Search for the rare decay $K_L \to \pi^0 \nu \bar{\nu}$ at J-PARC KOTO experiment

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on behalf of the KOTO collaboration

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- Results of 2015 physics run
- 2016~2018 data analysis
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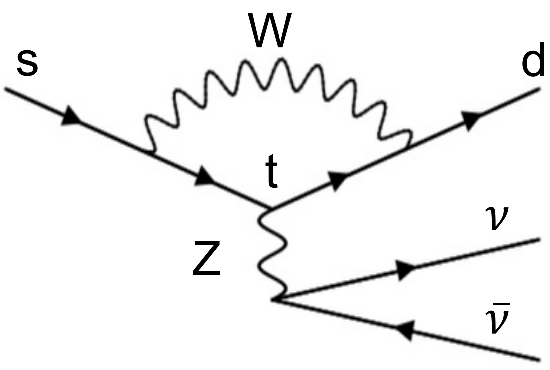
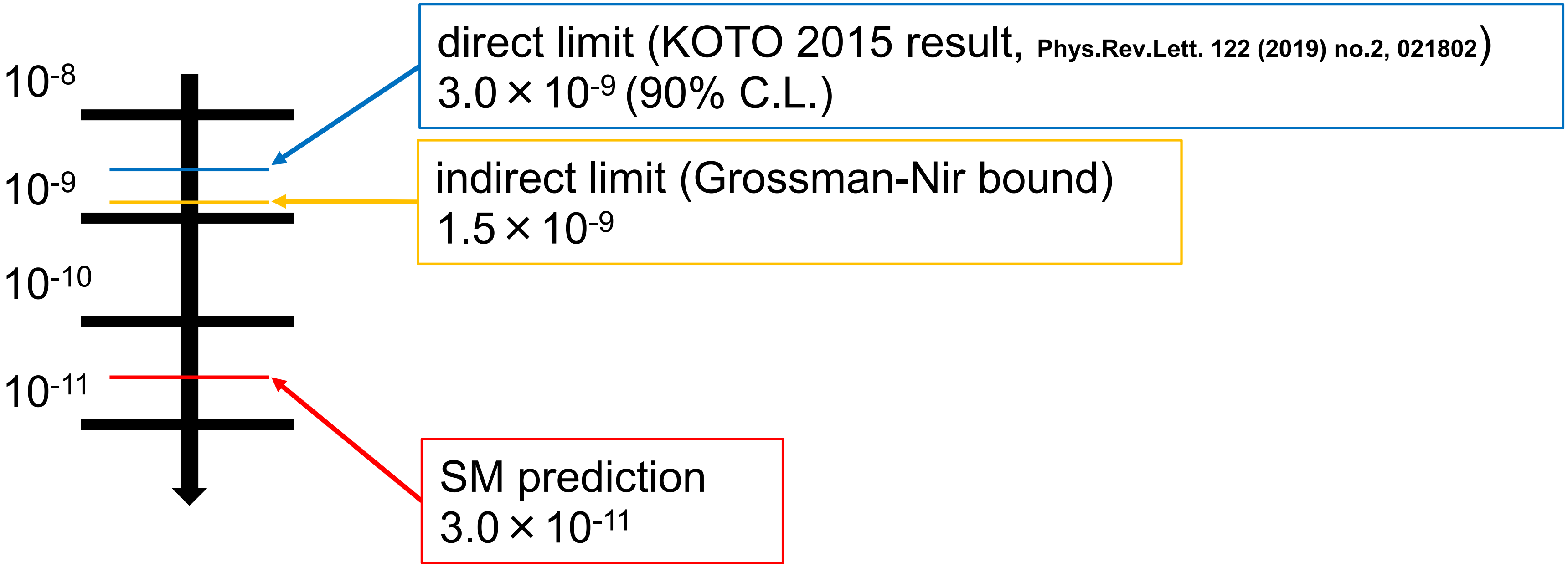
$K_L \to \pi^0 \nu \bar{\nu}$ decay

- Direct CPV
- FCNC : highly suppressed decay
  - BR (SM) : 3×10^{-11}
- Small theoretical uncertainty (~2%)

  → Good probe for new physics search





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

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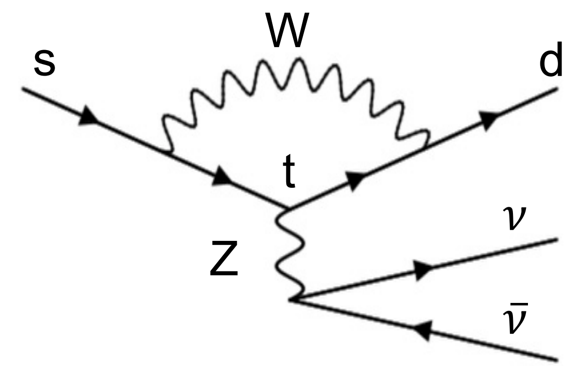
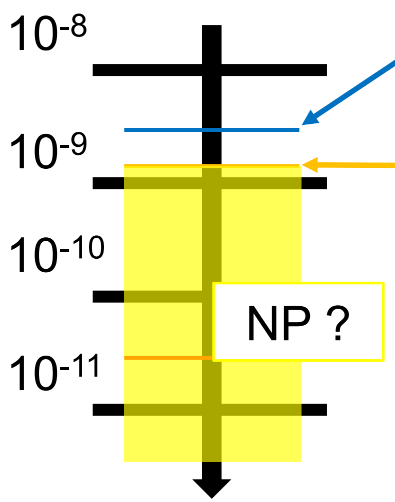
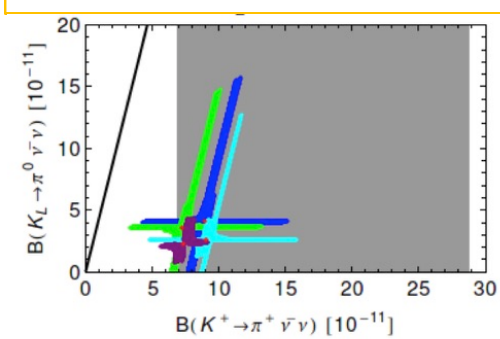


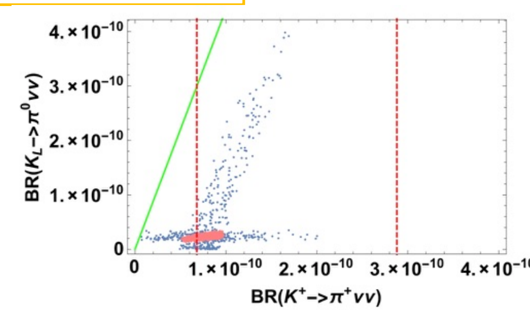


direct limit (KOTO 2015 result, Phys.Rev.Lett. 122 (2019) no.2, 021802)
3.0×10^{-9} (90% C.L.)

indirect limit (Grossman-Nir bound)
1.5×10^{-9}

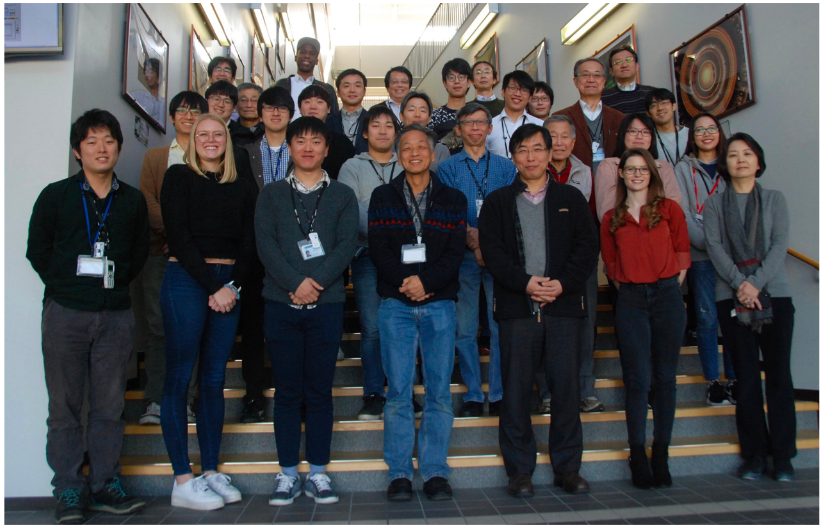


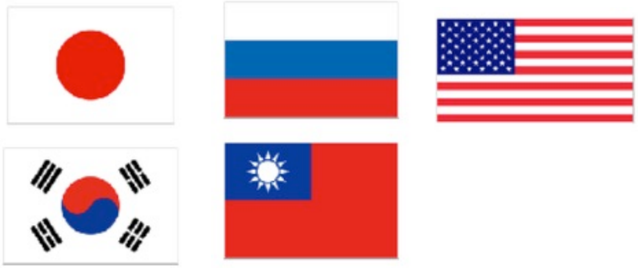
A.J.Buras, et al. JHEP11(2014)121

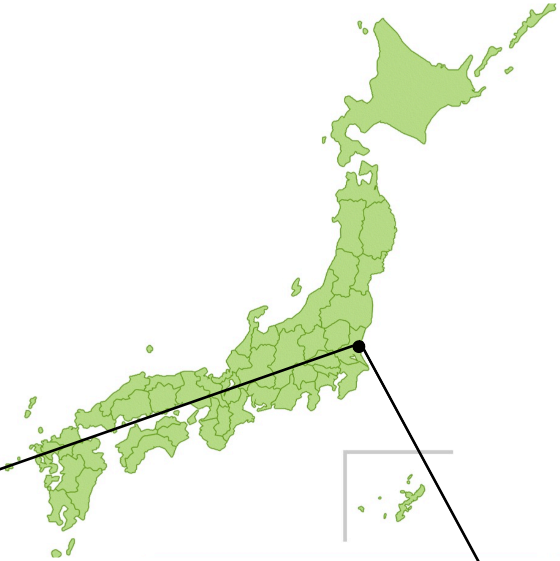


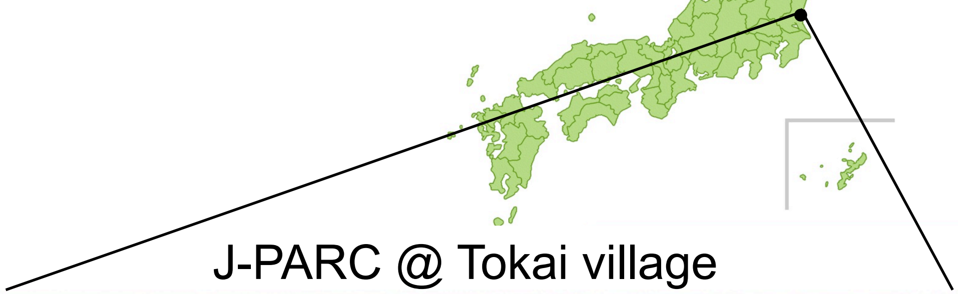
M.Tanimoto, K.Yamamoto PTEP 2016 (2016) no.12, 123B02

