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

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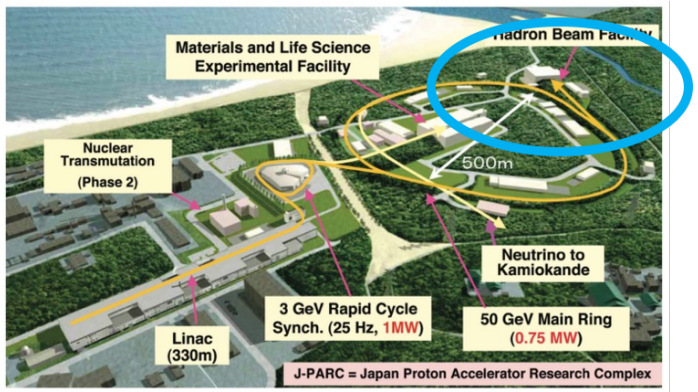
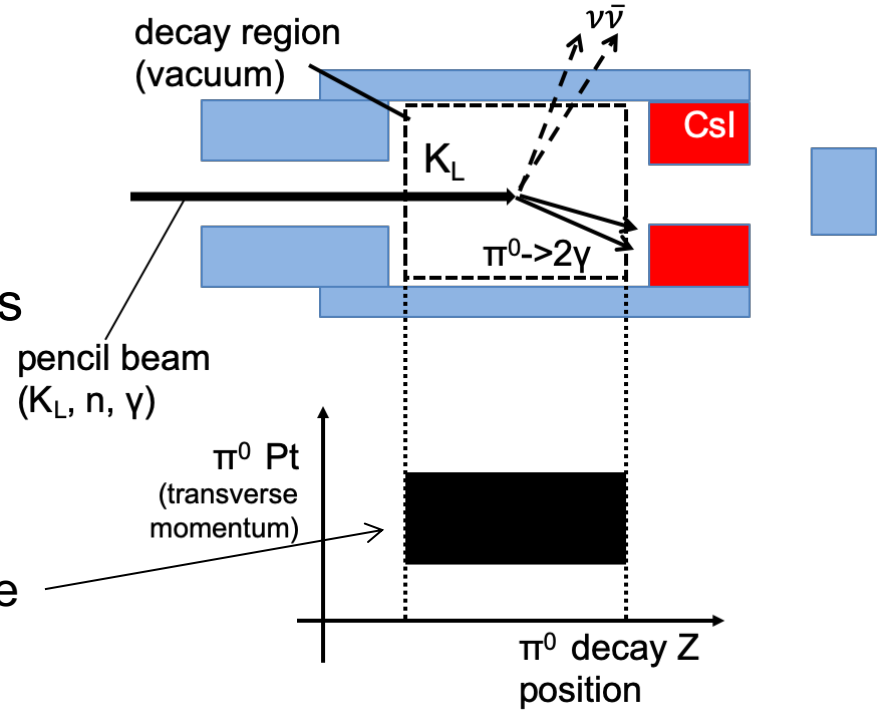
KOTO

- $K_L \to \pi^0 \nu\bar{\nu}$
  - FCNC : highly suppressed in SM BR(SM) = 3.0×10^{-11}
  - Small theoretical uncertainty
  - → Good probe for new physics search

- Signal : ($\pi^0 \to 2\gamma$)+ Nothing
  - $2\gamma \to$ CsI calorimeter
  - Nothing → Hermetic veto detectors around the decay region

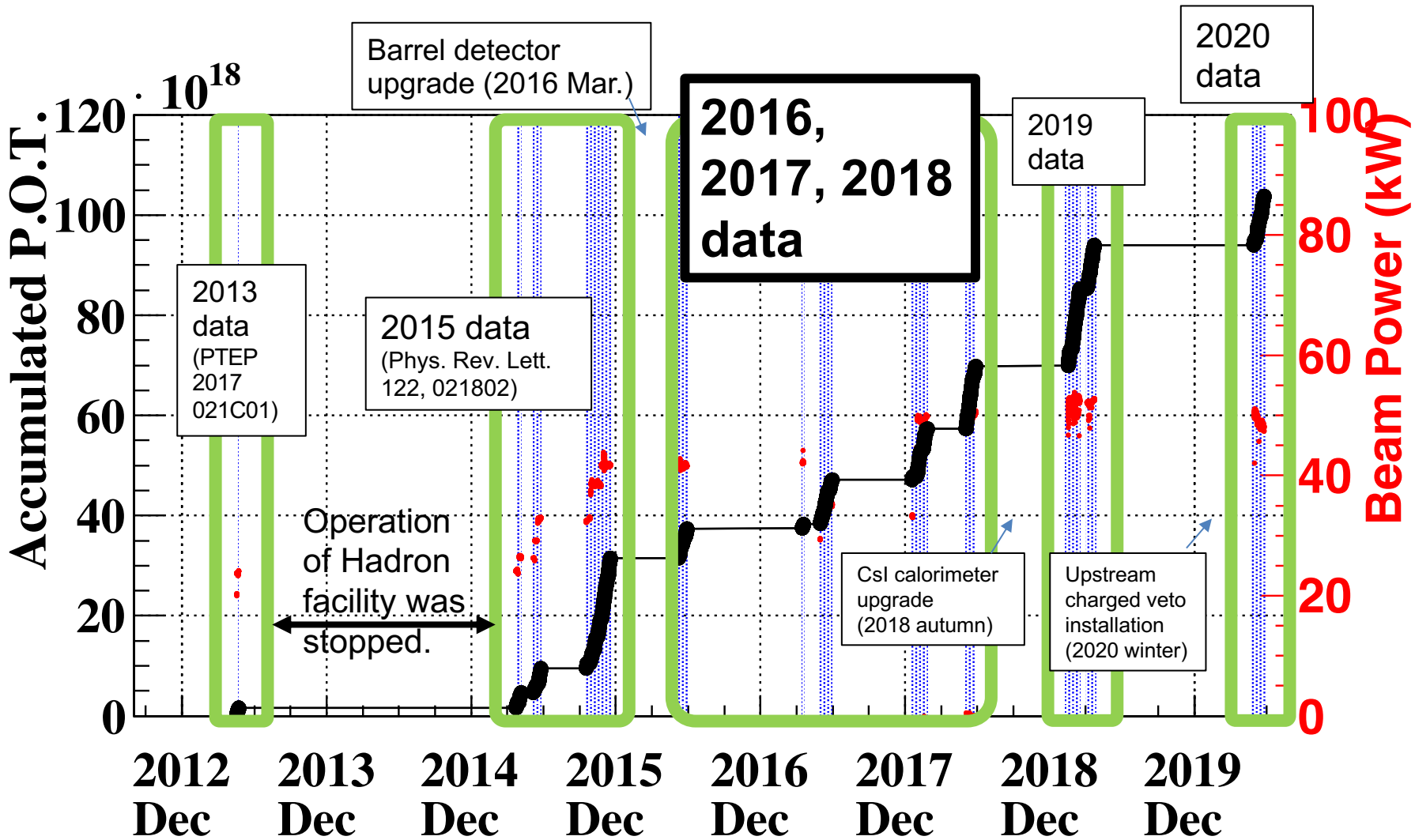
J-PARC





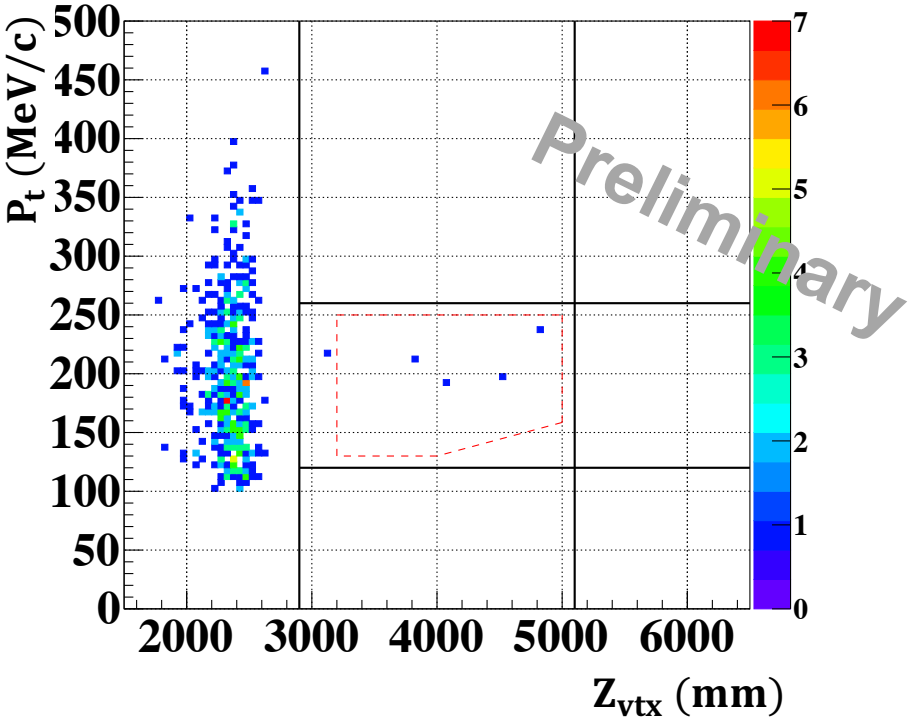
signal region on the Pt vs. Z plane (blind analysis)

History of data taking



2016 -2018 data analysis

Reported @ KAON2019 (Sep. 2019)



