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

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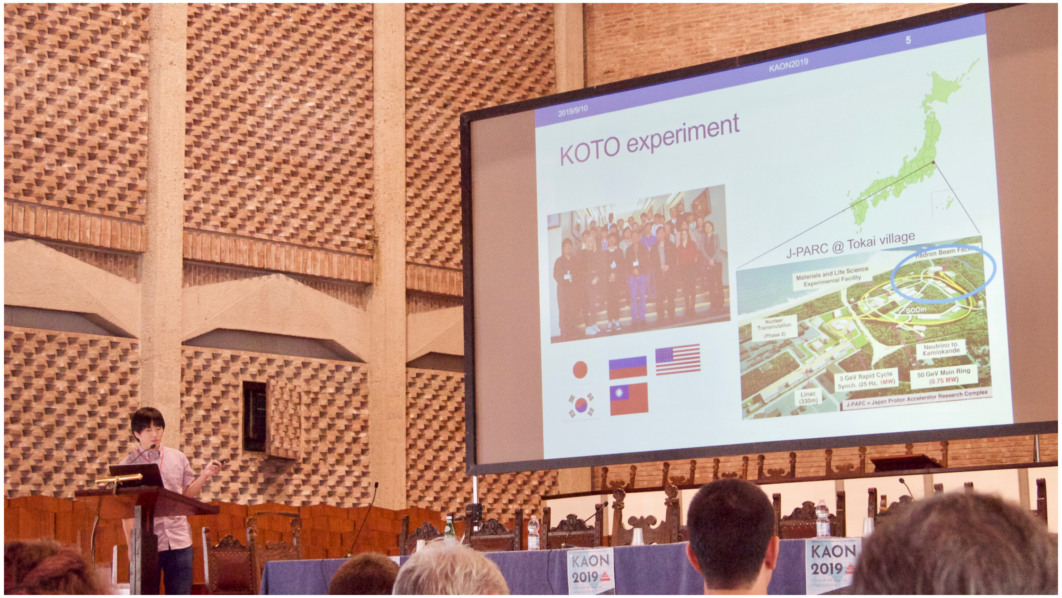
2019/12/23

Kuno and Yamanaka Groups
End-of-the Year
Presentation

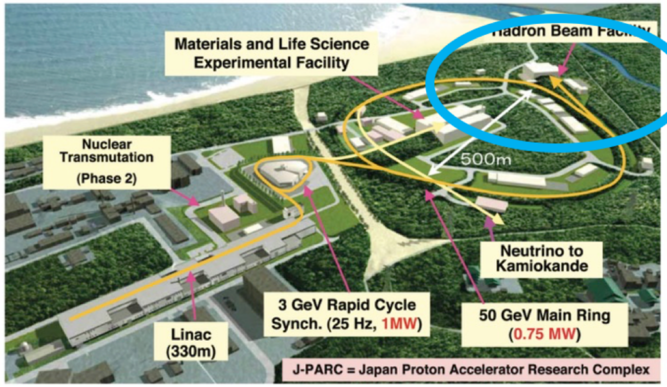


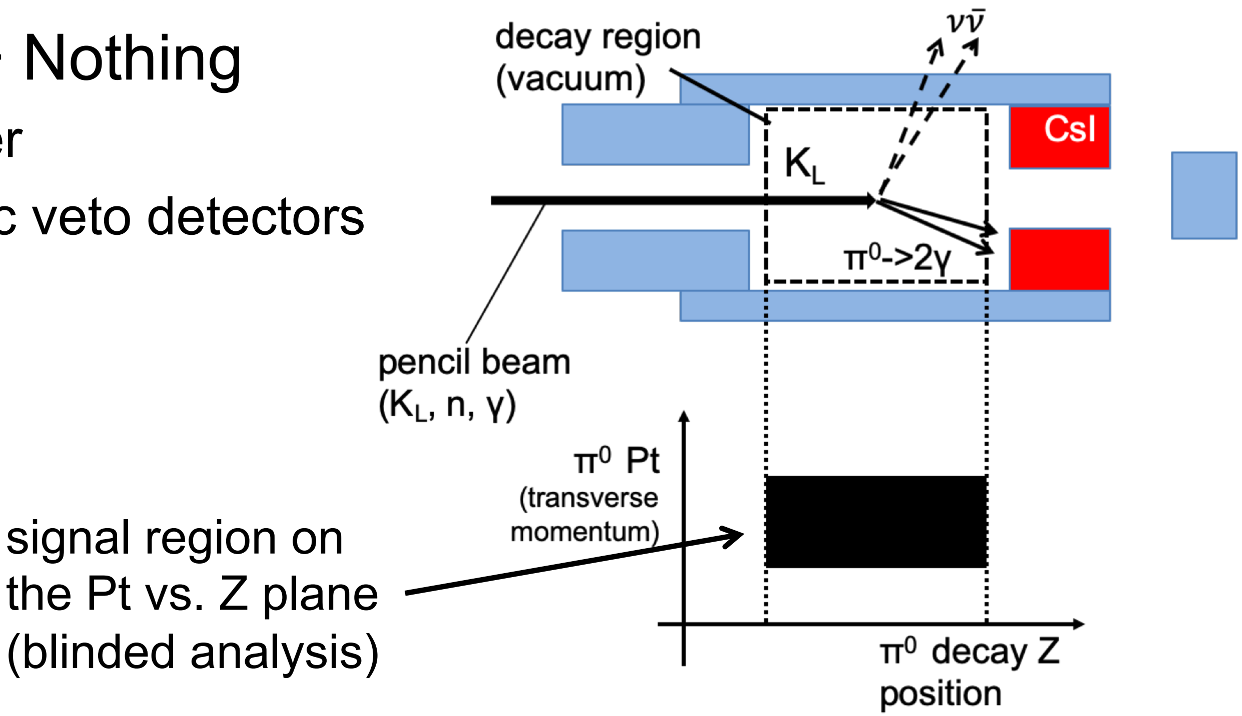
KAON2019 @ Perugia Univ. Italy

KOTO

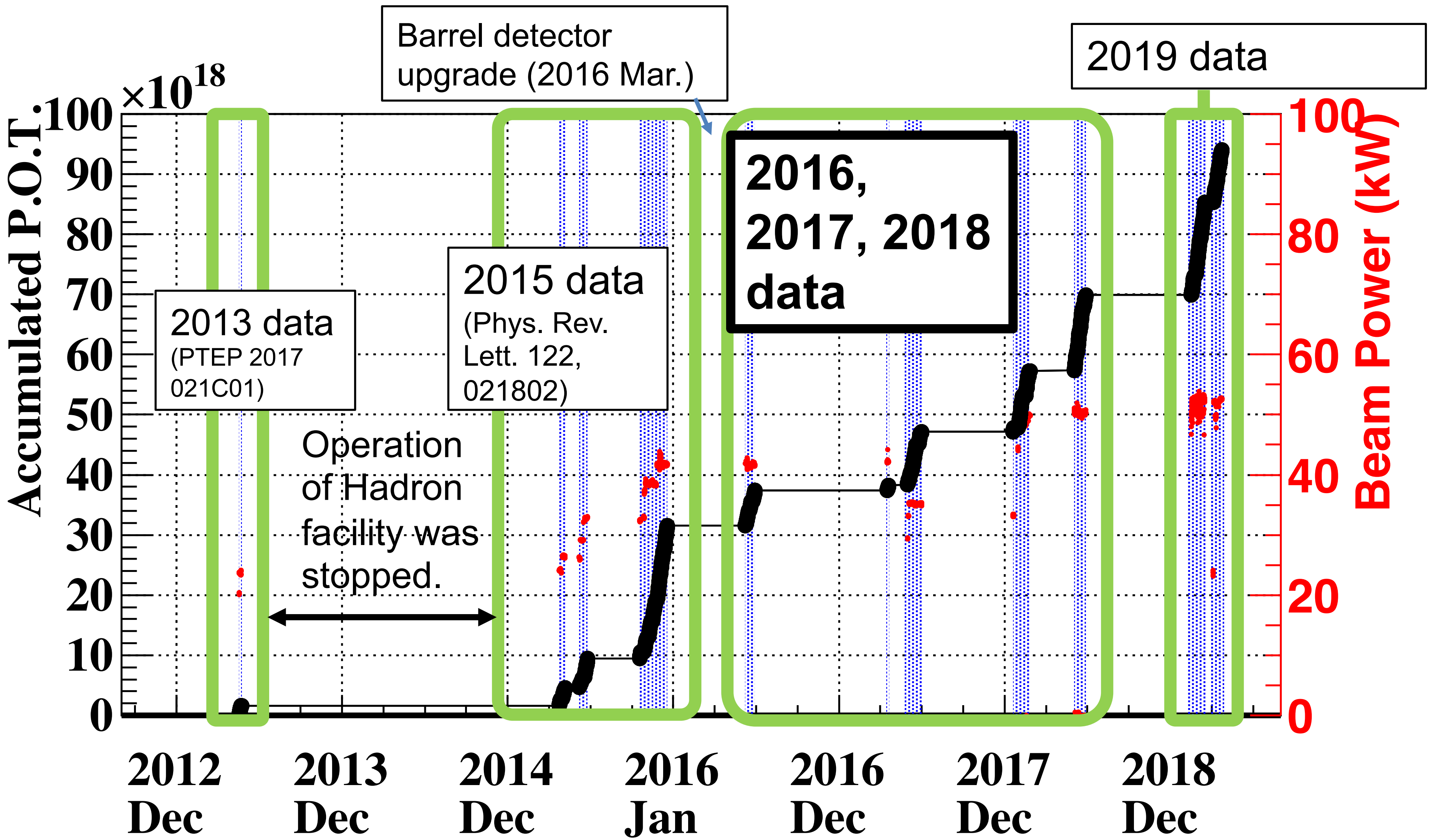
- $K_L \to \pi^0 \nu \bar{\nu}$
  - highly suppressed : BR(SM) : 3.0×10^{-11}
  - small theoretical uncertainty (~2%)
  - → good probe for new physics search
- signal : ($\pi^0 \to 2\gamma$)+ Nothing
  - $2\gamma \to$ CsI calorimeter
  - Nothing → Hermitic veto detectors

