KOTO
Status and Prospects

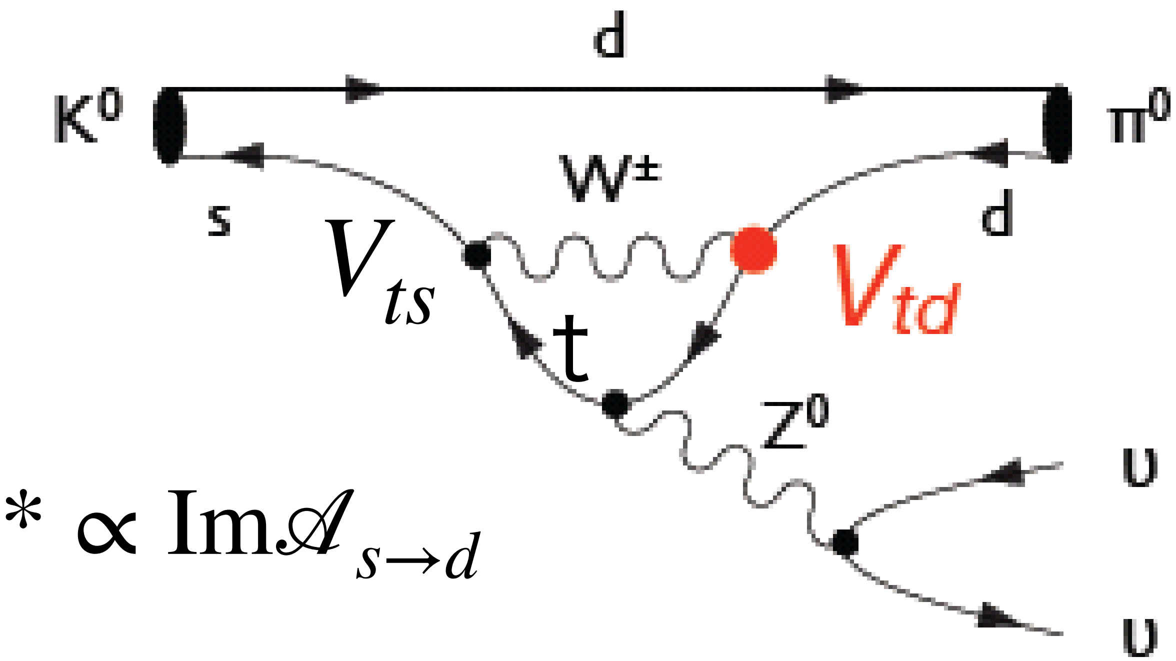
Koji Shiomi for the KOTO collaboration

(KEK)

BEAUTY 2020

2020/9/23

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



- Standard Model : FCNC
  - CP-violating:

    $K_L \propto K^0 - \overline{K^0}$

    $\mathscr{A}_{K_L \to \pi^0 \nu \nu} \propto \mathscr{A}_{s \to d} - (\mathscr{A}_{s \to d})^* \propto \mathrm{Im}\mathscr{A}_{s \to d}$

  - Rare:

    $BR(SM) = 3 \times 10^{-11} \propto \left| V_{ts} V_{td}^* \right|^2$

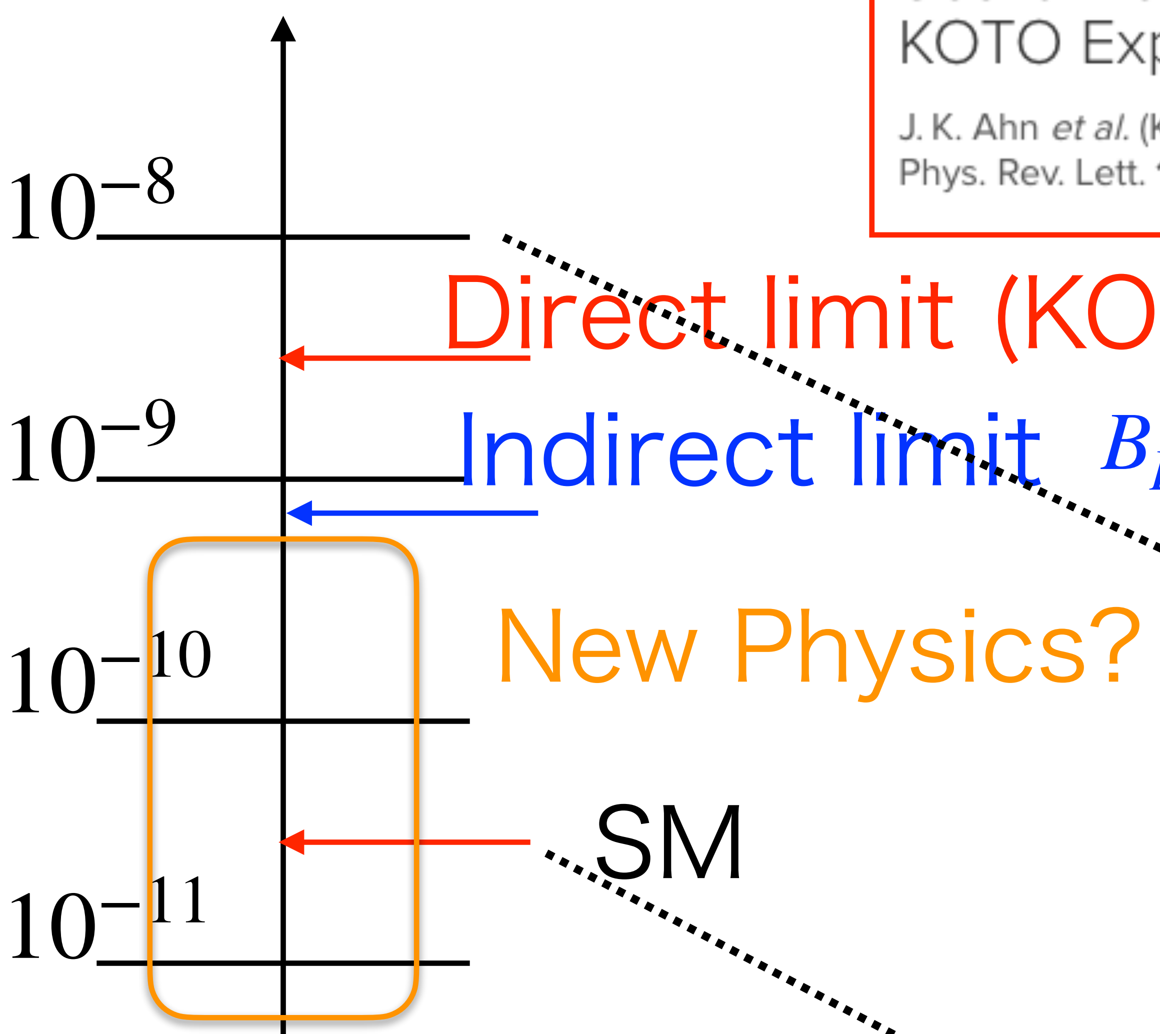
  - Accurate:
    - theoretical uncertainty < 2%
- Good probe for New Physics search

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

Open Access

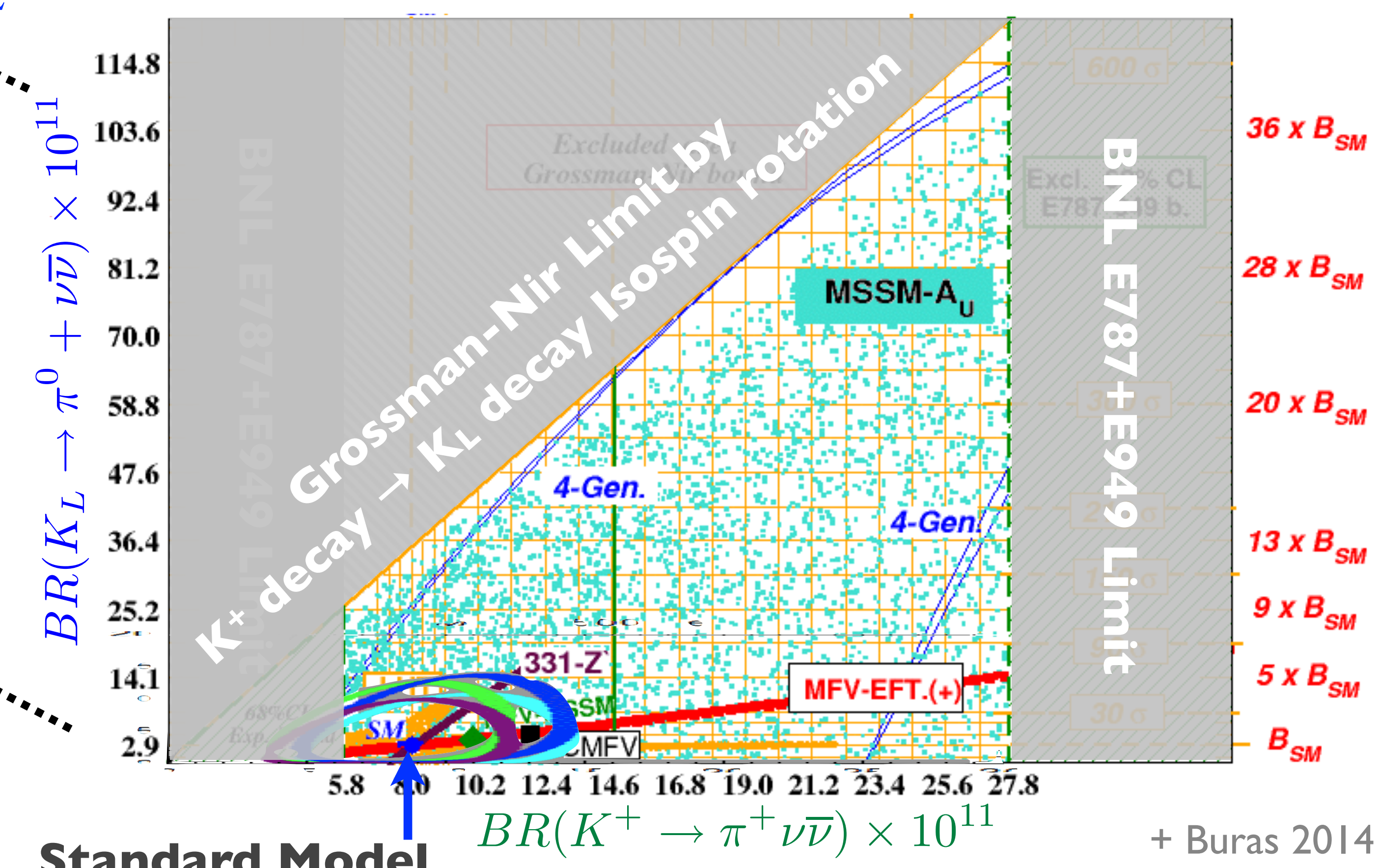
Search for $K_L \to \pi^0 \nu \bar{\nu}$ and $K_L \to \pi^0 X^0$ Decays at the J-PARC KOTO Experiment

J. K. Ahn *et al.* (KOTO Collaboration)
Phys. Rev. Lett. **122**, 021802 – Published 15 January 2019



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

Indirect limit $B_{K_L \to \pi^0 \nu \nu} < 8.1 \times 10^{-10} (90\,\%\,\mathrm{CL})$

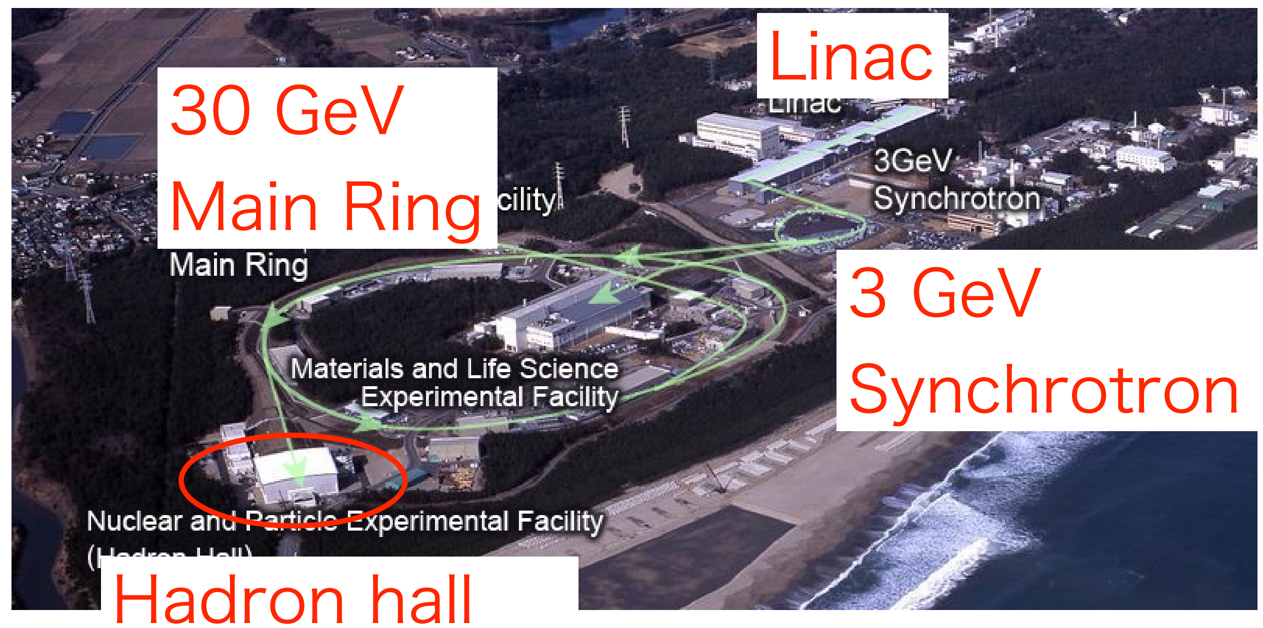


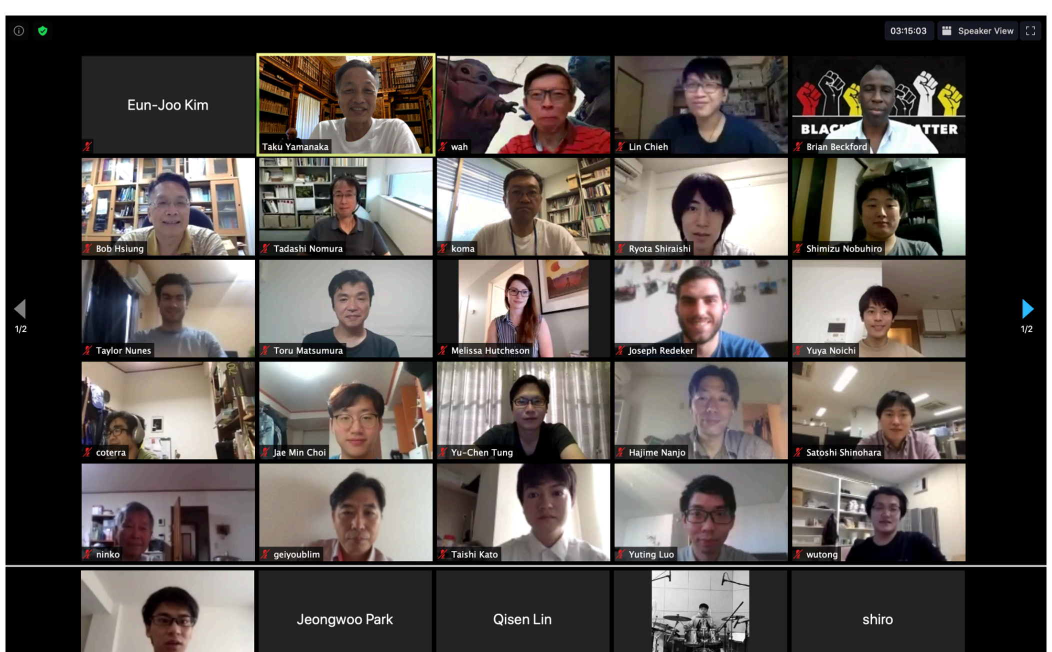
+ Buras 2014

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

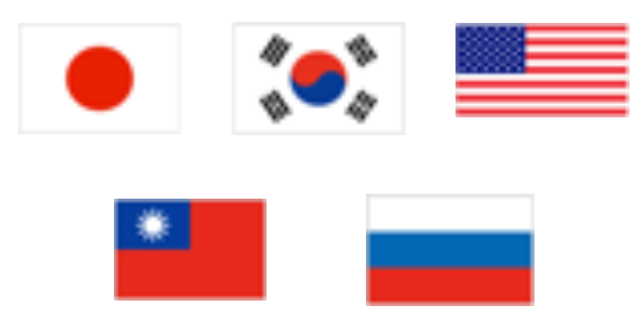
KOTO experiment

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



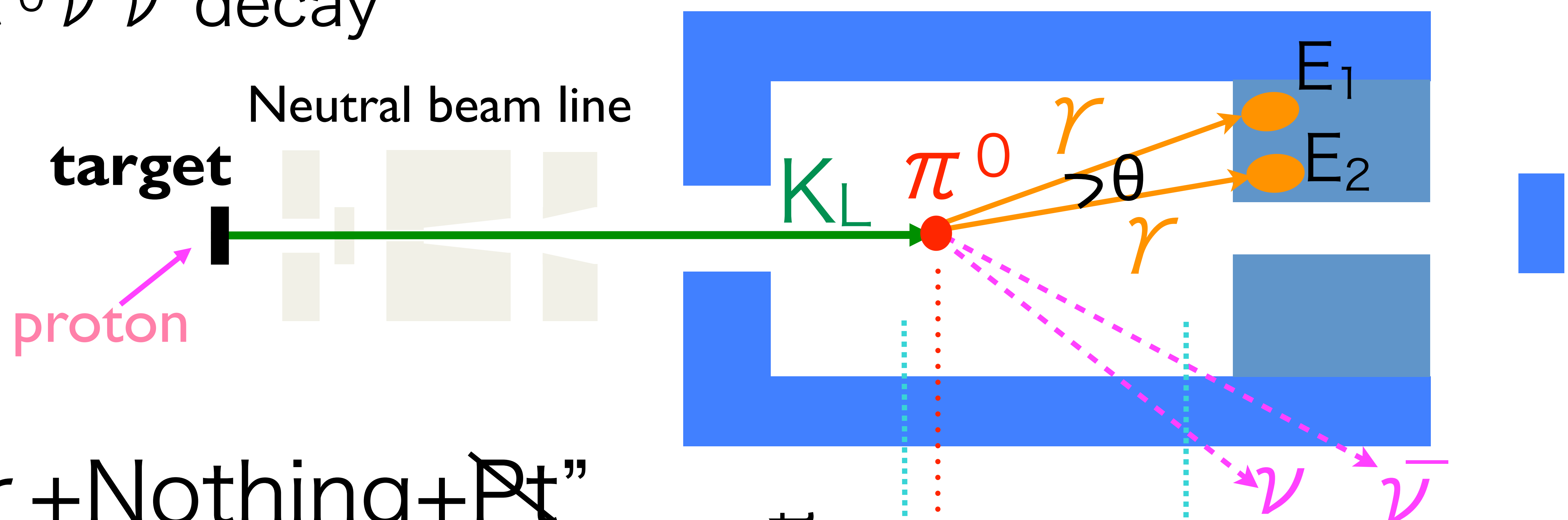


Collaboration meeting
with Zoom(July 2020)

