Search for $K_L \to \gamma + $ dark photon$(\bar{\gamma})$ at the KOTO experiment

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*$\bar{\gamma}$: massless dark photon

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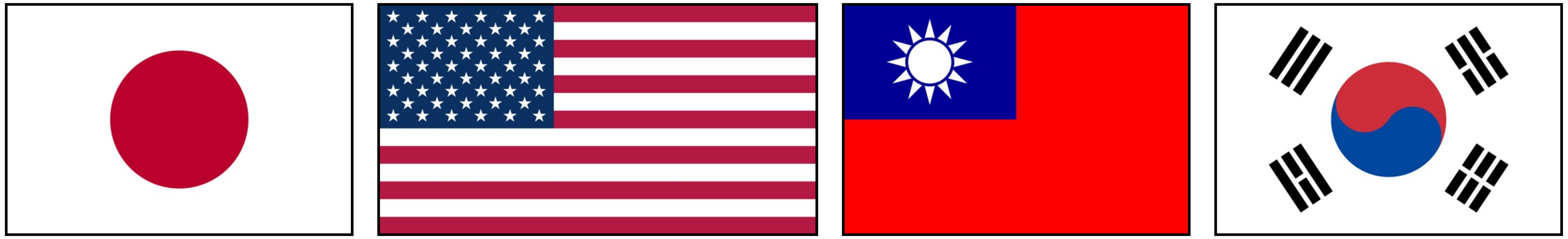
Massless dark photon search in $K_L^0 \to \gamma\bar{\gamma}$

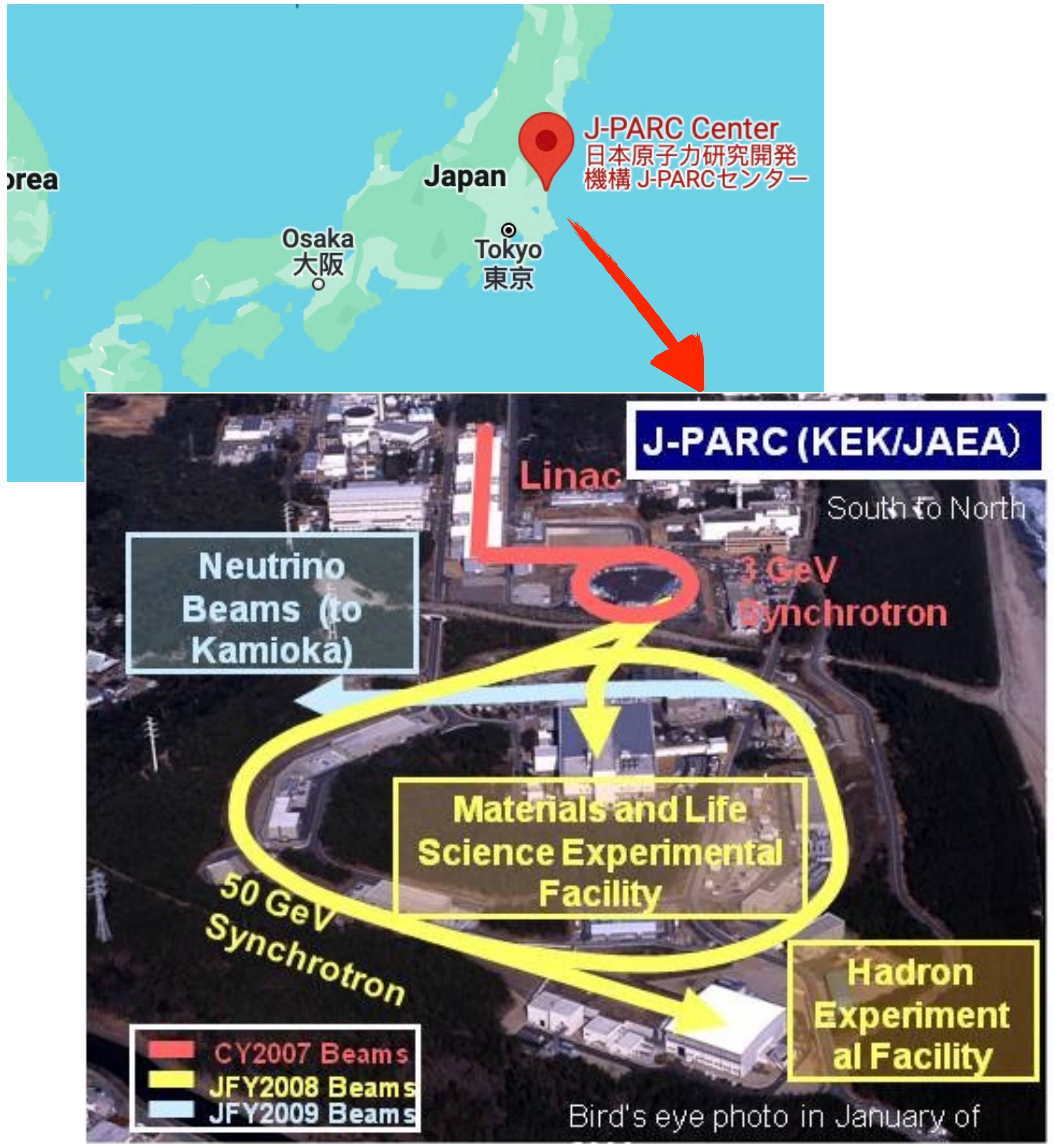
- $\bar{\gamma}$ is a hypothetical massless dark photon.
- Massless dark photon does not directly mix with the ordinary photon but could interact with Standard Model (SM) particles through direct coupling to quarks.
- In theoretical calculation: BR $(K_L \to \gamma\bar{\gamma}) < 1 \times 10^{-3}$ *
- For this study, we took a 2-hour special run in June 2020 as the physics data.
    - The number of K_L^0 decay $\approx 1.29 \times 10^{10}$

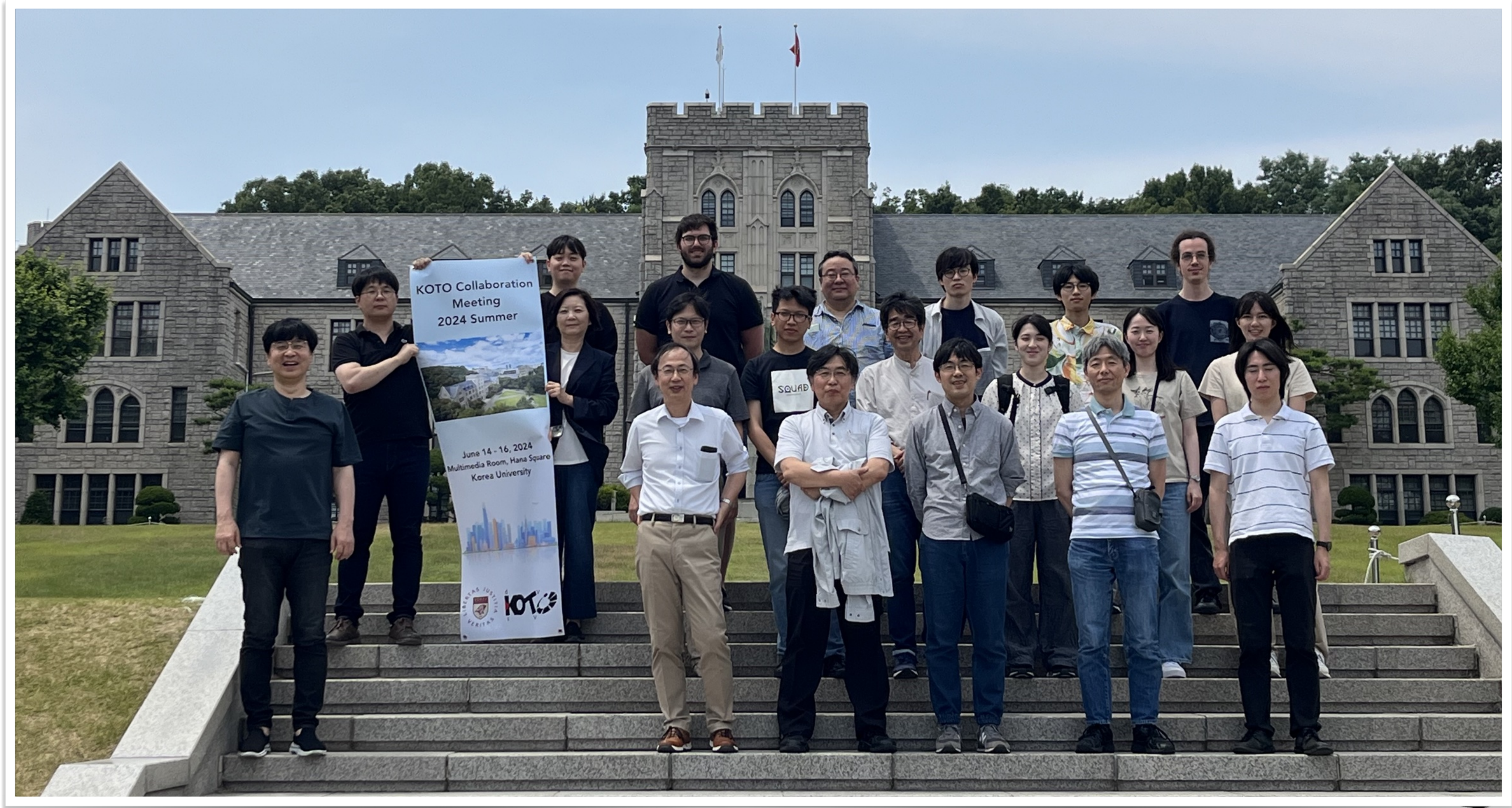
*Su, JY., Tandean, J. *Eur. Phys. J. C* **80**, 824 (2020).
https://doi.org/10.1140/epjc/s10052-020-8338-3

