Latest KOTO Results from 2021 Data on $K_L \to \pi^0 \nu \bar{\nu}$

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on behalf of the KOTO collaboration

58th Rencontres de Moriond
24th March–1st April 2024

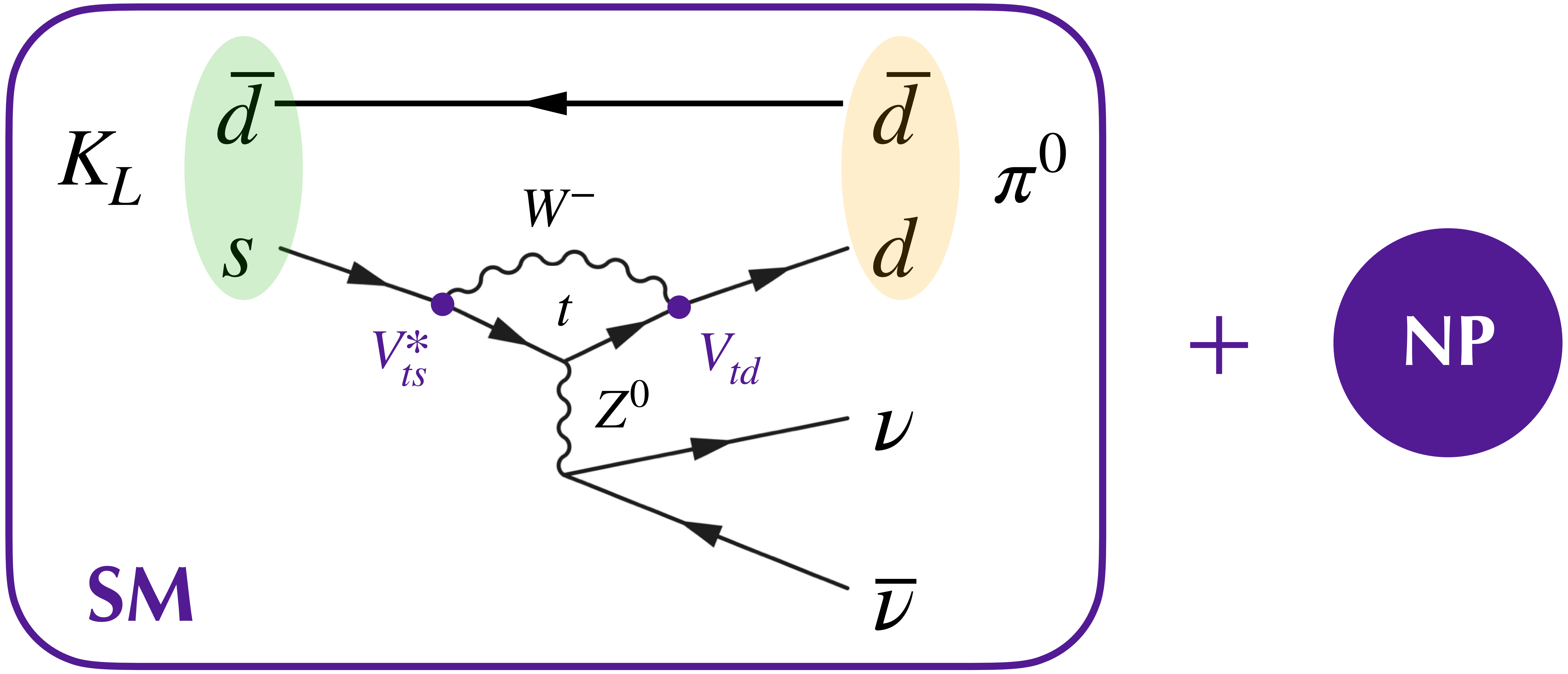
$K_L \to \pi^0 \nu \bar{\nu}$

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

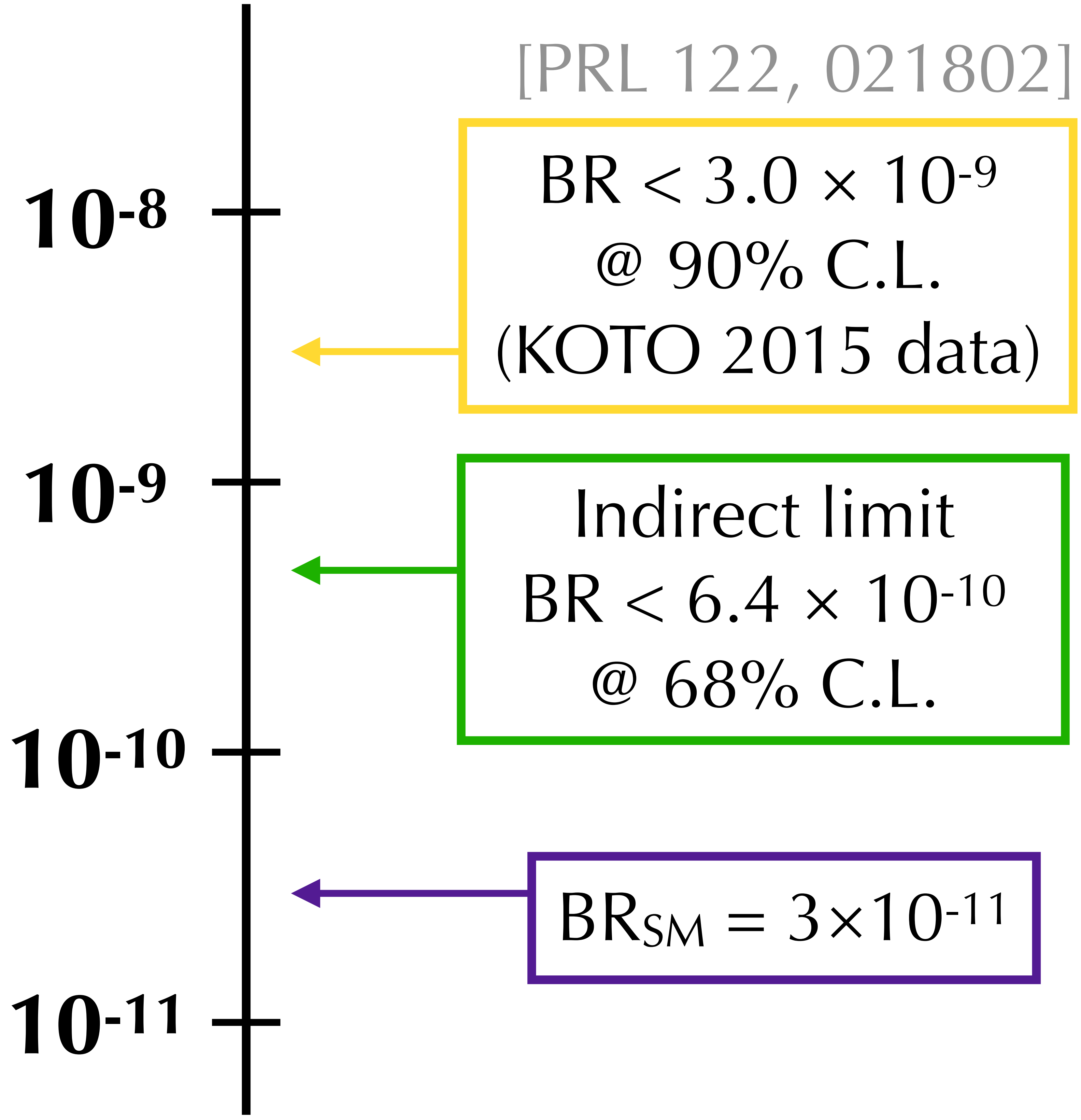
[EPJ-C (2023) 83:66]

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

→ Good probe to search for New Physics



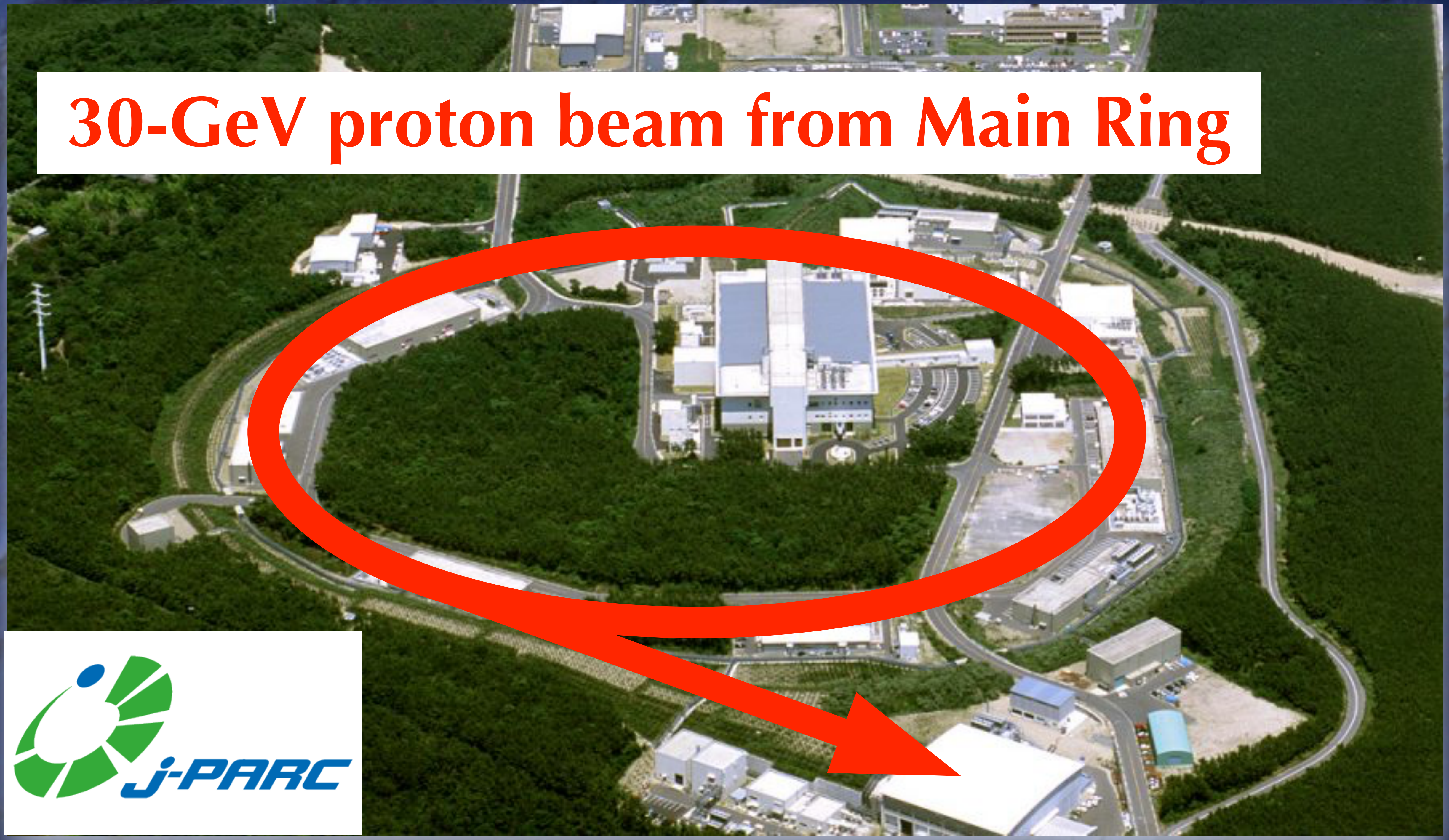
Experimental uppper limit on $BR(K_L \to \pi^0 \nu \bar{\nu})$



KOTO Experiment @ J-PARC

Japan | Korea | Taiwan | U.S.

J-PARC



Hadron Experimental Facility

Experimental Principle

Signature of the $K_L \to \pi^0 \nu \bar{\nu}$ decay:

$(\pi^0 \to)\ 2\gamma$ → calorimeter

Nothing else → veto

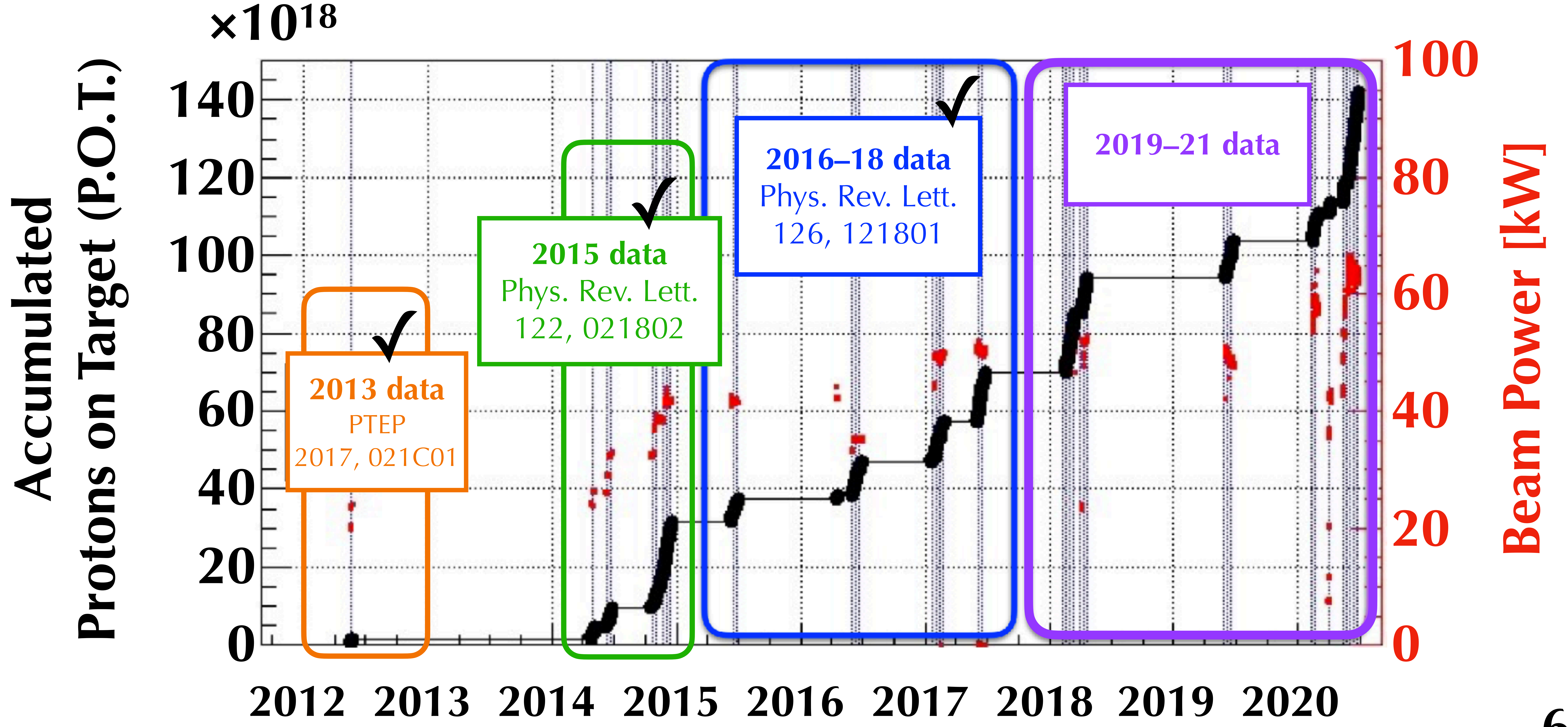
Reconstruction

Reconstruction of vertex

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

(assuming the vertex is on the beam axis)

Data Taking History



Results from 2016–2018 Data

[Phys. Rev. Lett. 126, 121801]

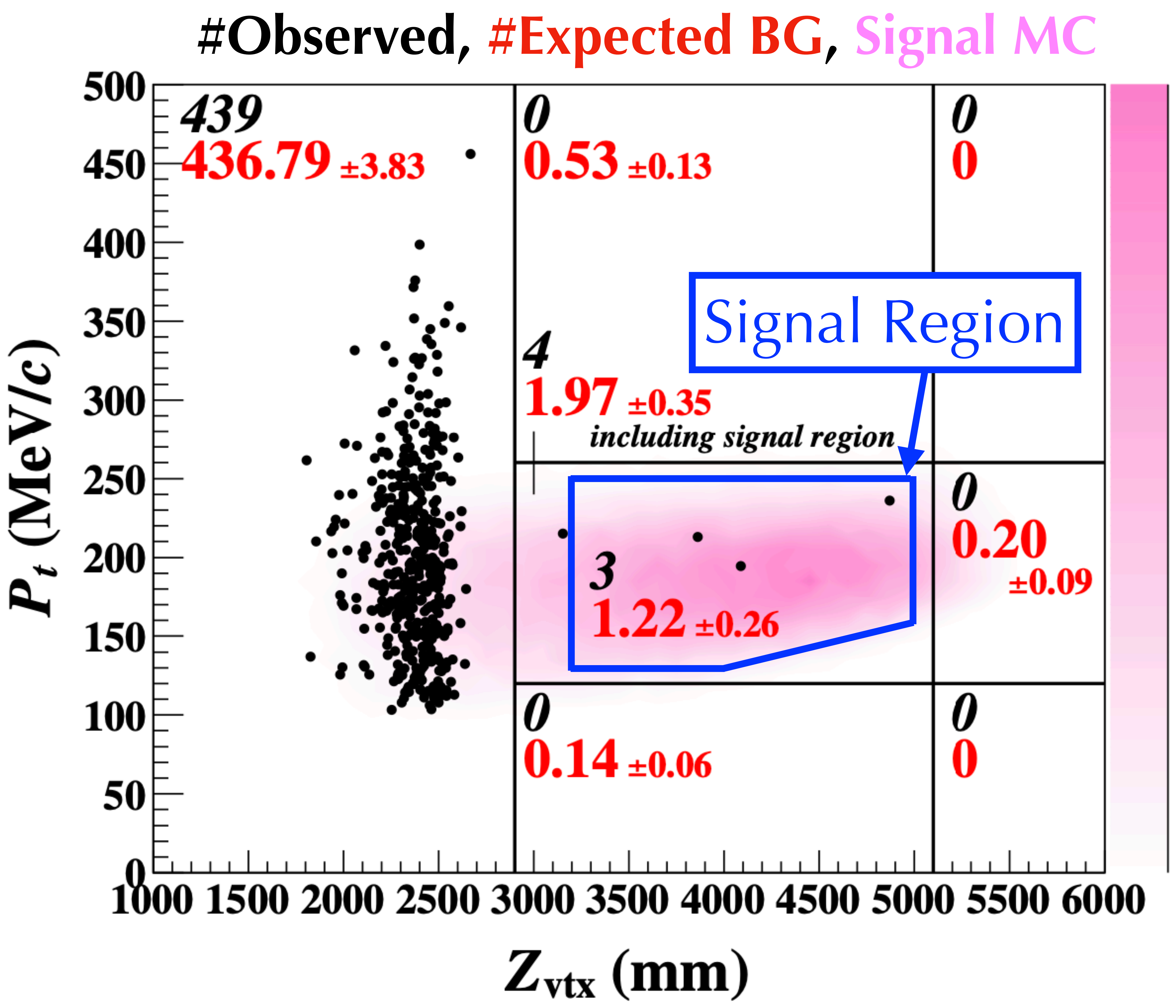
- Single Event Sensitivity (SES):

$$\mathrm{SES} = \frac{1}{N_{K_L} \times A_{signal}} = 7.2 \times 10^{-10}$$

- Observed 3 events ==> consistent to #BG

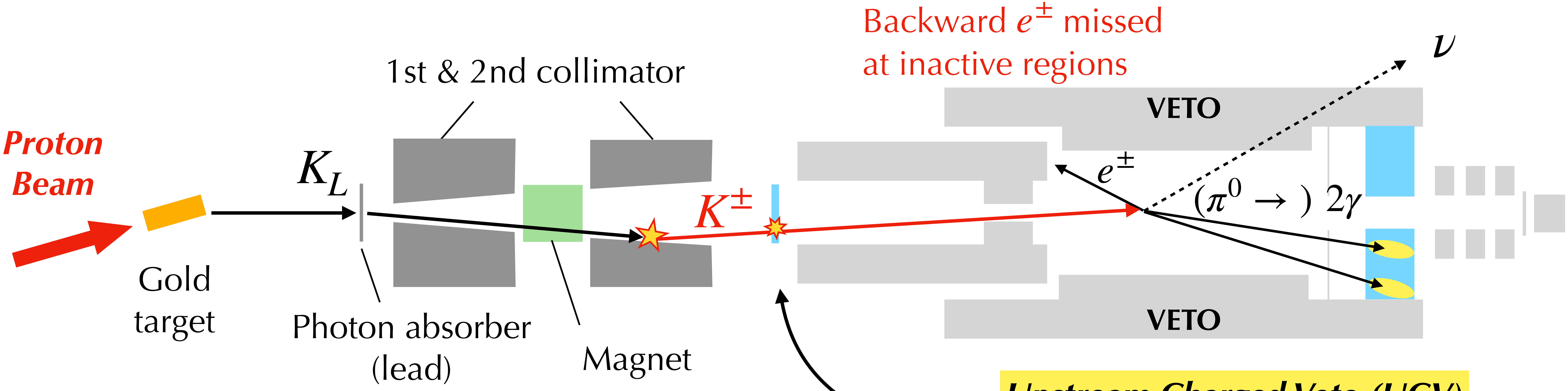
Total #BG in signal region	: **1.22 ± 0.26**
<u>Major background events</u>	
$K^{\pm}$	: 0.87 ± 0.25
$K_L \to 2\gamma$ (beam halo)	: 0.26 ± 0.07

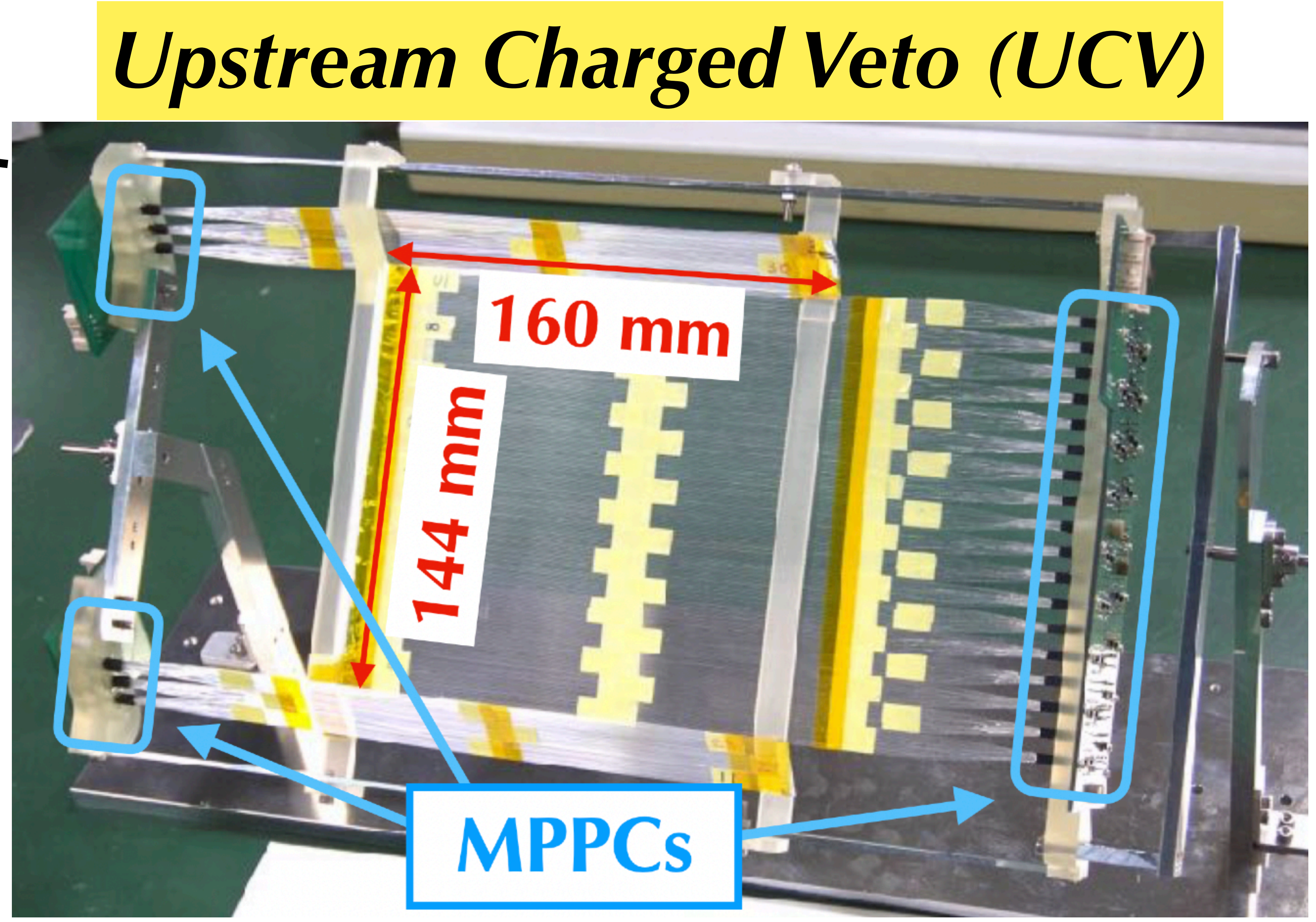
- Set an upper limit of $BR(K_L \to \pi^0 \nu \bar{\nu}) < 4.9 \times 10^{-9}$ (90% C.L.)



==> Need to reduce these dominant background events!

Reduction of $K^{\pm}$ Background





Installed a charged particle detector to veto $K^{\pm}$ (2021)

- 0.5-mm square scintillating fibers
- Readout by MPPCs(SiPM) from the fiber edge

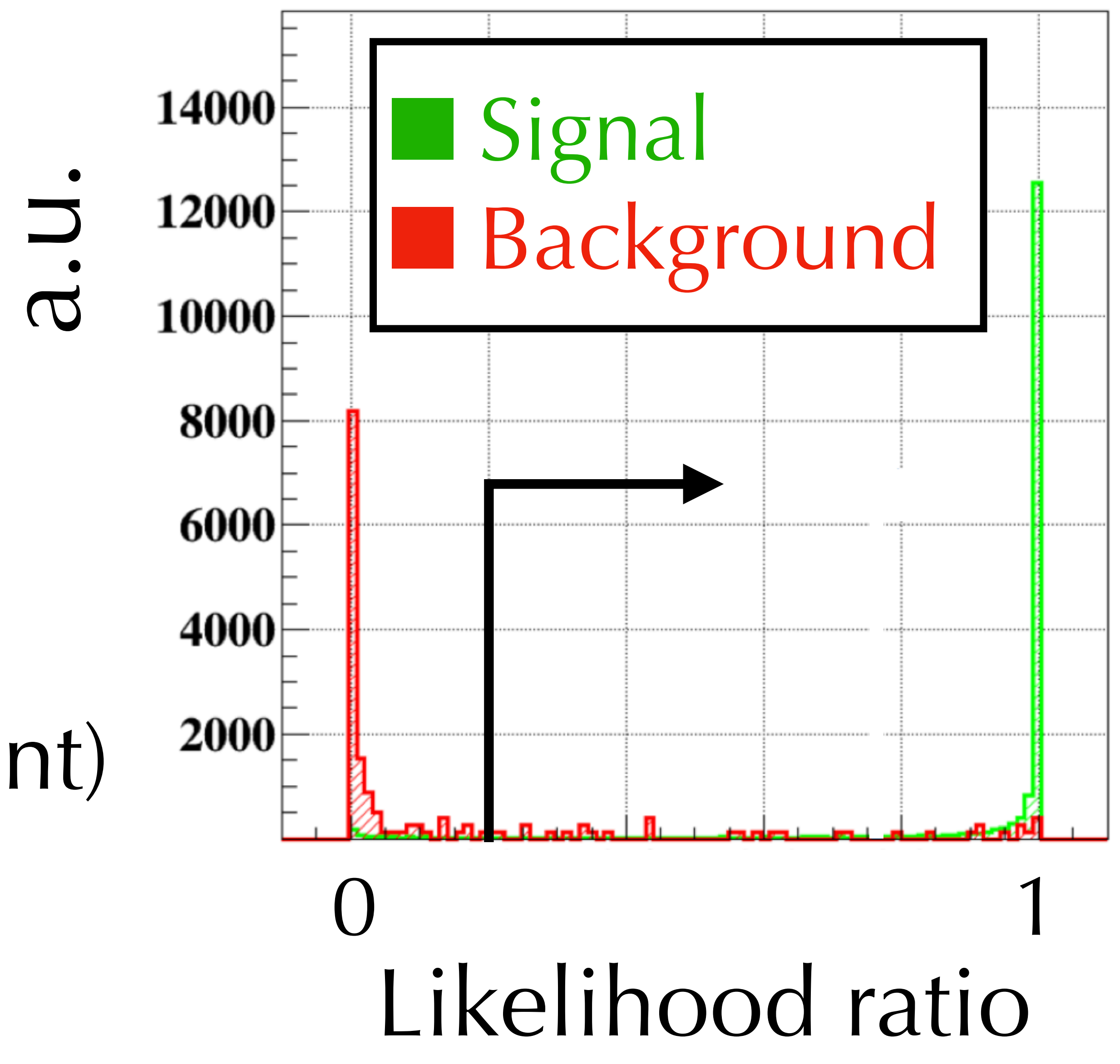
==> Reduced #BG($K^{\pm}$) by a factor of 13 with a signal efficiency of 96%