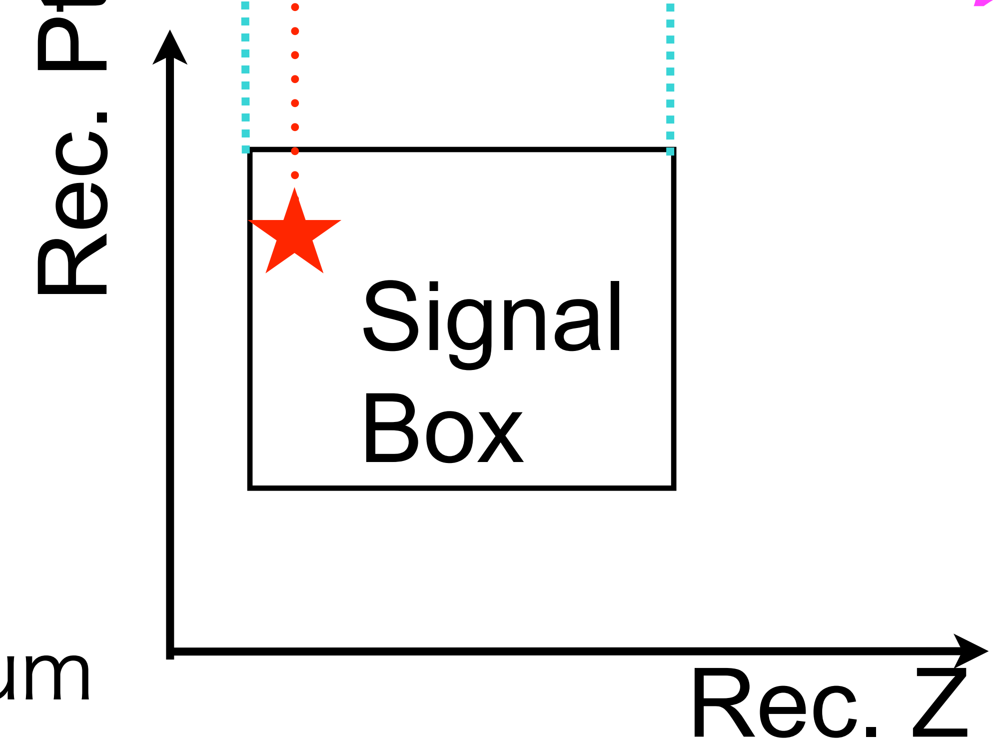


Experimental principle

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



"2γ+Nothing+~~Pt~~"



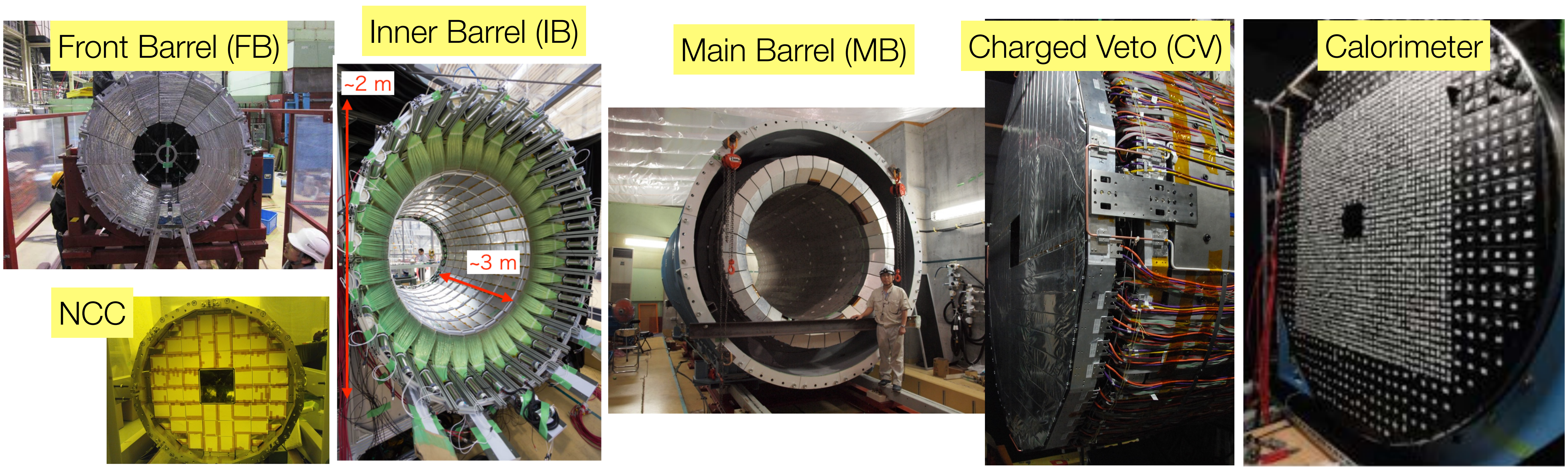
Assuming 2γ from π^0,

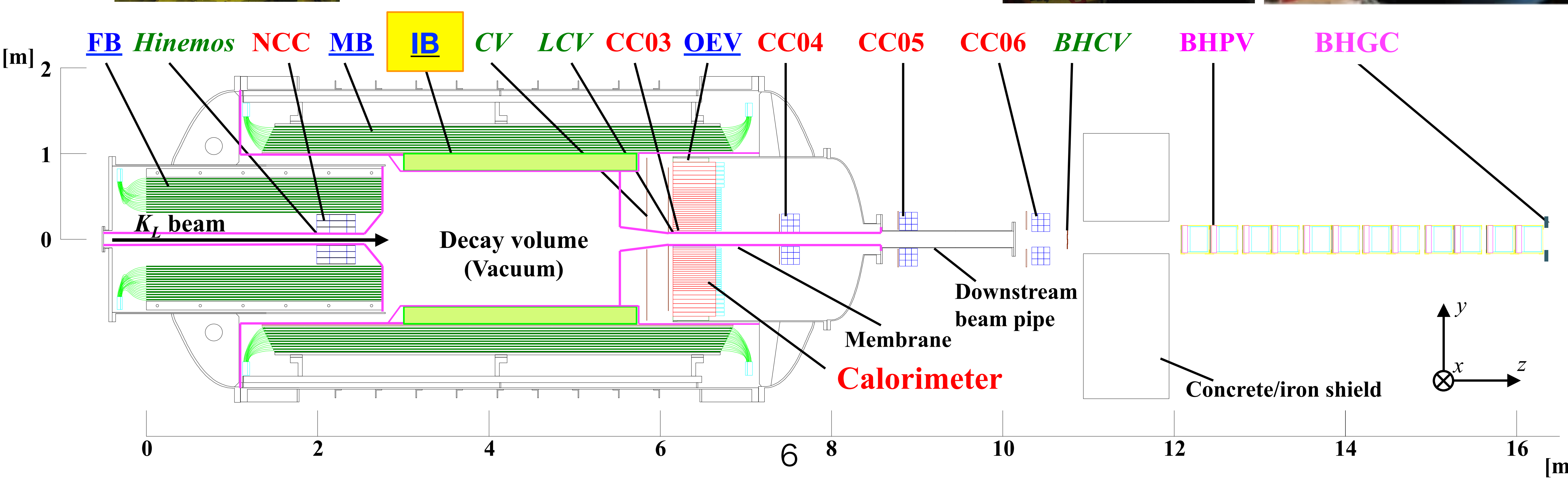
Calculate z vertex.

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

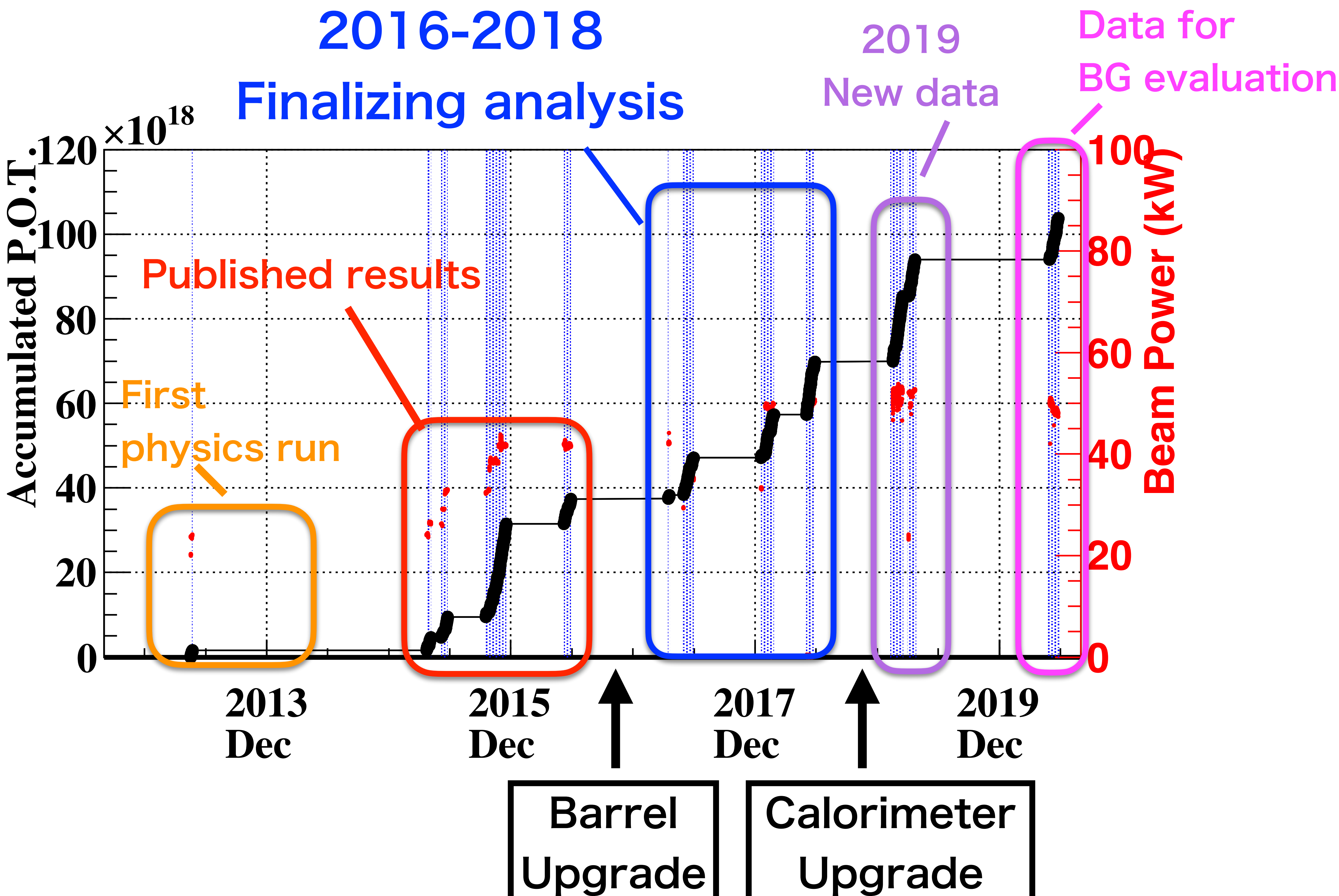
Calculate π^0 transverse momentum

KOTO detector





History of data taking

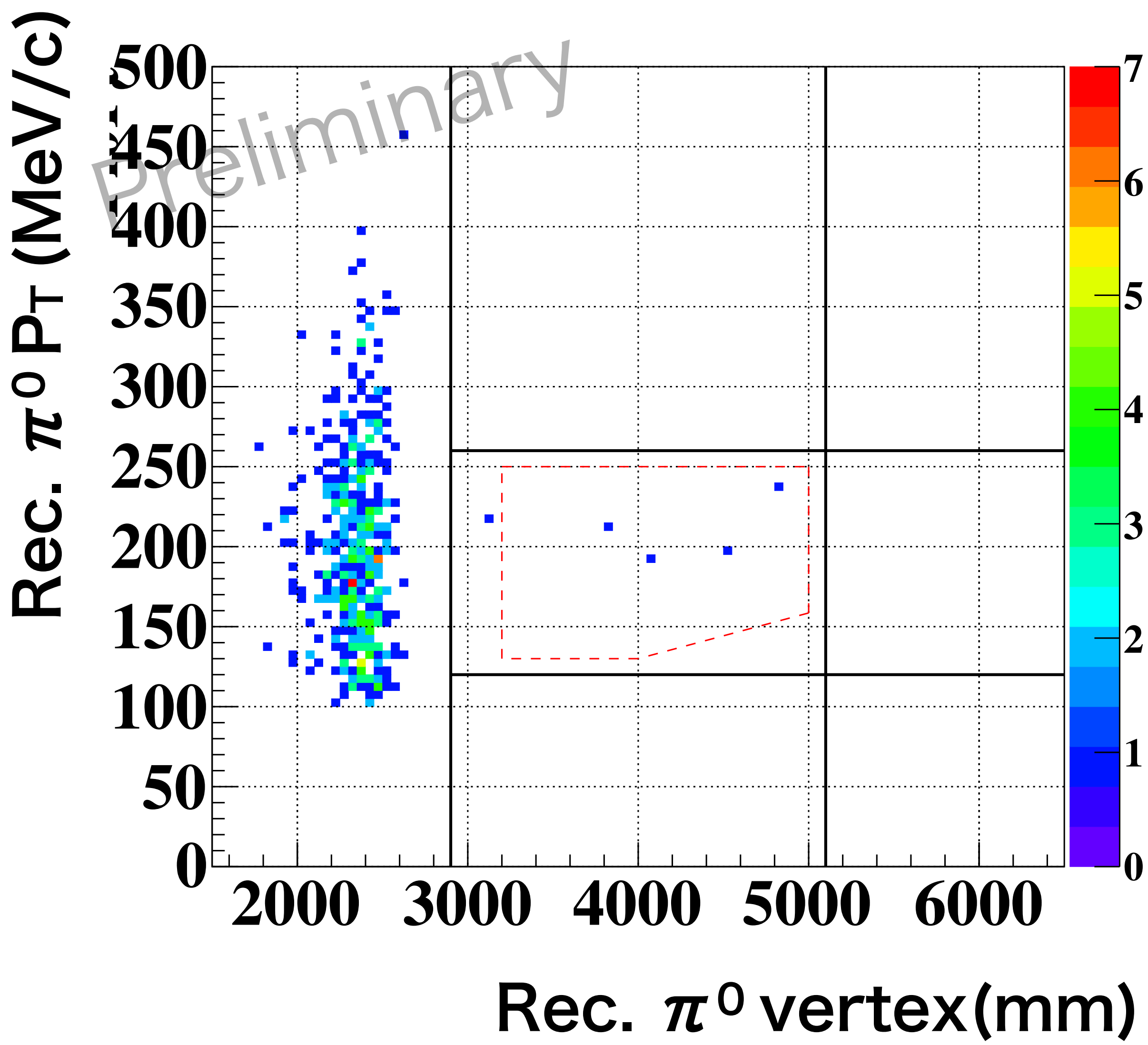


Analysis status of 2016-2018 data

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

S.E.S:6.9×10^{-10}

x1.9 better than 2015 analysis

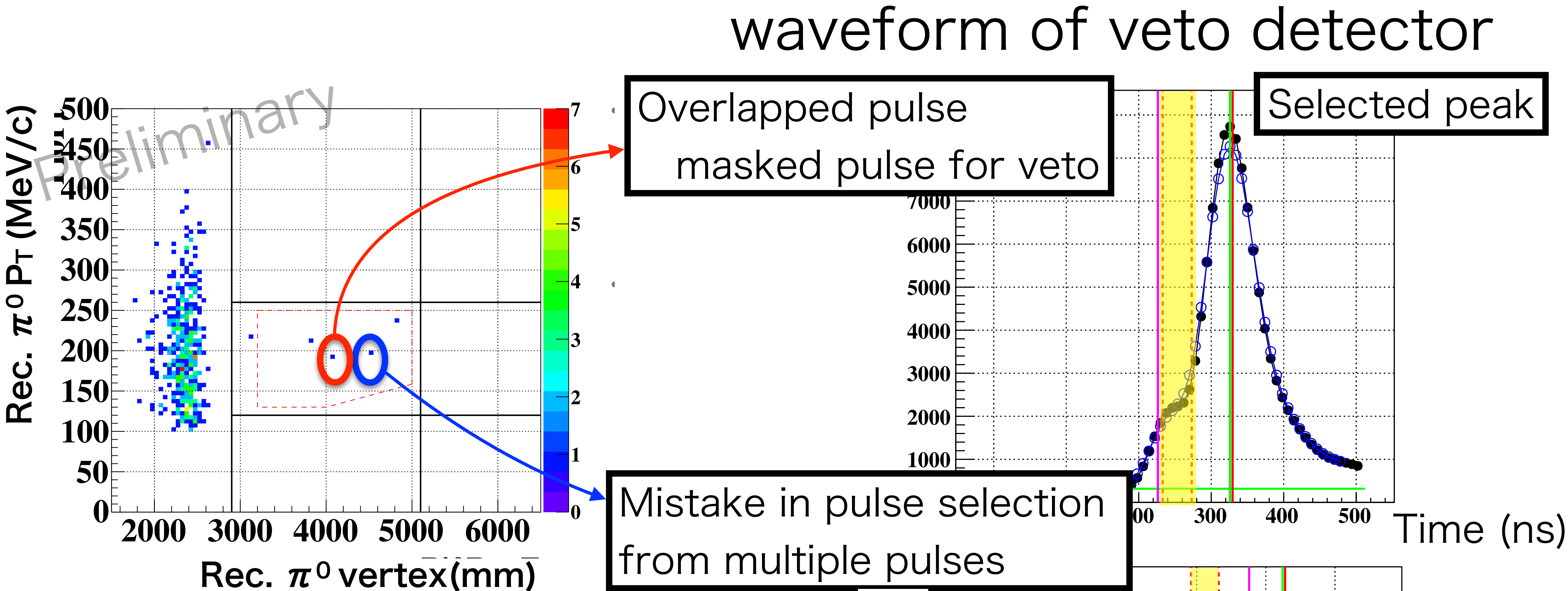


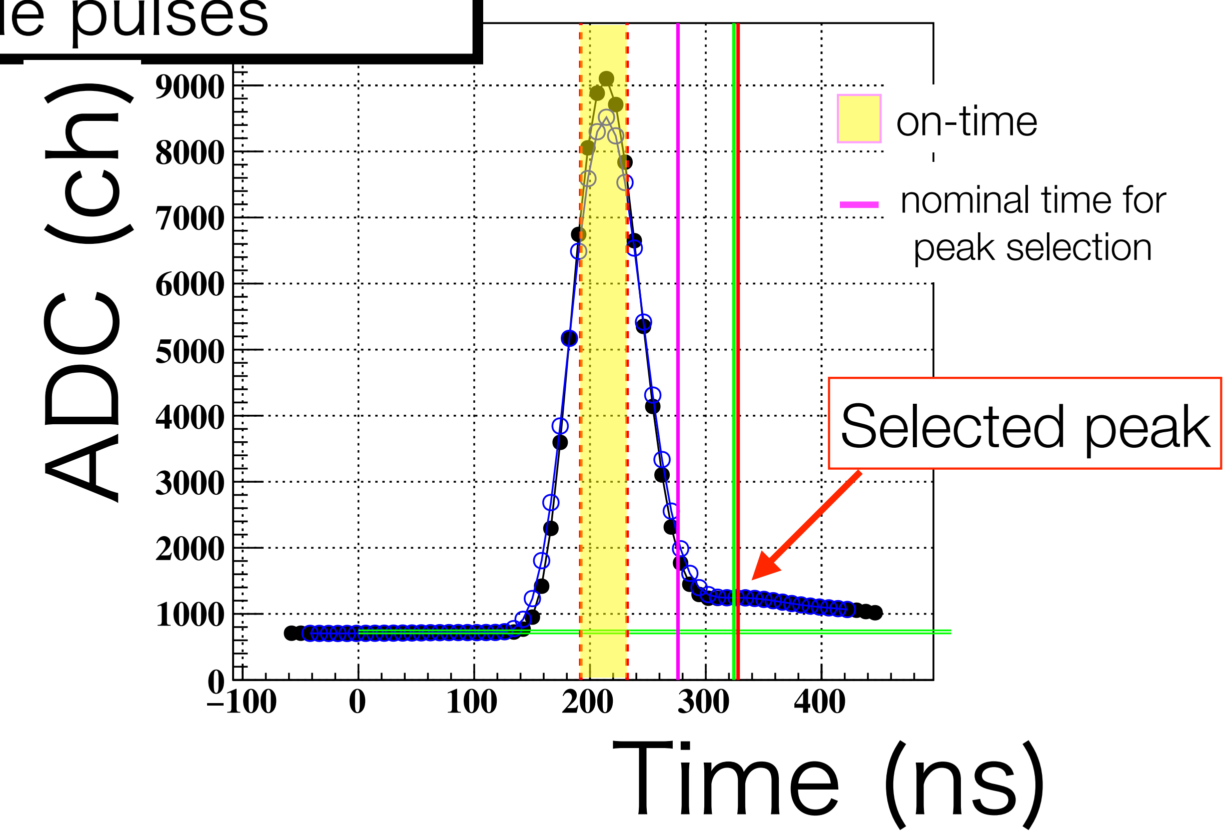
#Bkg estimation table before opening signal box

