KOTO: Search for $K_L^0 \to \pi^0 \nu \bar{\nu}$

BEACH 2024

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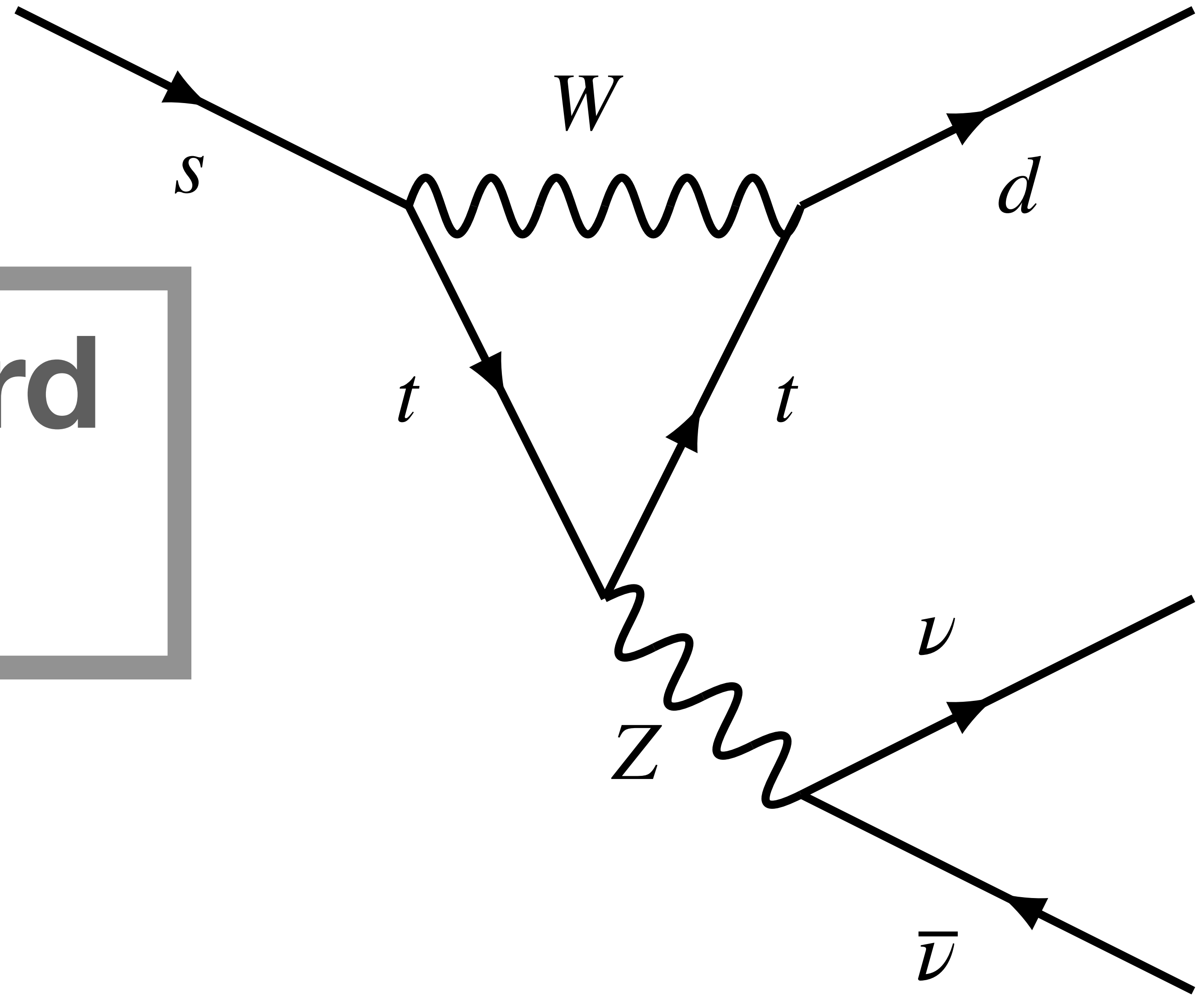
Search for New Physics via $K_L^0 \to \pi^0 \nu \bar{\nu}$

CP- CP+

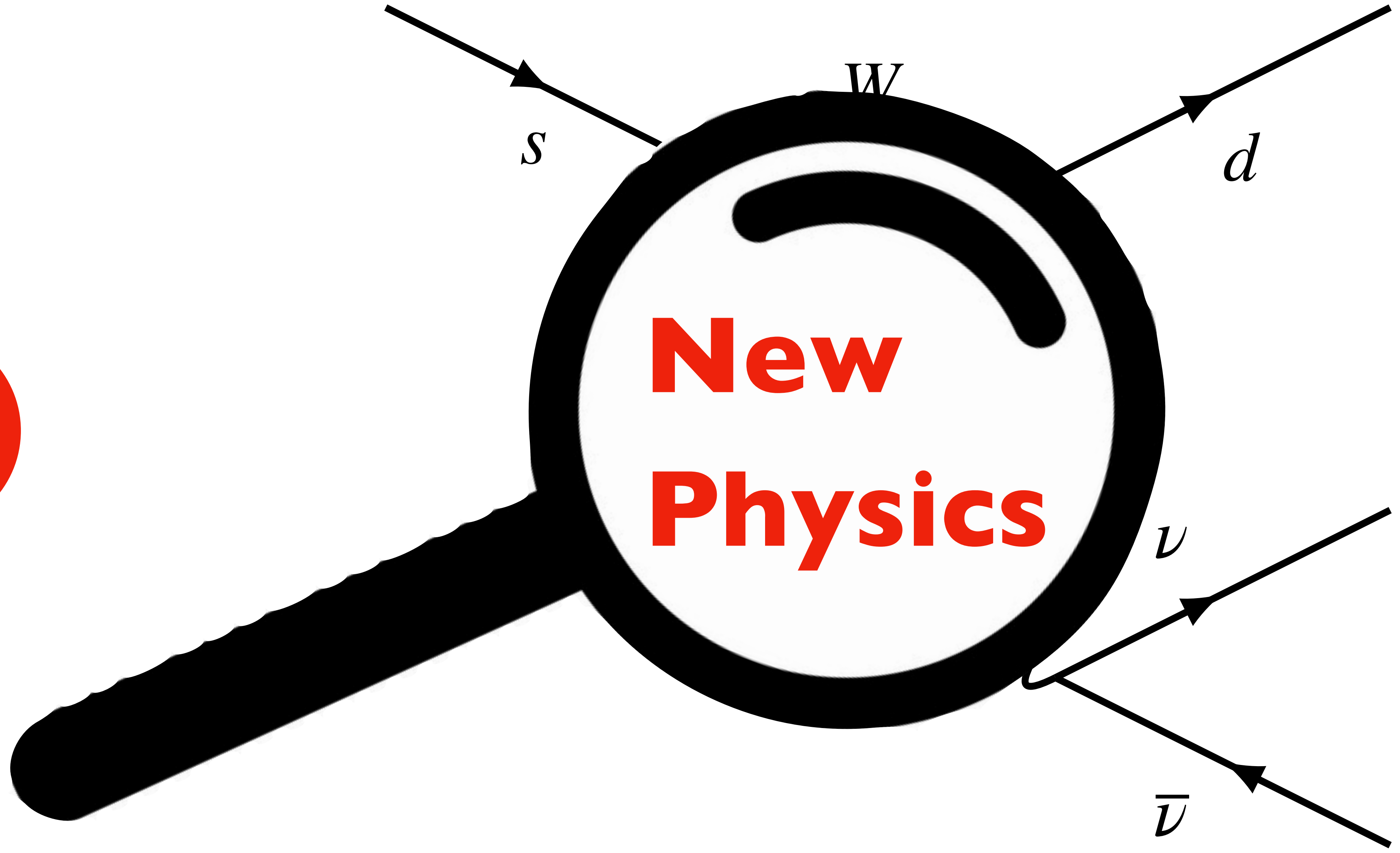
$$K_L^0 \to \pi^0 \nu \bar{\nu}$$

Standard Model



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

(2% error only)



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

Rare & Precisely-predicted
→ Sensitive to New Physics

The regime where colliders cannot explore.

New Physics Scenarios via $K \to \pi\nu\bar{\nu}$

Indirect upper limit given by NA62

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

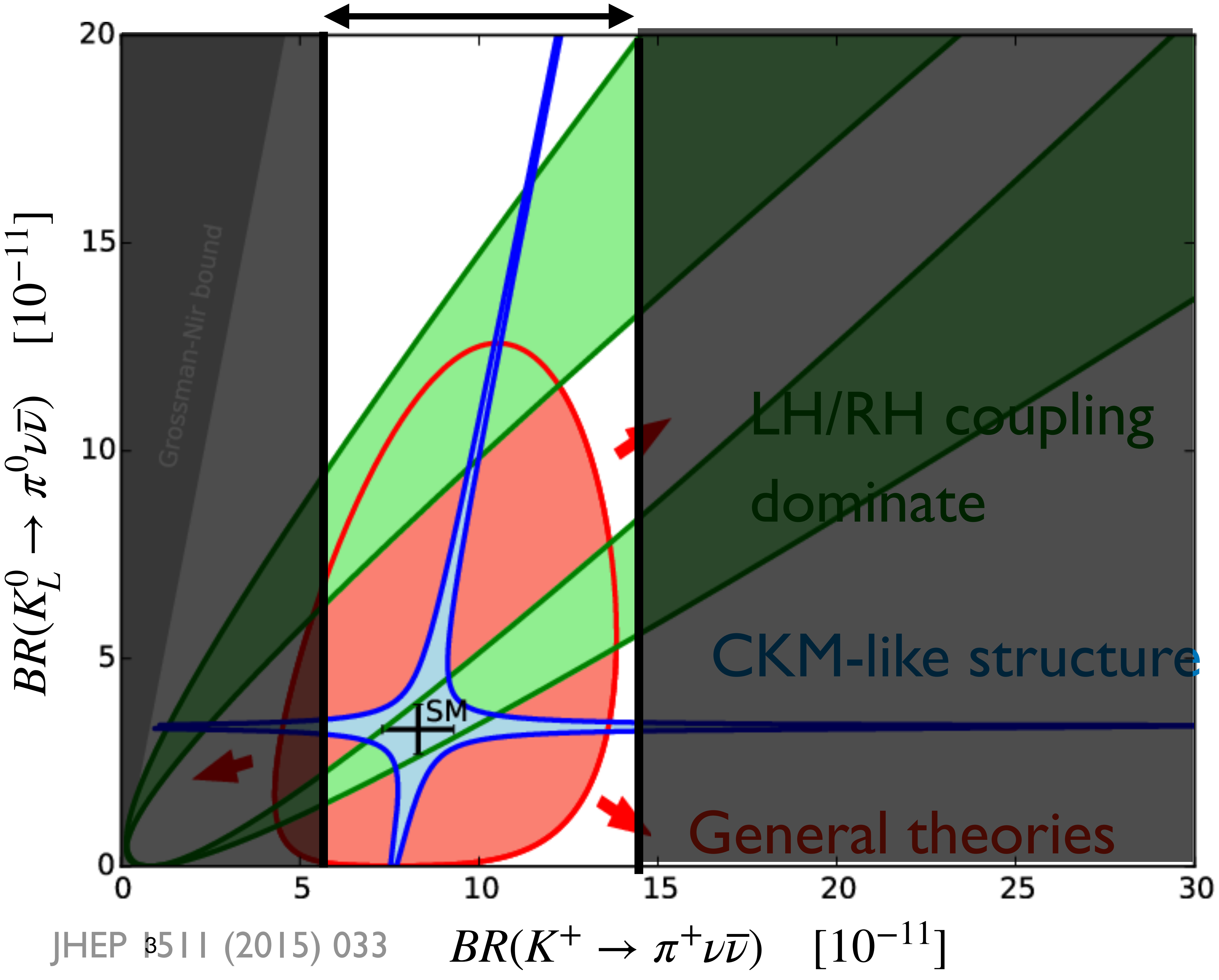
JHEP 1511 (2015) 033

Grossman-Nir (GN) bound

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

$\leq 6.4 \times 10^{-10}$ (68% C.L.)

1-σ window by NA62 (2021)



JHEP 1511 (2015) 033

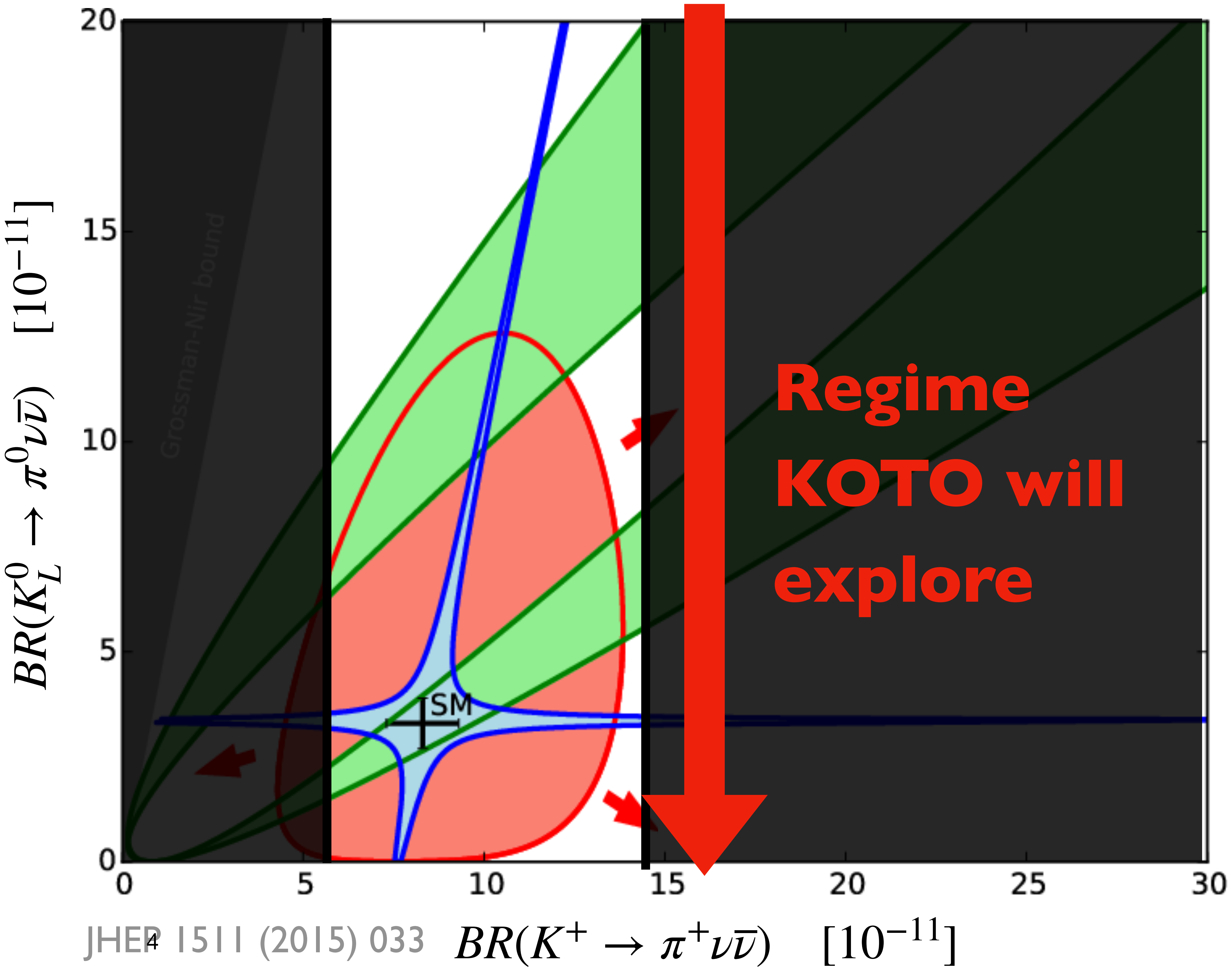
New Physics Scenarios via $K \rightarrow \pi\nu\overline{\nu}$

Scenarios for KOTO

Experimental result of $B(K_L^0 \rightarrow \pi^0\nu\overline{\nu})$

$< 3.0 \times 10^{-9}$ (90% C.L.)

Two orders of magnitudes from the SM.



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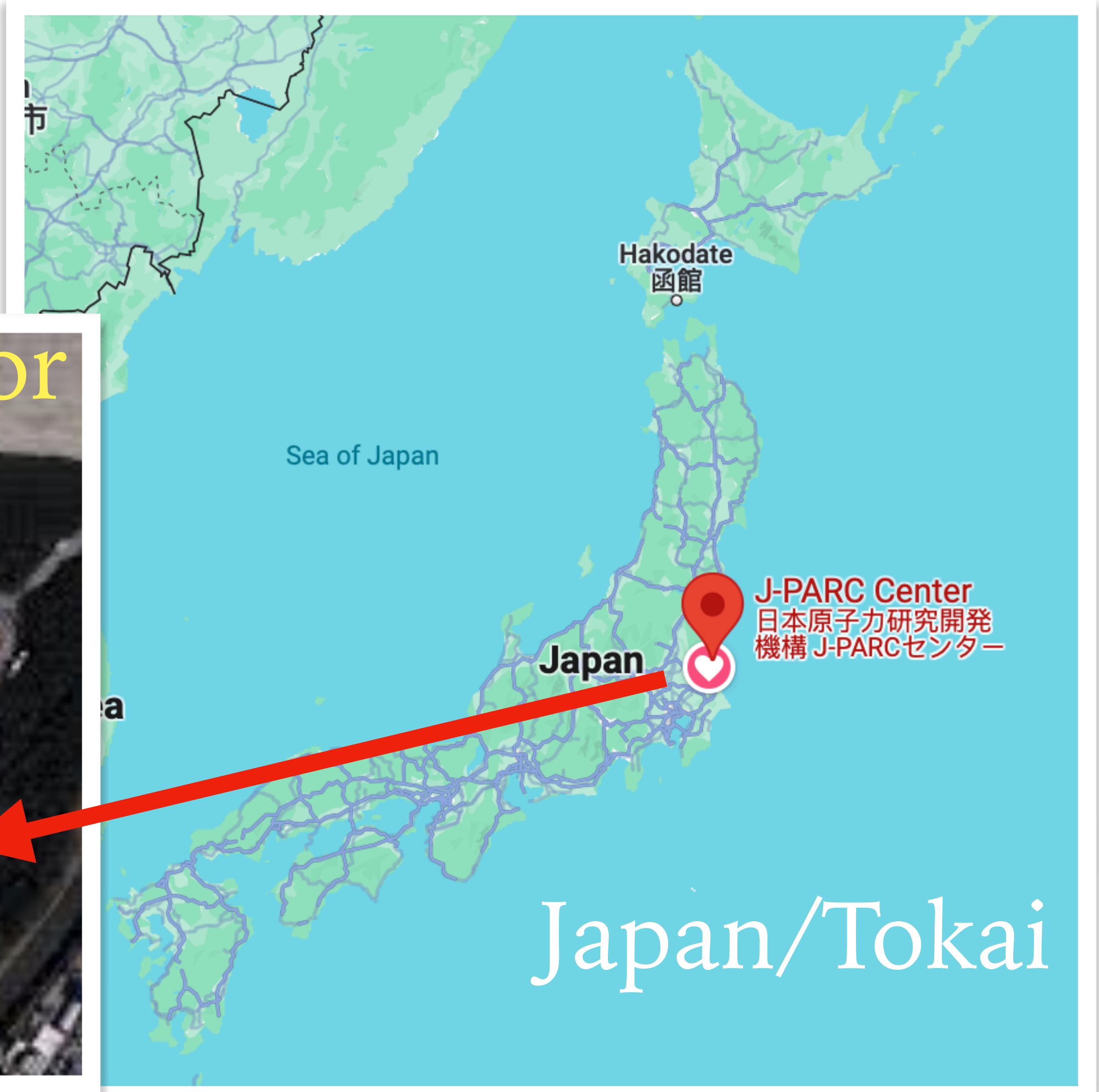
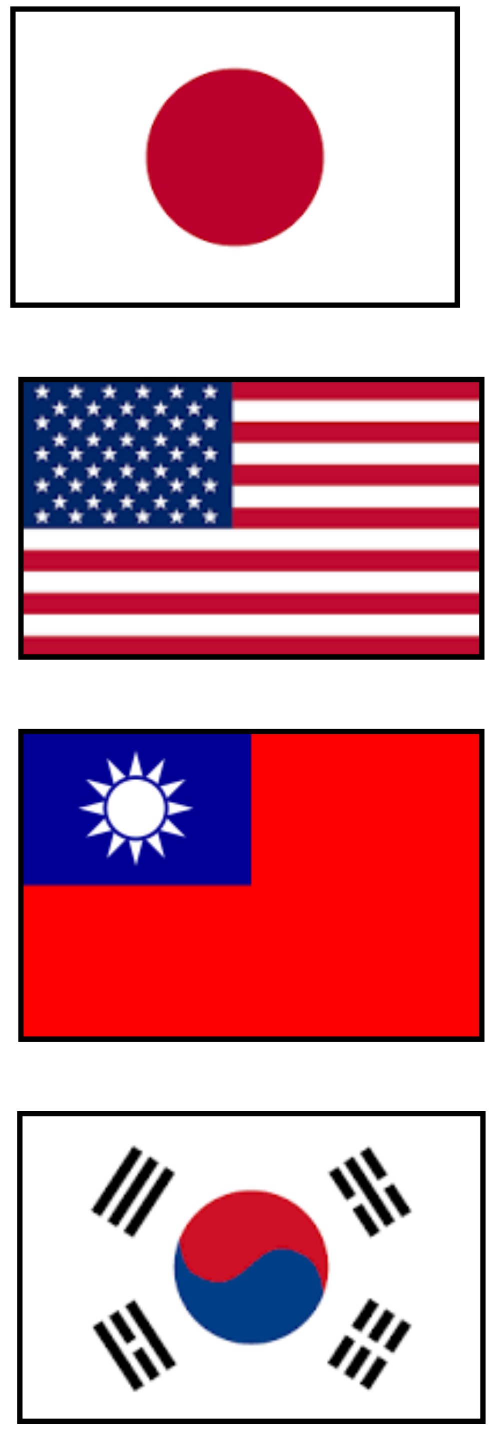
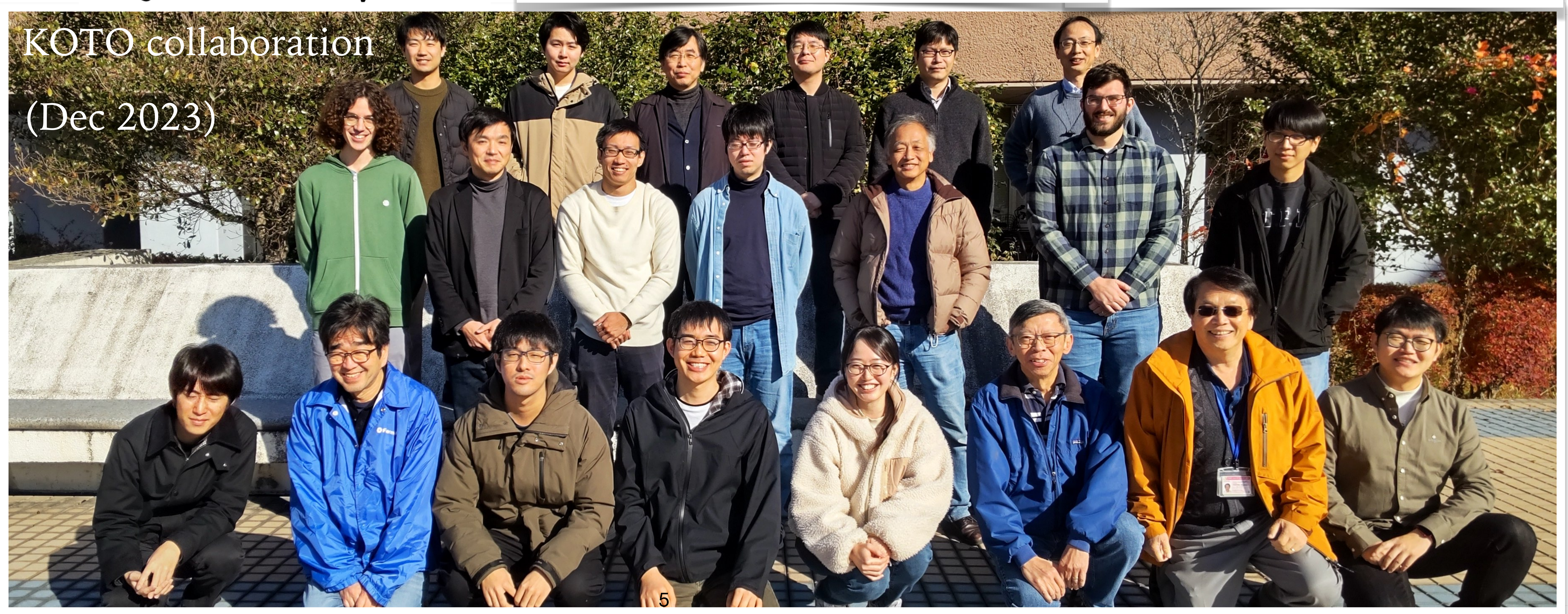
The KOTO Experiment