KOTO experiment

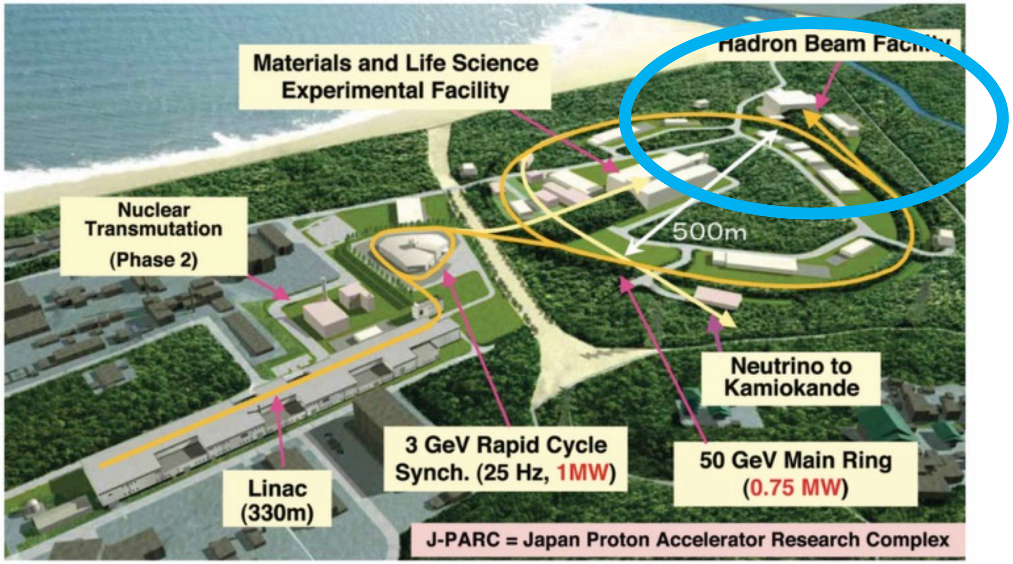






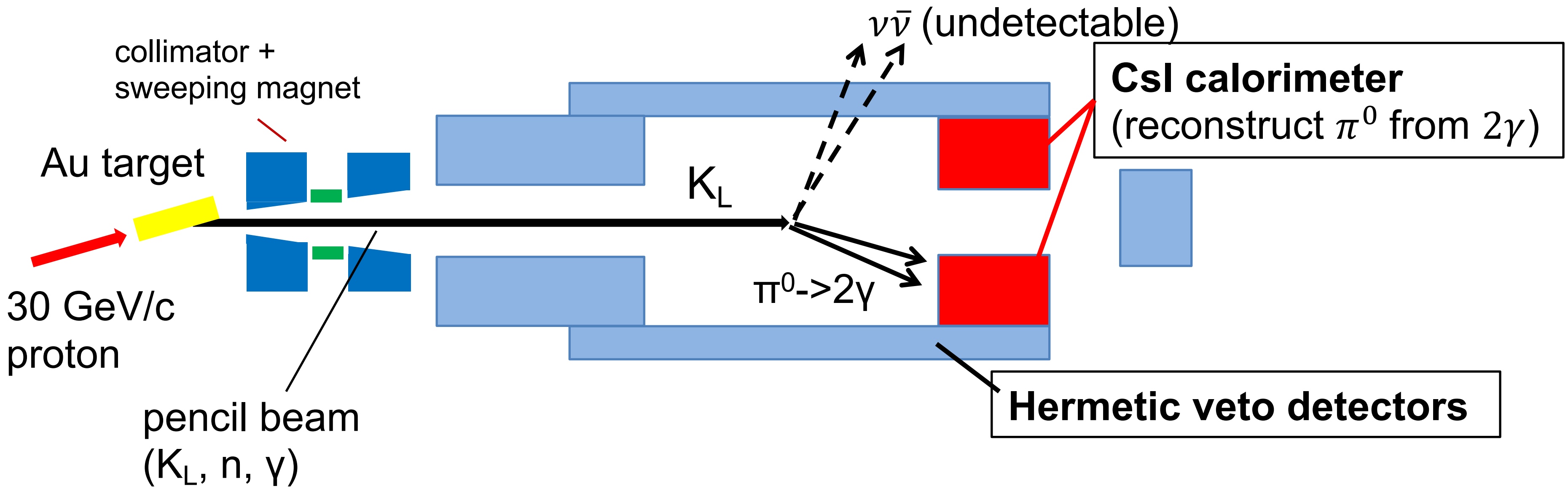


J-PARC @ Tokai village



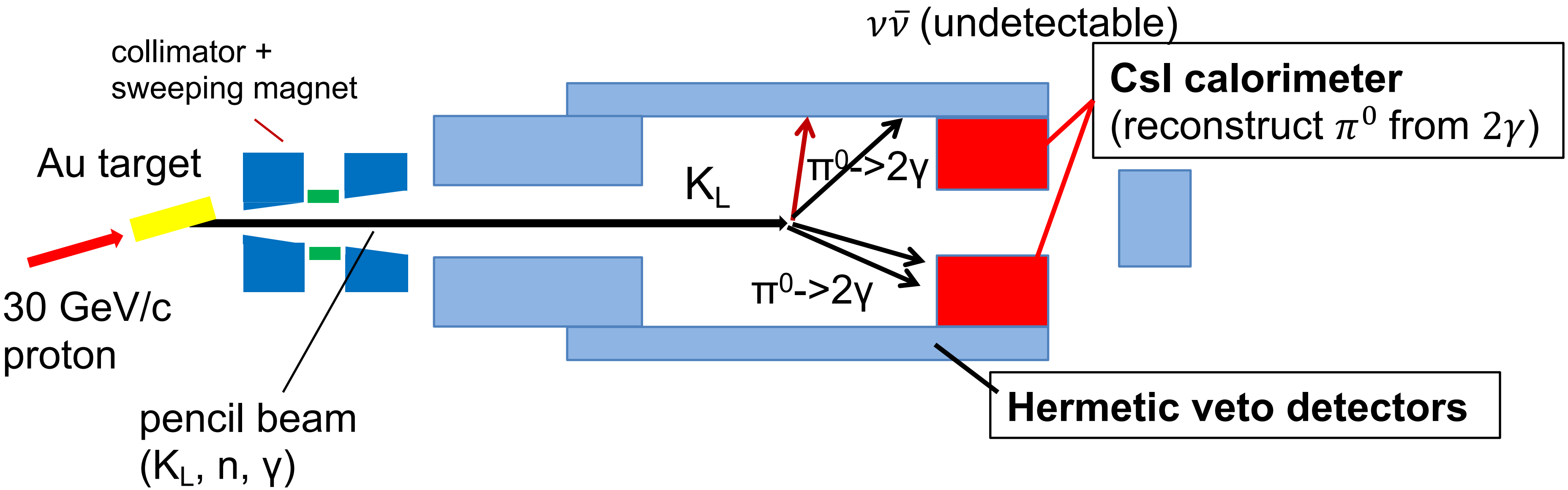
Signal

$K_L \to \pi^0 \nu\bar{\nu}$: $(\pi^0 \to)$ 2γ + nothing



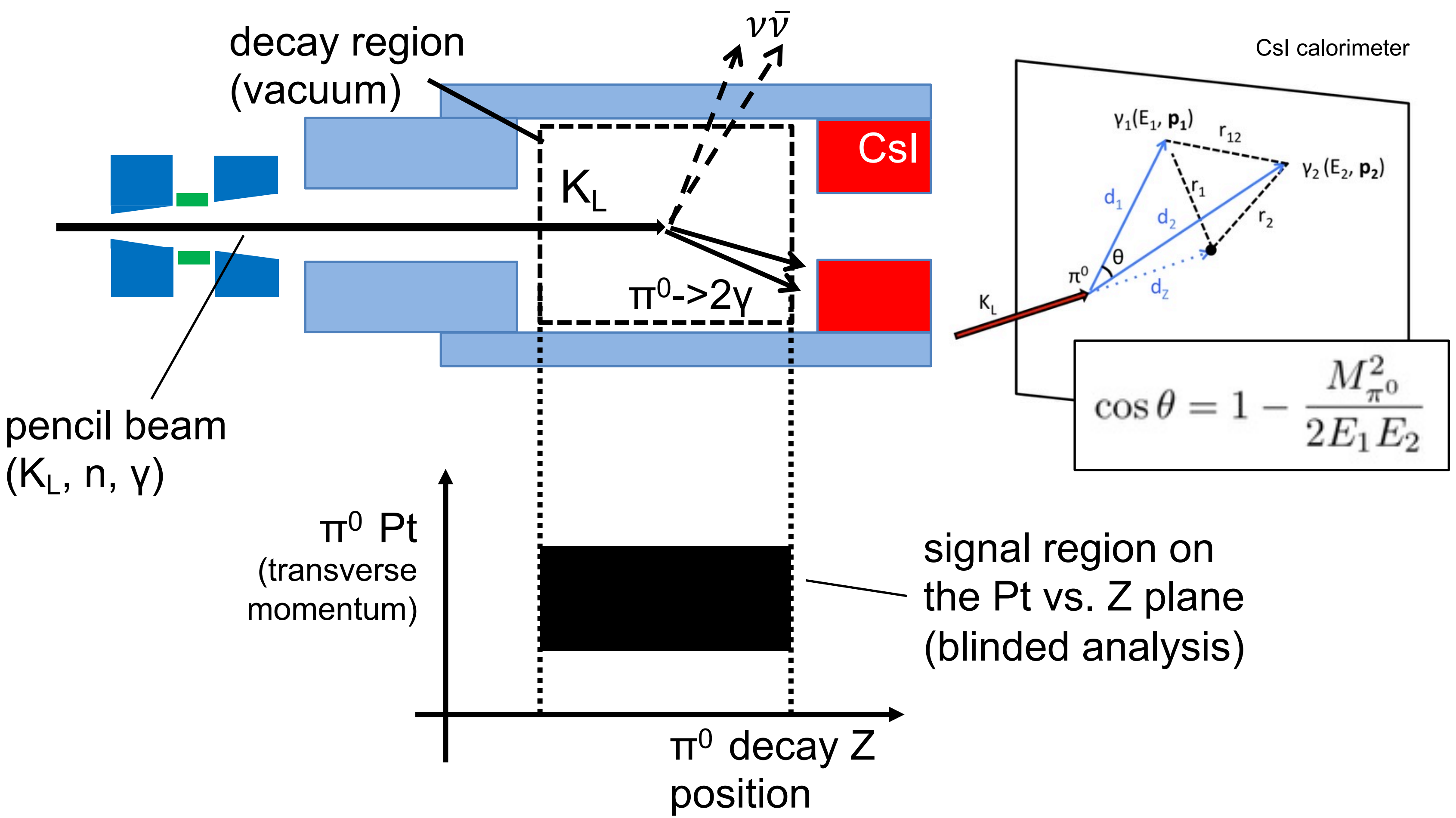
Background

ex.) $K_L \rightarrow 2\pi^0 \rightarrow 4\gamma$

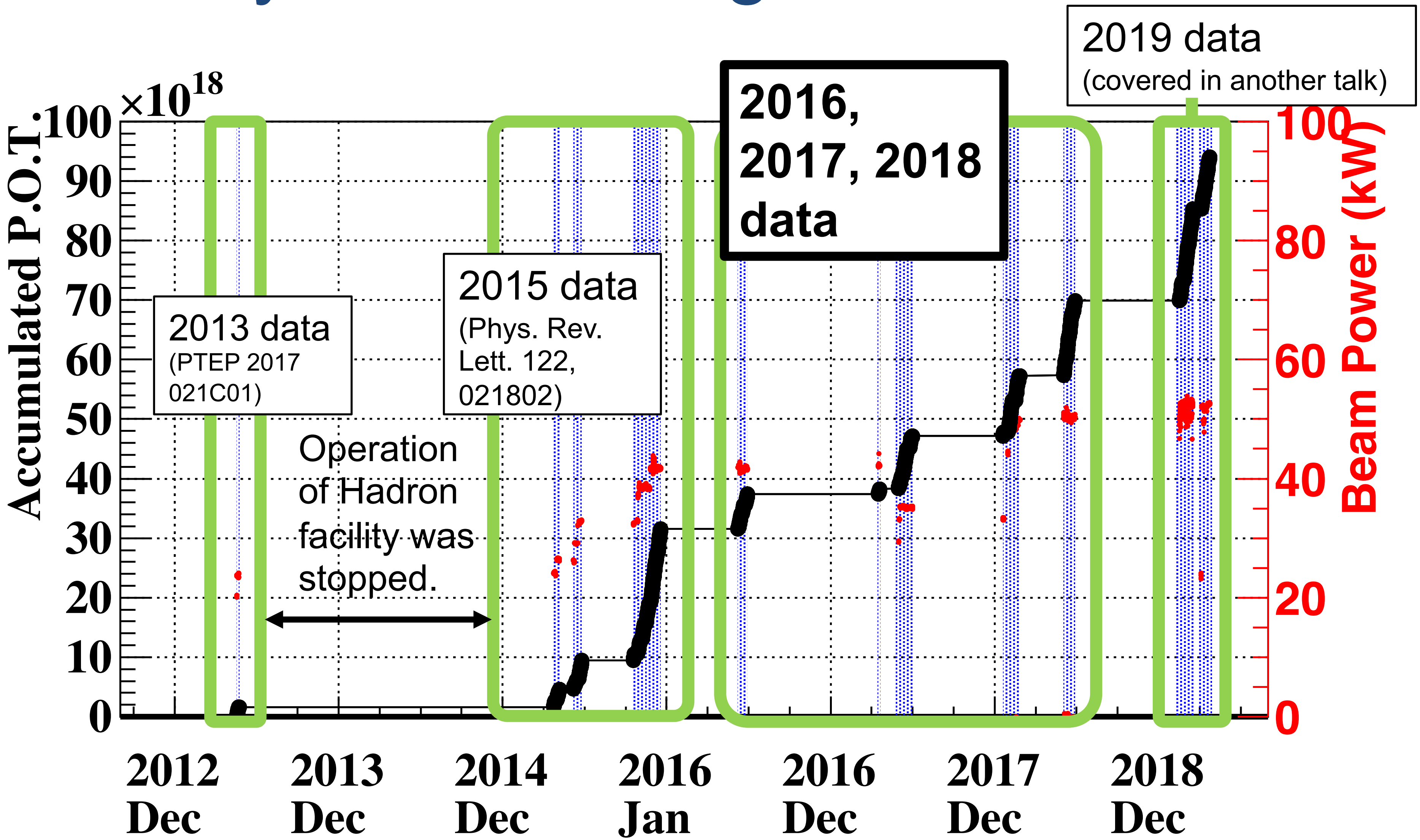


Reconstruction

Missing transverse momentum → finite π^0 p_t

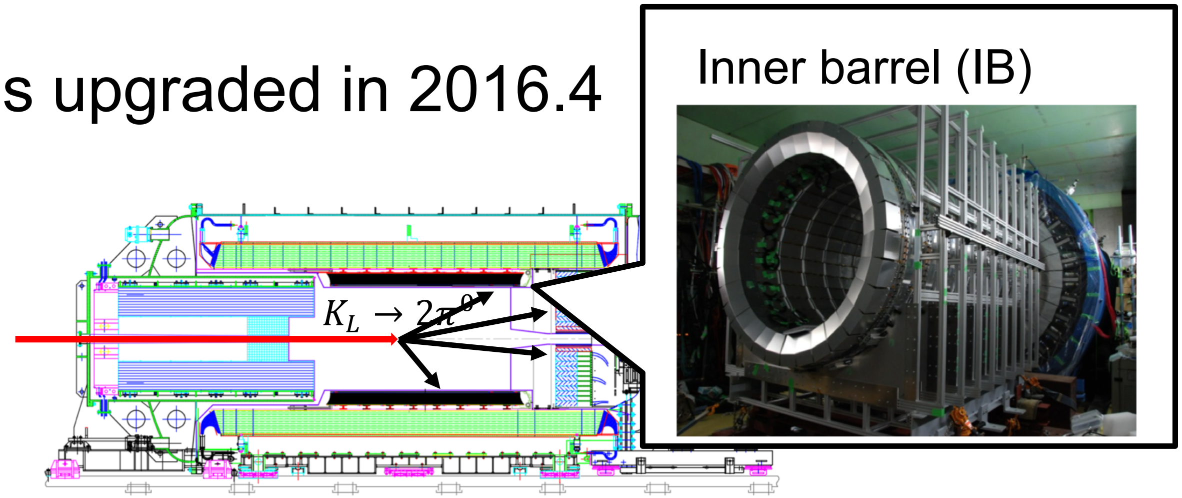


History of data taking

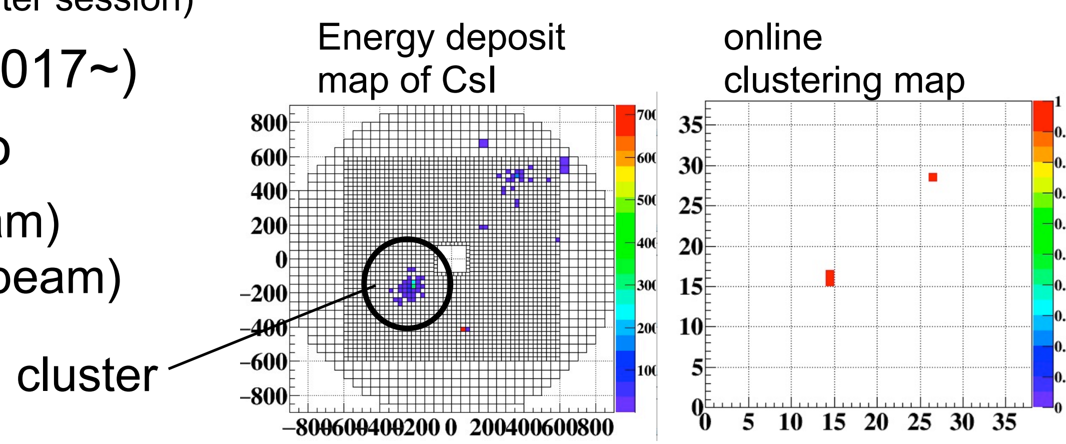


Detector and DAQ upgrade in 2016-2018

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

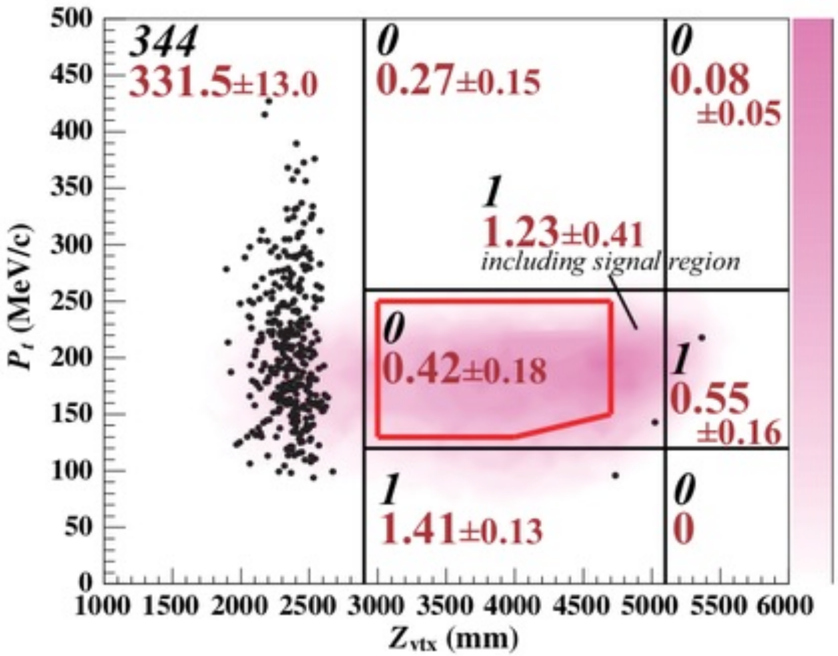


- DAQ upgrade (covered in poster session)
  - Online cluster counting (2017~)
  - Higher DAQ live time ratio
    - ~80% (2015 @ 42kW beam) → ~99% (2018 @ 51kW beam)

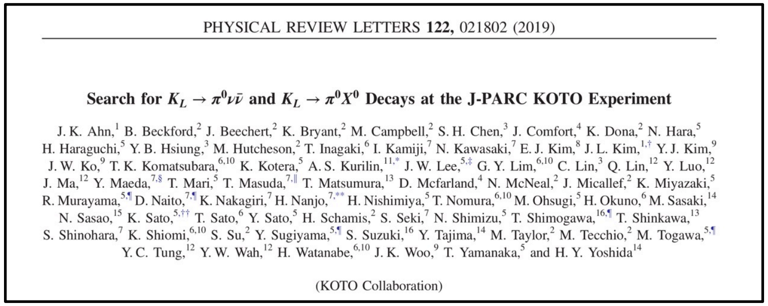


Result of 2015 physics run

Phys. Rev. Lett. 122, 021802



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



PHYSICAL REVIEW LETTERS 122, 021802 (2019)

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,[1] B. Beckford,[2] J. Beechert,[2] K. Bryant,[2] M. Campbell,[2] S. H. Chen,[3] J. Comfort,[4] K. Dona,[2] N. Hara,[5] H. Haraguchi,[5] Y. B. Hsiung,[3] M. Hutcheson,[2] T. Inagaki,[6] I. Kamiji,[7] N. Kawasaki,[7] E. J. Kim,[8] J. L. Kim,[1,†] Y. J. Kim,[9] J. W. Ko,[9] T. K. Komatsubara,[6,10] K. Kotera,[5] A. S. Kurilin,[11,*] J. W. Lee,[5,‡] G. Y. Lim,[6,10] C. Lin,[3] Q. Lin,[12] Y. Luo,[12] J. Ma,[12] Y. Maeda,[7,§] T. Mari,[5] T. Masuda,[7,‖] T. Matsumura,[13] D. Mcfarland,[4] N. McNeal,[2] J. Micallef,[2] K. Miyazaki,[5] R. Murayama,[5,¶] D. Naito,[7,¶] K. Nakagiri,[7] H. Nanjo,[7,**] H. Nishimiya,[5] T. Nomura,[6,10] M. Ohsugi,[5] H. Okuno,[6] M. Sasaki,[14] N. Sasao,[15] K. Sato,[5,††] T. Sato,[6] Y. Sato,[5] H. Schamis,[2] S. Seki,[7] N. Shimizu,[5] T. Shimogawa,[16,¶] T. Shinkawa,[13] S. Shinohara,[7] K. Shiomi,[6,10] S. Su,[2] Y. Sugiyama,[5,¶] S. Suzuki,[16] Y. Tajima,[14] M. Taylor,[2] M. Tecchio,[2] M. Togawa,[5,¶] Y. C. Tung,[12] Y. W. Wah,[12] H. Watanabe,[6,10] J. K. Woo,[9] T. Yamanaka,[5] and H. Y. Yoshida[14]

(KOTO Collaboration)

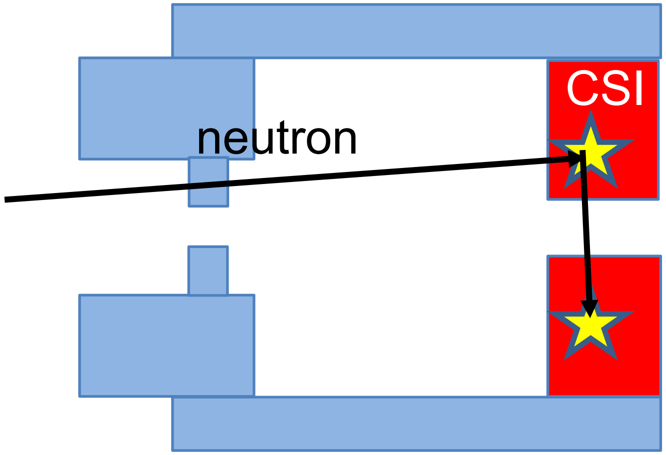
- Single event sensitivity : $(1.30 \pm 0.01_{stat} \pm 0.14_{syst}) \times 10^{-9}$
  - No event in the signal region

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

× 10 improvement from previous limit (KEK E391a)

Toward 2016-2018 data 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**	

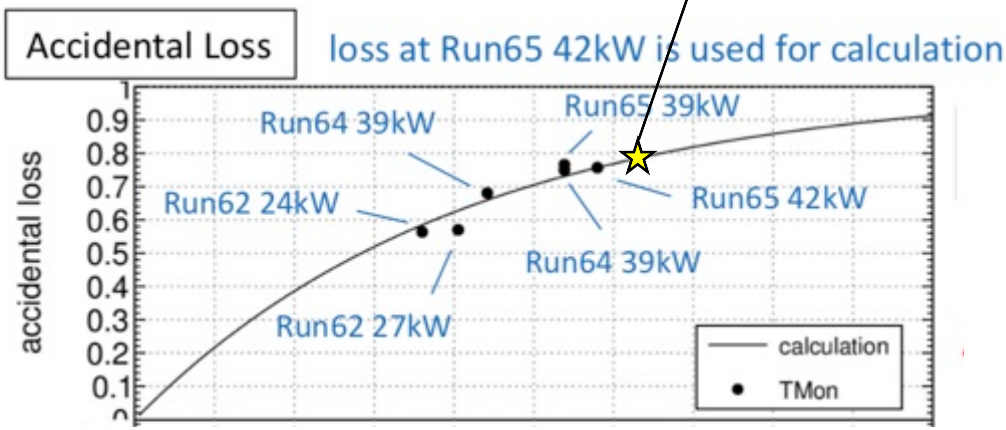
Phys. Rev. Lett. 122, 021802

- To suppress hadron cluster BG is important
  - Need more understanding
  - Need more reduction