Preliminary

	#BG
$K_L\to2\pi^0$	<0.18
$K_L\to\pi^+\pi^-\pi^0$	<0.02
$K_L\to3\pi^0$+ accid.	<0.04
Ke3 + accid.	<0.09
$K_L\to2\gamma$	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

Properties of candidate events





-Mis-selection was due to mis-setting of the nominal timing.

-Corrected the setting and re-processed all events.

-No significant effect on other events.

-Decided not to take this event as a candidate: N_{obs}: 4 → 3

Updated background table (ICHEP2020)

Preliminary

source		#BG (U.L. at 90% C.L.)	#BG (U.L. at 68% C.L.)
KL	$K_L \to 2\pi^0$	<0.09	<0.05
	$K_L \to \pi^+\pi^-\pi^0$	<0.02	<0.01
	$K_L \to 3\pi^0$ (overlapped pulse)	0.01±0.01	0.01±0.01
	Ke3 (overlapped pulse)	<0.09	<0.05
	$K_L \to 2\gamma$	0.001±0.001	0.001±0.001
	Ke3 (π^0 produced)	<0.04	<0.02
	Ke3 (π^+ beta decay)	<0.01	<0.01
	radiative Ke3	<0.046	<0.023
	Ke4	<0.04	<0.02
	$K_L \to ee\gamma$	<0.09	<0.05
	$K_L \to \pi^+\pi^-$	<0.03	<0.02
	$K_L \to 2\gamma$ (core-like)	<0.11	<0.06
	$K_L \to 2\gamma$ (halo)	<0.19	<0.10

New (Ke3 (π^0 produced) through $K_L \to 2\gamma$ (halo))

Preliminary

source		#BG (U.L. at 90% C.L.)	#BG (U.L. at 68% C.L.)
$K^\pm$	$K^\pm \to \pi^0\pi^\pm$	0.03±0.03	0.03±0.03
	$K^\pm \to \pi^0 e^\pm \nu$	**0.30±0.09**	**0.30±0.09**
	$K^\pm \to \pi^0 \mu^\pm \nu$	<0.07	<0.04
Neutron	Upstream π^0	0.001±0.001	0.001±0.001
	Hadron cluster	0.02 ±0.00	0.02 ±0.00
	CV-π^0	<0.10	<0.05
	CV-η	0.03±0.01	0.03±0.01
Total	central value	0.39(±0.10)	0.39(±0.10)

New ($K^\pm$ rows)

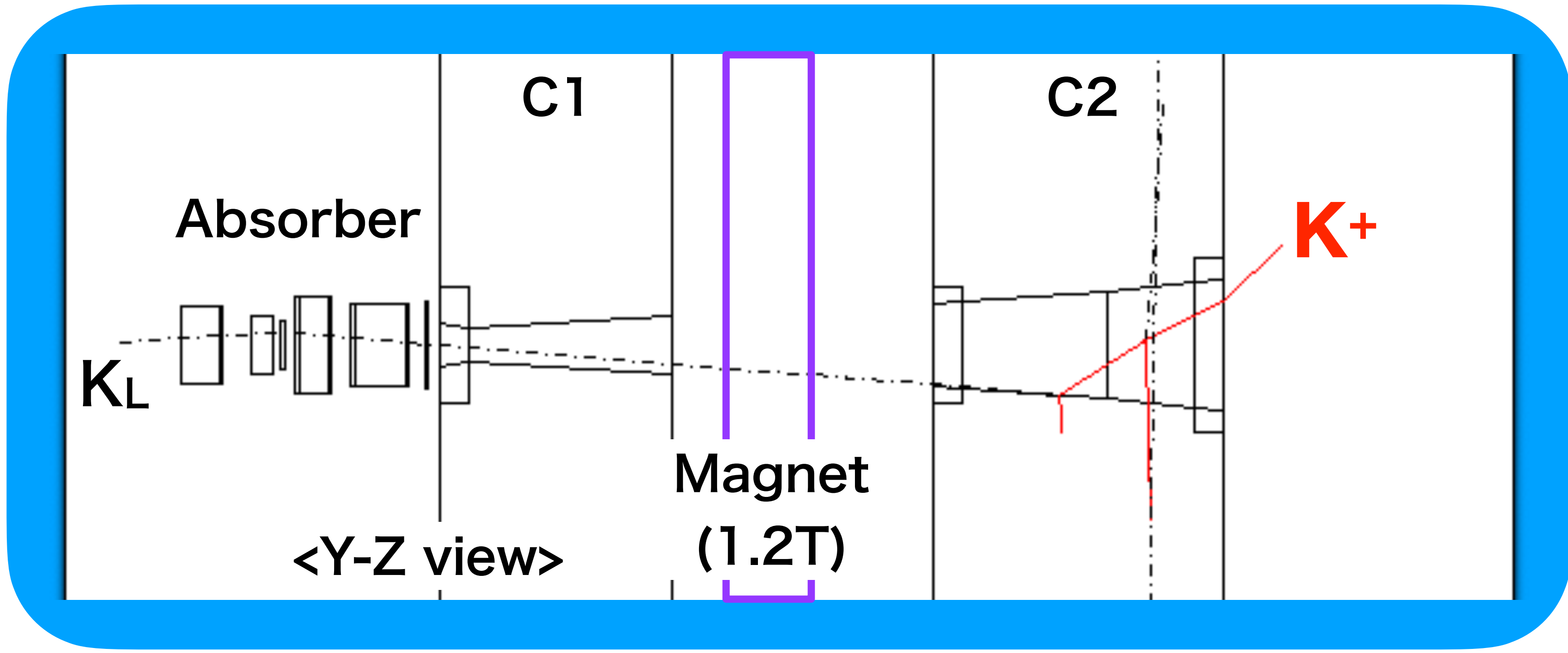
$K^\pm$	Branching ratio
$K^\pm \to \pi^0\pi^\pm$	20.7%
$K^\pm \to \pi^0 e^\pm \nu$	5.1%
$K^\pm \to \pi^0 \mu^\pm \nu$	3.4%

Charged Kaon Backgrounds

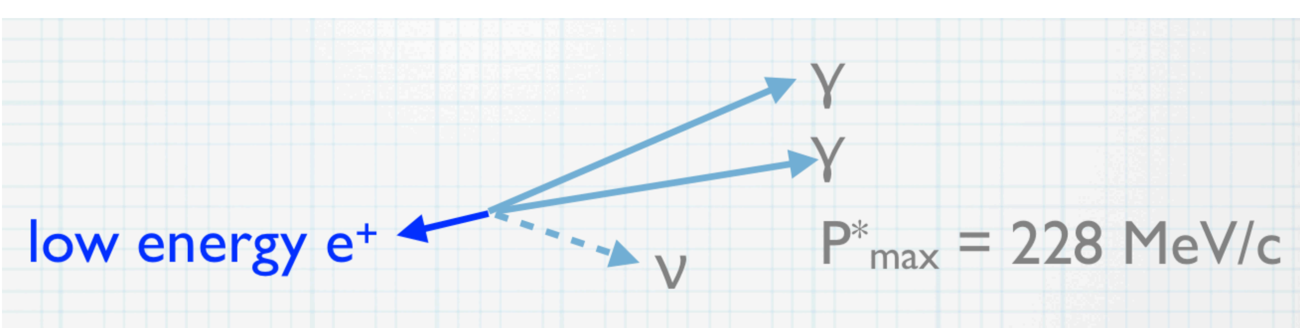
K^+ generated in the beam line

$K^+/K_L \sim 1.3\times10^{-6}$

Based on GEANT3

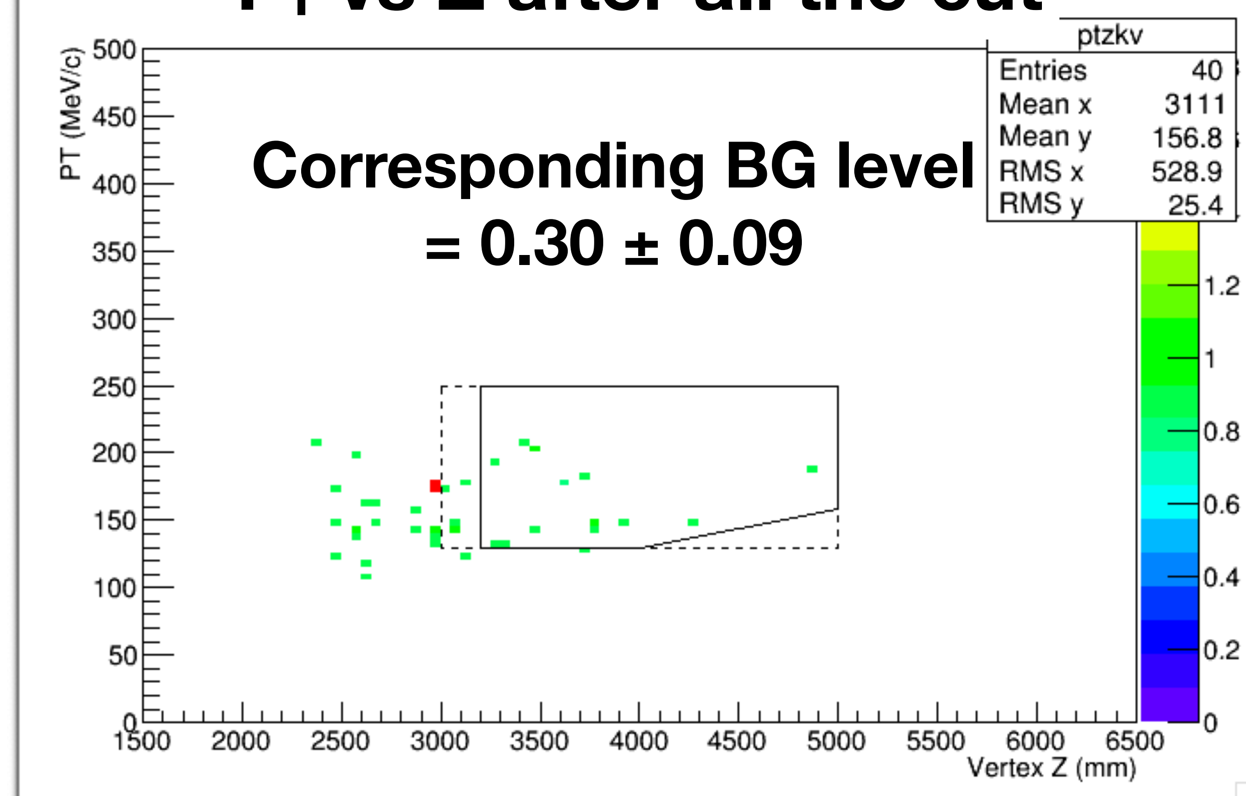


$$K^{\pm} \rightarrow \pi^0 e^{\pm} \nu$$



#Bkg events depends on $K^{\pm}$ flux

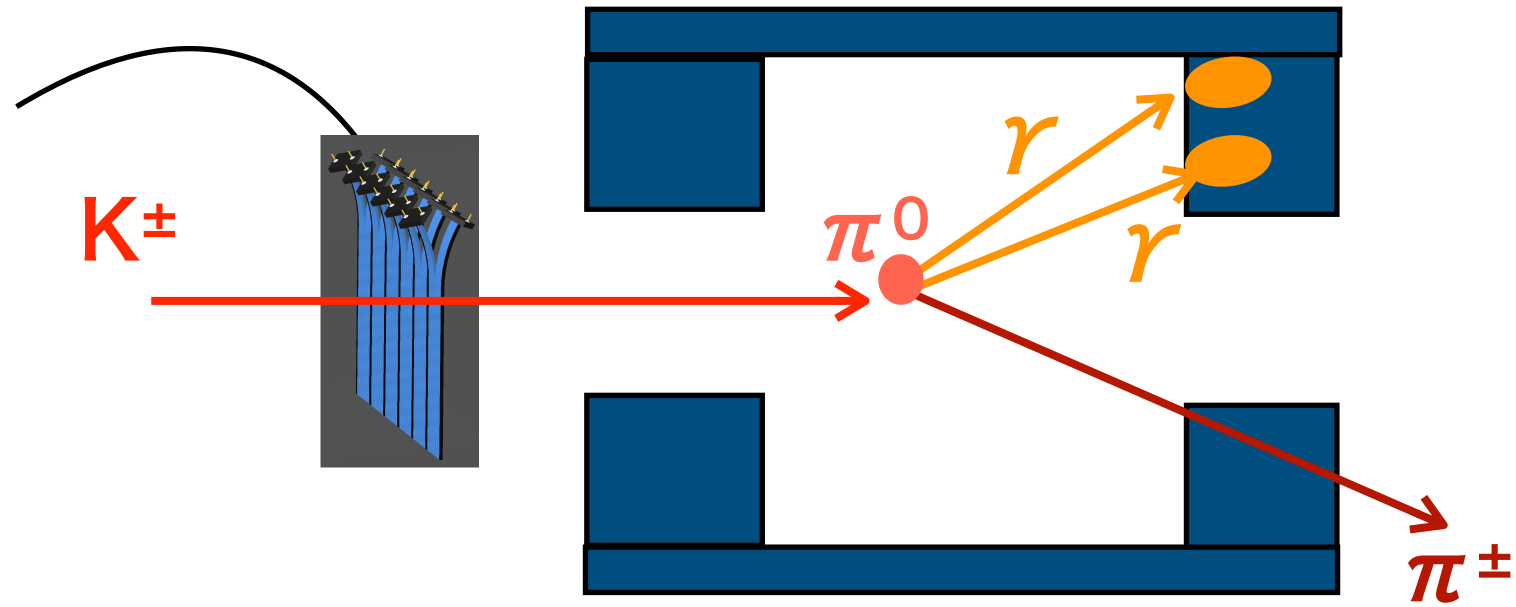
P_T vs Z after all the cut



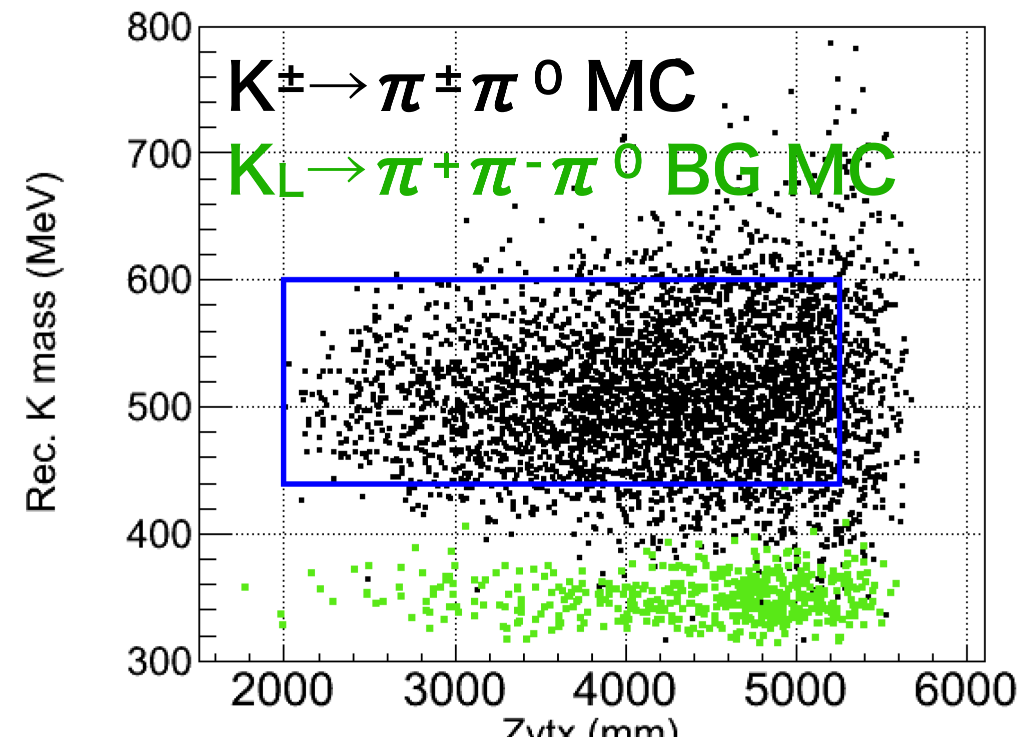
K± flux measurement

Installed a new detector

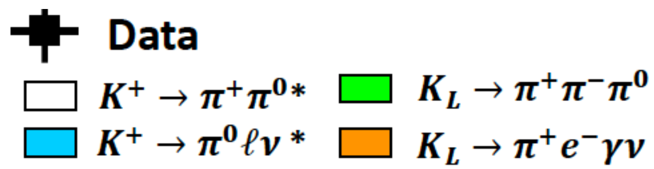
$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}$



