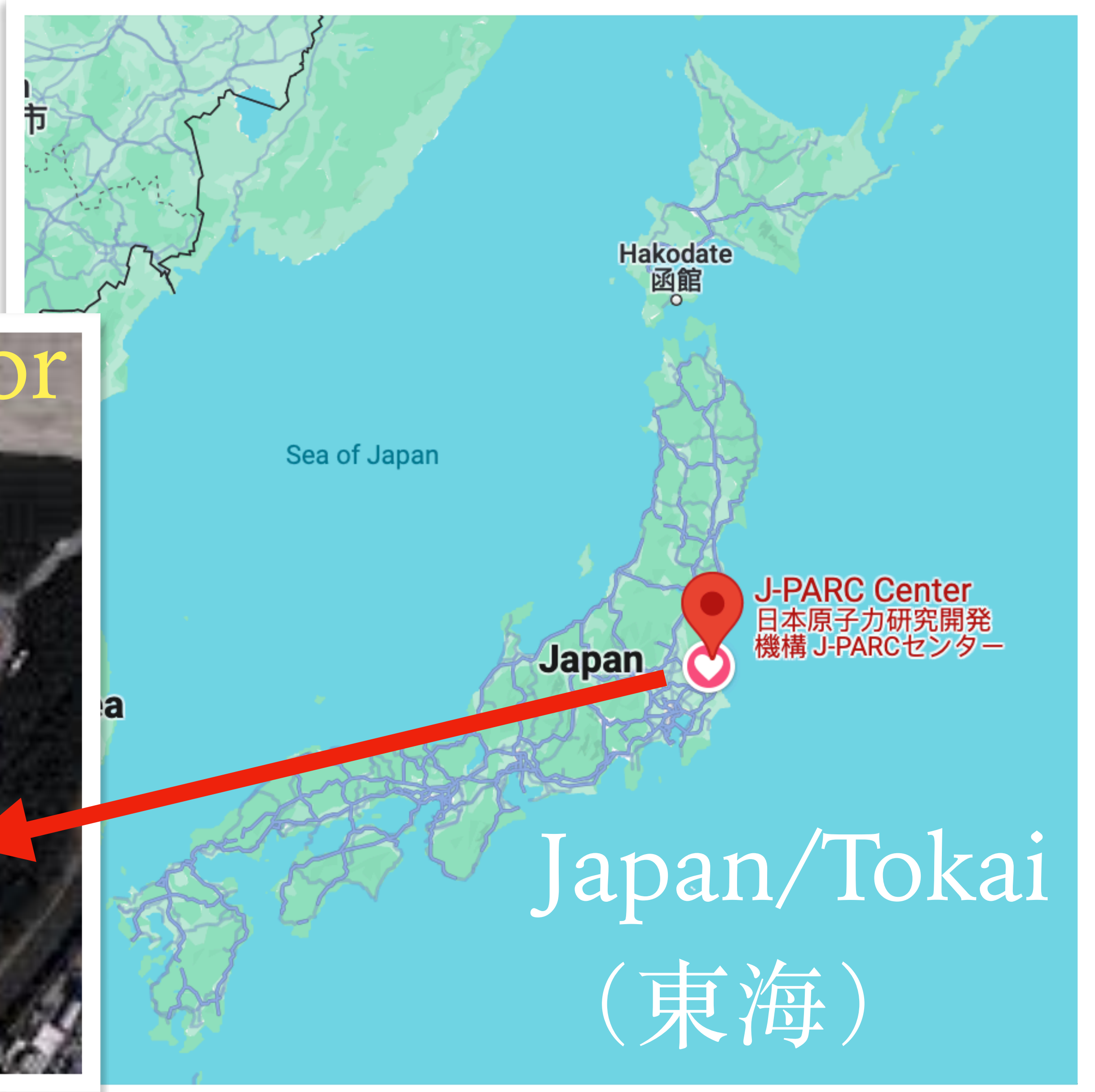
Two orders of magnitudes from the SM.

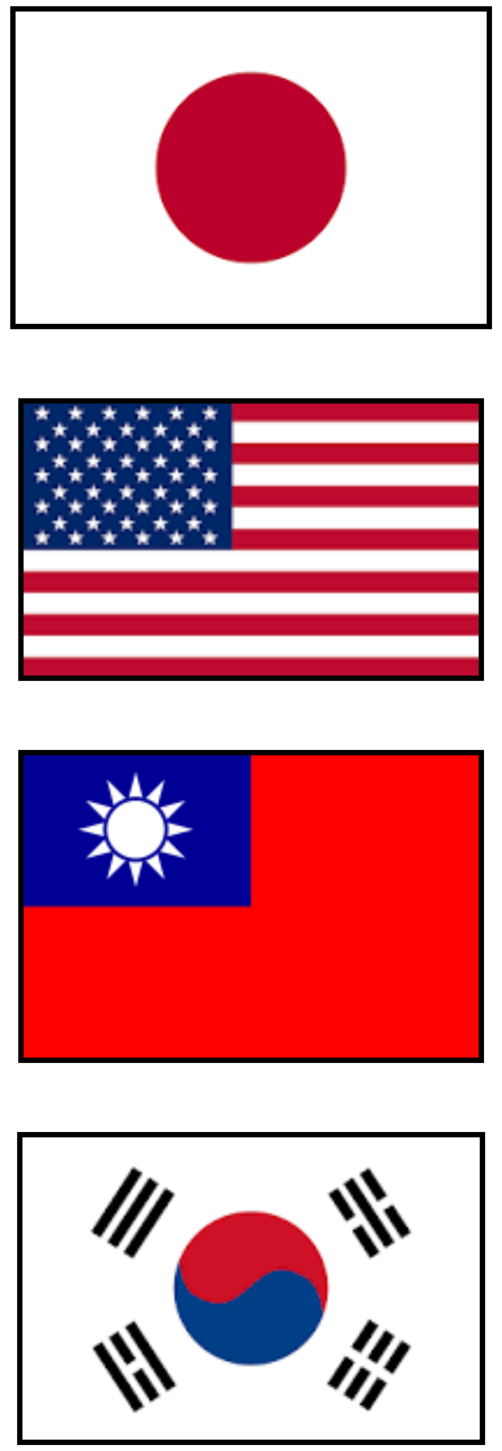


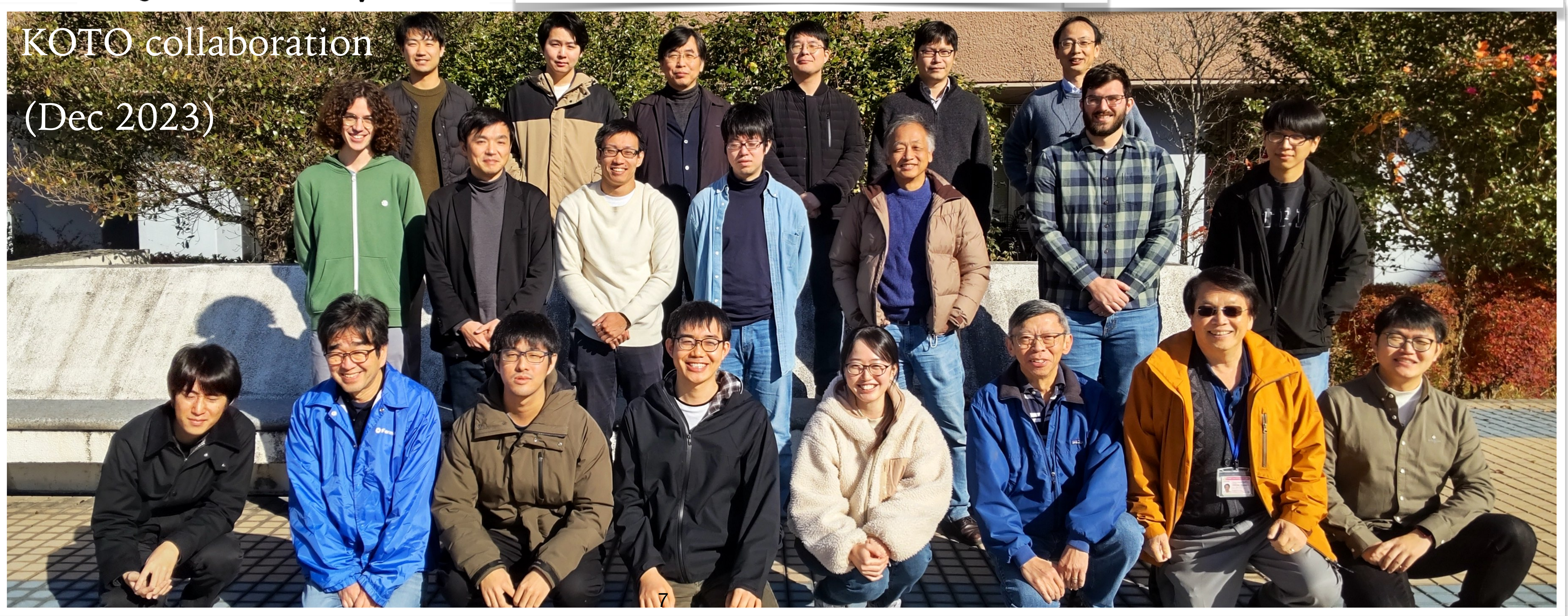
JHEP 1511 (2015) 033

The KOTO Experiment

KOTO (<u>K0</u> at <u>TO</u>kai) aims to search for the rare kaon decay at J-PARC.

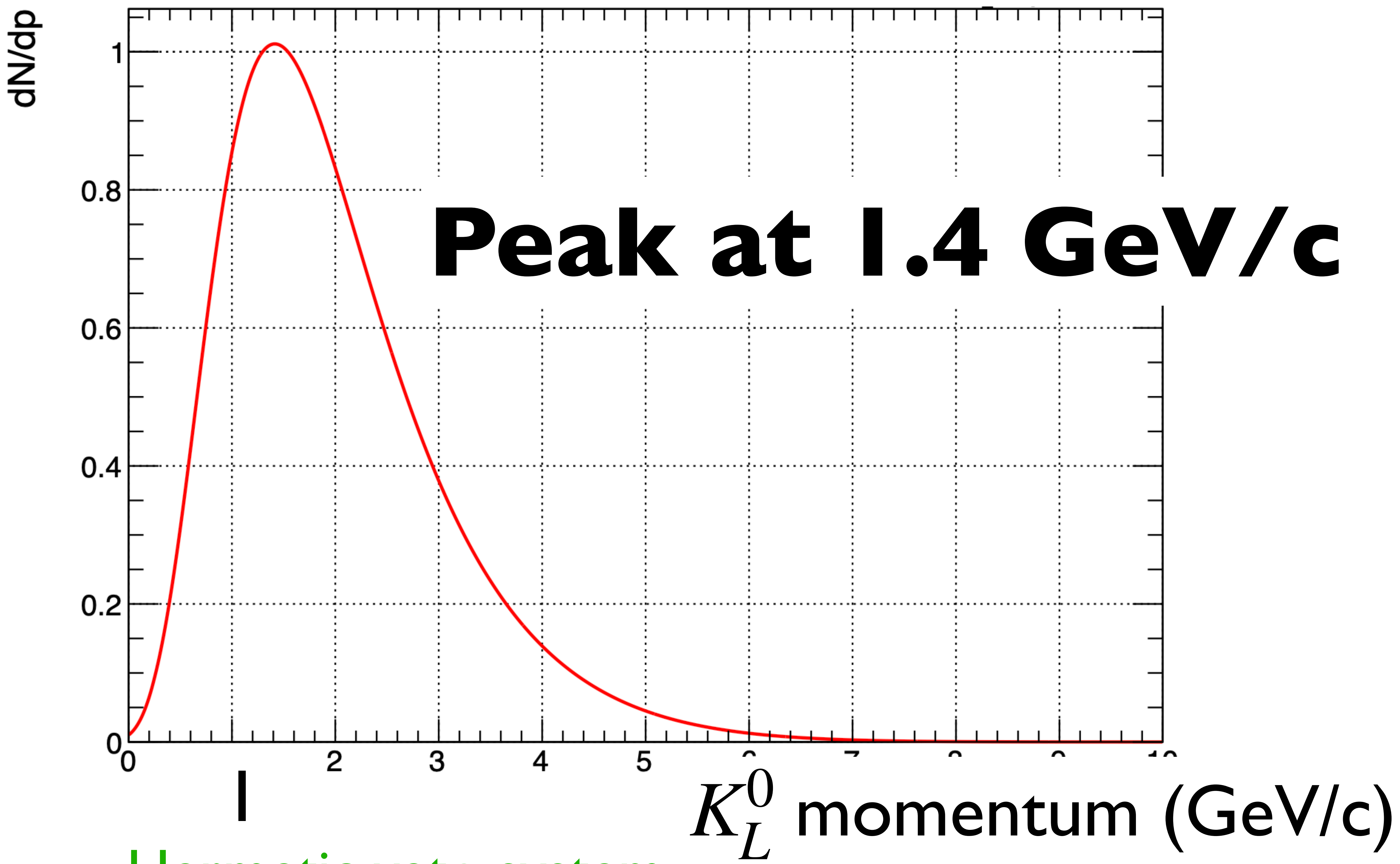


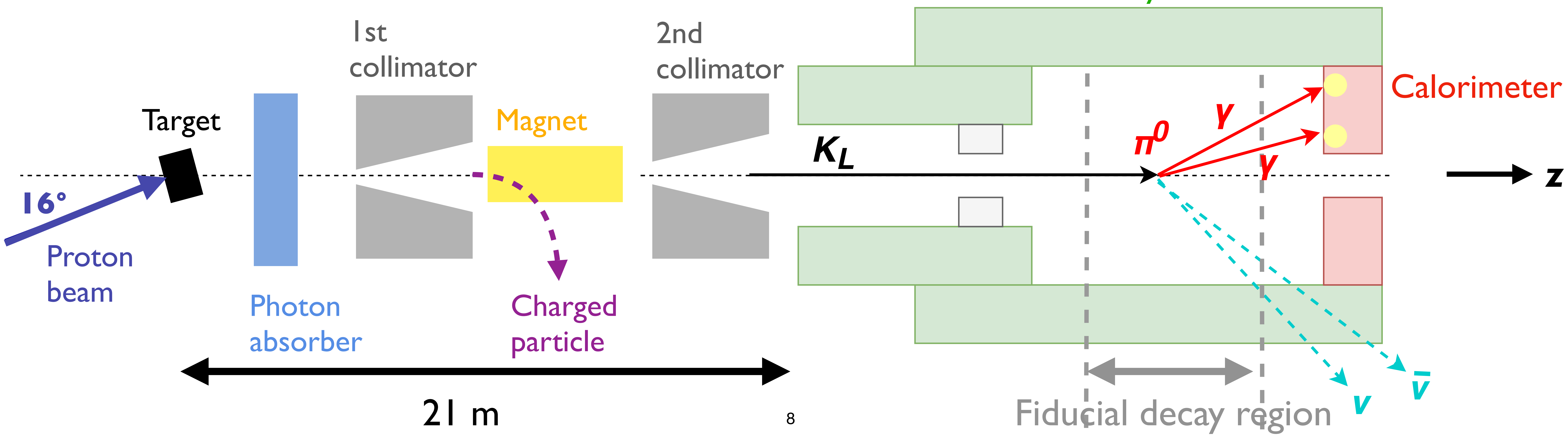




Neutral Kaon Beam

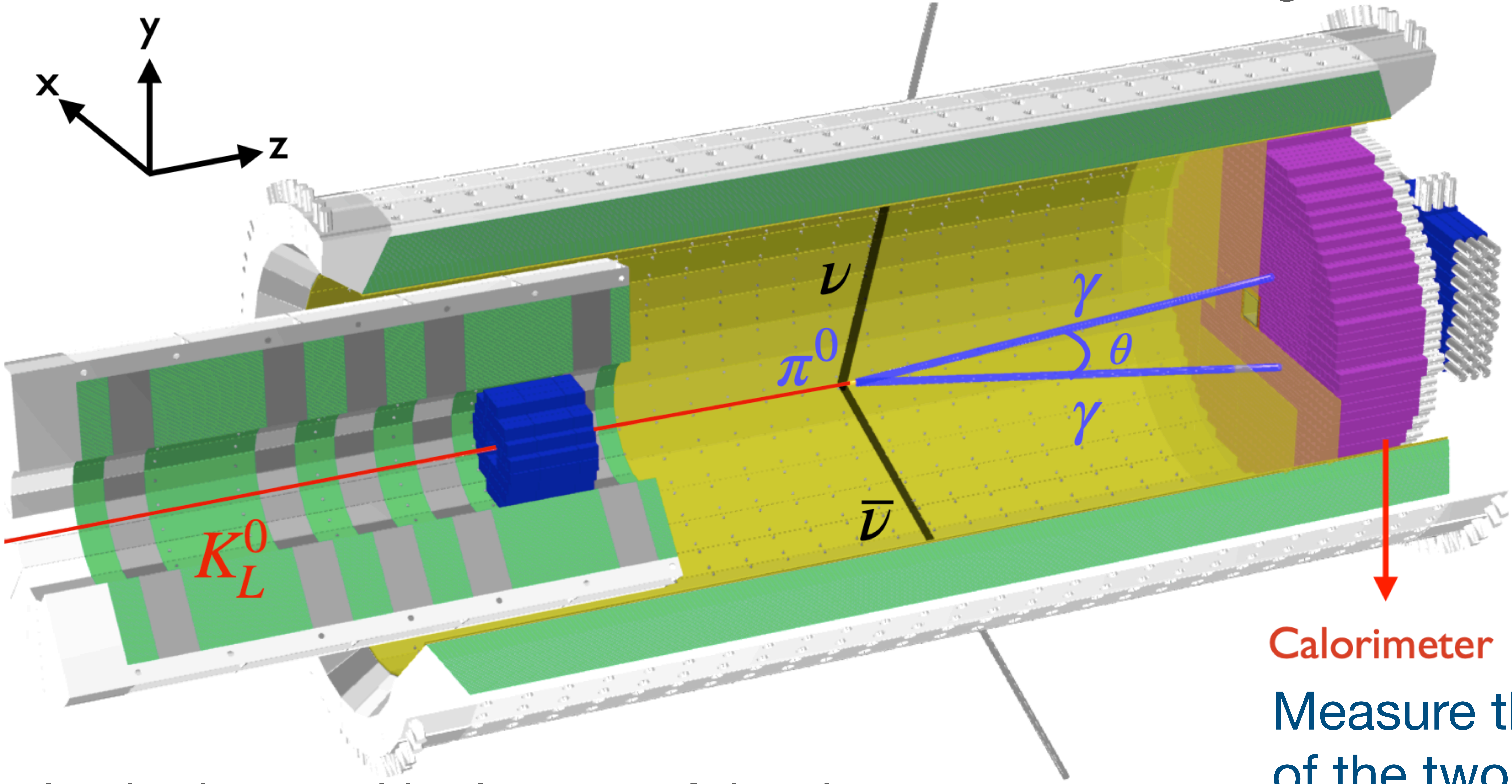
- 21-m-long beamline → Long-lived neutral particles (K_L^0, n, γ) are dominated.
- Two collimators → Sharpen the K_L^0 beam to measure the missing P_T of π^0.





Experimental Principle

Neutrinos cannot be detected.
→ The π^0 should have missing transverse momentum.



