New results from KOTO

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Kaon2023@CERN 2023 September 11

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- Feature of 2021 data analysis
- New Results of 2021 data analysis on the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ search
- Prospect
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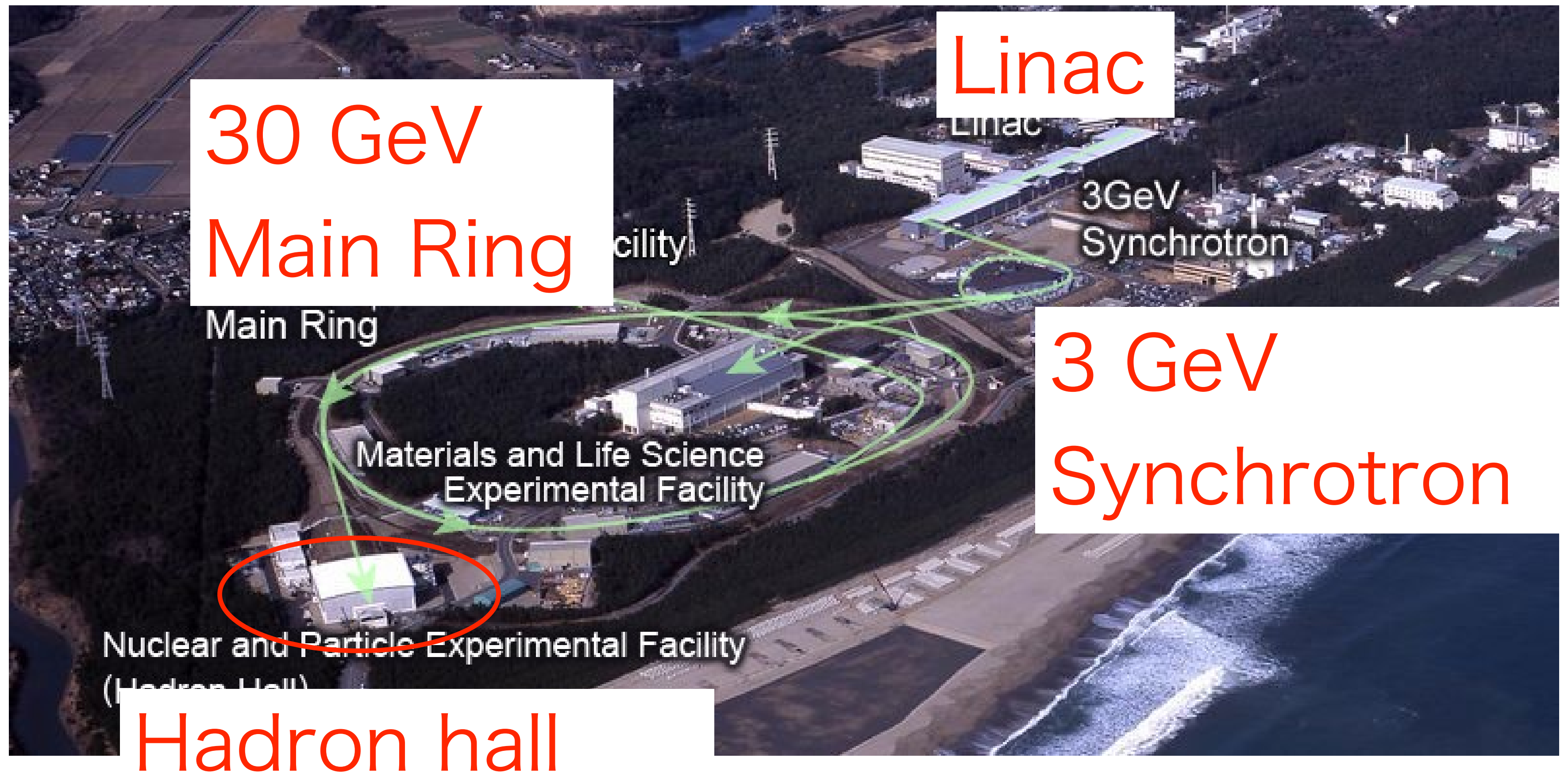
KOTO experiment

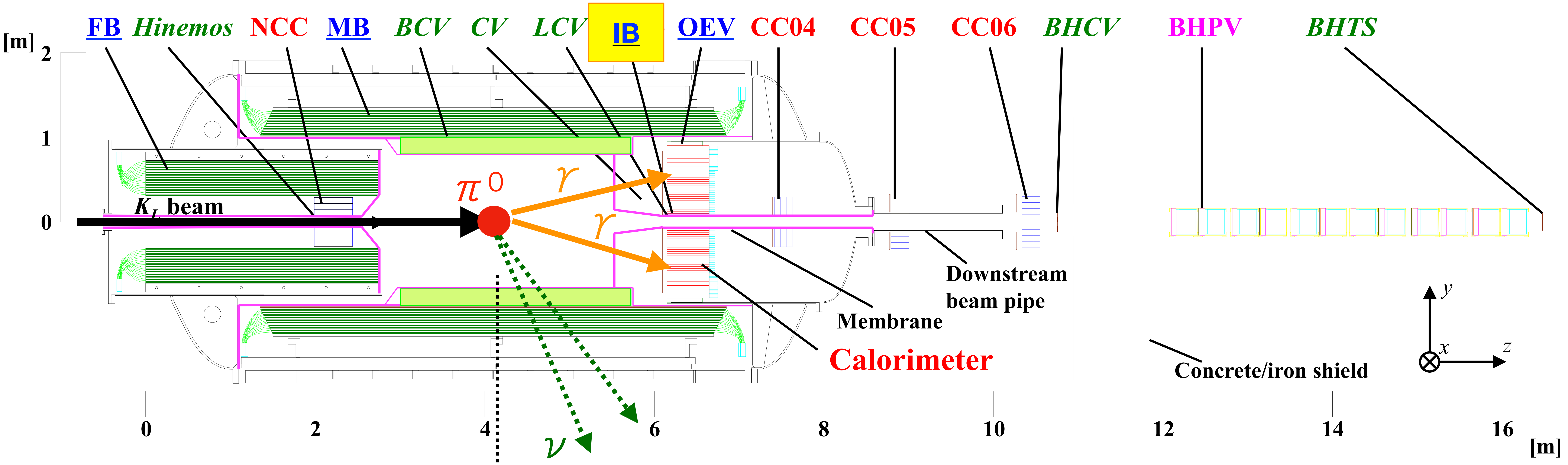
- Study of $K_L \to \pi^0 \nu \nu$@J-PARC 30GeV Main Ring.

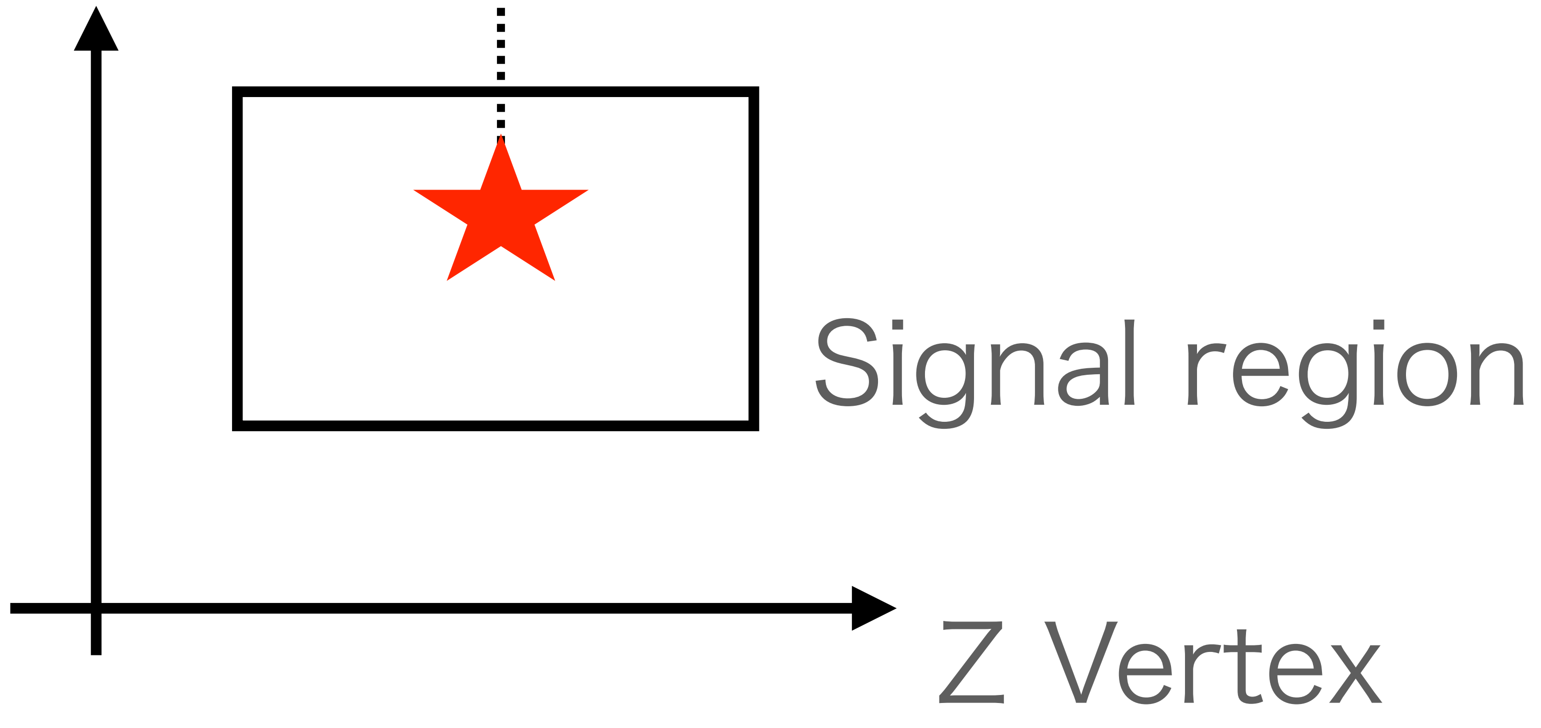


@ collaboration meeting (hybrid) on June 30- July 2, 2023

Experimental principle

Signature of $K_L \to \pi^0 \nu \nu$ = "2γ+Nothing+Pt"