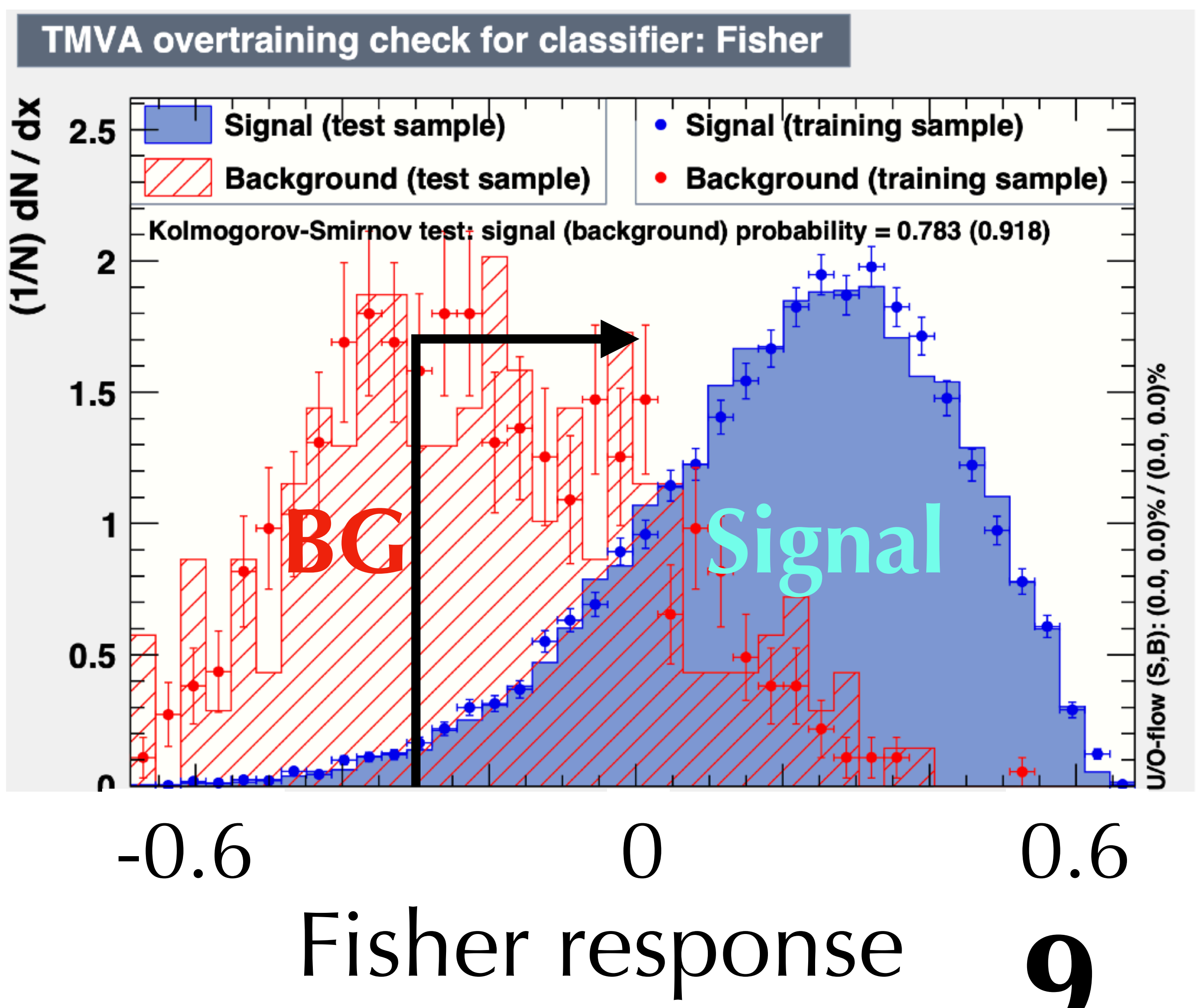
Reduction of Halo $K_L \to 2\gamma$ Background

Developed new analysis methods:

- Shower-shape consistency in the calorimeter
  → Likelihood ratio
- Kinematical distributions
  → Multivariate analysis (Fischer Discriminant)

==> Reduced #BG(Halo $K_L \to 2\gamma$) by a factor of 8 with a signal efficiency of 94%



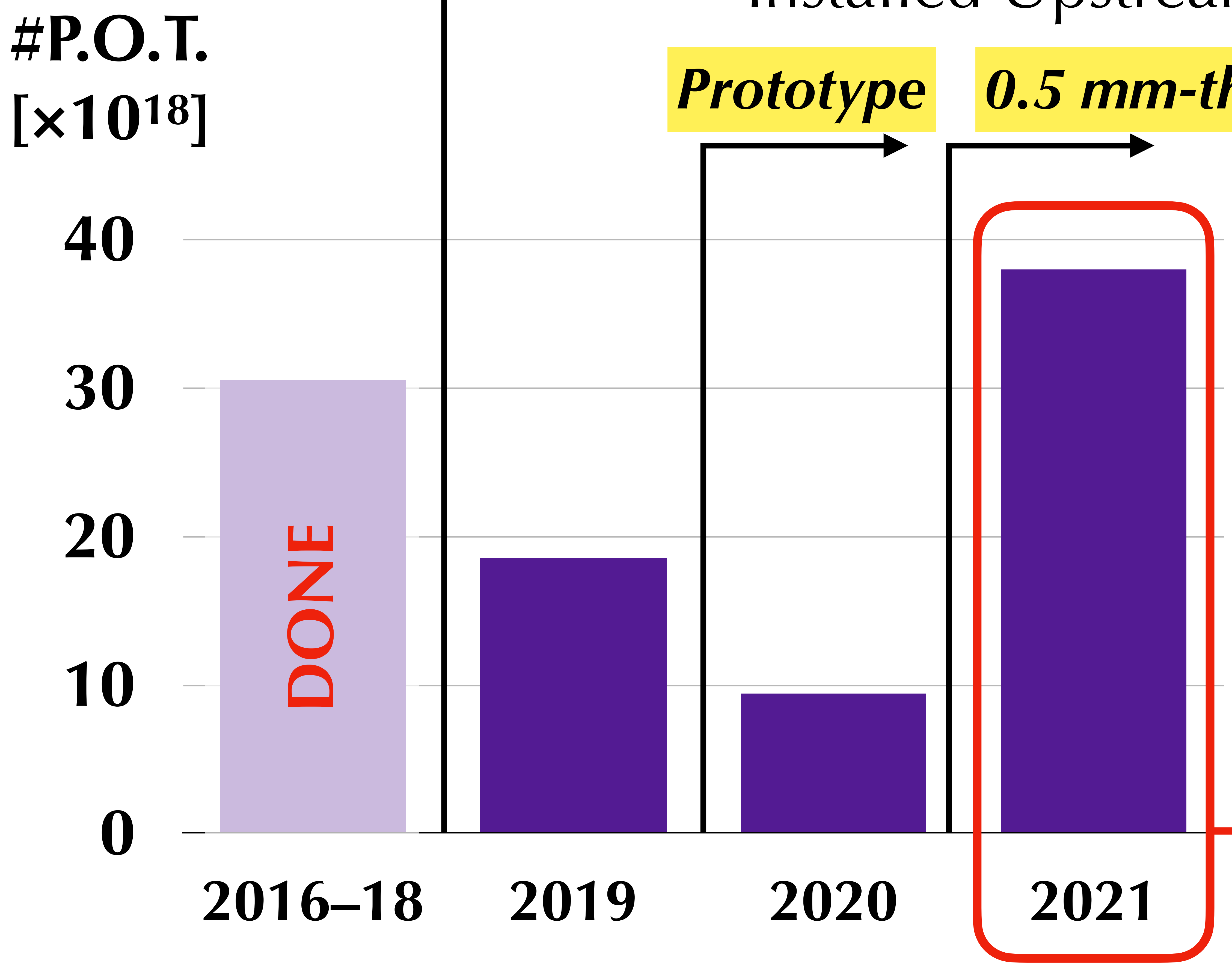


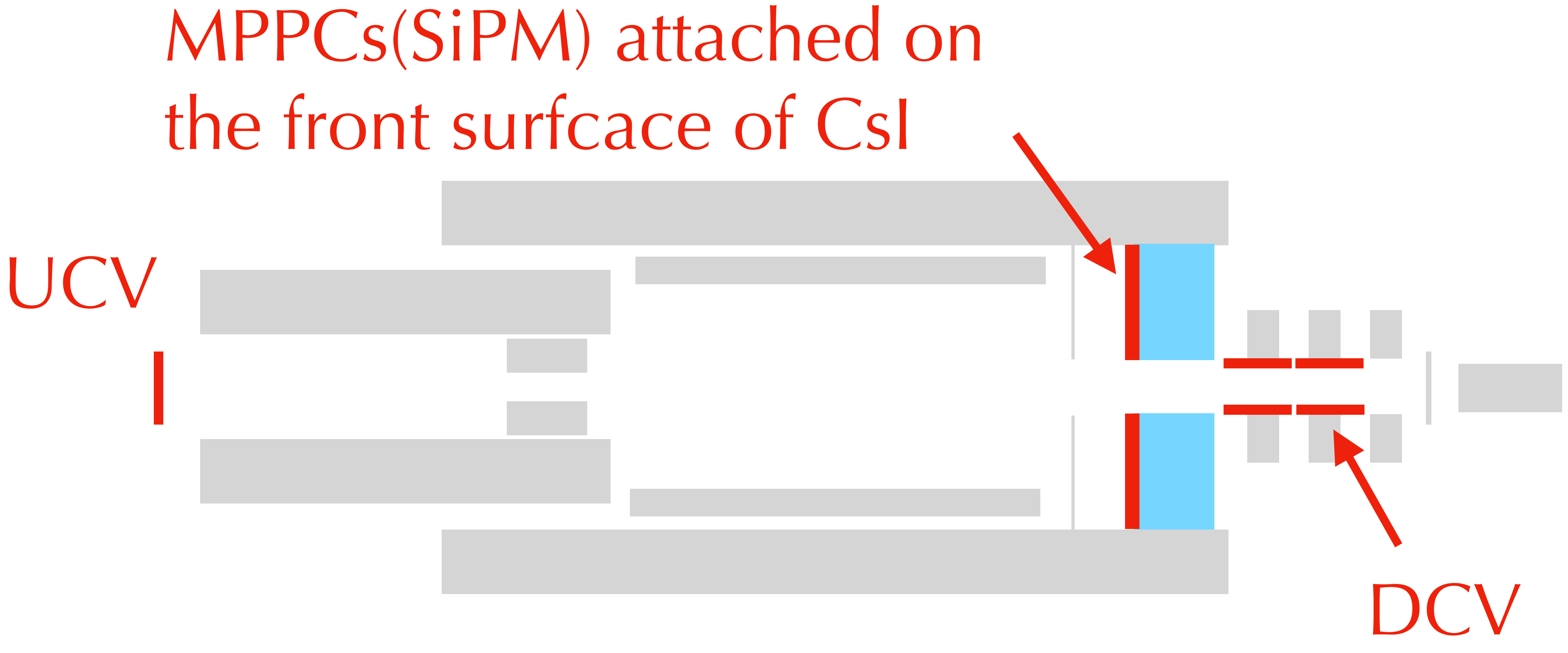
Analysis of 2021 Data

2021 Data

- Upgraded the calorimeter (CsI)
- Installed Downstream Charged Veto (DCV)
- Installed Upstream Charged Veto (UCV)

For background rejection





Our recent analysis focus

Executive Summary of the 2021 Data Analysis

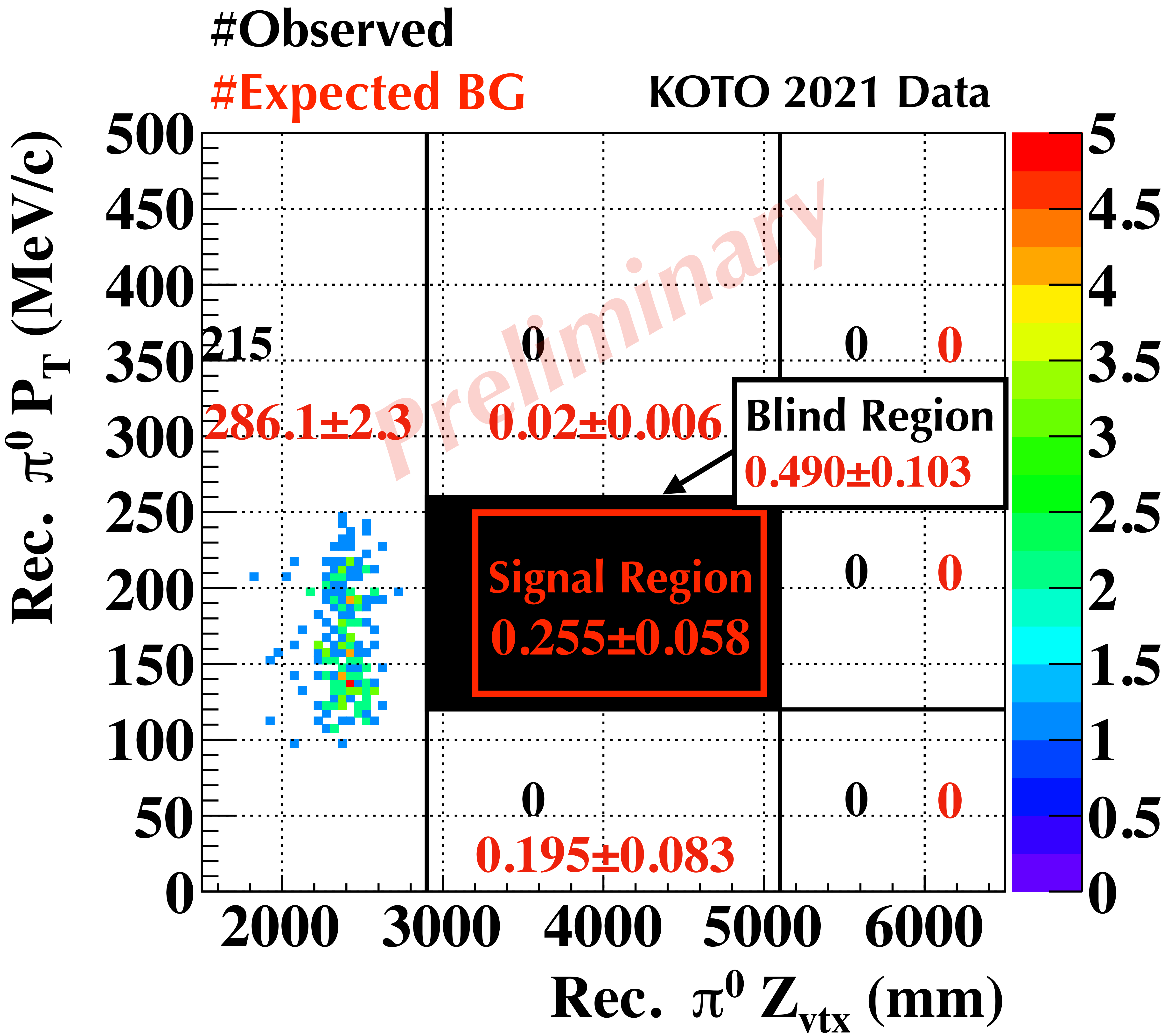
Single Event Sensitivity:

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

$(\mathrm{cf.\ SES}_{2016-18\ \mathrm{data}} = 7.2 \times 10^{-10})$

Background:

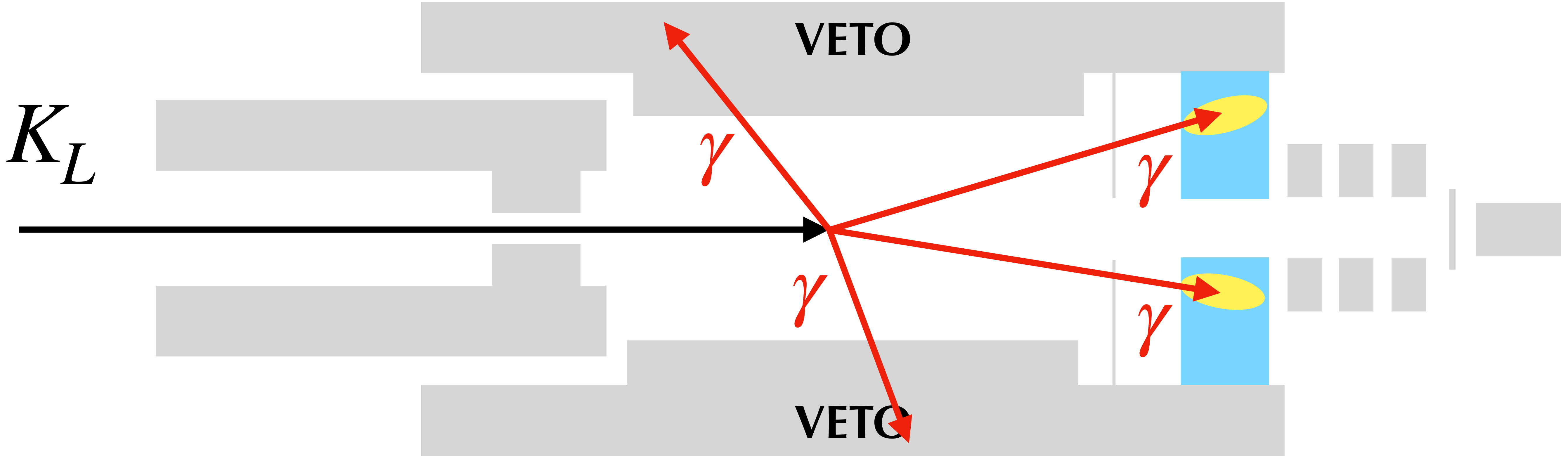
- Reduced the background contributions from $K^{\pm}$ and halo $K_L \to 2\gamma$
  - $N_{\mathrm{BG}}(K^{\pm}) < \mathcal{O}(10^{-1})$
  - $N_{\mathrm{BG}}(\mathrm{Halo}\ K_L \to 2\gamma) < \mathcal{O}(10^{-1})$
- Introduced data-driven evaluations for more accurate estimation



$K_L \to 2\pi^0$ Background

$K_L \to 2\pi^0$ (Br $= 8.64 \times 10^{-4}$)

- $2\gamma \to$ calorimeter
- $2\gamma \to$ missed ($\Leftrightarrow$ **must be vetoed**)



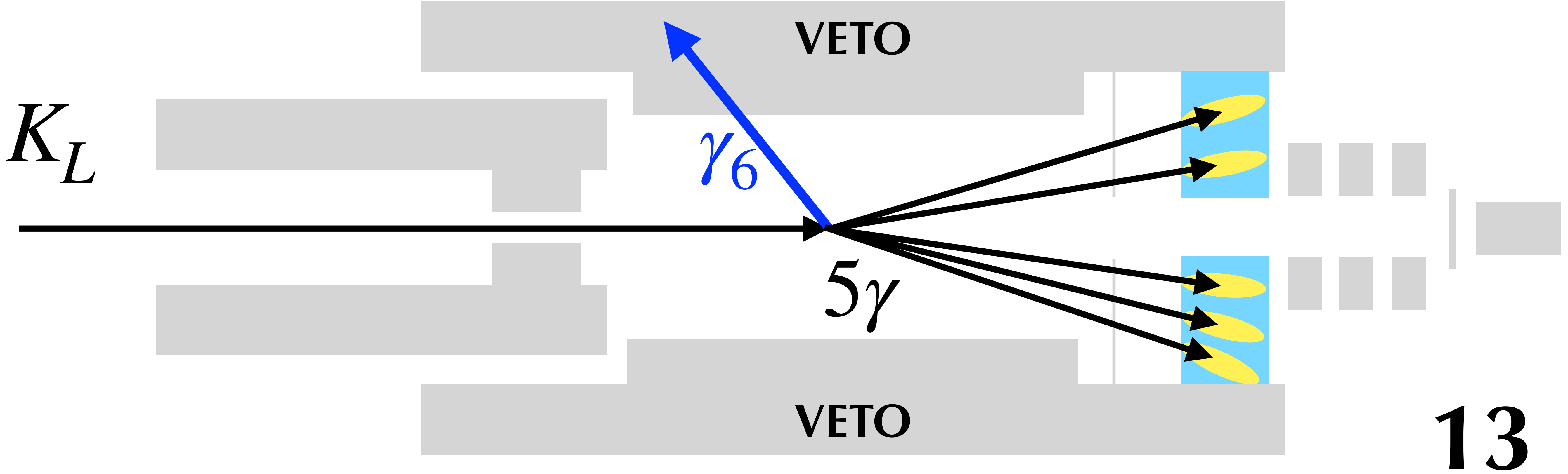
Key: Inefficiency of veto detectors

Geant4-based MC simulation shows version dependence in the inefficiency

Evaluated the inefficiency with $K_L \to 3\pi^0(\to 6\gamma)$ events

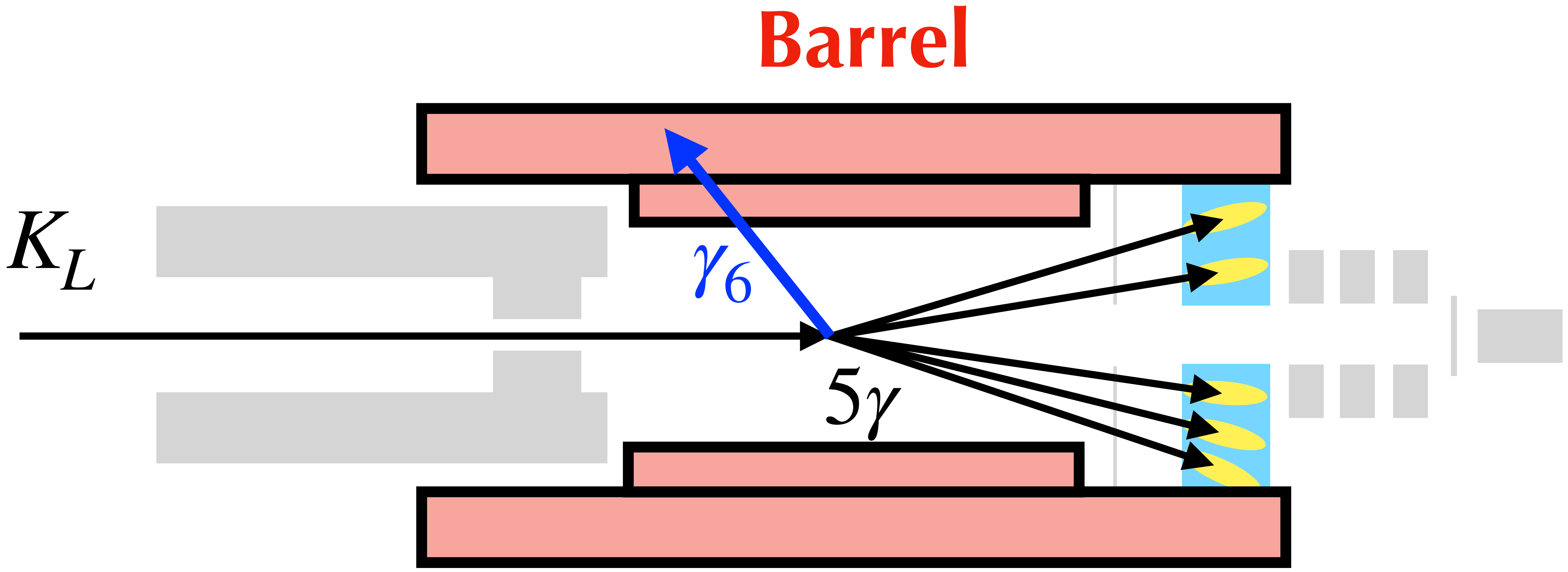
- $5\gamma \to$ calorimeter
- $\gamma_6 \to$ veto detector

$$\text{Inefficiency} = \frac{N_{E_{dep}<\text{threshold}}}{N_{5\gamma \text{ in CSI}}}$$



Evaluation of Inefficiency

In case of **barrel detectors** with $E_{\gamma_6} > 200$ MeV,

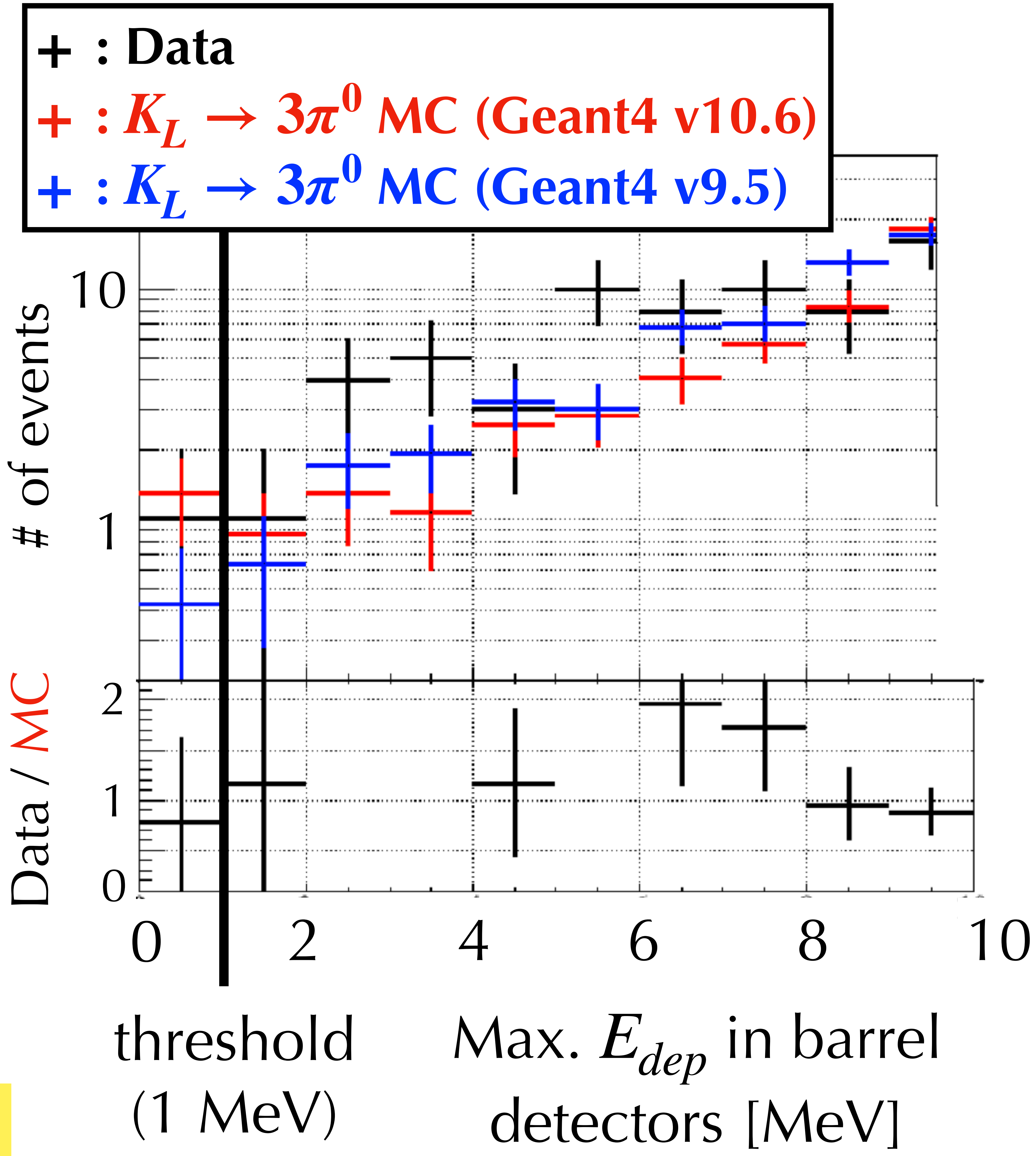


Inefficiency(Data) = $(4.8 \pm 4.8) \times 10^{-5}$

Inefficiency(MC) = $(6.2 \pm 2.5) \times 10^{-5}$ (G4 v10.6)

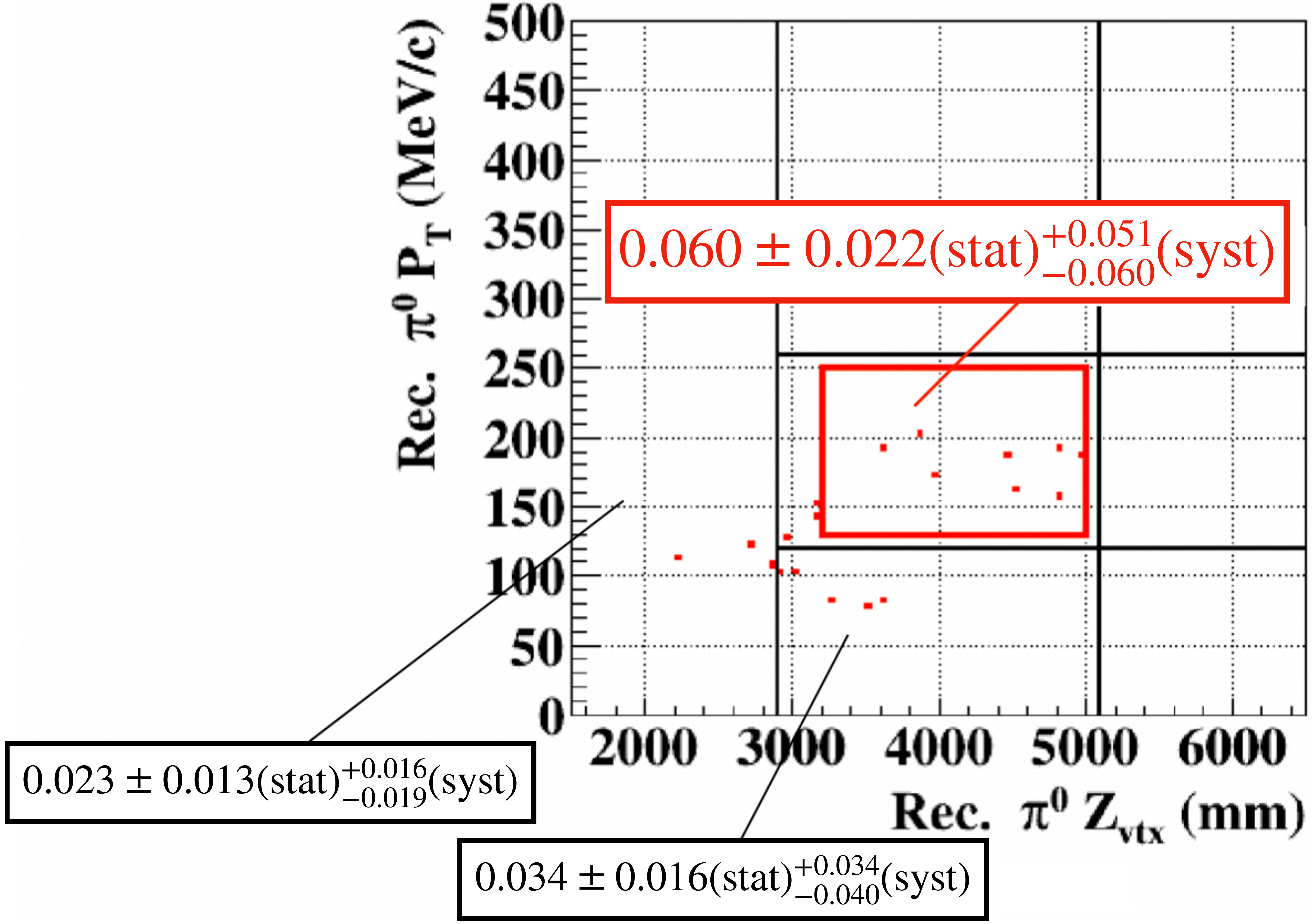
(We used Geant4 v10.6 in the 2021 data analysis)

Correction factor (= Ineff.(Data) / Ineff.(MC))
= 0.77 (with 100% systematic error from the statistics)