Examined the masked region at the end of Aug. 2019

Single event sensitivity (S.E.S) = $1/(NK_L \times A_{signal})$: 6.9×10^{-10}

	#BG
$K_L \to 2\pi^0$	<0.18*
$K_L \to \pi^+\pi^-\pi^0$	<0.02*
$K_L \to 3\pi^0$ (overlapped pulse)	<0.04*
$K_L \to \pi^\pm e^\mp \nu$ (overlapped pulse)	<0.09*
$K_L \to 2\gamma$ (beam window)	0.005 ± 0.005
Upstream π^0	0.001±0.001
Hadron cluster	0.017 ±0.002
CV-pi0	<0.10*
CV-eta	0.03±0.01
Total	**0.05±0.02****

Preliminary

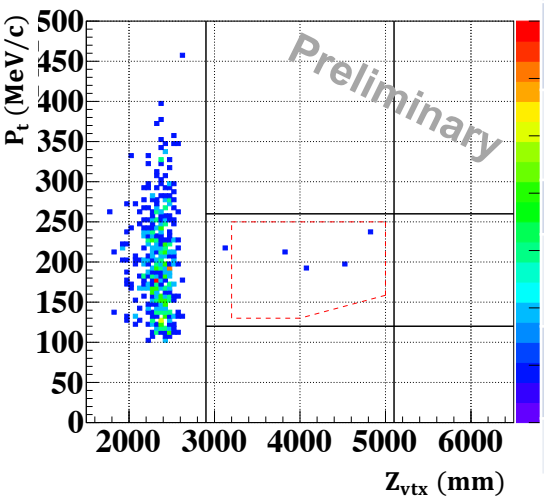
* 90% C.L.
** Added the central values of #BG

Updates after KAON2019

Preliminary

S.E.S = $(7.20 \pm 0.66_{syst.} \pm 0.05_{stat.}) \times 10^{-10}$, Total #BG : 1.22 ± 0.26

Reported @ KAON2019 (Sep. 2019)



source		#BG
K_L	$K_L \to 2\pi^0$	<0.08*
	$K_L \to \pi^+\pi^-\pi^0$	<0.02*
	$K_L \to 3\pi^0$ (overlapped pulse)	0.01±0.01
	$K_L \to \pi^\pm e^\mp \nu$ (overlapped pulse)	<0.08*
	$K_L \to 2\gamma$ (beam window)	0.005±0.005
	$K_L \to \pi^\pm e^\mp \nu$ ($\pi^\pm \to \pi^0$ conversion)	<0.04*
	$K_L \to \pi^\pm e^\mp \nu$ ($\pi^\pm$ beta decay)	<0.01*
	$K_L \to \pi^\pm e^\mp \gamma \nu$	<0.05*

source		#BG
K_L	$K_L \to \pi^0 \pi^\pm e^\mp \nu$	<0.04*
	$K_L \to \pi^+\pi^-$	<0.03*
	$K_L \to ee\gamma$	<0.09*
	$K_L \to K^\pm e^\mp \nu$	<0.04*
	$K_L \to 2\gamma$ (core-like)	<0.11*
	$K_L \to 2\gamma$ (halo-K)	0.26±0.07
$K^\pm$		0.87±0.25
Neutron	Upstream π^0	0.03±0.03
	Hadron cluster	0.017±0.002
	CV-pi0	<0.10*
	CV-eta	0.03±0.01
Total	**central value**	**1.22 ± 0.26****

1. One candidate event was due to mis-selection of timing peak; N_{obs} should be 3, not 4.
2. S.E.S : Updated a correction factor of offline cut (3%) and online trigger (1%)
3. **N_{obs} is statistically consistent with total #BG (p-value : 13%)**

* 90% C.L., ** Added the central values of #BG

Updates after KAON2019

Preliminary

S.E.S = $(7.20 \pm 0.66_{syst.} \pm 0.05_{stat.}) \times 10^{-10}$, Total #BG : 1.22 ± 0.26

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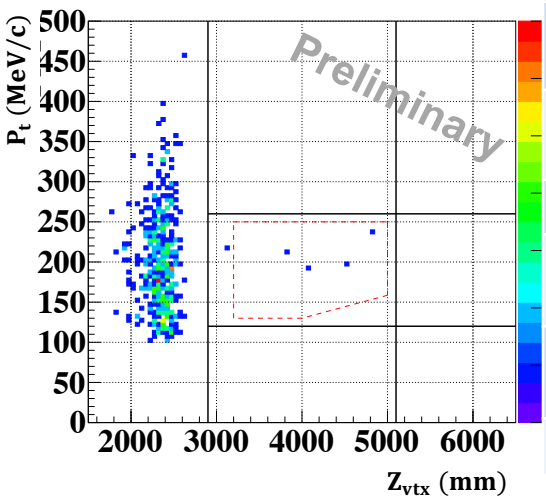

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source		#BG
K_L	$K_L \to \pi^0\pi^\pm e^\mp \nu$	<0.04*
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	[illegible]	<0.04*
	$K_L \to 2\gamma$ (cosmic-like)	<0.11*
	$K_L \to 2\gamma$ (halo-K)	0.26±0.07
$K^\pm$		0.87±0.25
Neutron	Upstream π^0	0.03±0.03
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previous talk (by Noichi)

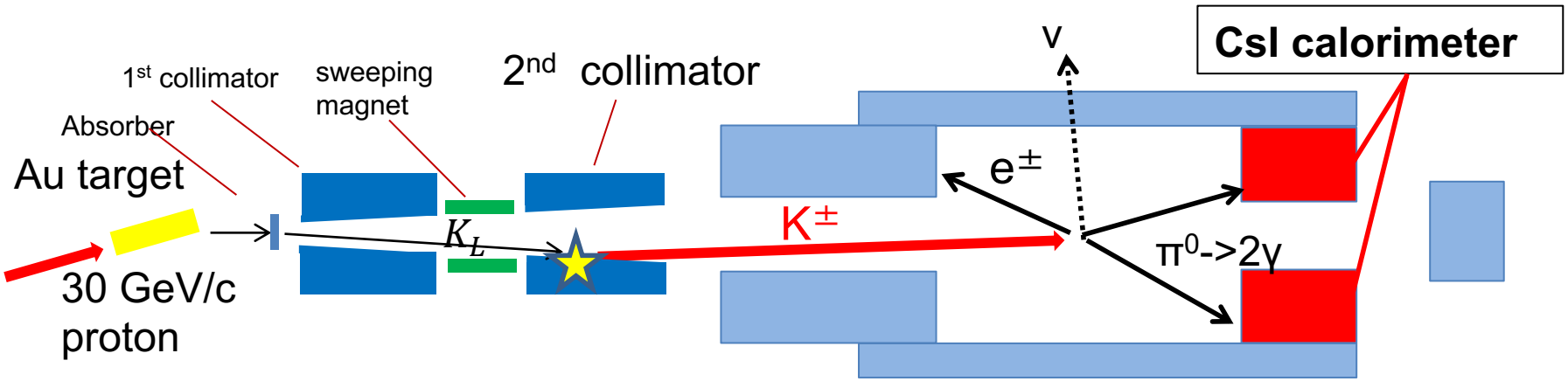
This talk

1. One candidate event was due to mis-selection of timing peak; N_{obs} should be 3, not 4.
2. S.E.S : Updated a correction factor of offline cut (3%) and online trigger (1%)
3. **N_{obs} is statistically consistent with total #BG (p-value : 13%)**

* 90% C.L., ** Added the central values of #BG

$K^{\pm}$ DECAY BACKGROUND

$K^{\pm}$ decay background



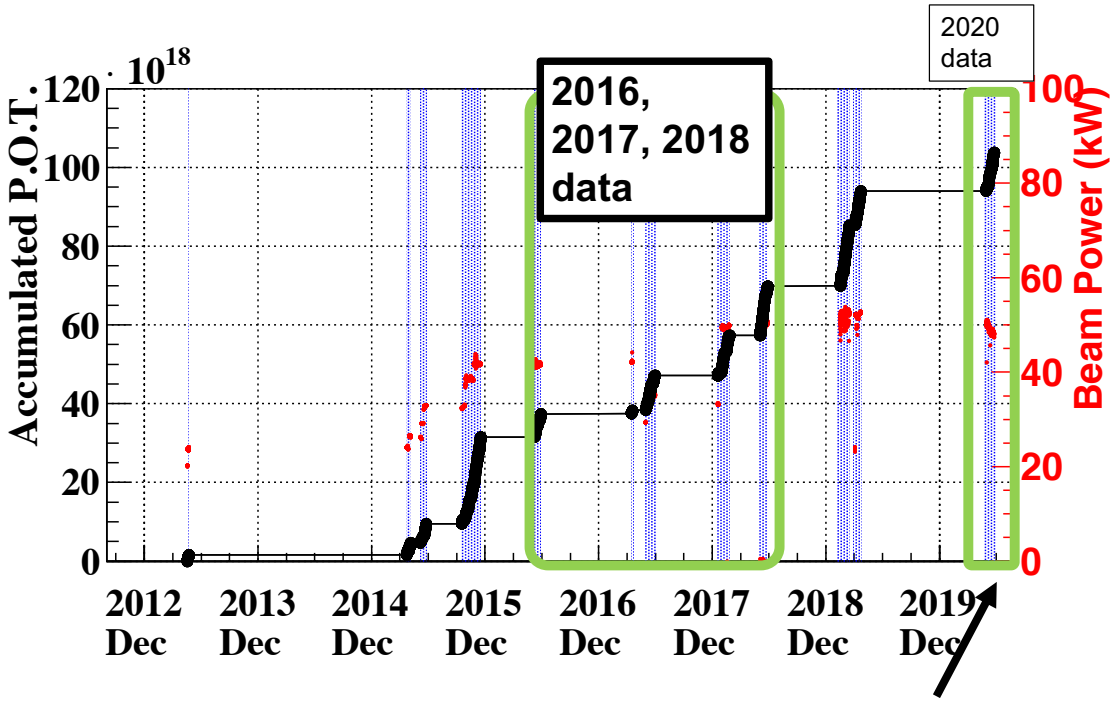
One of the charged kaon generation mechanism
$K_L \rightarrow K^{\pm}$ @ 2nd collimator