The KOTO Experiment

KOTO (K0 at TOkai) experiment aims to search for the rare Kaon decay at J-PARC





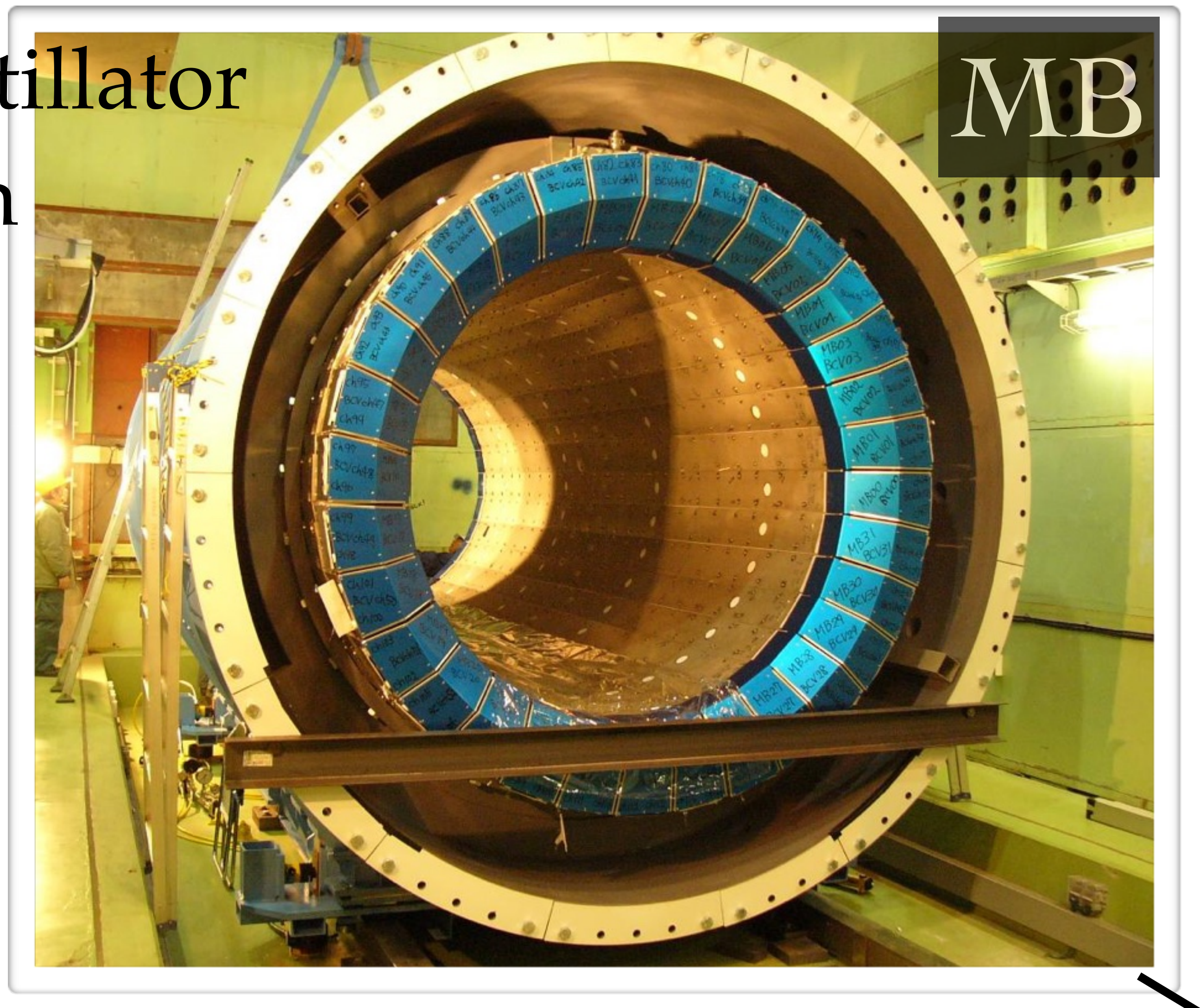


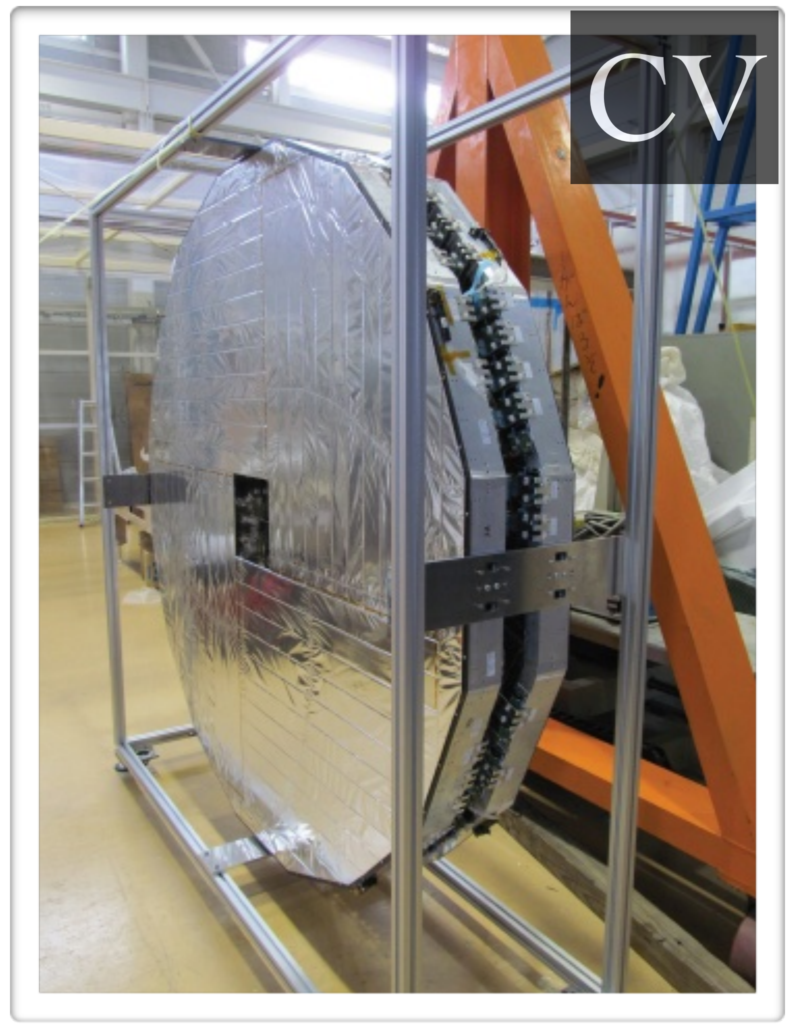
Photon from KOTO collaboration meeting in Seoul, Korea, June 2024