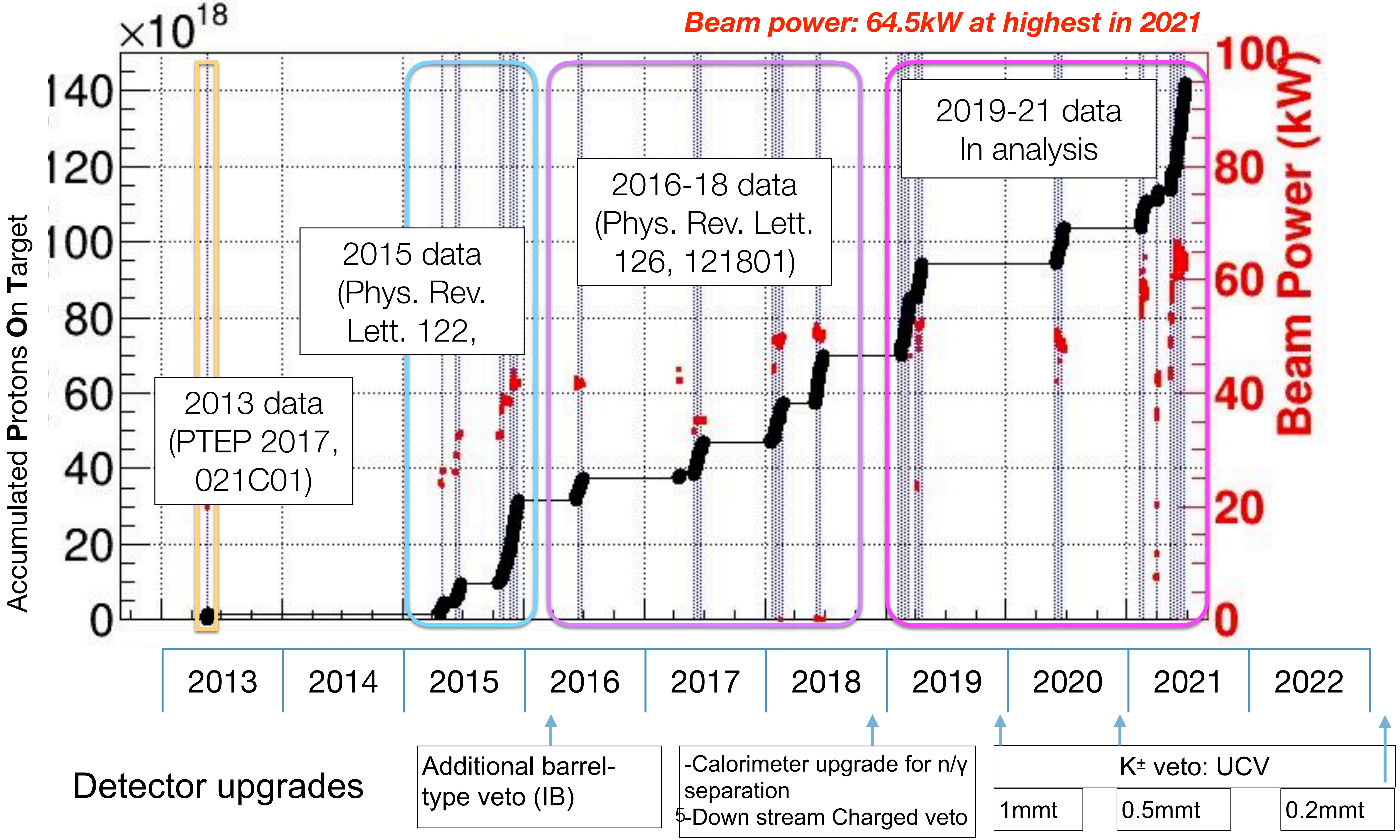
Assuming 2γ from π^0,

Calculate z vertex on the beam axis

$$M^2(\pi^0)=2E_1E_2(1-\cos\theta)$$

Calculate π^0 transverse momentum

Data accumulation history

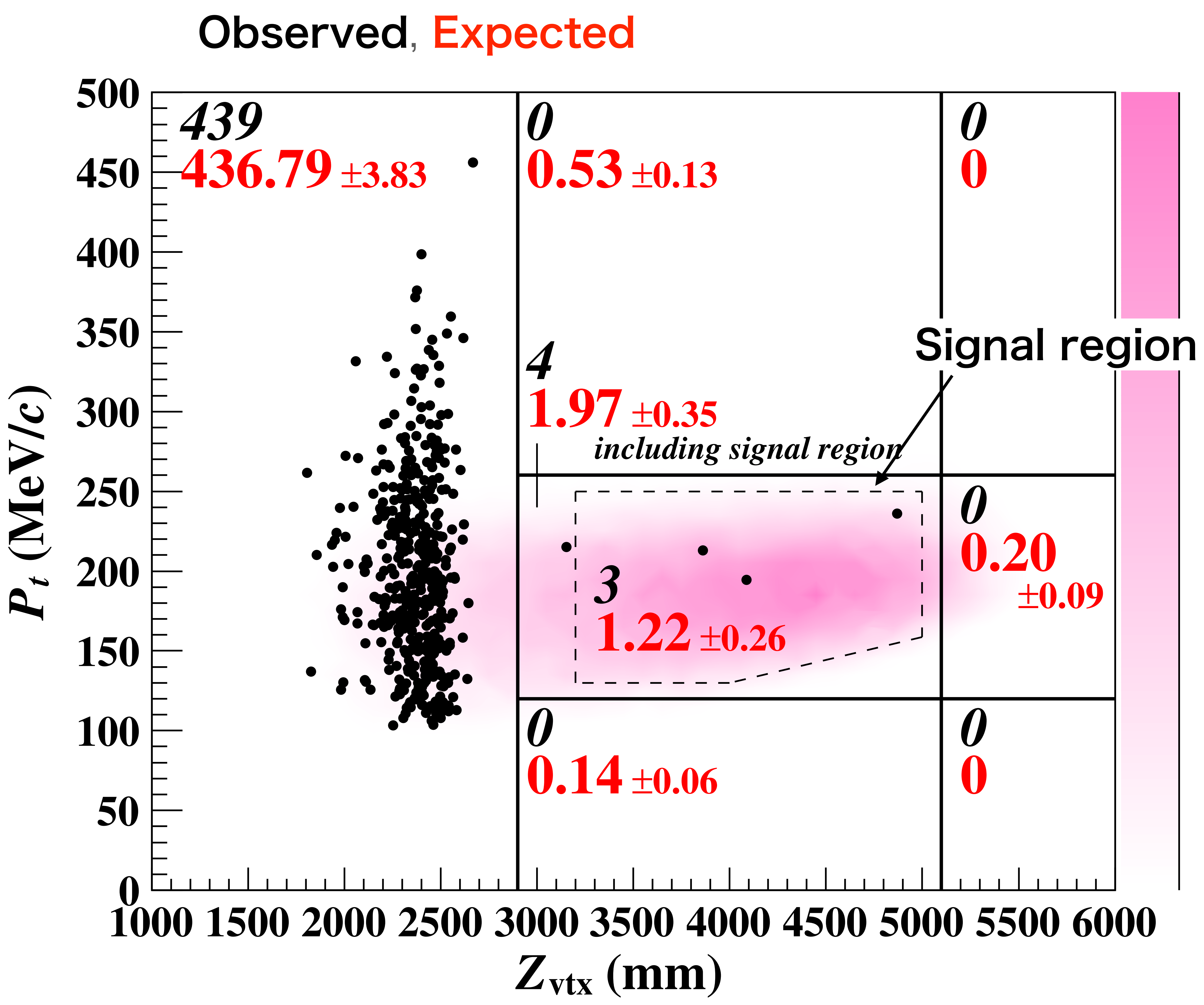


Review of 2016-2018 analysis results

- Observed 3 events with 1.22 predicted background(BG)
  - BR($K_L \to \pi^0 \nu \bar{\nu}$)<$4.9\times10^{-9}$ @ 90% C.L.

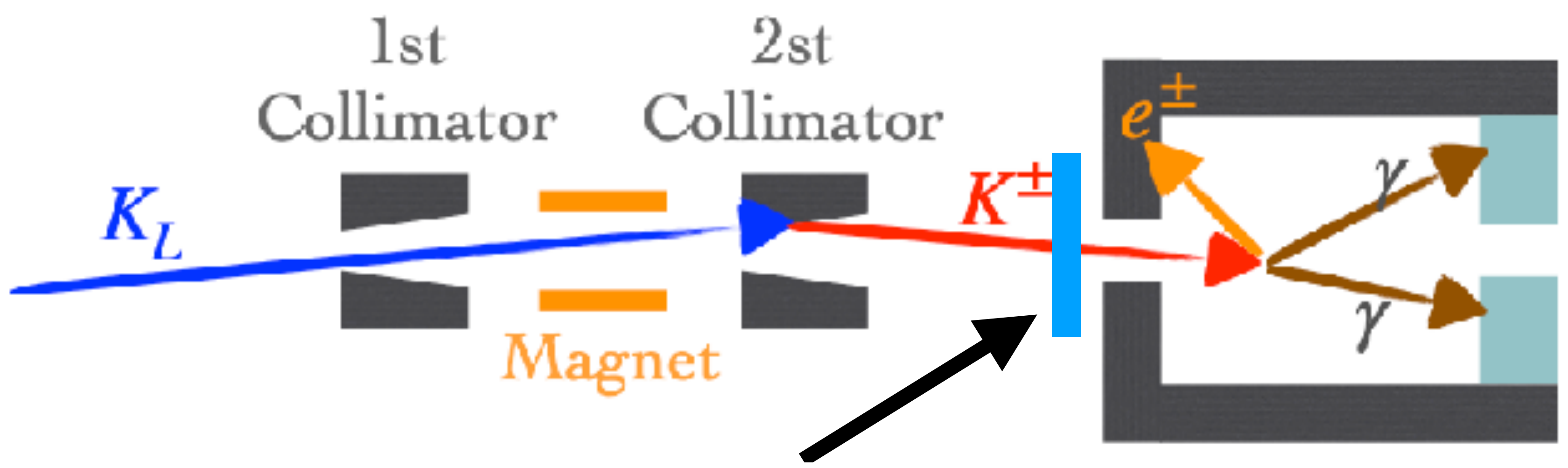
Background Table

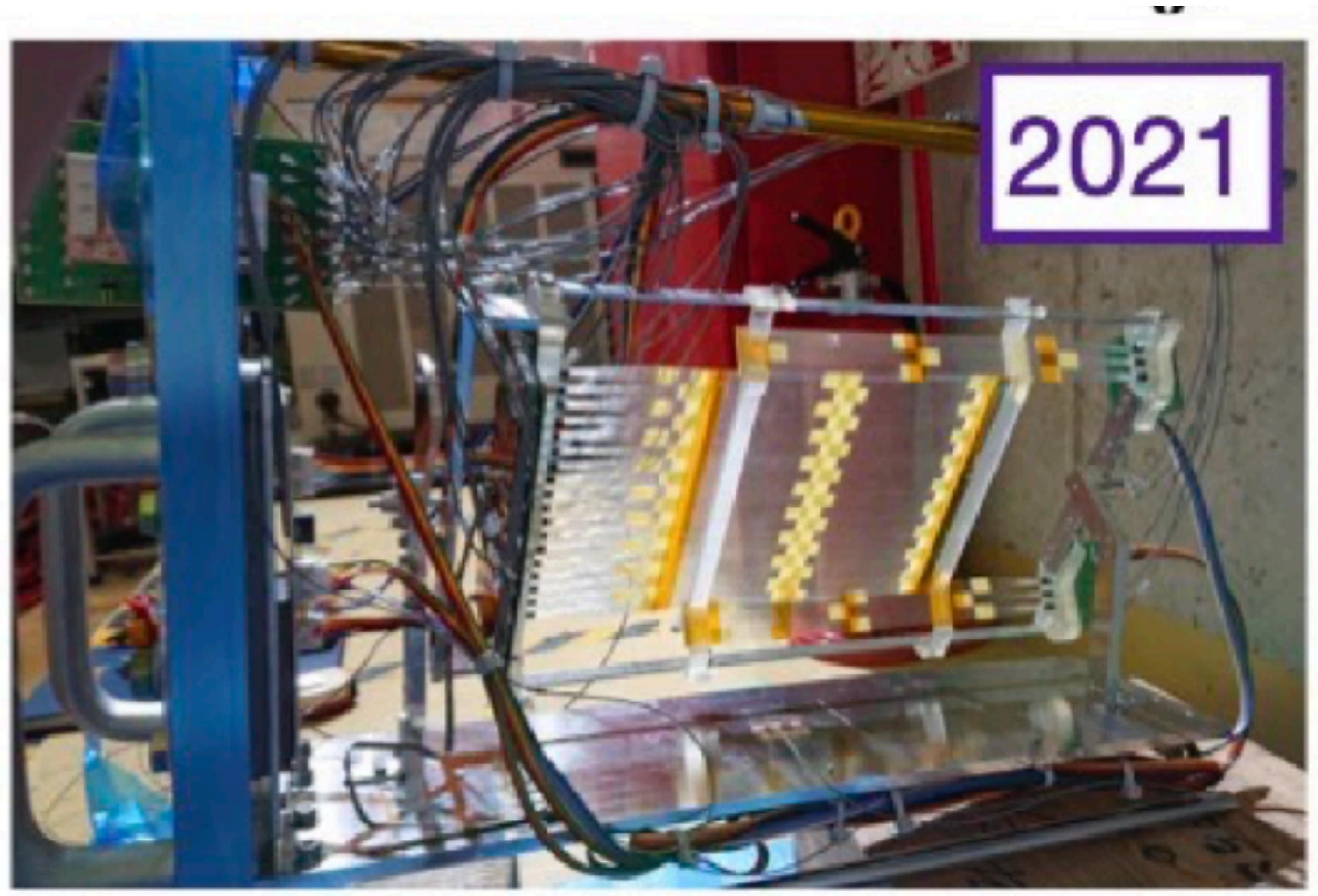
	Number of events
$K_L \to 3\pi^0$	0.01 ± 0.01
$K_L \to 2\gamma$ (beam halo)	0.26 ± 0.07[a]
Other K_L decays	0.005 ± 0.005
$K^\pm$	0.87 ± 0.25[a]
Hadron cluster	0.017 ± 0.002
CV η	0.03 ± 0.01
Upstream π^0	0.03 ± 0.03
	1.22 ± 0.26



Measures against dominant BG sources

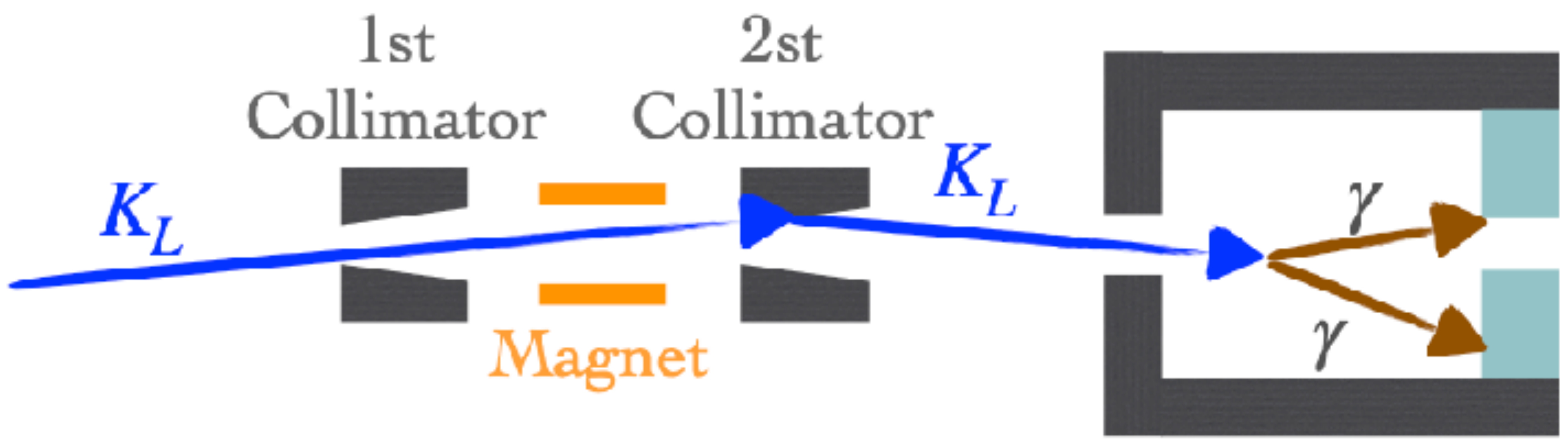
K± BG ($K^{\pm} \rightarrow \pi^{0} e^{\pm} \nu$)





- Installed Upstream Charged Veto(UCV) for K± detection
  →Reduced by a factor of 13 with 97% signal efficiency.

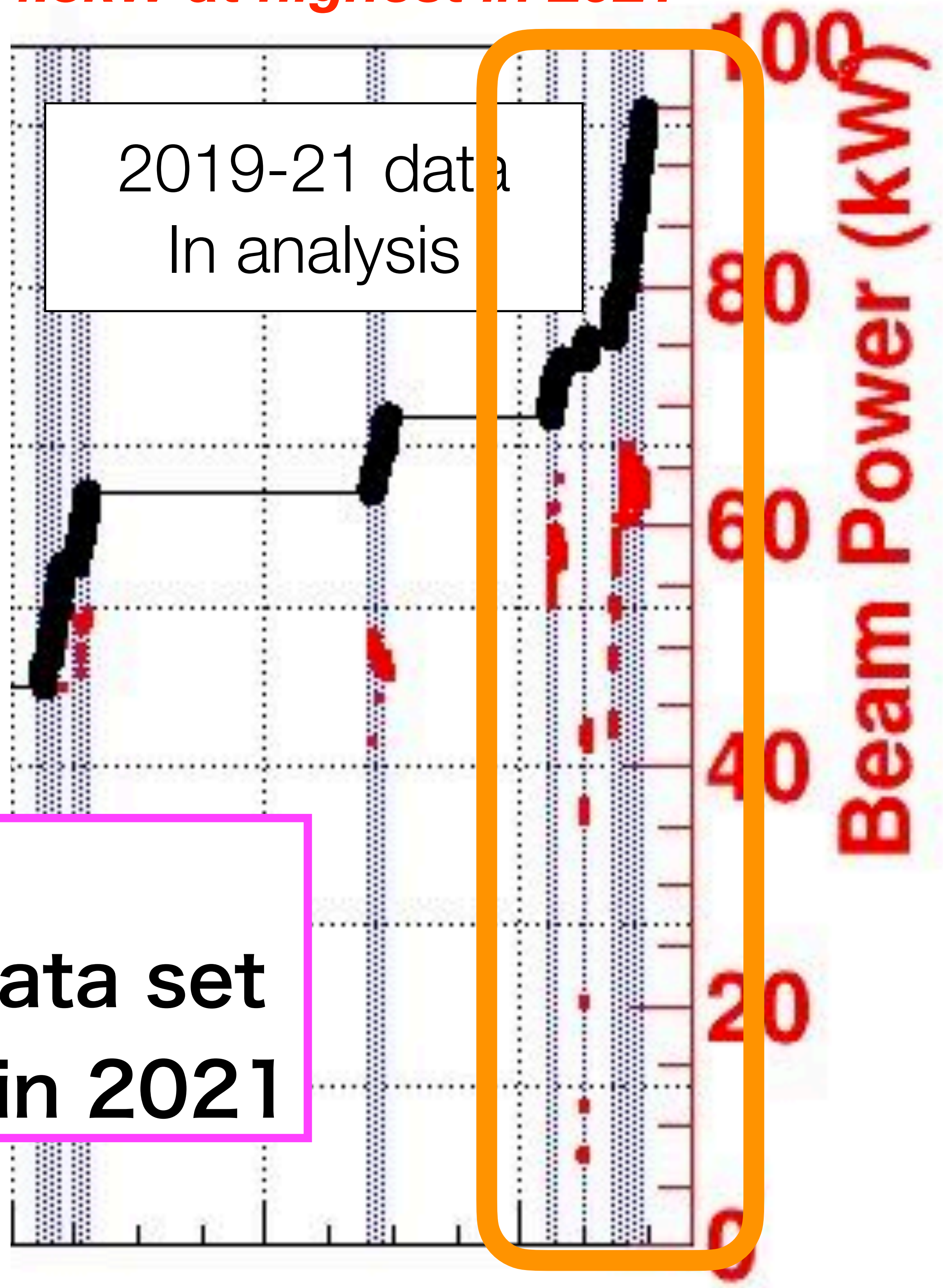
Halo $K_L \rightarrow 2\gamma$



- Developed a likelihood ratio cut based on shower shape and a Multi variable analysis cut based on kinematical variables
  →Reduced by a factor of 8 with 94% signal efficiency.