Dangerous BG : $K^{\pm} \rightarrow \pi^0 e^{\pm} \nu$ decay

- π^0 kinematics : similar to the π^0 from $K_L \rightarrow \pi^0 \nu \bar{\nu}$
- Only 1 extra particle ($e^{\pm}$) for vetoing

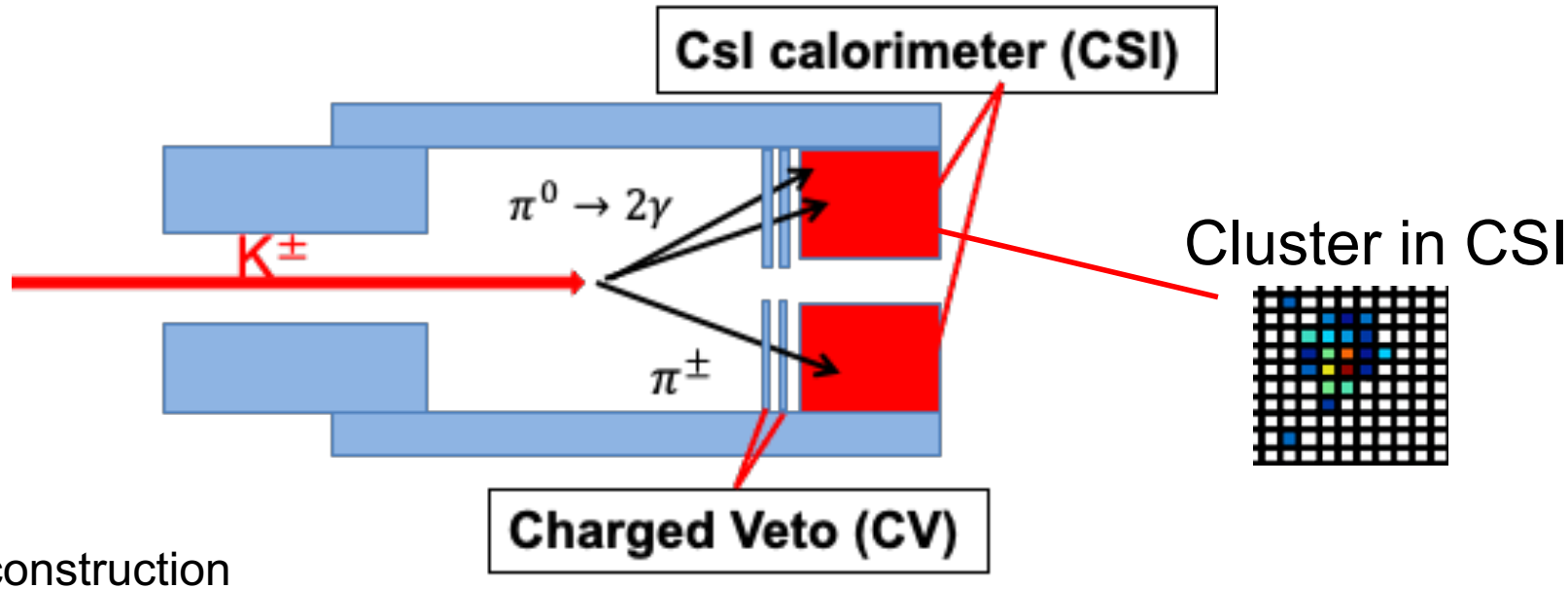
Need to measure $K^{\pm}$ flux to normalize $K^{\pm}$ BG yield

$K^{\pm}$ flux measurement



- $K^{\pm} \to \pi^0\pi^{\pm}$ decay (BR=20%) sample in <u>2020</u>
  - 2016-2018 runs : Most events with charged particles in the final state were discarded by the online triggers
    => developed a new trigger scheme and collected the sample in 2020

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

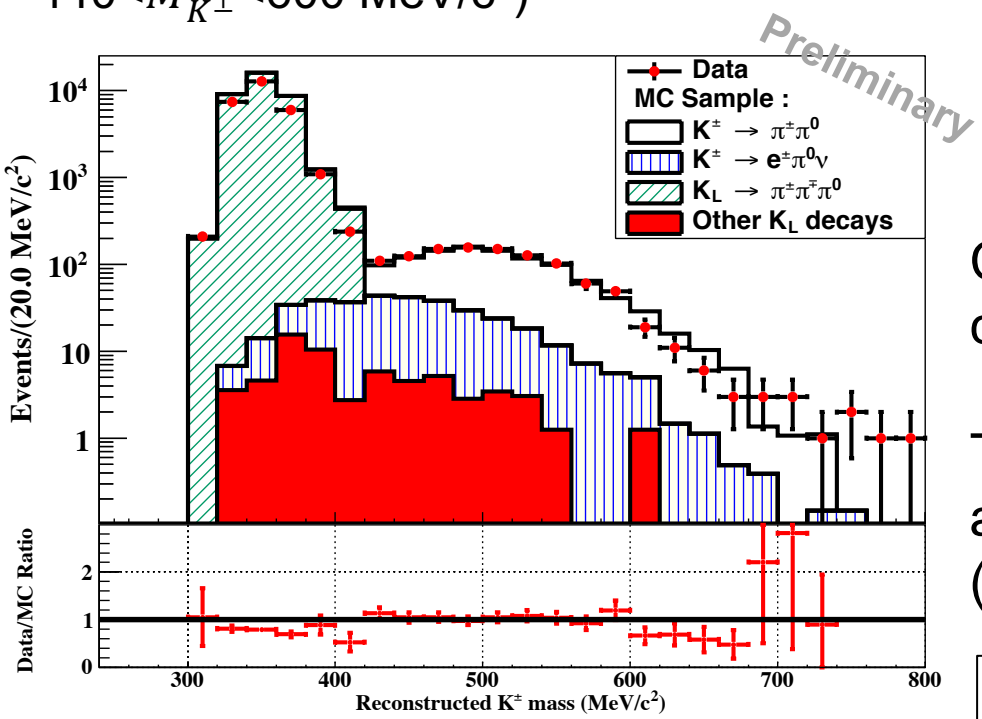


Reconstruction

- Three-cluster events in CSI
  - One charged particle cluster
    → select one closest to the extrapolated position of the CV hit into CSI
  - π^0 : reconstructed from the other two neutral clusters
    → define $K^{\pm}$ decay vertex
    → obtain $\pi^{\pm}$ direction
    → calculate $\pi^{\pm}$ absolute momentum assuming Pt valance of π^0 and $\pi^{\pm}$
  - Calculate $M_{K^{\pm}}$

$K^{\pm}$ flux measurement

Reconstructed $K^{\pm}$ mass distribution (except for the requirement of 440<$M_{K^{\pm}}$<600 MeV/c^2)



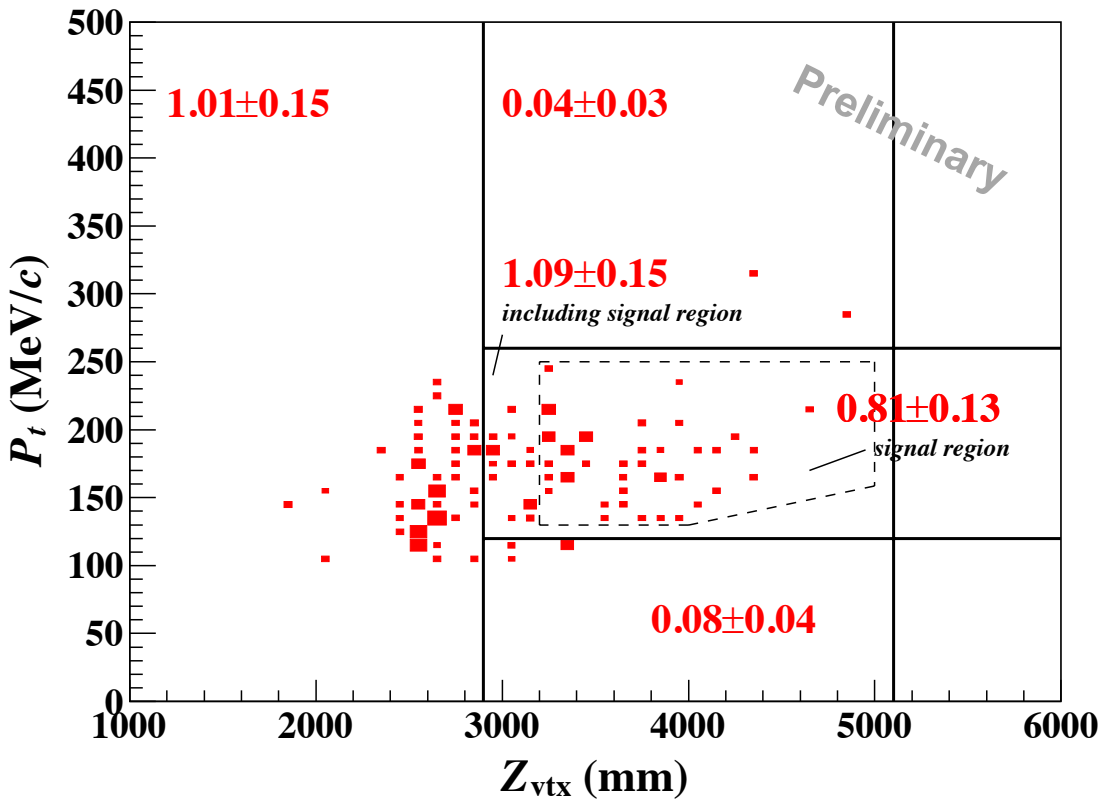
Collected 847 $K^{\pm} \to \pi^0\pi^{\pm}$ candidate events in data