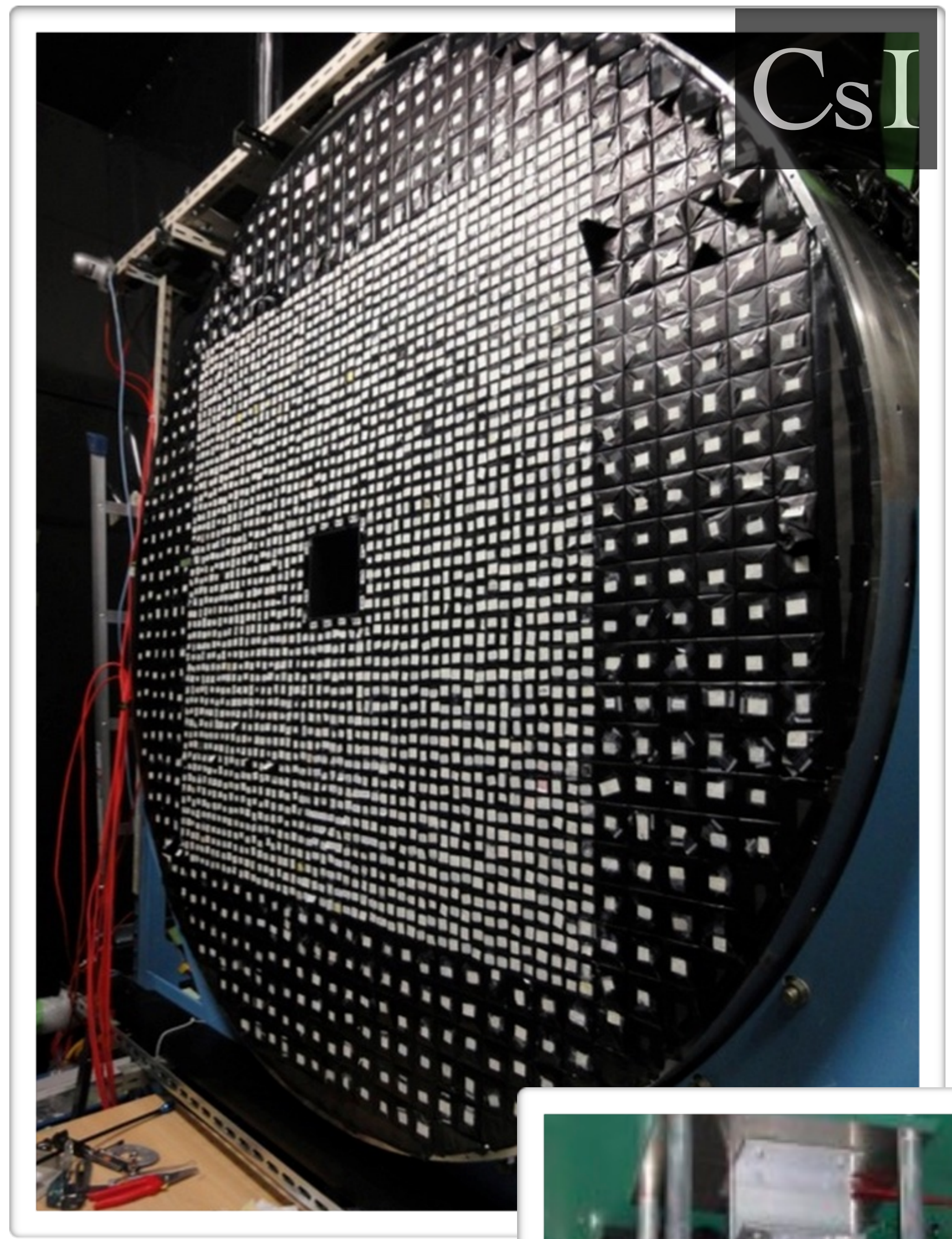
KOTO Detector

Hermetic veto system

lead-scintillator sandwich



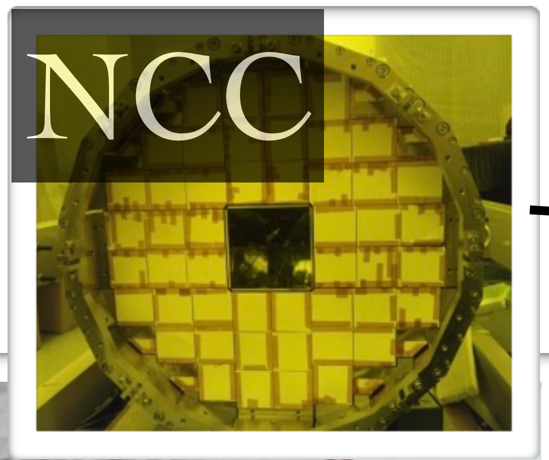


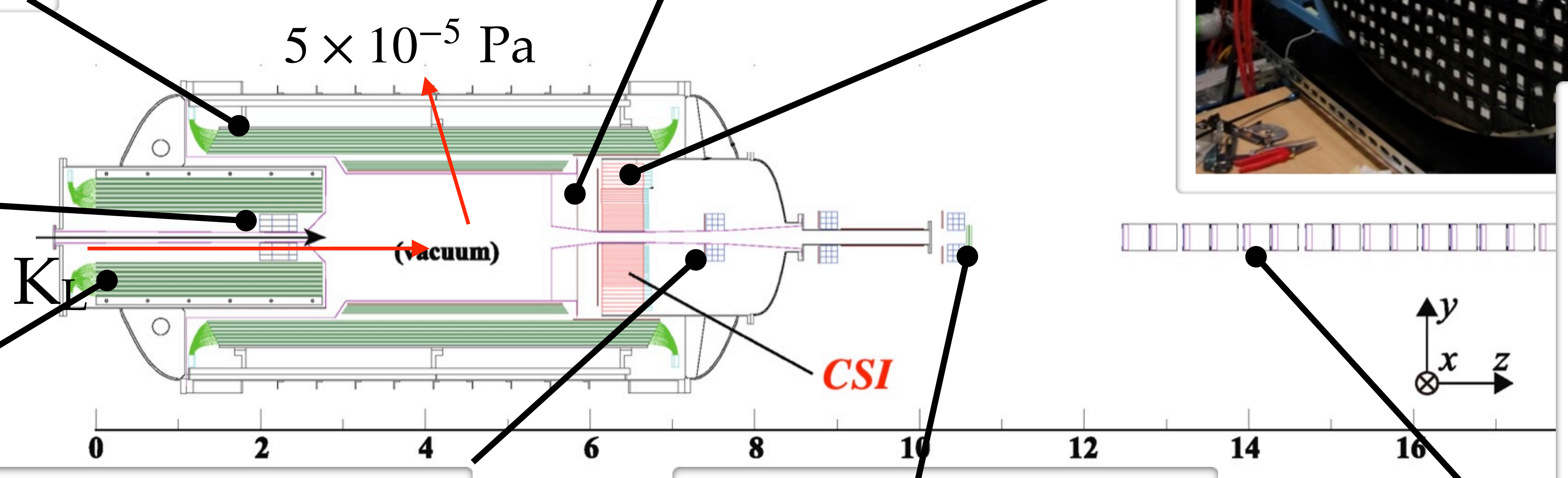


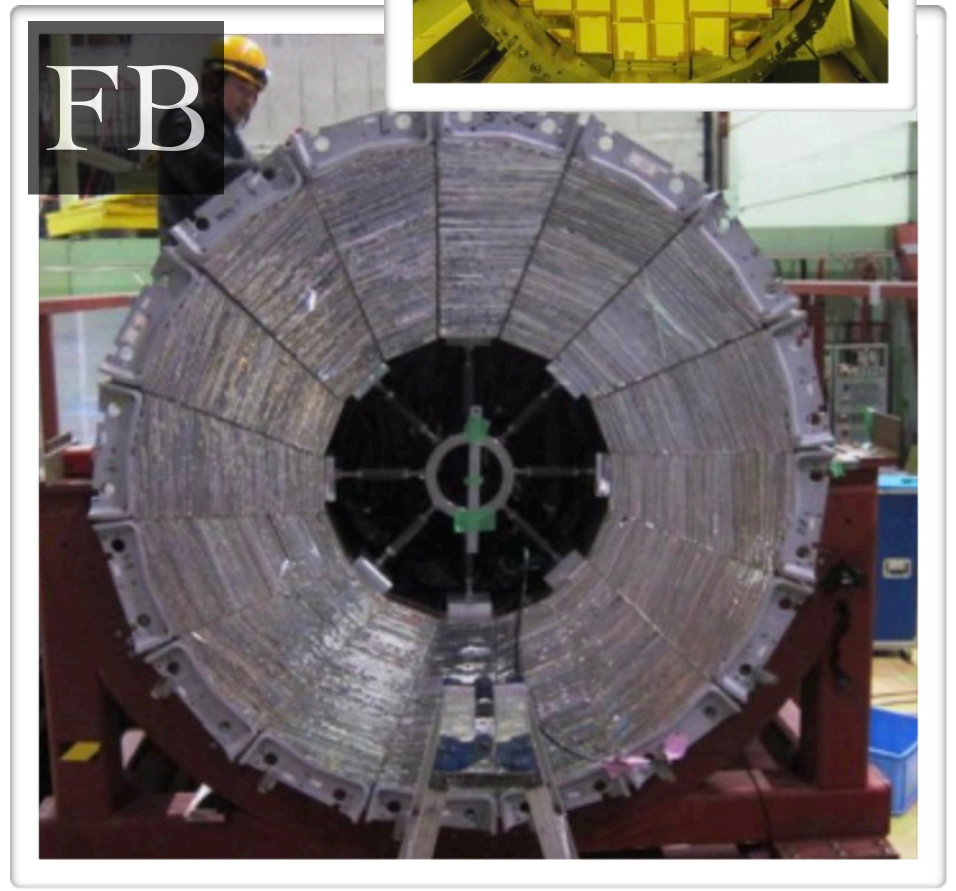
Calorimeter

- cesium iodide crystal
- Photon detector
- Front: MPPC
- Back: PMT

CsI crystal







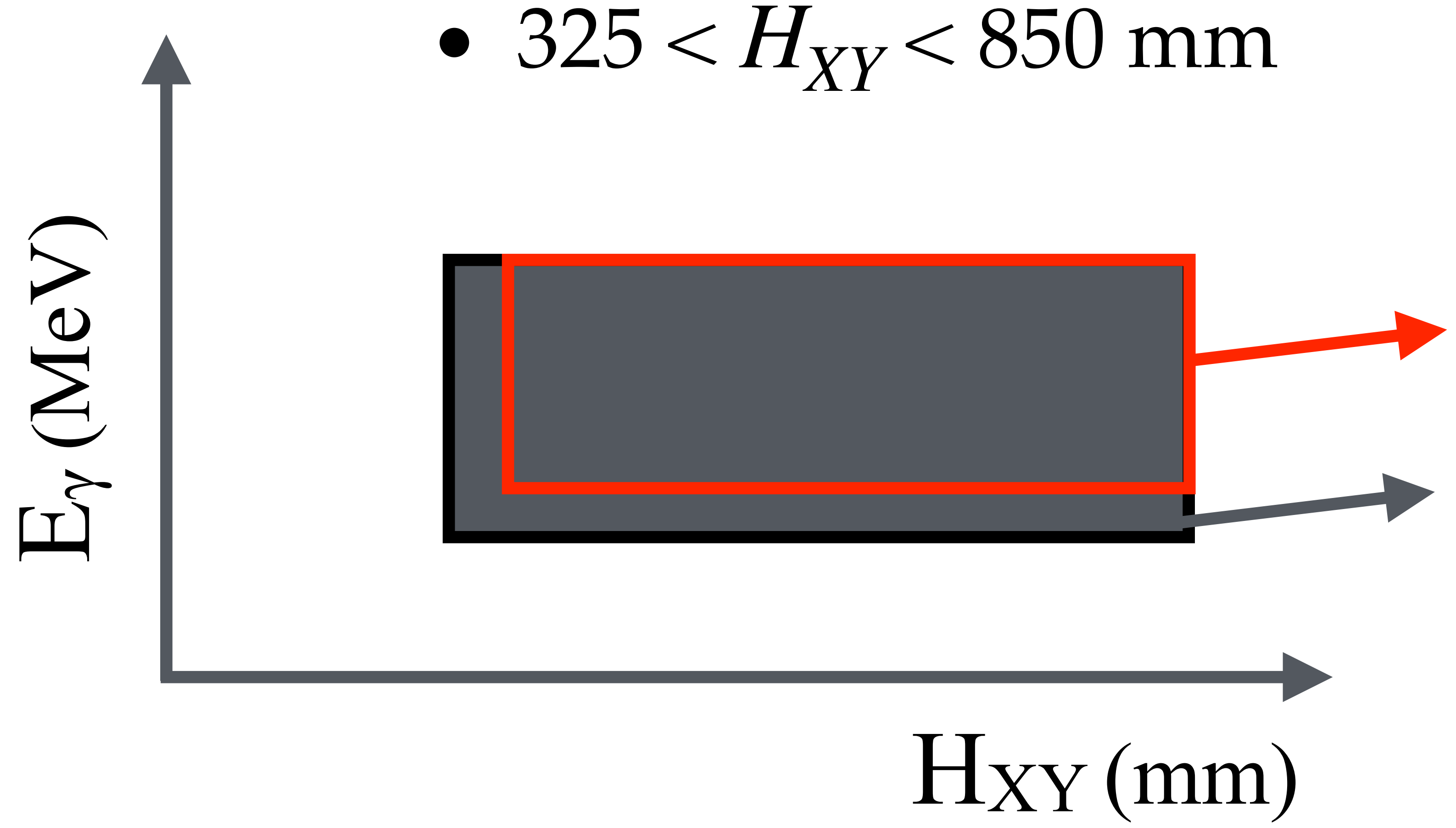
Signal Identification for single γ

Signal Signature

- Only 1 photon cluster on CsI
- No in-time hit on other veto detectors.

Signal Region

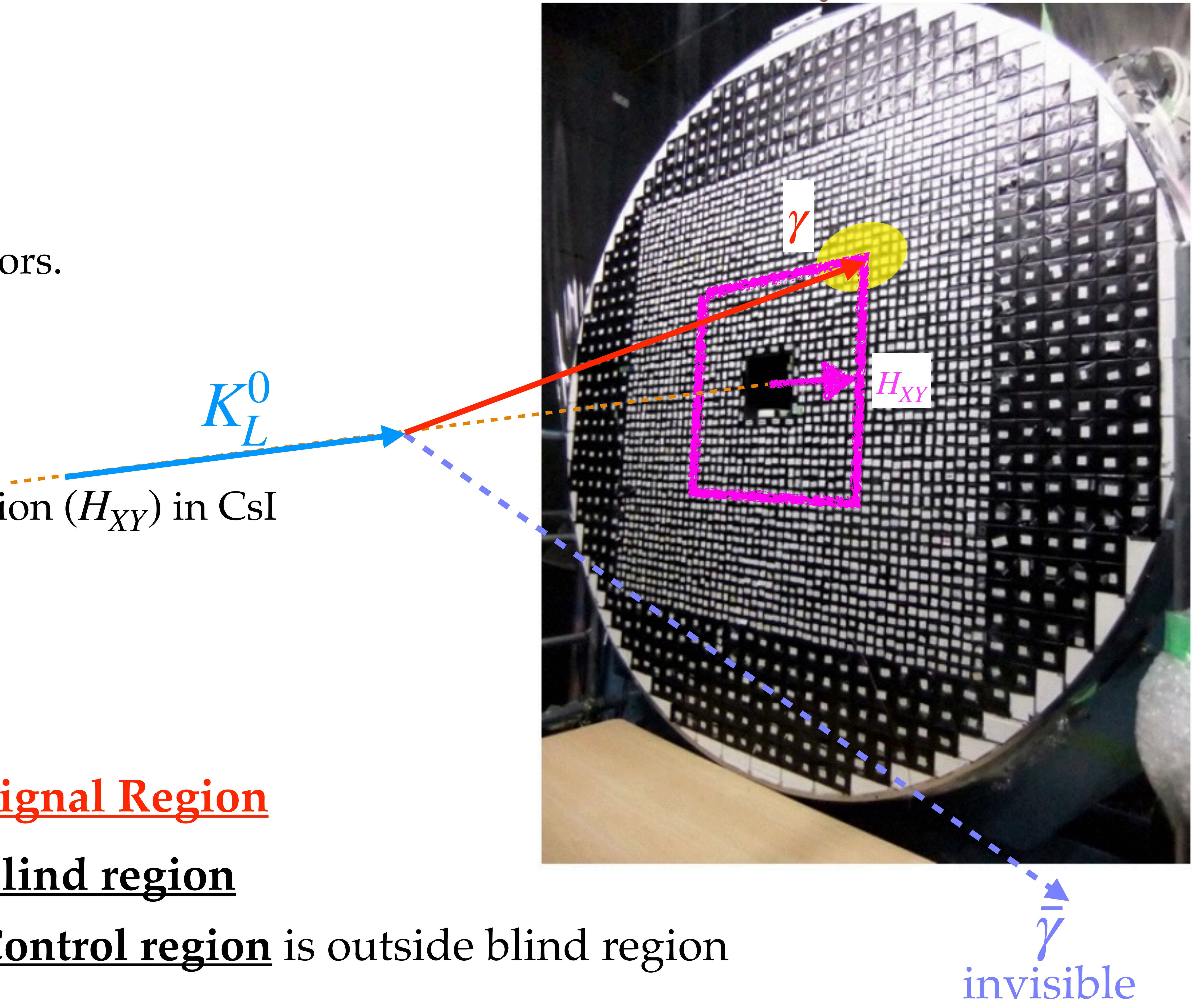
- Signal region defined as:
  - Cluster Energy (E_γ) vs. Hit position (H_{XY}) in CsI
    - $900 < E_\gamma < 3000$ MeV
    - $325 < H_{XY} < 850$ mm