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

2018 June, 51kW



study from 2015 data

2016~2018 data analysis

Single event sensitivity

BG analysis

2016~2018 data analysis

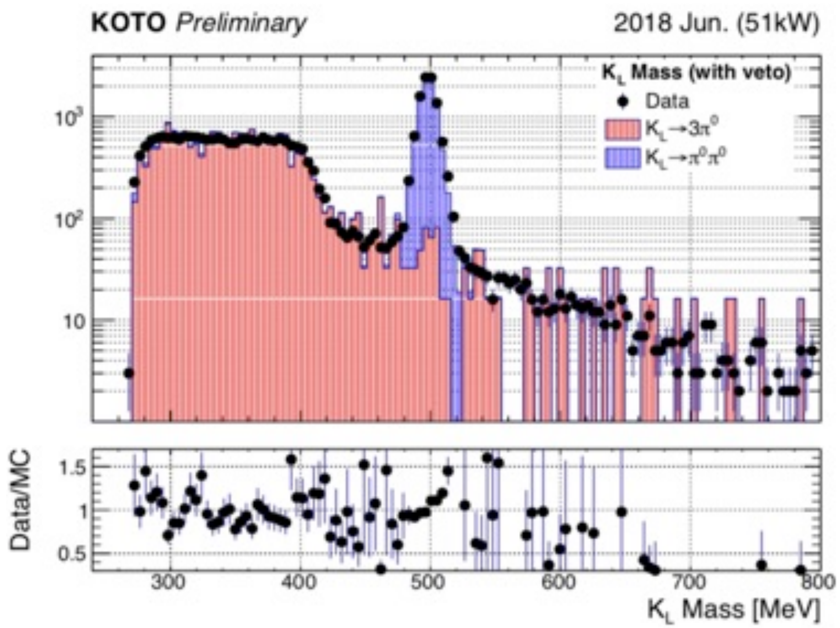
Single event sensitivity

BG analysis

Single event sensitivity (S.E.S)

- S.E.S = ($\underline{K_L \text{ yield}}$) × (signal acceptance)

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



Preliminary

K_L yield (@ beam exit) :
7.1×10^{12}

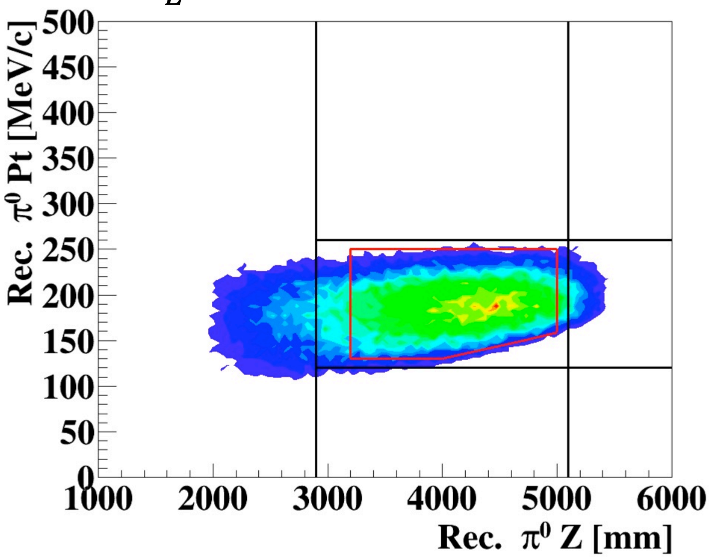
(increase by a factor of 1.5 from 2015 data)

(covered in poster session)

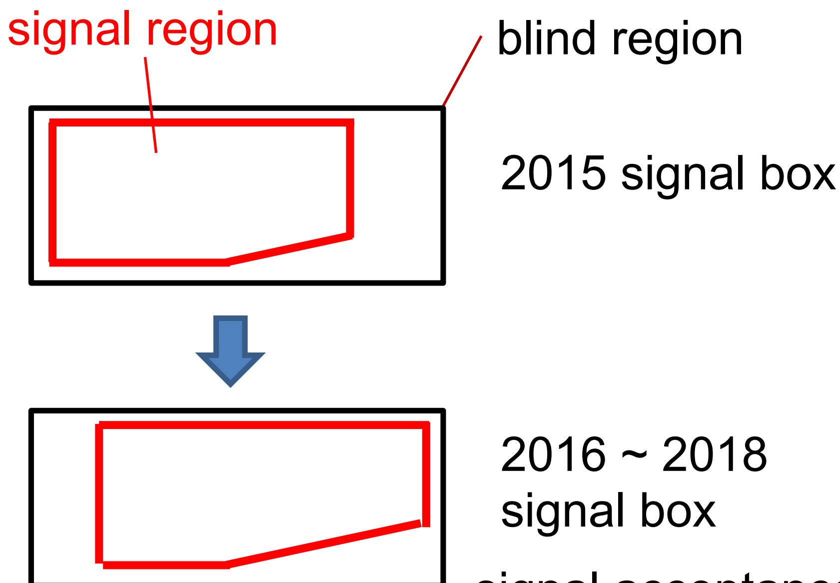
Single event sensitivity (S.E.S)

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

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

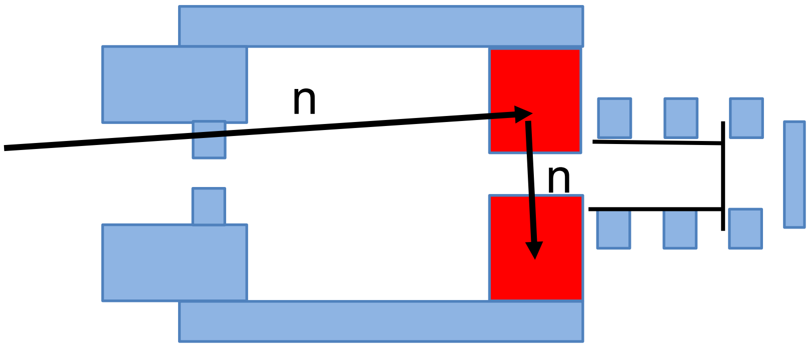
2016~2018 data analysis

Single event sensitivity

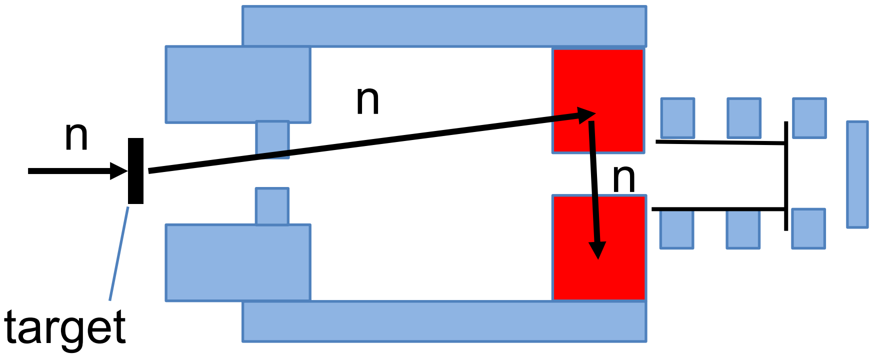
BG analysis

Hadron cluster BG

Physics run

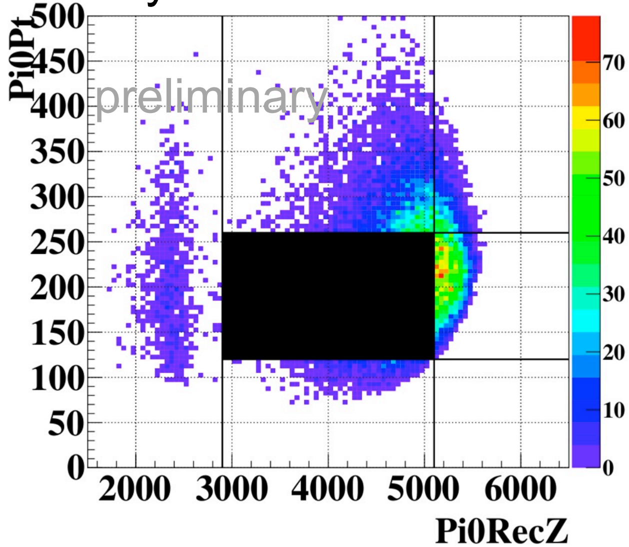


Special run

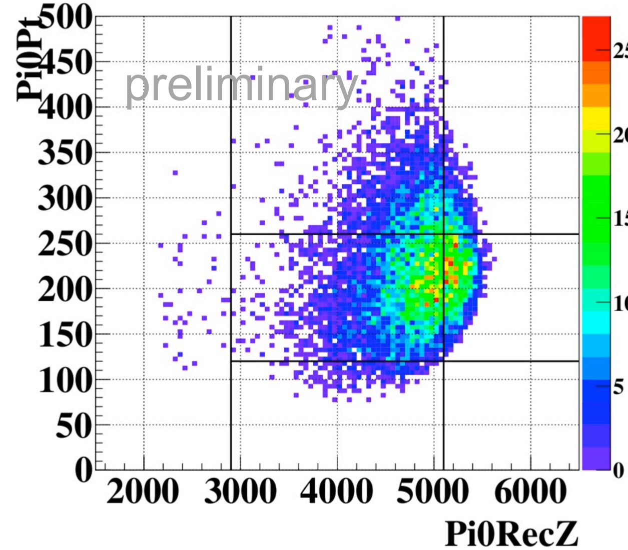


Al target
(10 mm thickness)

Physics data

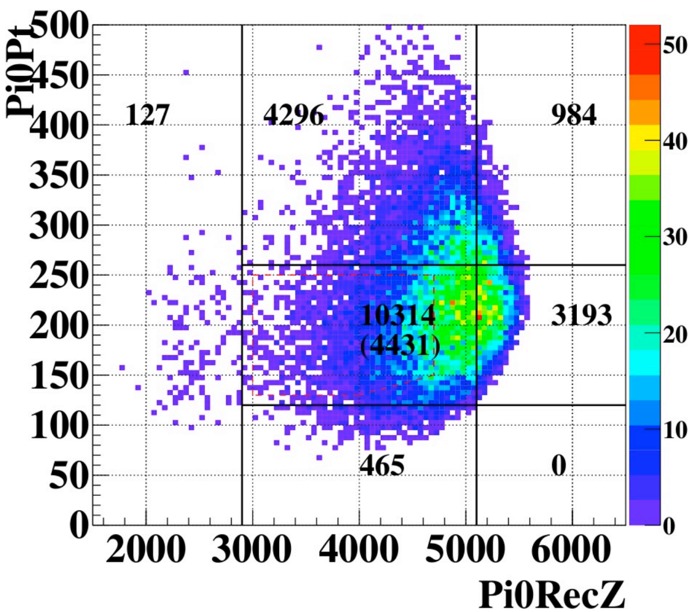


Control sample



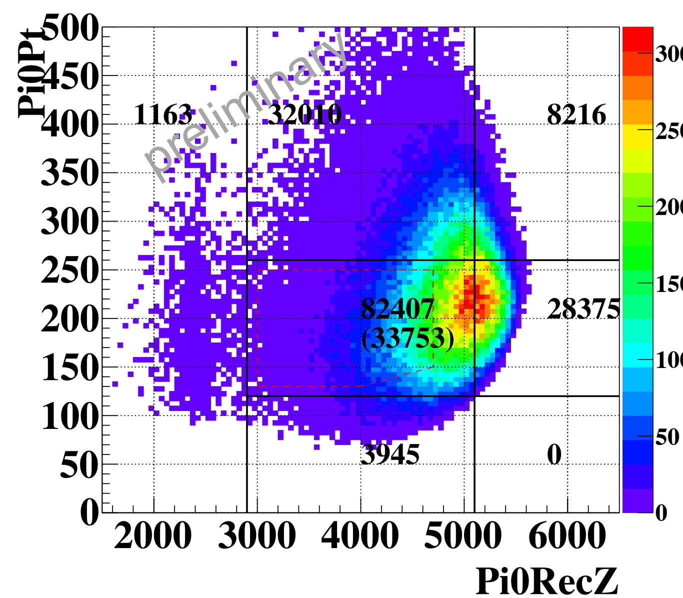
Hadron cluster BG update from 2015 (statistics)

control sample (2015)



