

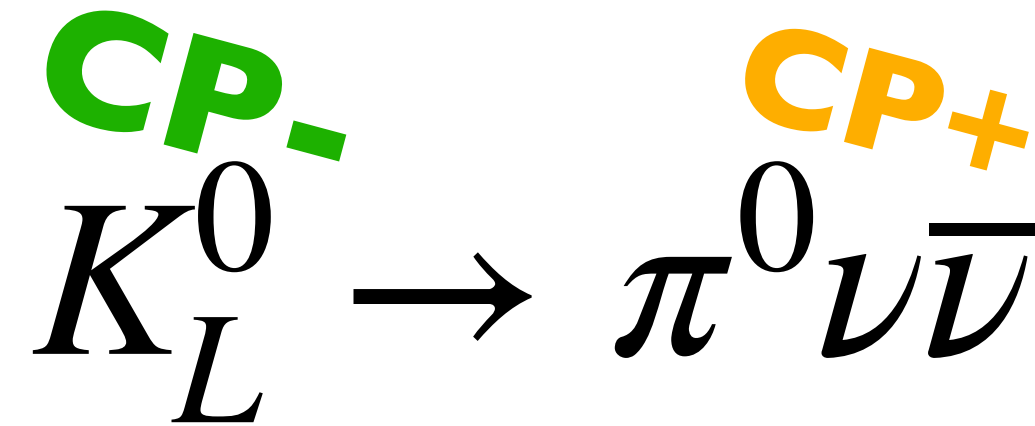
KOTO upgrade

TIDC 2025 (2026.01.06)

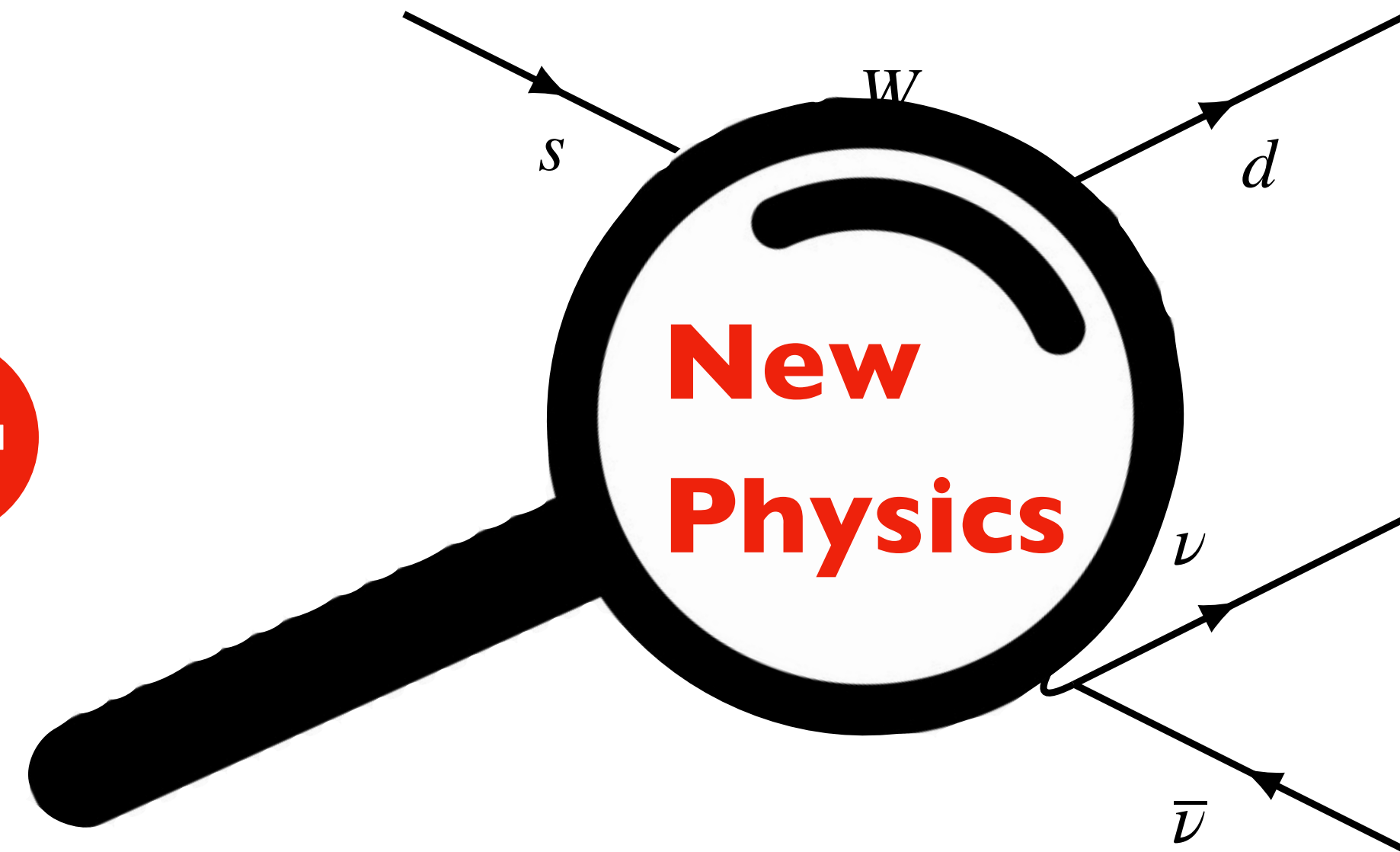
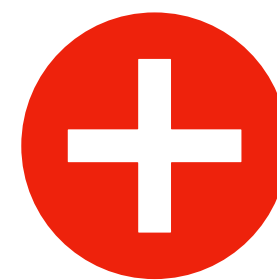
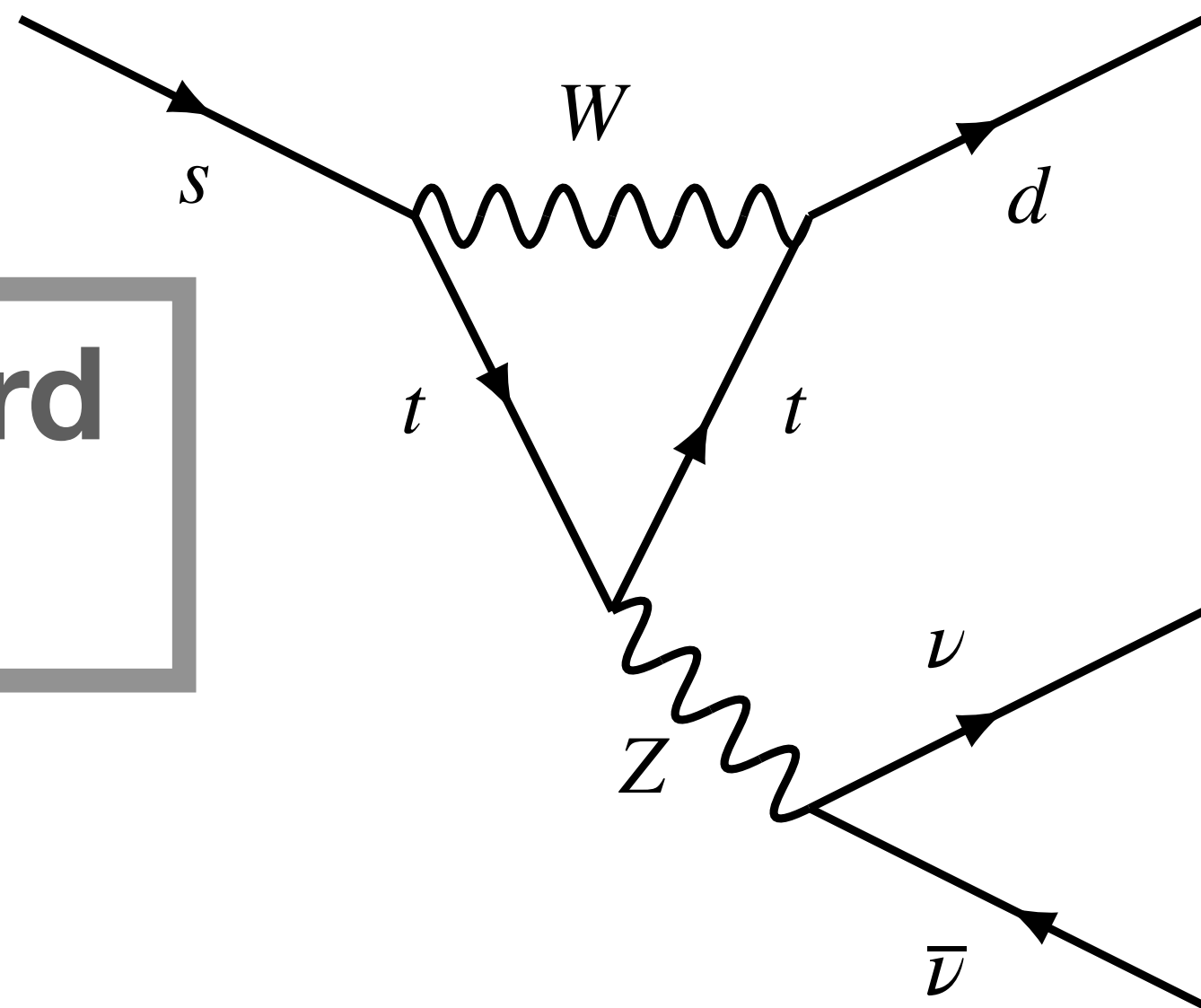
Chieh Lin (National Changhua University of Education)



Search for new physics via $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$



Standard Model



$$\mathcal{B}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})_{SM} = 3 \times 10^{-11}$$

(2% error only)

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

Rare & Precisely-predicted
 → Sensitive to New Physics

The regime where colliders can hardly explore.

New physics sensitive regime

Indirect upper limit given by NA62



Experimental result of $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$
 $(13.0^{+3.3}_{-3.0}) \times 10^{-11}$ JHEP 02 (2025) 191

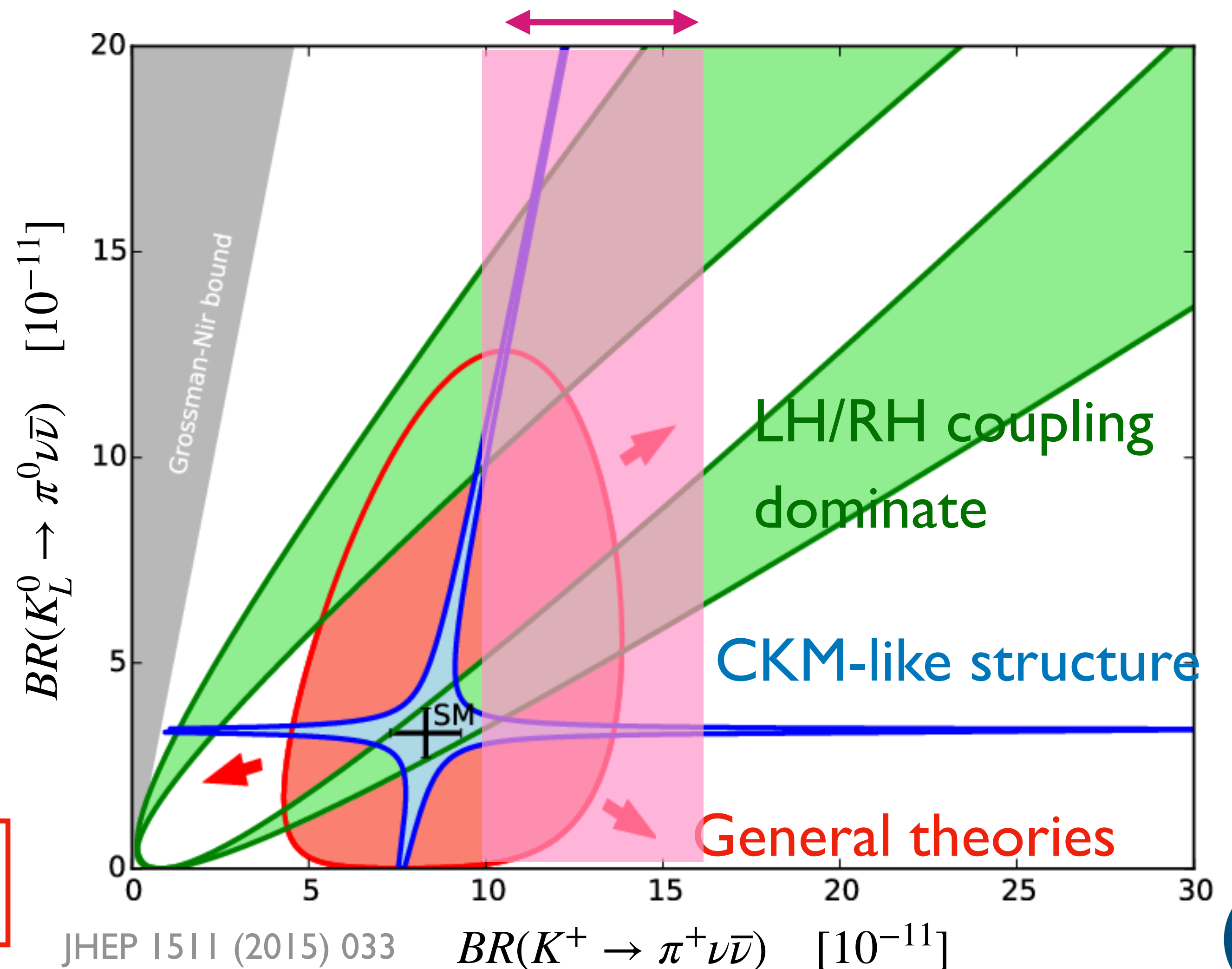
Agrees with SM $(9.11 \pm 0.72) \times 10^{-11}$
 with 1.7σ JHEP 1511 (2015) 033

Model-independent constraint
Grossman-Nir (GN) bound

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

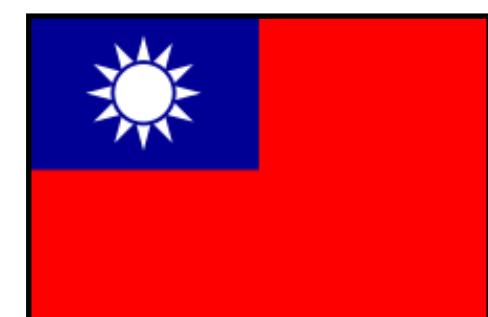
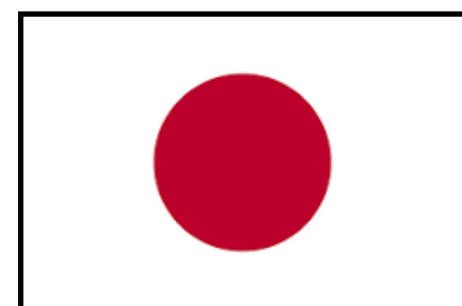
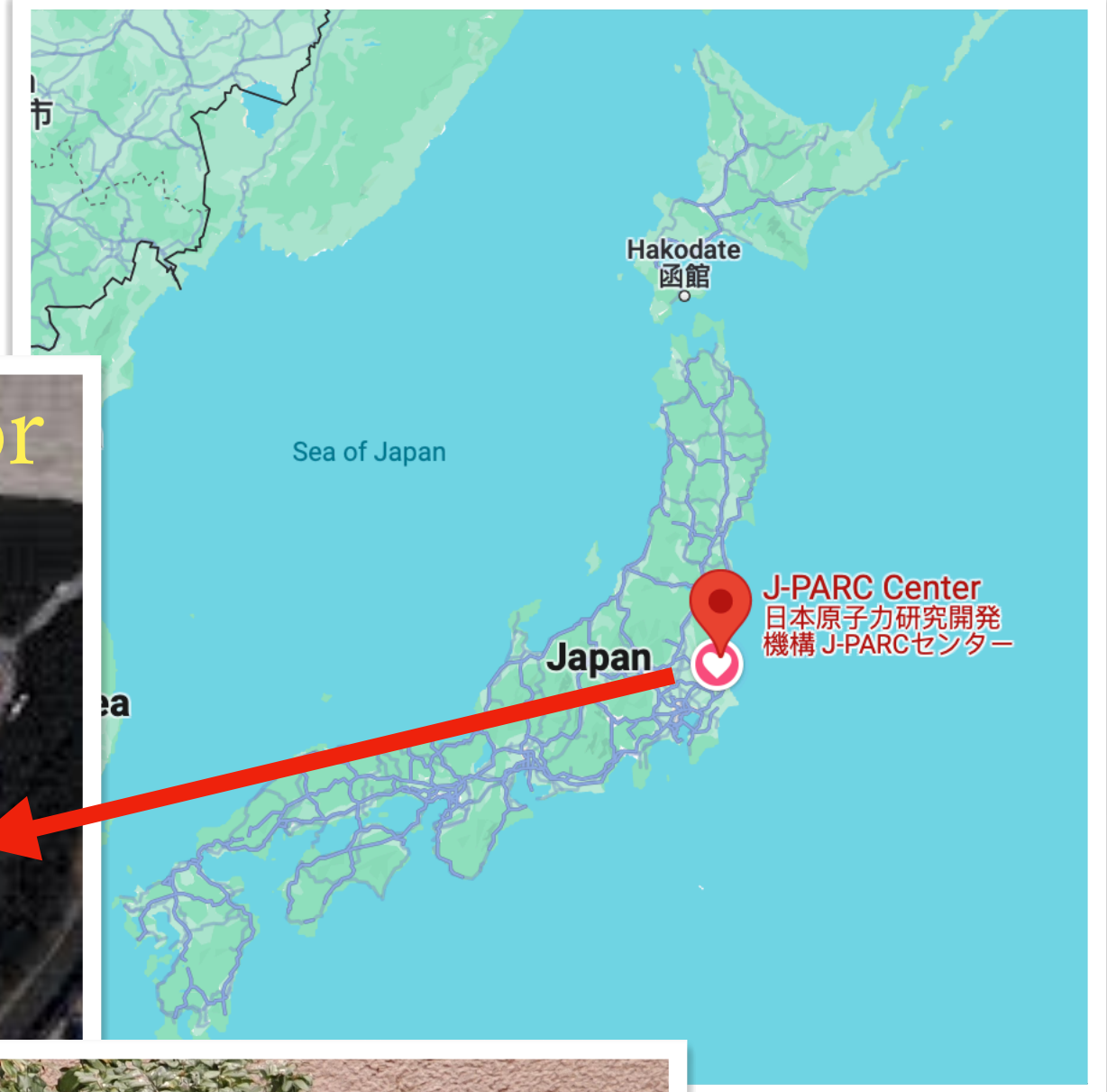
$$\leq 7.0 \times 10^{-10} \text{ (68\% C.L.)}$$

