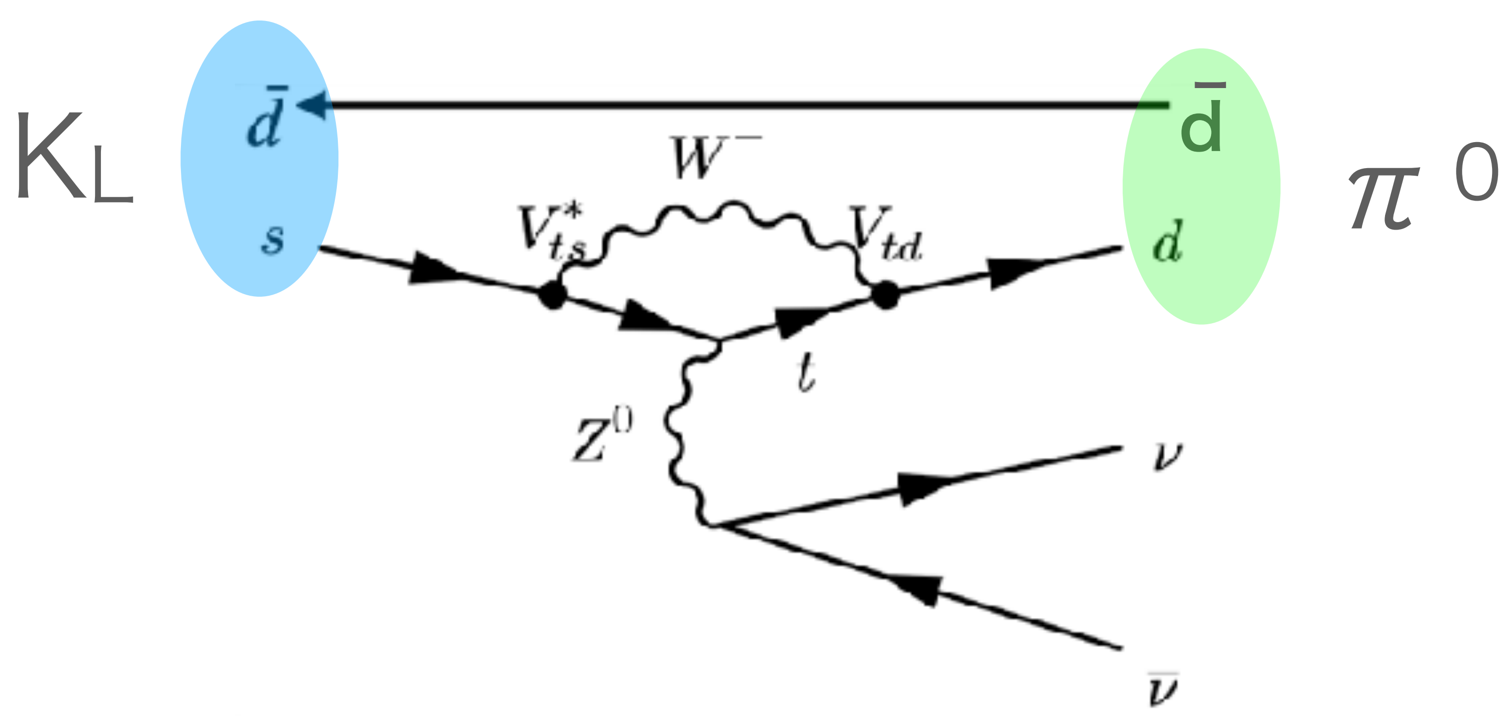
Search for $K_L \rightarrow \pi^0 \nu \bar{\nu}$ at KOTO

Koji Shiomi (KEK) for the KOTO collaboration

September 19, 2023@CKM 2023, Santiago de Compostela, Spain

Physics on $K_L \to \pi^0 \nu \nu$

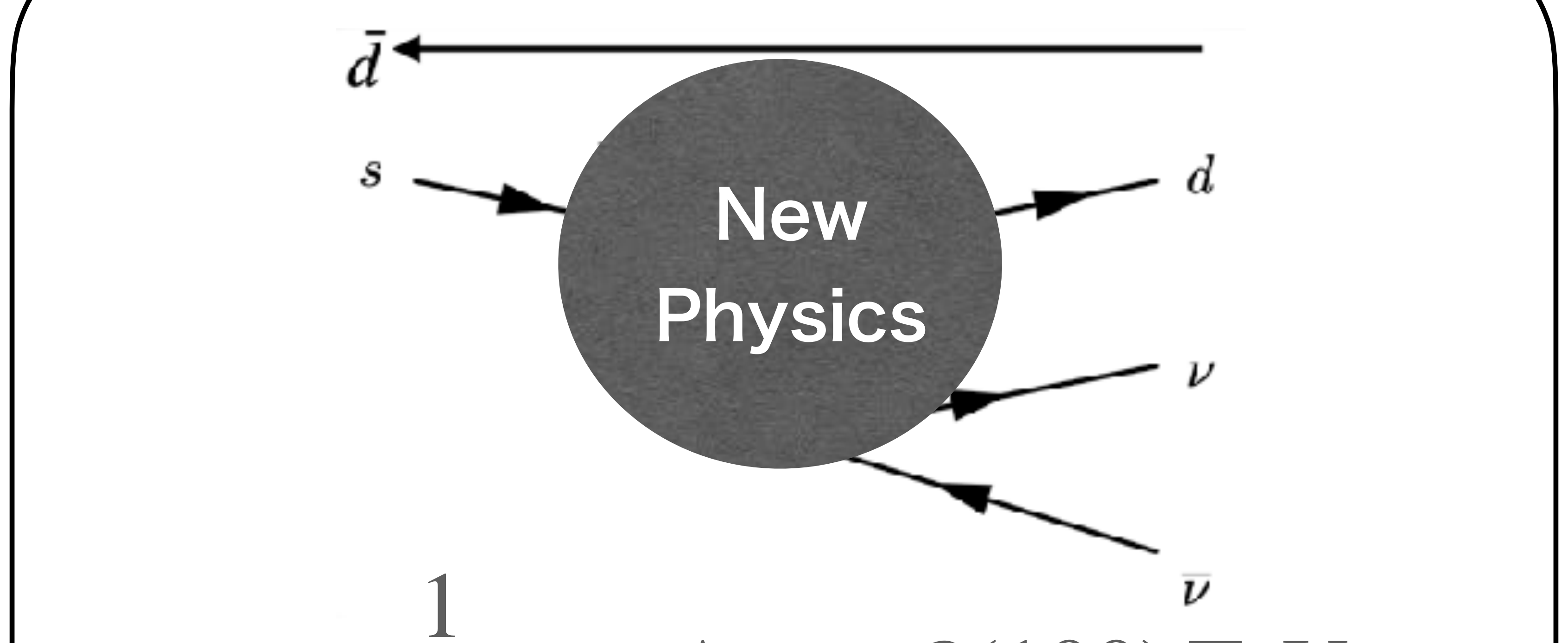
$K_L \to \pi^0 \nu \nu$ decay in Standard Model



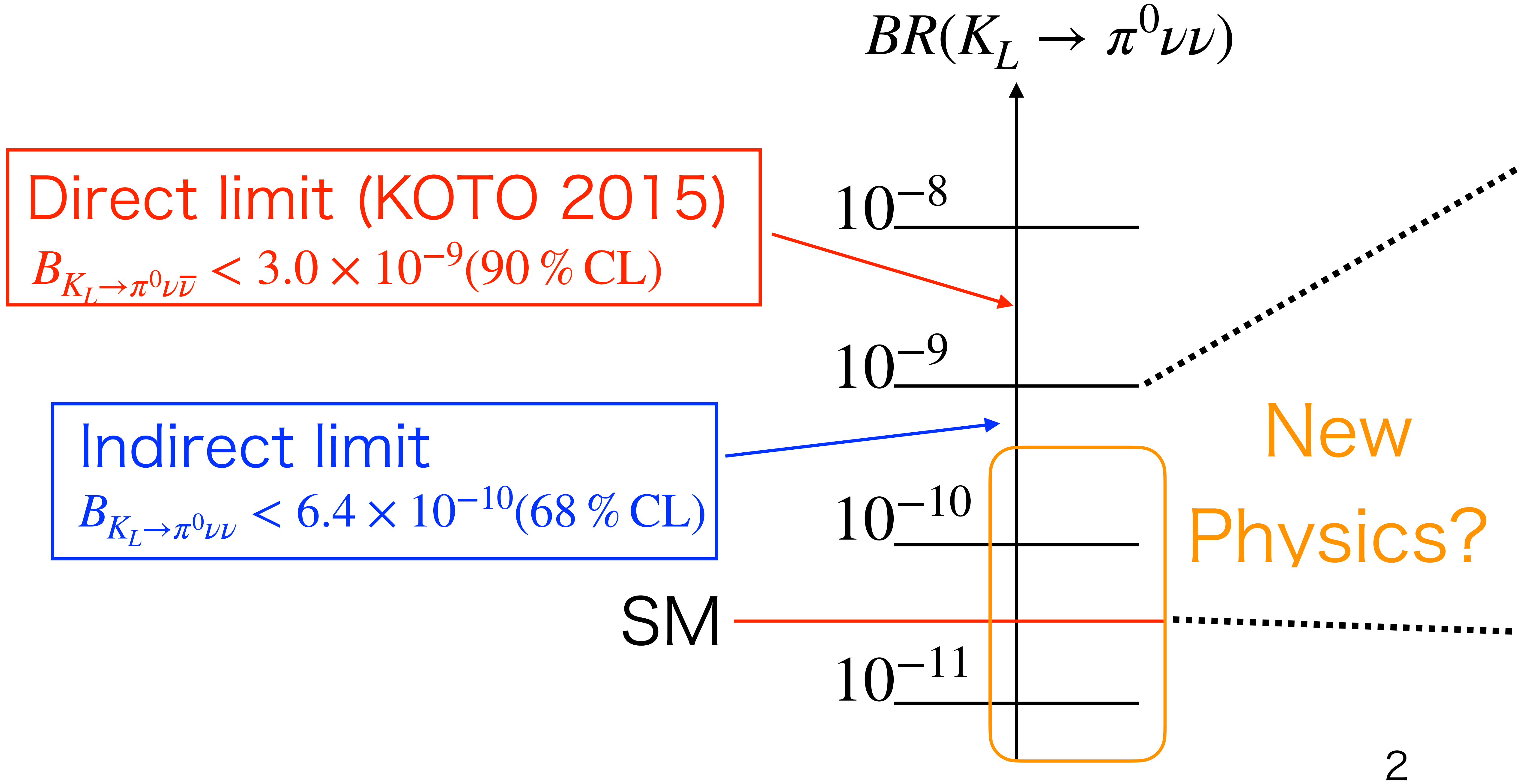
- Very rare CP violating process
  - BR(SM) = 3.0×10^{-11}
- ~2% theoretical uncertainty

+

New Physics Contribution??



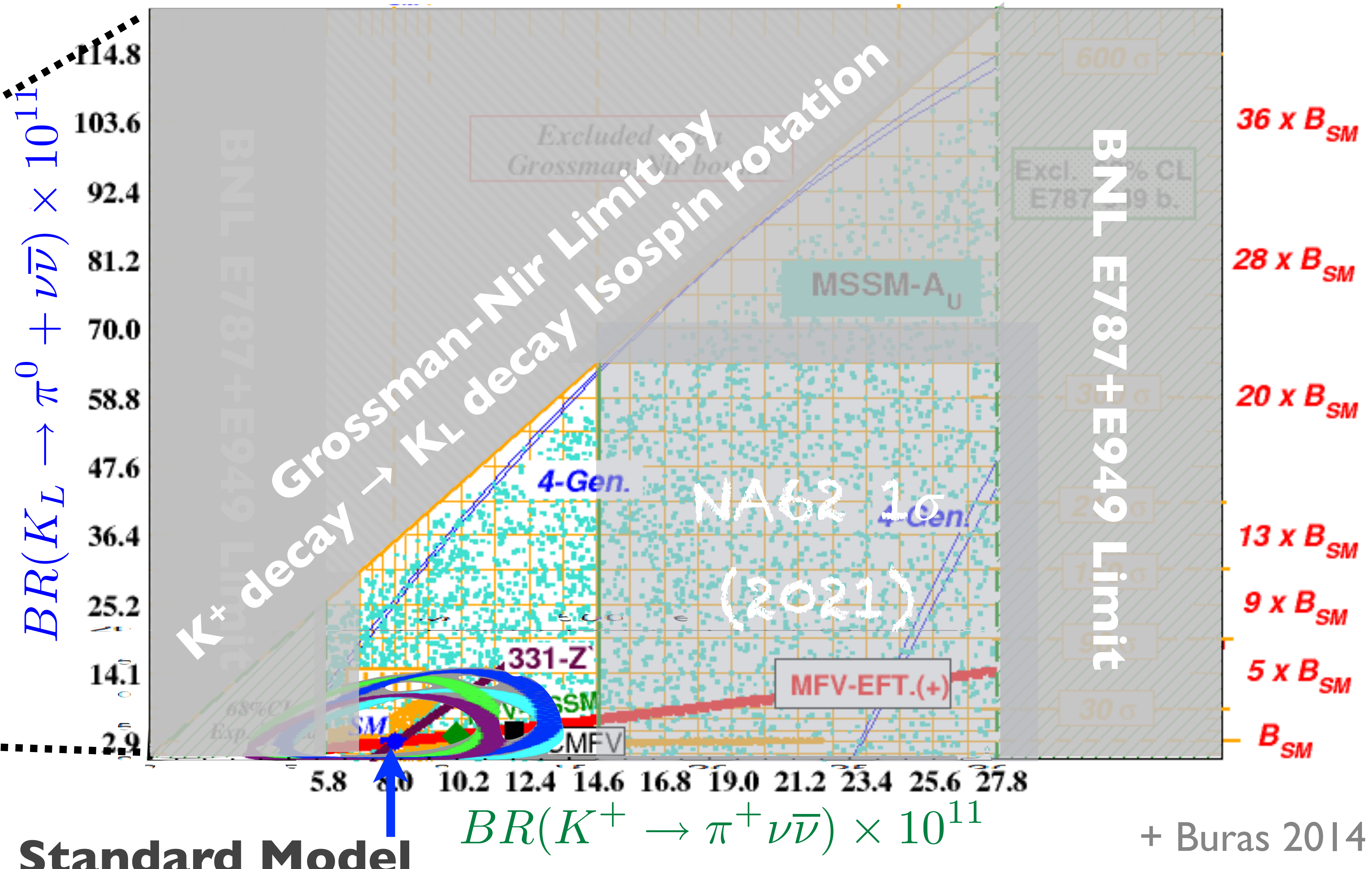
$$\frac{1}{\Lambda_{NP}^2} \to \Lambda_{NP} : O(100)\,\mathrm{TeV}$$



Direct limit (KOTO 2015)
$B_{K_L \to \pi^0 \nu \bar{\nu}} < 3.0 \times 10^{-9} (90\,\%\,\mathrm{CL})$

Indirect limit
$B_{K_L \to \pi^0 \nu \nu} < 6.4 \times 10^{-10} (68\,\%\,\mathrm{CL})$

New Physics?



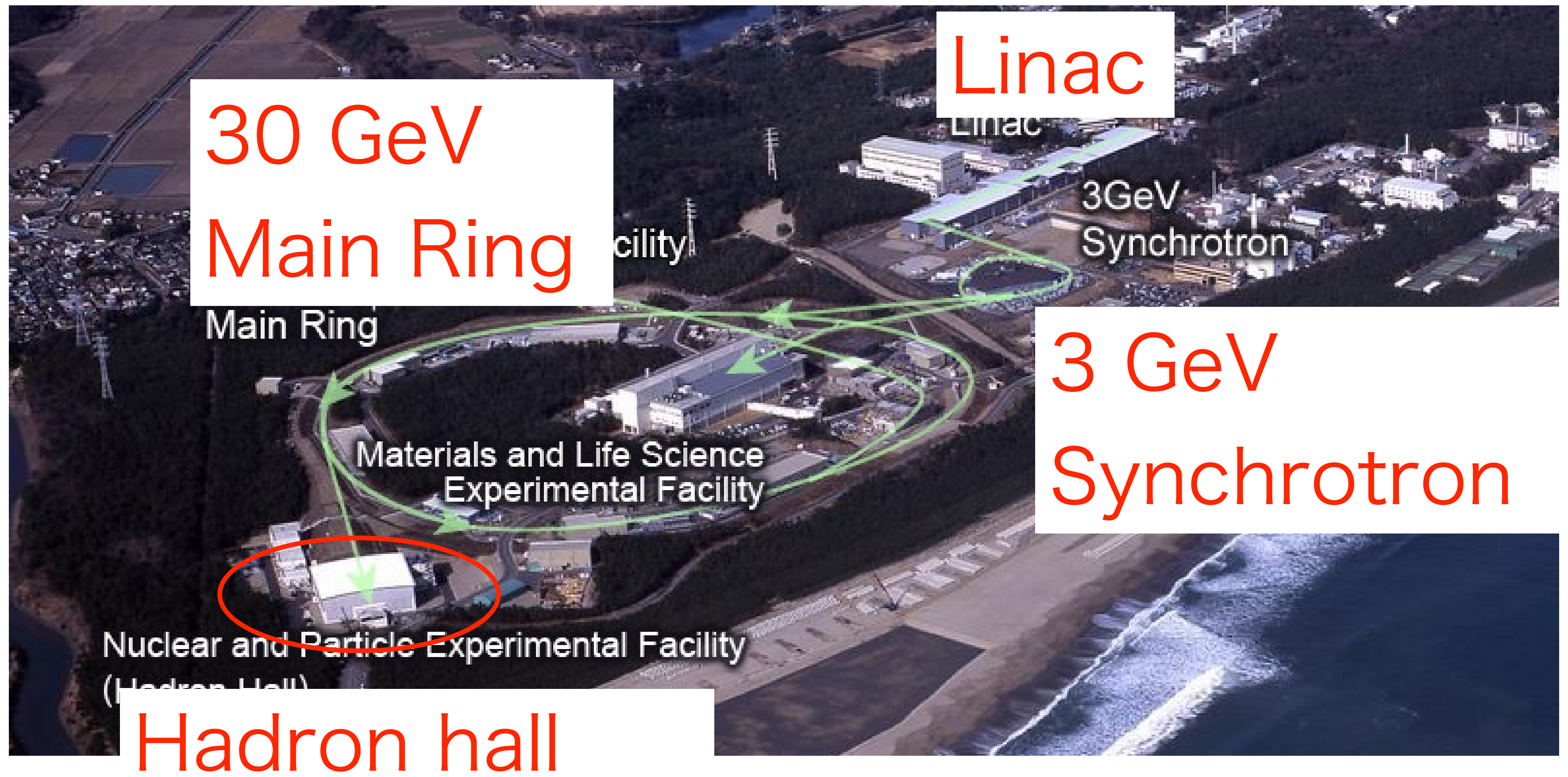
Standard Model

+ Buras 2014

http://www.lnf.infn.it/wg/vus/content/Krare.html

KOTO experiment

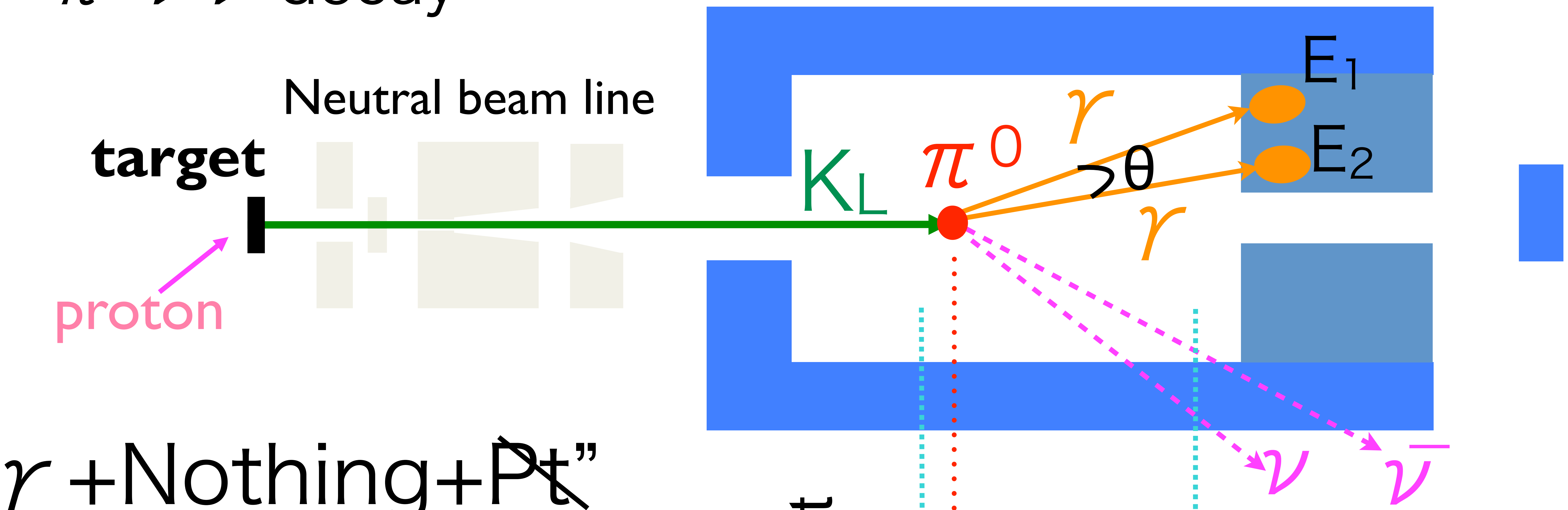
- Study of $K_L \to \pi^0 \nu \nu$@J-PARC 30GeV Main Ring.