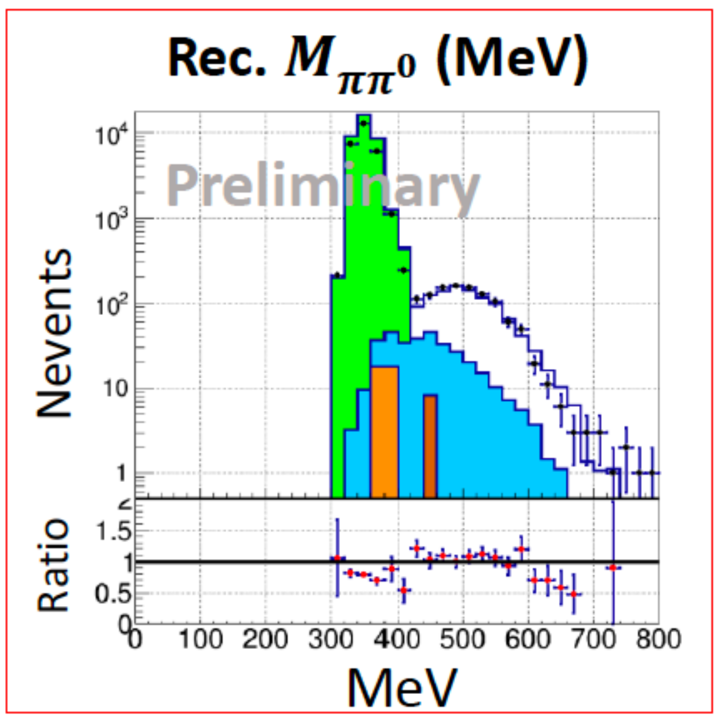
2020 May-Jun Run
- -Took data for K+ flux measurement with a dedicated trigger
- -Checked the performance and effect of upstream charged veto counter



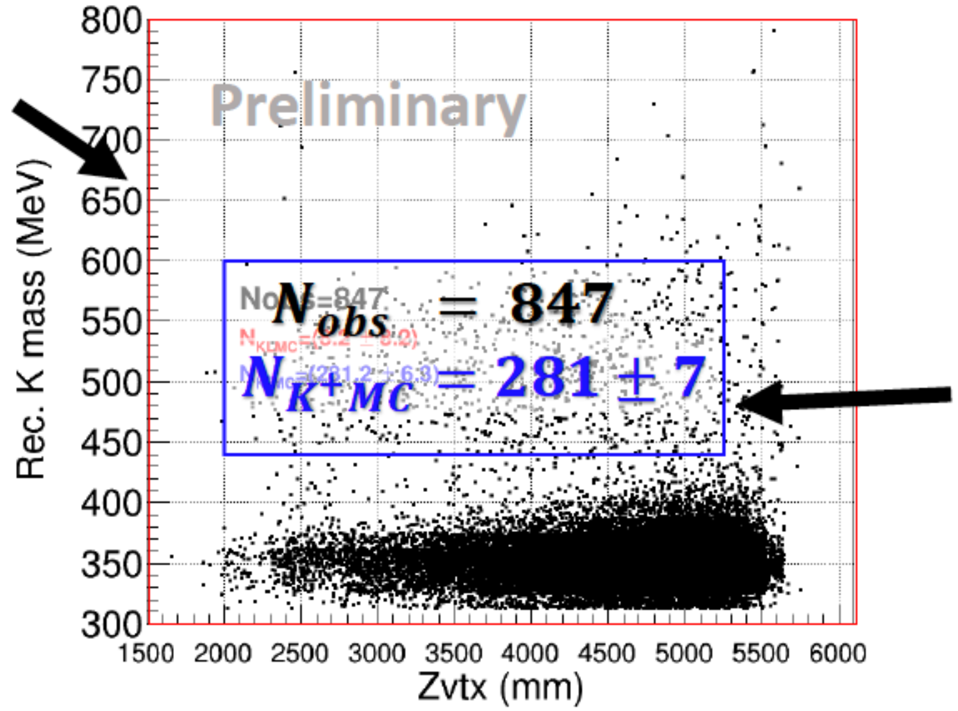
Measured K± flux



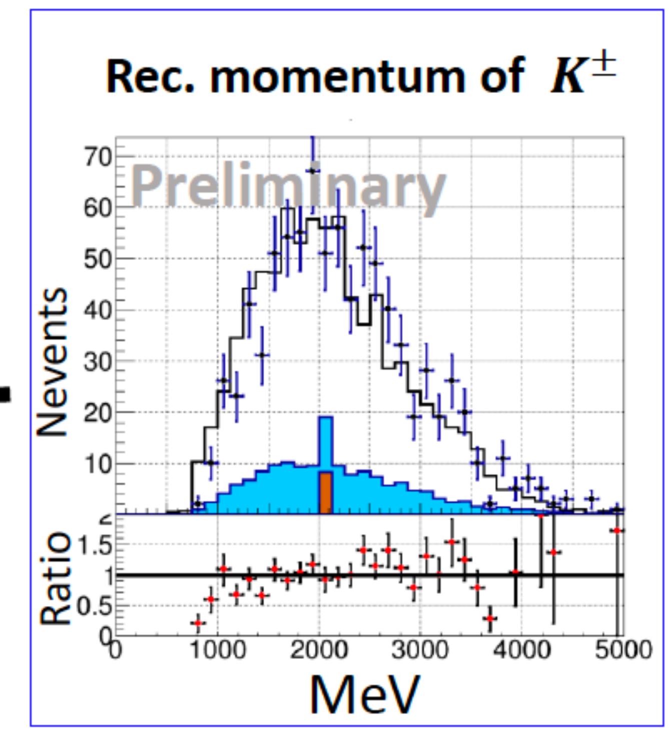
Projected mass distribution



Data in 2020 run



Distribution of events in the signal region



- The distribution of selected events are well reproduced by MC simulation of K± decays (K+ distribution is scaled by best fit)

- K± flux ratio:

$$R_{K^\pm} = F_{K^\pm}/F_{K_L}$$

- Comparison between data and MC

$$R_{K^\pm}^{meas.}/R_{K^\pm}^{MC} = 3.0 \pm 0.1$$

Measured K± flux is 3 times larger than MC.

Updates of BG table with $K^{\pm}$ measurement

Preliminary

source		#BG (90% C.L.)	#BG (68% C.L.)
KL	$K_L \to 2\pi^0$	<0.09	<0.05
	$K_L \to \pi^+\pi^-\pi^0$	<0.02	<0.01
	$K_L \to 3\pi^0$ (overlapped pulse)	0.01±0.01	0.01±0.01
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	$K_L \to \pi^+\pi^-$	<0.03	<0.02
	$K_L \to 2\gamma$ (core-like)	<0.11	<0.06
	$K_L \to 2\gamma$ (halo-K)	<0.19	<0.10

Preliminary

source		#BG (90% C.L.)	#BG (68% C.L.)
K+/-	$K^{\pm} \to \pi^0\pi^{\pm}$	0.09±0.09	0.09±0.09
	$K^{\pm} \to \pi^0 e^{\pm}\nu$	0.90±0.27	0.90±0.27
	$K^{\pm} \to \pi^0 \mu^{\pm}\nu$	<0.21	<0.12
Neutron	Upstream π^0	0.001±0.001	0.001±0.001
	Hadron cluster	0.02 ±0.00	0.02 ±0.00
	CV-pi0	<0.10	<0.05
	CV-eta	0.03±0.01	0.03±0.01
Total	central value	1.05±0.28	1.05±0.28

New

New

-BG table was updated based on the result of the $K^{\pm}$ flux

-Tentative total BG estimation: 1.05±0.28

→N_{obs}(3) is not significantly larger than total #BG.

We will finalize the analysis and report the results in this autumn

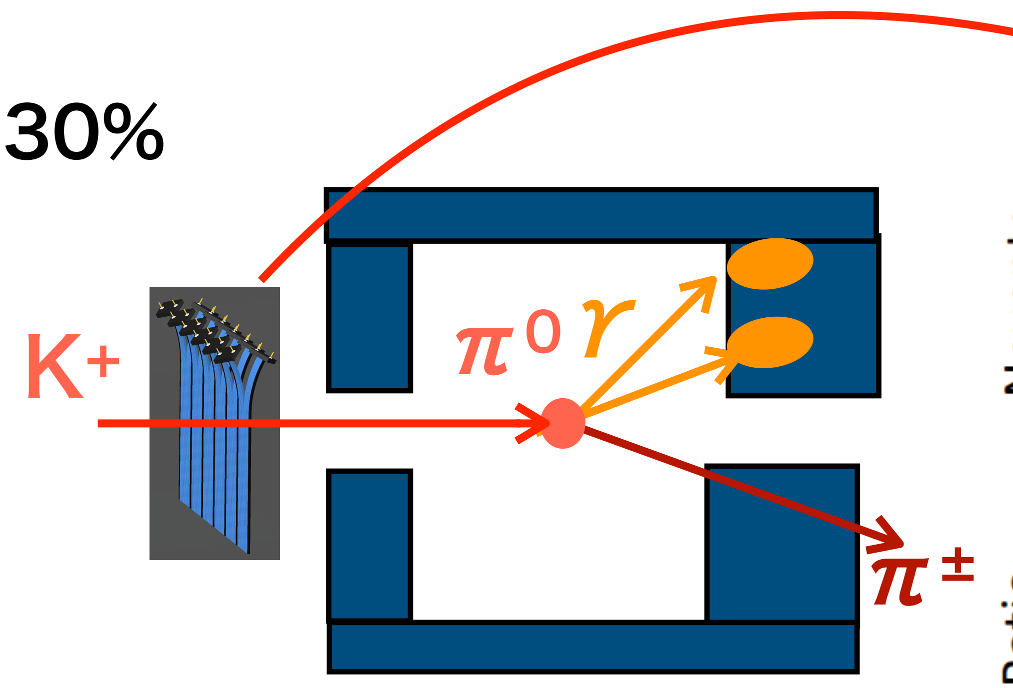
To suppress K± BG

Prototype module has 30% inefficiency due to

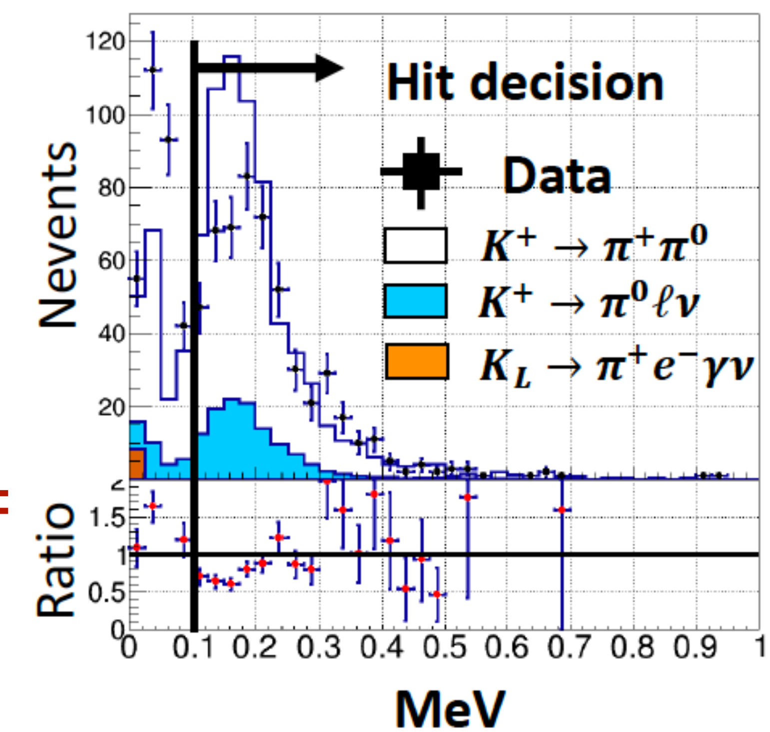
①Limited coverage.

②Insensitive region in the fiber.

③Noise fluctuation.

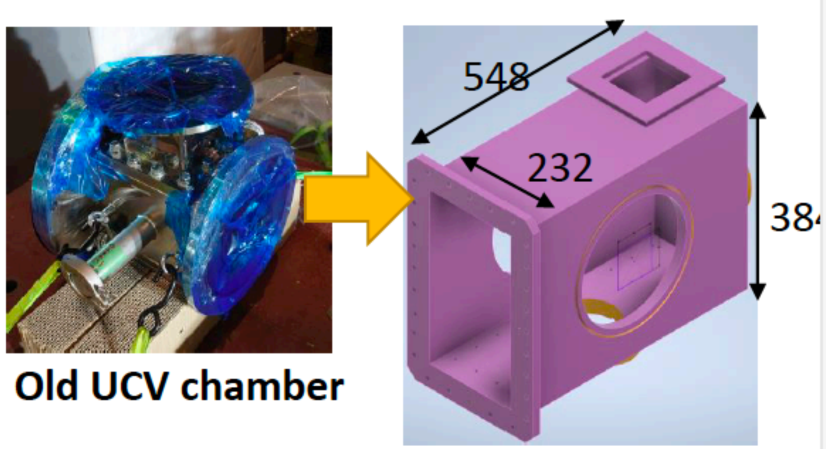


Energy distribution



->Developing a new upstream charged veto counter

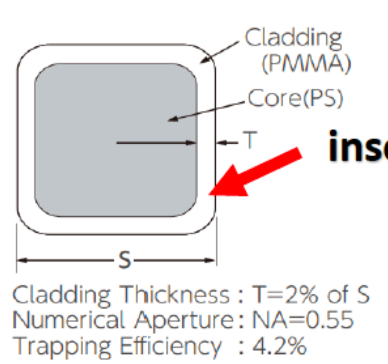
①Enlarge the detector



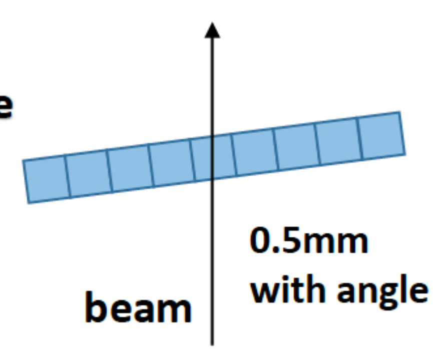
Old UCV chamber

New UCV chamber

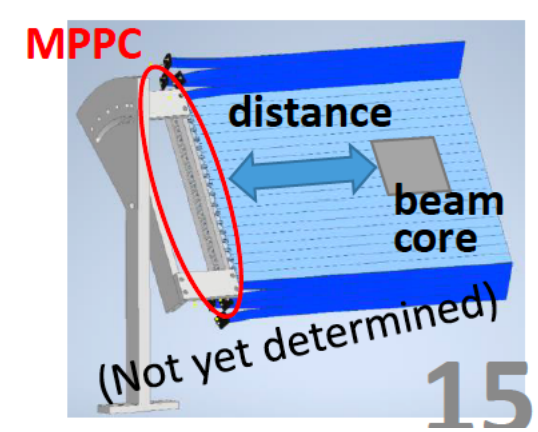
②Tilt the detector



From Kuraray's brochure



③Keep away from beam core



Prospects for future runs

- Have 2 month beam time before 2021 long shutdown.
  -> We can reach a sensitivity of ∼3 x 10^{-10} by suppressing $K^{\pm}$ BG.
- After long shutdown,
  ->Beam power will increase up to 100 kW. (Current power:50kW)
  ->Slow-extraction spill structure would be better.

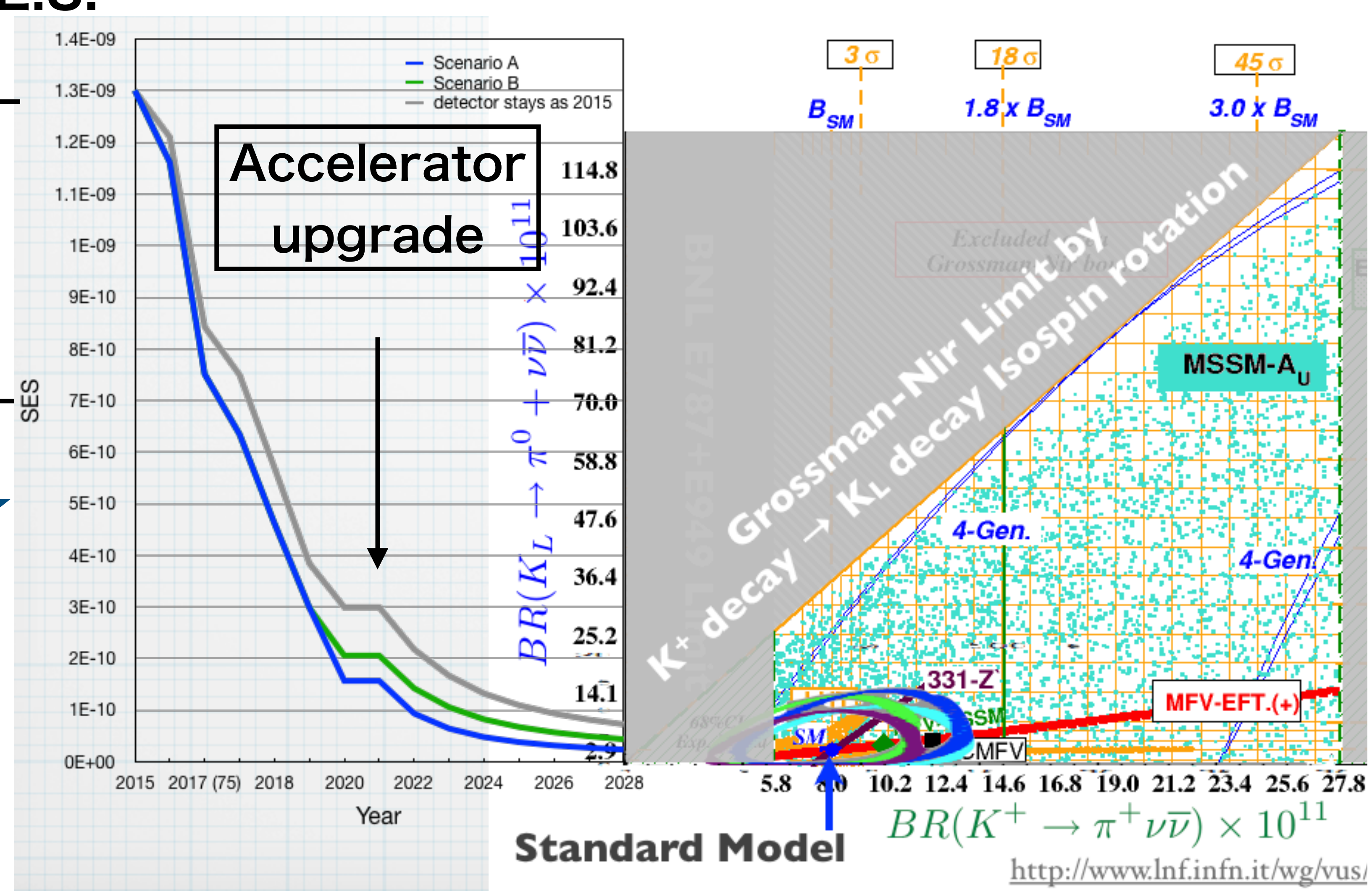
S.E.S.