1- σ window by NA62 (2025)



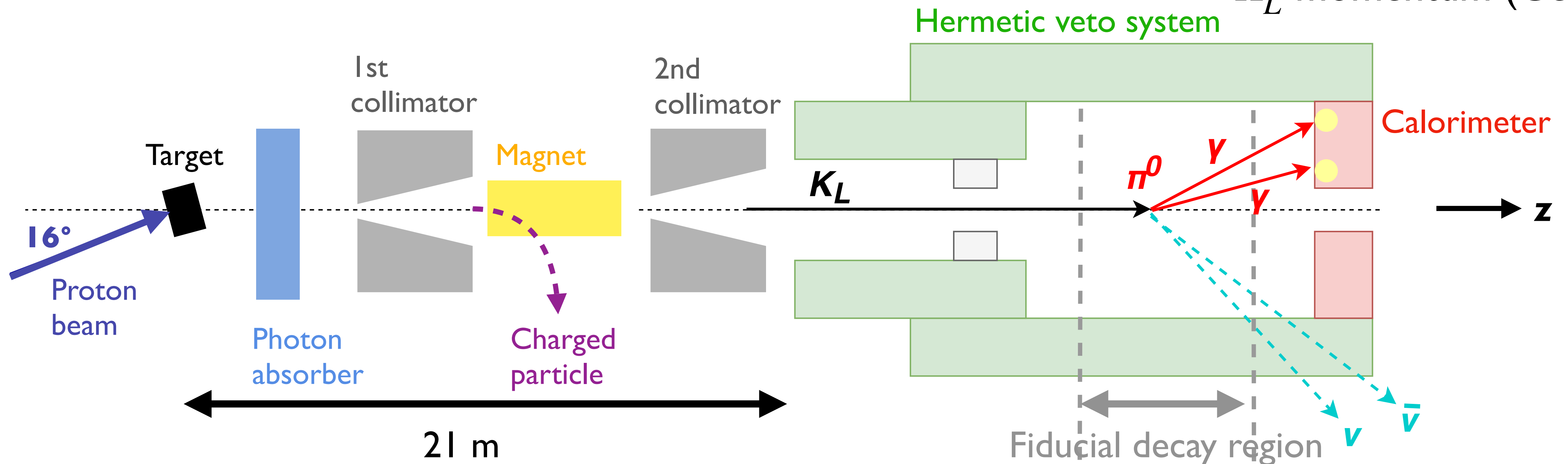
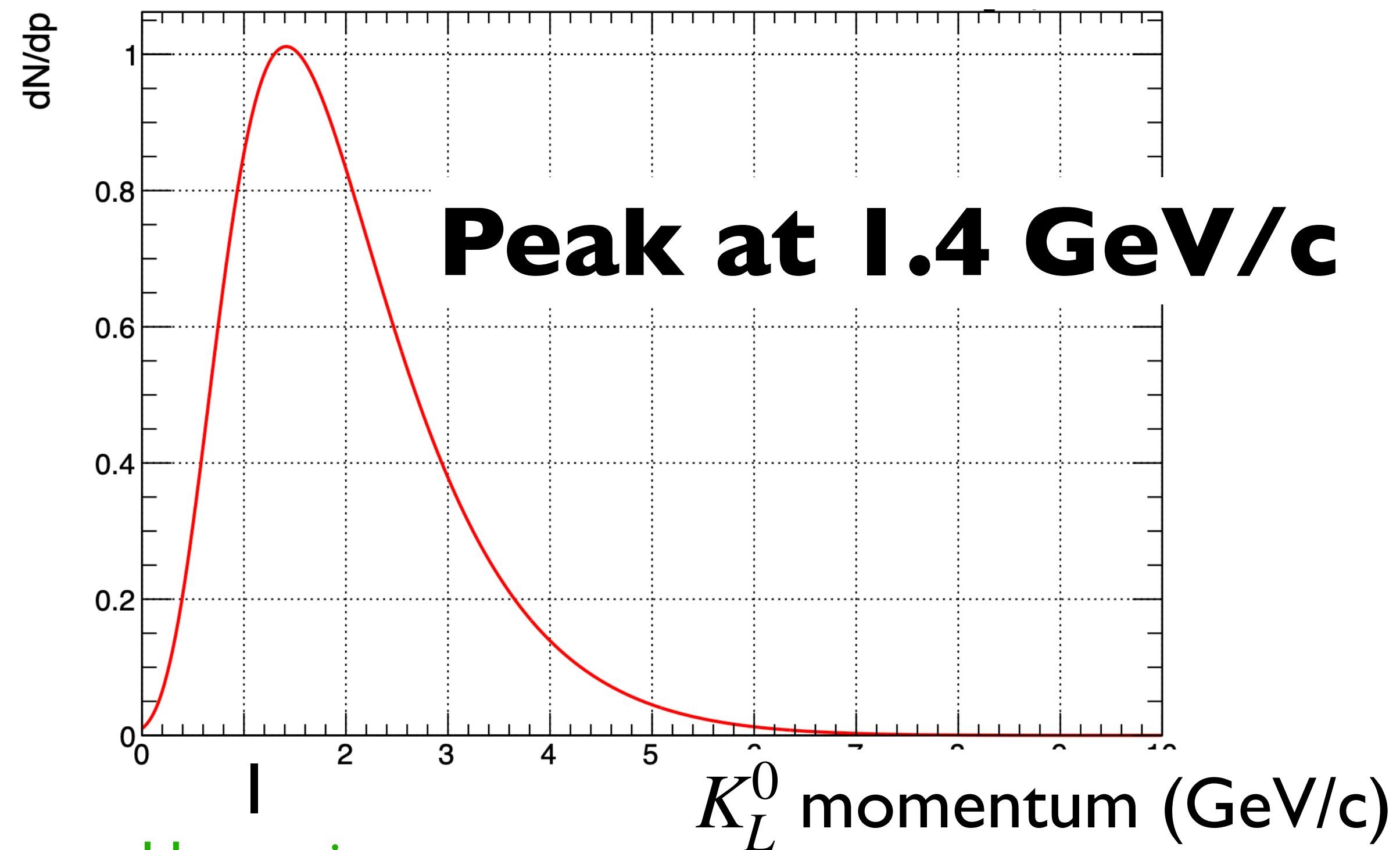
The KOTO experiment

KOTO (K0 at T0kai) aims to search for the rare kaon decay at J-PARC.



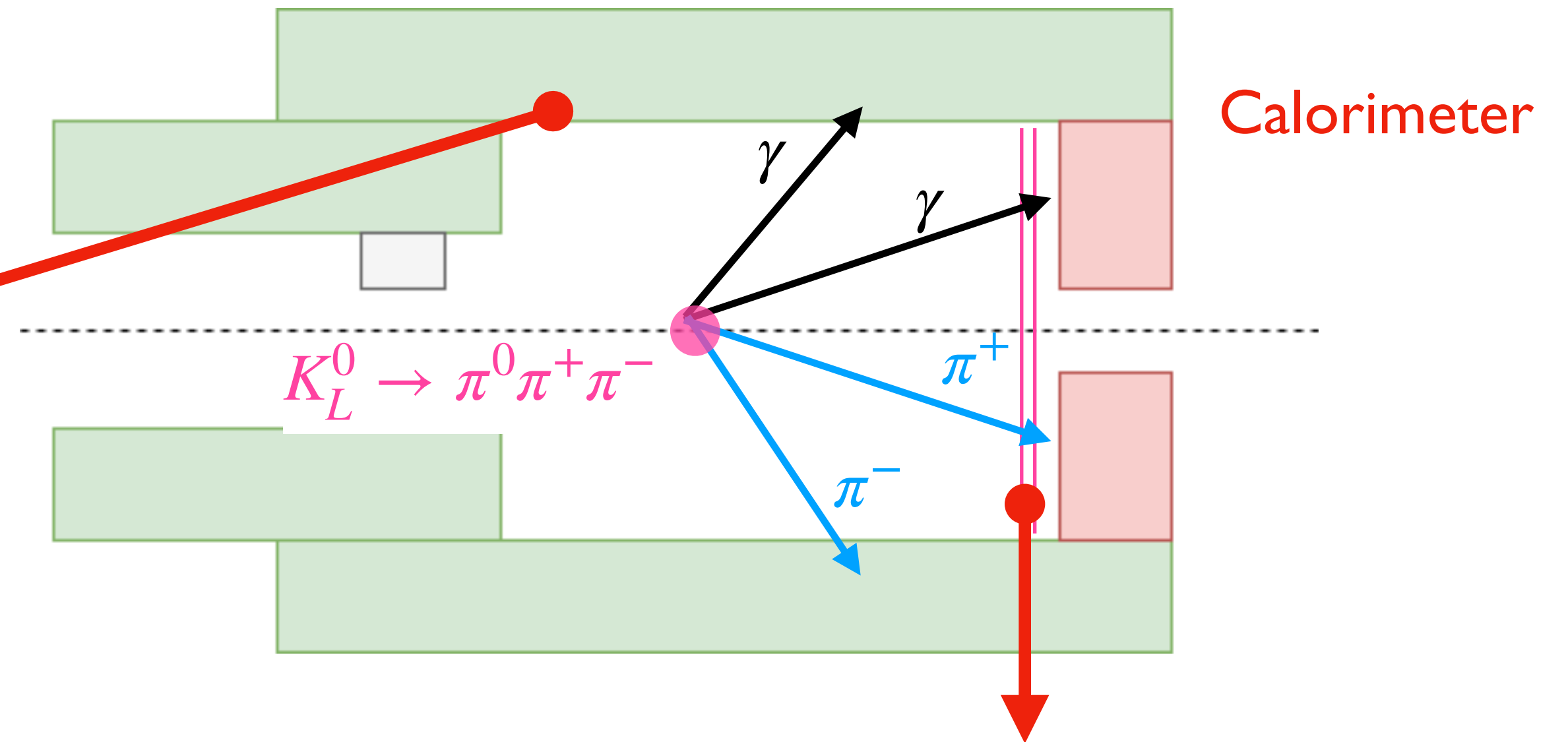
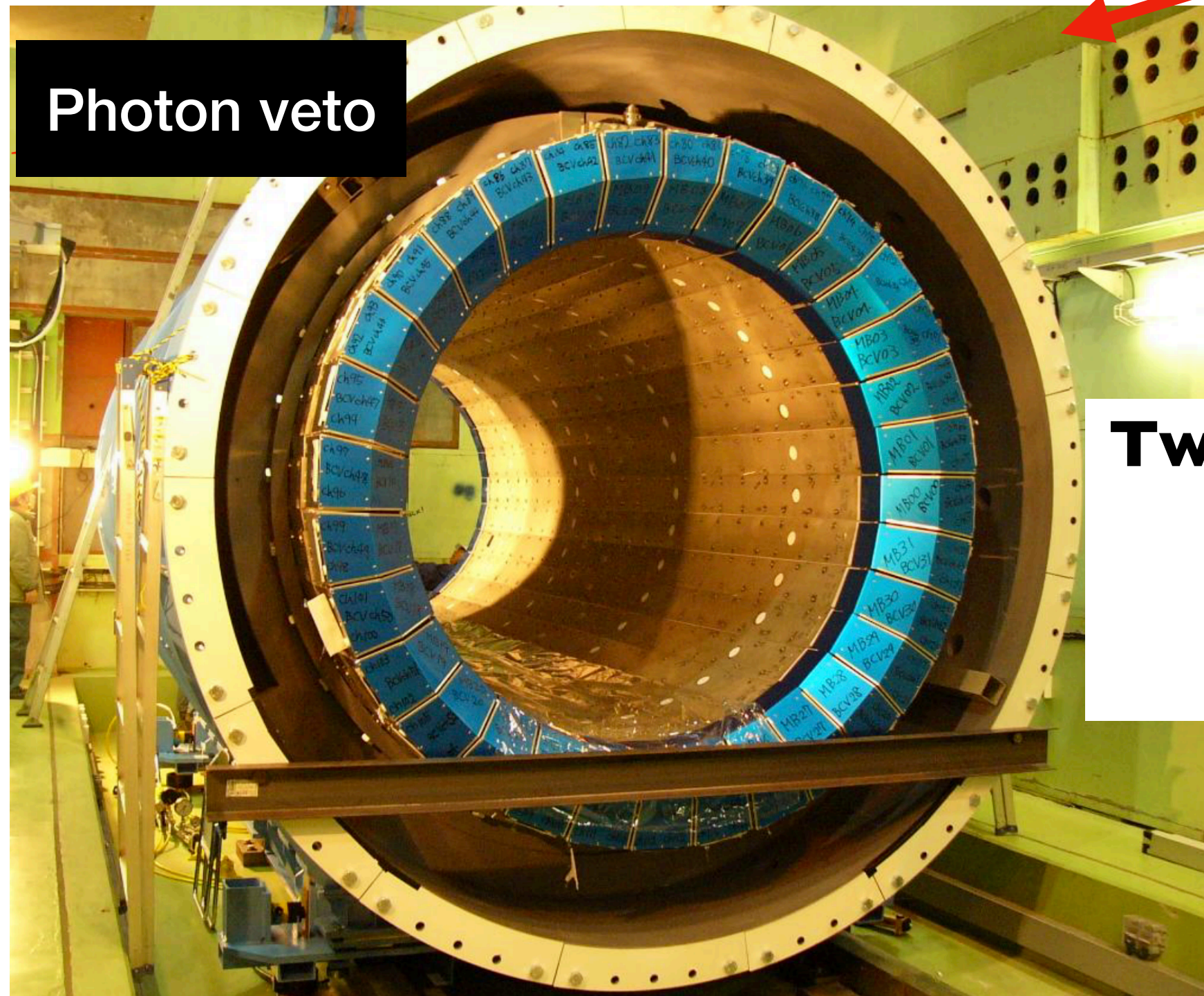
Neutral Kaon Beam

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



Detector Design

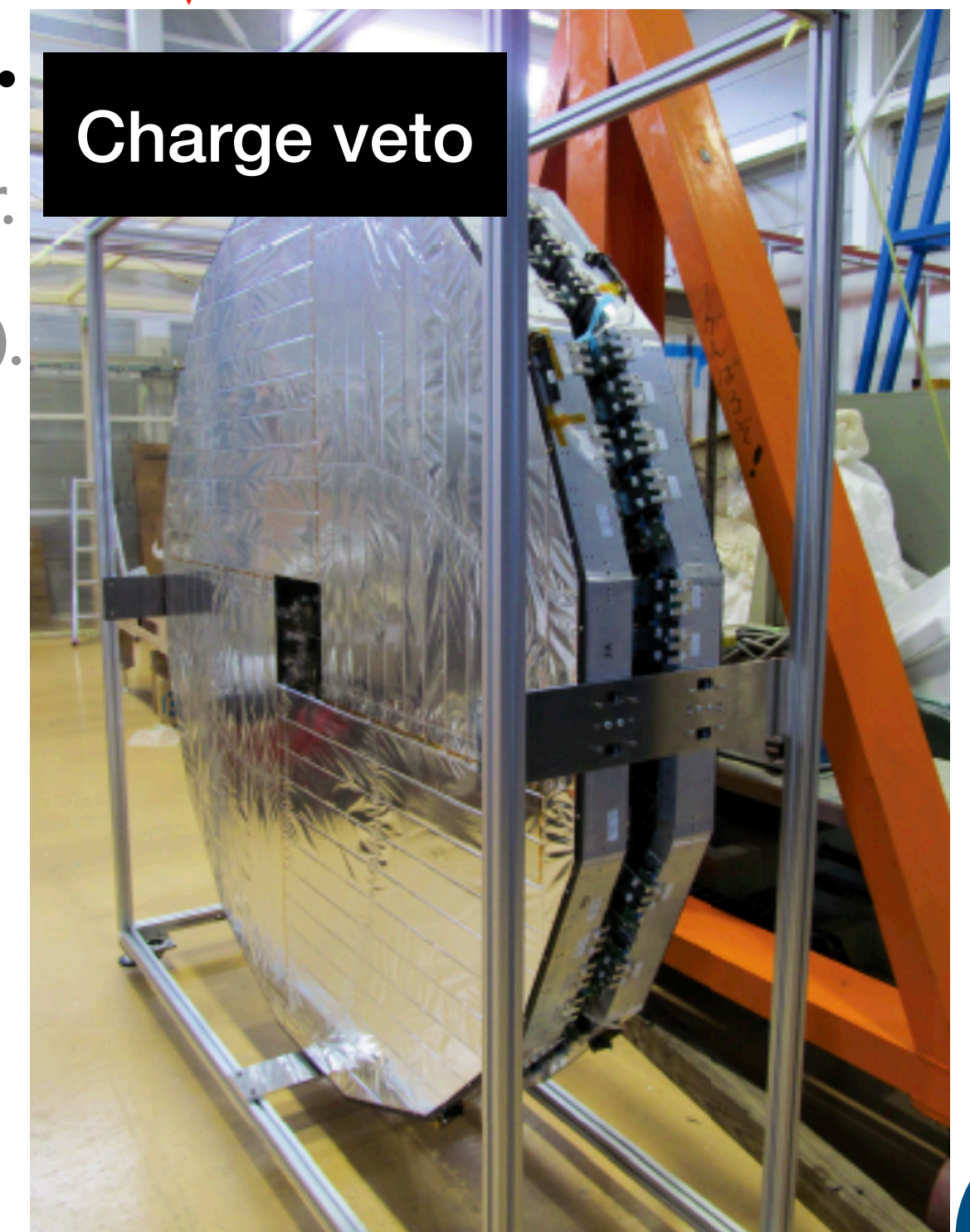
Hermetic veto system



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 = $19 X_0$.