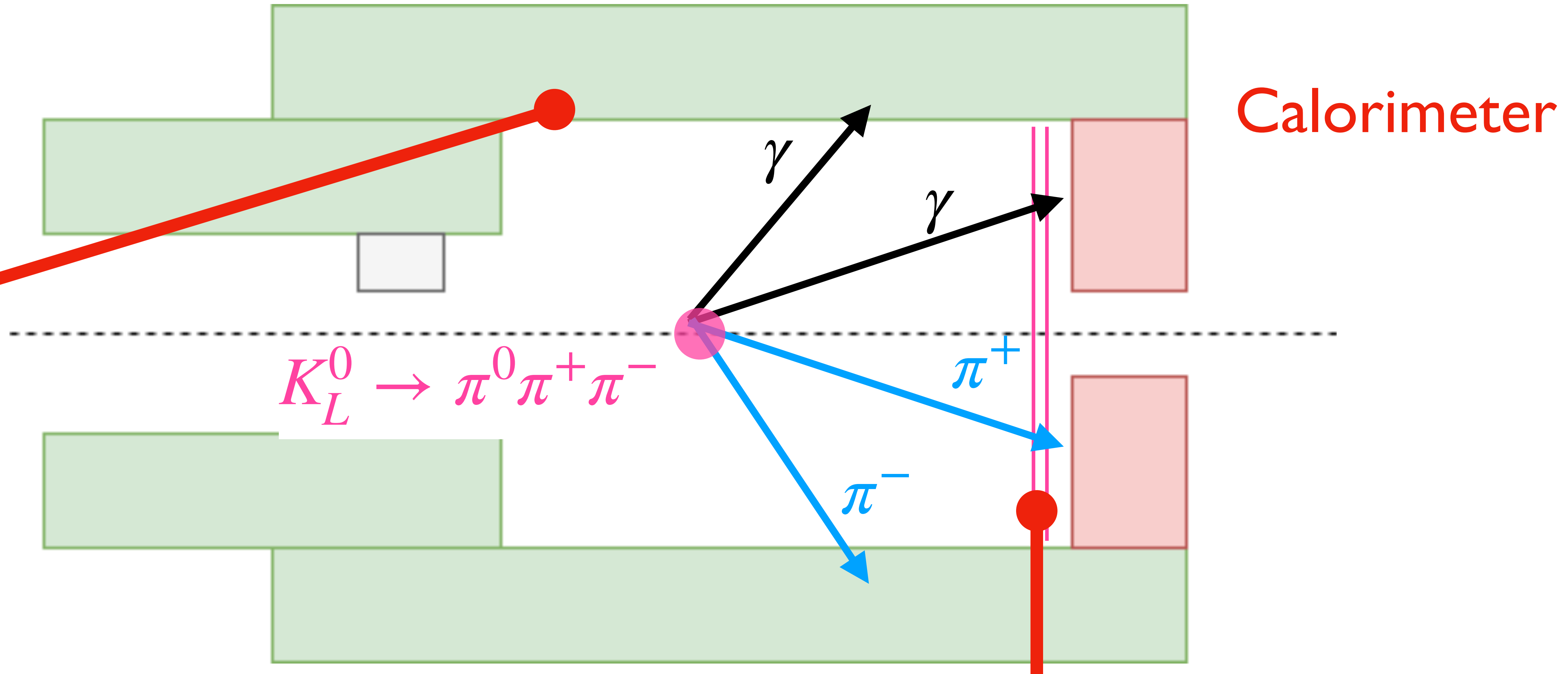
Calorimeter

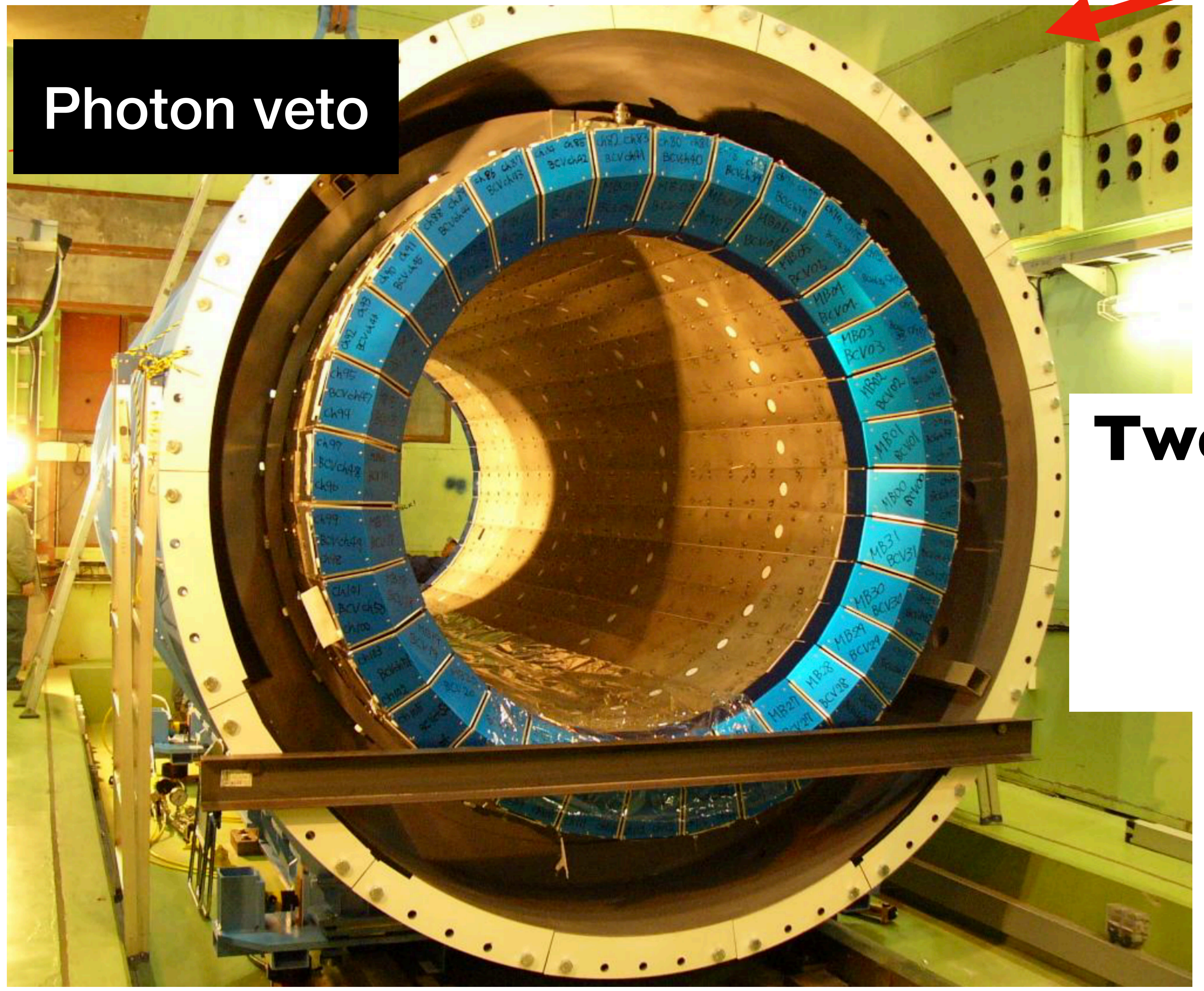
Measure the energies of the two photons.

Nothing else is detected in the rest of the detector.

Detector Design

Hermetic veto system

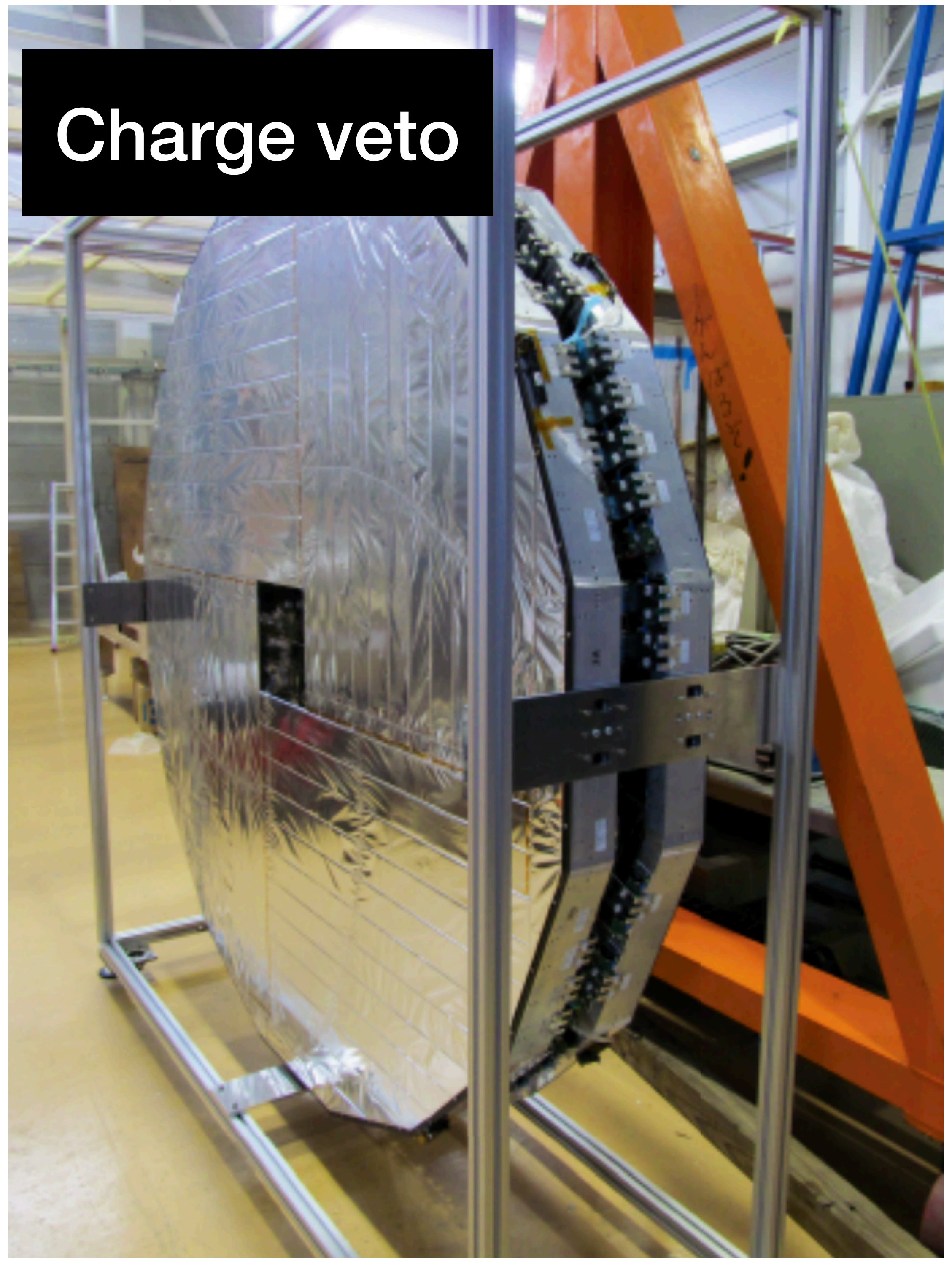




Two layers of thin plastic scintillators.

Reject charged particle hits in the calorimeter.

Inefficiency $\sim \mathcal{O}(10^{-5})$.



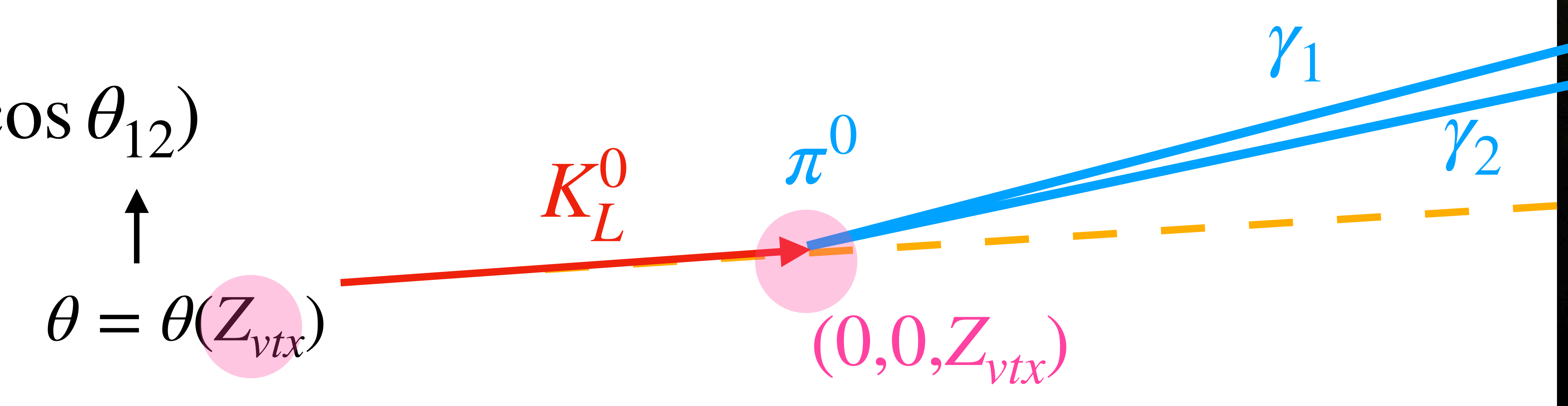
Barrel counter sandwiched by lead and scintillators.

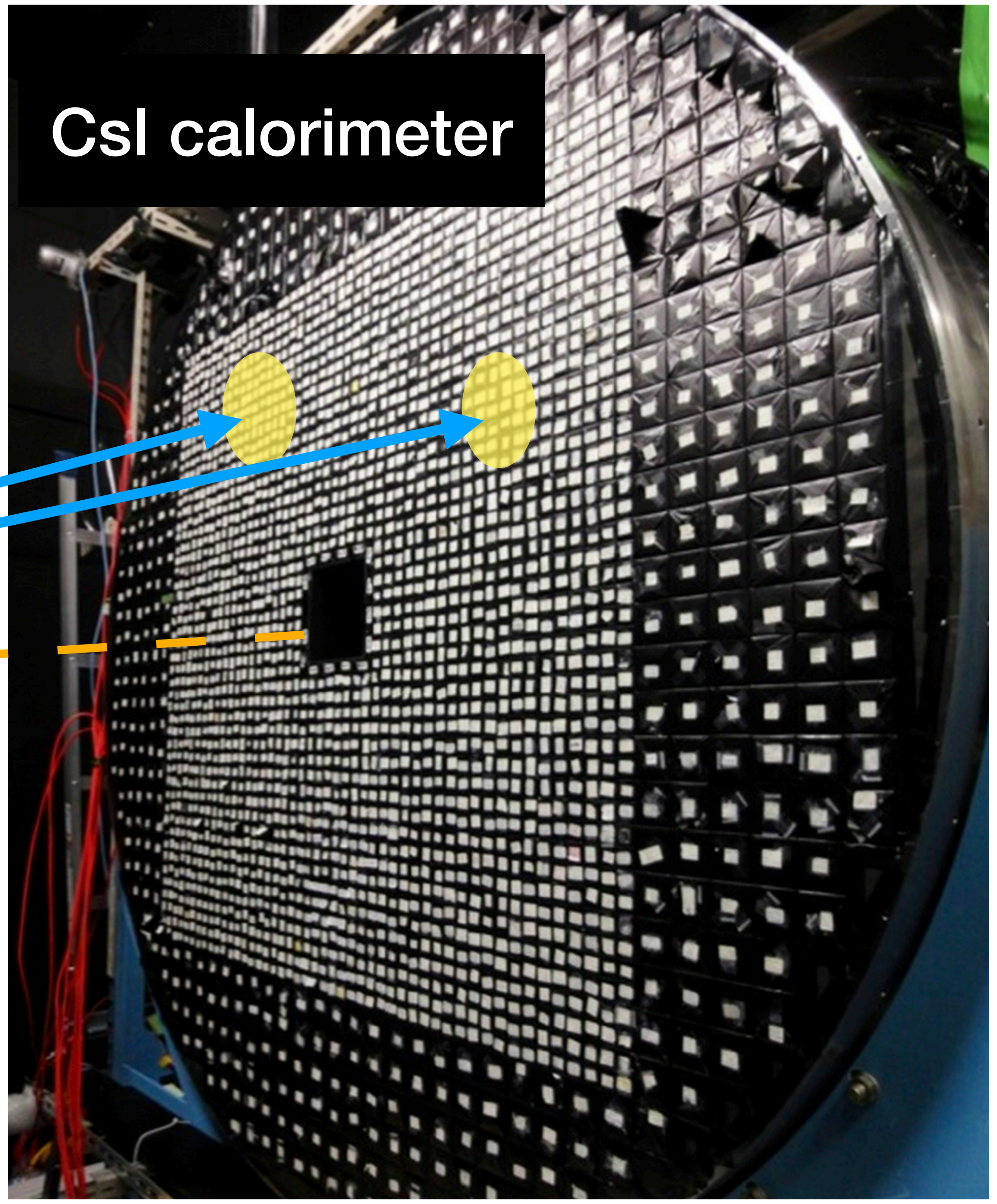
Enclose the decay volume to maximally detect additional photons.

Thickness = *19* X_0.

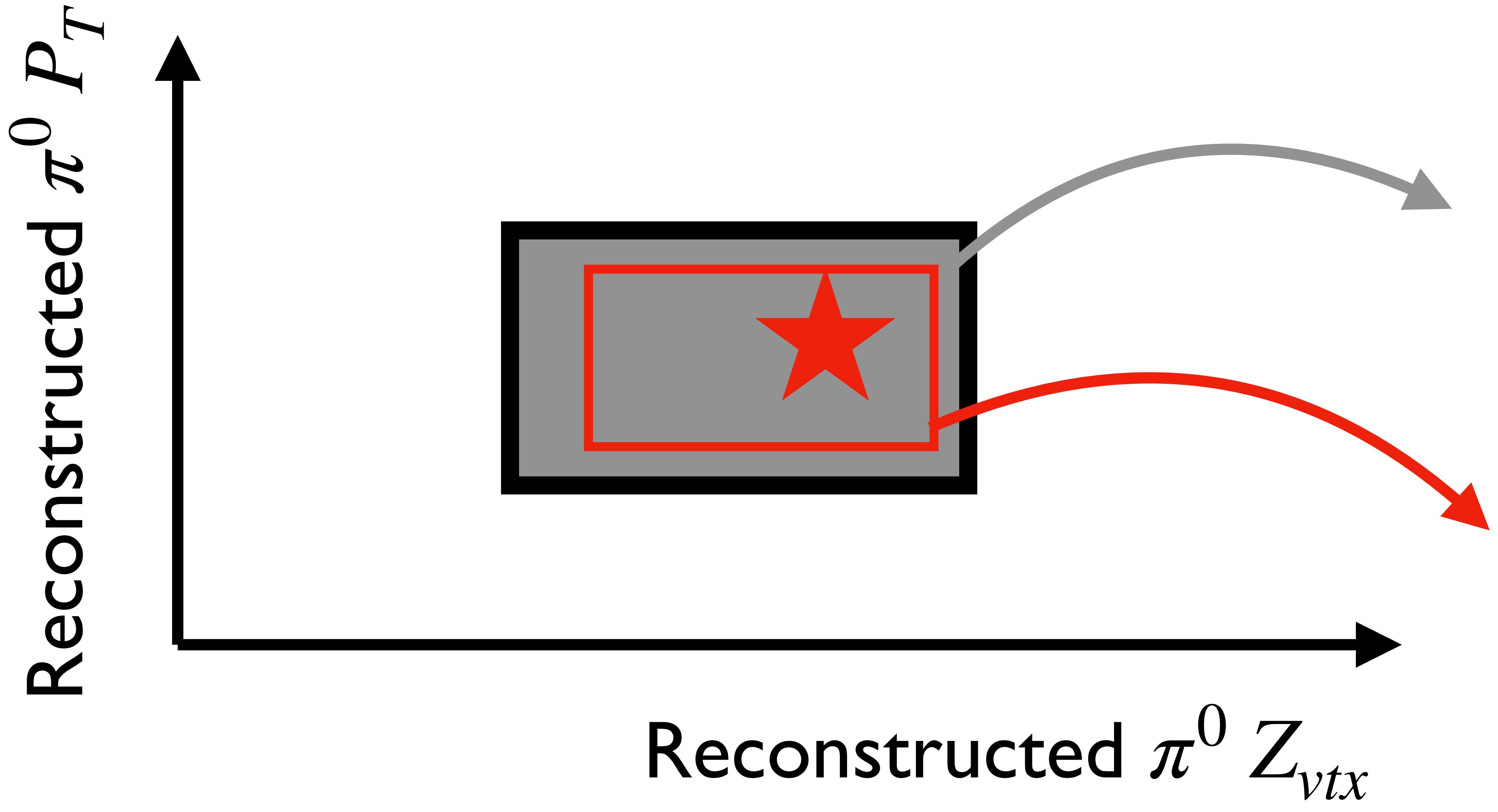
Analysis strategy

$$M_{\pi^0}^2 = 2E_1E_2(1 - \cos\theta_{12})$$





- A signal should have its decay vertex in fiducial region and large P_T due to undetected neutrinos.