× ~9

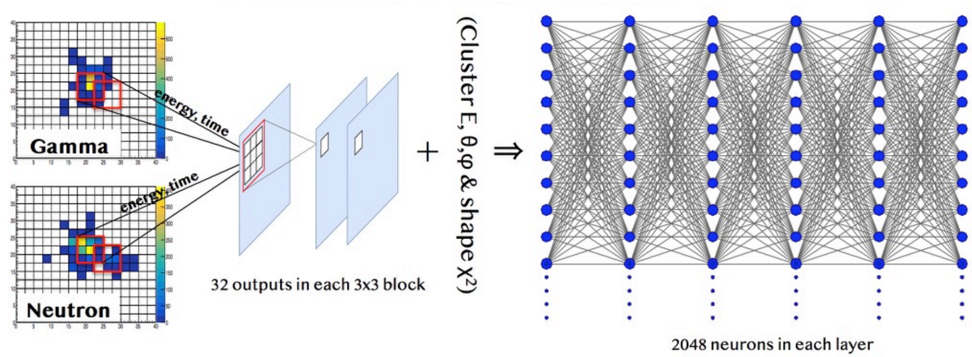
control sample (2016~2018)



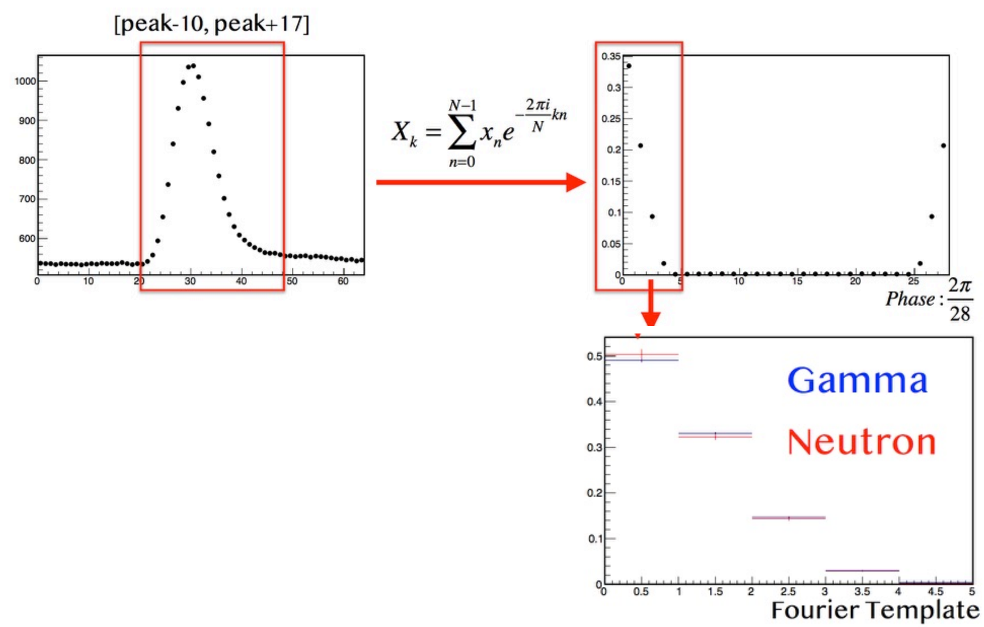
The collection efficiency of control sample was improved by DAQ upgrade

Hadron cluster BG update from 2015 (cut)

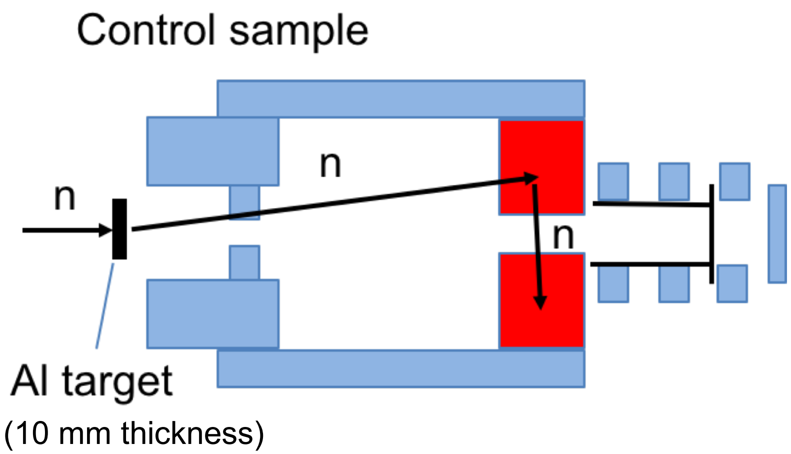
1. Cluster shape cut with deep learning
   – S/N : × ~2 from 2015

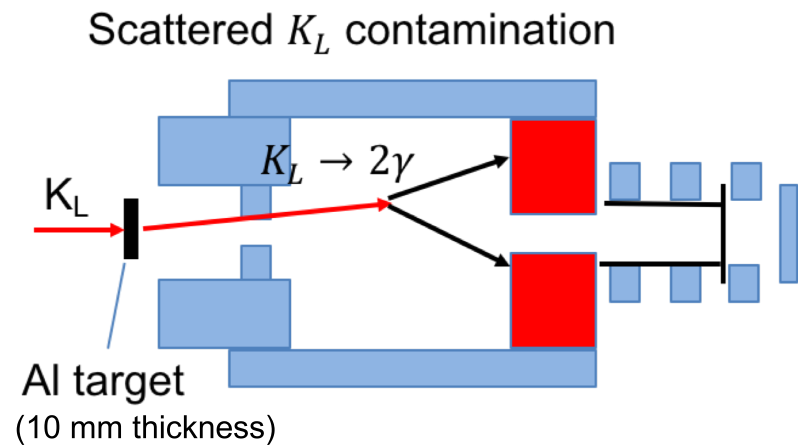


2. Pulse shape discrimination with Fourier transformation
   – S/N : × ~1.8 from 2015



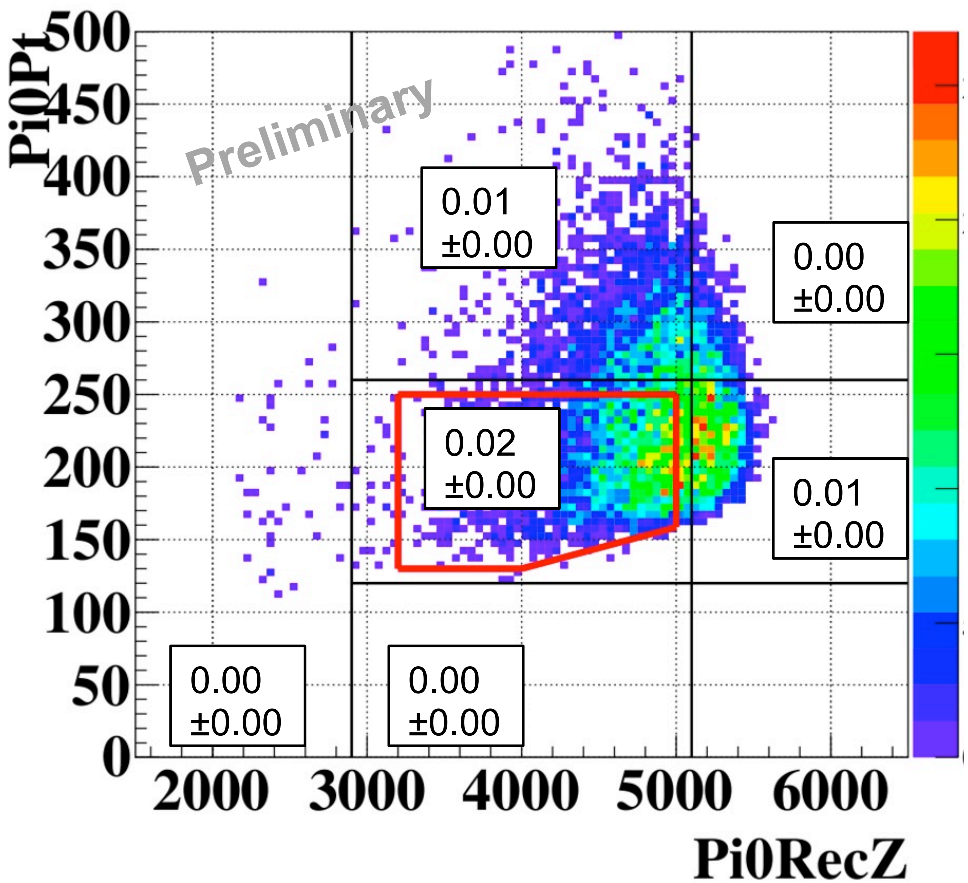
Hadron cluster BG update from 2015 (estimation)





- Found contamination in the control sample
  - Developed more reliable estimation method
  - reduction : ×~27 with the new method

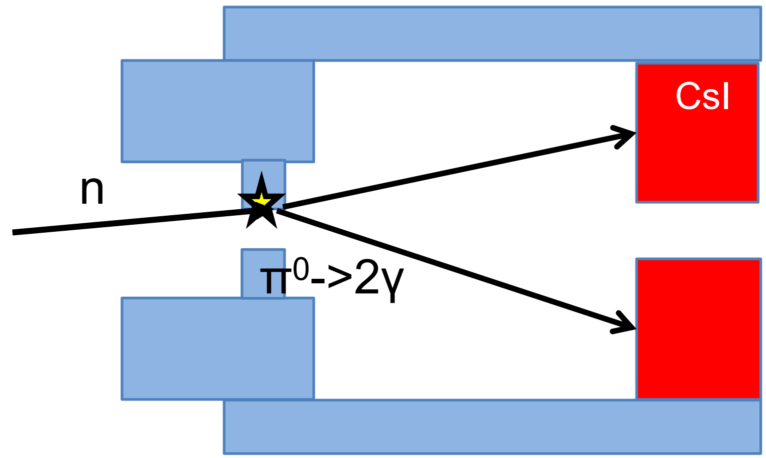
Hadron cluster BG

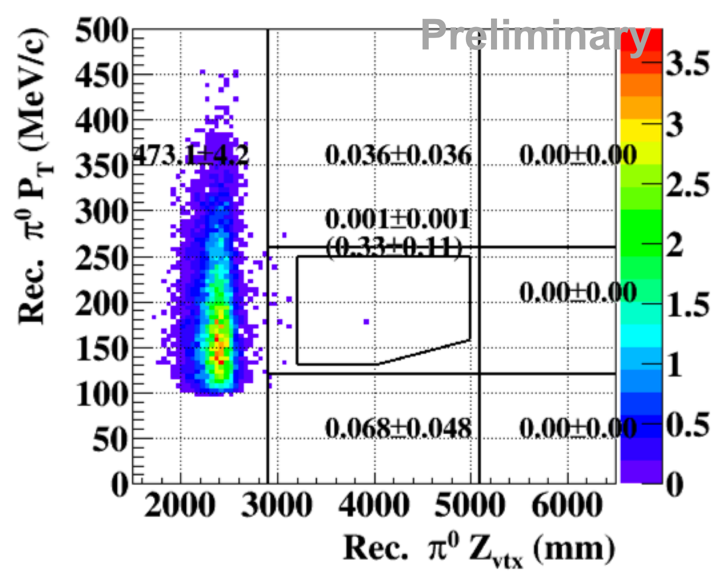


Extended signal region to downstream from this result

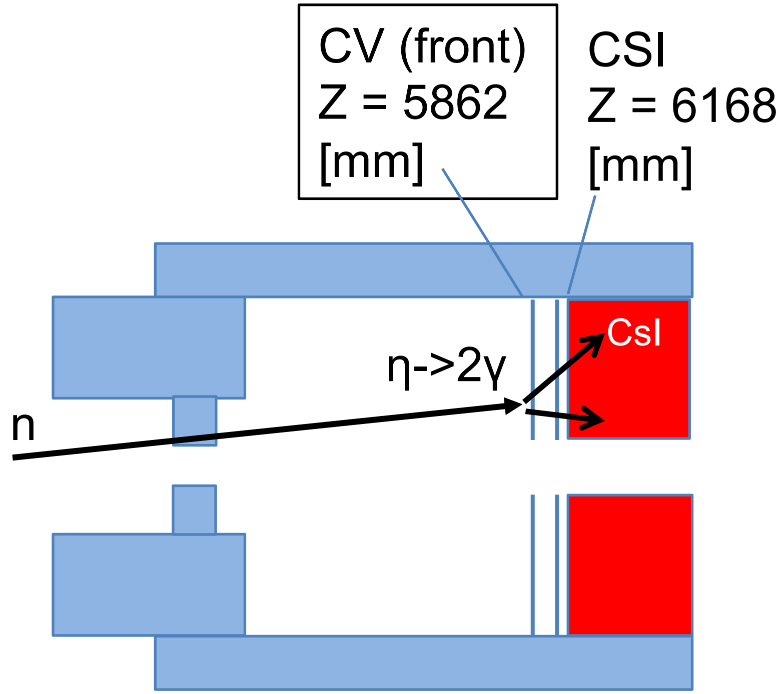
Upstream-π^0 BG

- 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
- $\#BG_{upstream\text{-}\pi0}$: 0.00 ± 0.00





