Search for rare kaon decays at the J-PARC KOTO experiment

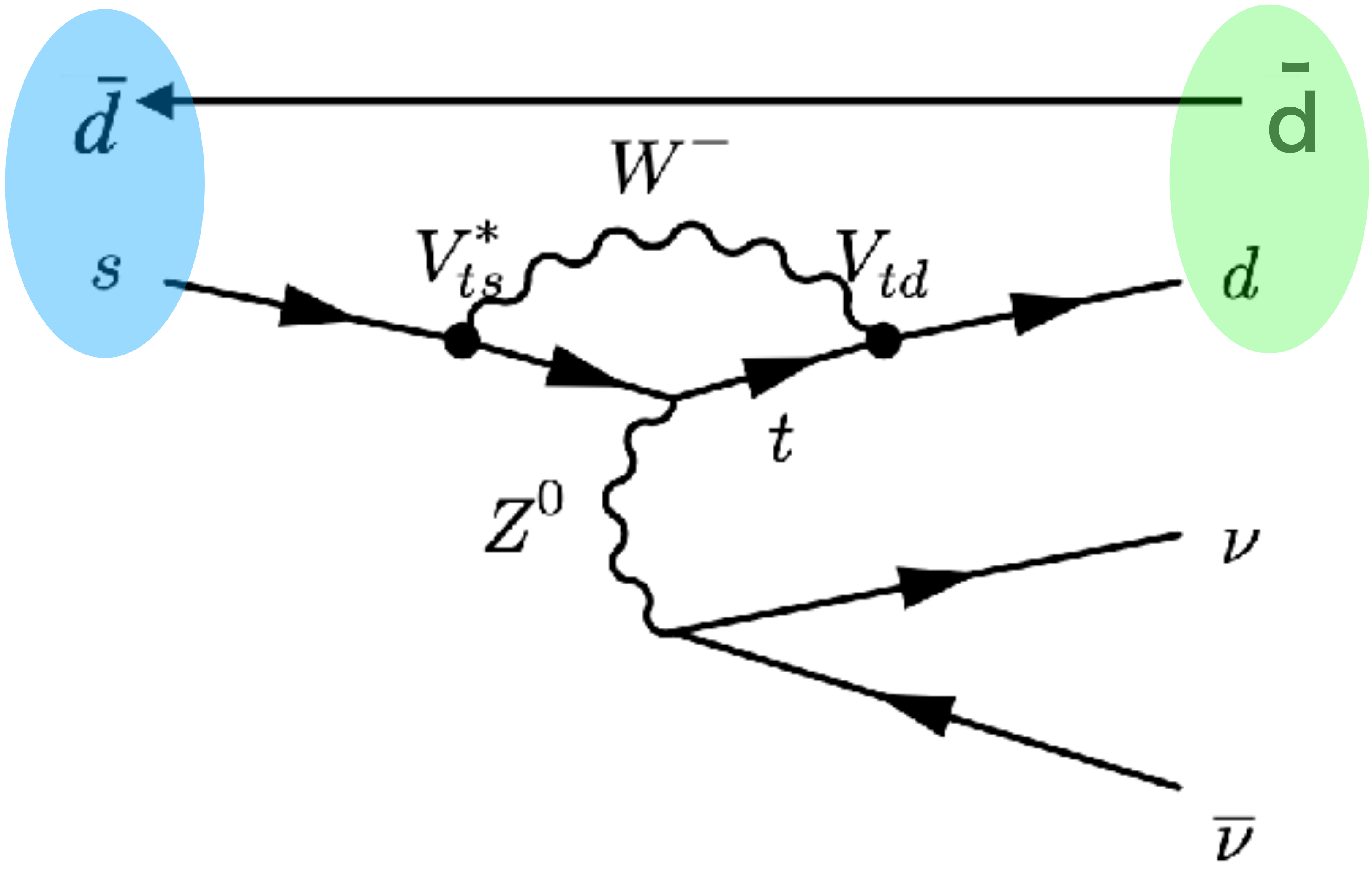
Koji Shiomi (KEK) for the KOTO collaboration
20th LOMONOSOV CONFERENCE 2021/8/21

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

Standard Model

CP odd

K_L



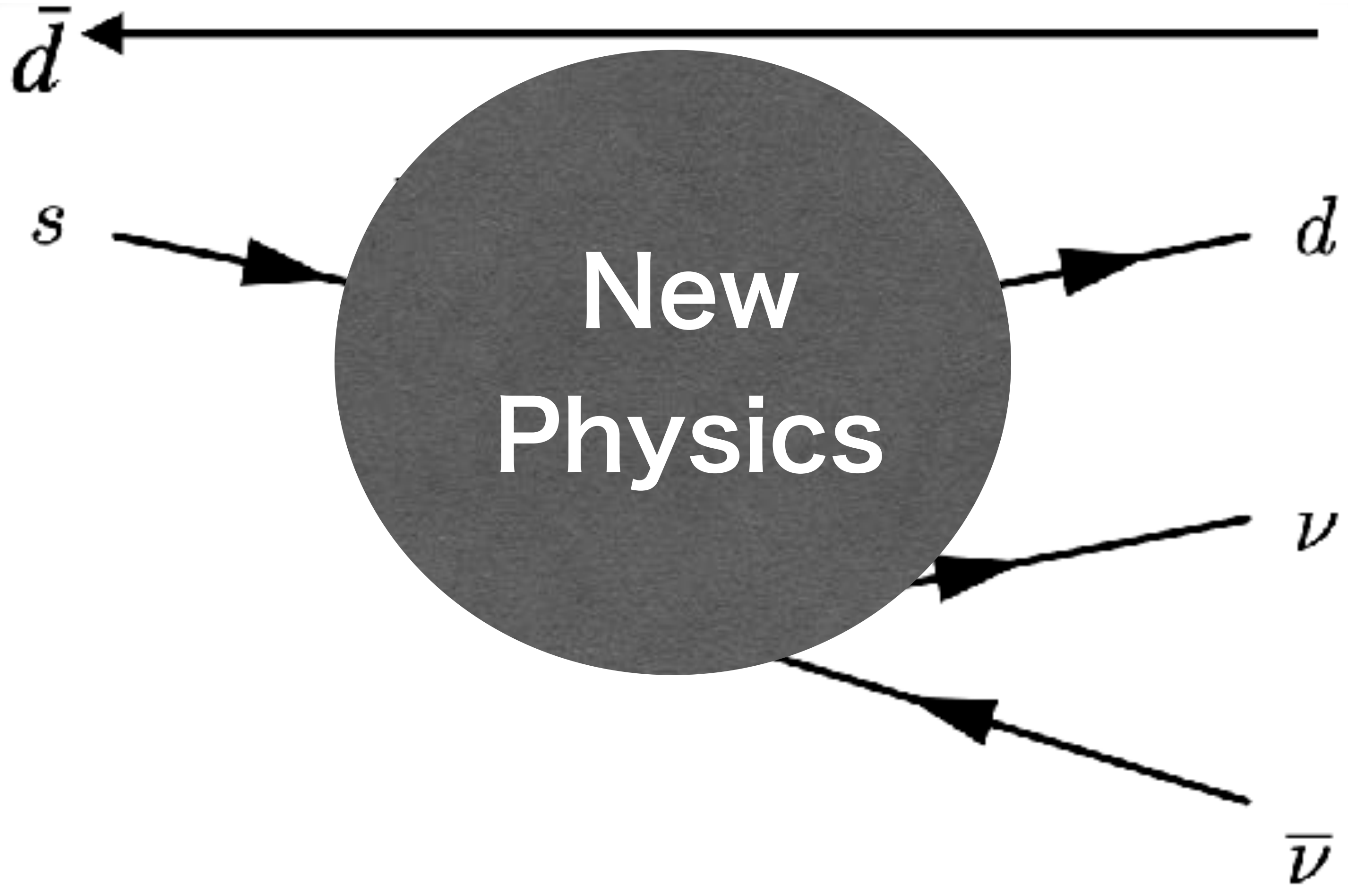
π^0

CP even
||
CP odd
×
CP odd

- Rare, Theoretical clean, CP violation

Branching ratio(BR) = (3.0±0.3)×10^{-11}

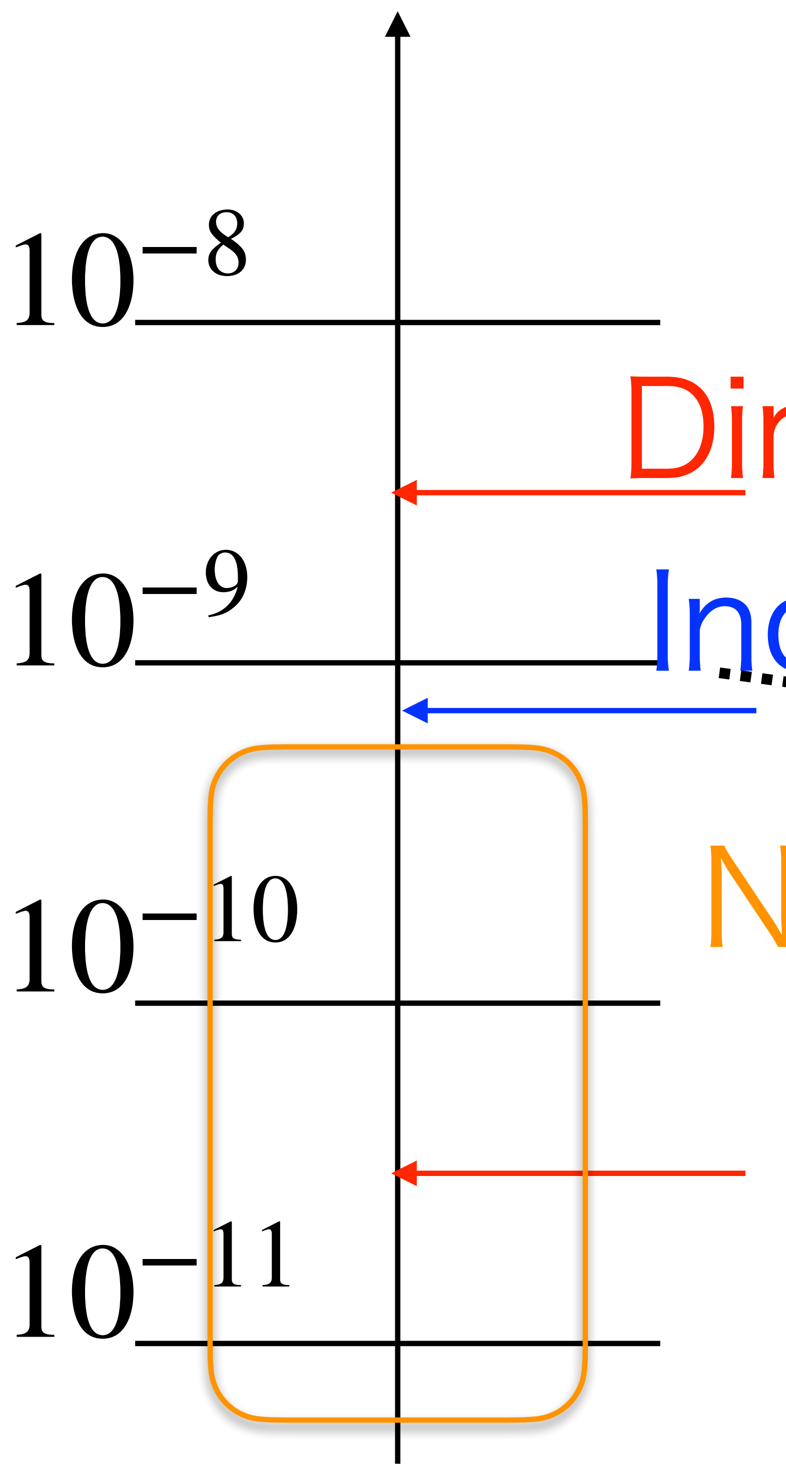
The uncertainties mainly come from the CKM parameter errors,
The theoretical uncertainties are only 2% .



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

Experimental search for $K_L \to \pi^0 \nu \nu$

$BR(K_L \to \pi^0 \nu\nu)$



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?

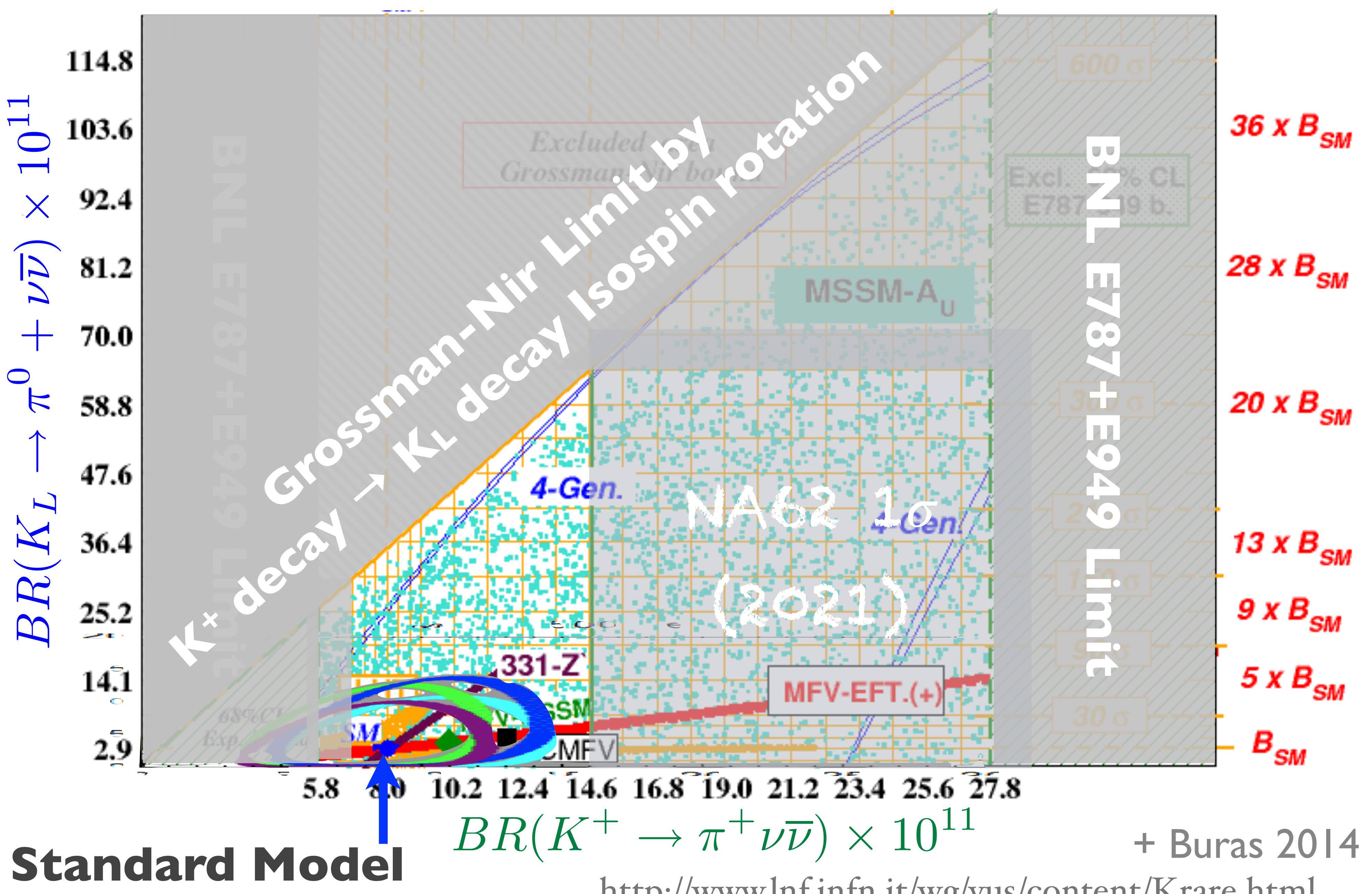
SM

Open Access

Search for $K_L \to \pi^0 \nu\bar{\nu}$ and $K_L \to \pi^0 X^0$ Decays at the J-PARC KOTO Experiment