Blind analysis

Events inside the blind region were inaccessible until the selection criteria were determined.

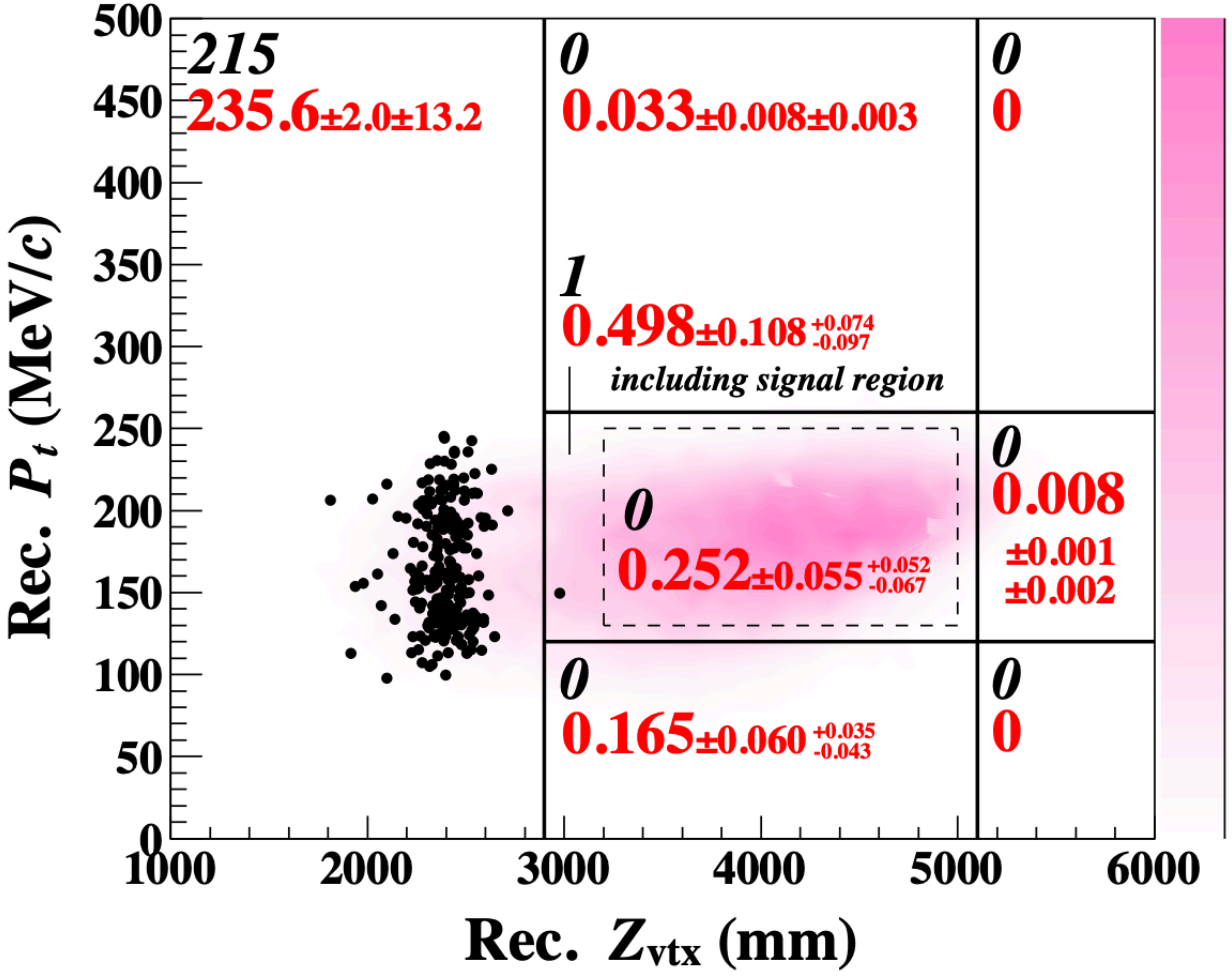
Signal region

Events inside this region will be identified as signal candidates.

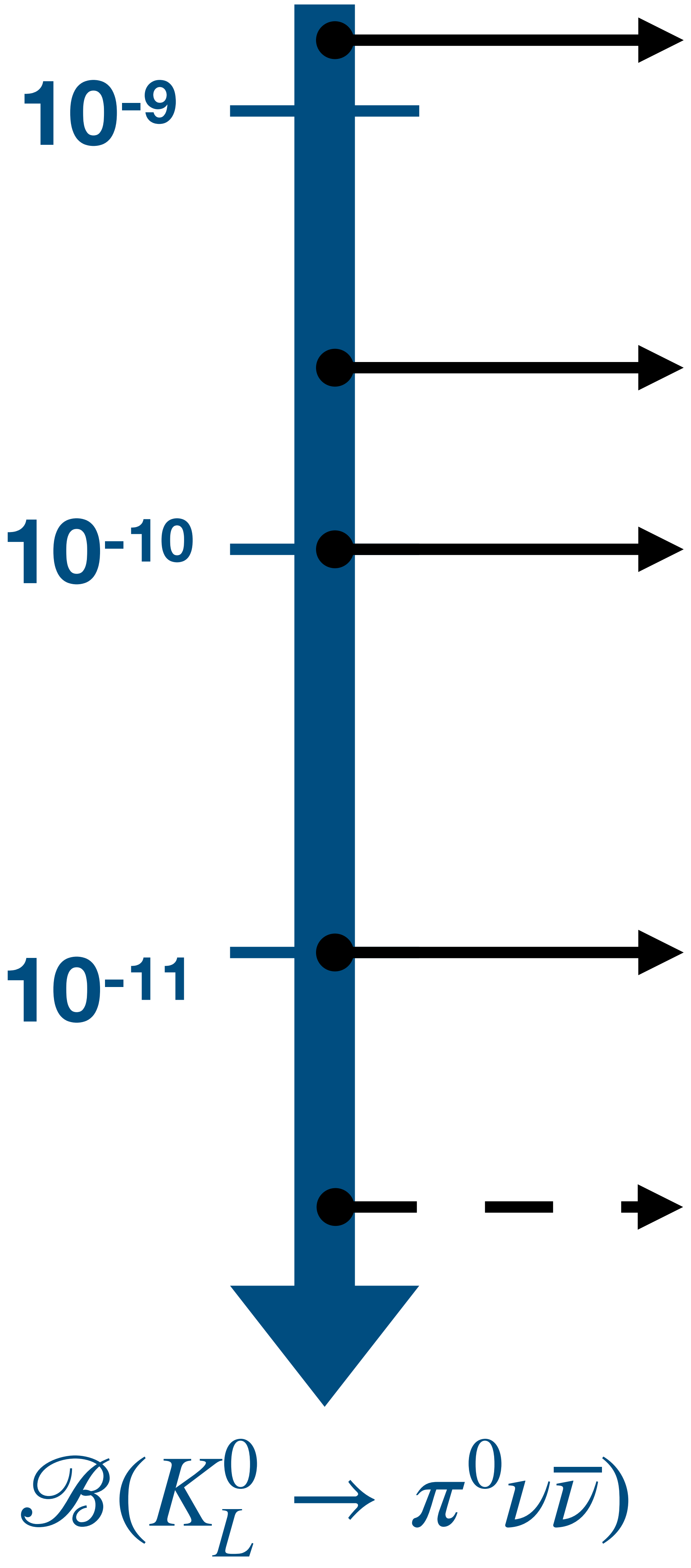
Latest KOTO result

- No signal candidate was observed.
- This sets an upper limit of
  $B(K_L^0 \to \pi^0 \nu \bar{\nu}) < 2.2 \times 10^{-9}$ (90% C.L.)

Source		Number of events
$K^{\pm}$		$0.042 \pm 0.014 ^{+0.004}_{-0.028}$
K_L	$K_L \to 2\gamma$ (beam-halo)	$0.045 \pm 0.010 \pm 0.006$
	$K_L \to 2\pi^0$	$0.059 \pm 0.022 ^{+0.050}_{-0.059}$
Neutron	Hadron-cluster	$0.024 \pm 0.004 \pm 0.006$
	CV-η	$0.023 \pm 0.010 \pm 0.005$
	Upstream-π^0	$0.060 \pm 0.046 \pm 0.007$
Total		$0.252 \pm 0.055 ^{+0.052}_{-0.067}$



Status and projection



- **KOTO set the worldwide best limit of < 2.2 x 10^{-9}** (90% C.L.)
  Paper was submitted to PRL in Nov 2024.

- **New physics sensitive regime < 6.3 x 10^{-10}** (68% C.L.)

- KOTO expects to reach sensitivity of O(10^{-10}) at 2028.
  In order to further improve the sensitivity, an upgrade to "KOTO-II" is needed. Will submit the proposal in the end of 2024.

- **Standard Model prediction = 3.0 x 10^{-11}.**

- KOTO-II targets to explore the sensitivity of O(10^{-13}).

Other physics topics

Uniqueness of the kaon experiment

New Physics Searches at Kaon and Hyperon Factories

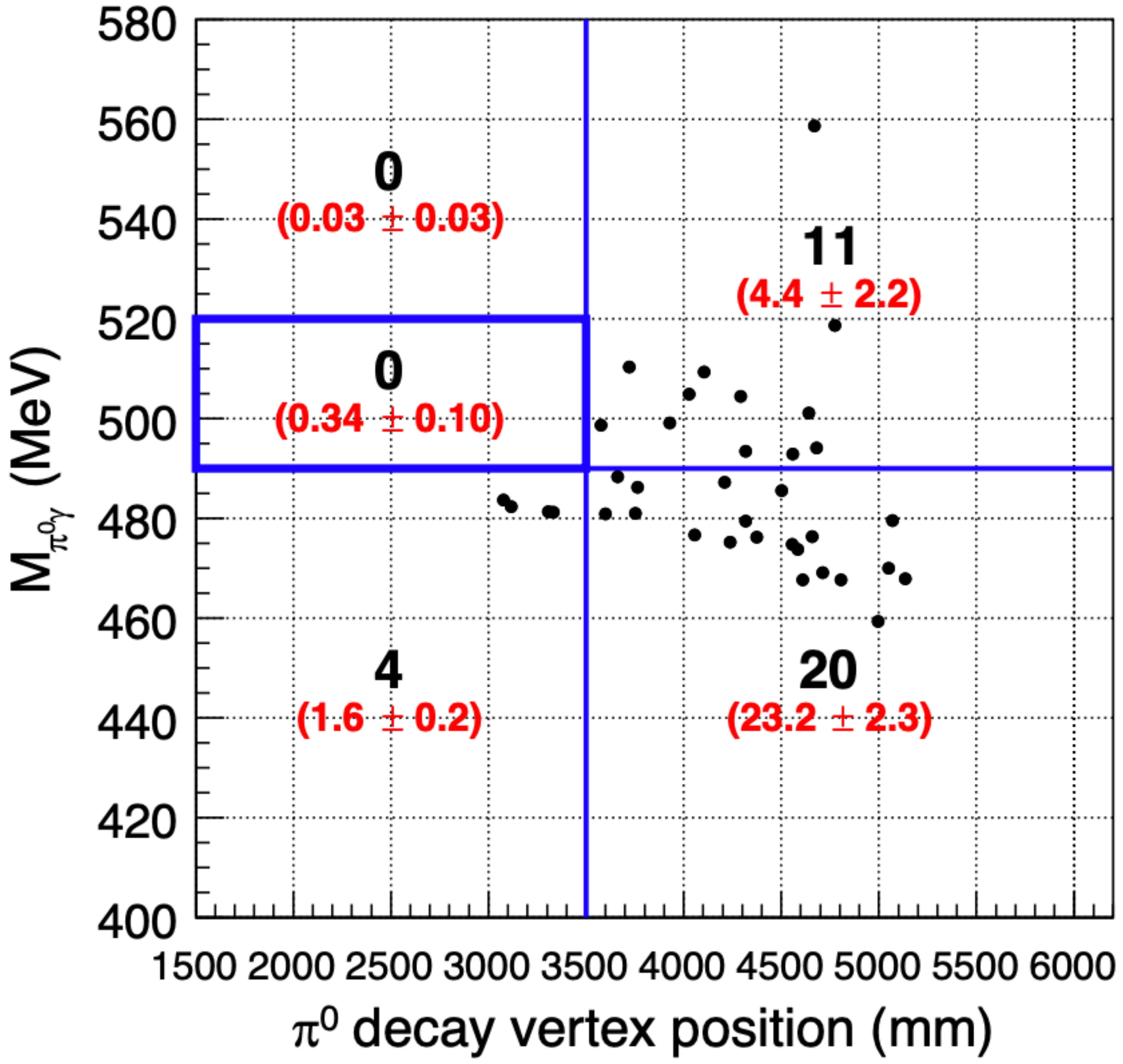
: arXiv:2201.07805 [hep-ph]

Rare kaon decays are among the most sensitive probes of both heavy and light new physics, as a combined consequence of both experimental and theoretical considerations. On one hand, large datasets are available in the current and future kaon experiments, two to three orders of magnitude larger than the usable B and D meson datasets at Belle, BaBar and LHCb. At the same time the kaon decay width is power suppressed, $\Gamma_K \propto m_K^5/m_W^4$, compared to the B and D mesons, $\Gamma_{B,D} \propto m_{B,D}^5/m_W^4$. For example, the total K^+ decay width is almost four orders of magnitude smaller than for the B^+ meson, $\Gamma_{B^+}/\Gamma_{K^+} \simeq 7.5 \times 10^3$.

The small total decay width enhances the sensitivity to NP decay channels, $\mathcal{B}(K \to X_{\rm NP}) = \Gamma(K \to X_{\rm NP})/\Gamma_K$, so that the sensitivity to the same branching ratio value in reality corresponds to a sensitivity to a smaller NP partial decay width for rare kaon decays. This is particularly important for searches for kaon decays to light new physics particles. In models where the NP particles couple to the

Lorentz invariance test via $K_L^0 \to \pi^0\gamma$

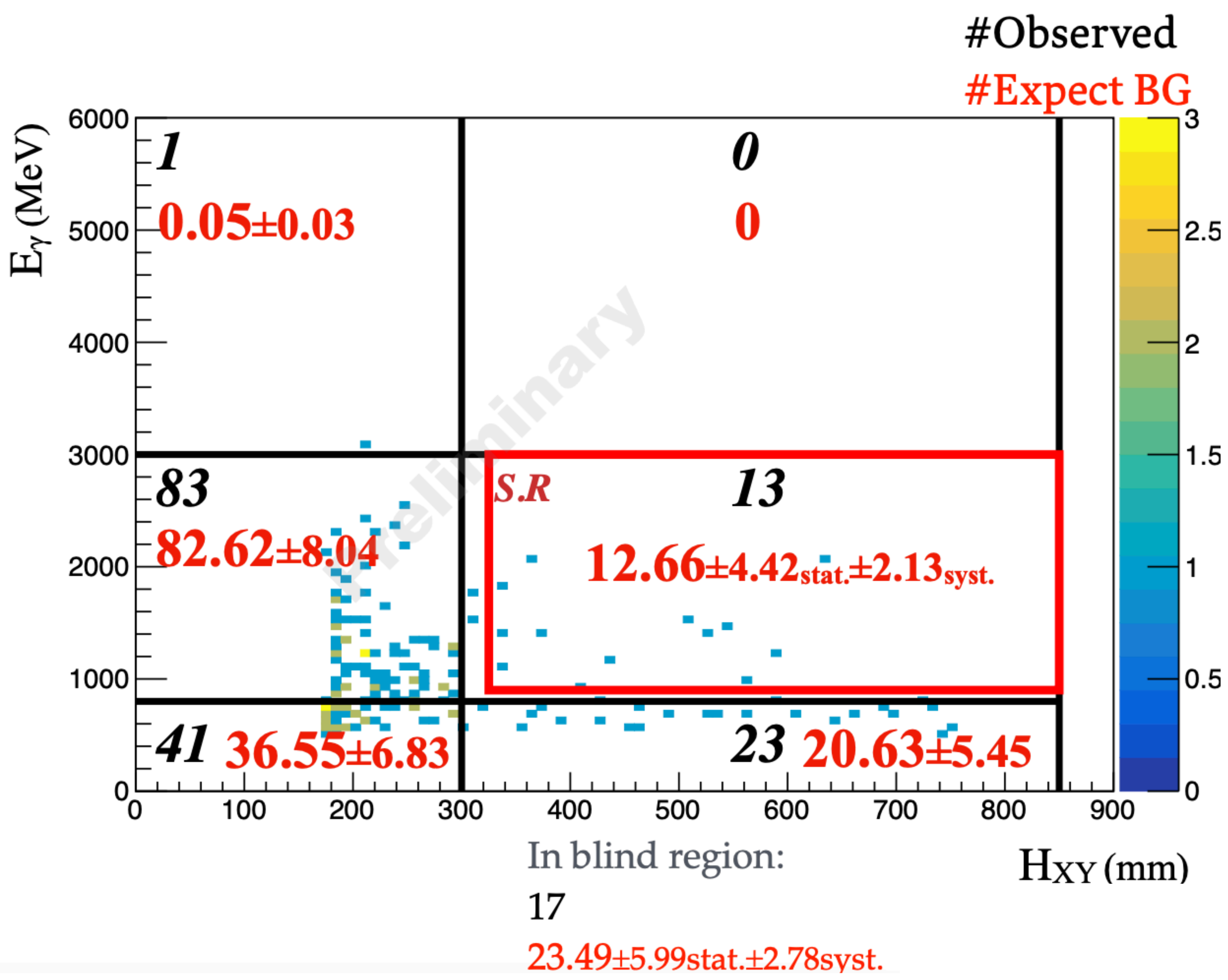
- The $K_L^0 \to \pi^0\gamma$ decay violates the angular momentum. It can occur only if the Lorentz invariance is broken.
- The signal signature is 3 photon hits in the calorimeter + nothing else detected.
  - Use both K_L^0 and π^0 mass constraints to suppress the and $K_L^0 \to \pi^0\pi^0$ and $K_L^0 \to 3\pi^0$ backgrounds.
- The number of background events was predicted to be 0.34 ± 0.1.
- No signal was found in the signal region, resulting in an upper limit of branching ratio $B(K_L^0 \to \pi^0\gamma) < 1.7 \times 10^{-7}$ (90% C.L.)