The ratio of the number of $K^{\pm}$ to K_L at the entrance of KOTO detector ($R_{K^{\pm}/K_L}$) was estimated as :

$$R_{K^{\pm}/K_L} = (2.6 \pm 0.1)\times 10^{-5}$$

$K^{\pm} \to \pi^0 e^{\pm} \nu$ background

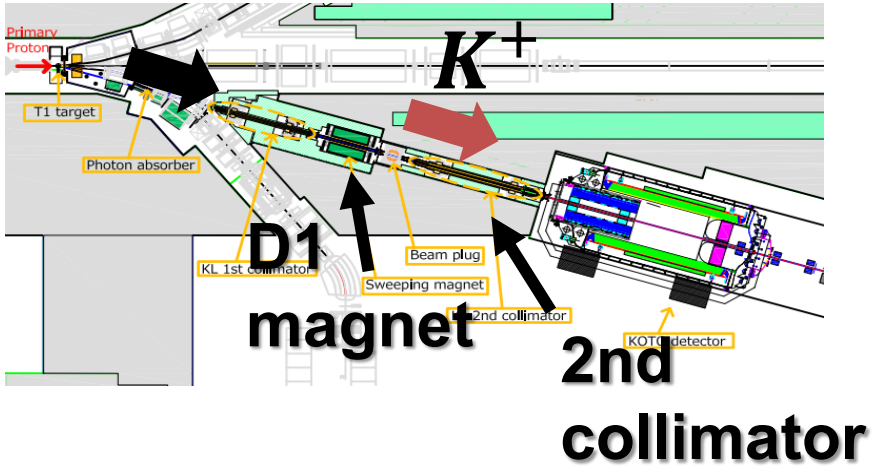
- #BG ($K^{\pm} \to \pi^0 e^{\pm} \nu$) : 0.81 ± 0.13 (preliminary)
  - BG yield was normalized with $R_{K^{\pm}/K_L}$



slide from N.Shimizu

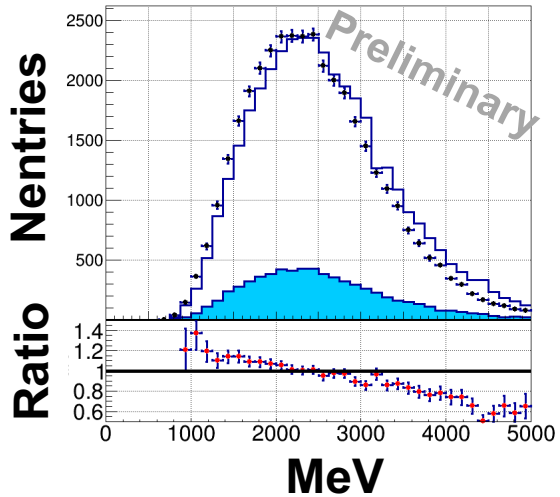
Evaluation of K^+ BG on $K_L \to \pi^0 \nu\bar{\nu}$ analysis

- 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
  - 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



slide from N.Shimizu

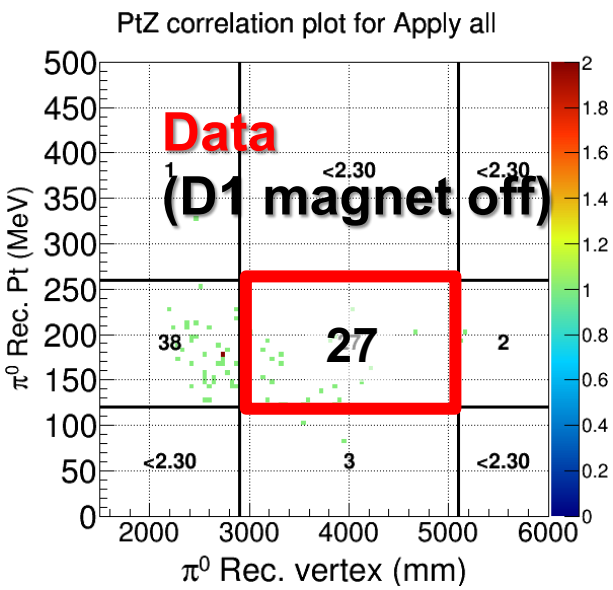
Evaluation of K^+ BG on $K_L \to \pi^0 \nu\bar{\nu}$ analysis

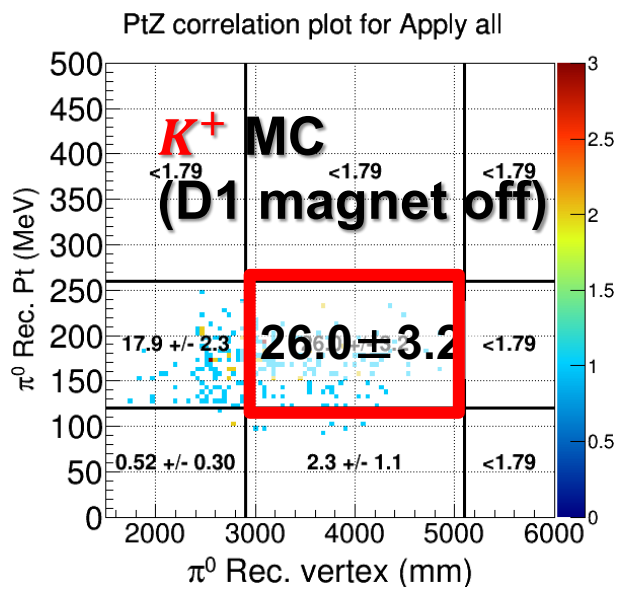
Data (D1 magnet off) → $K_L \to \pi^0 \nu\bar{\nu}$ **selection** → N_{remain}^{Data}

K^+ MC (D1 magnet off) → $K_L \to \pi^0 \nu\bar{\nu}$ **selection** → $N_{remain}^{K^+MC}$

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%

Preliminary

$$R_{D_1\text{off}} = \varepsilon_{Data}^{K^+\text{decays}} / \varepsilon_{MC}^{K^+\text{decays}} = 1.04 \pm 0.26$$

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

Total $K^{\pm}$ BG

- #total $K^{\pm}$ BG = (#total $K^{\pm}$ BG from MC) × (uncertainties of MC ($R_{D_1\mathrm{off}}$))
  - #total $K^{\pm}$ BG from MC : 0.84 ± 0.13
    - BG contribution from each $K^{\pm}$ decay : $K^{\pm} \to \pi^0 e^{\pm}\nu$: 97.3%, $K^{\pm} \to \pi^0 \mu^{\pm}\nu$: 2.3%, $K^{\pm} \to \pi^0 \pi^{\pm}$: 0.4%
  - uncertainties of MC ($R_{D_1\mathrm{off}}$) : 1.04 ± 0.26

#total $K^{\pm}$ BG : 0.87 ± 0.25

Preliminary

source		#BG
K_L	$K_L \to 2\pi^0$	<0.08*
	$K_L \to \pi^+\pi^-\pi^0$	<0.02*
	$K_L \to 3\pi^0$ (overlapped pulse)	0.01±0.01
	$K_L \to \pi^{\pm}e^{\mp}\nu$ (overlapped pulse)	<0.08*
	$K_L \to 2\gamma$ (beam window)	0.005±0.005
	$K_L \to \pi^{\pm}e^{\mp}\nu$ ($\pi^{\pm} \to \pi^0$ conversion)	<0.04*
	$K_L \to \pi^{\pm}e^{\mp}\nu$ ($\pi^{\pm}$ beta decay)	<0.01*
	$K_L \to \pi^{\pm}e^{\mp}\gamma\nu$	<0.05*

Preliminary

source		#BG
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	$K_L \to K^{\pm}e^{\mp}\nu$	<0.04*
	$K_L \to 2\gamma$ (core-like)	<0.11*
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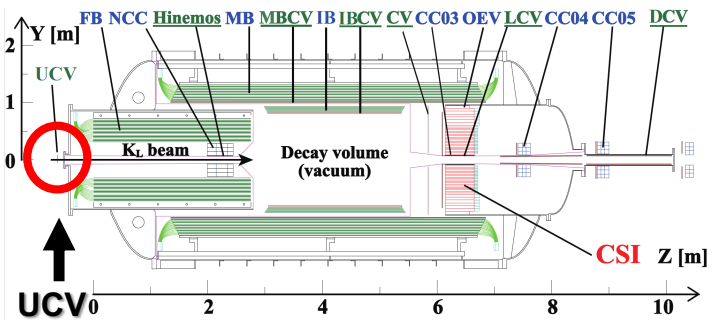
Total	**central value**	**1.22 ± 0.26****