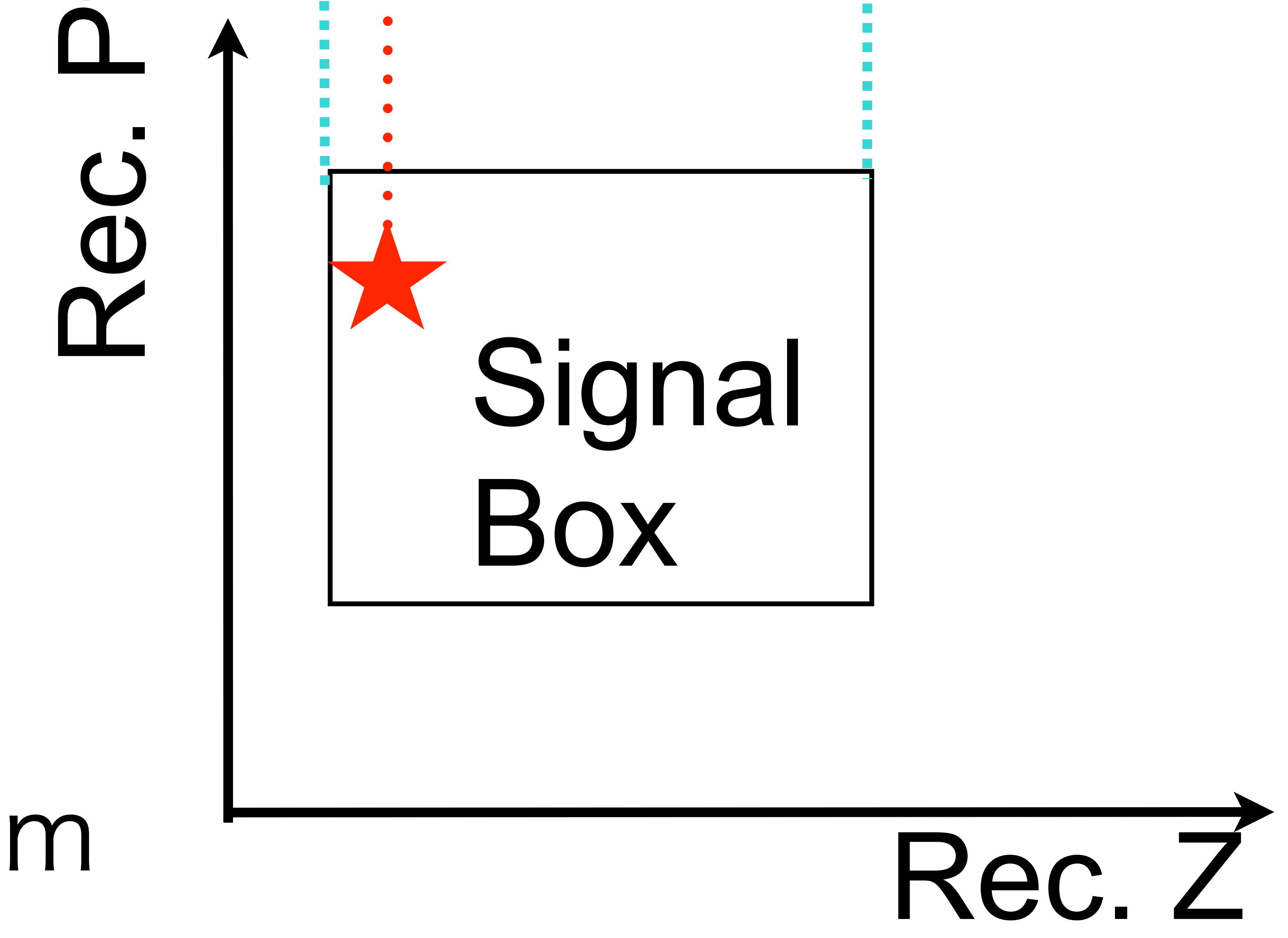
@ collaboration meeting (hybrid) on June 30- July 2, 2023

Experimental principle

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



“2γ+Nothing+~~Pt~~”



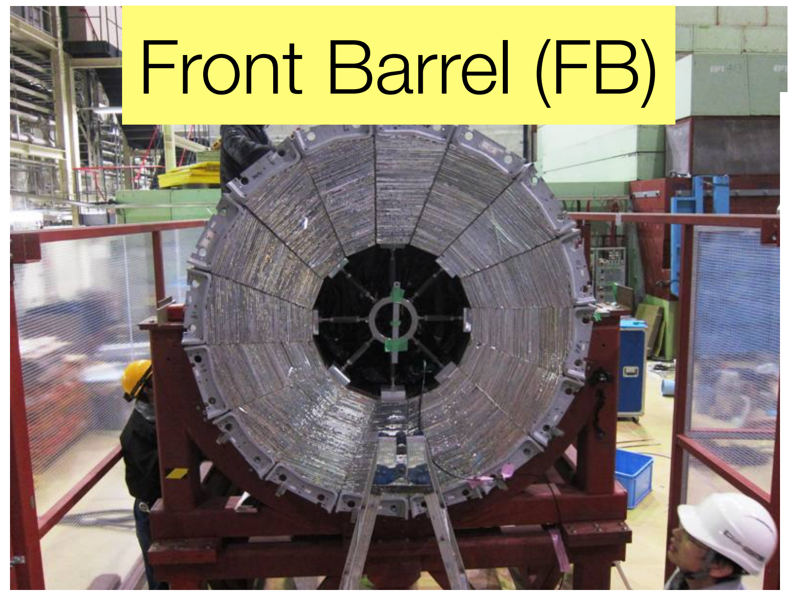
Assuming 2γ from π^0,
Calculate z vertex.

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

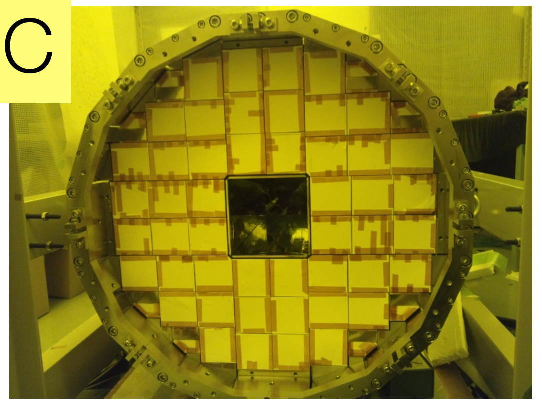
Calculate π^0 transverse momentum

KOTO detector

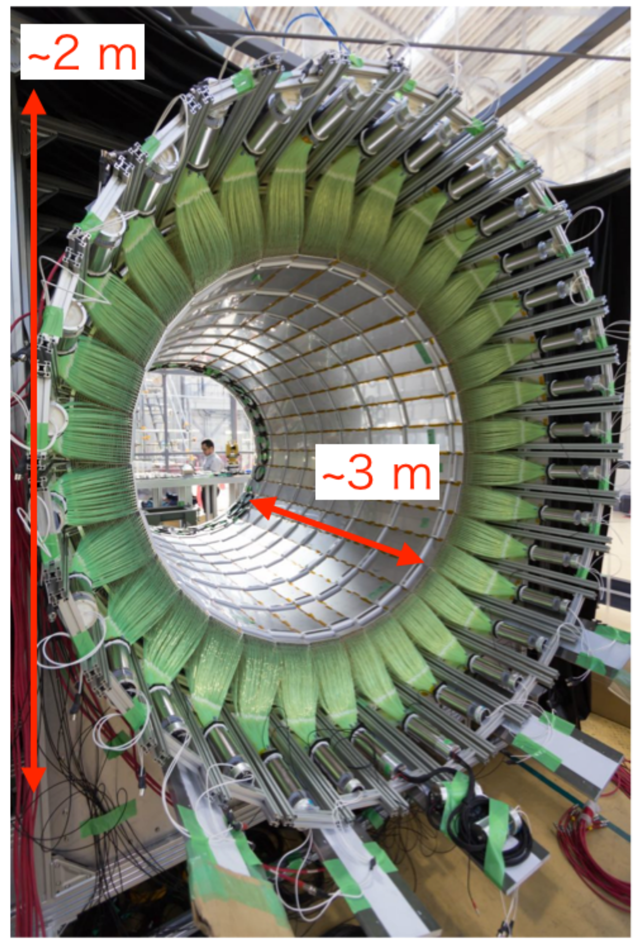
Front Barrel (FB)



NCC

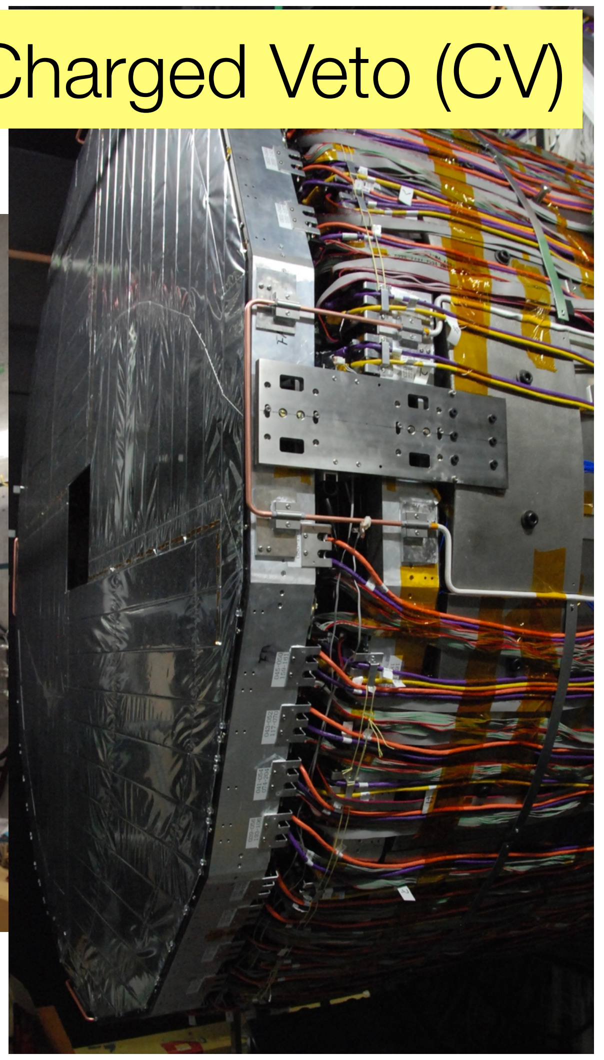


Inner Barrel (IB)

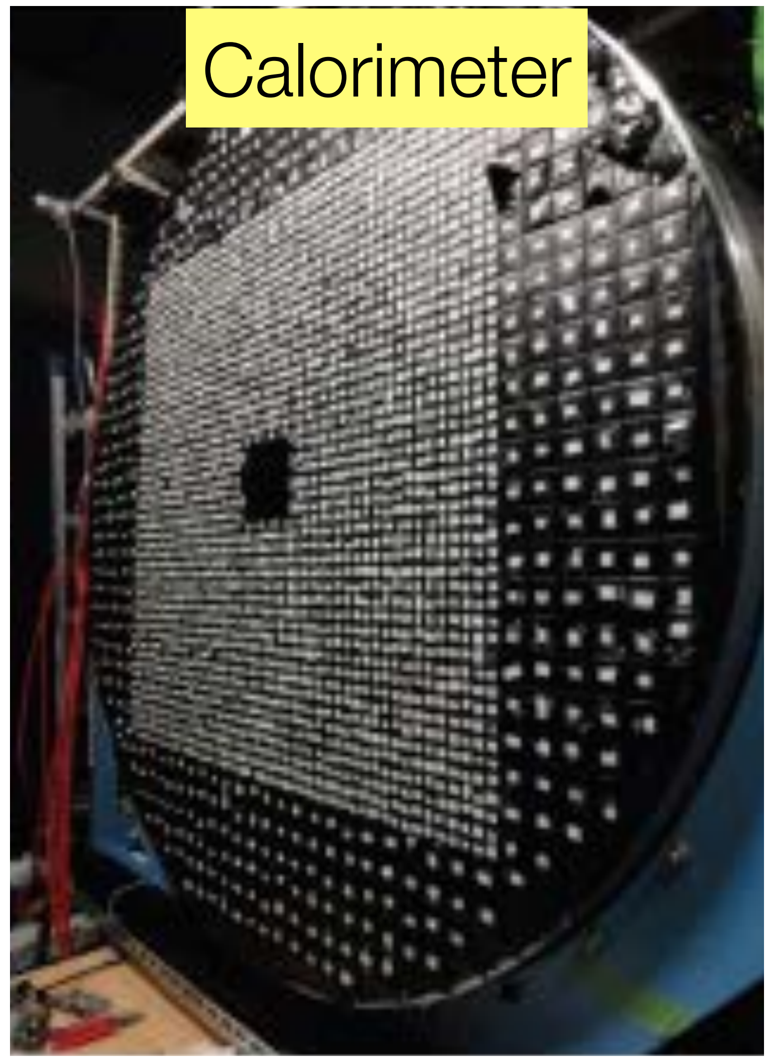


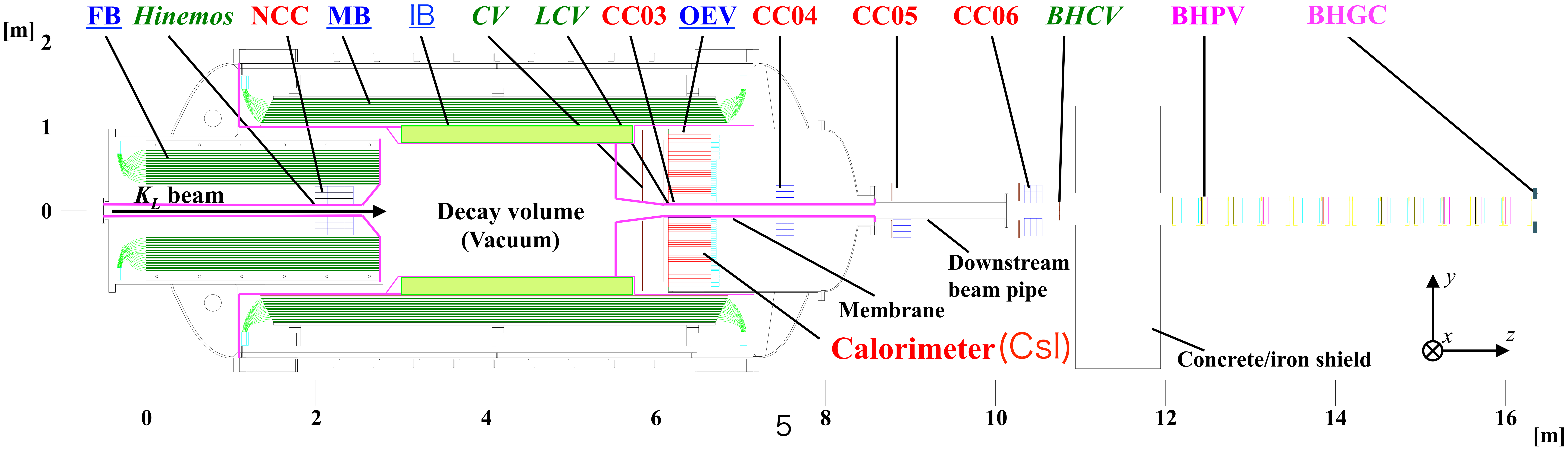
Main Barrel (MB)

Charged Veto (CV)



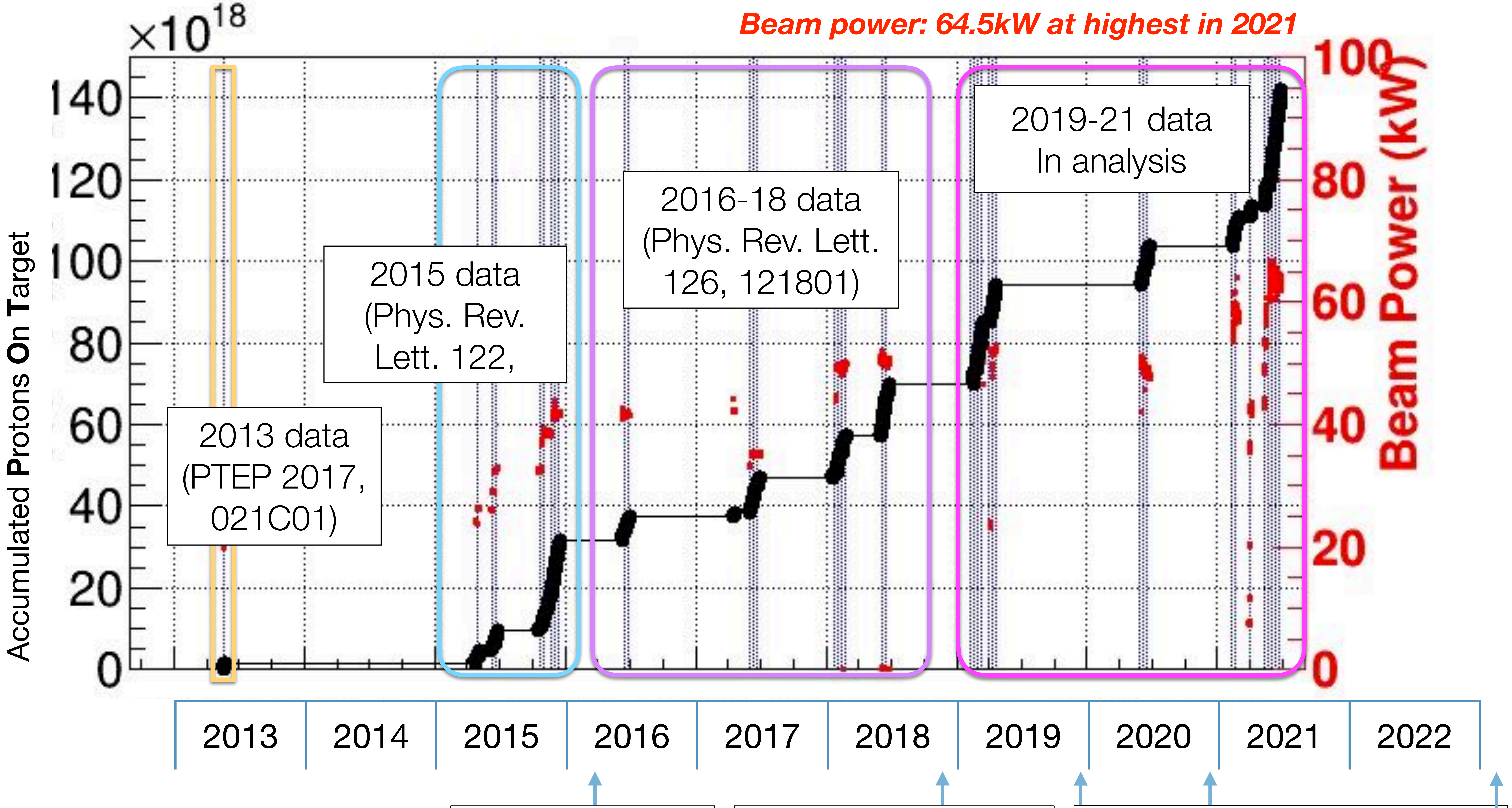
Calorimeter





Data accumulation history

Beam power: 64.5kW at highest in 2021



2013 data (PTEP 2017, 021C01)

2015 data (Phys. Rev. Lett. 122,

2016-18 data (Phys. Rev. Lett. 126, 121801)

2019-21 data In analysis

Detector upgrades

Additional barrel-type veto (IB)