Data set in the latest analysis

Beam power: 64.5kW at highest in 2021



We focus on the analysis of 2021 data
because the background level is smallest in this data set
thanks to Upstream Charged Veto newly installed in 2021

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022

Detector upgrades

- Additional barrel-type veto (IB)
- -Calorimeter upgrade for n/γ separation
  -Down stream Charged veto
- K± veto: UCV
  - 1mmt
  - 0.5mmt
  - 0.2mmt

Executive summary of the 2021 data analysis

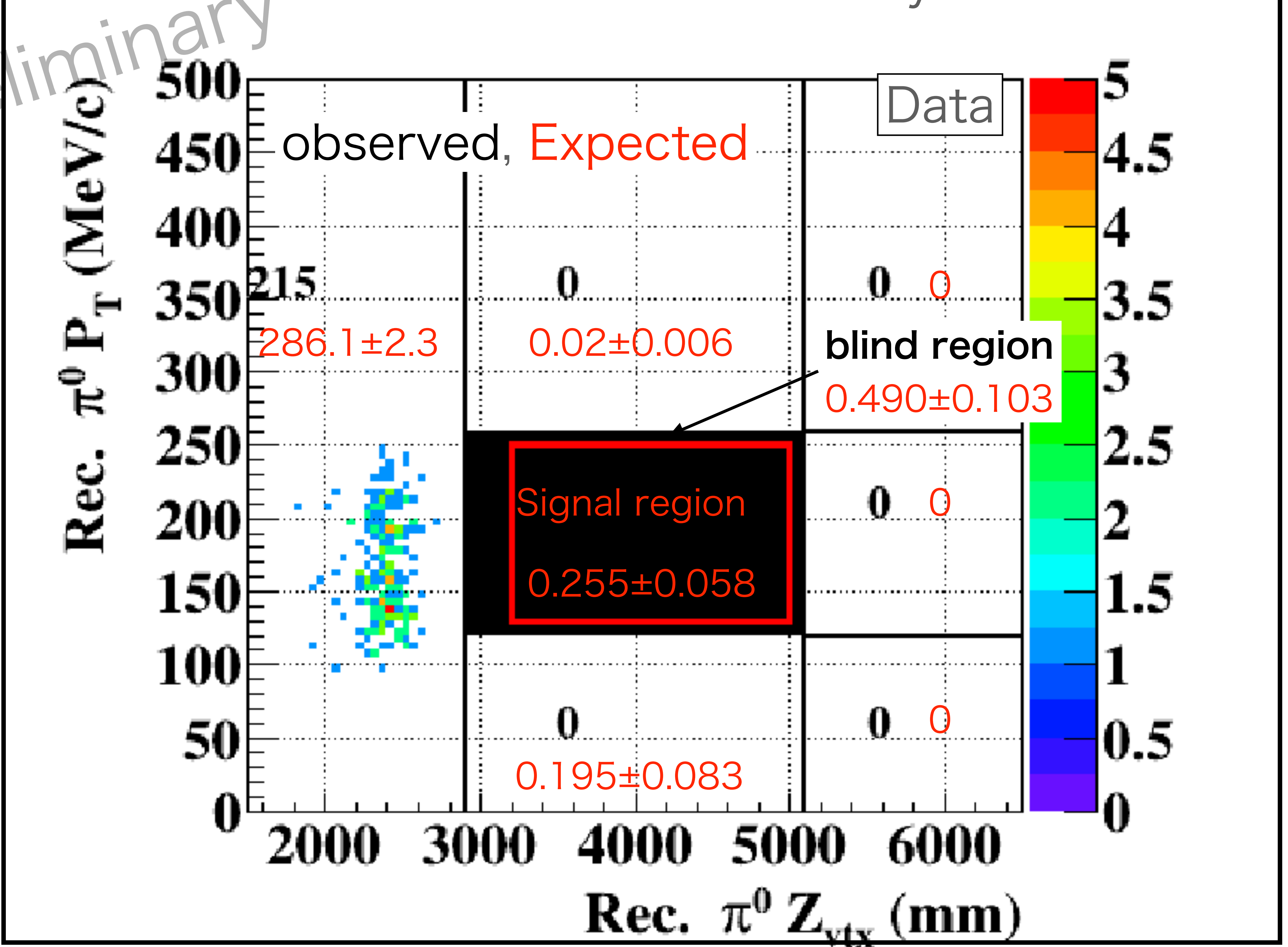
- Change from the 2016-2018 analysis
  - Extended signal box
  - Implemented measures to reduce the $K^{\pm}$ and Halo $K_L \to 2\gamma$ BG
    - #($K^{\pm}$ BG),#(Halo $K_L \to 2\gamma$ BG) < O(0.1)
  - Optimized the selection criteria against hadron cluster backgrounds.
  - Developed a new cut on $K_L \to 2\pi^0$ BG
  - Developed several analysis methods to estimate BG events more accurately.
  - Developed a new analysis method to investigate the situation inside the signal box

Single Event Sensitivity(S.E.S.):8.7×10^{-10}

c.f. 2016-2018 analysis:7.2×10^{-10}

BG Estimation

c.f. 2016-2018 analysis:1.22±0.26

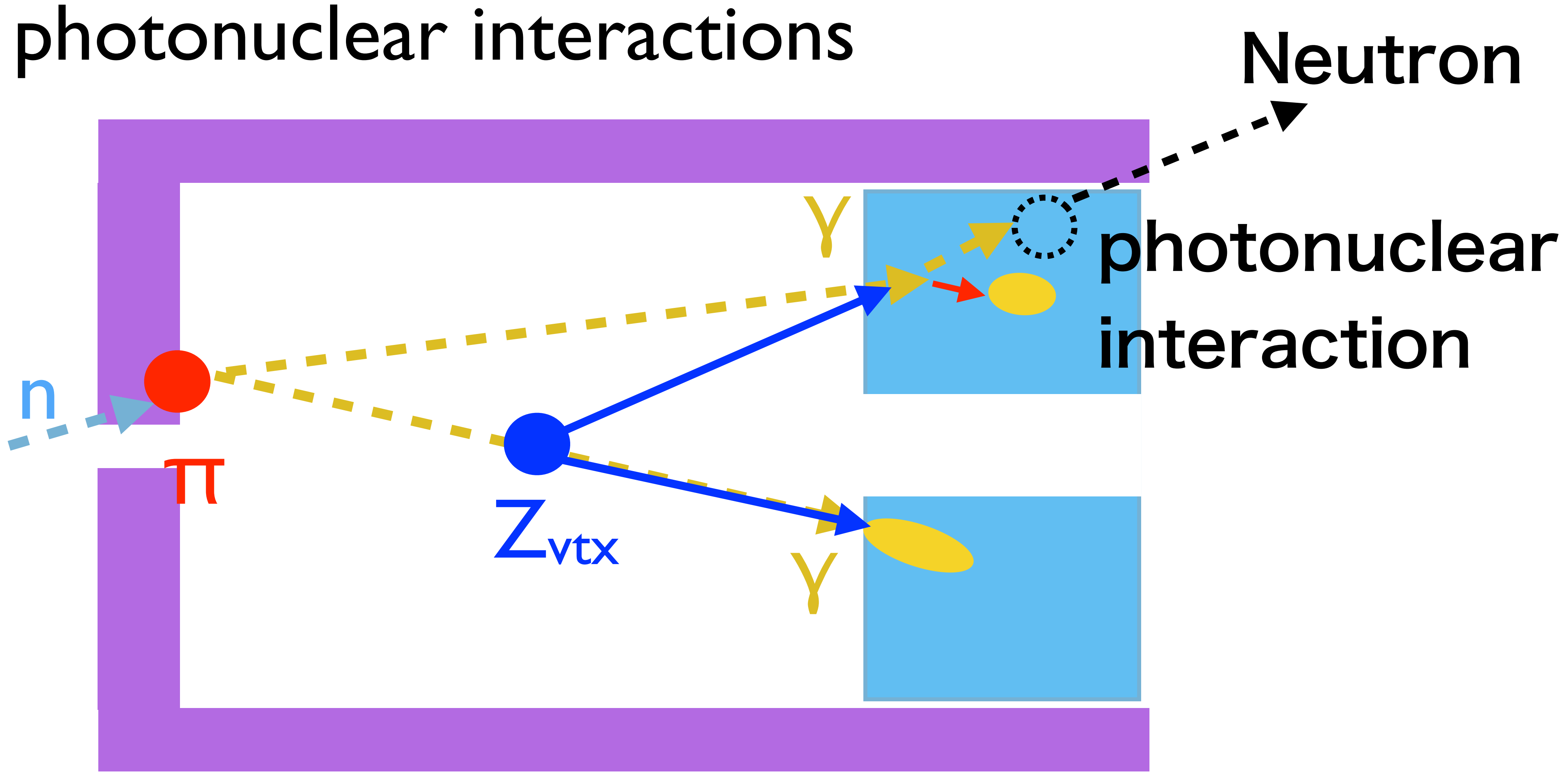


Summary of BG in 2021 data analysis

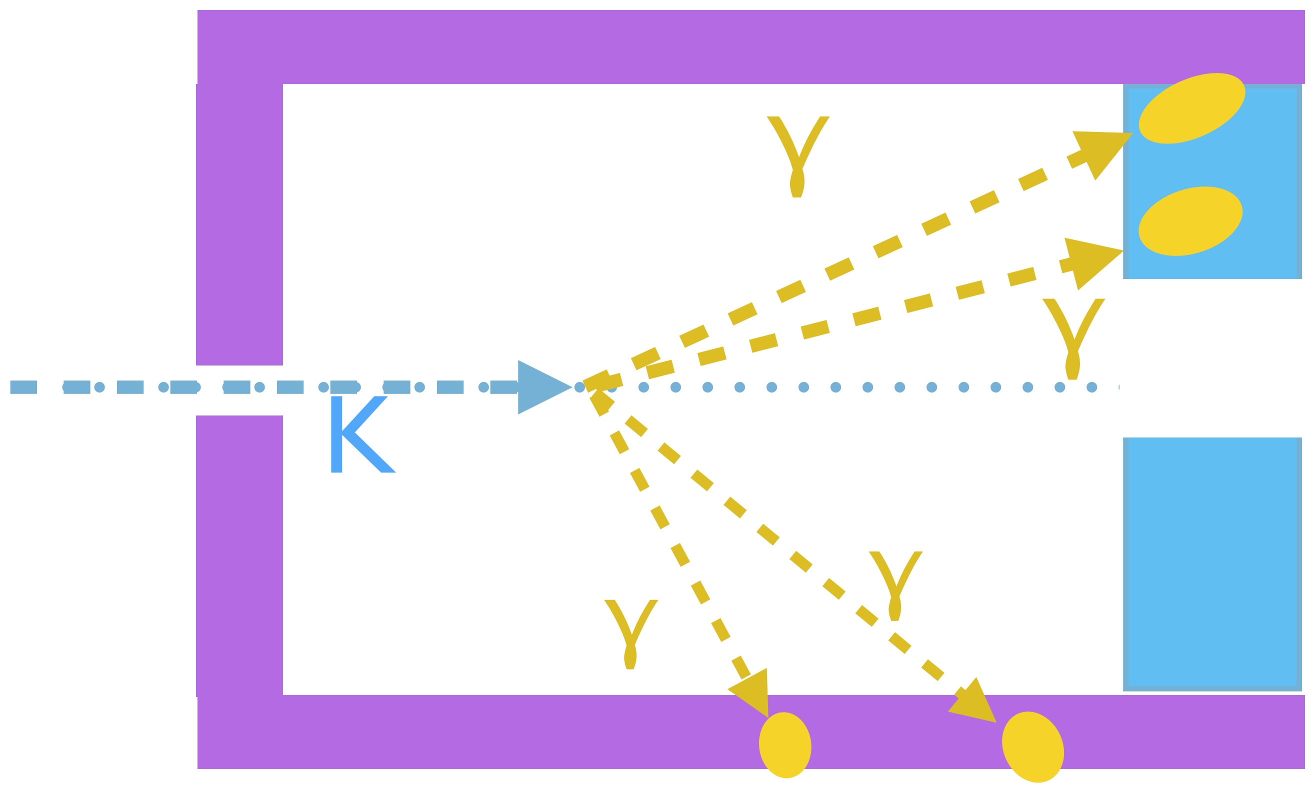
Preliminary

source	Current estimation
Upstream π^0	0.064±0.050(stat)±0.006(sys)
$K_L \to 2\pi^0$	$0.060 \pm (0.022)_{stat}(^{+0.051}_{-0.060})_{sys}$
K^+	$0.043 \pm (0.015)_{stat}(^{+0.004}_{-0.030})_{sys}$
Hadron cluster BG	0.024±0.004(stat)±0.006(sys)
Scattered $K_L \to 2\gamma$	0.022±0.005(stat)±0.004(sys)
Halo $K_L \to 2\gamma$	0.018±0.007(stat)±0.004(sys)
η production in CV	0.023±0.010(stat)±0.006(sys)
Sum	0.255±0.058(stat) $(^{+0.053}_{-0.068})_{sys}$