J-PARC





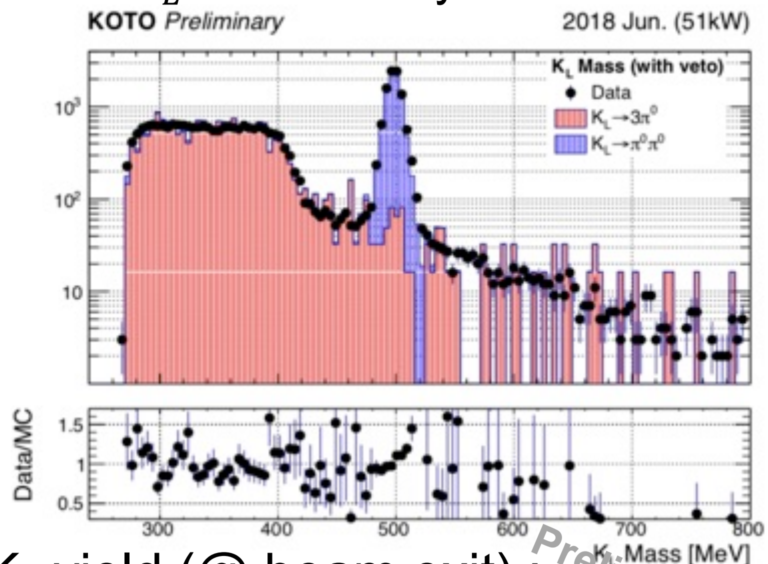
History of data taking



Single event sensitivity (S.E.S)

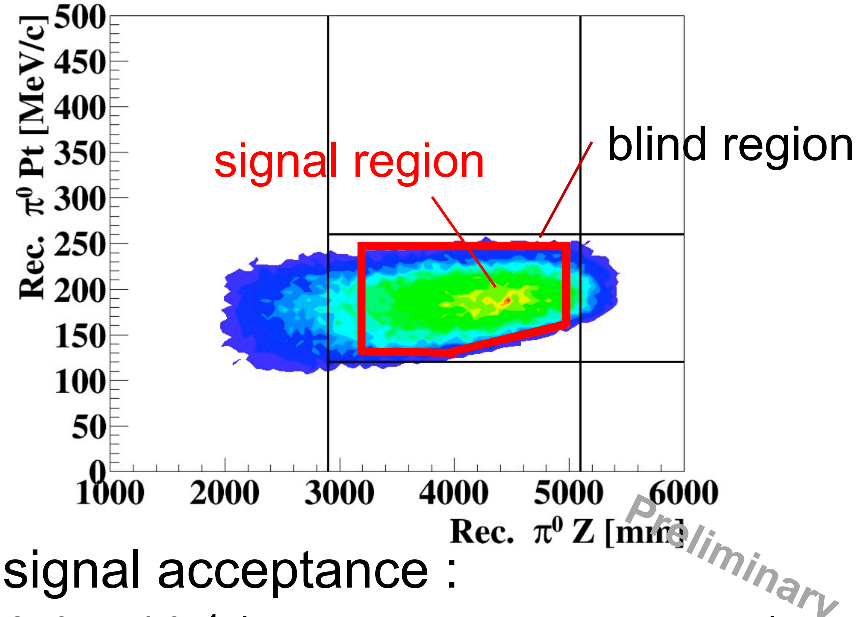
- S.E.S = 1/((K_L yield) × (signal acceptance))

reconstructed K_L mass distribution
from $K_L \to 2\pi^0$ analysis



K_L yield (@ beam exit) :
7.1×10^{12} (×~1.5 from 2015)

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

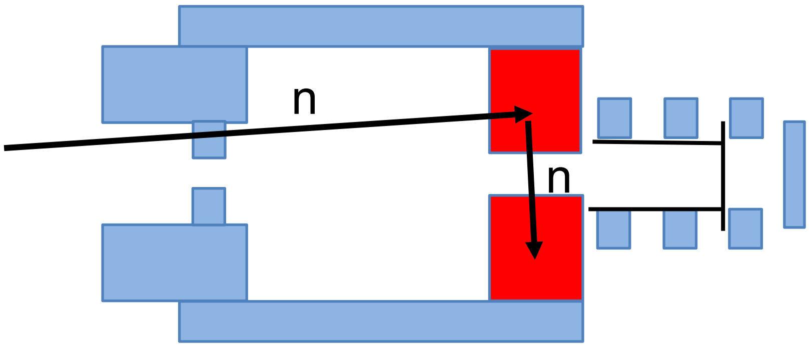


signal acceptance :
2.0×10^{-4} (×~1.3 improved from 2015)

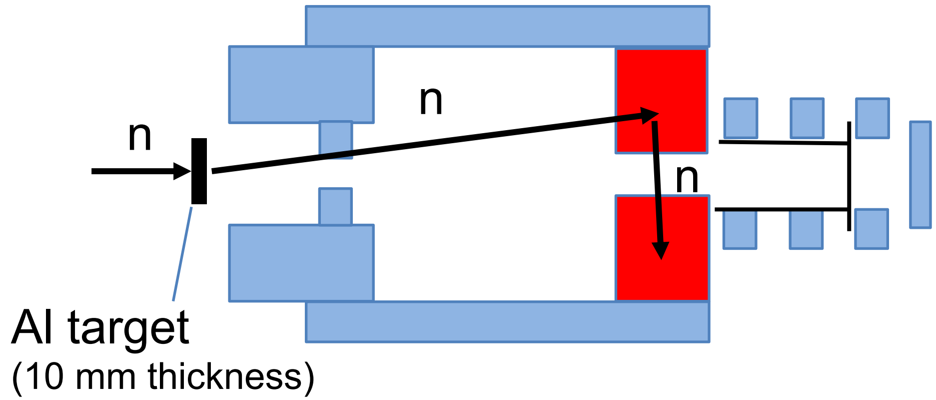
Signal box : optimized better for S/N
S.E.S : 6.9×10^{-10} (↔ S.E.S_{2015} : 1.3×10^{-9})

Hadron cluster BG

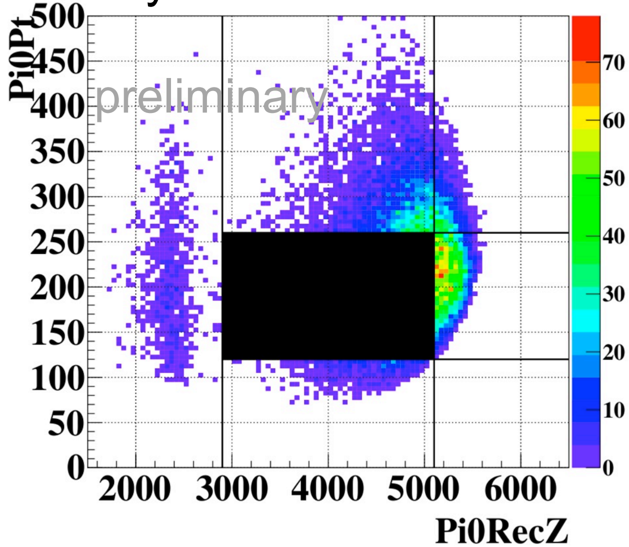
Physics run



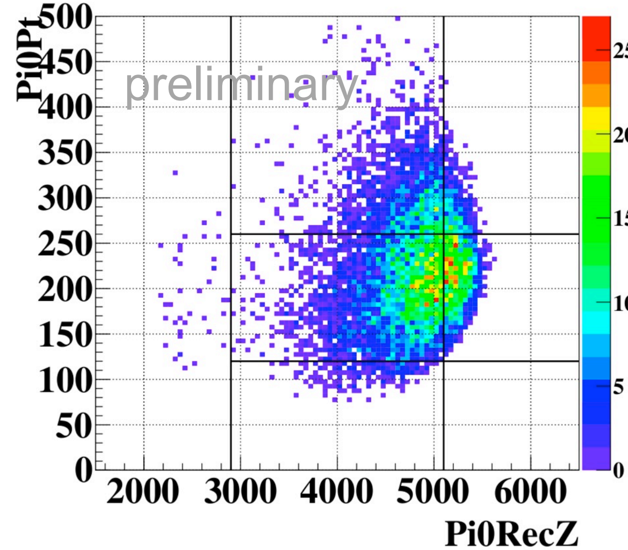
Special run



Physics data

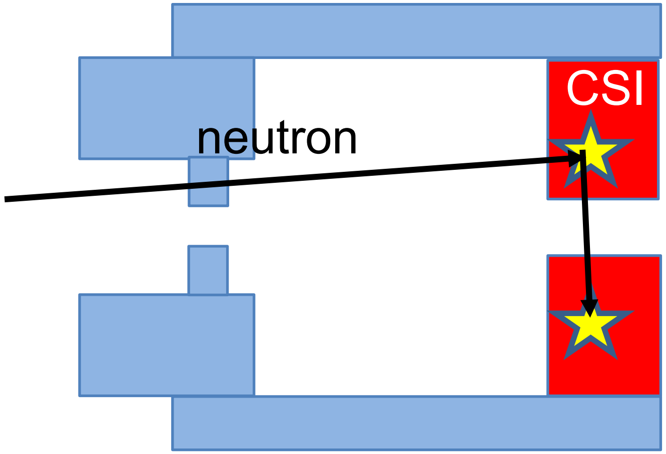


Control sample



Hadron cluster BG in 2015 analysis

Hadron cluster BG



2015 run background summary table

BG source	No. events	
$K_L \to \pi^+\pi^-\pi^0$	0.05 ± 0.02	K_L BG
$K_L \to 2\pi^0$	0.02 ± 0.02	
Other K_L decays	0.03 ± 0.01	
Hadron cluster	**0.24 ± 0.17**	Neutron related BG
Upstream π^0	0.04 ± 0.03	
CV η	0.04 ± 0.02	
Total	**0.42 ± 0.18**	