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

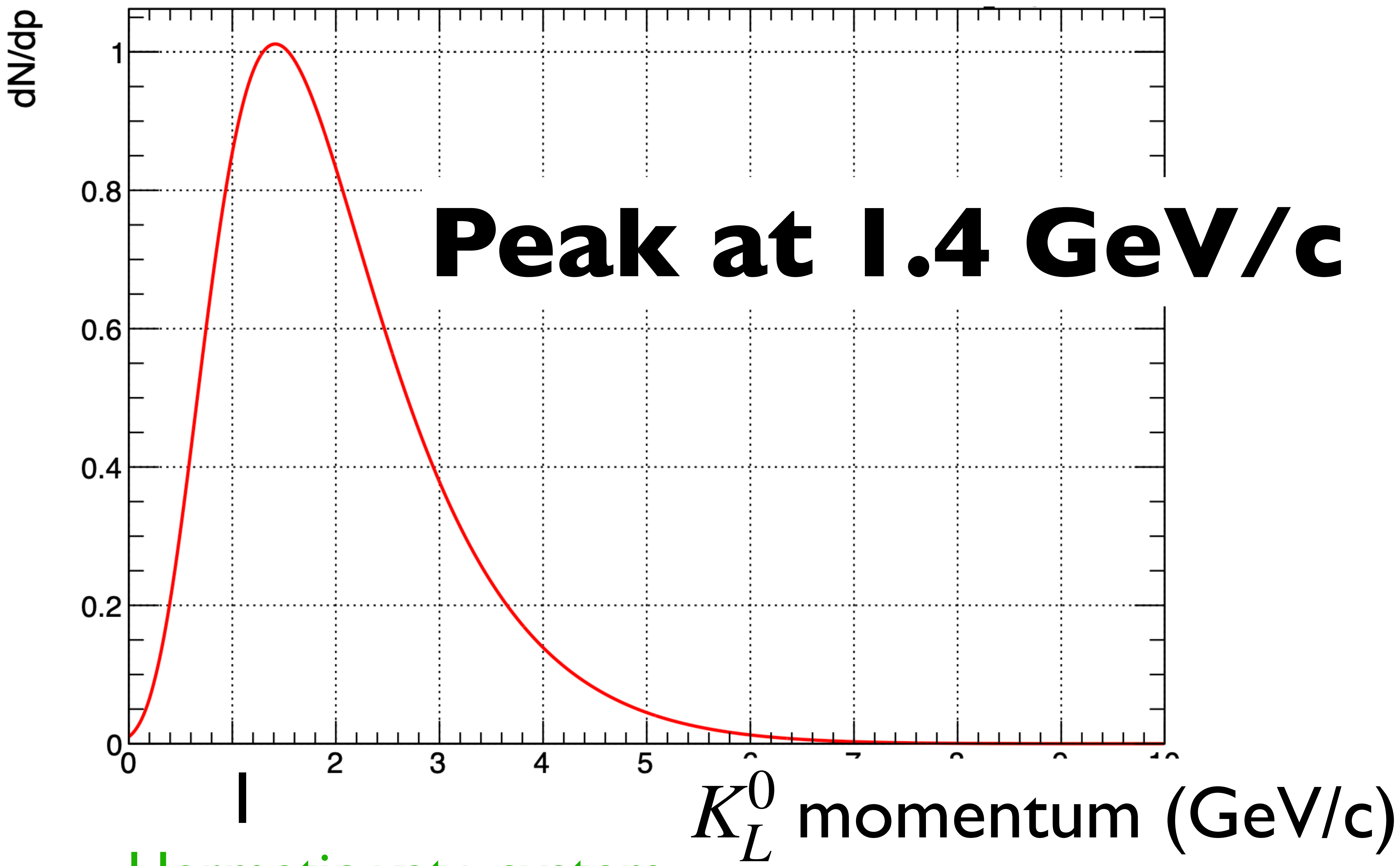


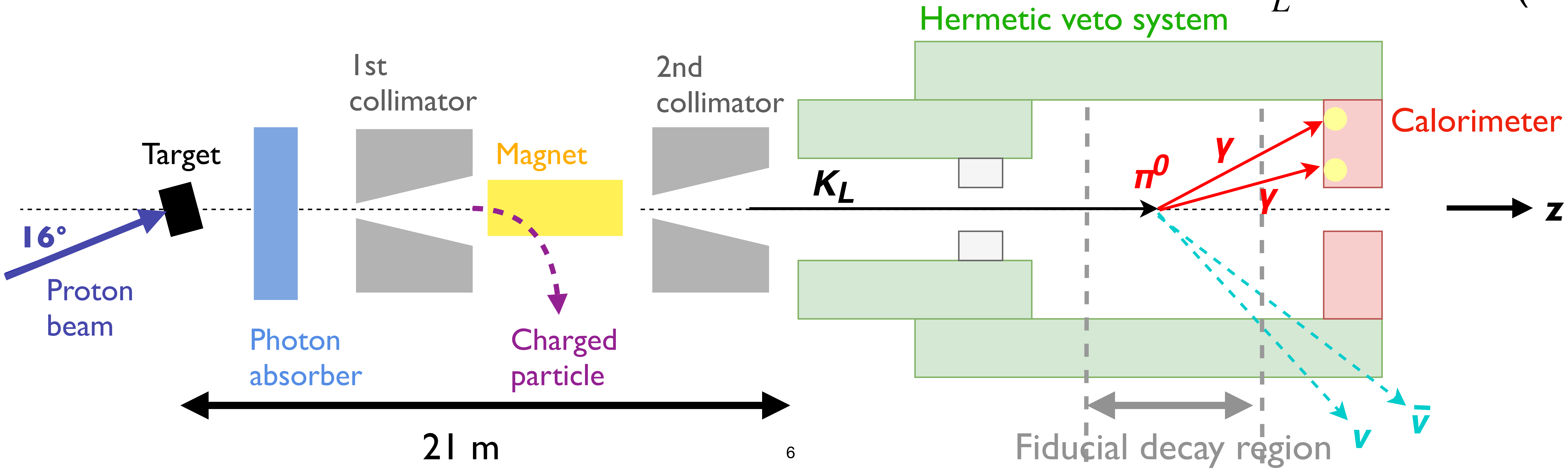




Neutral Kaon Beam

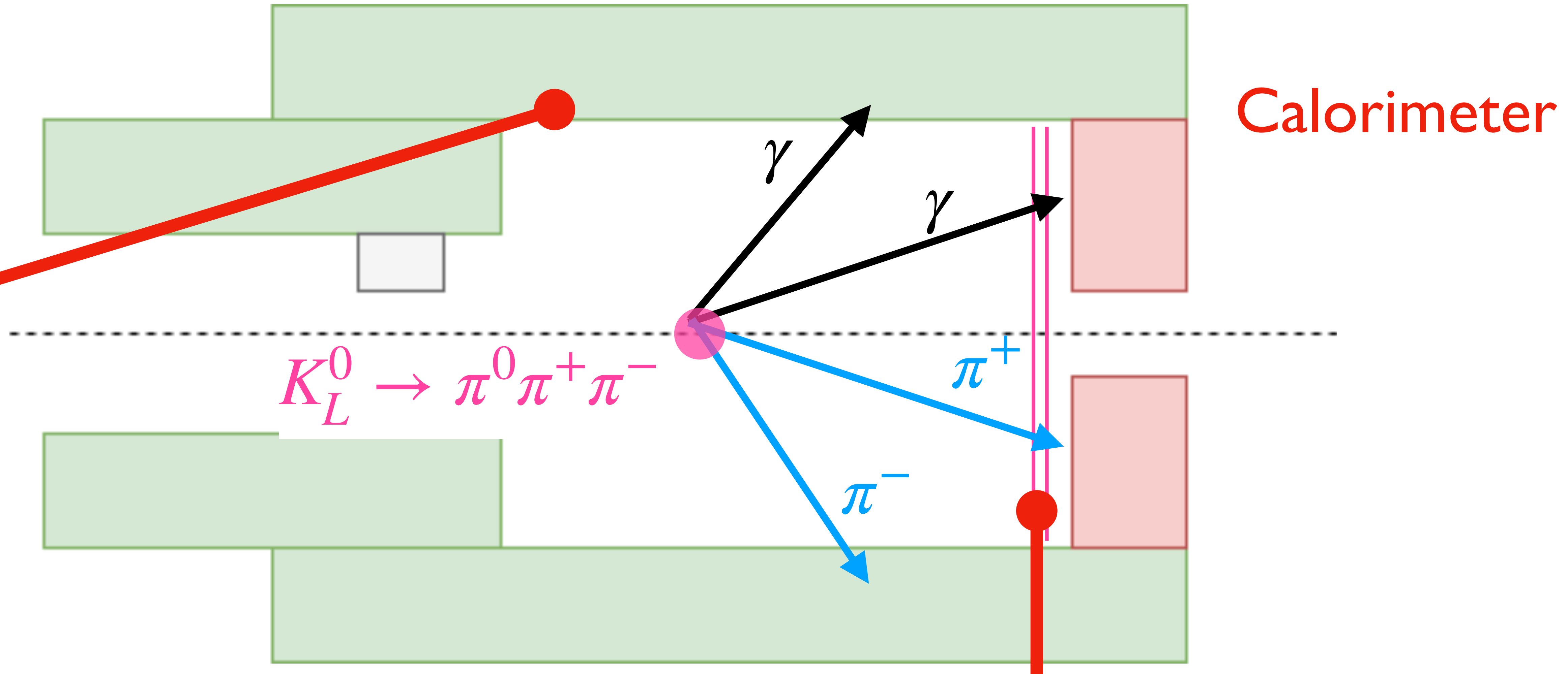
- 21-m-long beamline → Long-lived neutral particles (K_L^0, n, γ) are dominated.
- Two collimators → Sharpen the K_L^0 beam to measure the missing P_T of π^0.

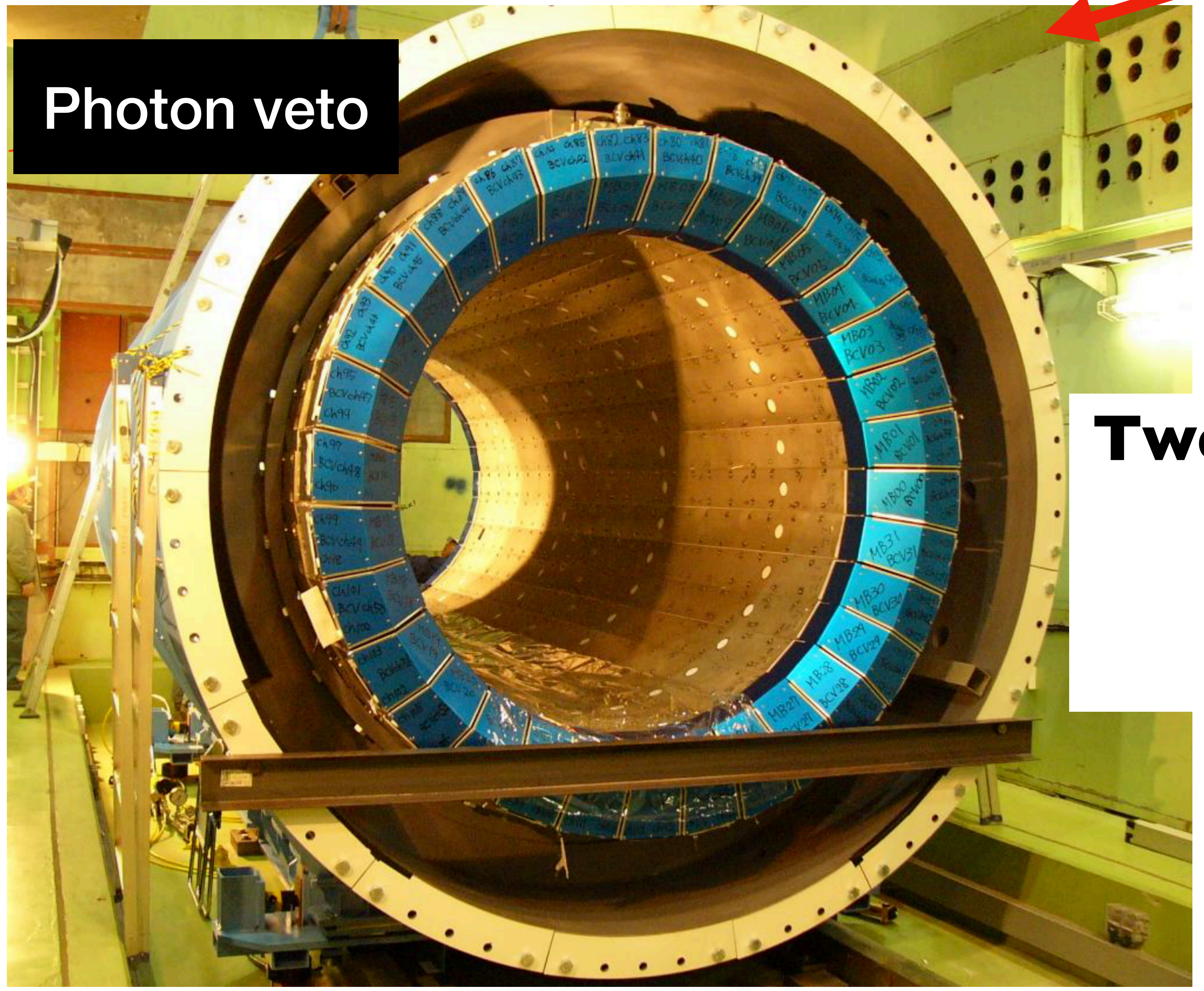




Detector Design

Hermetic veto system

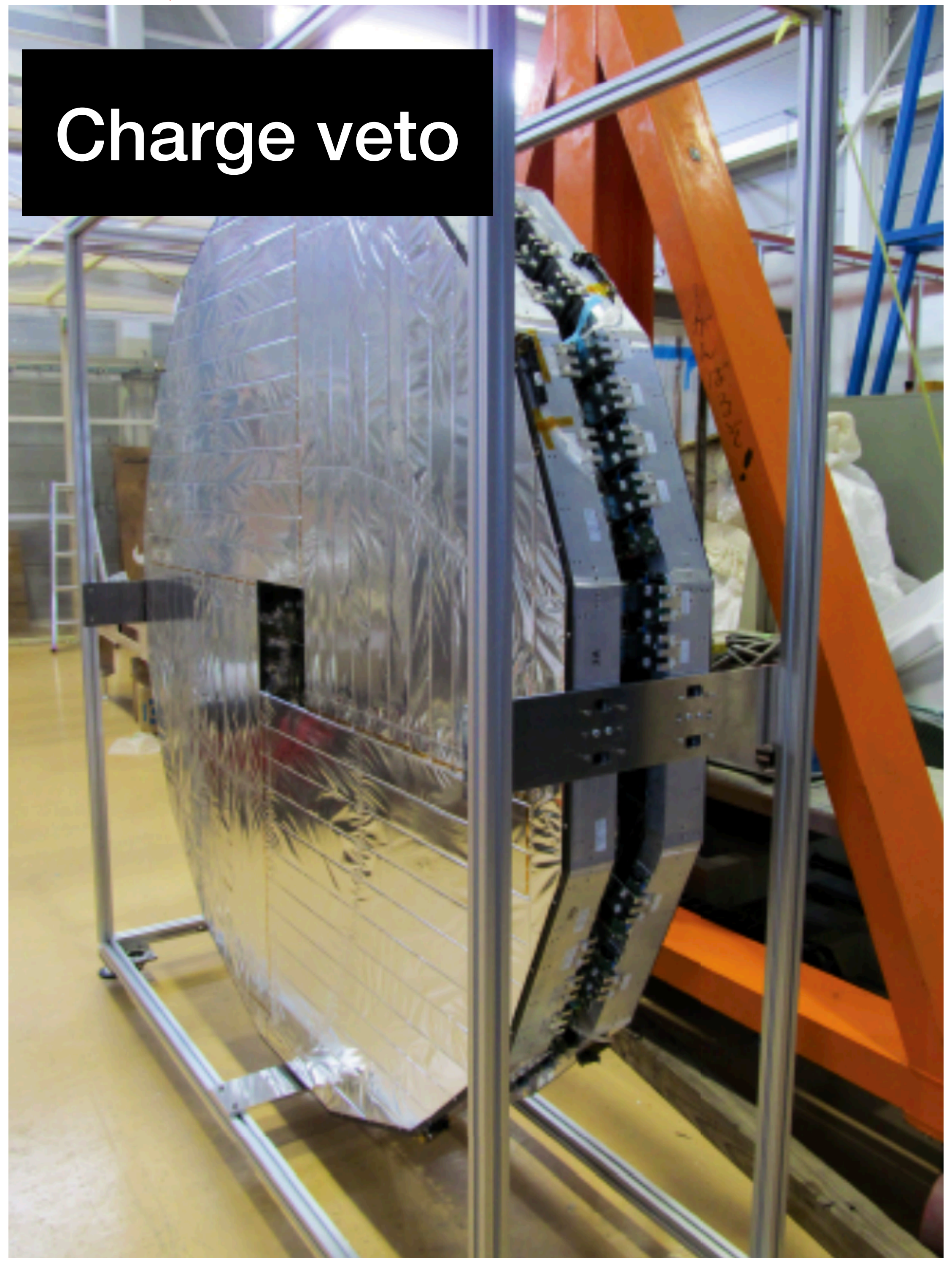




Two layers of thin plastic scintillators.

Reject charged particle hits in the calorimeter.

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



Barrel counter sandwiched by lead and scintillators.

Enclose the decay volume to maximally detect additional photons.

Thickness = 19 X_0.

Signal Identification

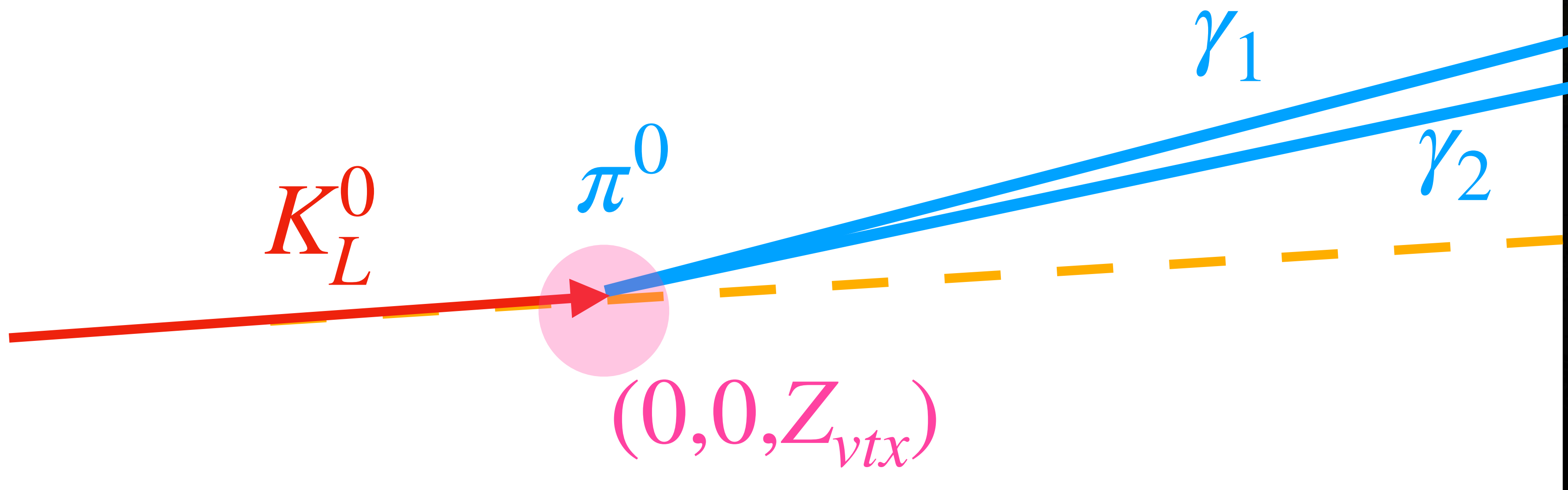
Reconstruction method

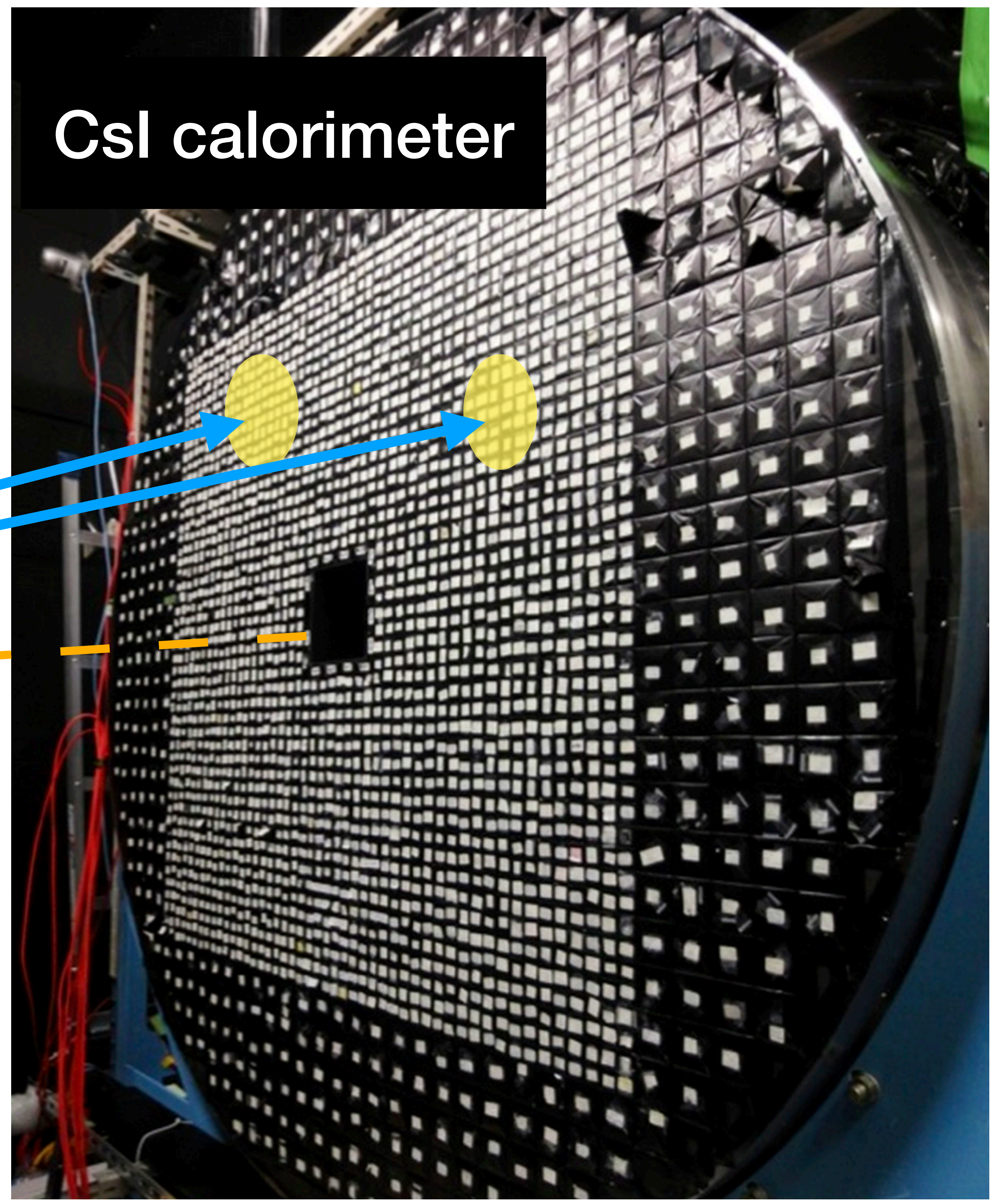
- Reconstruct decay vertex using π^0 mass constraint.

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

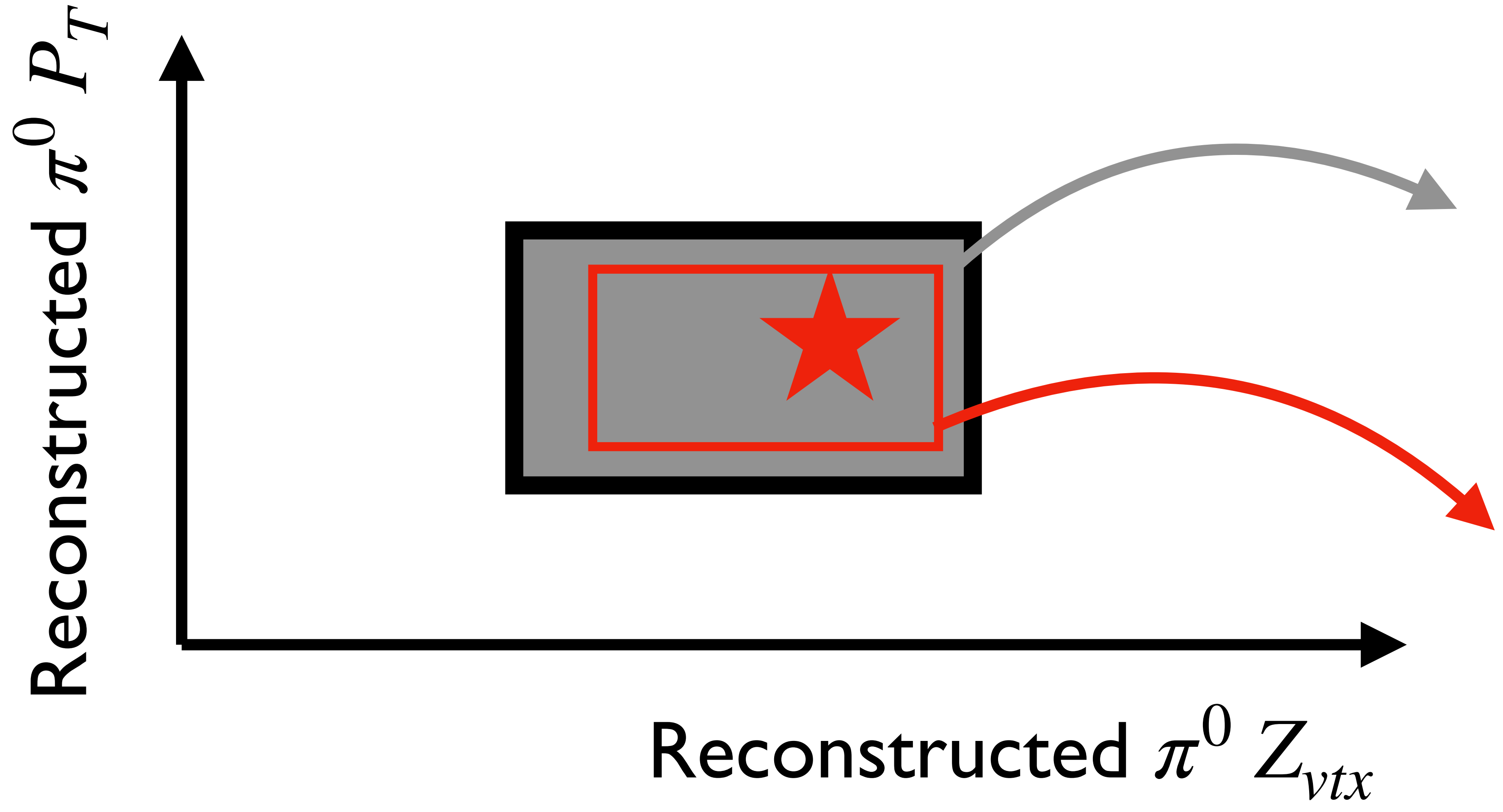
$$\uparrow$$

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





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



Blind analysis

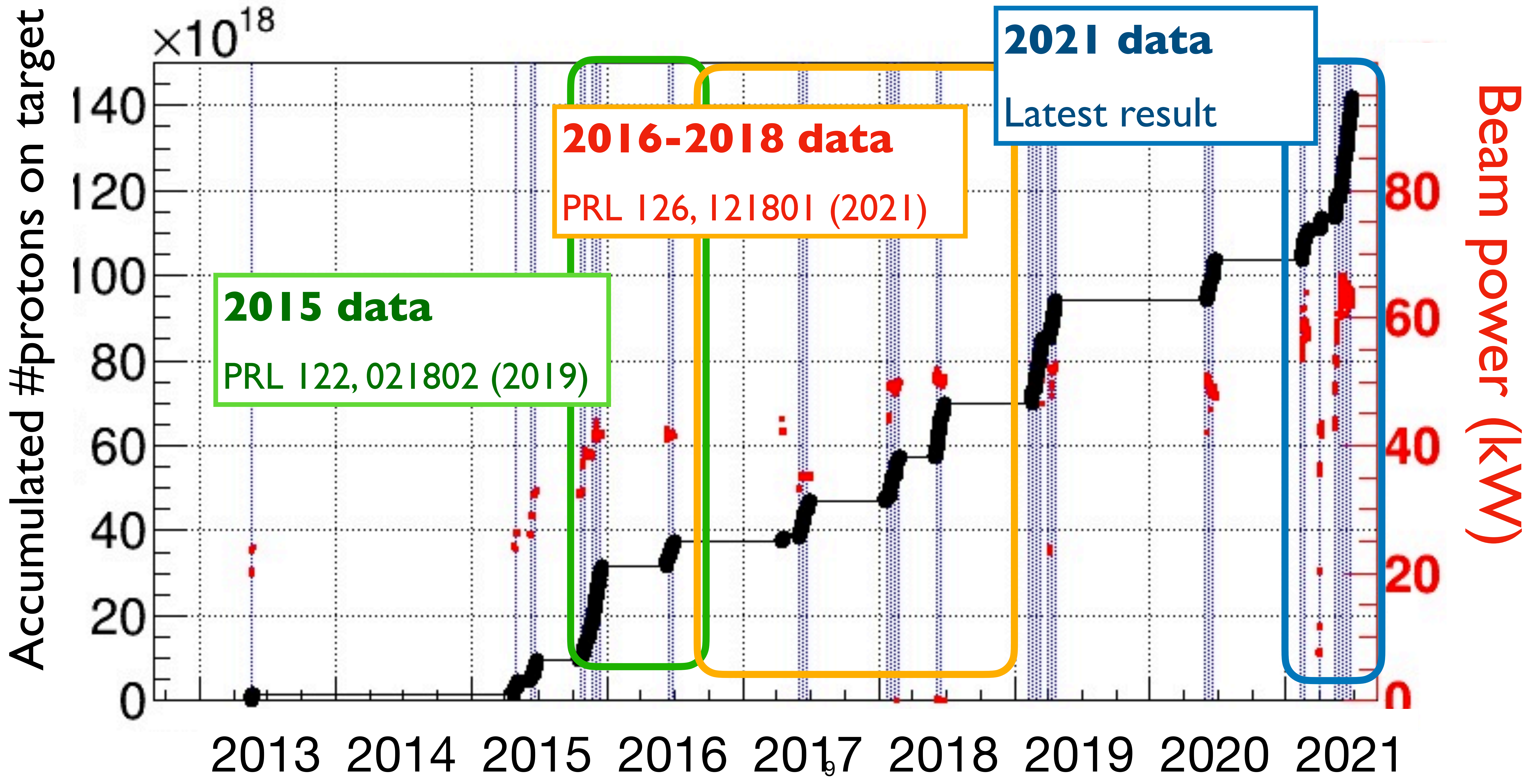
Events inside the blind region were inaccessible until the selection criteria were determined.