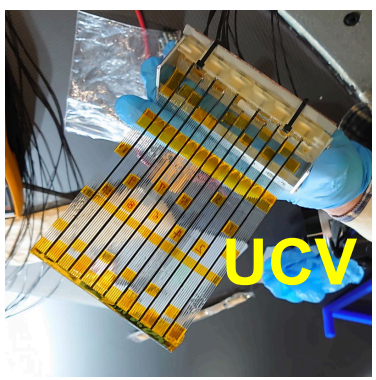
TO VETO $K^{\pm}$ BG

Upstream charged veto (2020)

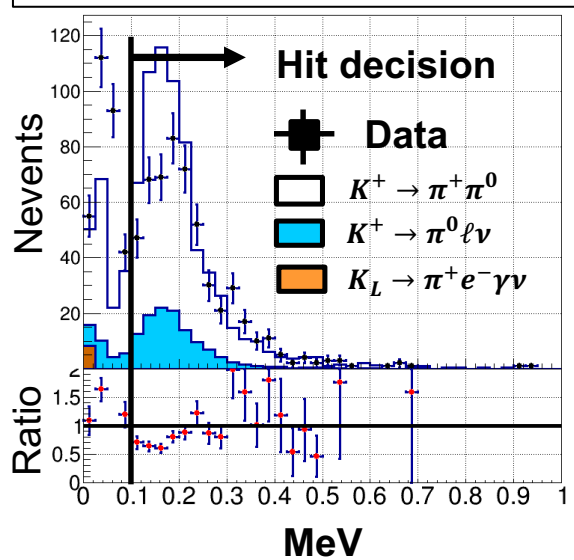


Prototype detector in front of the KOTO detector
- Upstream charged veto (UCV)
- installed before 2020
- 1.0 mm scintillation fibers + MPPC

Purpose
- To confirm the existence of $K^{\pm}$
- To veto $K^{\pm}$

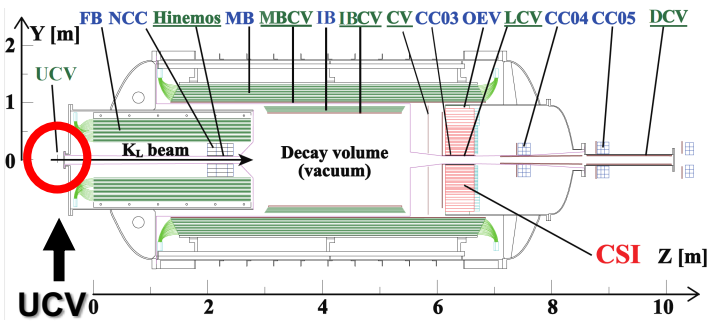


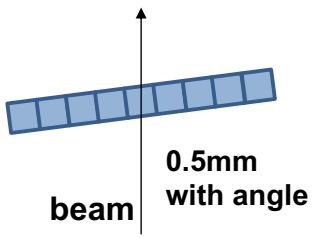
Energy deposit (only on-time hit) in UCV ($K^{\pm} \to \pi^0\pi^{\pm}$ sample in 2020)

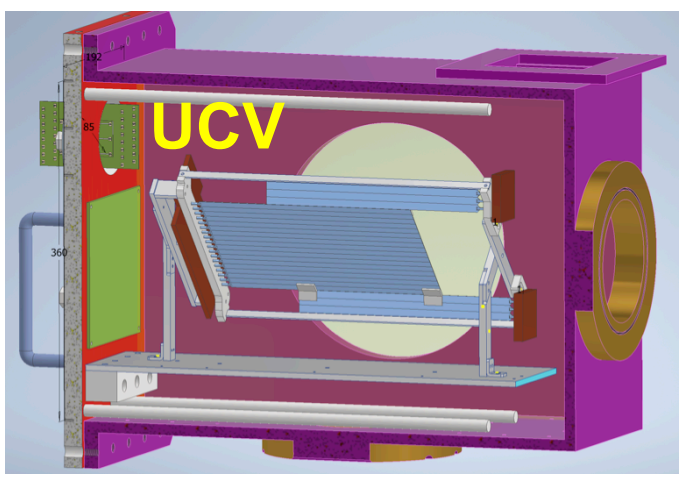


Lectures from prototype
- MIP like on-time hit in $K^{\pm} \to \pi^0\pi^{\pm}$ sample → **existence of $K^{\pm}$**
- 30% inefficiency came from
  - limited coverage
  - limited sensitive region of fibers
  - noise due to irradiation of MPPC

UCV upgrade (2021~)







To improve the UCV performance

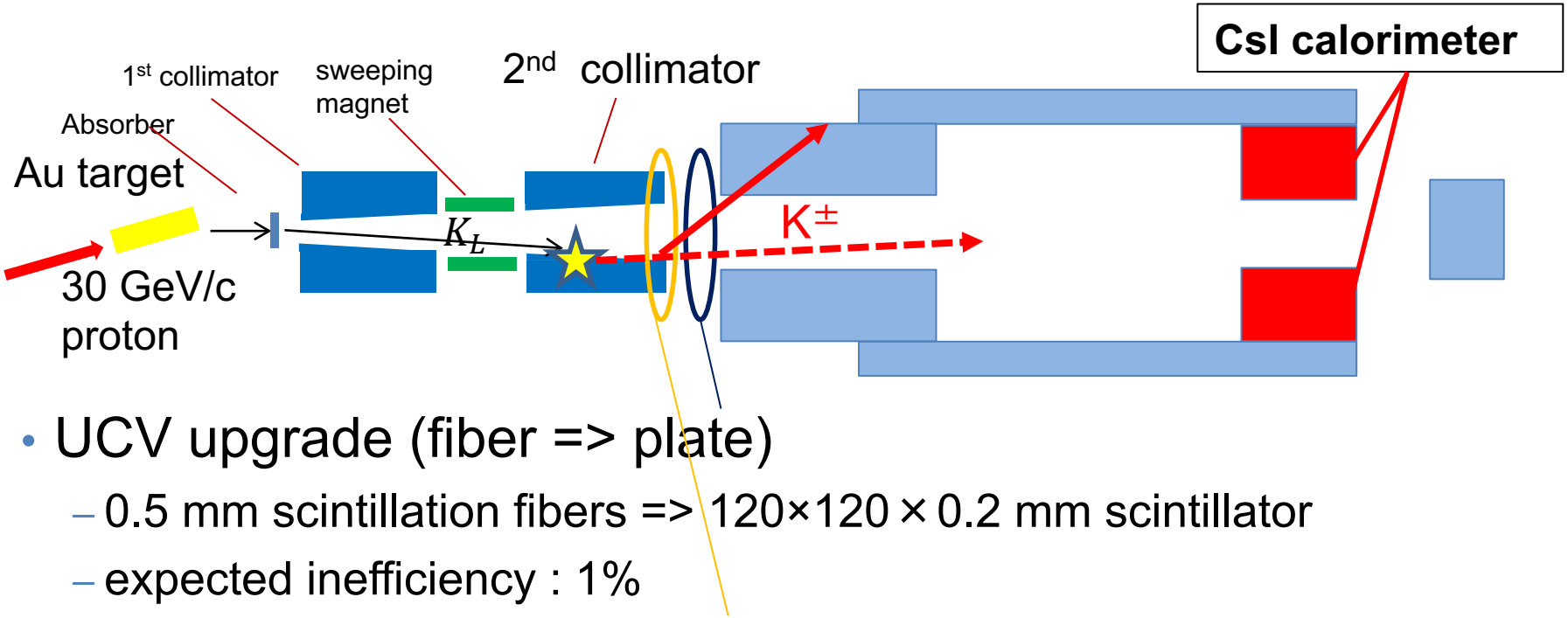
- Thinner material : 1mm → 0.5mm
  - to avoid neutron/K_L scattering, which may cause additional BG and signal loss
- Expected inefficiency : ~5%
  - Enough coverage
  - With angle
  - Enough distance between MPPC and beam

We plan to test UCV @ ELPH (Dec. 1st and 2nd 2020)

- measure the performance
- determine the angle

We will install UCV before the next KOTO physics run (Jan. 2021)

Further suppress $K^{\pm}$ BG



- UCV upgrade (fiber => plate)
  - 0.5 mm scintillation fibers => 120×120 × 0.2 mm scintillator
  - expected inefficiency : 1%
- Additional sweeping magnet
  - #$K^{\pm}$ entering the KOTO detector → ×1/10

<u>=> #BG from $K^{\pm}$: × 1/1000</u>

Summary

- **S.E.S : $(7.20 \pm 0.66_{syst.} \pm 0.05_{stat.}) \times 10^{-10}$ (preliminary)**
- **#BG : 1.22 ± 0.26 (preliminary)**
  - **N_{obs} (=3) is statistically consistent with total #BG (p-value : 13%)**
    - There are two major BGs :
      $K^{\pm}$: 0.87±0.25, Halo $K_L \to 2\gamma$: 0.26±0.07 (previous talk by Noichi)
    - Studies to suppress these BGs are on-going for the future datasets
      - $K^{\pm}$: hardware effort, Halo $K_L \to 2\gamma$: software effort
- **We will finalize the analysis for 2016-2018 dataset and report the results soon.**