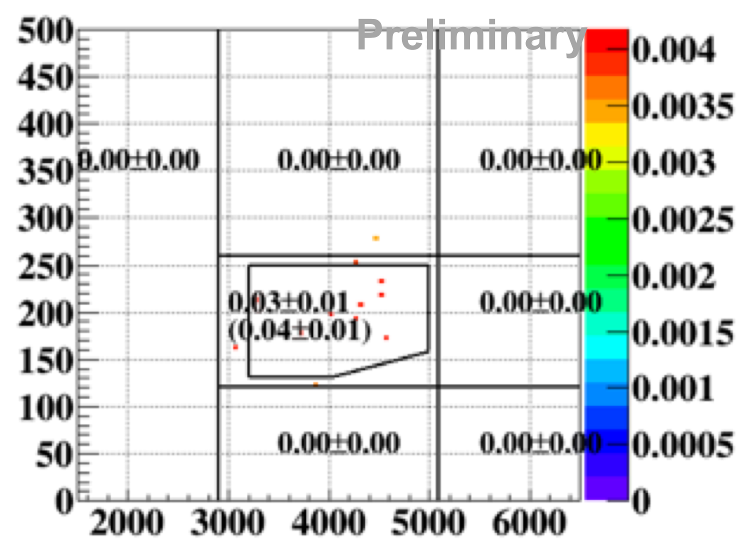
CV-η BG



- 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

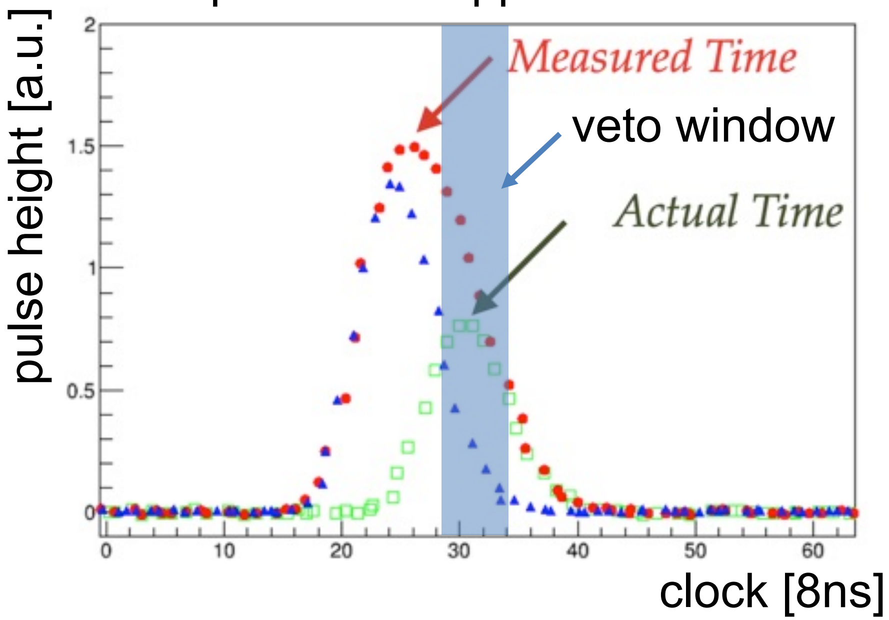
$\#BG_\eta = 0.03 \pm 0.01$



Overlapped pulse BG

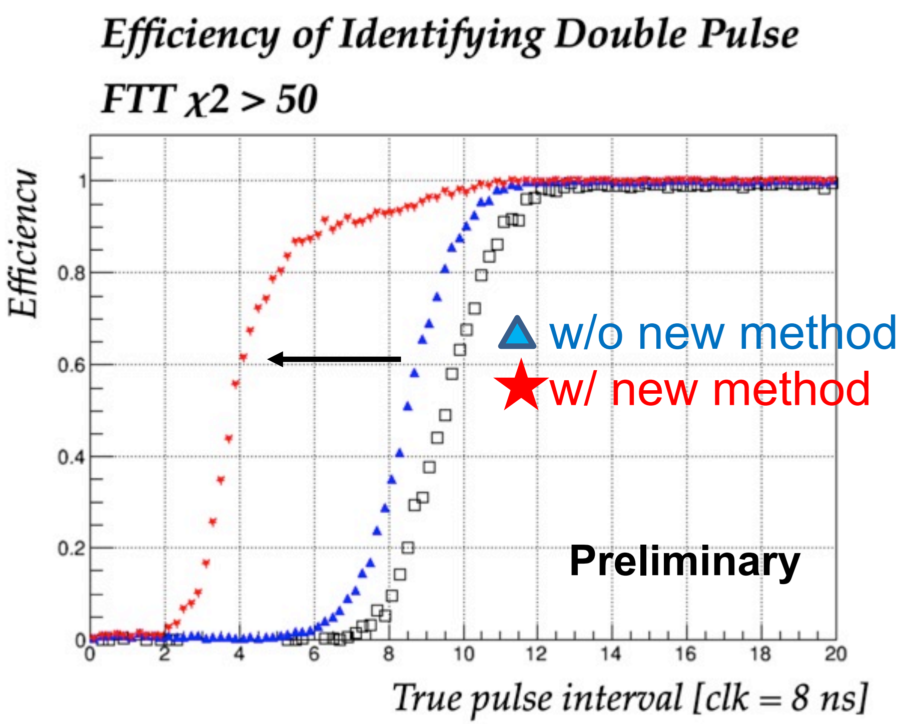
- Overlapped pulse shifts measured time
  - Narrower veto window
    - recover signal acceptance
    - increase BG from overlapped pulse