Signal region

Events inside this region will be identified as signal candidates.

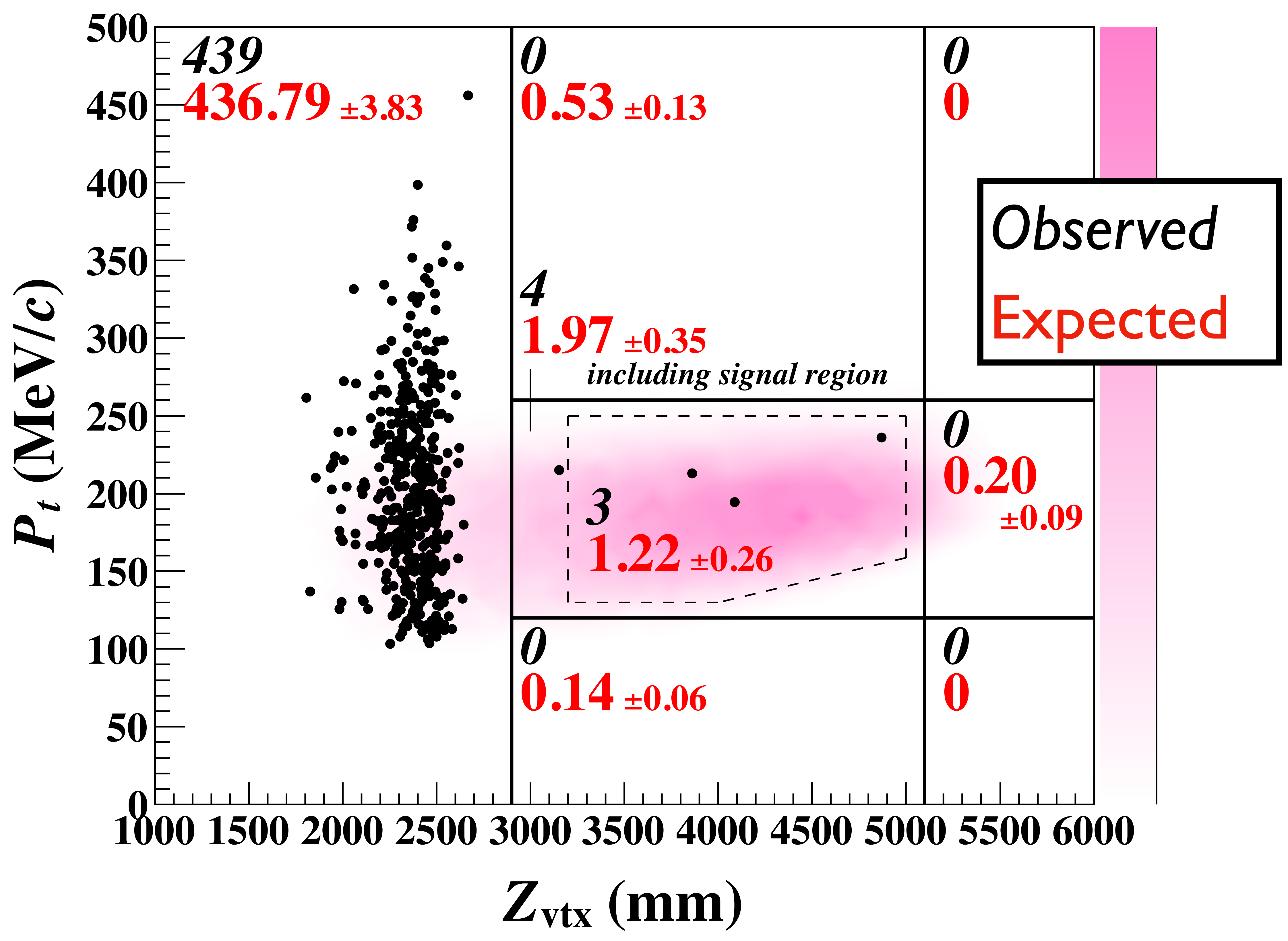
Data Collection History

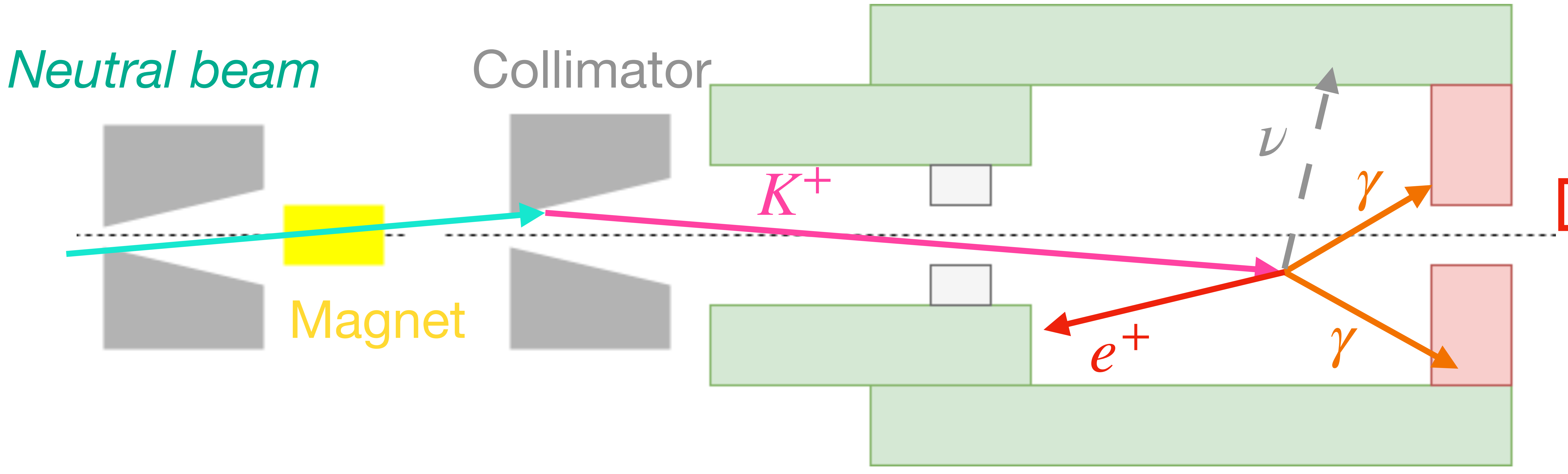
- The accumulated POT in 2021 is comparable with 2016-2018 data.



KOTO's Previous 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.)





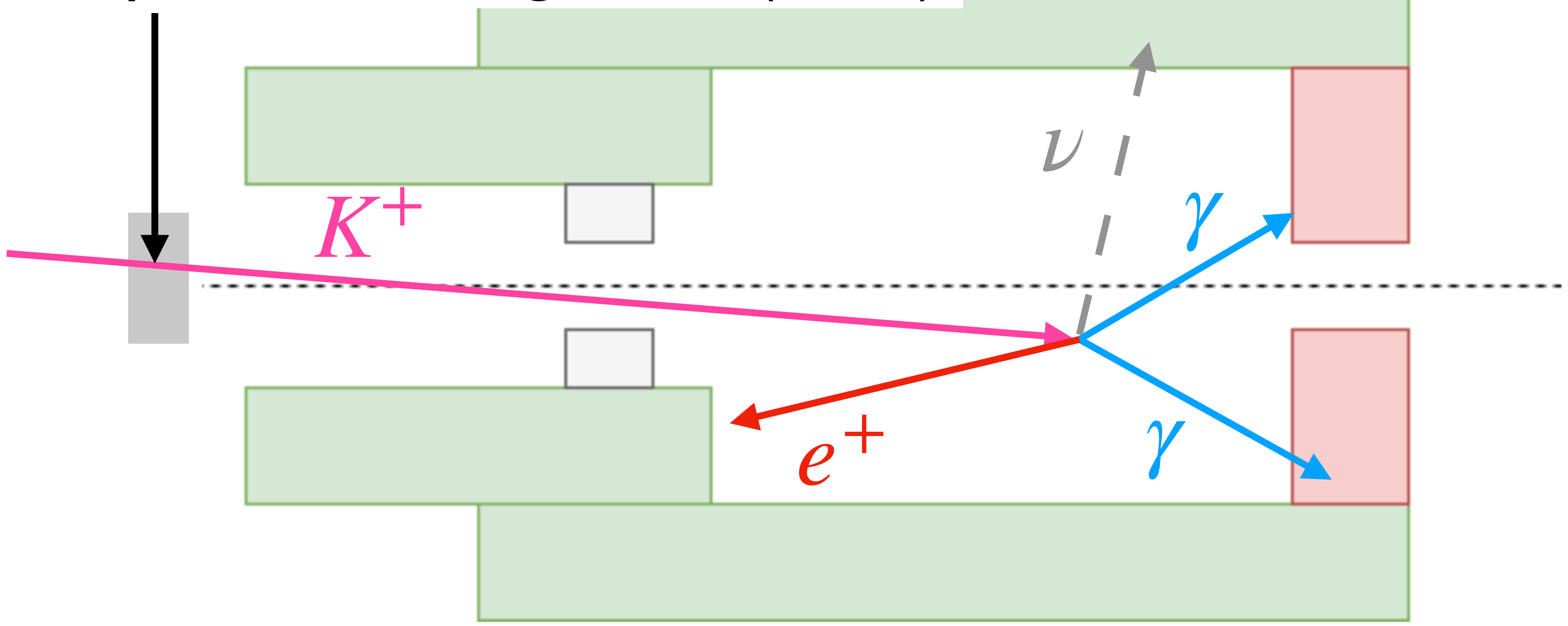
Source		Number of events
K_L	$K_L \to 3\pi^0$	0.01 ± 0.01
	$K_L \to 2\gamma$ (beam halo)	0.26 ± 0.07[a]
	Other K_L decays	0.005 ± 0.005
$K^\pm$		0.87 ± 0.25[a]
Neutron	Hadron cluster	0.017 ± 0.002
	CV η	0.03 ± 0.01
	Upstream π^0	0.03 ± 0.03
Total		1.22 ± 0.26

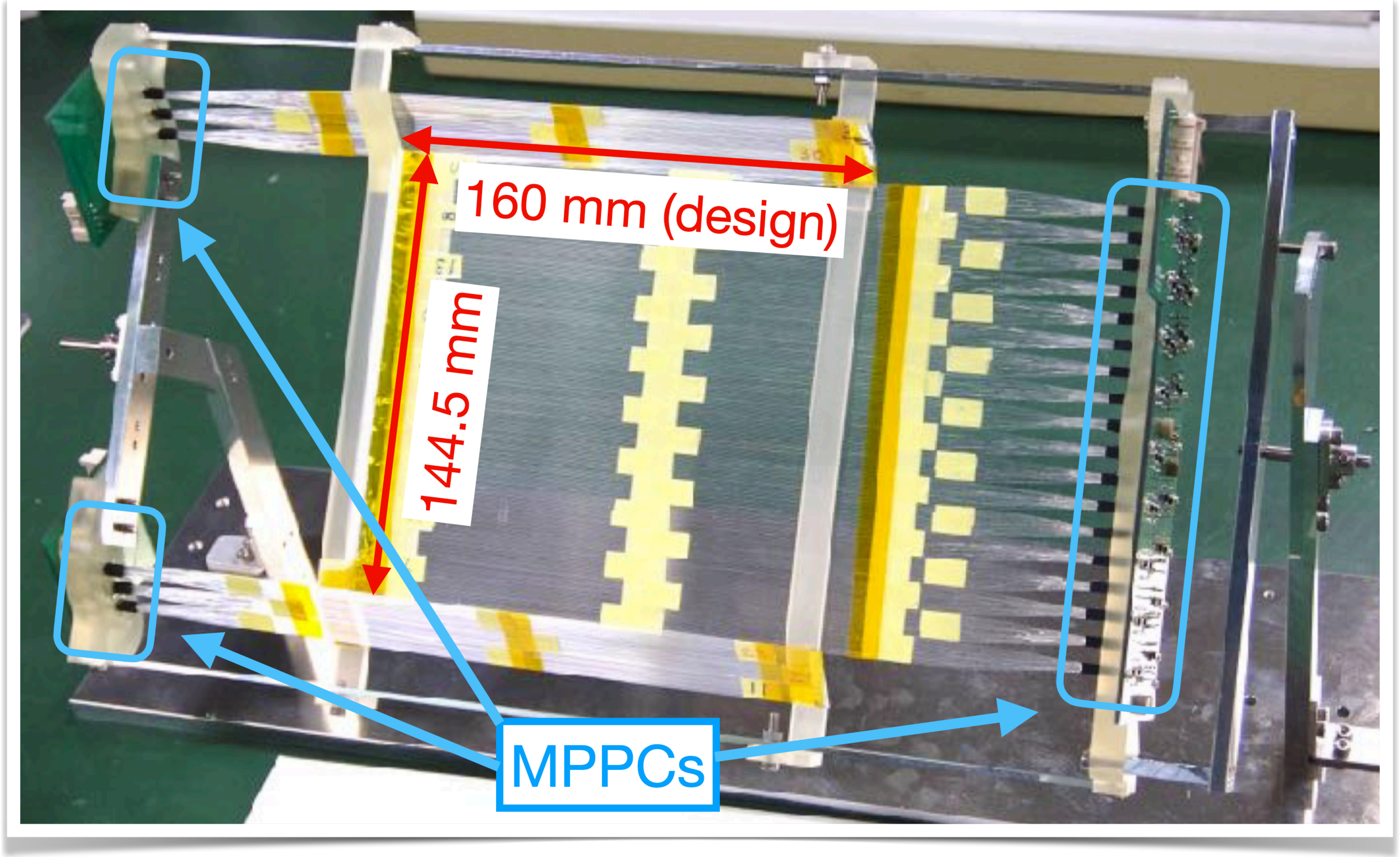
[a]Background sources studied after looking inside the blind region.

K^+ Background Reduction

- 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.

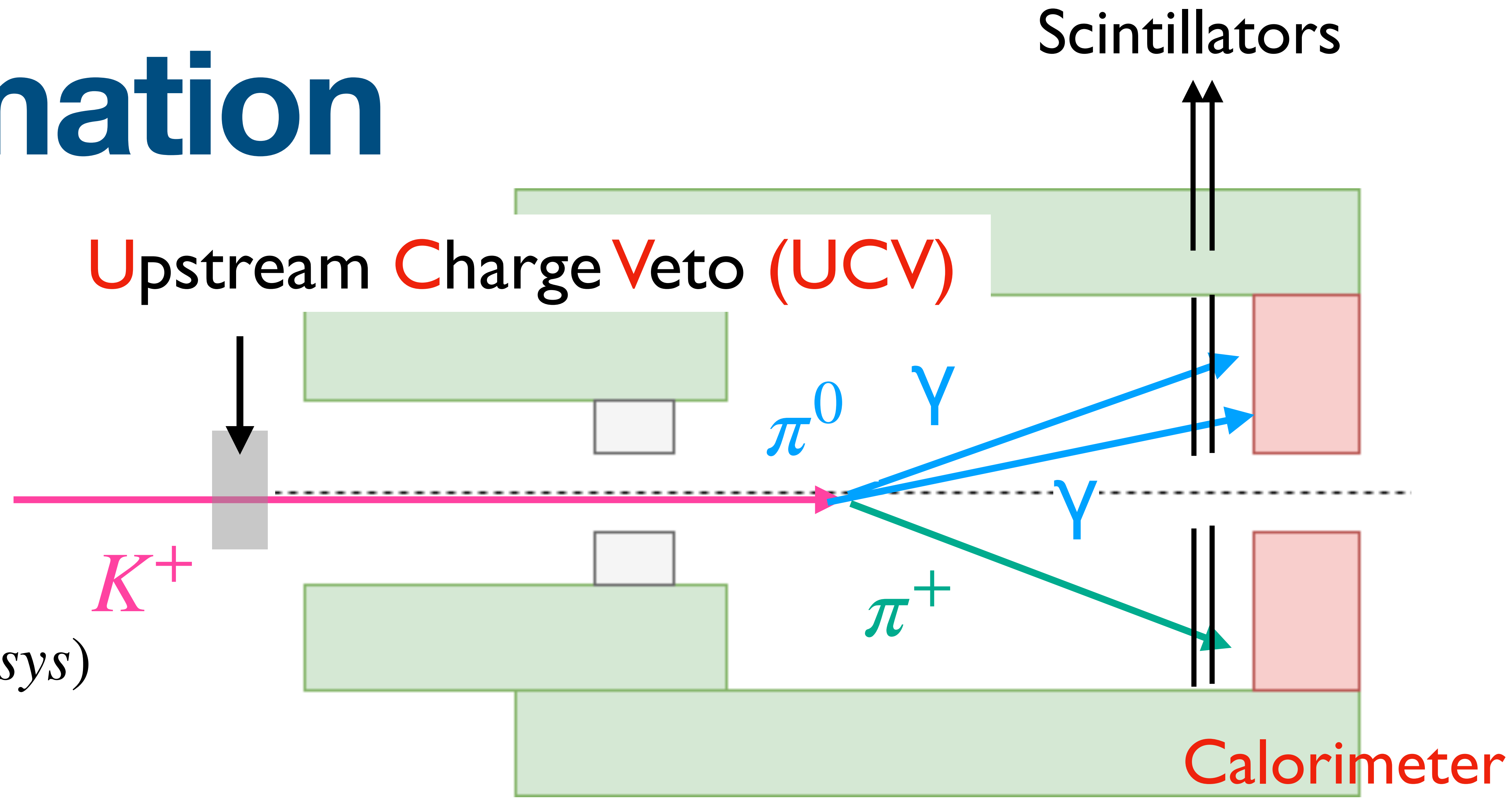
Upstream Charge Veto (UCV)