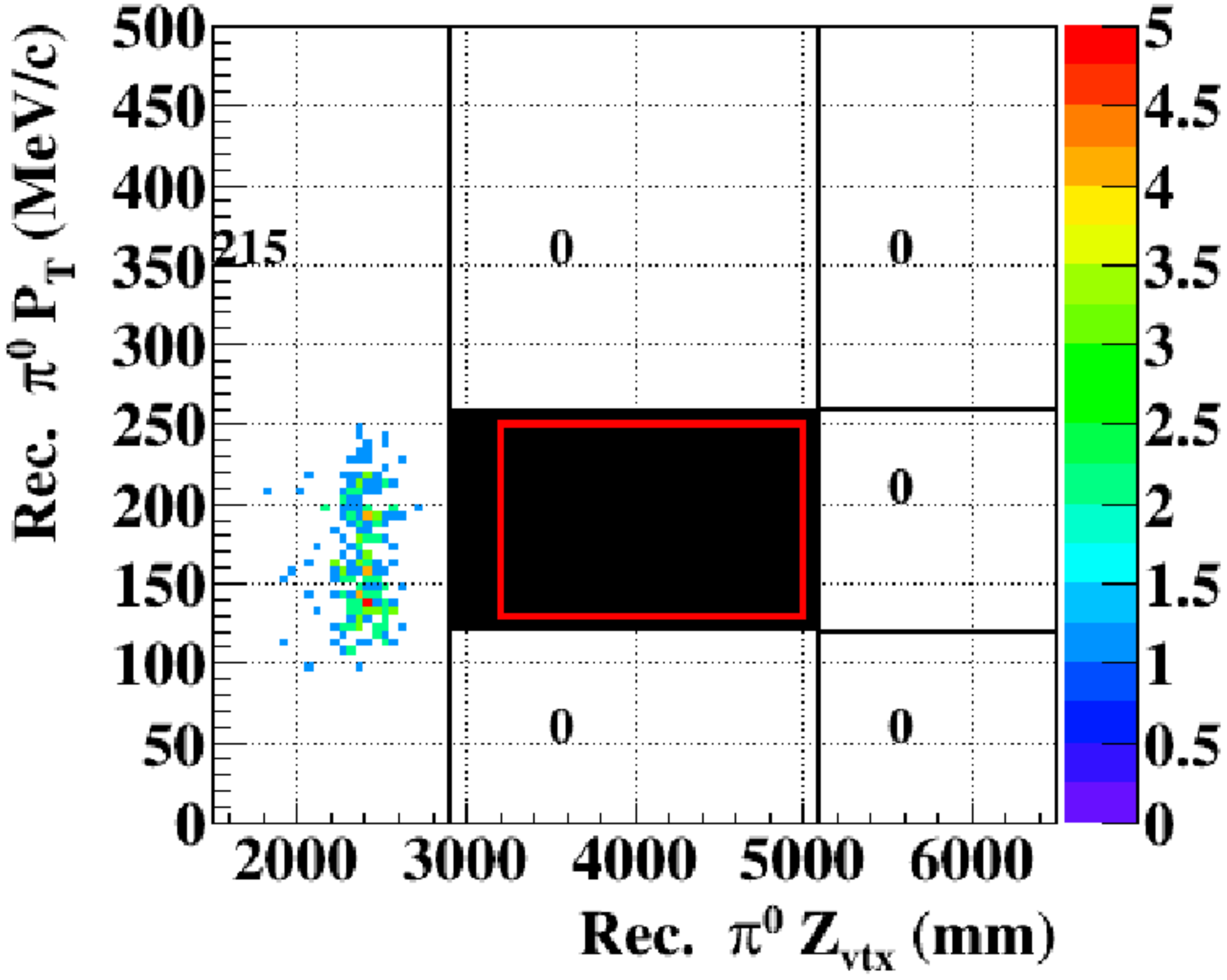
Upstream π^0 events deu to photonuclear interactions



$K_L \to 2\pi^0$



Open the signal box

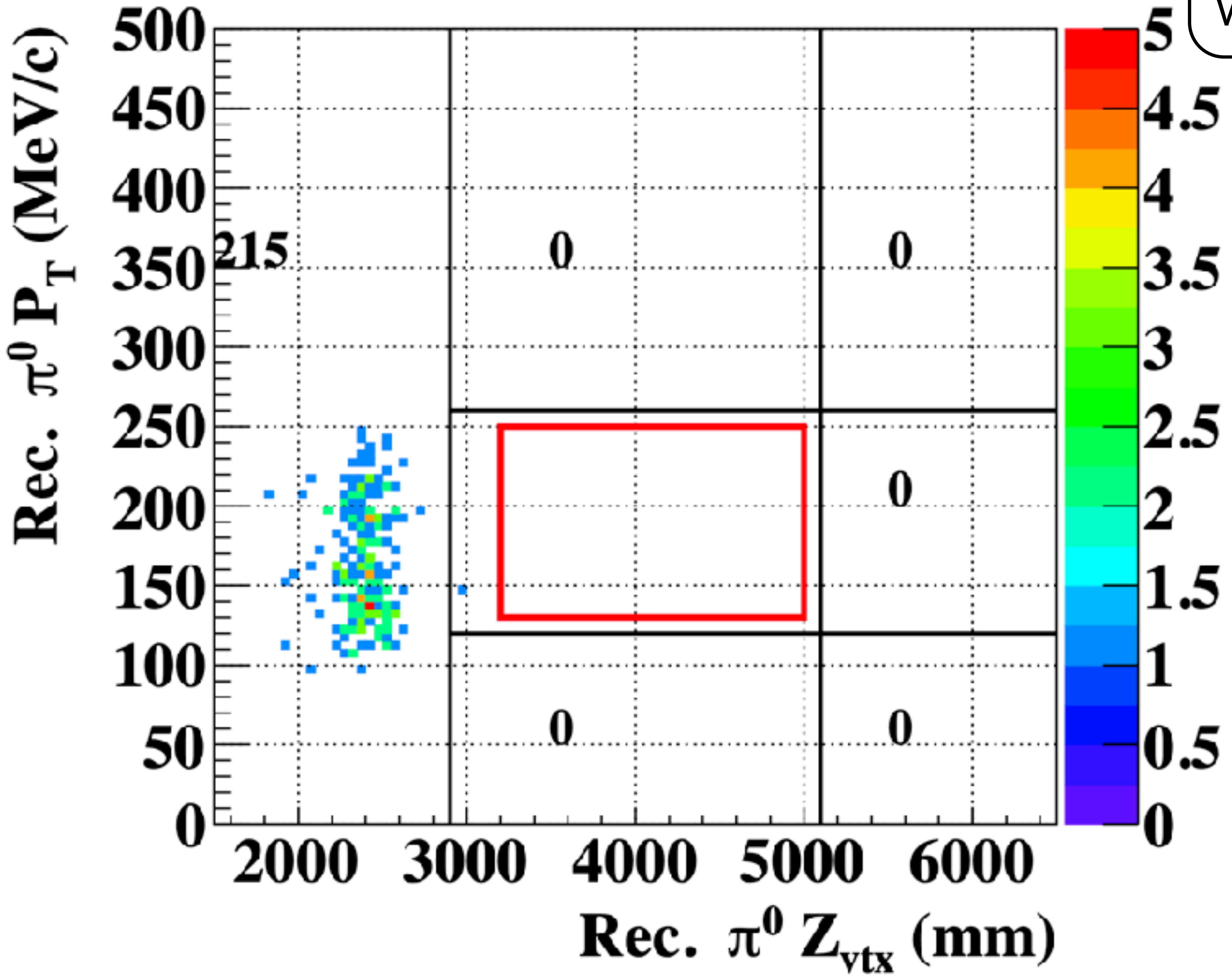


Open the signal box

- No signal candidate was observed
    - BR<2.0x10^{-9}@90% C.L.

Preliminary

S.E.Sx 2.3
with Poisson statistics



Prospect

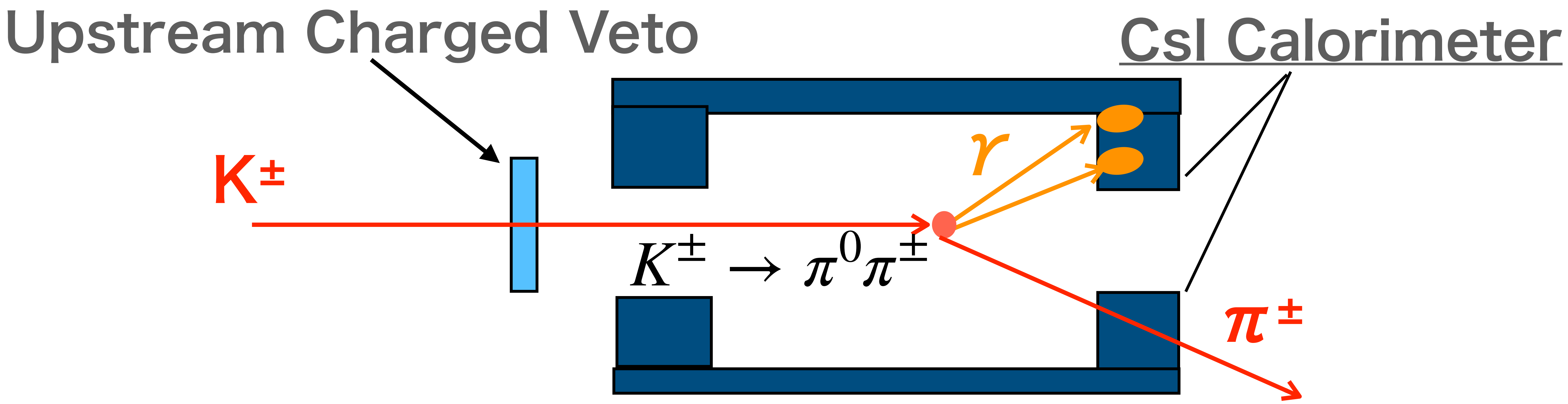
- Analysis of 2020 and 2019 data
  - Deteriorate performance of a prototype detector for K^+ detection due to irradiation of MPPC in 2020 data.
  - Develop a new cut to reduce K^+ background without a detector for K^+ detection in 2019 data
- Future physics run
  - Collect 10 times more POT in 3-4 years by assuming 60 days data taking per year.
  - Reach a sensitivity below 10^{-10}

Summary

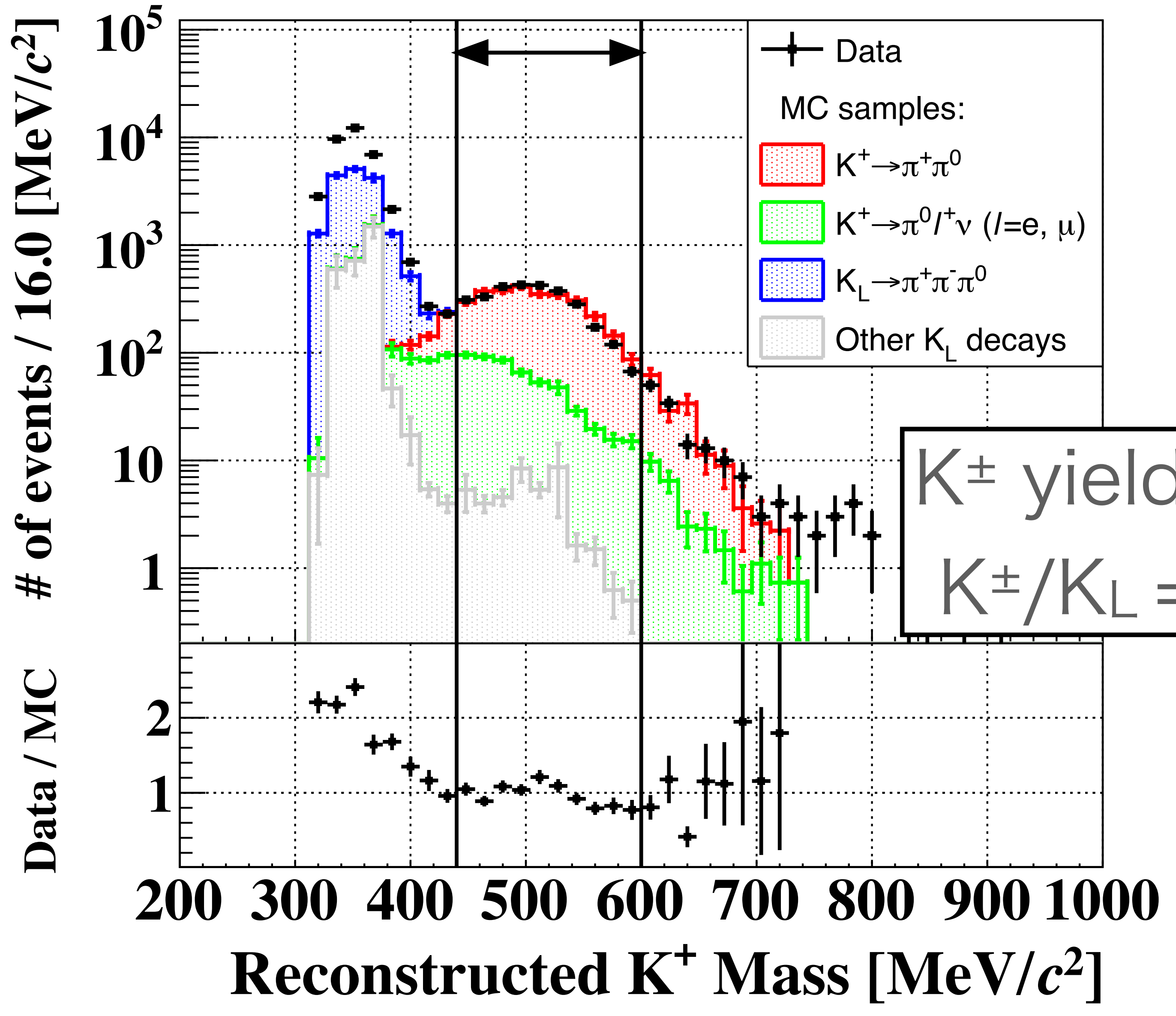
- The KOTO experiment studies the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay.
- No signal candidate was observed in 2021 data
  - Preliminary
  - $BR < 2.0 \times 10^{-9}$ @90% C.L.
    - Improved the current upper limit by 50% with a 5 times smaller background level.
- Continue to take physics data to achieve the sensitivity below 10^{-10}.