J. K. Ahn *et al.* (KOTO Collaboration)

Phys. Rev. Lett. **122**, 021802 – Published 15 January 2019

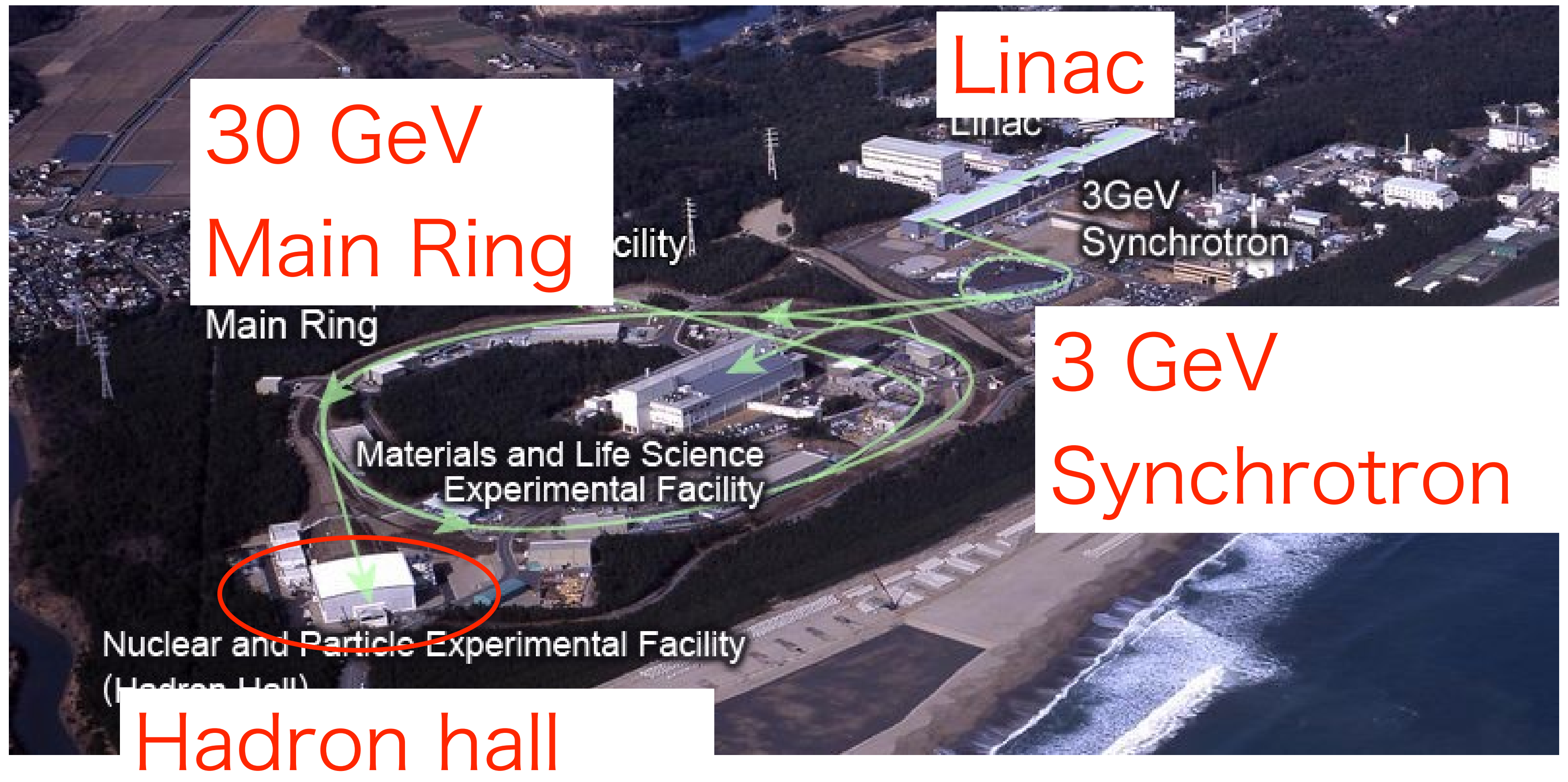


+ Buras 2014

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

KOTO experiment

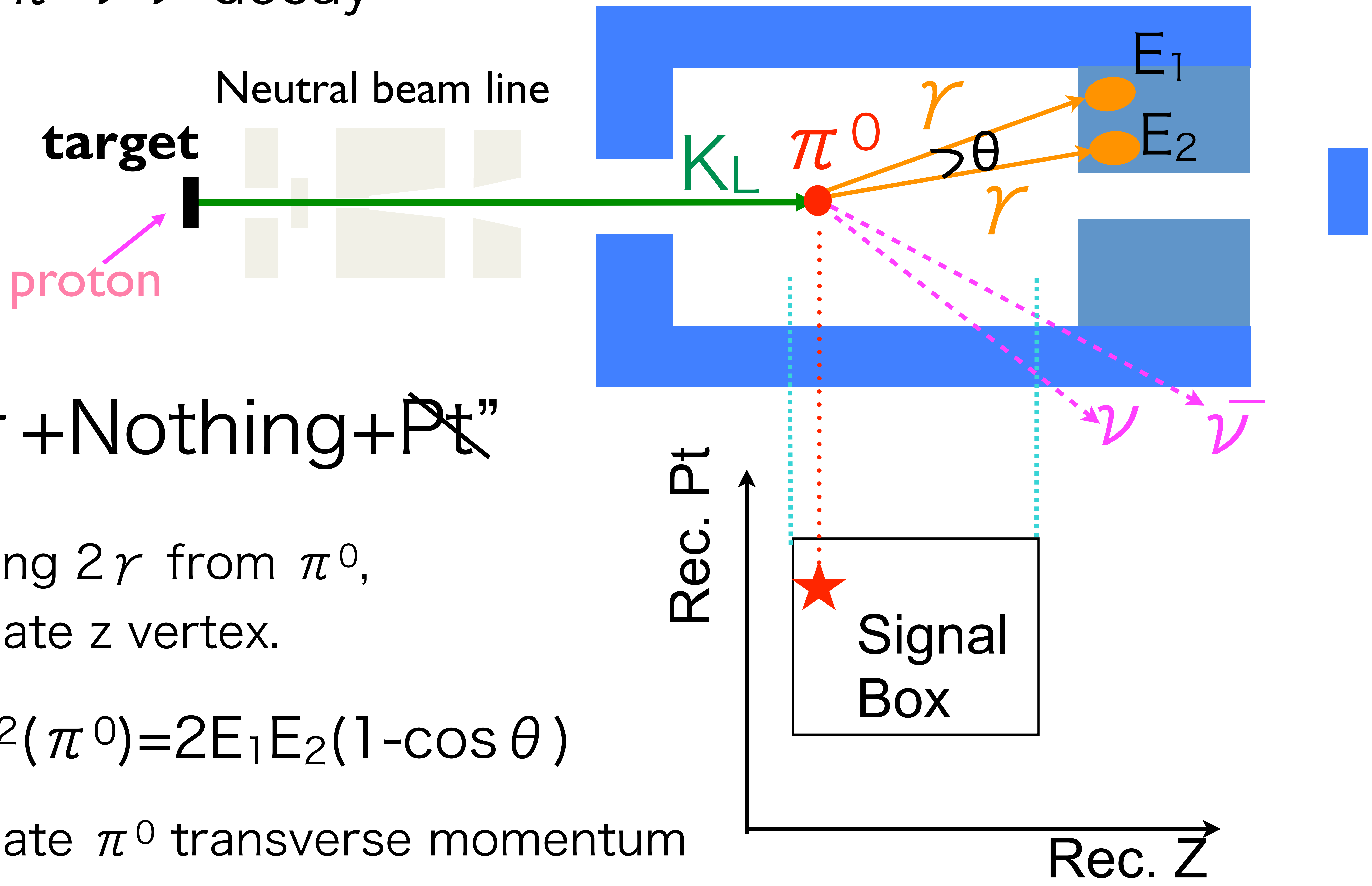
- Study of $K_L \to \pi^0 \nu \bar{\nu}$ @J-PARC 30GeV Main Ring.



Collaboration meeting
with Zoom(July 2021)

Experimental principle

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



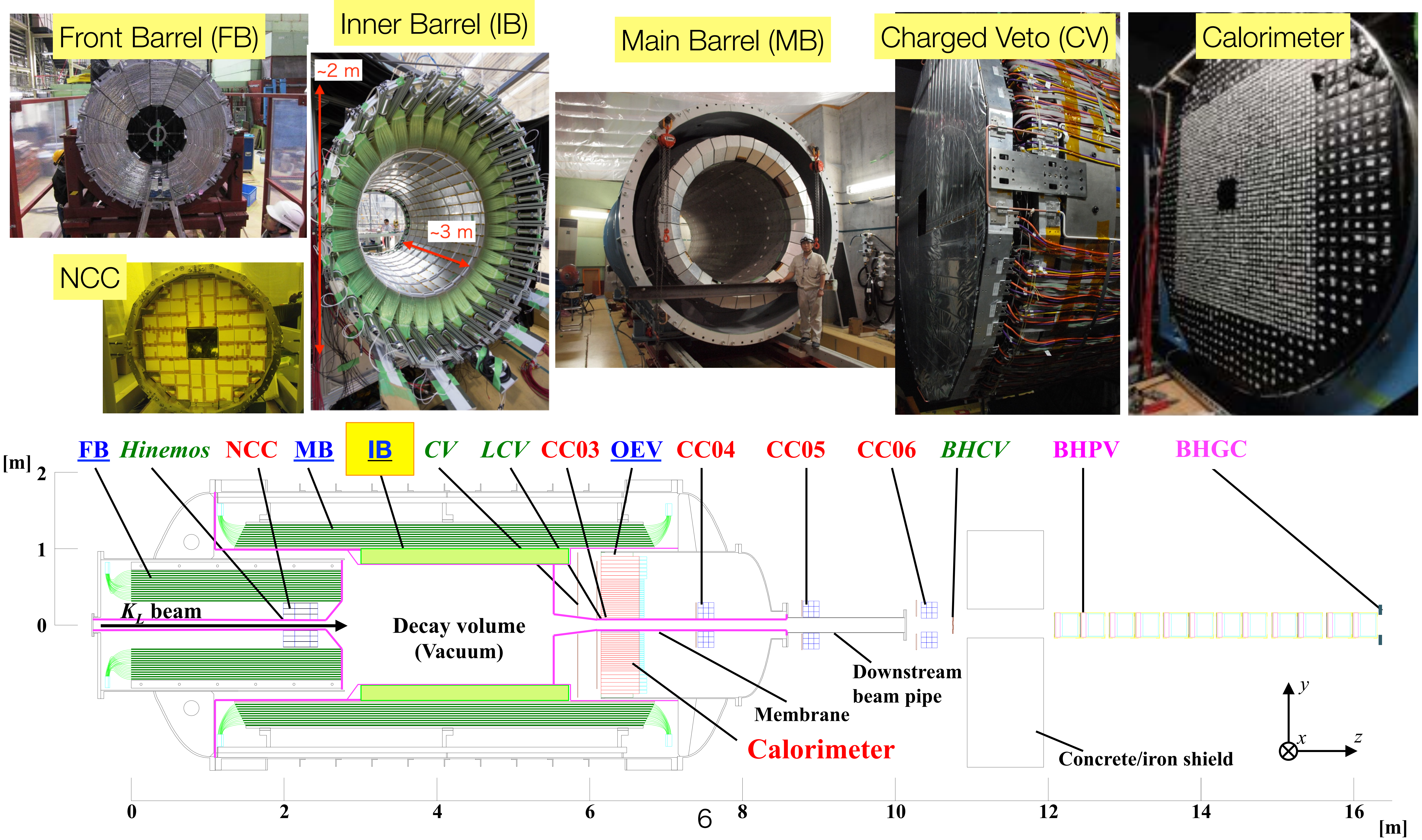
"2γ+Nothing+~~Pt~~"

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

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

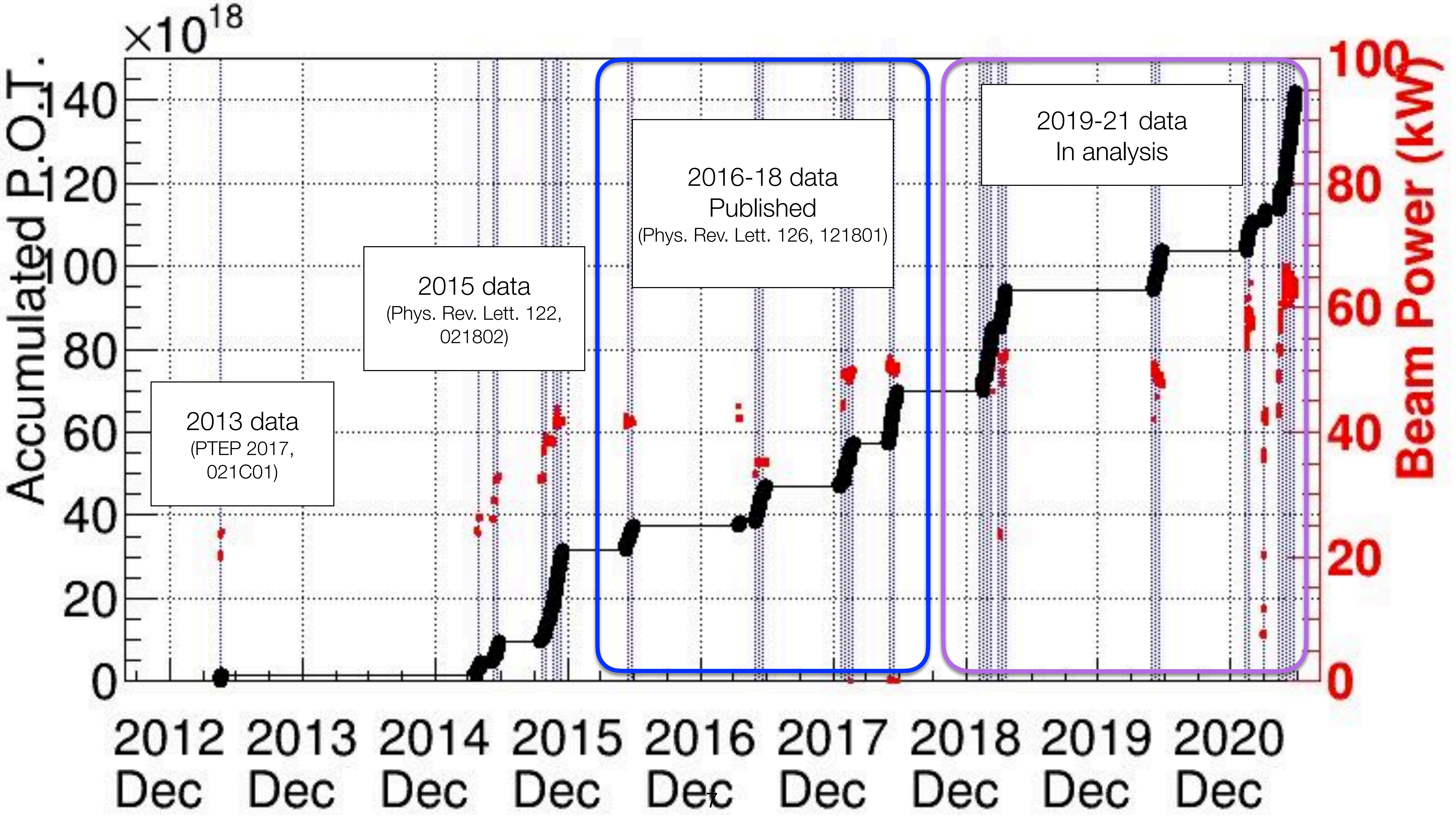
Calculate π^0 transverse momentum

KOTO detector



Data Accumulation History

P. O. T = Proton On Target

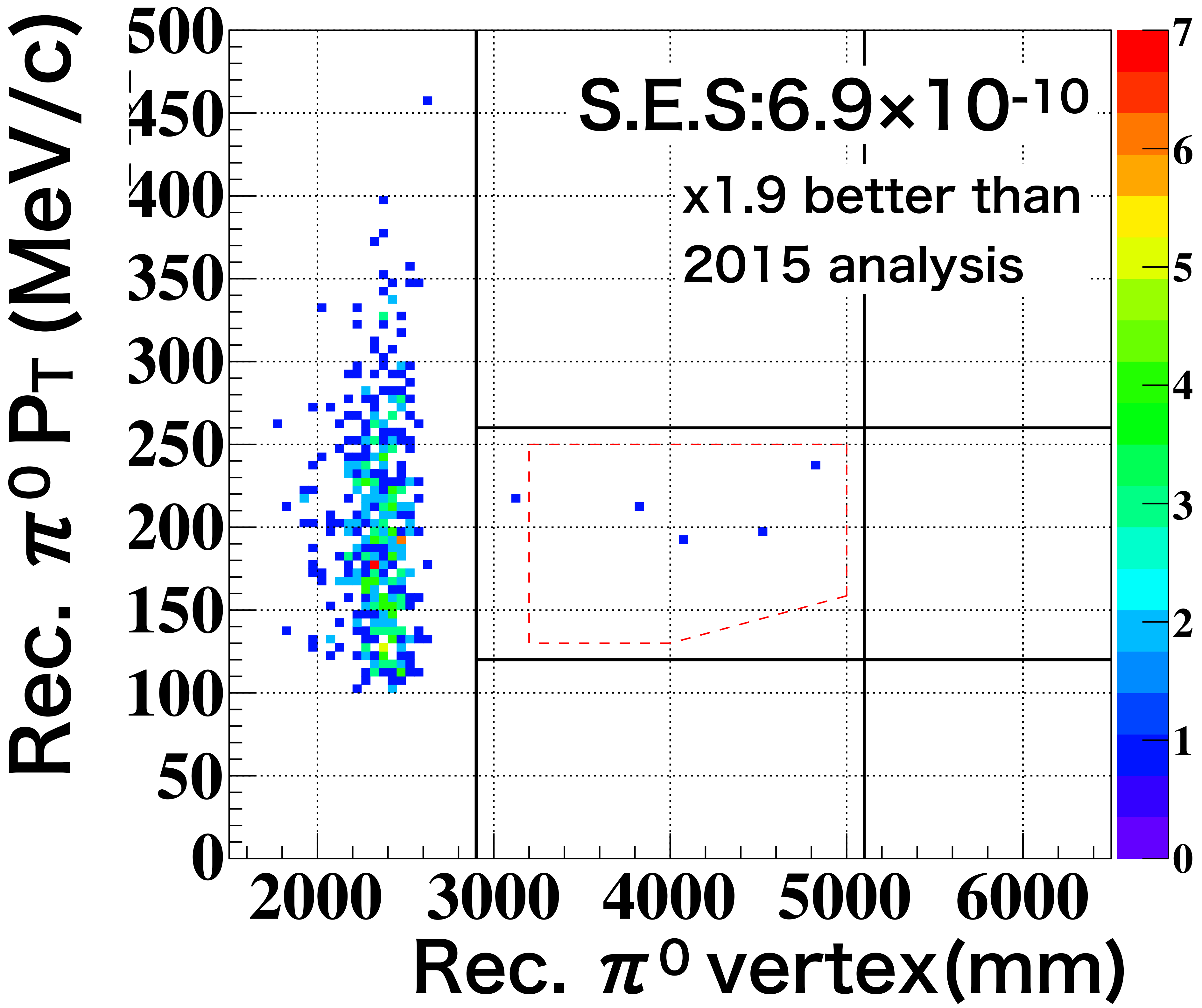


2016-18 data analysis

- Preliminary results at Kaon conference in September 2019
- Post-unblind analysis
- Final results