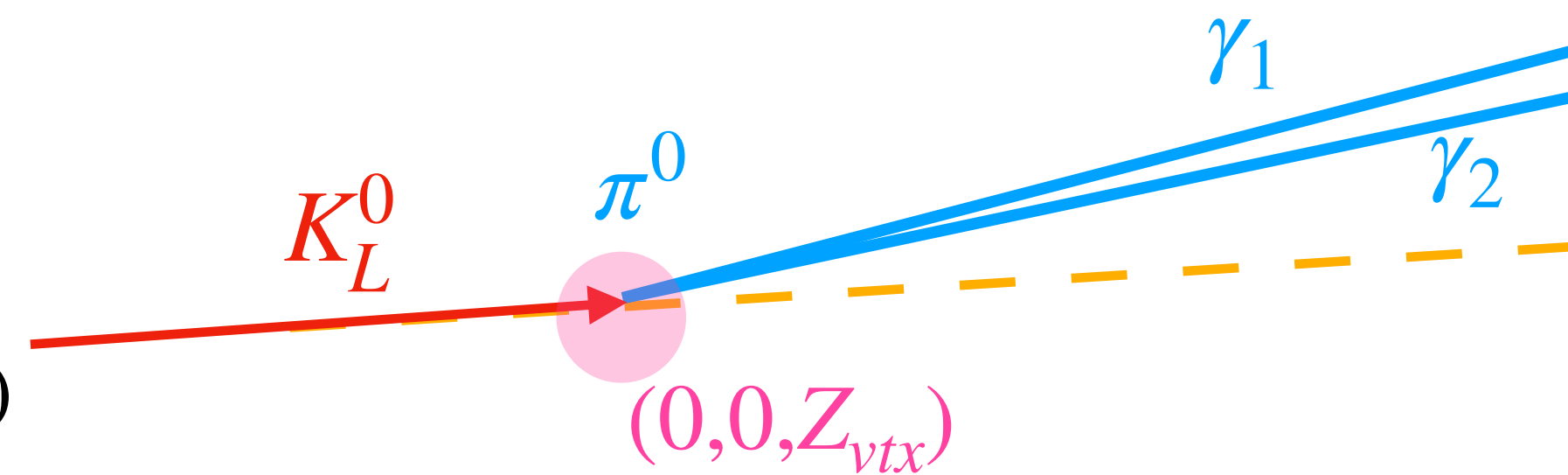
Signal Identification

Reconstruction method

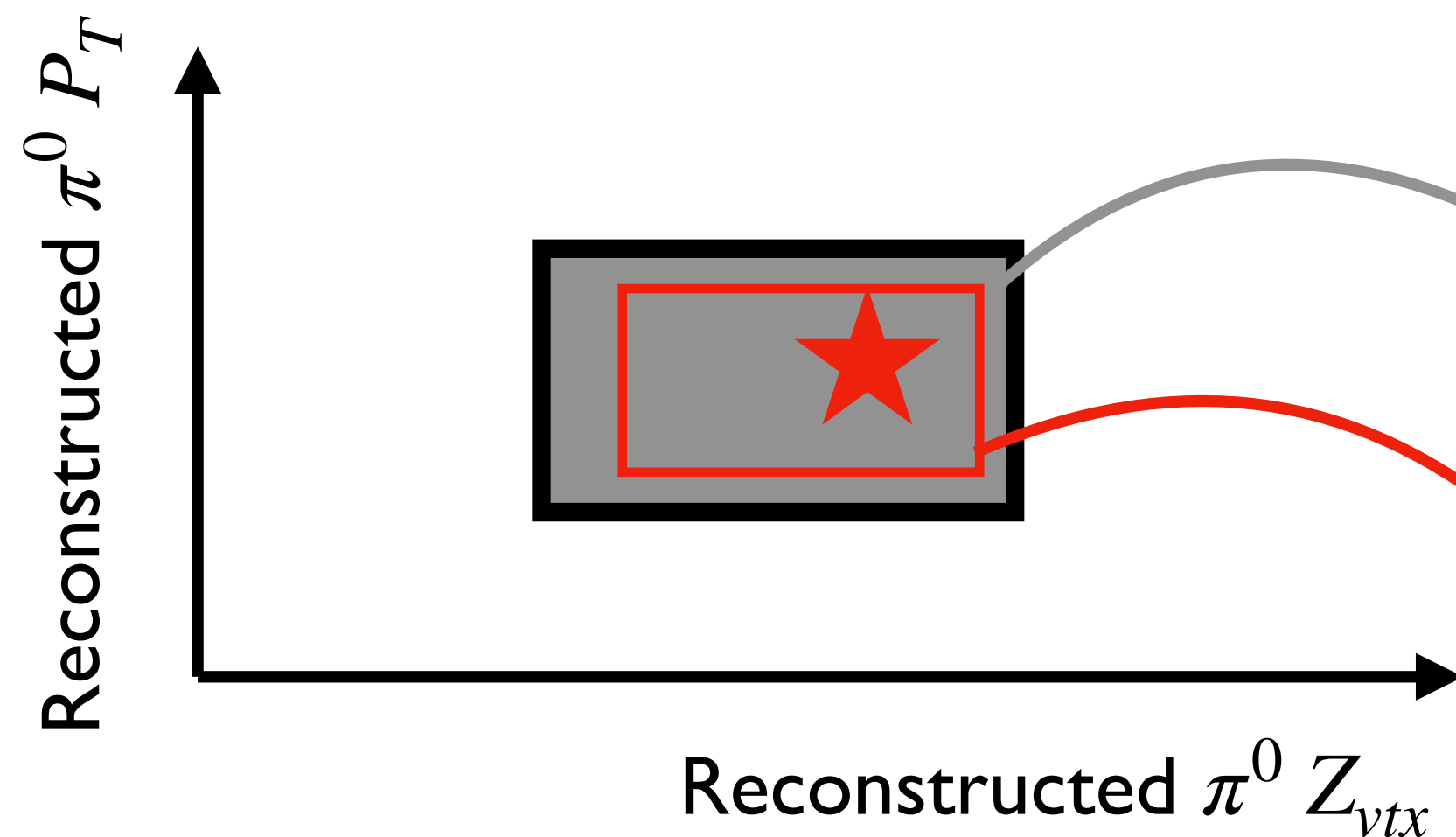
- Reconstruct decay vertex using π^0 mass constraint.

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

$$\theta = \theta(Z_{vtx})$$



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

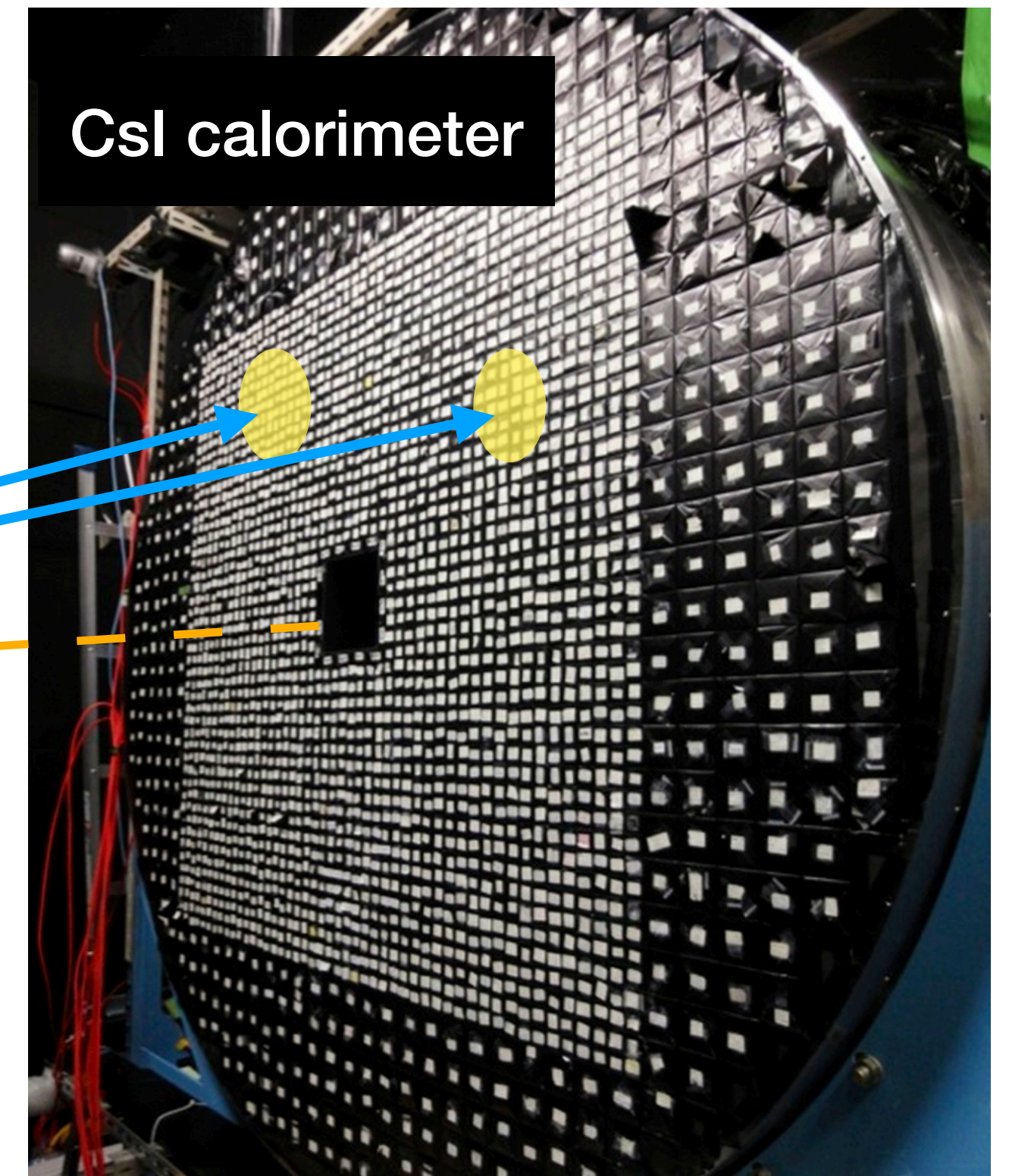


Blind analysis

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

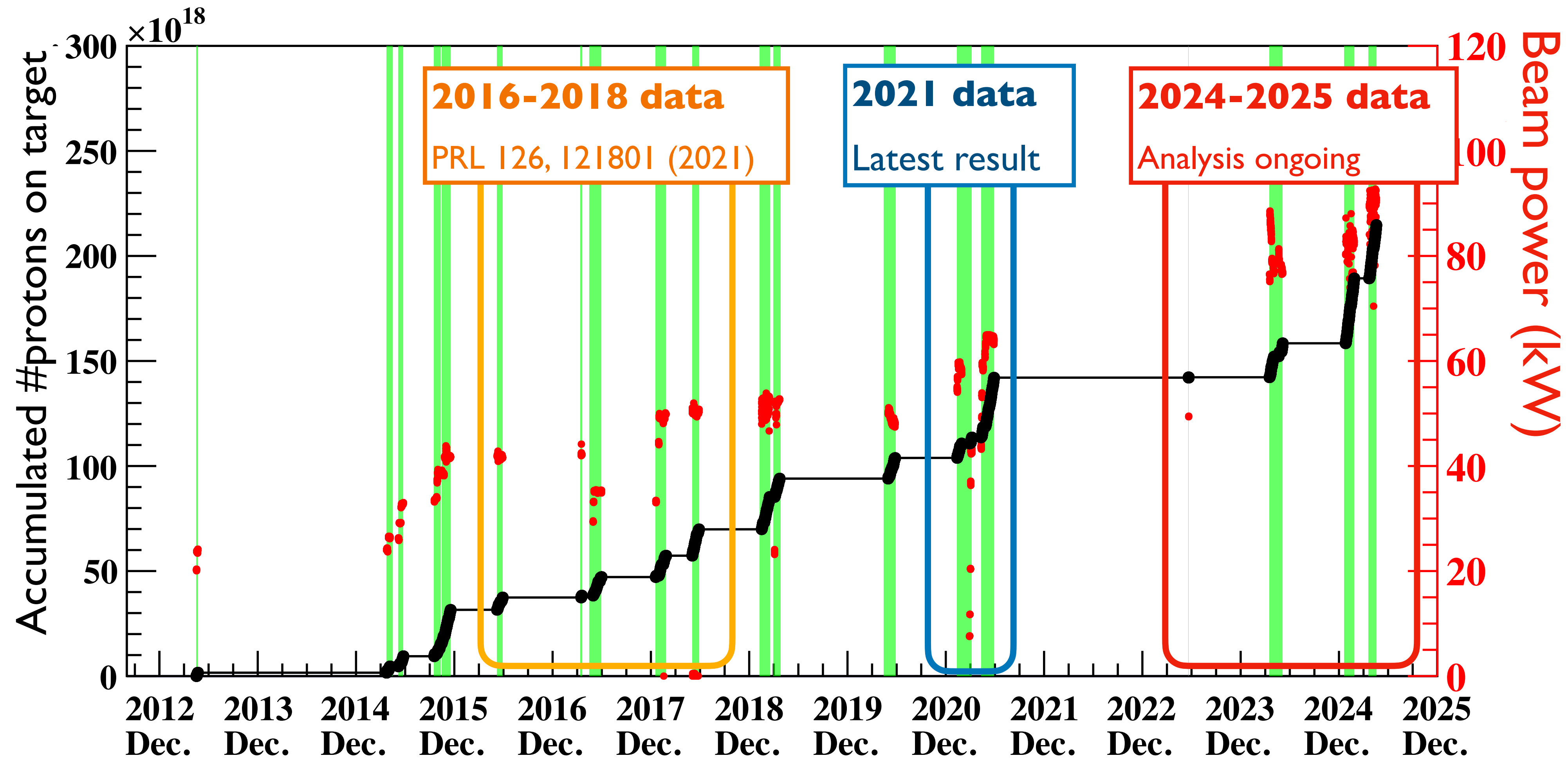
Signal region

Events inside this region will be identified as signal candidates.



KOTO data collection history

- KOTO expects to improve the sensitivity by another factor of 2 using the data collected during 2024- 2025.



Single event sensitivity

Latest results

Single Event Sensitivity (*SES*)

(The branching ratio if one signal is observed)

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

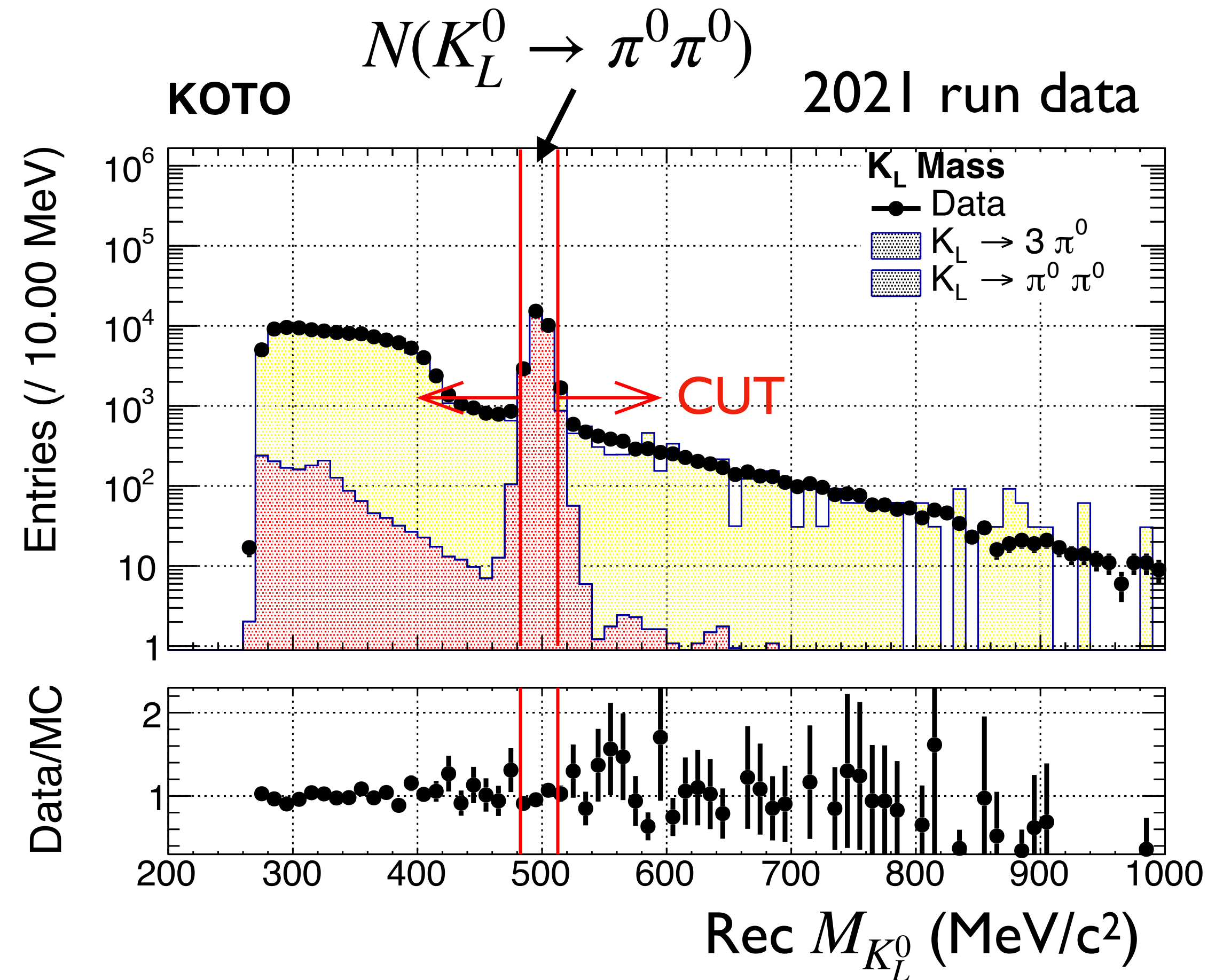
Calculated via well-known
decay $K_L^0 \rightarrow \pi^0 \pi^0$

Evaluated by MC

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

From PDG

(at the entrance of the KOTO detector.)