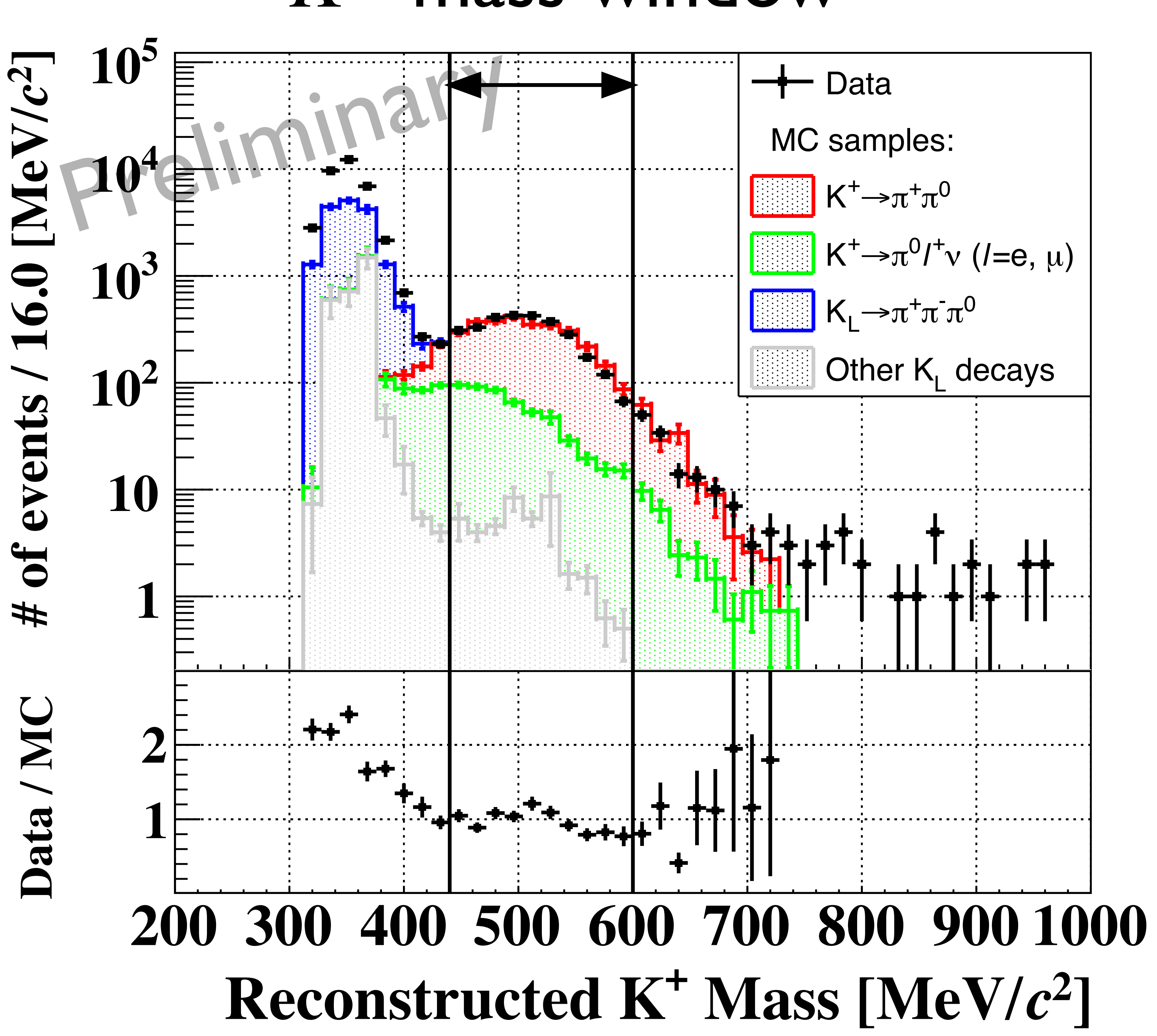


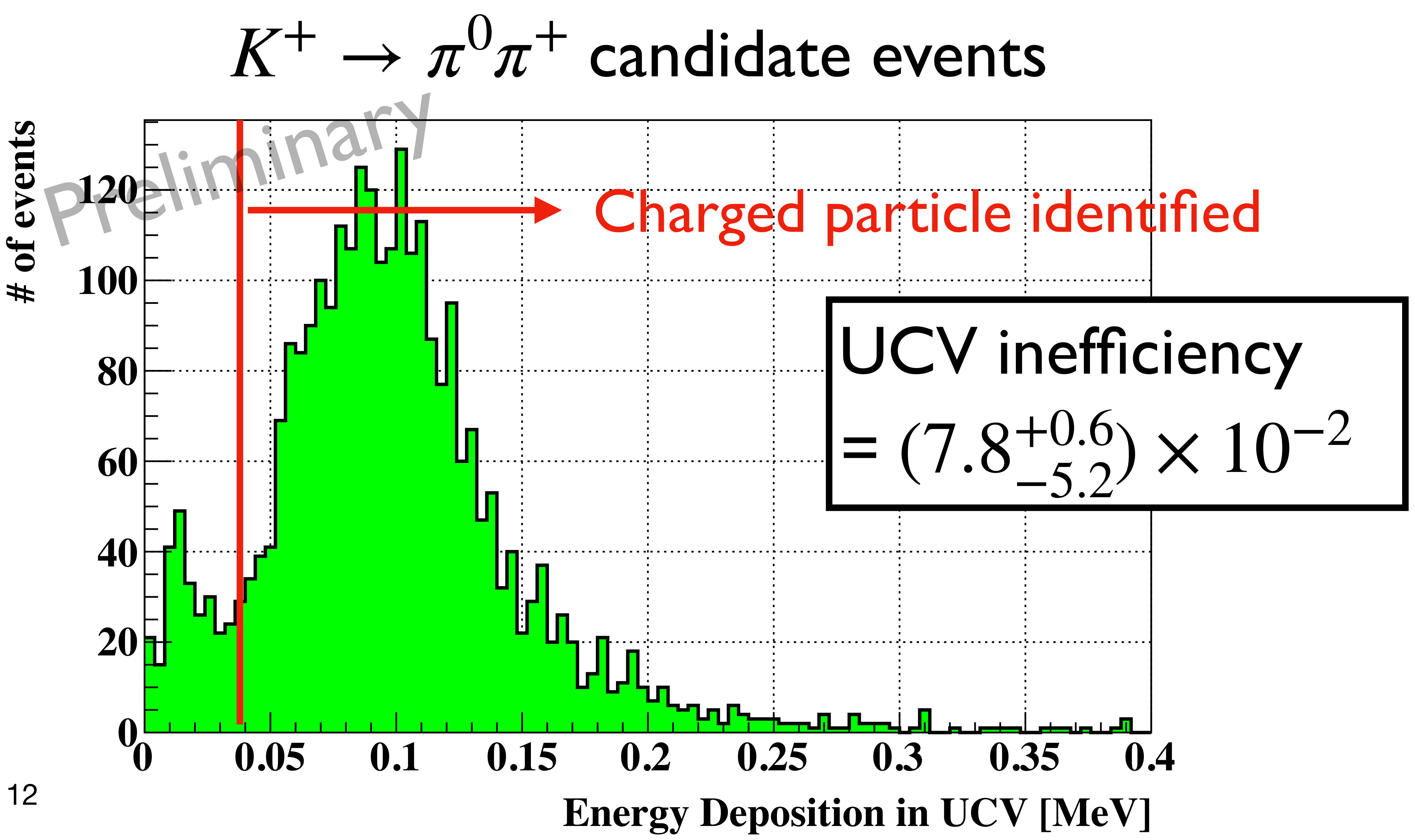


N(K^+ Background) Estimation

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

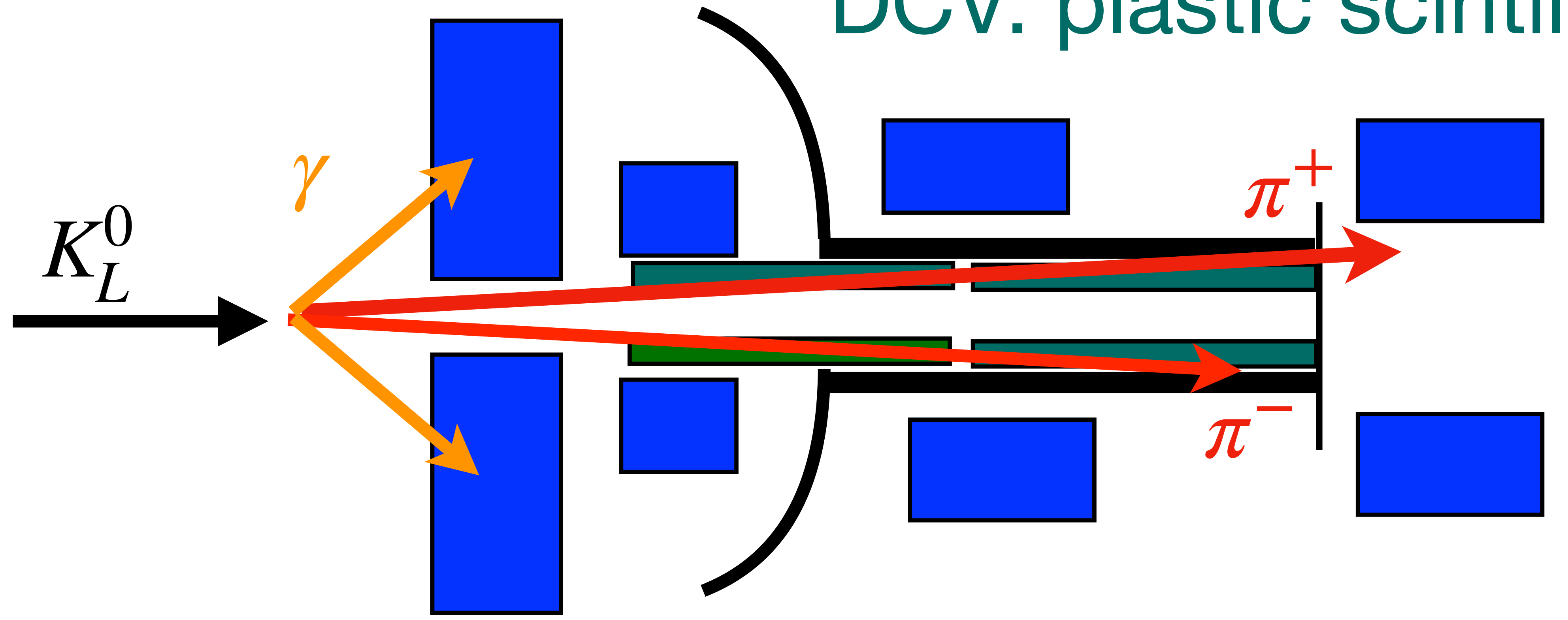




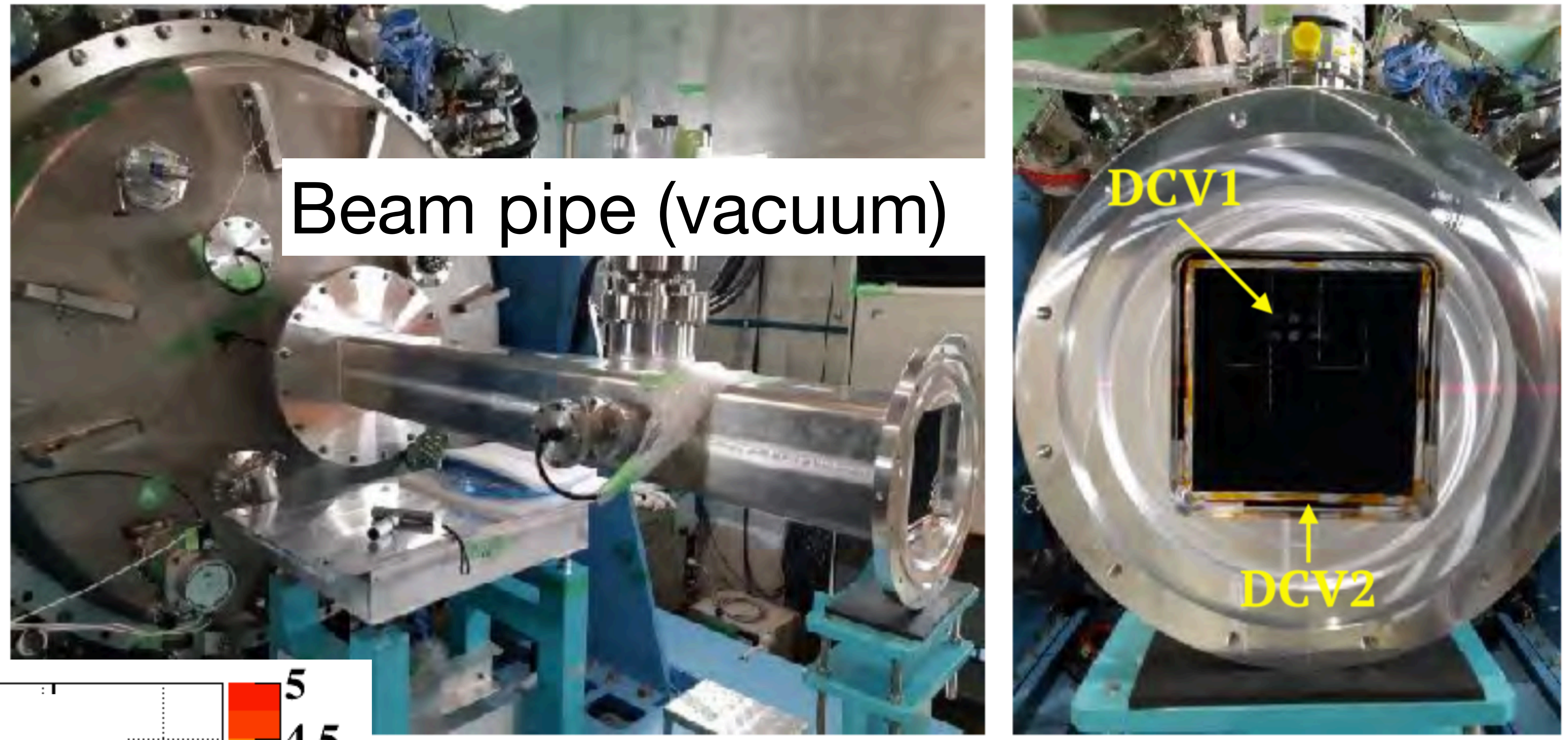


$K_L^0 \to \pi^0\pi^+\pi^-$ Background Reduction

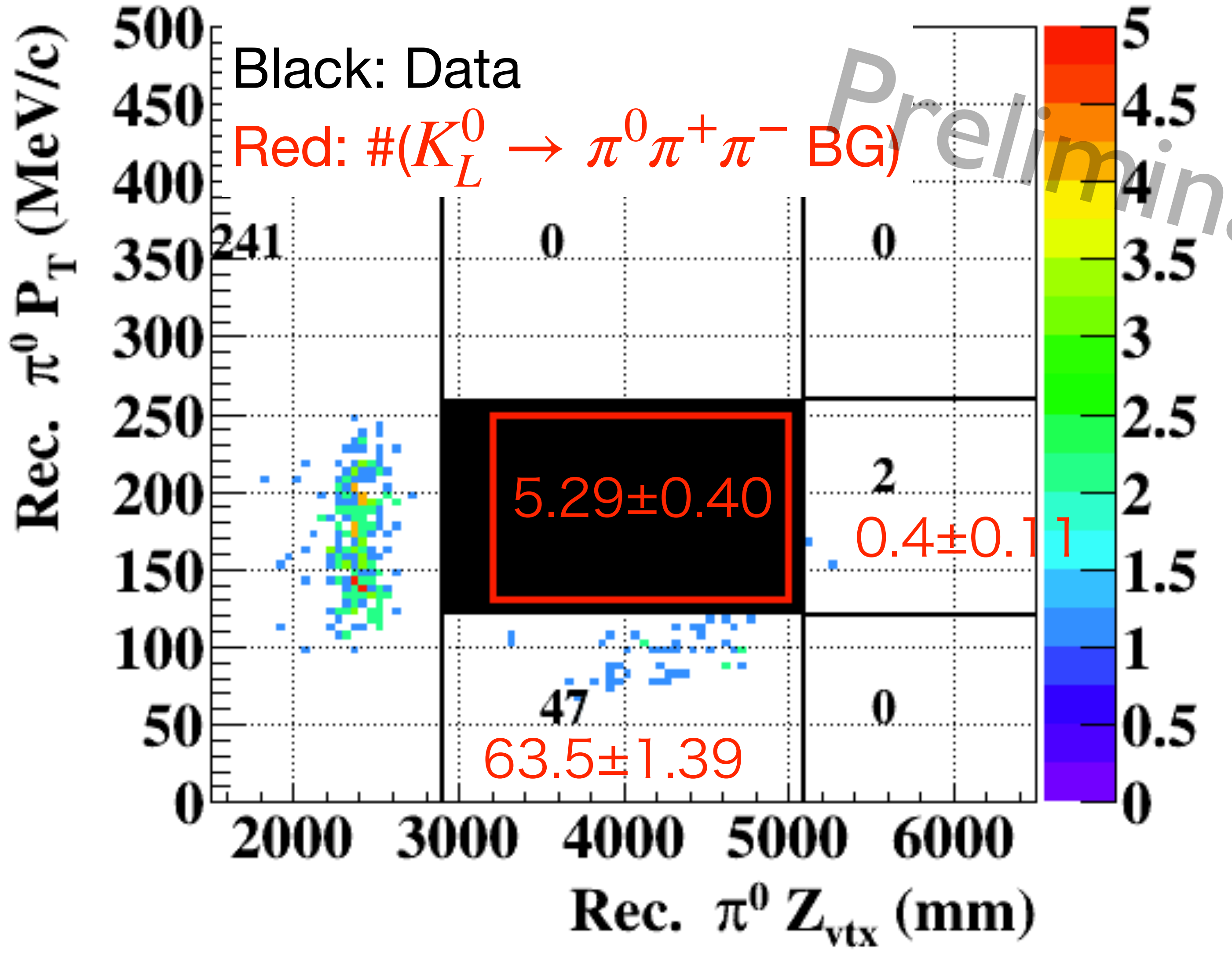
DCV: plastic scintillators on the inner surface of the beam pipe.



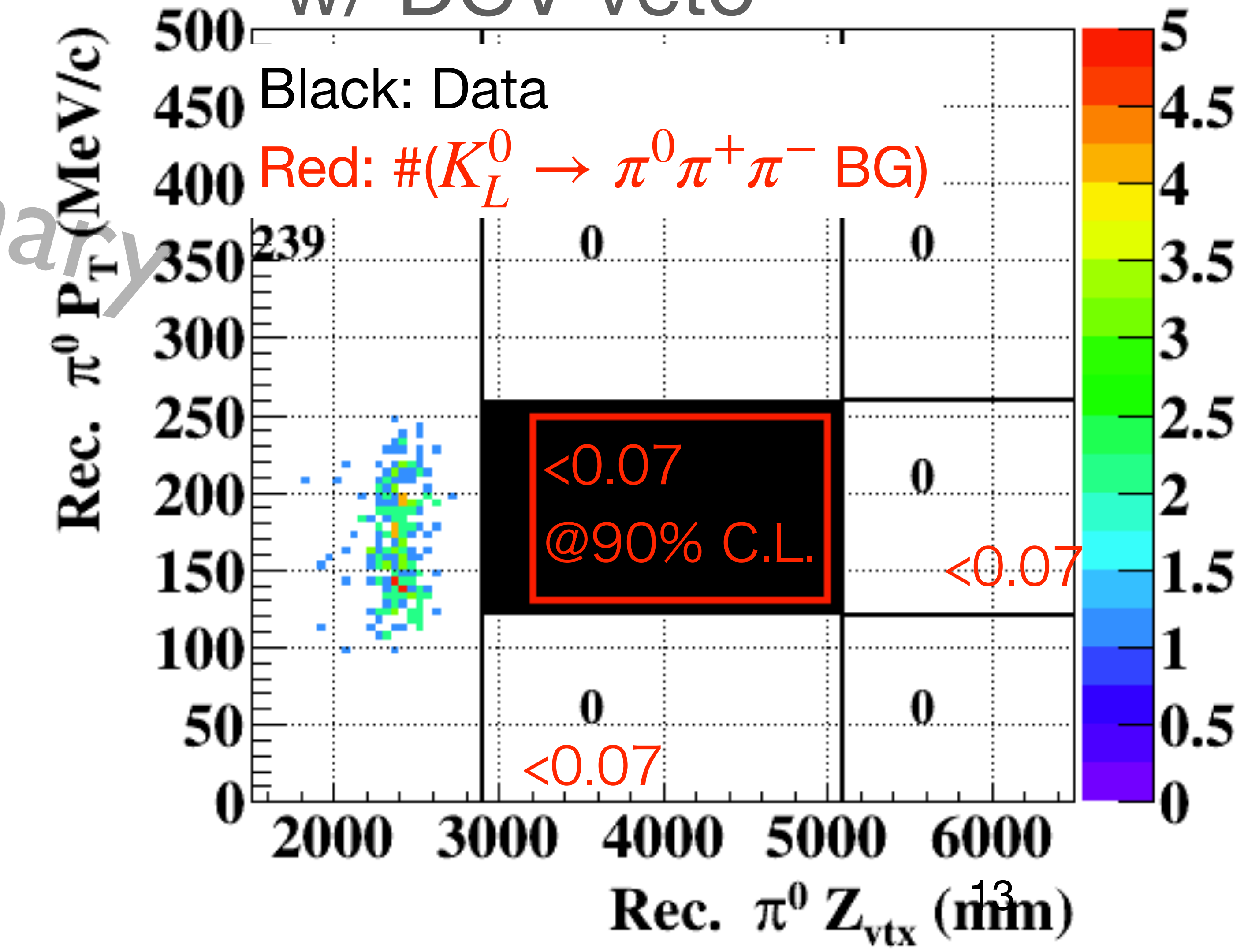
Calorimeter



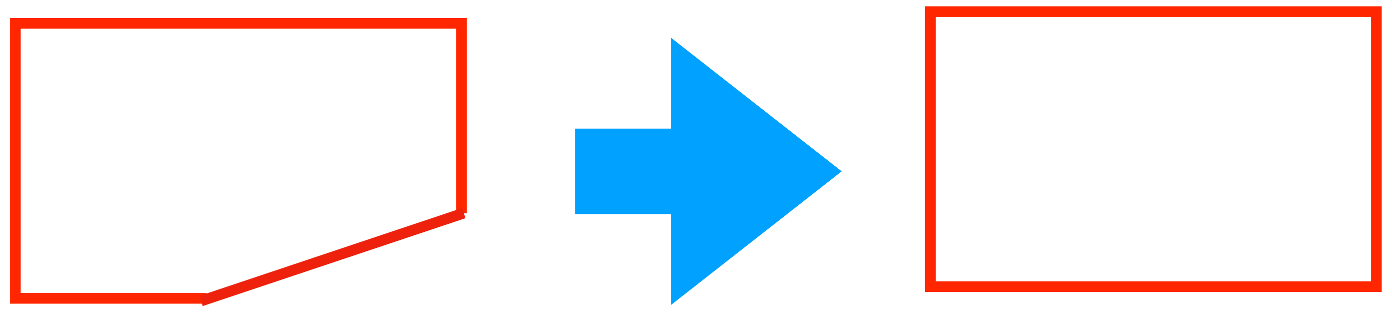
w/o DCV veto



w/ DCV veto



2016-2018 signal box 2021 signal box



The edge was cut to reduce the $K_L^0 \to \pi^0\pi^+\pi^-$ background.

Single Event Sensitivity Estimation

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 $K_L^0 \to \pi^0\pi^0$

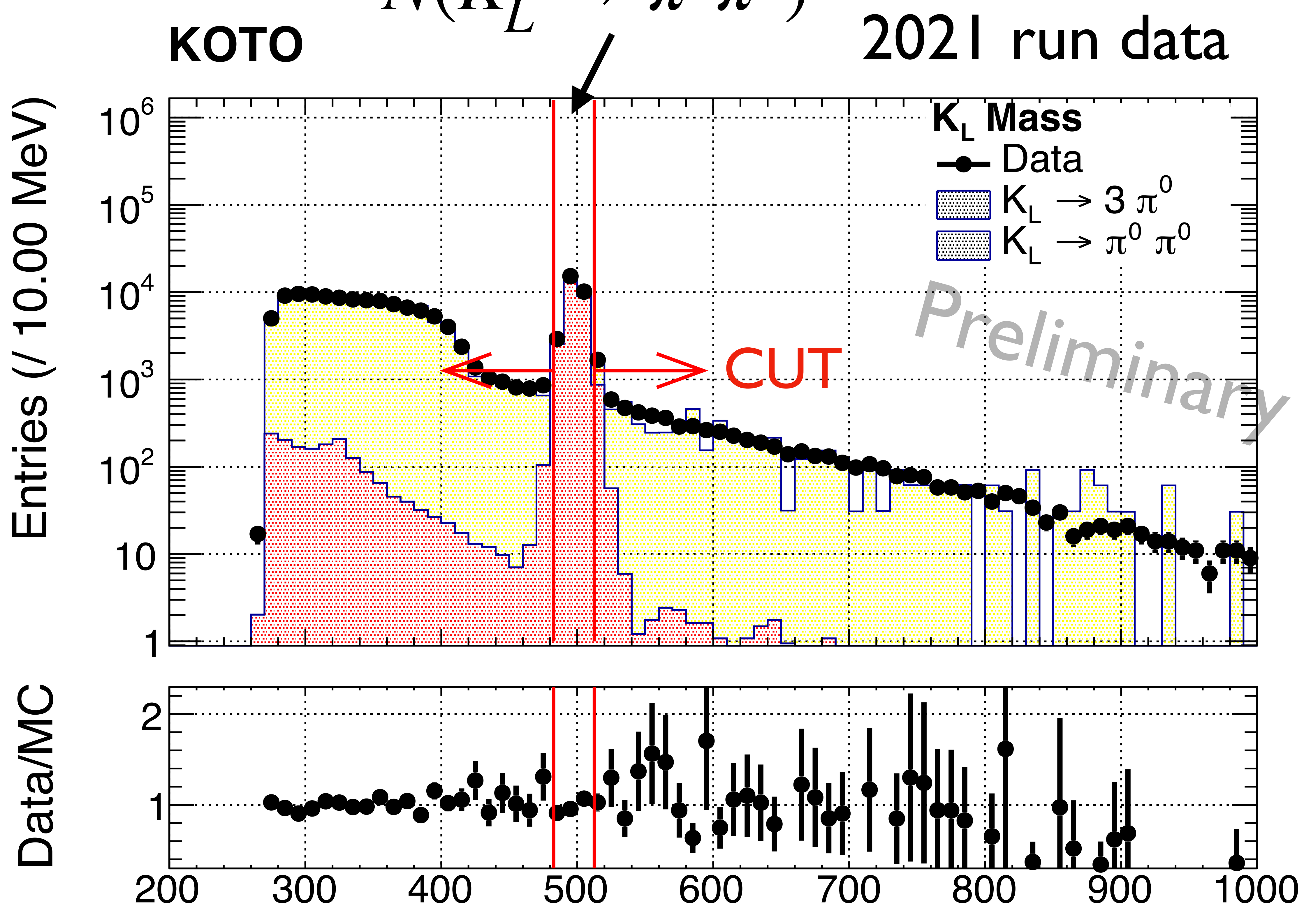
Acceptance evaluated by MC

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

From PDG

(at the entrance of the KOTO detector.)

$N(K_L^0 \to \pi^0\pi^0)$



Summary of the 2021 Data Analysis

- $SES = 8.7 \times 10^{-10}$

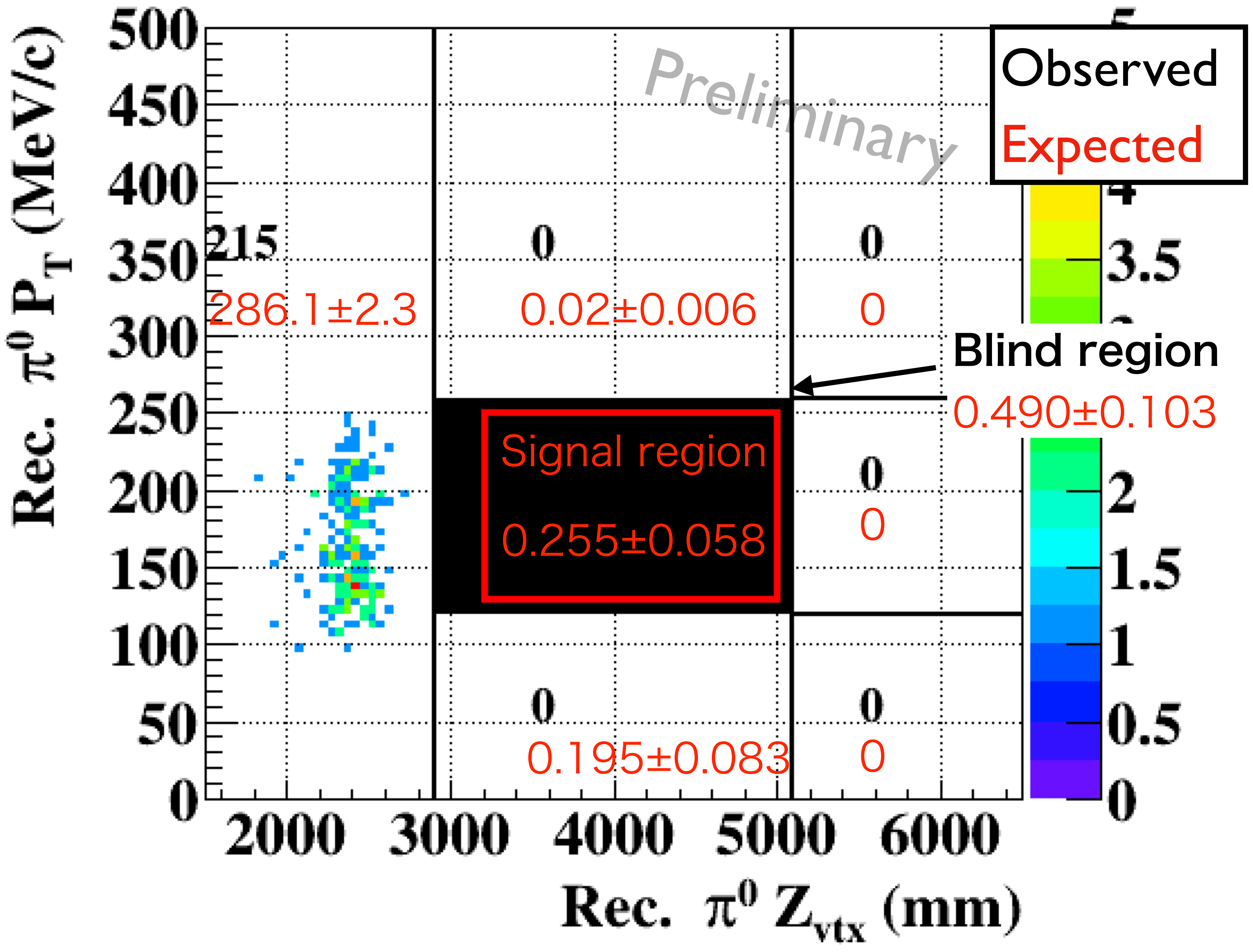
  2016-2018 data: $SES = 7.2 \times 10^{-10}$

- N(background) = 0.255 ± 0.058

  2016-2018 data N(background) = 1.23 ± 0.26

Major sources	Estimation
Upstream π^0	$0.064 \pm 0.050_{(stat)} \pm 0.006_{(syst)}$
$K_L \to \pi^0\pi^0$	$0.060 \pm 0.022_{(stat)}{}^{+0.051}_{-0.060}\ (sys)$
K^+	$0.043 \pm 0.015_{(stat)}{}^{+0.004}_{-0.030}\ (sys)$

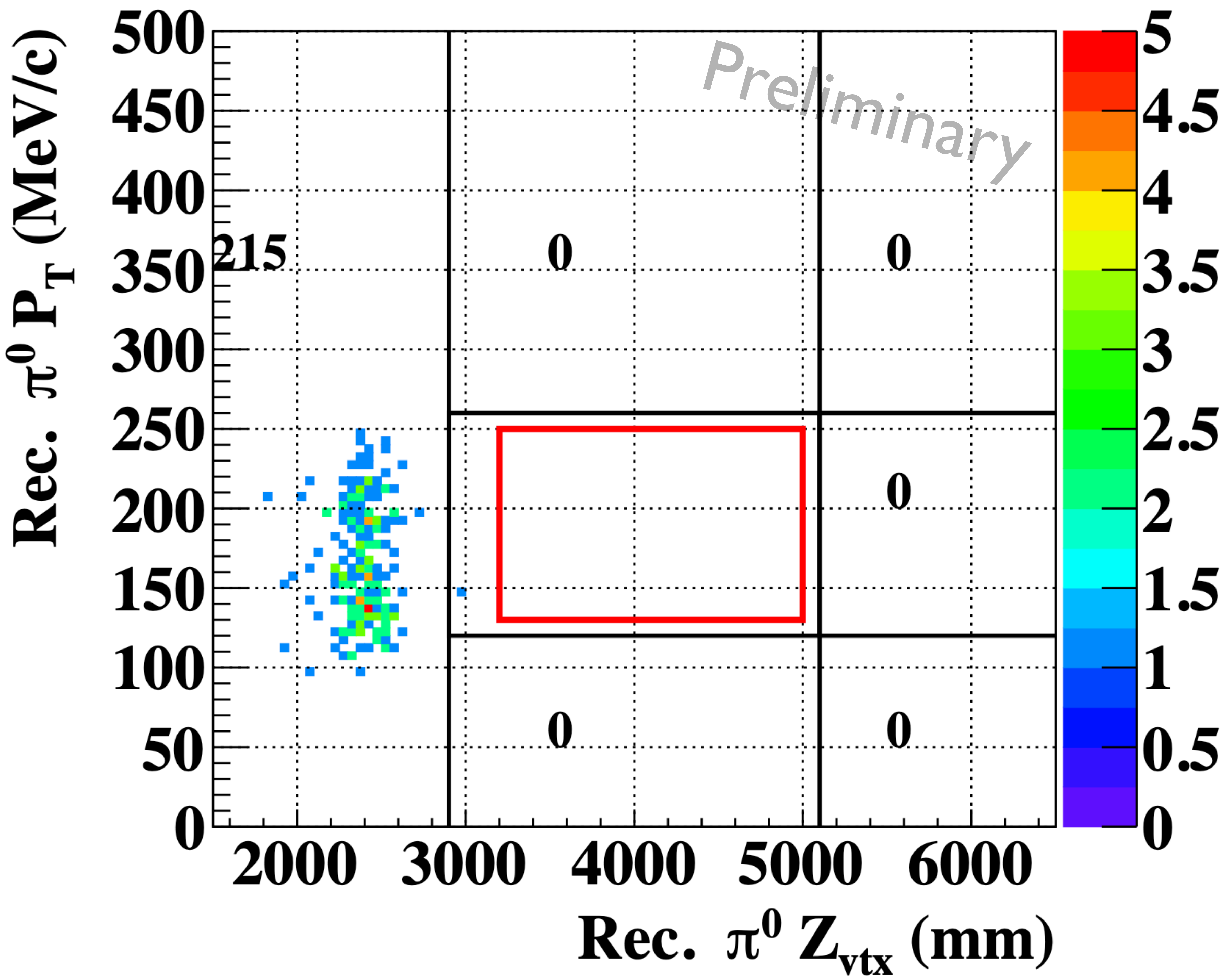
Signal-to-noise ratio is improved by a factor of 5.