Preliminary results at Kaon 2019

- -Determined selection criteria and opened signal box in Aug. 2019.
  - -Observed 4 candidate events inside the signal box
  - -Reported @ Kaon2019



#Bkg estimation table
before opening signal box

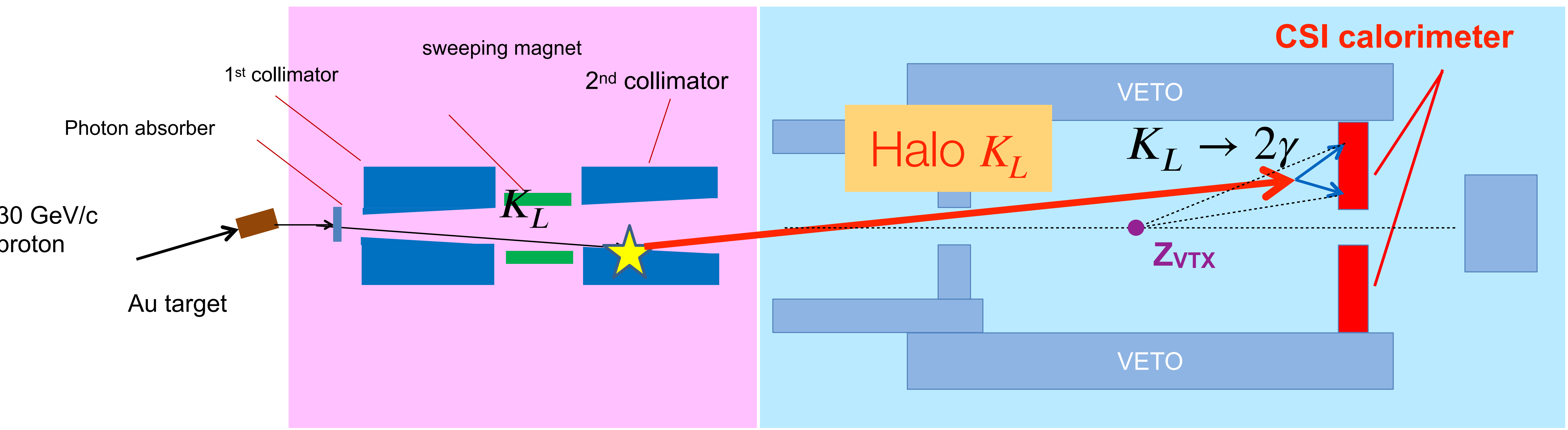
	#BG
$K_L \to 2\pi^0$	<0.18
$K_L \to \pi^+\pi^-\pi^0$	<0.02
$K_L \to 3\pi^0$+ accid.	<0.04
Ke3 + accid.	<0.09
$K_L \to 2\gamma$	0.00±0.00
Upstream π^0	0.00±0.00
CV-π0	<0.1
CV-η	0.03±0.01
Hadron cluster	0.02±0.00
Total	0.05±0.02

Post-unblind analysis

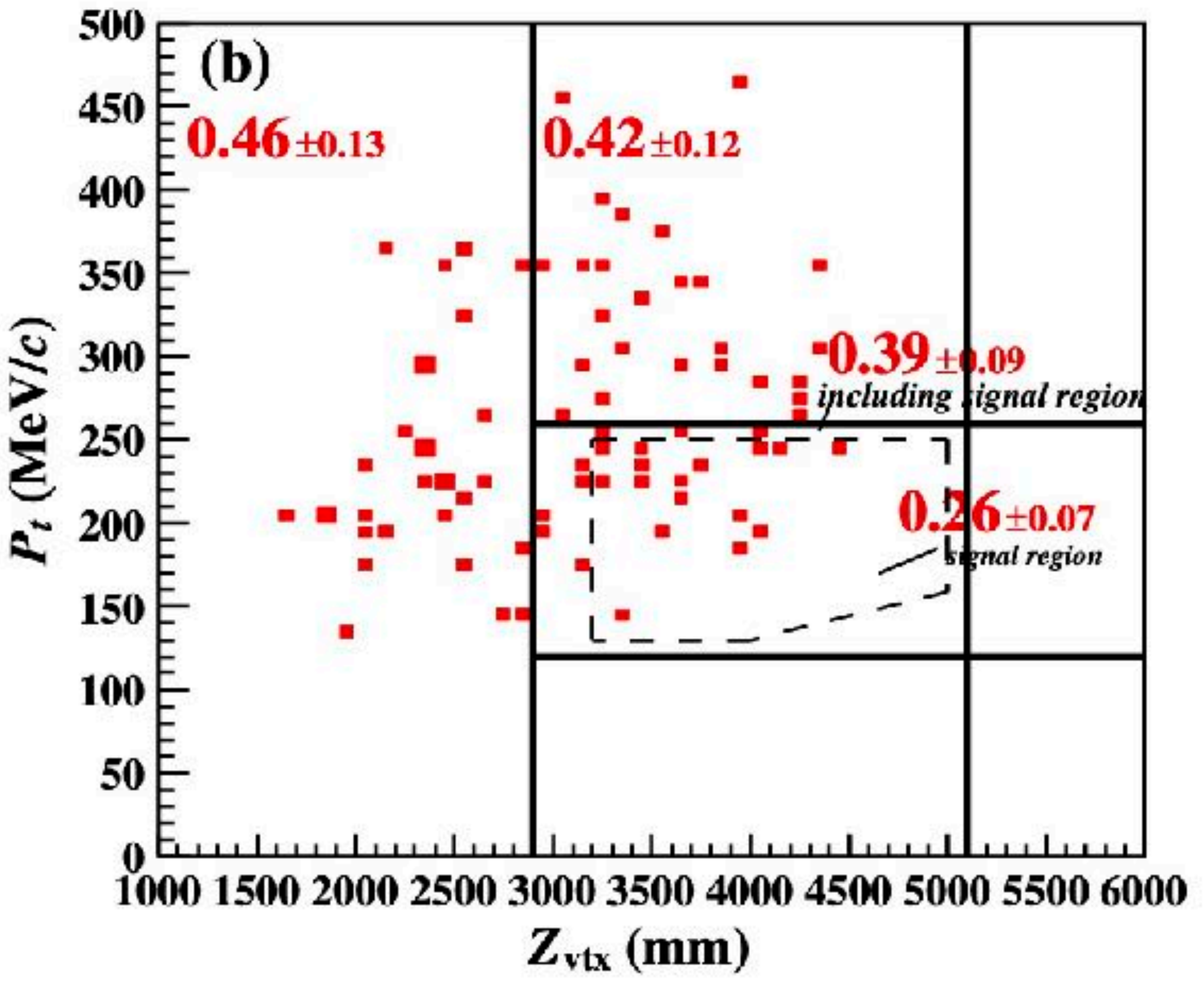
- No change in cuts
- Found an error in timing parameters.
  4→3 events by fixing it.
- Found two new background sources, and updated background estimation.

Halo $K_L \to 2\gamma$

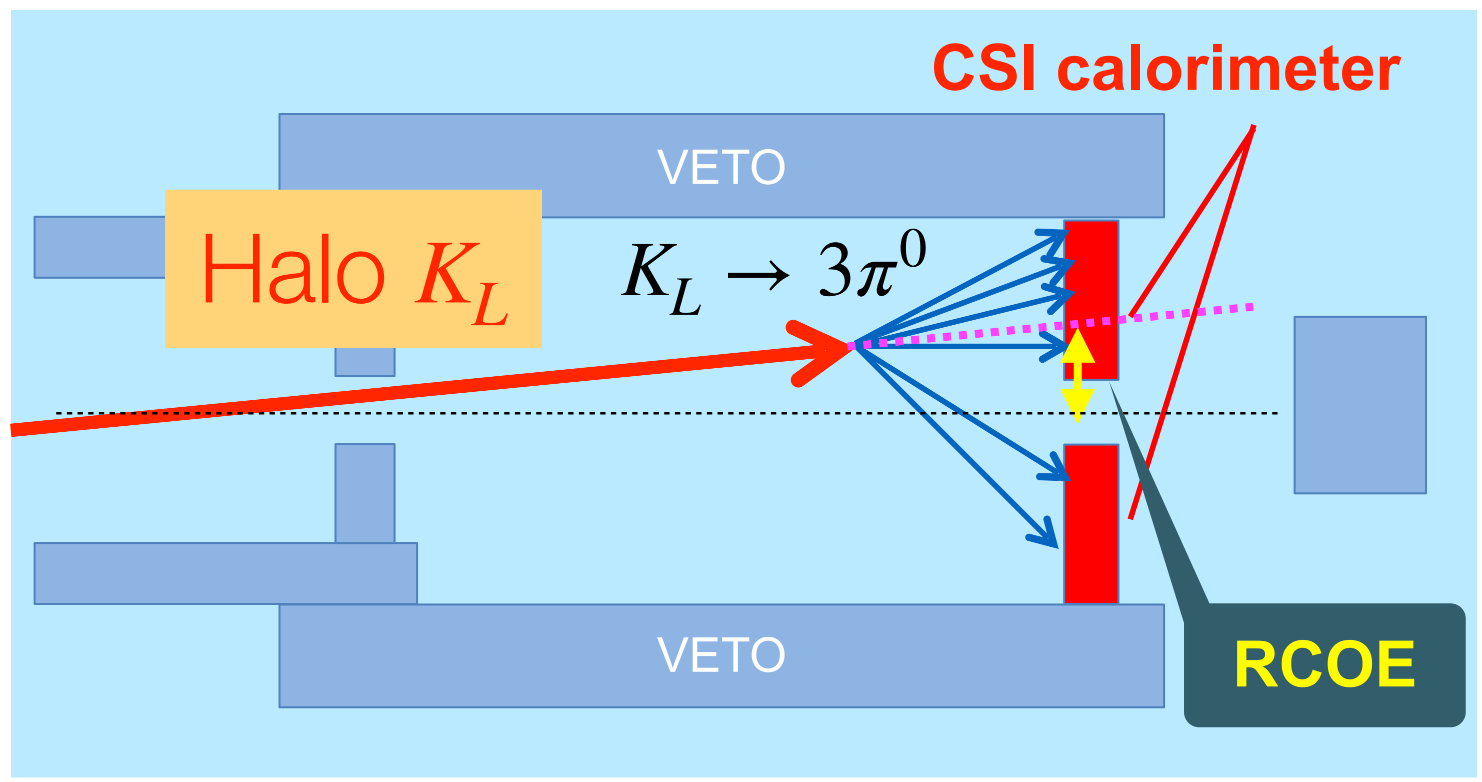
Backgrounds found in post-unblind analysis