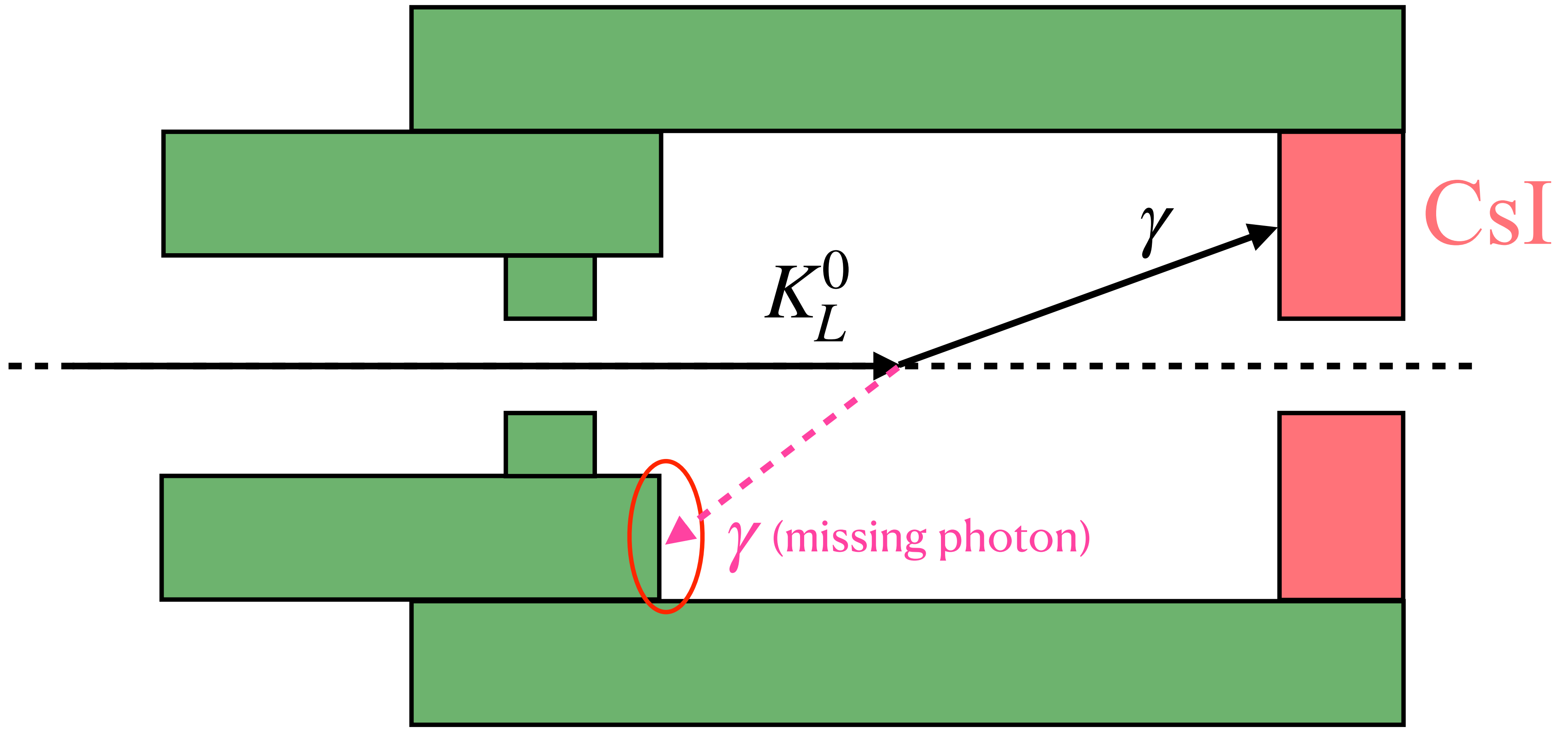
Signal Region

Blind region

Control region is outside blind region



K_L^0 decay backgrounds

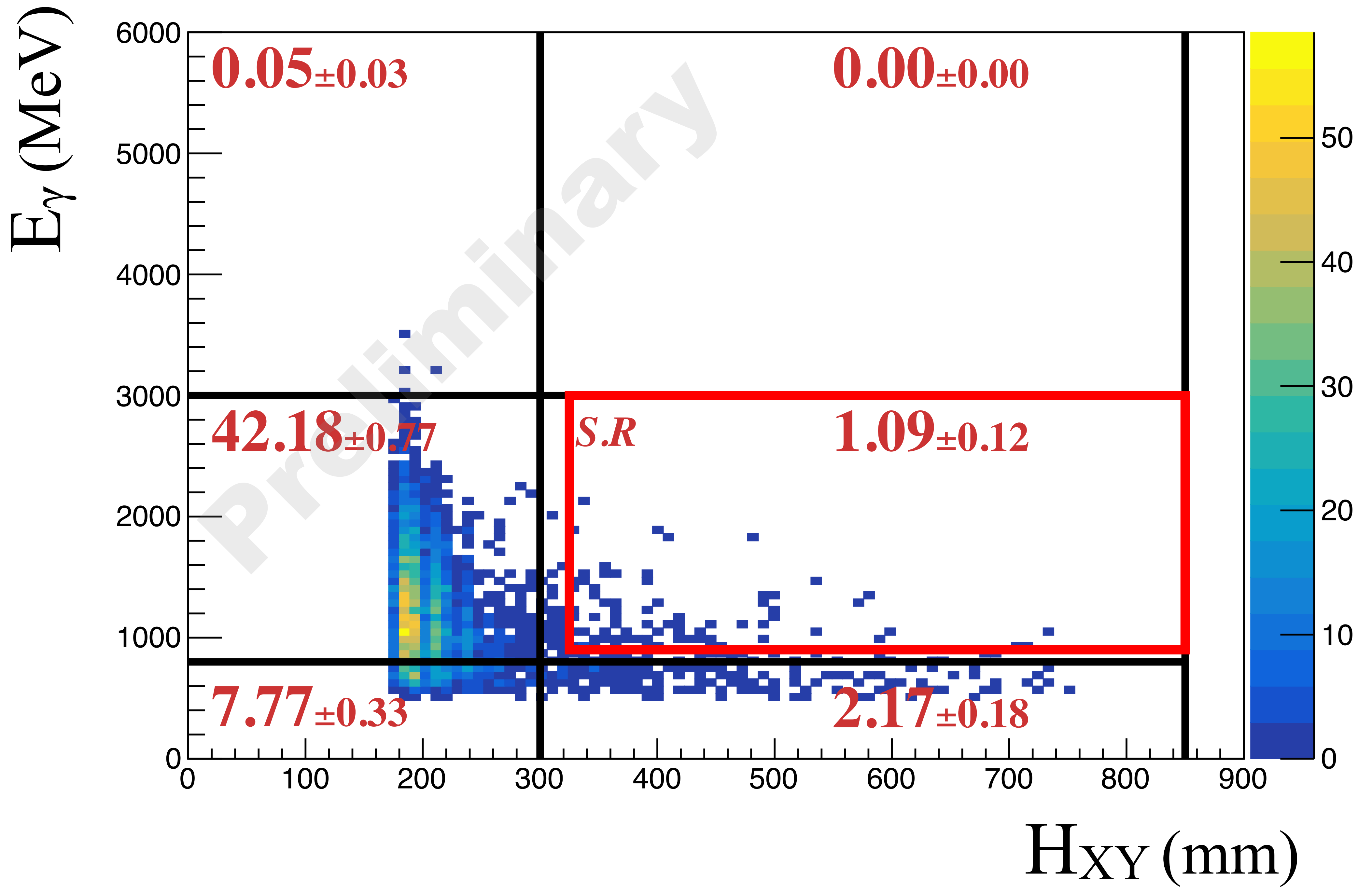


- $K_L^0 \to 2\gamma$ is the major BG from K_L^0 decay
  - with one missing γ due to detection inefficiency
  - N($K_L^0 \to 2\gamma$) = $1.09 \pm 0.12_{\text{stat.}} \pm 0.05_{\text{syst.}}$ based on MC simulation
- BG sources from other KL decays were negligible.

TABLE. Summary of K_L decay background estimation.

Decays	#Events in S.R. (90% C.L.)
$K_L^0 \to 2\gamma$	$1.09 \pm 0.12_{stat.} \pm 0.05_{syst.}$
$K_L^0 \to \pi^\pm e^\mp \nu_e$	< 0.27
$K_L^0 \to \pi^\pm \mu^\mp \nu_\mu$	< 0.25
$K_L^0 \to \pi^+\pi^-\pi^0$	< 0.17
$K_L^0 \to 3\pi^0$	< 0.18
$K_L^0 \to \pi^0\pi^0$	< 0.05
Total	$1.09 \pm 0.12_{stat.} \pm 0.05_{syst.}$

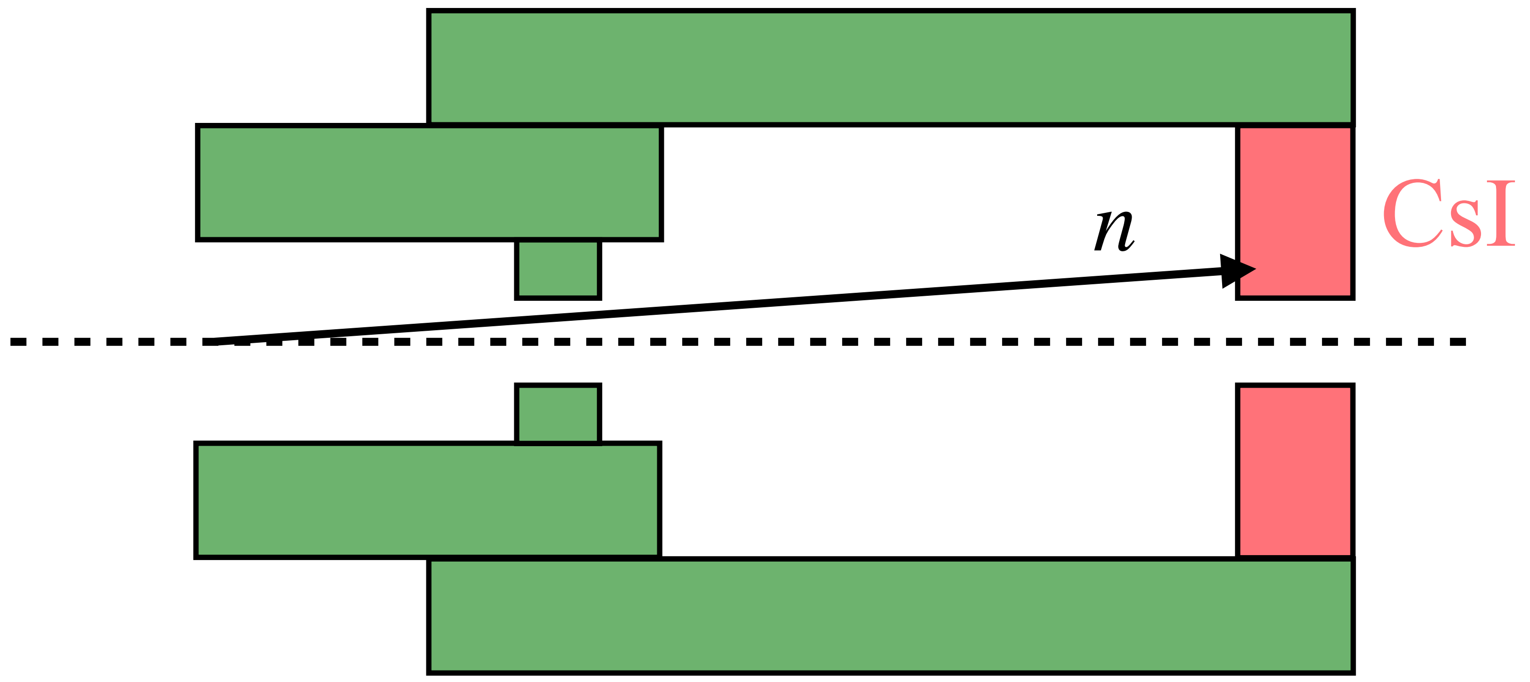
MC: $K_L \to 2\gamma$



*In blind region: 2.26±0.18

Neutron background

- Beam neutron hit CsI can have same signature as signal.
  - Single cluster on CsI
  - No in-time hit on veto



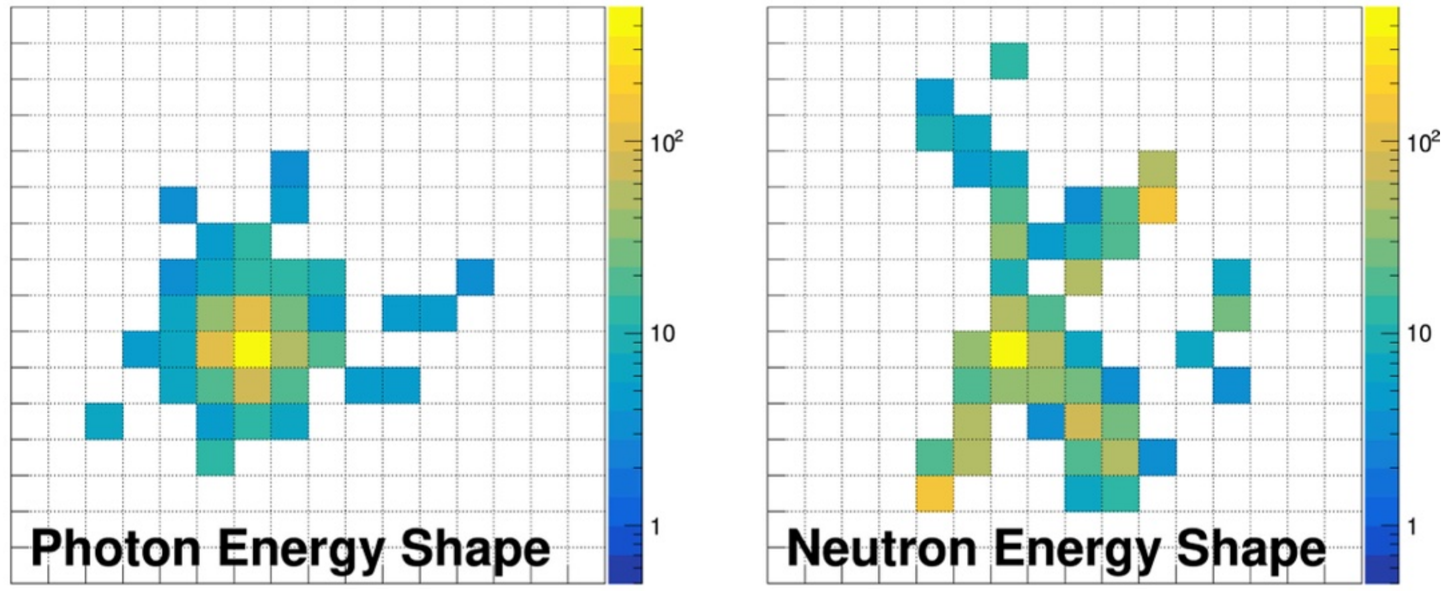
- Three techniques based on n-γ discrimination to suppress neutron background
  - Cluster Shape Discrimination with deep learning (**<u>CSD</u>**)
  - Pulse Shape Discrimination by using Fourier transform (**<u>PSD</u>**)
  - Shower Depth Measurement by CsI Both-End-Readout timing difference
- Neutron Sample (Al target runs)
  - Inserted an 3mm thickness aluminum plate target in front of the detector entrance to enhance the neutron in the beam.