Experimental status

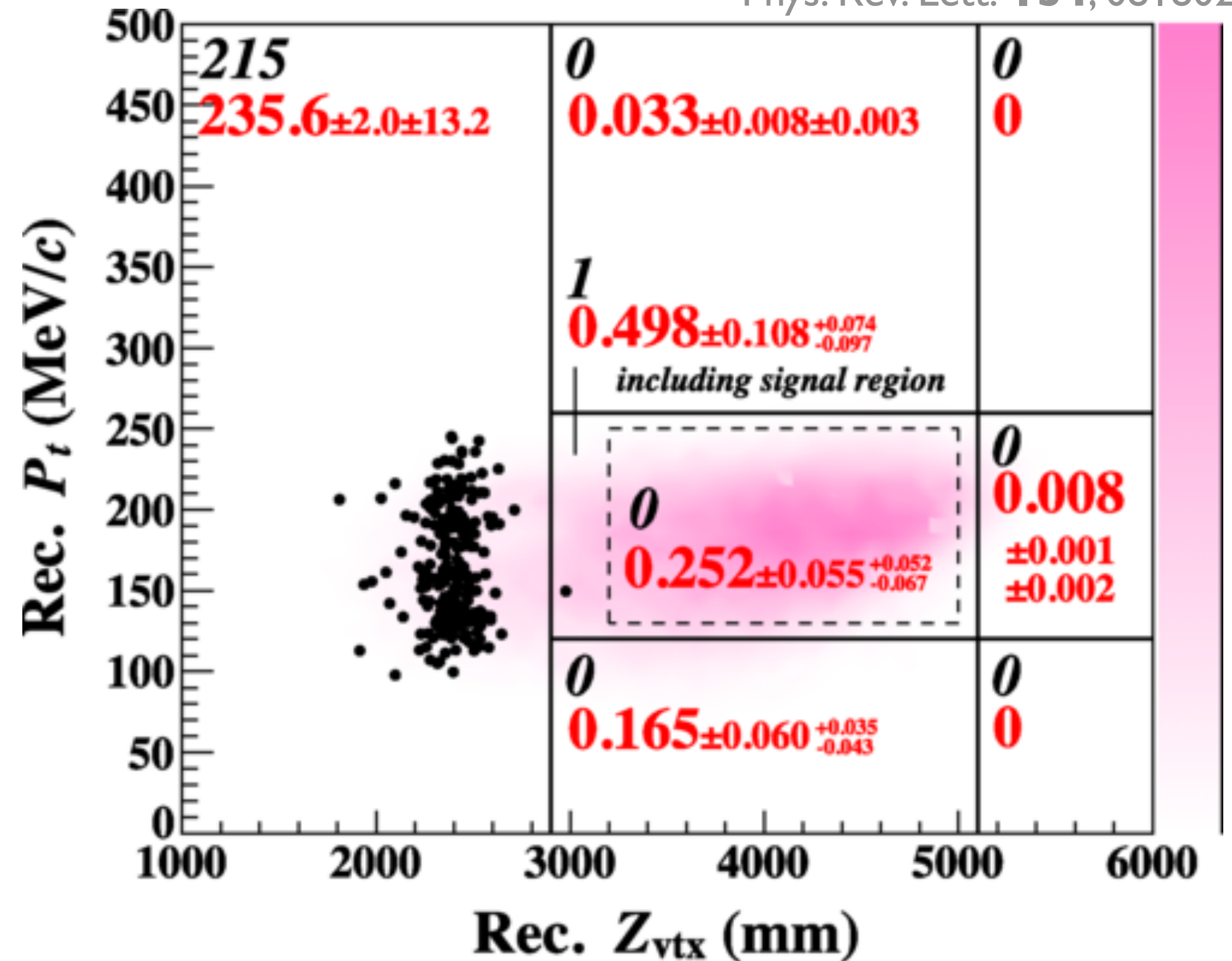
Latest results

- Worldwide best limit is set by KOTO using data collected in 2021:

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

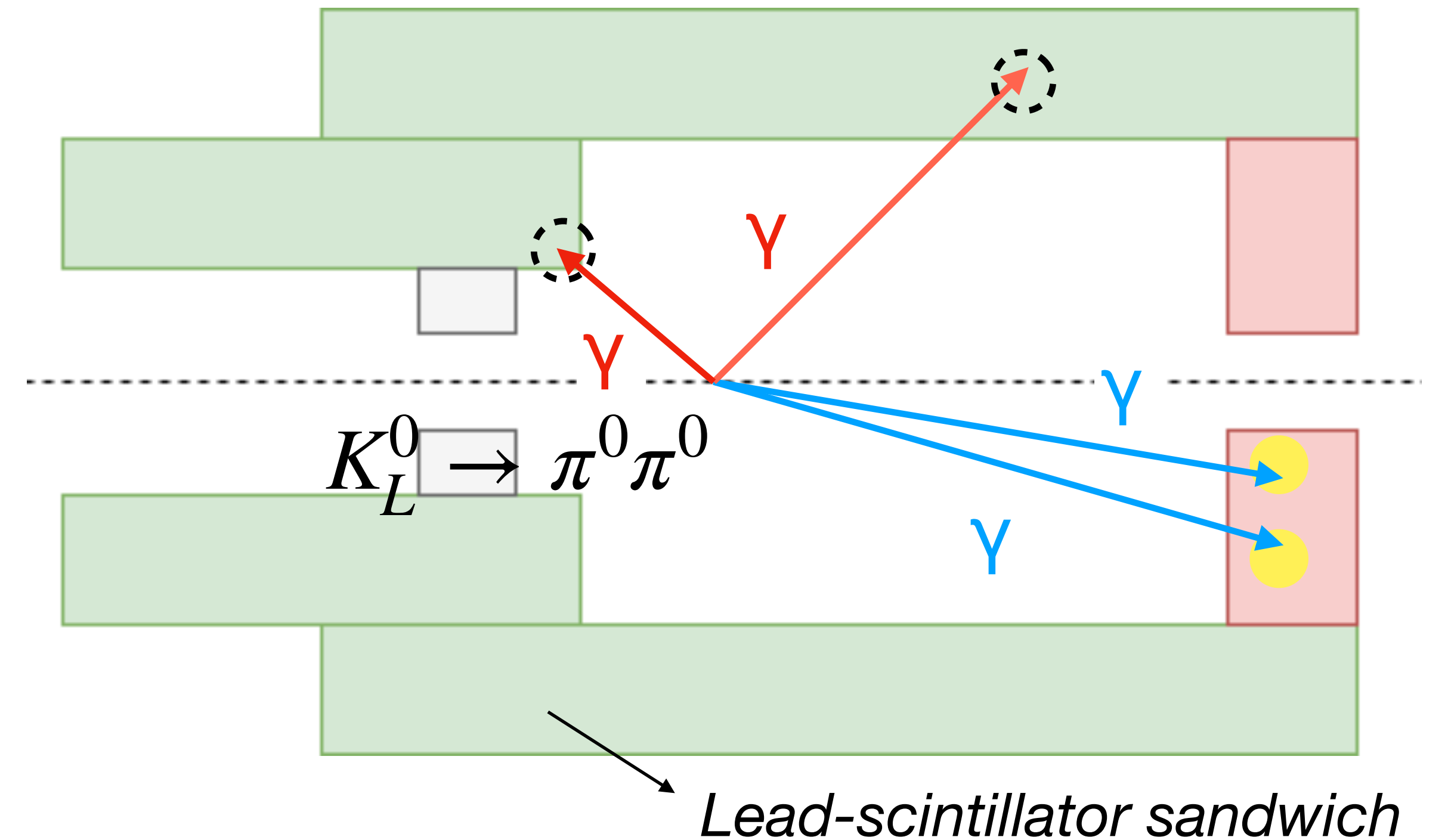
| Source | Number of events |
|---|-------------------------------------|
| K^\pm | $0.042 \pm 0.014^{+0.004}_{-0.028}$ |
| K_L ★ $K_L \rightarrow 2\gamma$ (beam-halo) | $0.045 \pm 0.010 \pm 0.006$ |
| K_L $K_L \rightarrow 2\pi^0$ | $0.059 \pm 0.022^{+0.050}_{-0.059}$ |
| Neutron hadron-cluster | $0.024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

Phys. Rev. Lett. **134**, 081802



$K_L^0 \rightarrow \pi^0 \pi^0$ background

- One of the major background sources
 $K_L^0 \rightarrow \pi^0 \pi^0$ decay is formidable.
- One of the π^0 s decays into two γ s but both γ s are not detected due to the veto inefficiency.



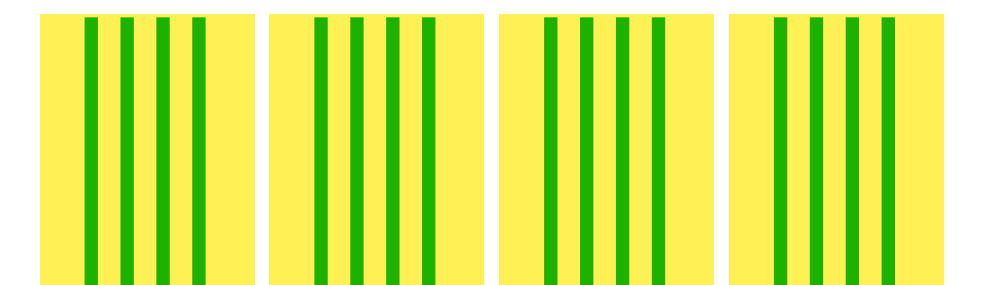
KOTO II experiment

- Higher intensity beam \rightarrow better signal strength.
- Higher kaon momentum and new detector configuration
 \rightarrow better detection efficiency