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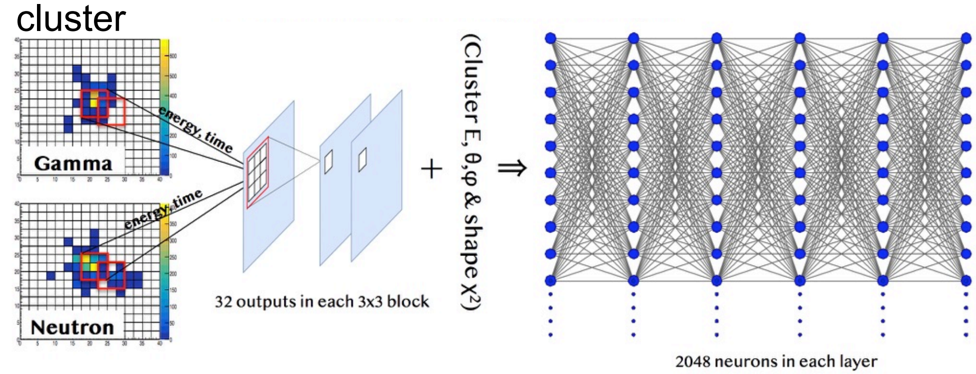
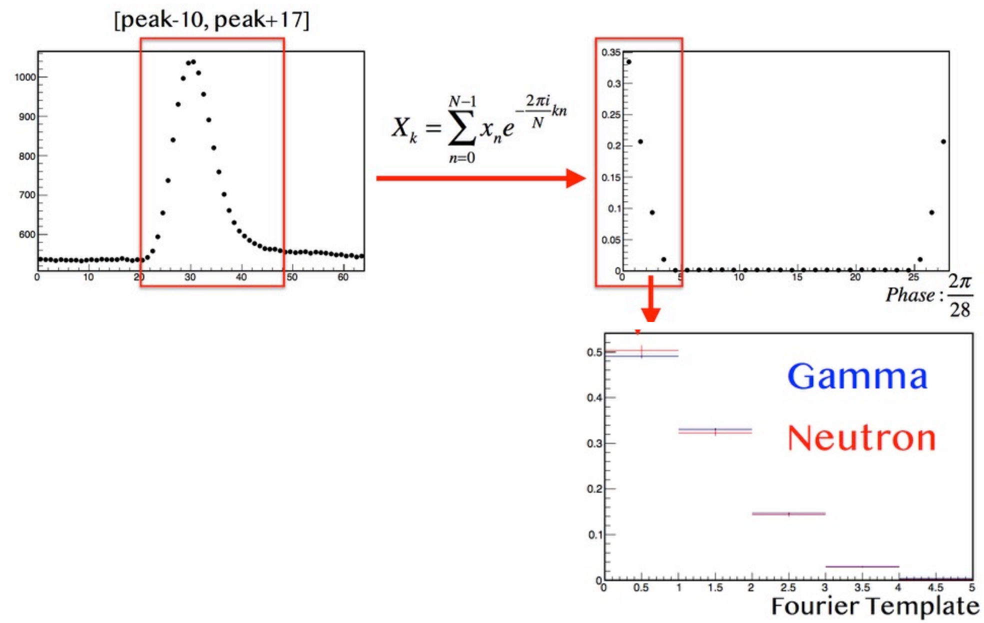
Hadron cluster BG update from 2015 (cut)

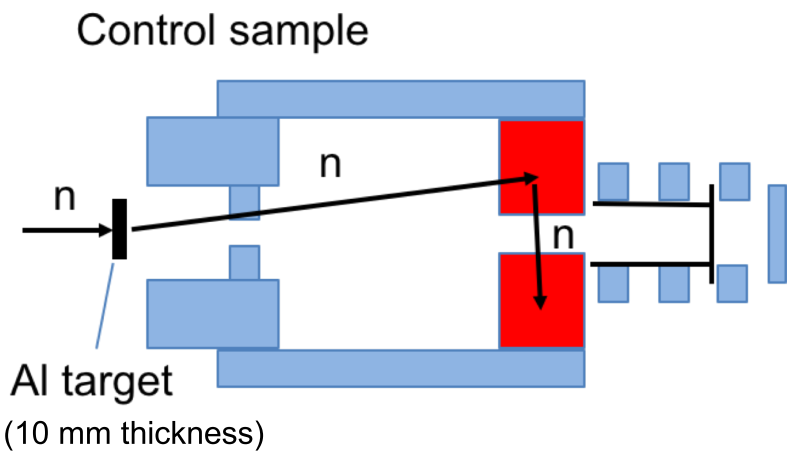
1. Cluster shape cut with deep learning
   - S/N : ×~2 from 2015

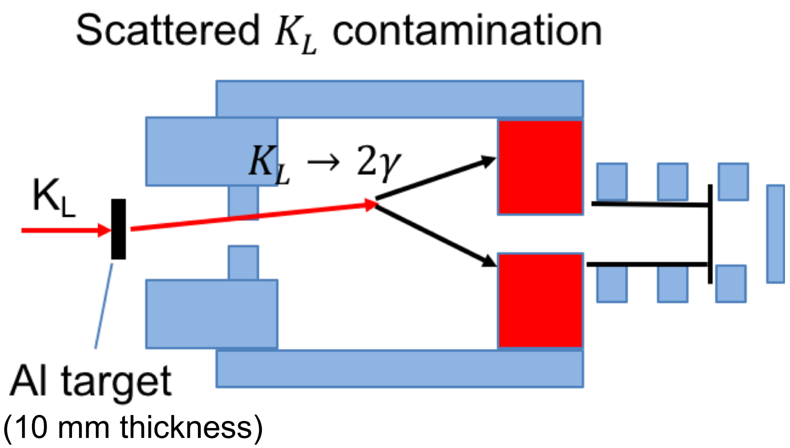


2. Pulse shape discrimination with Fourier transformation
   - S/N : ×~1.8 from 2015



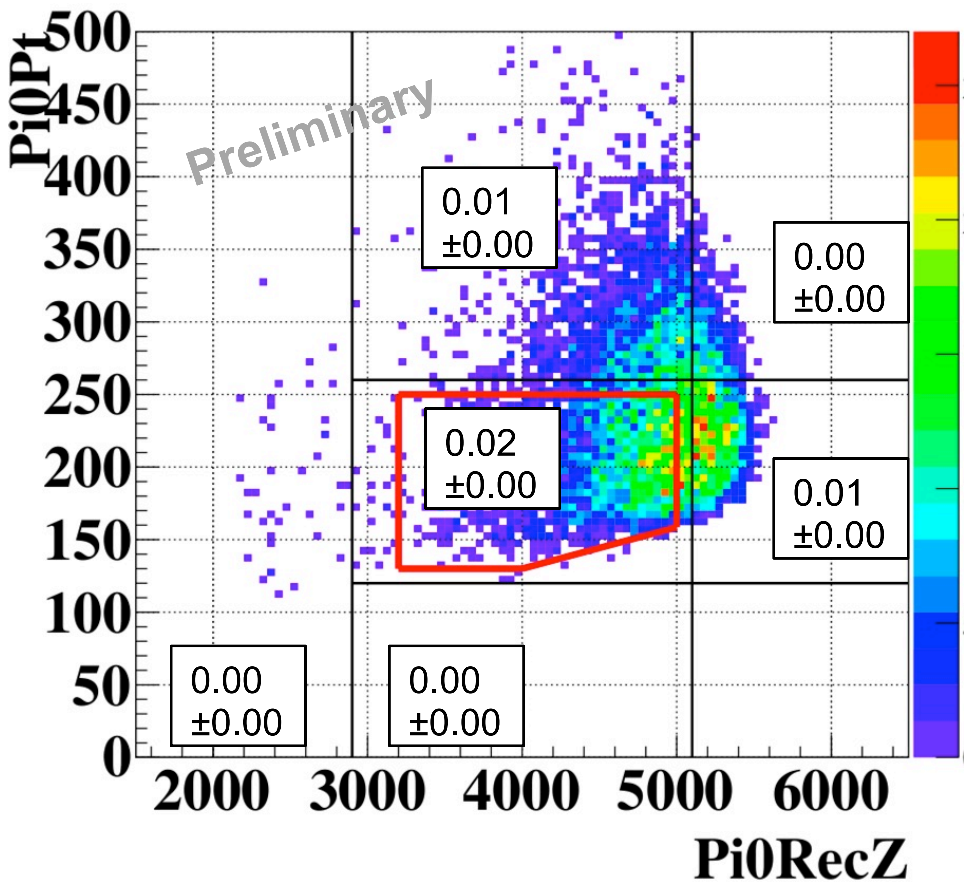
Hadron cluster BG estimation





- Found contamination in the control sample
  - Developed more reliable estimation method
    - based on single cluster reduction
  - reduction : ×27(±19) from w/o concerning scatter $K_L \rightarrow 2\gamma$