[1] Y. C. Tung et al. 2024 Nucl. Instrum. Meth.848 A 1059 (2024), p. 169010.
[2] H Nanjo 2020 J. Phys.: Conf. Ser. **1526** 012025

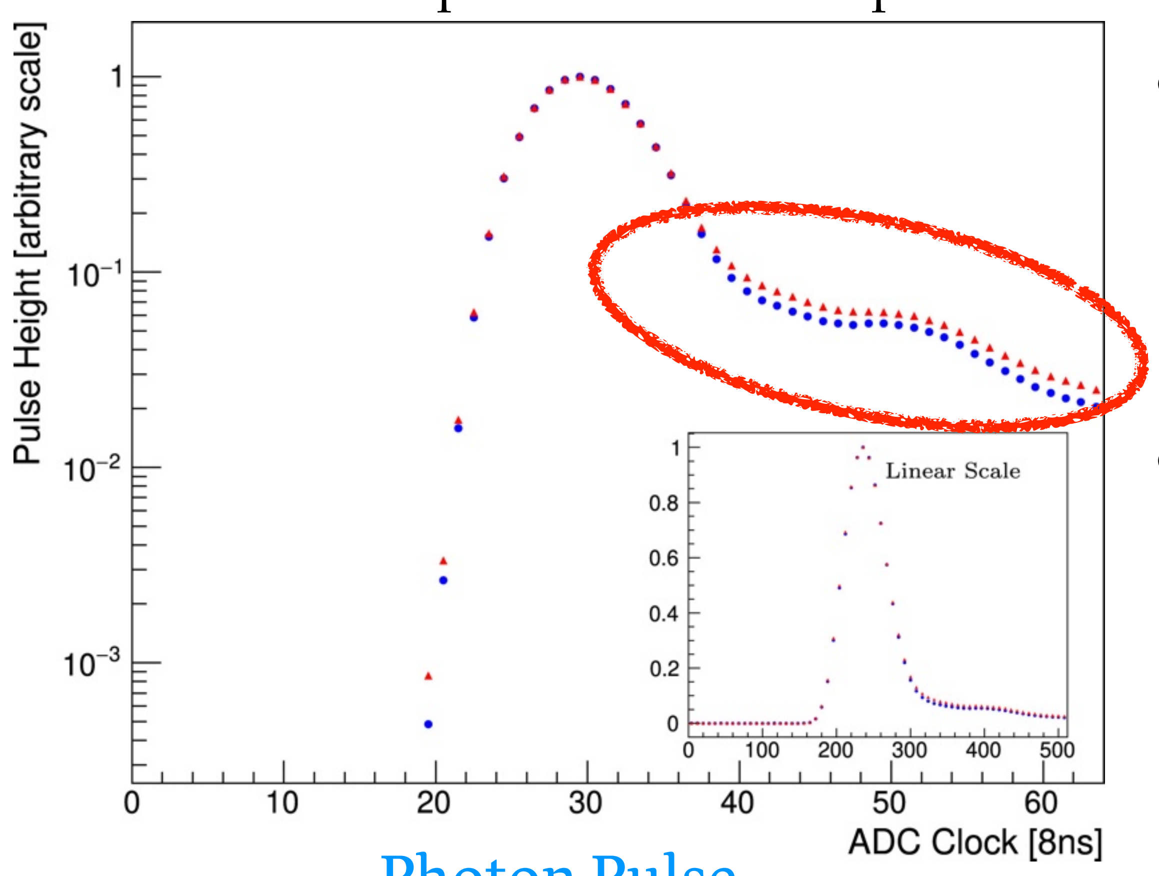
Neutron background

Three techniques to suppress neutron background

- Cluster Shape Discrimination (CSD)[1]
  - using CNN via Tensorflow



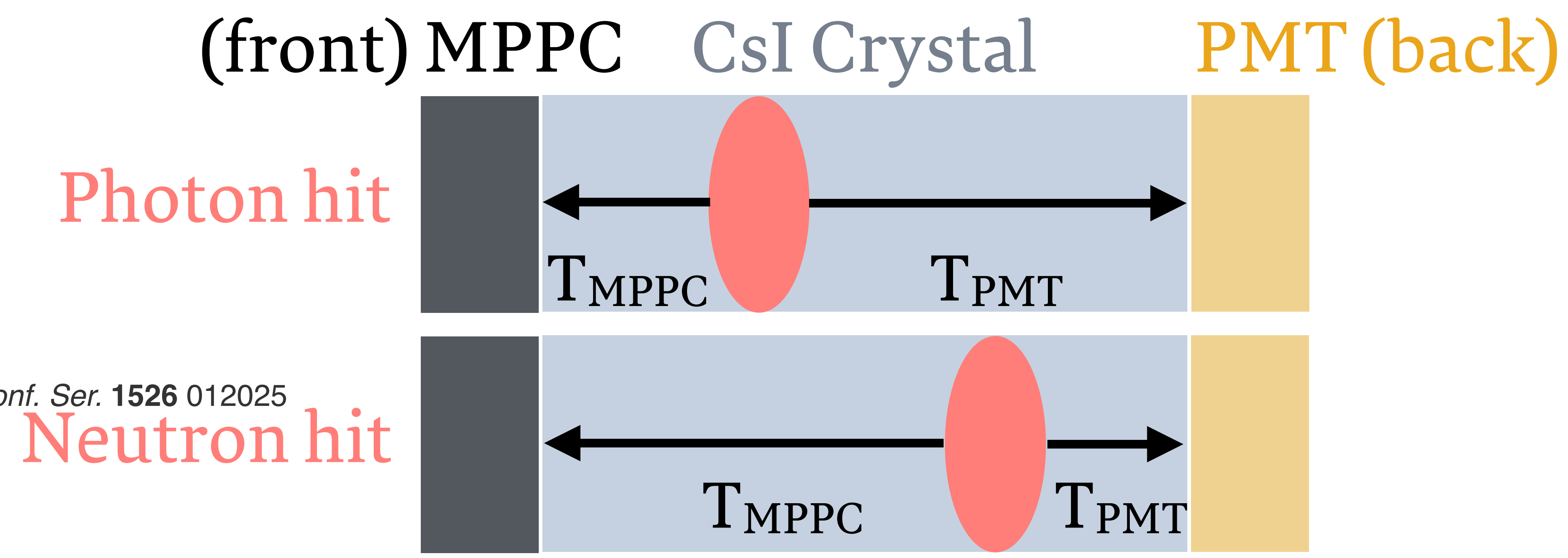
- Pulse Shape Discrimination (PSD)[1]



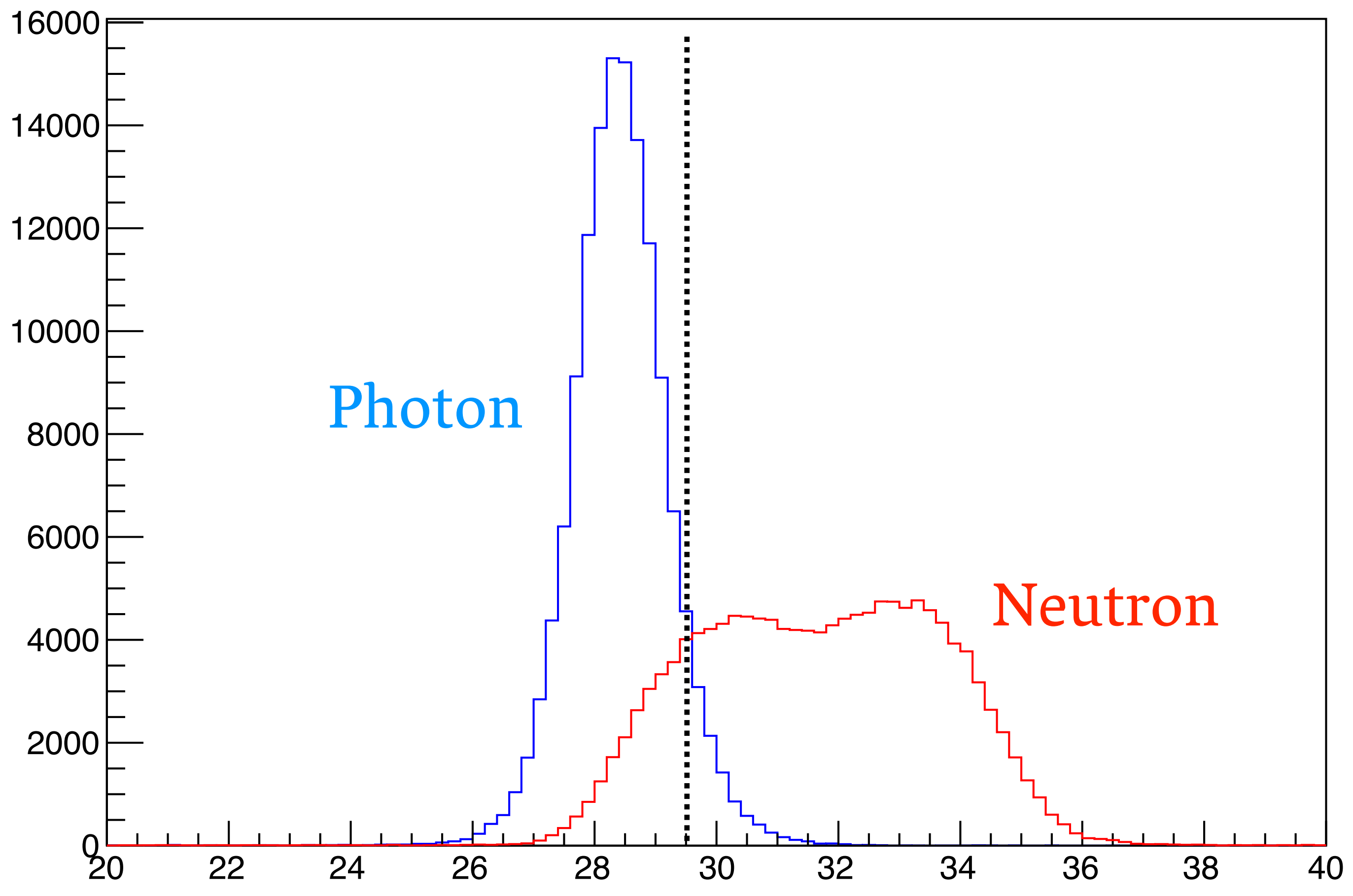
Photon Pulse
Neutron Pulse

- Neutron pulse have a longer tail compare to photon pulse in CsI.
- Extract the pulse difference by using Discrete Fourier Transformation (DFT)

- Shower Depth Measurement[2]