-Calorimeter upgrade for n/γ separation
-Down stream Charged veto

K± veto: UCV

1mmt

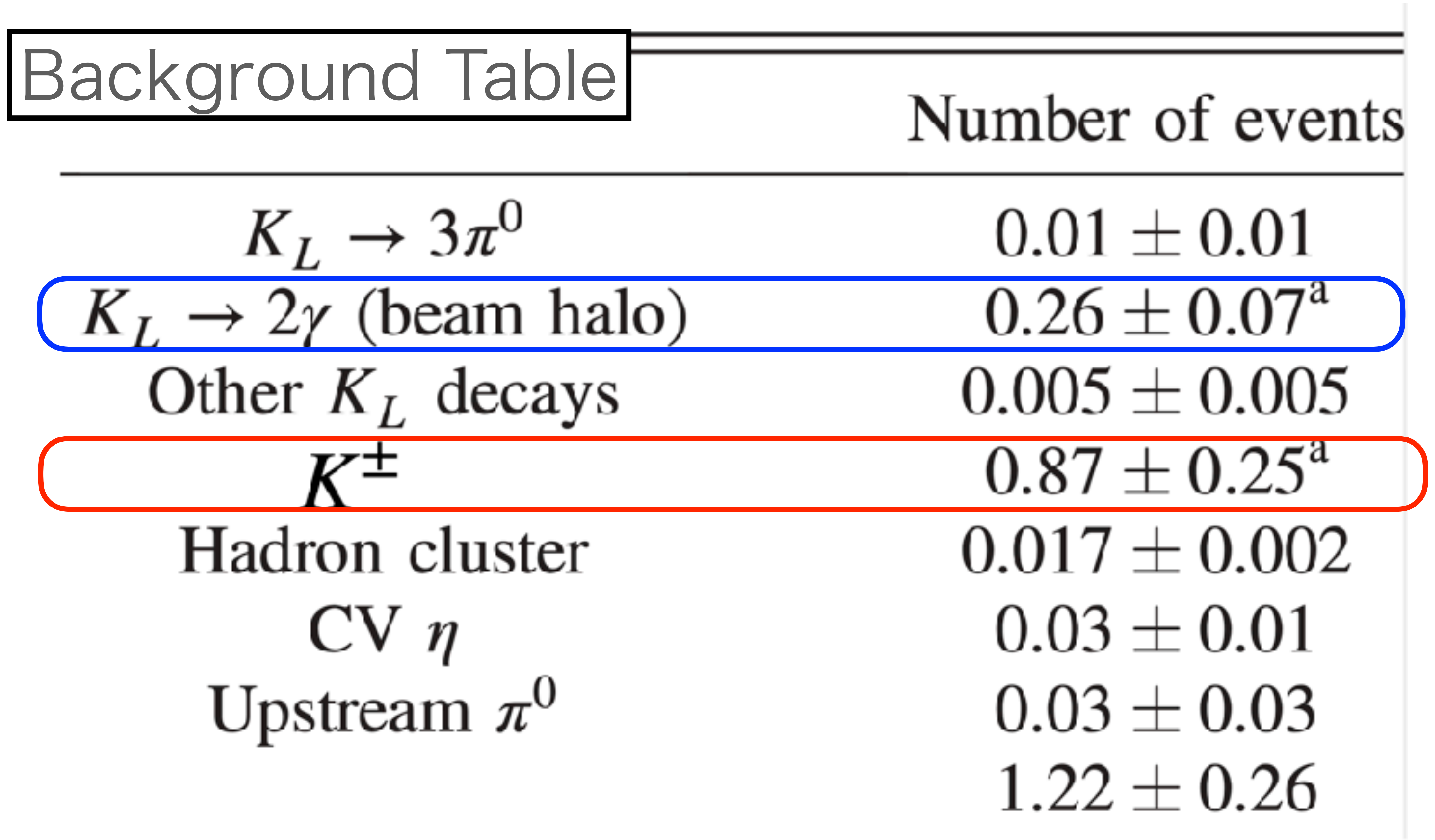
0.5mmt

0.2mmt

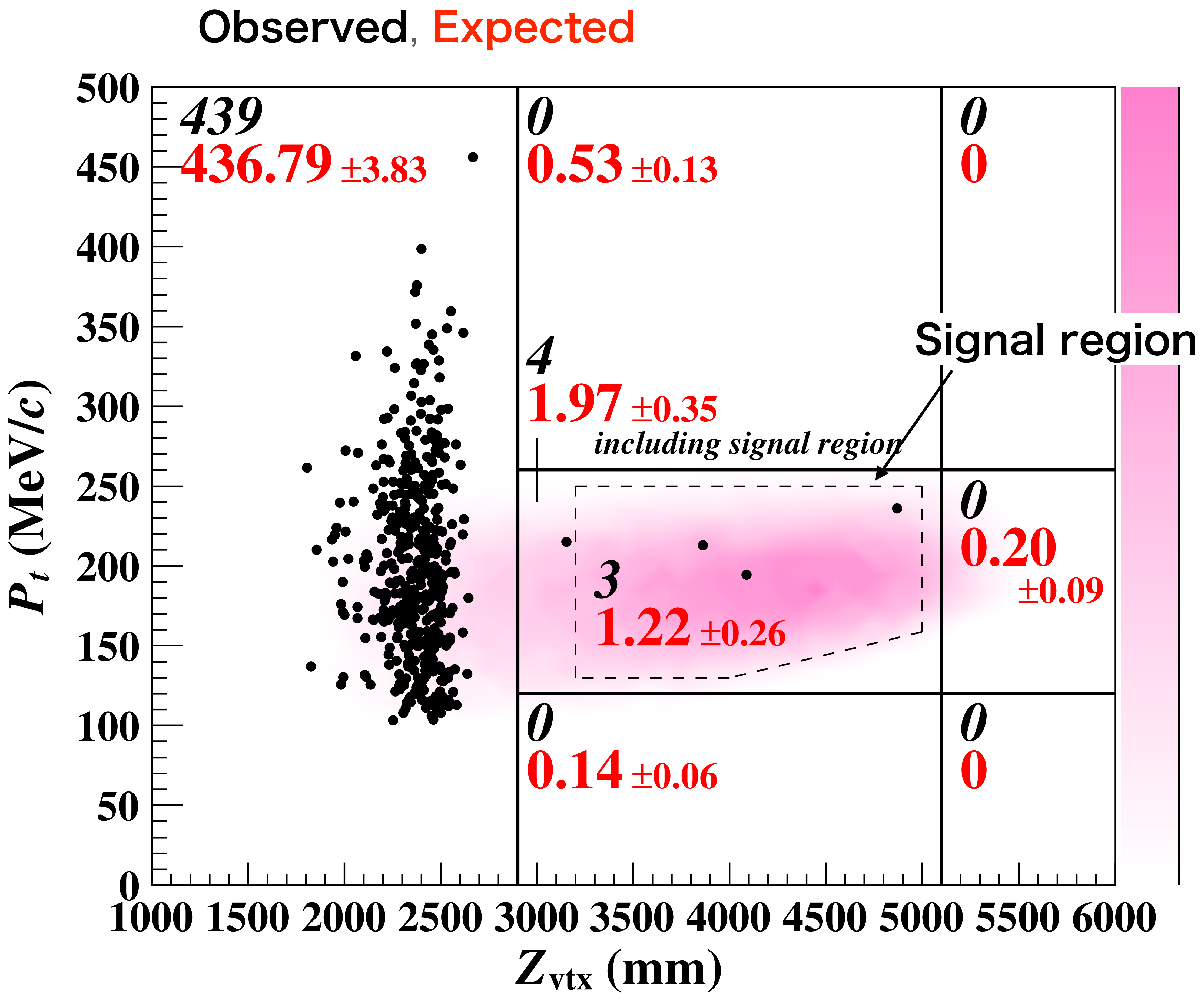
Review of 2016-2018 analysis results

- 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

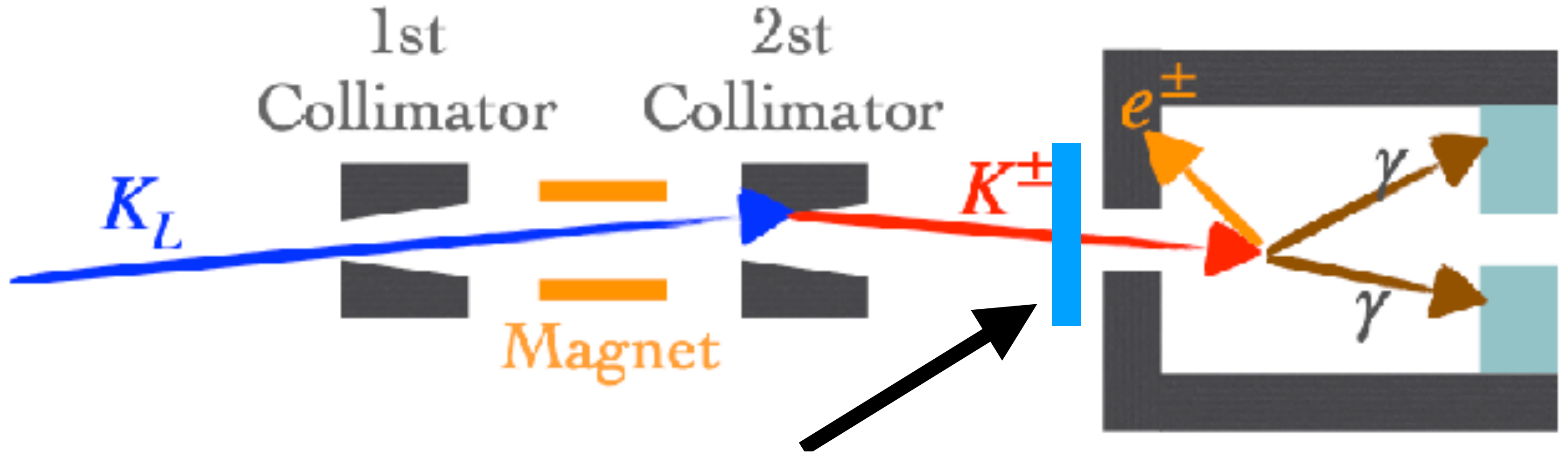


	Number of events
$K_L \to 3\pi^0$	0.01 ± 0.01
$K_L \to 2\gamma$ (beam halo)	0.26 ± 0.07^{a}
Other K_L decays	0.005 ± 0.005
$K^{\pm}$	0.87 ± 0.25^{a}
Hadron cluster	0.017 ± 0.002
CV η	0.03 ± 0.01
Upstream π^0	0.03 ± 0.03
	1.22 ± 0.26



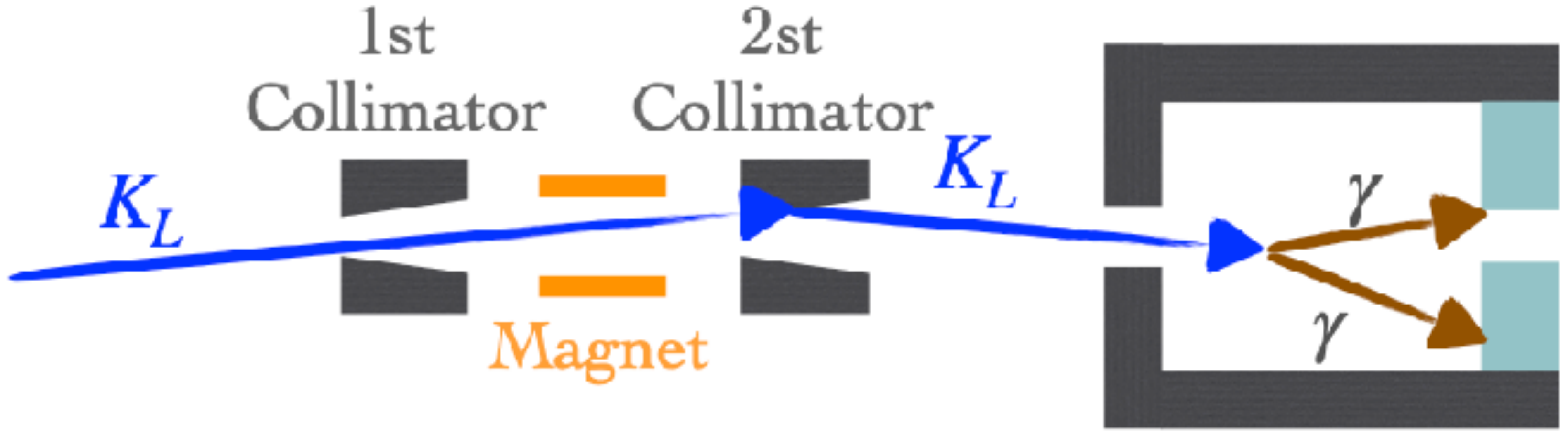
Measures against dominant BG sources

K± BG ($K^\pm \to \pi^0 e^\pm \nu$)



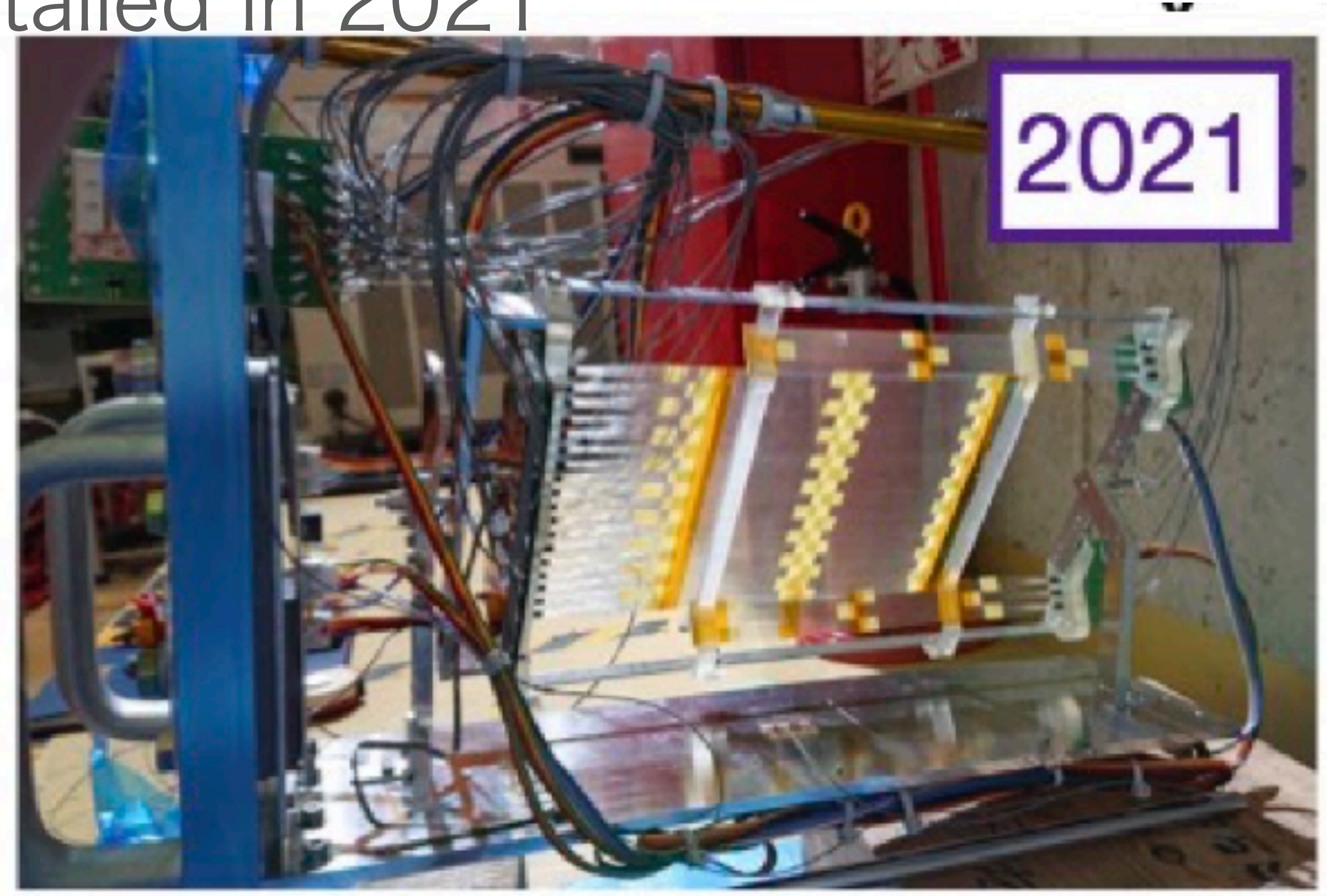
- Installed Upstream Charged Veto(UCV) for K± detection
  →Reduced by a factor of 13 with 97% signal efficiency.

Halo $K_L \to 2\gamma$



- 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.

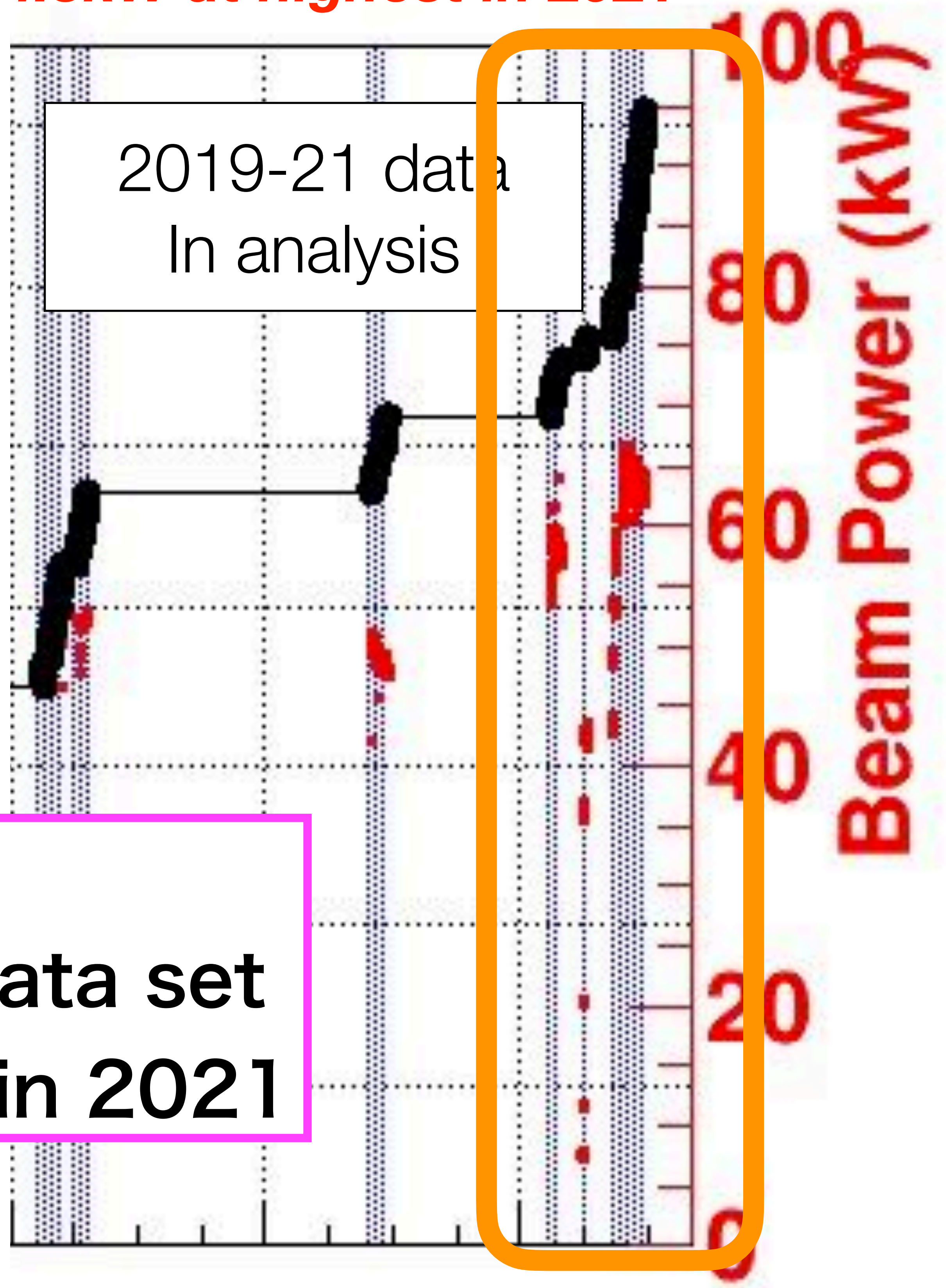
Upstream charged veto counter(UCV) installed in 2021



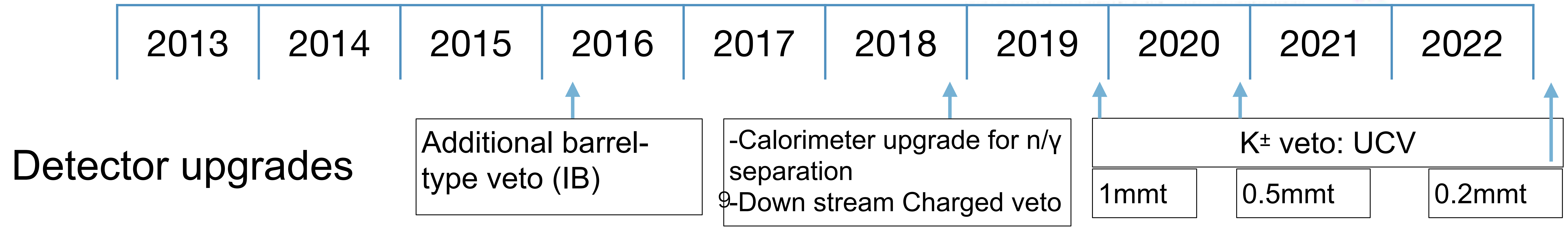
A plane of 0.5 mm-square scintillation fibers read by MPPC

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



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

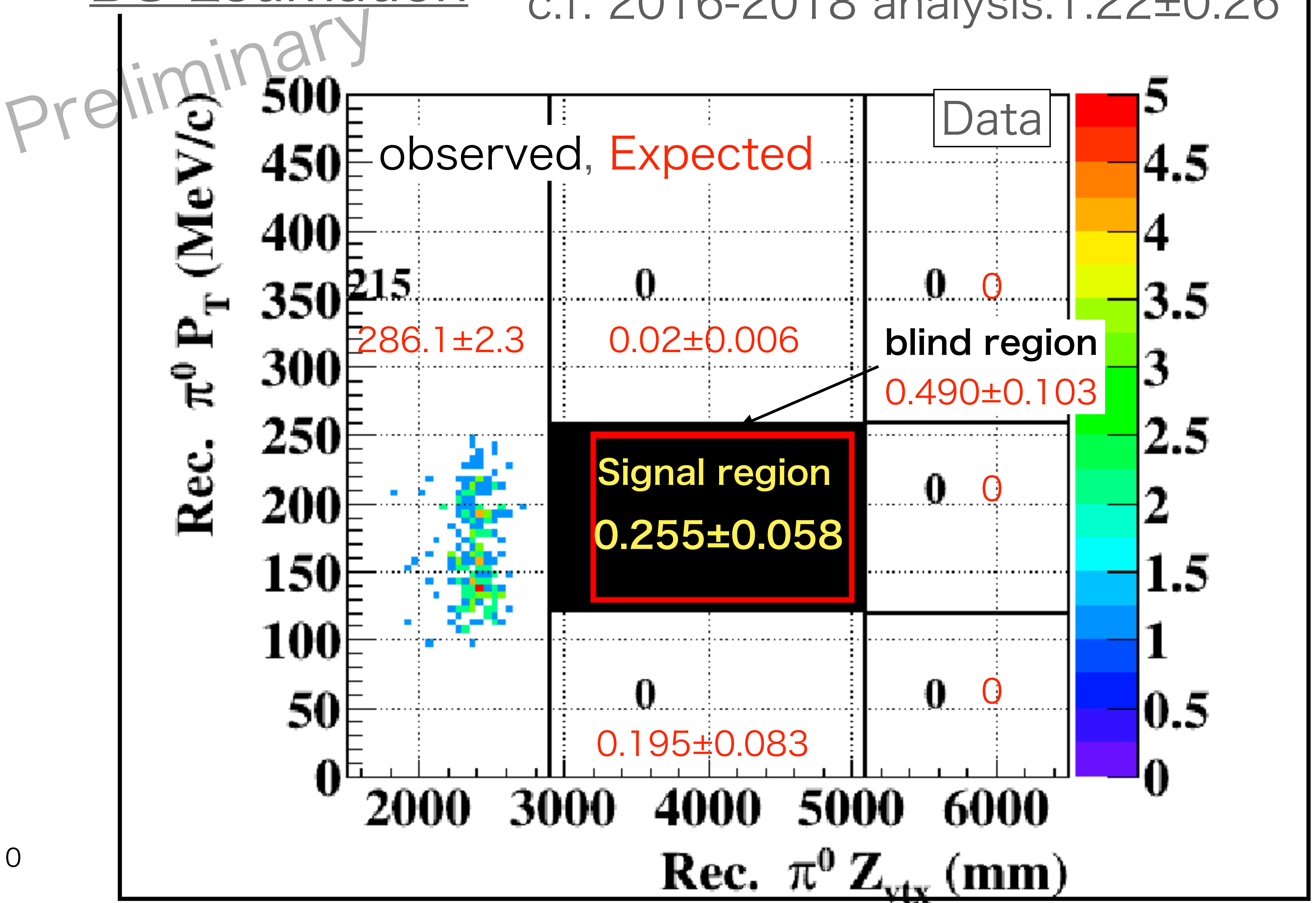
- Key points on the 2021data analysis
  - Implemented measures to reduce the K± and Halo $K_L \to 2\gamma$ BG
    - #(K± BG),#(Halo $K_L \to 2\gamma$ BG) < O(0.1)
  - Developed several analysis methods to estimate BG events more accurately.