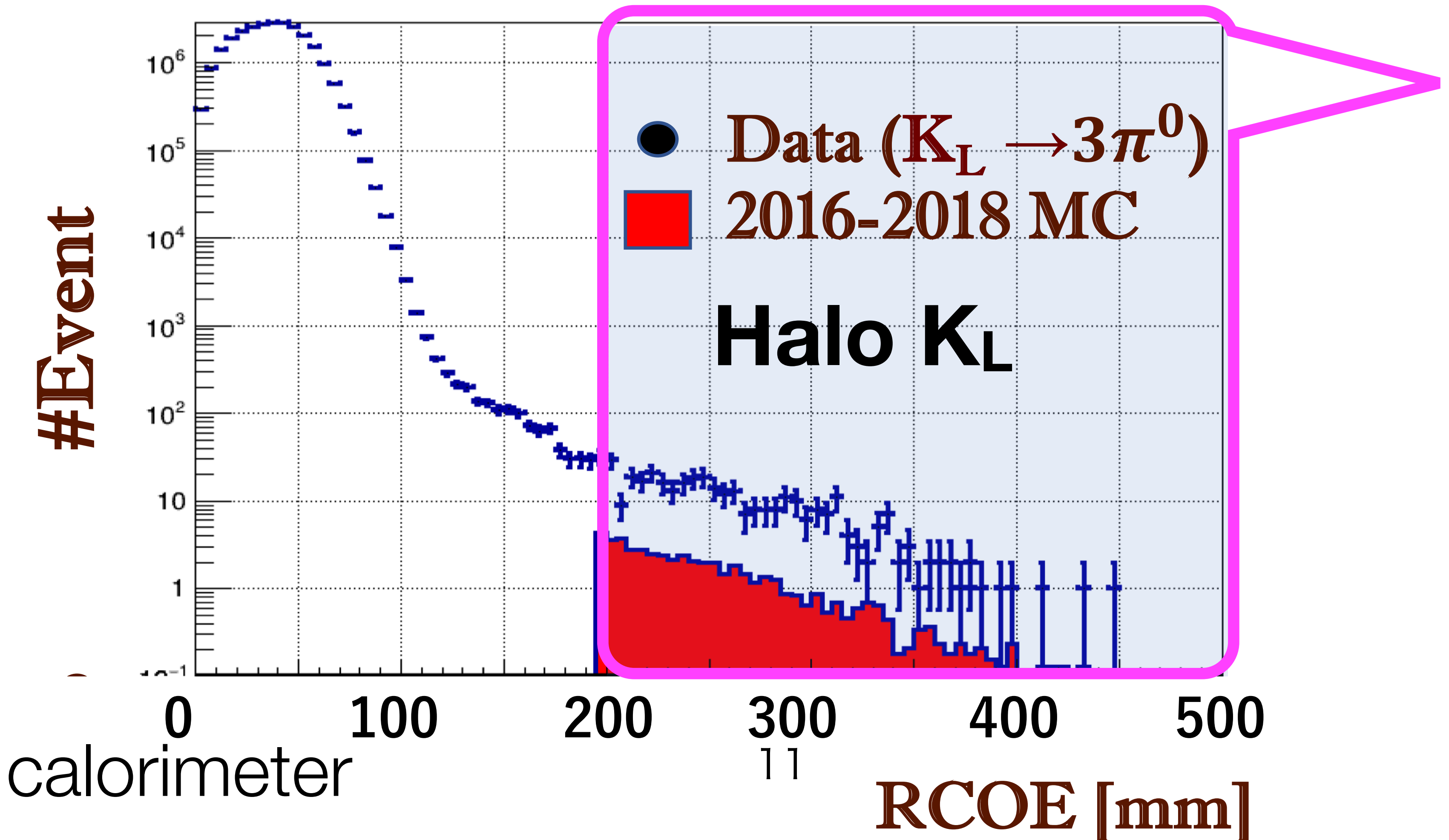
0.26 inside the signal region

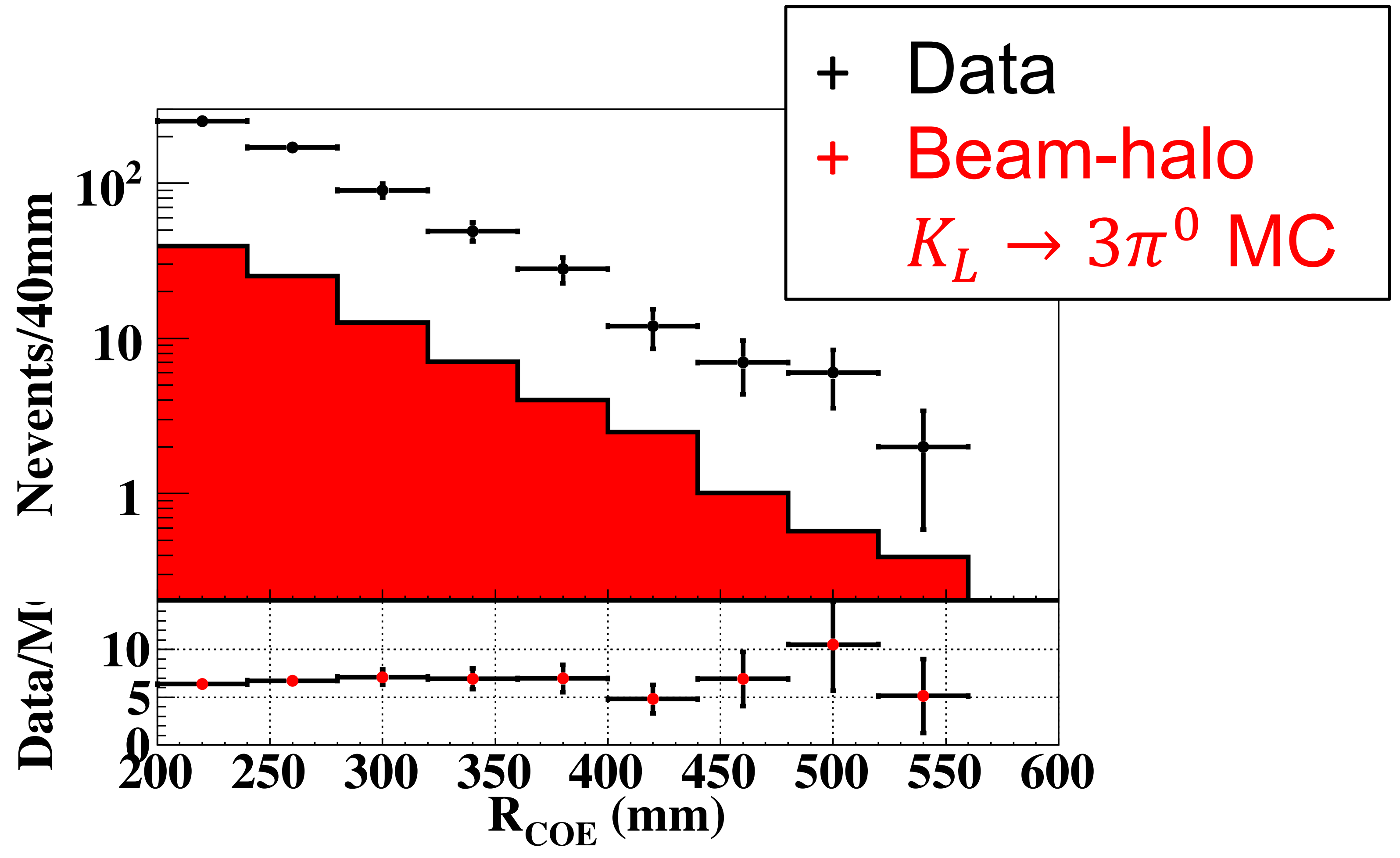


- Halo KL flux was evaluated by using $K_L \to 3\pi^0$ sample



RCOE=Radius of Center Of Energy on CSI calorimeter

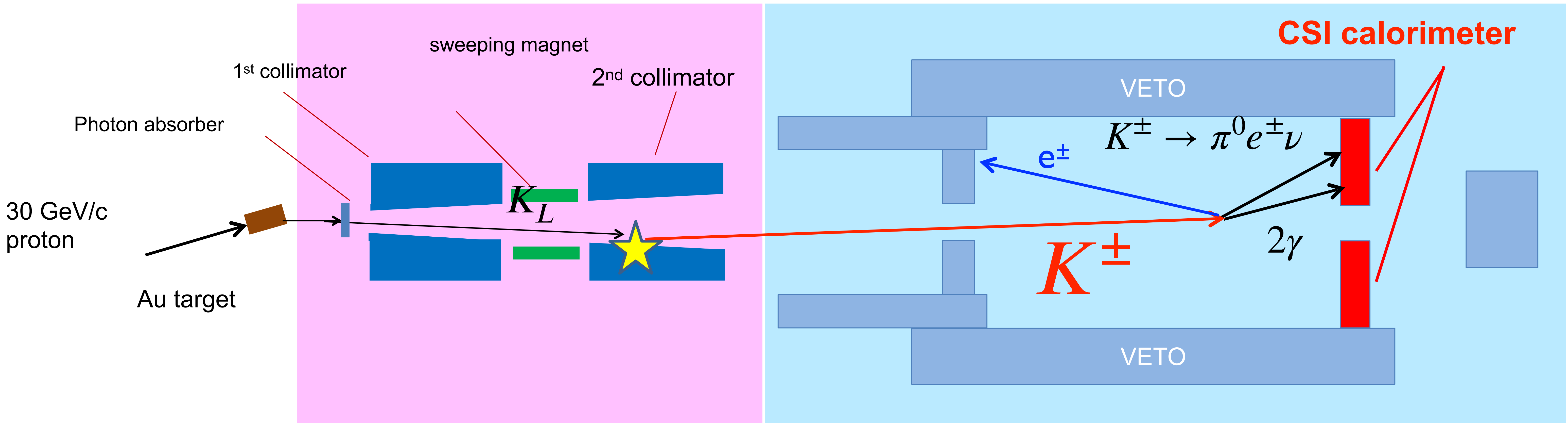




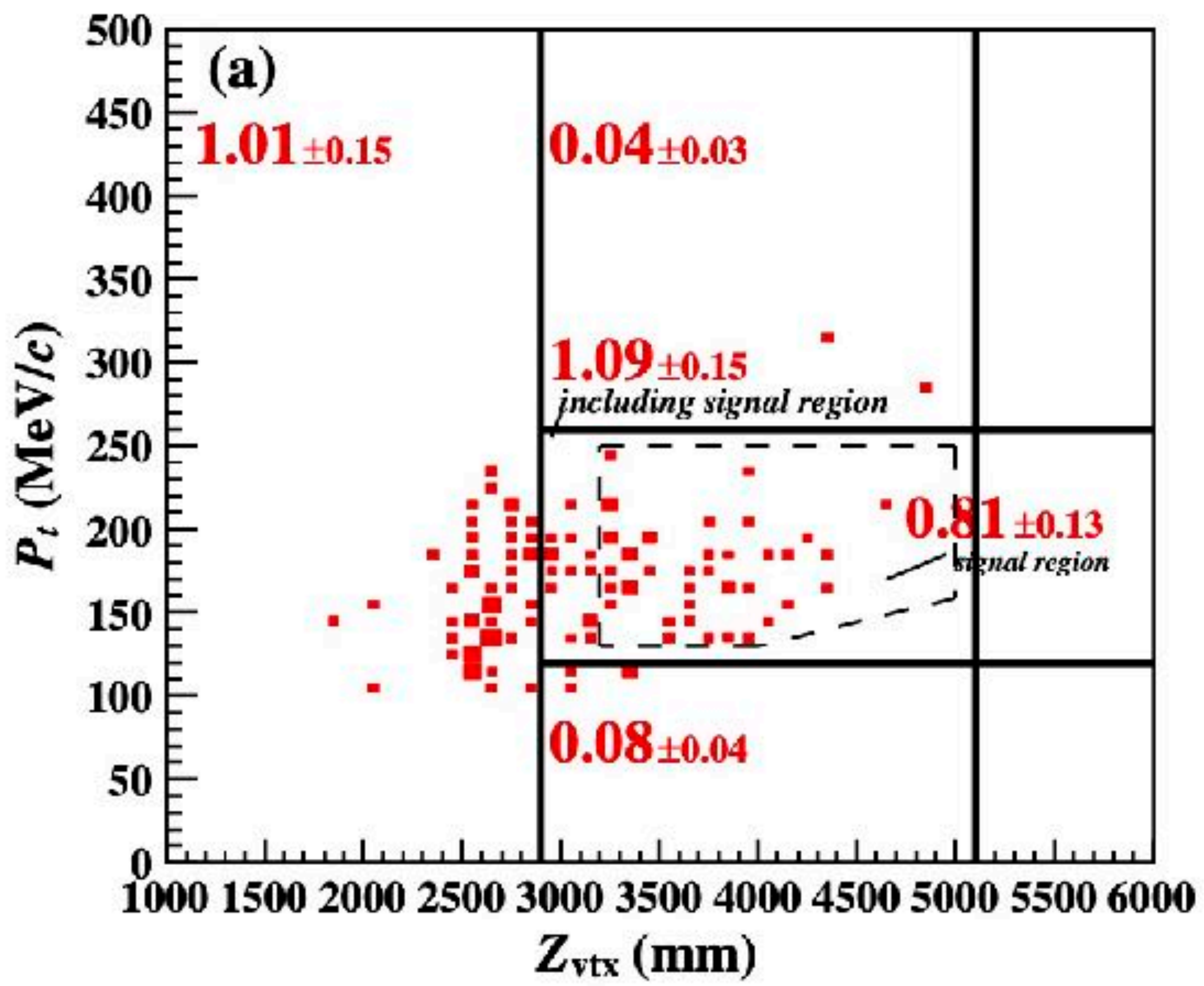
Halo KL flux: ~ × 7 of MC

K± in the beam

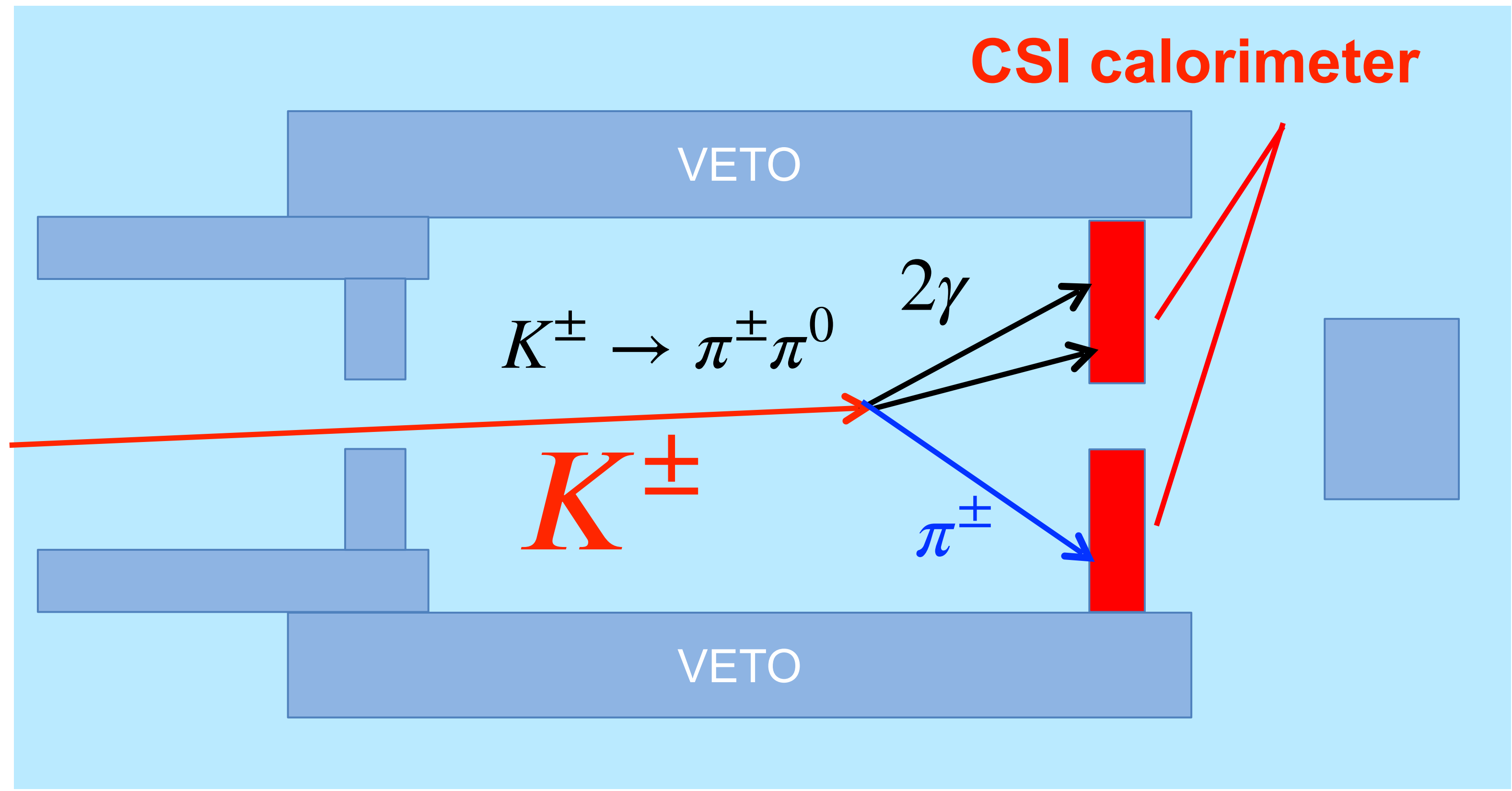
Backgrounds found in post-unblind analysis



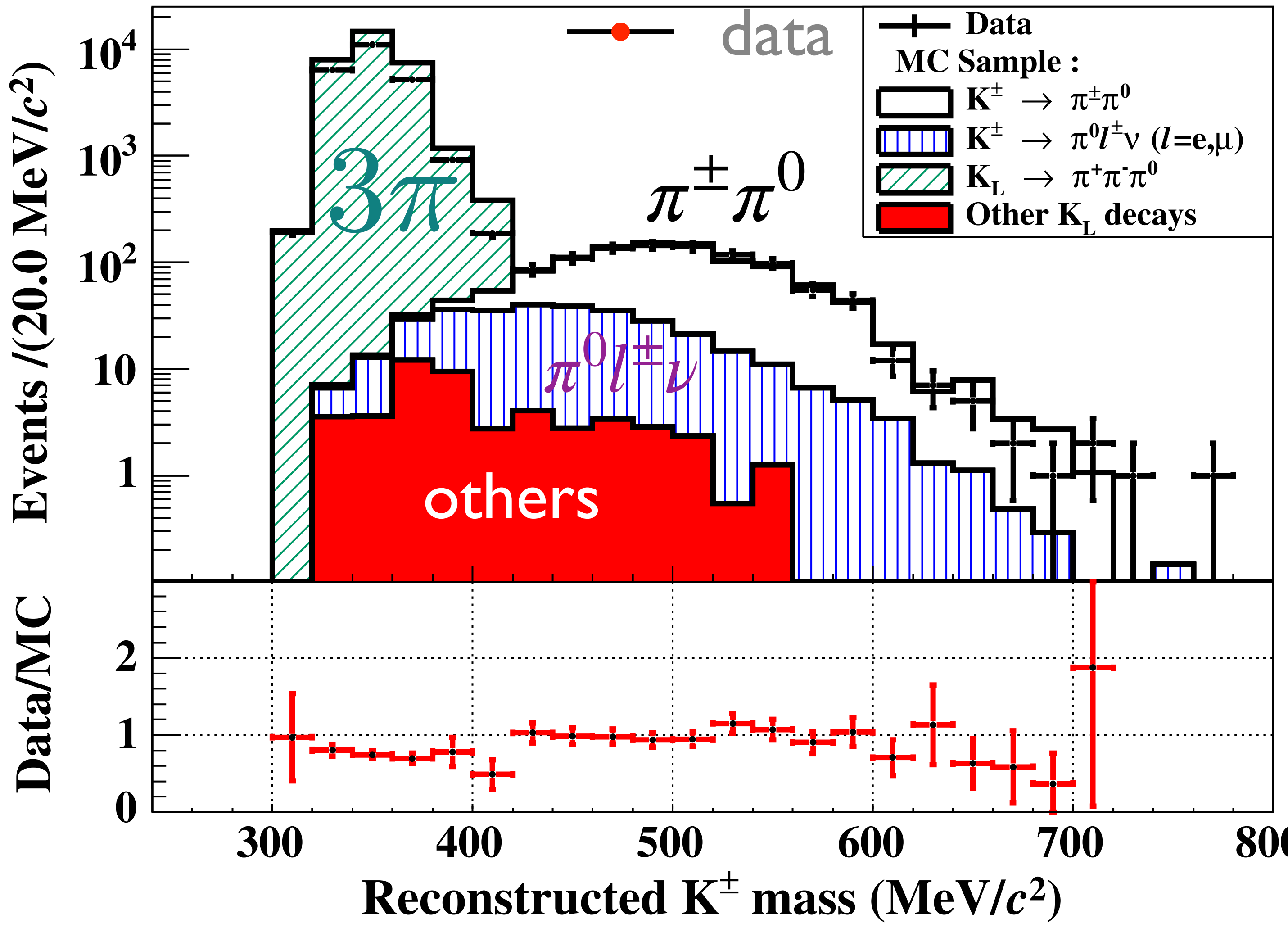
0.81 inside the signal region



- K± yield was evaluated by a special run to collect $K^{\pm} \to \pi^{\pm}\pi^0$ in June 2020.