Result of the 2021 Run Data

- No signal candidate was observed.
- This sets an upper limit of $B(K_L^0 \to \pi^0 \nu \overline{\nu}) < 2.0 \times 10^{-9}$ (90% C.L.)

Preliminary

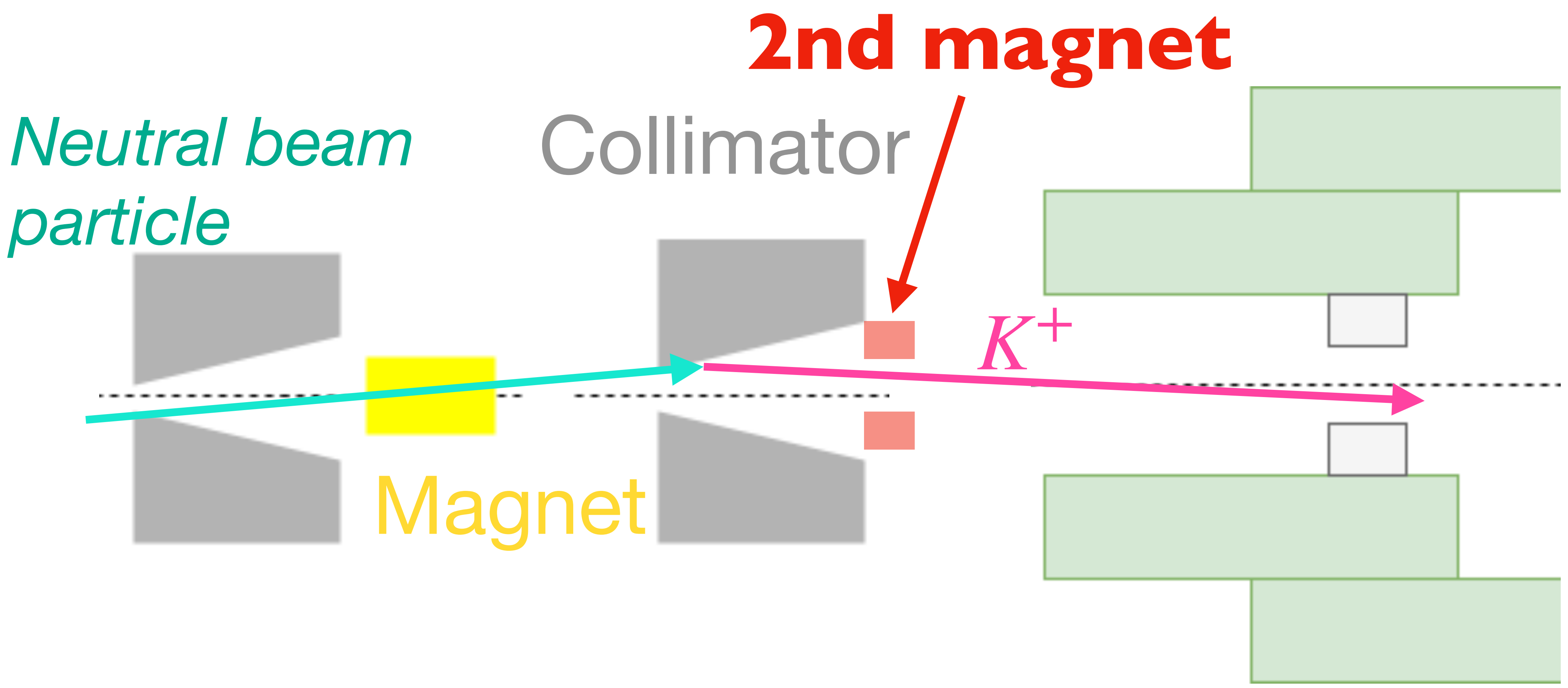


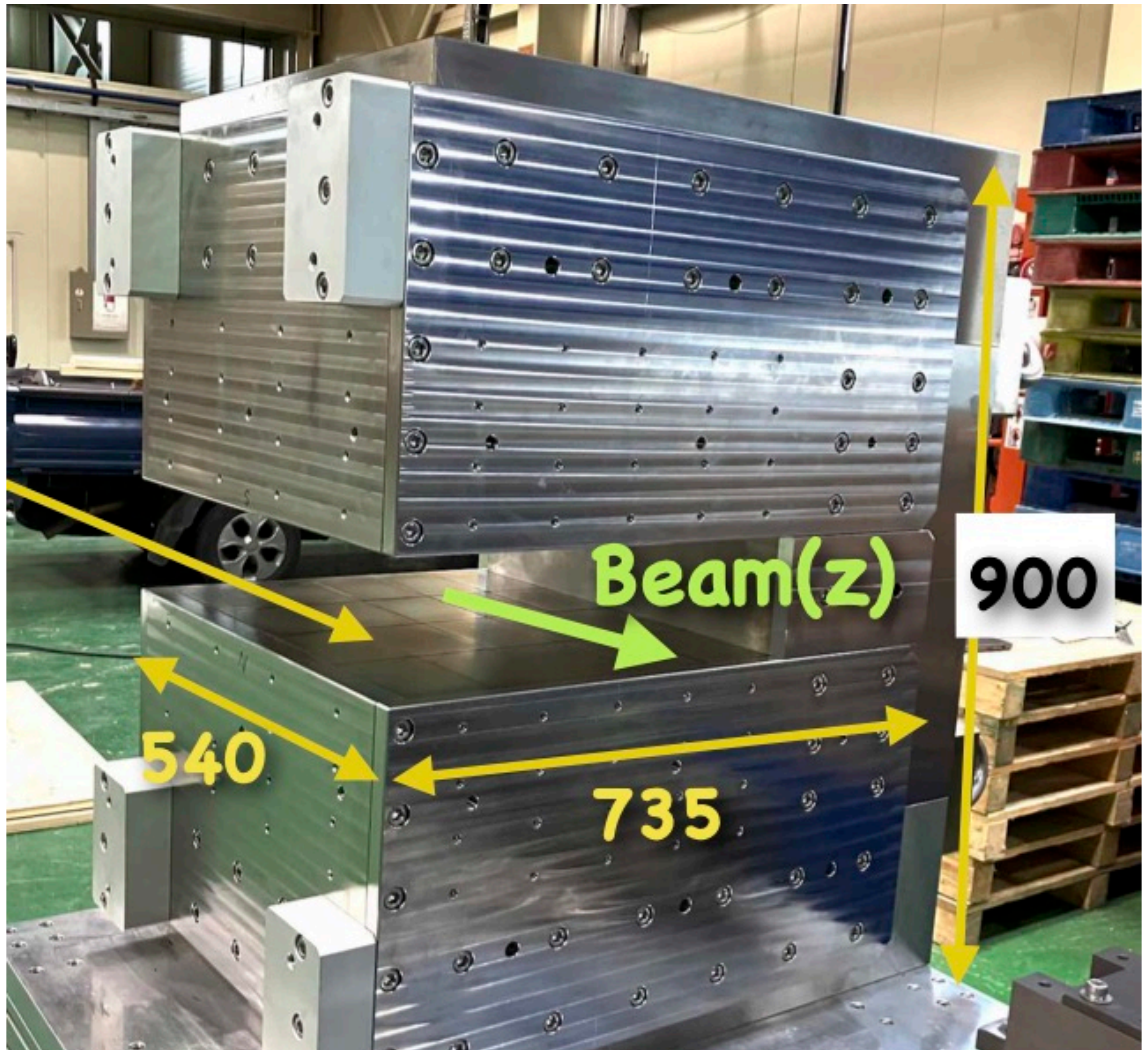
Major Detector Upgrades

Further Suppression against the K^+ Background

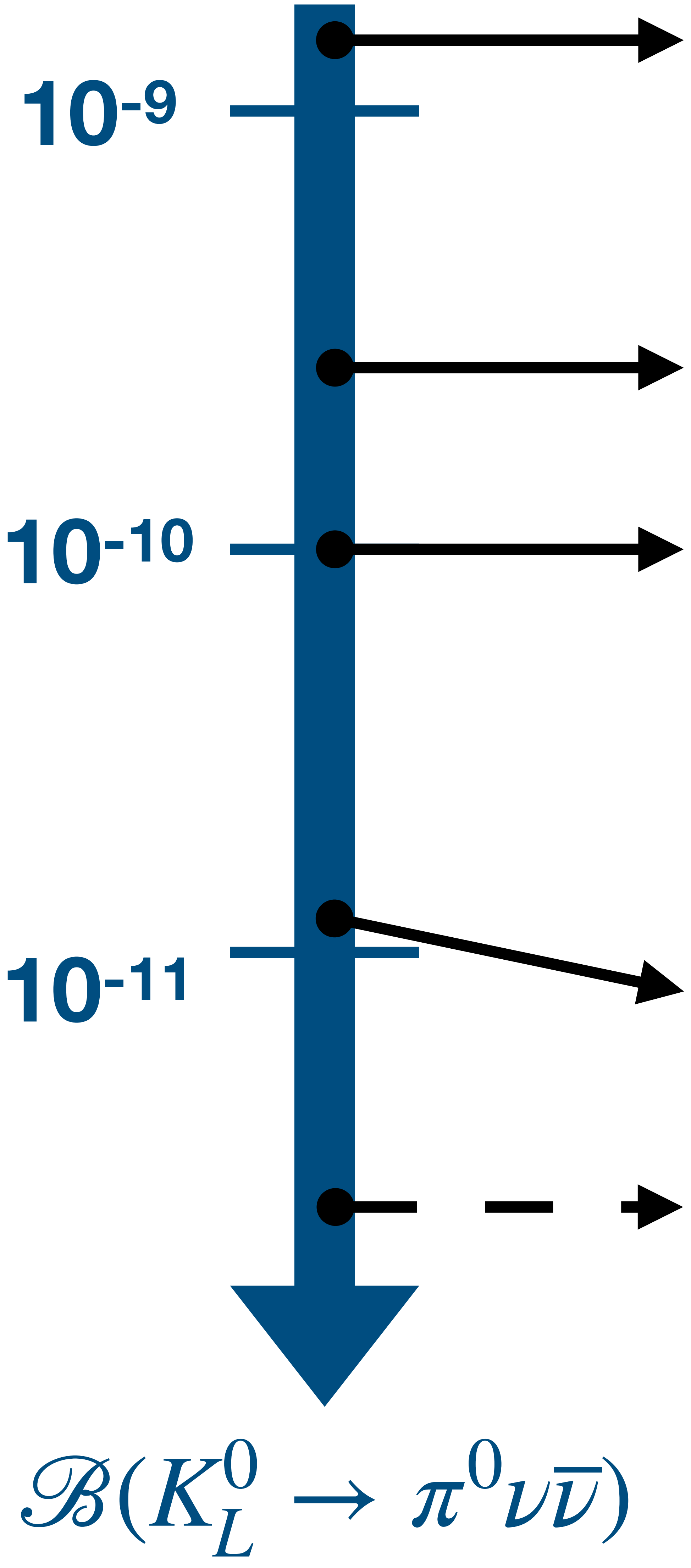
Permanent magnet (B = 0.98T at center)

- An extra magnet was installed at the downstream end of the 2nd collimator in summer 2023.
- The K^+ flux is expected to be suppressed by another order of magnitude.





Roadmap of $K_L^0 \to \pi^0 \nu \bar{\nu}$ Search



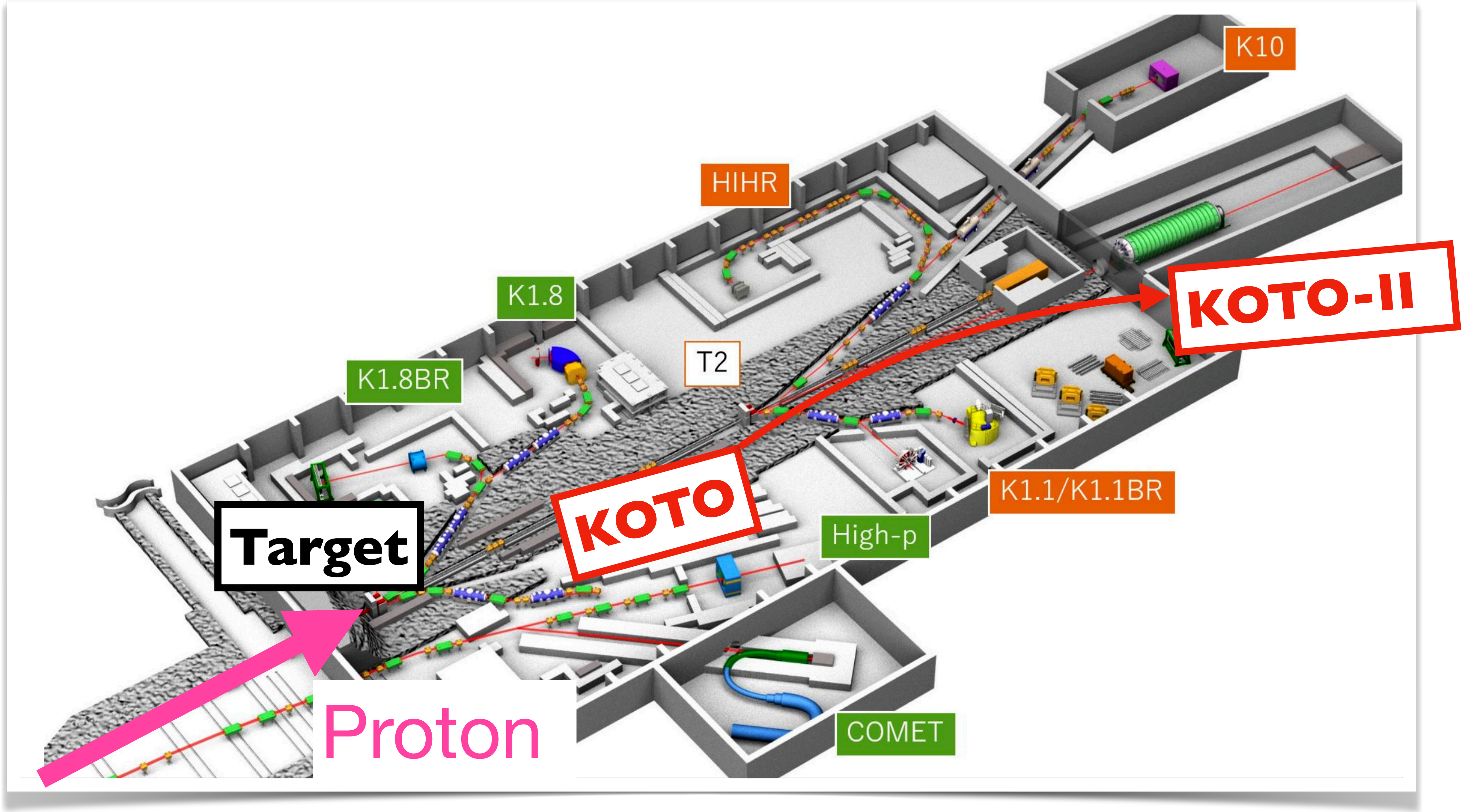
- **KOTO set the worldwide best limit of < 2.0×10^{-9}** (90% C.L.)
  Paper will be submitted by the end of 2024.
- **New physics sensitive regime < 6.4×10^{-10}** (68% C.L.)
- KOTO expects to reach sensitivity $O(10^{-10})$ at 2027.
  An upgrade to "KOTO-II" is needed to suppress the irreducible backgrounds in the KOTO experiment.
- **Standard Model prediction = 3.0×10^{-11}.**
- KOTO-II targets to explore the sensitivity of $O(10^{-13})$.

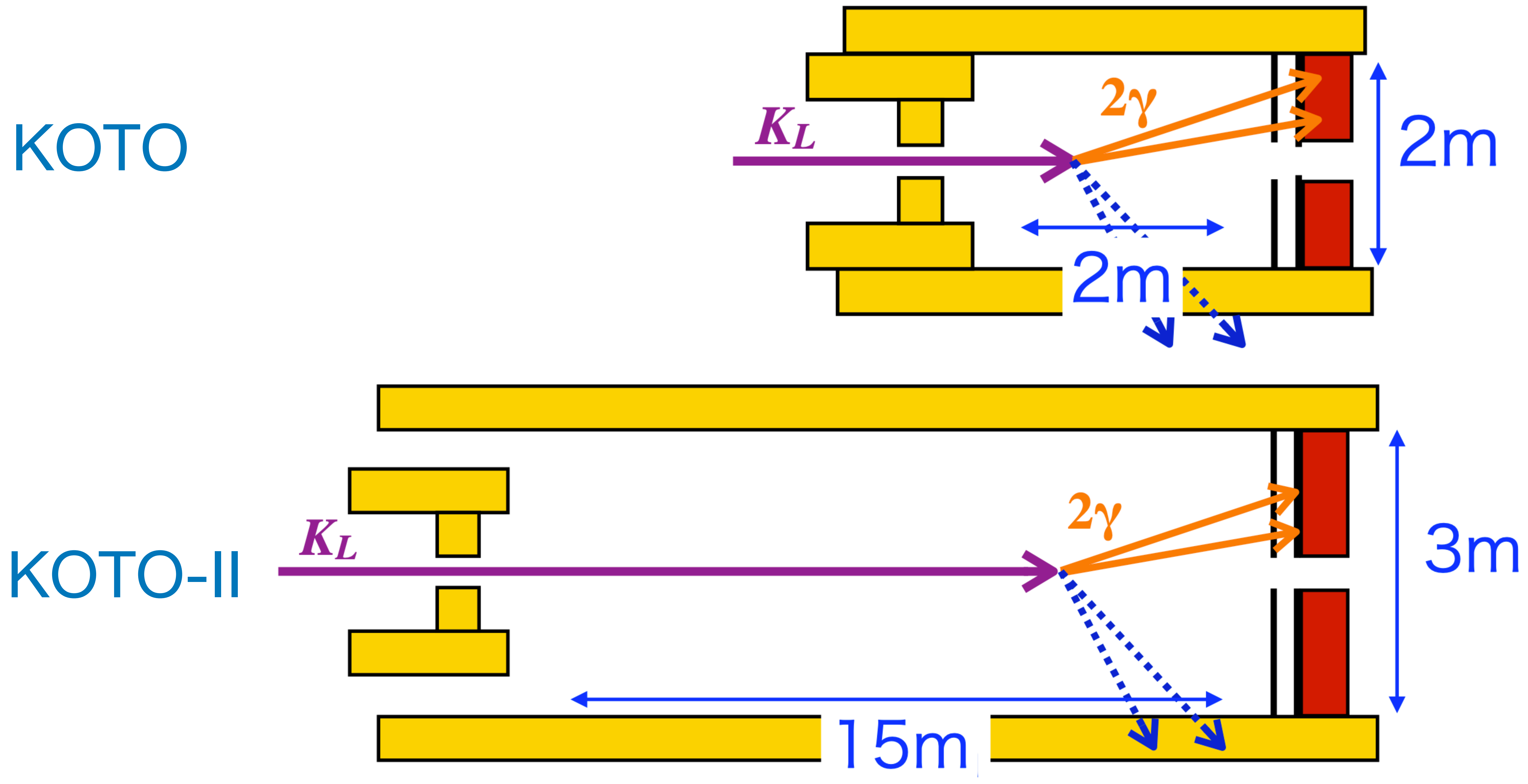
The KOTO-II Project

- 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 = 0.9.
  - $B(K_L^0 \to \pi^0 \nu \bar{\nu}) \approx SM$ → 5.6 σ discovery.
  - $|B(K_L^0 \to \pi^0 \nu \bar{\nu}) - SM| > 40\% \times SM$ → New Physics implication (90% C.L.).





Summary

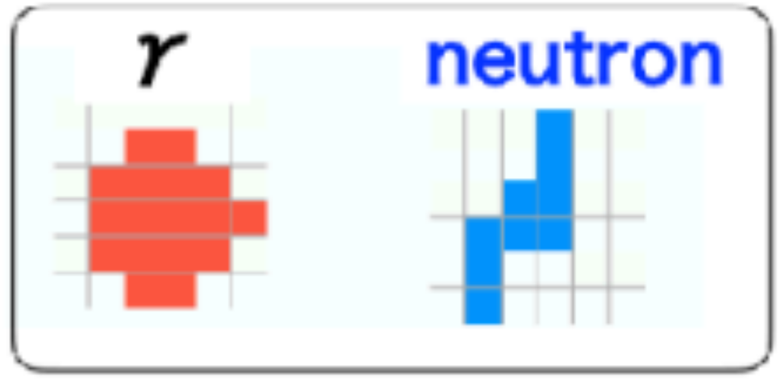
- The $K_L^0 \to \pi^0 \nu \overline{\nu}$ decay is the golden channel sensitive to New Physics.
- The KOTO experiment searches for the $K_L^0 \to \pi^0 \nu \overline{\nu}$ decay using 2021 run data.
  - Number of background events is predicted to be (0.255 ± 0.058). Preliminary
  - No signal candidate was observed.
  - This set a worldwide best limit of $B(K_L^0 \to \pi^0 \nu \overline{\nu}) < 2.0 \times 10^{-9}$ (90% C.L.). Preliminary
- We are expecting to explore the New Physics sensitive regime in the next four years and preparing for the KOTO-II experiment to enhance the physics impact.

Supplemental

Neutron Background

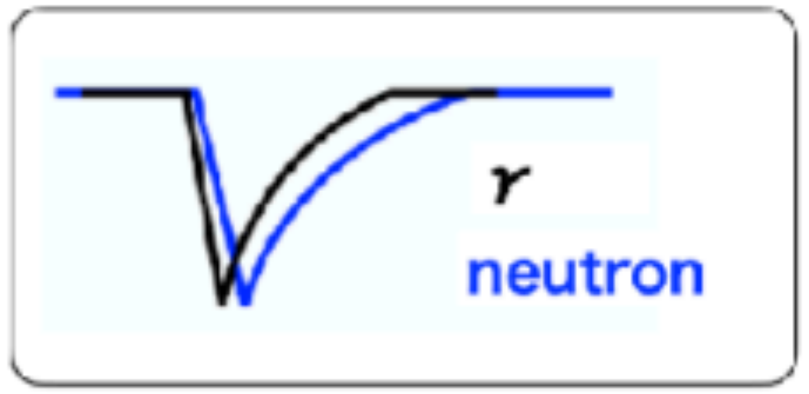
CSDDL

Cluster Shape Discriminator with Deep Leaning



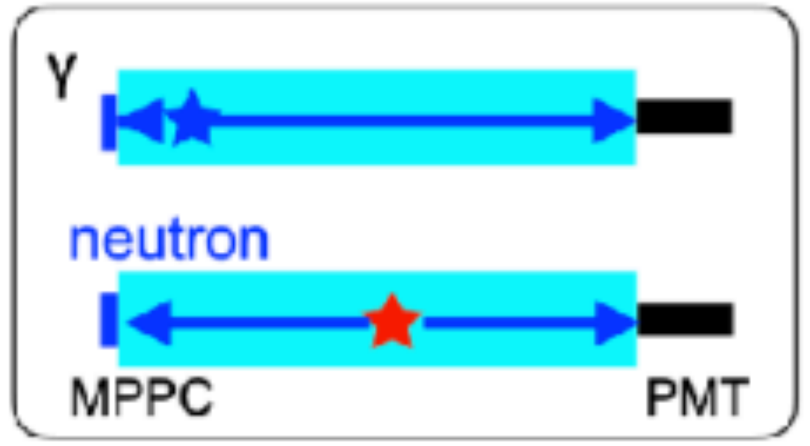
FPSD

Fourier Pulse Shape Discriminator



DT

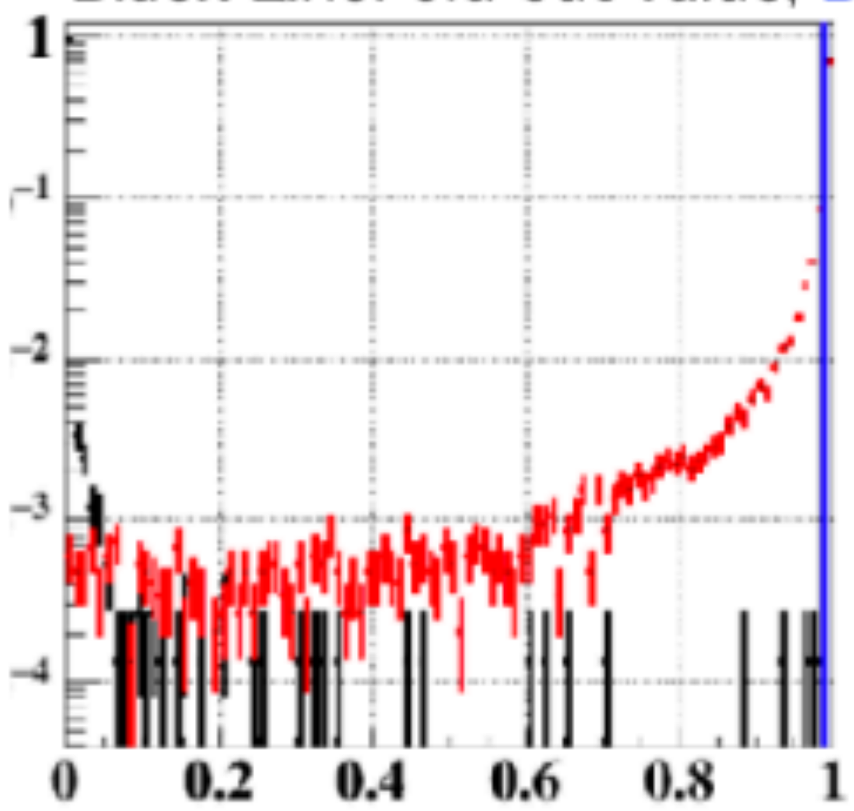
Both-side readout DT



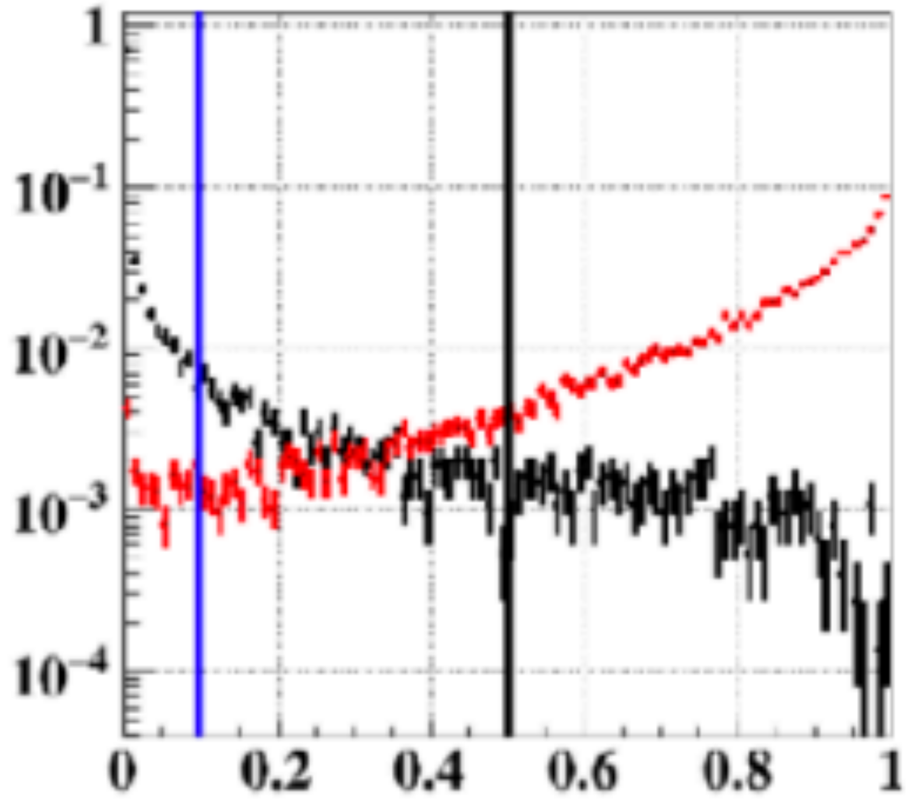
New (since 2019)