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

c.f. 2016-2018 analysis:7.2×10^{-10}

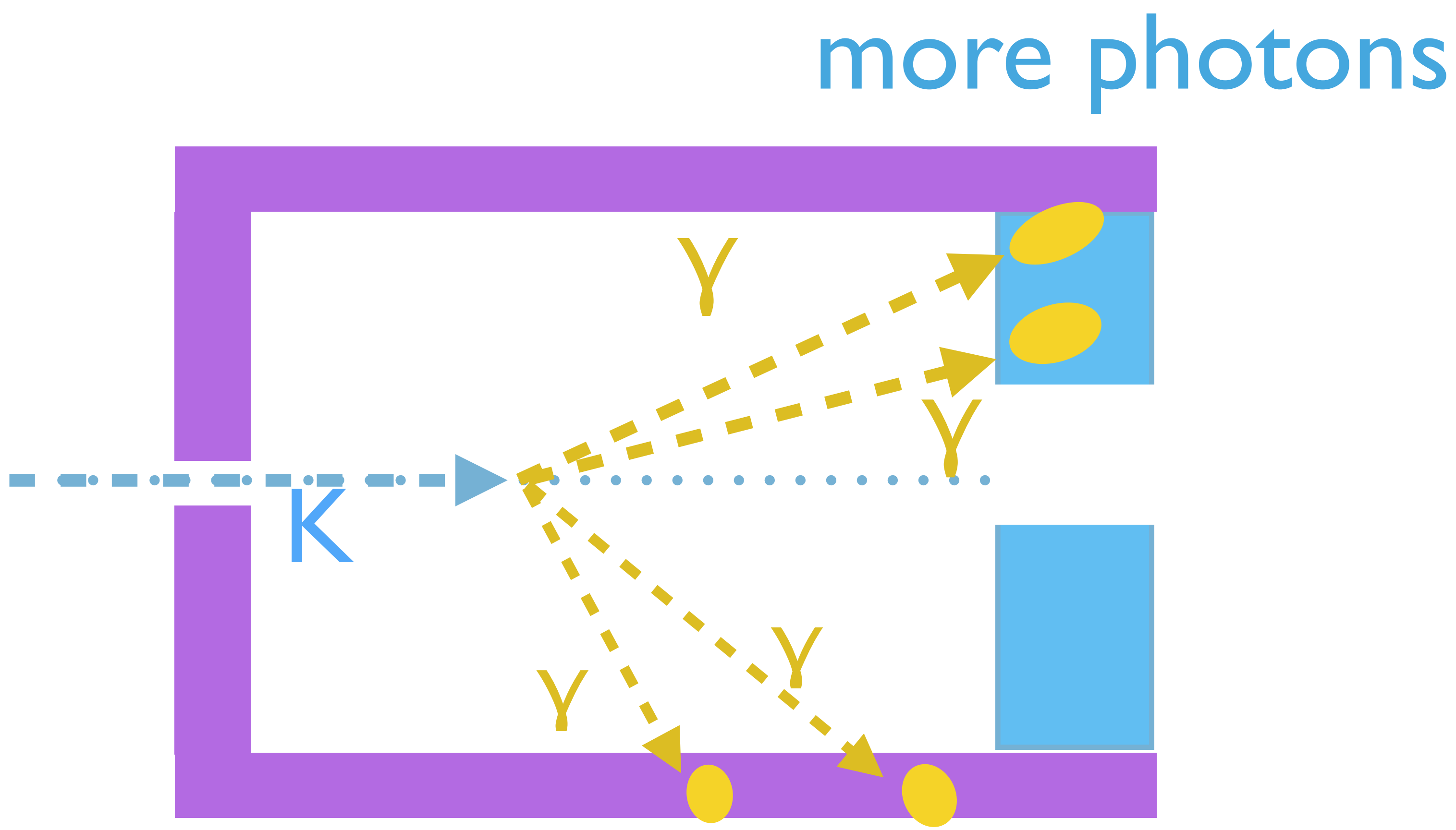
BG Estimation

c.f. 2016-2018 analysis:1.22±0.26



Photon inefficiency in veto detectors

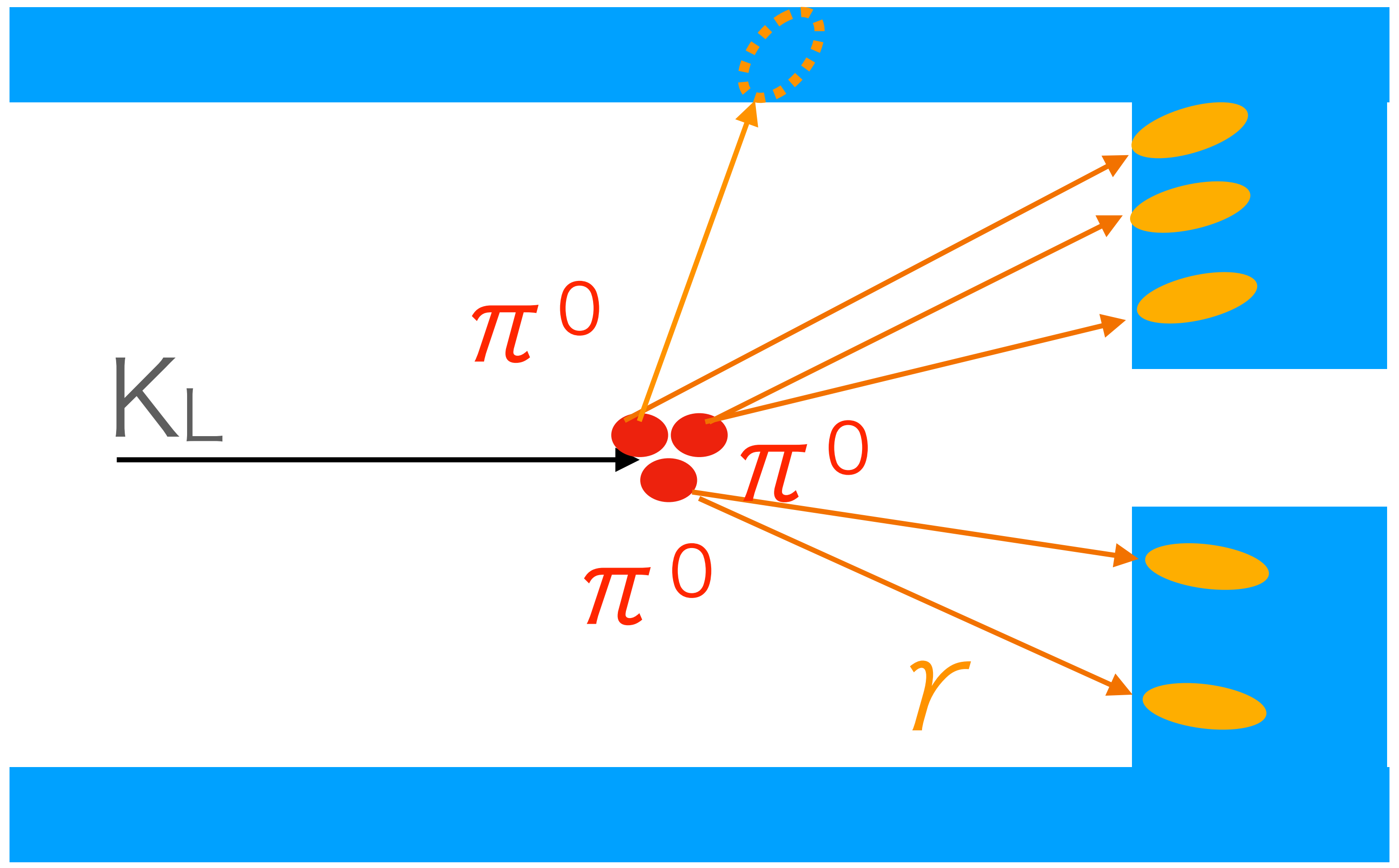
$K_L \to \pi^0\pi^0$ Background(BG)



- Photon inefficiency in veto detectors are critical to estimate the KL→2π^0 BG

- Photon inefficiency evaluated by MC depends on the MC version.

Photon inefficiency evaluation by using 5γ samples from $K_L \to 3\pi^0$ decay



- Reconstruct the momentum of the remaining 1γ and the π^0 vertex by a constrain fit

- Check the energy deposit in the detector of destination

$$\mathrm{Ineffi} = \frac{N_{\mathrm{Edep<Threshold}}}{N_{\mathrm{all}}}$$

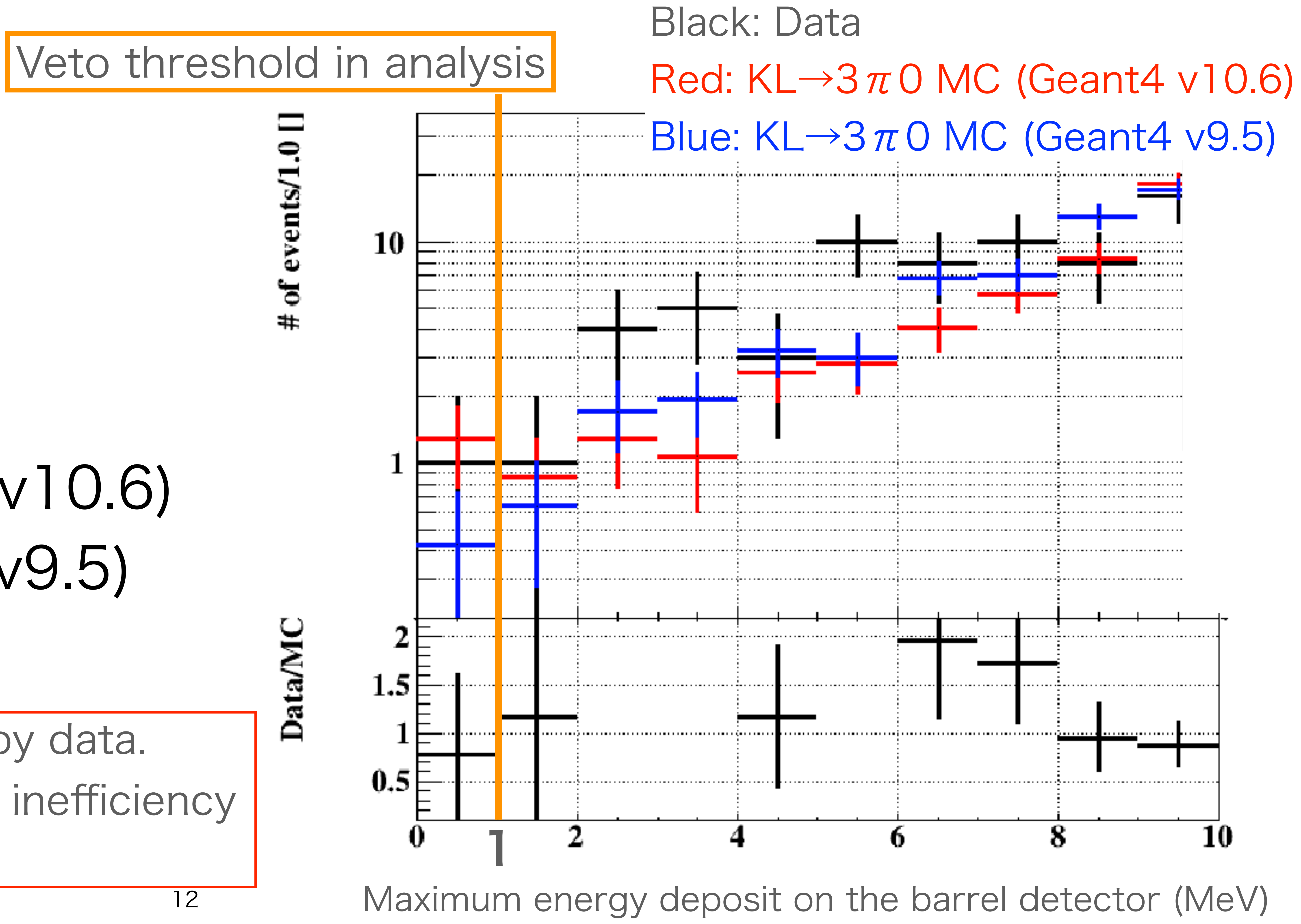
Inefficiency evaluation with 5γ data

6 th γ with high energy into barrel detector

Reconstructed $E_{6\gamma}$>200MeV
Destination: Barrel detector

- For 1 MeV threshold
  - $\mathrm{Ineffi}_{\mathrm{Data}}=(4.8\pm4.8)\times10^{-5}$
  - $\mathrm{Ineffi}_{\mathrm{MC}}=(6.2\pm2.5)\times10^{-5}$ (for v10.6)
    $=(2.1\pm1.5)\times10^{-5}$(for v9.5)

Need more statistics to evaluate inefficiency by data.
-Set 100% systematic uncertainty on photon inefficiency of the barrel detector.



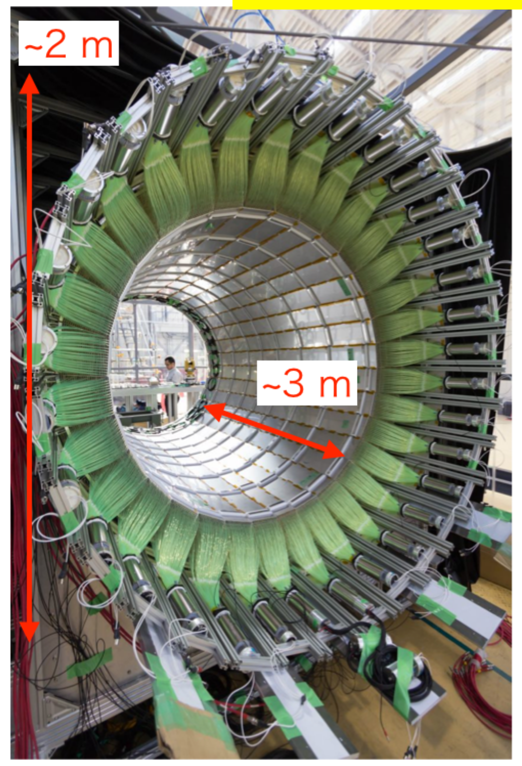
Evaluation of the number of $K_L \to 2\pi^0$ BG

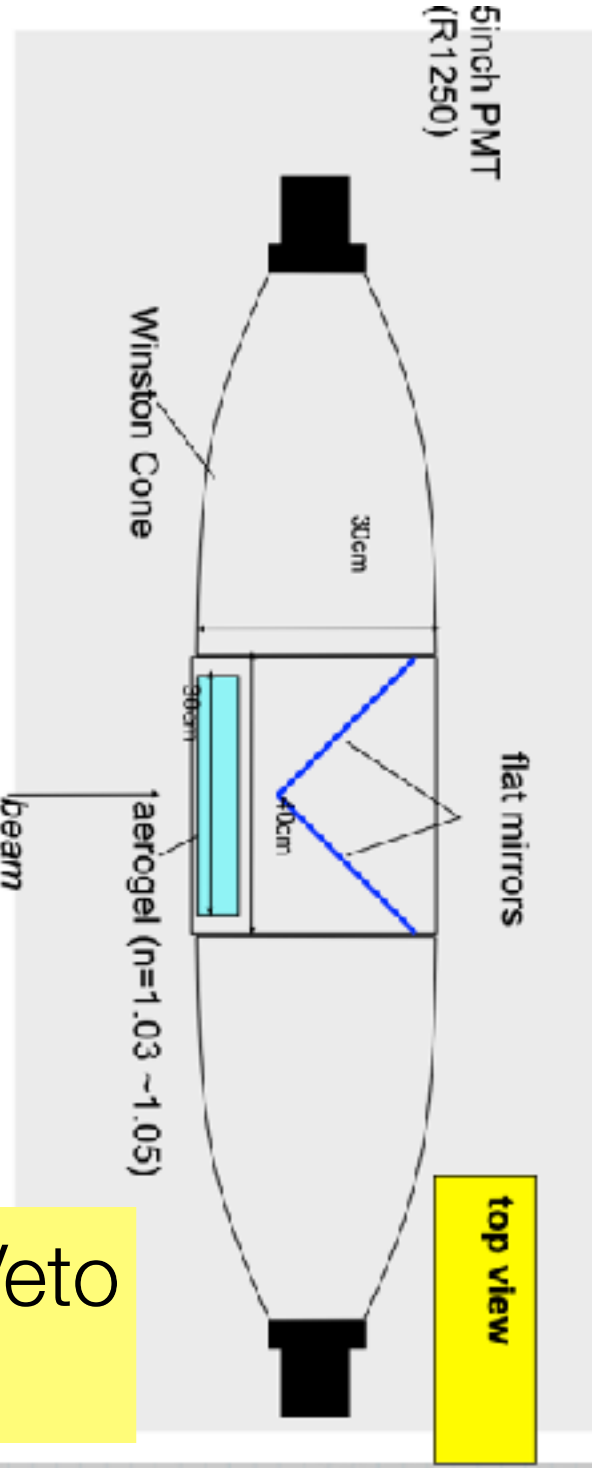
$$SF = \frac{\mathrm{Ineffi}_{\mathrm{Data}}}{\mathrm{Ineffi}_{\mathrm{MC}}} \qquad \#BG = \Sigma(SF_{\mathrm{det1}} \times SF_{\mathrm{det2}})$$

Errors on SF are considered as systematic uncertainties

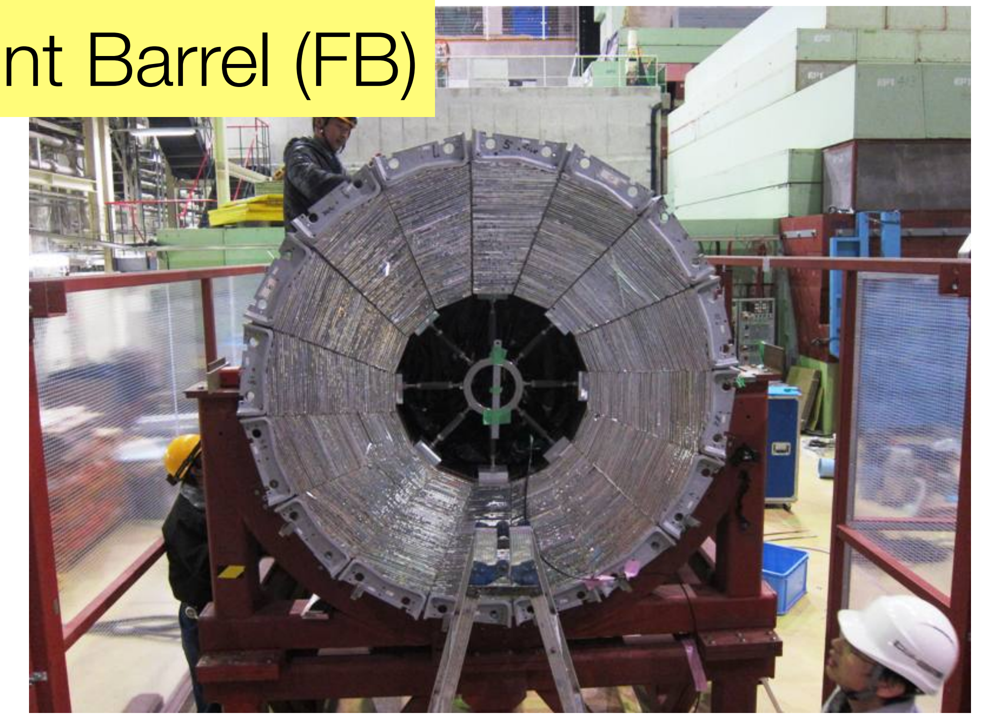
Main Barrel

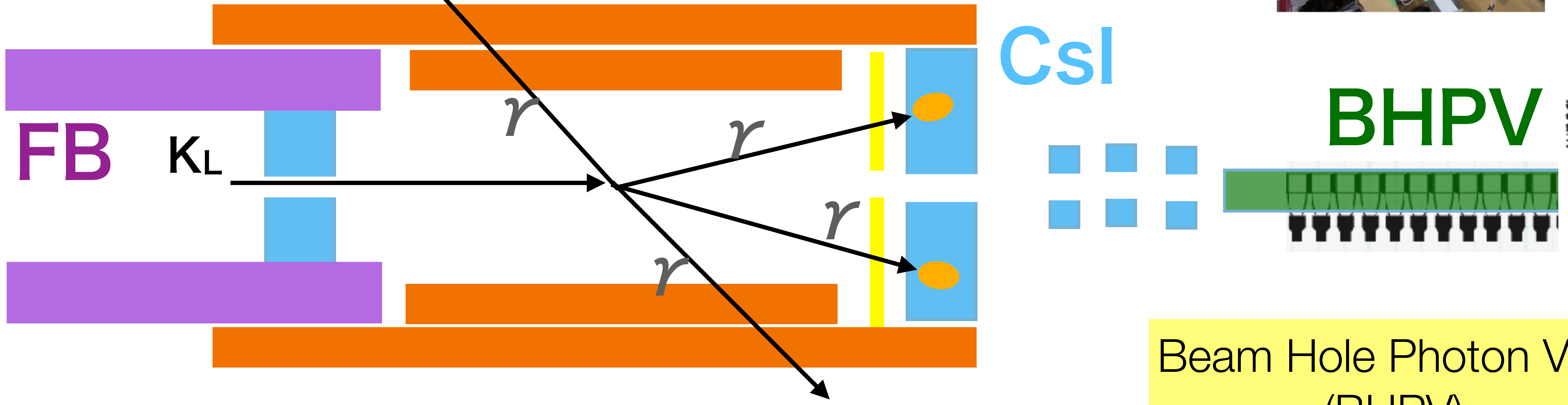
Inner Barrel (IB)





Front Barrel (FB)

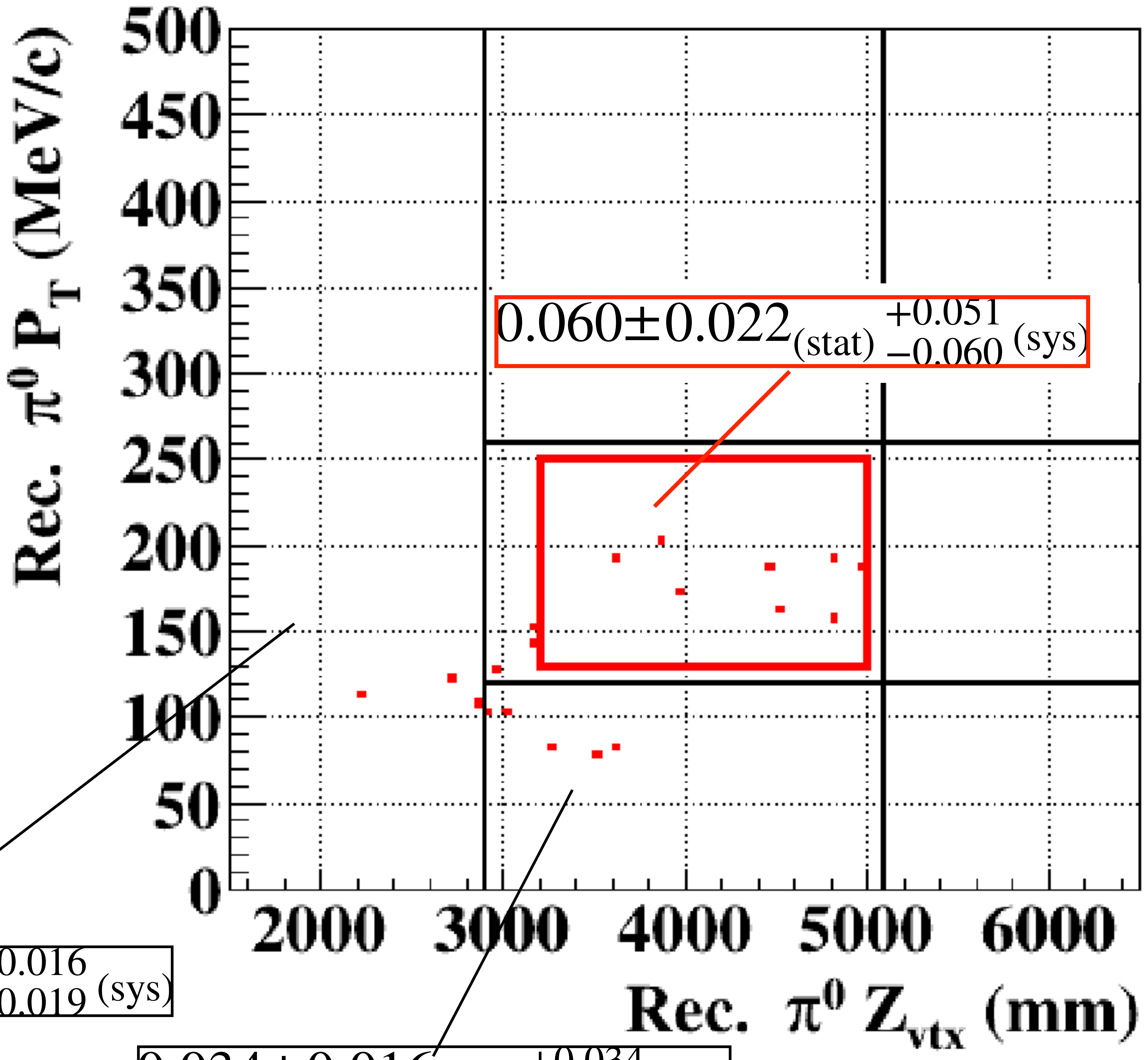




Beam Hole Photon Veto (BHPV)