Phys.Rev.D 102 (2020) 5, 051103

Massless dark photon search through $K_L^0 \to \gamma\bar{\gamma}$

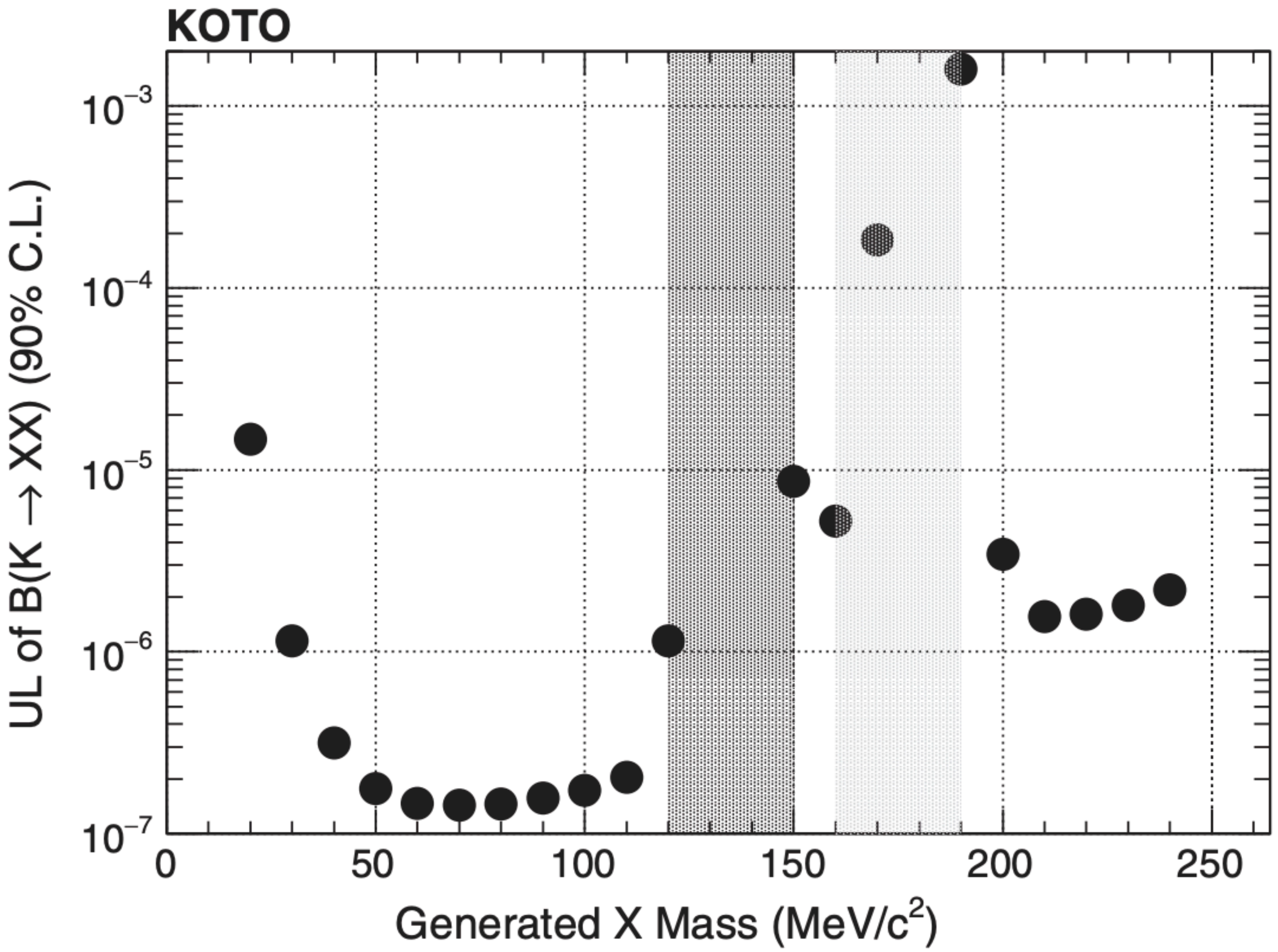
- If dark photons directly couple to a SM quark (without the mix of ordinary photons) $B(K_L^0 \to \gamma\bar{\gamma}) < 1 \times 10^{-3}$,
  [Su, JY., Tandean, J. Eur. Phys. J. C 80, 824 (2020]
- Signal signature: 1 large-incident-angle photon hit in the calorimeter + nothing else detected.
  - No kinematic constraint: very difficult to study.
- The estimated number of background events $= 12.66 \pm 4.42_{\text{stat.}} \pm 2.13_{\text{syst.}}$
- An upper limit of branching ratio is set: $B(K_L^0 \to \gamma\bar{\gamma}) < 3.5 \times 10^{-7}$ (90% C.L.)



ICHEP 2024, T. Wu

Pair production of dark particles via $K_L^0 \to XX, X \to \gamma\gamma$

- Dark particles may only appear in a pair. Under such scenario, K_L^0 can examine a wider mass regime than K^+ due to the charge conservation.
- Signal signature: 4 photon hits in the calorimeter + nothing else detected.
  - Use K_L^0 mass constraint to reconstruct the signal and require two diphoton invariant masses are identical.
- No signal is found. An upper limit of branching ratio is set for different dark particle masses.

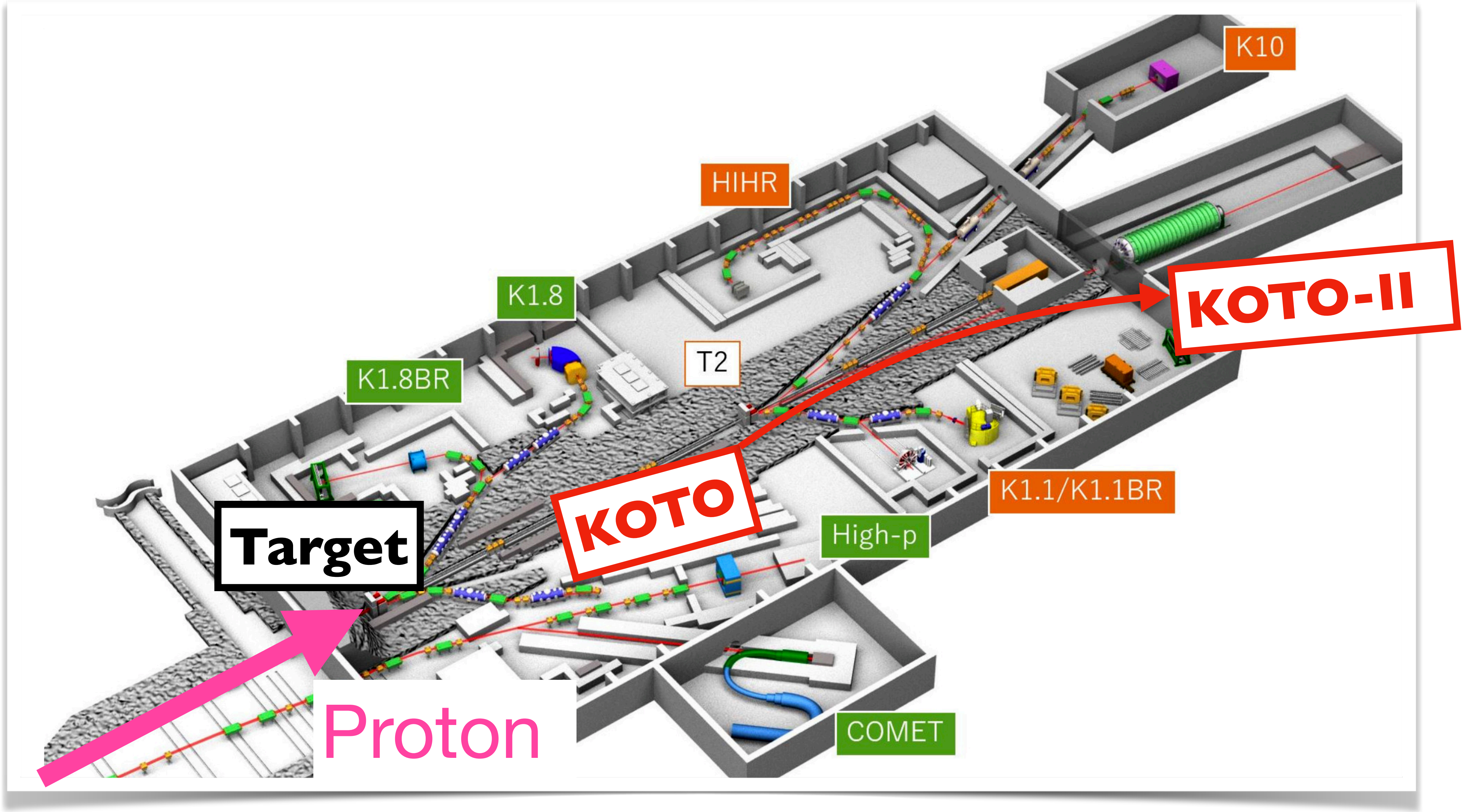


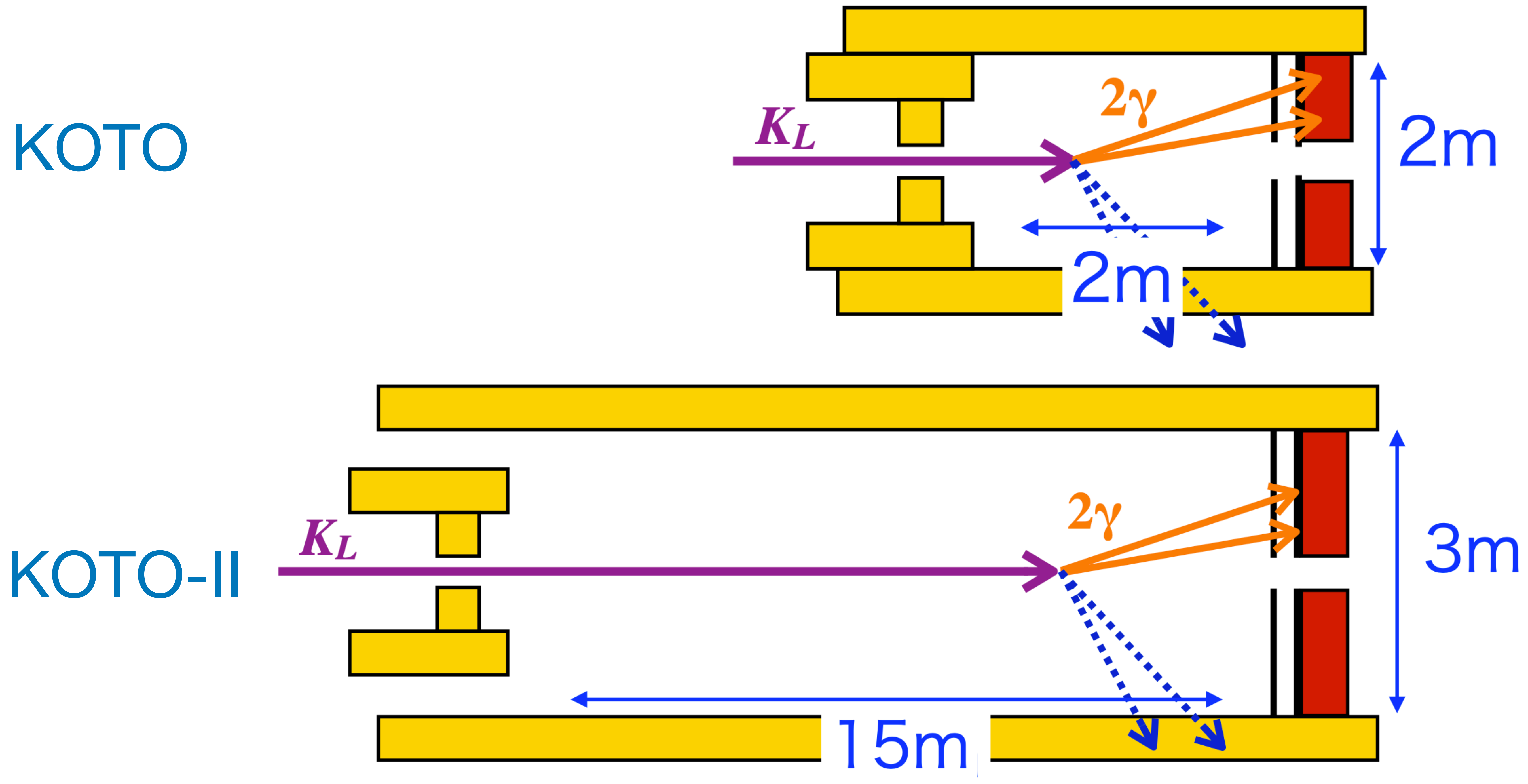
Phys.Rev.Lett. 130 (2023) 11, 111801

Future prospects

The KOTO-II Project

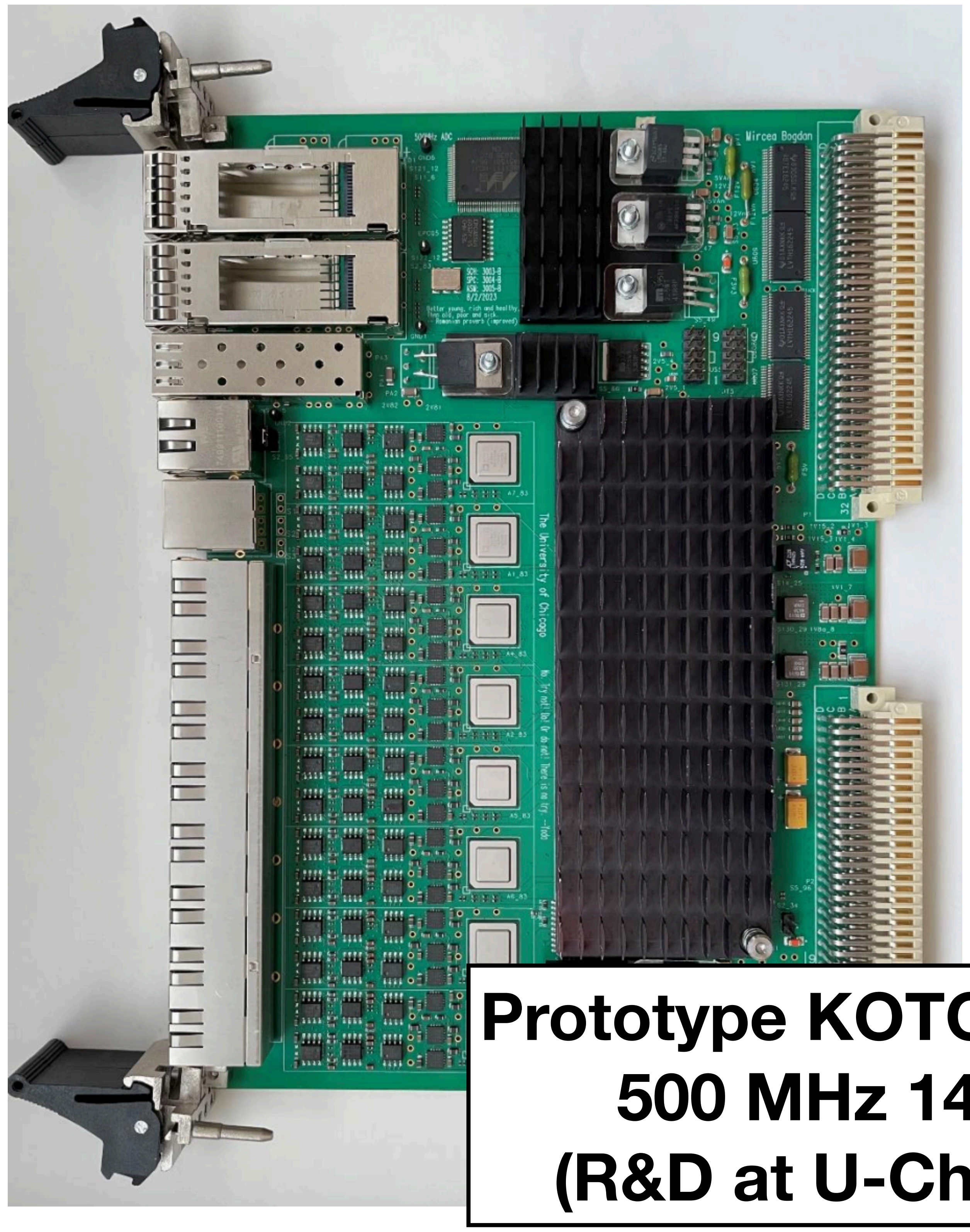
- Compared with KOTO-I: higher K_L^0 flux (KOTO x 2.4) and higher K_L^0 momentum (3 GeV/c). [arXiv:2110.04462v1]
- Experimental goal: Observe 35 SM events with signal-to-noise ratio = 0.6.
  - $B(K_L^0 \to \pi^0 \nu \bar{\nu}) \approx SM$ → 5σ discovery.
  - $|B(K_L^0 \to \pi^0 \nu \bar{\nu}) - SM| > 44\% \times SM$ → New Physics implication.