H Nanjo 2020 *J. Phys.: Conf. Ser.* **1526** 012025



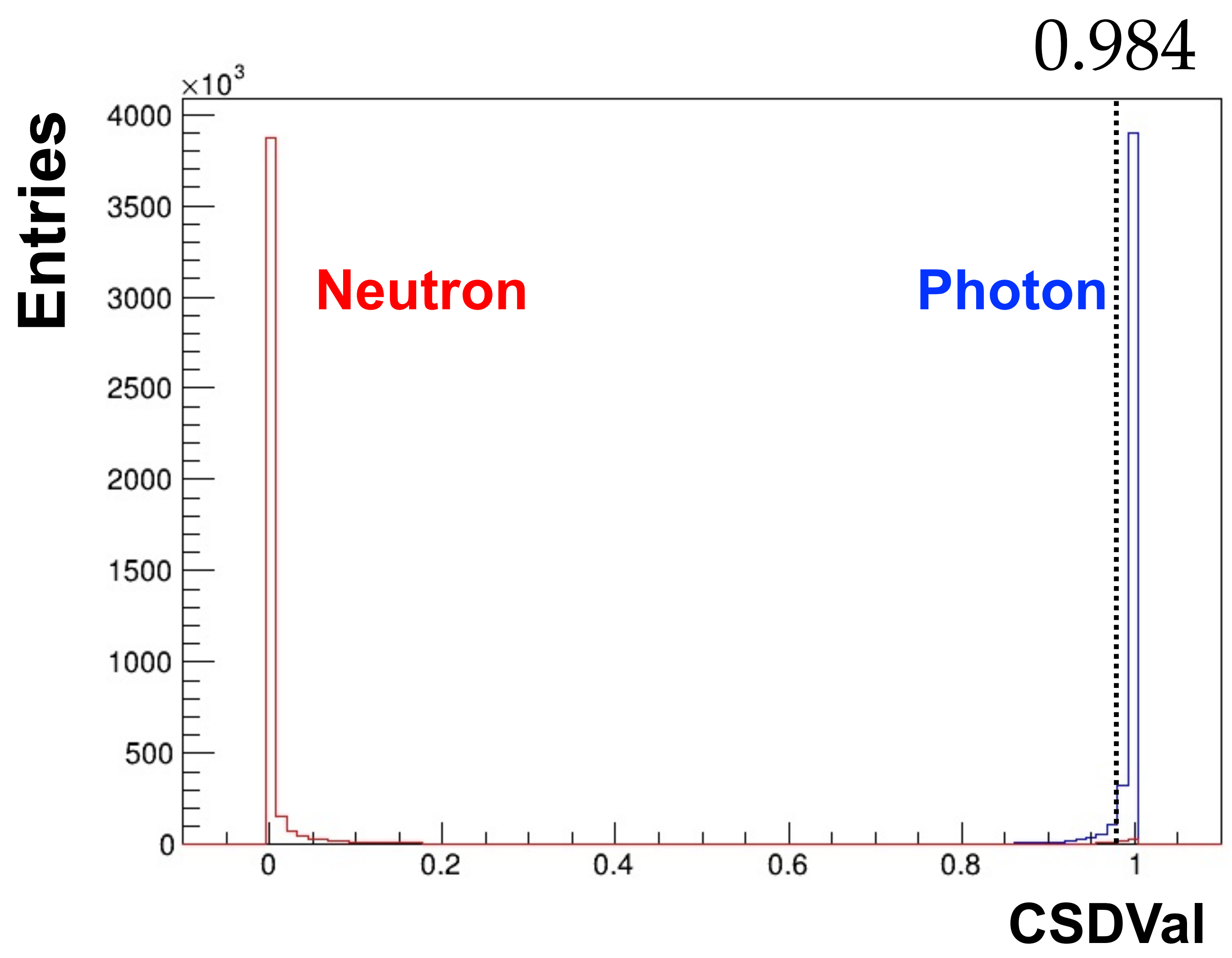
ΔT (ns) = T_{MPPC} - T_{PMT}

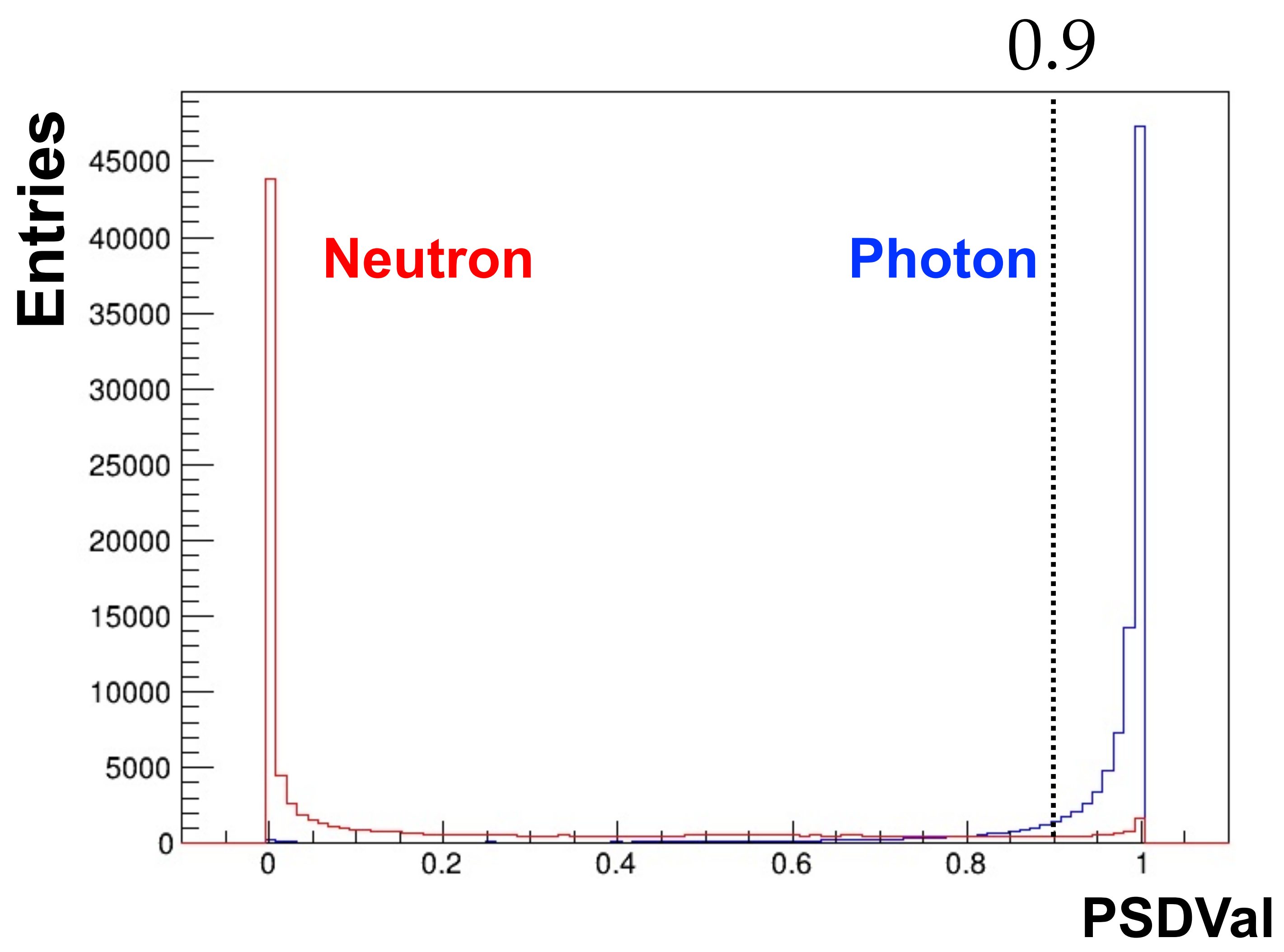
Neutron background Estimation

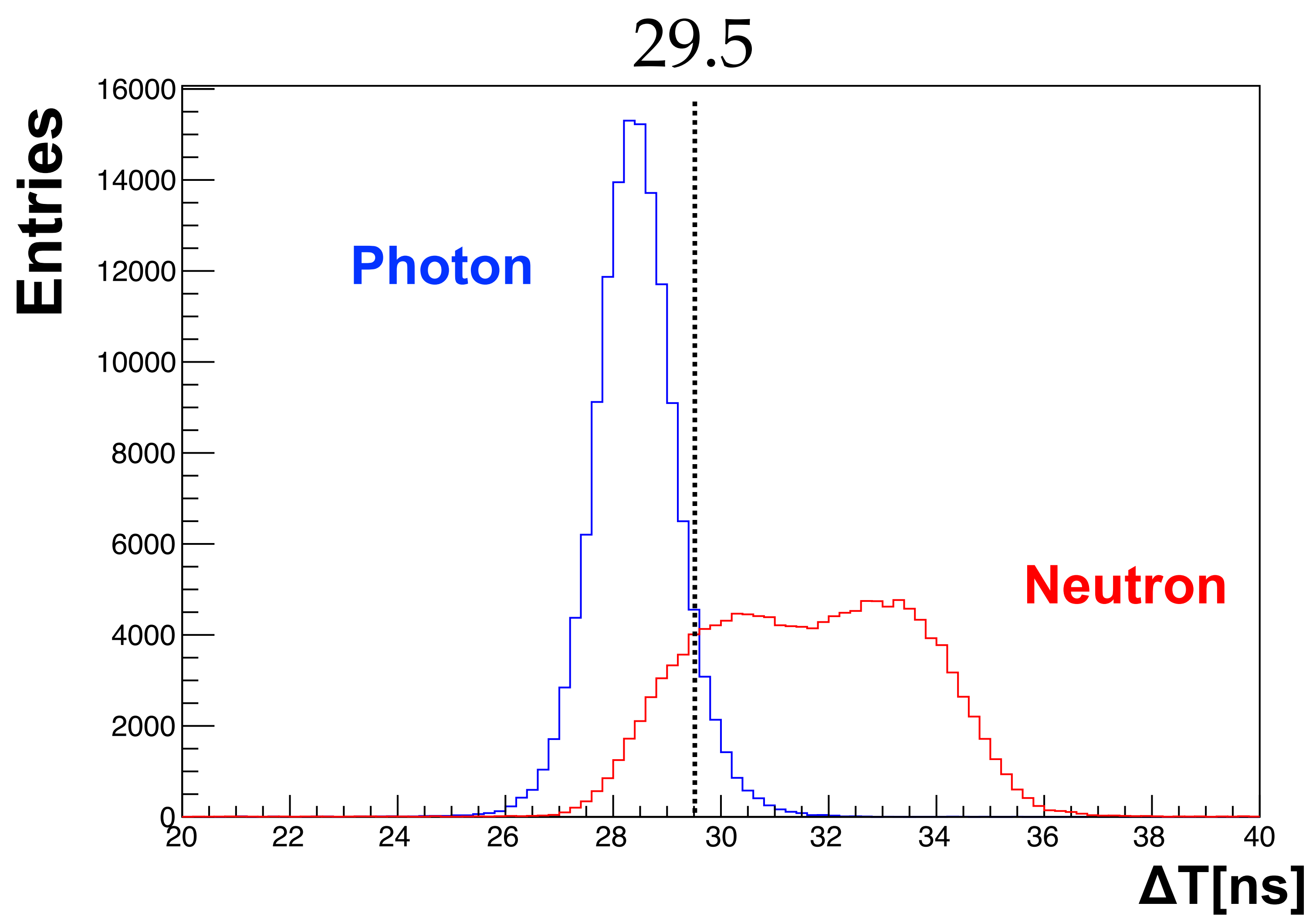
- Combine three techniques rejected the neutron background by $\mathcal{O}(10^{-3})$ for *single cluster* with 83.9% γ acceptance.
- Number of neutron background in this analysis $N(\text{neutron}) = 11.57 \pm 4.42_{\text{stat.}} \pm 2.13_{\text{syst.}}$

Preliminary

Cut	Signal Efficiency	Neutron Rejection
ΔT	95.3%	1.86×10^{-1}
ΔT+PSD	85.6%	4.88×10^{-2}
ΔT+PSD+CSD	83.9%	1.78×10^{-3}







Single Event Sensitivity

- Single Event Sensitivity (SES)
  - The branching ratio if one signal event is observed

$$SES = \frac{1}{A_{sig} \times N(K_L^0)}$$

A_{sig}: Signal Acceptance evaluated by MC

$N(K_L^0)$: K_L^0 yield calculated by $K_L^0 \to 3\pi^0$ decay

$$N(K_L^0) = \frac{N(K_L^0 \to 3\pi^0)}{A_{K_L^0 \to 3\pi^0} \times BR(K_L^0 \to 3\pi^0)} = 1.29 \times 10^{10}$$

$$A_{sig} = 2.66 \times 10^{-3}$$

Summary of the Background estimation

$$SES = (2.91 \pm 0.05_{stat.} \pm 0.30_{syst.}) \times 10^{-8}$$

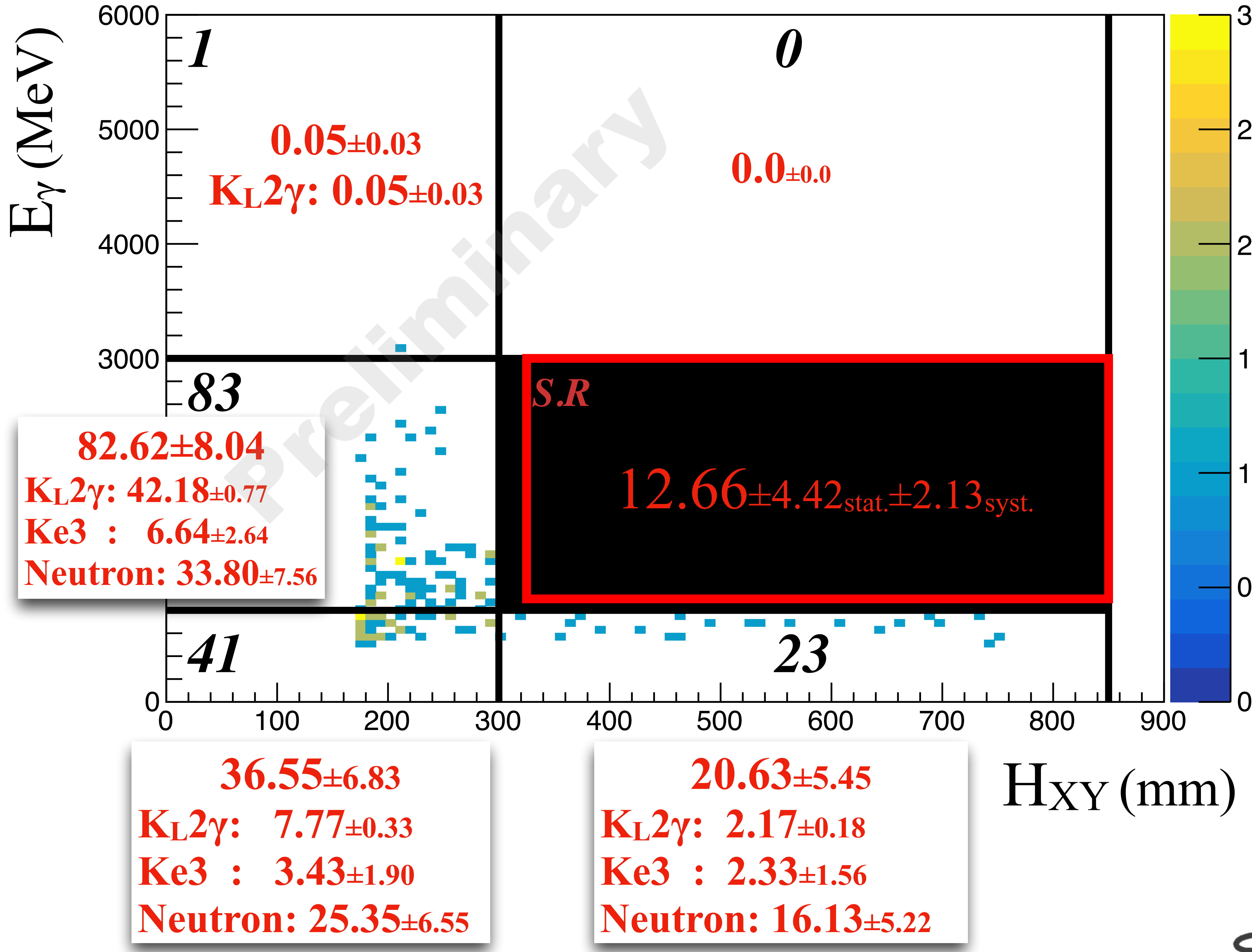
N (background) = 12.66 ± 4.42

TABLE. Summary of background estimation.