2015 1.3×10^{-9}

2016-2018
7×10^{-10}

By 2021:3×10^{-10}

By 2025:$O(10^{-11})$



Summary

- The KOTO experiment studies the $K_L \to \pi^0 \nu \nu$ decay
- 3 events were observed in 2016-2018 data.
  - Found a possibility of K± background contamination.
  - Measured $K^{\pm}$ flux was 3 times larger than the MC expectation.
  - Updated BG level is 1.05±0.25 and not negligible compared with N_{obs}(=3)

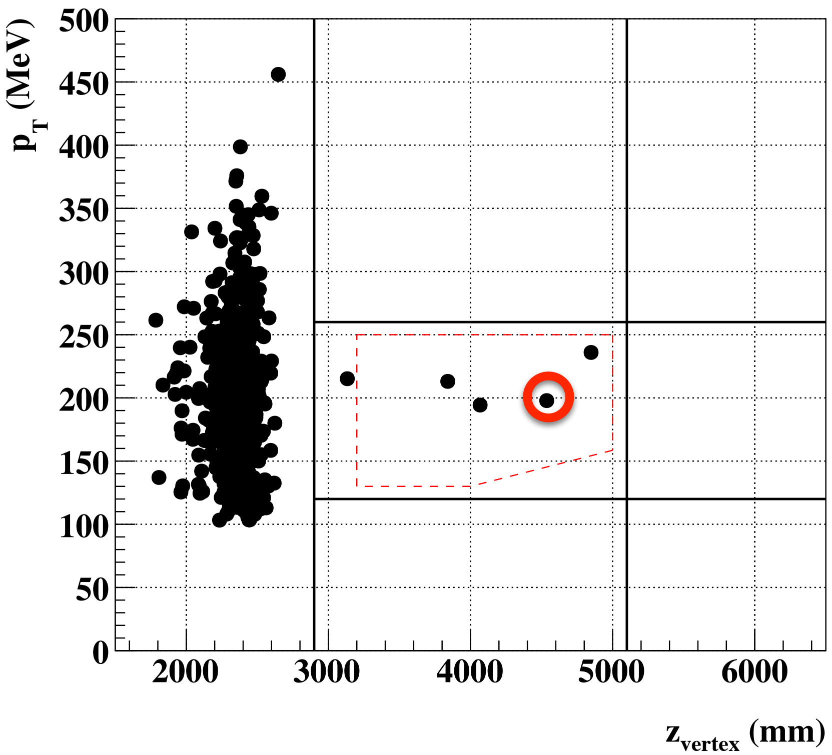
⇒ **We will finalize the analysis and report the results in this autumn**

- Developing a new detector to suppress $K^{\pm}$ BG and Continue to take physics data to reach the sensitivity of O(10^{-11}).

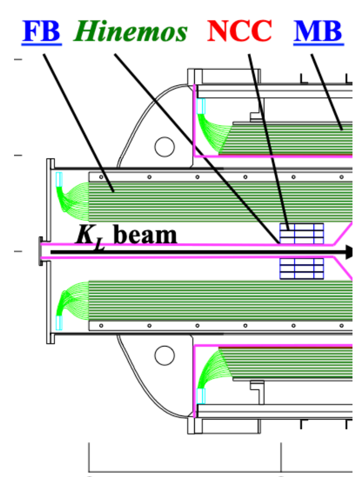
Backup

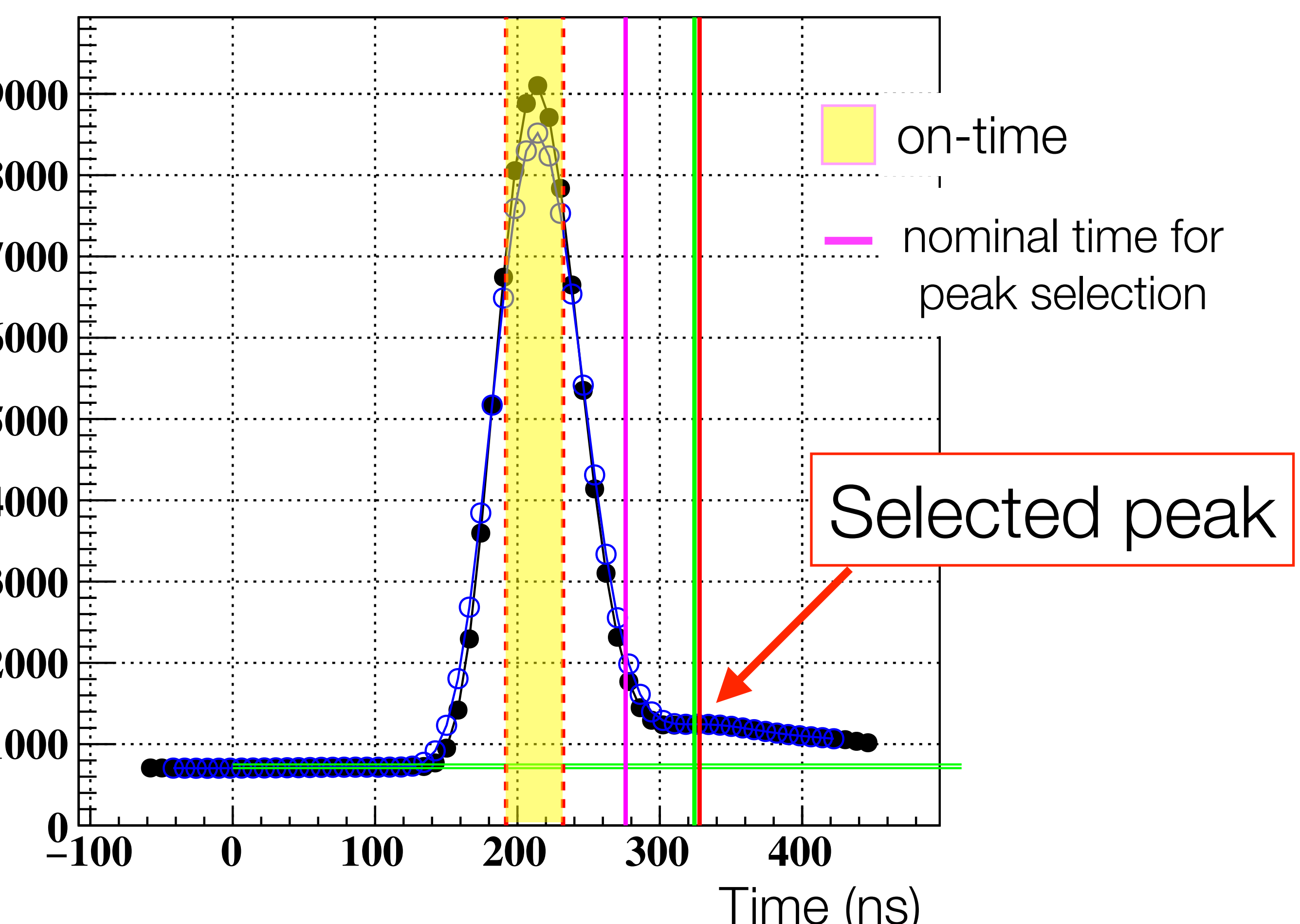
Property of Event #3

This event remained due to a mistake…



- Event in Run74
- CV hits in neighboring two strips (each less than the threshold)
- **HINEMOS (inner scintillator of NCC) had a hit but the timing was mis-measured.**



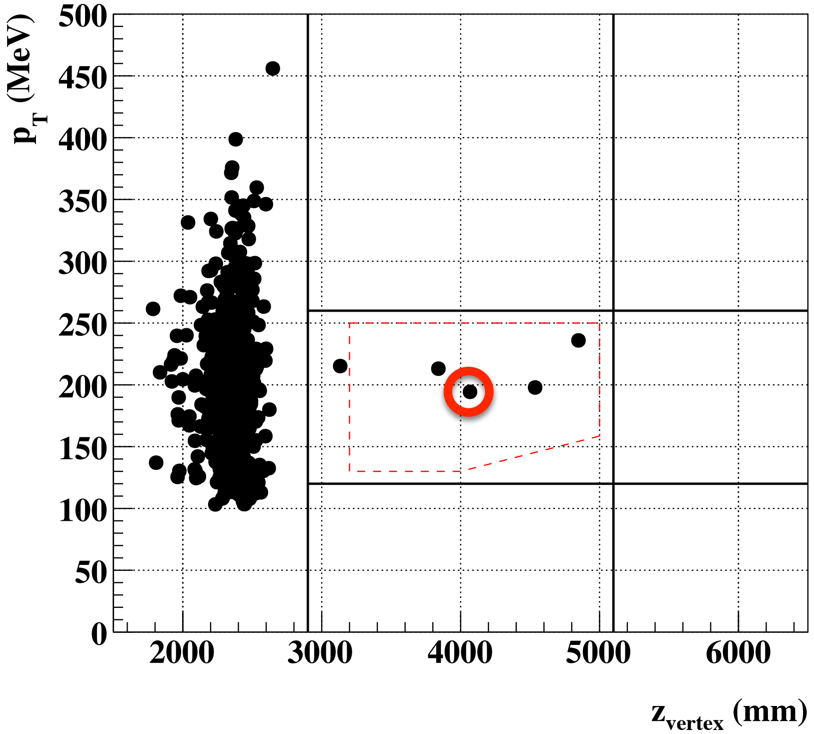


The on-time hit was lost due to a wrong parameter for peak selection in this run period.

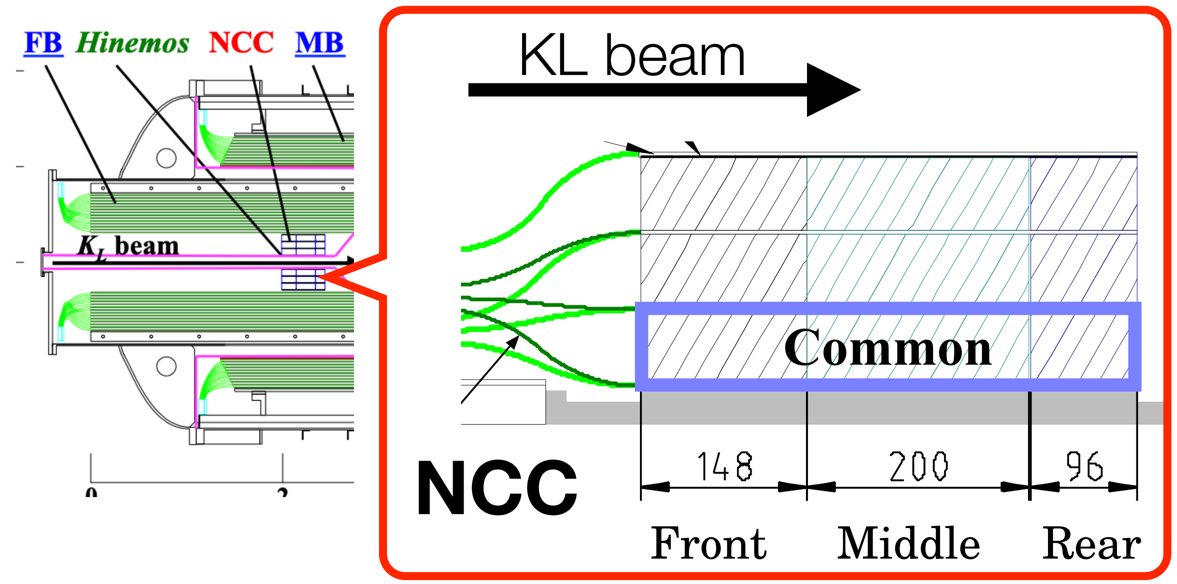
(The large deviation existed in this detector and in this run period.)

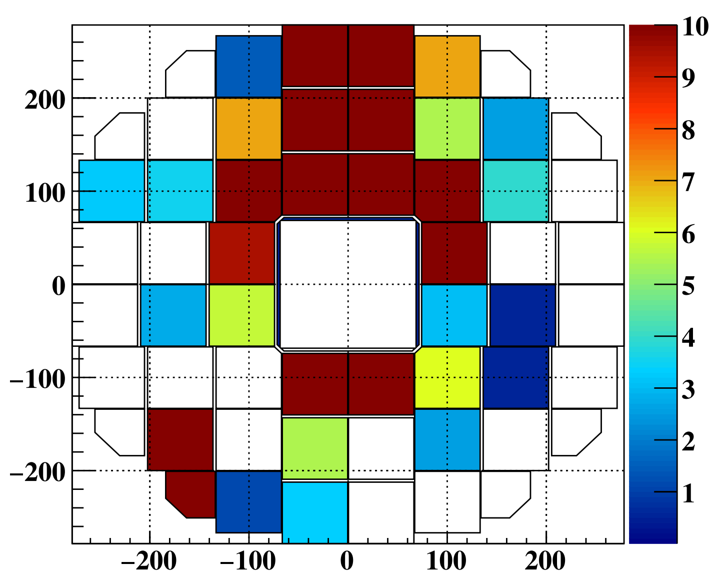
Property of Event #1

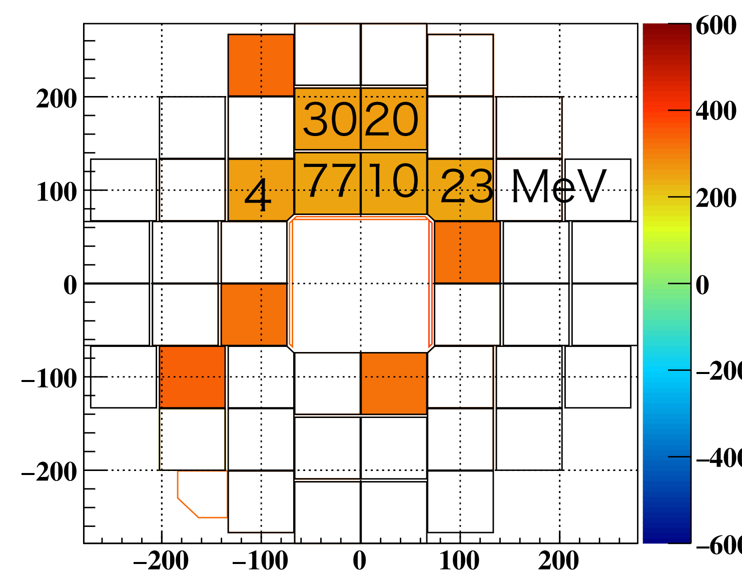
This must be accounted in our BG estimation