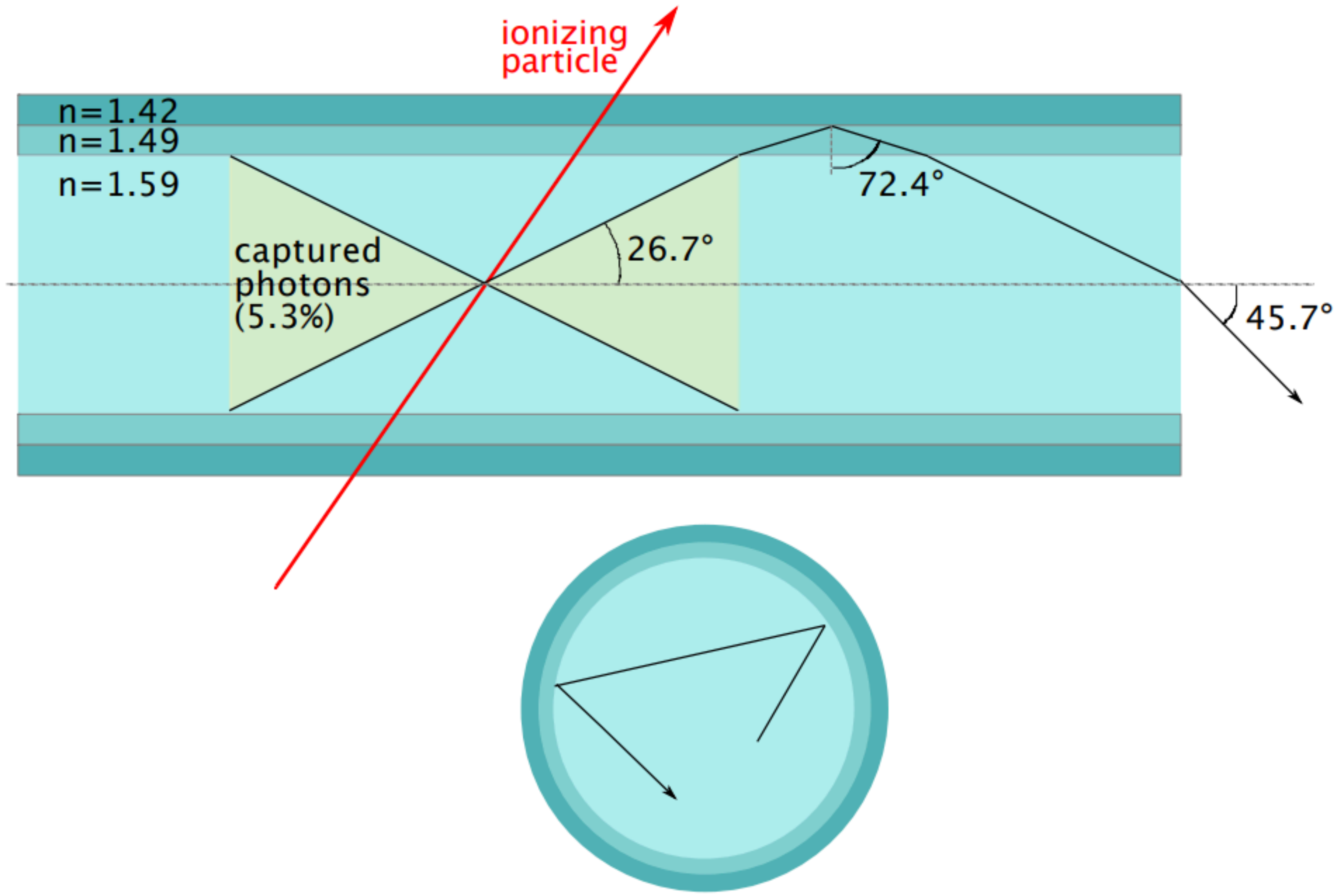
Taiwan efforts toward KOTO-II

- **Computing resources**: Introduce the KOTO/KOTO-II analysis at ASGC.
- **DAQ system development**: Coordinate with U-Chicago to construct the upstream DAQ system.
- Initiate a project of developing scintillating fiber detector in Taiwan as a charge tracker to study kaon decays with charged particles in the final state.



Prototype KOTO-II ADC
500 MHz 14-bit
(R&D at U-Chicago)

Scintillating fiber design



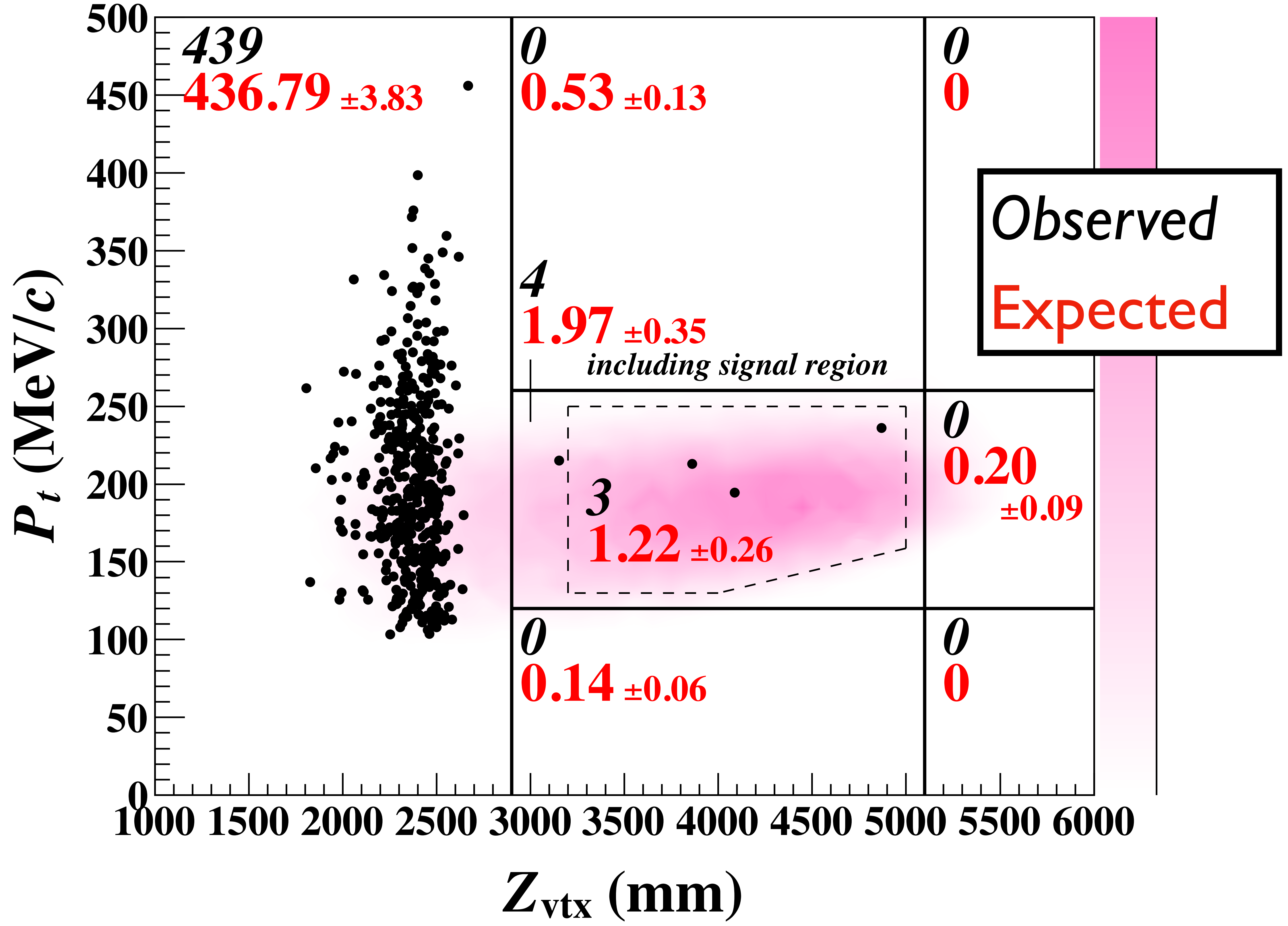
Summary

- The KOTO experiment is searching for the new physics via rare kaon decays.
  - We have successfully improved the sensitivity to $O(10^{-9})$, which is two orders of magnitude larger than the SM prediction.
- KOTO/KOTO-II is also ideal to search for the dark sector particles.
- The upgrade of the KOTO experiment, KOTO-II, is prepared to further explore the unprecedented regime and examined the correctness of the SM at the $O(10^{-11})$ sensitivity.

Supplemental

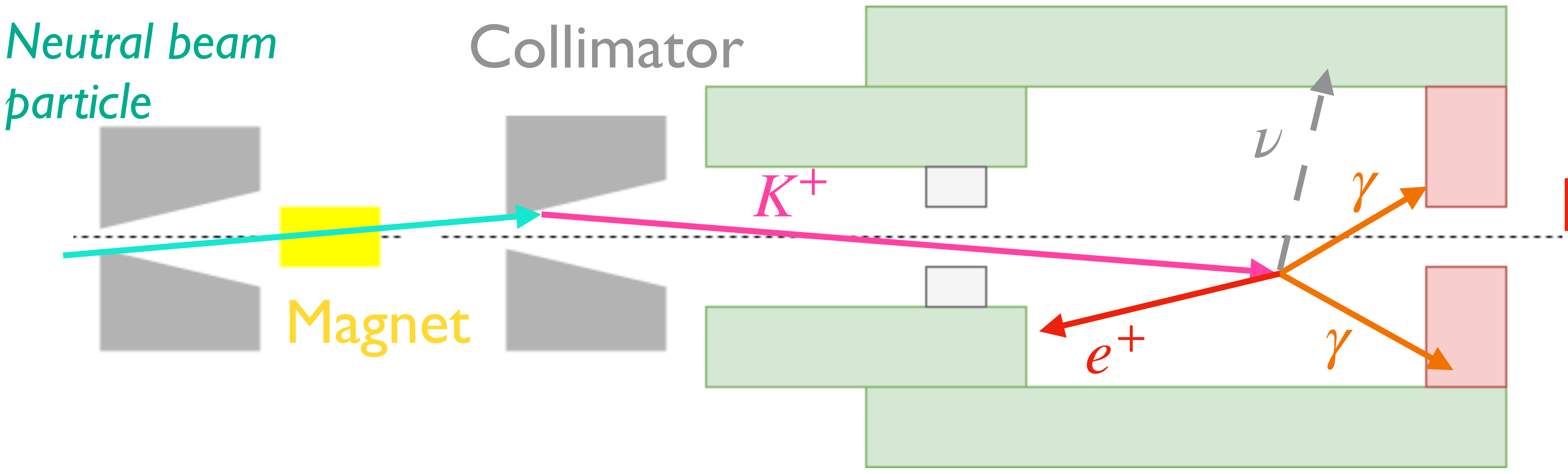
Previous KOTO result

- The latest KOTO result (2016-2018 data) showed 3 signal candidate events.
- Largest background source: A K^+ particle is generated upstream and enters the decay region.
  (Found after opening the box)
- $B(K_L^0 \to \pi^0 \nu \bar{\nu}) < 4.9 \times 10^{-9}$ (90% C.L.)



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

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

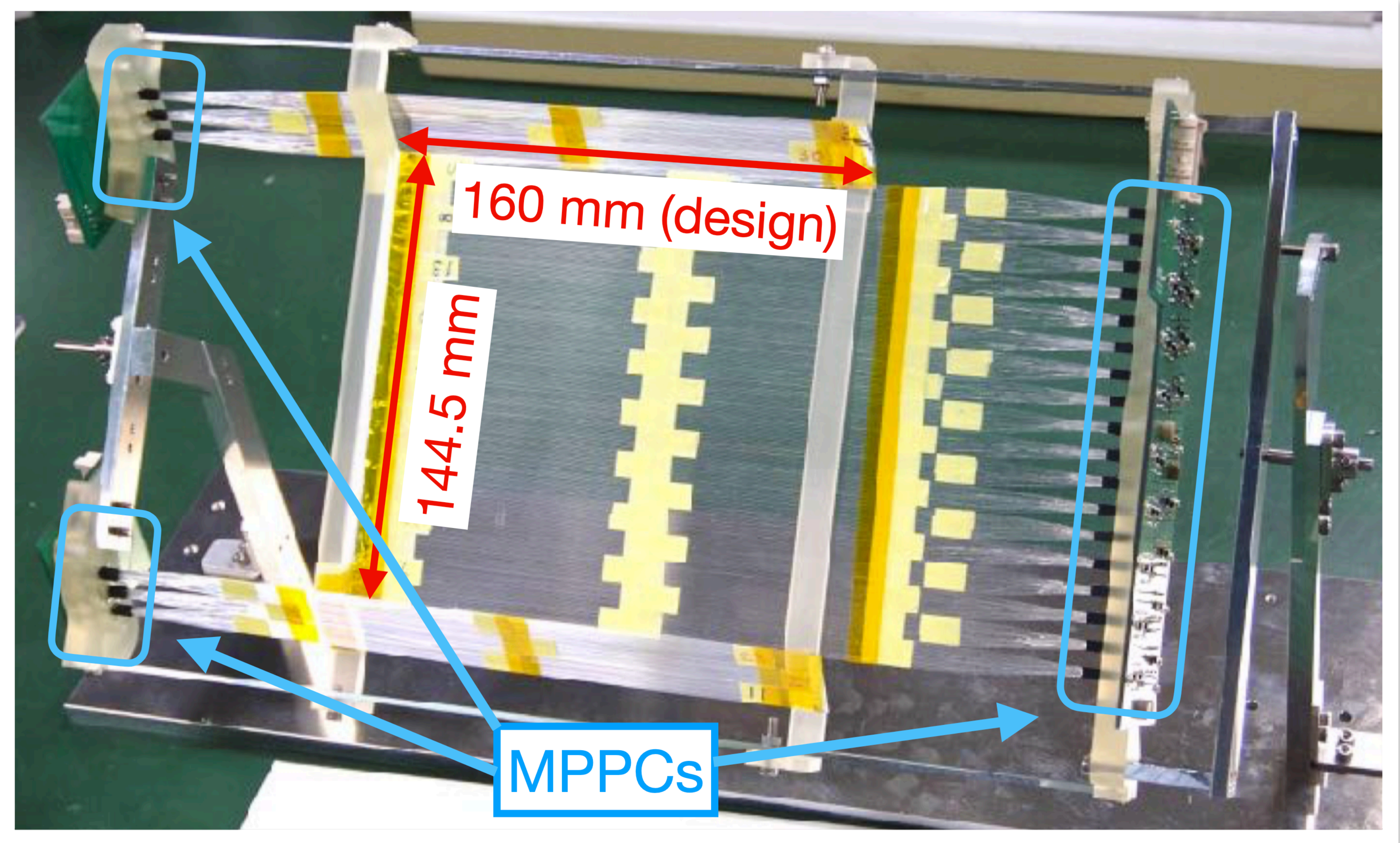


Questions about K^+ background

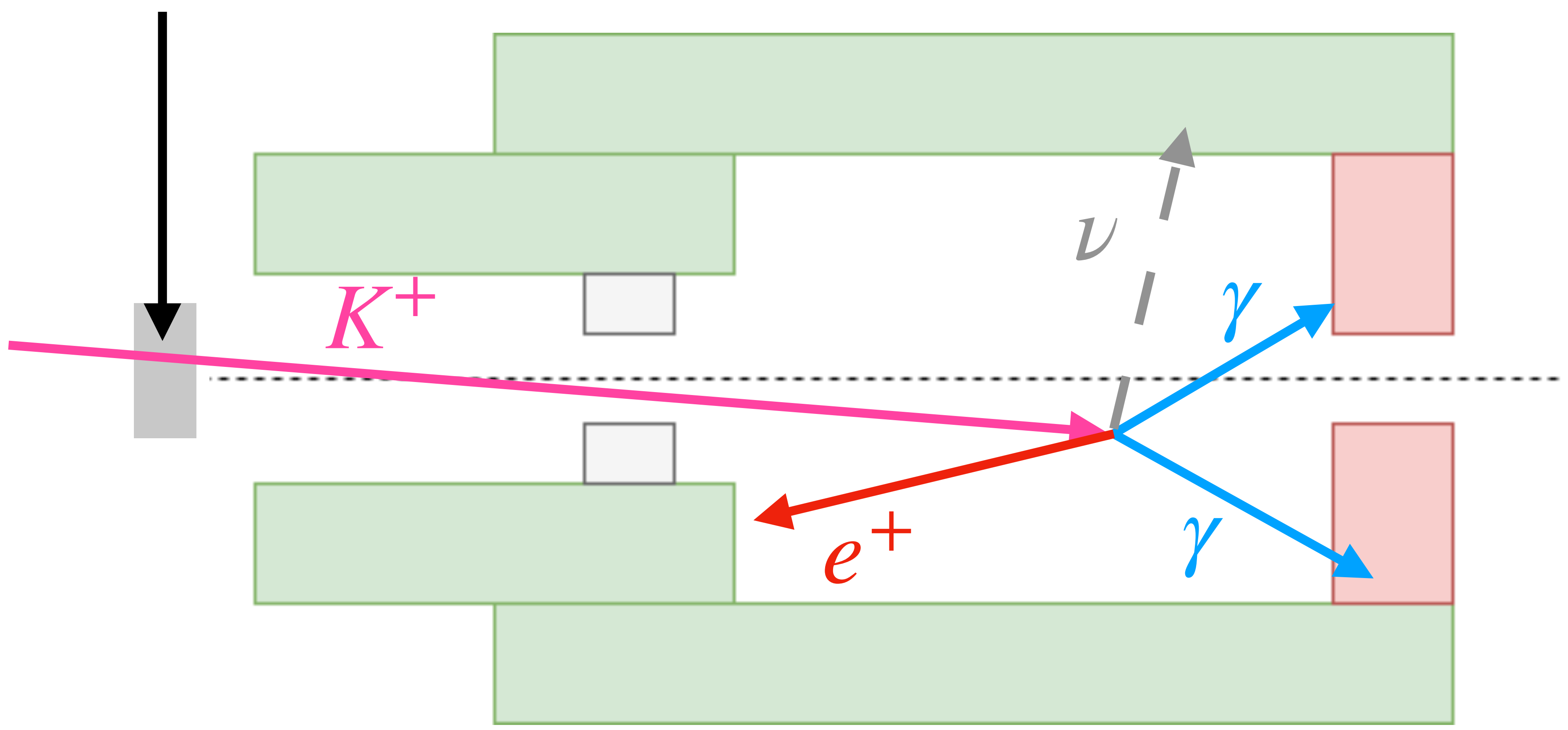
- How do we suppress the K^+ background?
- Why did we barely notice the K^+ background before opening the box?

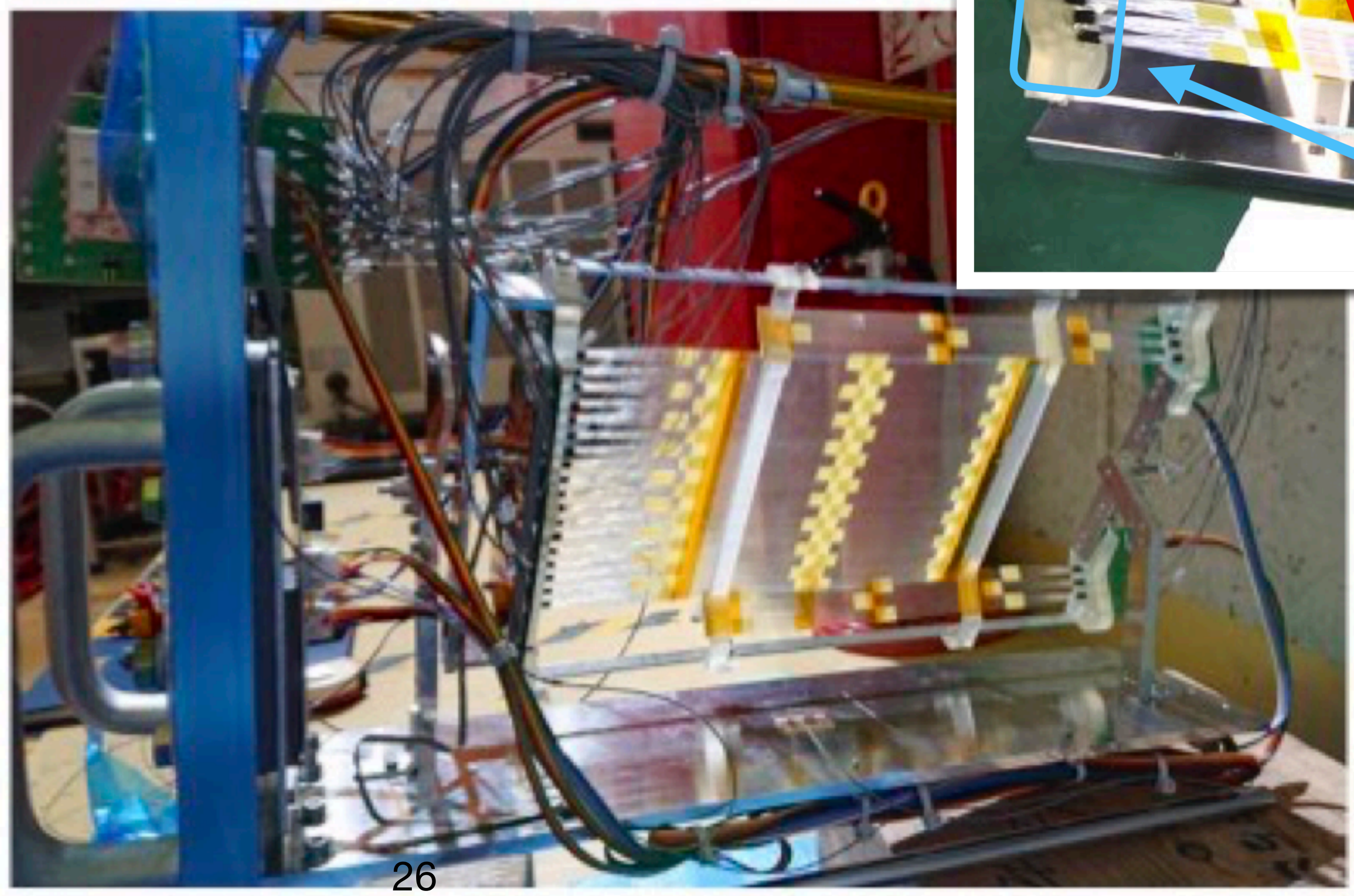
K^+ background suppression

- Place a plastic scintillator at the entrance of the KOTO detector to detect charged particles.
  - A plane of square scintillation fibers read by MPPC.
  - It was installed in 2021 .
    $\Longrightarrow$ Concentrate on analyzing 2021 run data.