Estimation of N(K± BG)

- K± yield and the inefficiency of Upstream Charged Veto(UCV) were evaluated by identifying $K^{\pm} \to \pi^{\pm}\pi^{0}$ decay



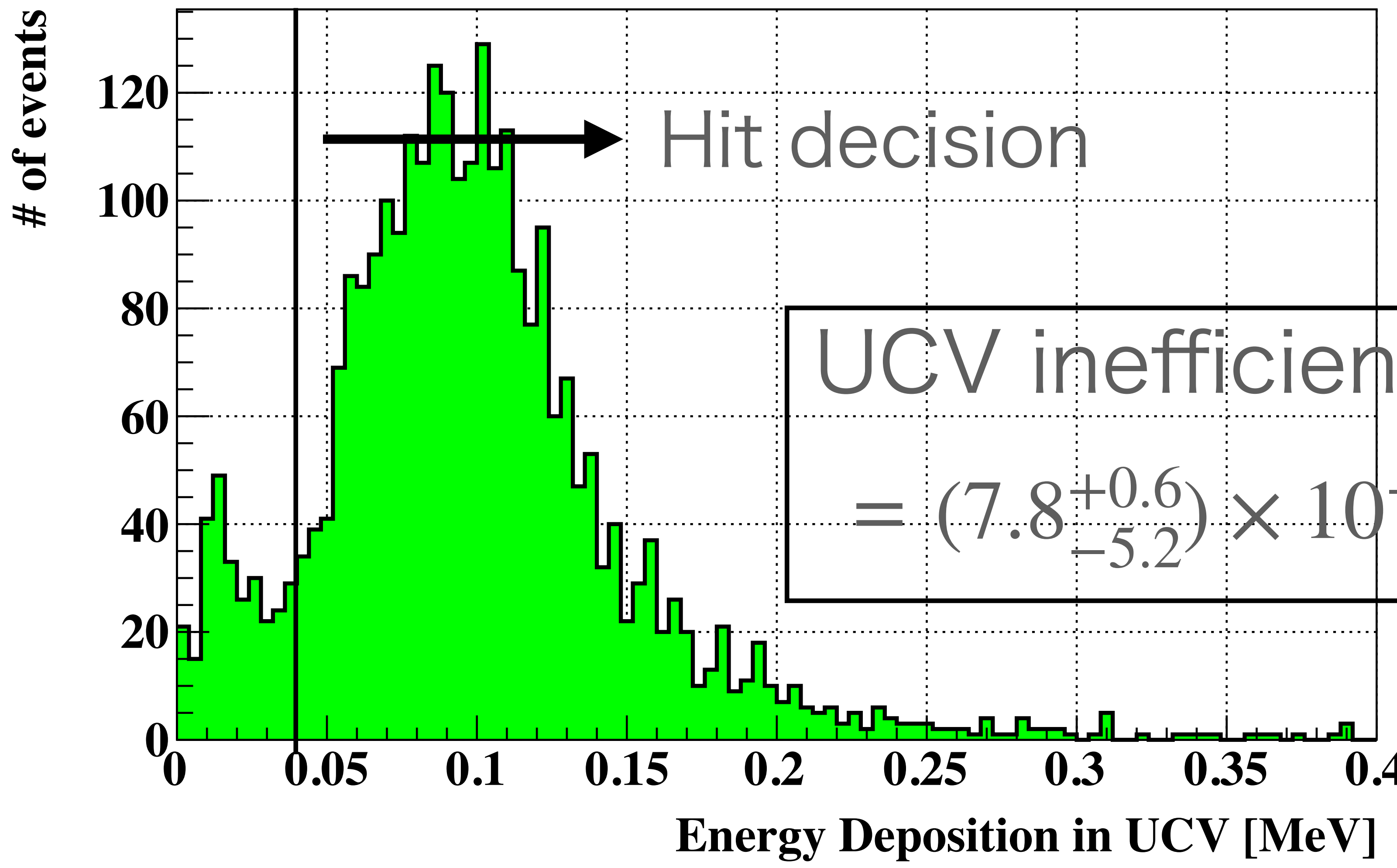
- 3-Cluster events
- π^{0} vertex reconstruction from 2γ
- $\pi^{\pm}$ reconstruction assuming transverse momentum balance



K± yield estimation

$K^{\pm}/K_L = 3.2\times10^{-5}$

$K^{\pm}\to\pi^{+}\pi^{0}$ candidate events



Hit decision

UCV inefficiency

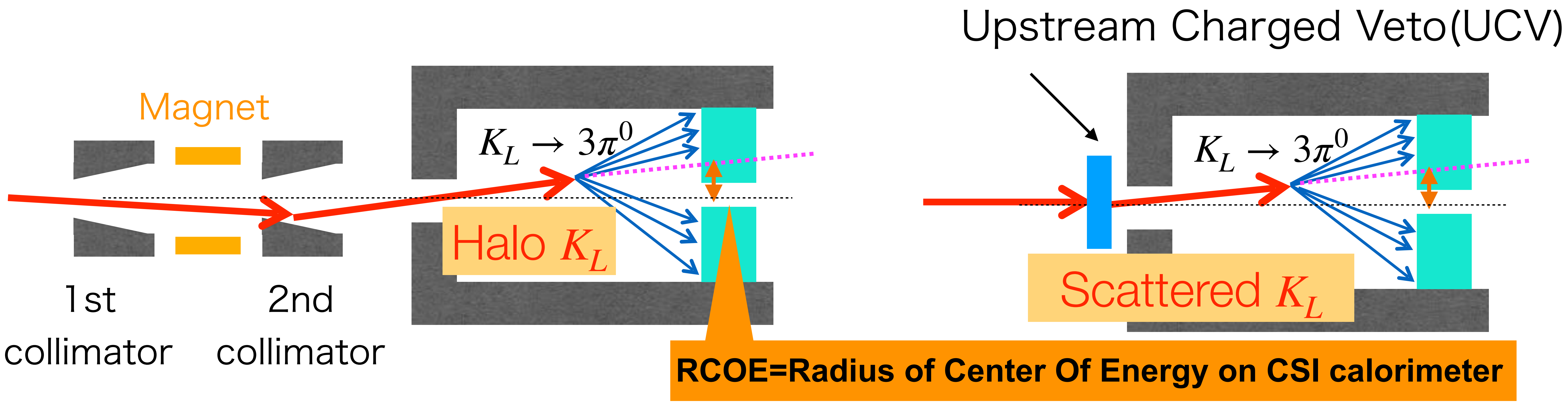
$= (7.8^{+0.6}_{-5.2}) \times 10^{-2}$

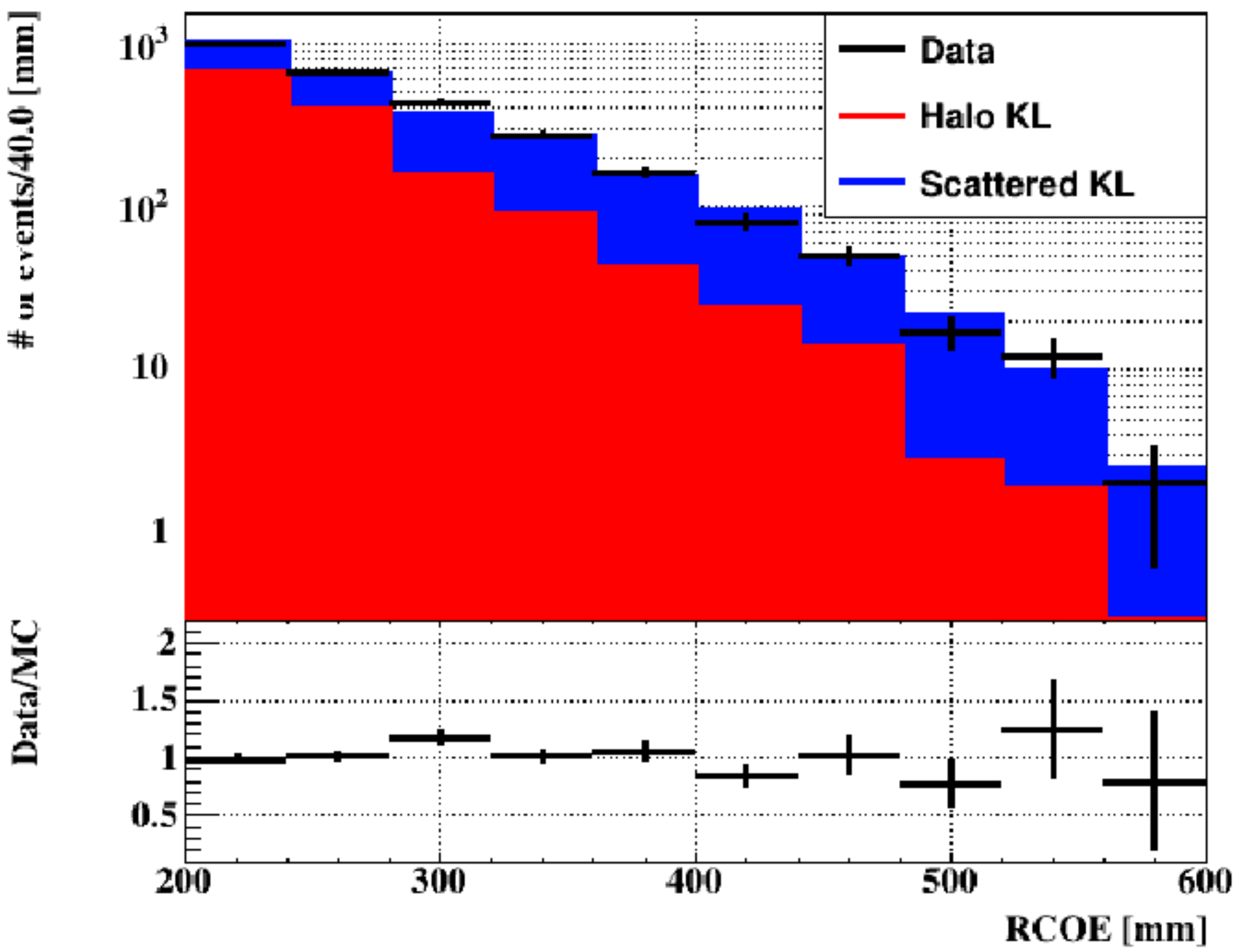
$\#(K^{\pm}\ BG) = 0.043 \pm 0.015_{(stat)}\ ^{+0.004}_{-0.030}\ (sys)$ based on the K± decay simulation, measured K± yield, and evaluated UCV inefficiency

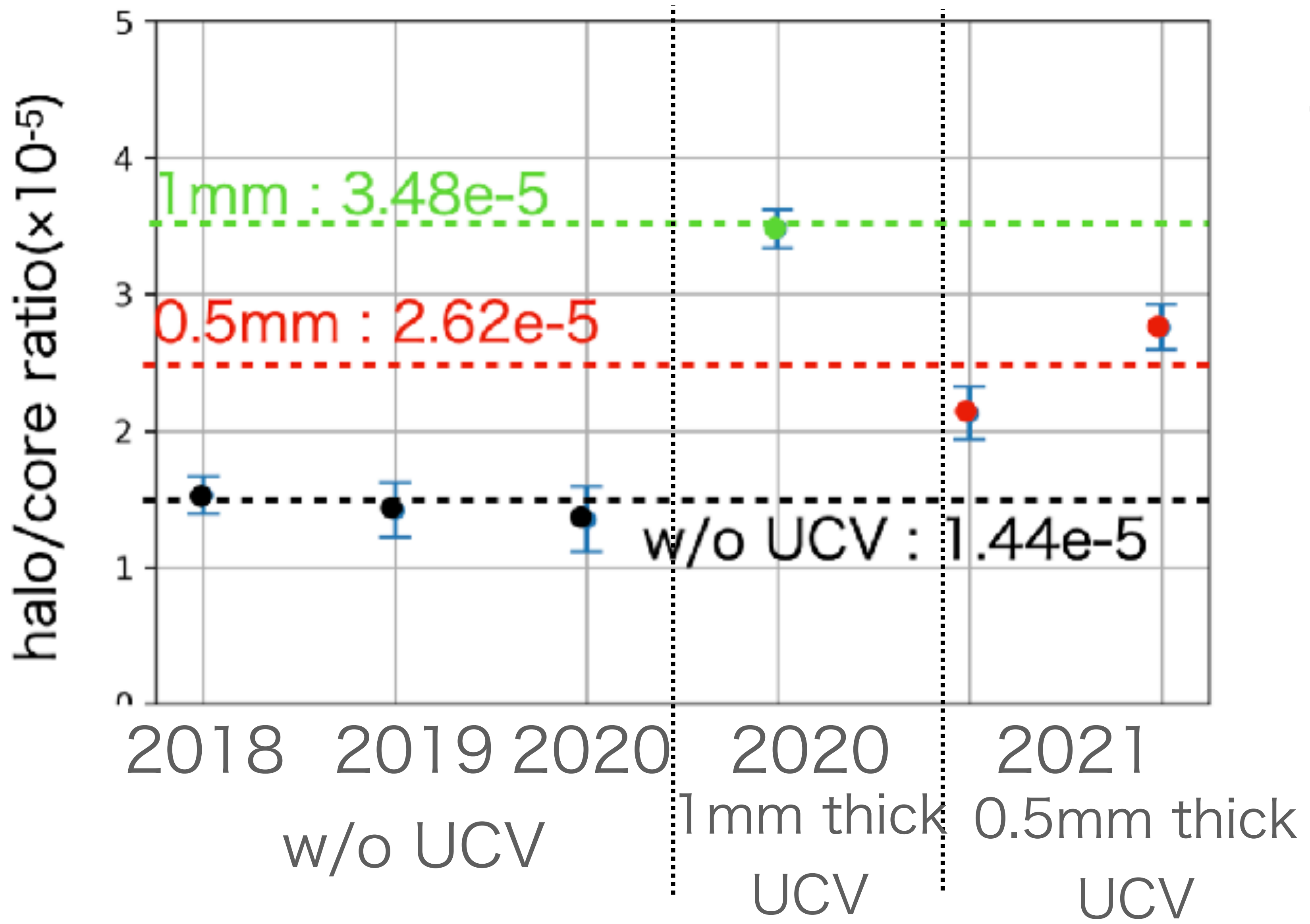
Estimation of N(Halo $K_L \to 2\gamma$ BG)