example of overlapped waveform

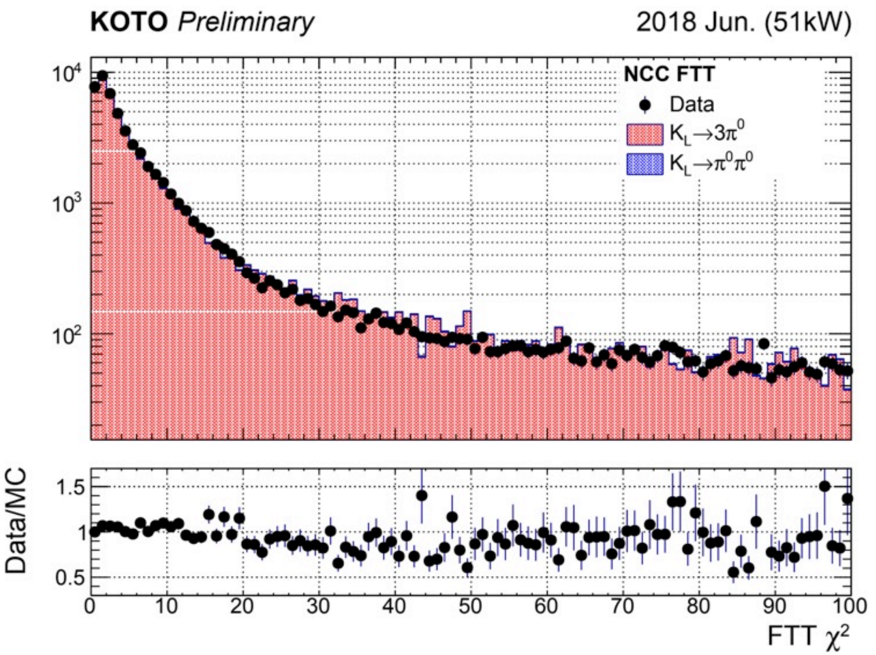


Overlapped pulse BG

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



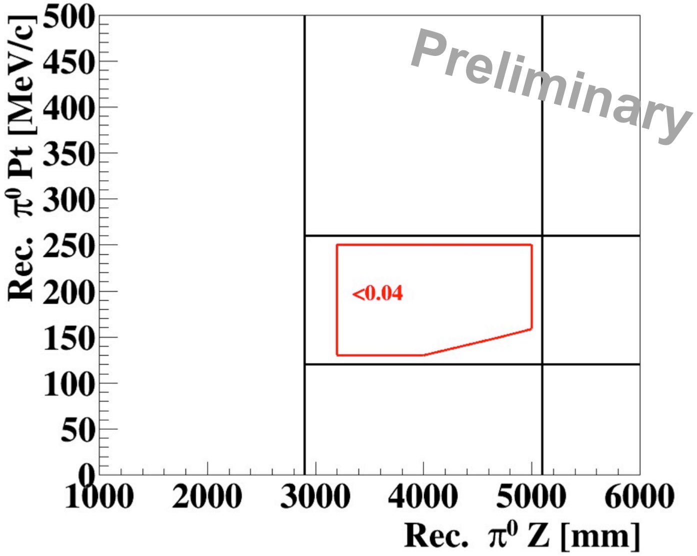
χ^2 distribution of upstream detector



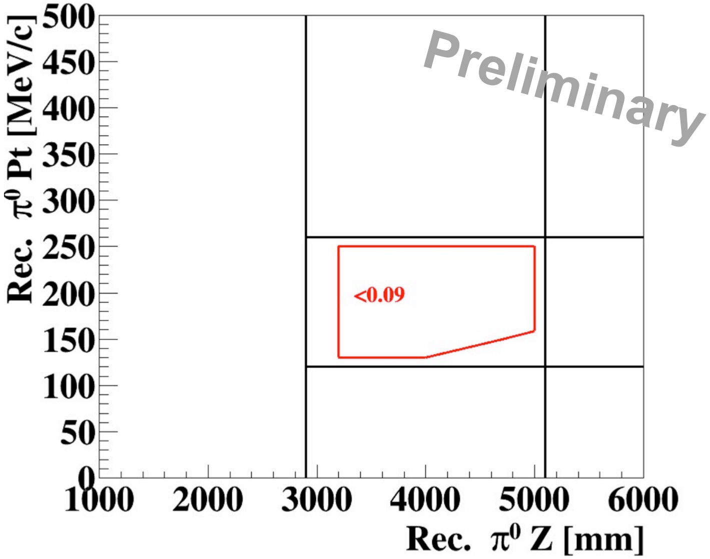
Overlapped pulse BG

- 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

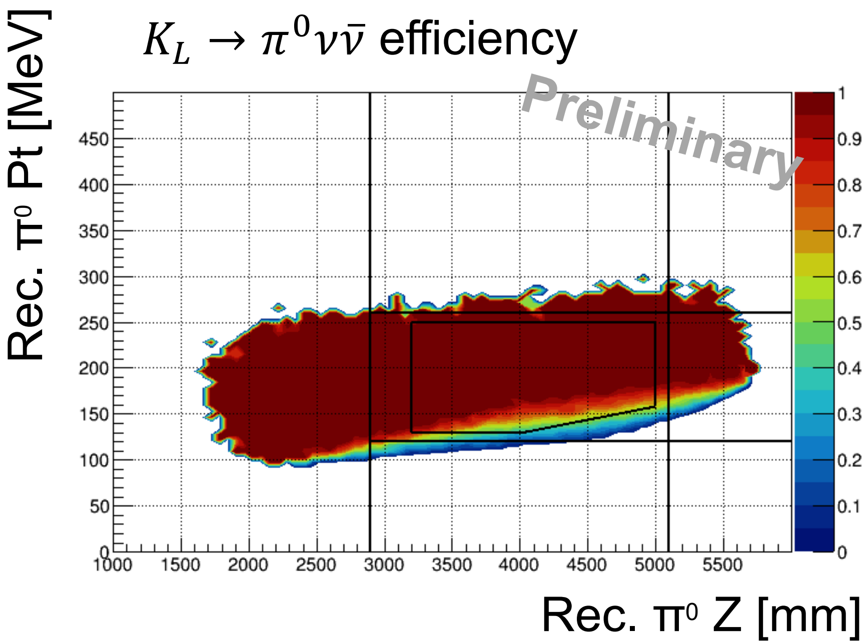


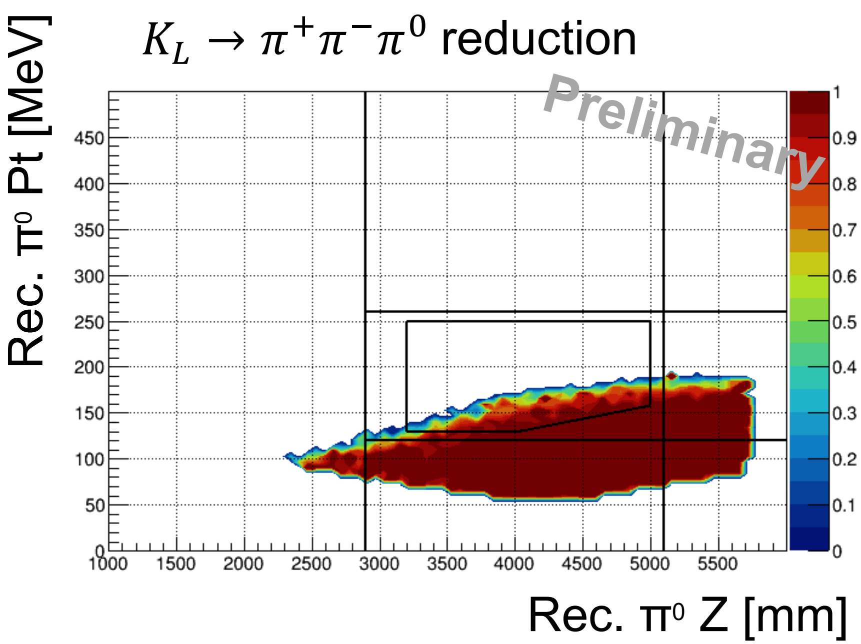
Narrower veto window : Recovered 10% signal acceptance

No remaining event due to overlapped pulse

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

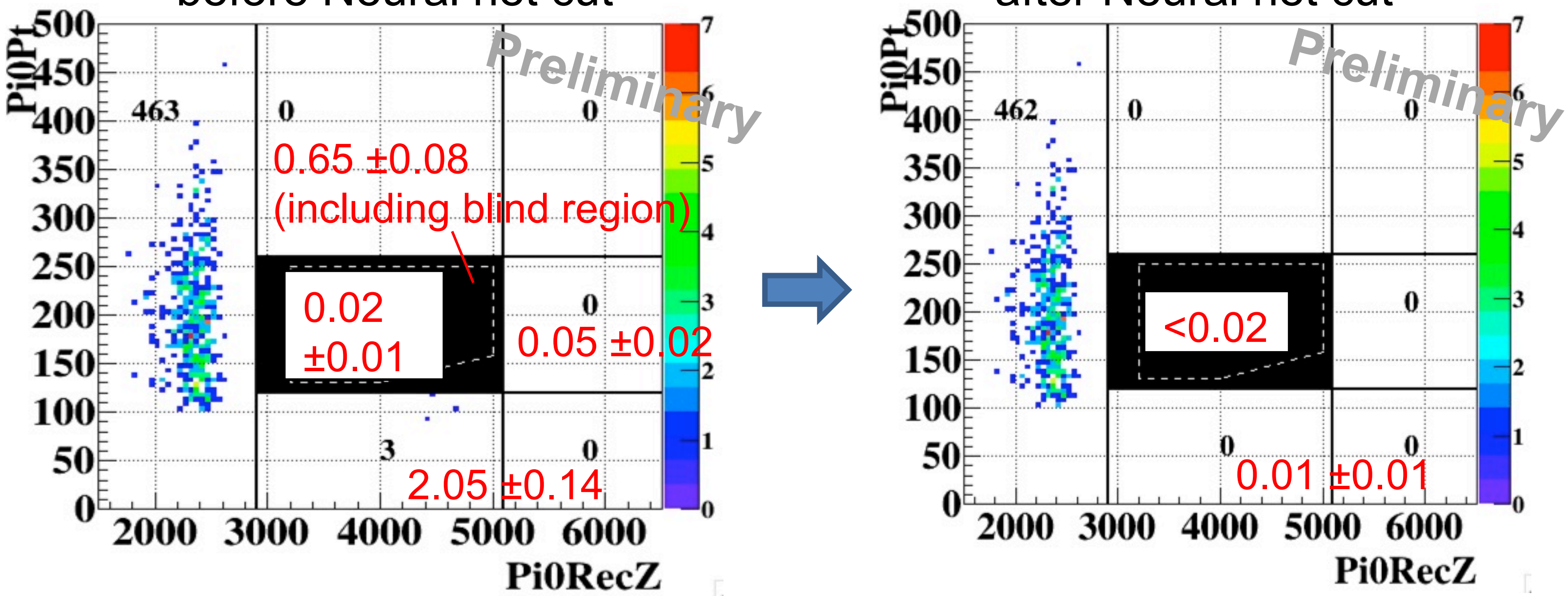




$K_L \to \pi^+\pi^-\pi^0$ BG

- 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%

before Neural net cut after Neural net cut

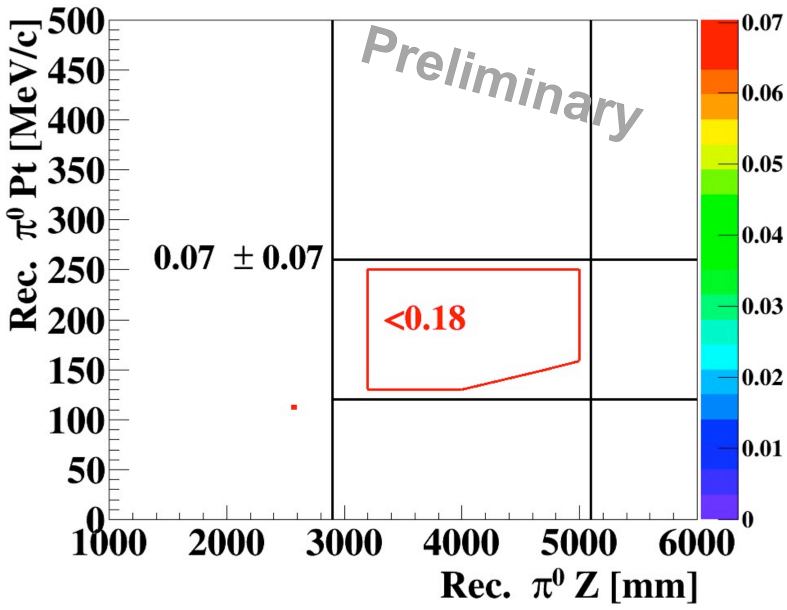


observed

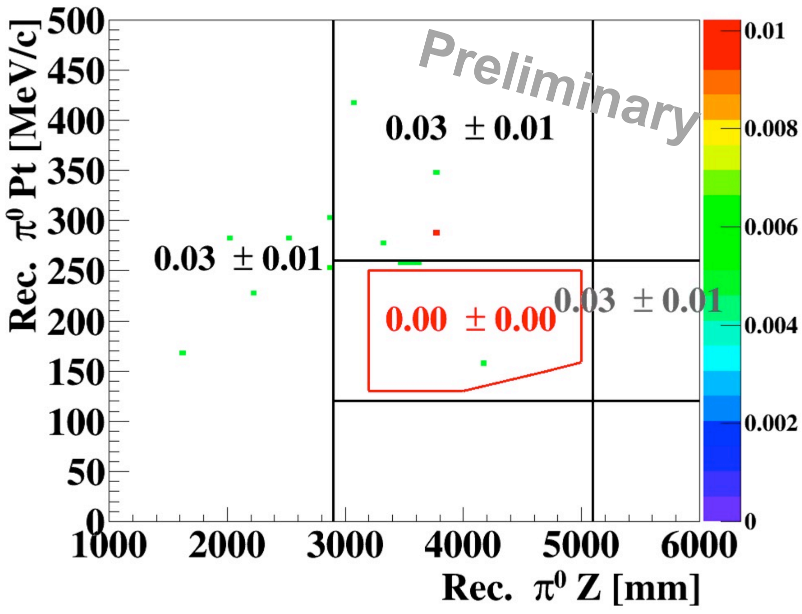
expectation of $K_L \to \pi^+\pi^-\pi^0$ BG