Upstream charge veto

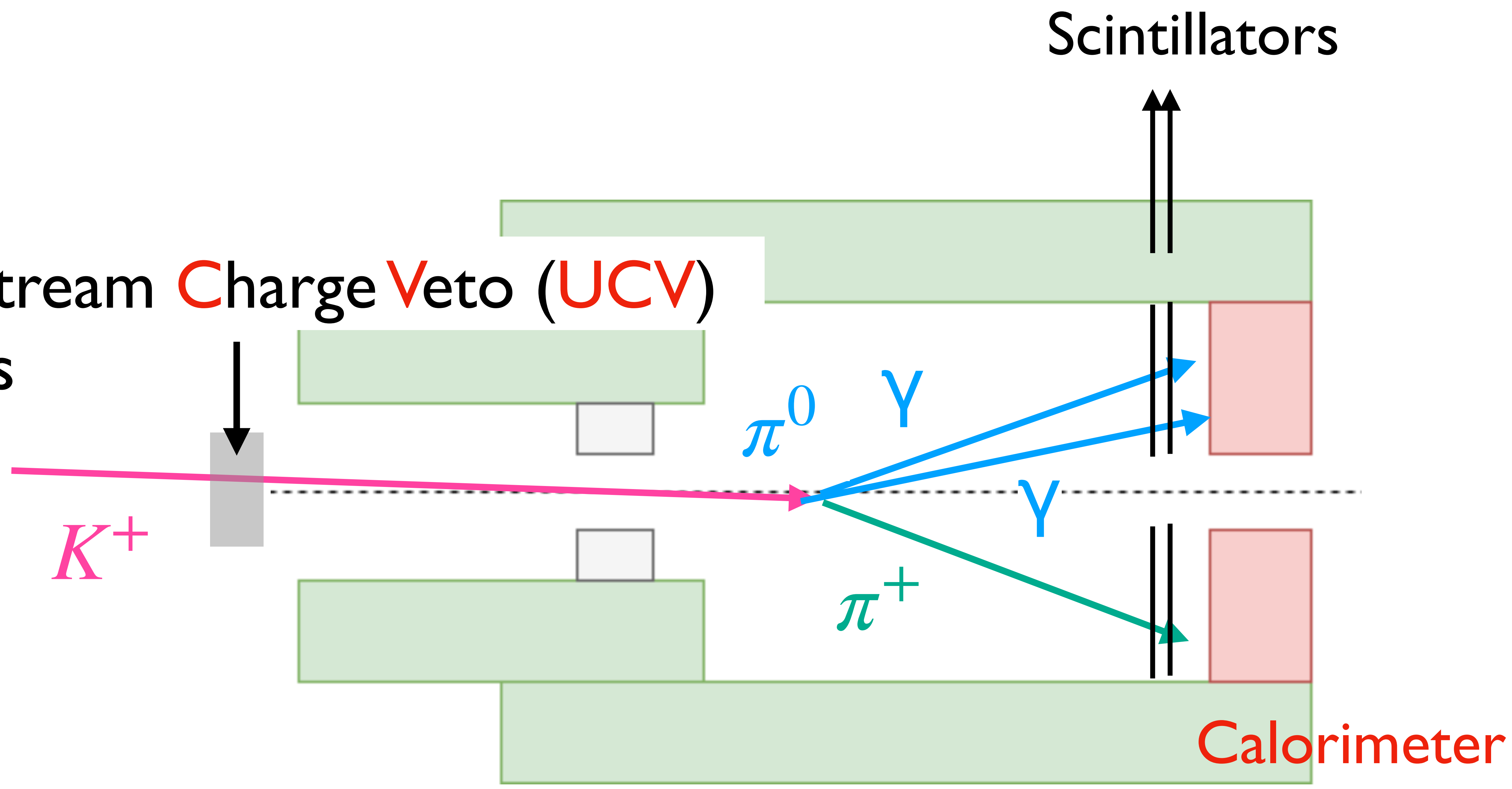




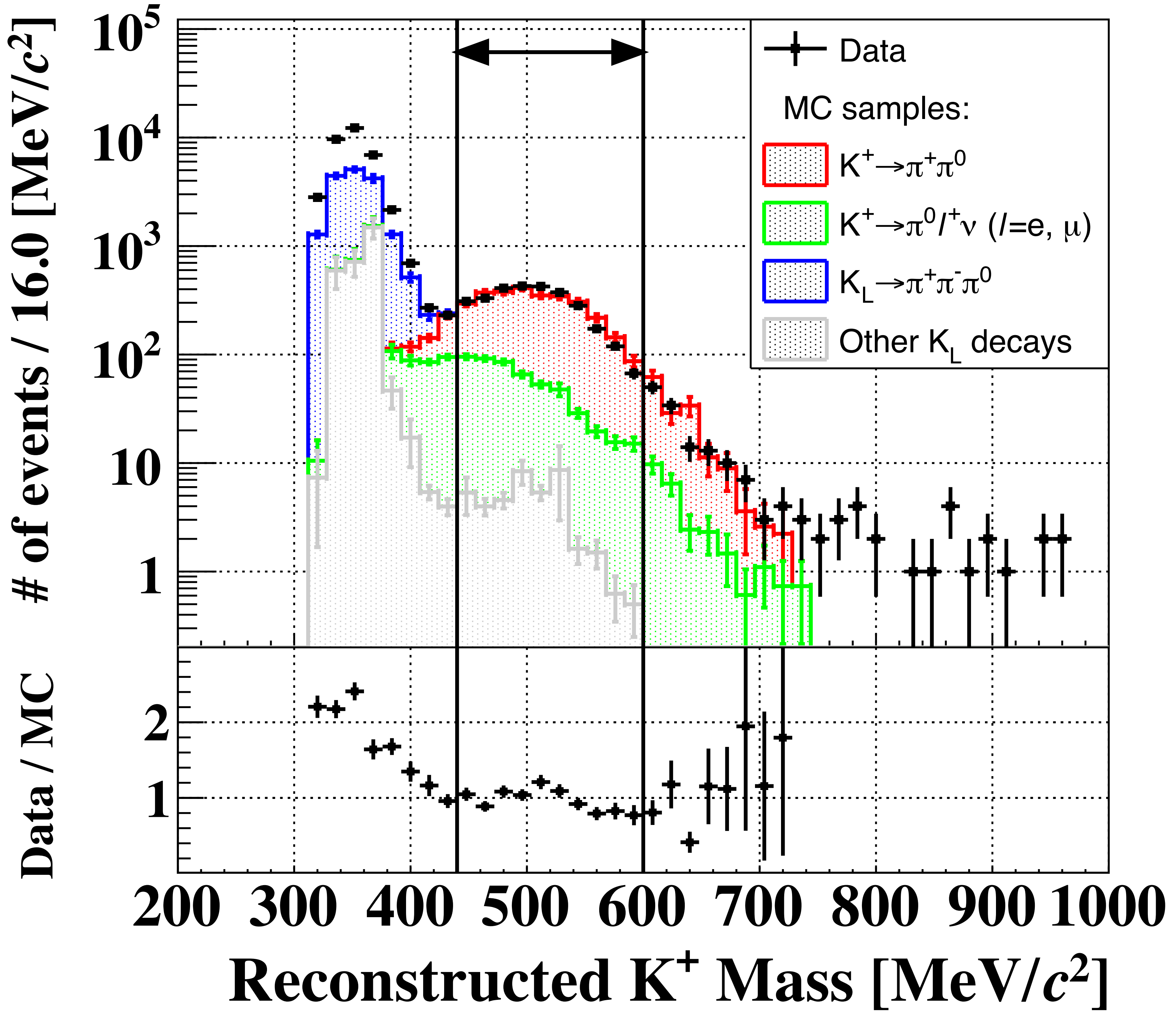
Tilted at 25 degrees.

N(K^+ background)

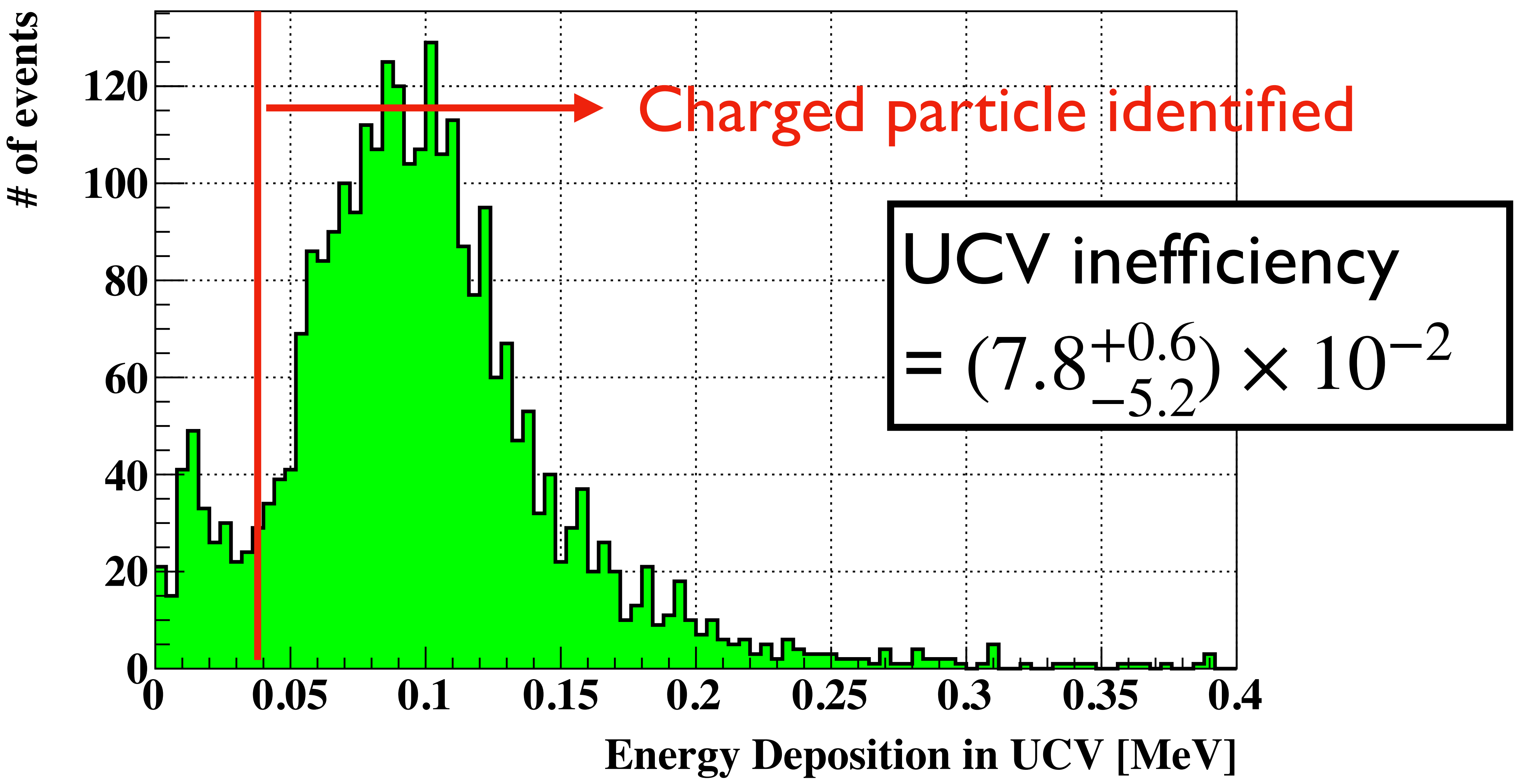
- Measure K^+ flux by identifying $K^+ \to \pi^0\pi^+$ decays (branching ratio ~ 20%).
- N(K^+ background) = $0.043 \pm 0.015_{(stat)}{}^{+0.004}_{-0.030}\ (sys)$



K^+ mass window

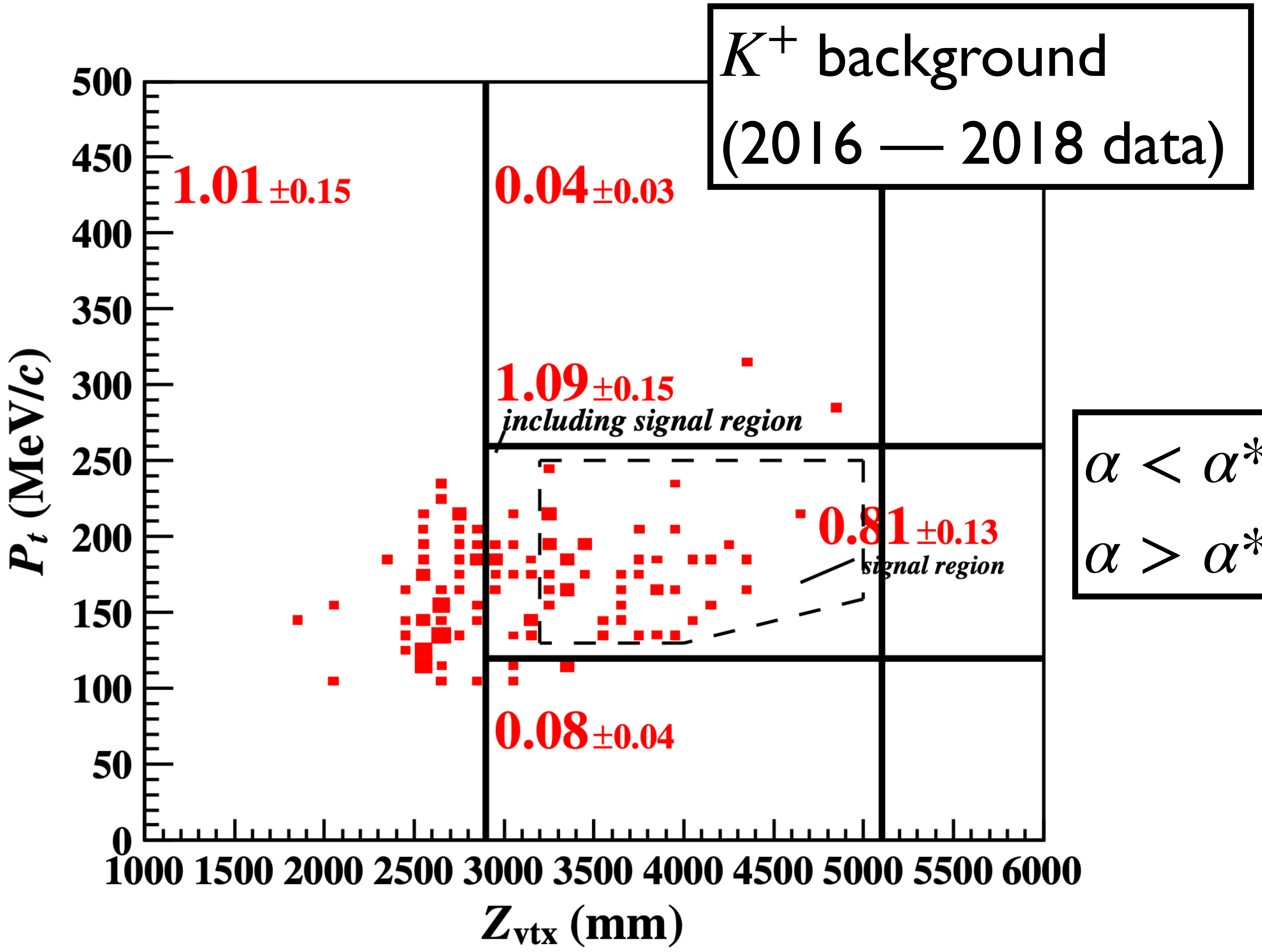


$K^+ \to \pi^0\pi^+$ candidate events

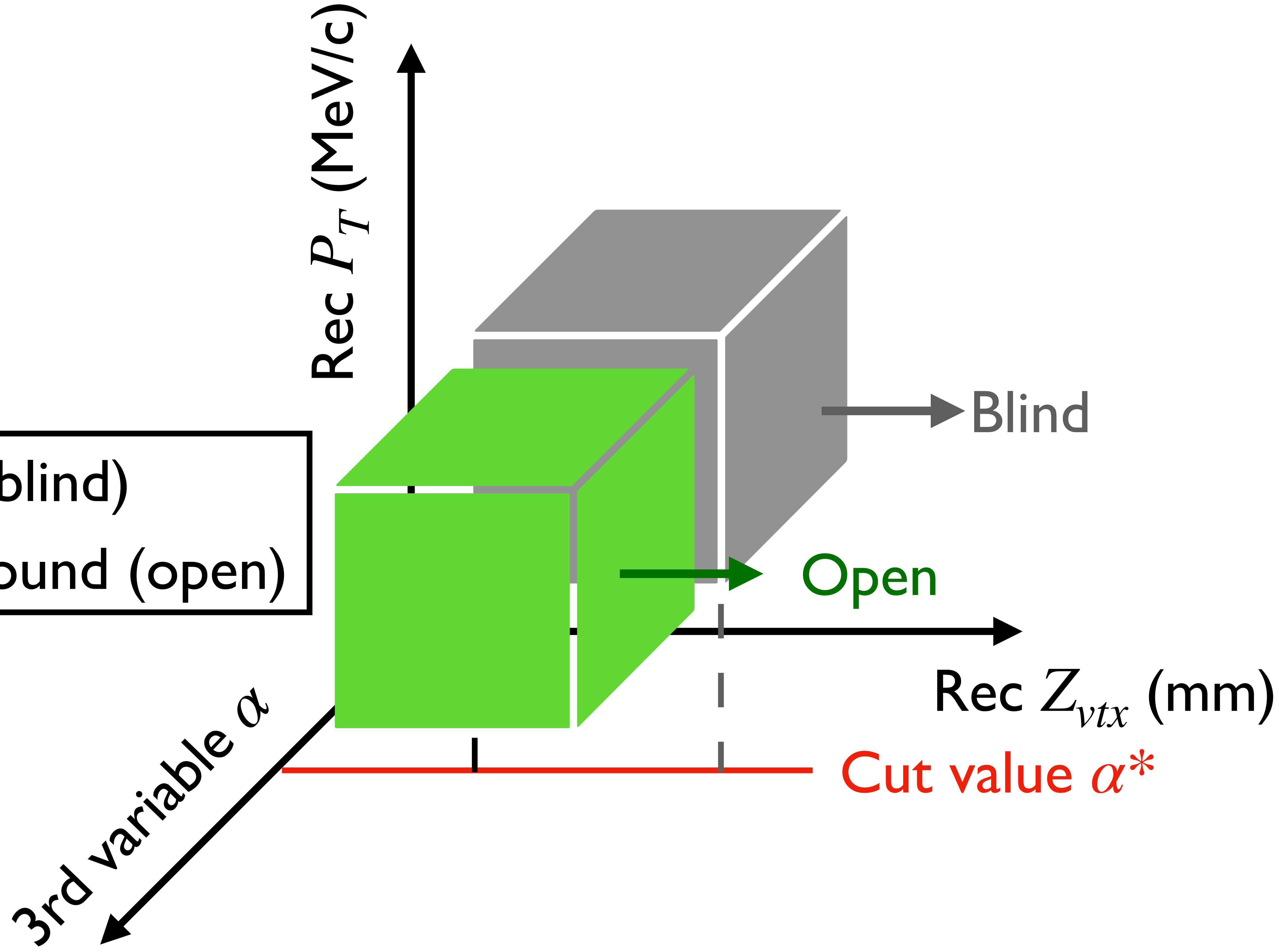


New blind analysis strategy for 2021 data

- A background source is barely noticeable if it only populates inside the blind region.
- Introduce an extra dimension to examine the background prediction.