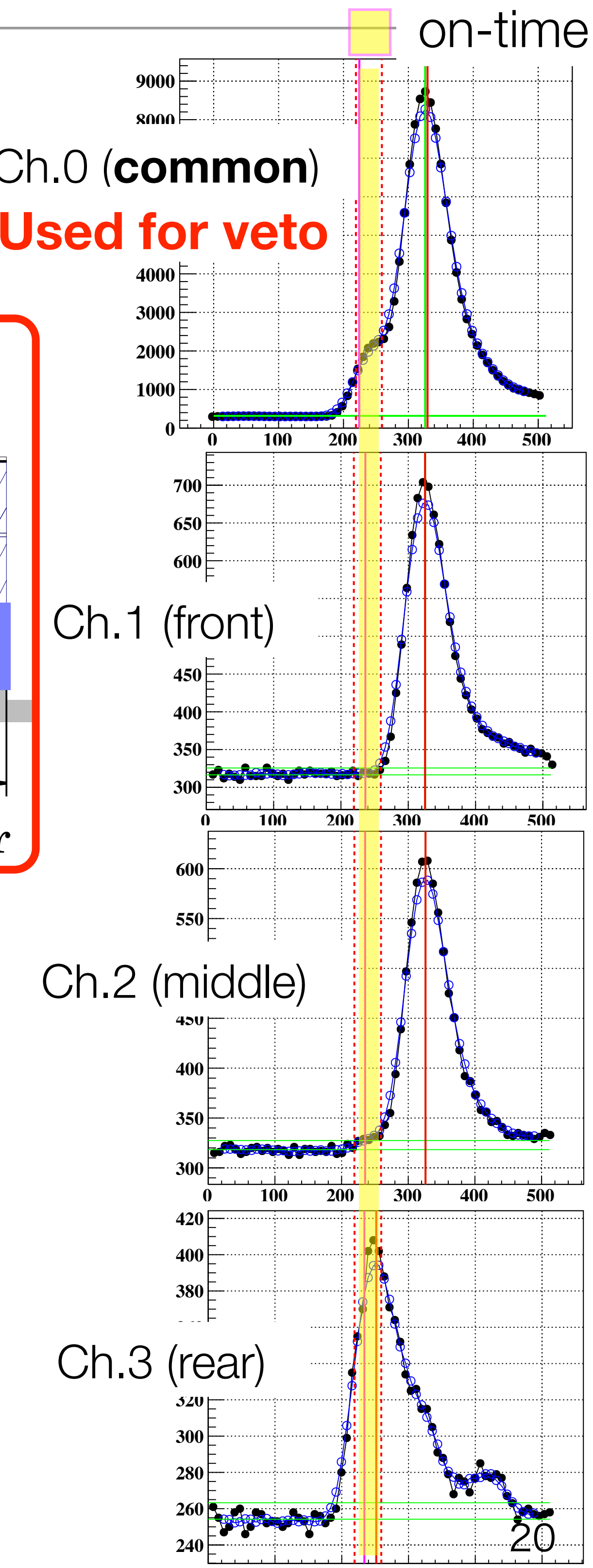


- Event in Run69
- **Overlapped pulse in NCC**



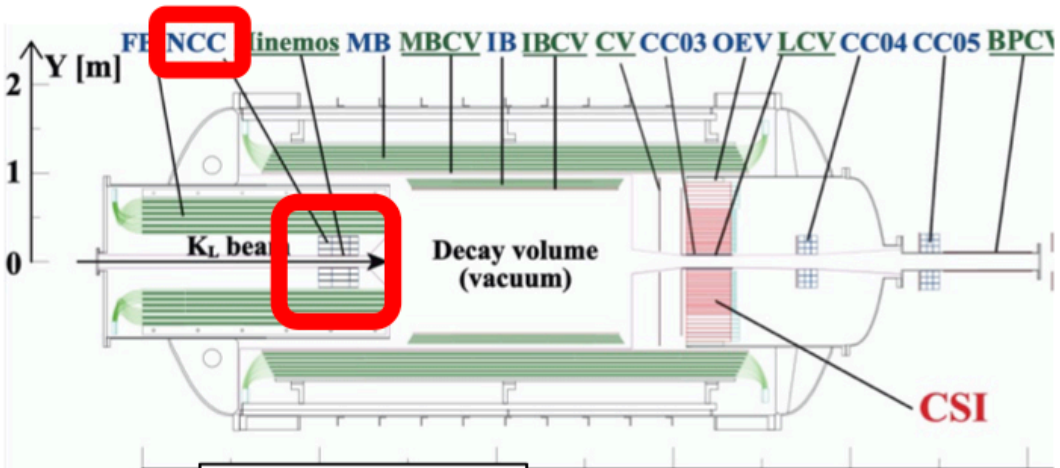




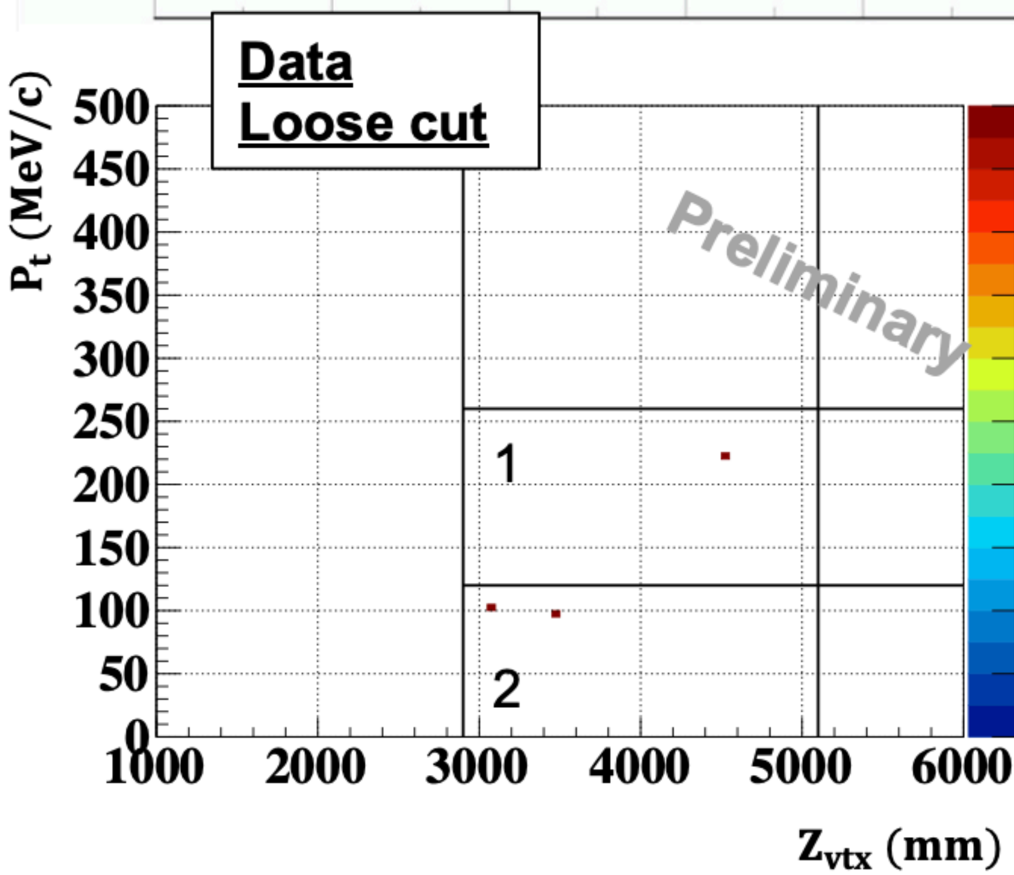


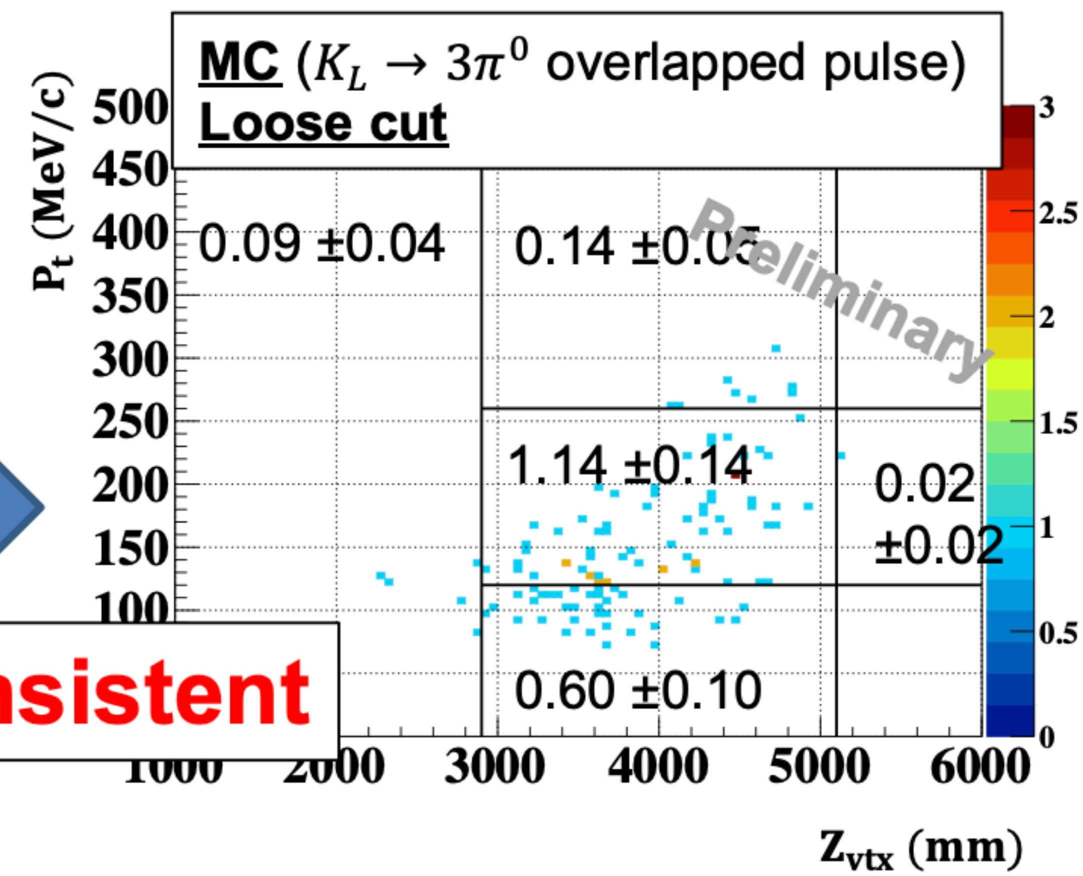
Study with loose cuts

- Study with loose cuts to enhance overlapped pulse events



* Loose cuts
- Selected events vetoed by overlapped pulse discriminator
- Loose NCC veto was applied to avoid online veto effect

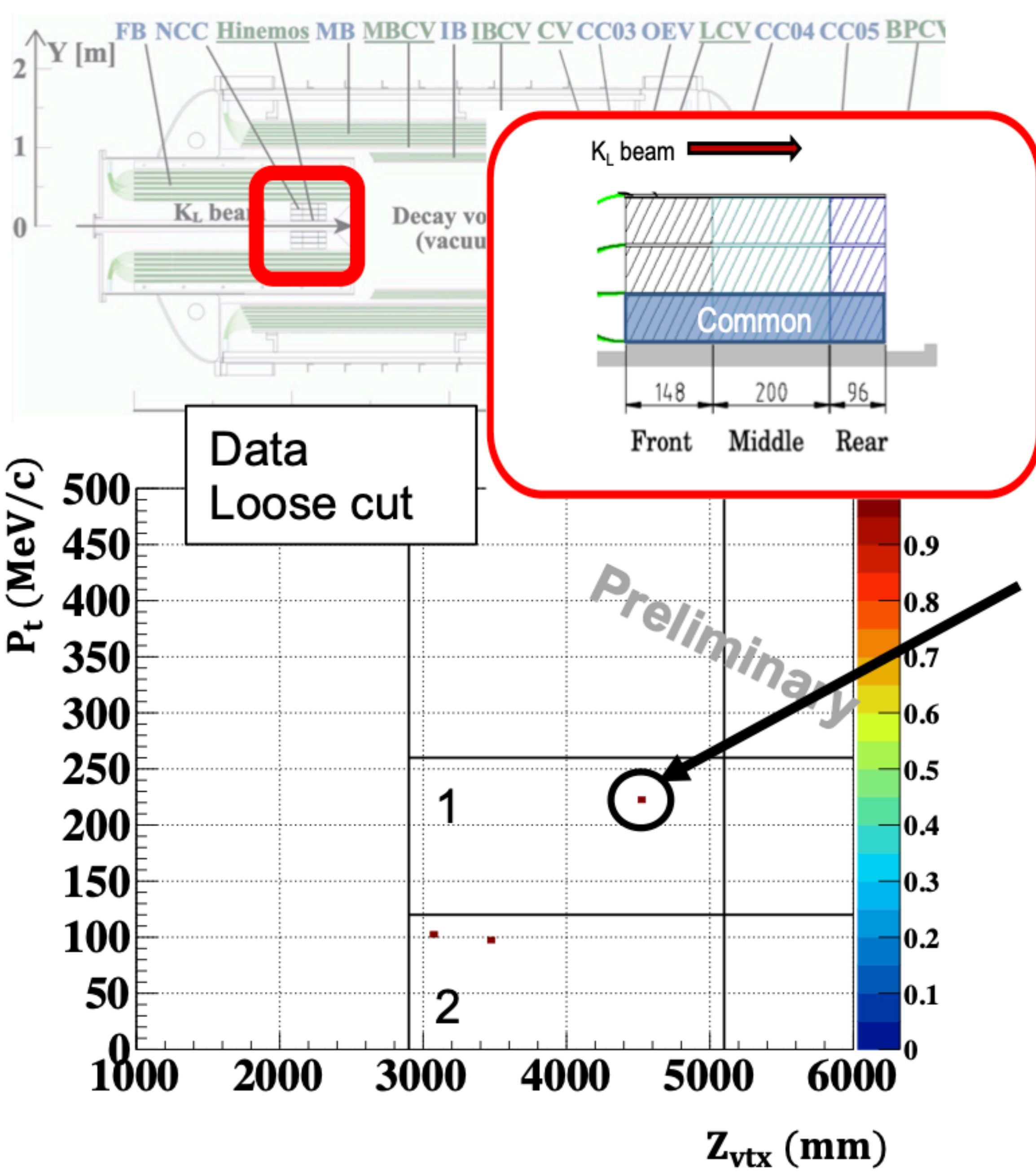


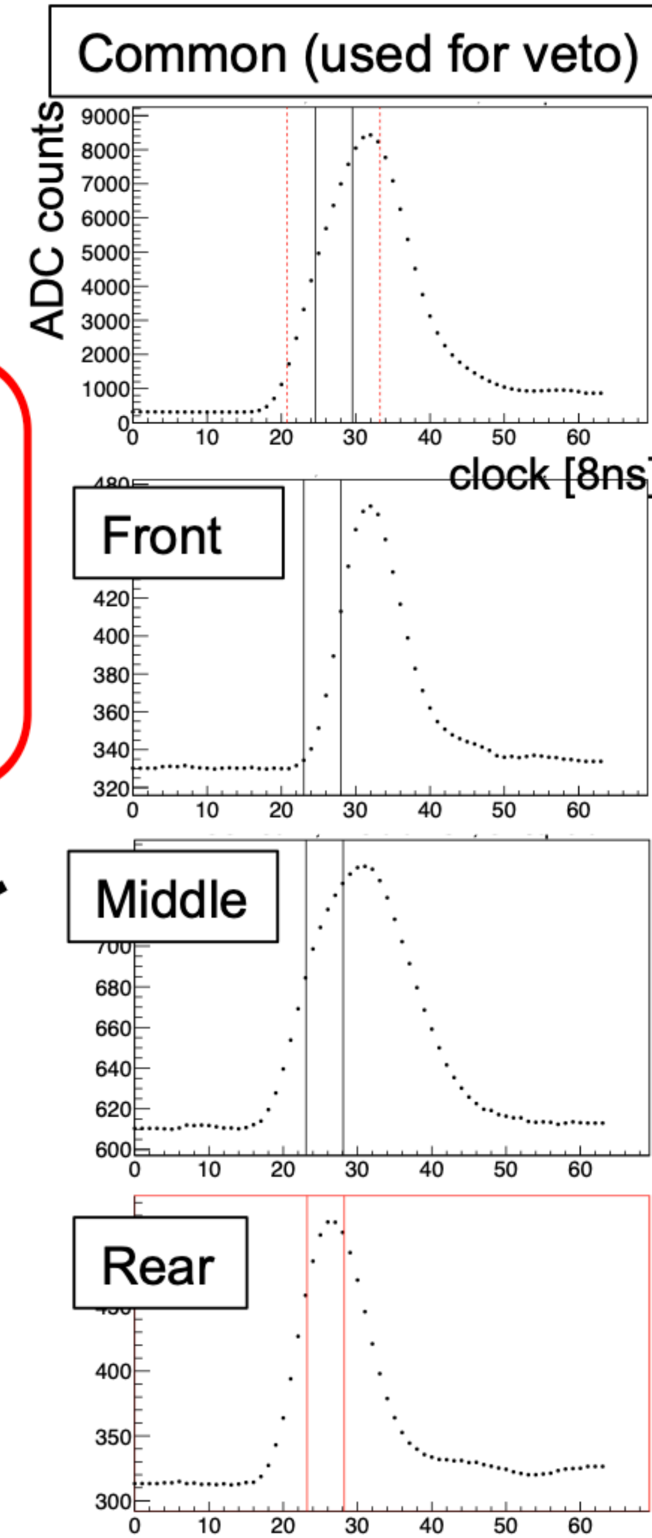


Consistent

Study with loose cuts

- One of the waveforms display





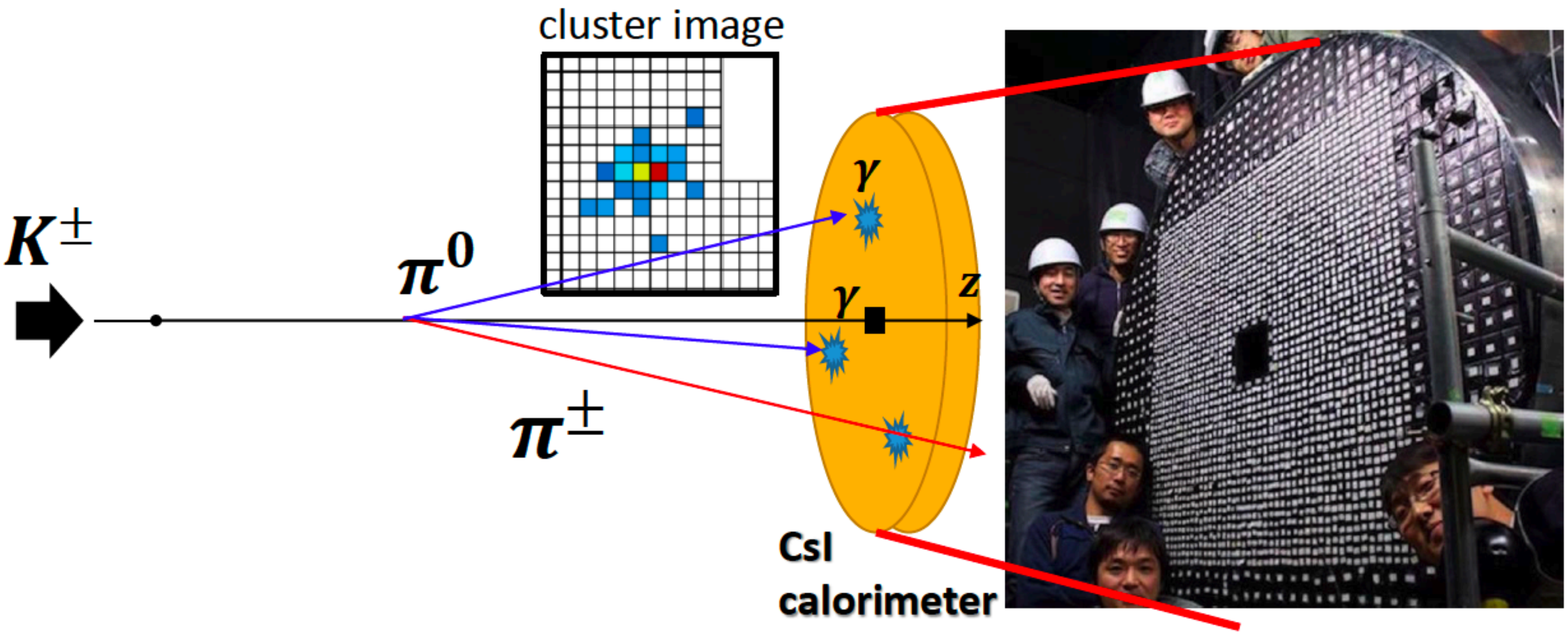
The other two events also had similar overlapped pulse

→

The discriminator could select overlapped pulse events and MC reproducibility was good

Measurement of $K^{\pm} \to \pi^{\pm}\pi^{0}$ decay

7



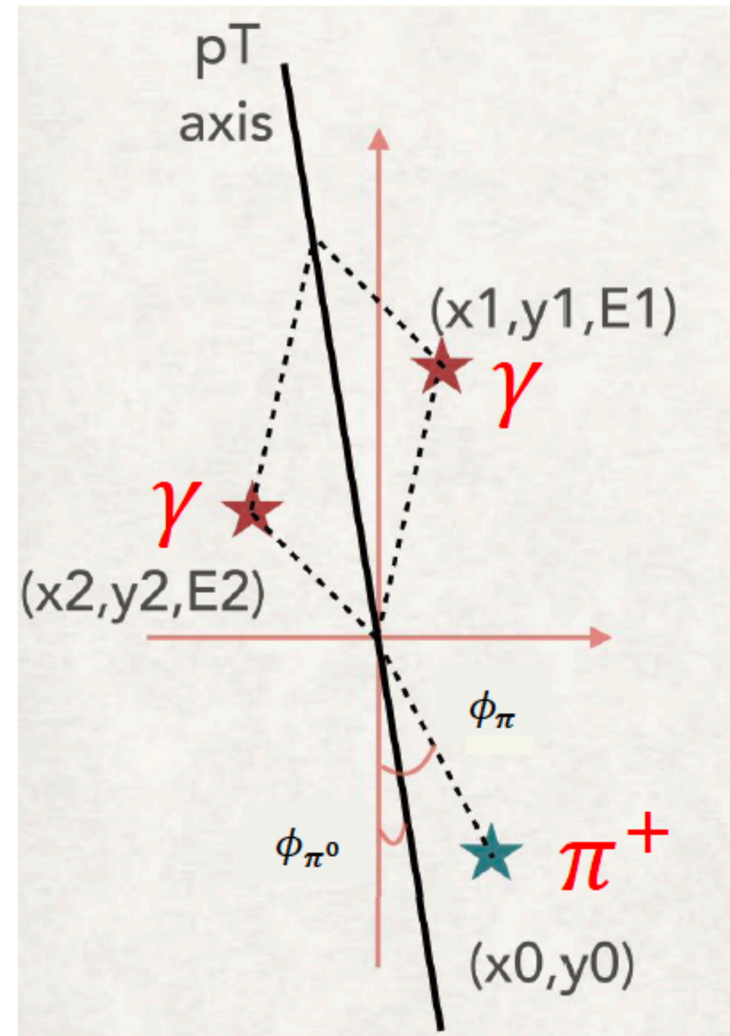
- Measure $K^{\pm} \to \pi^{\pm}\pi^{0}$ decay (BR=20%)
- Trigger three cluster events in the calorimeter
- Reconstruction
  - For two neutral hits, impose $M_{\gamma\gamma} = M_{\pi^0}$ → define $\boldsymbol{K}^{\pm}$ decay vertex
  - For a charged hit, from the hit position and assumption of Pt balance of $\pi^{\pm}$ and π^{0}
    → calculate the magnitude of the momentum
    → reconstruct four vectors of all the particles
  - Calculate $M_{\pi\pi^0}$