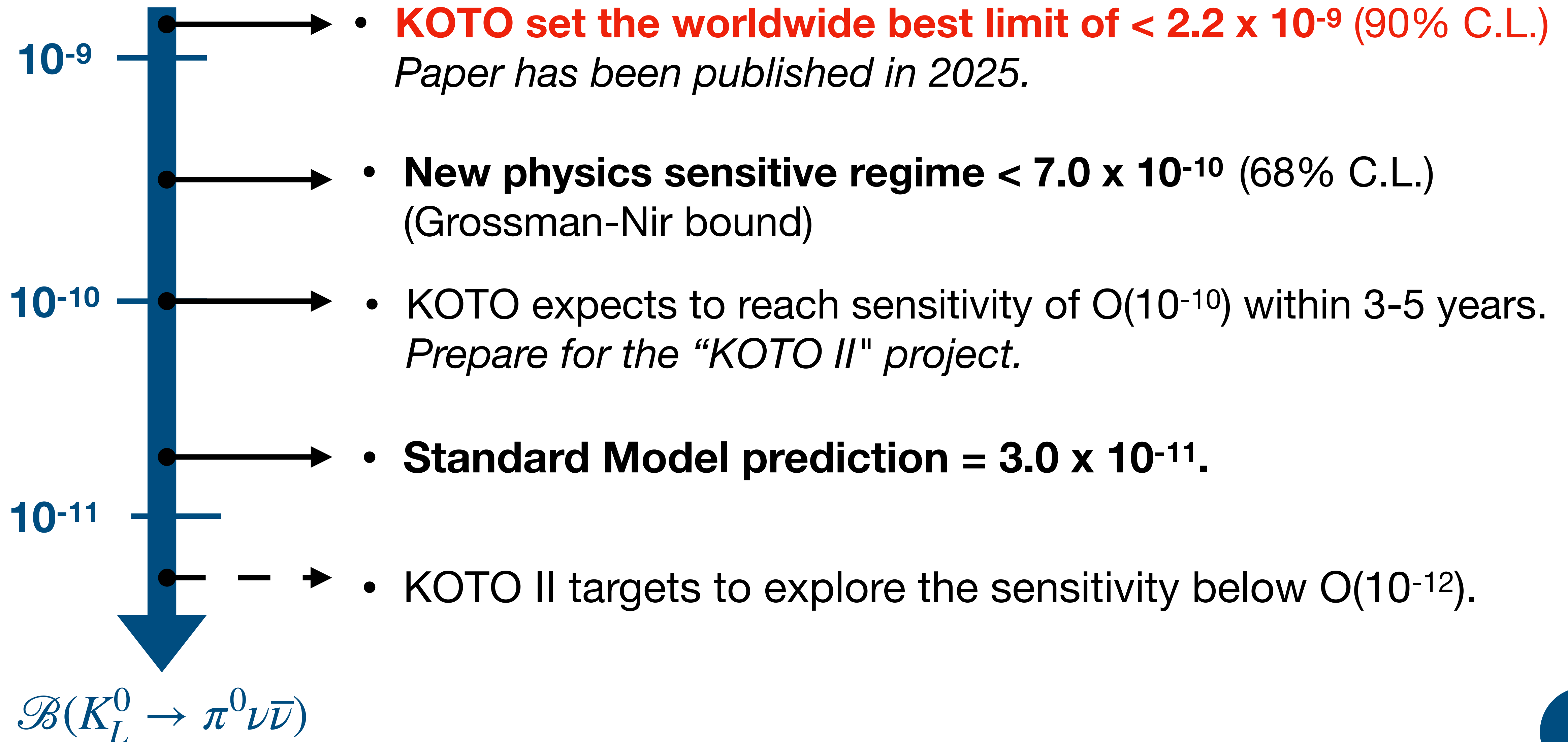
KOTO



KOTO-II

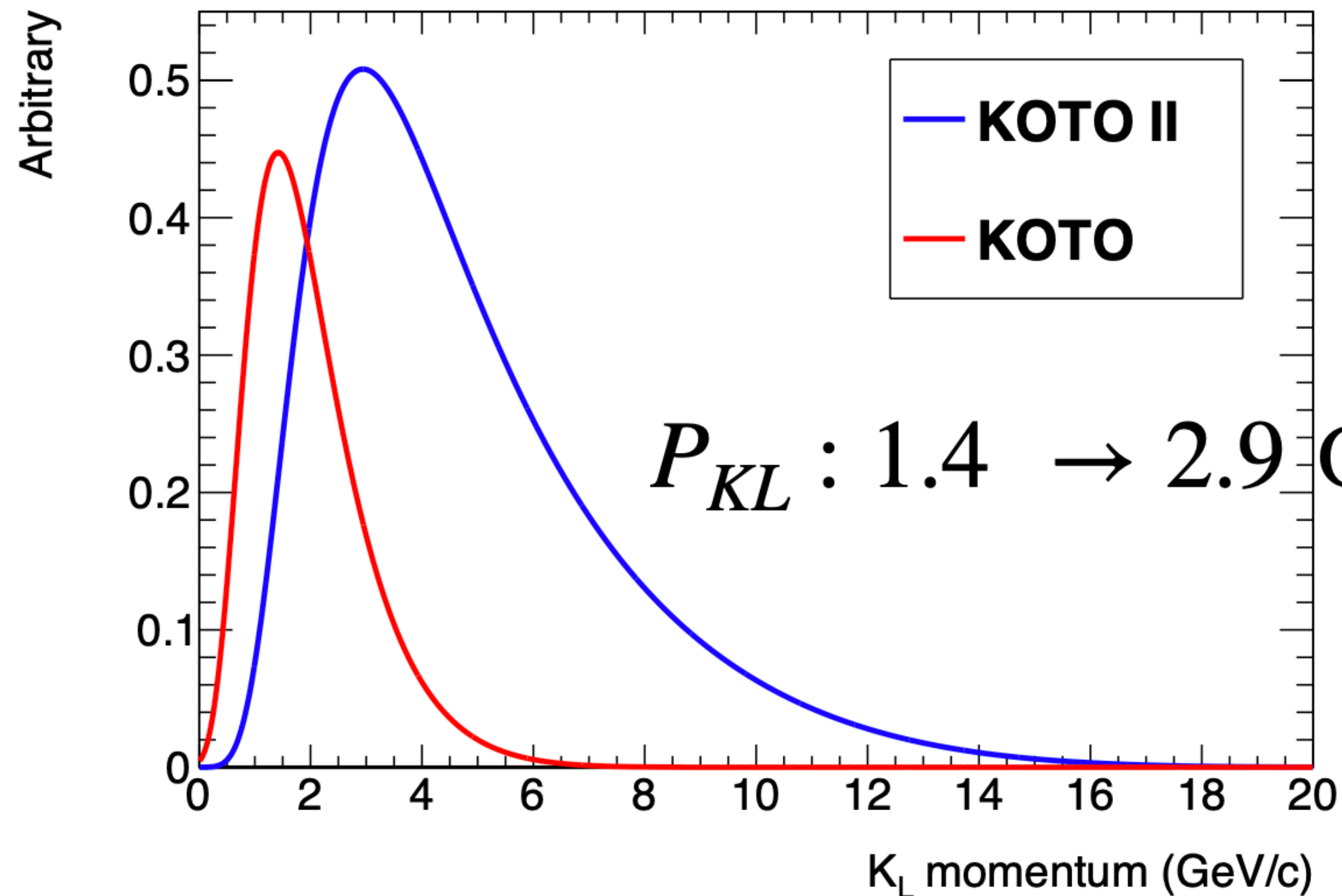
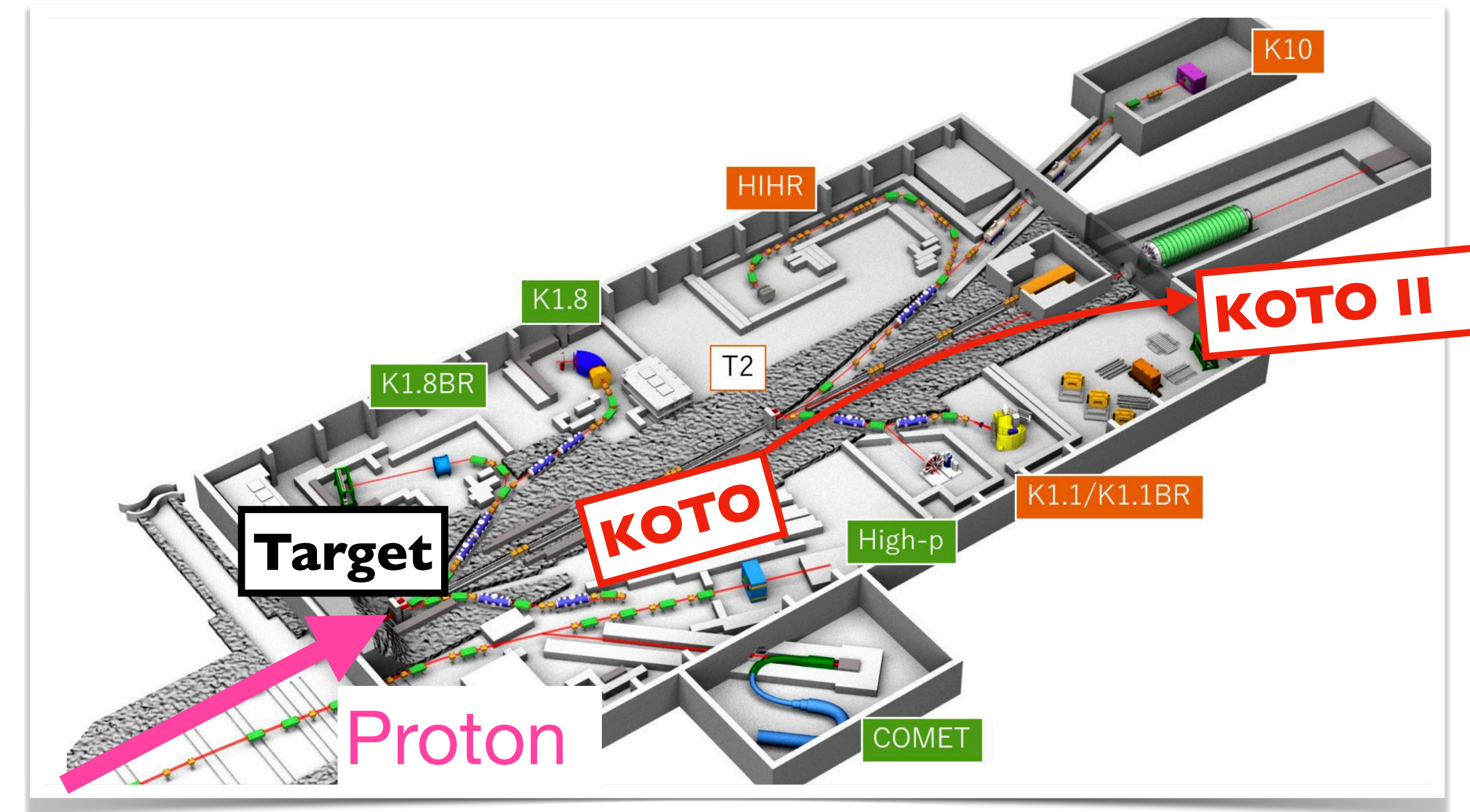


Roadmap of $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ search

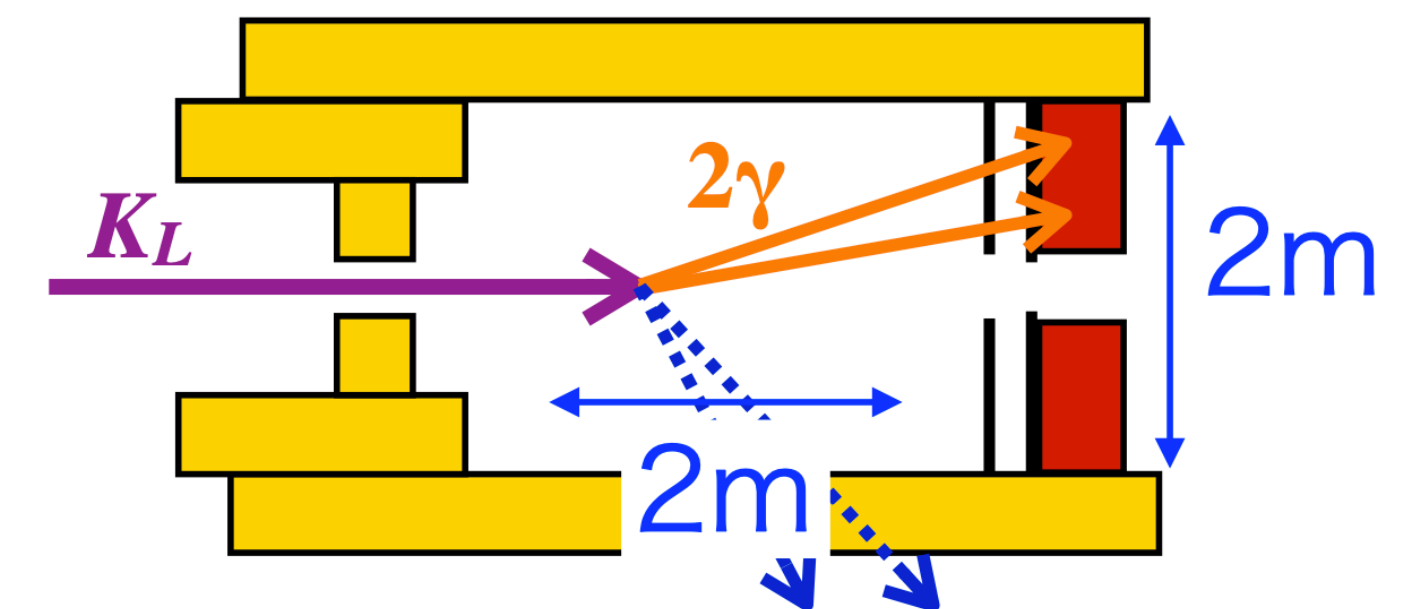


The KOTO II project

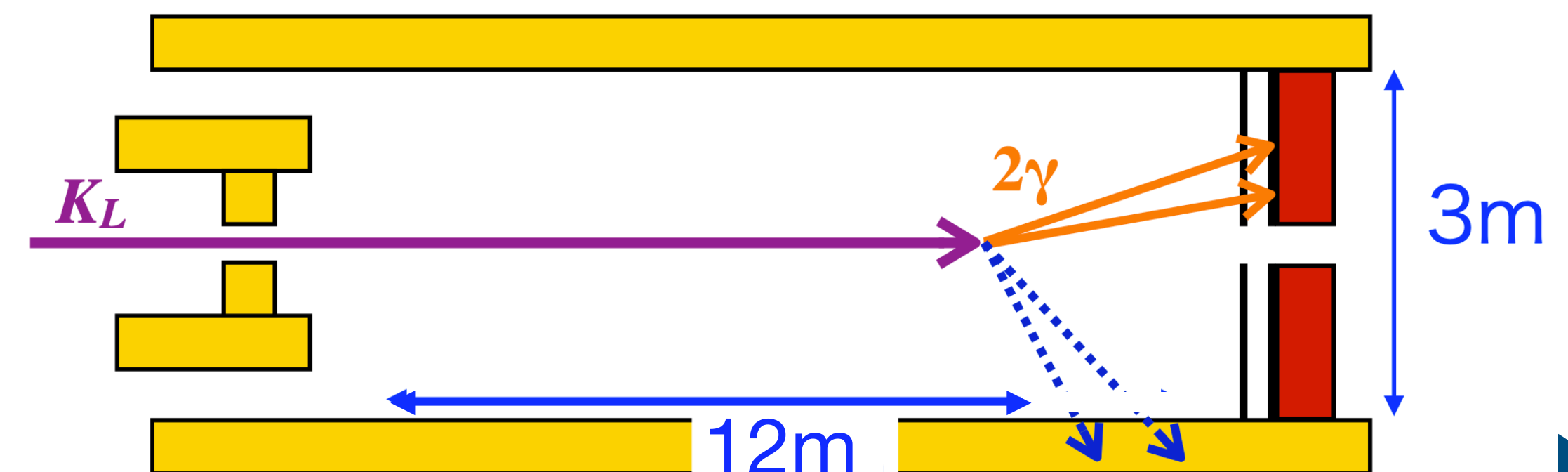
- Compared with KOTO:
- Longer signal region: **2 → 12 m**.
- Higher K_L^0 momentum: 1.4 → 2.9 GeV/c.
- Higher K_L^0 flux (KOTO x 2.4).



KOTO



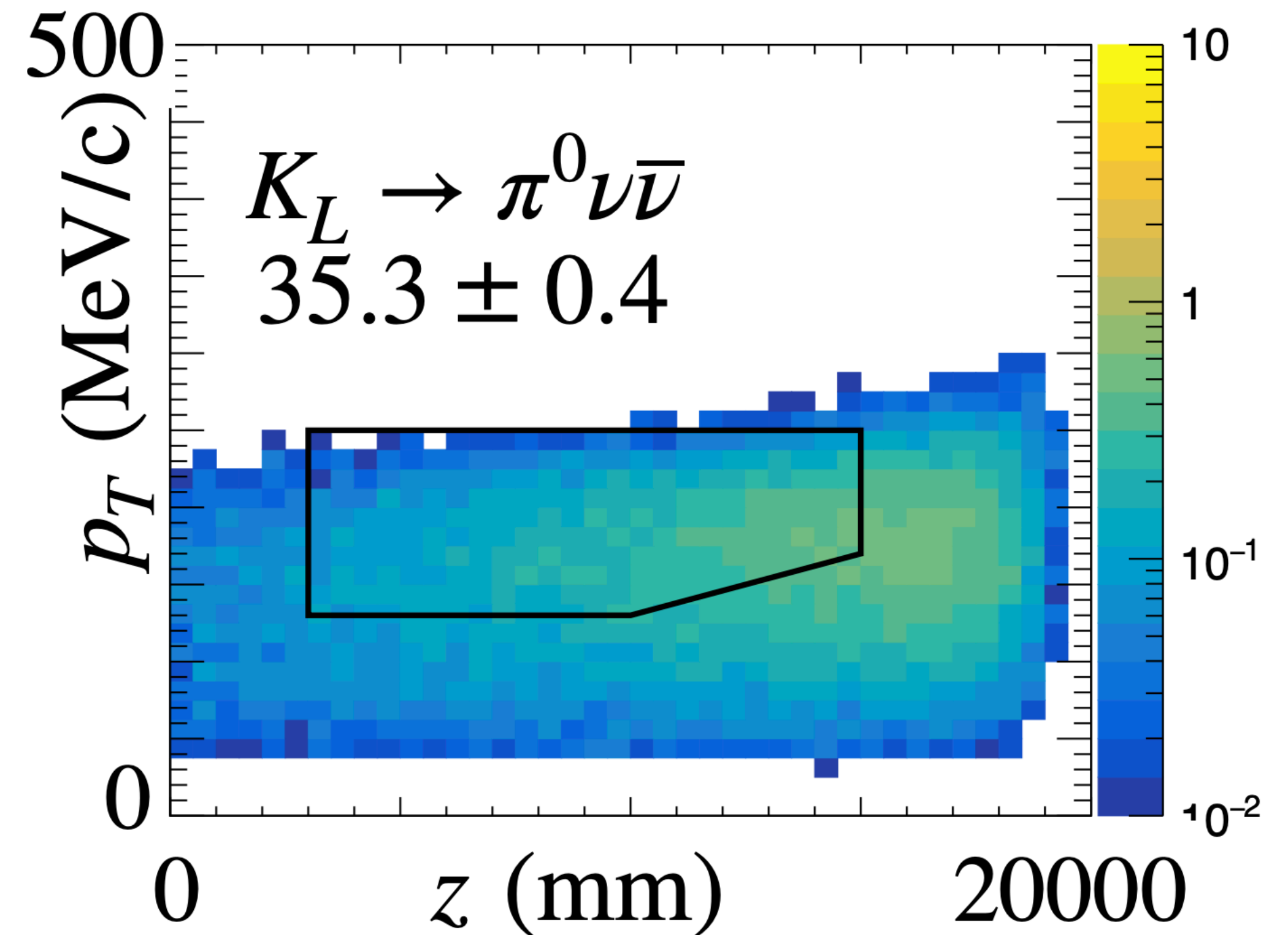
KOTO II



Expected impact from KOTO II

Two scenarios:

- If $B(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) \approx SM$
 - Observe 35 signals + 40 background events.
 - $> 5\sigma$ significance.
(Uncertainty of the branching fraction $\sim 25\%$)
- If $|B(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) - SM| > 40\% \times SM$
 - New Physics implication (90% C.L.).



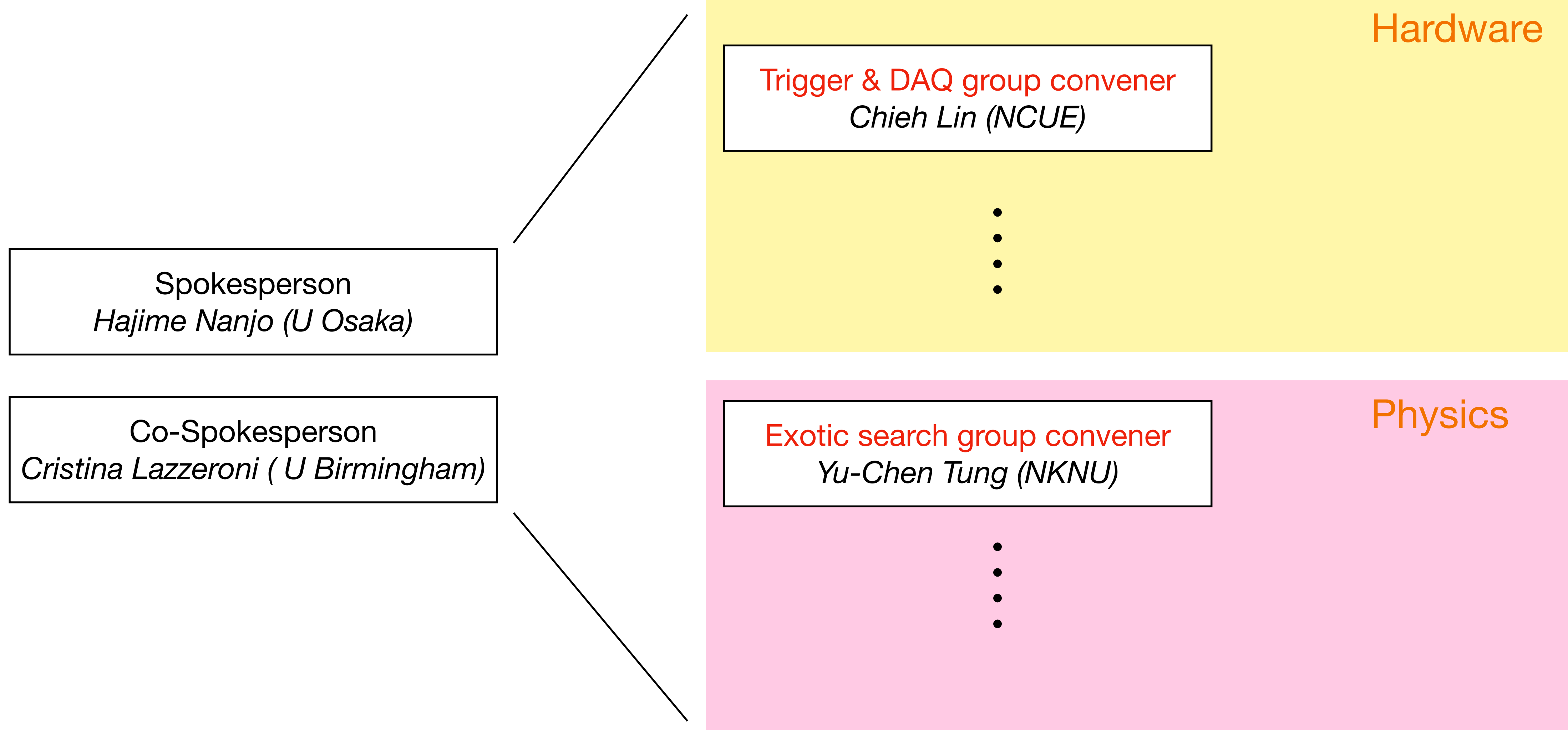
Status of the KOTO II collaboration

- The KOTO-II collaboration has 77 members from 11 countries.