END

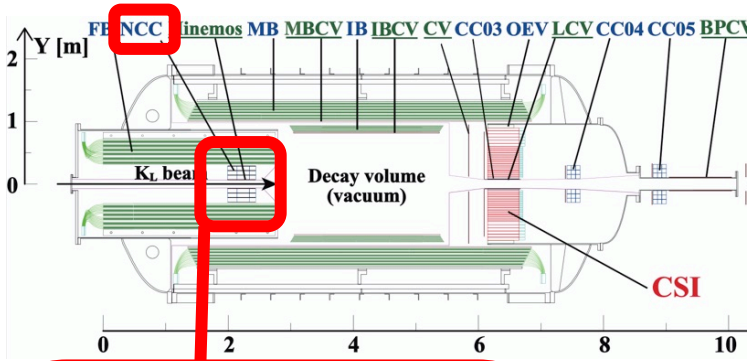
BACKUP

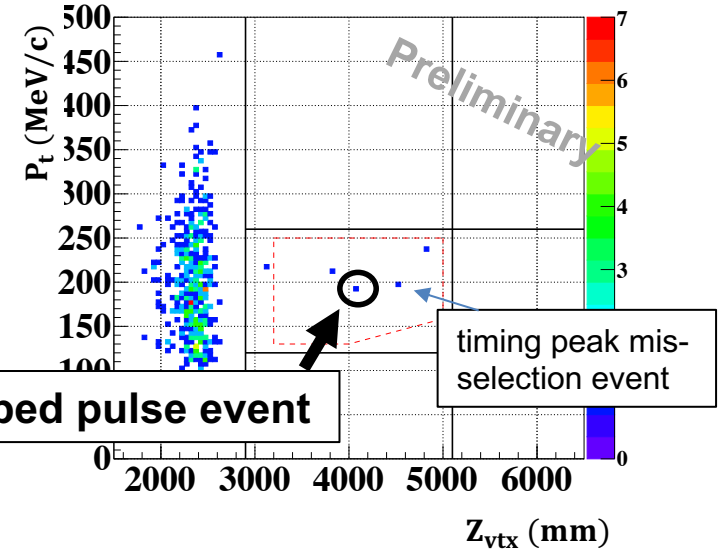
EVENT PROPERTY

Overlapped pulse event

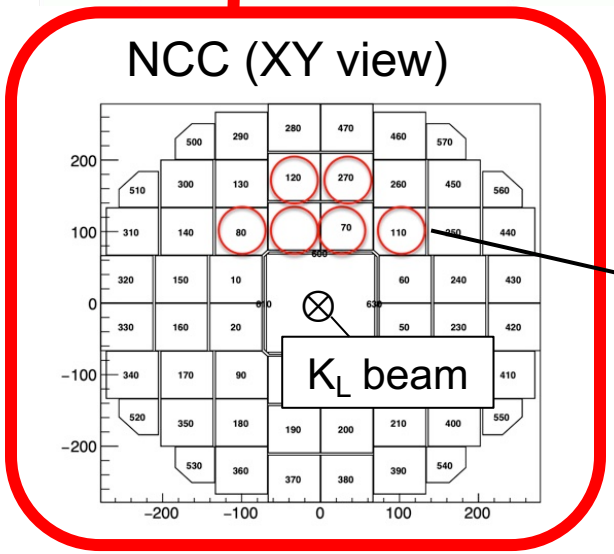
Overlapped pulse event

One of the three events has overlapped pulse in the upstream detector (NCC)

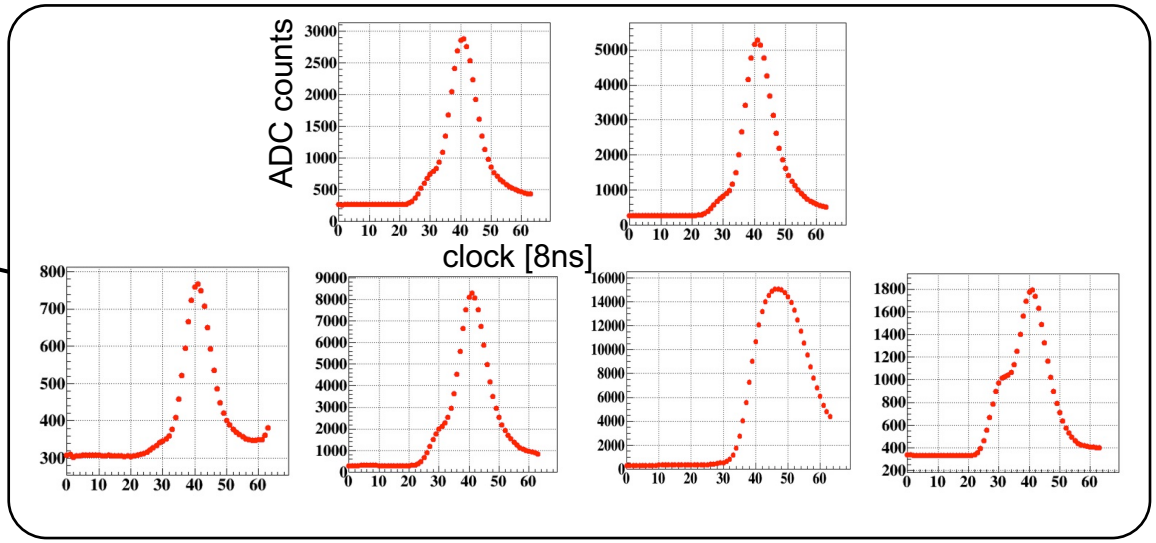




NCC (XY view)