- 3 clusters on CSI
- π^0 vertex reconstruction
- $\pi^{\pm}$ reconstruction assuming transverse momentum balance



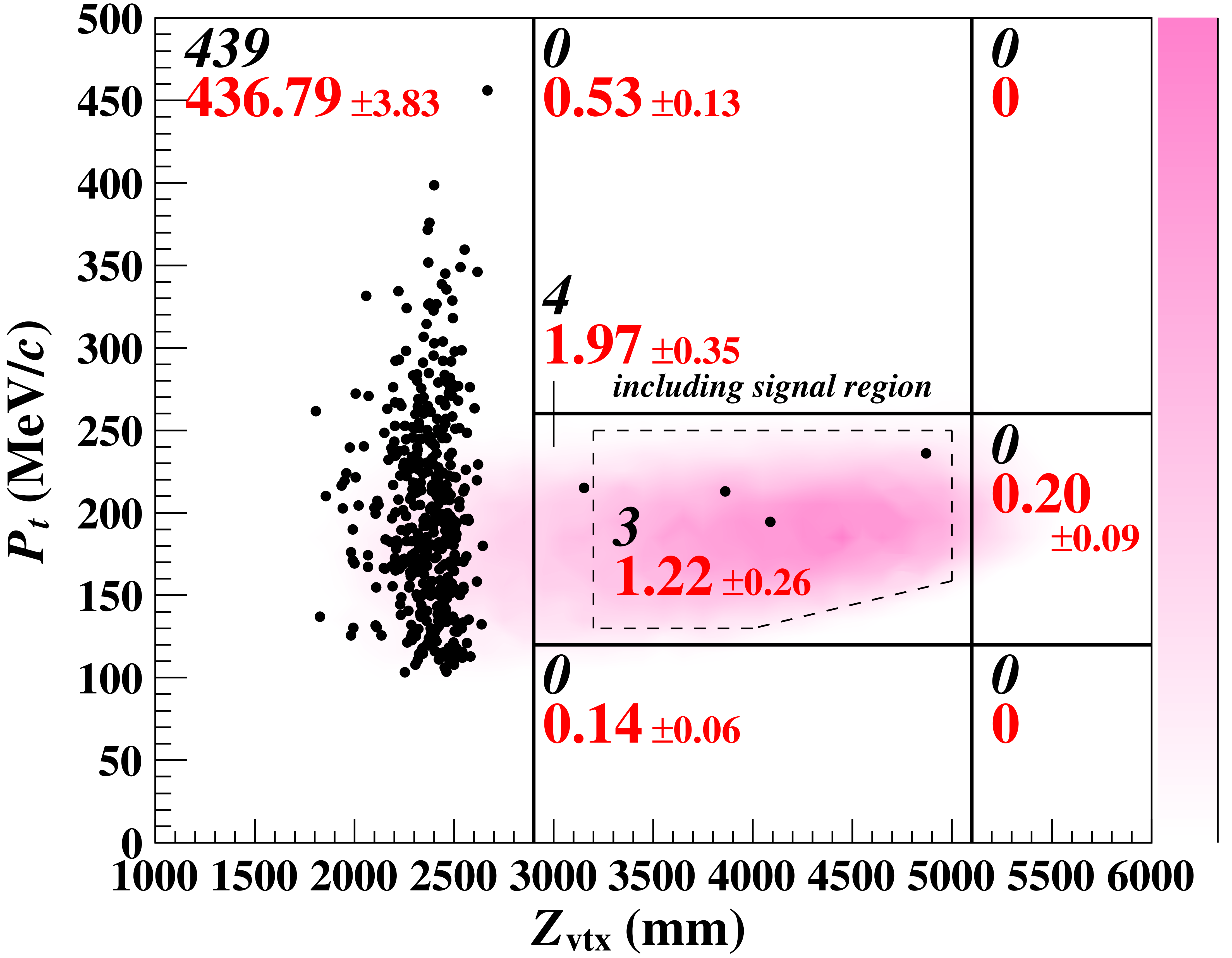
- $K^{\pm}/K_L$ ratio = 2.6×10^{-5}, ~3 times larger than MC expectation

The Final results of 2016-2018 data analysis

Single Event Sensitivity = $(7.20 \pm 0.05_{stat} \pm 0.66_{syst}) \times 10^{-10}$

<u>Final PT vs Z plot</u>

Black: observed, Red: expected BG, Contour: signal MC



PHYSICAL REVIEW LETTERS **126,** 121801 (2021)

Editors' Suggestion

Study of the $K_L \to \pi^0 \nu \bar{\nu}$ Decay at the J-PARC KOTO Experiment

J. K. Ahn,[1] B. Beckford,[2] M. Campbell,[2] S. H. Chen,[3] J. Comfort,[4] K. Dona,[2] M. S. Farrington,[5] K. Hanai,[6] N. Hara,[6] H. Haraguchi,[6] Y. B. Hsiung,[3] M. Hutcheson,[2] T. Inagaki,[7] M. Isoe,[6] I. Kamiji,[8] T. Kato,[6] E. J. Kim,[9] J. L. Kim,[9] H. M. Kim,[9] T. K. Komatsubara,[7,10] K. Kotera,[6] S. K. Lee,[9] J. W. Lee,[6,*] G. Y. Lim,[7,10] Q. S. Lin,[5] C. Lin,[3] Y. Luo,[5] T. Mari,[6] T. Masuda,[11] T. Matsumura,[12] D. Mcfarland,[4] N. McNeal,[2] K. Miyazaki,[6] R. Murayama,[6,†] K. Nakagiri,[8,‡] H. Nanjo,[8,§] H. Nishimiya,[6] Y. Noichi,[6] T. Nomura,[7,10] T. Nunes,[6] M. Ohsugi,[6] H. Okuno,[7] J. C. Redeker,[5] J. Sanchez,[2] M. Sasaki,[13] N. Sasao,[11] T. Sato,[7] K. Sato,[6,∥] Y. Sato,[6] N. Shimizu,[6] T. Shimogawa,[14,¶] T. Shinkawa,[12] S. Shinohara,[8,§] K. Shiomi,[7,10] R. Shiraishi,[6] S. Su,[2] Y. Sugiyama,[6,¶] S. Suzuki,[14] Y. Tajima,[13] M. Taylor,[2] M. Tecchio,[2] M. Togawa,[6,¶] T. Toyoda,[6] Y.-C. Tung,[5,**] Q. H. Vuong,[6] Y. W. Wah,[5] H. Watanabe,[7,10] T. Yamanaka,[6] H. Y. Yoshida,[13] and L. Zaidenberg[2]

(KOTO Collaboration)

Background Table

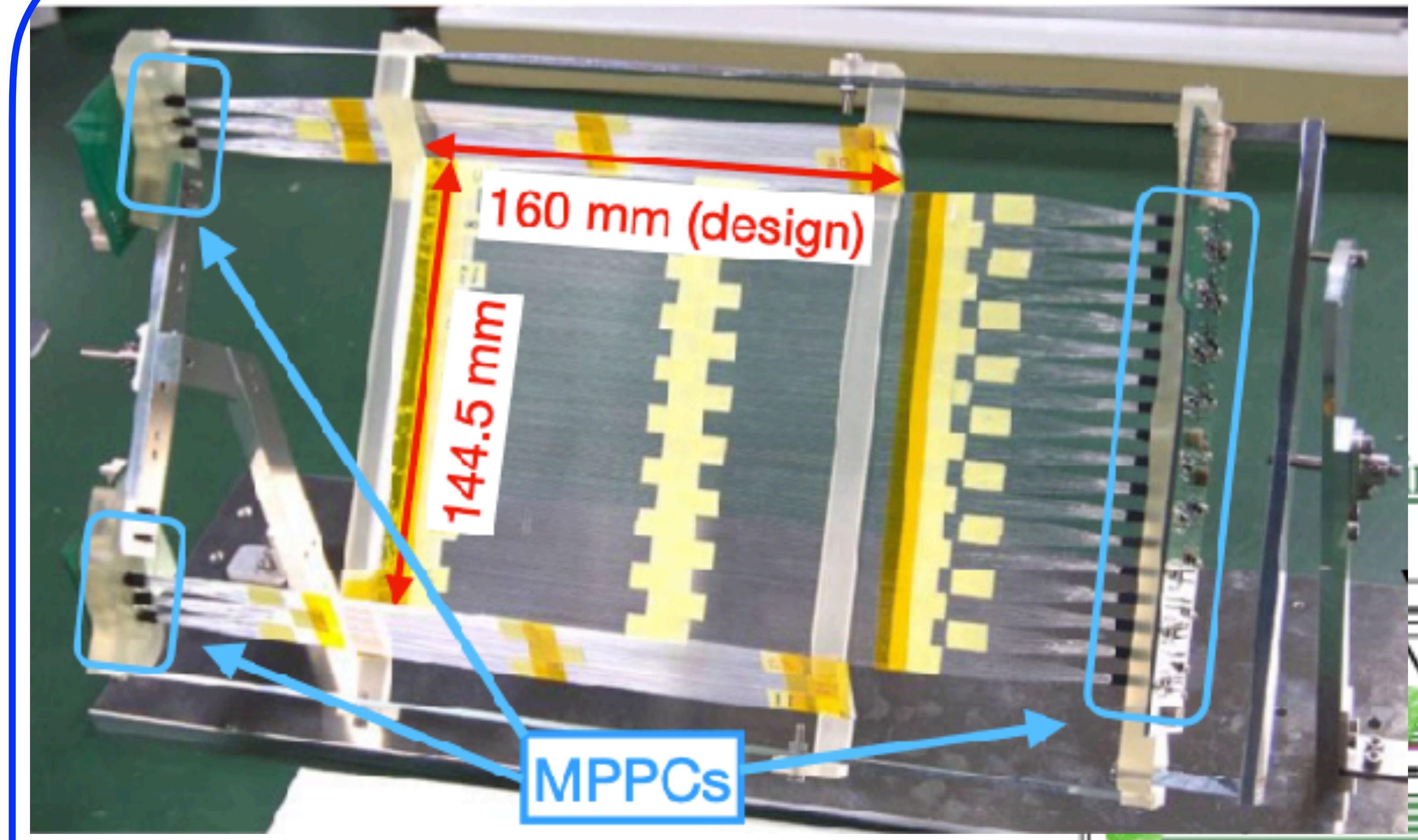
	Number of events
$K_L \to 3\pi^0$	0.01 ± 0.01
$K_L \to 2\gamma$ (beam halo)	0.26 ± 0.07^a
Other K_L decays	0.005 ± 0.005
$K^\pm$	0.87 ± 0.25^a
Hadron cluster	0.017 ± 0.002
CV η	0.03 ± 0.01
Upstream π^0	0.03 ± 0.03
Total	1.22 ± 0.26

N_{obs} (=3) is statistically consistent with N_{BG} (=1.22±0.26).

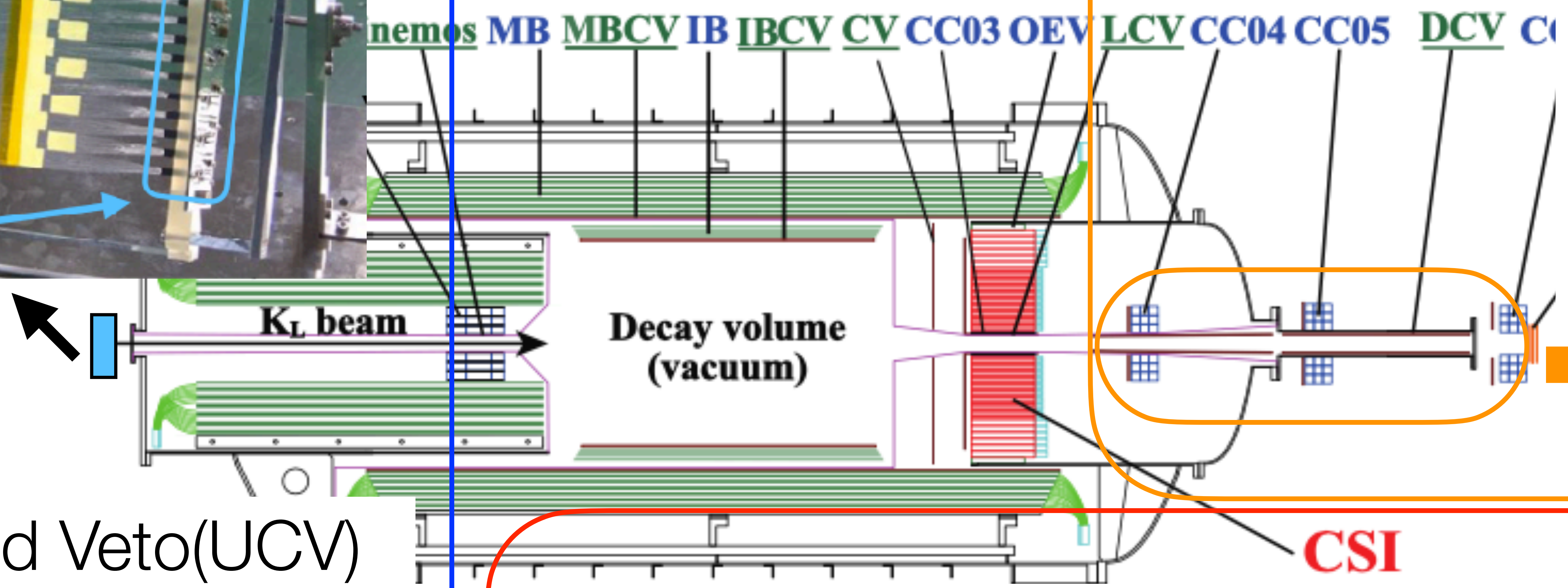
2019-2021 data analysis

- Detector upgrade
- Further Background rejection

Detector upgrade

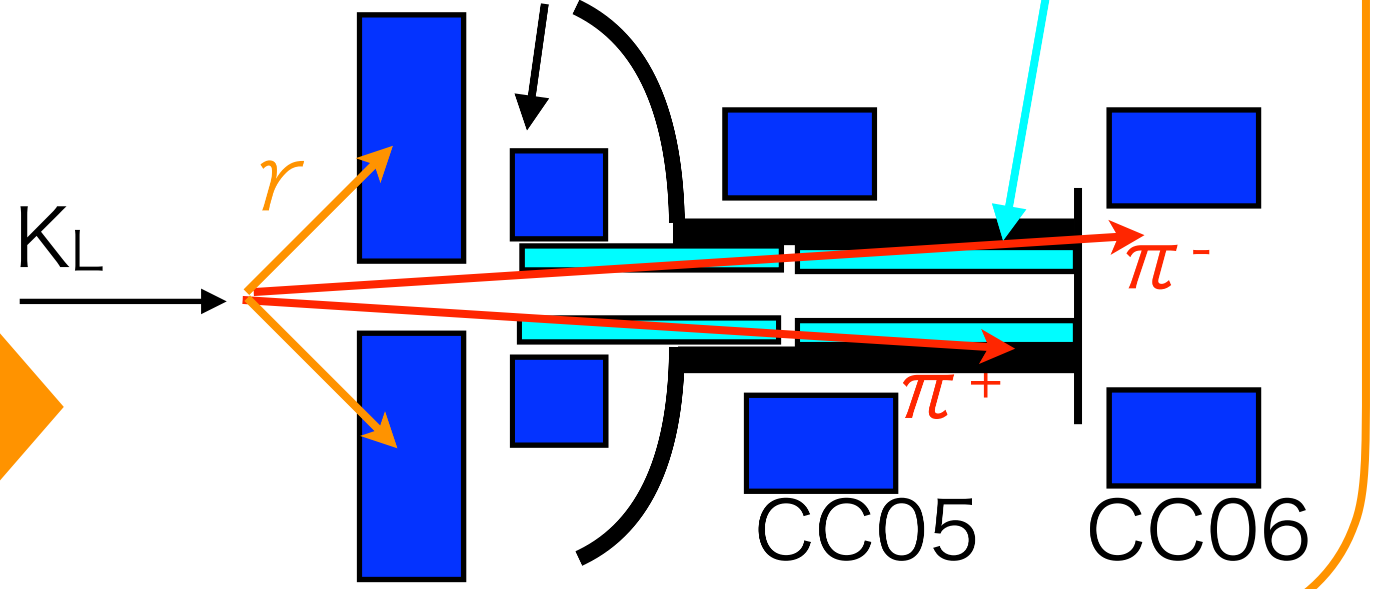


- Upstream charged Veto(UCV) against $K^{\pm}$ background
  - Installed a prototype in 2020.
  - Upgraded in 2021



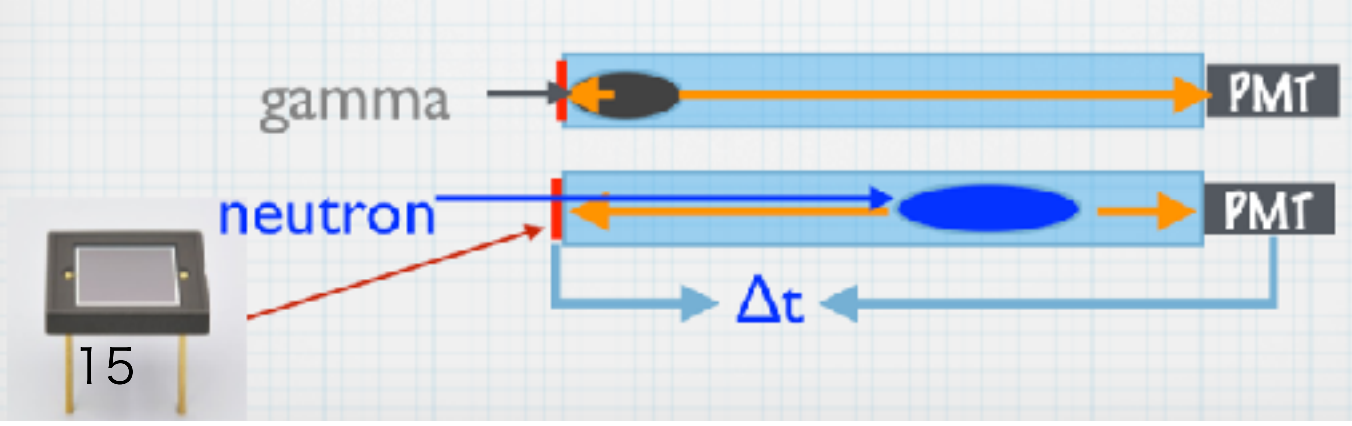
- Downstream charged veto(DCV) against $K_L \to \pi^+\pi^-\pi^0$ background