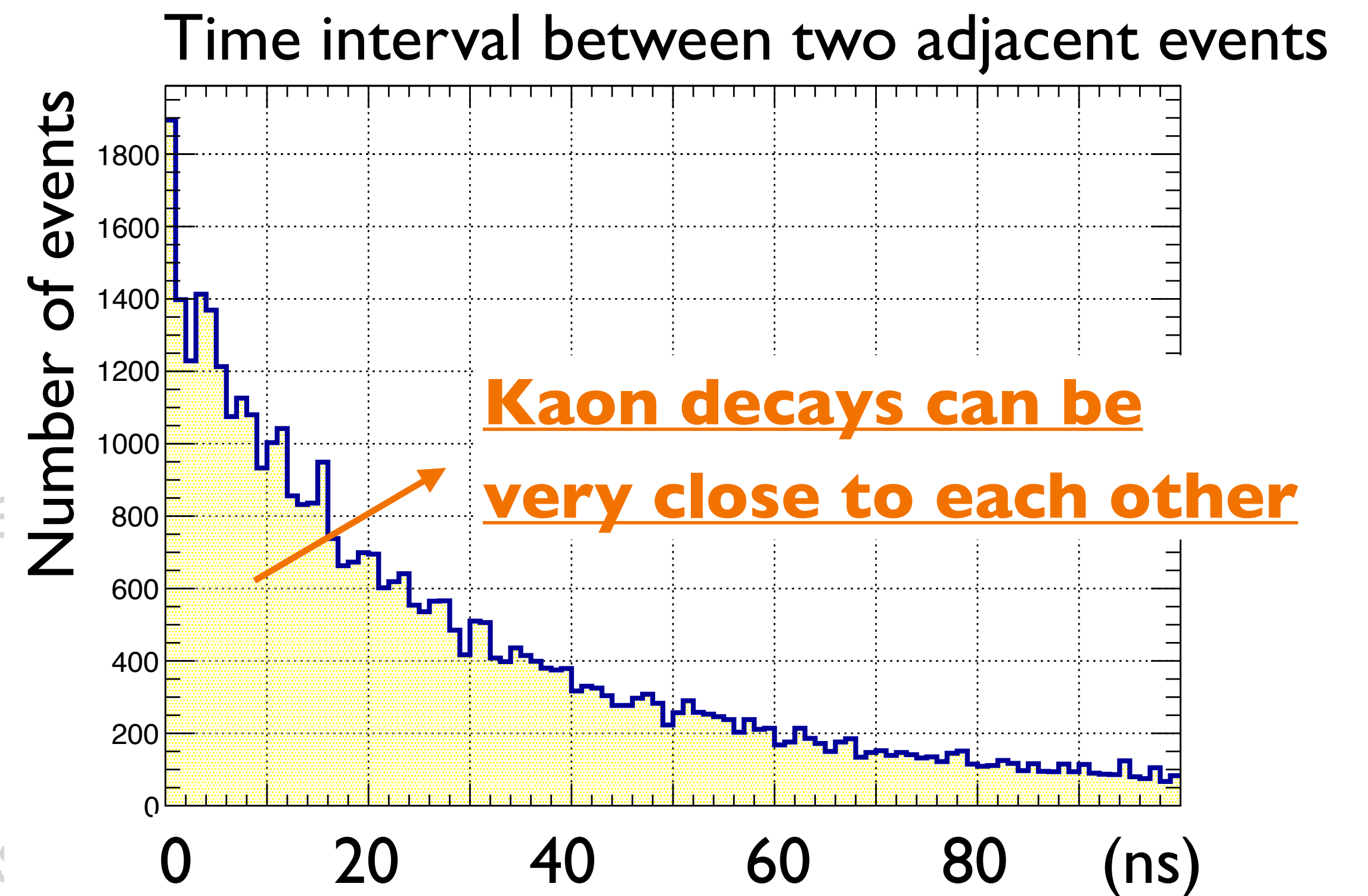
- Proposal has been submitted ([hep-ex 2501.14827](https://hep-ex.slac.stanford.edu/2501.14827)) and scientifically approved (stage-1 approval) by J-PARC.
- J-PARC E107 experiment.
- Aim to start the operation from 2030s.

Taiwan contribution to KOTO-II experiment



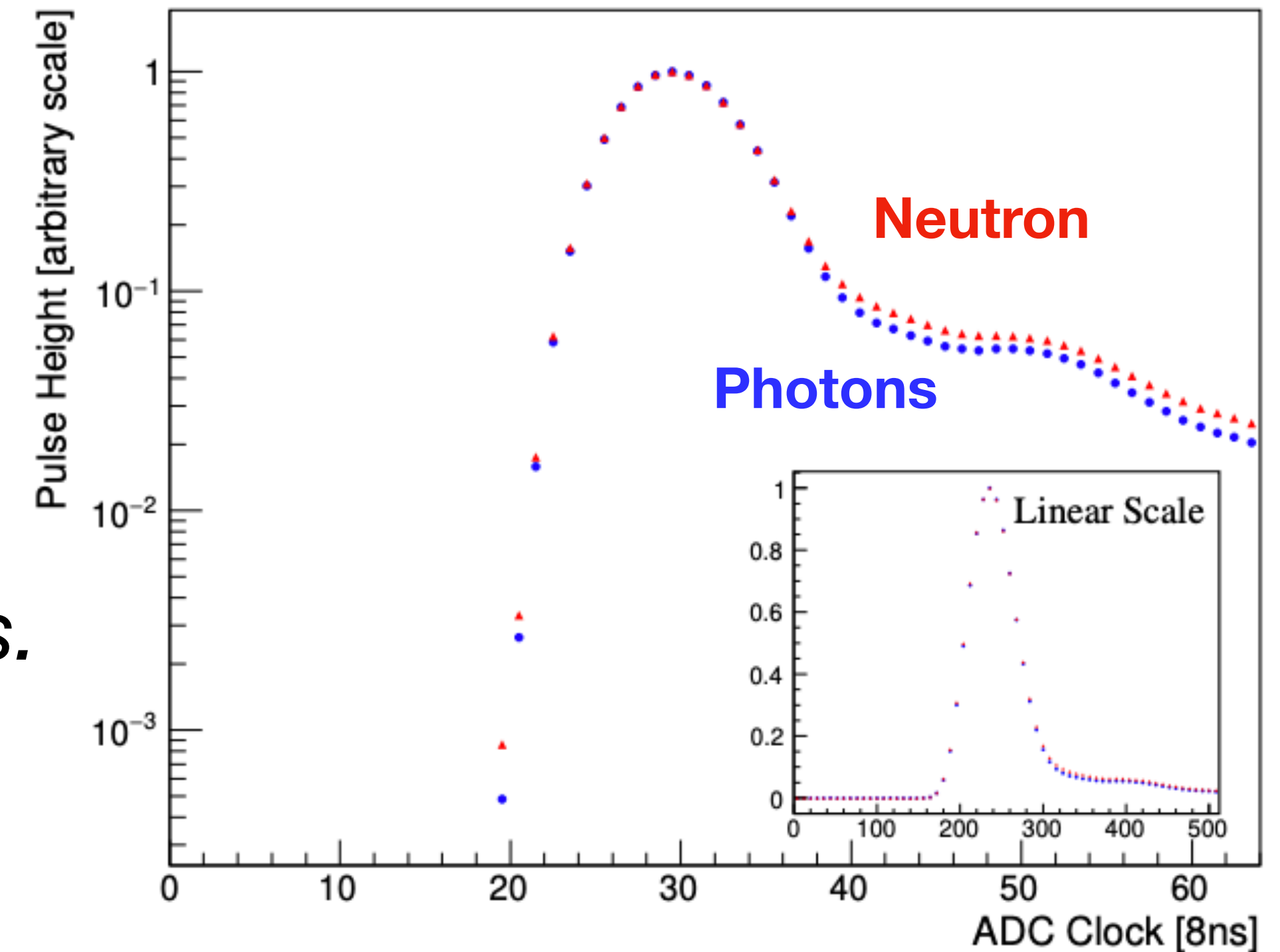
DAQ challenges to study the K_L^0 rare decays

- **High intensity K_L^0 beam is required.**
→ *Triggers need to be processed fast.*
- **Backgrounds are also rare.**
→ *The waveform shapes are utilized to further suppress the rare background events.*
- **Many accidental activities.**
→ *Online timing window needs to be accurate to avoid overkilling signal events.*



DAQ challenges to study the K_L^0 rare decays

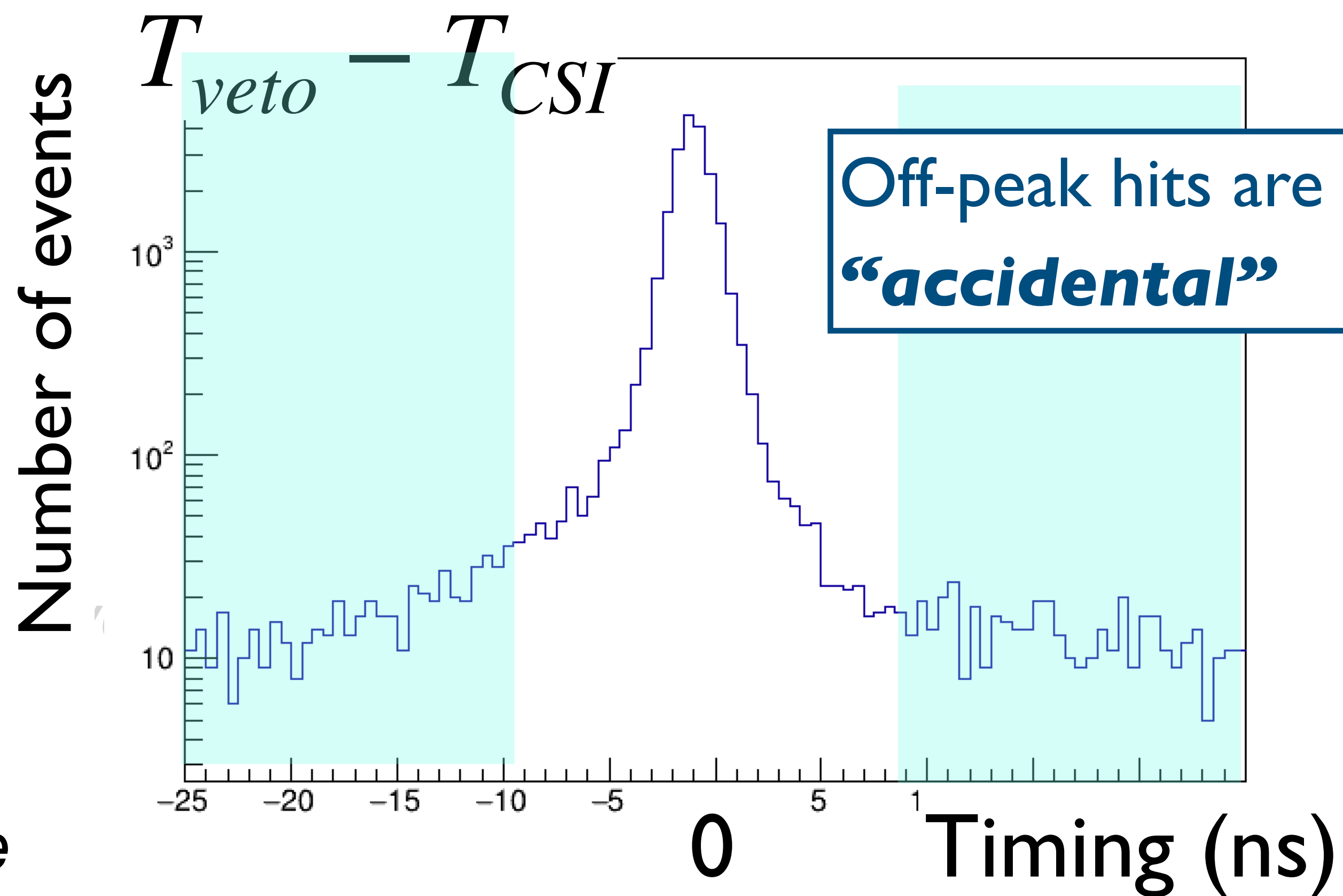
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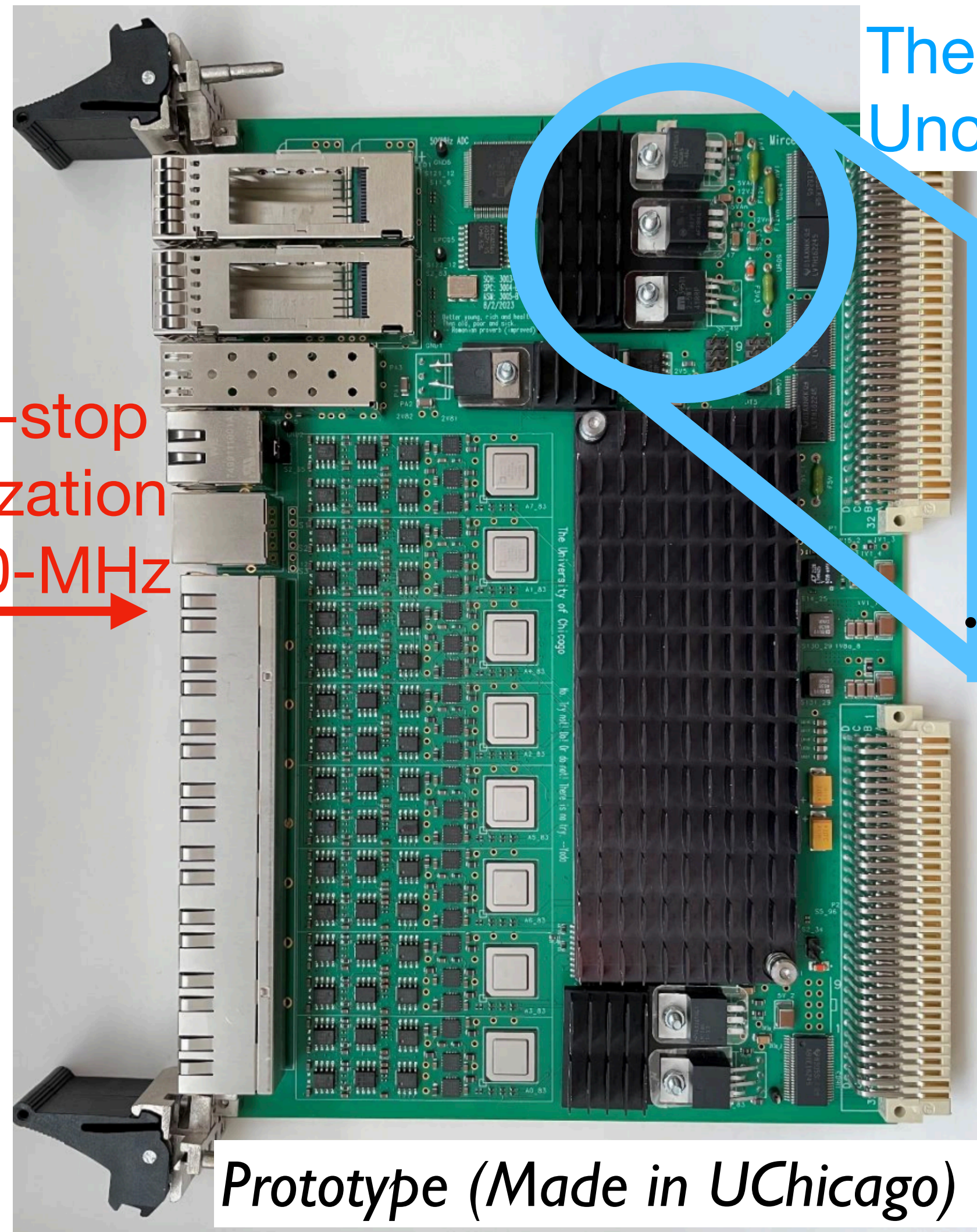
[Y.C. Tung, NIM A, 1059 (2024) 169010]

DAQ challenges to study the K_L^0 rare decays

- High intensity K_L^0 beam is required
→ Triggers need to be processed fast
- Backgrounds are also rare.
→ The waveform shapes are utilized further suppress the rare background
- **Many accidental hits.**
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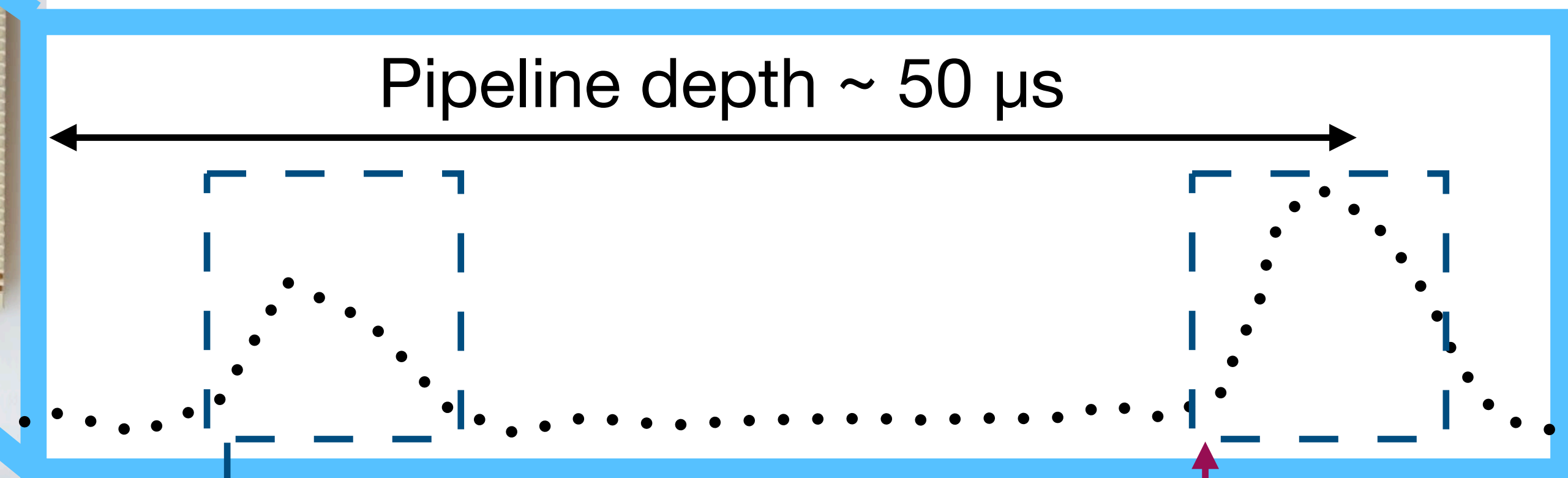
Pipeline trigger design



The pipeline is realized by the on-chip memory (FPGA).
Uncertainties from delay cables are eliminated.