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

The number of $K_L \to 2\pi^0$ BG



$0.060 \pm 0.022_{(stat)}\,{}^{+0.051}_{-0.060}\,(sys)$

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

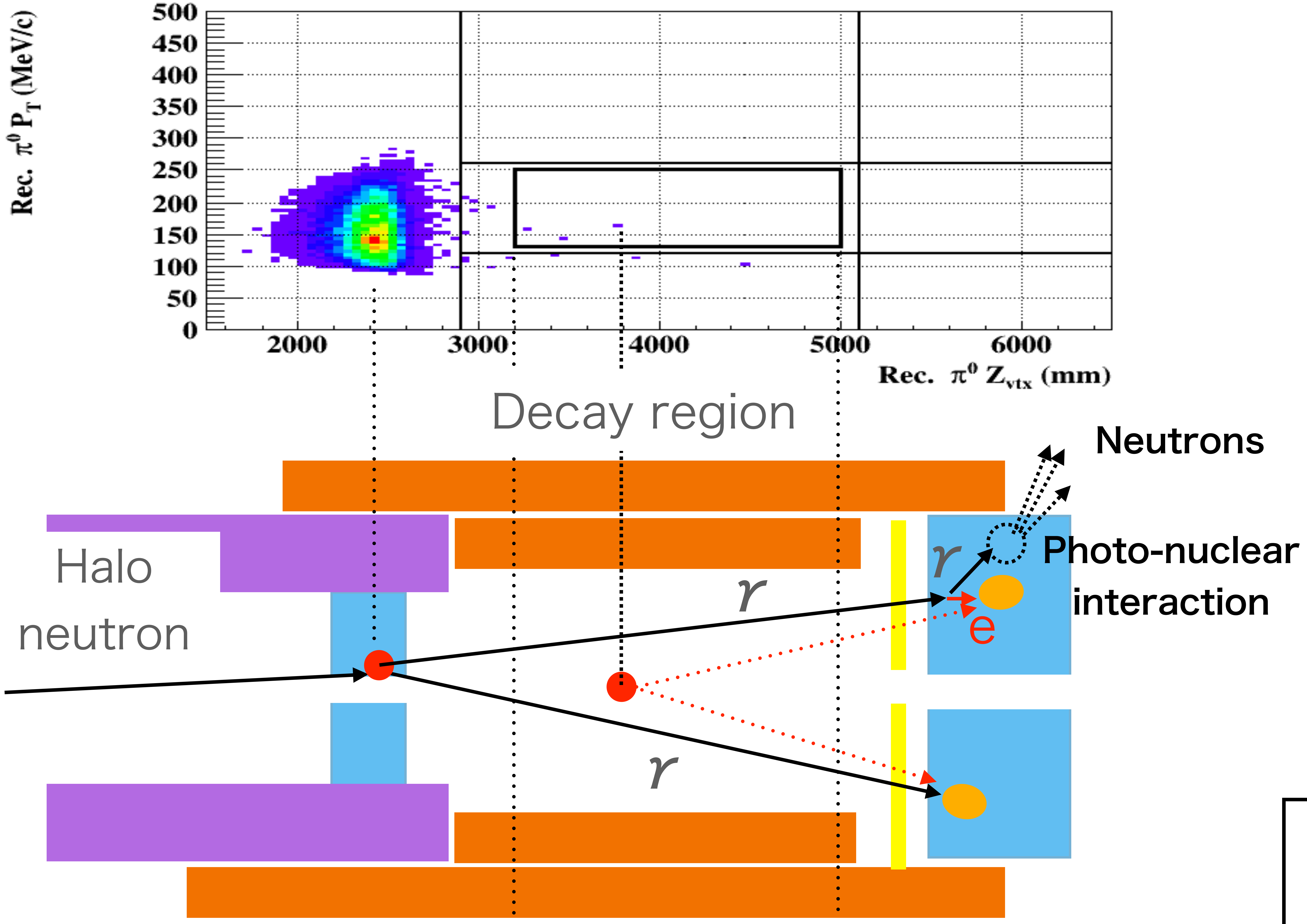
$0.034 \pm 0.016_{(stat)}\,{}^{+0.034}_{-0.040}\,(sys)$

cf. :N($K_L \to 2\pi^0$) BG

before SF correction

$-0.049 \pm 0.018_{(stat)}$

Upstream π^0 BG caused by photo nuclear interaction



Mechanism

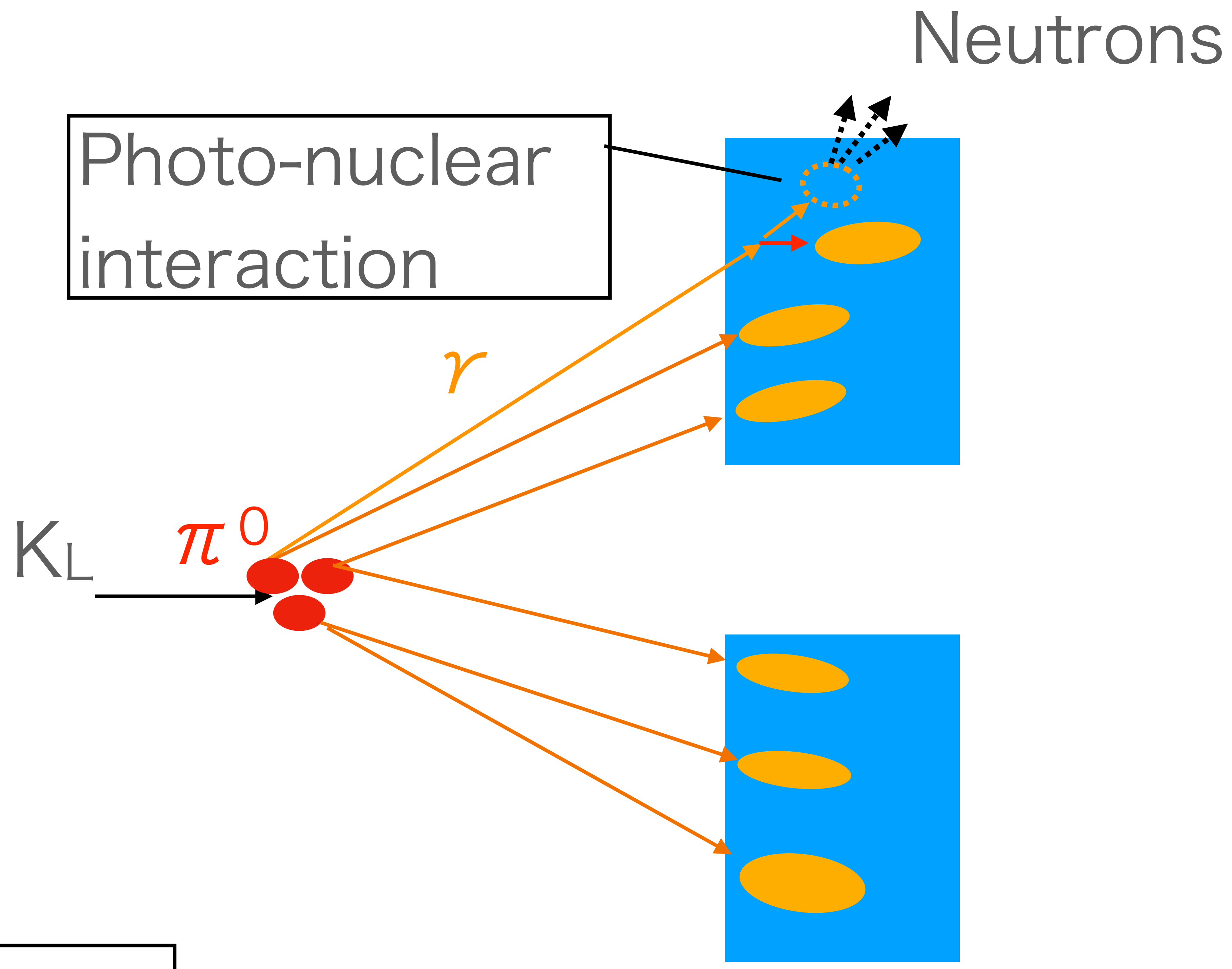
- Neutrons generated in photo-nuclear interaction take away a part of energy from the CsI
- Reconstructed vertex shifts to downstream and enters the signal box

How to estimate

- Simulate the π production in upstream detectors with halo neutrons
- MC is normalized to data using events around z=2400 mm under a loose cut condition

Key: Probability of energy mismeasurement in CsI

Confirm probability of energy mismeasurement in CsI by using $K_L \to 3\pi^0$ samples



$K_L \to 3\pi^0$ samples

with large Radius of Center of Energy (RCOE) in CsI

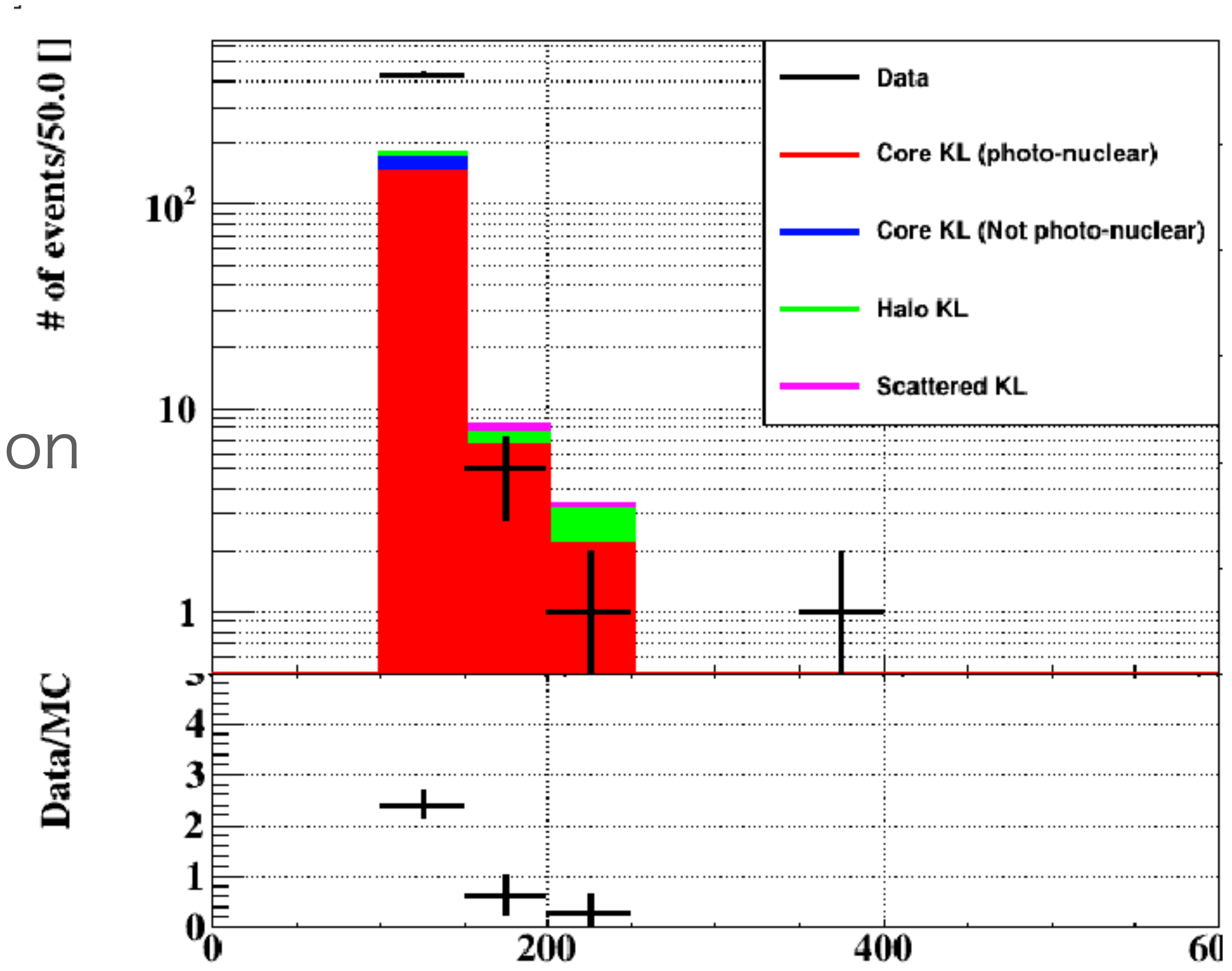
$M_{6\gamma} \neq M_{KL}$

Confirm probability of energy mismeasurement in CsI by using $K_L \to 3\pi^0$ samples

-Compare the number of events in the region of 100 mm <RCOE<200 mm between data and MC.

-Assume that the difference between data and MC is caused by the core KL events due to photo-nuclear interaction

-An additional scale factor is applied to the photo-nuclear events to reach the agreement between data and MC
  -Additional scale factor : 2.64±0.35
    -Used for the estimation of upstream π^0 background



600

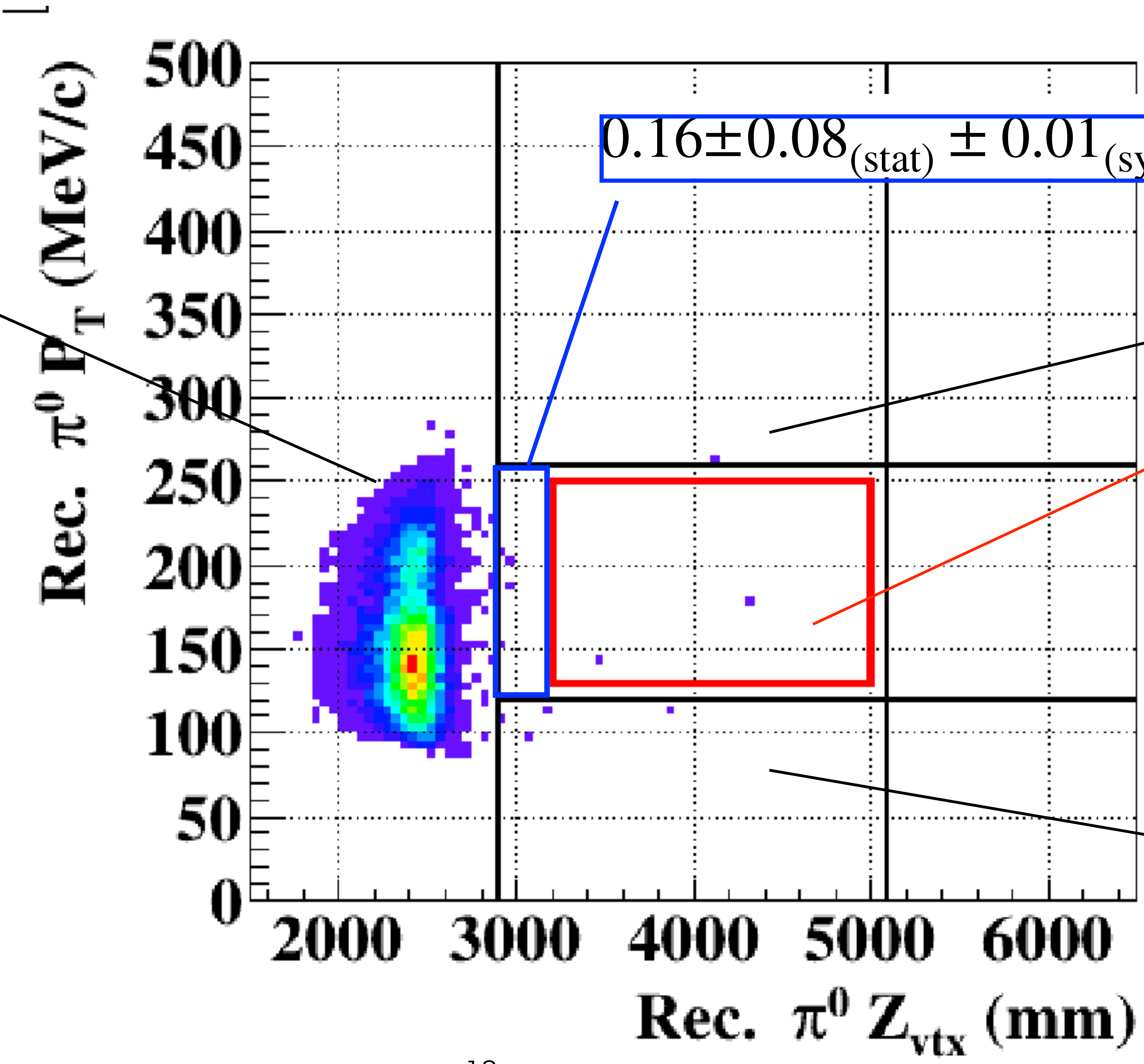
RCOE (mm)

of upstream π^0 background events

$286.1\pm2.3_{(stat)}$

$\Leftrightarrow N_{obs} = 215$

25% difference between data/MC comes from an imperfect reproducibility of π^0's kinematics



$0.16\pm0.08_{(stat)} \pm 0.01_{(sys)}$

$0.0018\pm0.0018_{(stat)}$

$0.064\pm0.050_{(stat)} \pm 0.006_{(sys)}$

cf. :N(upstream π^0) BG before correction
-($0.035\pm0.025_{(stat)}$)

$0.14\pm0.08_{(stat)} \pm 0.01_{(sys)}$

Results of 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) $(^{+0.053}_{-0.068})_{sys}$

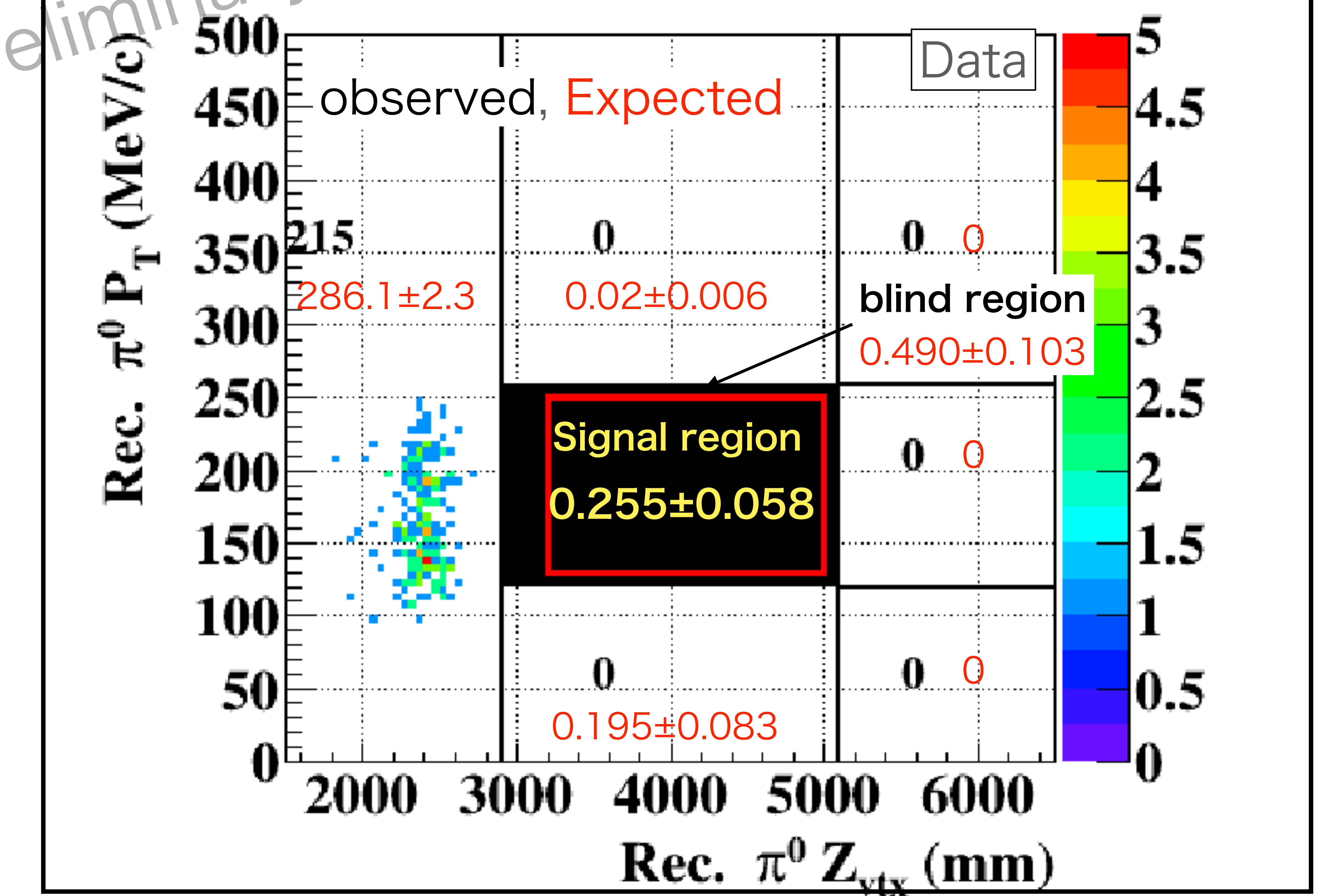
Single Event Sensitivity(S.E.S.):8.7×10^{-10}