Source		Number of events
K_L	$K_L \to 2\gamma$	$1.09 \pm 0.12_{stat.} \pm 0.05_{syst.}$
	Other K_L decays	< 0.92
Neutron		$11.57 \pm 4.42_{stat.} \pm 2.13_{syst.}$
Total (Exclude upper limit)		$12.66 \pm 4.42_{stat.} \pm 2.13_{syst.}$

#Observed

#Expect BG

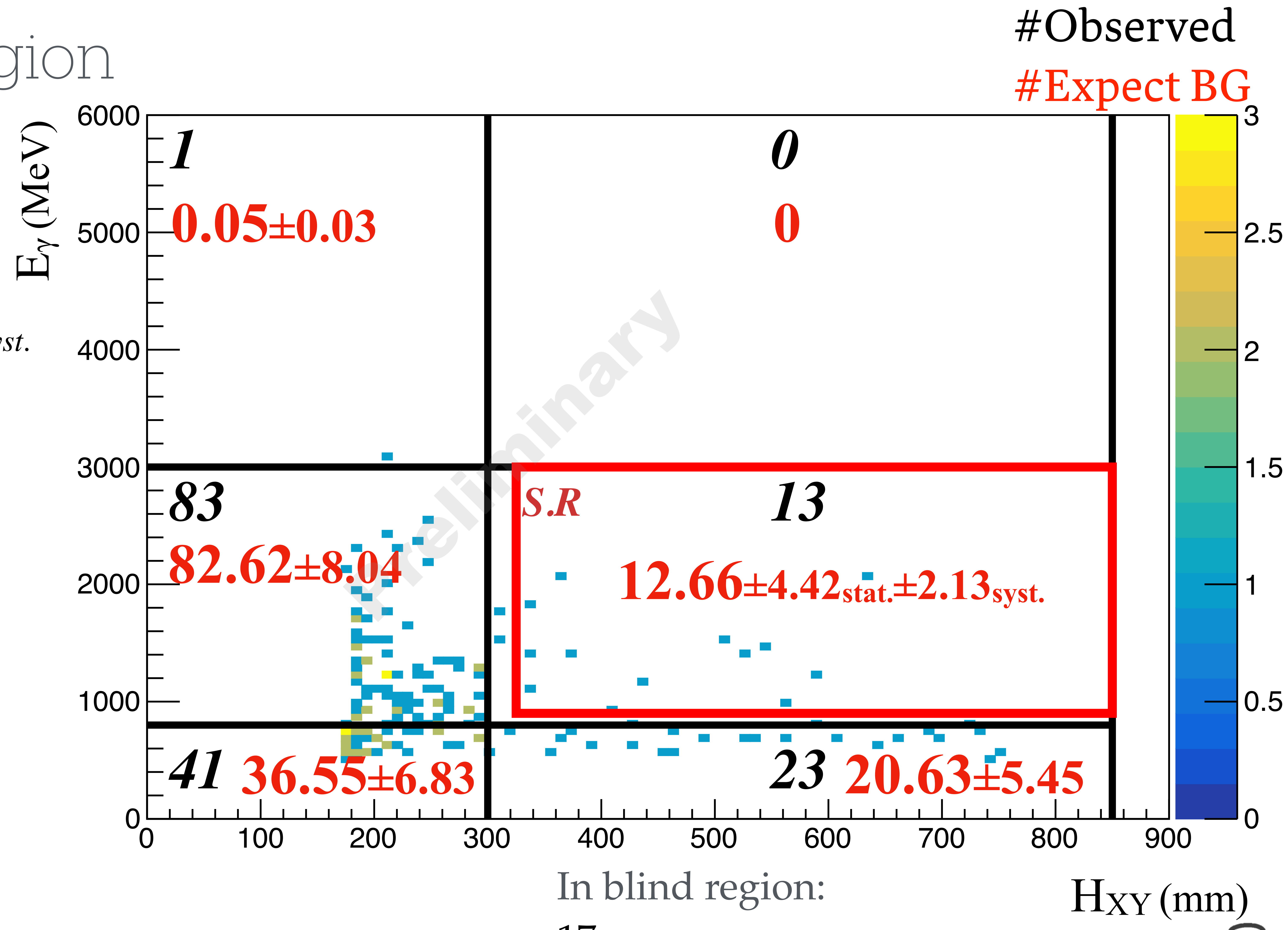


In blind region: 23.49

Result of $K_L \to \gamma\bar{\gamma}$ analysis

After opening the blind region

- #Observed = 13
- Estimated #BG = $12.66 \pm 4.42_{stat.} \pm 2.13_{syst.}$
- $SES = (2.91 \pm 0.05_{stat.} \pm 0.30_{syst.}) \times 10^{-8}$
- Feldman Cousins (90% C.L.)
    - $BR < 3.47 \times 10^{-7}$



In blind region:

17

23.49±5.99stat.±2.78syst.

Summary

- We performed the first search of massless dark photon in $K_L^0 \to \gamma\bar{\gamma}$ at KOTO
- 13 events were observed in the S.R. with the predicted #BG of 12.66
- With the SES of $(2.91 \pm 0.05_{stat.} \pm 0.30_{syst.}) \times 10^{-8}$ (based on data collected in 2 hour special run)
    - $\mathcal{B}(K_L^0 \to \gamma\bar{\gamma}) < 3.47 \times 10^{-7}$ (at 90% C.L.)