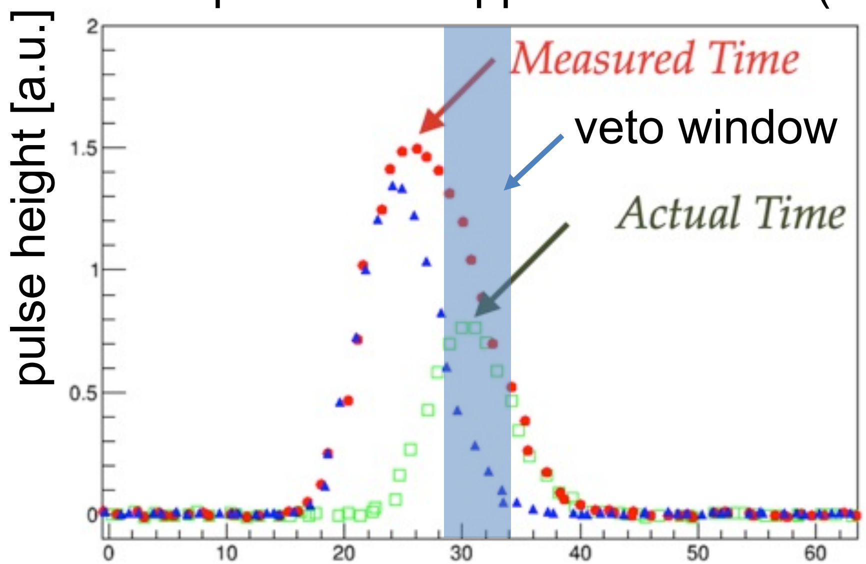
Hadron cluster BG



Overlapped pulse BG

- Overlapped pulse shifts measured time for veto detectors
  - Narrower veto window
    - recover signal acceptance
    - increase BG from overlapped pulse

example of overlapped waveform (MC)

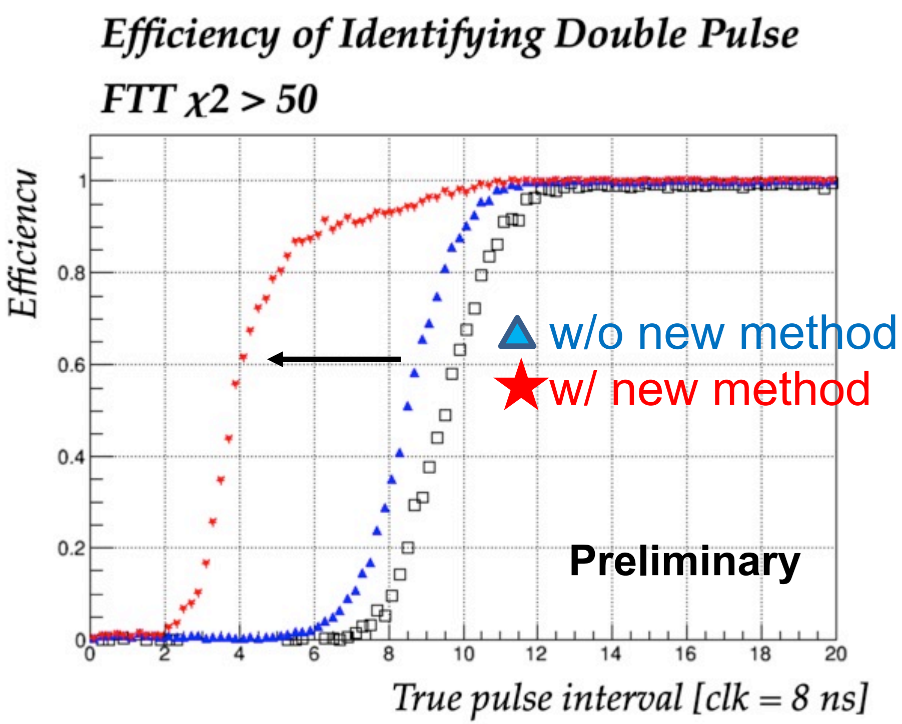


clock [8ns]

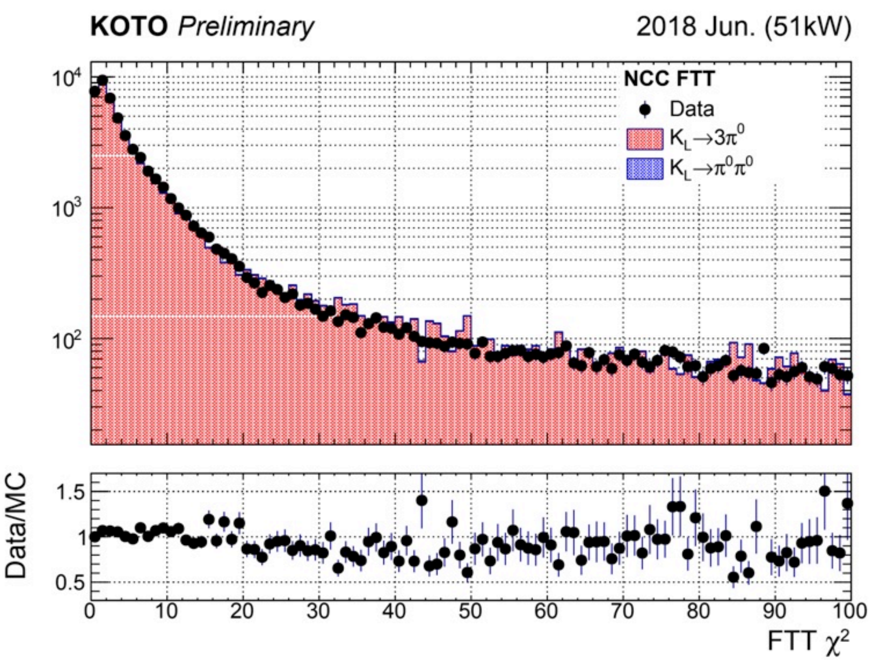
(125MHz waveform digitizer)

Overlapped pulse BG

- Overlapped pulse discriminator
  - Pulse shape information : Fourier transformation
  - χ^2 : compared with single hit template