Black:Neutron, Red: π^0 in $K_L \to 2\pi^0$

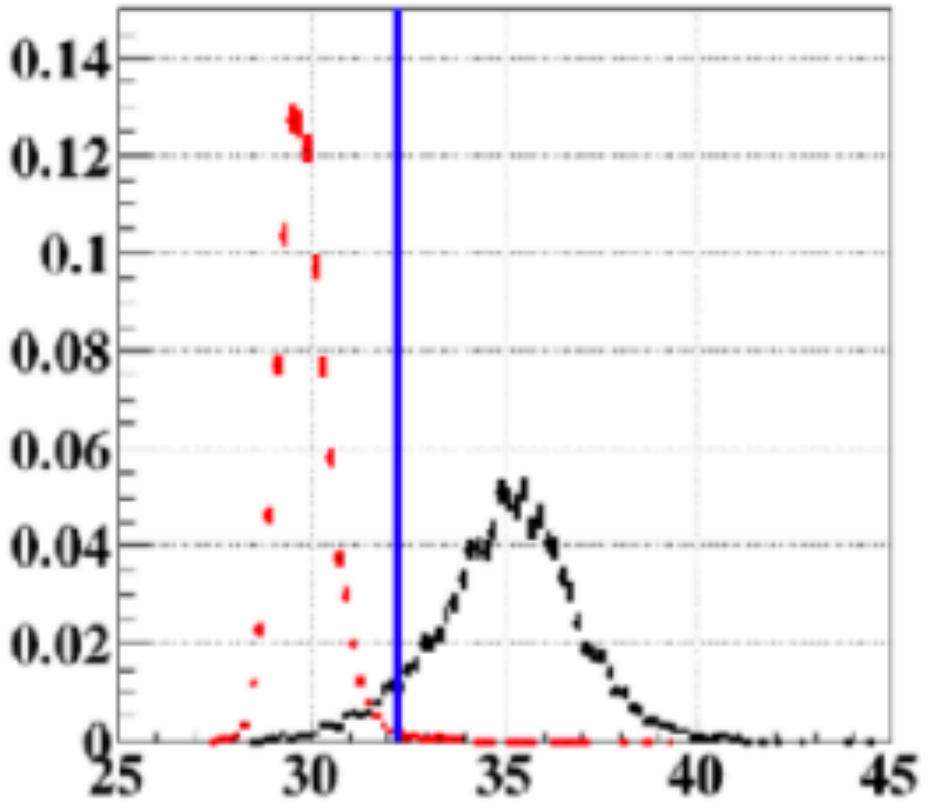
Black Line: old cut value, Blue Line: Optimized cut value



CSDDL Output



FPSD Output



DT (ns)

Optimizing the thresholds among three cuts,

2016-2018

$N_{\text{Hadron cluster BG}}$=0.042±0.007(stat)±0.010(sys)

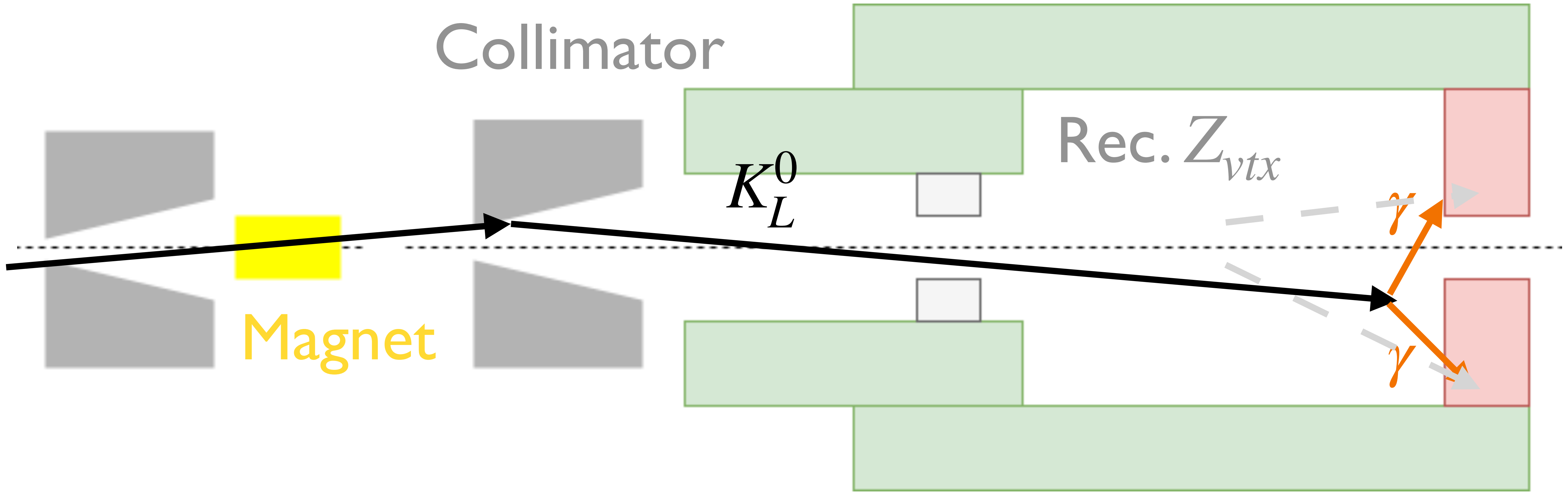
2021

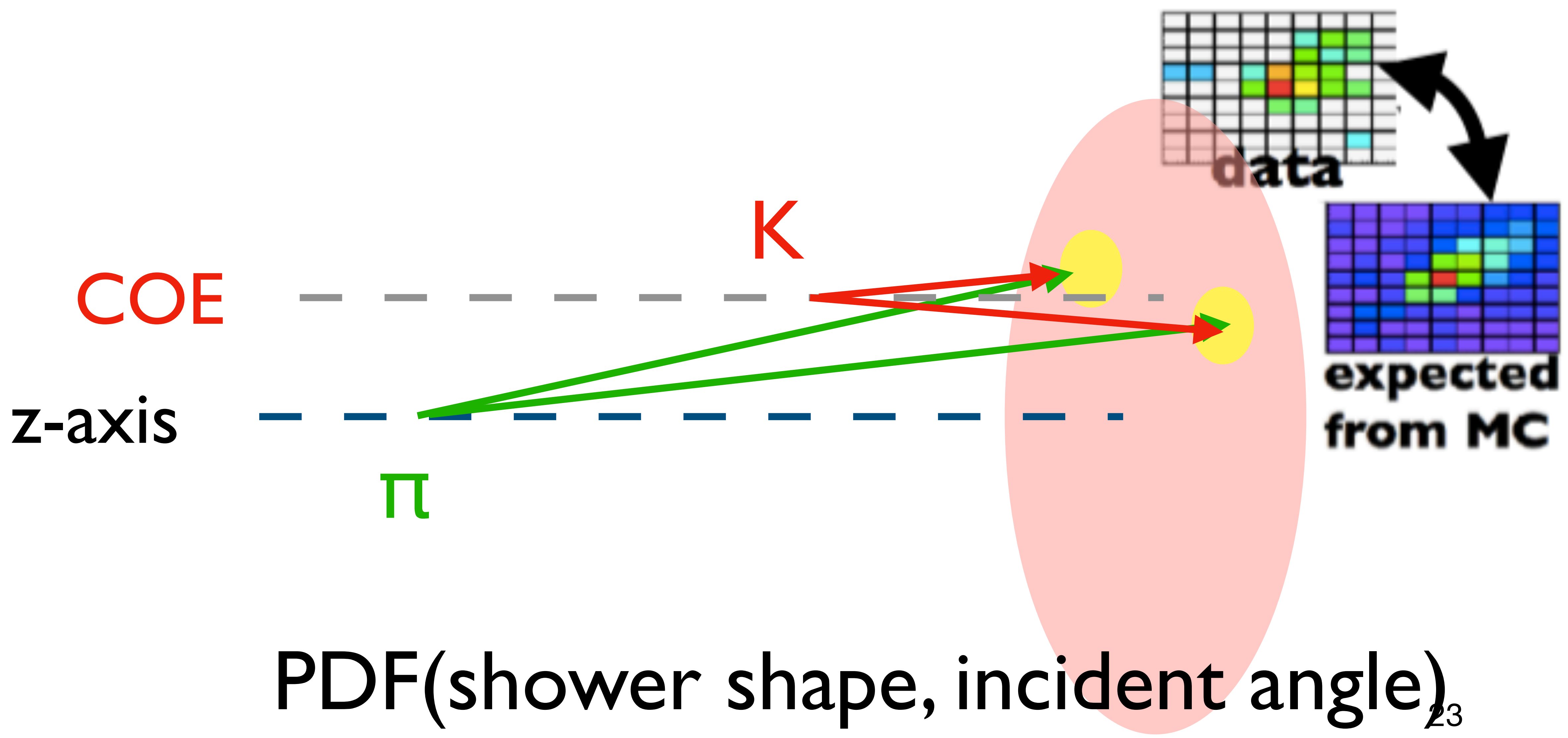
$N_{\text{Hadron cluster BG}}$=0.024±0.004(stat)±0.006(sys)

with almost the same signal efficiency

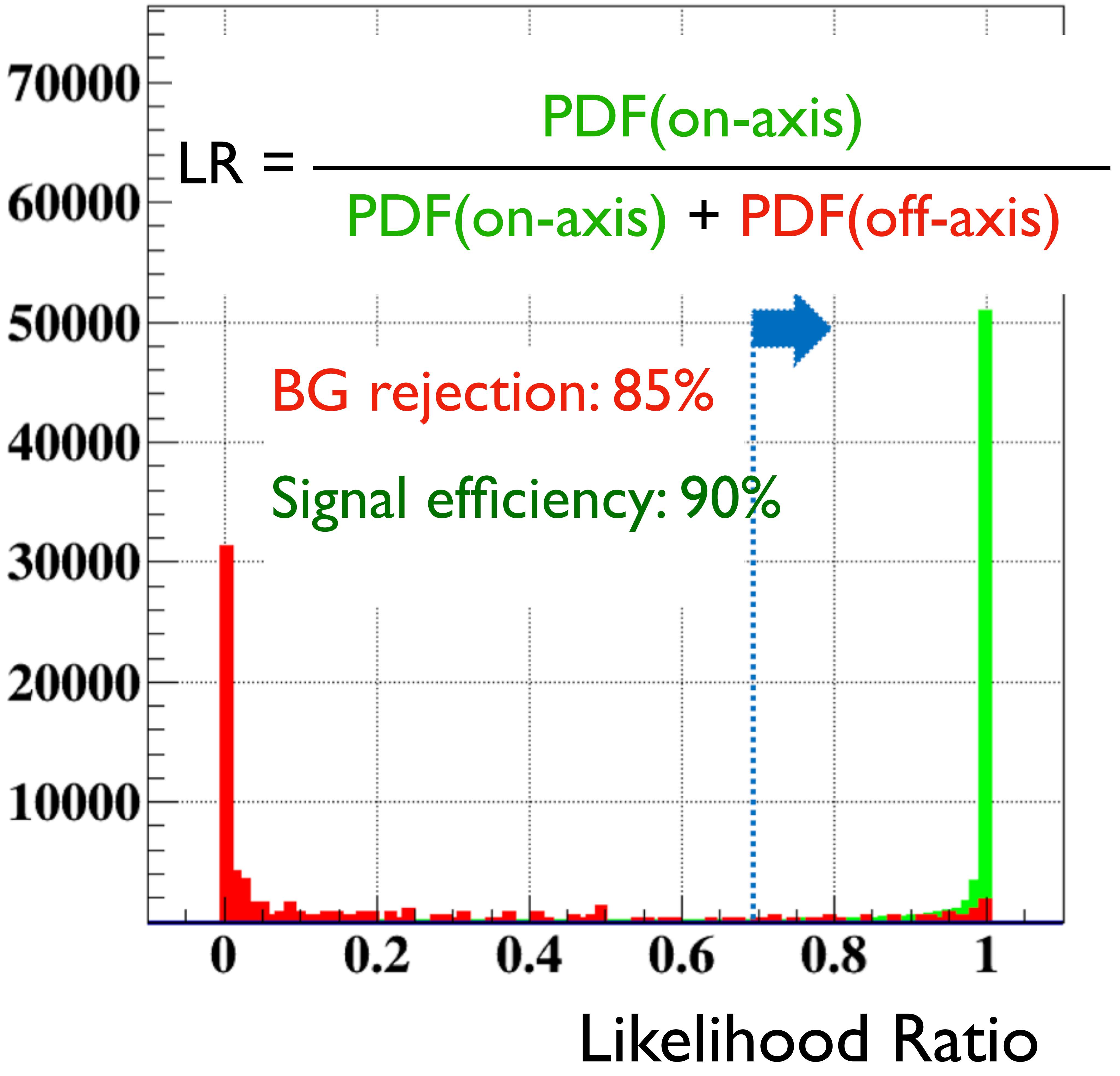
Halo K_L^0 background

2nd largest background source in 2016-2018 data



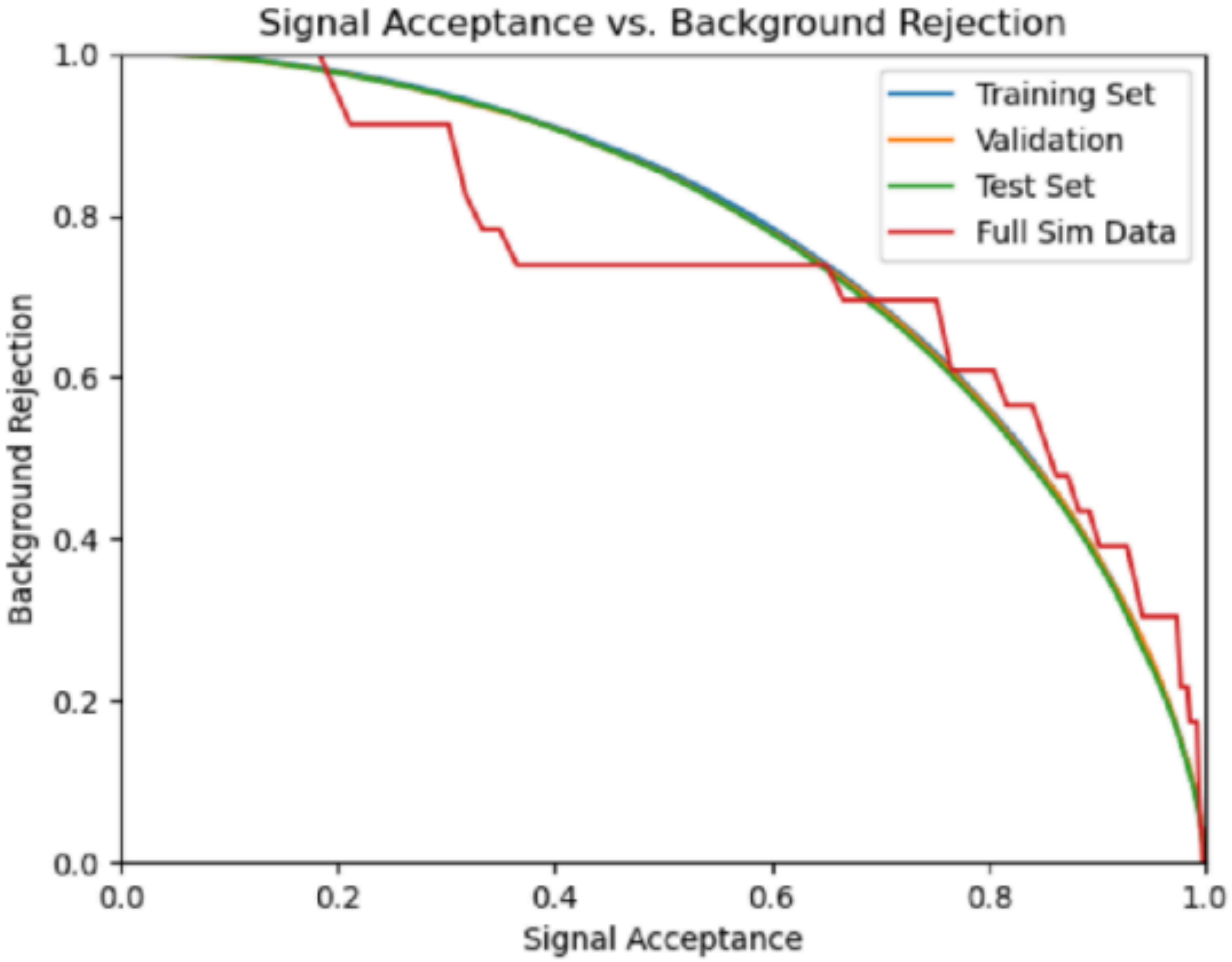


PDF(shower shape, incident angle)



Neural Network Cut against $K_L^0 \to \pi^0\pi^0$

- Developed a neural net cut based on the kinematical distribution.
  - π^0 P_t, Z_{vtx}, E_γ, etc.
- Background samples
  - $K_L \to 2\pi^0$ MC samples after applying selection criteria to enhance events which could not be vetoed
- Signal samples
  - Signal MC samples



$K_L \to 2\pi^0$ BG can be reduced by 40% with 90% signal efficiency

Largest background source: Upstream π^0

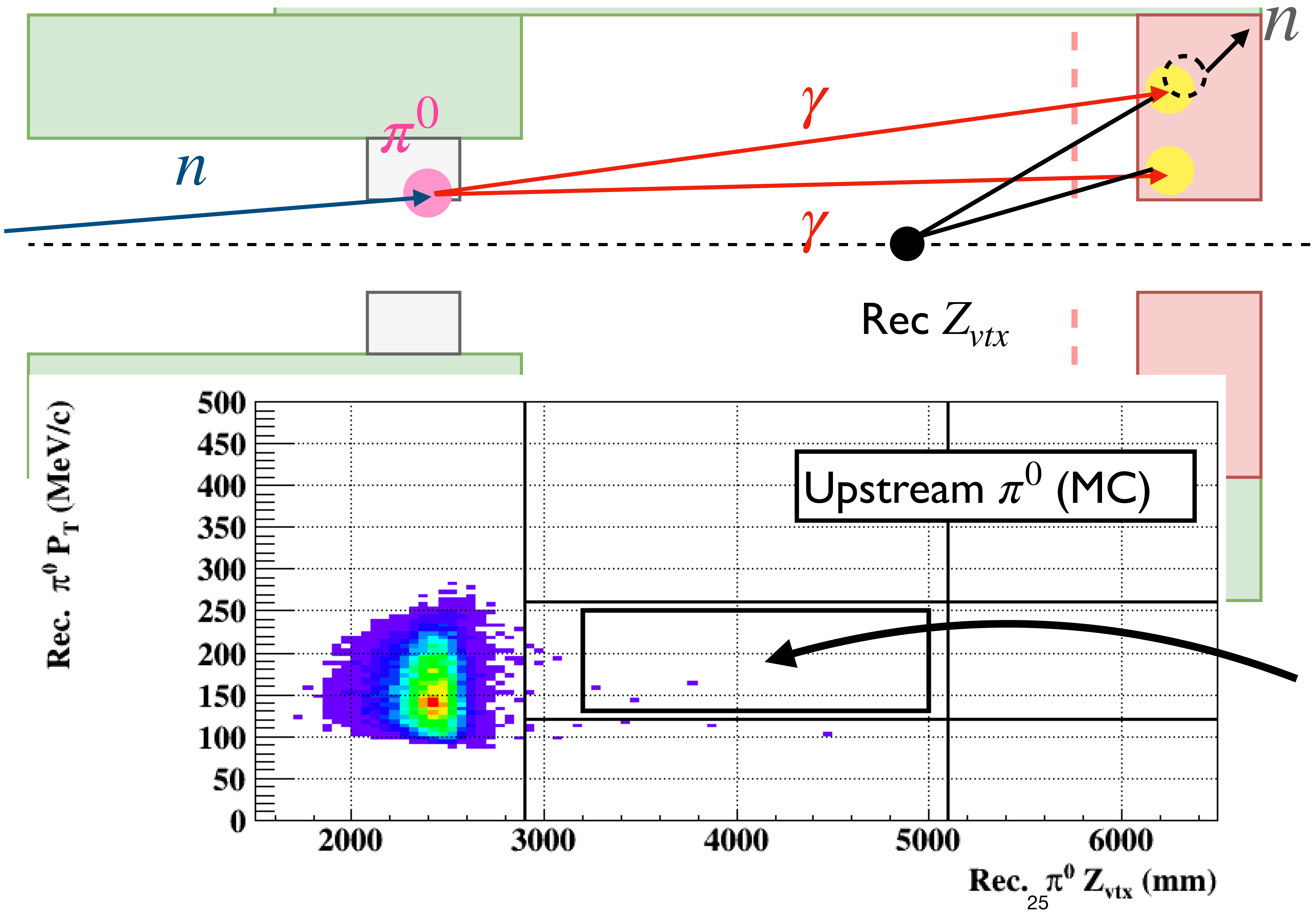


Photo-nuclear interactions

→ Measured energy is smaller.

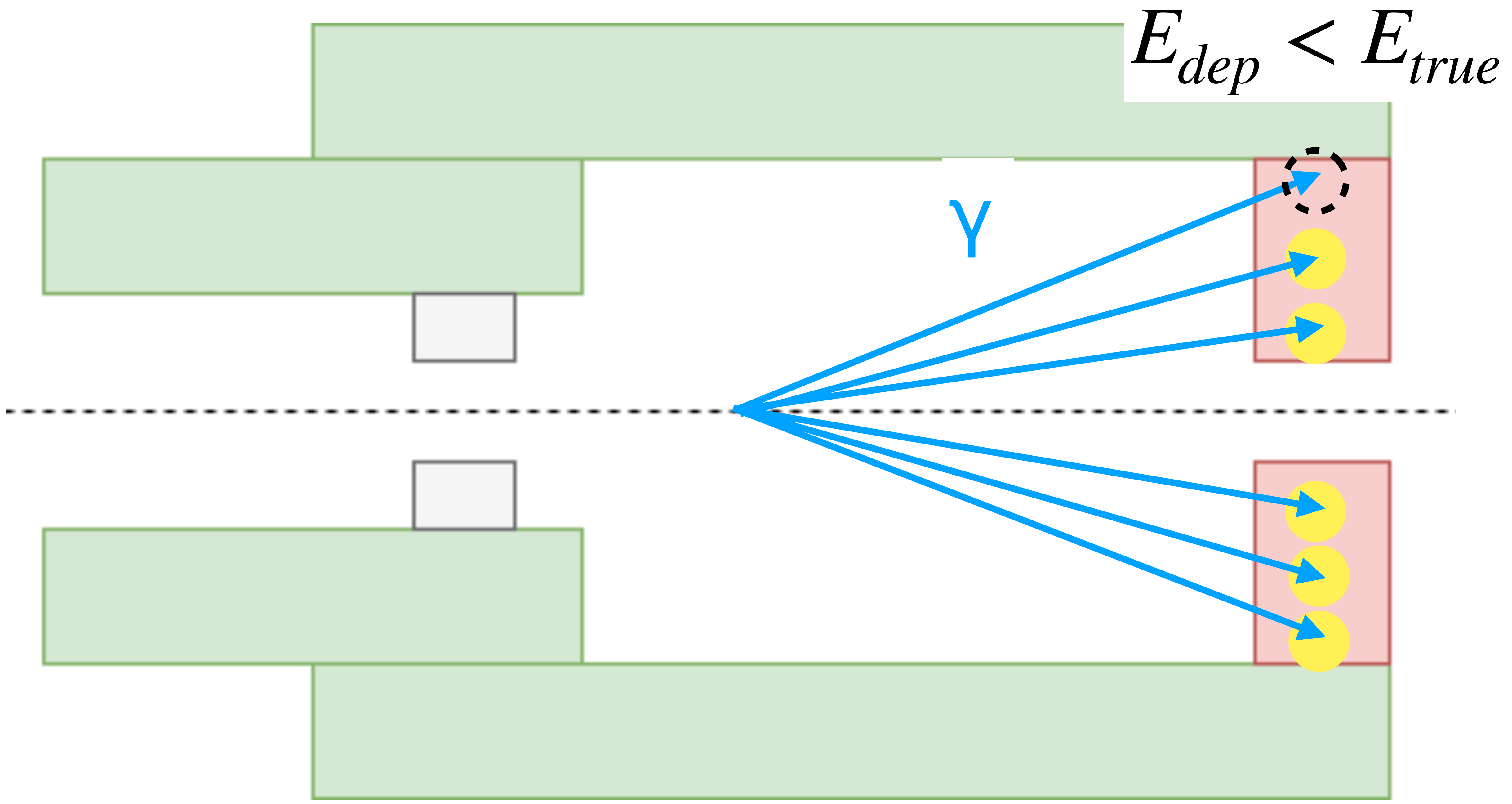
Does MC correctly predict the probability of wrong energy measurement?

How to study the photo-nuclear interactions in CSI?

Enhance events having photo-nuclear interactions by

- Distance between center of energy and beam axis (R_{COE}) should be large.
- Reconstructed $M_{K_L^0}$ should NOT be close to nominal value.