Thanks

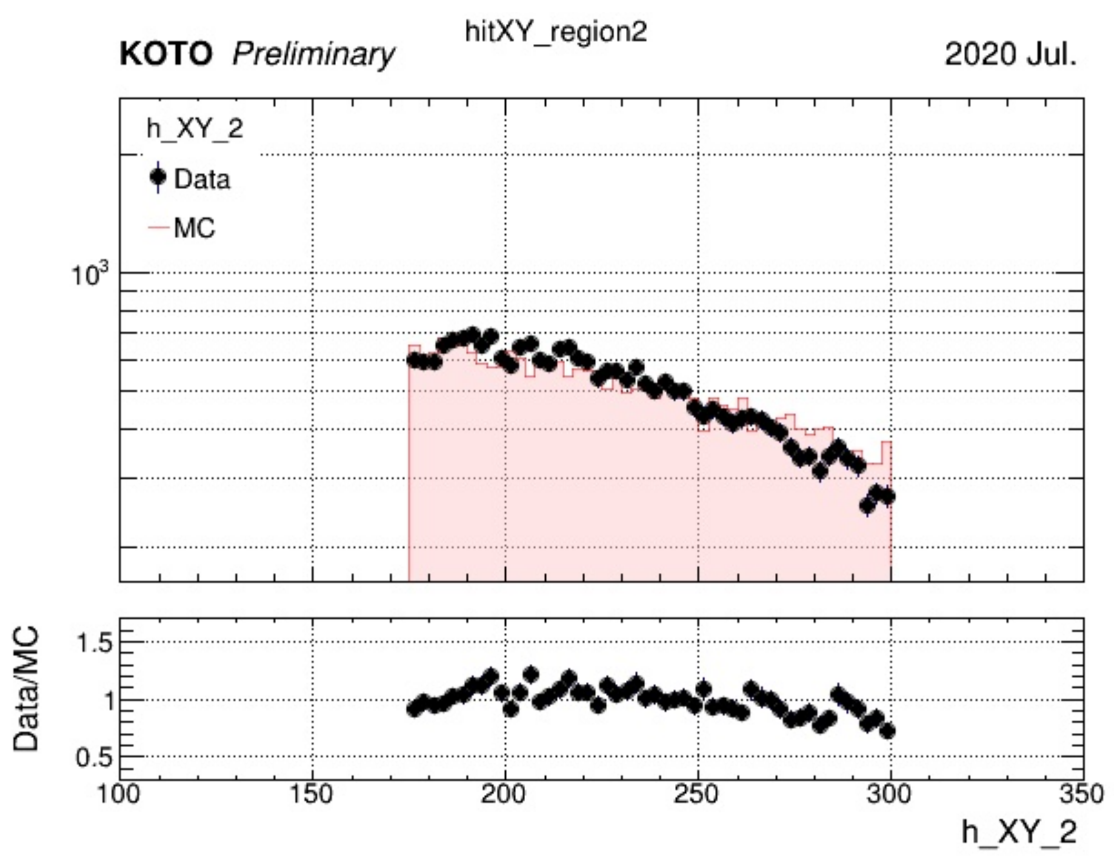
Backup

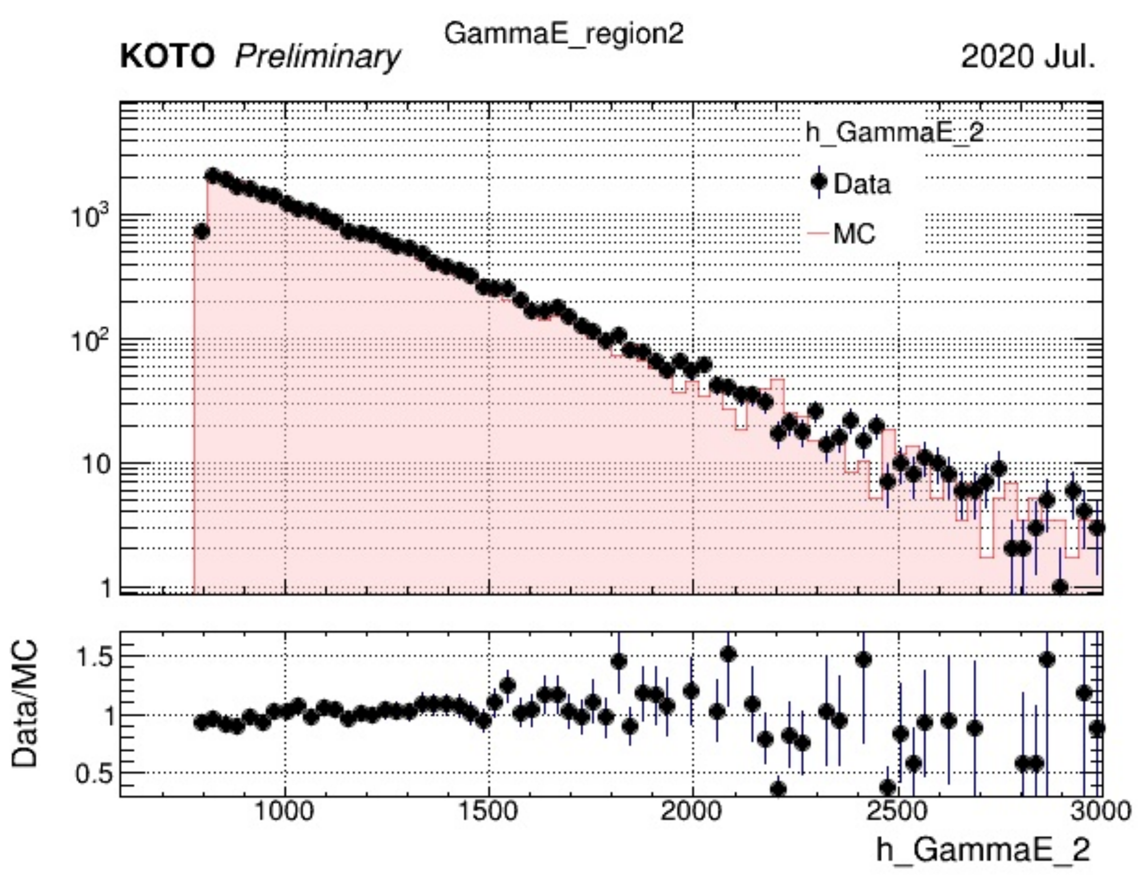
Veto threshold

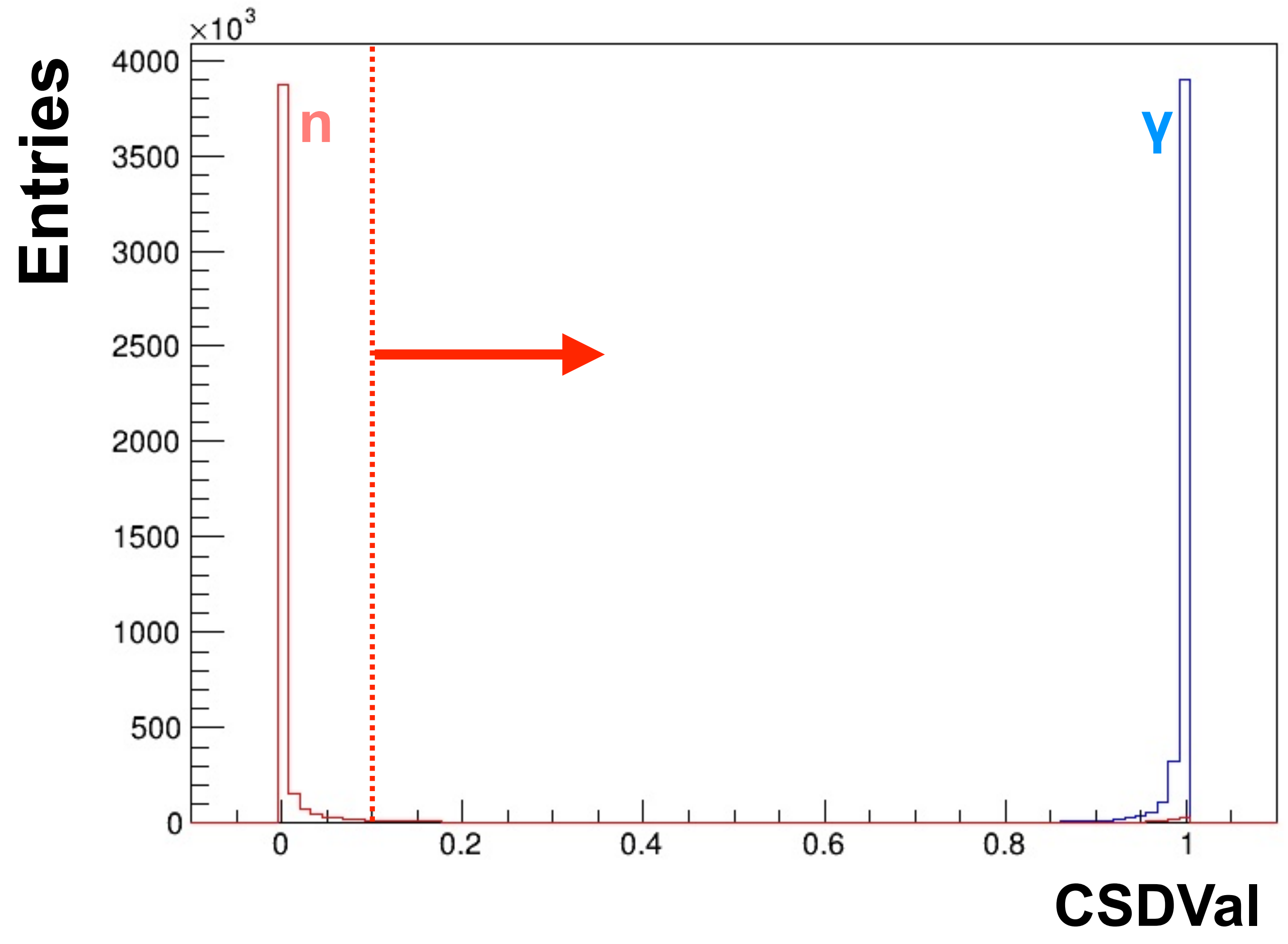
Veto	Threshold
CV	0.2 MeV
FB, MB, IB, NCC	1 MeV
MBCV, IBCV	1 MeV
CC03, CC04, CC05, CC06	3 MeV
OEV	1 MeV
BHPV	2.5
BHGC	2.5

Normalization of Neutron sample

- Inverse Neutron Cut to purify the Neutron sample.
  - CSDVal < 0.1
- Obtain the Scale Factor through area normalization of the sideband region.







Systematic Uncertainty

Single Event Sensitivity

$$SES = \frac{A_{3\pi^0}}{A_{sig}} \times \frac{BR(K_L \to 3\pi^0)}{N_{K_L \to 3\pi^0}}$$

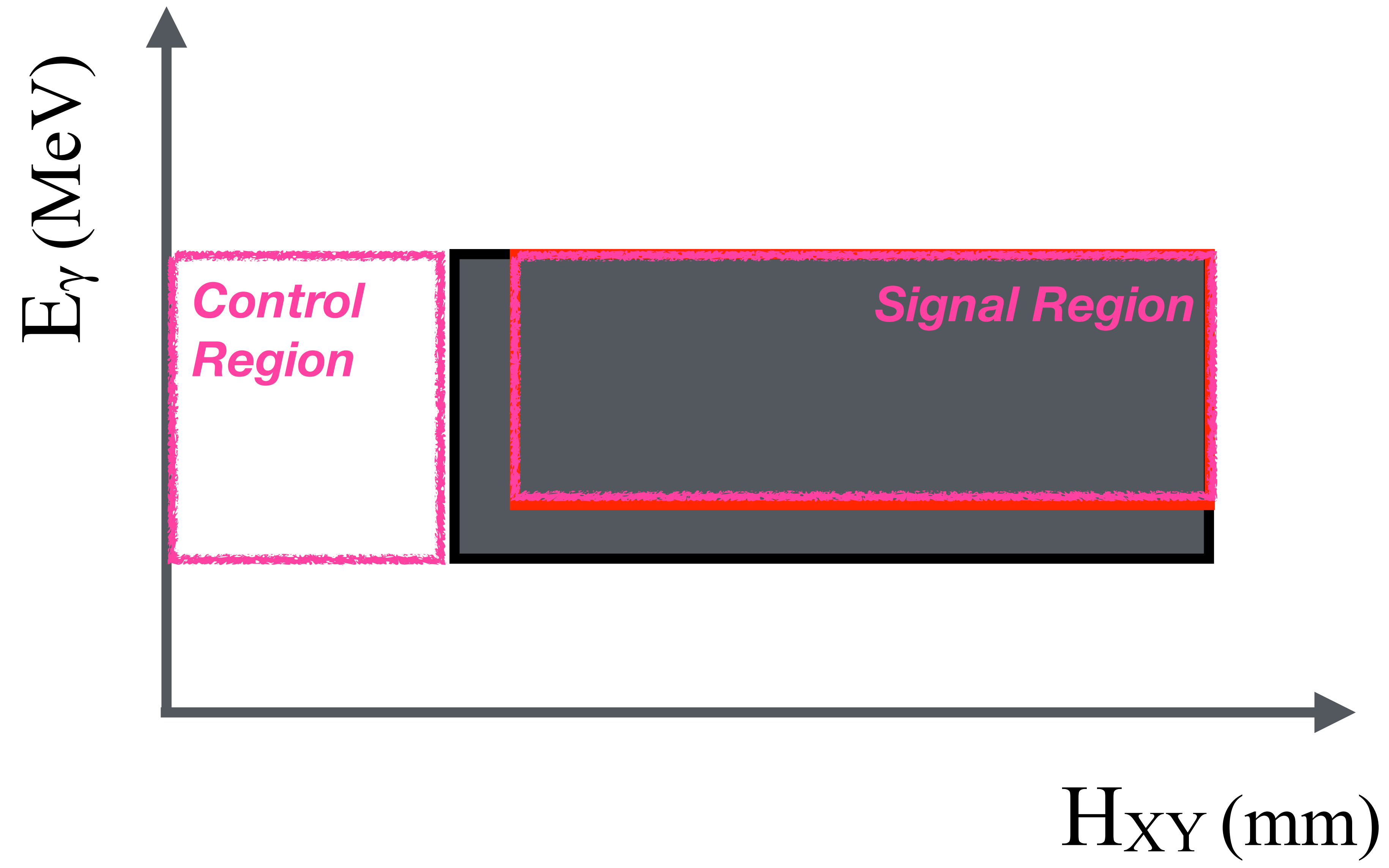
- $A = A_{veto} \times A_{kin} \times A_{neutron} \times A_{geometric} \times A_{trigger}$
- Uncertainty: $\sigma = \sqrt{\sum D_i^2}$
- Deviation of of i-th cut: $D_i = \frac{a_i(MC) - a_i(Data)}{a_i(Data)}$
- Exclude acceptance of i-th cut: $a_i = \frac{\#\text{events with all cuts}}{\#\text{events with all cuts except the } i\text{-th cut}} = \frac{N(\text{w/ all cut})}{N(\text{w/o cut } i)}$

Source	Uncertainty
Veto cuts	6.6%
Kinematic cuts for $K_L \to 3\pi^0$	3.3%
Kinematic cuts for $K_L \to \gamma\bar{\gamma}$	1.4%
Neutron cuts for $K_L \to \gamma\bar{\gamma}$	4.8%
K_L momentum spectrum	0.9%
Trigger effect	1.6%
$K_L \to 3\pi^0$ branching ratio	0.6%
Total	9.1%

Systematic Uncertainty

$K_L \rightarrow 2\gamma$ backgrounds

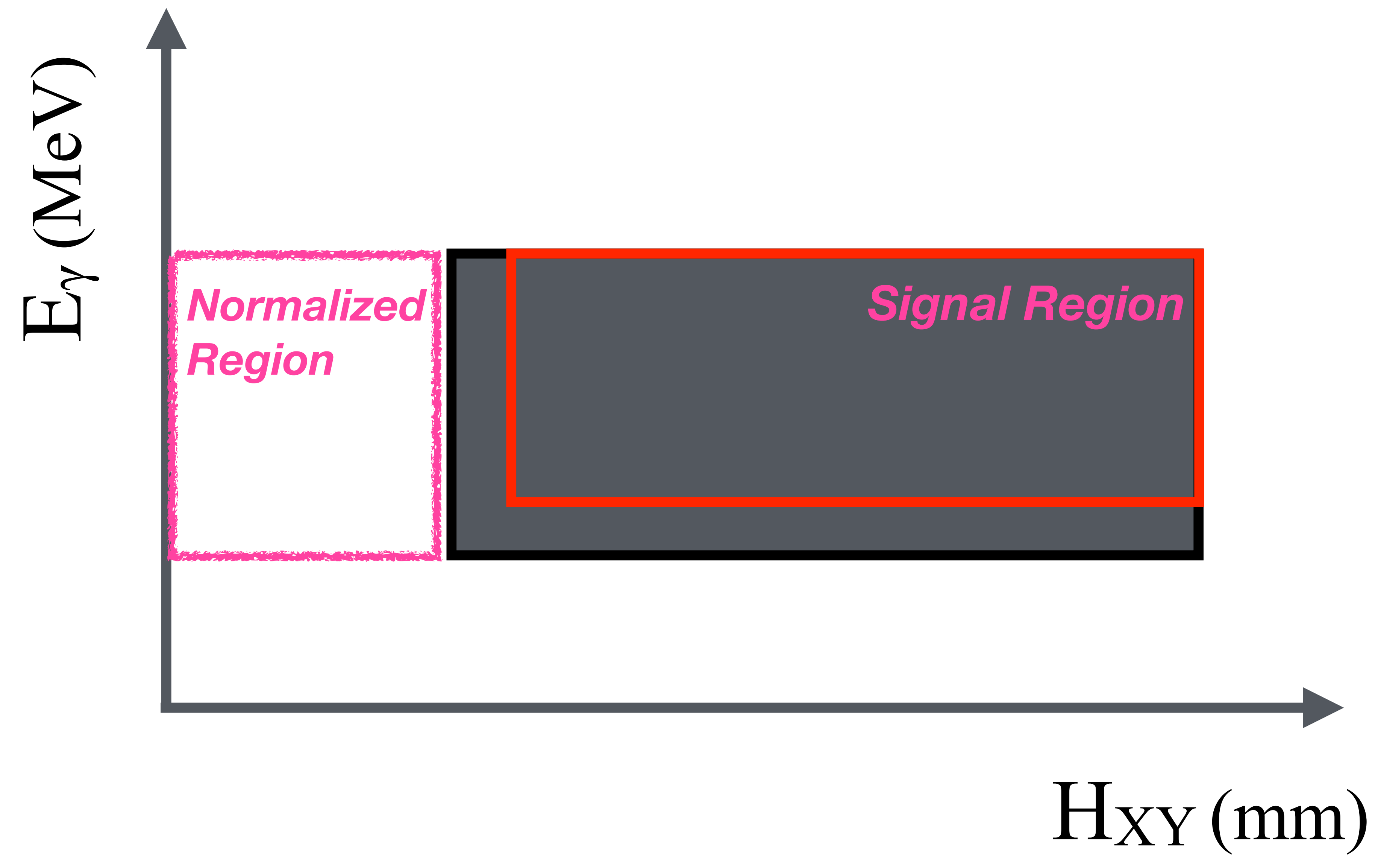
- Ratio of *Signal* and *Control* region: $R = \dfrac{N(Signal)}{N(Control)}$
- Deviation: $D = \dfrac{R(\text{Neutron}) - R(Data)}{R(Data)}$
- Uncertainty: $\sigma = \sqrt{\sum D_i^2} = 4.86\,\%$



Systematic Uncertainty

Neutron backgrounds

- Normalization
  - Apply Inverse CSD cut to purify neutron sample
  - Ratio of *Signal* and *Normalized* region: $R = \dfrac{N(\text{Signal})}{N(\text{Normalized})}$
  - Deviation: $D = \dfrac{R(\text{Neutron}) - R(\text{Data})}{R(\text{Data})}$
- Neutron Cut
  - Use the other two cuts as inverse cut
  - $a_i = \dfrac{N(\text{inverse cut} + \text{this cut})}{N(\text{inverse cut})}$
  - $D_i = \dfrac{a_i(\text{Data}) - a_i(\text{Neutron})}{a_i(\text{Neutron})}$
  - Uncertainty: $\sigma = \sqrt{\sum D_i^2}$



Source	Uncertainty
Normalization	12.7%
Neutron Cut	13.4%
Total	18.5%