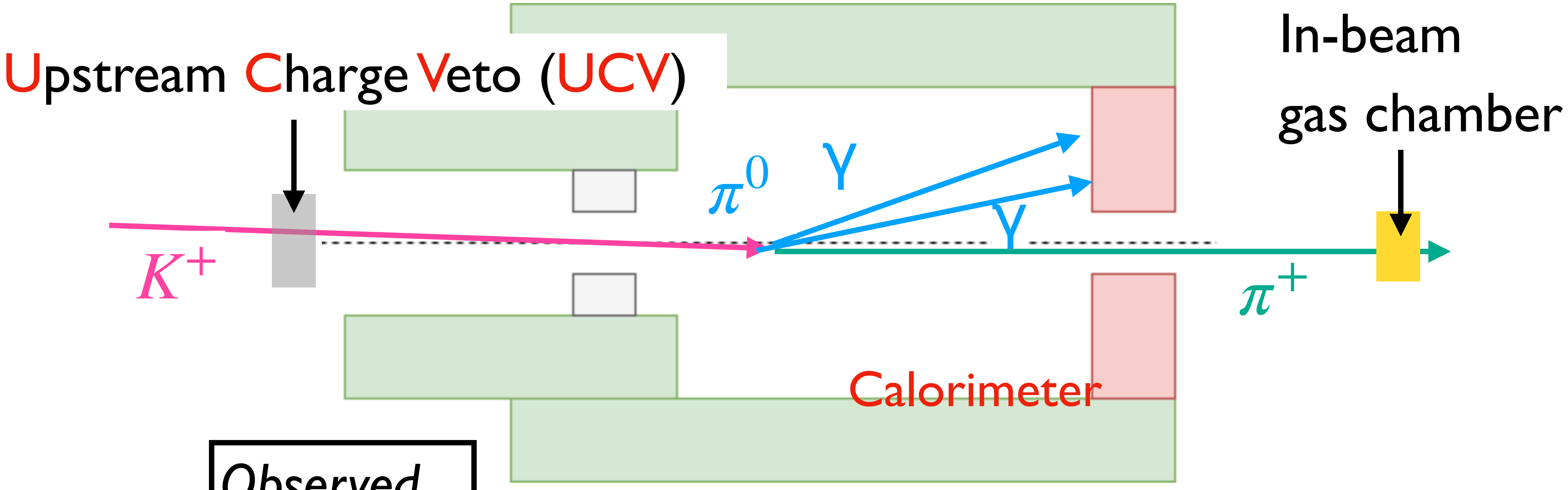


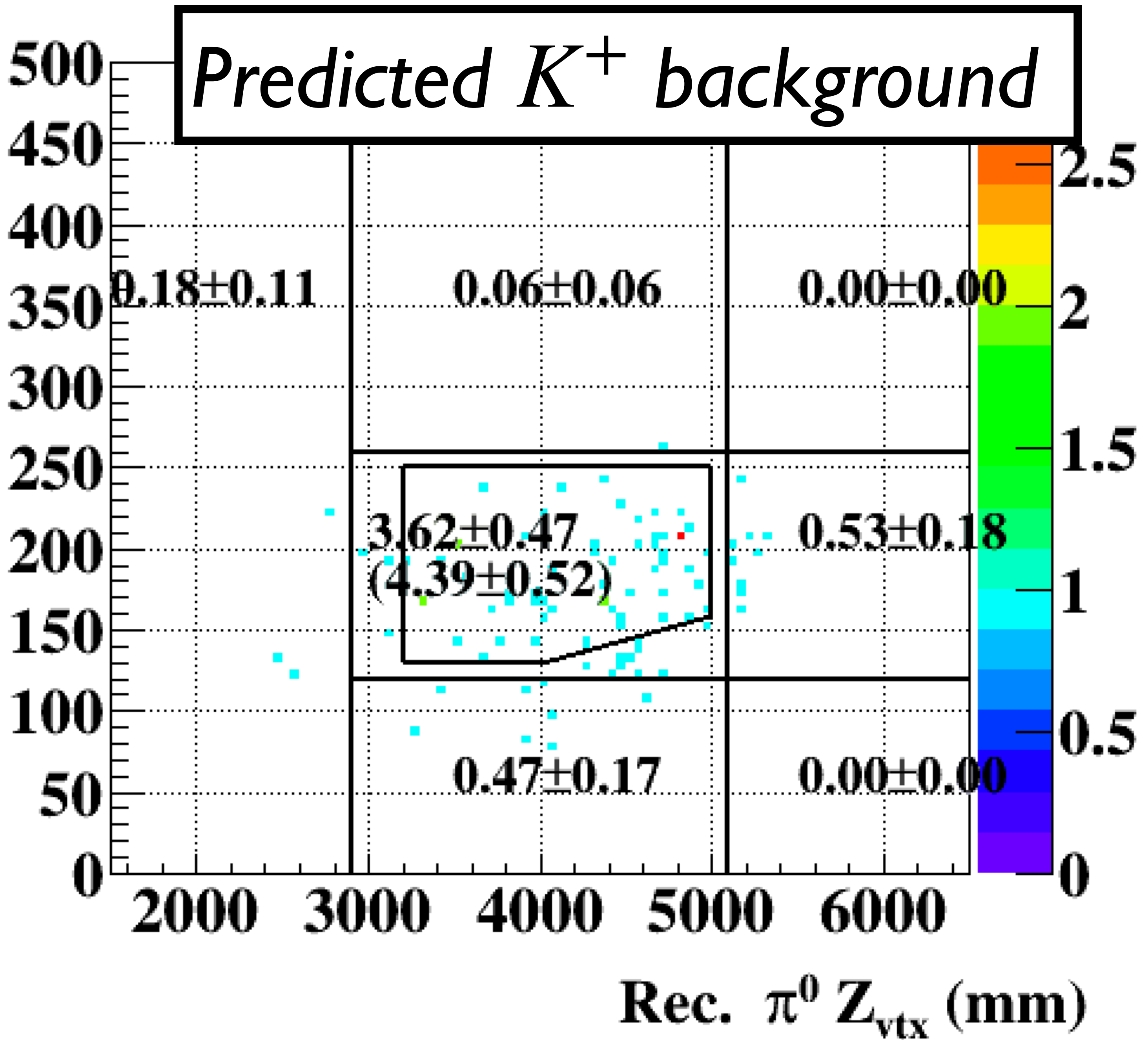
$\alpha < \alpha^*$: signal (blind)
$\alpha > \alpha^*$: background (open)

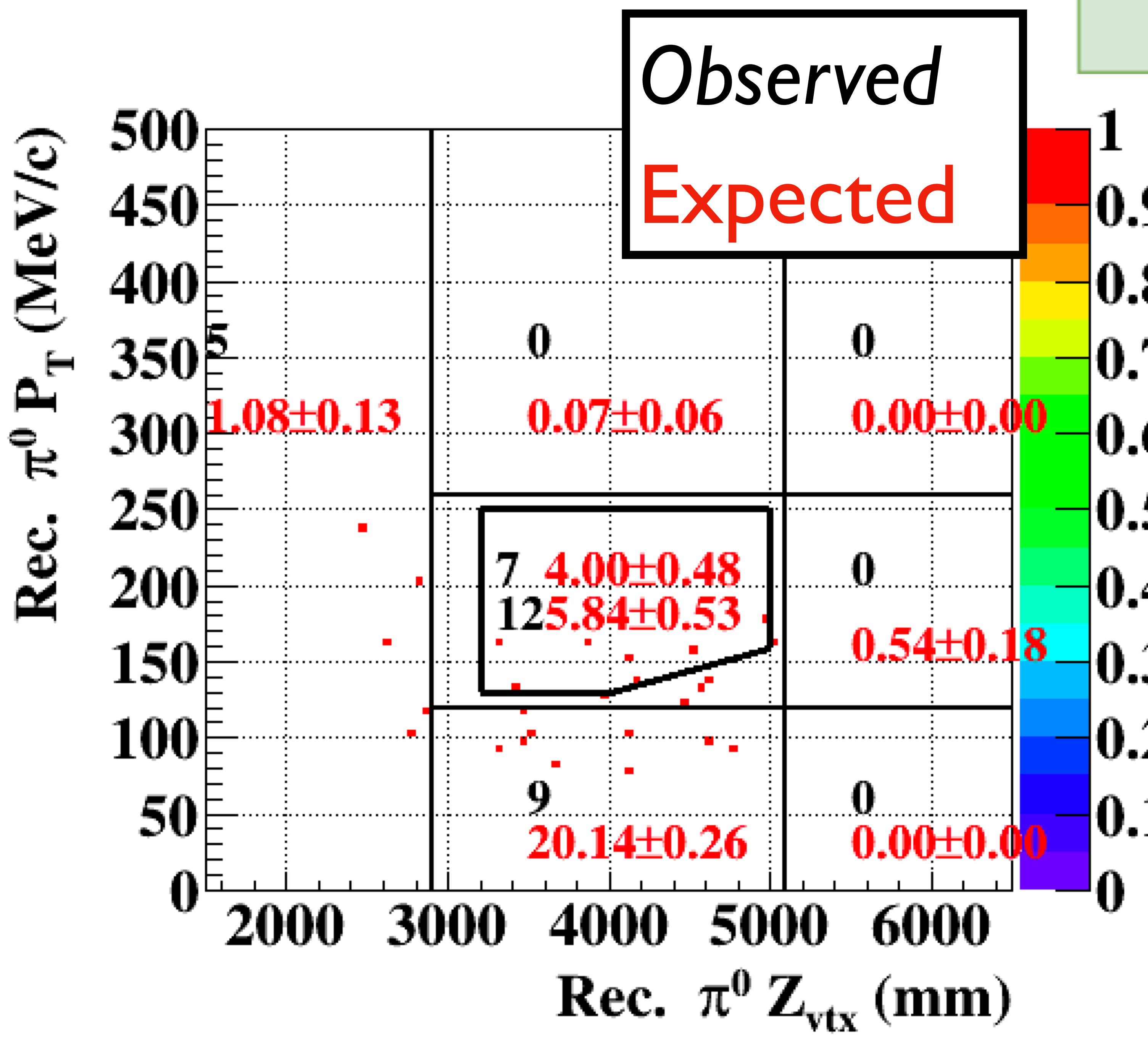


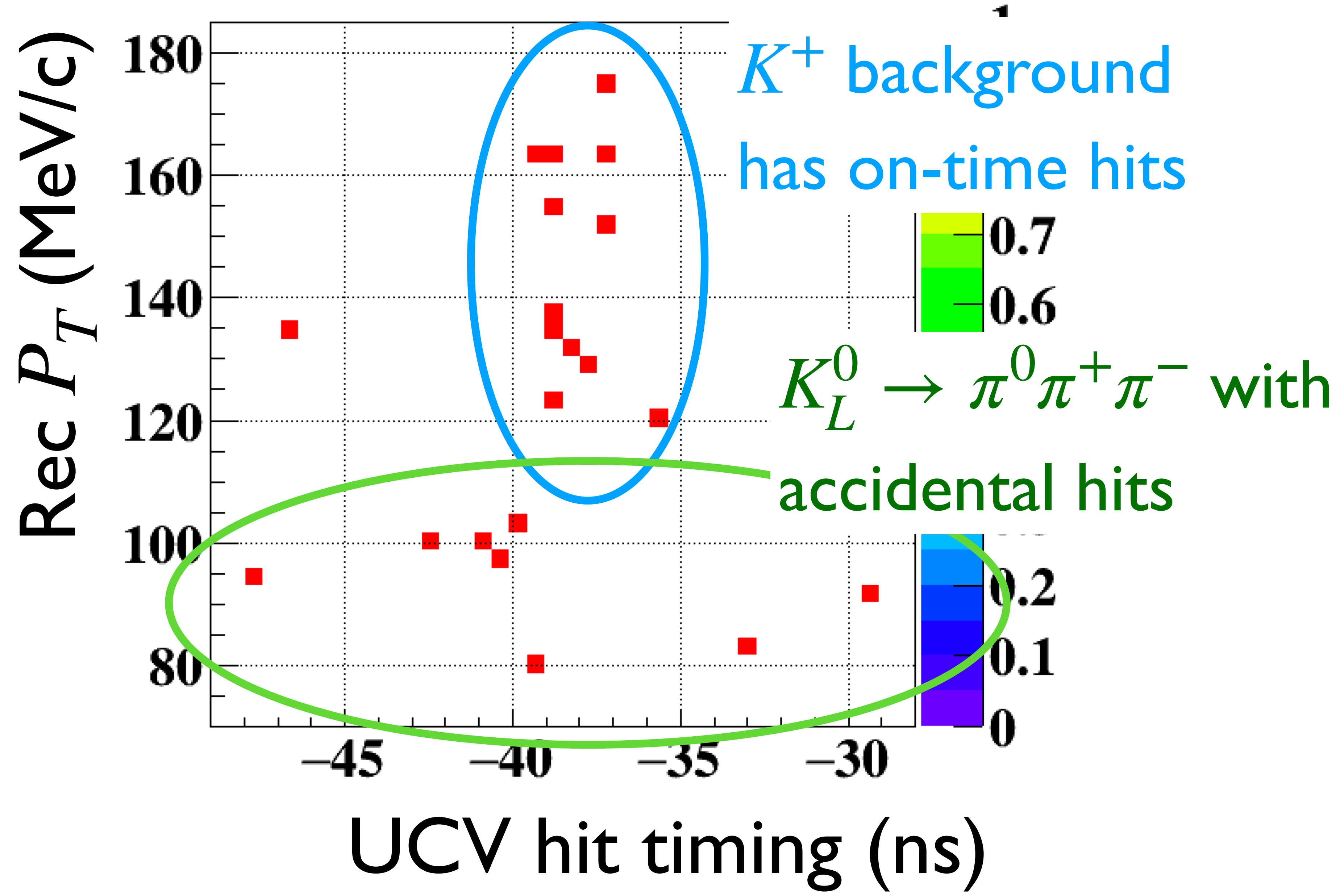
Example: validation of K^+ background

- Require that in-beam gas chamber has on-time hits to enhance $K^+ \to \pi^0\pi^+$ events.
- Events with on-time hits at UCV verifies this prediction.









Largest background source in 2021 data

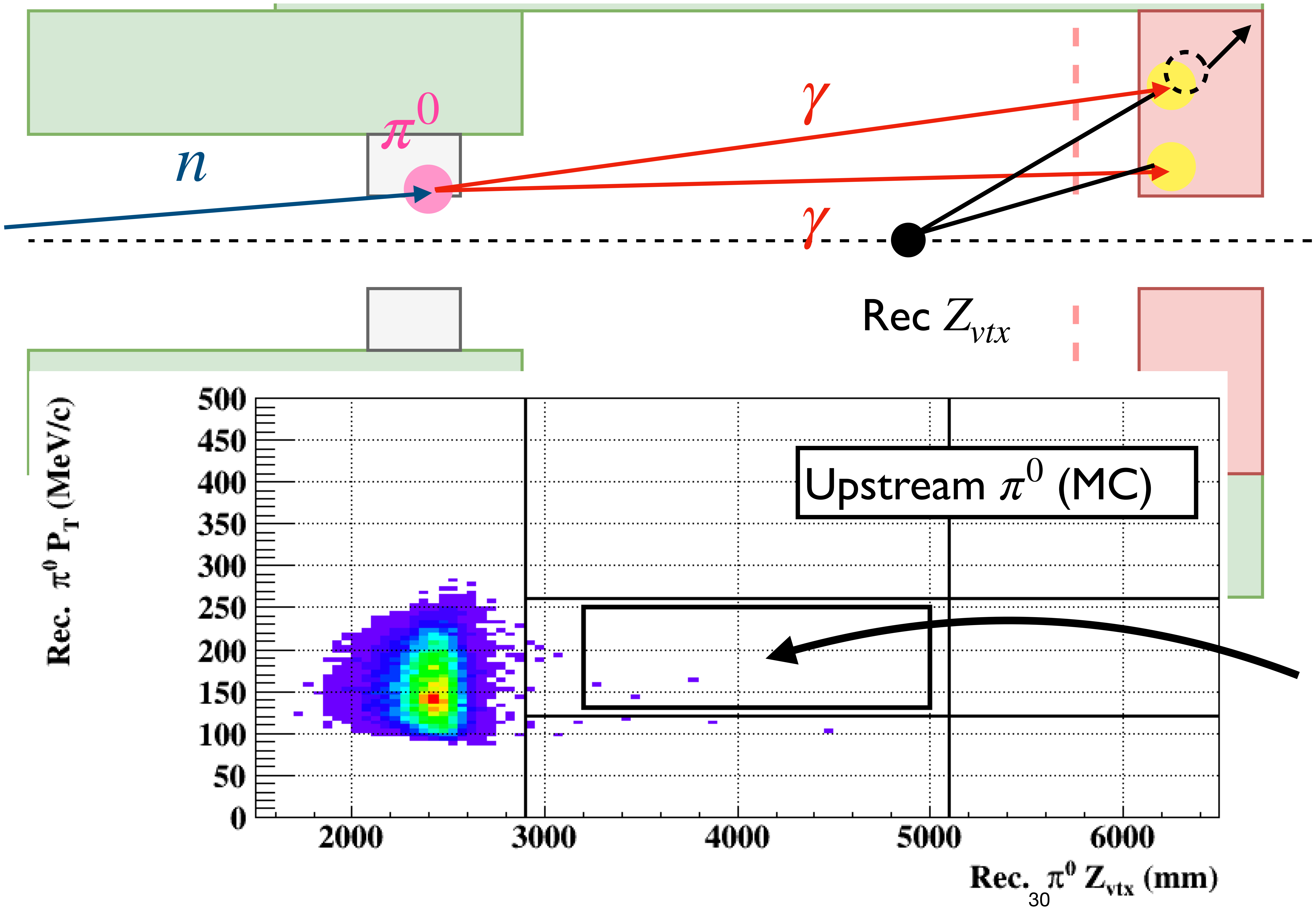


Photo-nuclear interactions

→ Measured energy is smaller.