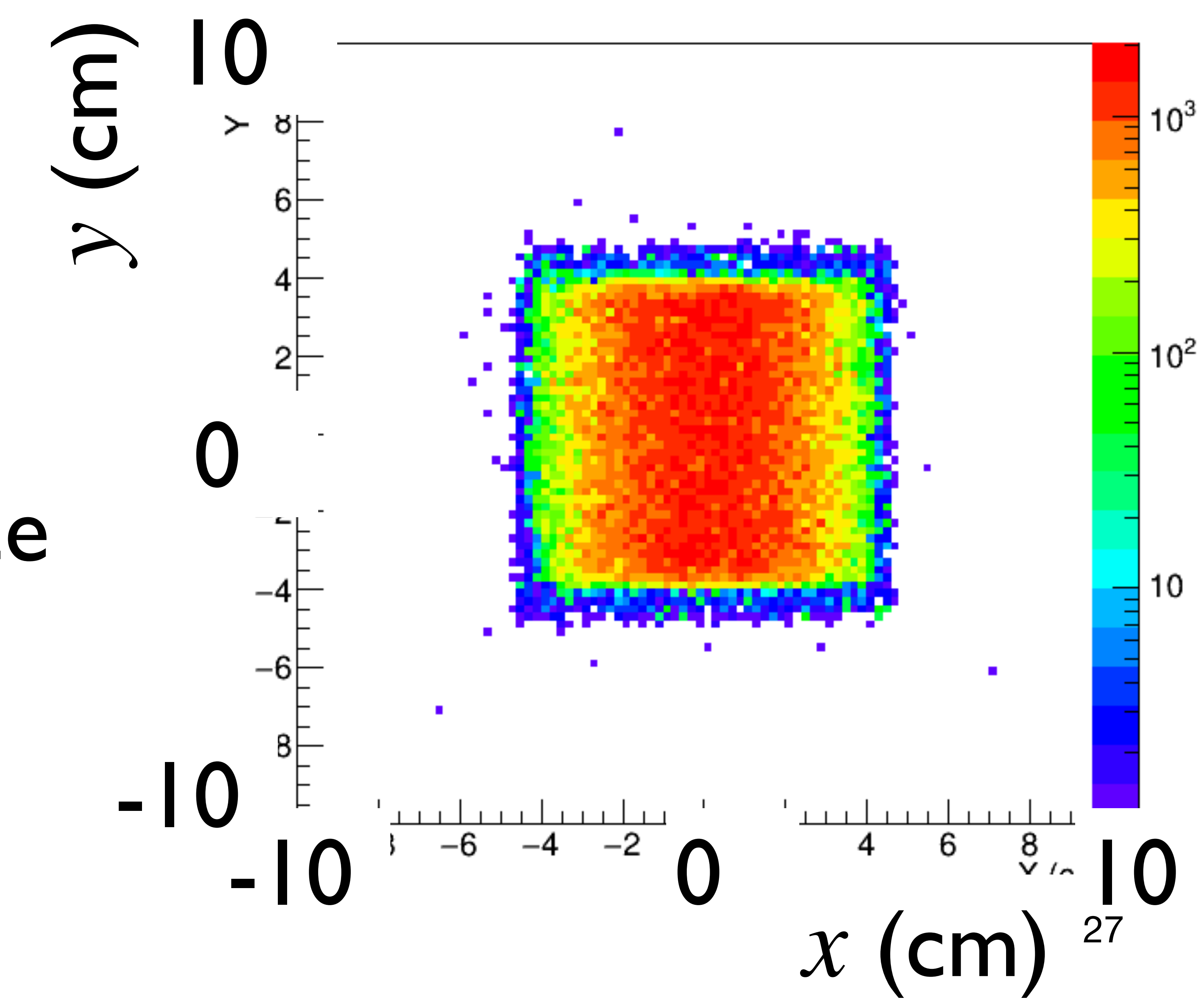
$K_L^0 \rightarrow 3\pi^0 \rightarrow 6\gamma$ is background free channel.

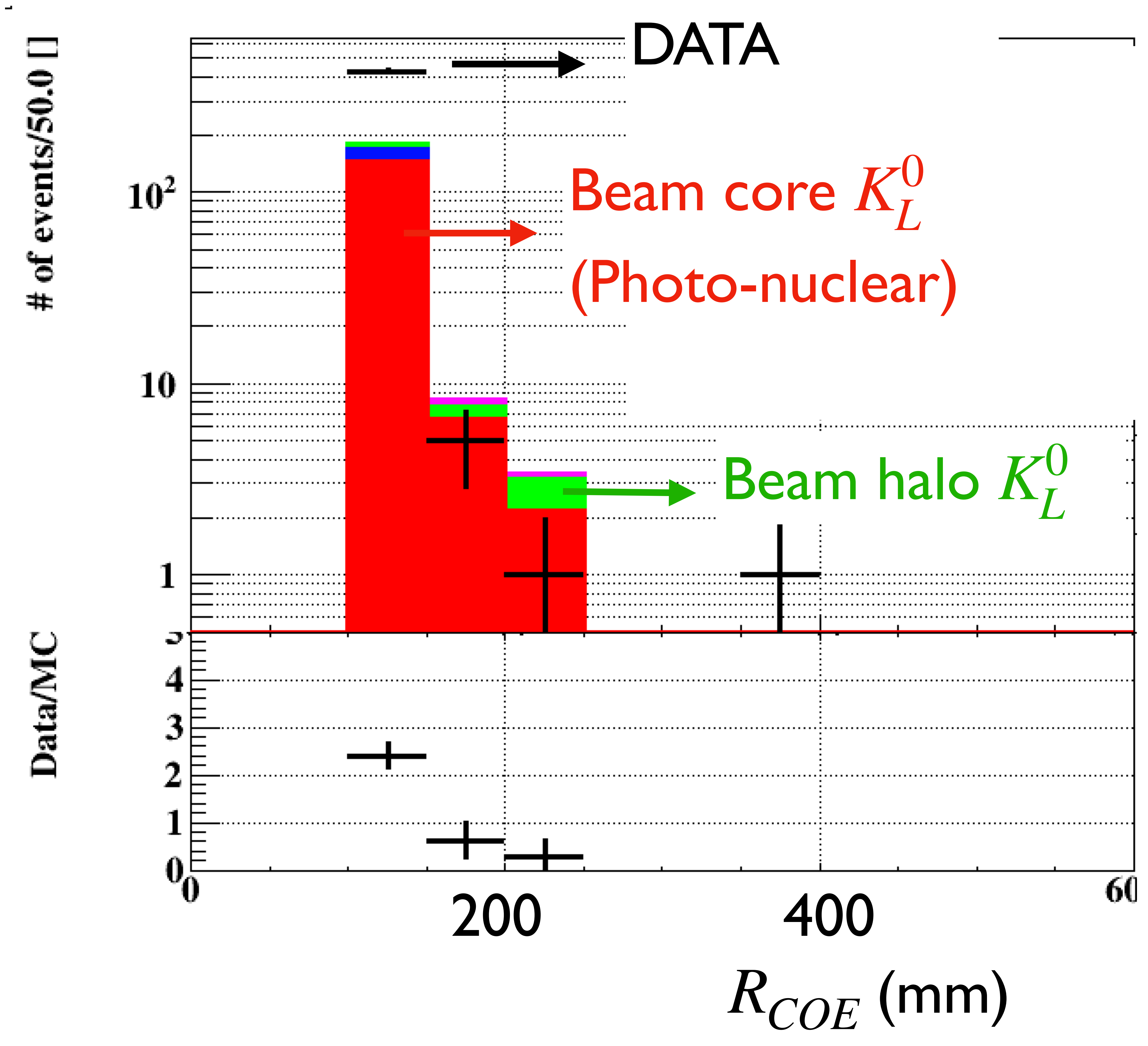


Probability of wrong energy measurement

- The difference between data and MC is presumably caused by the underestimation of photo-nuclear interactions.
- An additional factor of (2.64 ± 0.35)

K_L^0 beam profile
@detector entrance





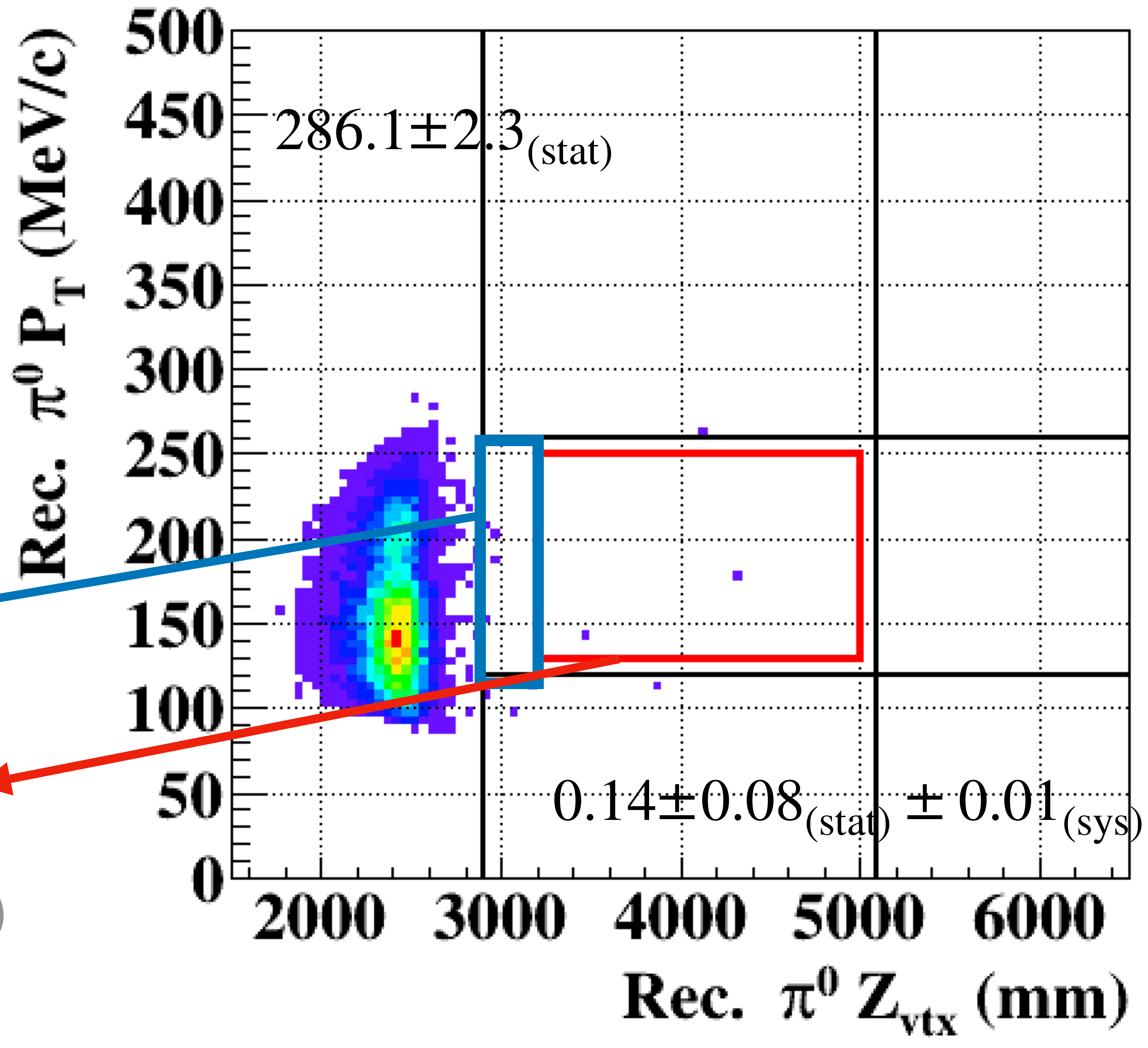
N(upstream π^0) estimation result

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

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

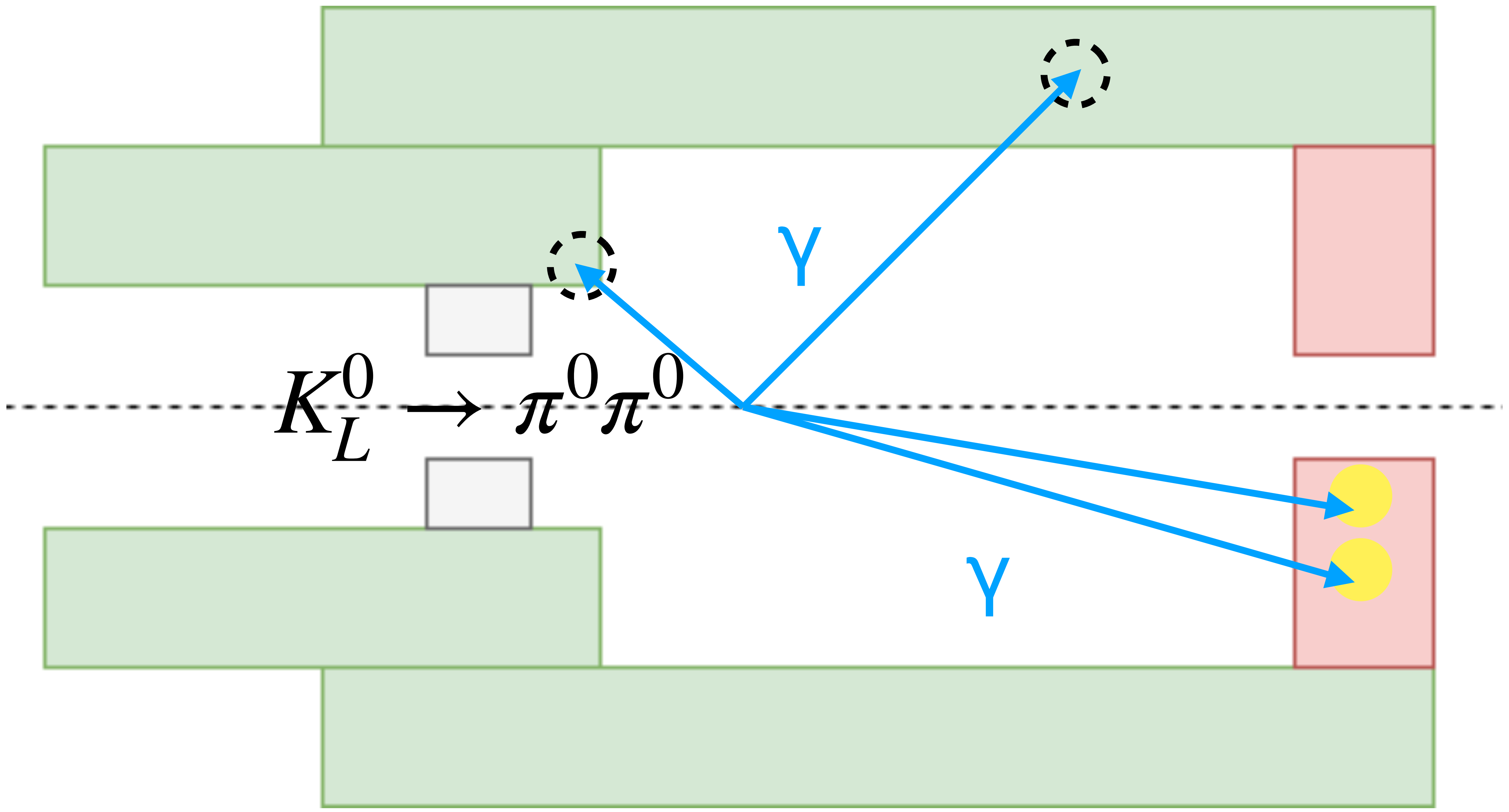
$0.064 \pm 0.050_{(stat)} \pm 0.06_{(sys)}$

($0.035 \pm 0.025_{(stat)}$ before correction)



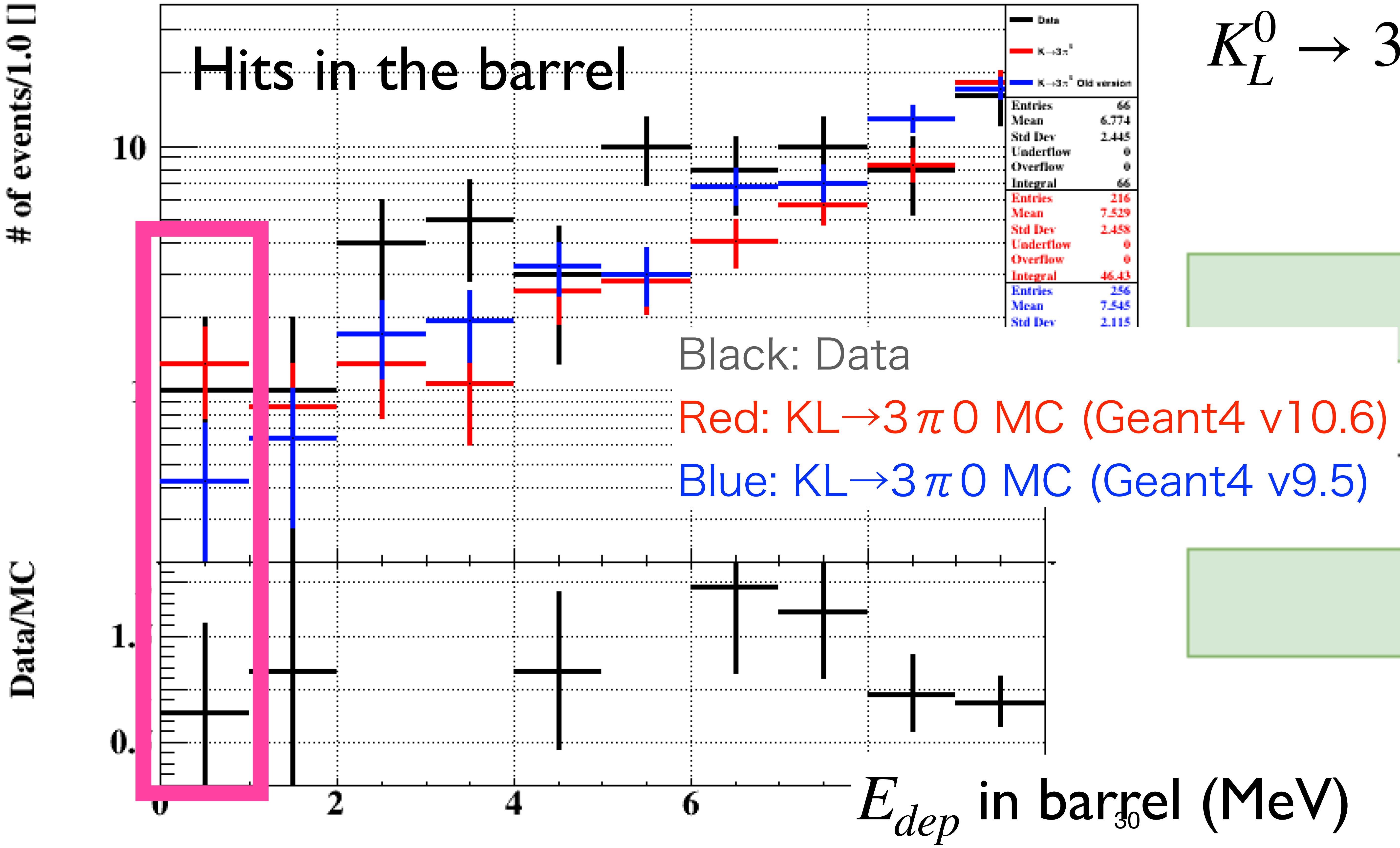
2nd Largest Background Source: $K_L^0 \to \pi^0\pi^0$

- If the two photons from π^0 are not detected, they are just like the two undetected neutrinos.
- Is the veto inefficiency modeled by GEANT4 reliable?

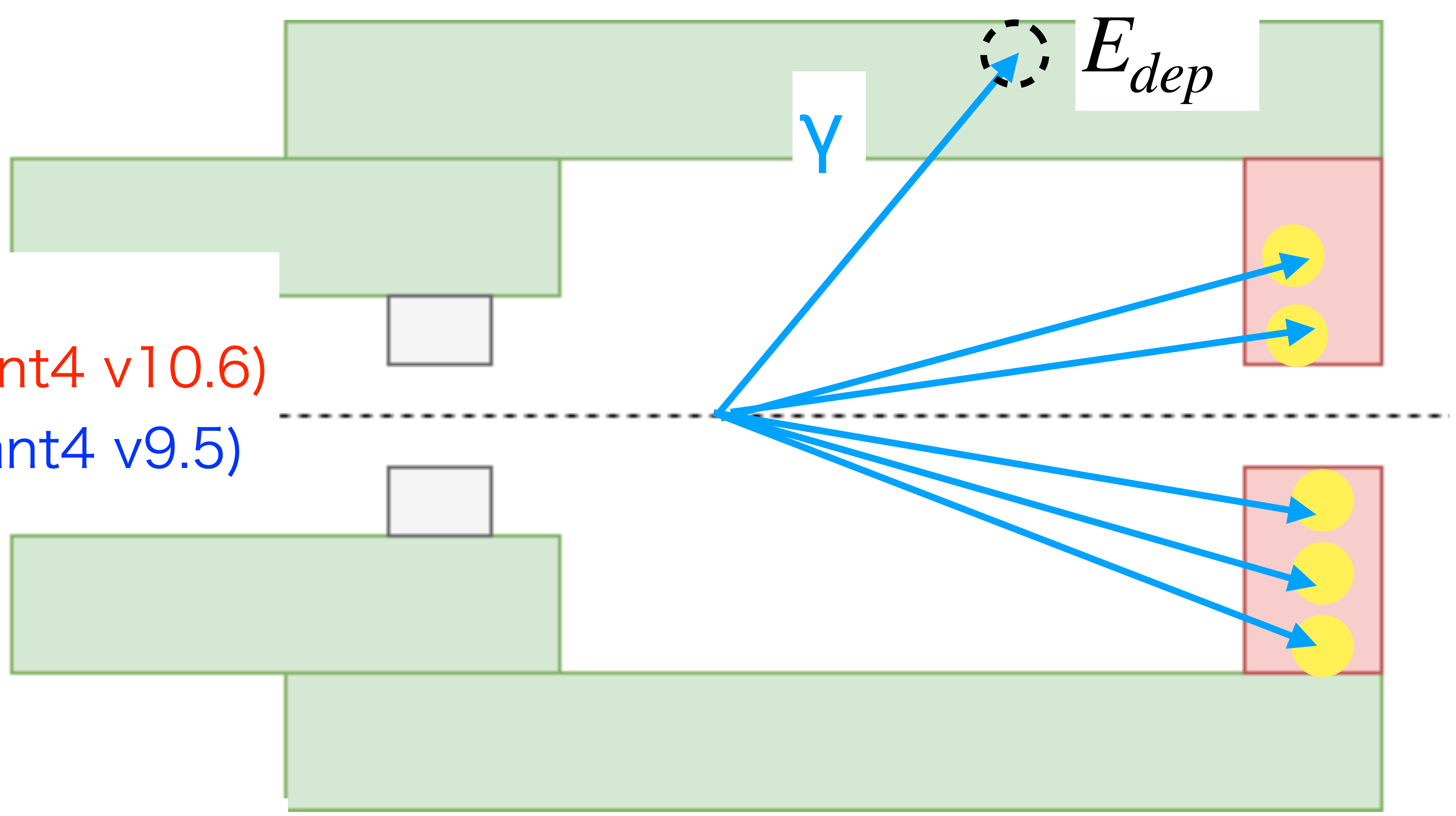


Veto Inefficiency Verification

- Use the kinematic constraints of $K_L^0 \rightarrow 3\pi^0$ to predict the 6-th photon's momentum.
- The energy deposit smaller than the offline threshold (1 MeV) is the inefficiency.
  - The difference is the extra factor to be applied to MC.



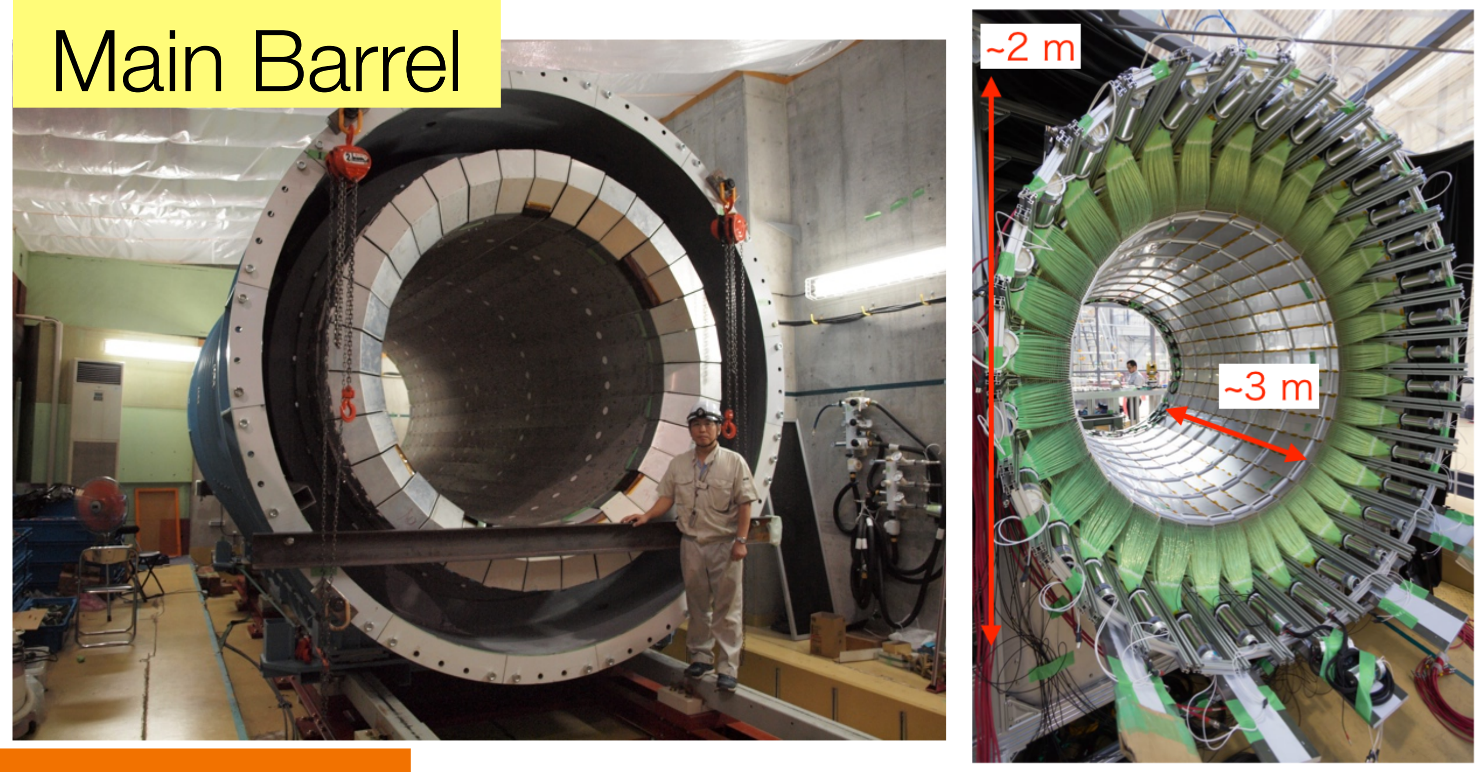
$K_L^0 \rightarrow 3\pi^0 \rightarrow 6\gamma$ is background free channel.