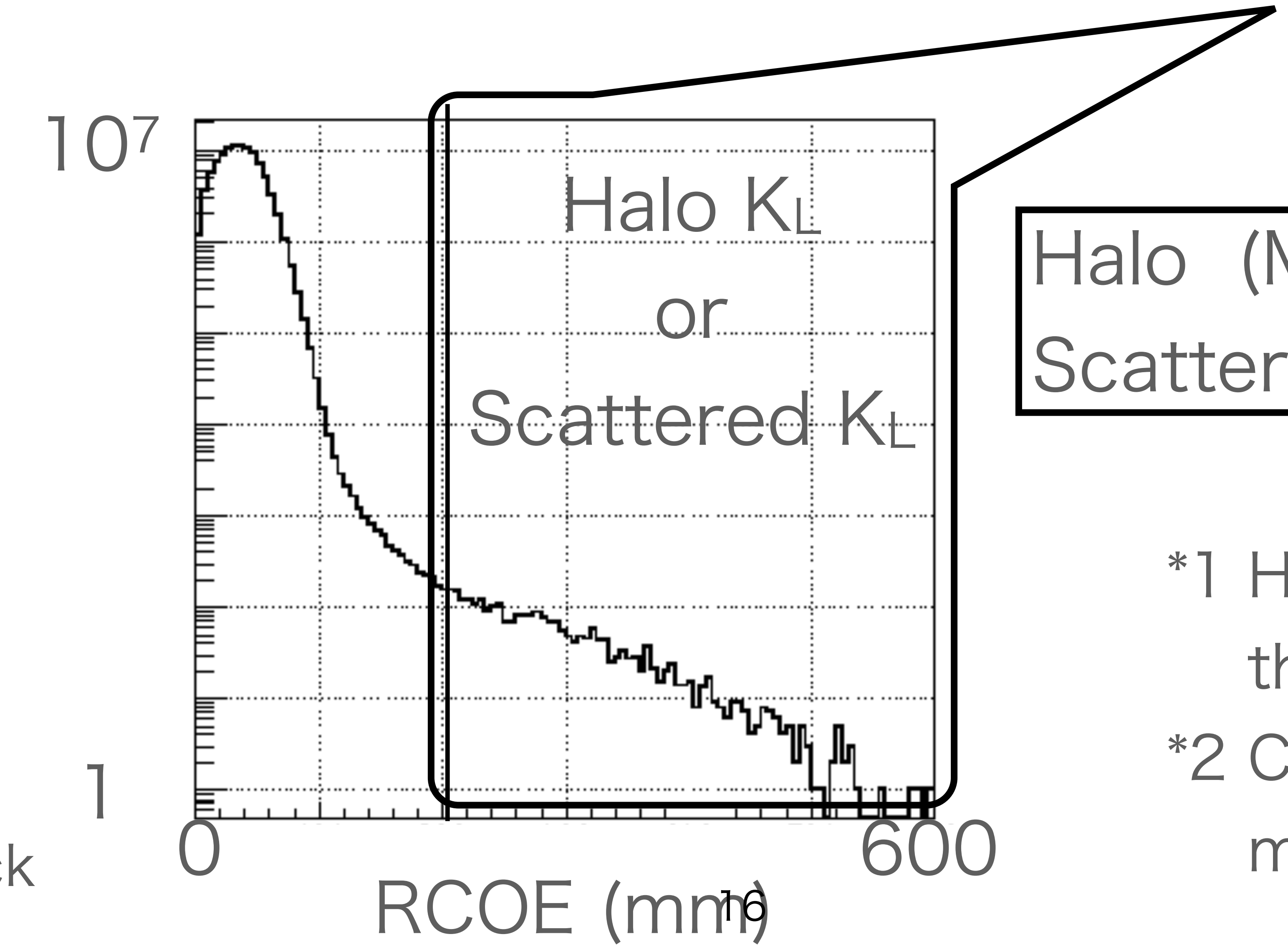
Estimation of Halo K_L flux

- Halo K_L flux was evaluated by using $K_L \to 3\pi^0$ sample









Halo (MC prediction)*1 x 5.74±0.76(stat)±1.11(sys)
Scatter (MC prediction)*2 x 1.54±0.21(stat)±0.29(sys)

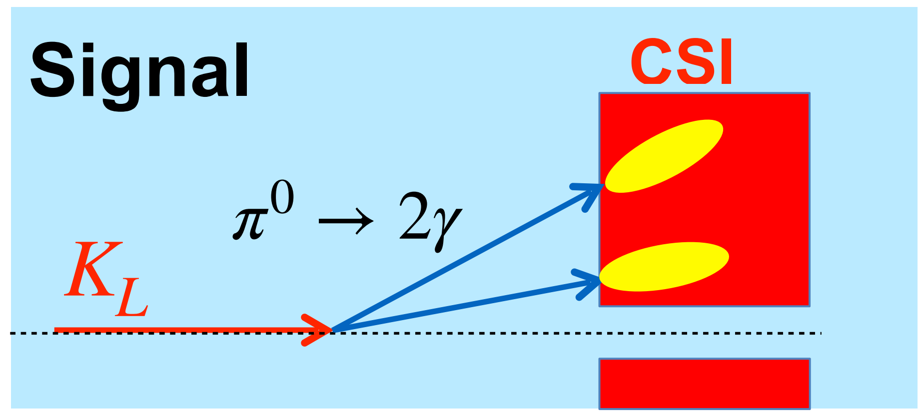
*1 Halo KLs are generated according to the results of the GEANT3-base beam line simulation.

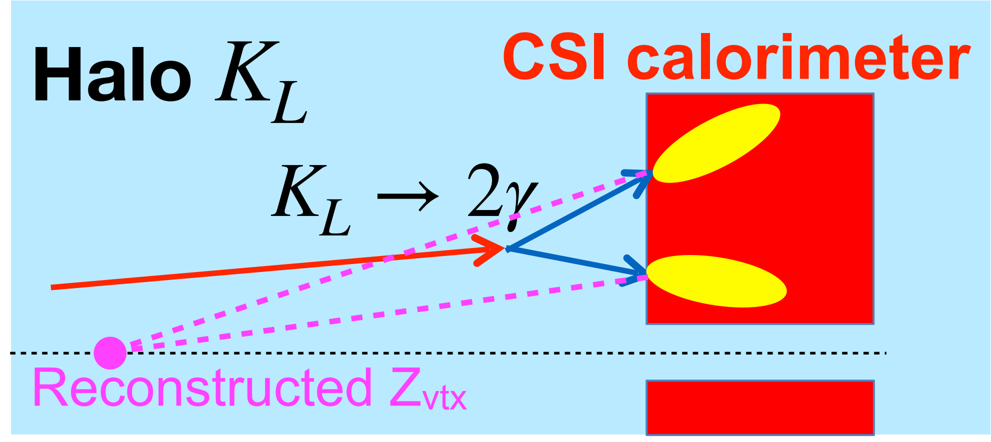
*2 Core KLs injected to UCV are generated by using a model function based on our KL flux measurement.

Estimation of N(Halo $K_L \to 2\gamma$ BG)

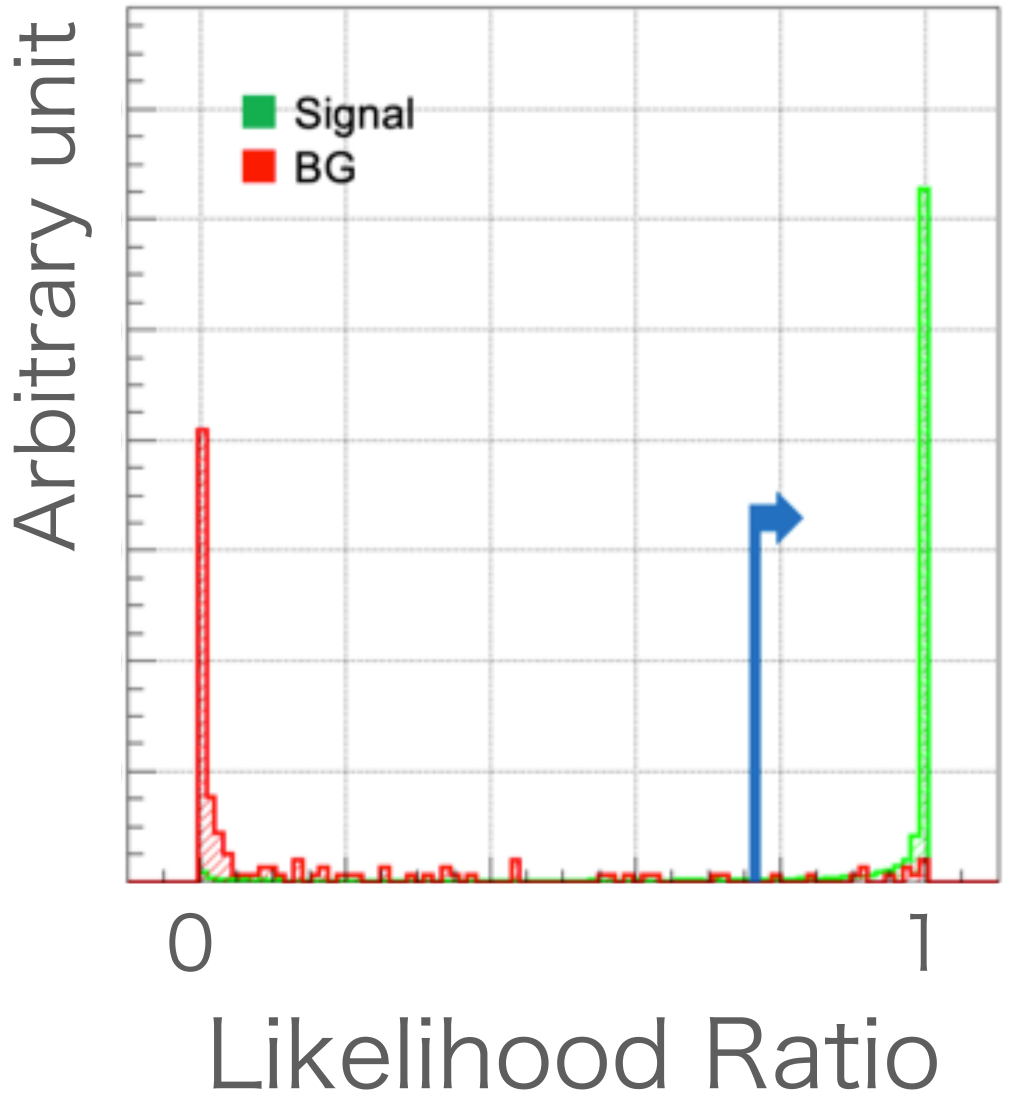
Newly developed cuts

- Shower shape consistency
  - Likelihood Ratio based on shower shape and reconstructed angle