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

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

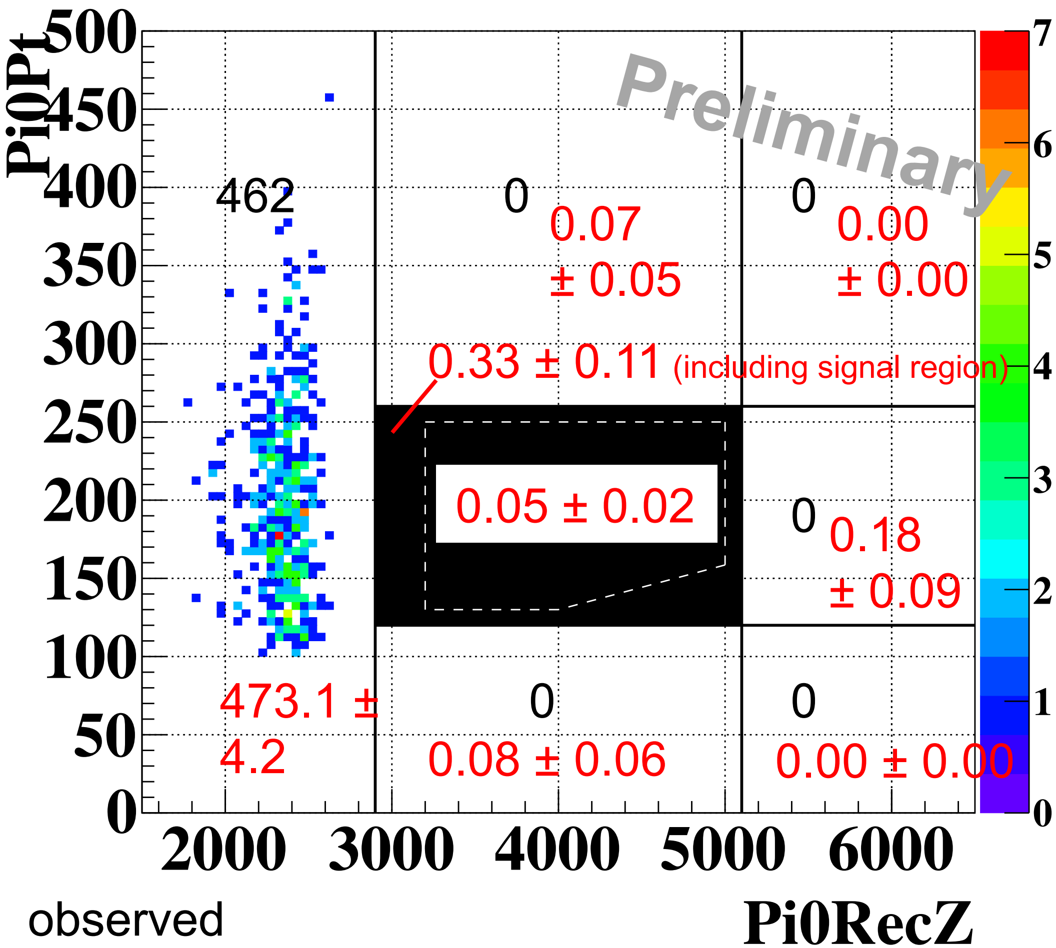


Result from $K_L \to 2\gamma$ MC study



BG summary

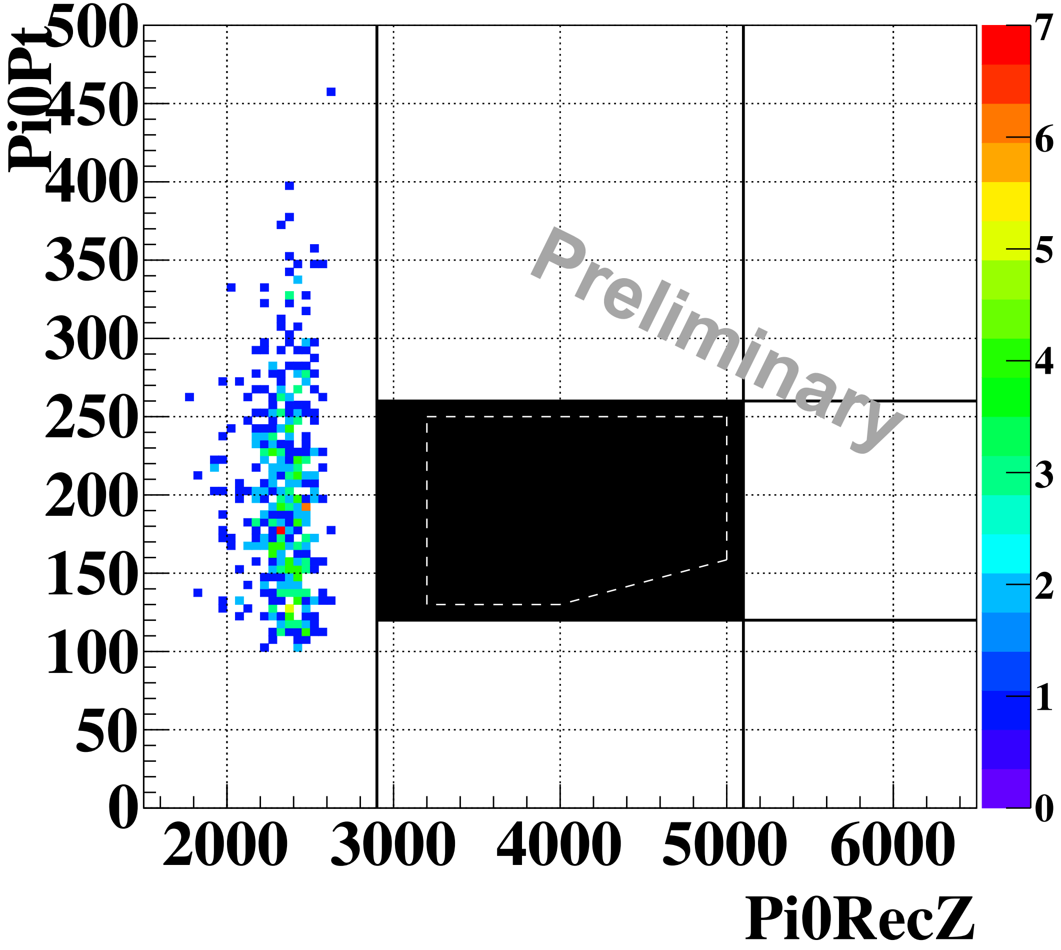
S.E.S : 6.9×10^{-10}

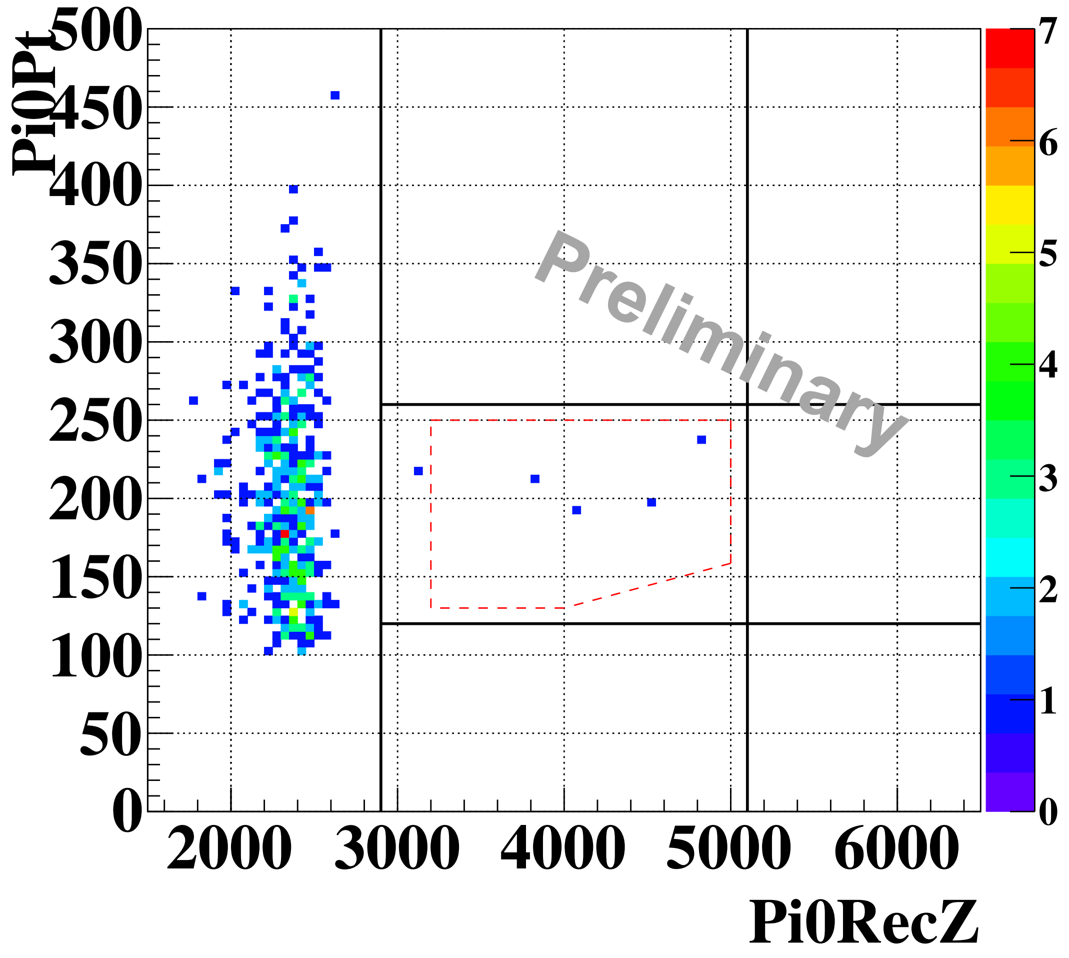


observed
expectation

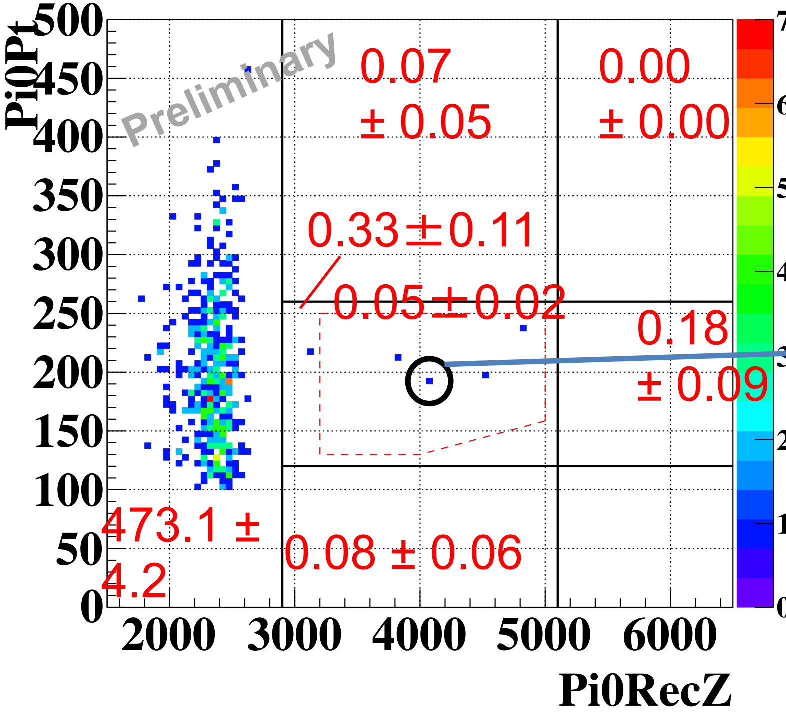
Preliminary

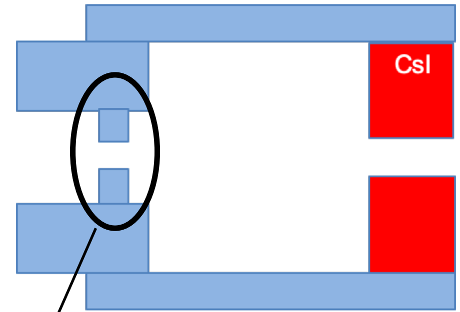
	#BG
KLpi0pi0	<0.18
KLpi+pi-pi0	<0.02
KL3pi0 (overlapped pulse)	<0.04
Ke3 (overlapped pulse)	<0.09
KL2gamma	0.00 ± 0.00
Upstream π^0	0.00±0.00
Hadron cluster	0.02 ±0.00
CV-pi0	<0.10
CV-eta	0.03±0.01
Total	0.05±0.02


Pi0Pt
500
450
400
350
300
250
200
150
100
50
0
2000
3000
4000
5000
6000
Pi0RecZ
Preliminary
7
6
5
4
3
2
1
0



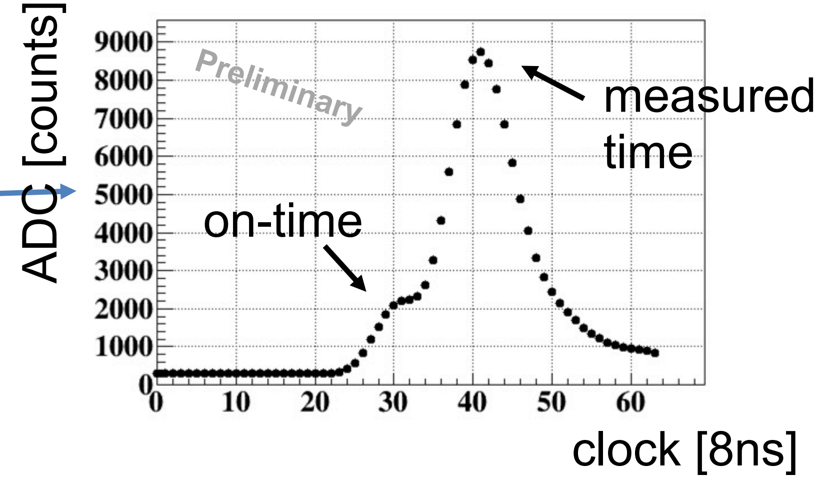
unblinded in the end of Aug. 2019





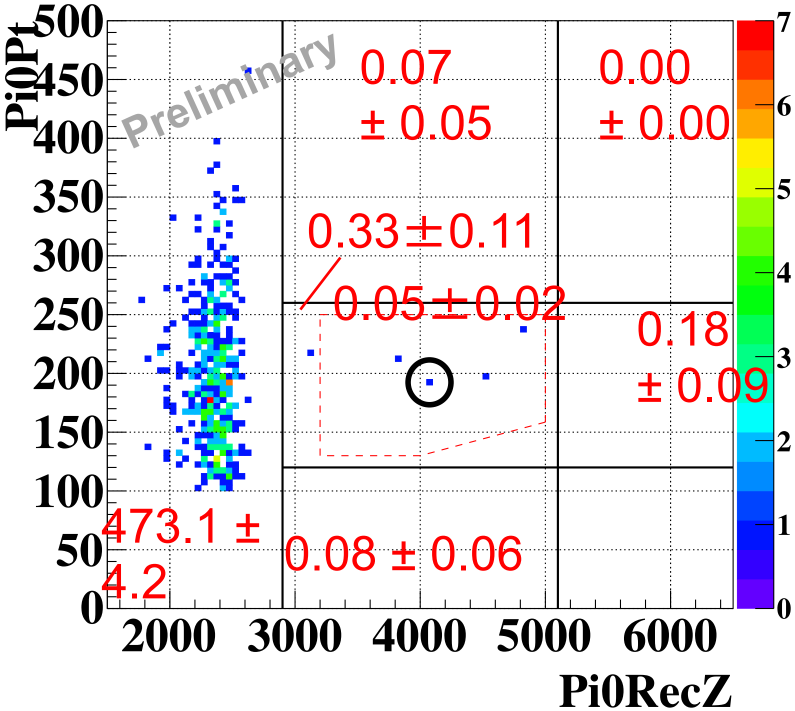
upstream detector

waveform of the event



On-timing peak is shifted by large pulse

expectation



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

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

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

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

END