In 2019



- Calorimeter's both-end readout against neutron background

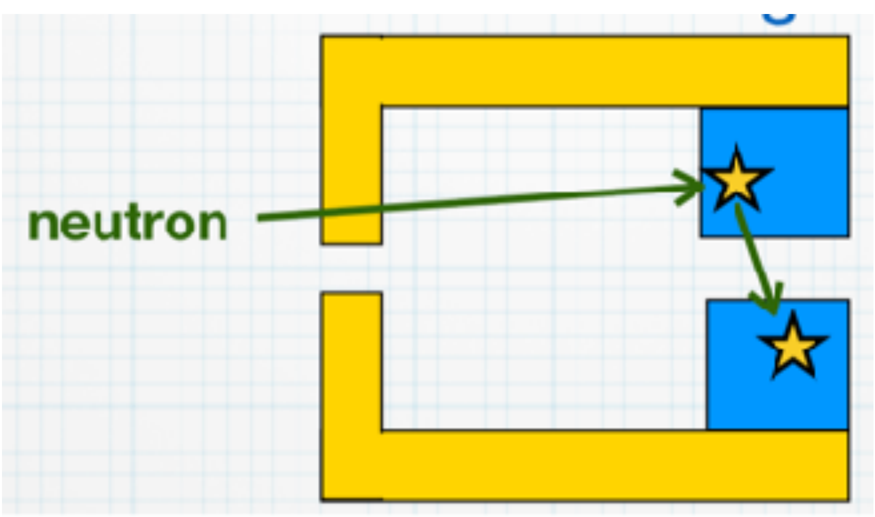
In 2019

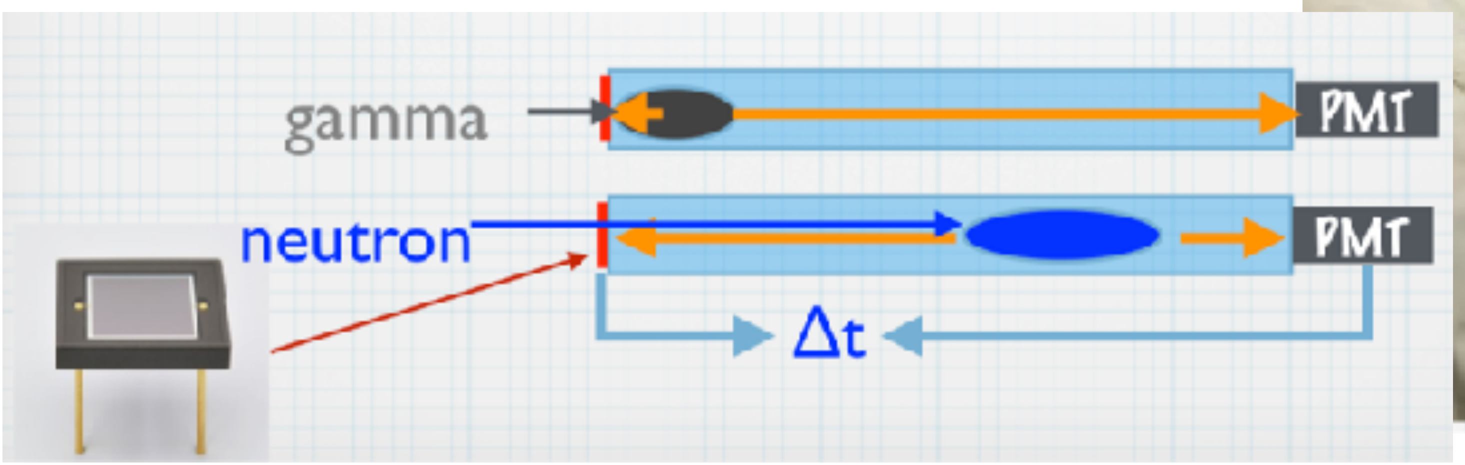


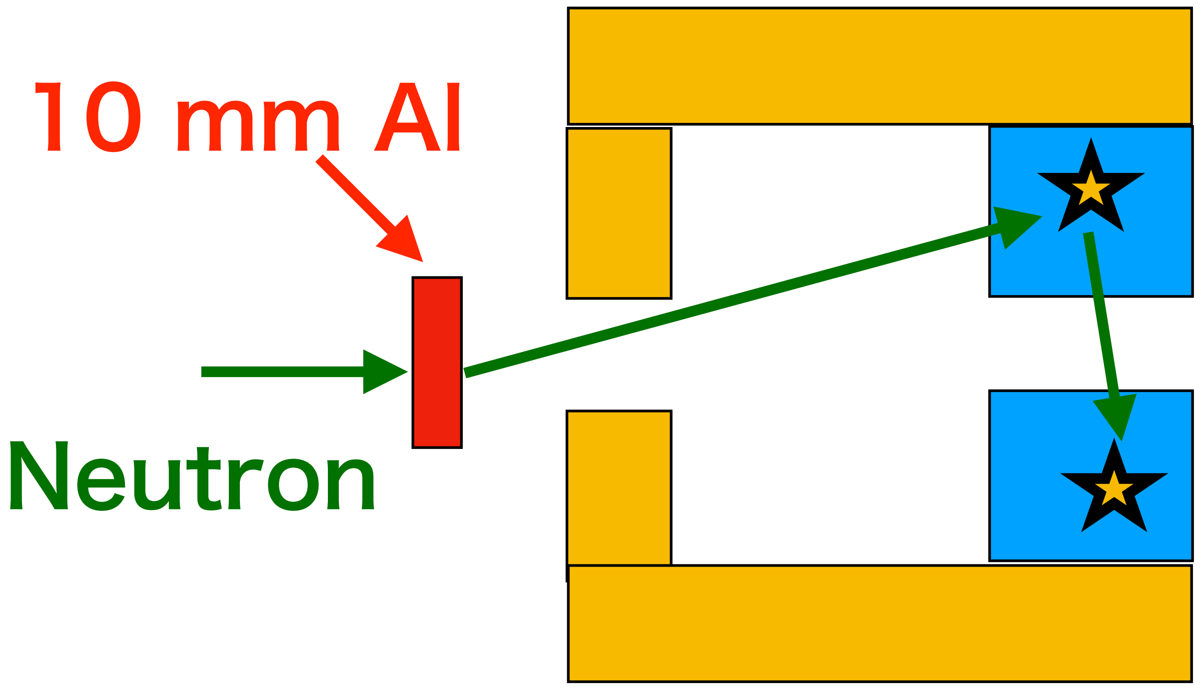
Calorimeter's both read out

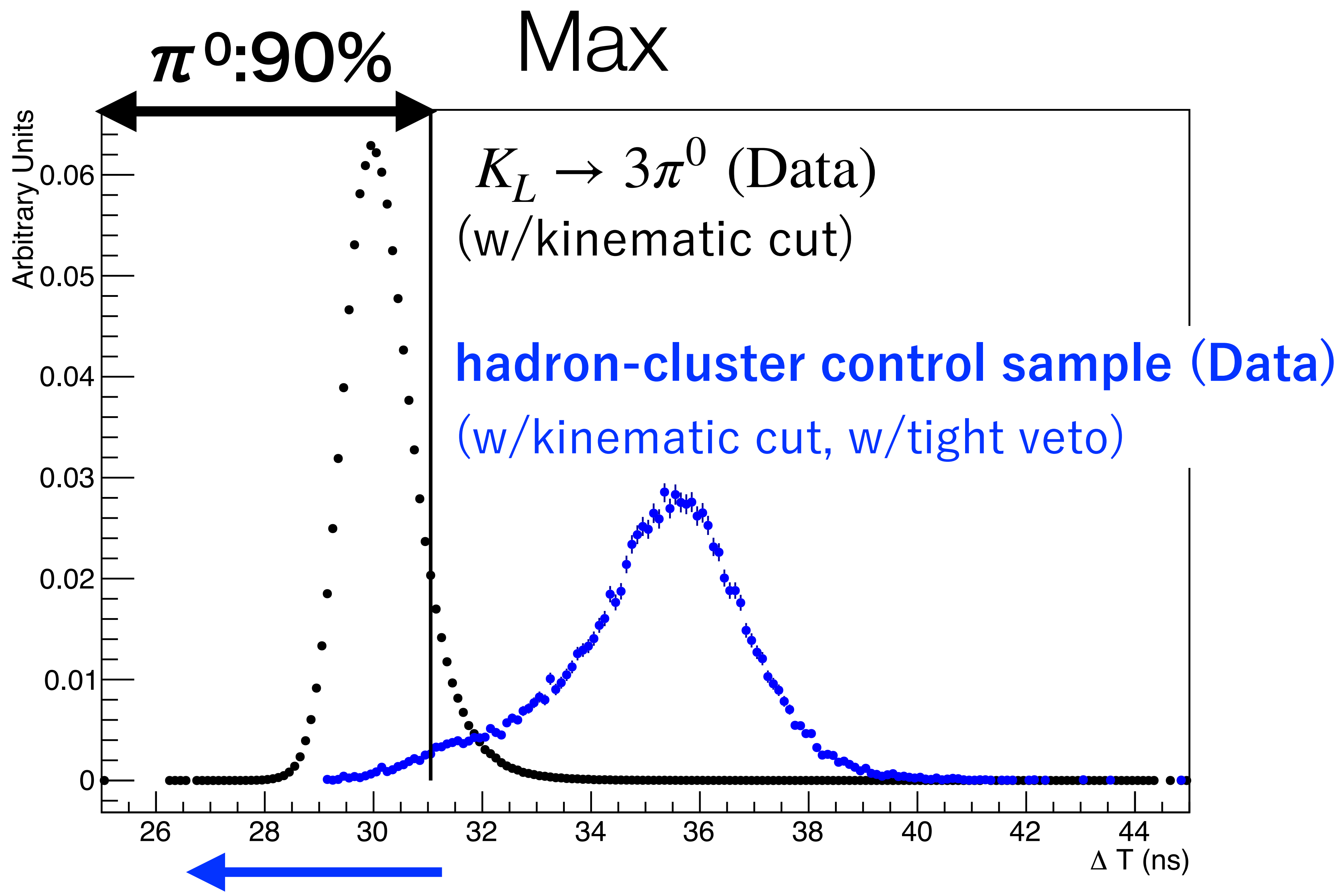
Calorimeter upgrade

to suppress the hadronic background







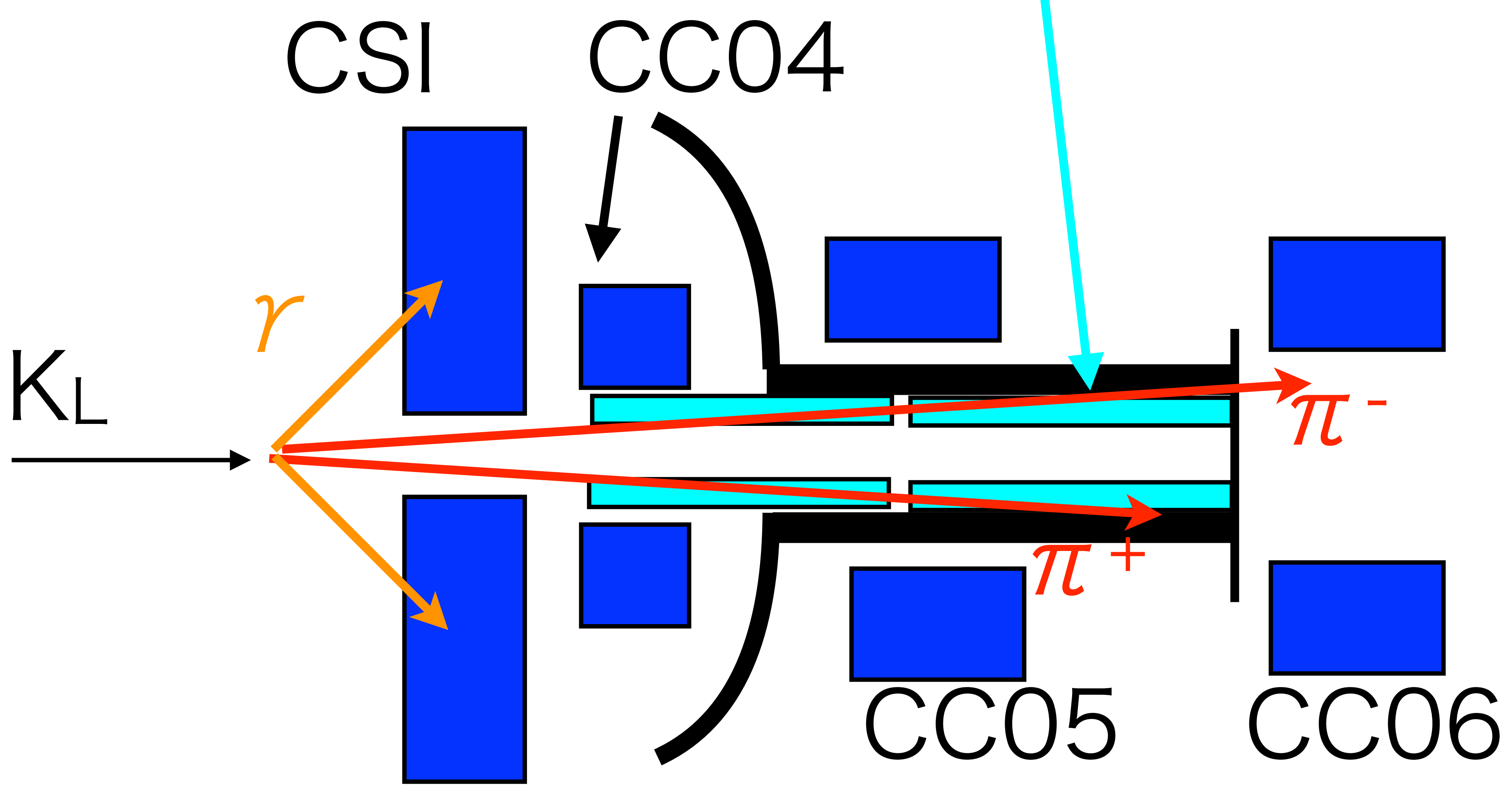


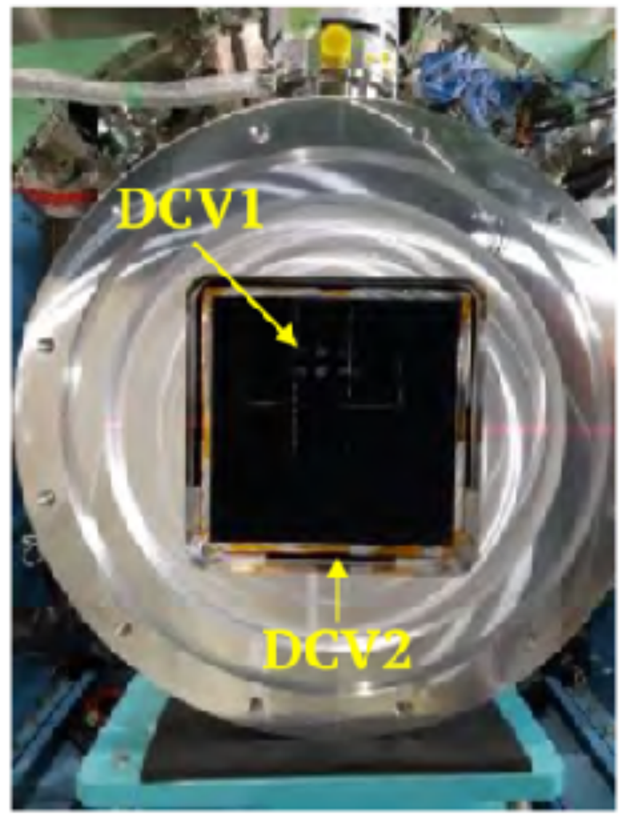
neutron bkg: 2.1×10^{-2}

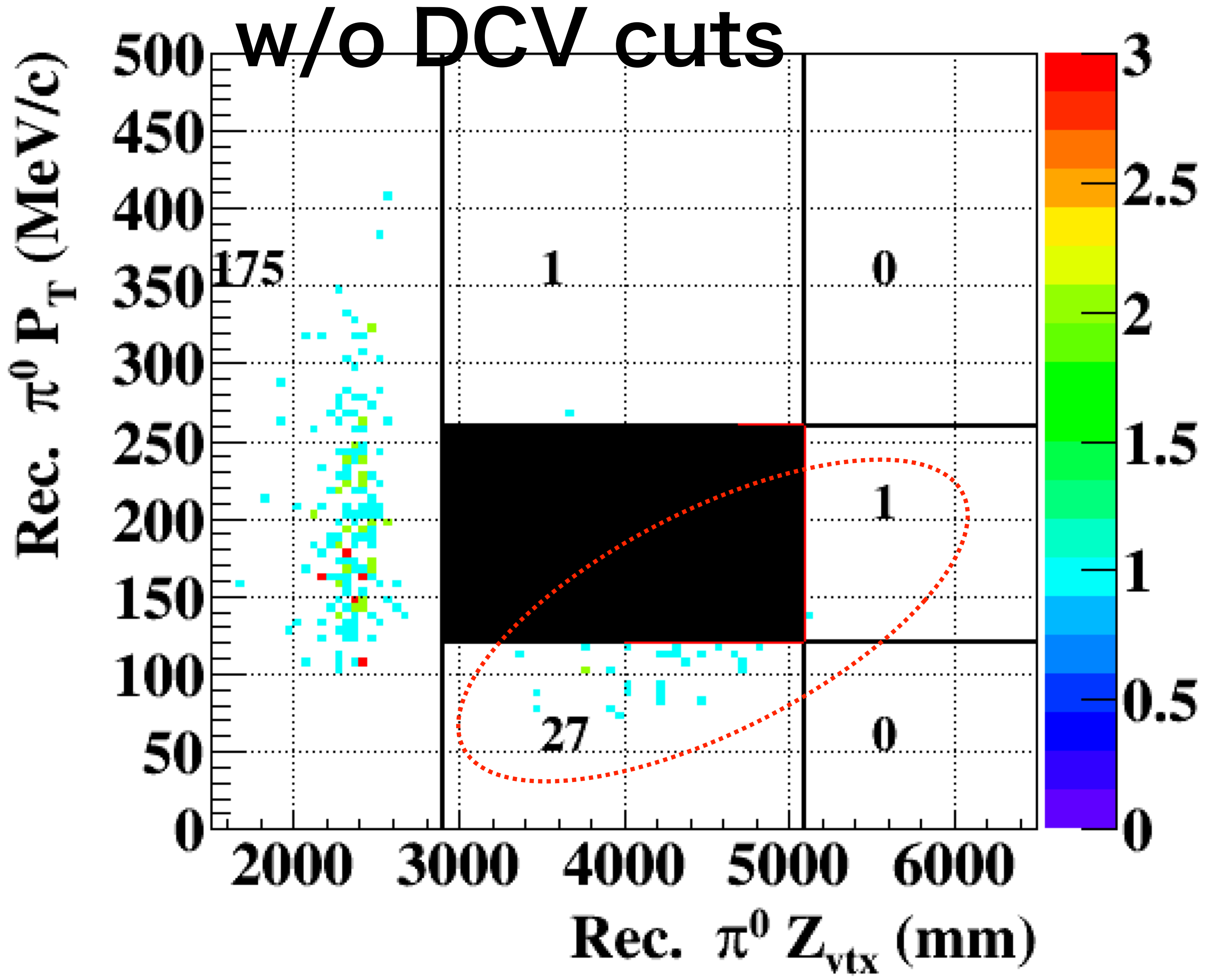
Confirmed good separation ability with 2019 data