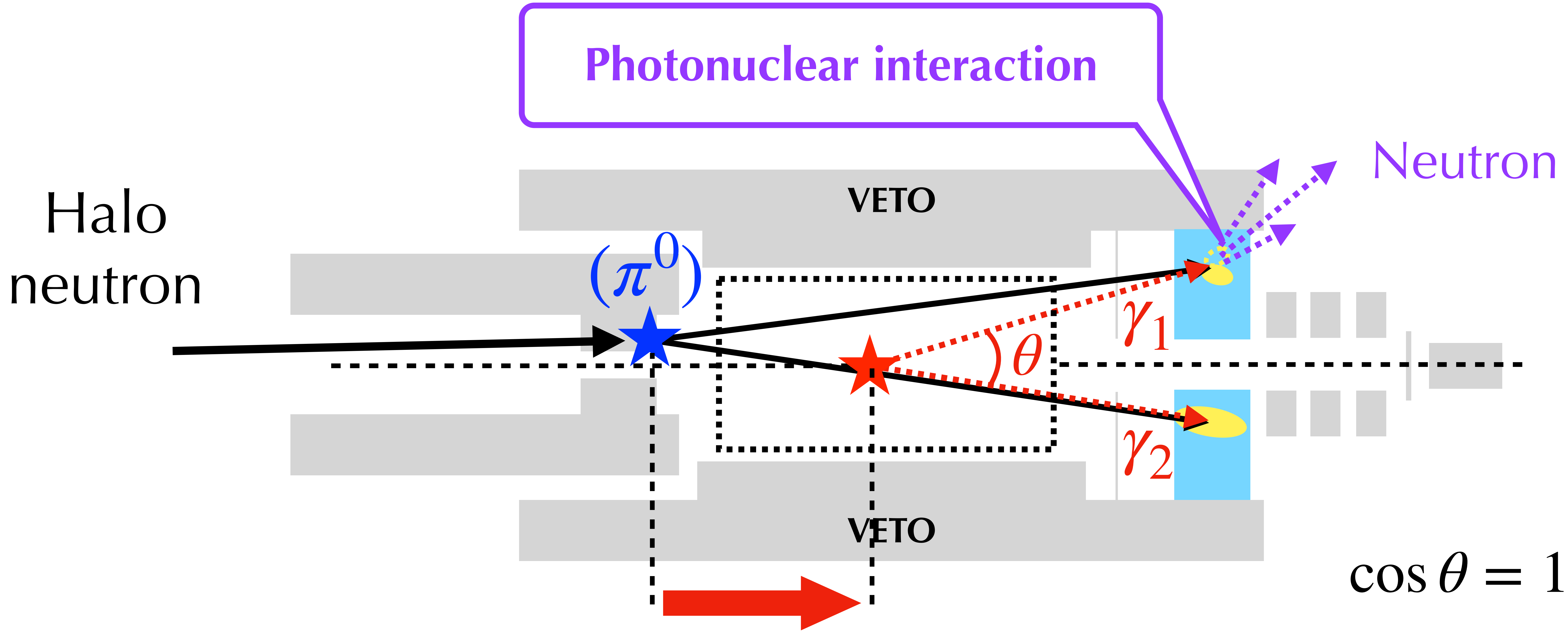
Number of $K_L \to 2\pi^0$ Background Events

$K_L \to 2\pi^0$ MC with all the event selection
(After $\#K_L$ normalization and inefficiency correction)



cf. $N_{\text{BG w/o correction}}(K_L \to 2\pi^0)$
$= 0.049 \pm 0.018(\text{stat})$

Upstream π^0 Background



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

Mis-measured $E_{\gamma_1(\gamma_2)}$

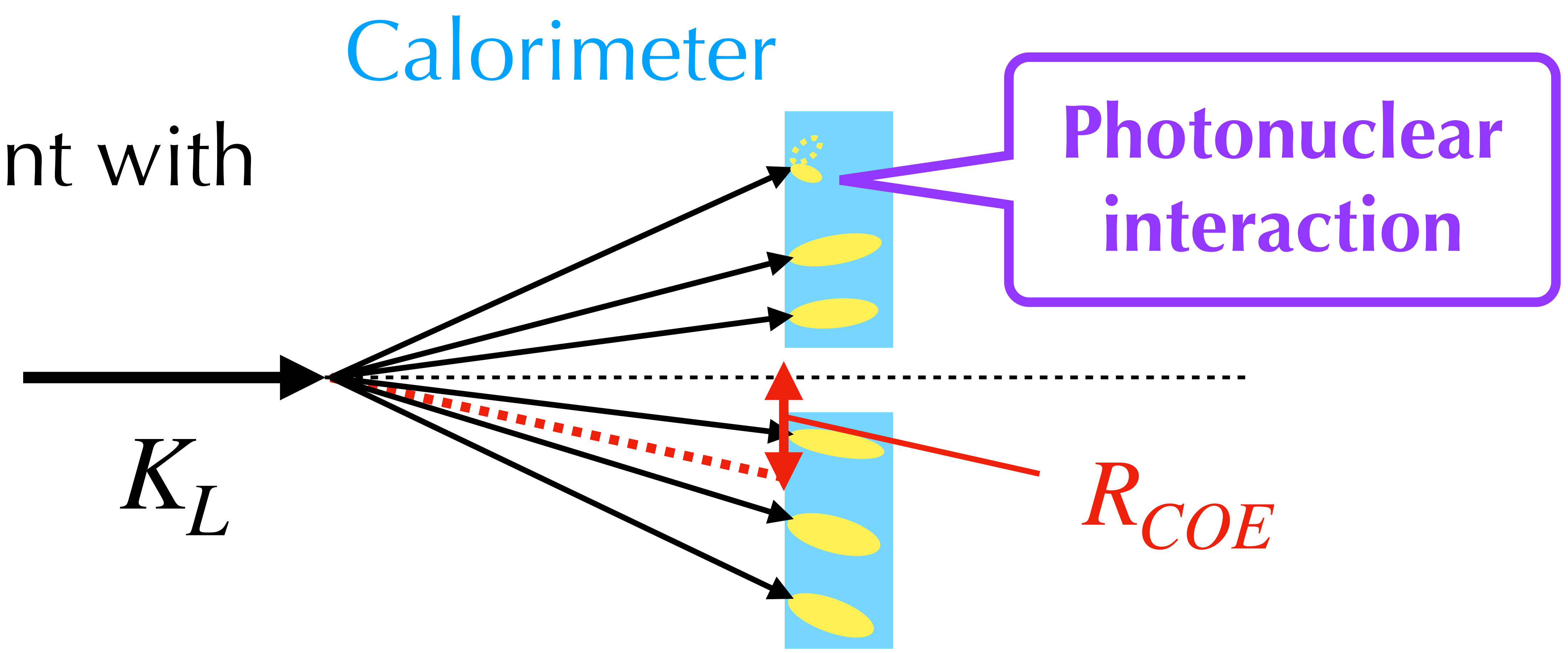
==> $Z_{\rm vtx}$ shifts downstream and can enter the signal region

Key: Probability of energy mis-measurement in calorimeter

Probability of Energy Mis-measurement

Evaluated the probability of energy mis-measurement with $K_L \rightarrow 3\pi^0(\rightarrow 6\gamma)$ events

- Reconstructed mass $M_{6\gamma} \neq M_{K_L}$
- Large center-of-energy radius (R_{COE})

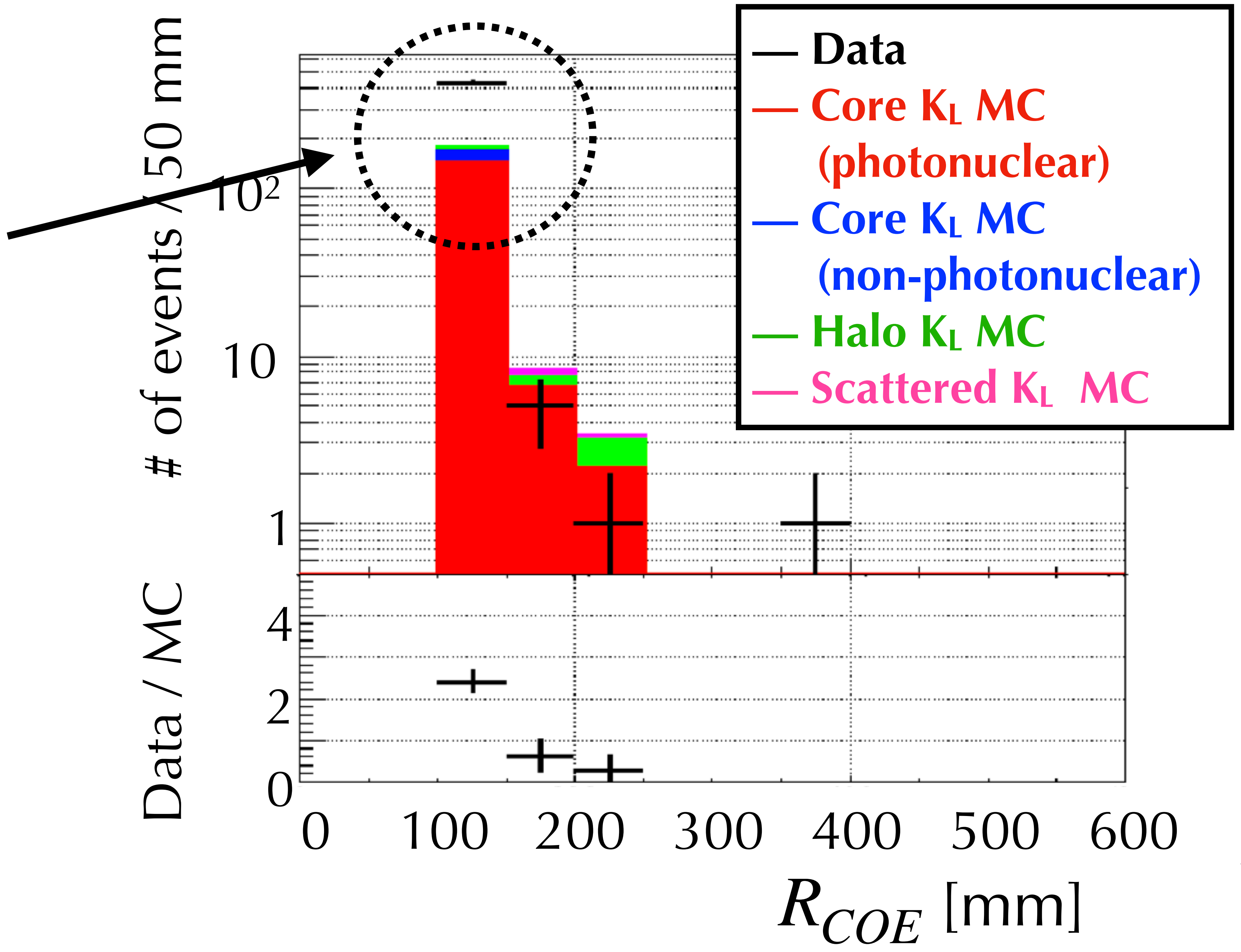


==> Enhanced events with a photonuclear interaction

Discrepancy between #events(data) and #events(MC)

Correction factor (= N_{Data} / N_{MC})
= 2.64 ± 0.35

==> Applied this correction factor in the background estimation of upstream-π^0

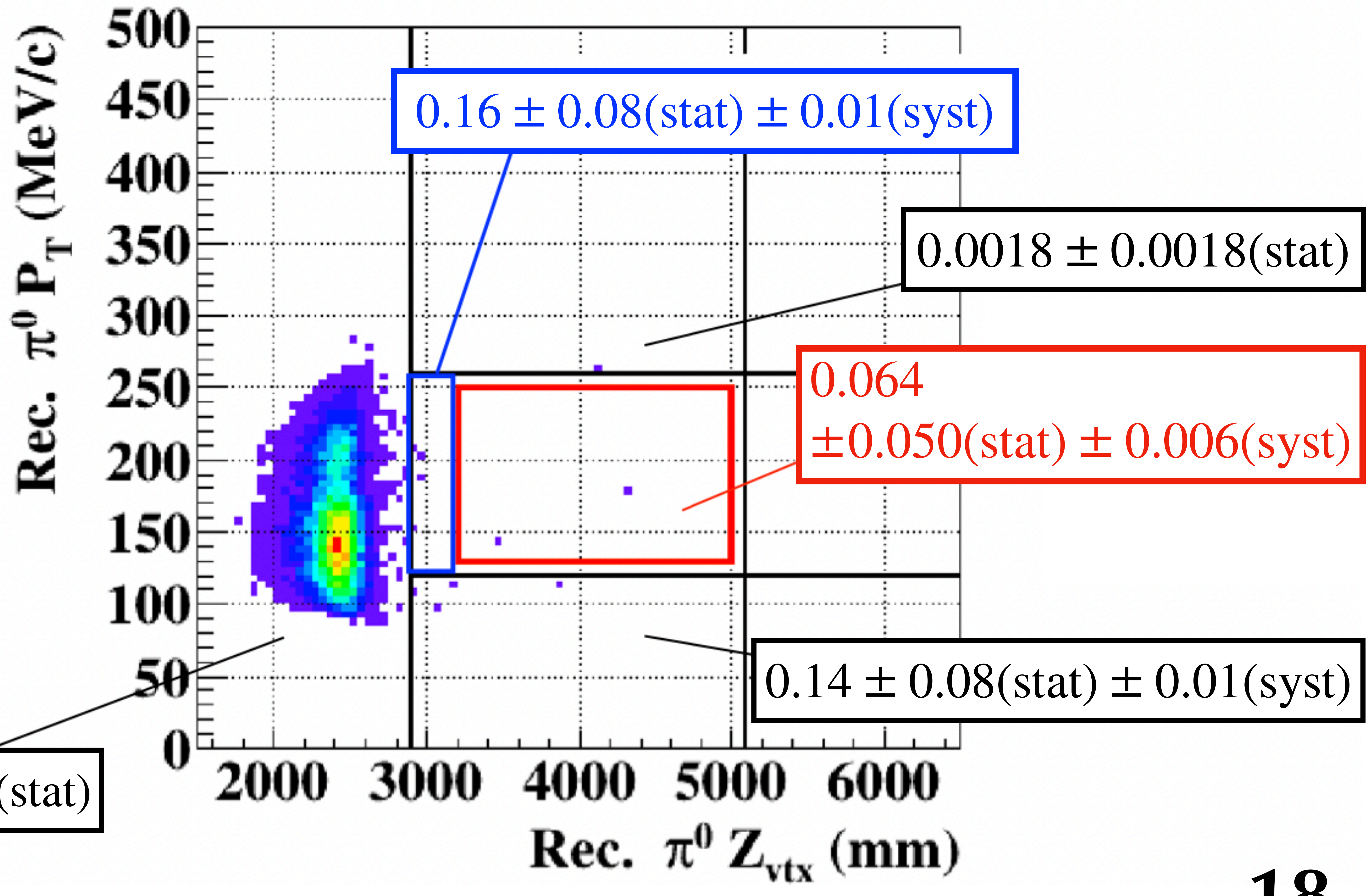


Number of Upstream π^0 Background Events

- MC was normalized with # of events in data in $Z_{vtx} < 2900$ mm under a loose cut condition
- 25% discrepancy in the upstream region comes from an imperfect reproducibility of π^0's kinematics in MC

cf.$N_{\text{BG w/o correction}}(\text{upstream } \pi^0)$
$= 0.035 \pm 0.025(\text{stat})$

Beam-halo neutron MC with all the event selection



$N_{obs} = 215$ ⬌ $286.1 \pm 2.3(\text{stat})$

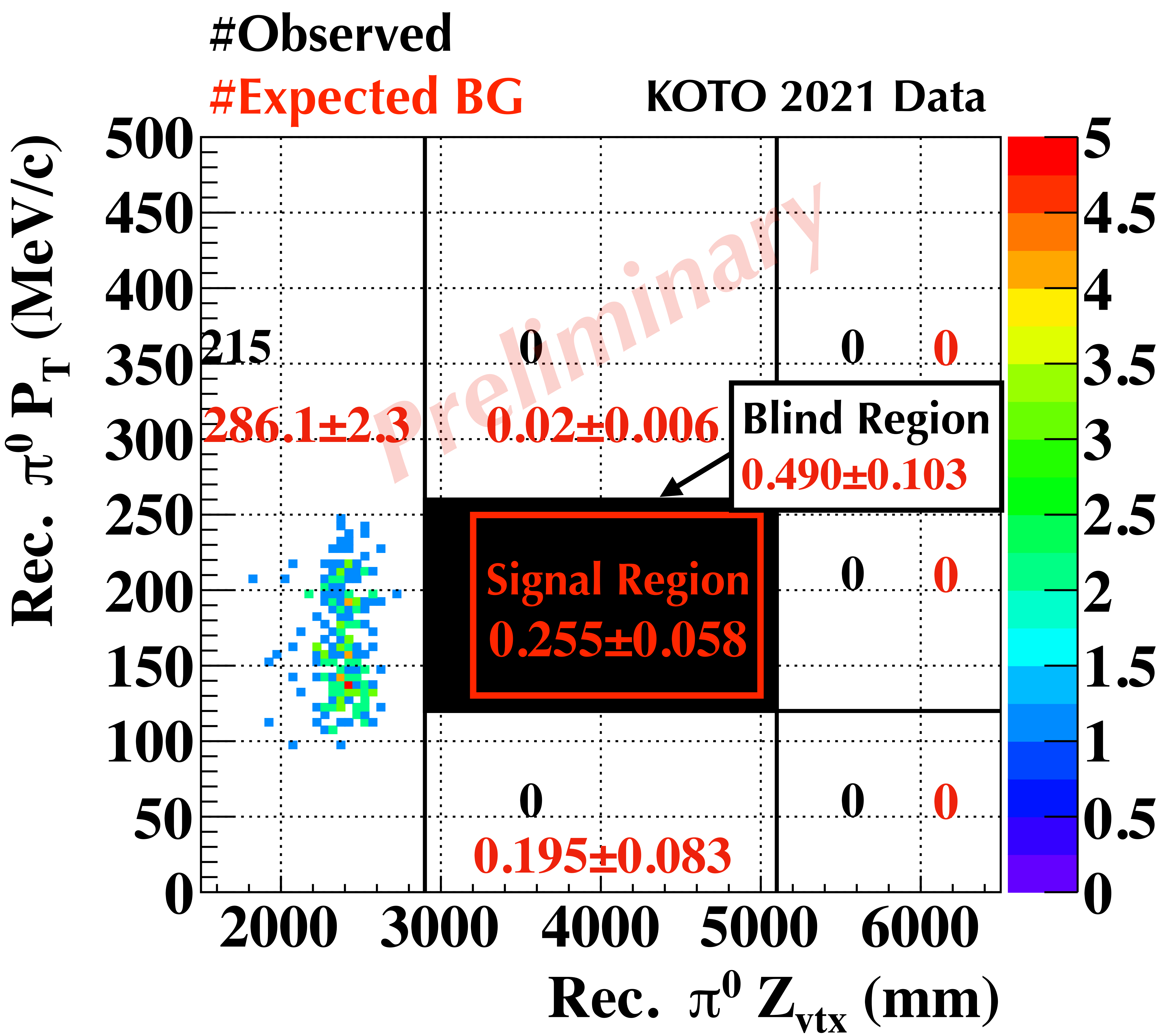
Summary of Background Estimation

Single Event Sensitivity (SES)

$$\text{SES} = 8.7 \times 10^{-10} \text{ (preliminary)}$$

Source	# of events in signal region
Upstream π^0	$0.064 \pm 0.050(\text{stat}) \pm 0.006(\text{syst})$
$K_L \to 2\pi^0$	$0.060 \pm 0.022(\text{stat})^{+0.051}_{-0.060}(\text{syst})$
$K^{\pm}$	$0.043 \pm 0.015(\text{stat})^{+0.004}_{-0.030}(\text{syst})$
Hadron cluster	$0.024 \pm 0.004(\text{stat}) \pm 0.006(\text{syst})$
η production in CV	$0.023 \pm 0.010(\text{stat}) \pm 0.006(\text{syst})$
Scattered $K_L \to 2\gamma$	$0.022 \pm 0.005(\text{stat}) \pm 0.004(\text{syst})$
Halo $K_L \to 2\gamma$	$0.018 \pm 0.007(\text{stat}) \pm 0.004(\text{syst})$
Total	$\mathbf{0.255 \pm 0.058(\text{stat})^{+0.053}_{-0.068}(\text{syst})}$

Preliminary



Result

KOTO 2021 data analysis

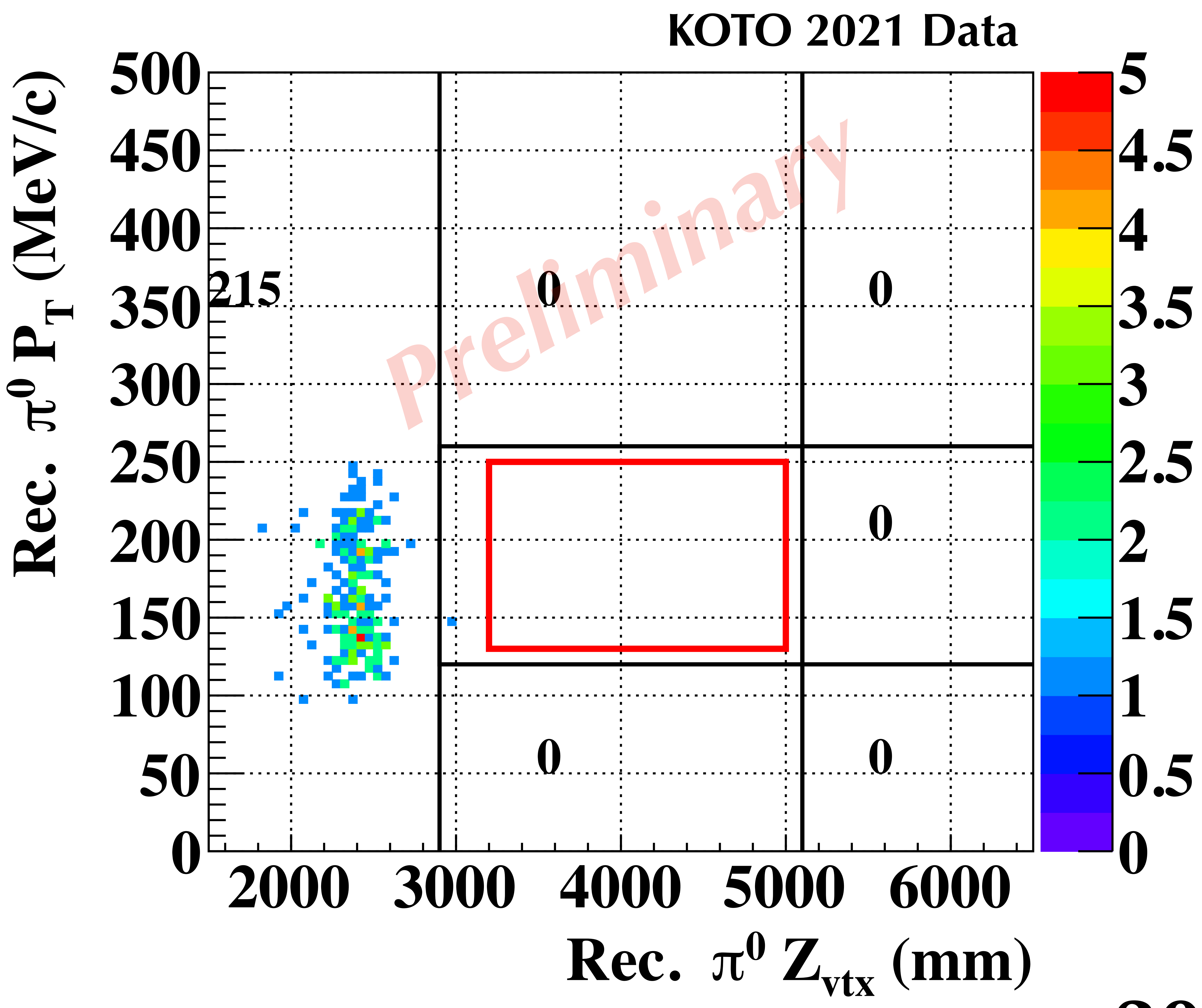
Single Event Sensitivity:

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

Number of backgound events:

$N_{\mathrm{BG}} = 0.255 \pm 0.058(\mathrm{stat})^{+0.053}_{-0.068}(\mathrm{syst})$

Observed no candidate events in the signal region



Result

KOTO 2021 data analysis

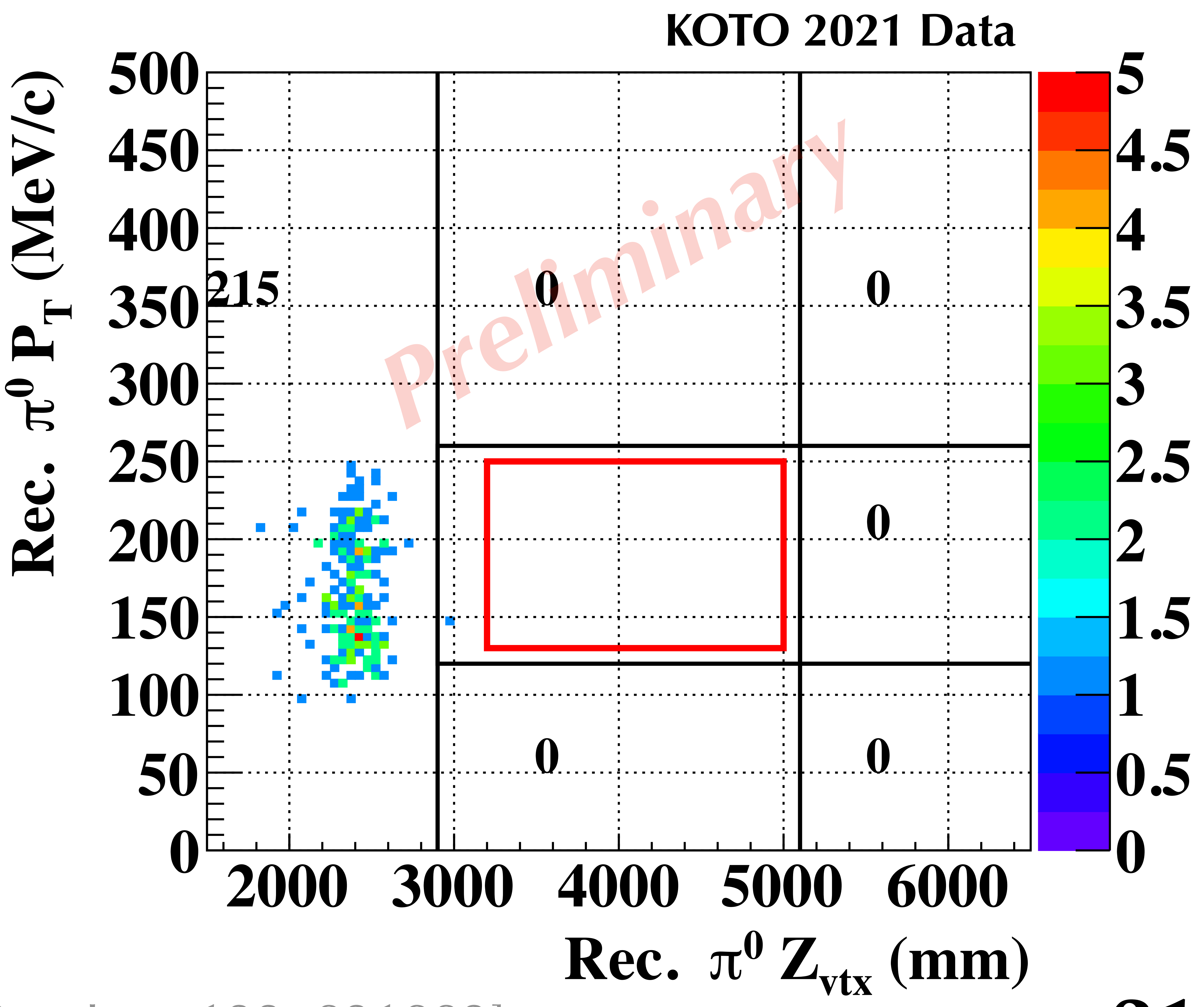
Single Event Sensitivity:

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

Number of backgound events:

$N_{\mathrm{BG}} = 0.255 \pm 0.058(\mathrm{stat})^{+0.053}_{-0.068}(\mathrm{syst})$

$BR(K_L \to \pi^0 \nu \bar{\nu}) < 2.0 \times 10^{-9}$
at 90% C.L. (preliminary)

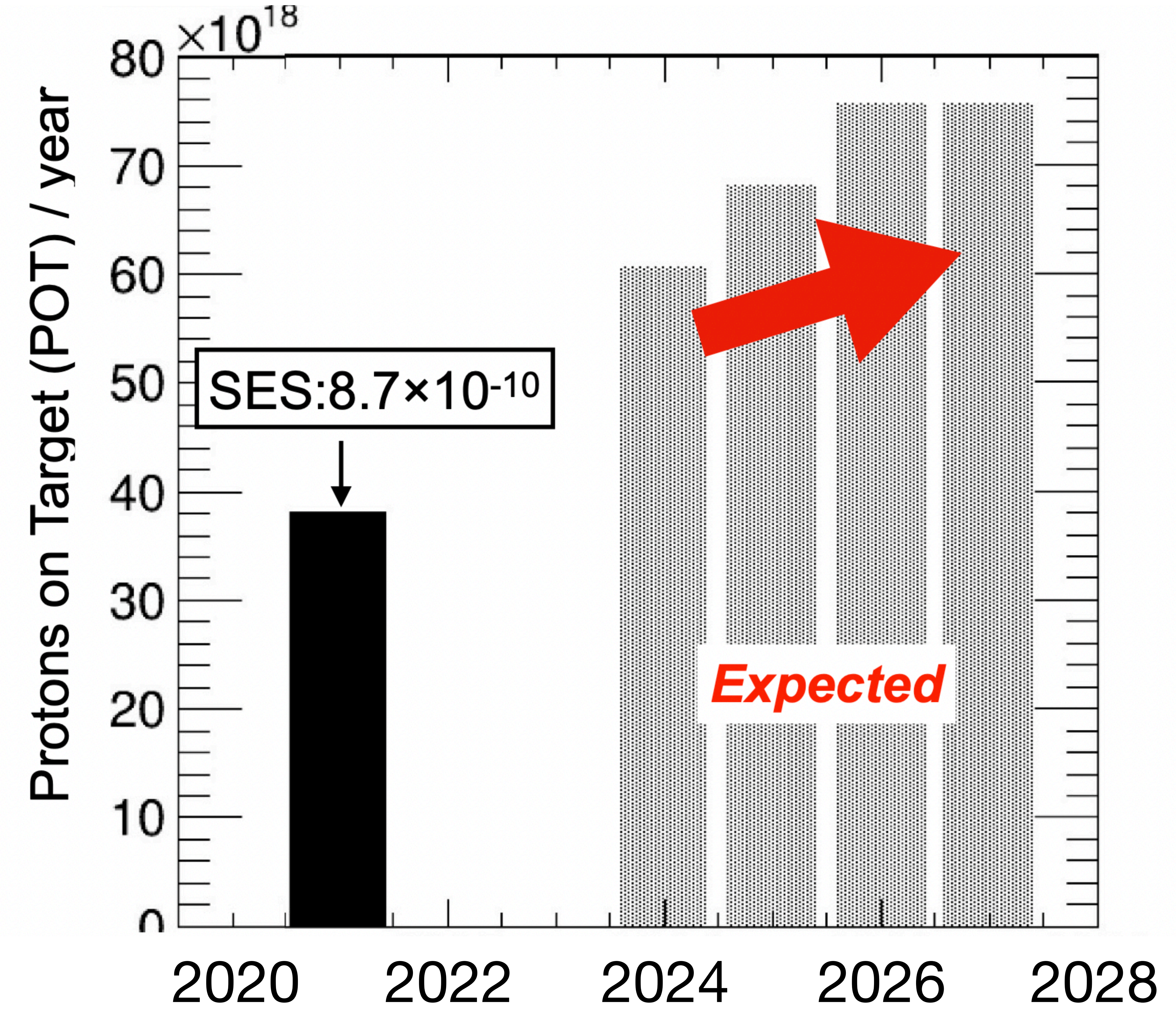


cf. Previous upper limit:
3.0×10^{-9} at 90% C.L. (KOTO 2015 data) [Phys. Rev. Lett. 122, 021802]