c.f. 2016-2018 analysis:7.2×10^{-10}

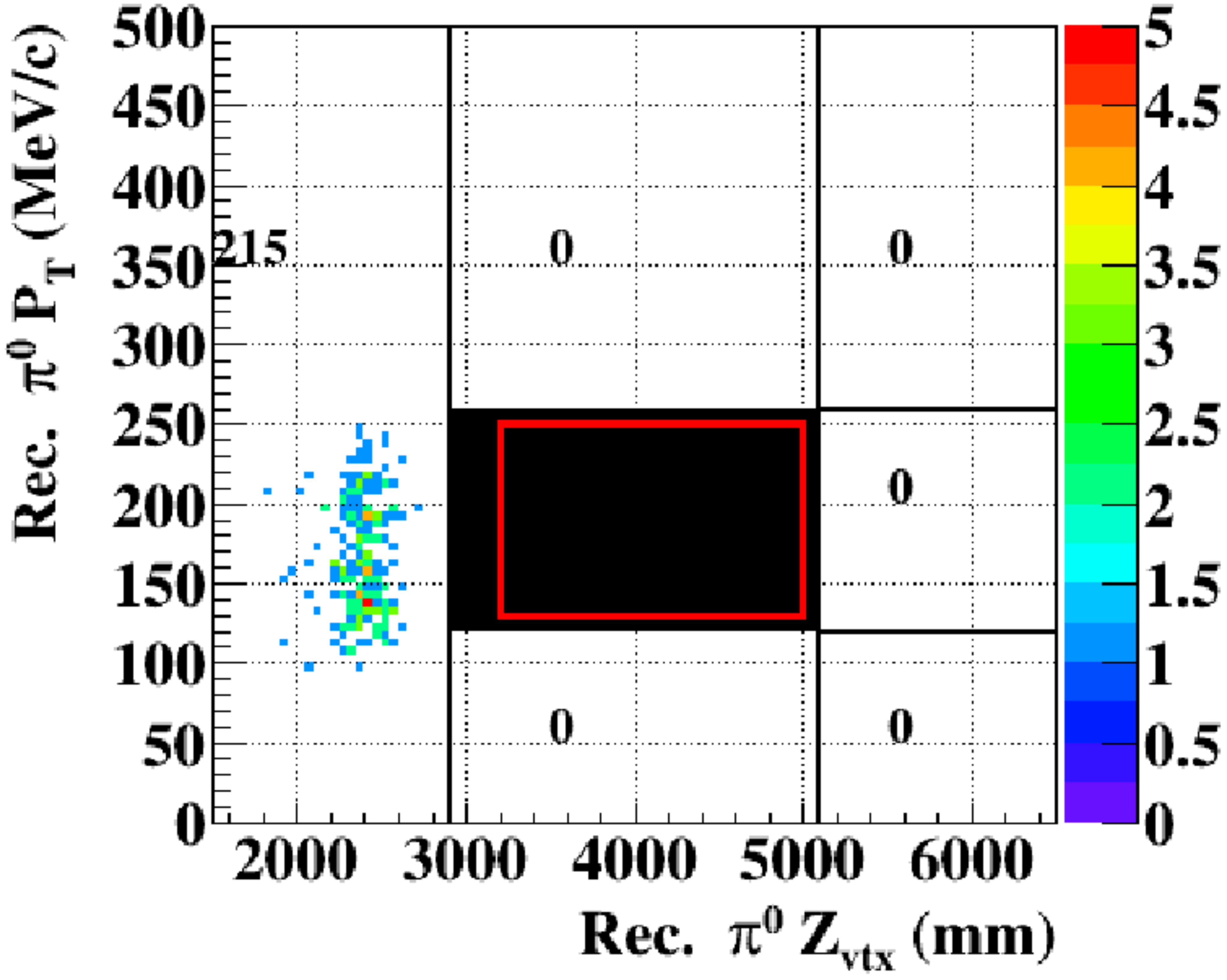
BG Estimation

c.f. 2016-2018 analysis:1.22±0.26

Preliminary



Open the signal box

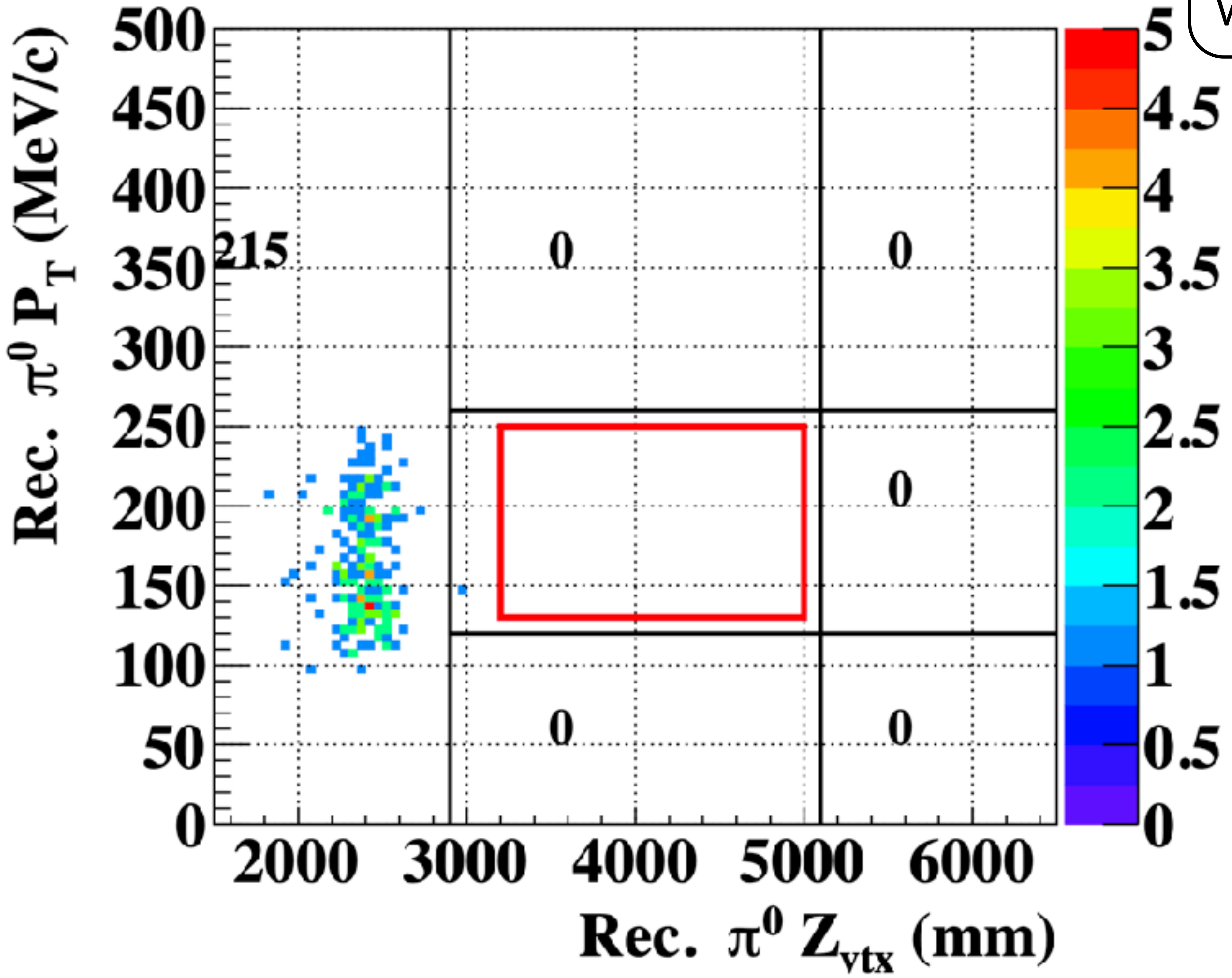


Open the signal box

- No signal candidate 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

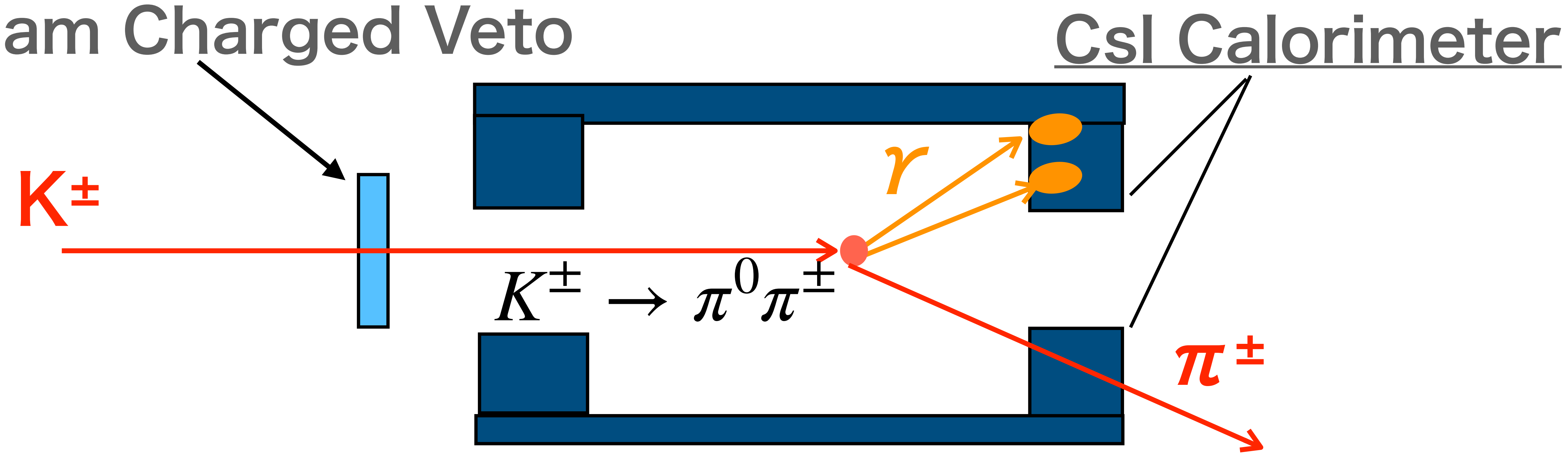
- The KOTO experiment studies the $K_L \rightarrow \pi^0 \nu \nu$ decay.
- No signal candidate was observed in 2021 data
  - $BR < 2.0 \times 10^{-9}$ @90% C.L.
    - Improved the current upper limit by 50% with a 5 times smaller background level.
- Continue to take physics data to achieve the sensitivity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

Preliminary

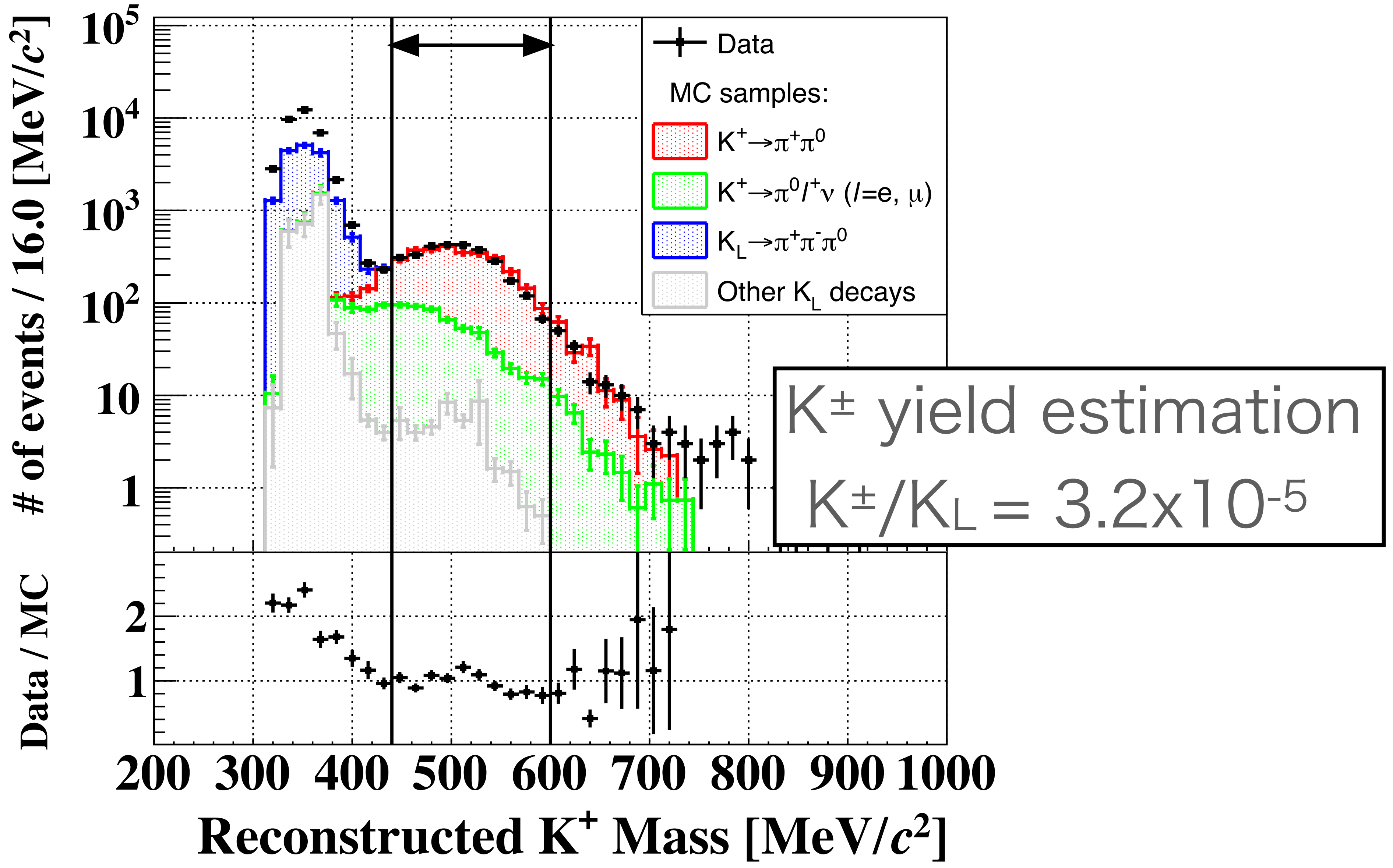
Backup

Estimation of N(K± BG)

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



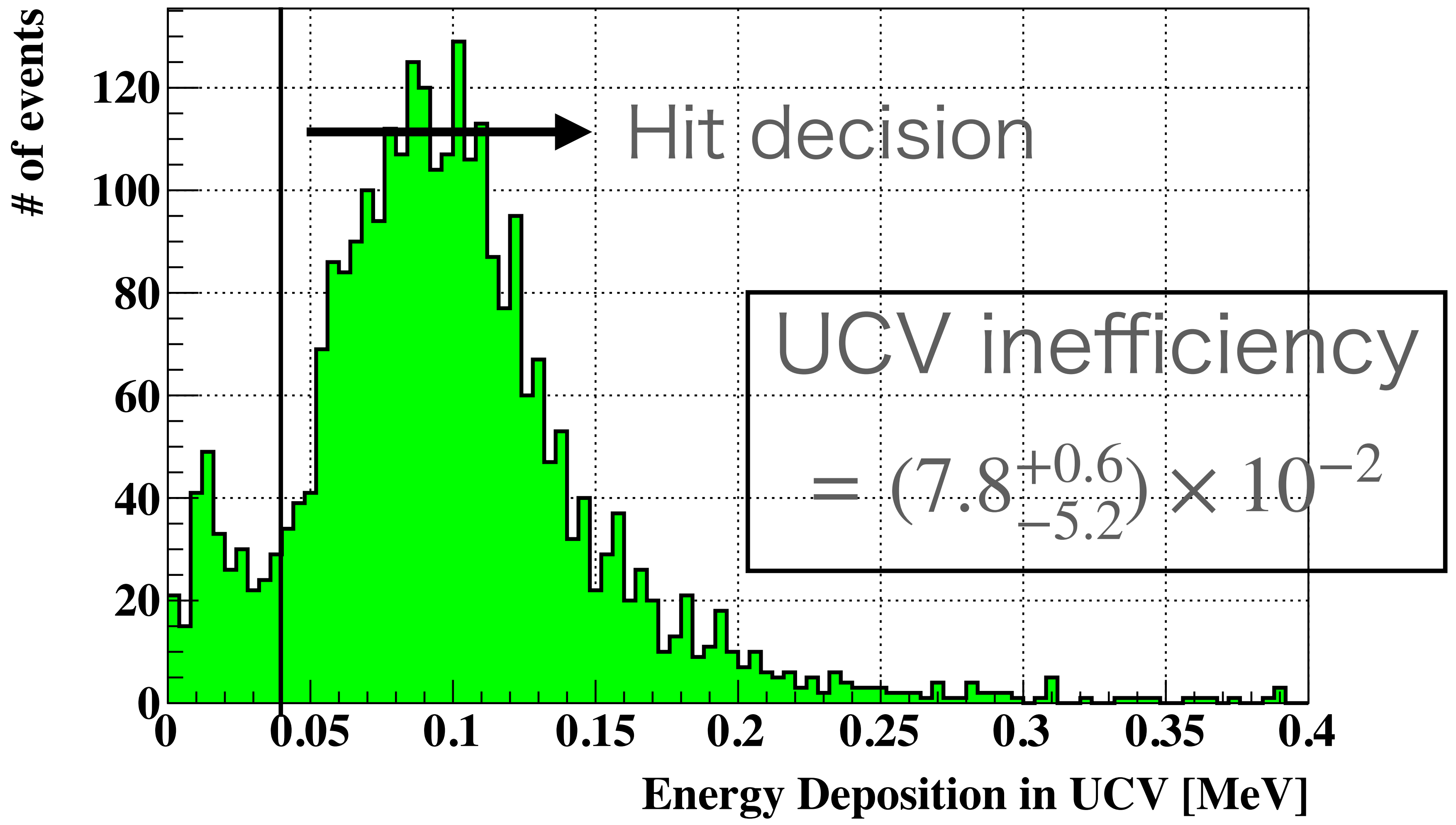
- 3-Cluster events
- π^{0} vertex reconstruction from 2γ
- $\pi^{\pm}$ reconstruction assuming transverse momentum balance



K± yield estimation

$K^{\pm}/K_L = 3.2\text{x}10^{-5}$

K±→$\pi^+\pi^0$ candidate events



UCV inefficiency

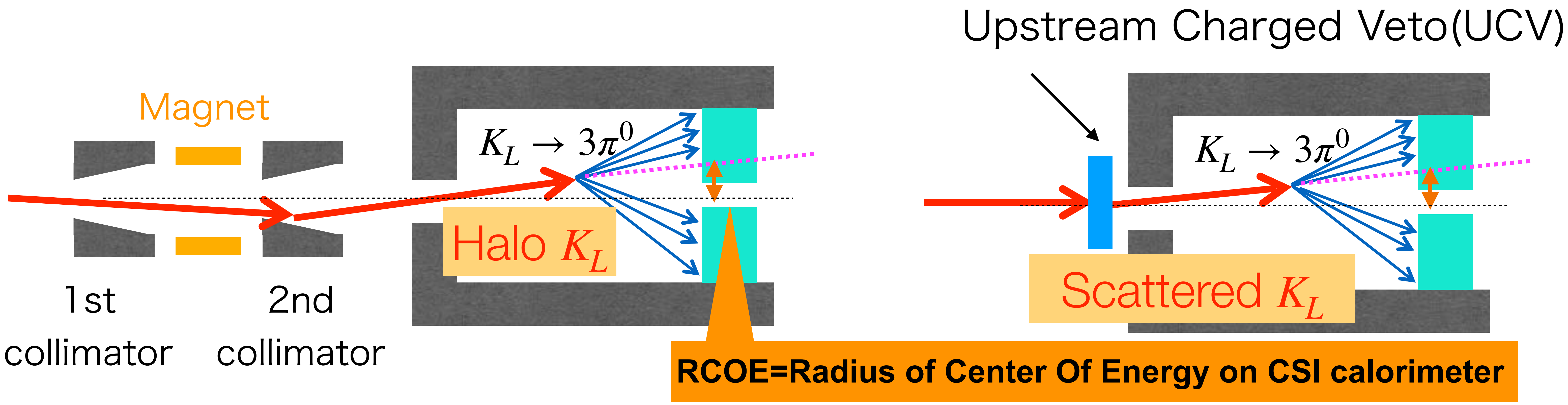
$= (7.8^{+0.6}_{-5.2}) \times 10^{-2}$

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

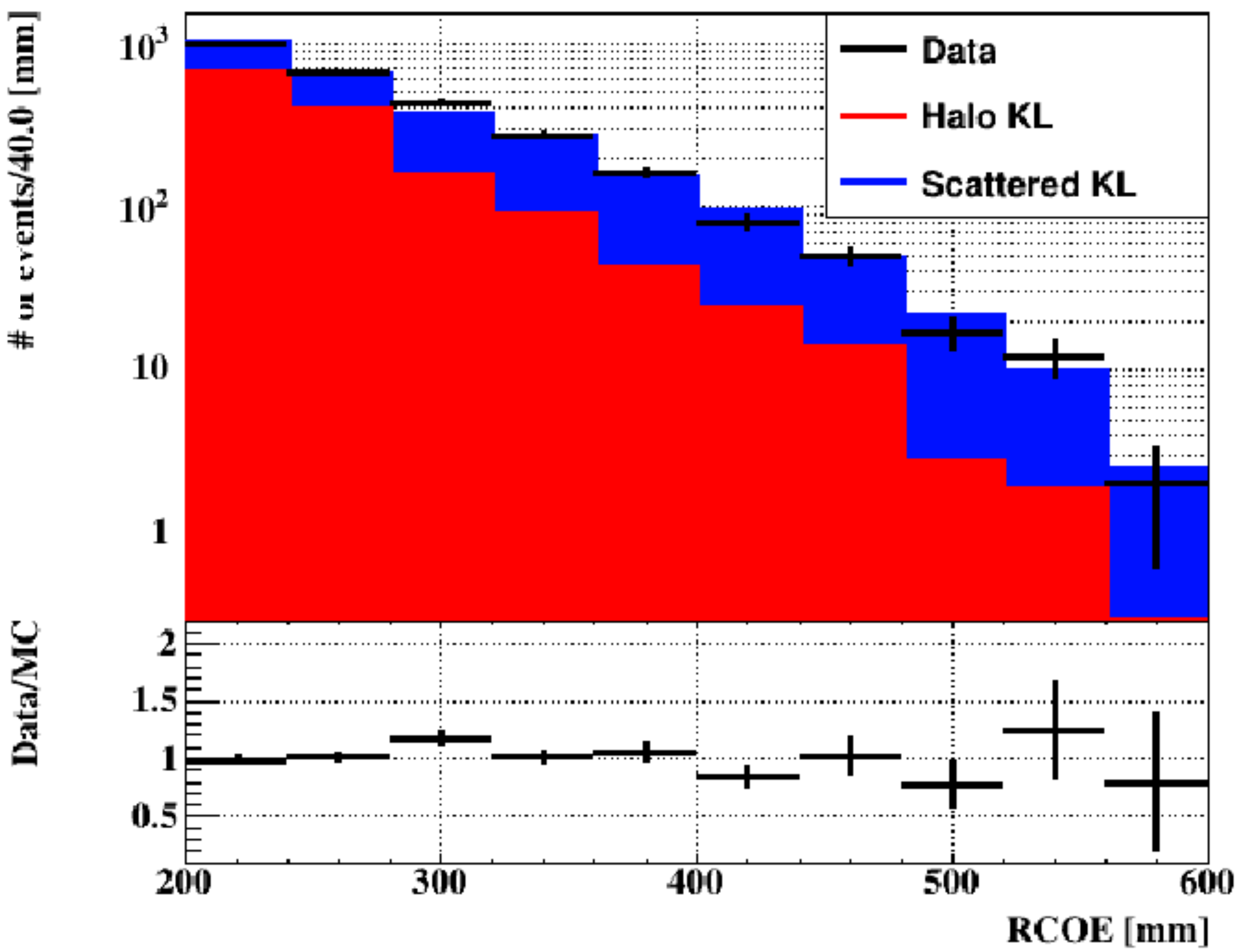
Estimation of N(Halo K$_L$→2γ BG)

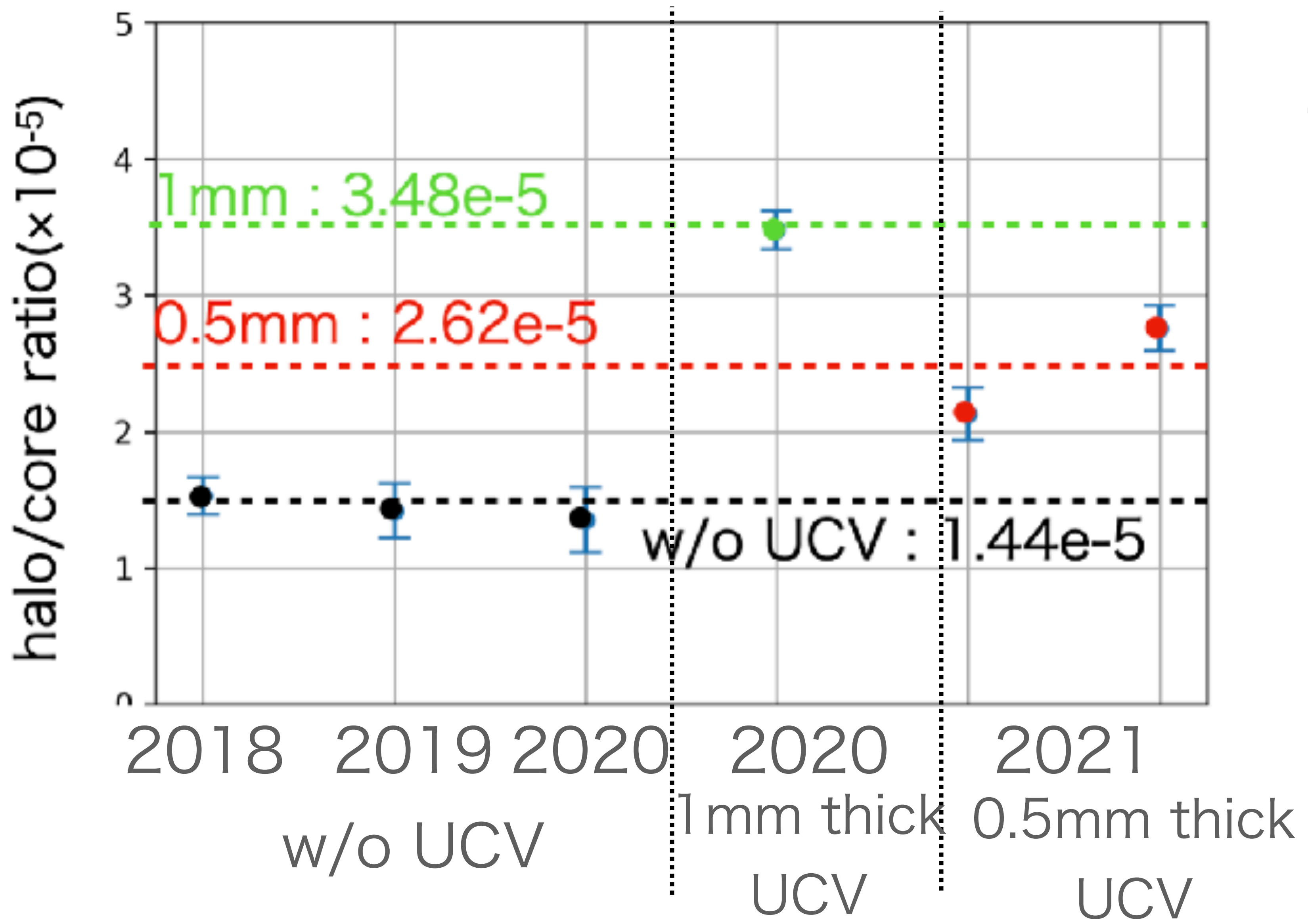
Estimation of Halo K$_L$ flux

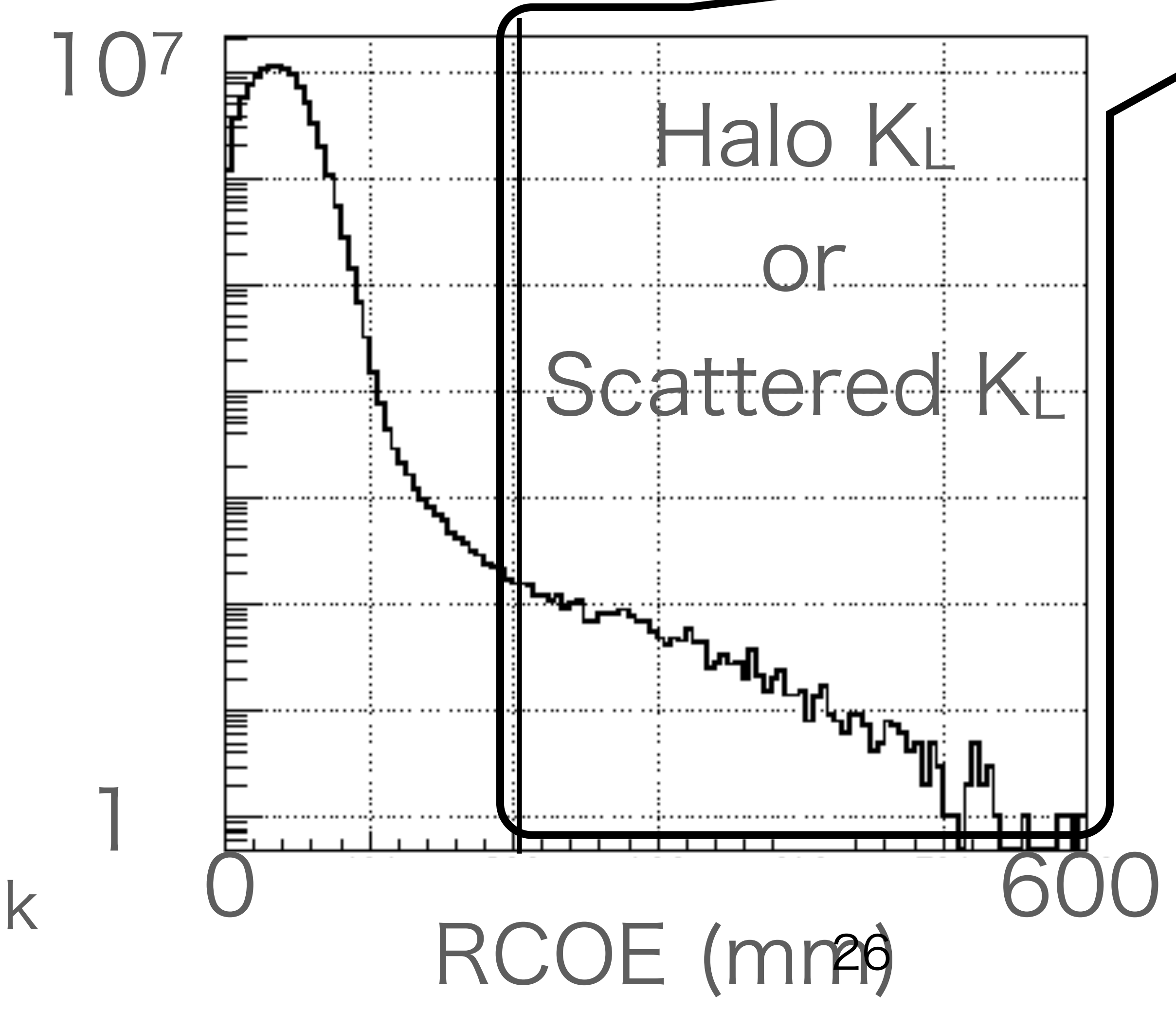
- Halo K$_L$ flux was evaluated by using $K_L \to 3\pi^0$ sample