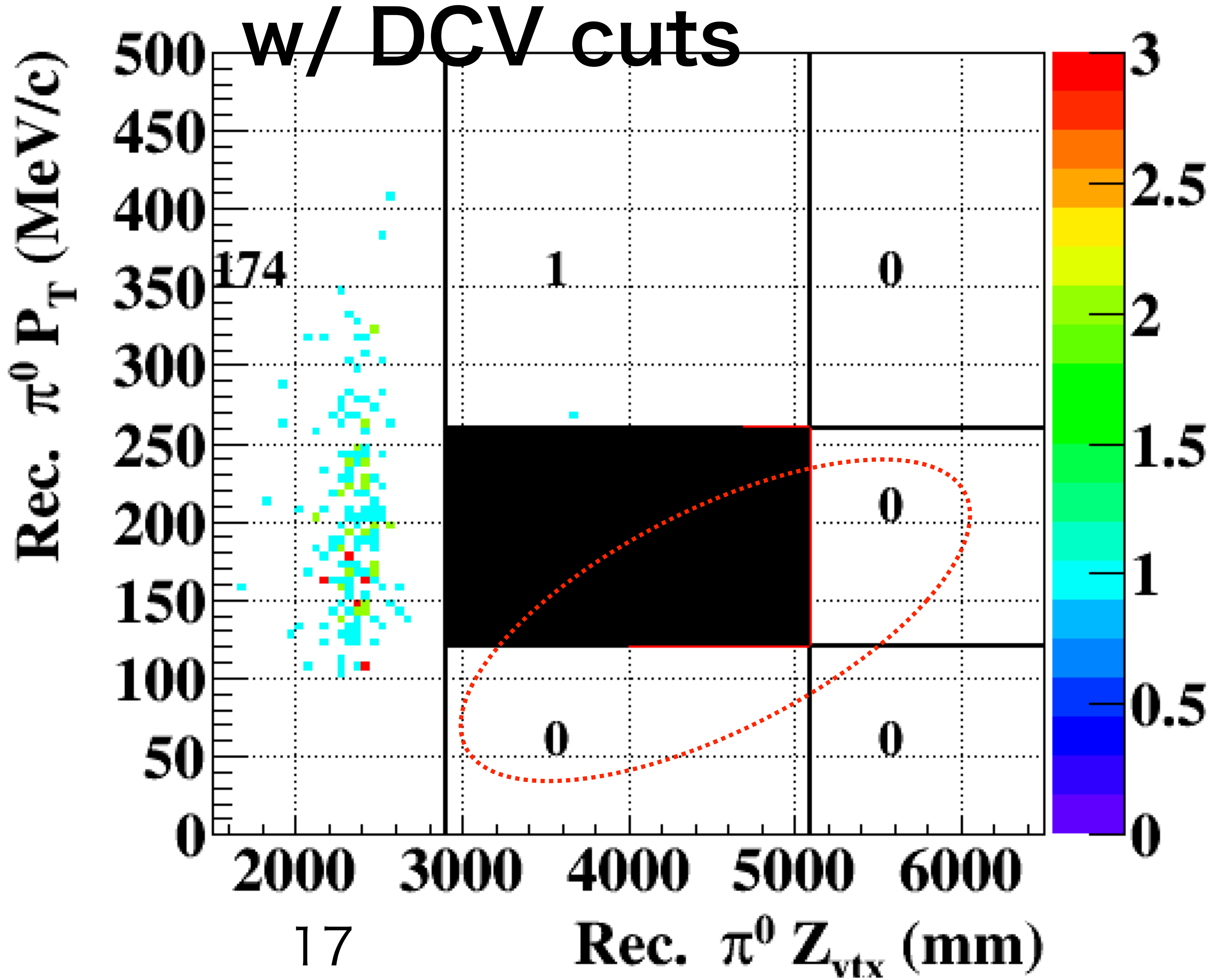
Downstream charged veto (DCV)

to suppress $K_L \to \pi^+\pi^-\pi^0$ background



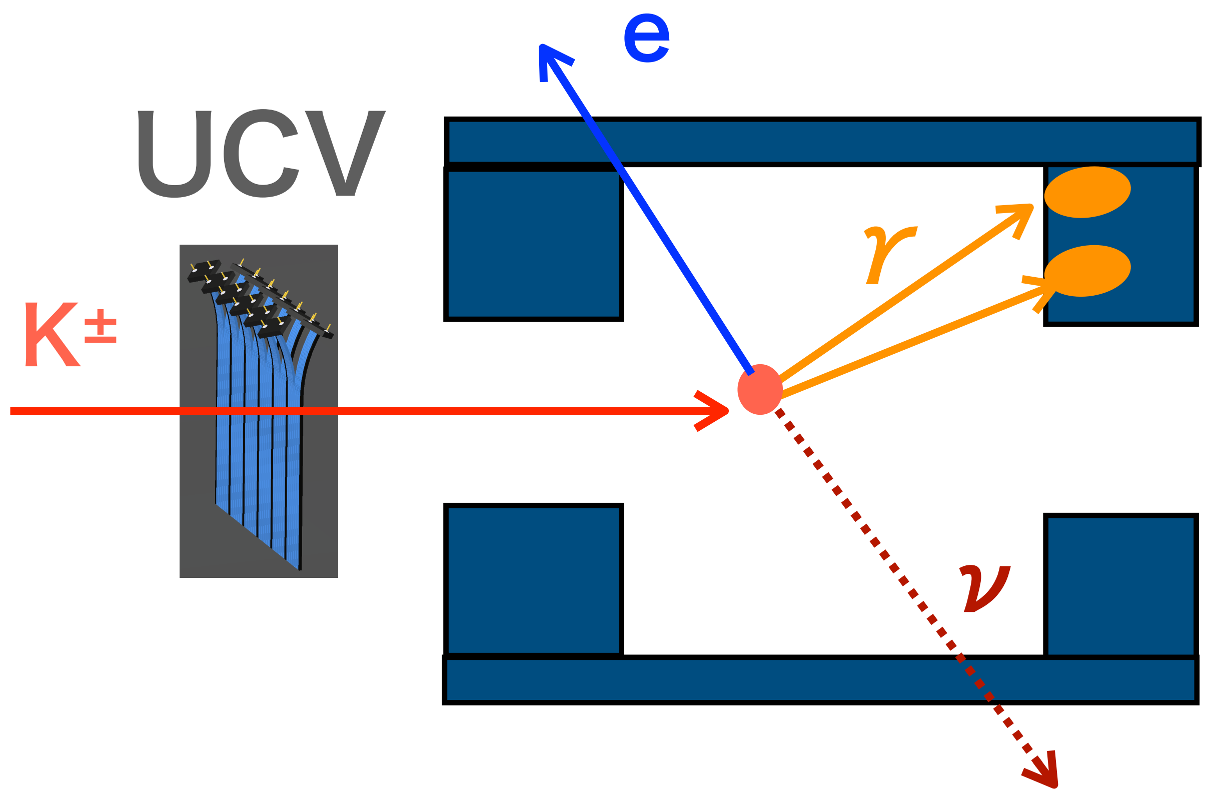






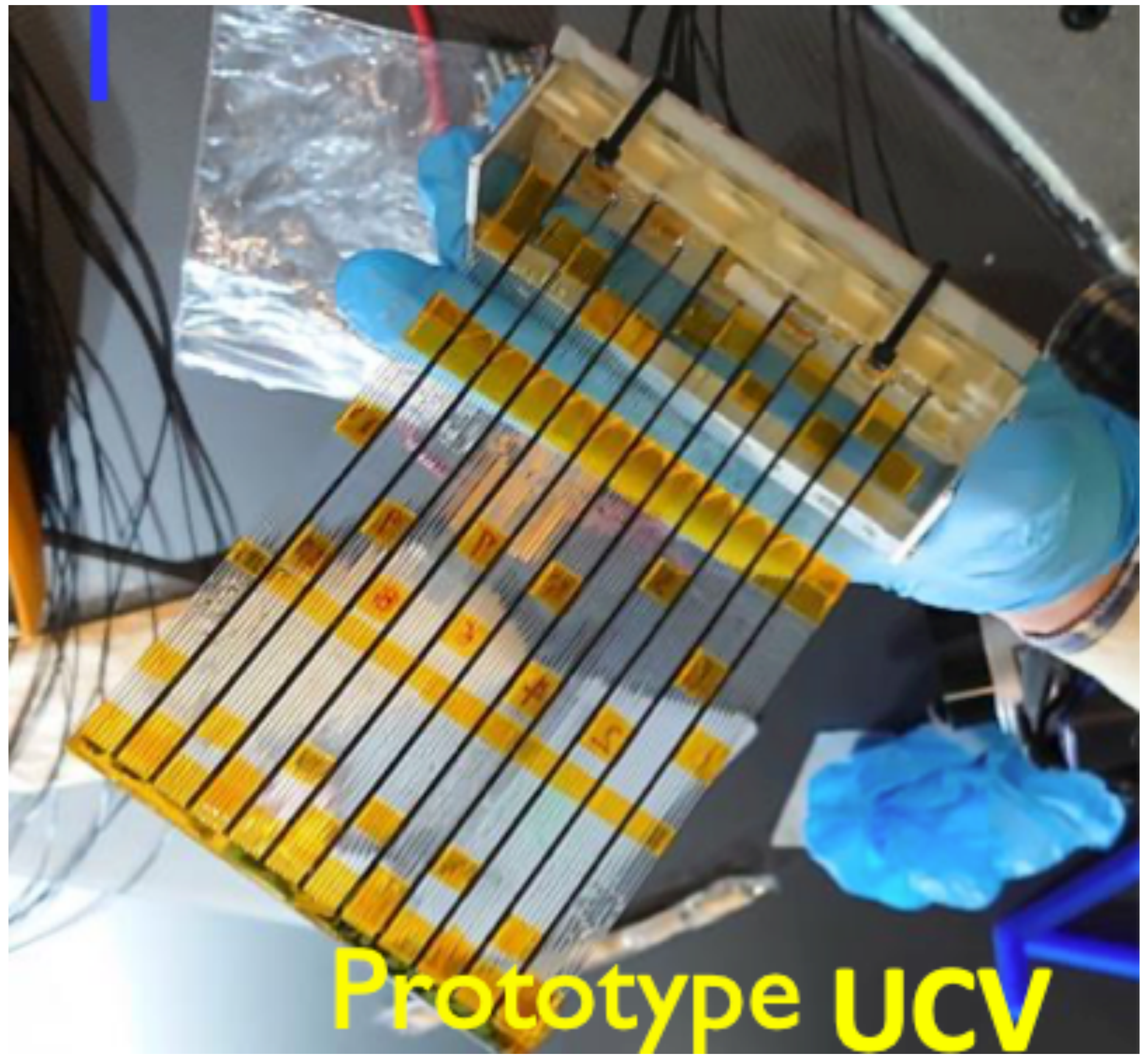
Low P_T events are effectively removed

Upstream charged veto(UCV)

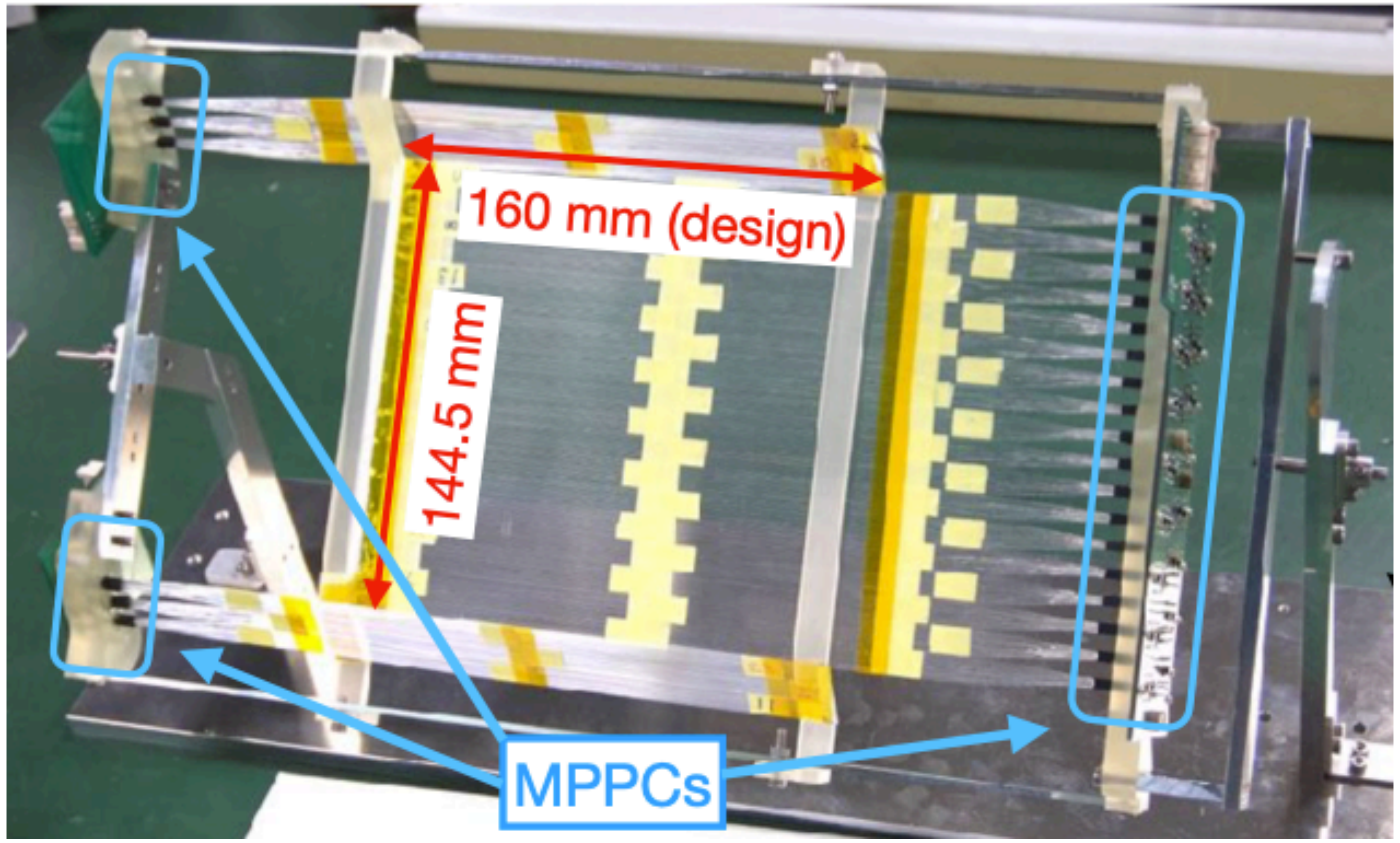


To veto K± in beam

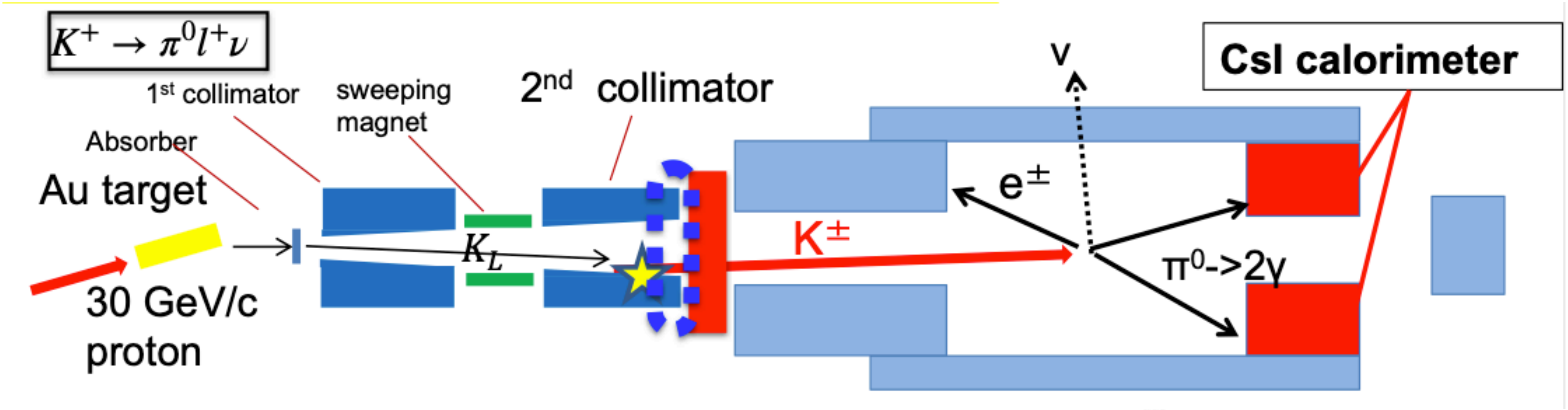
- Prototype (installed in 2020)
  - Plate with 1-mm square scintillating fibers read out by MPPC
  - 30% inefficiency due to a limited coverage, insensitive region, and irradiation effect.