Prospect

Future Sensitivity in KOTO

KOTO aims to reach sensitivity < 10^{-10} in 3–4 years



We will collect 10 times more POT assuming,

- 80–100 kW beam intensity (64.5 kW in 2021)
- 60 days/year beam time

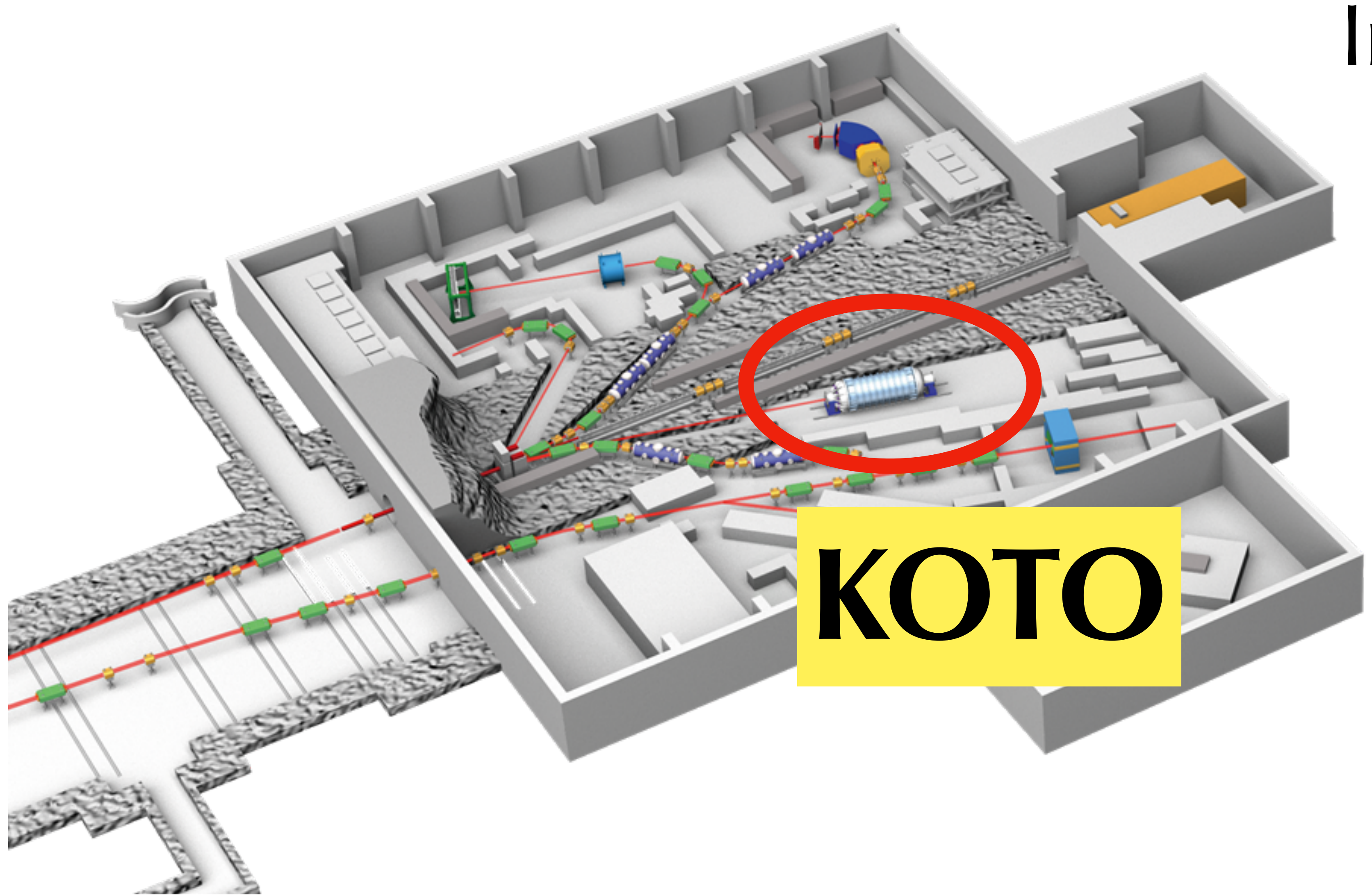
Next Step

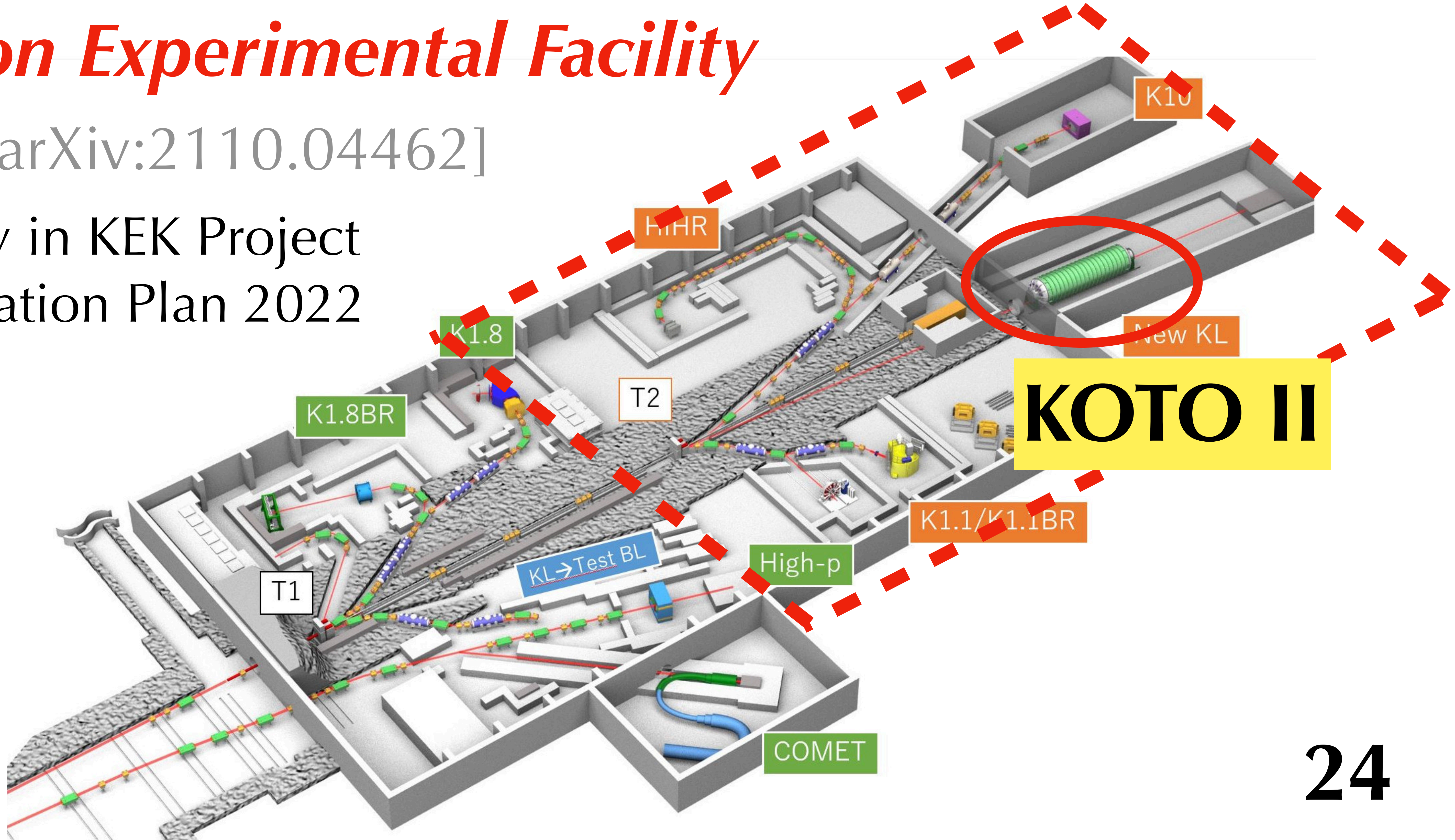
KOTO ➡ KOTO II

Extension of Hadron Experimental Facility

White paper [arXiv:2110.04462]

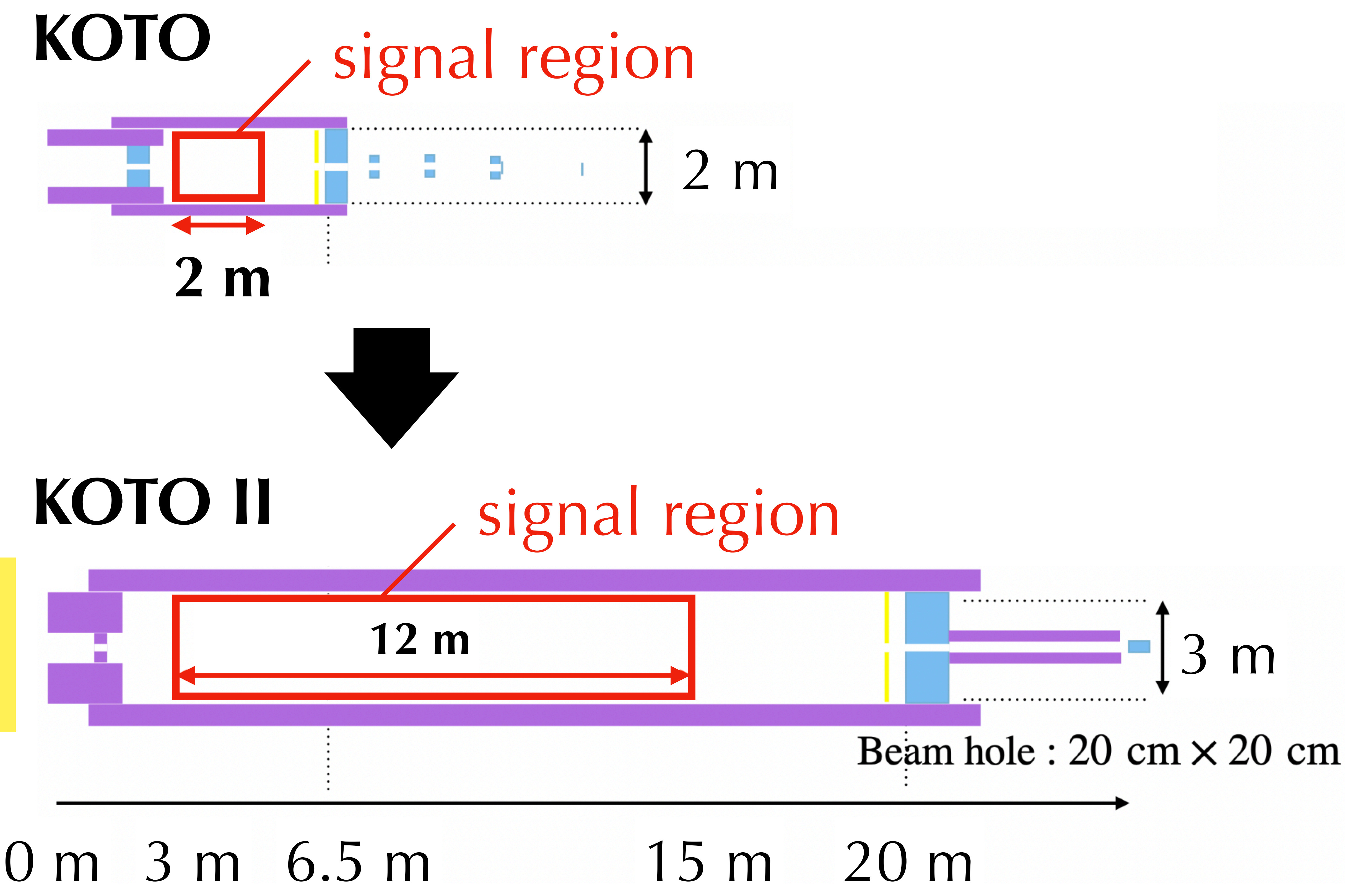
Top priority in KEK Project
Implementation Plan 2022





KOTO II @ Extended Hadron Exp. Facility

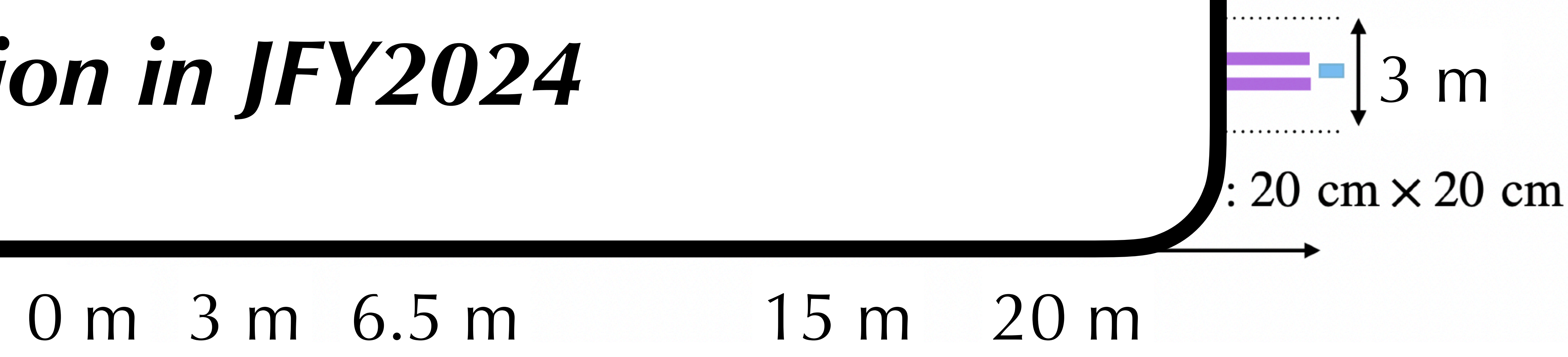
Smaller extraction angle (16° for KOTO → 5° for KOTO II)
==> Higher momentum K_L
==> Larger decay volume
==> More signal acceptance



KOTO II @ Extended Hadron Exp. Facility

- 100 kW beam, $3 \times 10^7\ s = 6.3 \times 10^{20}$ POT
- $\mathrm{SES} = 8.5 \times 10^{-13}$
- 35 SM signal / 40 background events
- 5.6σ observation of $K_L \to \pi^0 \nu \bar{\nu}$
- $\Delta BR/BR = 25\%$ for $BR_{SM}(K_L \to \pi^0 \nu \bar{\nu})$
- 44% deviation from SM → 90%-CL indication of NP

Preparing for proposal submission in JFY2024



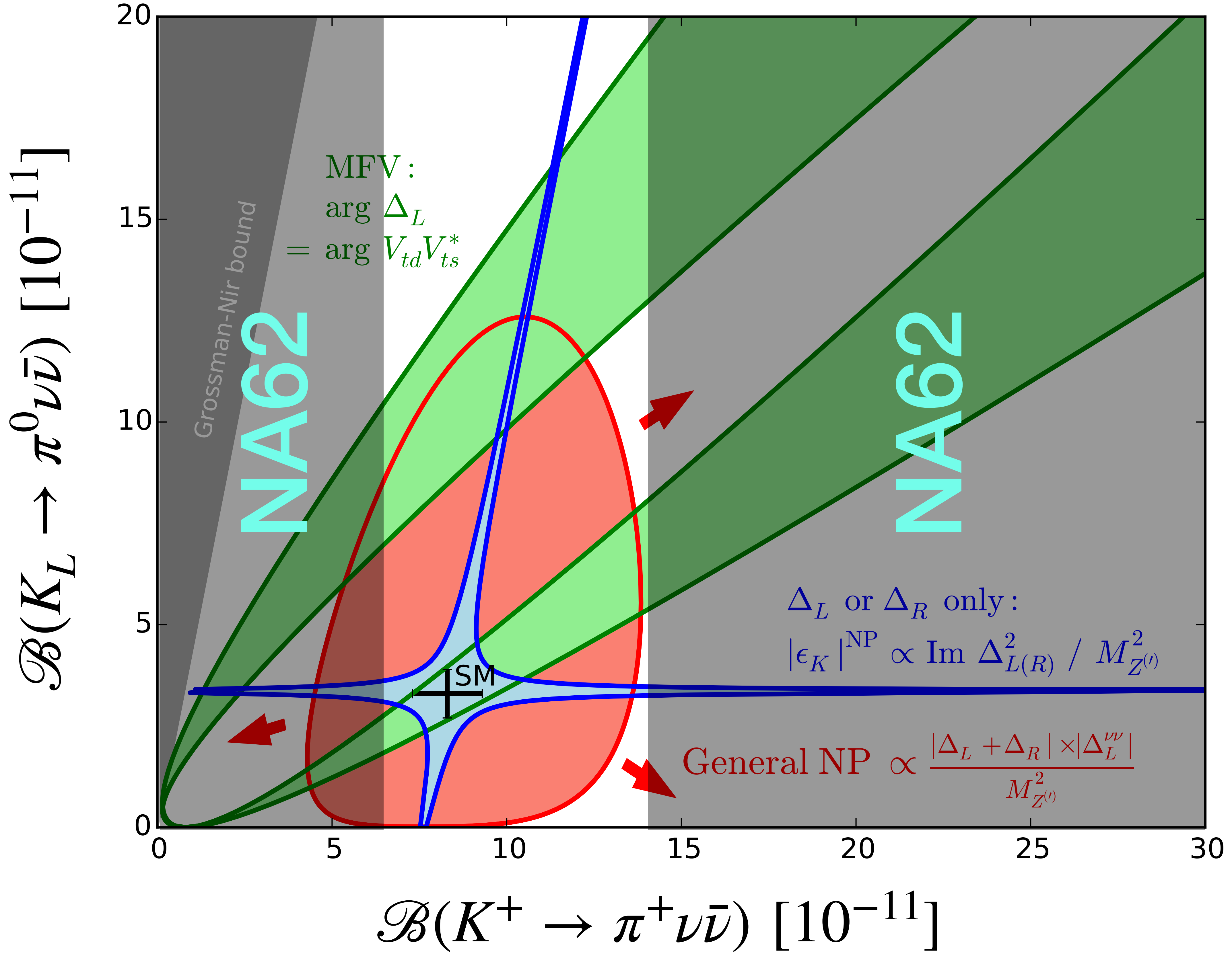
Summary

- KOTO 2021 data achieved $\mathrm{SES} = 8.7 \times 10^{-10}$ (preliminary)
- Observed no candidate events
  ==> New upper limit was obtained as
  $BR(K_L \to \pi^0 \nu \bar{\nu}) < 2.0 \times 10^{-9}$ at 90% C.L. (preliminary)
  (Preparing a paper for the 2021 data analysis)
- We will continue data taking for 3–4 years to achieve $\mathrm{SES} < 10^{-10}$
- We are preparing for KOTO II which aims to observe >30 SM events

Backup

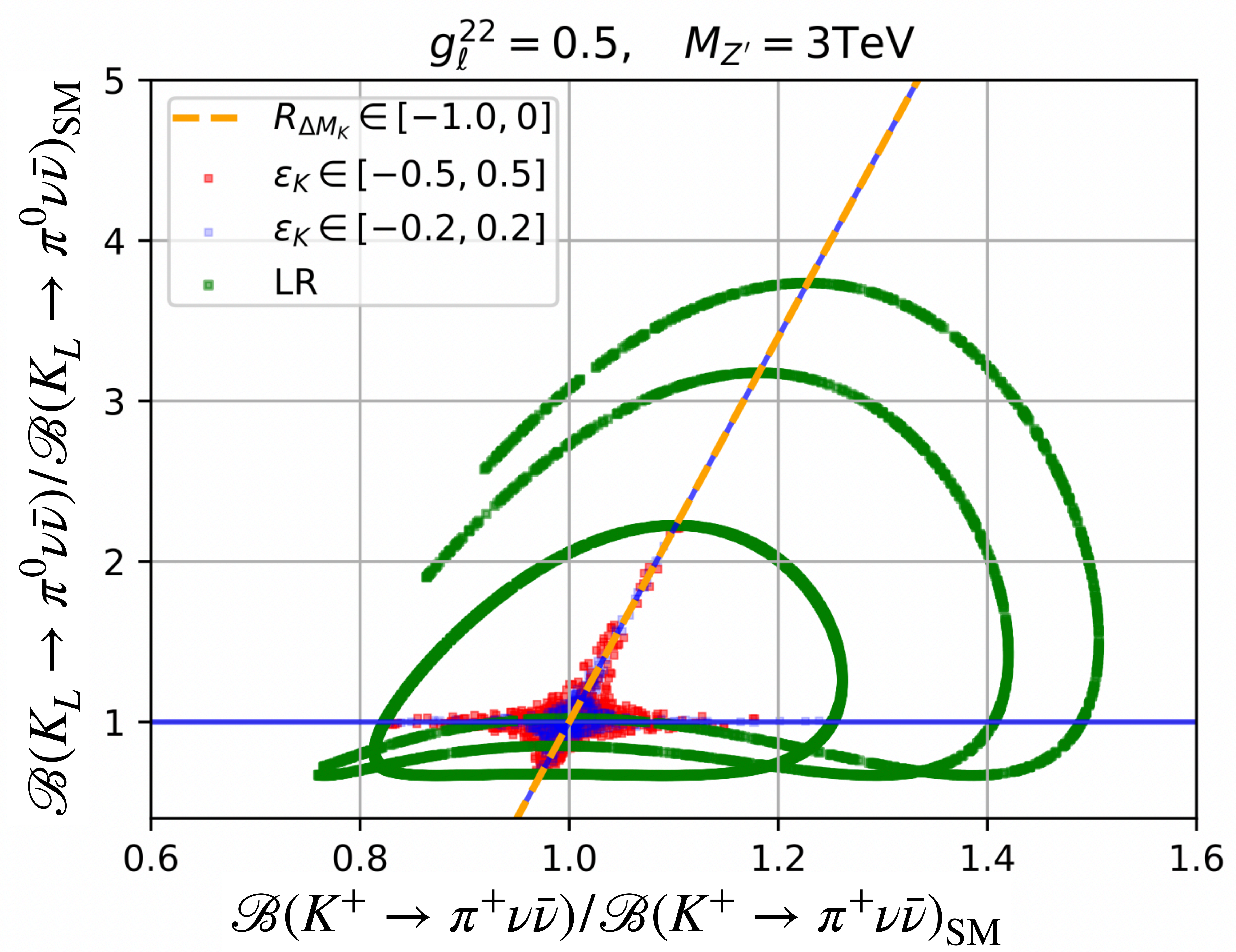
New Physics Models

[JHEP11(2015)166]



e.g. 3 TeV Z′ model

[JHEP12(2020)097]



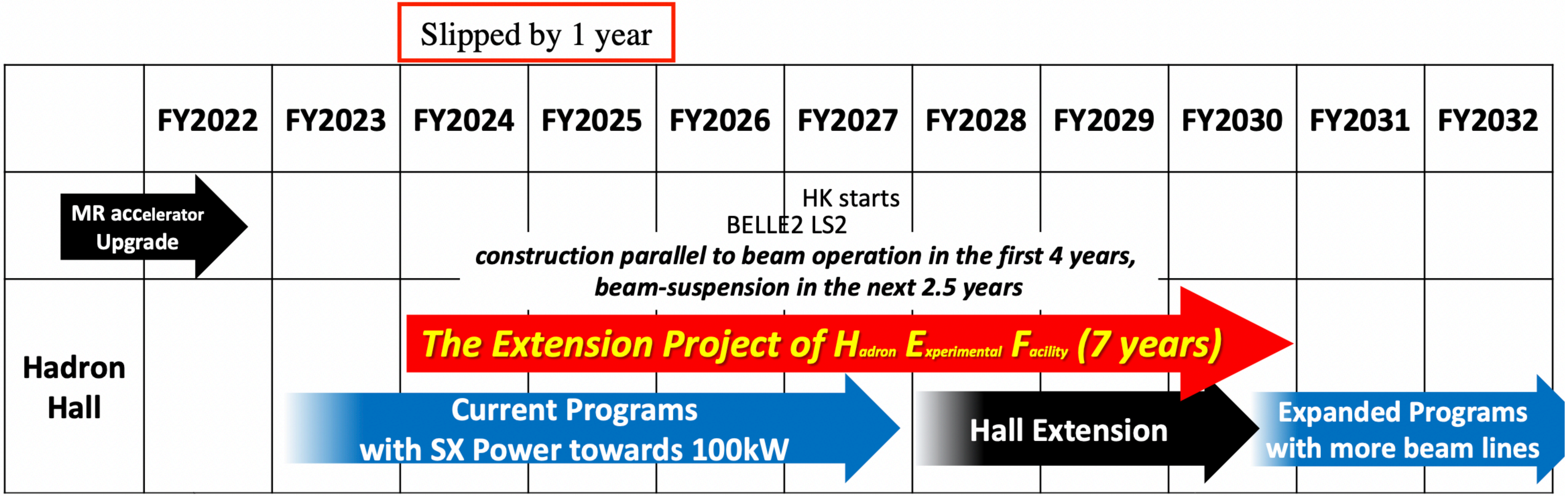
NA62 [JHEP06(2021)093]

$\mathscr{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\rm stat} \pm 0.9_{\rm syst}) \times 10^{-11}$ @68% CL

KOTO Detector

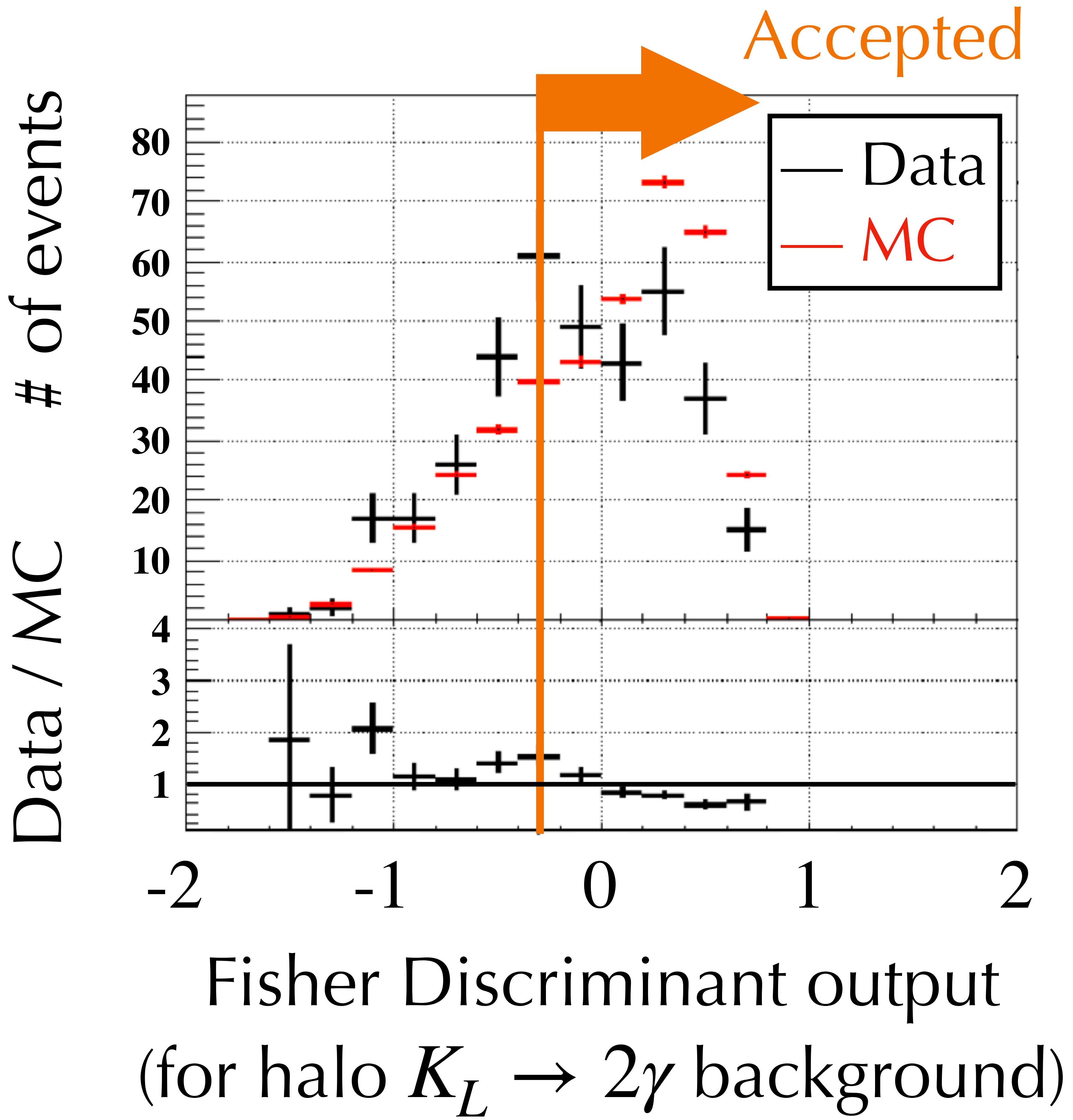
Timeline

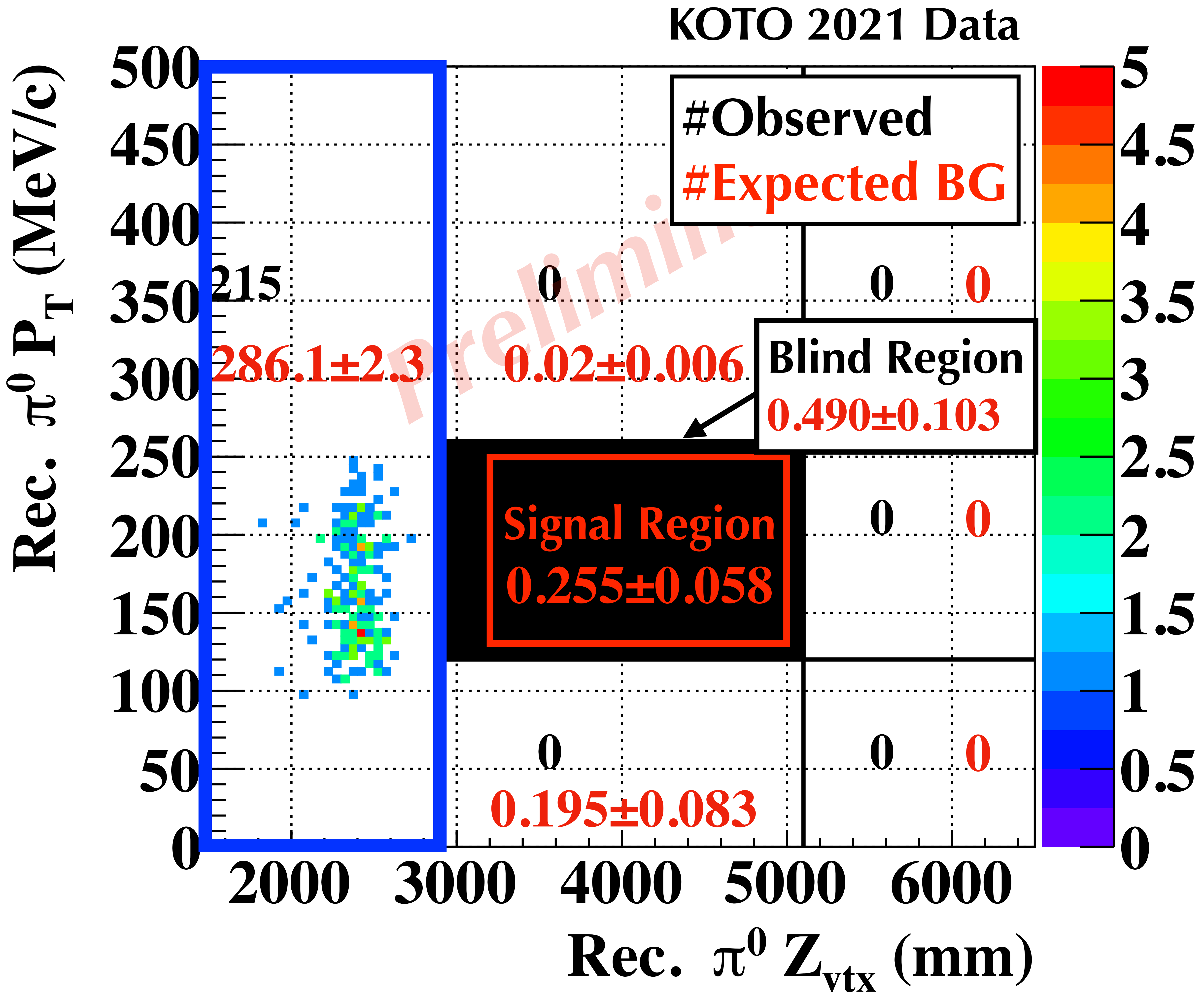
- Time line for the earliest case
  - 1st Priority to get budget on KEK PIP2020
  - Depends on the budget request (every one year)



Discrepancy in Upstream Region

Discrepancy appeared after the normalization of MC.