Reconstruction of $K^+ \to \pi^+\pi^0$

1. Repeat following procedure 2-6 for all the combinations
2. Reconstruct a π^0 from two γ's
   - ✓ Determine Z position of vertex assuming a π^0 decays on z-axis.
   - ✓ Polar angles of three momenta are determined.
   - ✓ Energies of γ clusters are reliable, so two four-vectors p_{γ_1} and p_{γ_2} are also determined
3. Calculate p_t of π^0 (← magnitude)
4. Assuming the transverse momentum of K^+ is zero, momentum conservation in the transverse plane gives

   $$|\vec{p}_\pi| = \frac{p_t^{\pi^0}}{\sin\theta_\pi}$$ → p_π is determined
5. Calculate *shape*-χ^2 of three clusters.
6. Sort all the combinations with respect to smallness of $\chi^2_{\gamma_1} + \chi^2_{\gamma_2}$. Choose the smallest.
7. For momenta of all the particles are now on ready
8. Calculate the invariant mass of K^+ as:

$$M_{\pi^0\pi} = \sqrt{(p_{\gamma_1} + p_{\gamma_2} + p_\pi)^2}$$

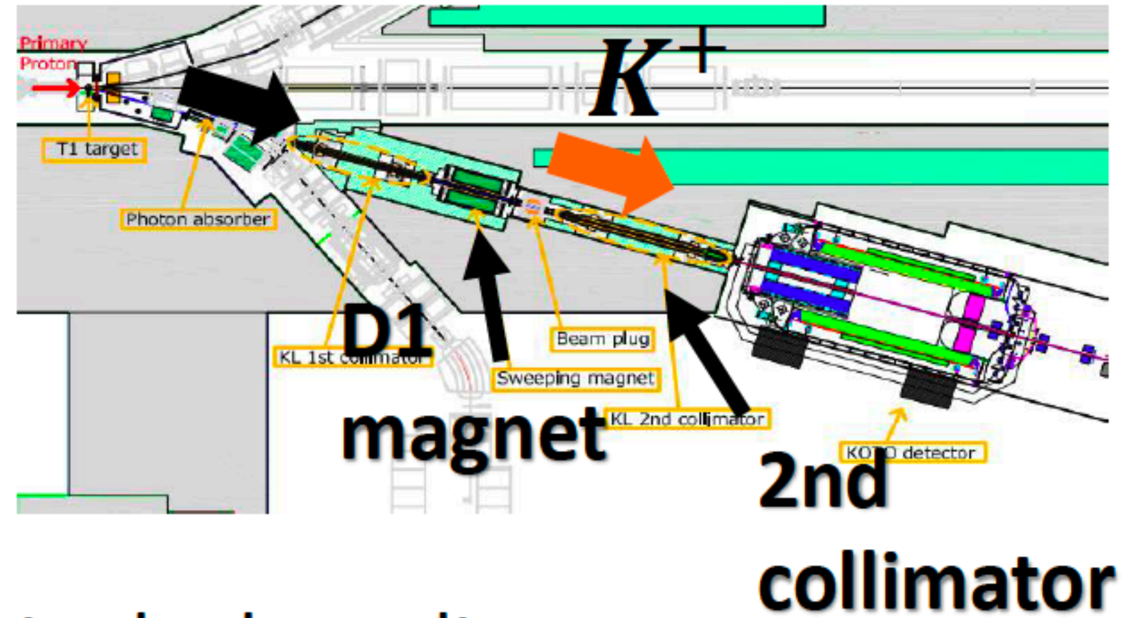


KOTO CSI calorimeter cannot directly measure momentum of π^+, but can measure hit position.

shape-χ^2 represents how the cluster's 2D energy deposit is likely to be that of γ. If a cluster is made by π^+, this becomes large.

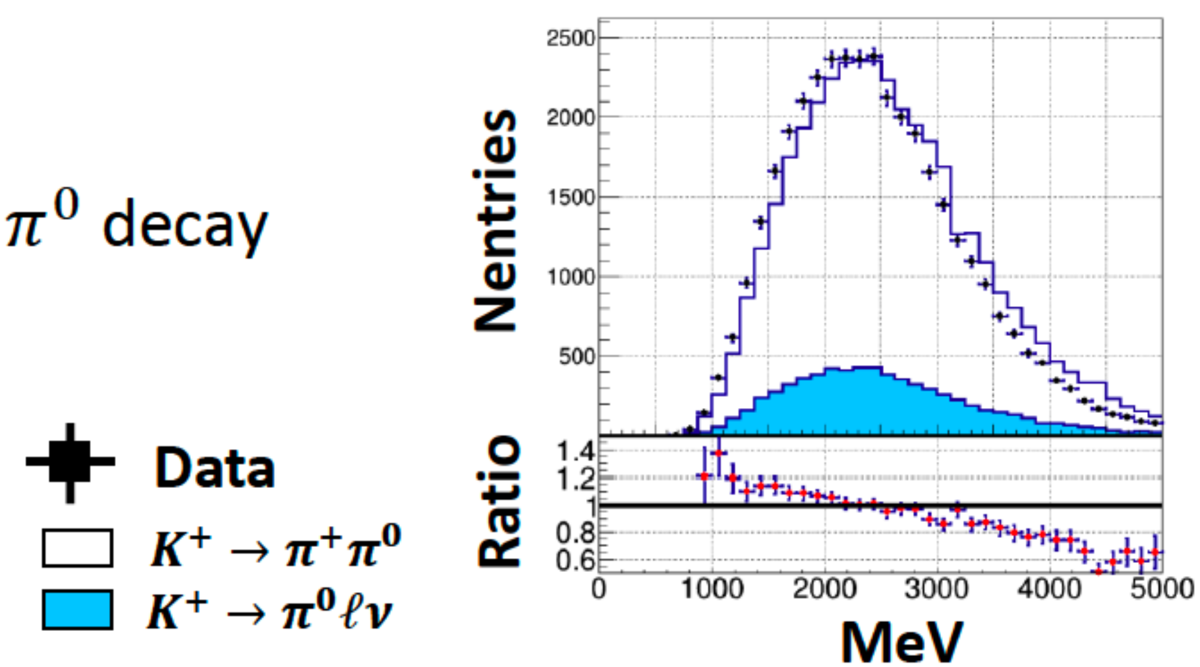
Evaluation of K^+ BG on $K_L \to \pi^0 \nu \bar{\nu}$ analysis

- **Purpose of this study**
  → Evaluation of the K^+ BG on $K_L \to \pi^0 \nu \bar{\nu}$ analysis by data-driven method



- **Collection of K^+ control sample**
  - Sweeping magnet (D1 magnet) in the beamline
  - Turned off D1 magnet to increase $K^\pm$ yield by a factor of **4000**
  - **Statistics**
    - ✓ 5 hours data
    - ✓ Measure K^+ yield by $K^+ \to \pi^+ \pi^0$ decay
    - → Corresponds to 2.5×10^{10} K^+

$P_{K^\pm}$ distribution obtained by $K^+ \to \pi^+ \pi^0$ analysis



Evaluation of K^+ BG on $K_L \to \pi^0 \nu \bar{\nu}$ analysis

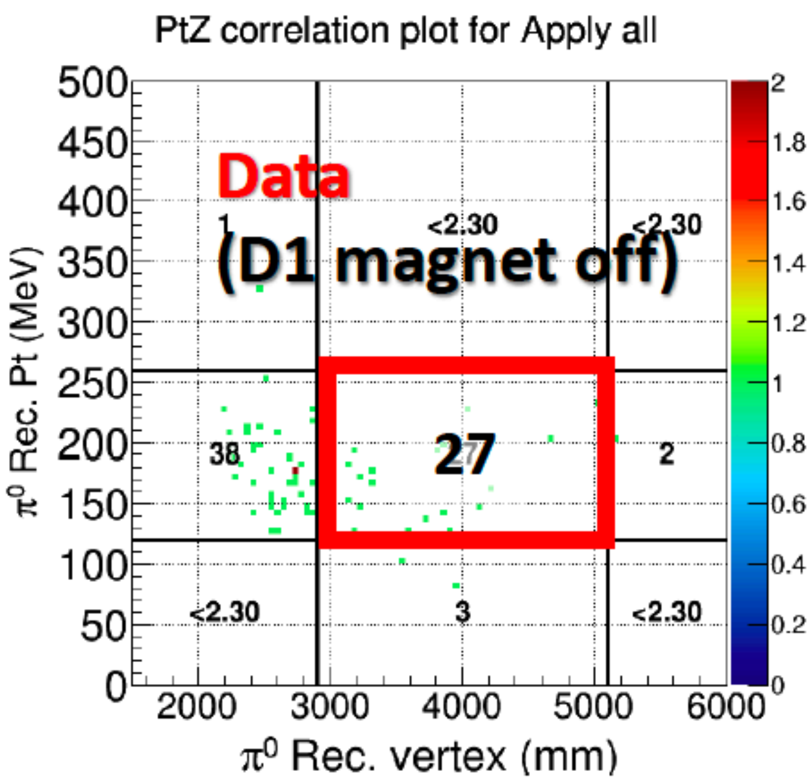
Data (D1 magnet off) → N^{Data}_{remain}

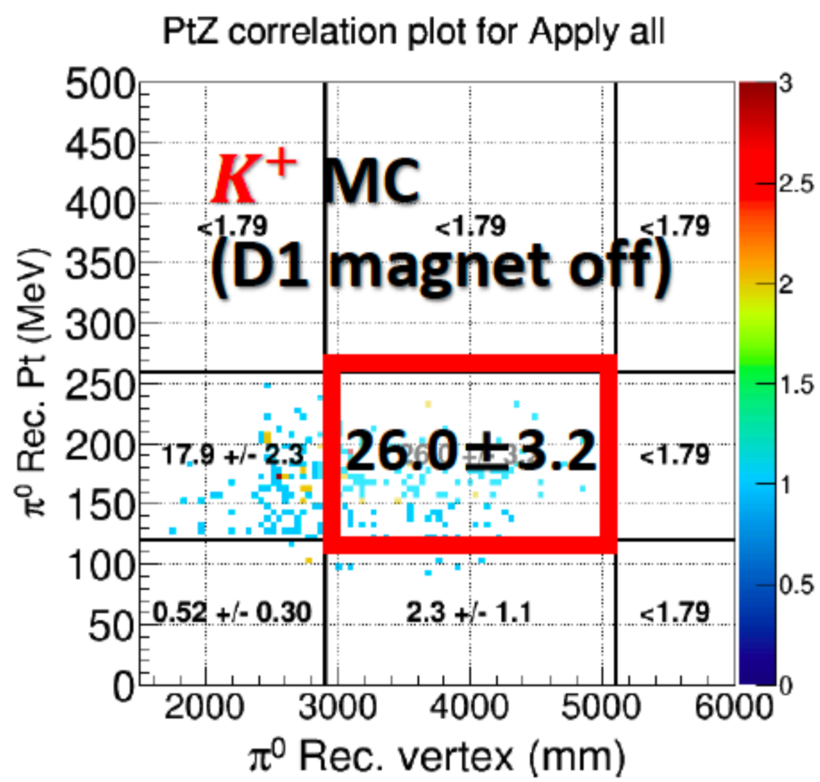
$K_L \to \pi^0 \nu \bar{\nu}$ **selection**

K^+ MC (D1 magnet off) → $N^{K^+ MC}_{remain}$

compare

K^+ yield measured by $K^+ \to \pi^+ \pi^0$ decay





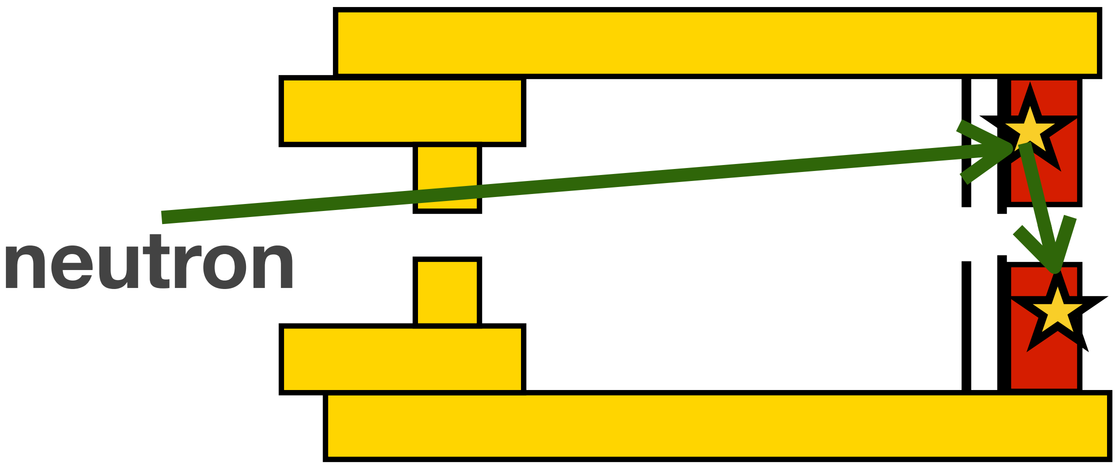
Source	Uncertainty
D1 off data statistics	19%
D1 off MC statistics	12%
$K^{\pm}$ spectrum	9%
Total	25%

$$R_{D_1 \mathrm{off}} = \varepsilon^{K^+ \mathrm{decays}}_{Data} / \varepsilon^{K^+ \mathrm{decays}}_{MC} = 1.04 \pm 0.26$$

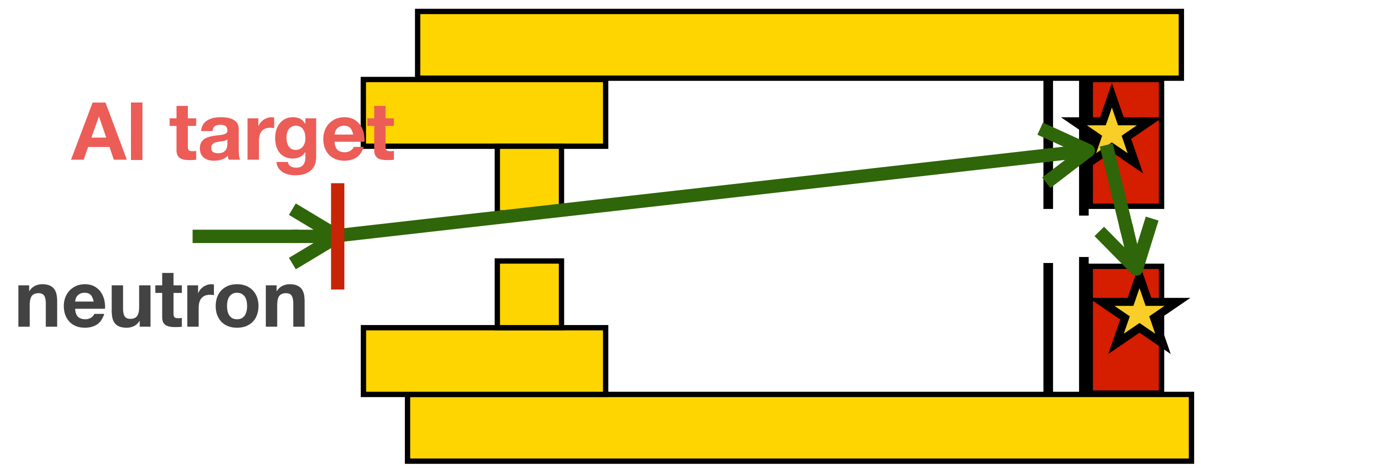
The # of events in the blind region is consistent between data and MC