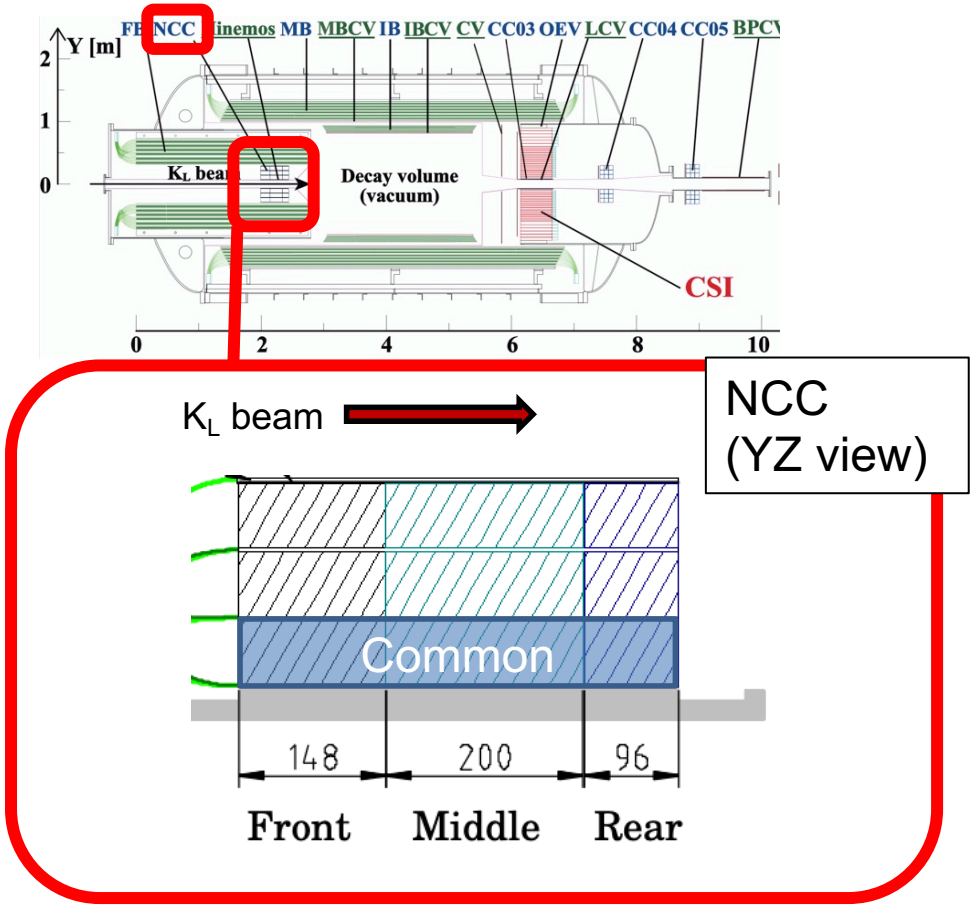


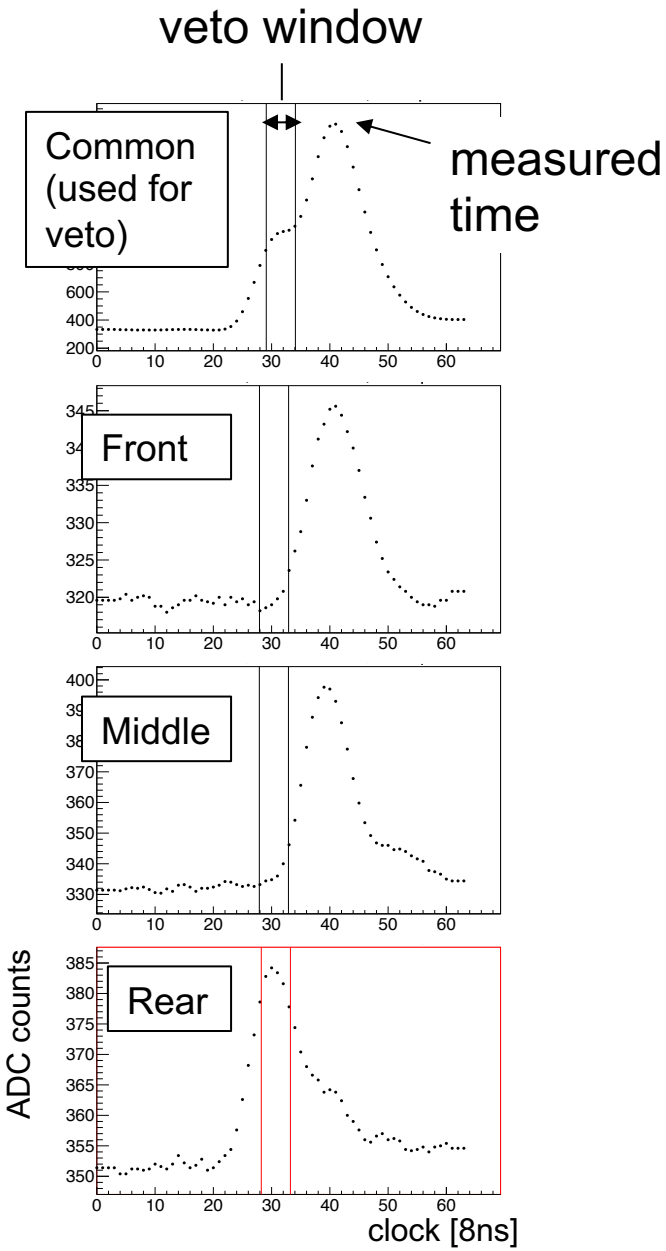
waveforms in the candidate event



Overlapped pulse event

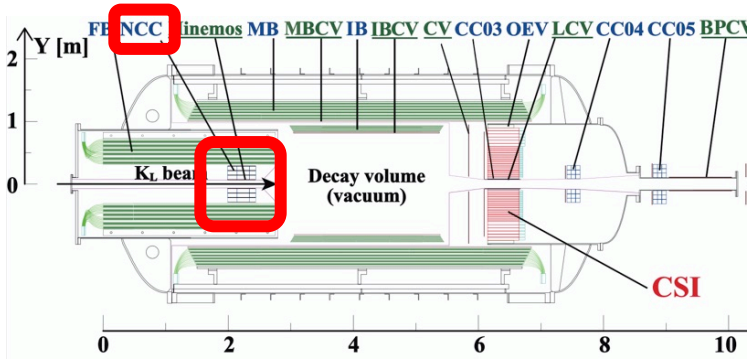
One of the three events has overlapped pulse in the upstream detector (NCC)





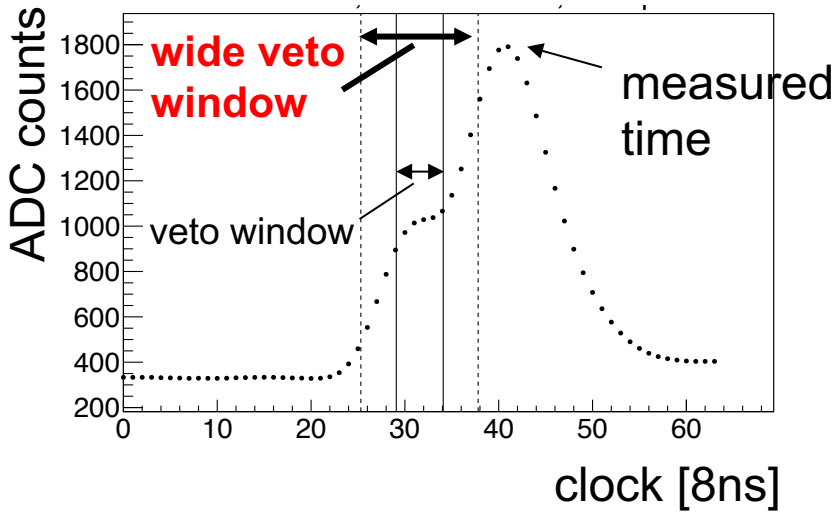
Overlapped pulse event

One of the three events has overlapped pulse in the upstream detector (NCC)



- Selection criteria of NCC
  - Used wide veto window
    if (χ^2 of overlapped pulse discriminator) > threshold
- Overlapped pulse discriminator
  - Pulse shape information : Fourier transformation
  - χ^2 : compared with single hit template

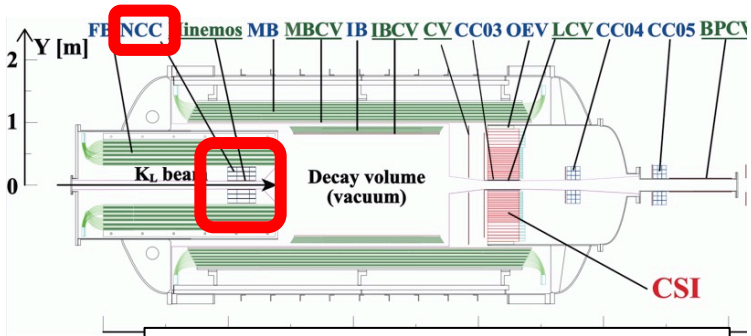
waveform in the candidate event



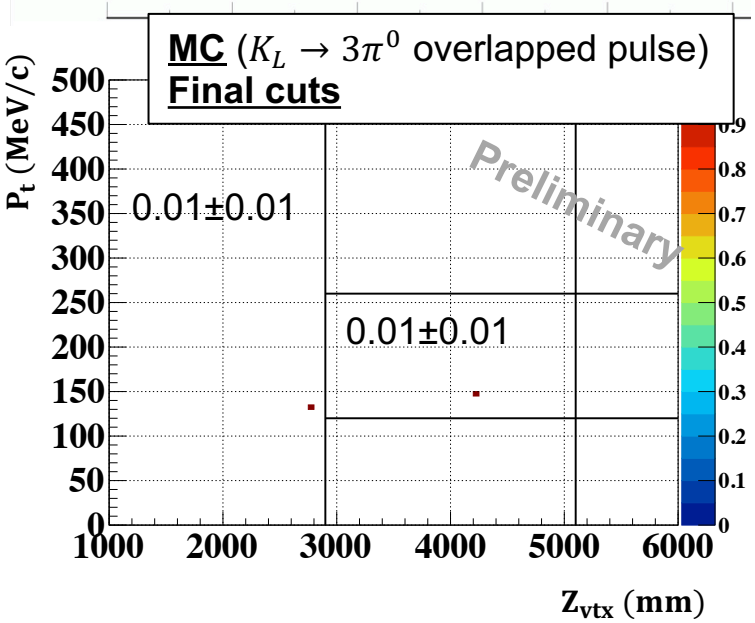
The candidate event :
$\chi^2_{candidate\ event}$ > threshold,
but **outside the wide veto window**

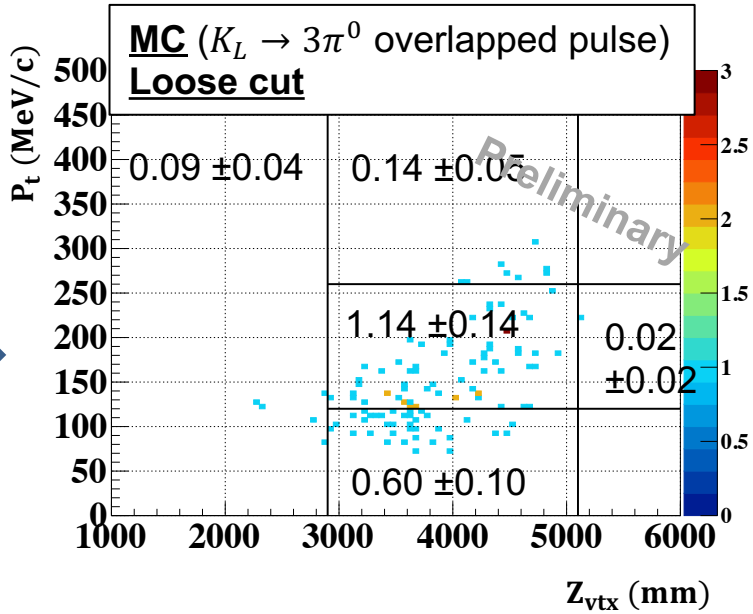
Study with loose cuts (MC)