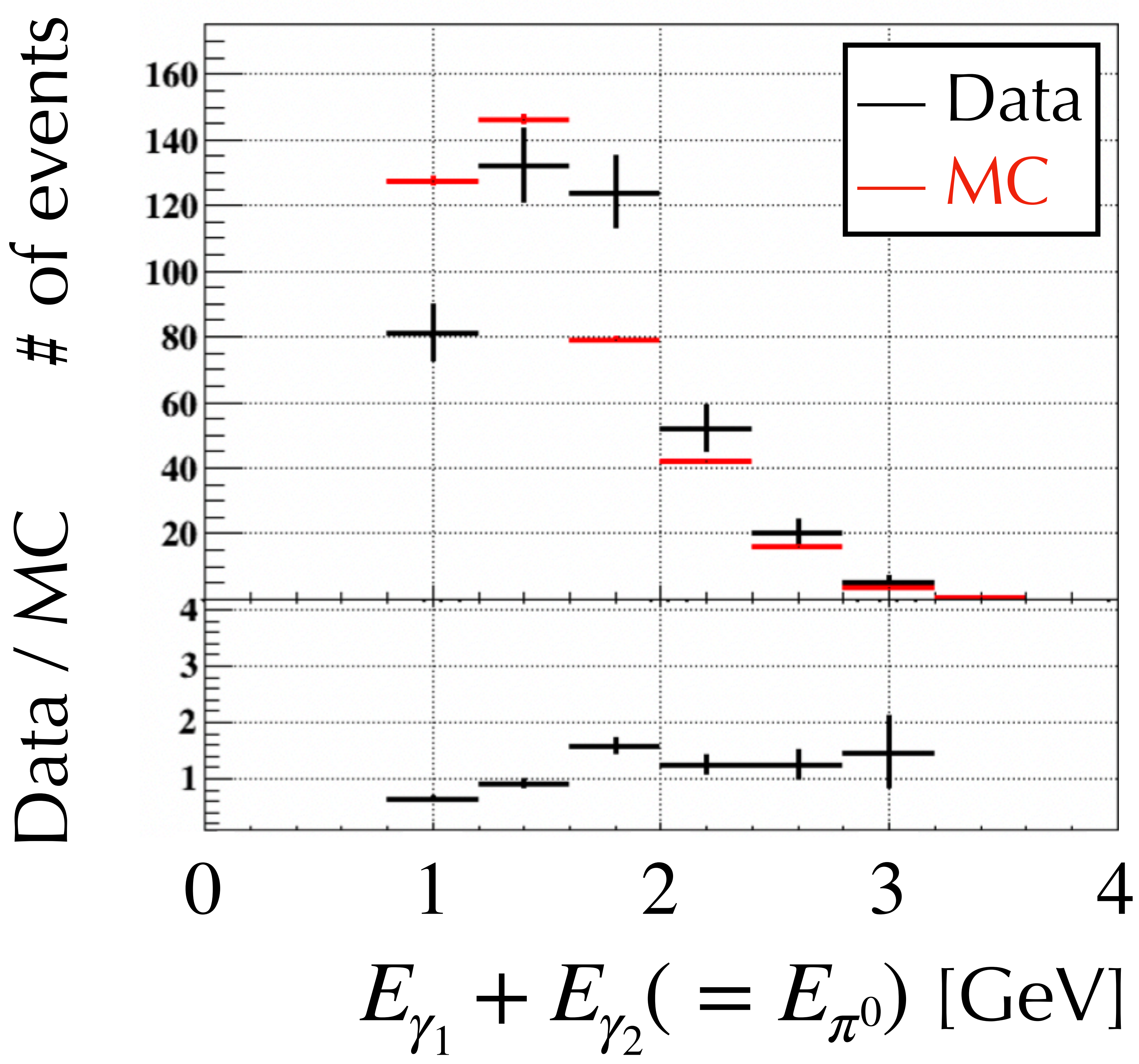


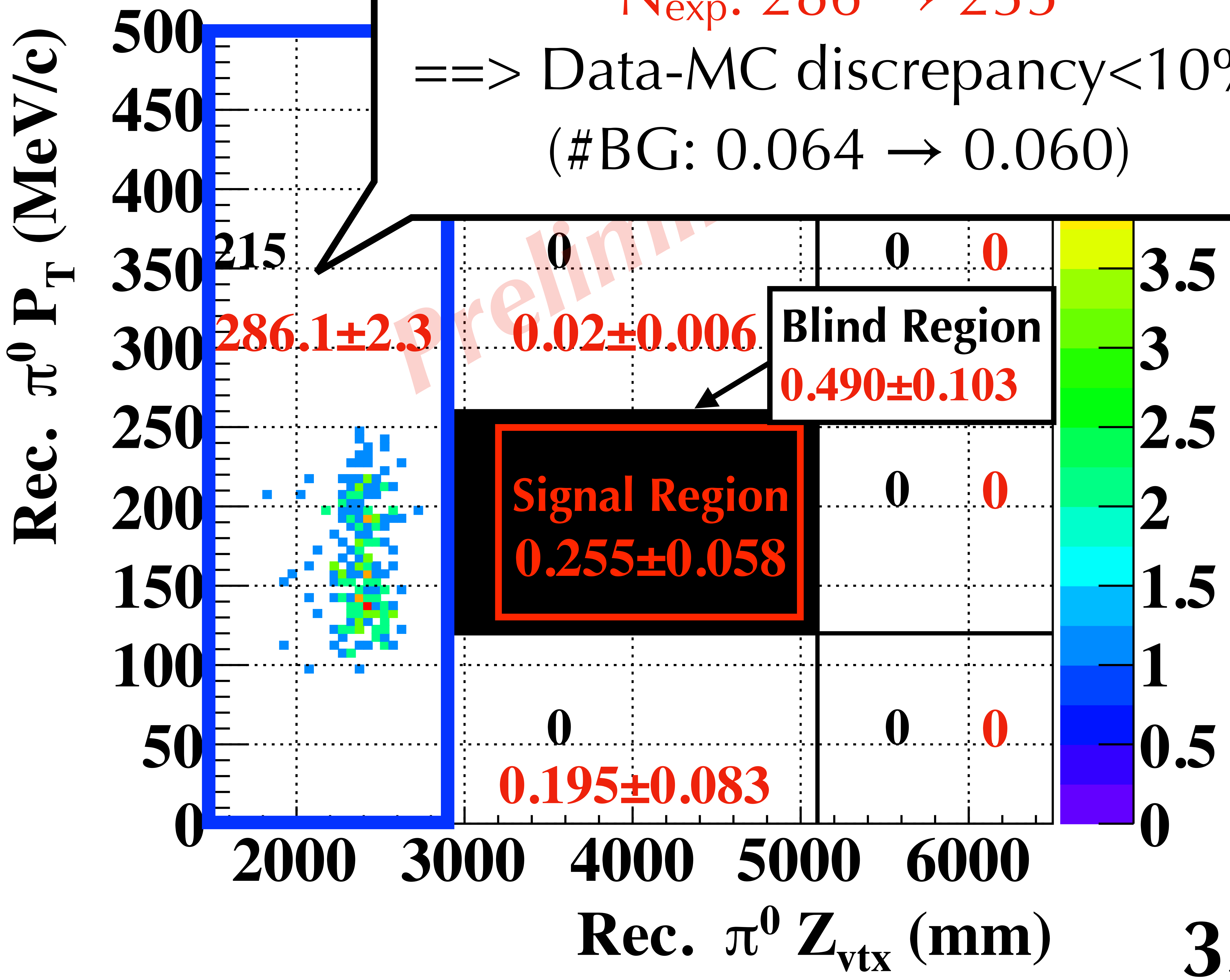


Discrepancy in Upstream Region

π^0 energy spectrum shows difference between data and MC

==> Re-estimated #BG based on E_{π^0} weight



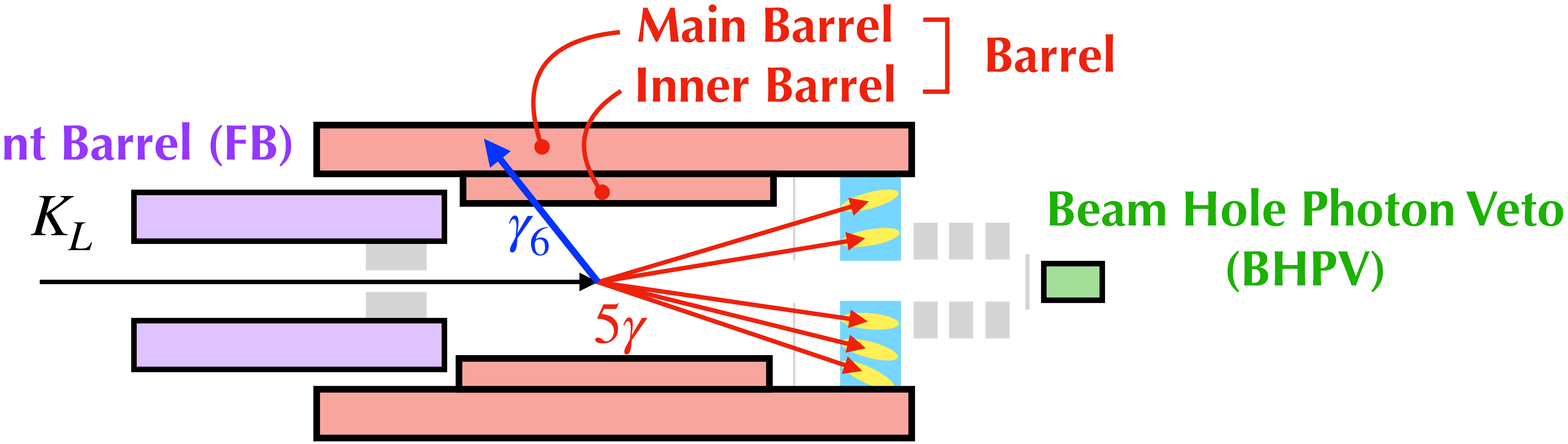


N_{exp}: 286 → 235

==> Data-MC discrepancy<10%

(#BG: 0.064 → 0.060)

Evaluation of Inefficiency



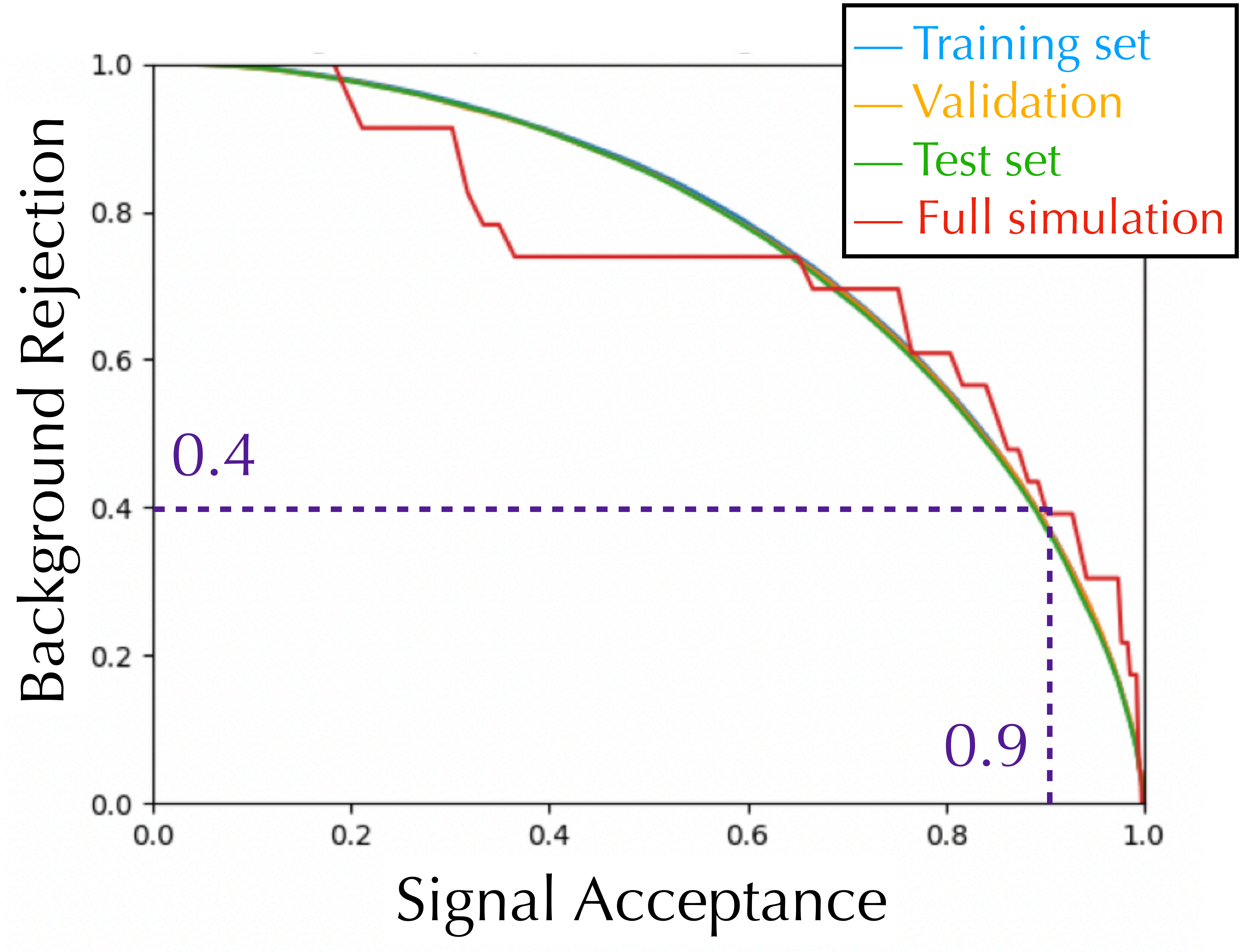
Summary of inefficiency evaluation with $K_L \to 3\pi^0$ events

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	$1.50^{+0.42}_{-0.51}$

==> Applied these correction factors in the background estimation of $K_L \to 2\pi^0$

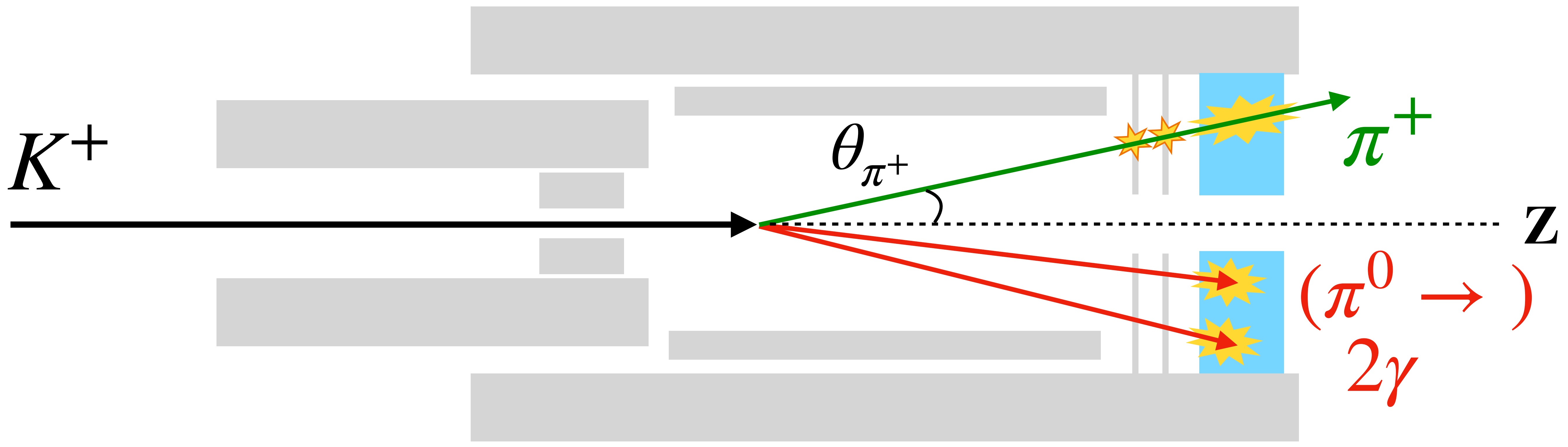
Neural Net Cut for $K_L \to 2\pi^0$ BG

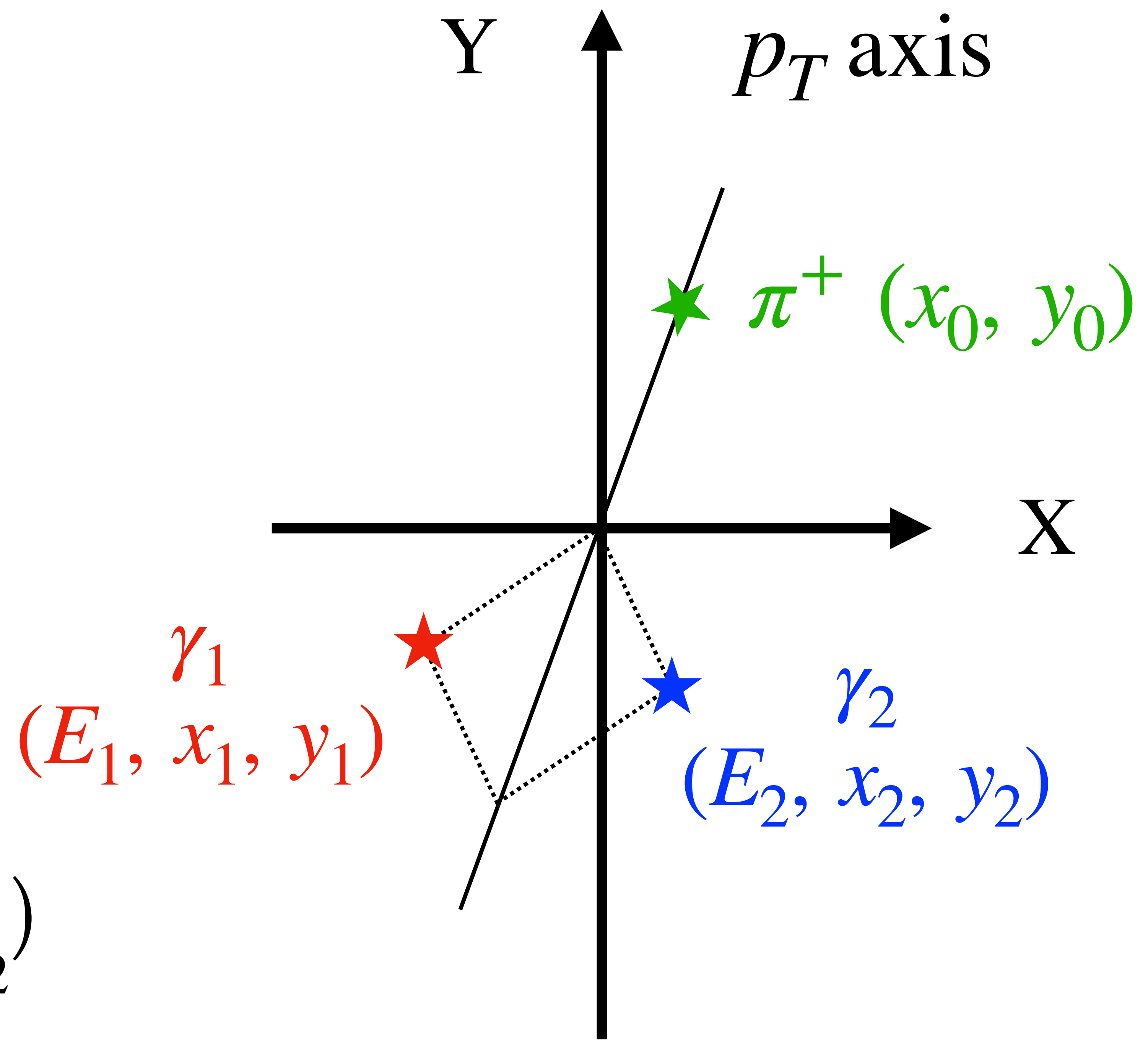
- Developed a neural net cut based on kinematical distributions
  - π^0 P_T , Z_{vtx} , E_γ , etc
- Background sample
  - $K_L \to 2\pi^0$ MC after applying the selection criteria
- Signal sample
  - $K_L \to \pi^0 \nu \bar{\nu}$ MC



→ Reduced the #BG by 40% with 90% signal efficiency

Reconstruction of $K^{\pm} \to \pi^{\pm}\pi^{0}$





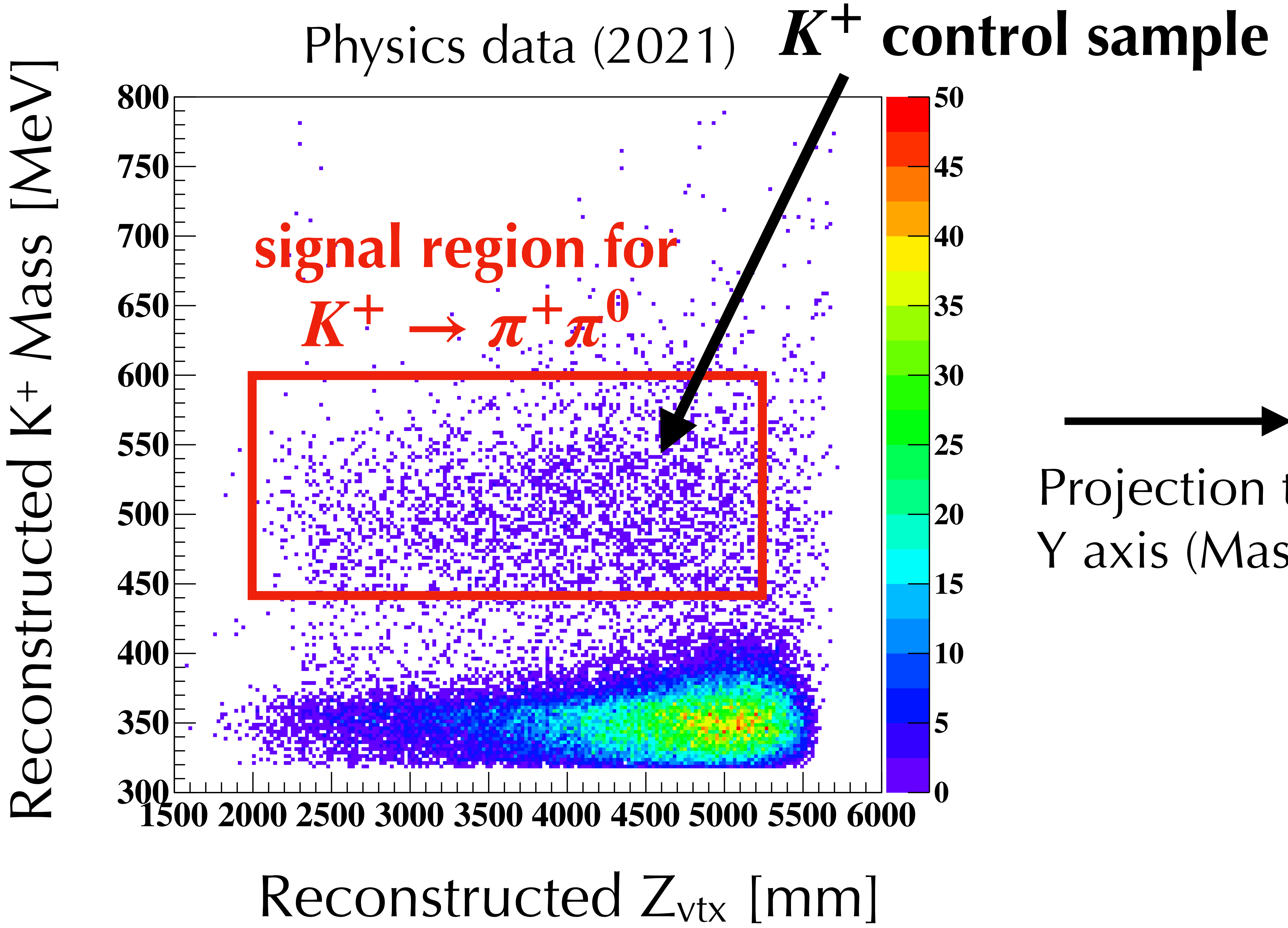
1. Reconstruct a π^0 from two photons ($\Longrightarrow Z_{vertex}, p_{\gamma_1}, p_{\gamma_2}$)
2. Calculate p_T of the π^0 using $p_{\gamma_1}, p_{\gamma_2}$
3. Assuming p_T of the K^+ is 0, $|\vec{p}_{\pi^+}| = p_T(\pi^0) \;/\; \sin\theta_{\pi^+}$ ($\Longrightarrow p_{\pi^+}$)

$\Longrightarrow$ Calculate invariant mass of K^+ as $M_{\pi^+\pi^0} = \sqrt{(p_{\gamma_1} + p_{\gamma_2} + p_{\pi^+})^2}$

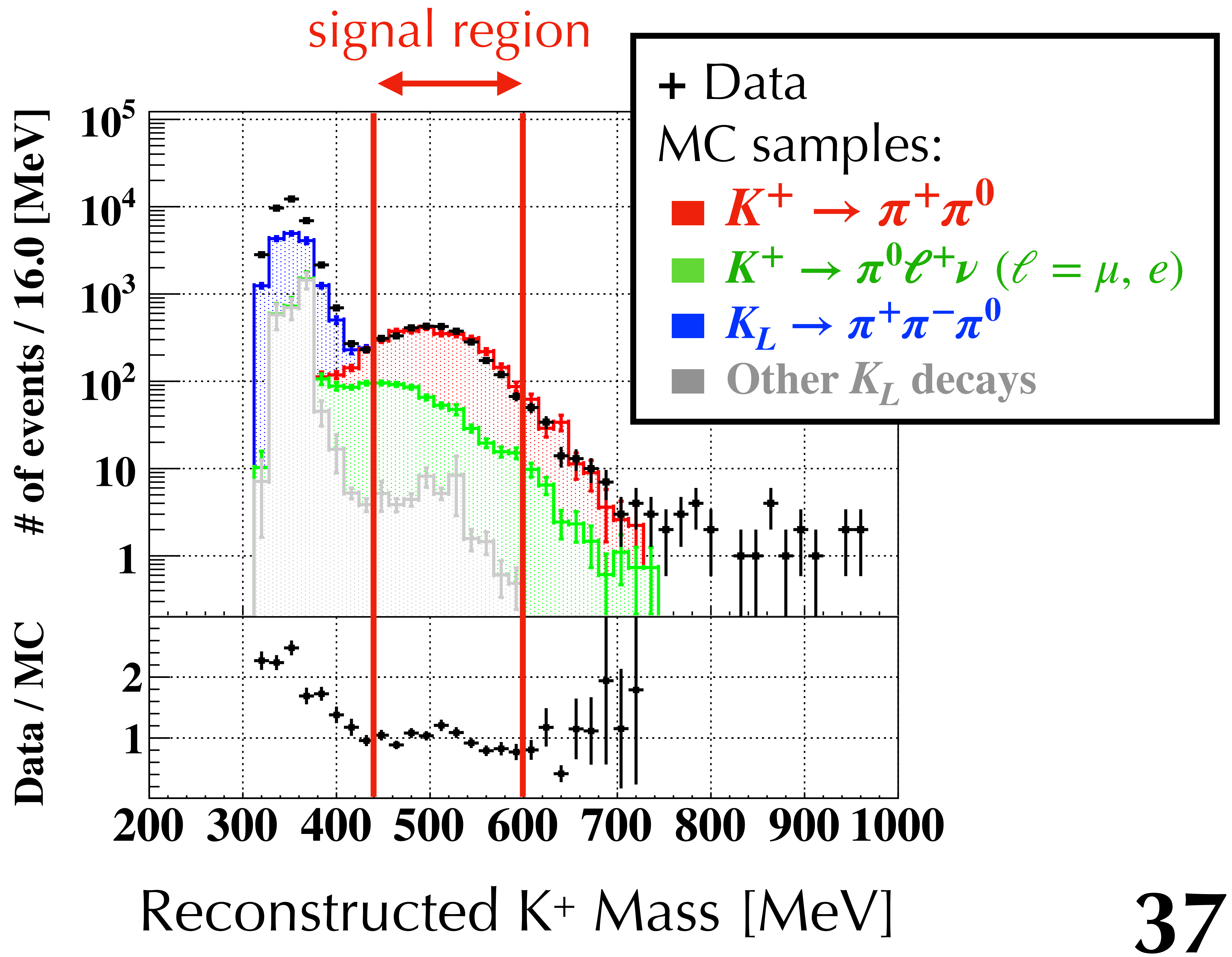
Measurement of $K^{\pm}$ Flux

Measured the flux ratio of K^+ to K_L to be $F_{K+}/F_{K_L} = (3.3 \pm 0.1) \times 10^{-5}$.