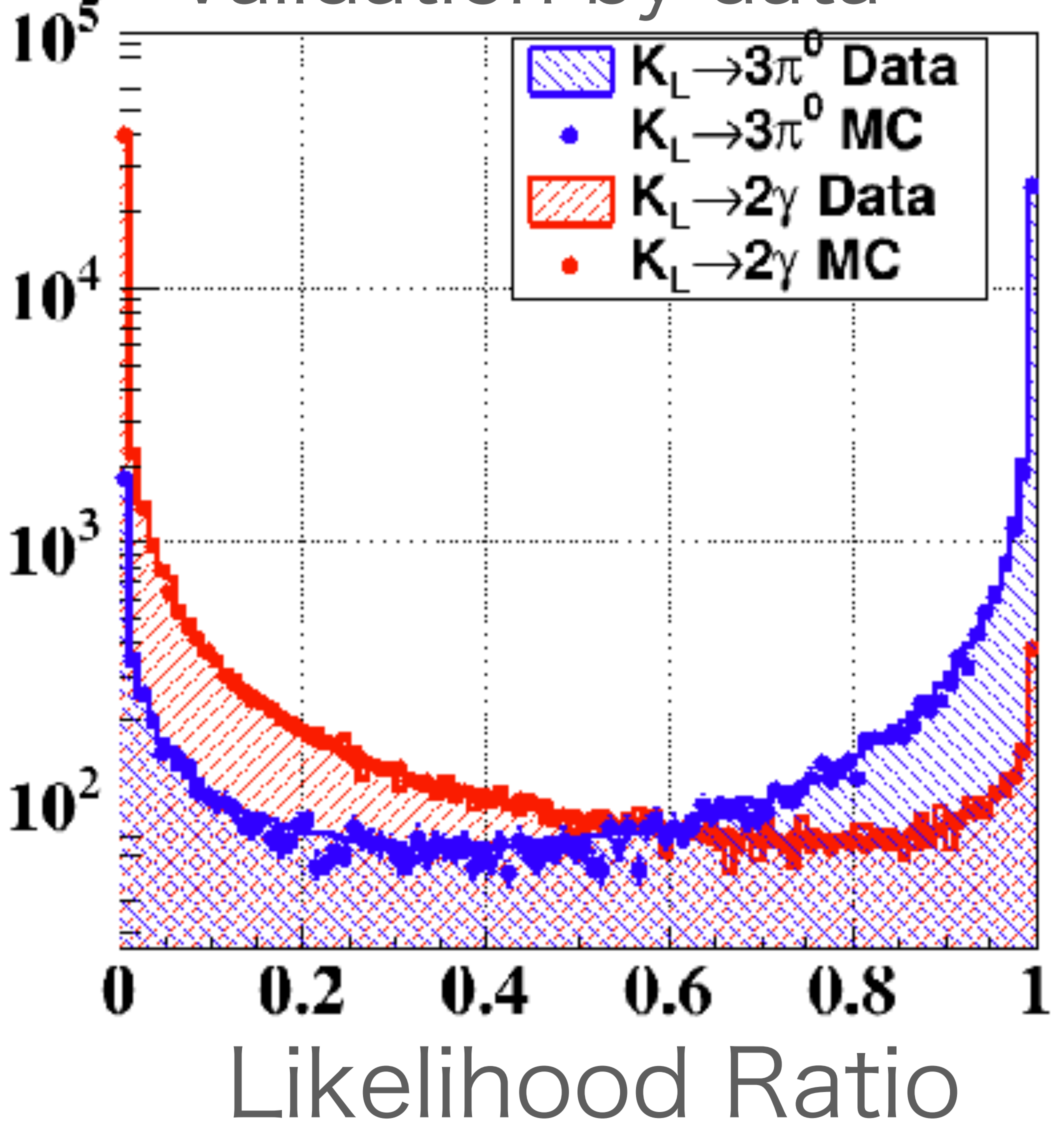




Performance

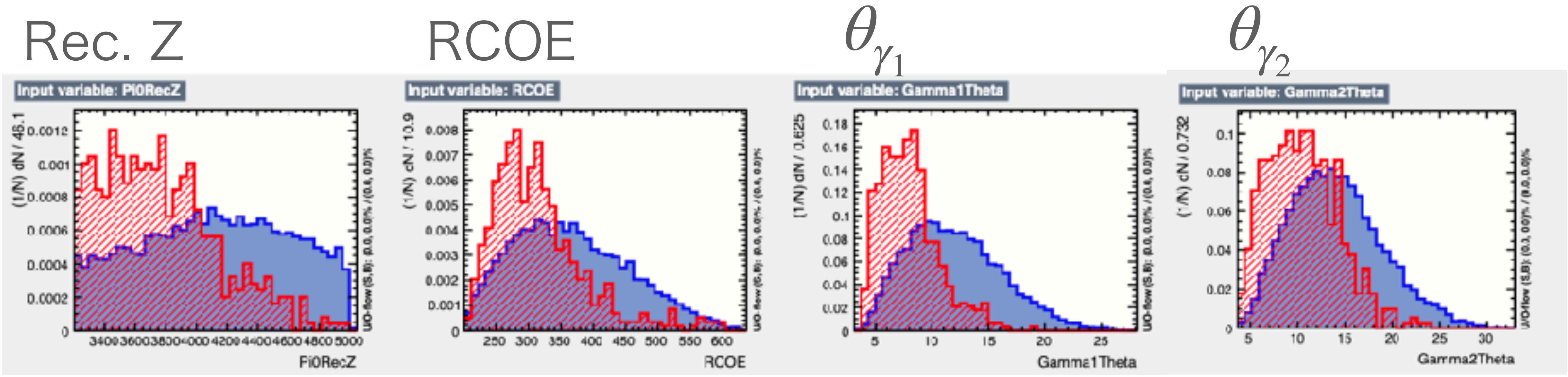


Validation by data

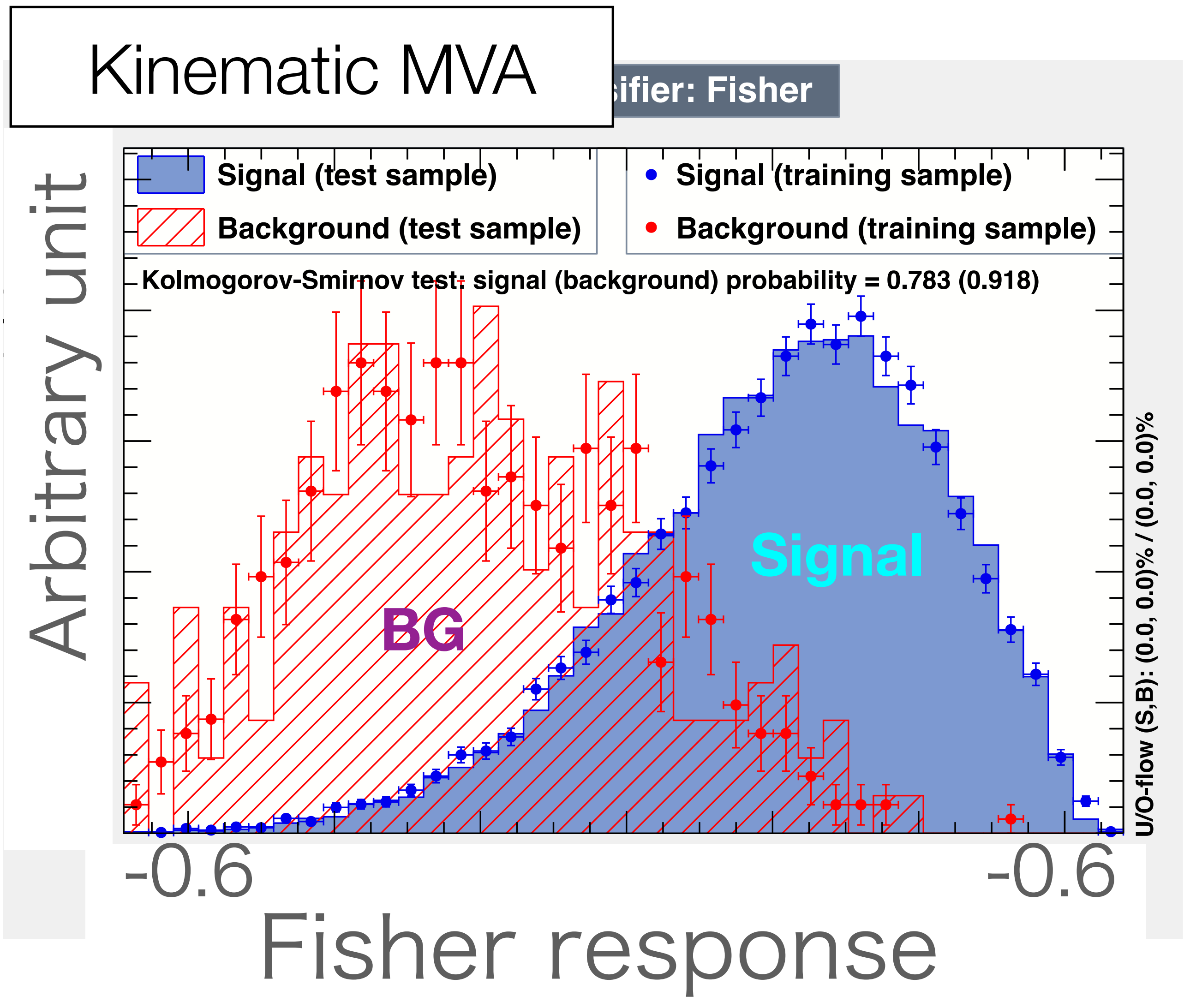


- Multi variable Analysis with kinematical variables

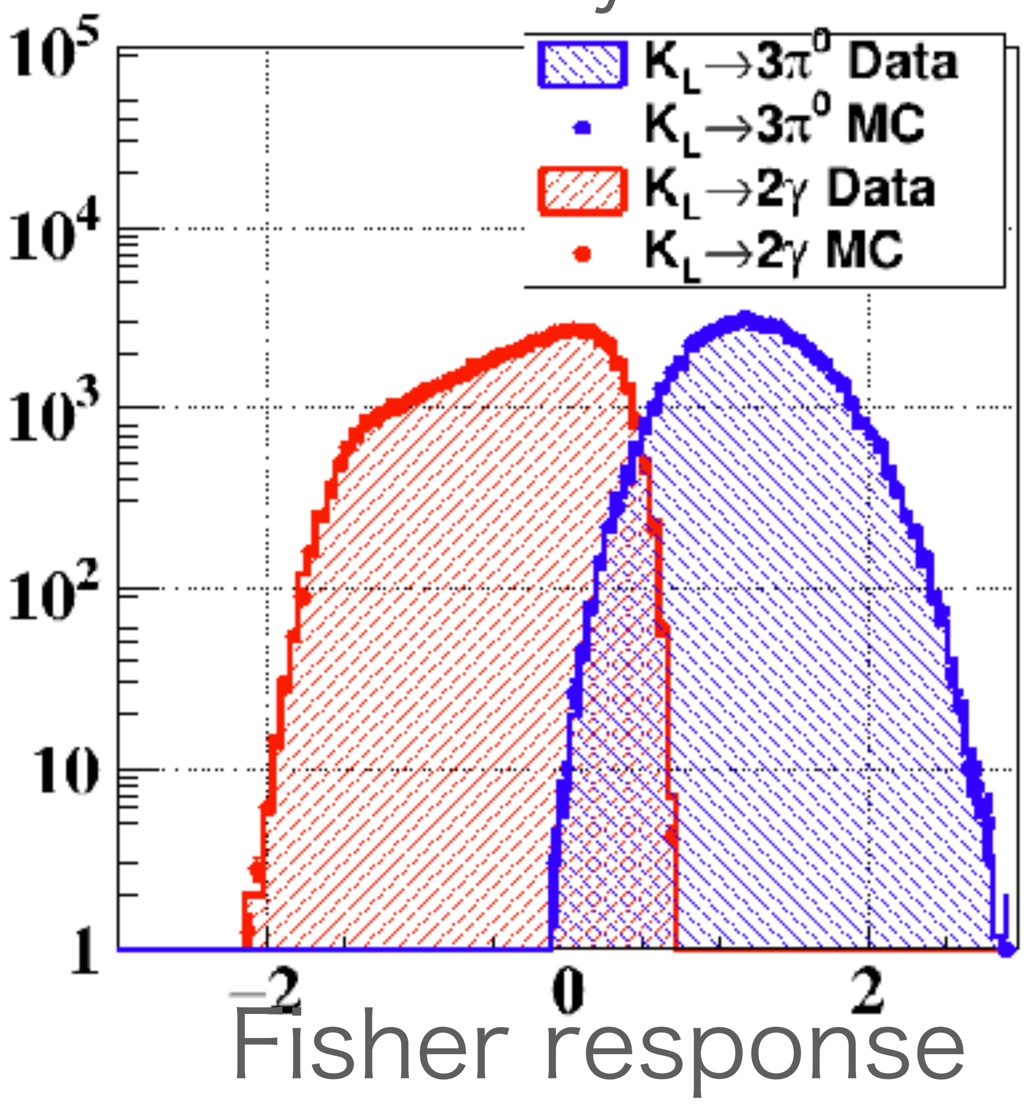
Input variables Blue:signal Red:Halo KL→2γ



Performance



Validation by data



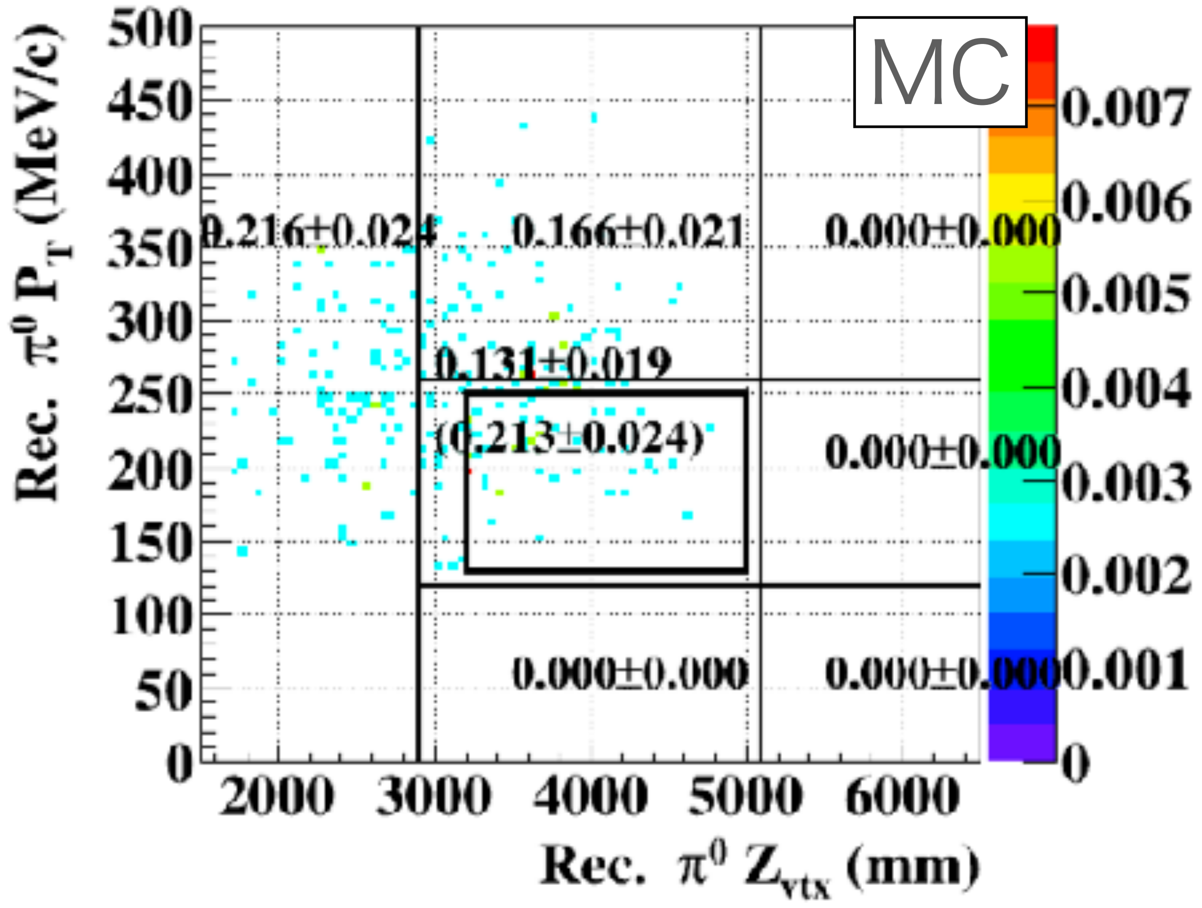
Estimation of N(Halo $K_L \to 2\gamma$ BG)