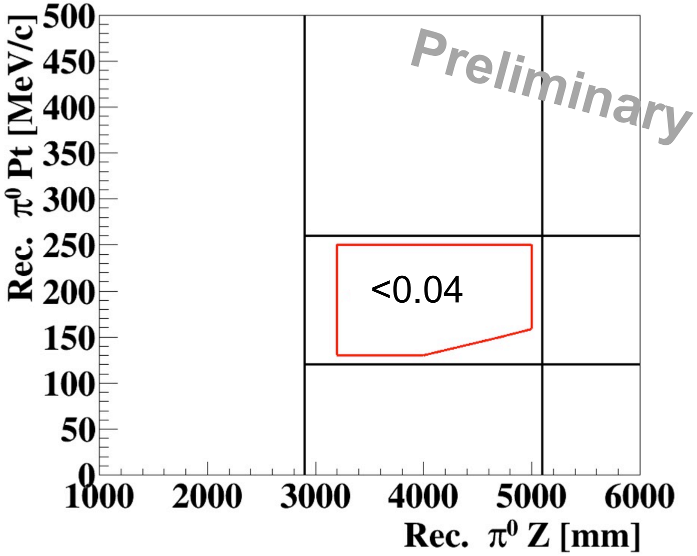
χ^2 distribution of upstream detector



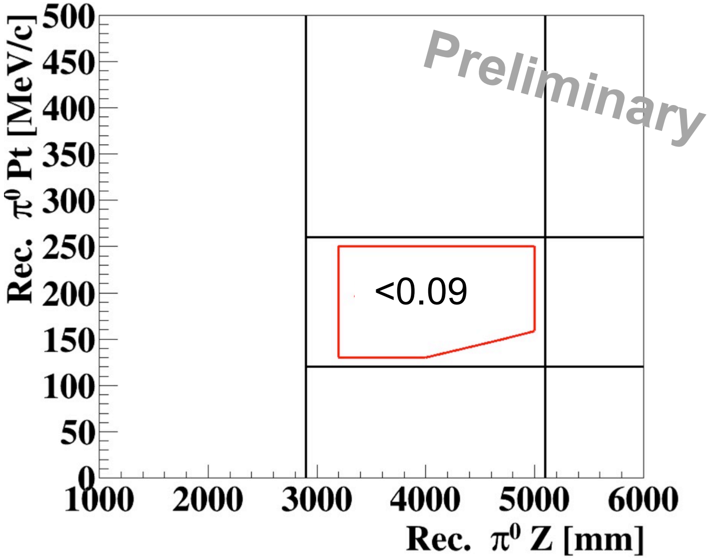
Overlapped pulse BG

- Narrower veto window + overlapped pulse discriminator

Overlapped pulse BG from $K_L \to 3\pi^0$ MC analysis



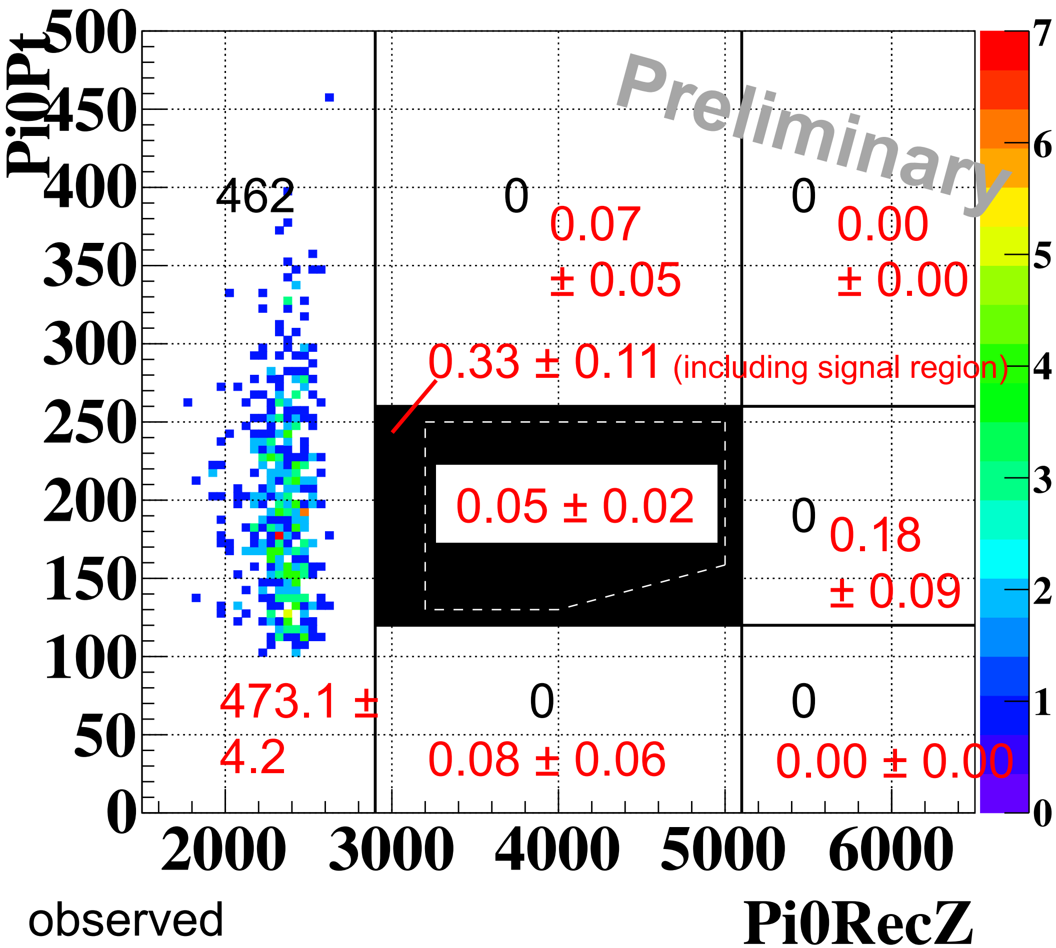
Overlapped pulse BG from $K_L \to \pi e \nu$ MC analysis



Narrower veto window : Recovered 10% signal acceptance
No remaining event due to overlapped pulse

BG summary

S.E.S : 6.9×10^{-10}



observed

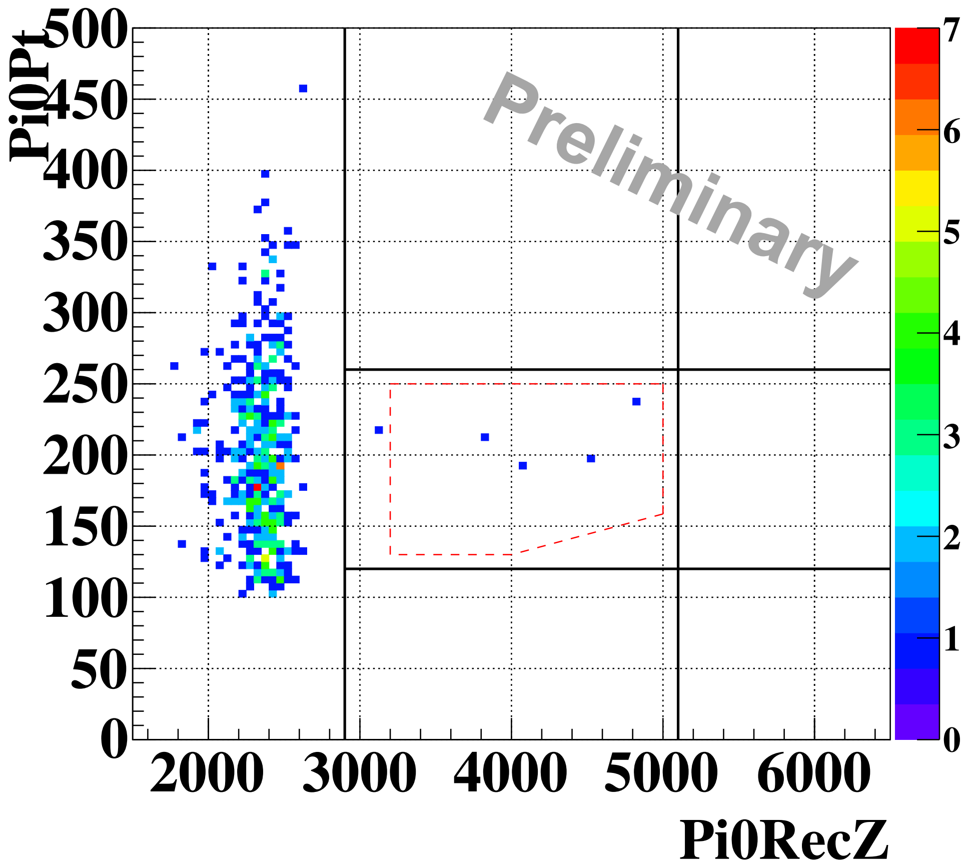
expectation

Preliminary

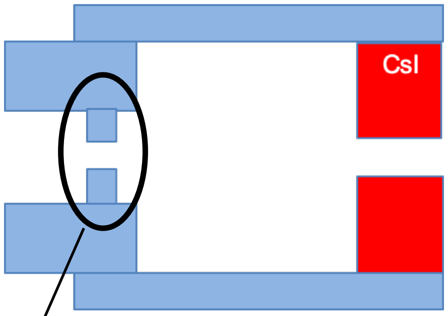
	#BG
$K_L \rightarrow 2\pi^0$	<0.18
$K_L \rightarrow \pi^+\pi^-\pi^0$	<0.02
$K_L \rightarrow 3\pi^0$ (overlapped pulse)	<0.04
Ke3 (overlapped pulse)	<0.09
$K_L \rightarrow 2\gamma$	0.001±0.001
Upstream π^0	0.001±0.001
Hadron cluster	0.02 ±0.00
CV-pi0	<0.10
CV-eta	0.03±0.01
Total	0.05±0.02