- K_L flux was measured under loose selection where $K_L \to \pi^+\pi^-\pi^0$ is dominant
- There is 1.4% of K_L contamination in the K^+ sample

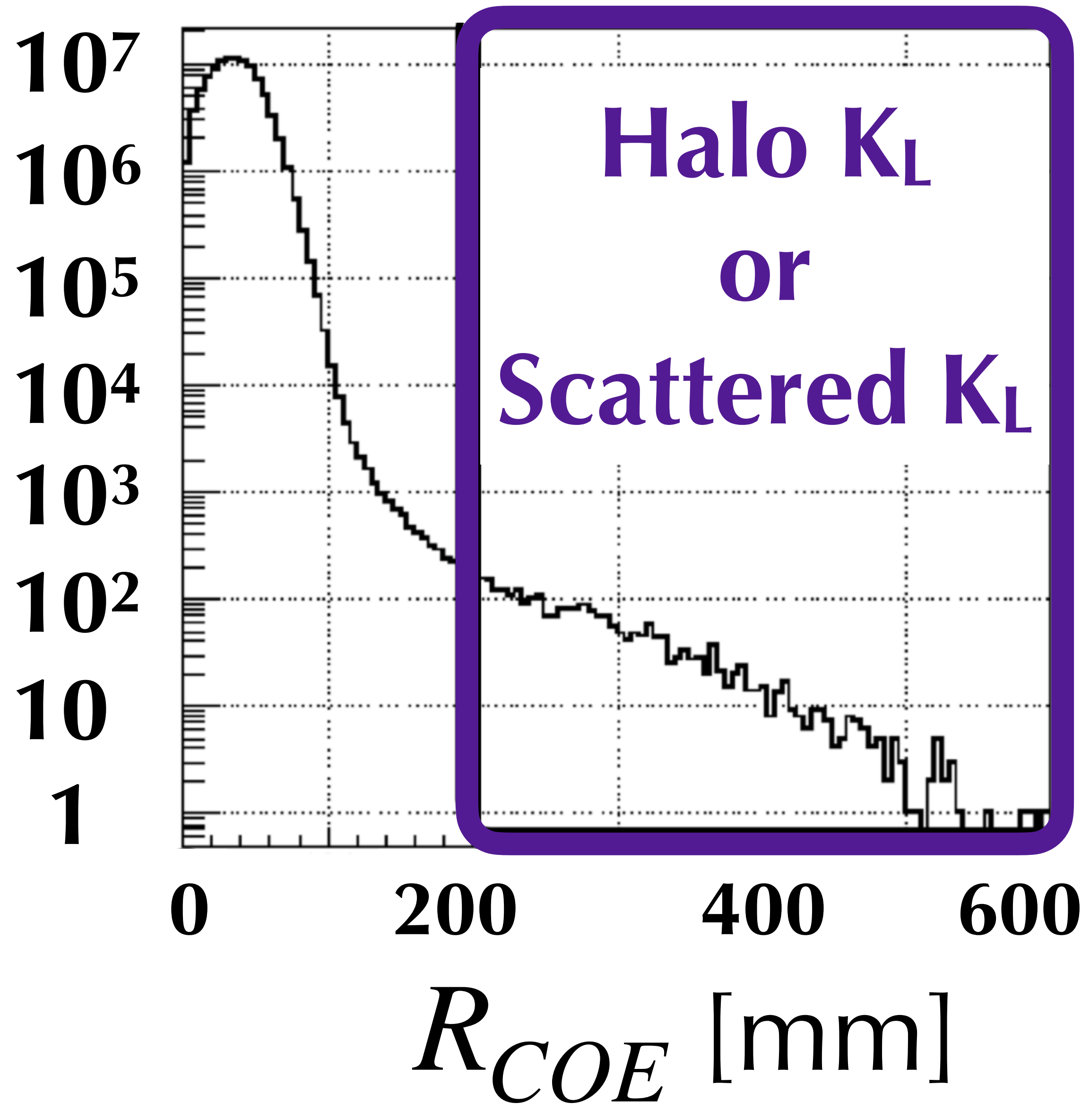


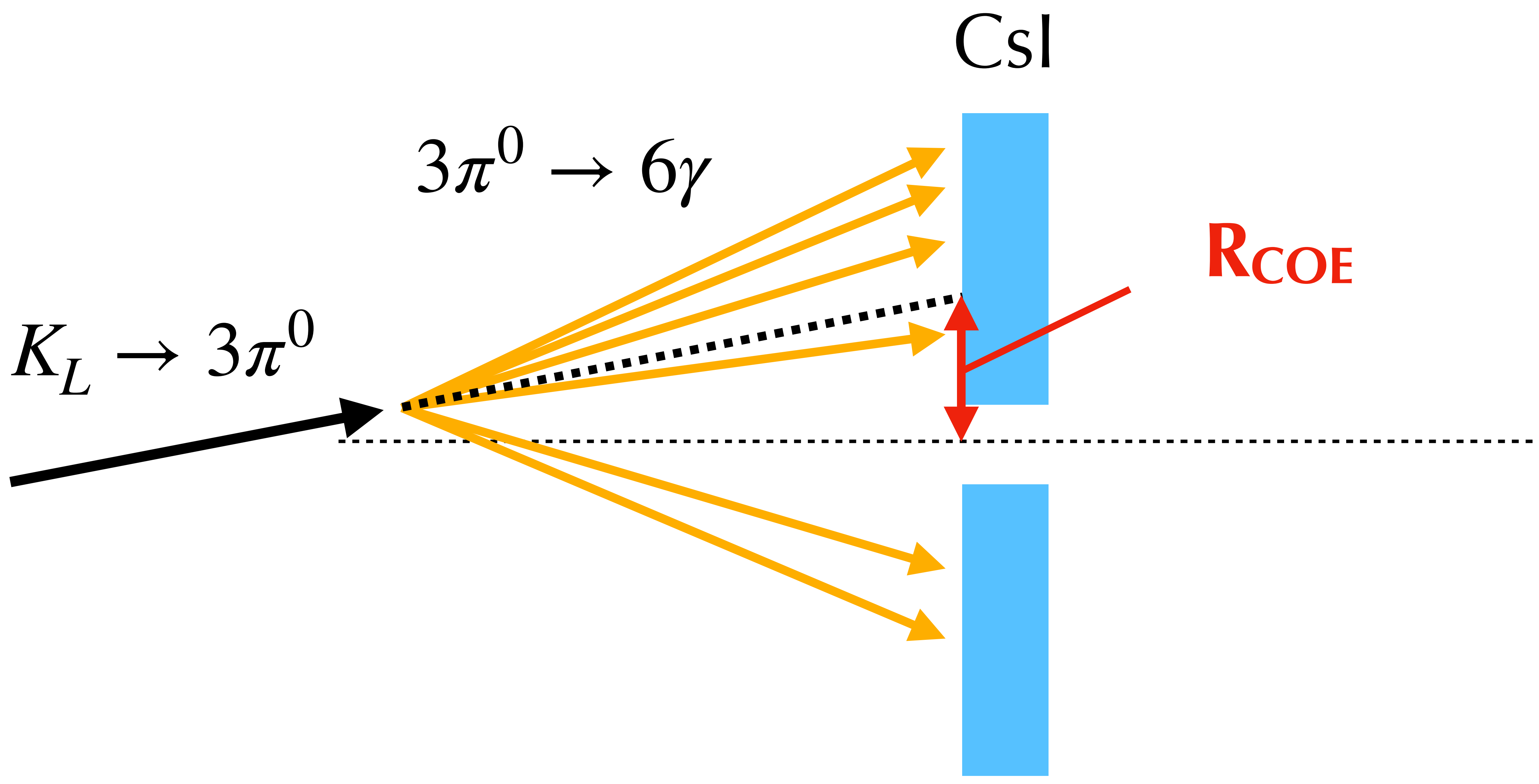
Projection to Y axis (Mass)

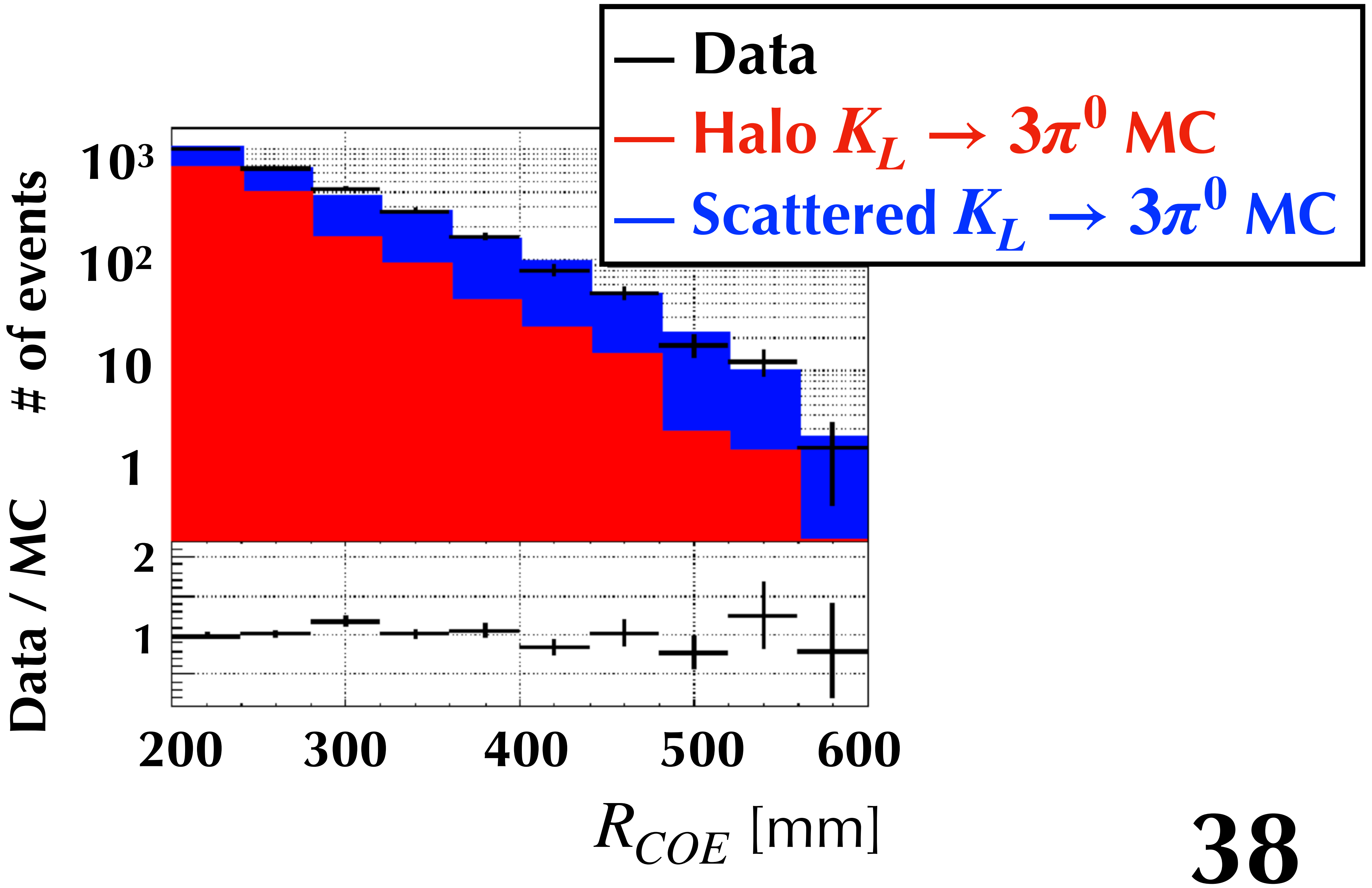


Measurement of Halo K_L Flux

Flux of halo K_L was evaluated using $K_L \to 3\pi^0$ events.
Definition: R_{COE} (center-of-energy radius) > 200 mm

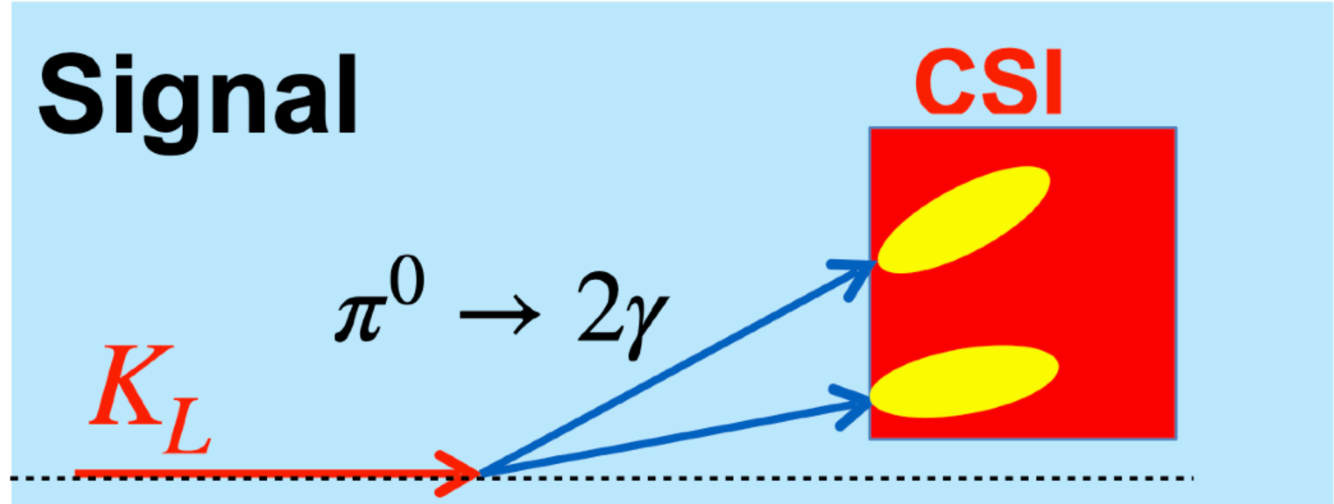


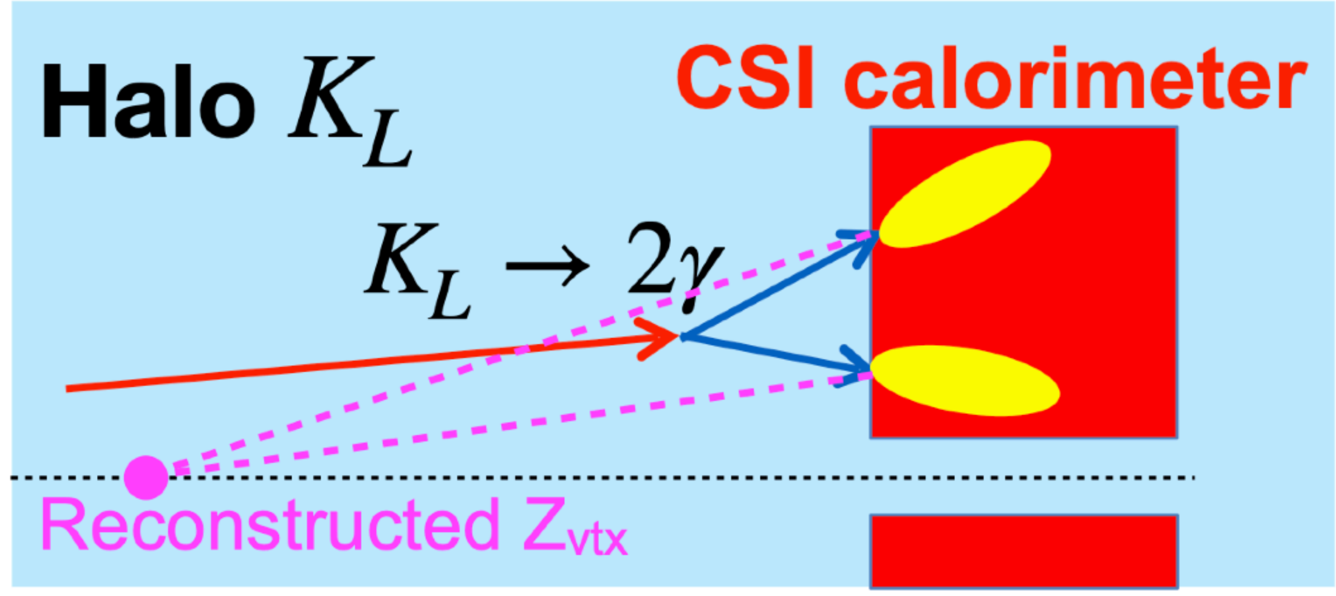


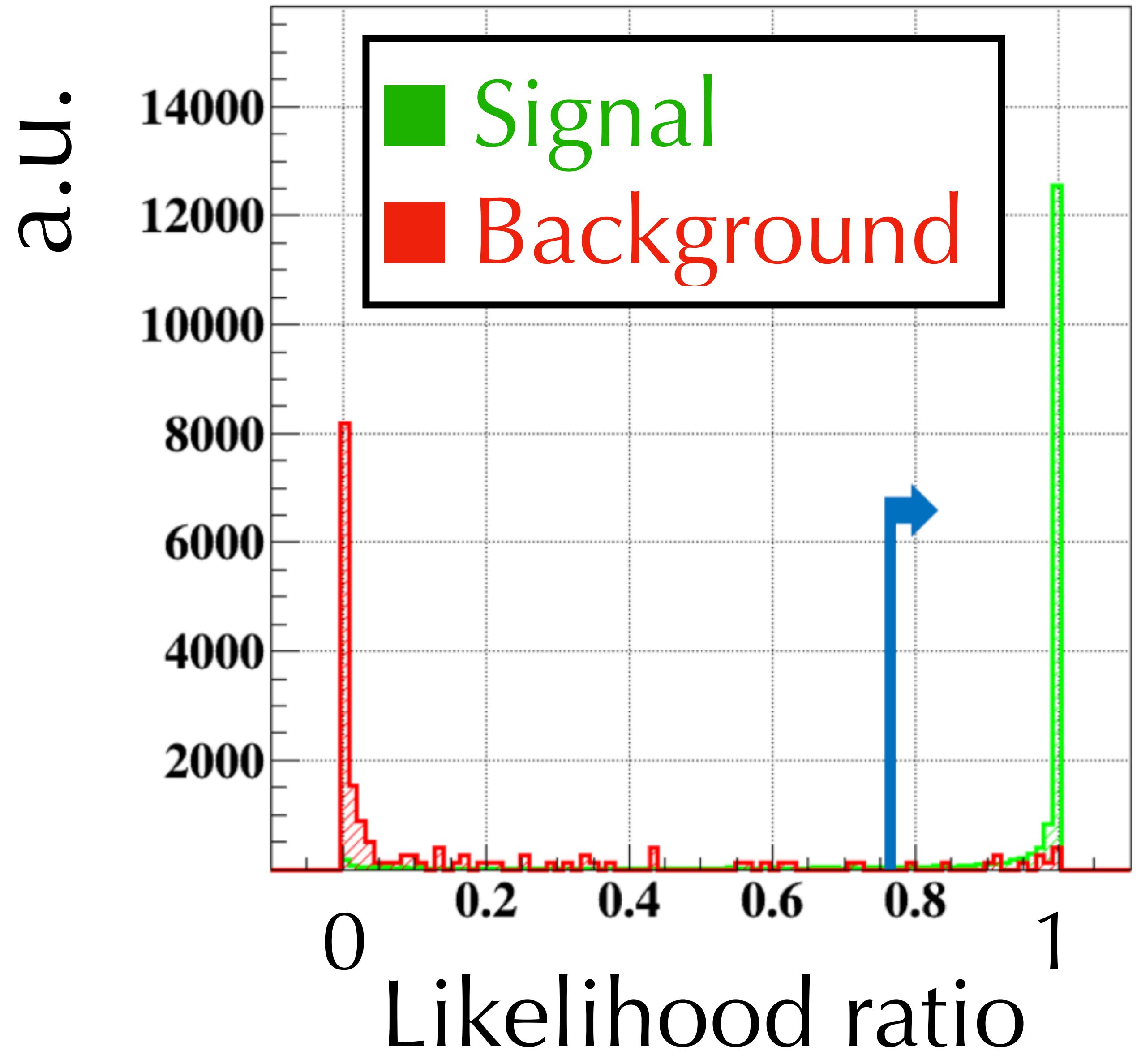


Cuts for Halo $K_L \to 2\gamma$ BG

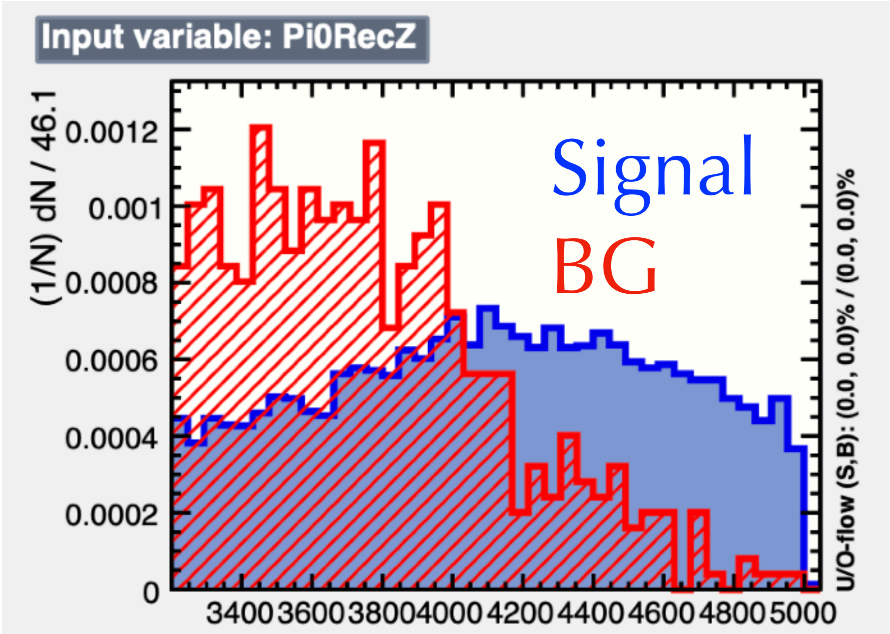
- Likelihood ratio based on shower shape consistency



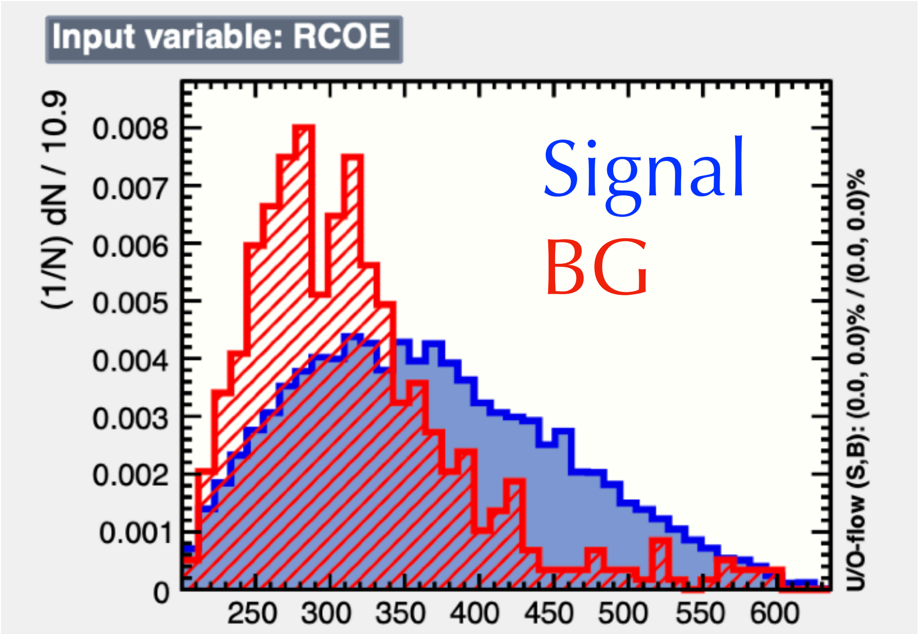




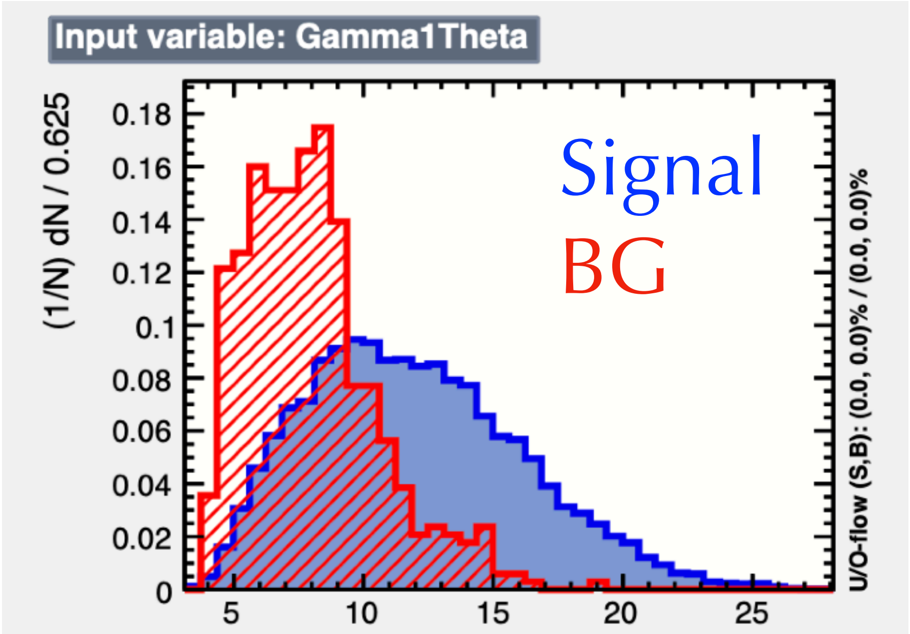
- Multivariate analysis using Fisher Discriminant