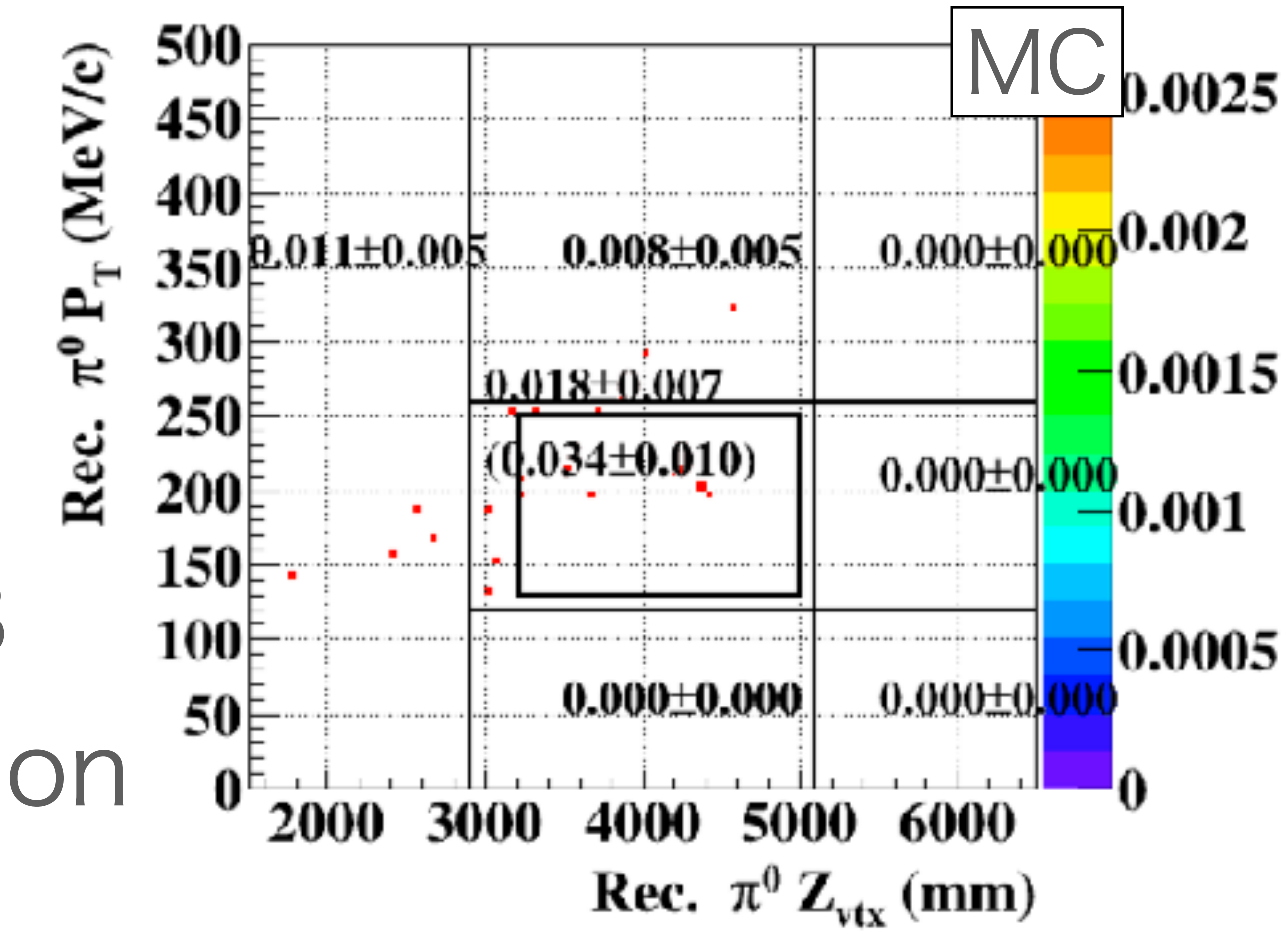
of Halo $K_L \to 2\gamma$ BG

Before applying Likelihood ratio cut and Kinematic MVA cut

After applying Likelihood ratio cut and Kinematic MVA cut

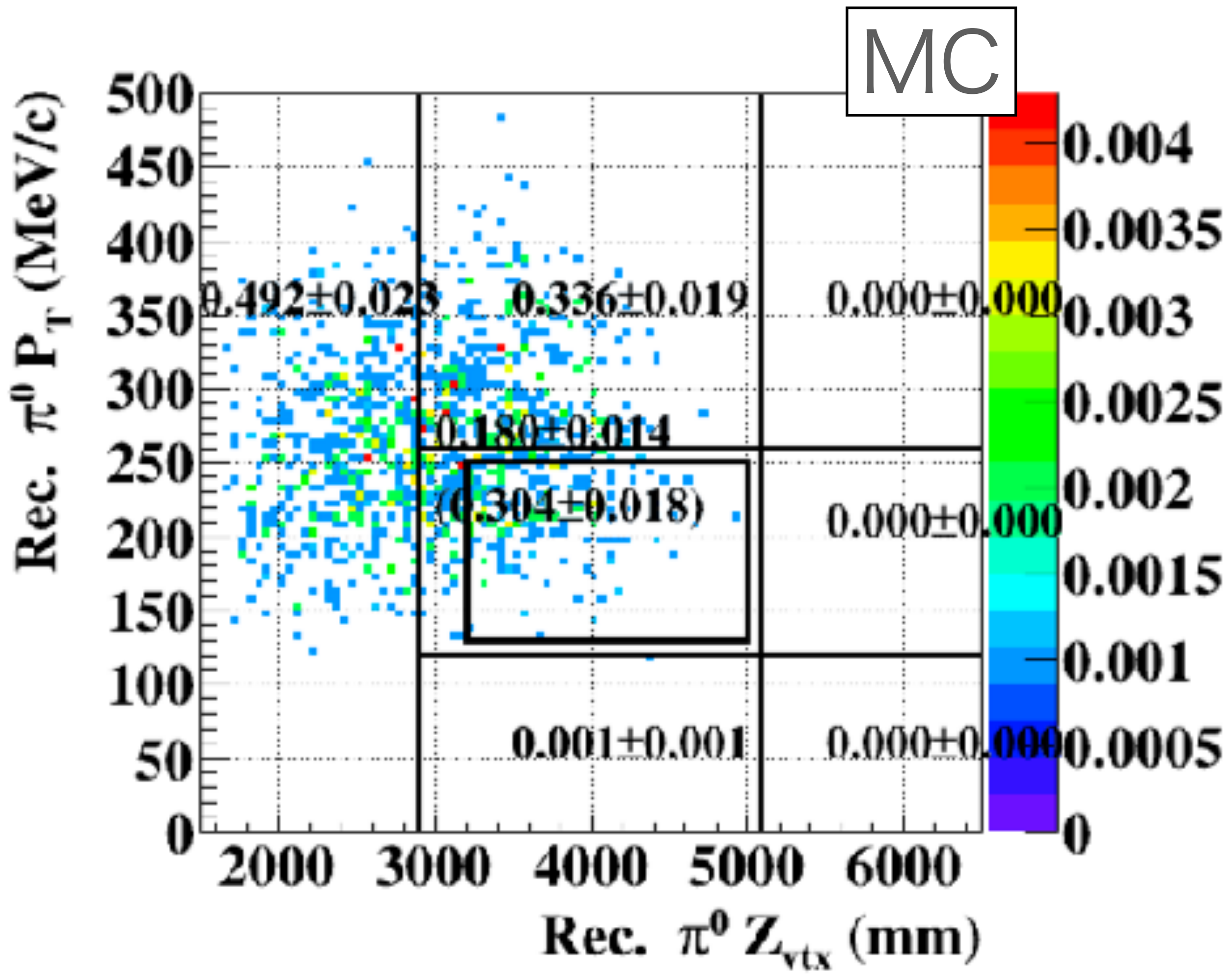
Halo KL

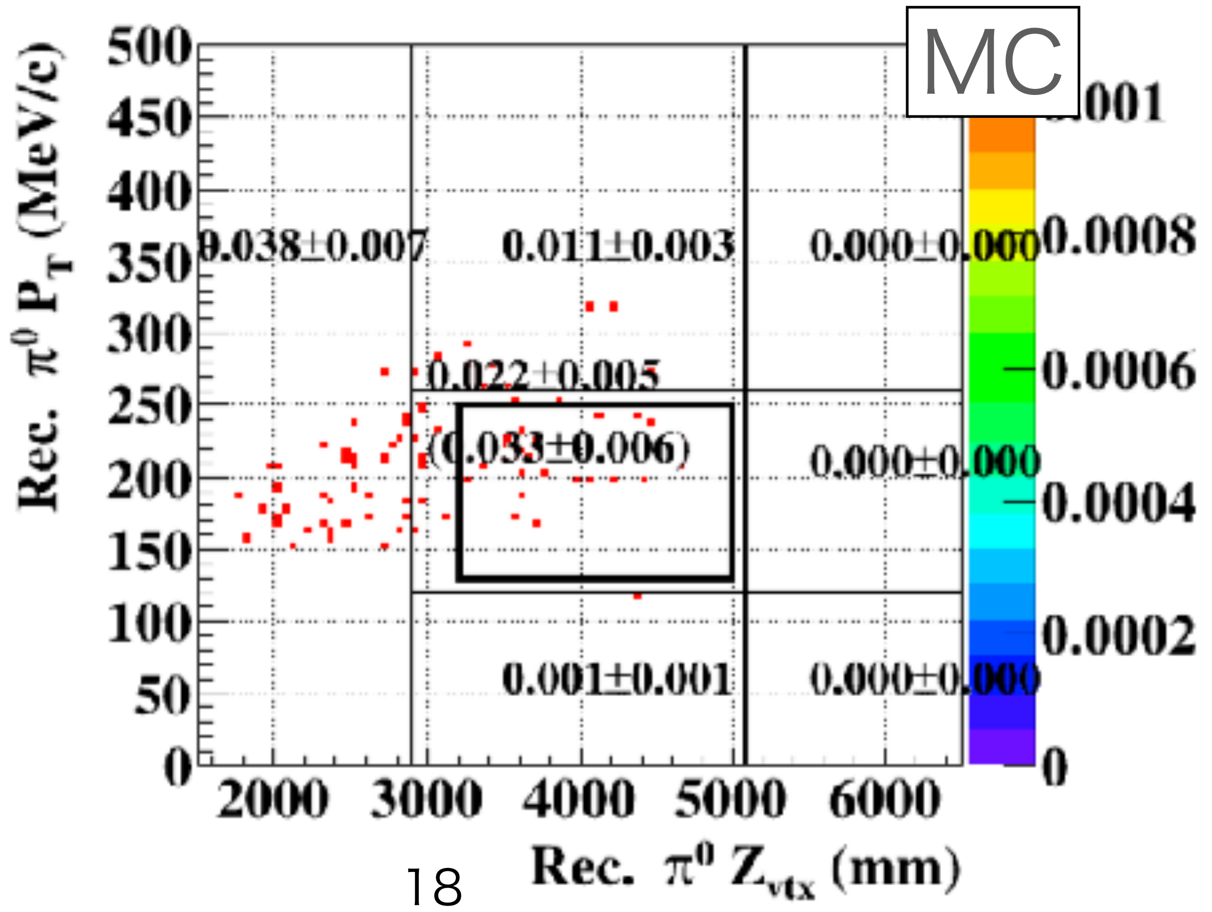




x1/8 reduction

Scatter KL





Signal acceptance of those cuts

-94%

# of BG expected in the signal box

-#(Halo $K_L \to 2\gamma$ BG)

0.13 → 0.018±0.007$_{(stat)}$±0.004$_{(sys)}$

-#(Scatter $K_L \to 2\gamma$ BG)

0.18 → 0.022±0.005$_{(stat)}$±0.004$_{(sys)}$

Reduction by a factor of 8 was achieved in both case

Summary of further BG reduction we are developing

Covered in the talk of beam line and detector

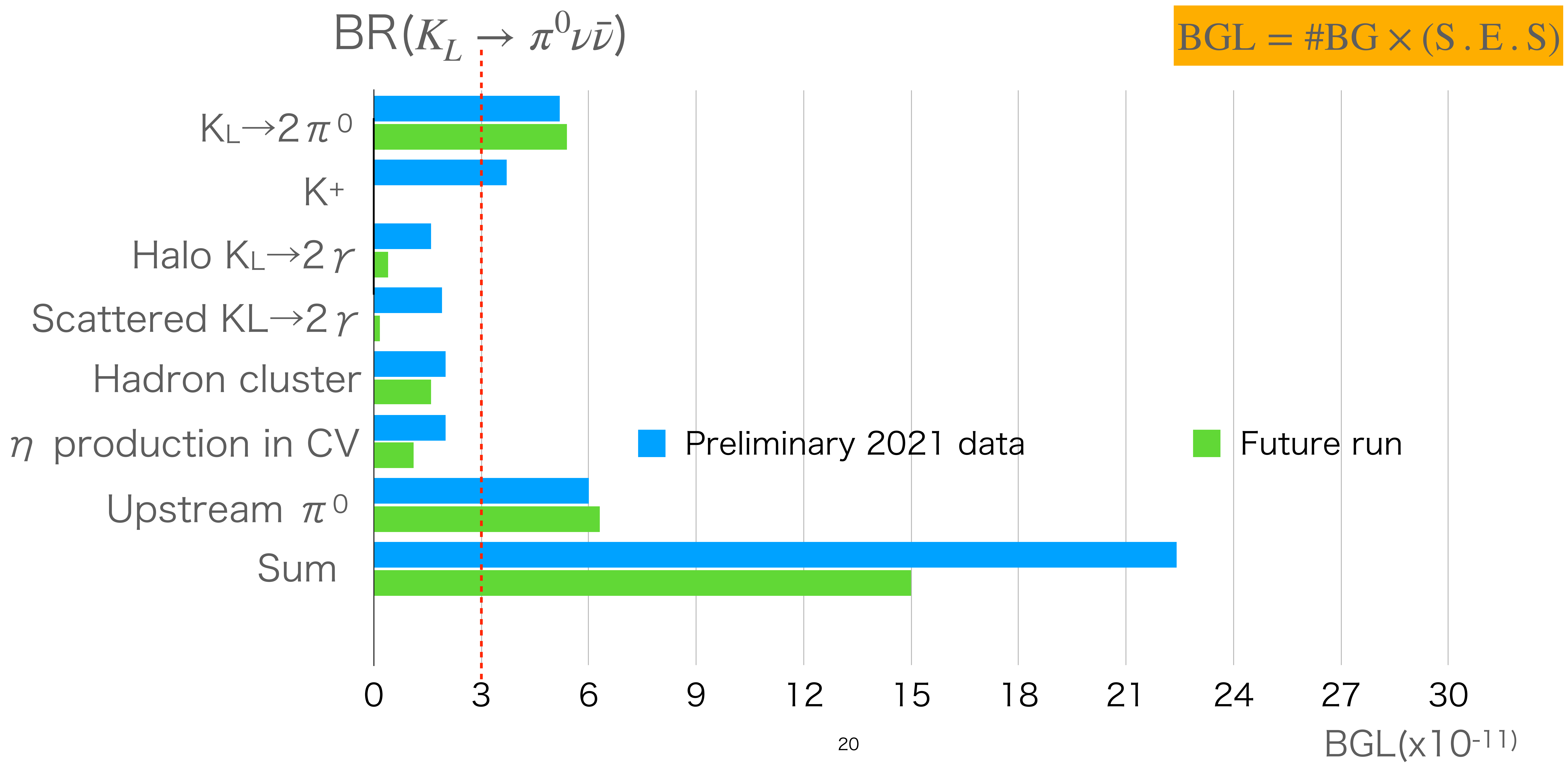
Covered in this talk

source	Film UCV	D2 Magnet	Analysis*	Total
$K_L \to 2\pi^0$	x1	x1	x1	x1
K^+	x0.01	x0.1	x1	x0.001
Hadron cluster BG	x0.7	x1.1	x1	x0.77
Halo $K_L \to 2\gamma$	x1	x1.3	x0.2	x0.26
Scattered $K_L \to 2\gamma$	x0.4	x1	x0.2	x0.08
η production in CV	x1	x1	x0.5	x0.5
Upstream π^0	x1	x1	x1	x1
$K_L \to 3\pi^0$	x1	x1	x1	x1
Signal acceptance	x1	x1	x0.95**	x0.95**

* Analysis improvement is obtained from the DL HaloKL cut for Halo, Scatter KL->2γ、 and CV eta

** Signal acceptance is calculated as ε (DL HaloK_L) = 0.95

Summary of future BGL



Z dependence of upstream π^0 BG events

- Based on the results with a simple MC setup to speed up the processing time