RCOE=Radius of Center Of Energy on CSI calorimeter







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$_{(sys)}$

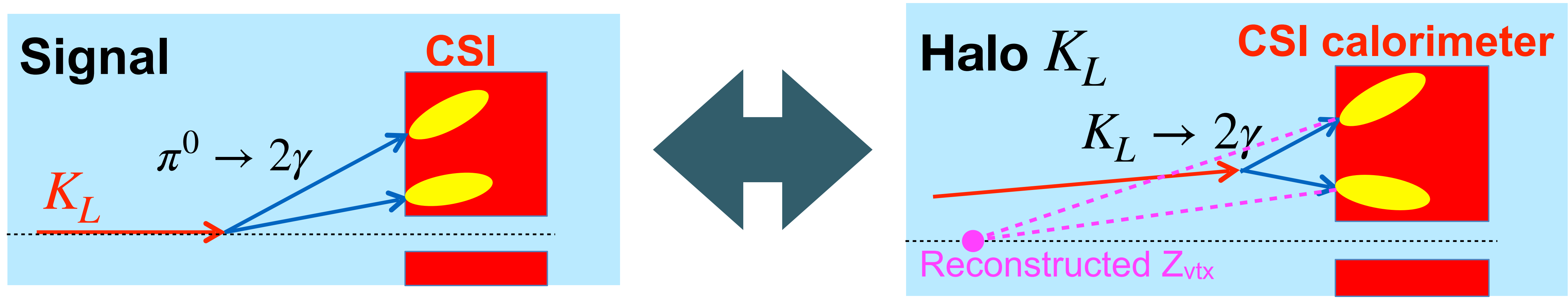
[*1] Halo K$_L$s are generated according to the results of the GEANT3-base beam line simulation.

[*2] Core K$_L$s injected to UCV are generated by using a model function based on our KL flux measurement.

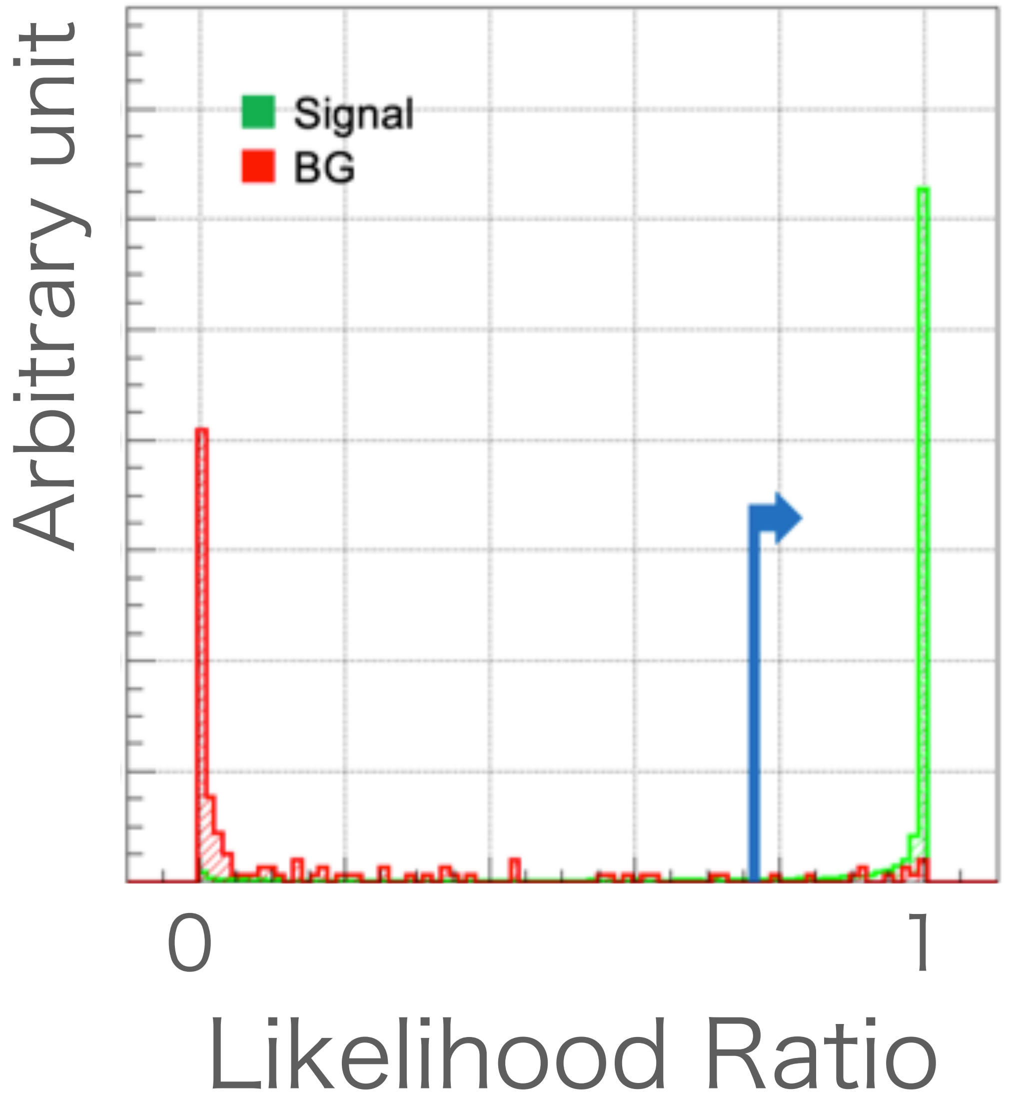
Estimation of N(Halo $K_L \to 2\gamma$ BG)

Newly developed cuts

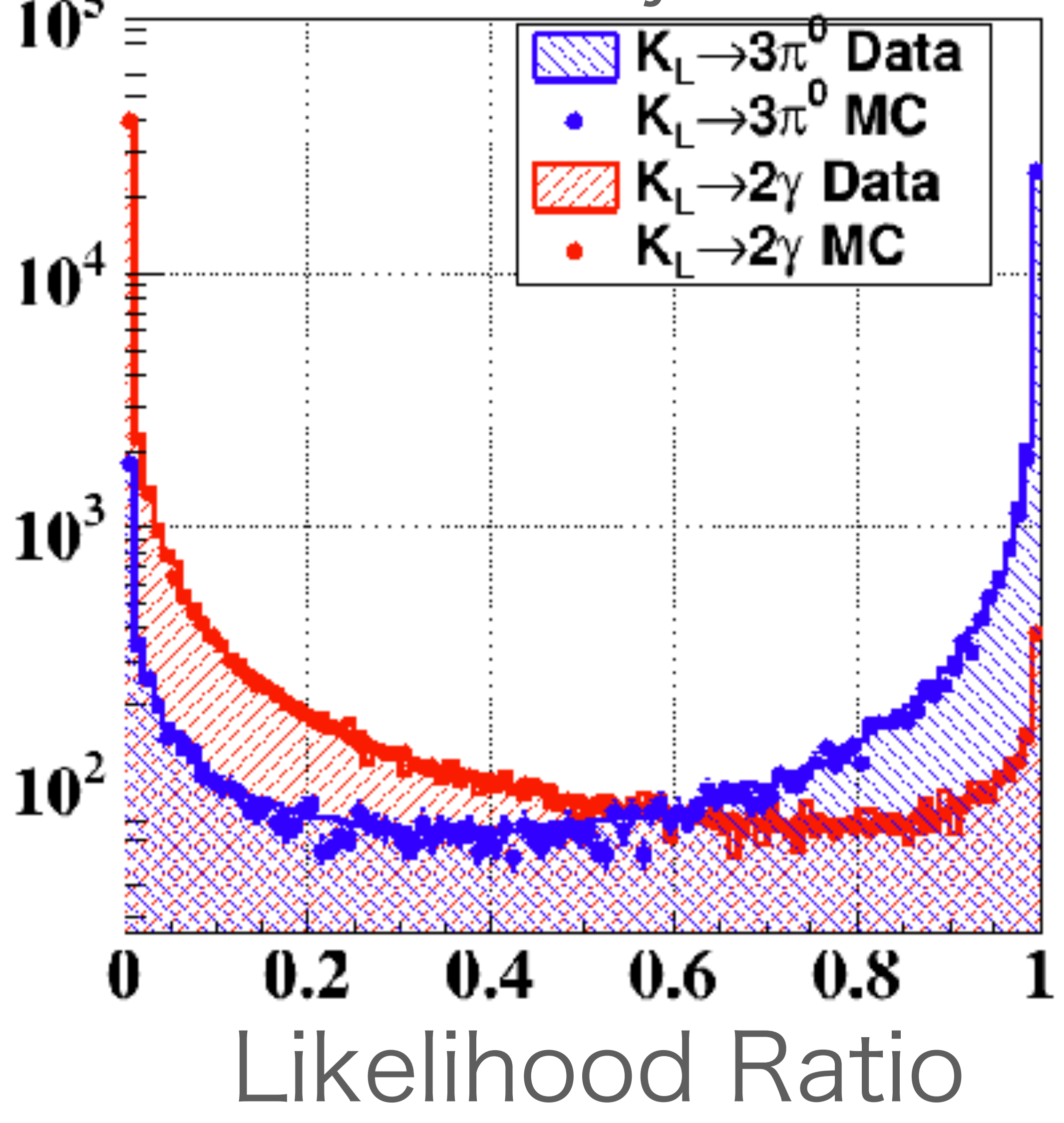
- Shower shape consistency
  - Likelihood Ratio based on shower shape and reconstructed angle



Performance



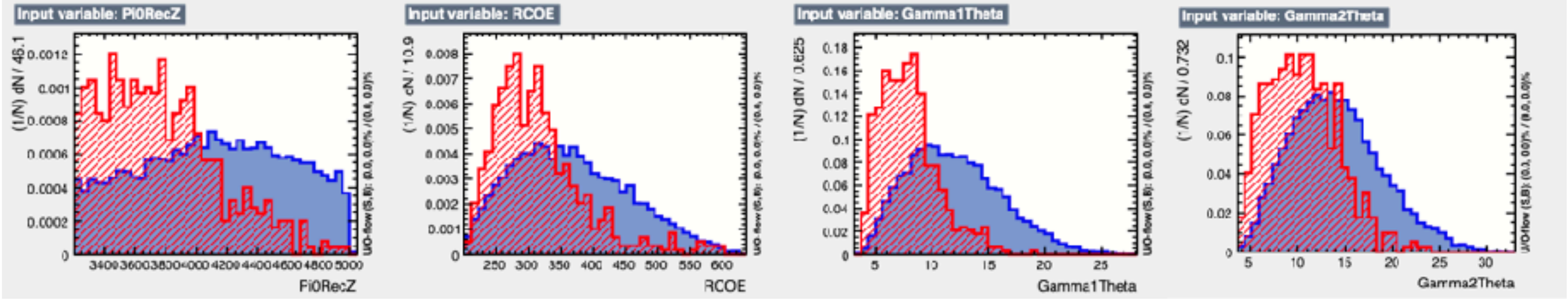
Validation by data



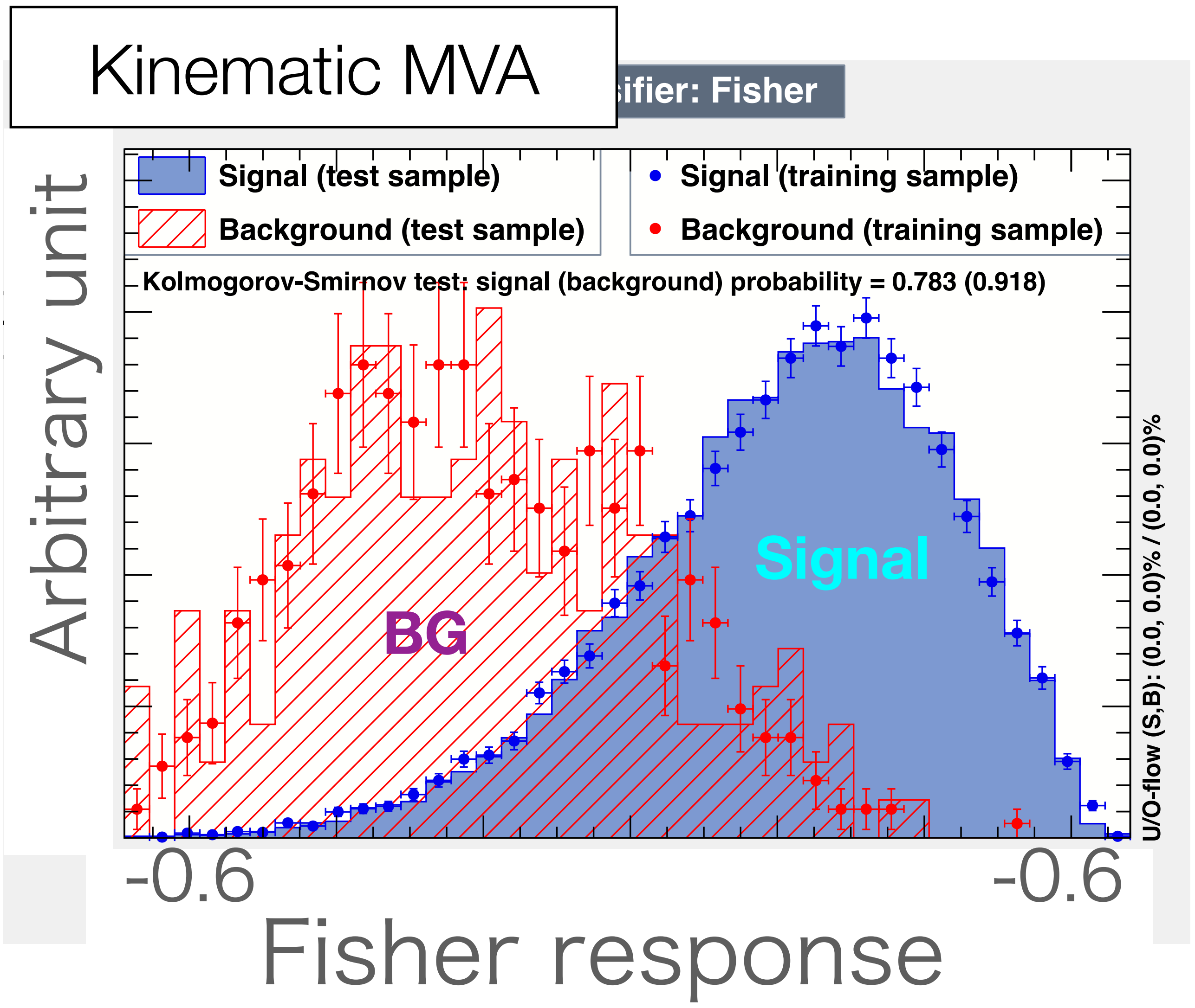
- Multi variable Analysis with kinematical variables

Input variables Blue:signal Red:Halo $K_L \to 2\gamma$

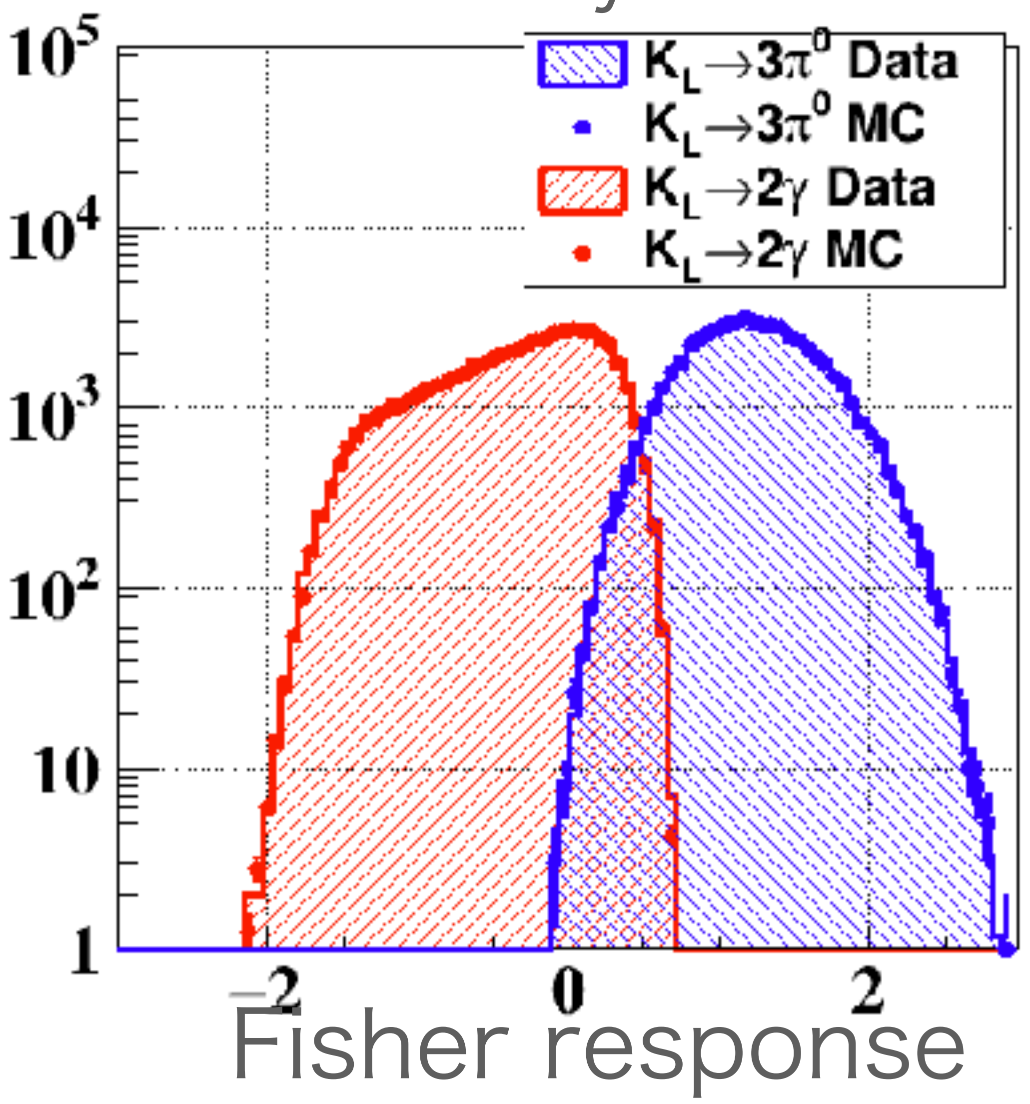
Rec. Z RCOE $\theta_{\gamma 1}$ $\theta_{\gamma 2}$



Performance



Validation by data

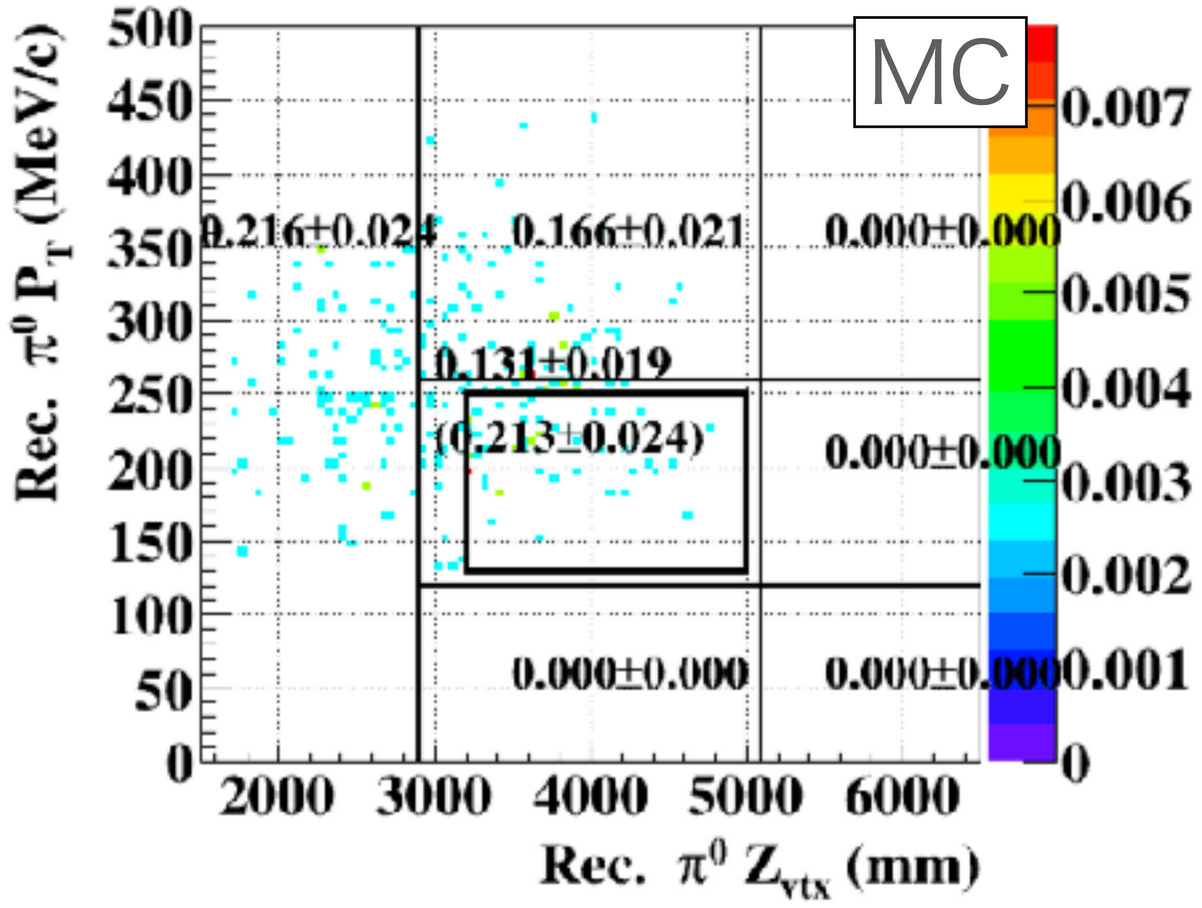


Estimation of N(Halo $K_L \to 2\gamma$ BG)