ReconstructedZ_{vtx}

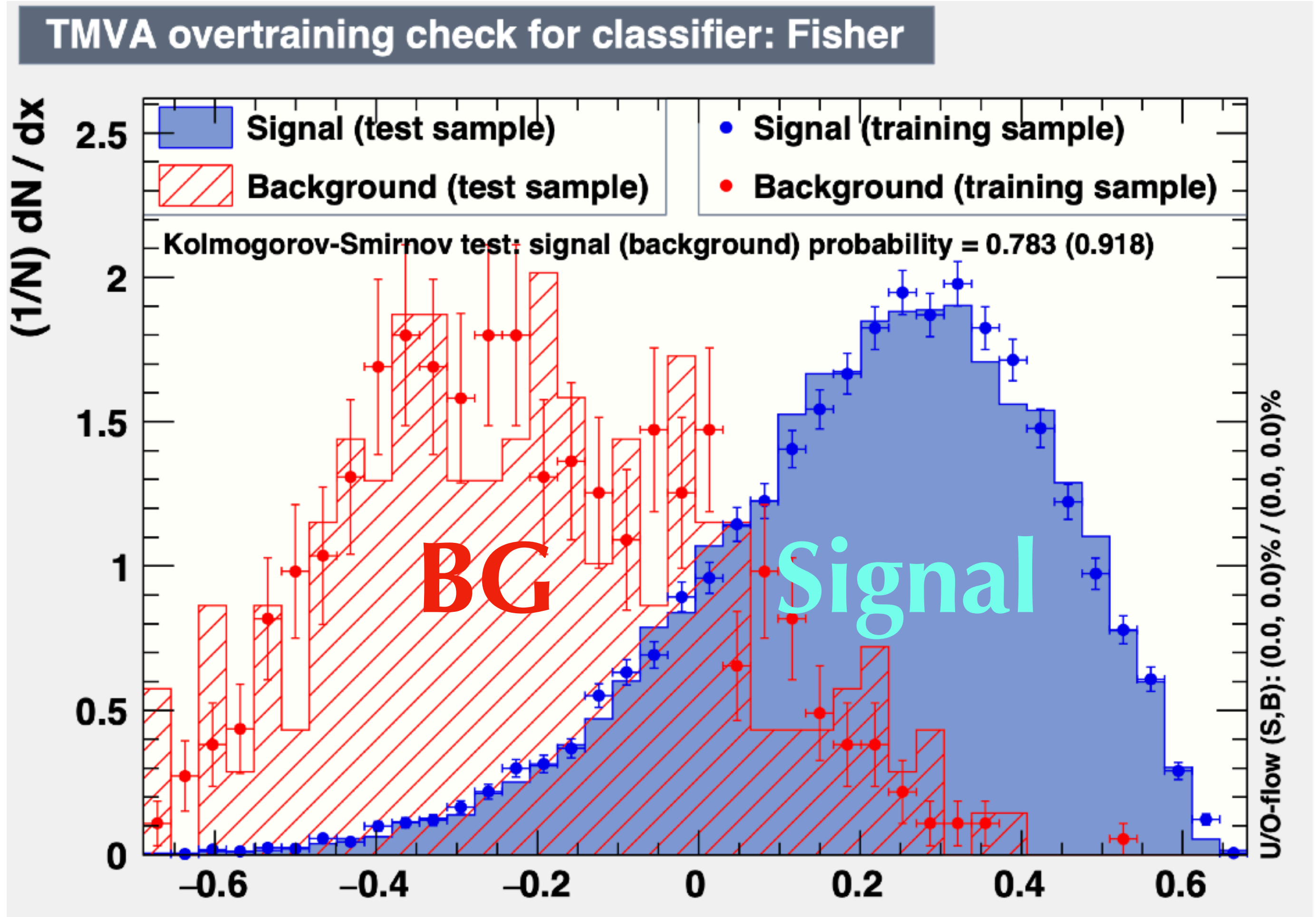


R_{COE}



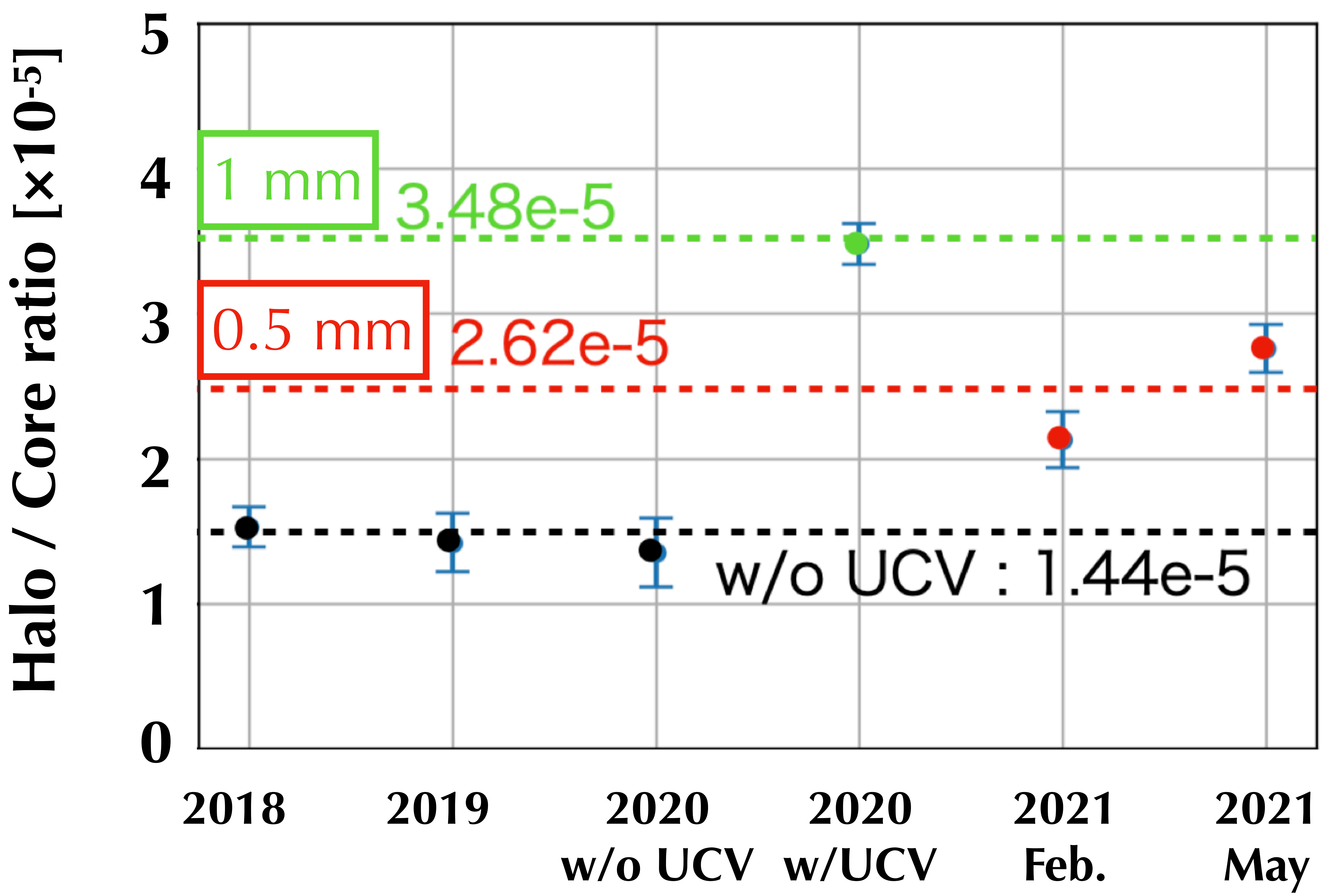
$\theta_{\gamma 1}$

, etc

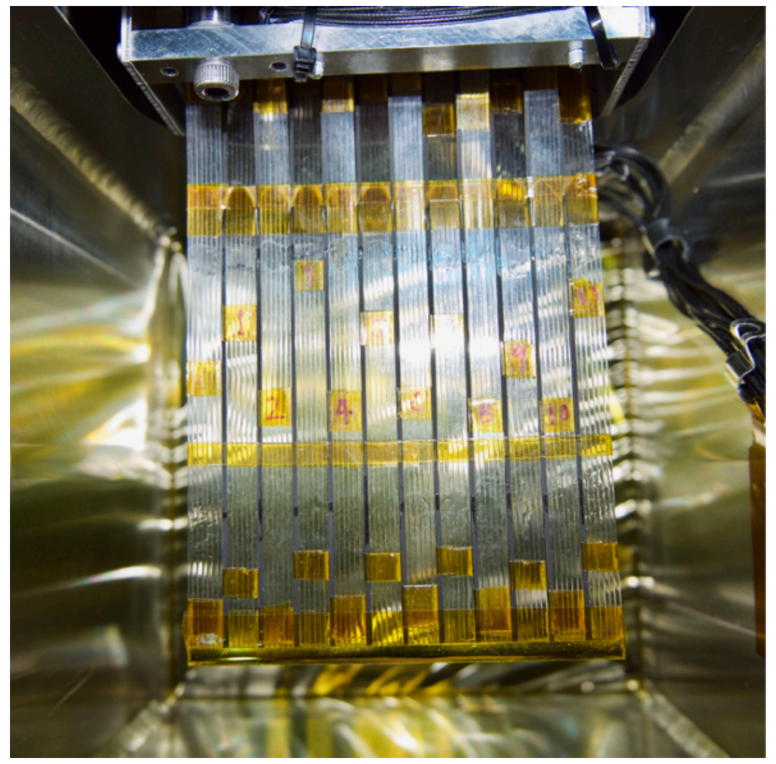


Fisher response

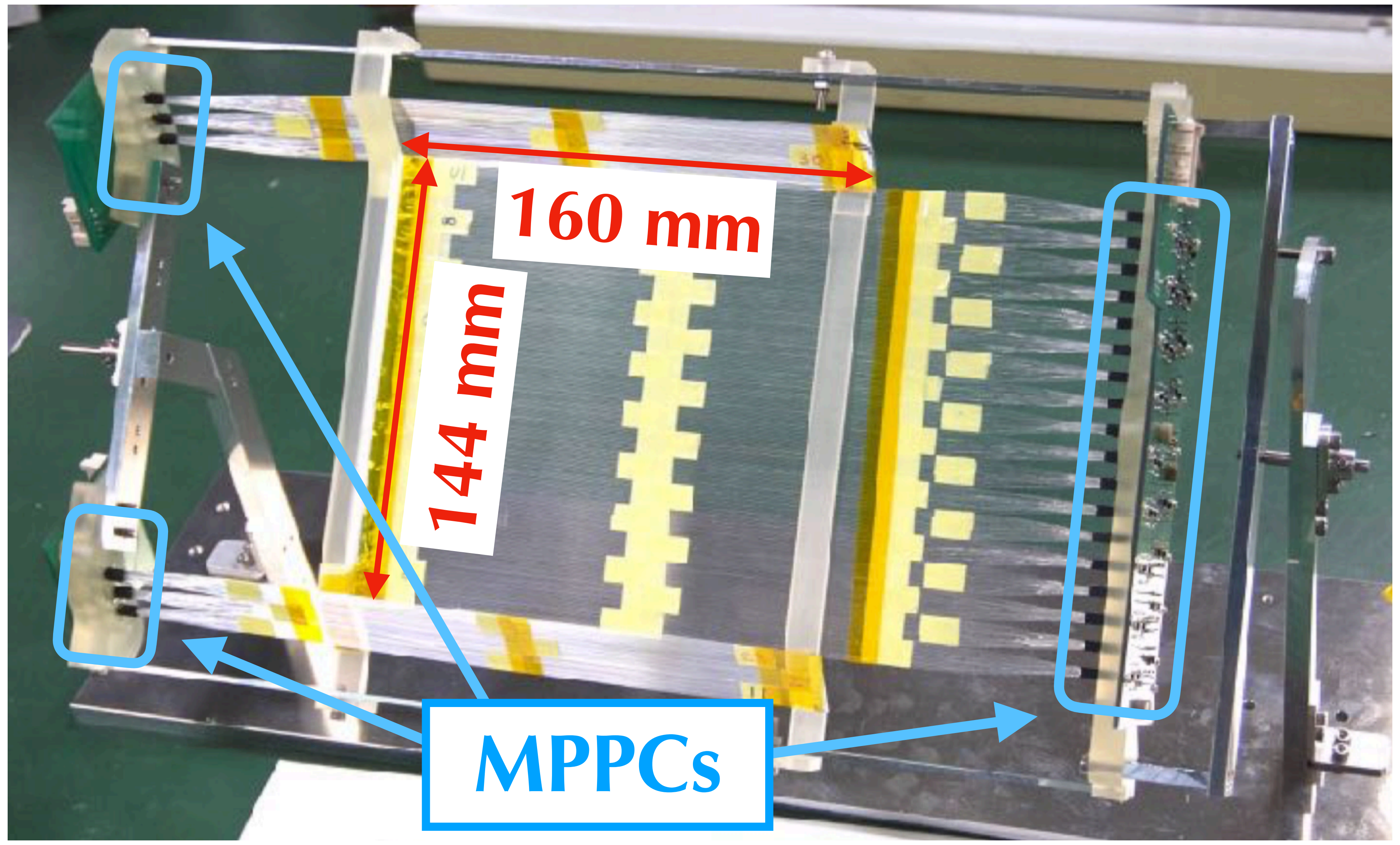
Halo K_L Flux



1 mm sq. fiber prototype UCV (2020)



0.5 mm sq. fiber UCV (2021)



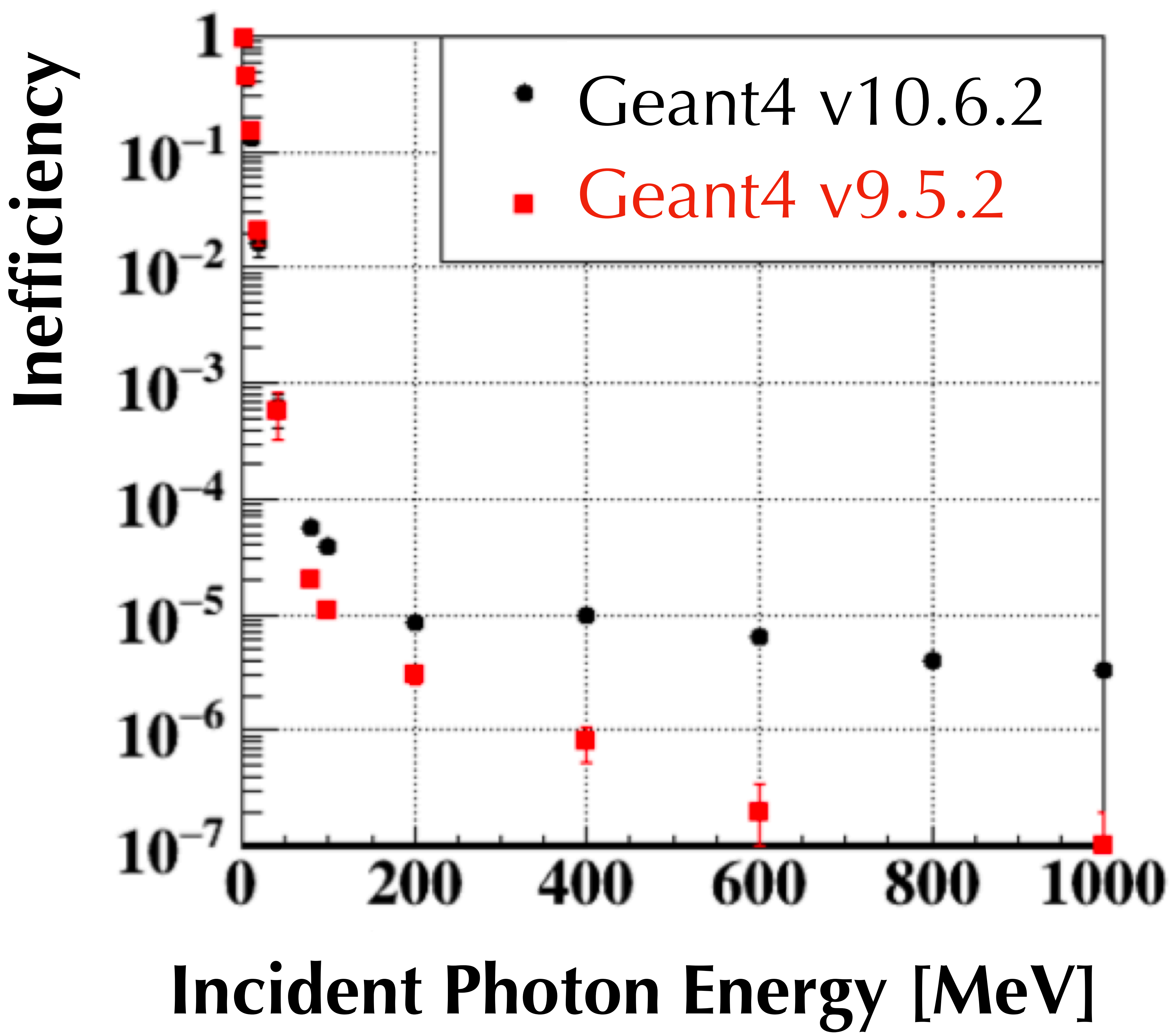
Genat4 Version Dependence

- **Photonuclear(PN) reaction** occurs in the $K_L \to 2\pi^0$ events that remain in the signal region.

- Inefficiency of the barrel detectors depends on the version of Geant4.

  (No difference when turning off the PN process.)

- The physics model of PN process was changed for better code management.

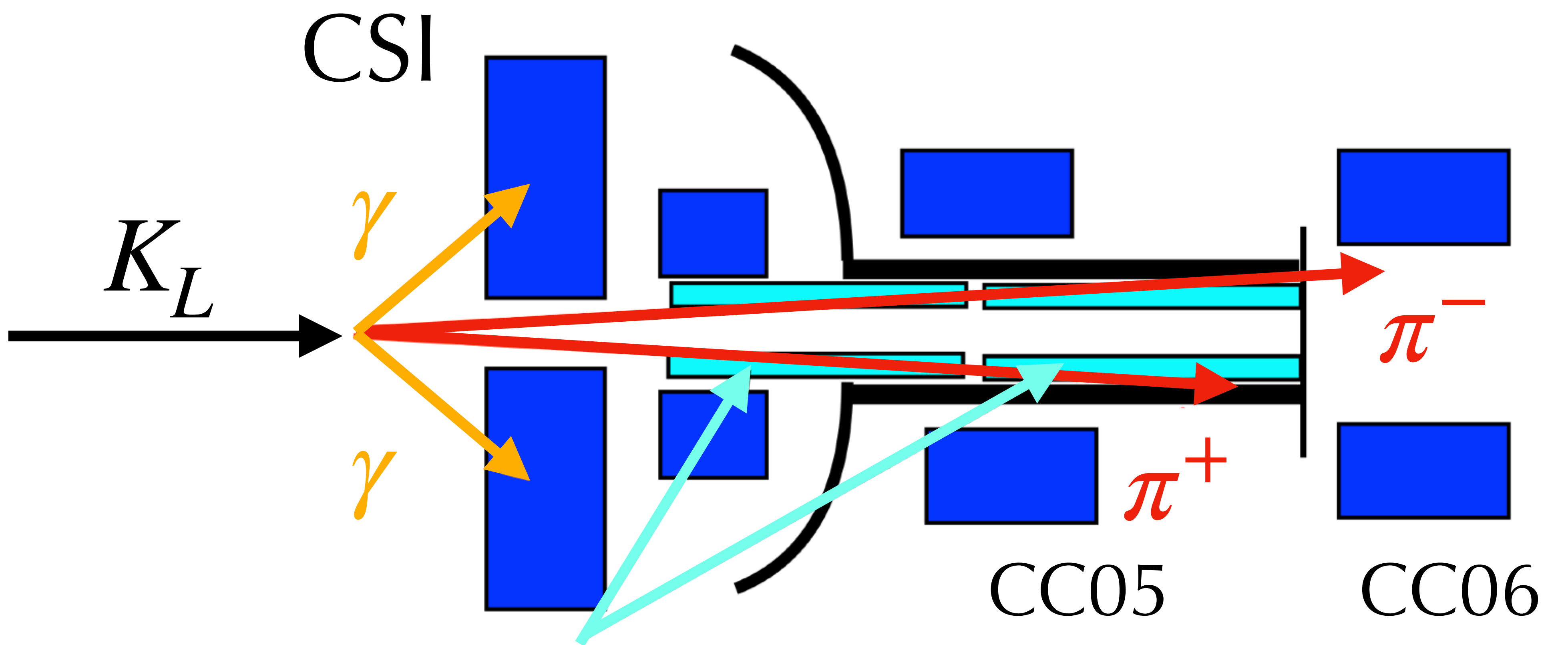


Downstream Charged Veto

Downstream Charged Veto (DCV) (2019–)

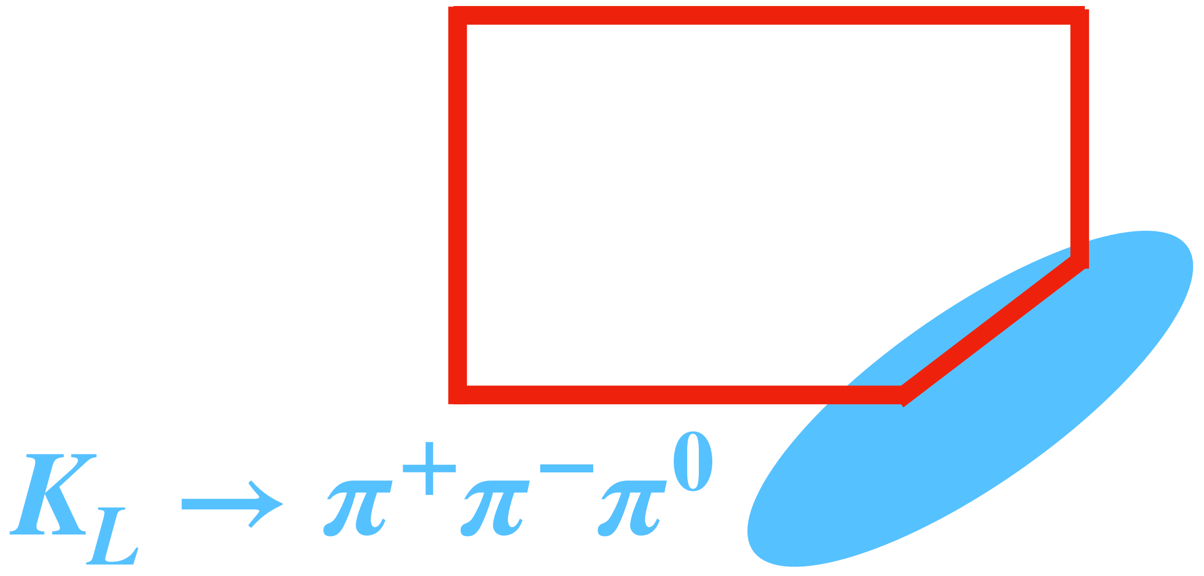
- Rejected the $K_L \to \pi^+\pi^-\pi^0$ BG (< 0.07 @90%CL)

  ==> acceptance recovery by extending the signal region

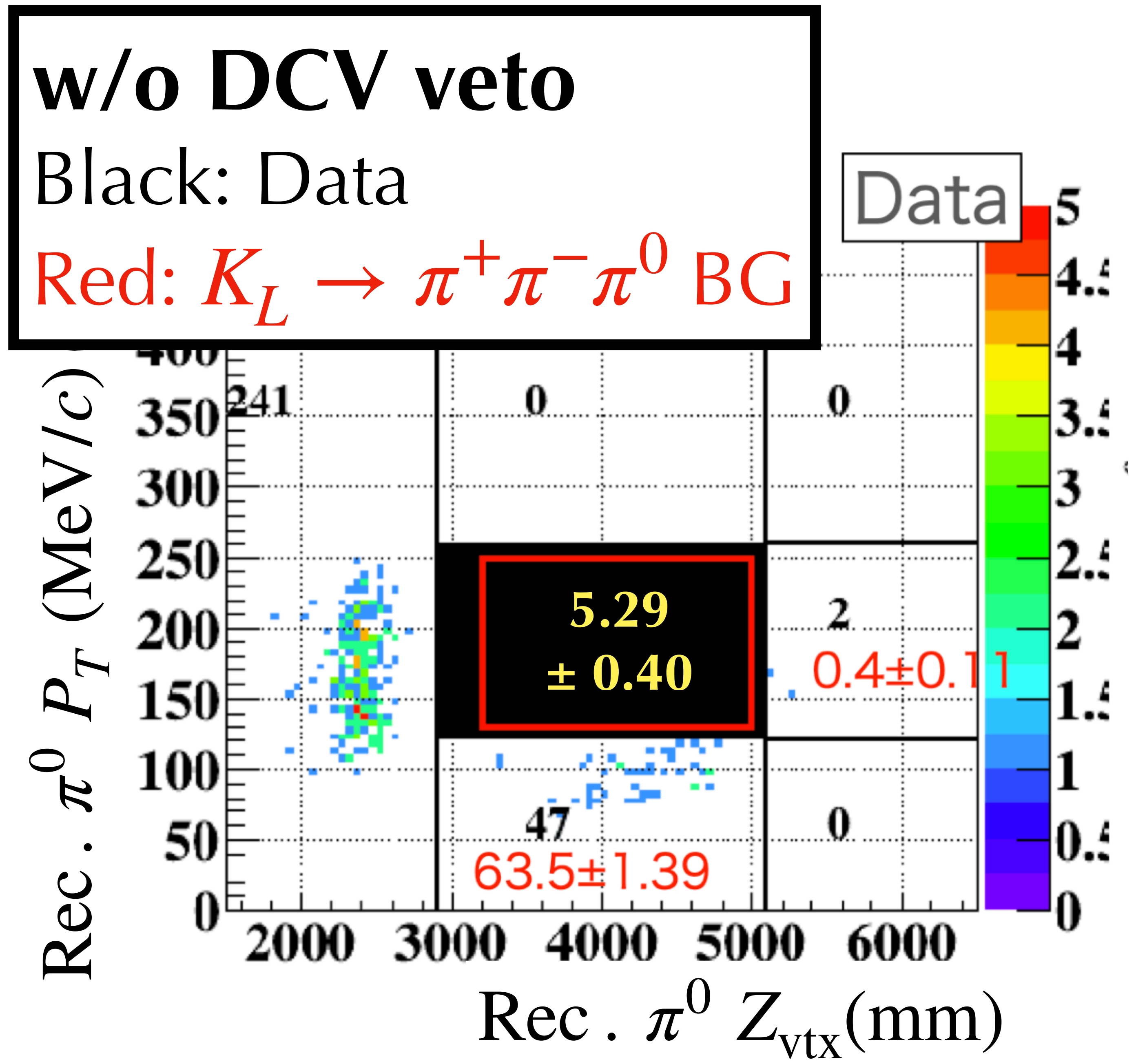


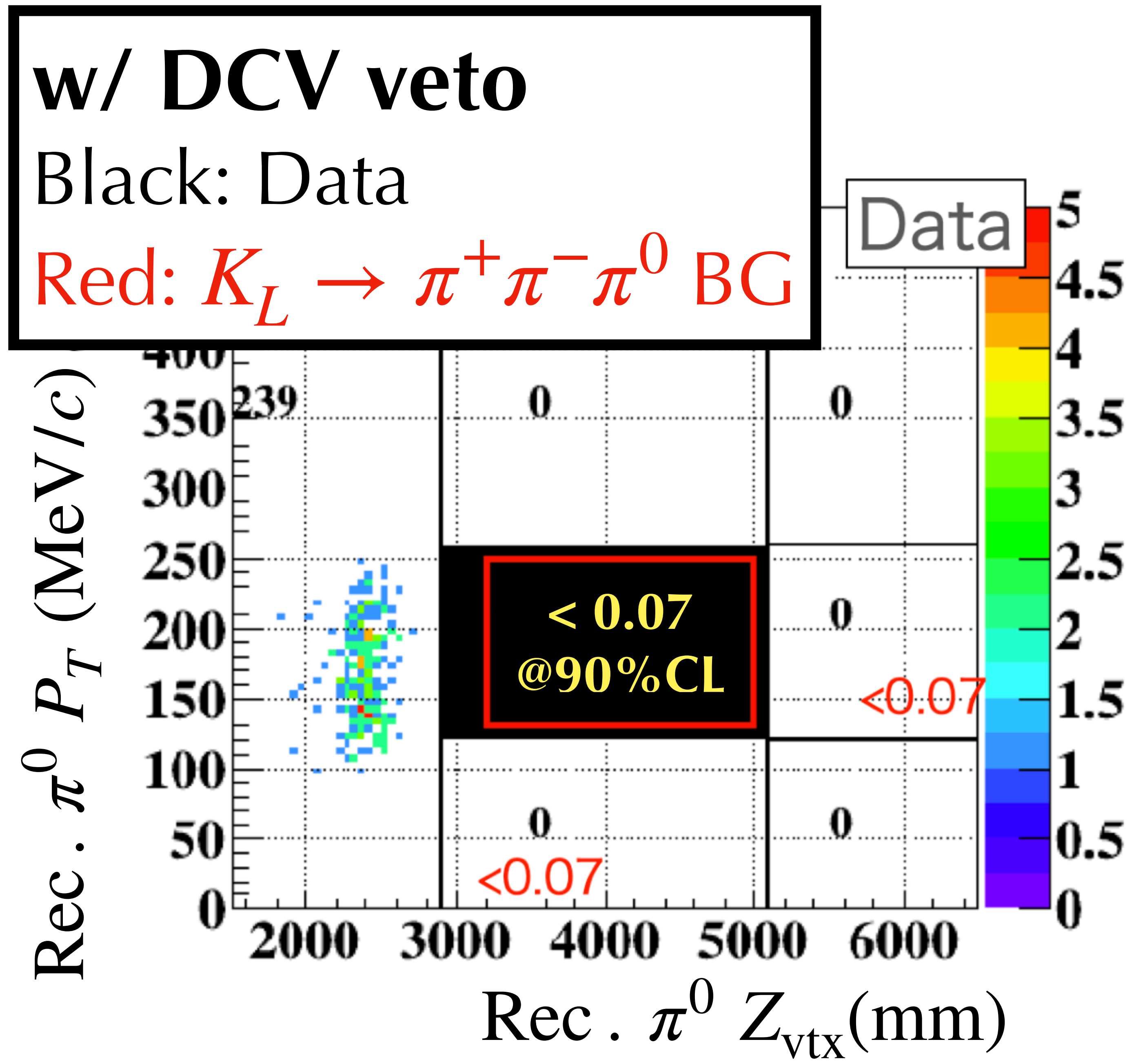
Plastic scintillator plates inside the beam pipe

2016–18 signal region



2021 signal region

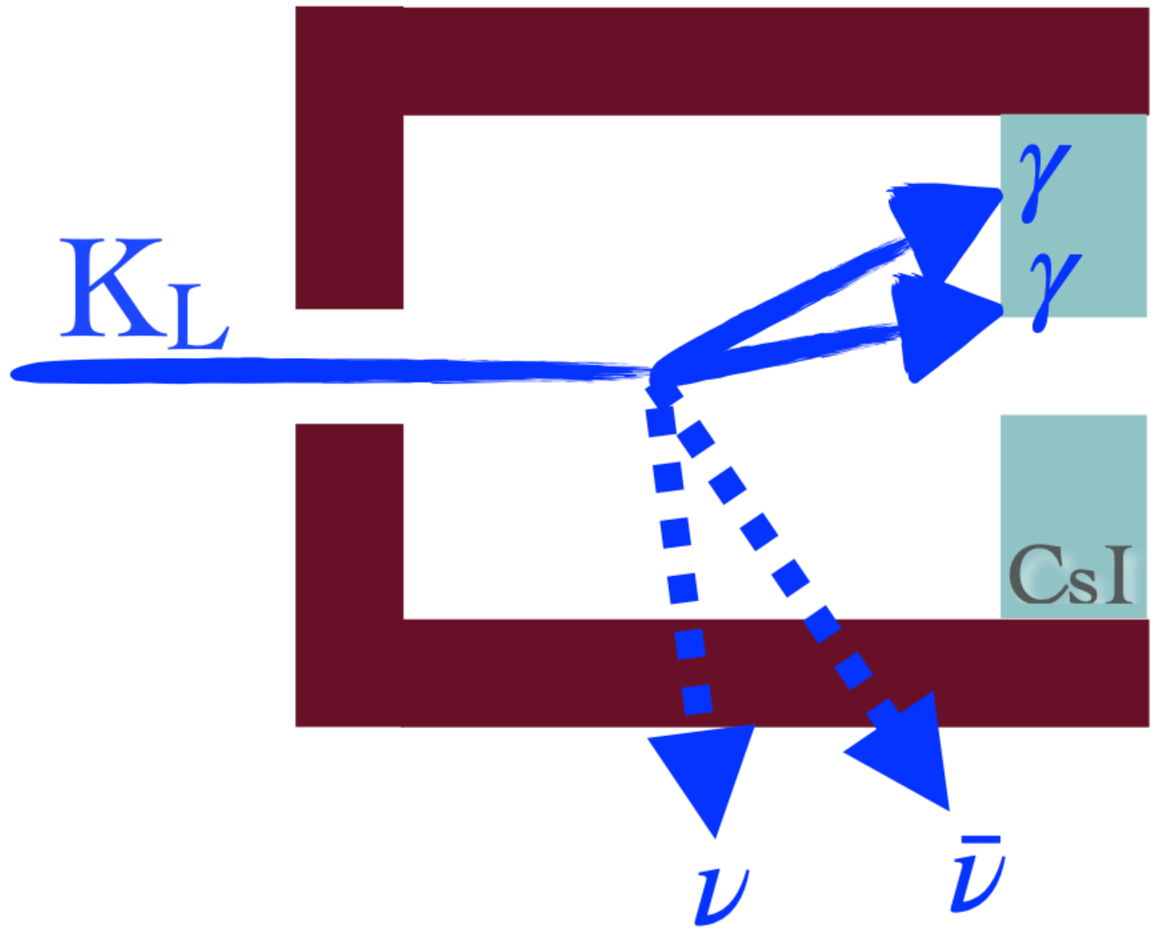




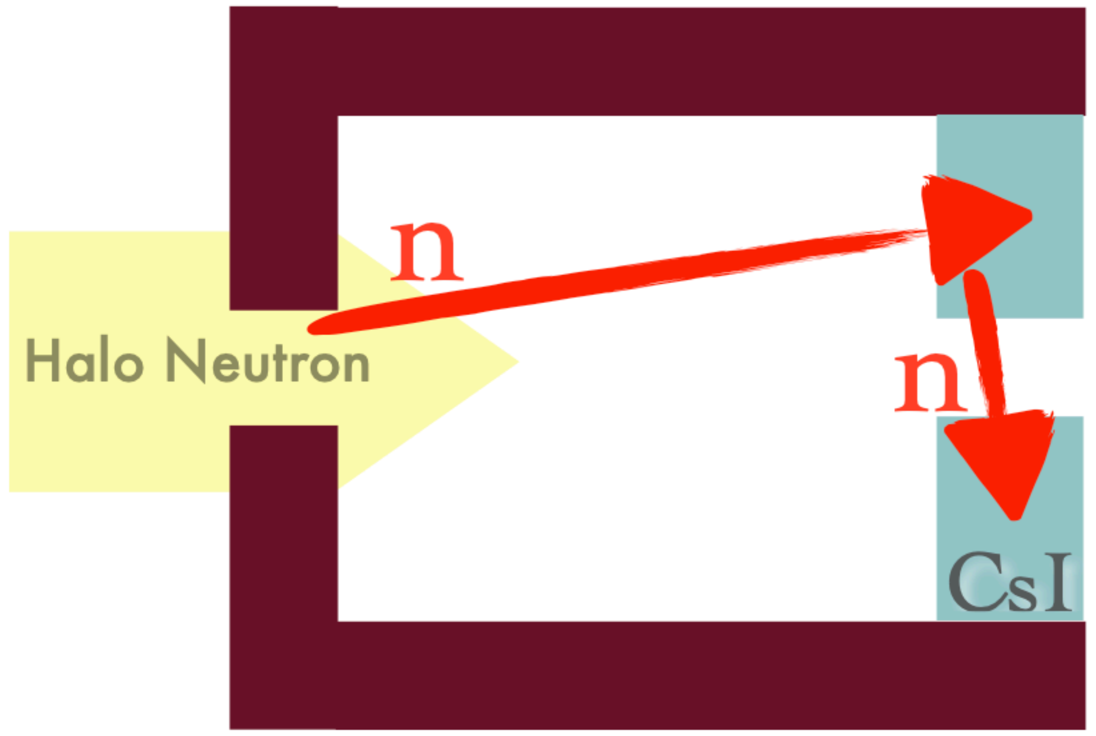
Upgrade of Calorimeter

- Hadron cluster background
  Halo neutron hits the calorimeter,
  which makes another cluster