Non-stop
digitization
@500-MHz

Analog input

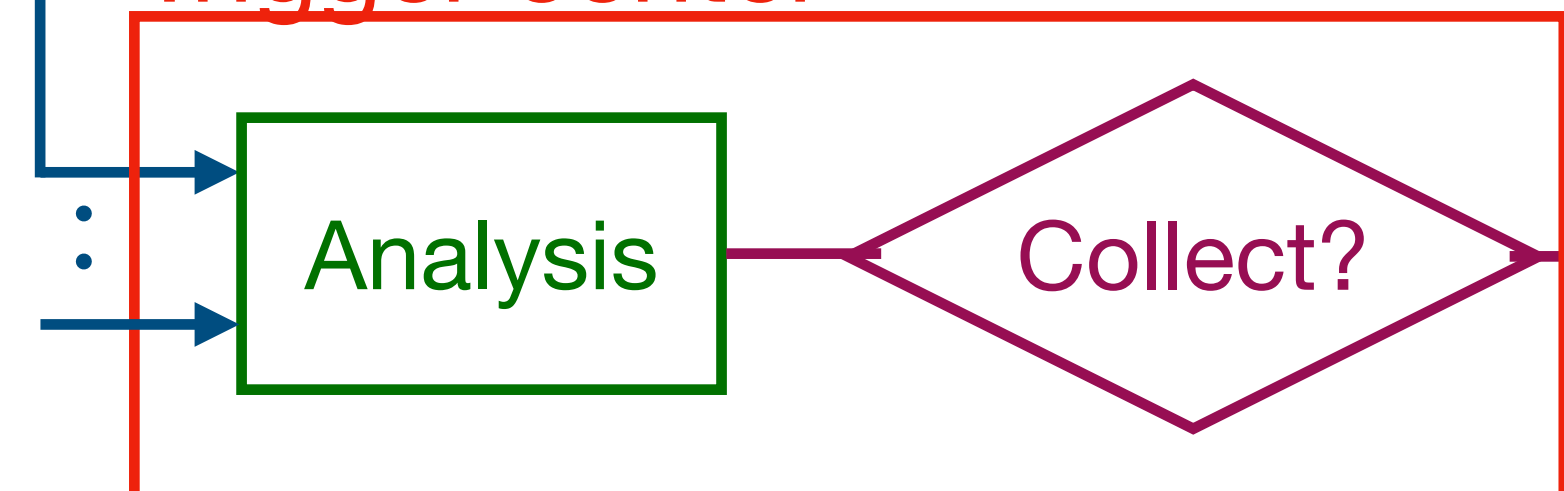


Energies converted
from pulse height

Record
Pulse

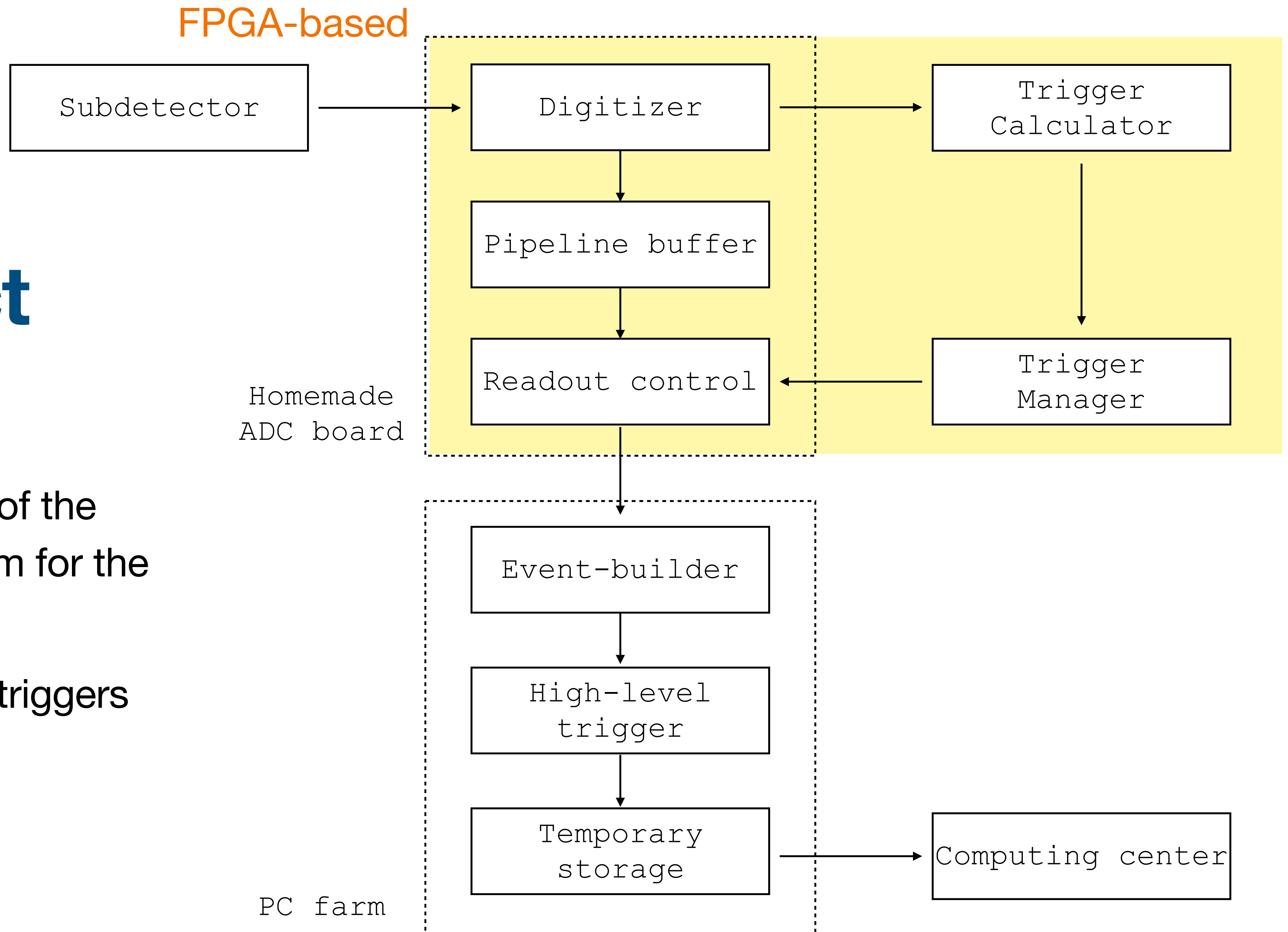
YES

Trigger center



R&D project in Taiwan

- Focus on the design of the upstream DAQ system for the KOTO-II experiment.
- Perform the Lv0/Lv1 triggers using FPGA.



Summary

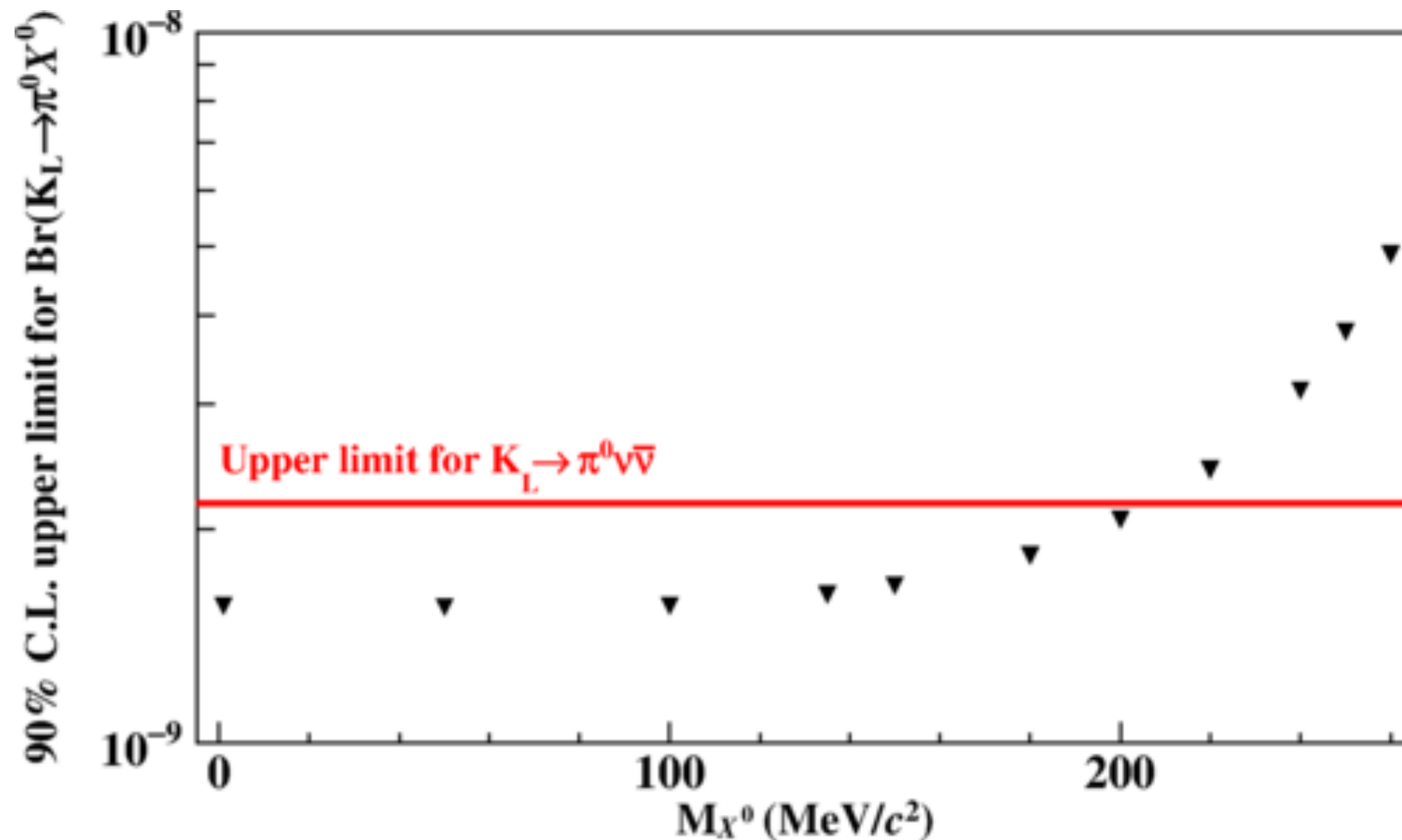
- The KOTO experiment has set the limit of $B(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) < 2.2 \times 10^{-9}$ (90% C.L.) using the data collected in 2021.
- We are expecting to explore the New Physics sensitive regime in the next 3-5 years and preparing for the KOTO II experiment to enhance the physics impact.

Supplemental

Interpretation of an invisible particle

- Interpretation of an invisible boson X with mass of 135 MeV/c² (M_{π^0}):

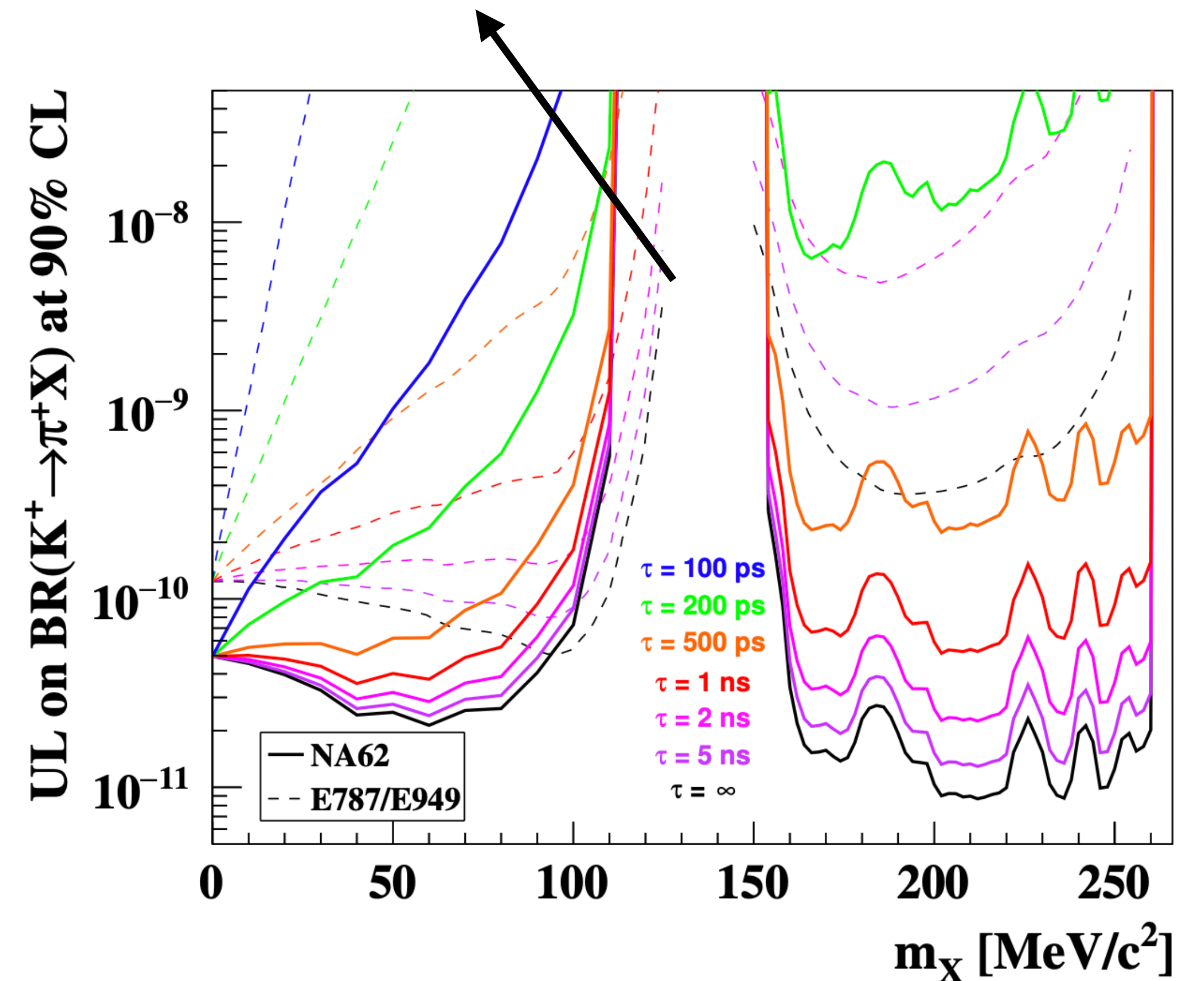
$$B(K_L^0 \rightarrow \pi^0 X) < 1.6 \times 10^{-9} \text{ (90\% C.L.)}$$