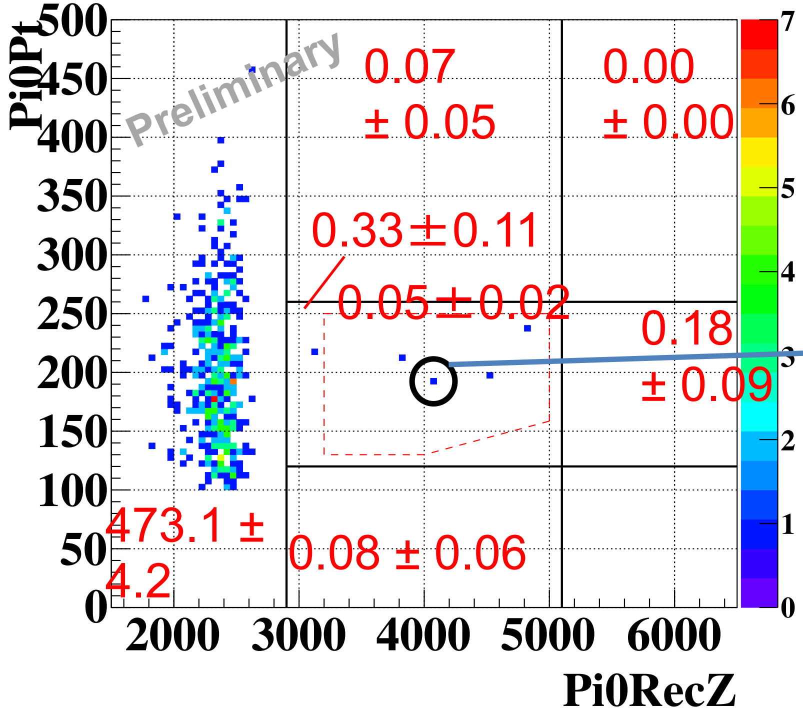
Unblinded

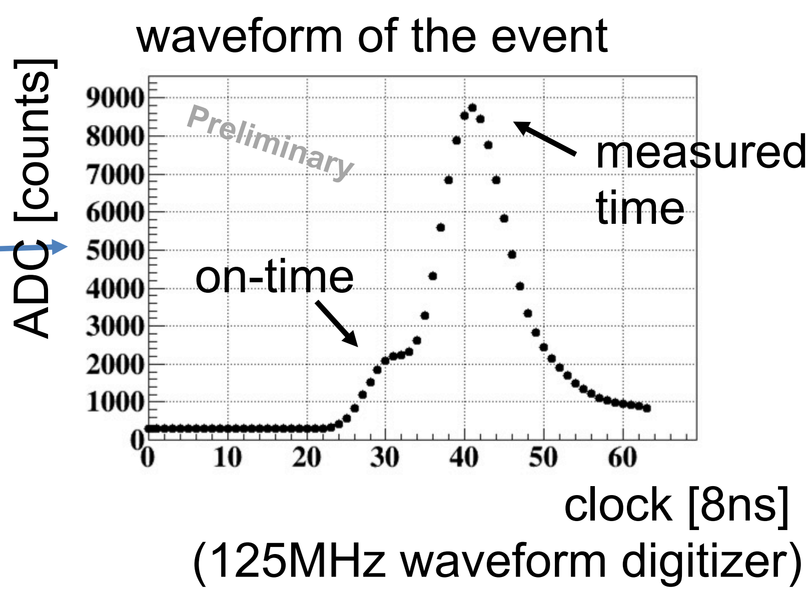
Unblinded



unblinded in the end of Aug. 2019

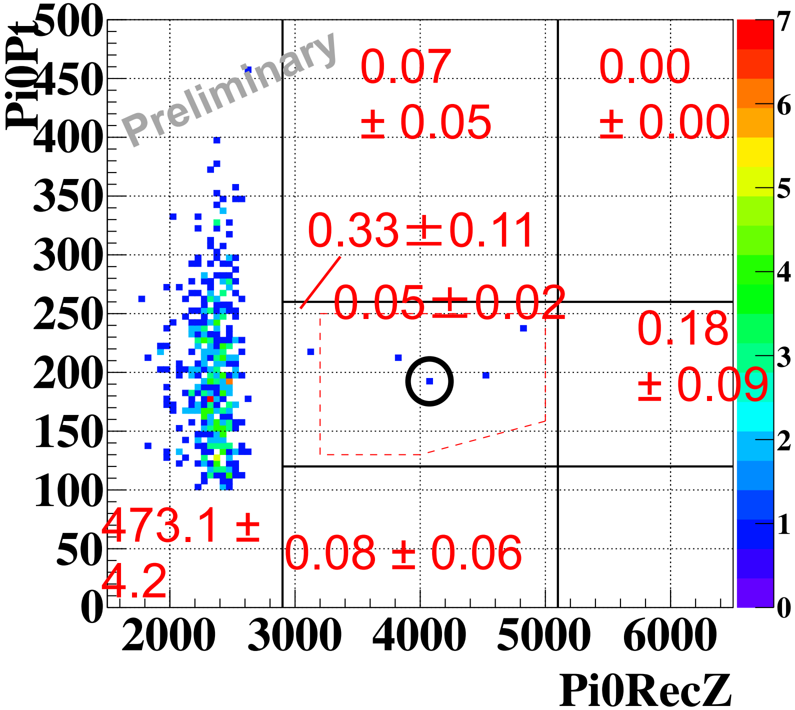






expectation

On-timing peak is shifted by large pulse



expectation

BG estimation related overlapped pulse

Preliminary

	#BG
KL3pi0 (overlapped pulse)	<0.04
Ke3 (overlapped pulse)	<0.09

Underestimated the BG from overlapped pulse?

- Checking the properties of the other candidates
- Did we miss other background sources?
  - planning to reevaluate other BG sources

Summary

- $K_L \rightarrow \pi^0 \nu \bar{\nu}$ at J-PARC KOTO experiment

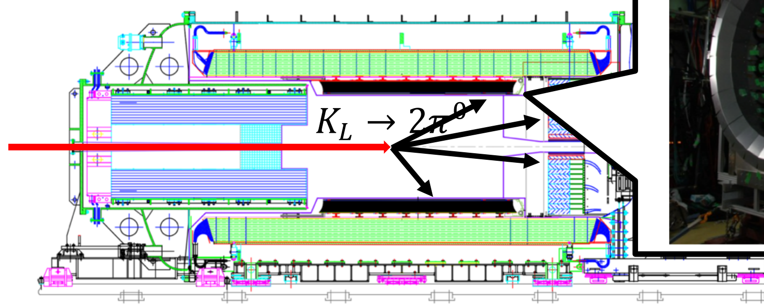
- S.E.S : 6.9×10^{-10}
- BG estimation : 0.05 ± 0.02

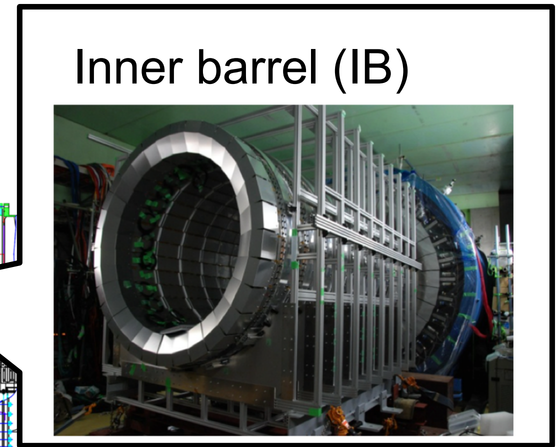
- Opened the box
  → 4 candidate events in the signal region
    Event properties:
      One event : overlapped waveform
   Checking other candidates carefully

END

Detector and DAQ upgrade in 2016-2018

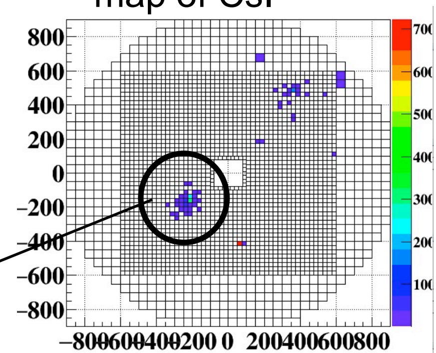
- Barrel detector was upgraded in 2016.4
  - $13.5X_0 \rightarrow 18.5X_0$
  - $K_L \rightarrow 2\pi^0$ BG : ×1/3





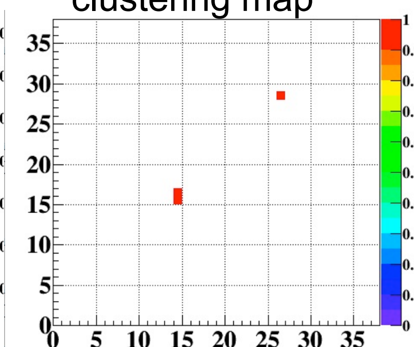
- DAQ upgrade (covered in poster session)
  - Online cluster counting (2017~)
  - Higher DAQ live time ratio
    - ~80% (2015 @ 42kW beam) → ~99% (2018 @ 51kW beam)

Energy deposit map of CsI



cluster

online clustering map



Result of 2015 physics run

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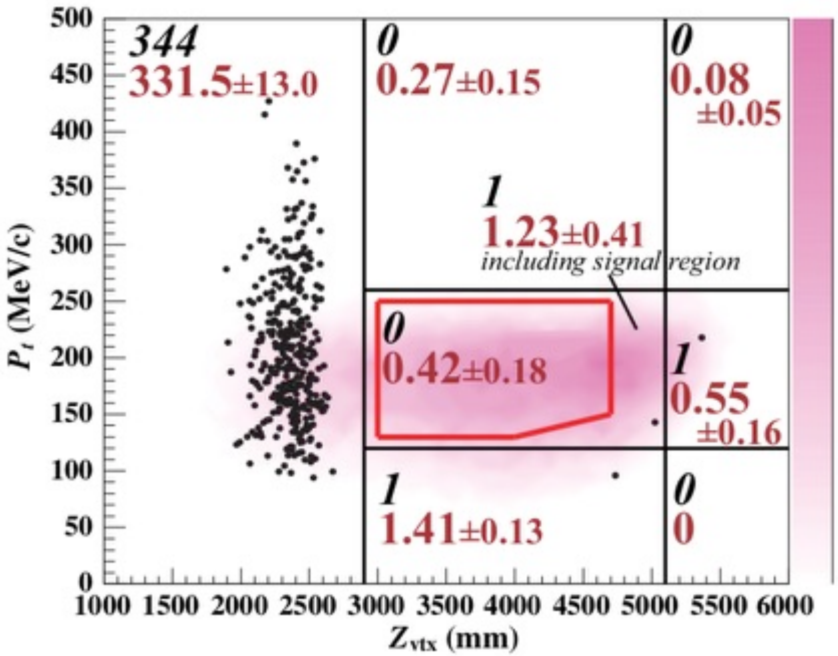

observed
expectation
contour : $K_L \to \pi^0 \nu\bar{\nu}$ (MC)

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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

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(KOTO Collaboration)

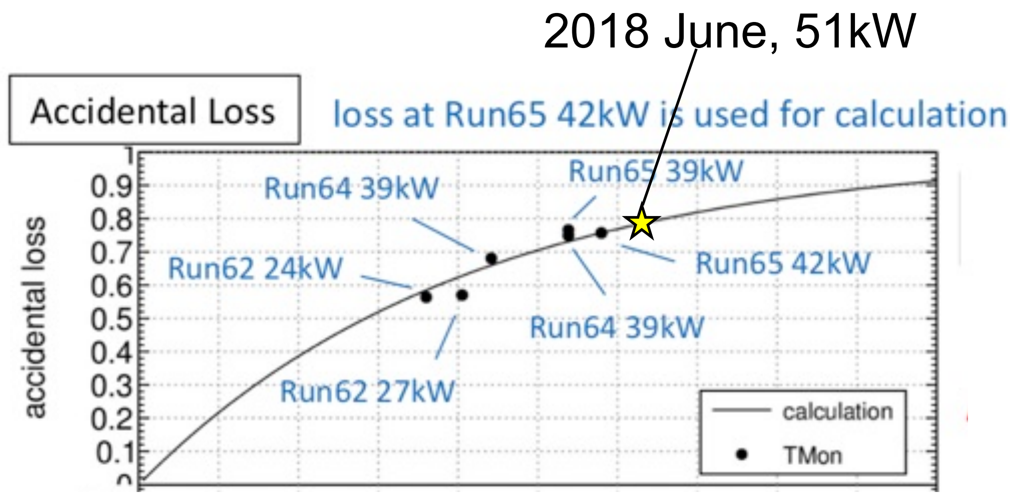
- Single event sensitivity :
  $(1.30 \pm 0.01_{stat} \pm 0.14_{syst}) \times 10^{-9}$
  - No event in the signal region