Signal

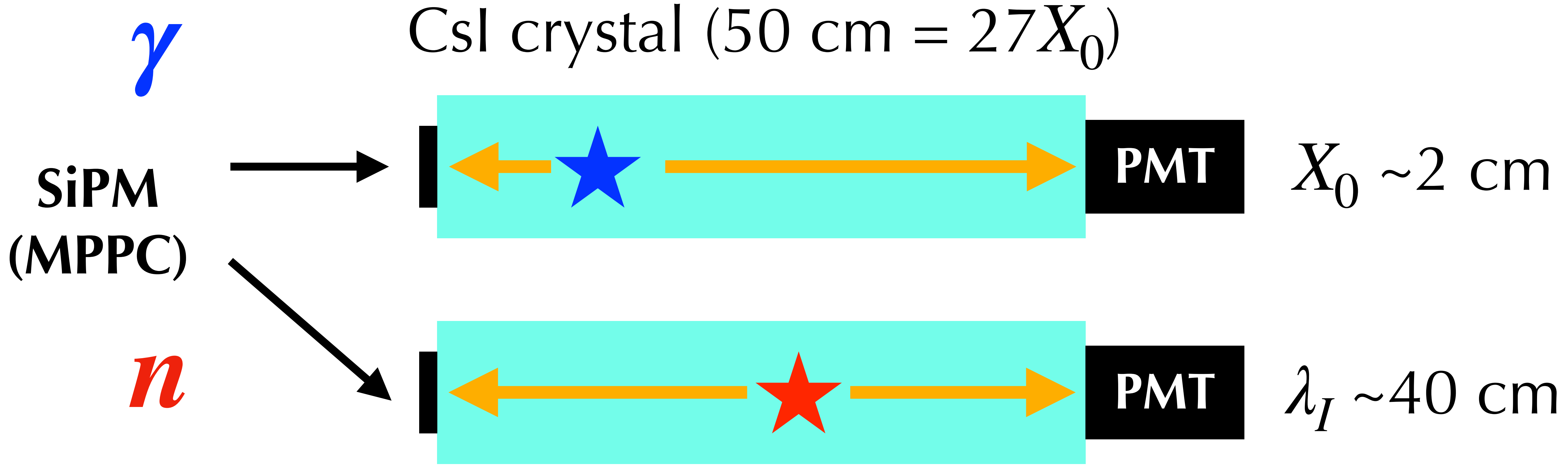


Hadron cluster BG

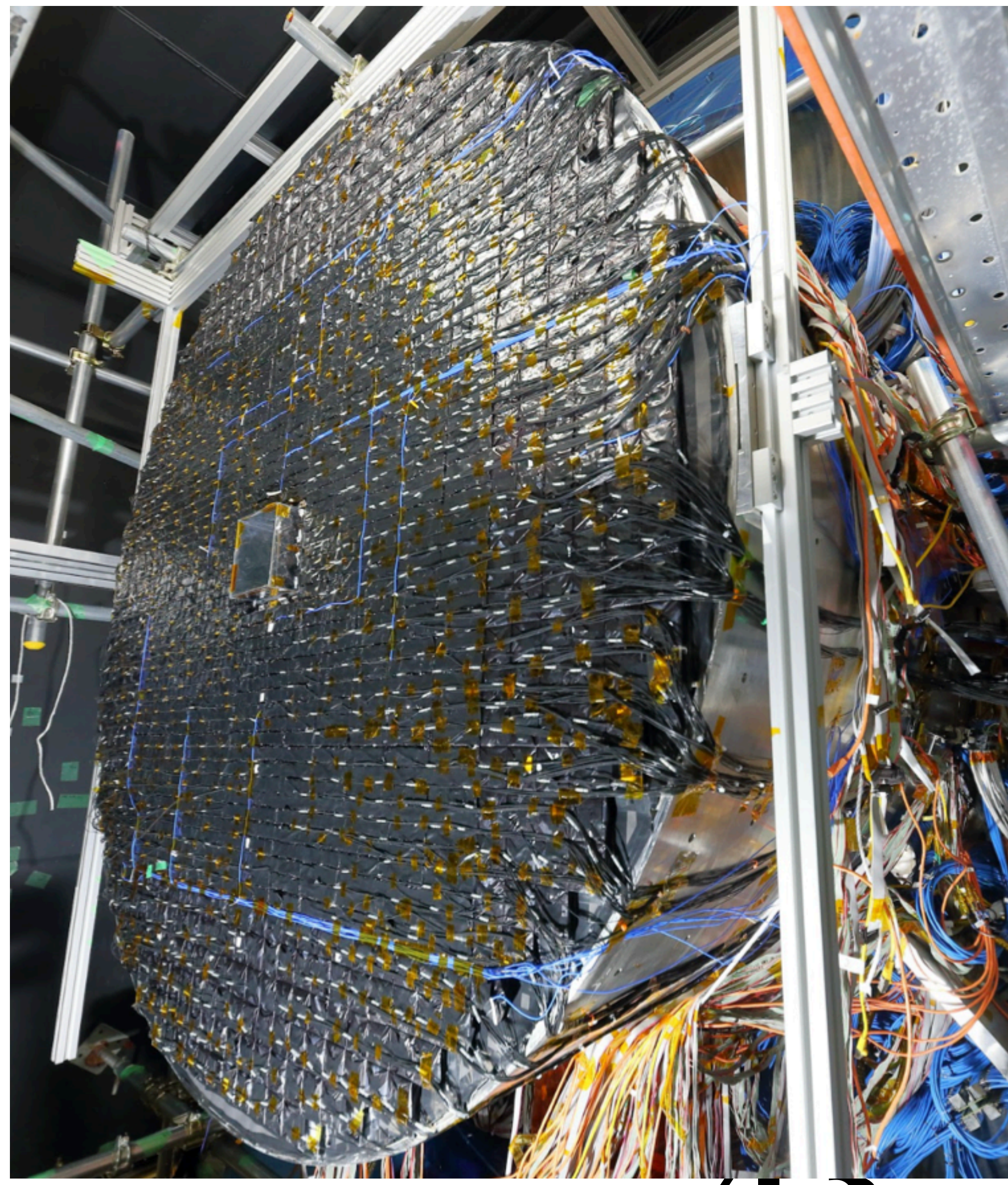


- Both-end readout
  ==> γ/n separation by ΔT between front-side(SiPM) & rear-side(PMT)

CsI crystal (50 cm = $27X_0$)



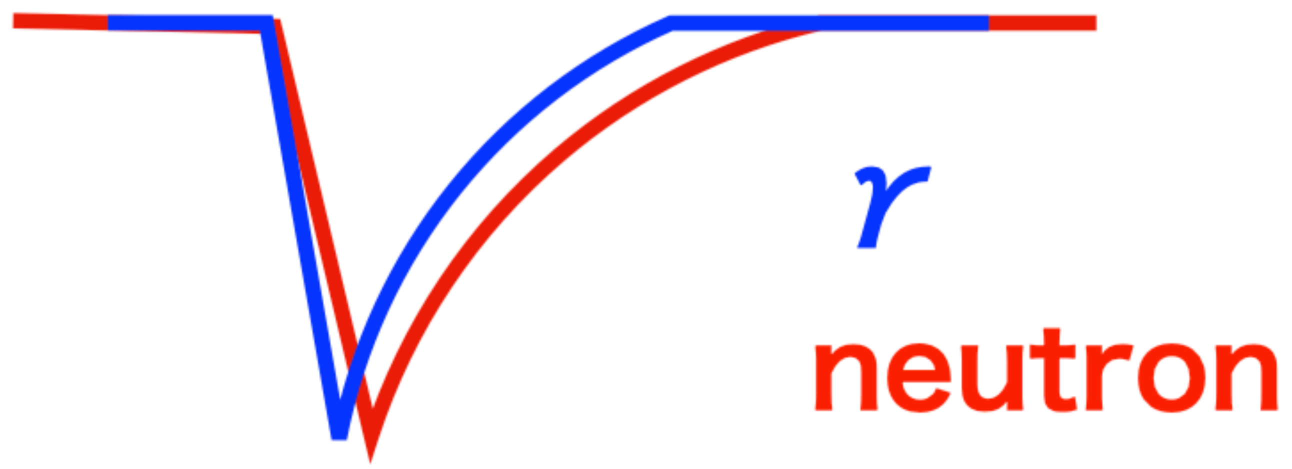
Front view
(~4000 MPPCs in total)

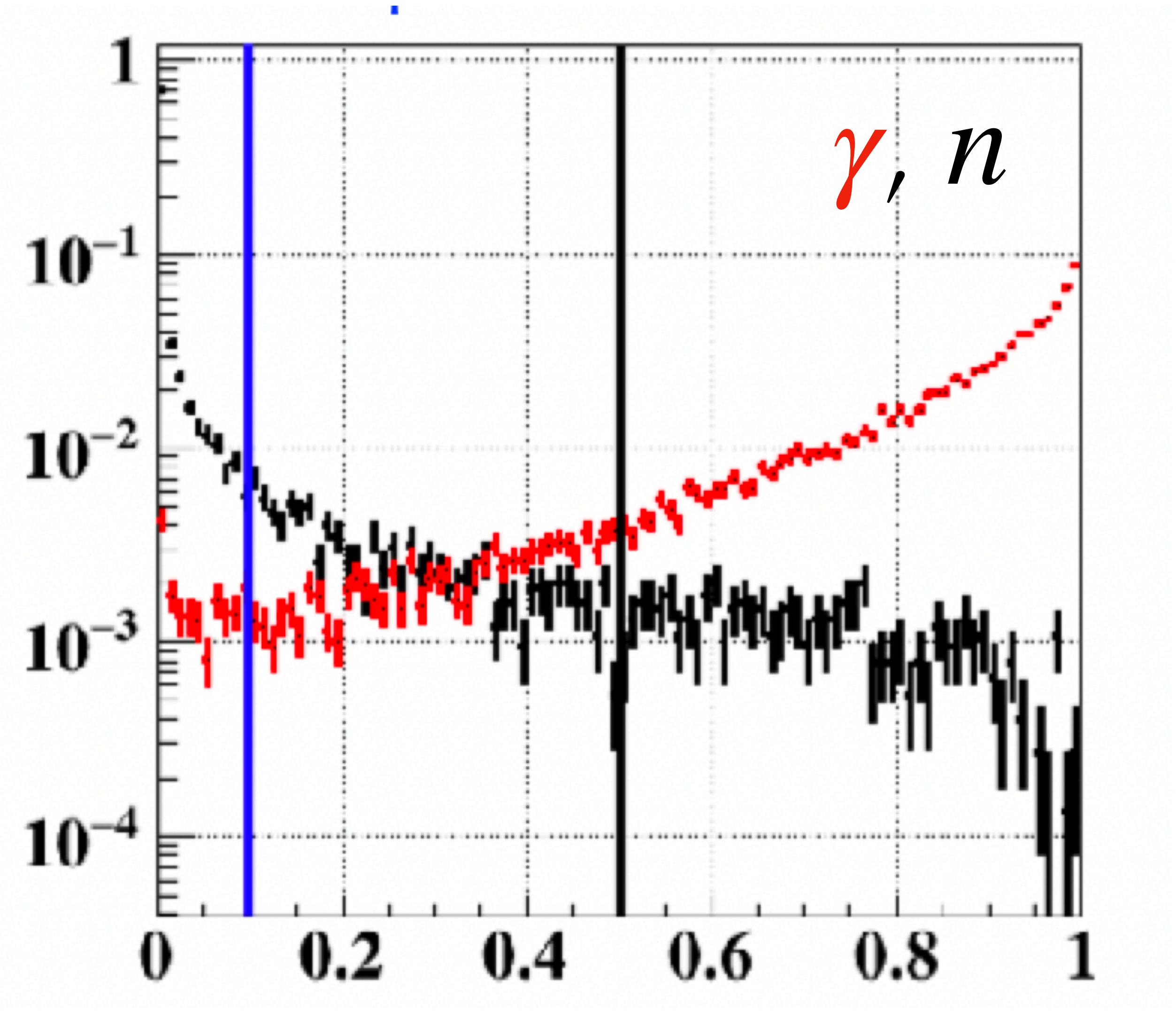


Cut for Hadron Cluster Background

New (2019–)

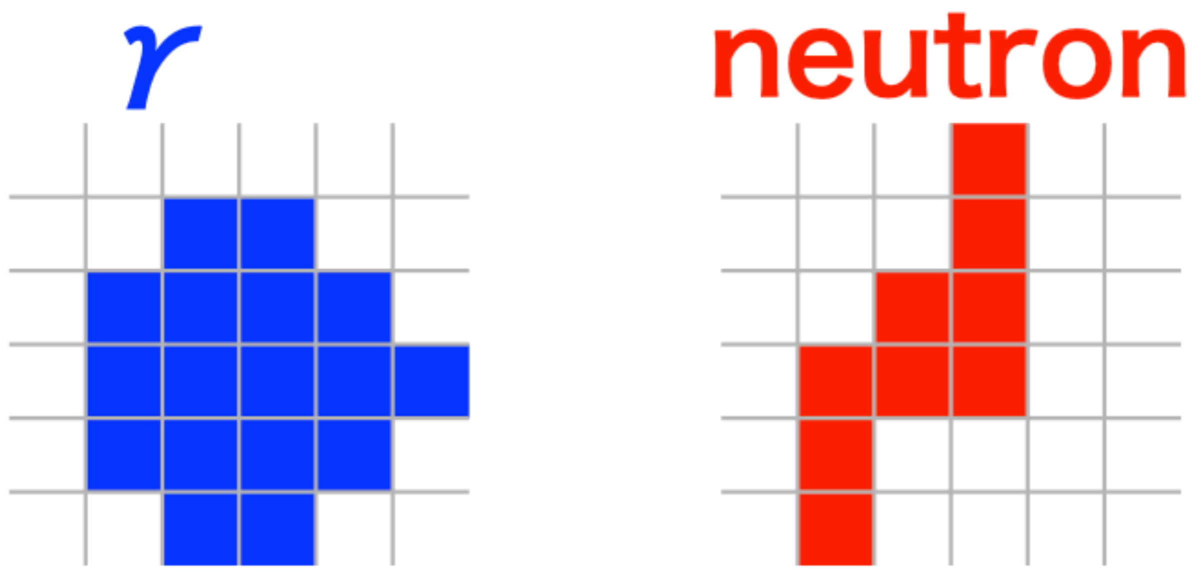
Fourier Pulse Shape Discrimination

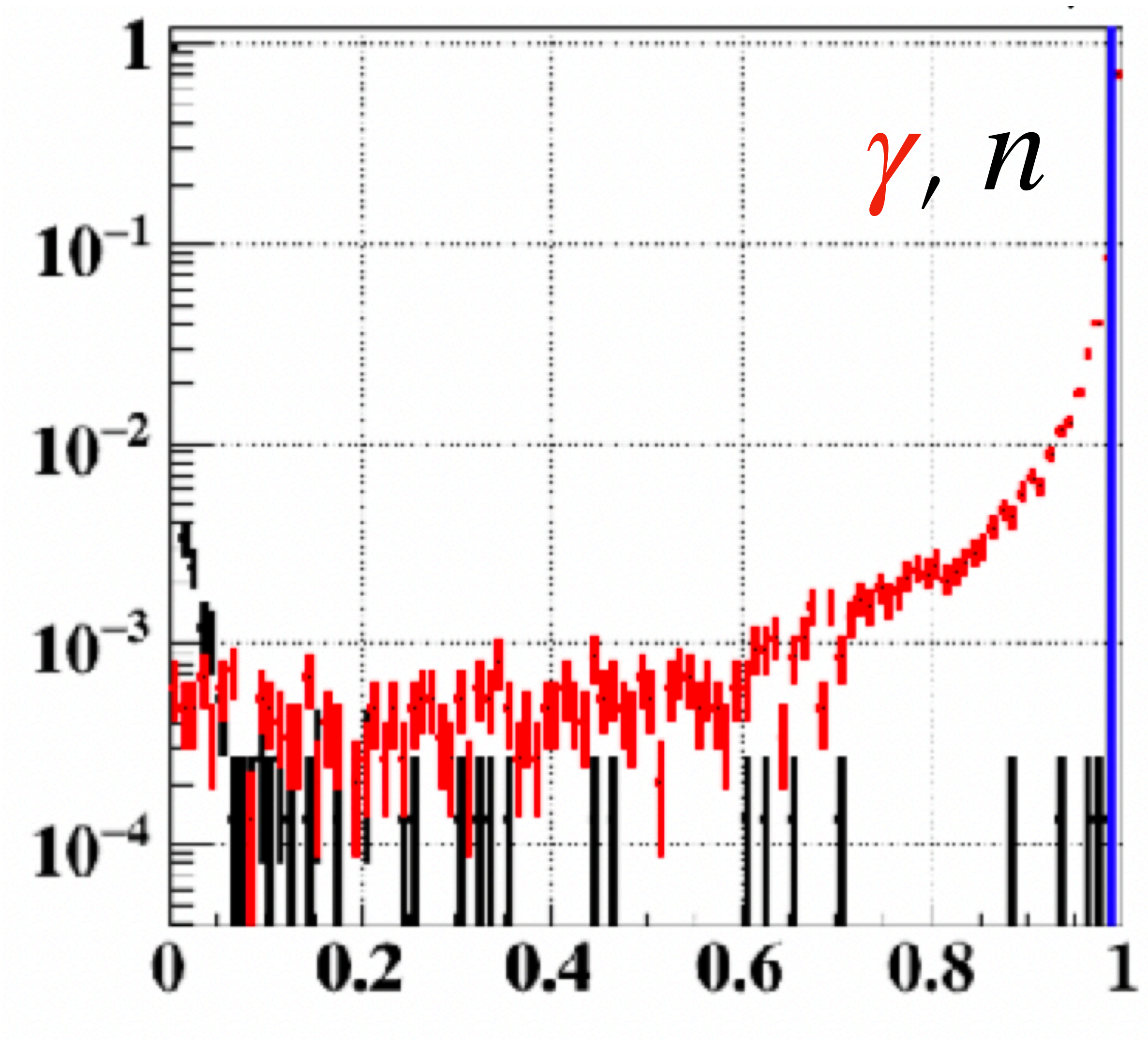




FPSD output

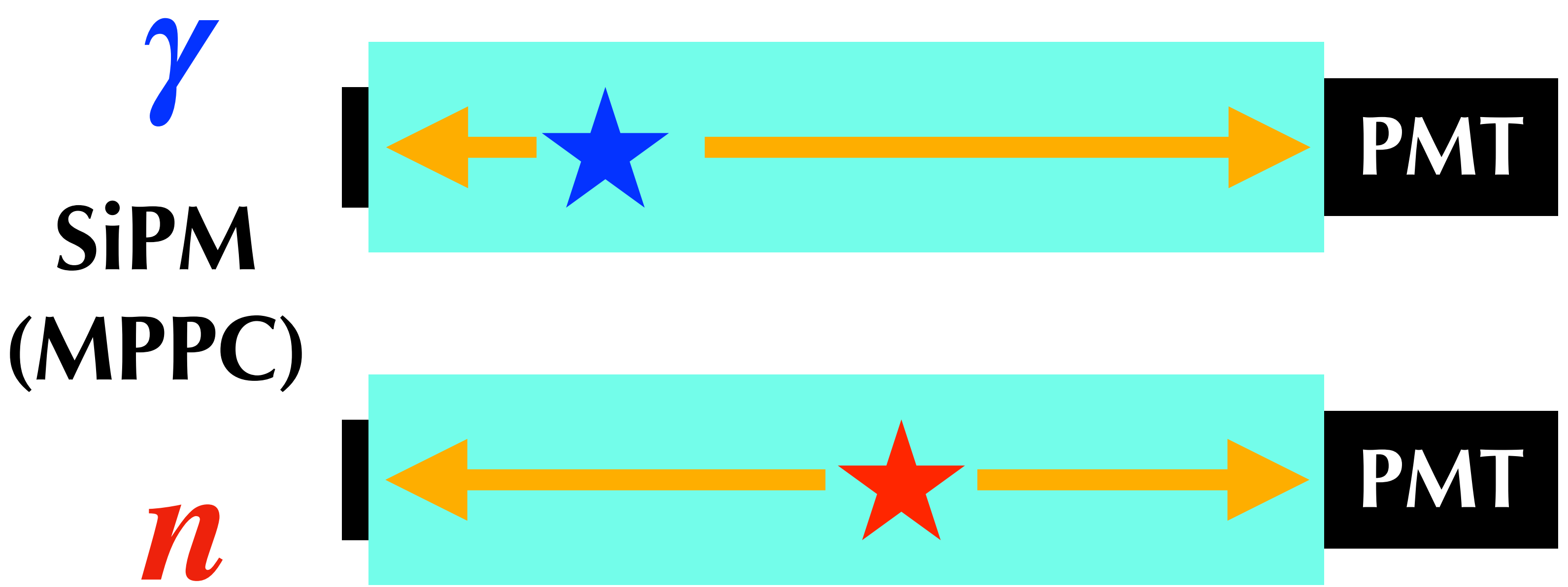
Cluster Shape Discrimination

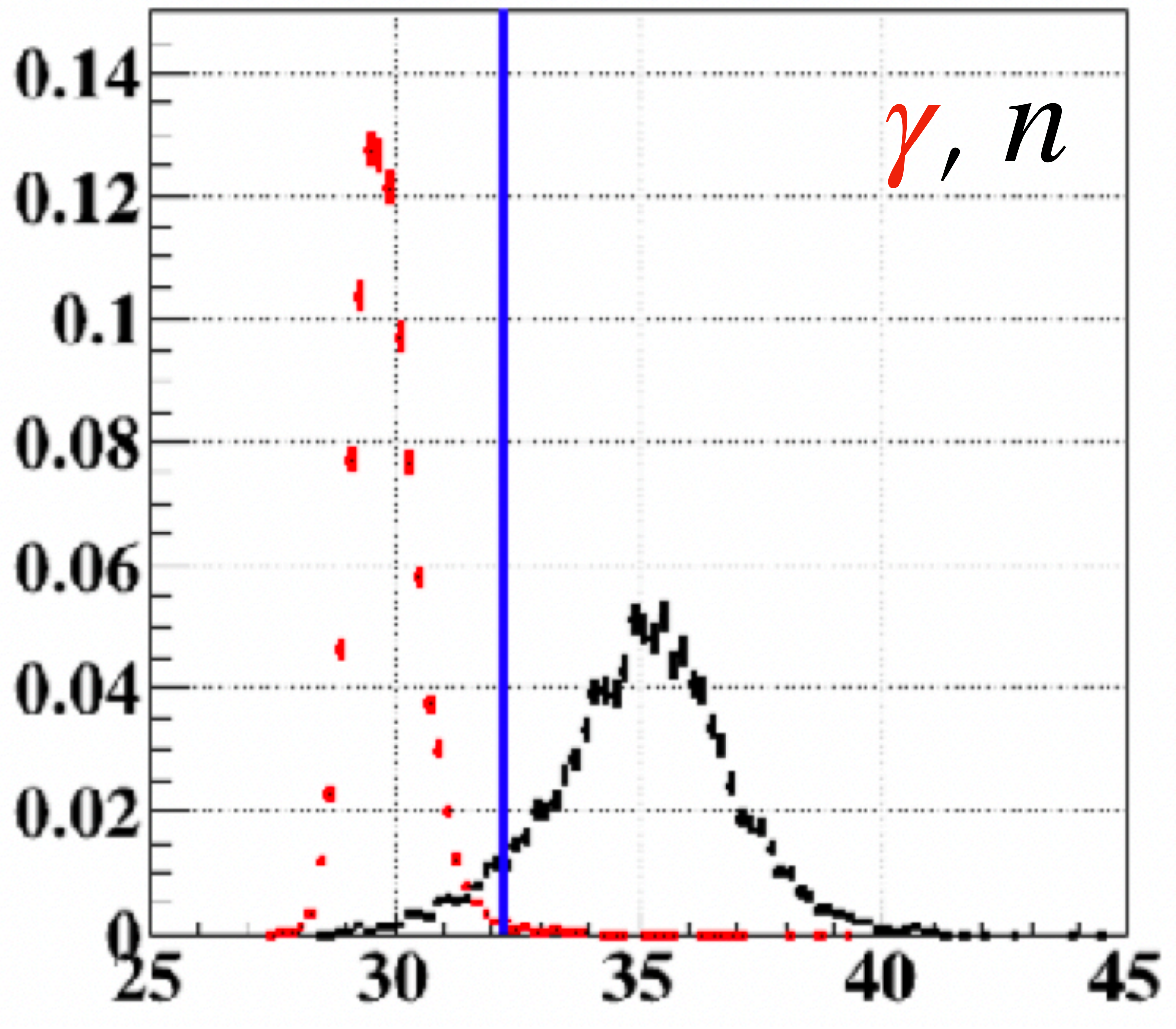




CSDDL output

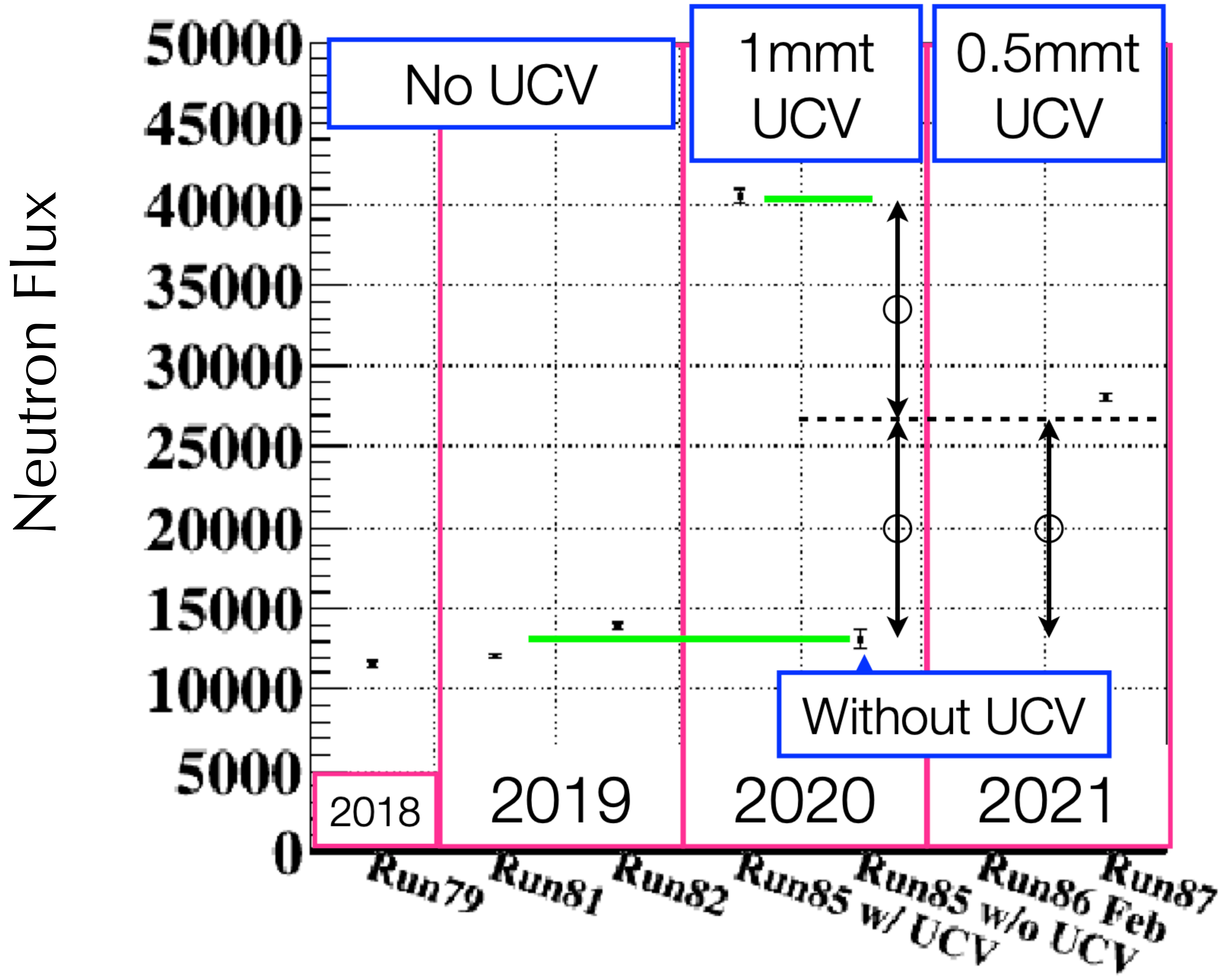
Both-end Readout



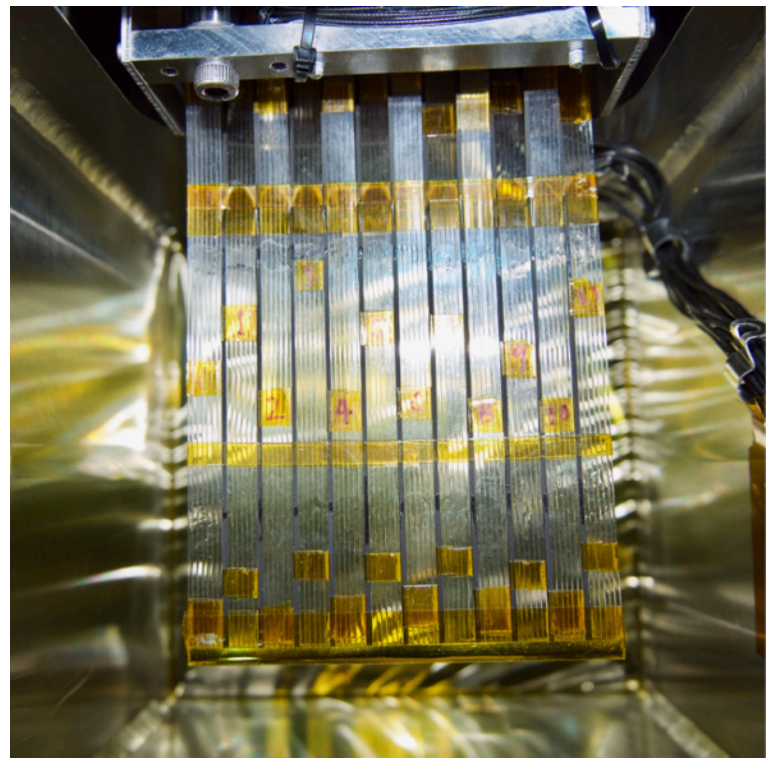


ΔT [ns]

Halo Neutron Flux



1 mm sq. fiber prototype UCV (2020)



0.5 mm sq. fiber UCV (2021)