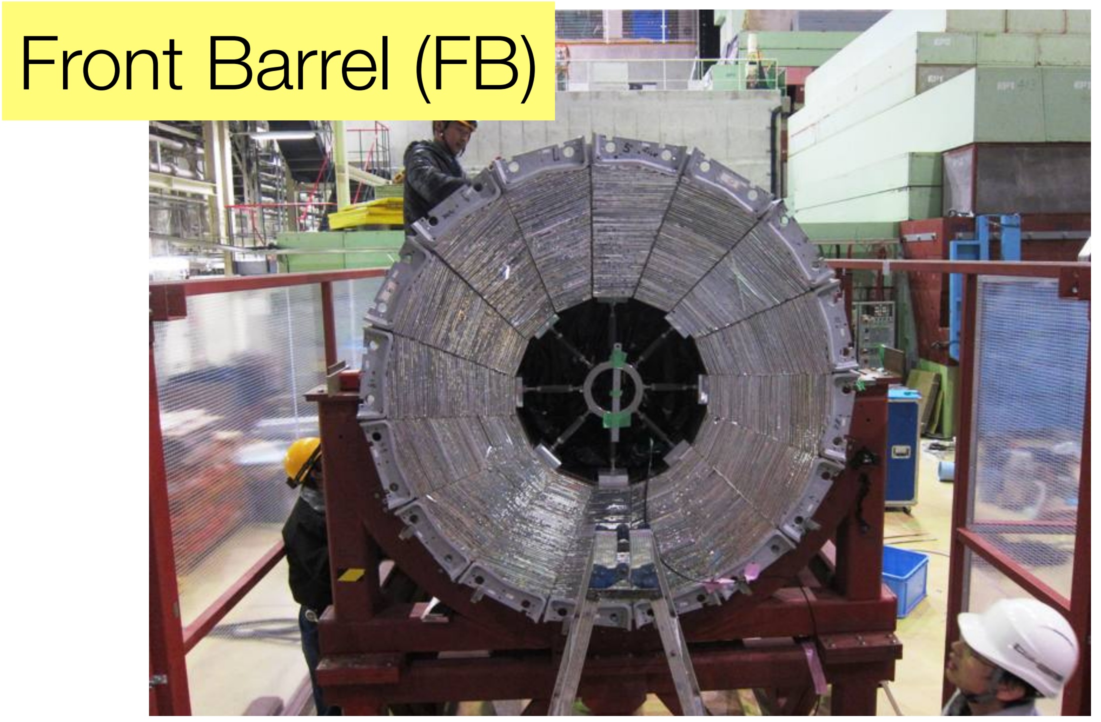


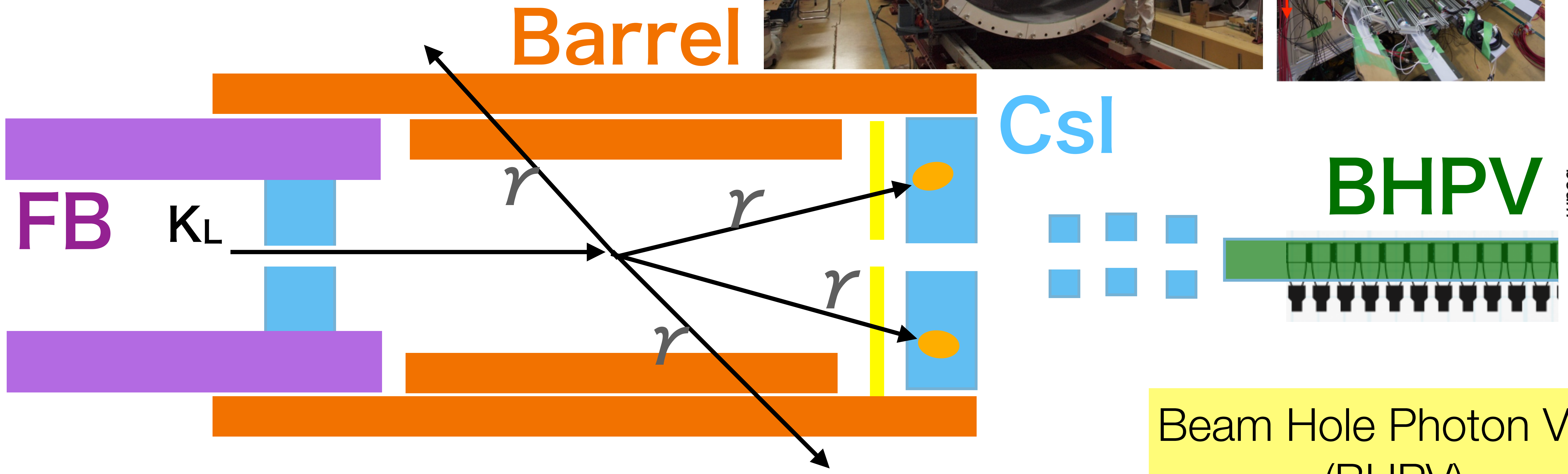
Scale Factor for Each Counter

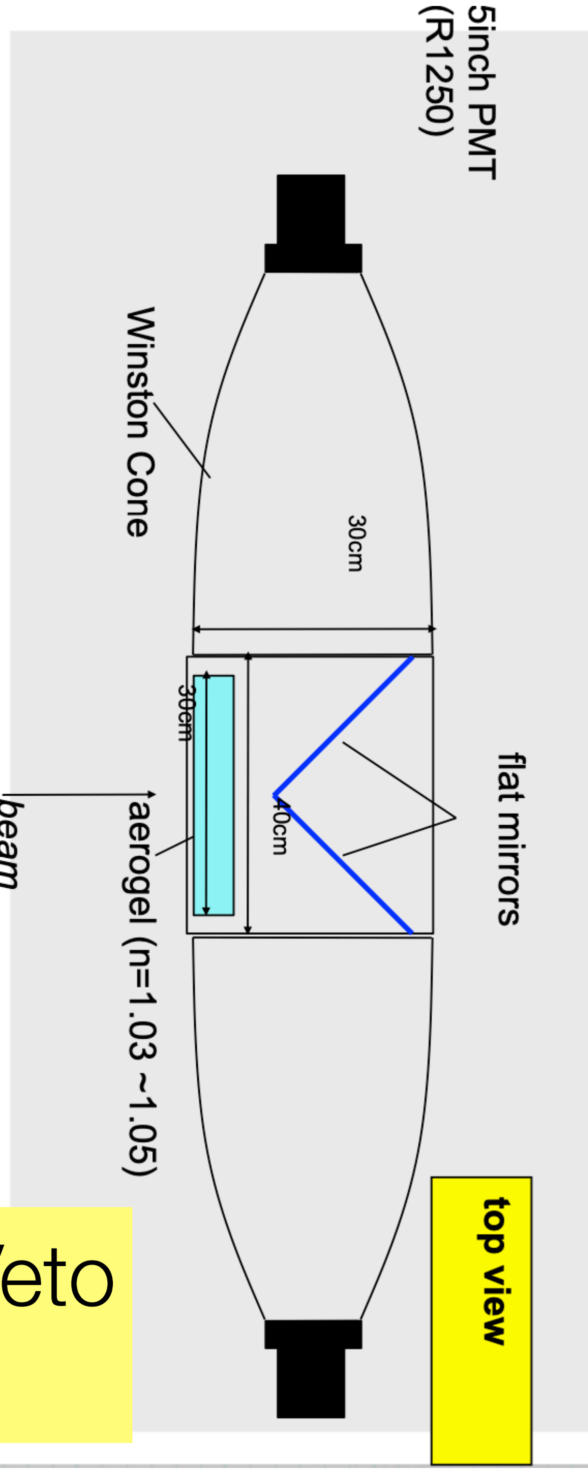
$$SF = \frac{\mathrm{Ineffi}_{\mathrm{Data}}}{\mathrm{Ineffi}_{\mathrm{MC}}} \qquad \#BG = \Sigma(SF_{det1} \times SF_{det2})$$

Errors on SF are considered as systematic uncertainties





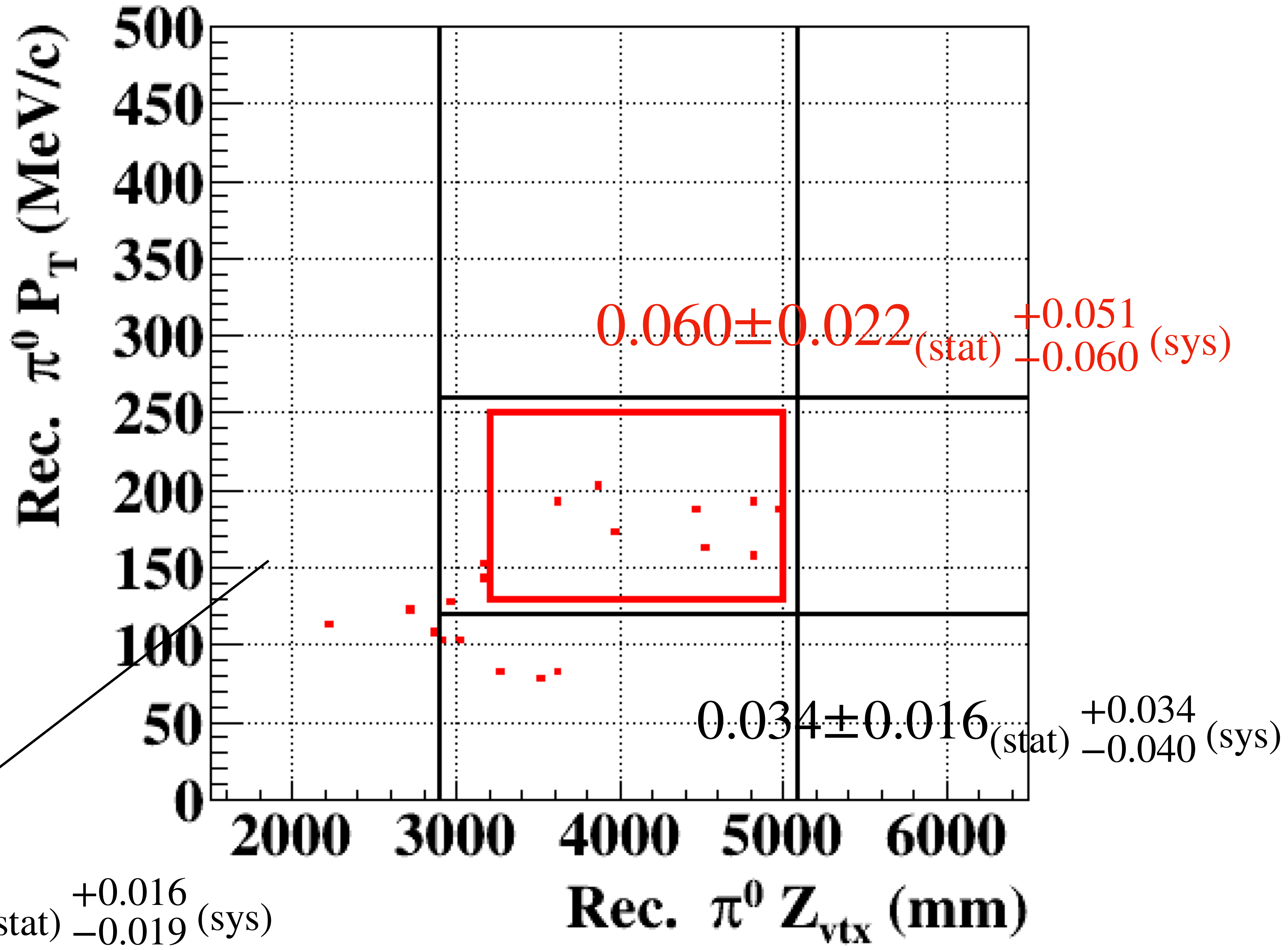




Beam Hole Photon Veto (BHPV)

	Barrel for high energy photon	Barrel for low energy photon	FBAR	BHPV
Scale factor (SF)	$0.77^{+0.85}_{-0.77}$	$1.10^{+0.10}_{-0.10}$	$1.42^{+0.13}_{-0.13}$	$1.50^{+0.42}_{-0.51}$

N($K_L^0 \to \pi^0\pi^0$ background) estimation



$0.023 \pm 0.013_{(stat)}\,^{+0.016}_{-0.019}\,(sys)$

Exotic Particle Interpretation

$K_L^0 \to \pi^0 X$ ($X \to$ invisible)

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

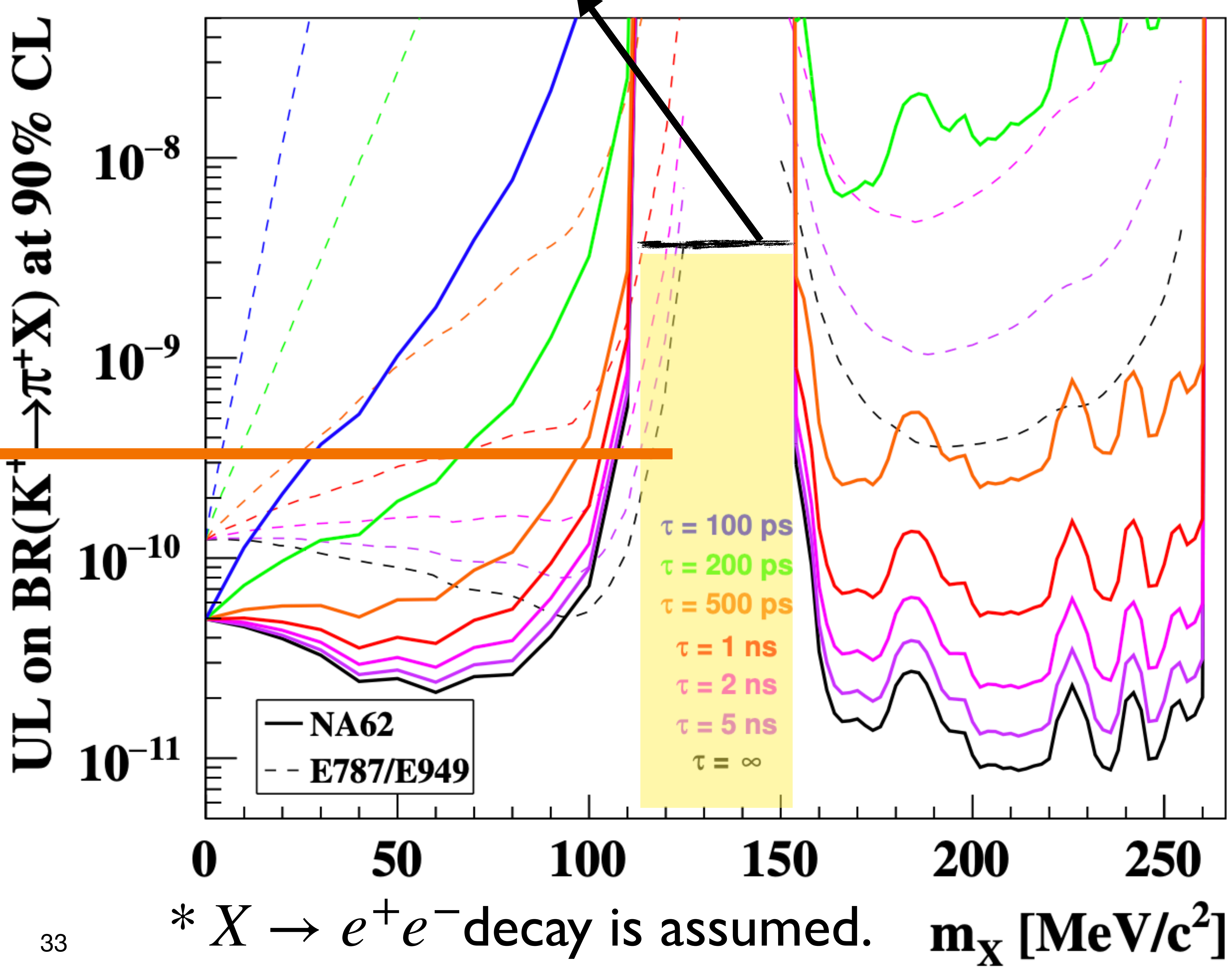
- KOTO is in a unique position to further explore the π^0 mass region.

[Fuyoto, W.S., Hou, Kohda '14]

$B(K^+ \to \pi^+\pi^0, \pi^0 \to$ invisible)

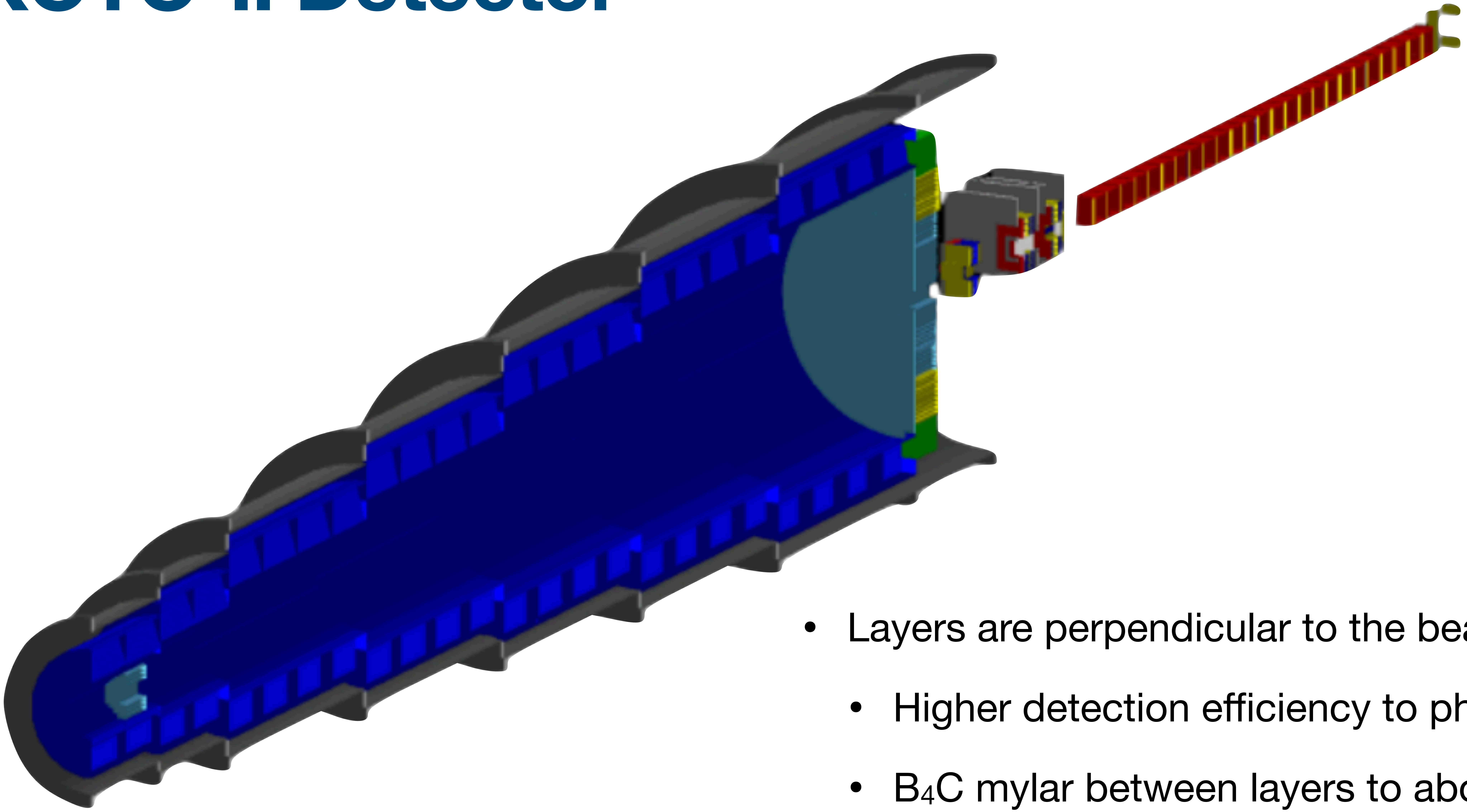
$< 4.4 \times 10^{-9}$ (90% C.L.)

JHEP 02 (2021) 201



$* \, X \to e^+e^-$ decay is assumed.

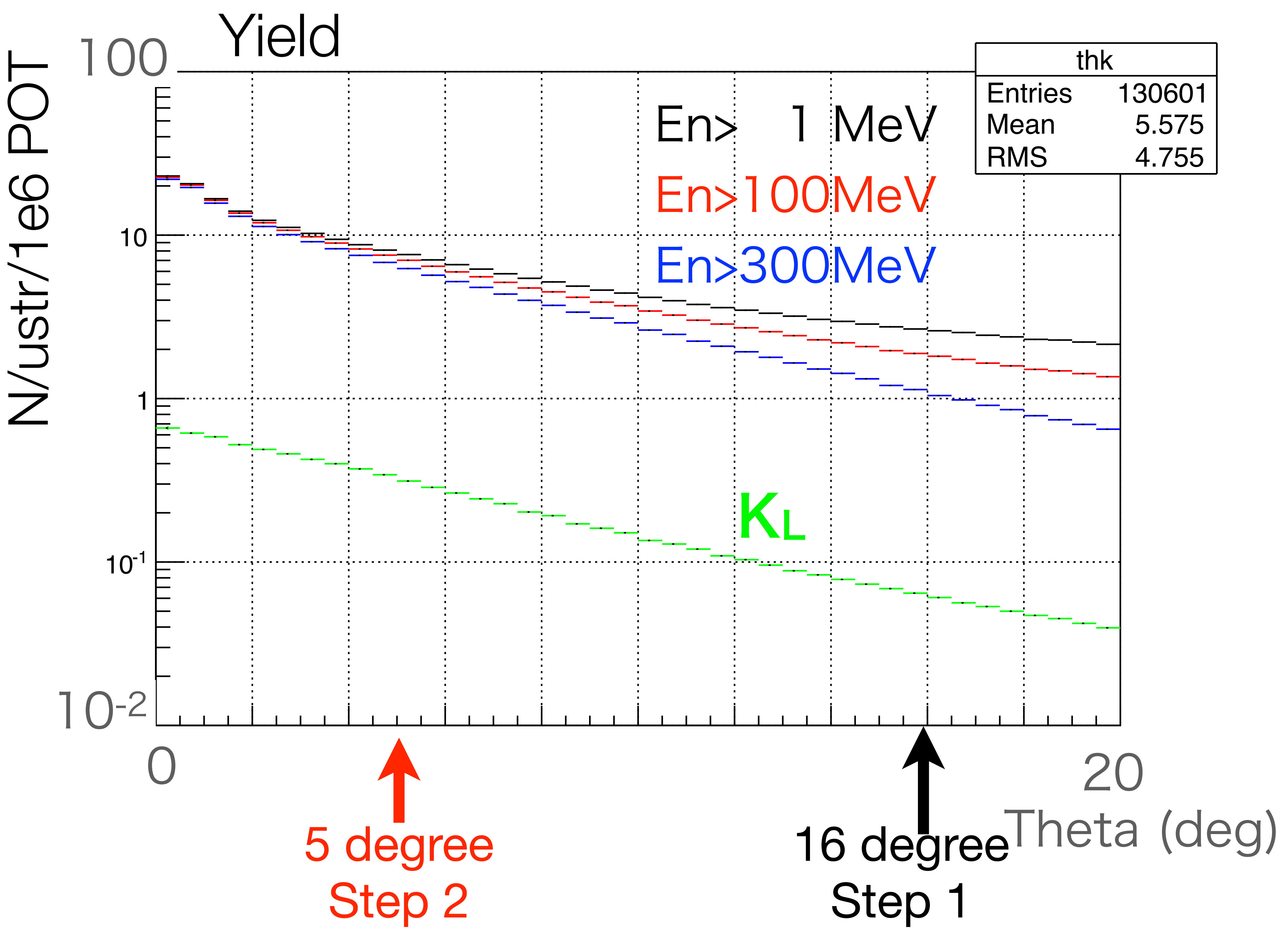
KOTO-II Detector

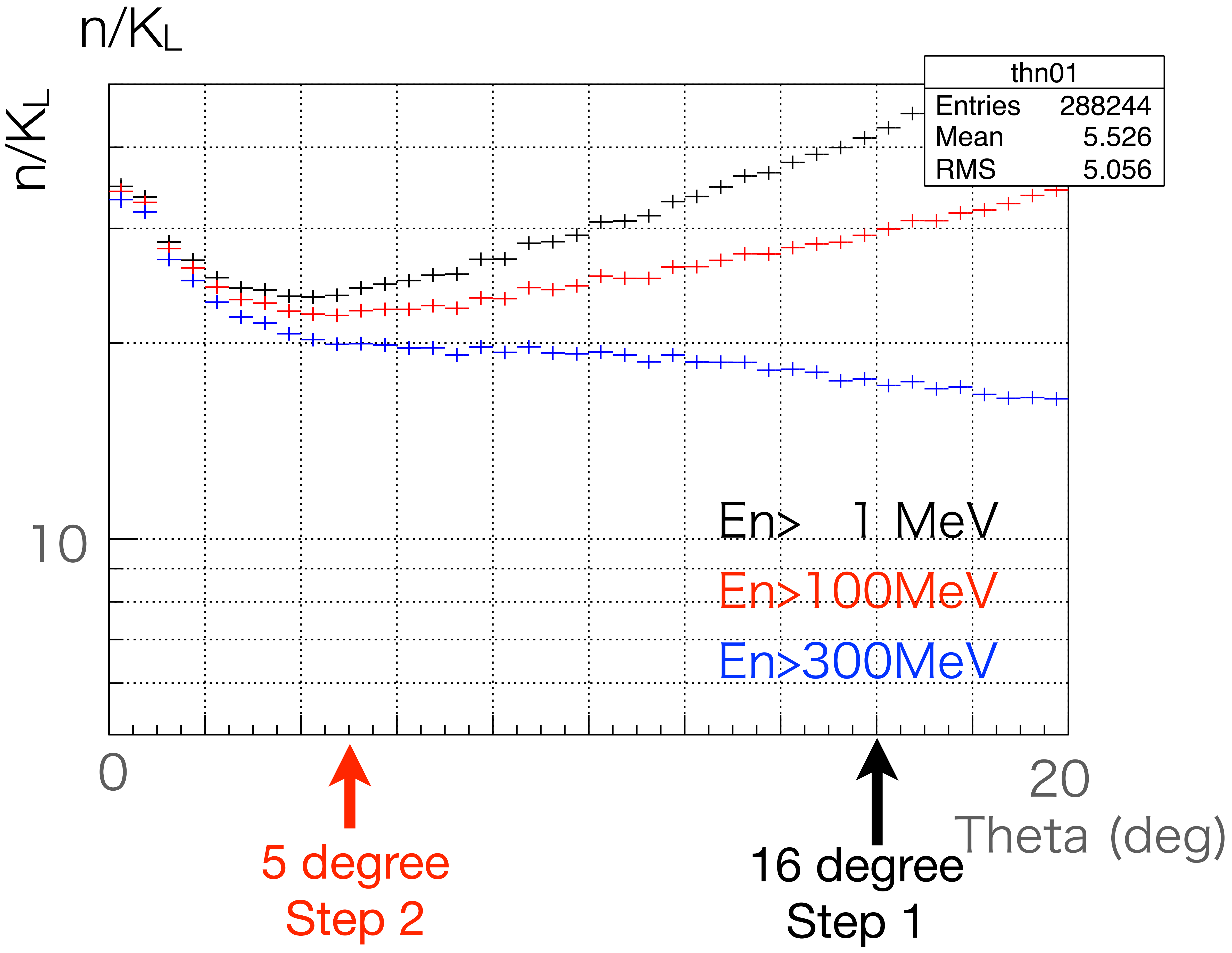


- Layers are perpendicular to the beam.
  - Higher detection efficiency to photons.
  - B_4C mylar between layers to aborb thermal neutrons (one of the accidental sources)

KOTO-II Simulation

Why KOTO-II adopts the targeting angle of 5 degrees?





KOTO-II #Background Prediction