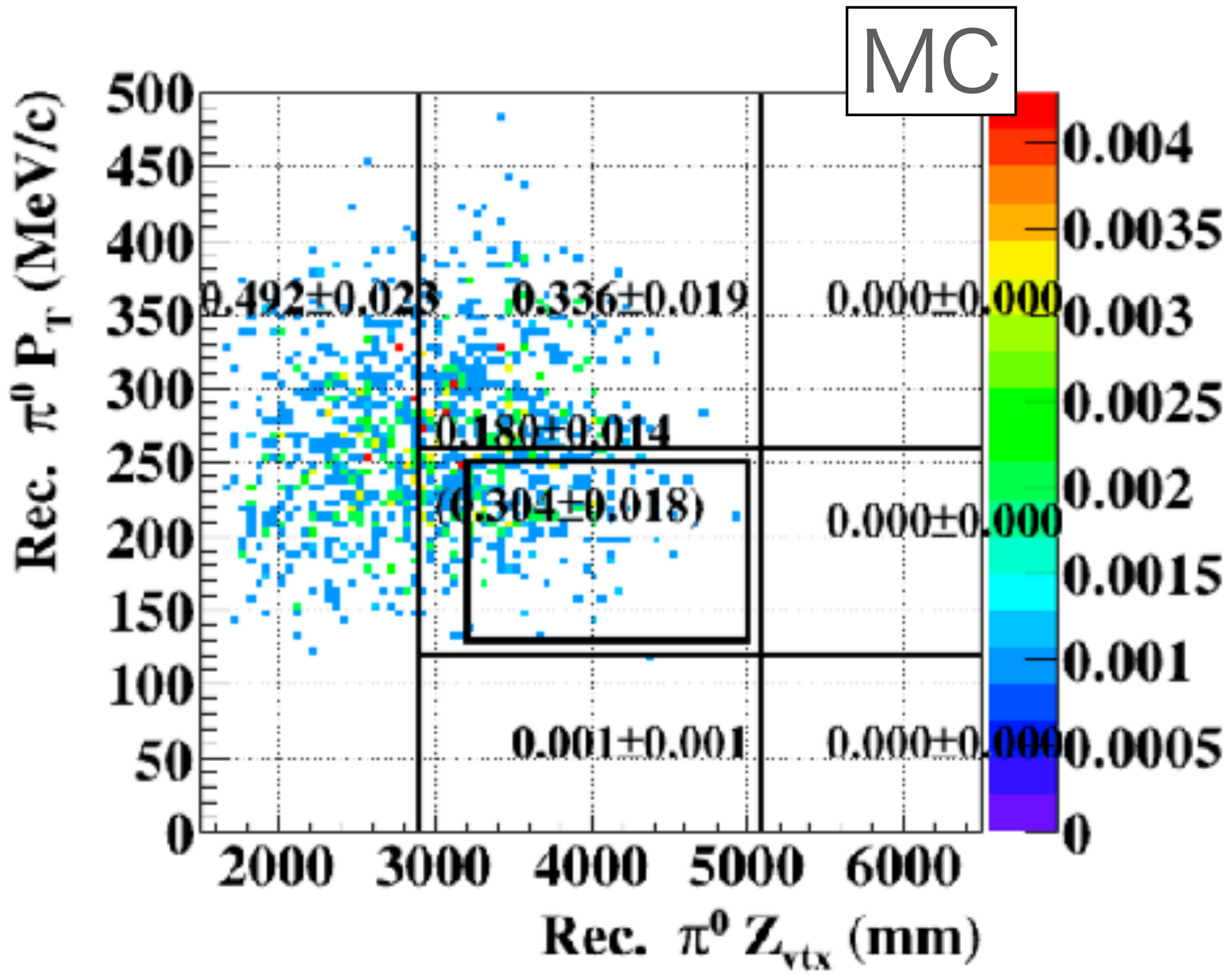
of Halo $K_L \to 2\gamma$ BG

Before applying Likelihood ratio cut and Kinematic MVA cut

Halo KL

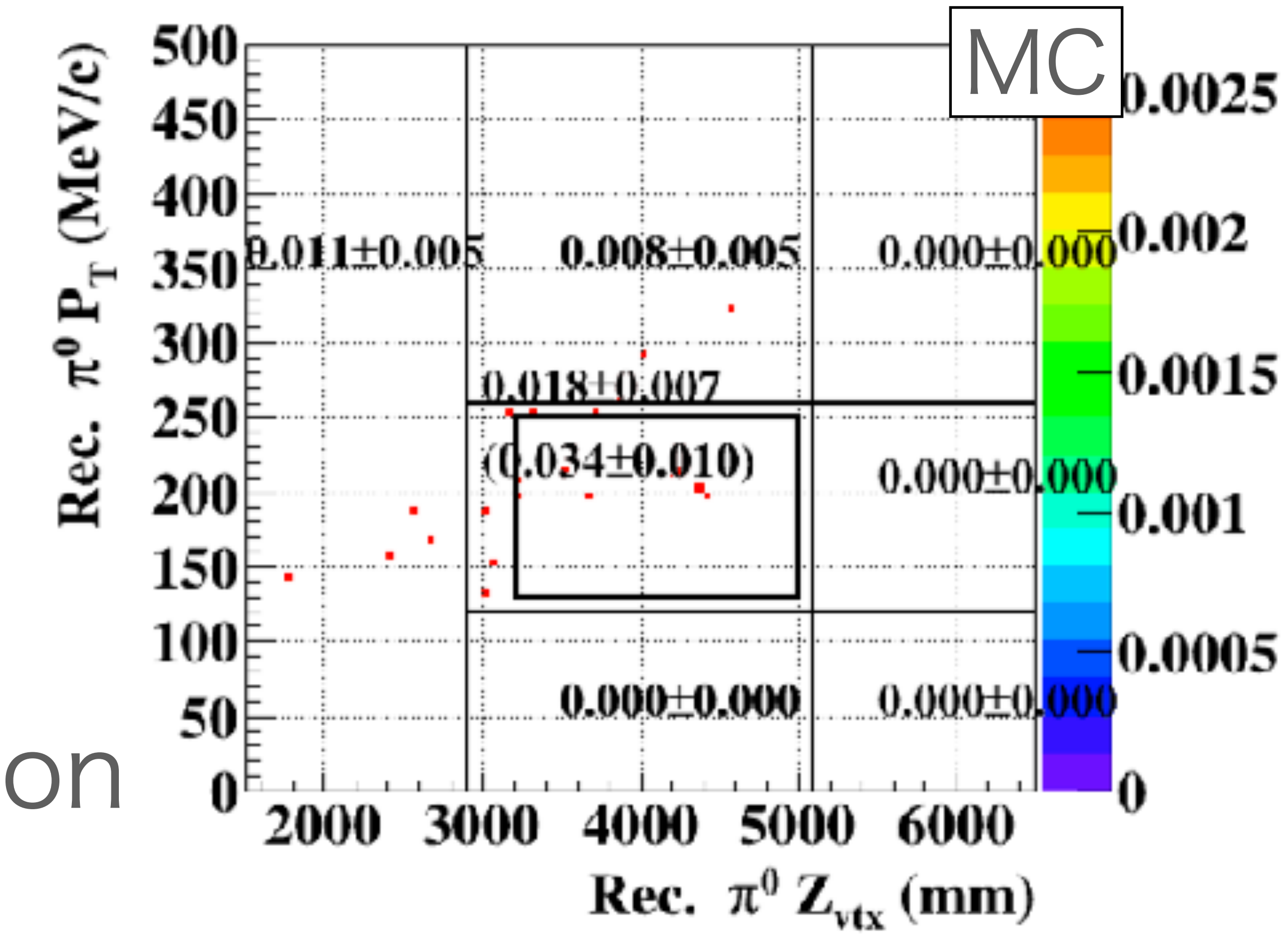


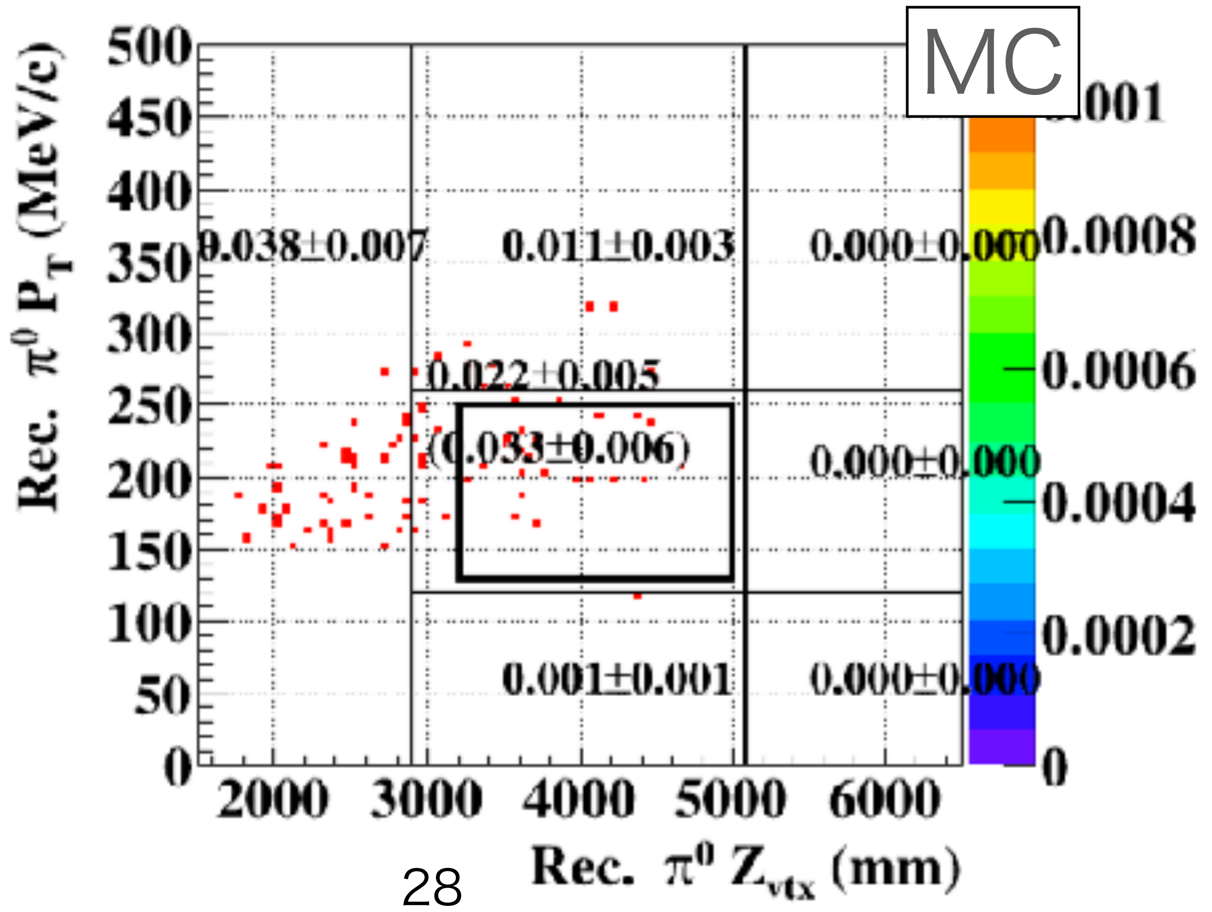
Scatter KL



x1/8 reduction

After applying Likelihood ratio cut and Kinematic MVA cut





Signal acceptance of those cuts

-94%

# of BG expected in the signal box

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

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

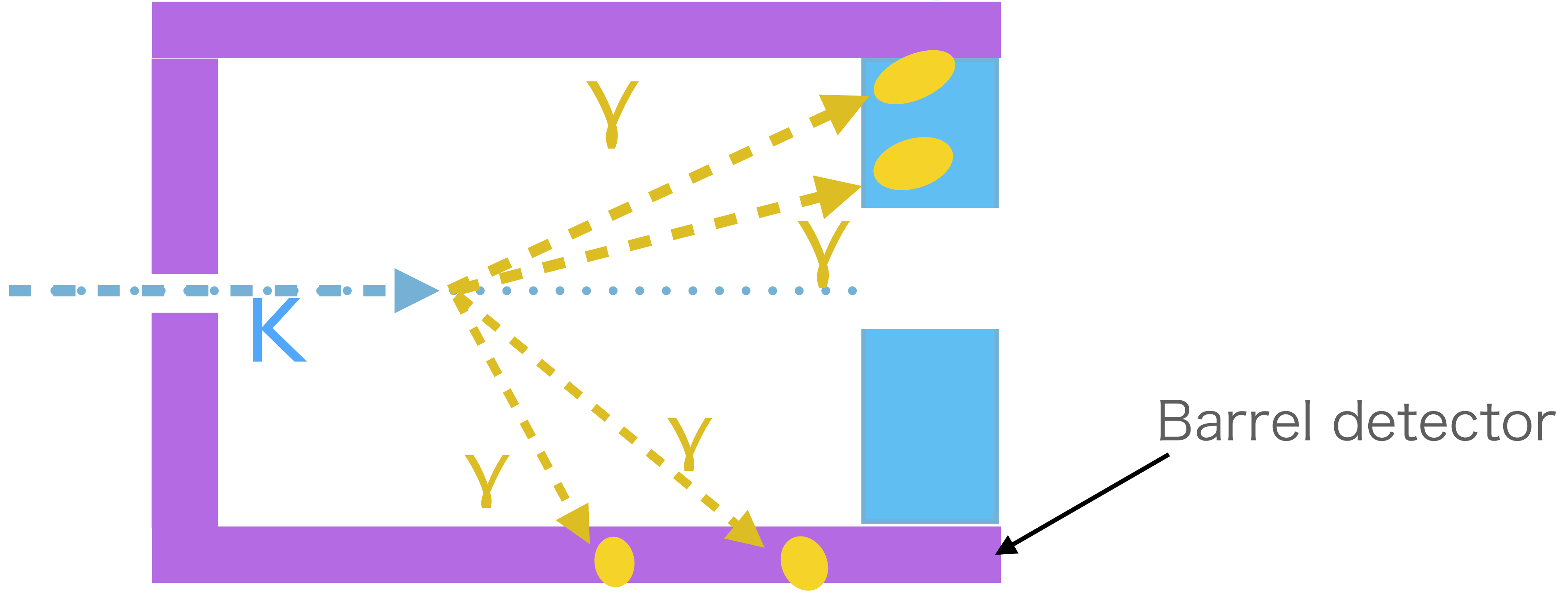
-#(Scatter $K_L \to 2\gamma$ BG)

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

Reduction by a factor of 8 was achieved in both case

Photon inefficiency in veto detectors

$K_L \to \pi^0\pi^0$ more photons



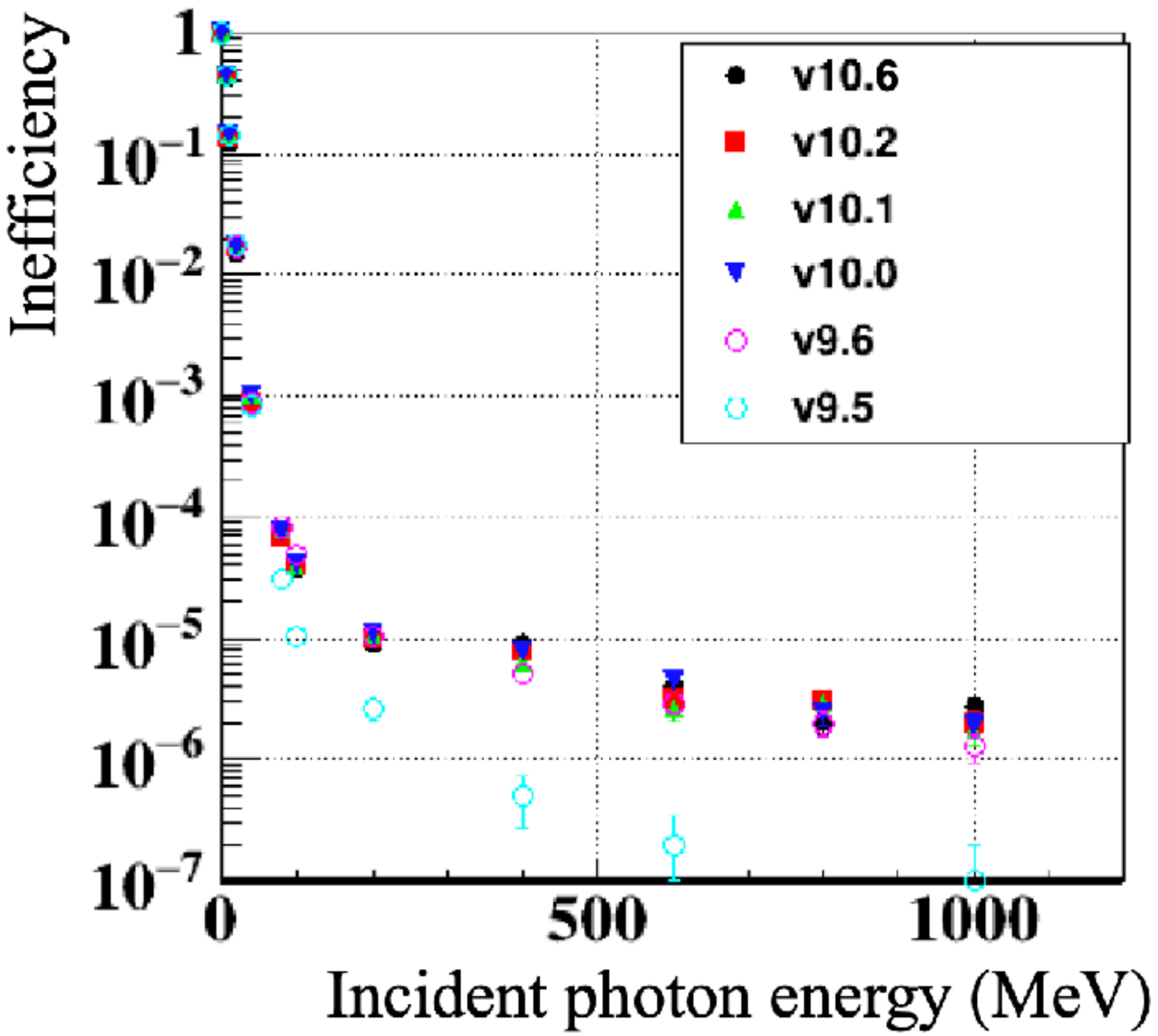
-Photon inefficiency in veto detectors are critical to estimate the KL→2π^0 BG

-But, the photon inefficiency evaluated by MC depends on the version.

  -Physics model was changed between two versions due to difficulty of code management.

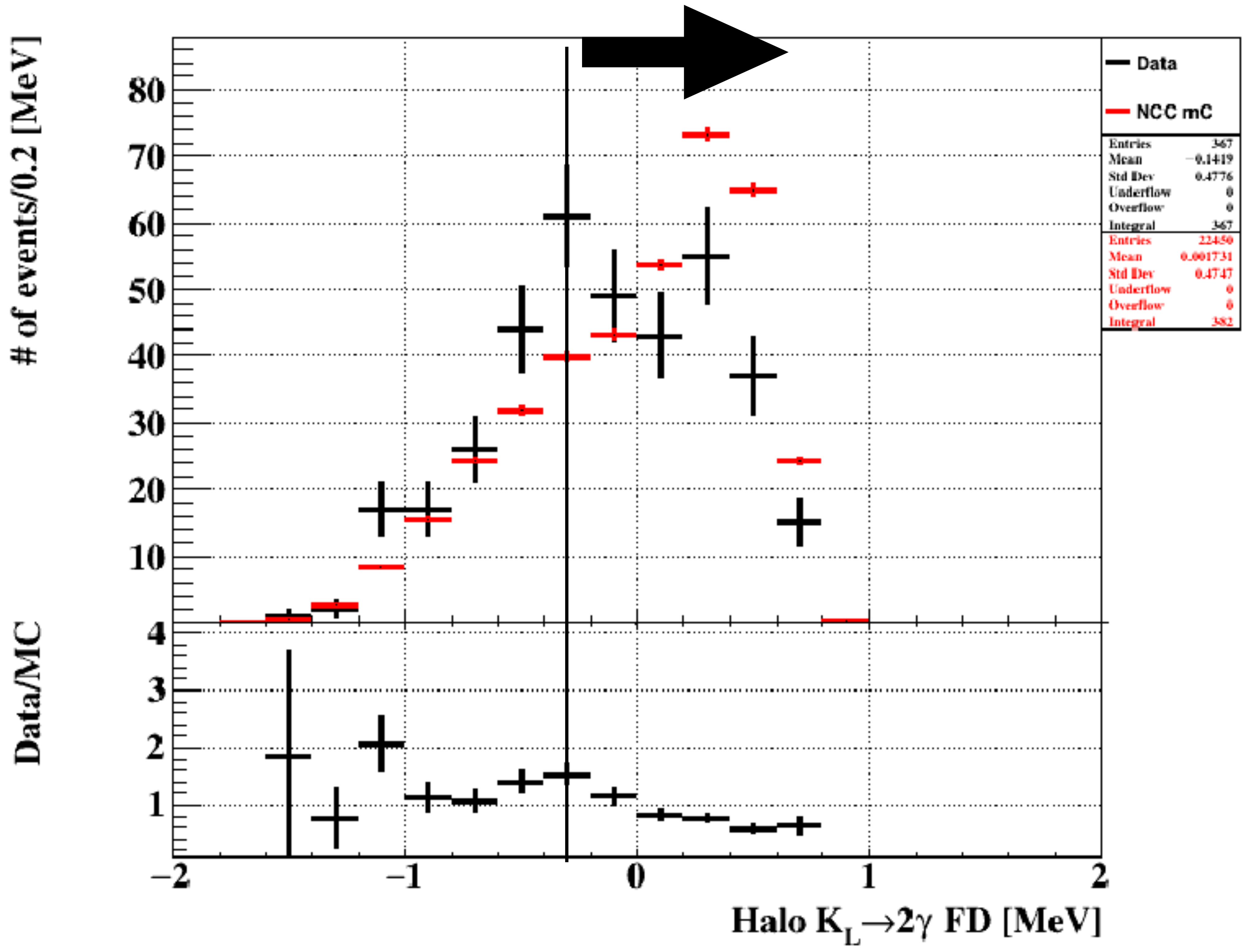
  (Info from a GEANT4 code manager)

Simulation study
with a modeled barrel detector



Halo KL→2γ MVA cut for upstream π^0 events

- Halo K$_L$→2γ MVA cut with kinematical variables



- π^0 energy in upstream π^0 events before applying the Halo K$_L$→2γ MVA cut