➡ Upper limit (90% C.L.) :
Br($K_L \to \pi^0 \nu\bar{\nu}$) < 3.0 × 10⁻⁹

× 10 improvement from previous limit (KEK E391a)

Toward 2016-2018 data analysis

- Higher beam power
  → larger signal loss due to the accidental hit
  (76% loss in 2015 analysis)
- To achieve better sensitivity
  → Narrower veto window
  - Need BG study due to the narrower veto window

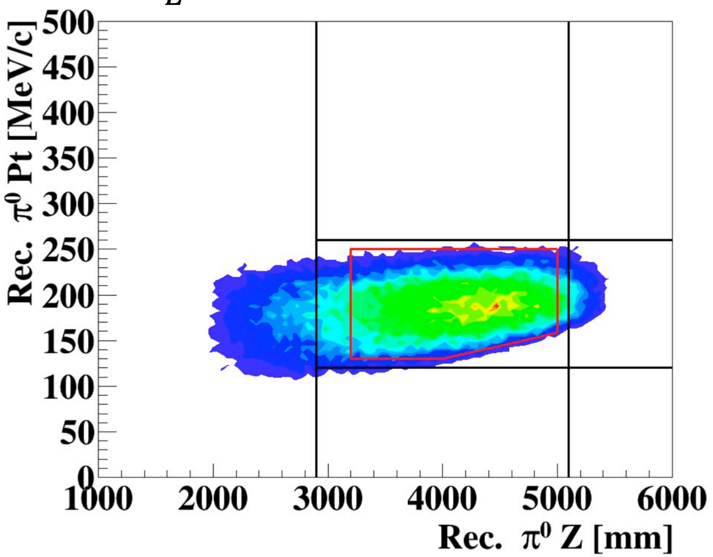


study from 2015 data

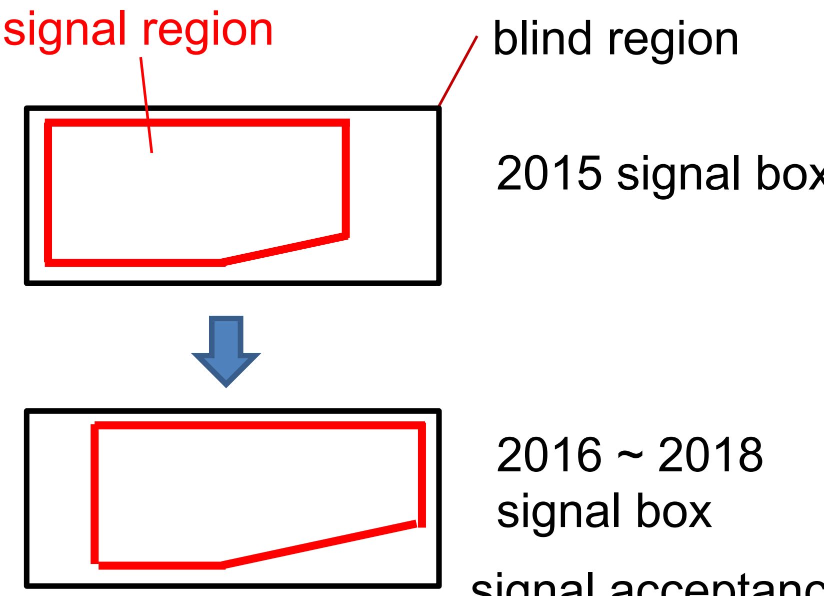
Single event sensitivity (S.E.S)

- S.E.S = 1/((K_L yield) × (signal acceptance))

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



signal acceptance : 2.0×10^{-4}

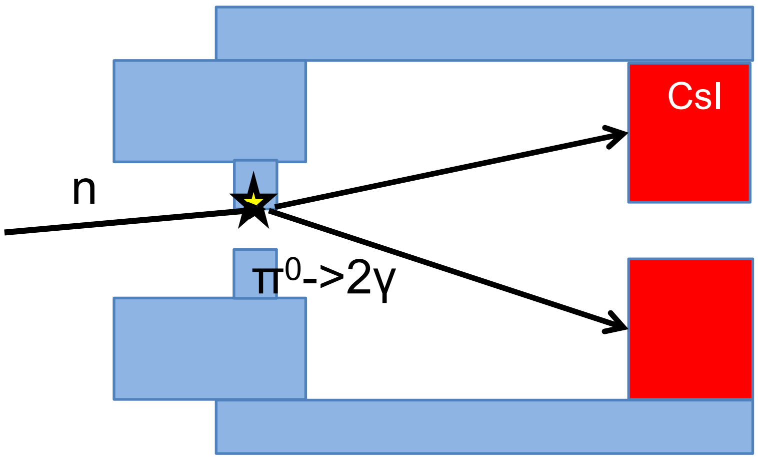


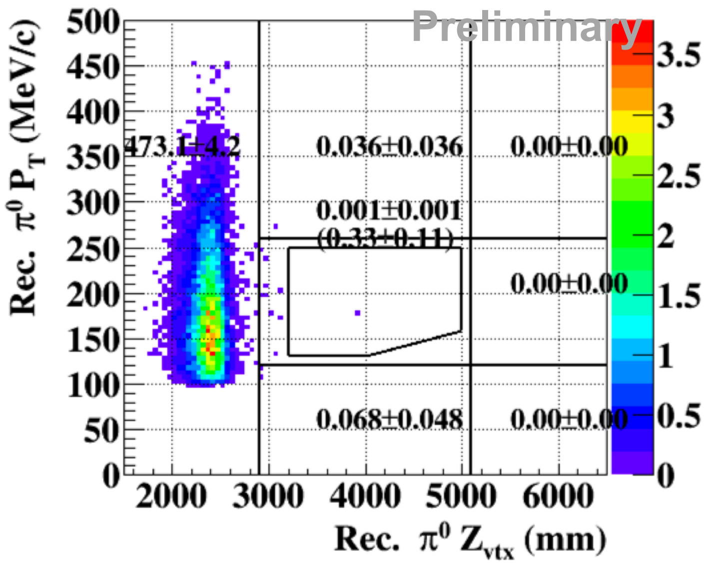
signal acceptance :
+ 6% (from 2015 signal box)

- Signal box : determined by S/N
- S.E.S : 6.9×10^{-10} Preliminary (S.E.S_{2015} : 1.3×10^{-9})

Upstream-π^0 BG

- Halo-neutron hits upstream detector
  - $\gamma + \gamma$
    - small visible energy shifted reconstructed Z position
  - $n + \gamma$
    - various reconstructed Z position
  - Shrink signal box of upstream Z
- $\#BG_{upstream\text{-}\pi0}$: 0.001 ± 0.001



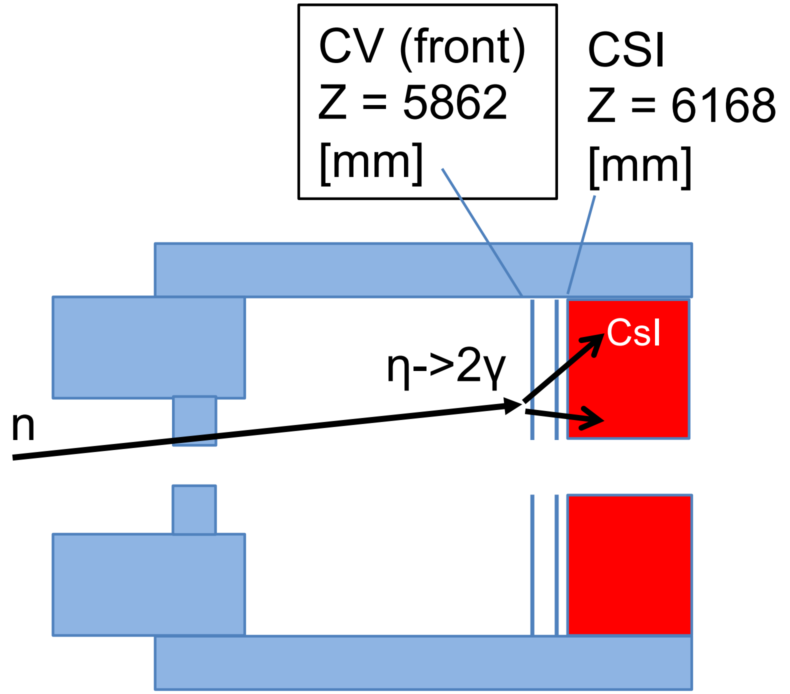


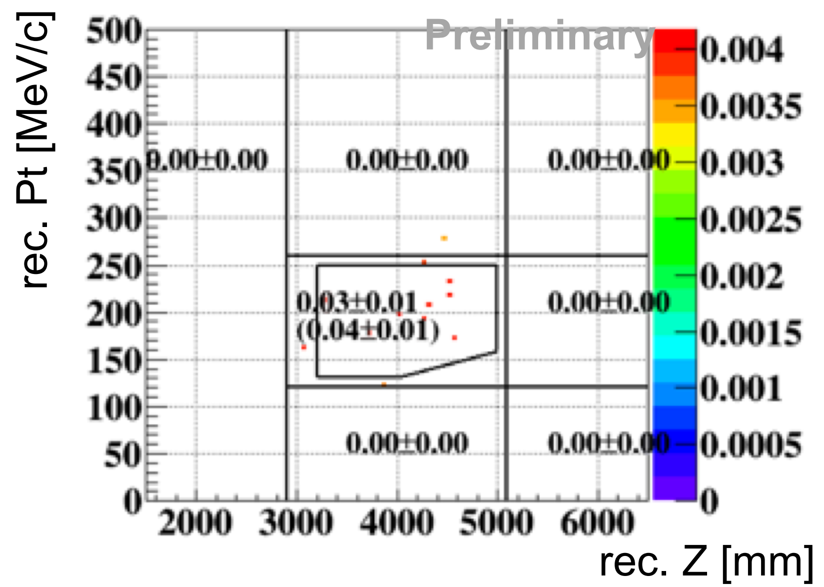
CV-η BG

- Neutron hits Charged Veto (CV) and generates η
  - reconstruction : assumed π^0 mass
  - $m_\eta \sim 4m_{\pi^0}$