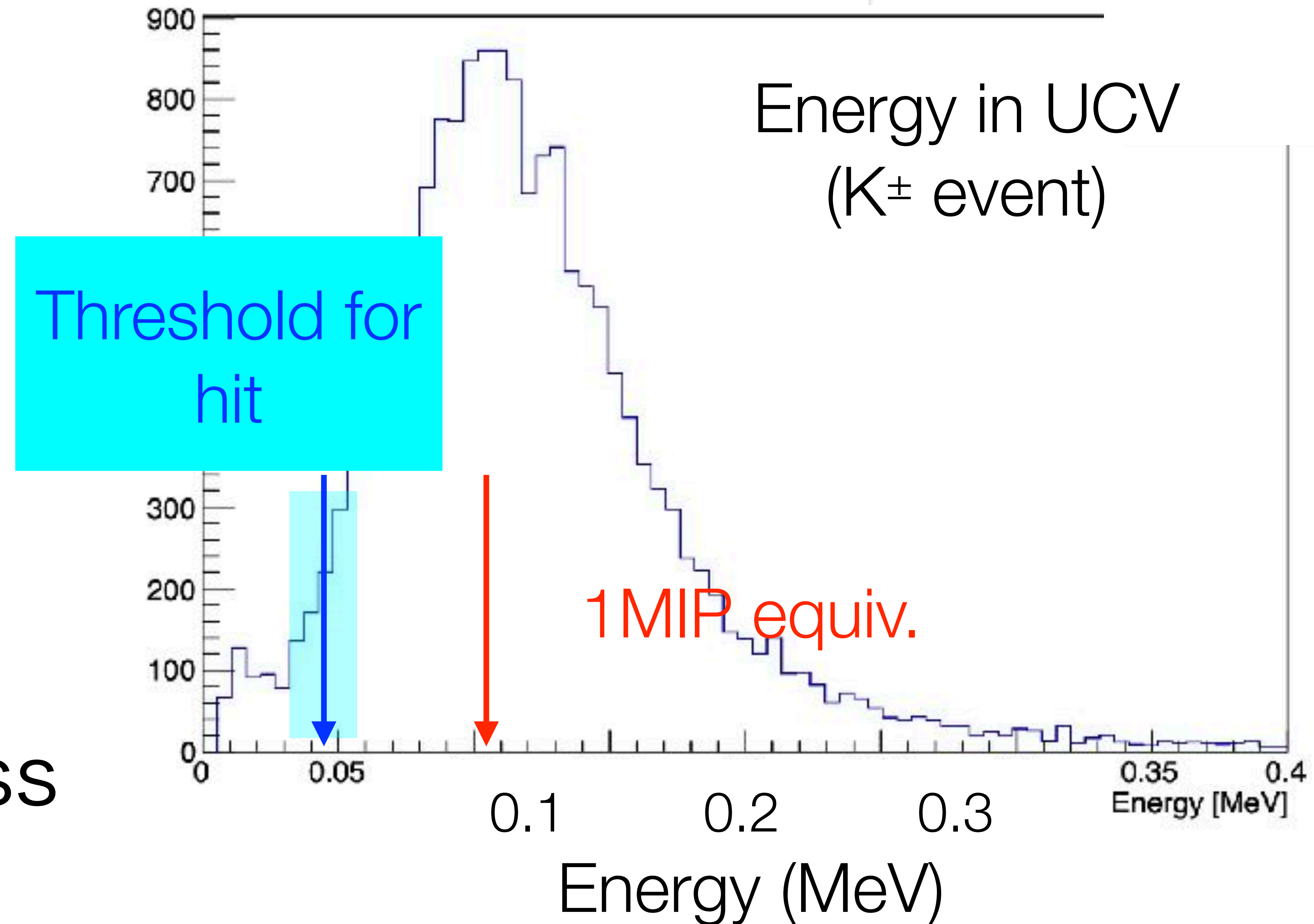
- New UCV (Updated in 2021)
  - Plate with 0.5-mm square scintillating fibers read out by MPPC
  - Fully cover beam, tilt detector, and put MPPC far from beam.



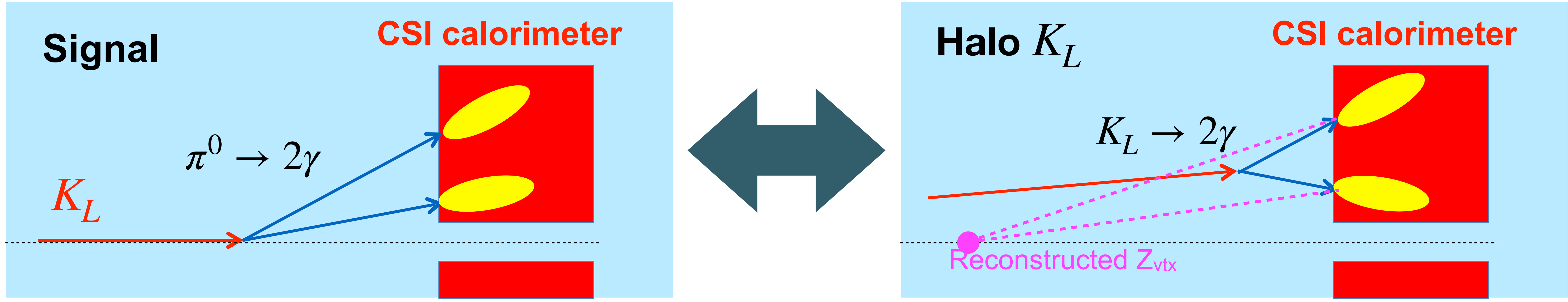
The performance of new UCV

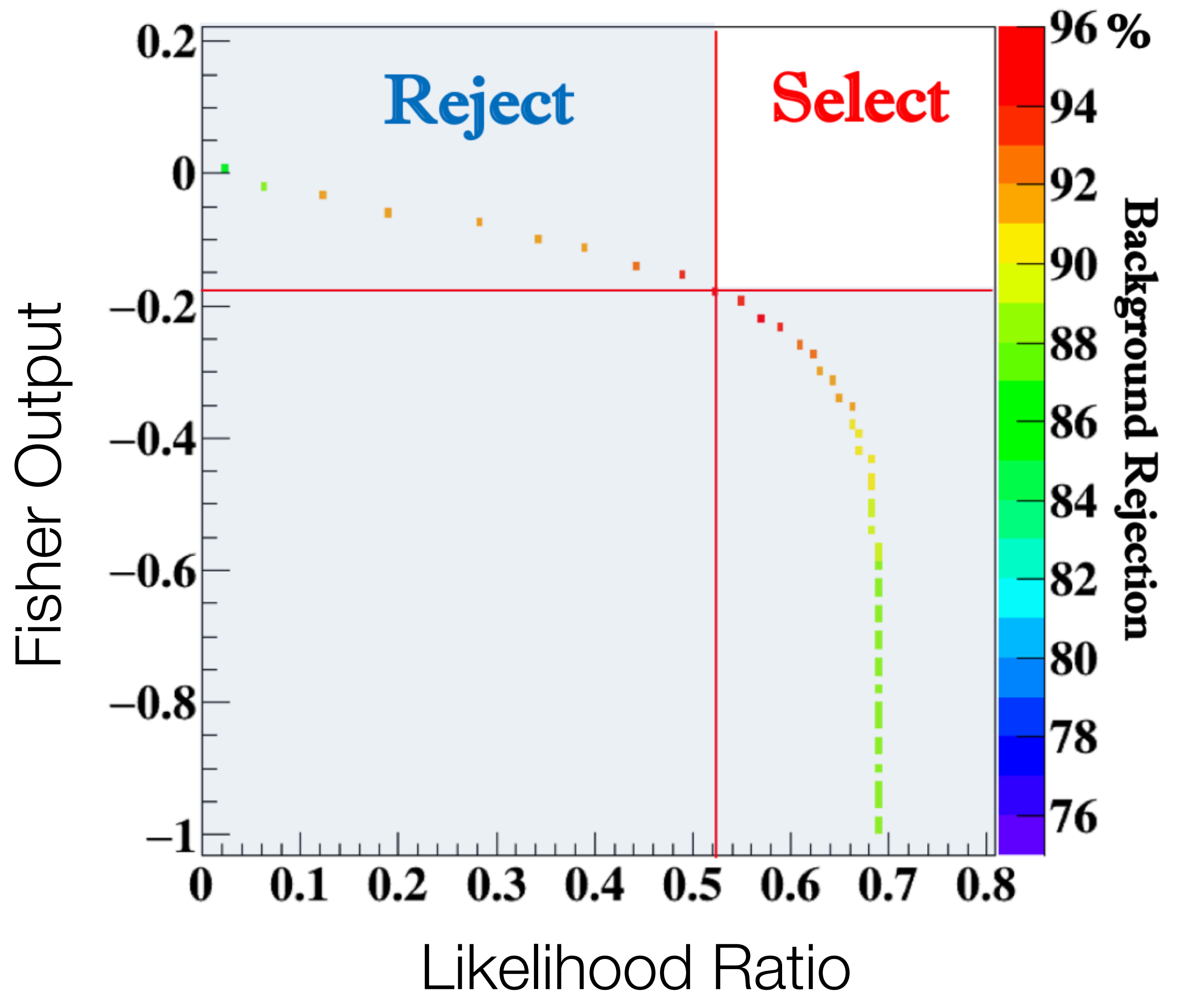


- Can correct enough $K^{\pm} \to \pi^{\pm}\pi^{0}$ samples to evaluate efficiency in a short time
  - With turning off the sweeping magnet in the beam line
- Achieved 95% efficiency with 5% accidental loss



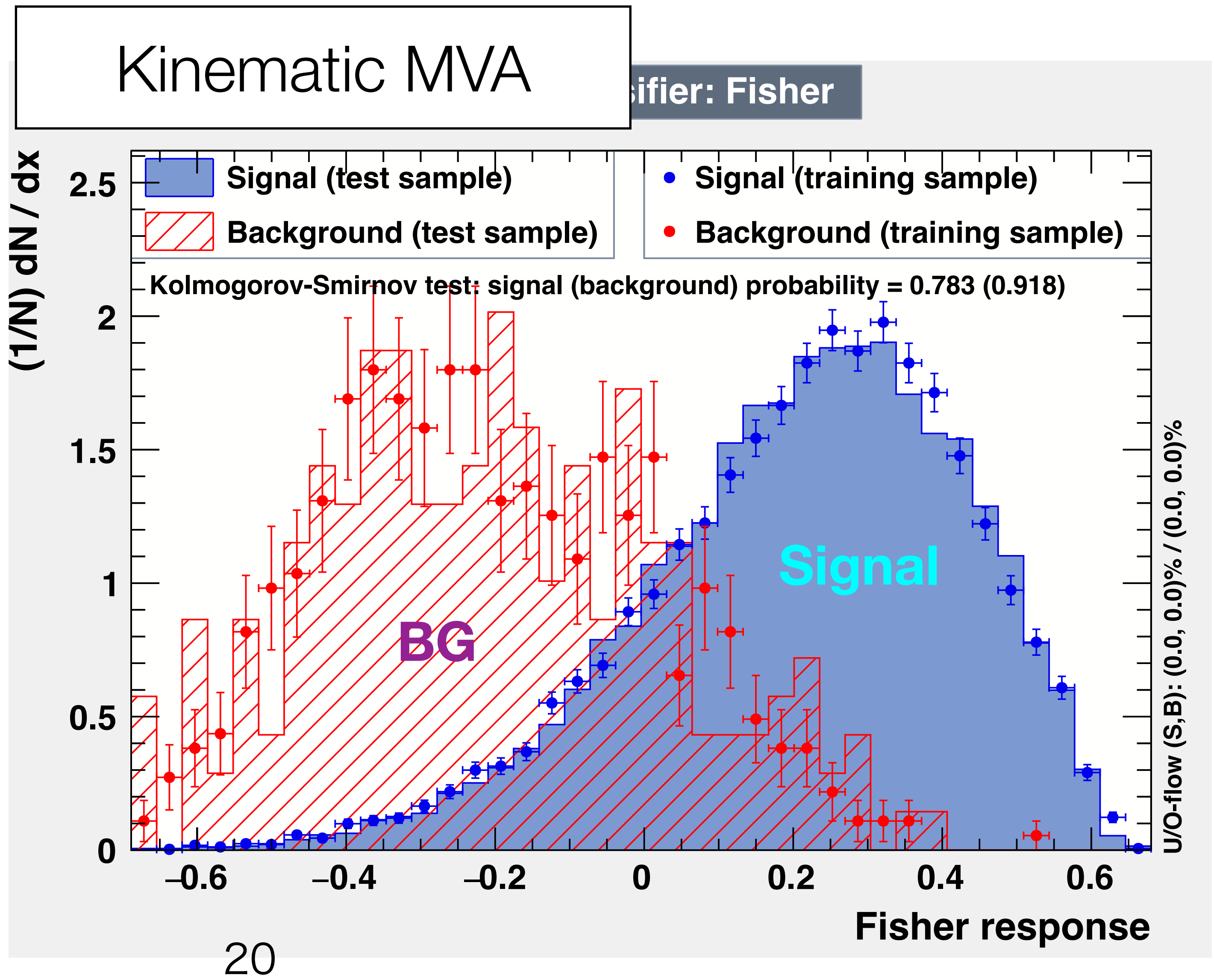
Reduction against halo $K_L \to 2\gamma$

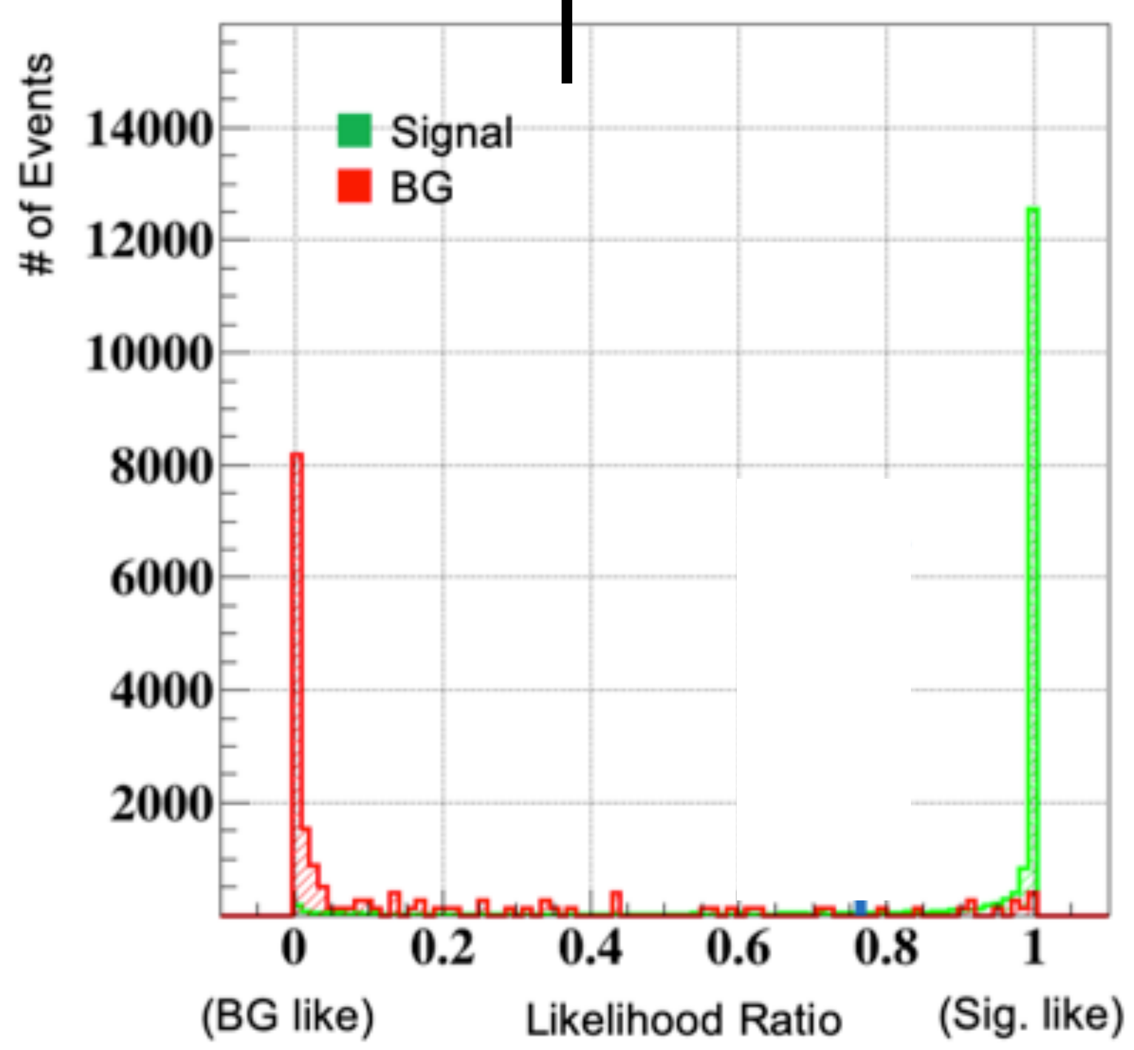




- Shower shape consistency
  - Likelihood Ratio

- MVA using the reconstructed kinematic variables





Reduce halo $K_L \to 2\gamma$ by a factor of ~15, while signal efficiency = 90%

Prospect

- Rough estimation of the single event sensitivity for Run81-87 is 5×10^{-10}
- Physics data taking will be resumed from fall (winter) of 2022 with a higher intensity beam (～100 KW) after the MR power supply upgrade.

Summary

- The KOTO experiment studies the $K_L \to \pi^0 \nu \nu$ decay
- Results of the 2016-2018 analysis has been published
  - The single event sensitivity is 7.2×10^{-10}
  - 3 observed events is consistent with the estimated 1.22±0.26 background events
- KOTO will continue to take data and improve sensitivity by reducing background events with new detectors and improved analysis methods.