$$B(K^+ \rightarrow \pi^+ \pi^0, \pi^0 \rightarrow \text{invisible})$$

$$< 4.4 \times 10^{-9} \text{ (90\% C.L.)}$$

JHEP 02 (2021) 201



Upstream π^0 background

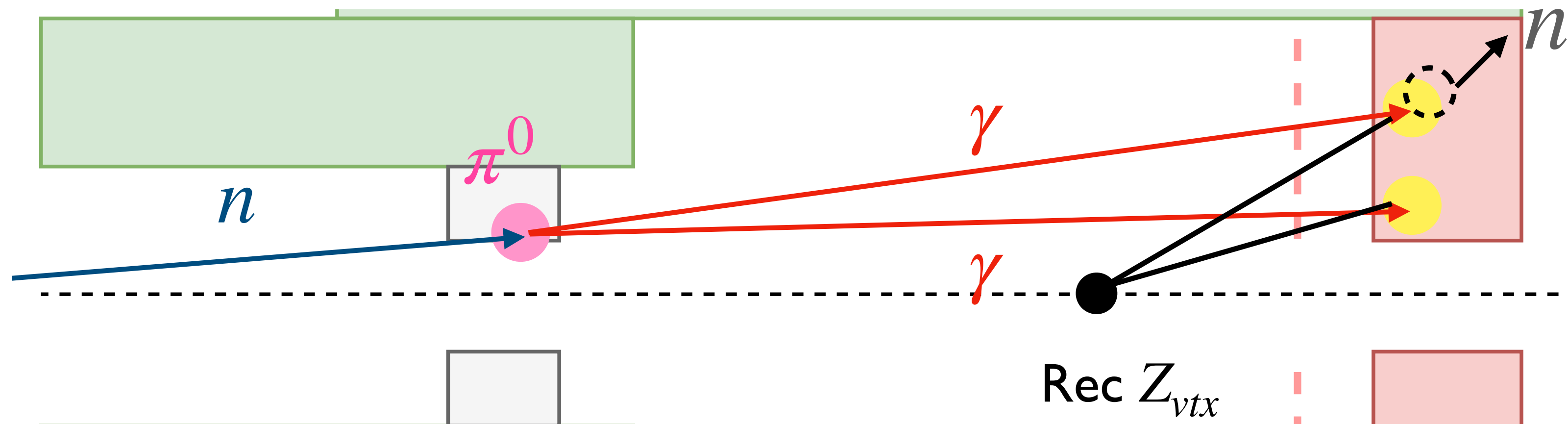
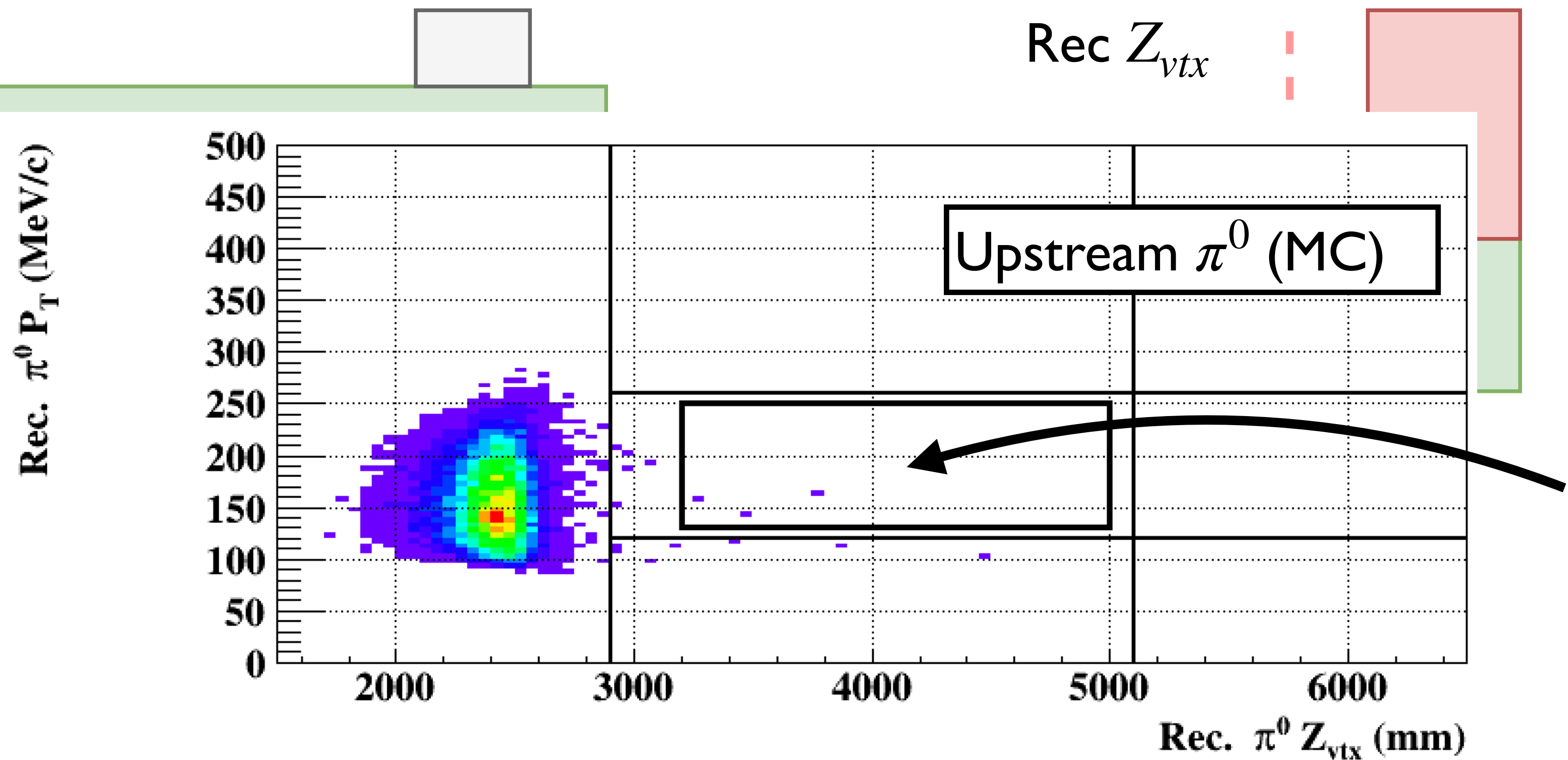


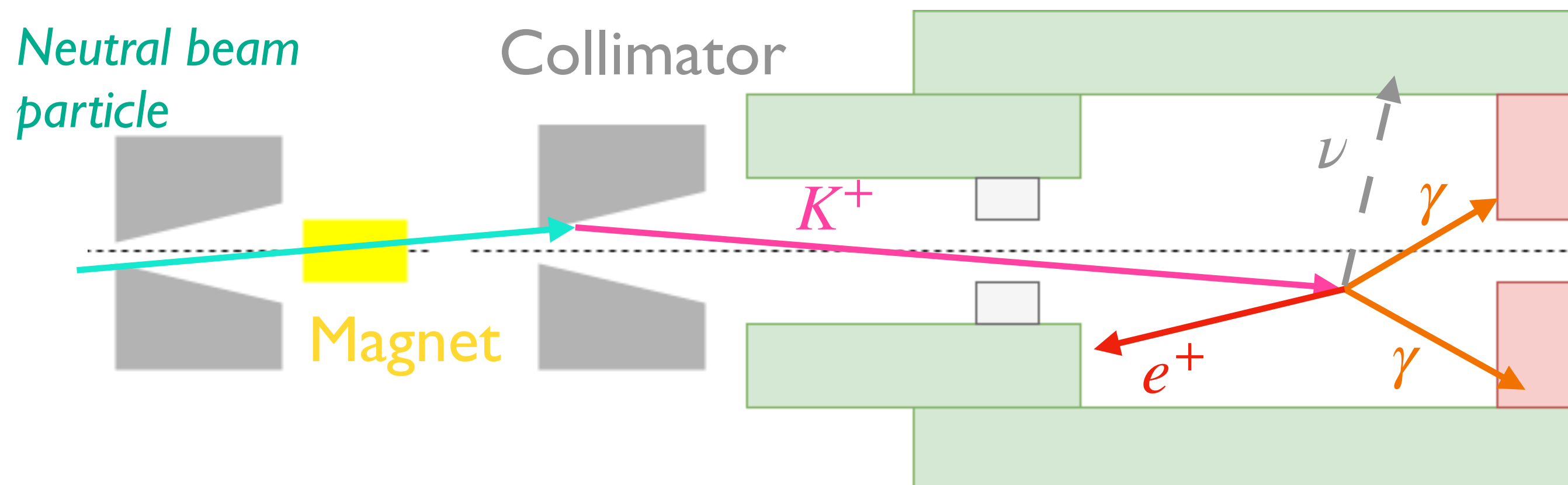
Photo-nuclear interactions
→ Measured energy is smaller.



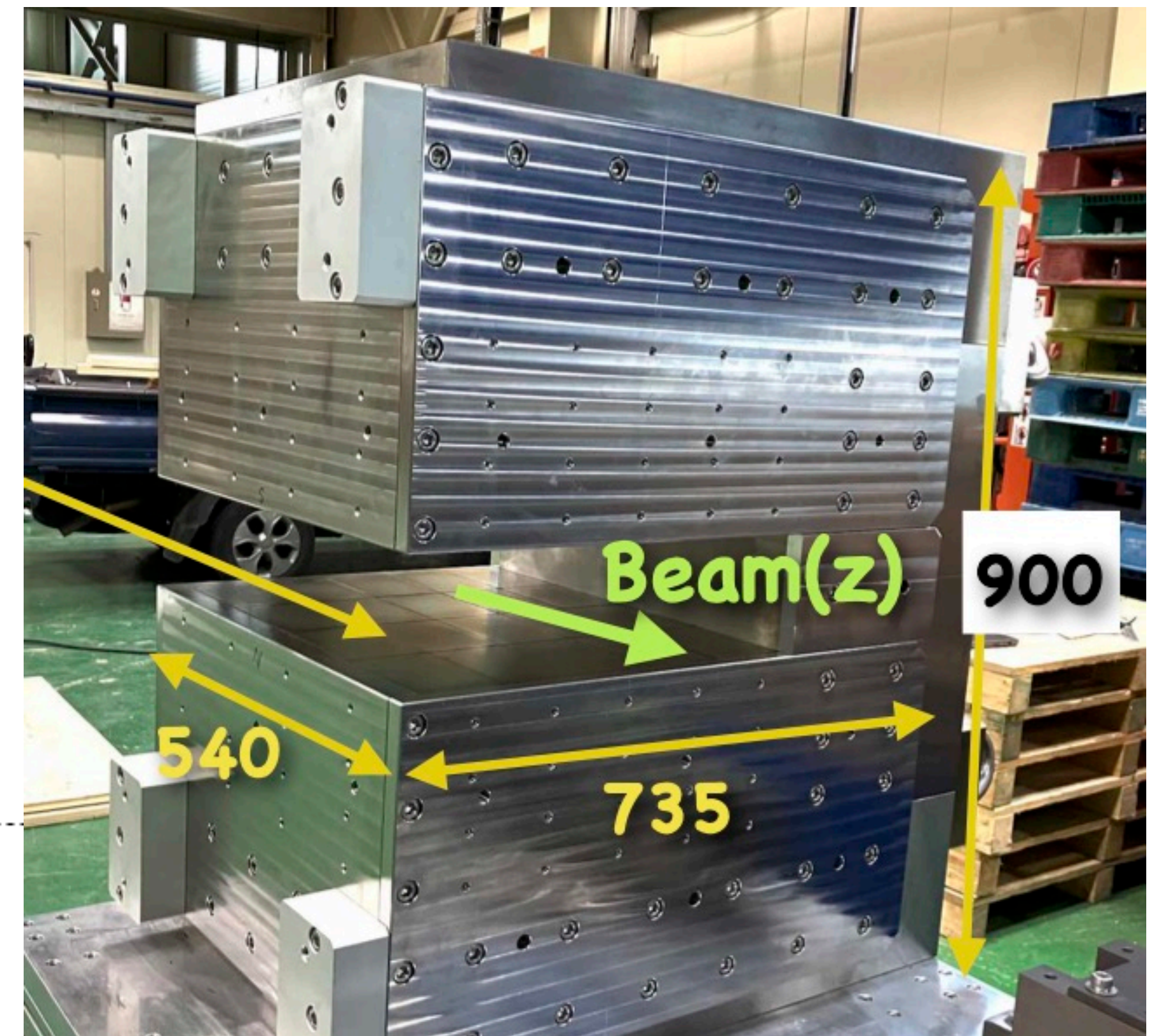
Tends to populate at the upstream side. Can suppress the background by shrinking the signal region.

K^+ background

- A K^+ particle may be produced at the 2nd collimator.
- An extra magnet at the upstream of the detector entrance highly suppresses the K^+ background.

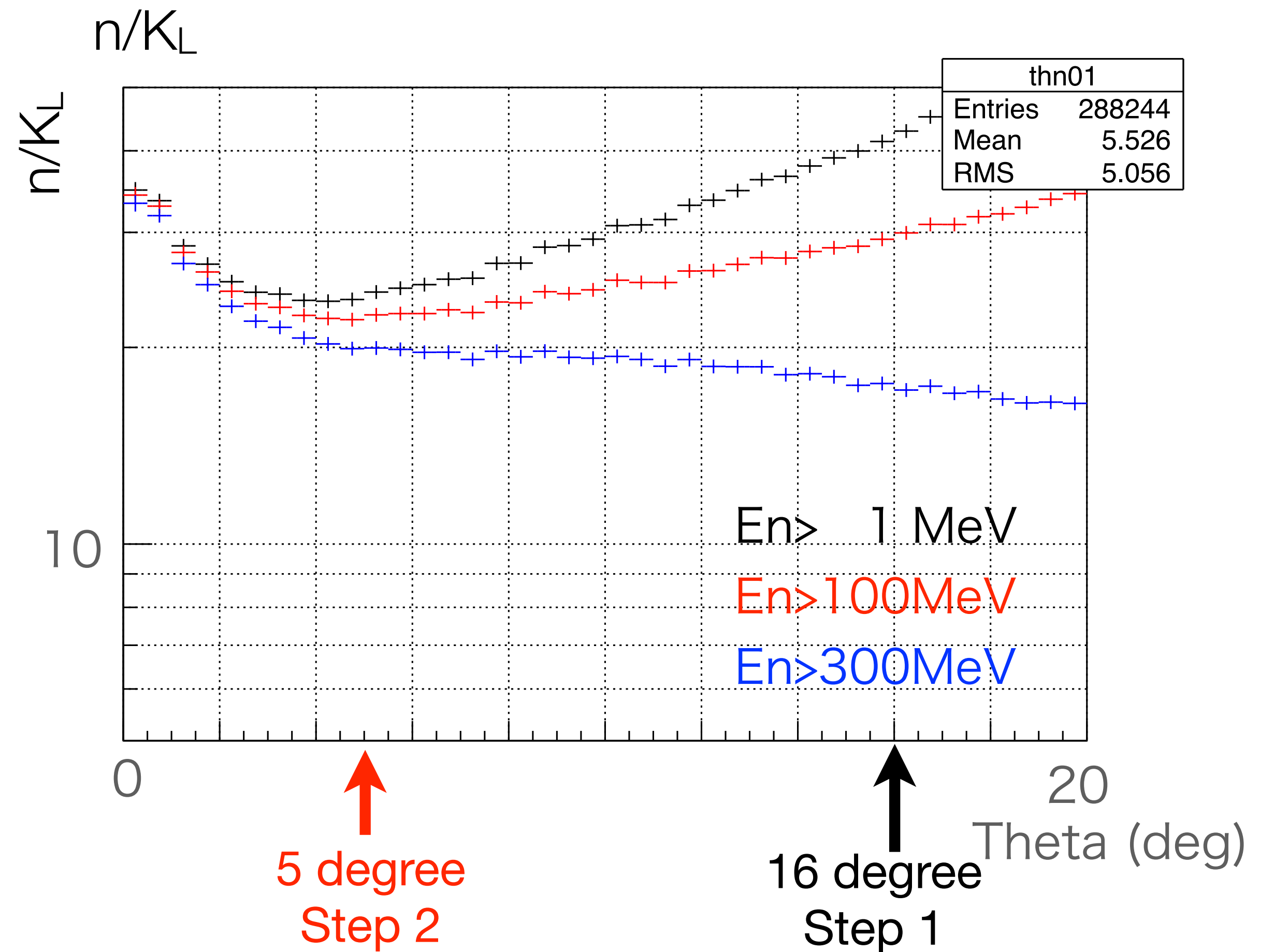
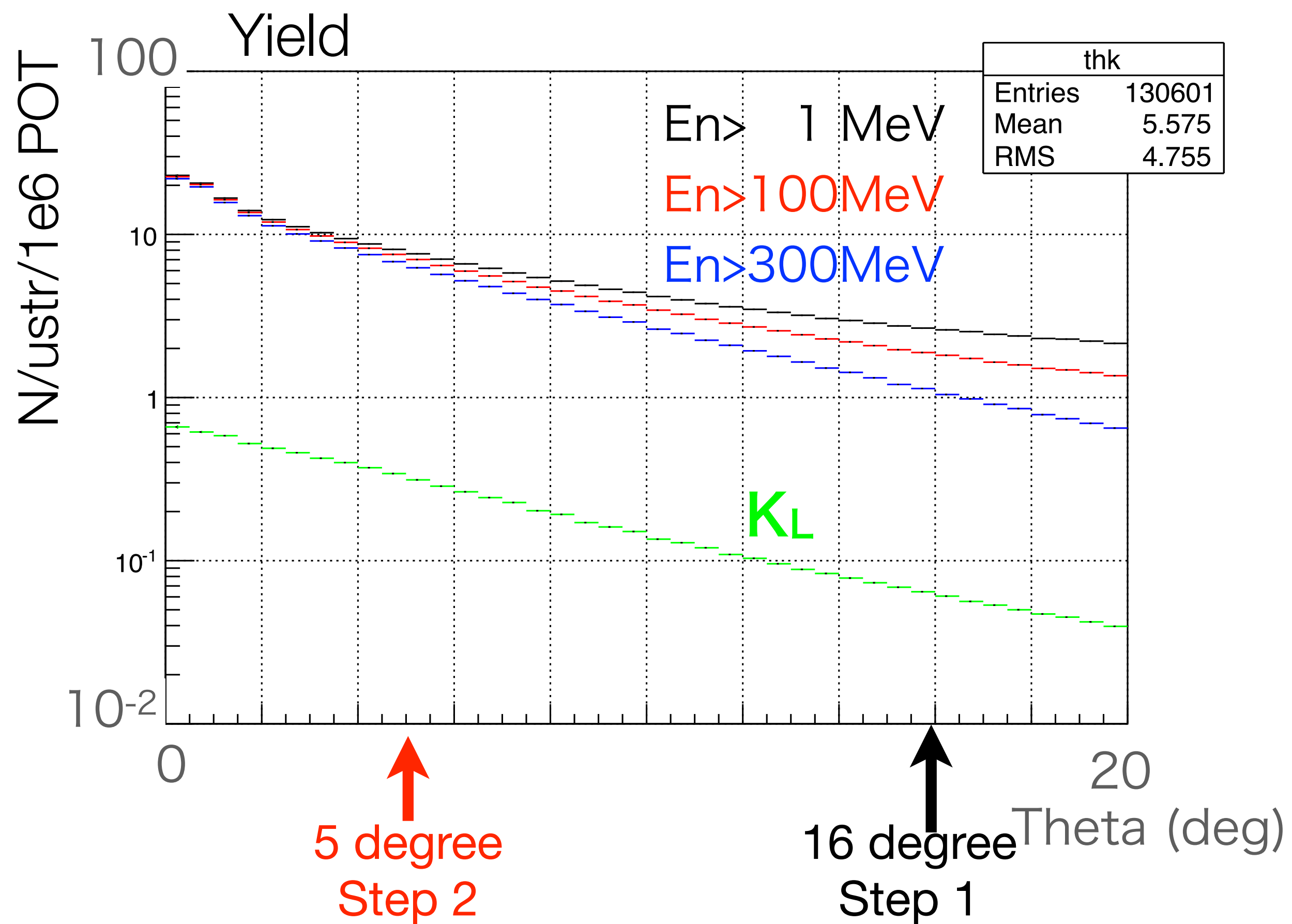


Permanent magnet ($B = 0.98\text{T}$ at center)



KOTO II Simulation

Why KOTO II adopts the targeting angle of 5 degrees?



KOTO II #Background Prediction