- Study with loose cuts to enhance overlapped pulse events



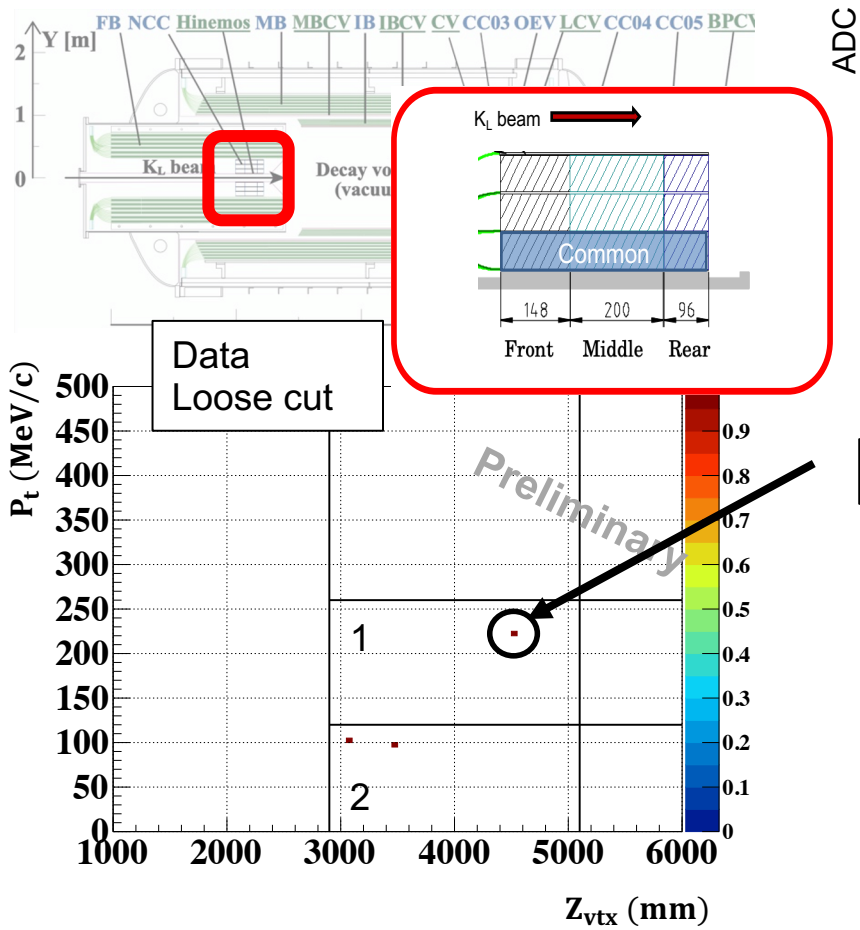
* Loose cuts
- Selected events vetoed by overlapped pulse discriminator
- Loose NCC veto was applied to avoid online veto effect

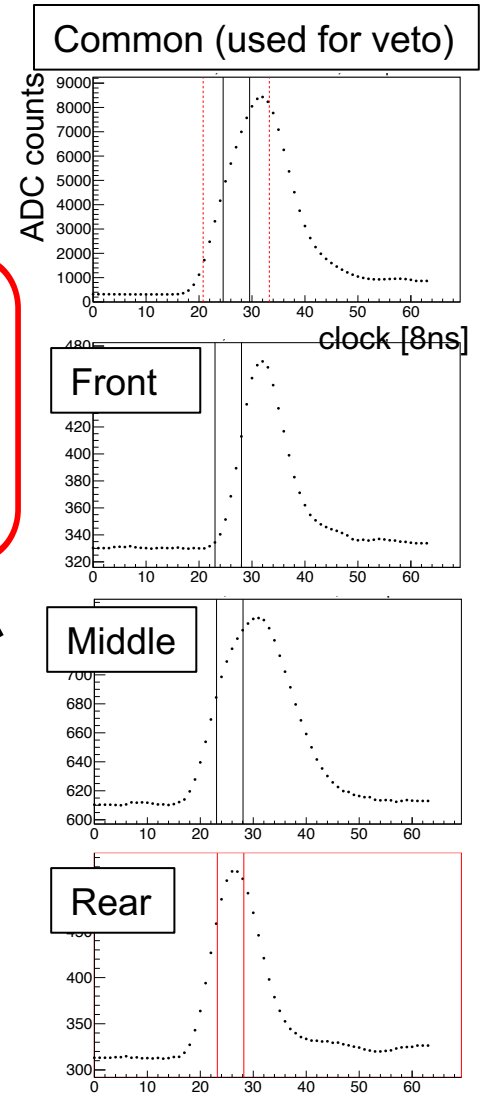




Study with loose cuts (data)

- One of the waveforms display





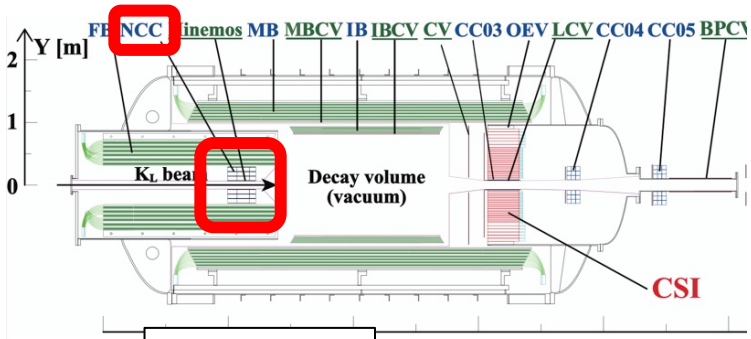
The other two events also had similar overlapped pulse

→

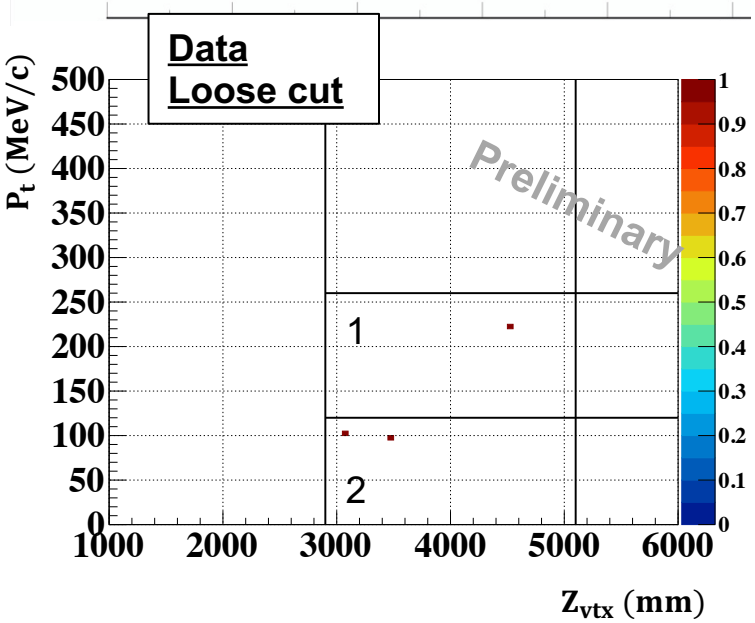
We could enhance overlapped events in data

Study with loose cuts (data and MC)

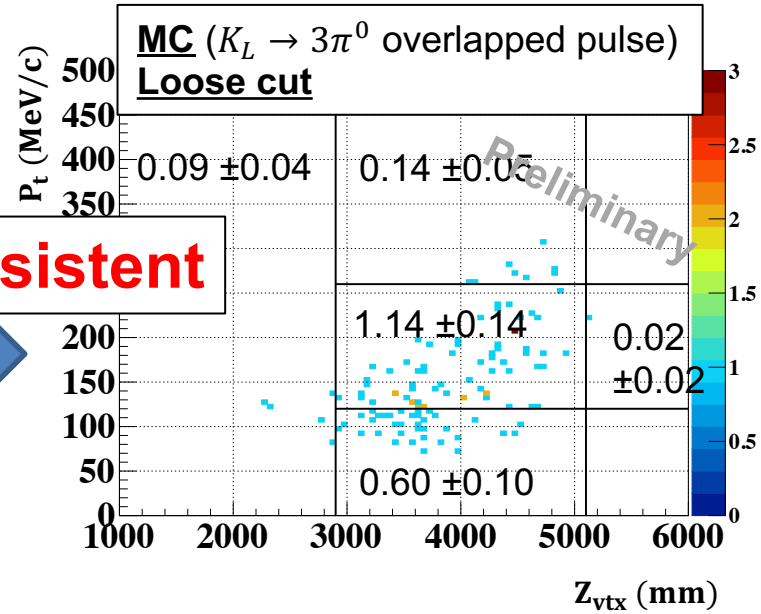
- Study with loose cuts to enhance overlapped pulse events



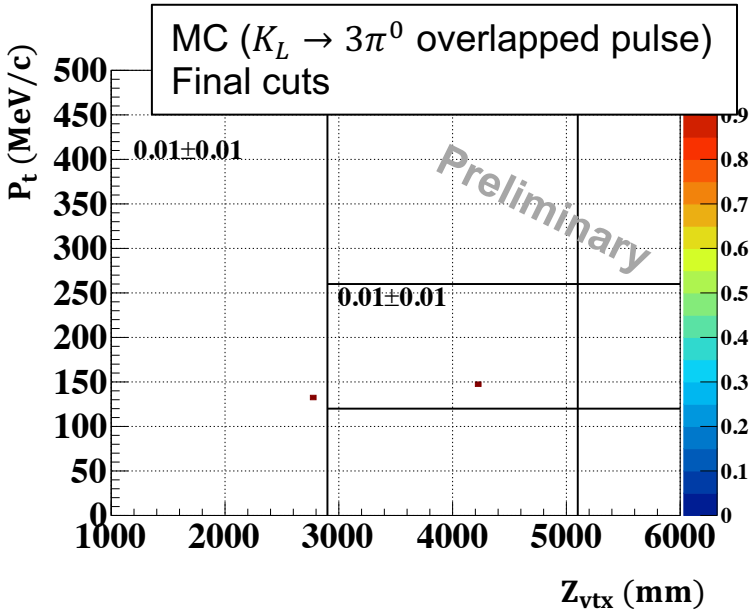
* Loose cuts
- Selected events vetoed by overlapped pulse discriminator
- Loose NCC veto was applied to avoid online veto effect



Consistent



Overlapped pulse event

- MC reproducibility
  - Loose cuts study : good
  - Pulse overlapped probability : good

- #BG : 0.01 ± 0.01
  - p-value (N_{obs}=1) : 1.1% (~2.5σ)