The smaller energy results in the downstream shift, and are thus misidentified as signals.

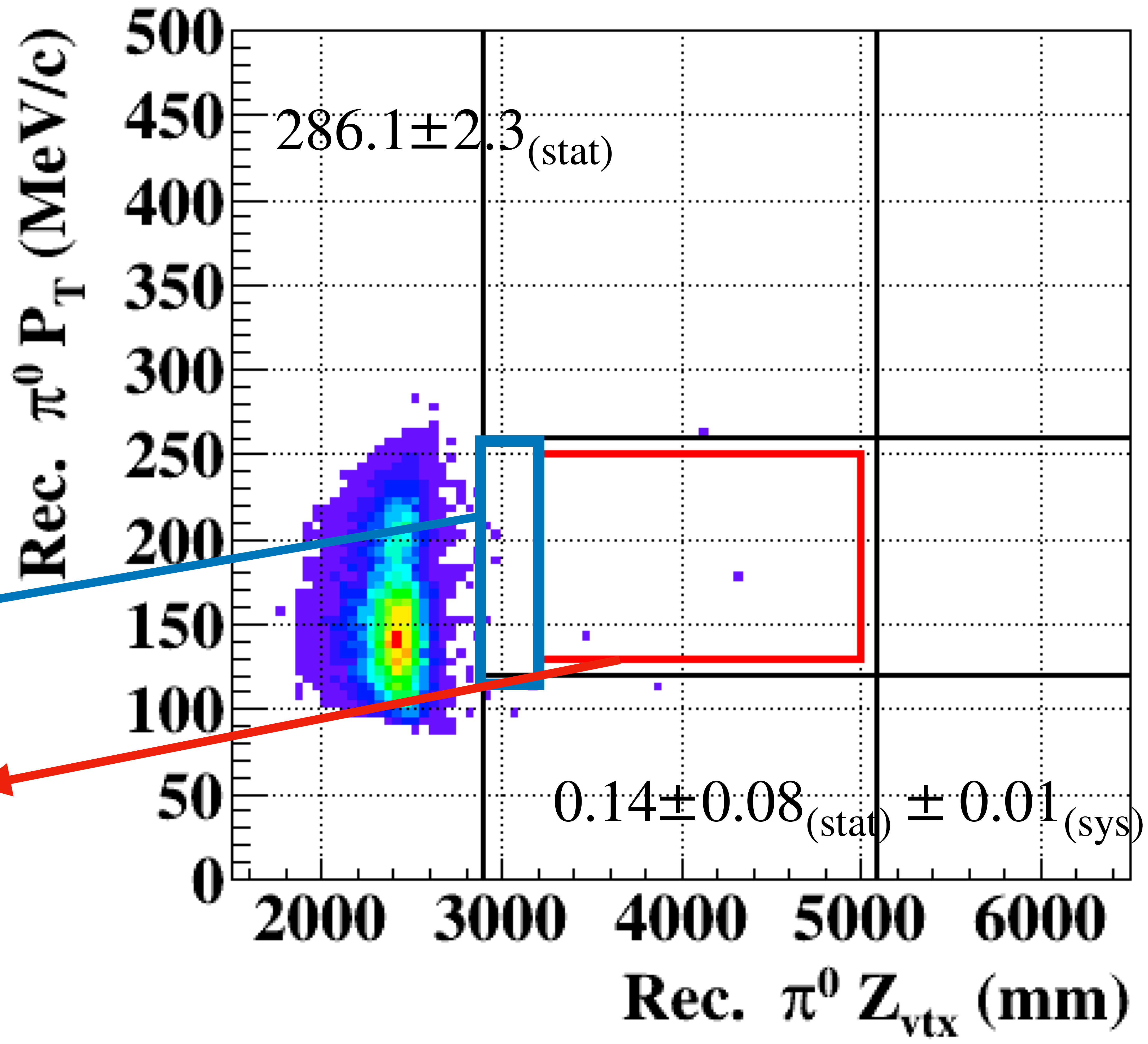
Adjustment of the signal region

The blind region is kept.

- Upstream boundary of the signal region is shifted to Z_{vtx} = 3.2 m to suppress the background.

$0.16 \pm 0.08_{(stat)} \pm 0.01_{(sys)}$

$0.064 \pm 0.050_{(stat)} \pm 0.06_{(sys)}$



Single event sensitivity

Single Event Sensitivity (SES)

(The branching ratio if one signal is observed)

$$SES = \frac{1}{N_{K_L^0} \times A_{sig}}$$

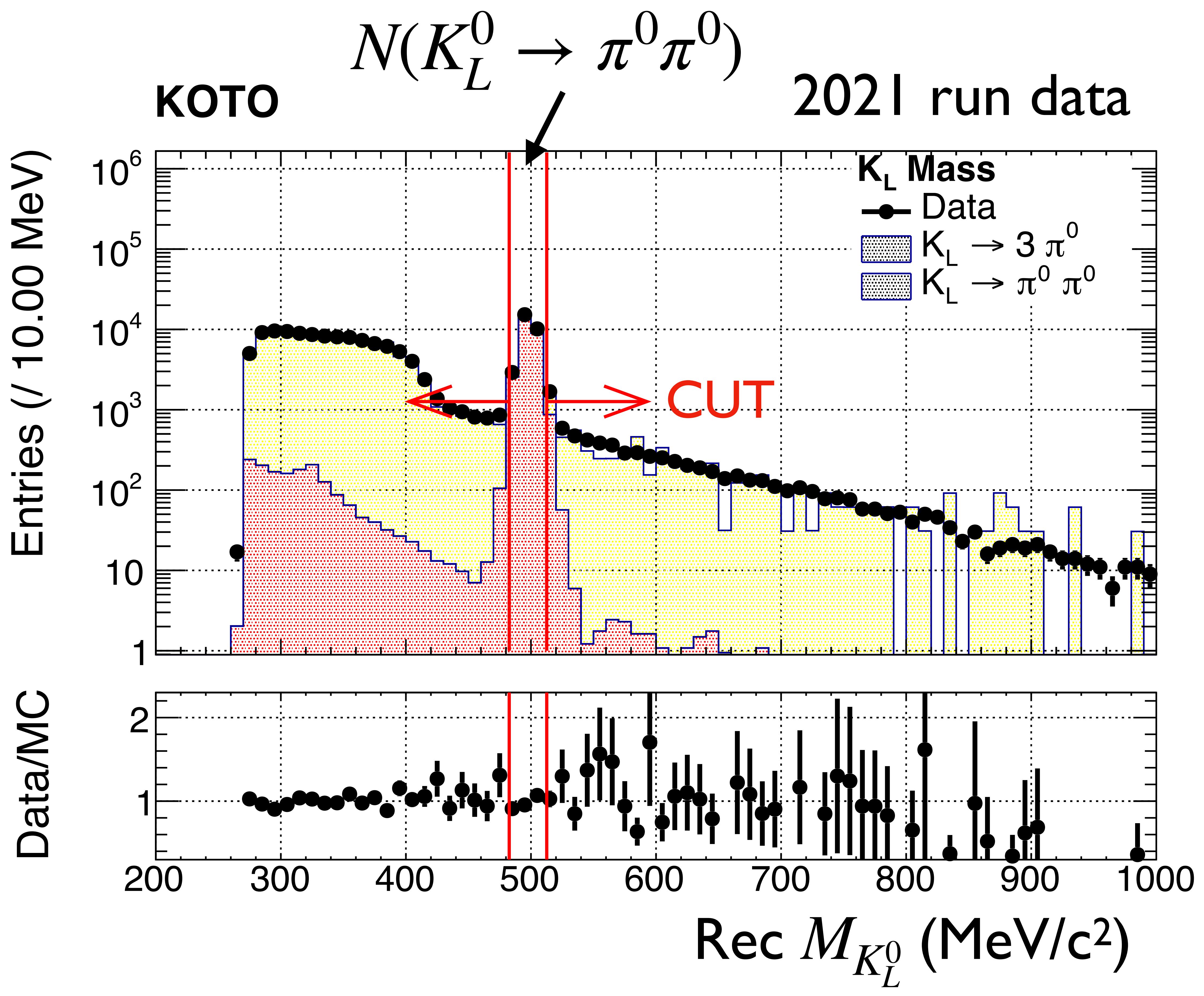
Calculated via well-known decay $K_L^0 \to \pi^0\pi^0$

Evaluated by MC

$$N_{K_L^0} = \frac{N(K_L^0 \to \pi^0\pi^0)}{A_{K_L^0\to\pi^0\pi^0} \times B(K_L^0 \to \pi^0\pi^0)} = 6.8 \times 10^{12}$$

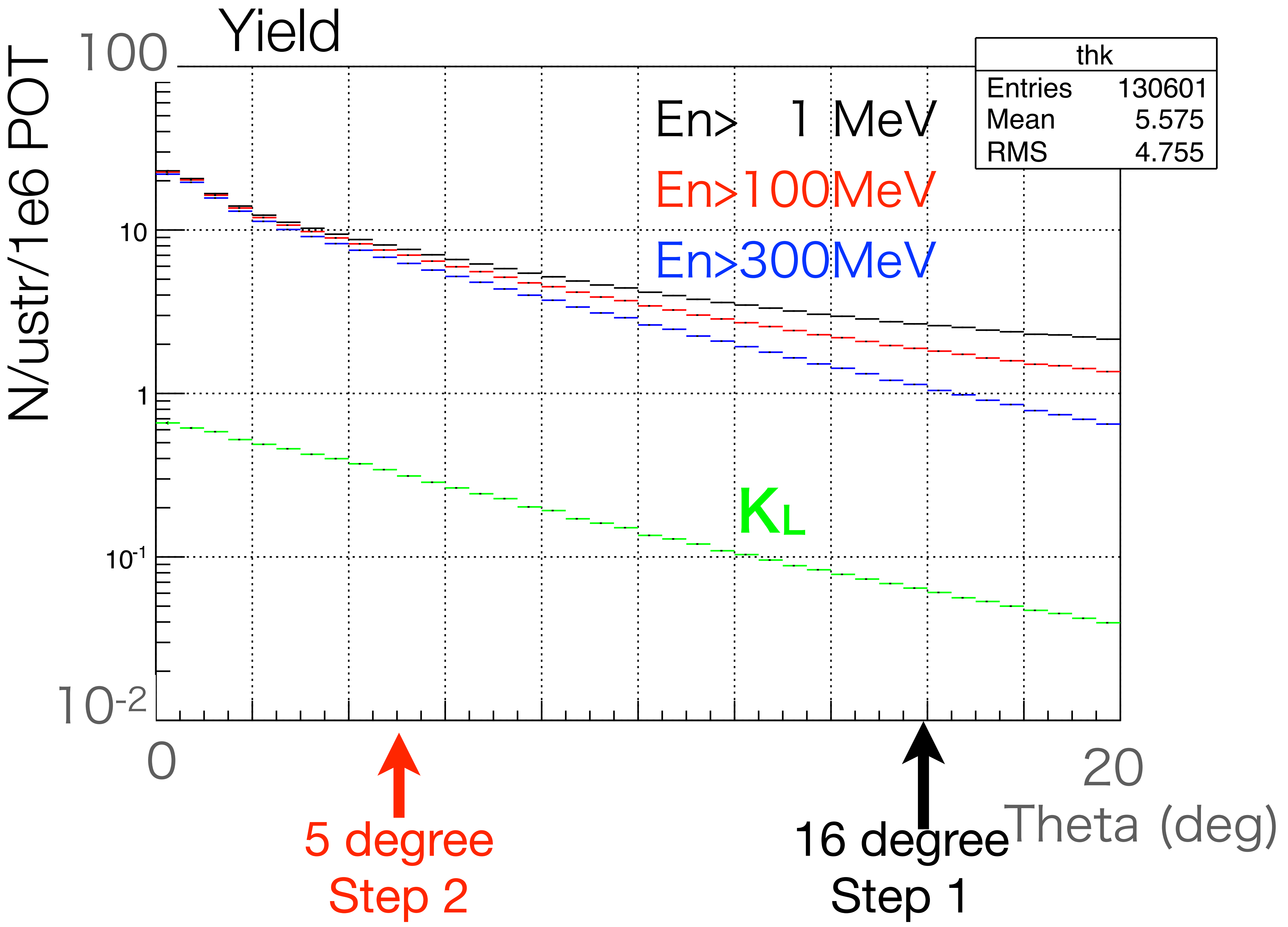
From PDG

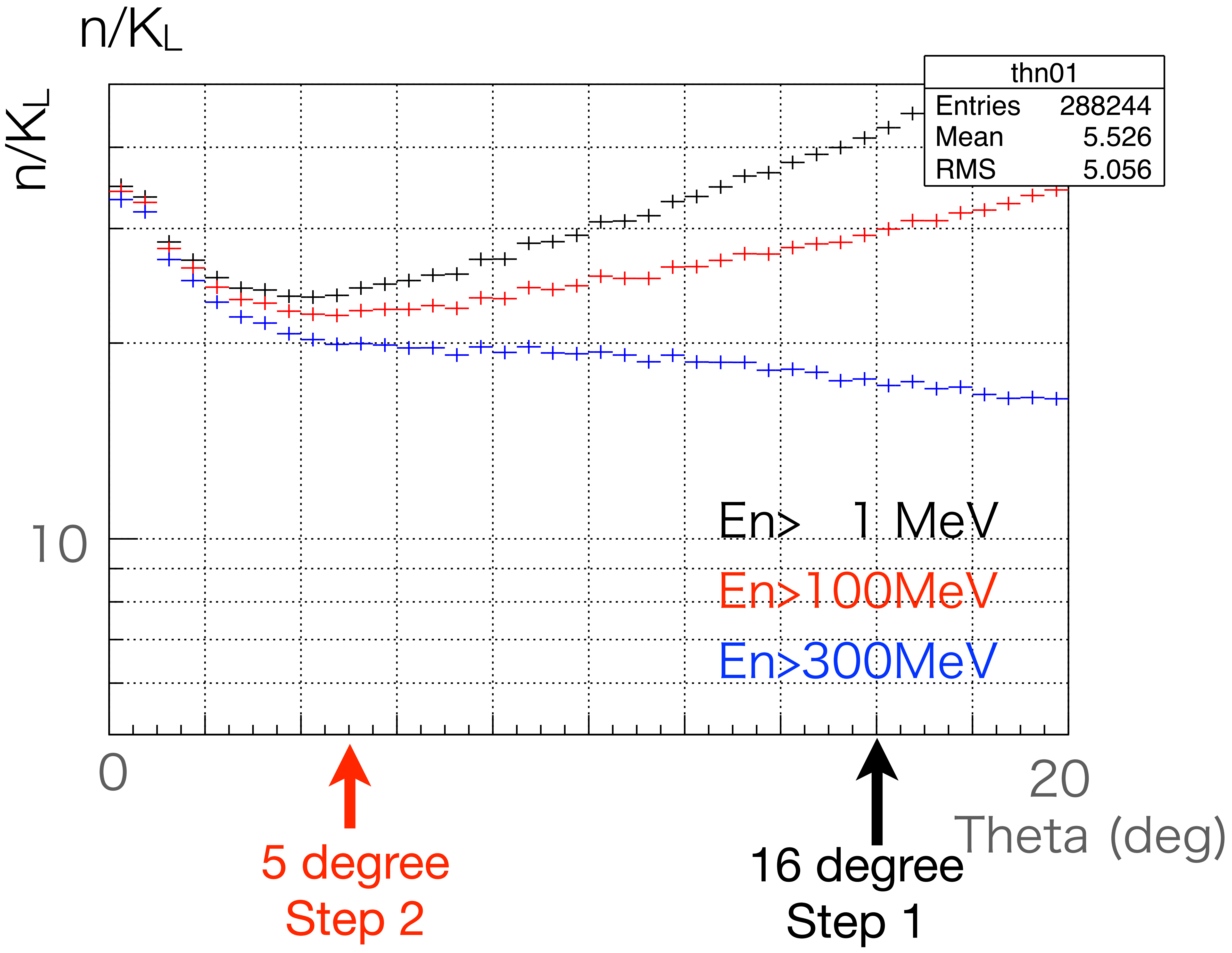
(at the entrance of the KOTO detector.)



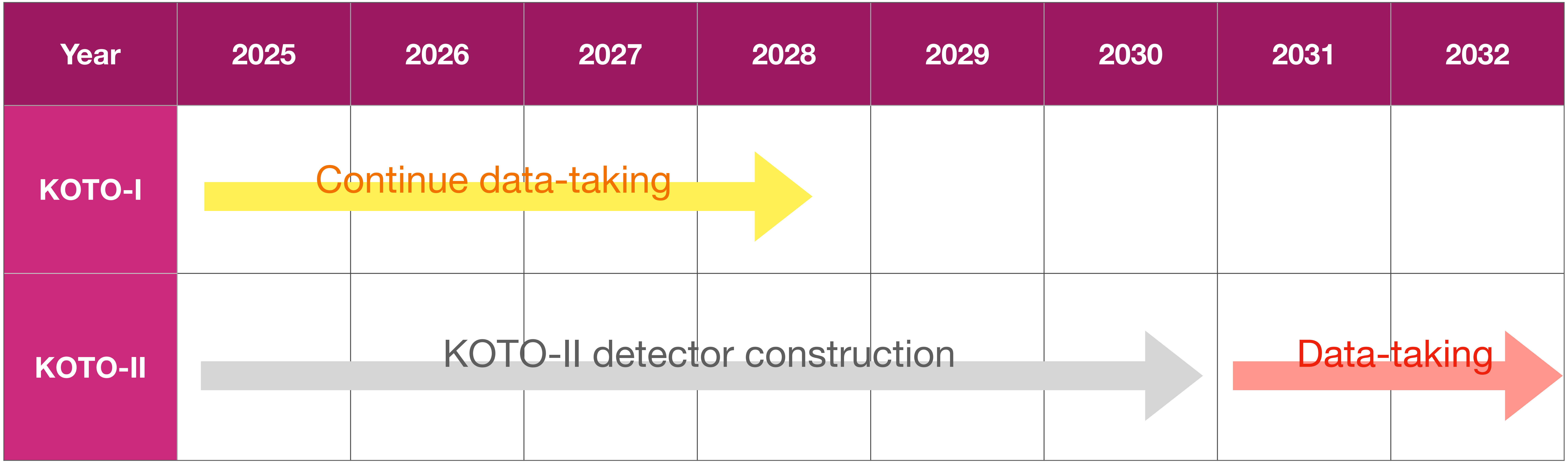
KOTO-II Simulation

Pros and cons of the shallow target angle





Roadmap of the KOTO-II Project



* The KOTO-II detector construction is parallel to the KOTO-I project for the first 4 years.
* The KOTO-I beam is then suspended for 2 years.