  → reconstructed Z position : shifted in the signal region

$\#BG_\eta = 0.03 \pm 0.01$

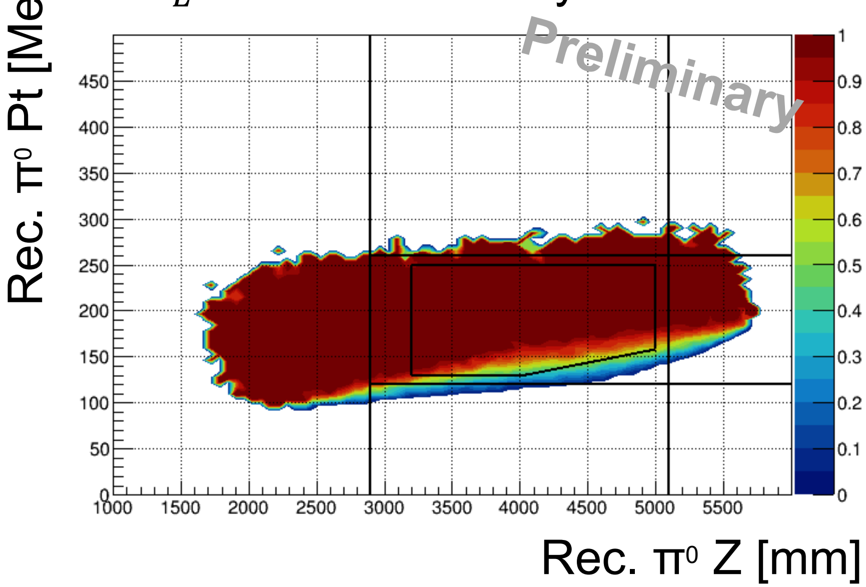




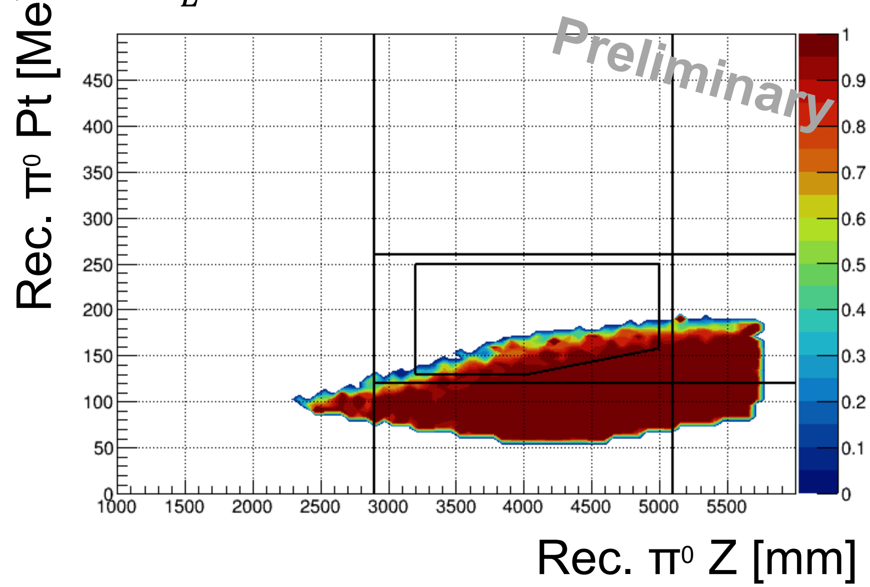
$K_L \to \pi^+\pi^-\pi^0$ BG

- Neural net with deep leaning for $K_L \to \pi^+\pi^-\pi^0$ BG
  - Similar behavior as π^0 P_t and Z cut
  - S/N : improved even after applying P_t and Z cut which is optimized $K_L \to \pi^+\pi^-\pi^0$ BG

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

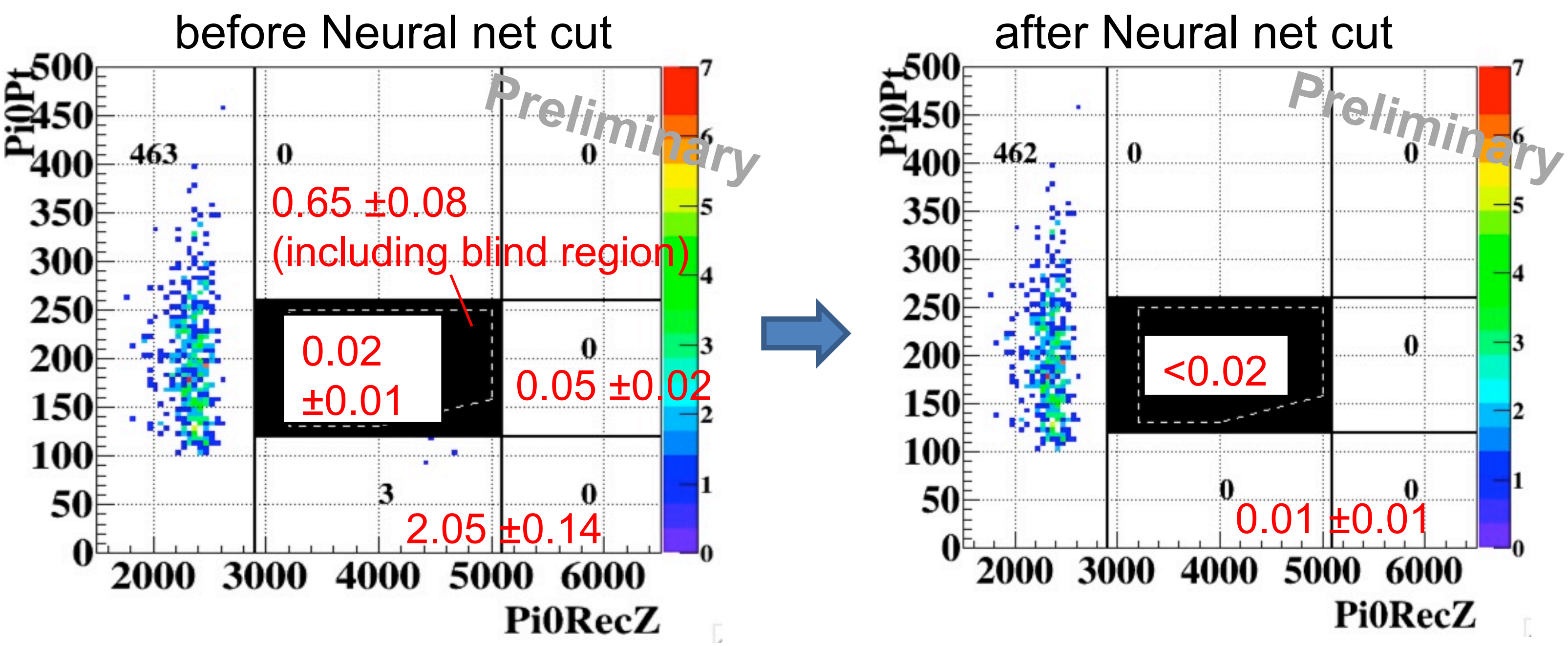


$K_L \to \pi^+\pi^-\pi^0$ reduction



$K_L \to \pi^+\pi^-\pi^0$ BG

- Applying neural net with deep leaning cut
  - #BG$_{K_L \to \pi^+\pi^-\pi^0}$: 0.02 → <0.02 (90% C.L.)
  - signal acceptance : 90%

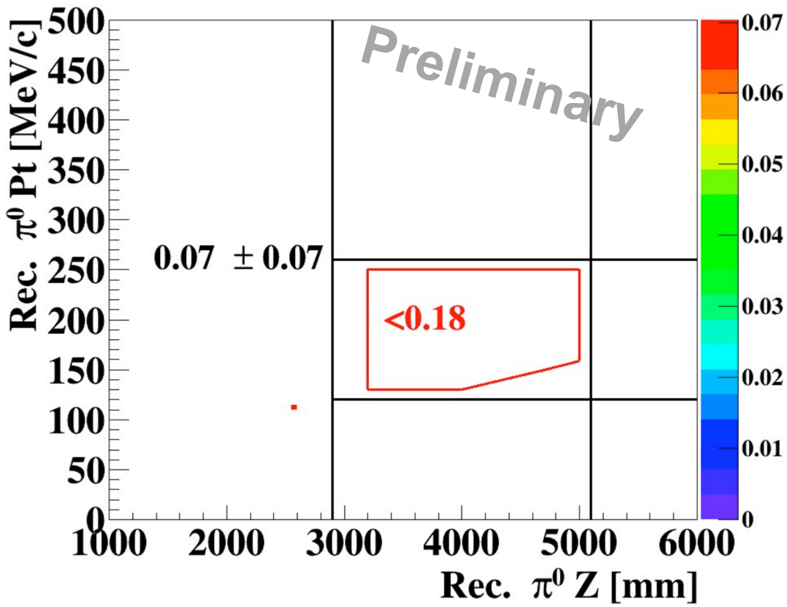


observed

expectation of $K_L \to \pi^+\pi^-\pi^0$ BG

$K_L \to 2\pi^0$, $K_L \to 2\gamma$ BG

Result from $K_L \to 2\pi^0$ MC study



Result from $K_L \to 2\gamma$ MC study