Special run to collect neutron samples

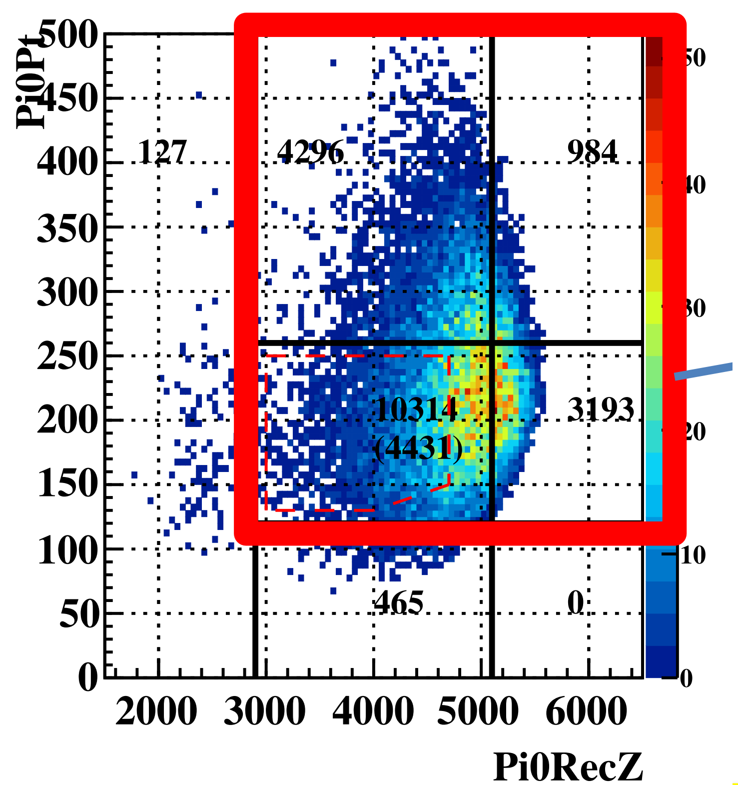
Hadron cluster BG



Special run to take control sample

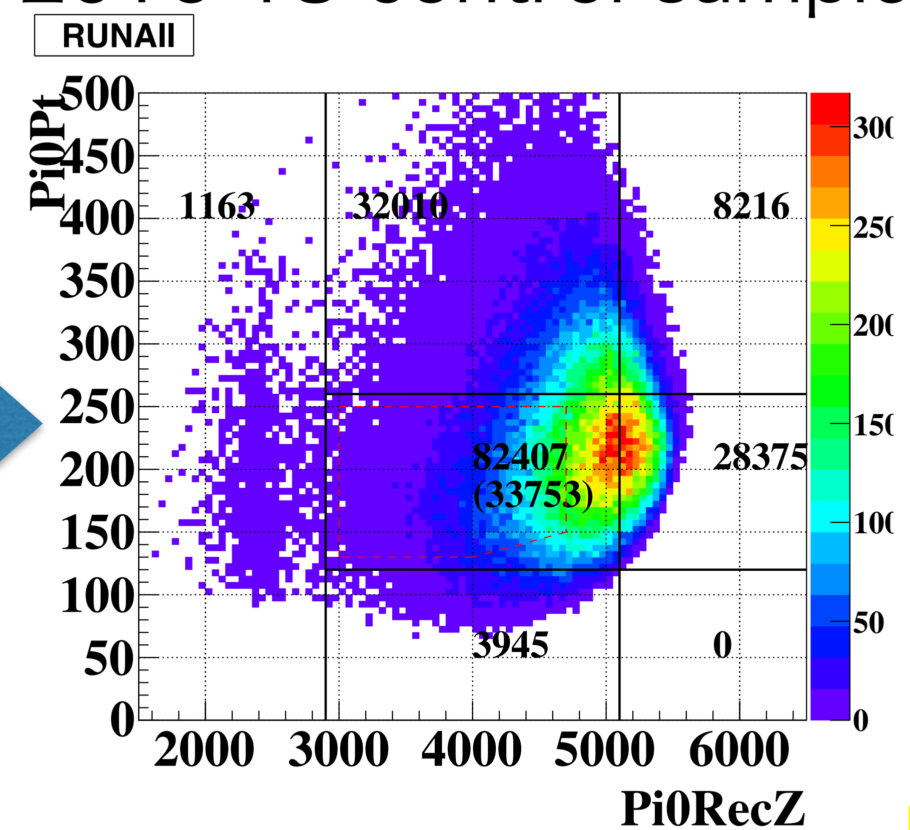


2015 control sample



×8

2016-18 control samples

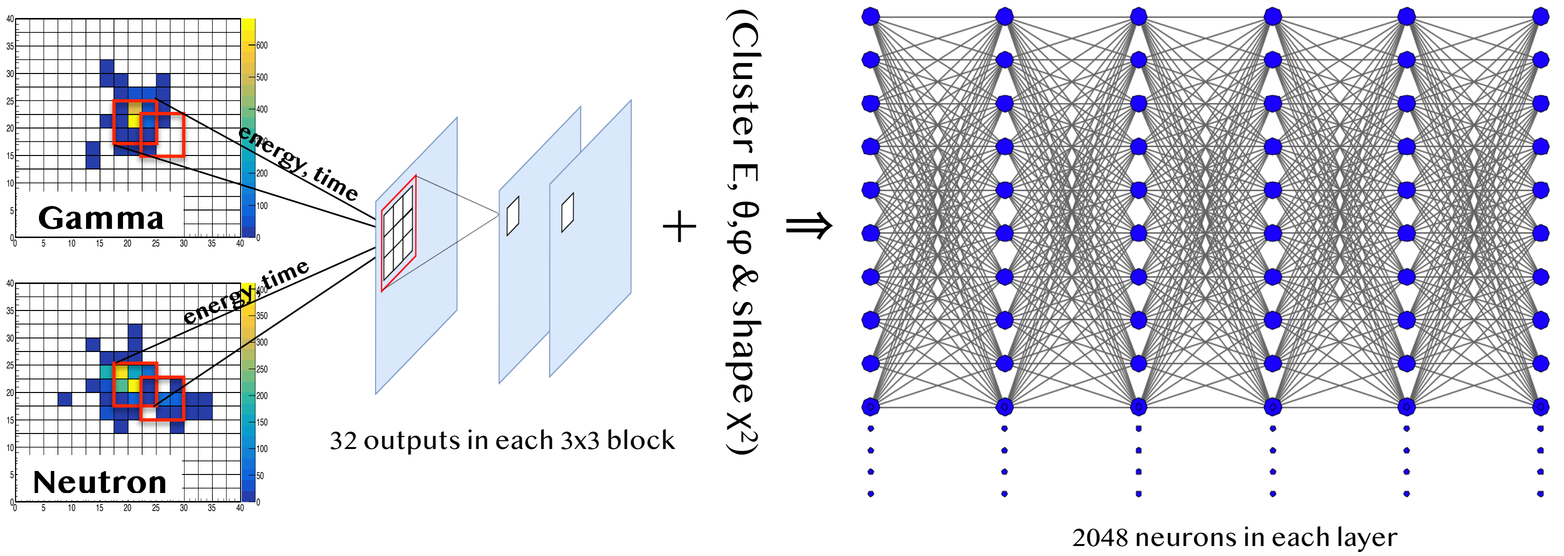


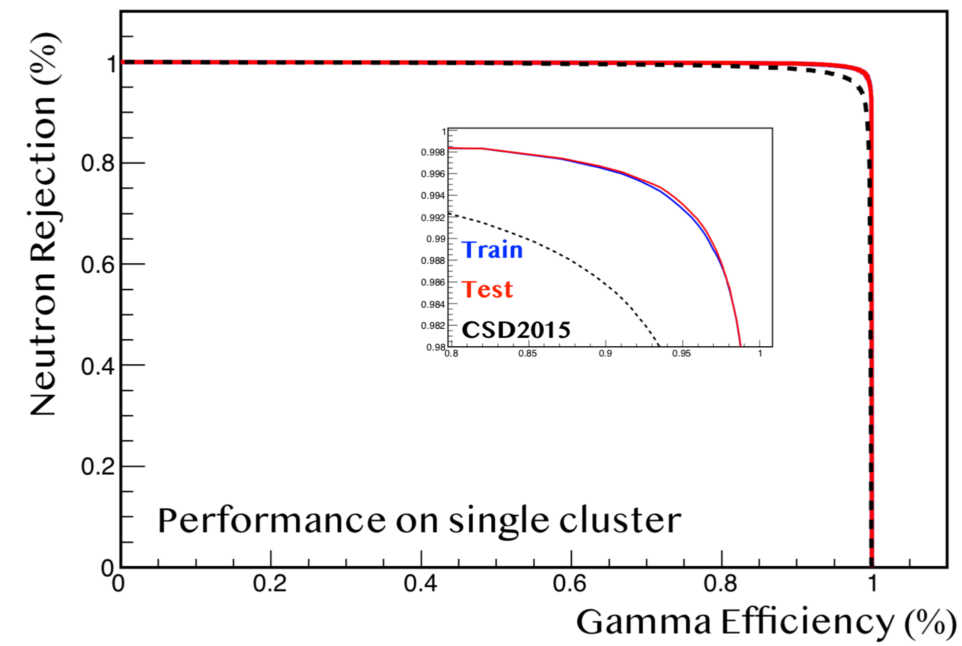
Develop more powerful discrimination.

New cuts against Hadron-cluster BGs

- Deep learning

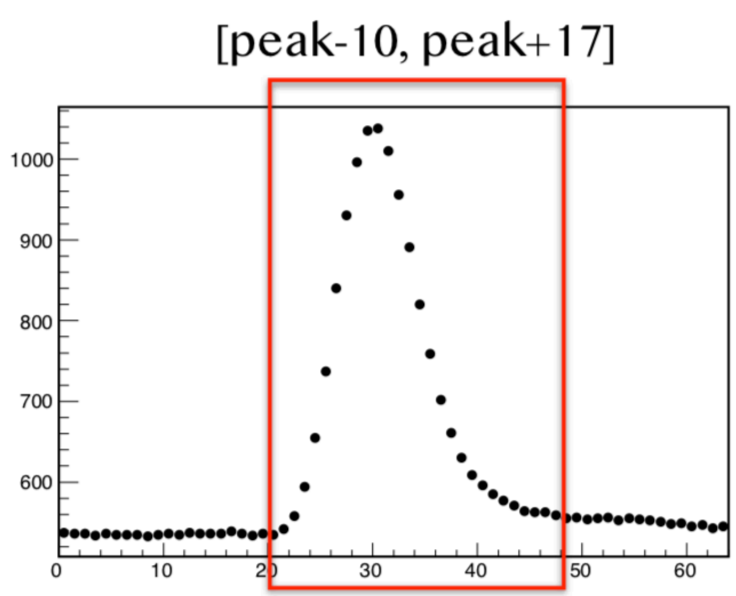
x2 improvement

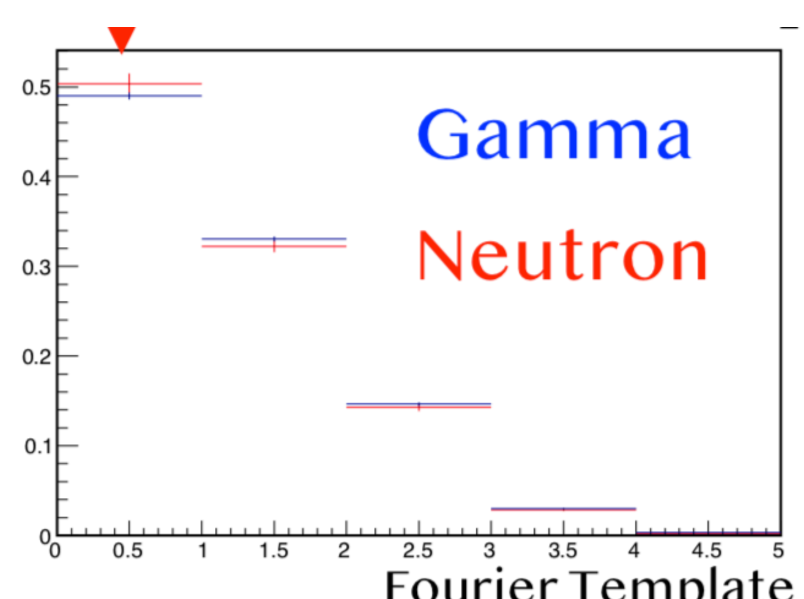


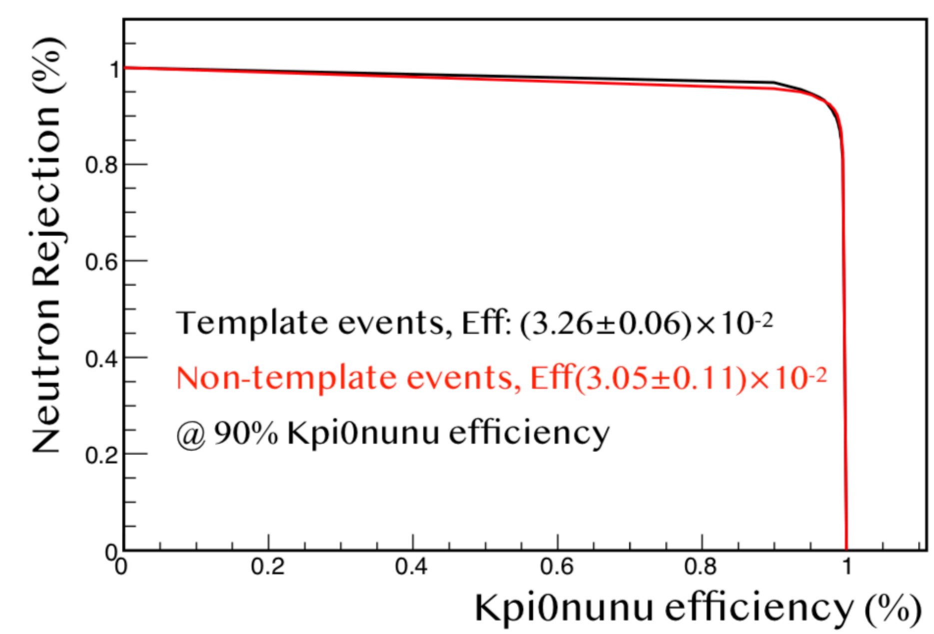


- Pulse shape discrimination by Fourier transformation

x1.8 improvement



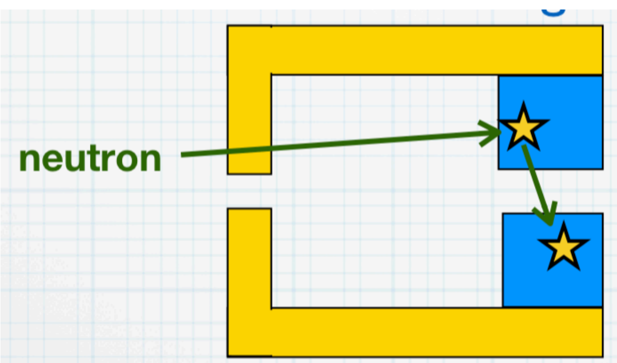


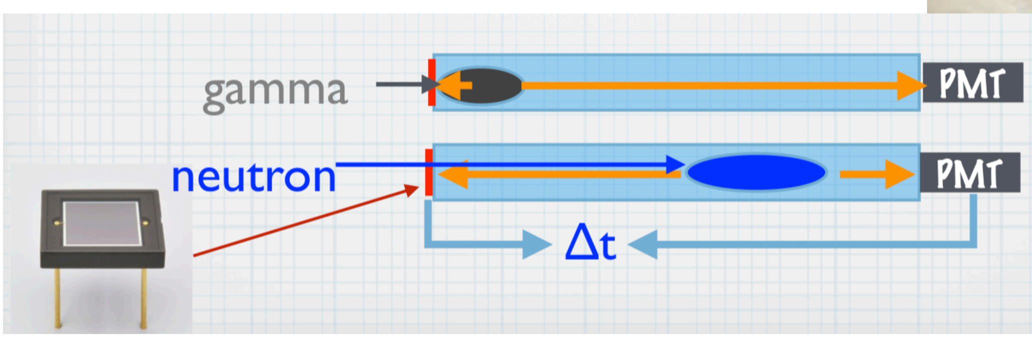


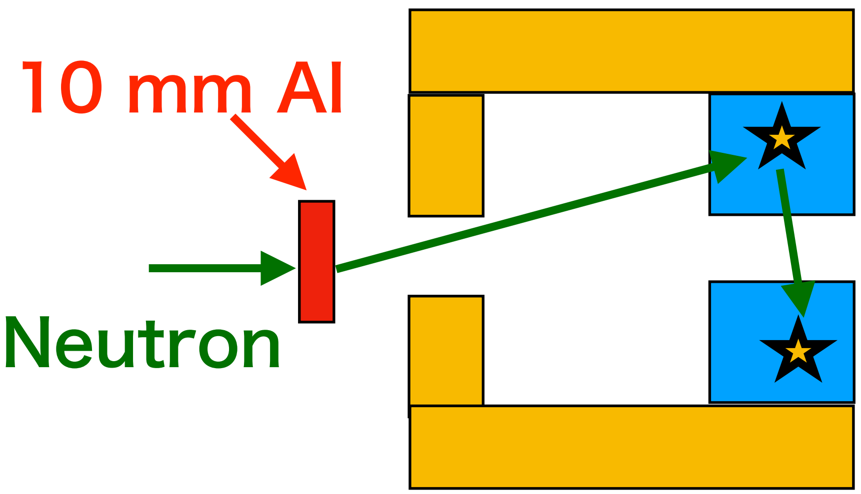
Detector upgrade in 2019

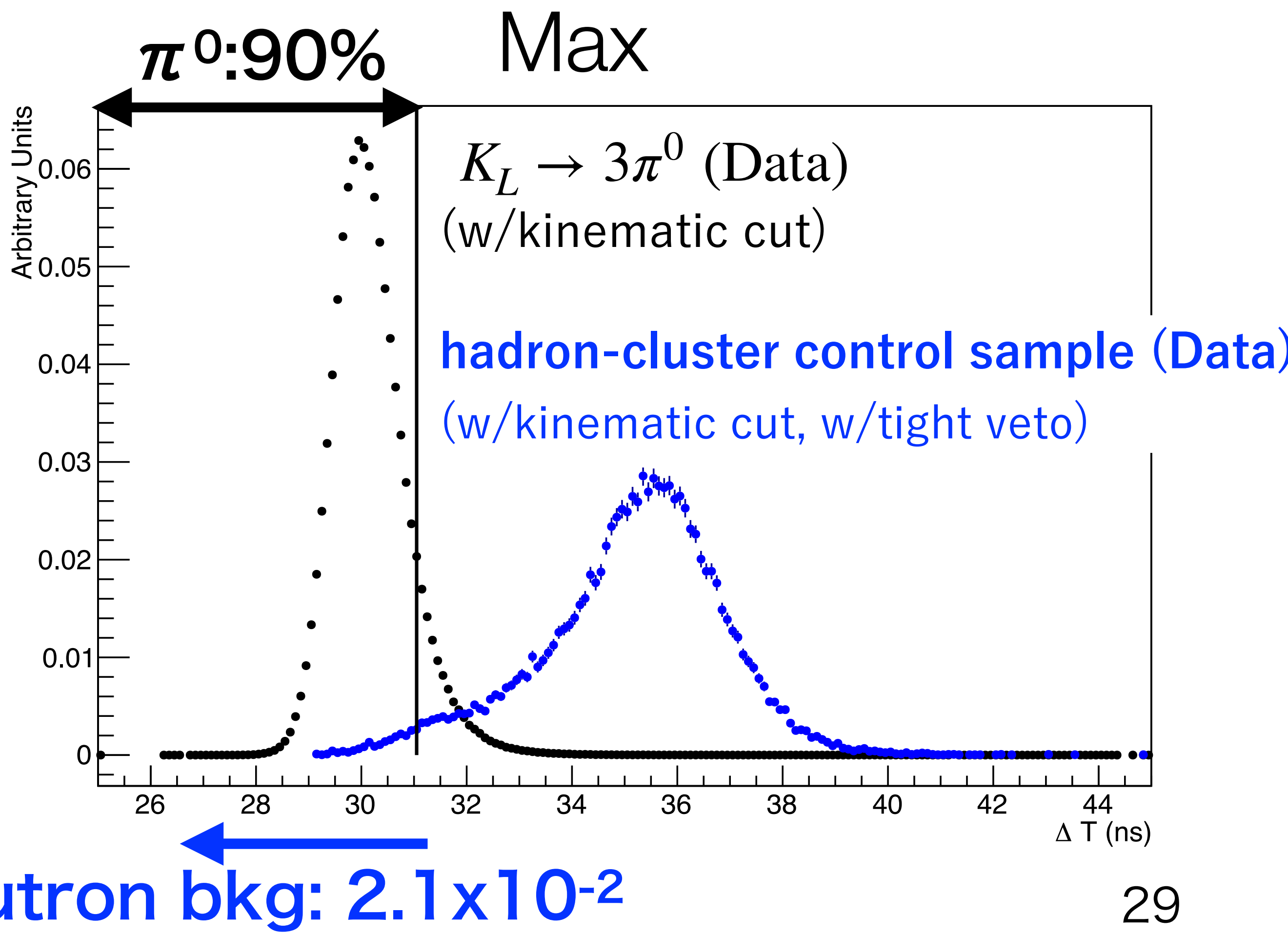
Calorimeter upgrade

to suppress the hadronic background









Confirmed good separation ability with 2019 data