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

-New results from the KOTO experiment-

Koji SHIOMI for the KOTO collaboration
(KEK)

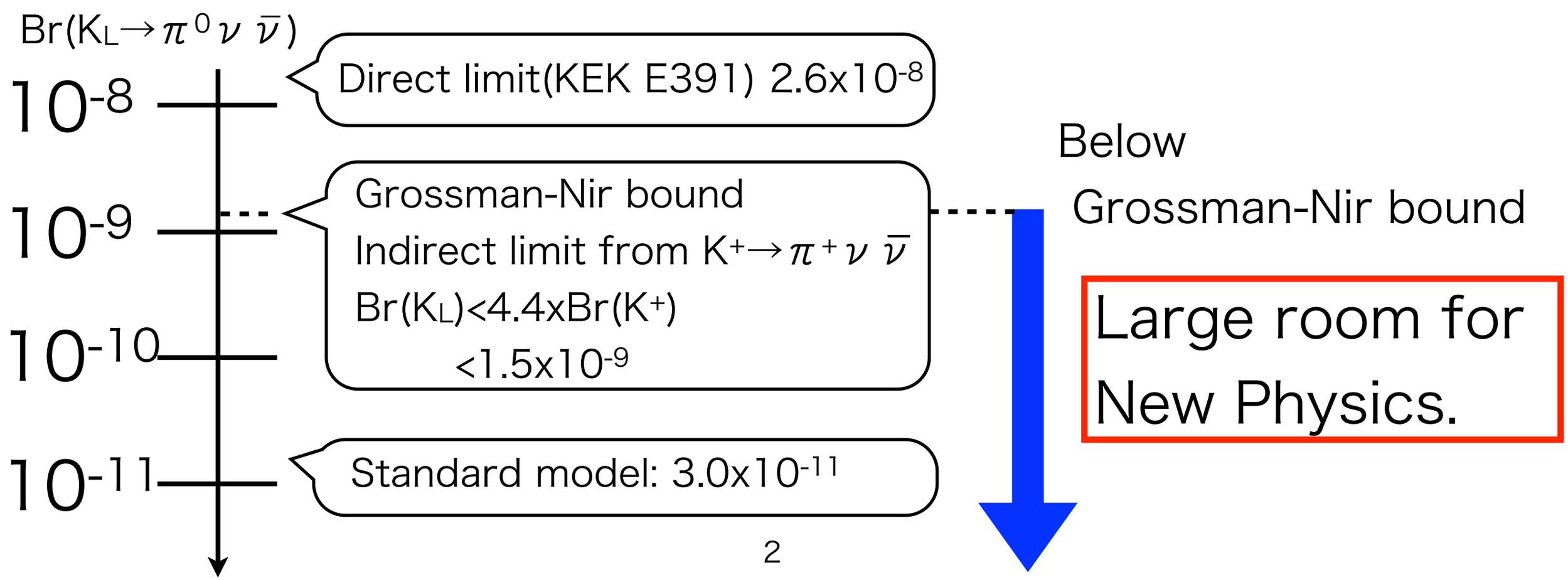
ICHEP 2018@Seoul

2018/07/07

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

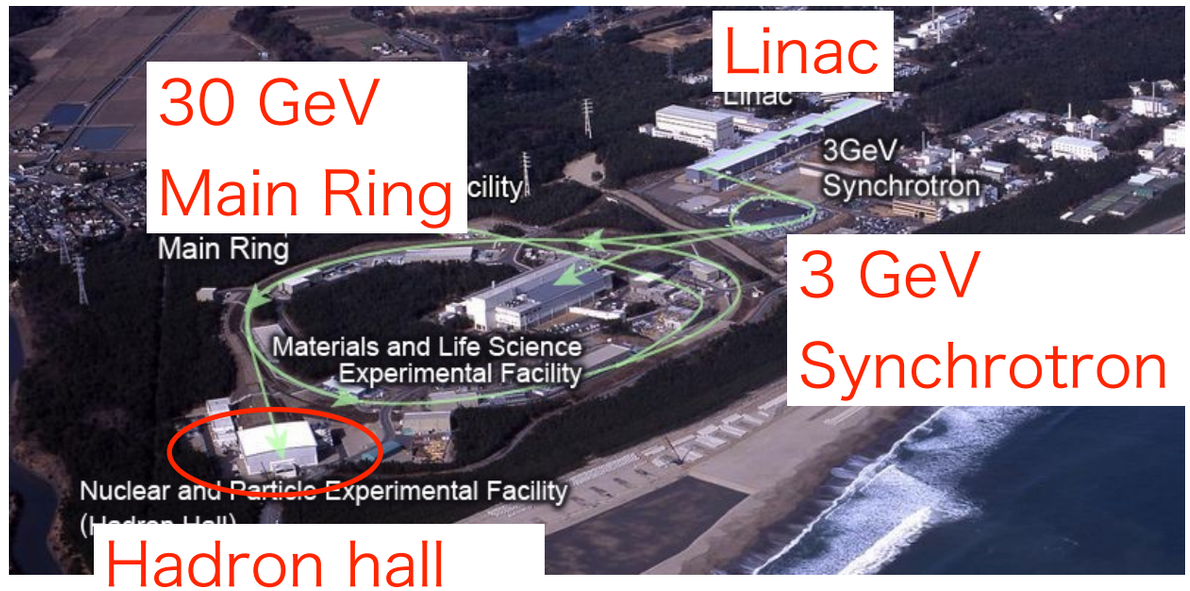
- Breaks CP symmetry directly
- Small theoretical uncertainty:2%
- Suppressed in the SM

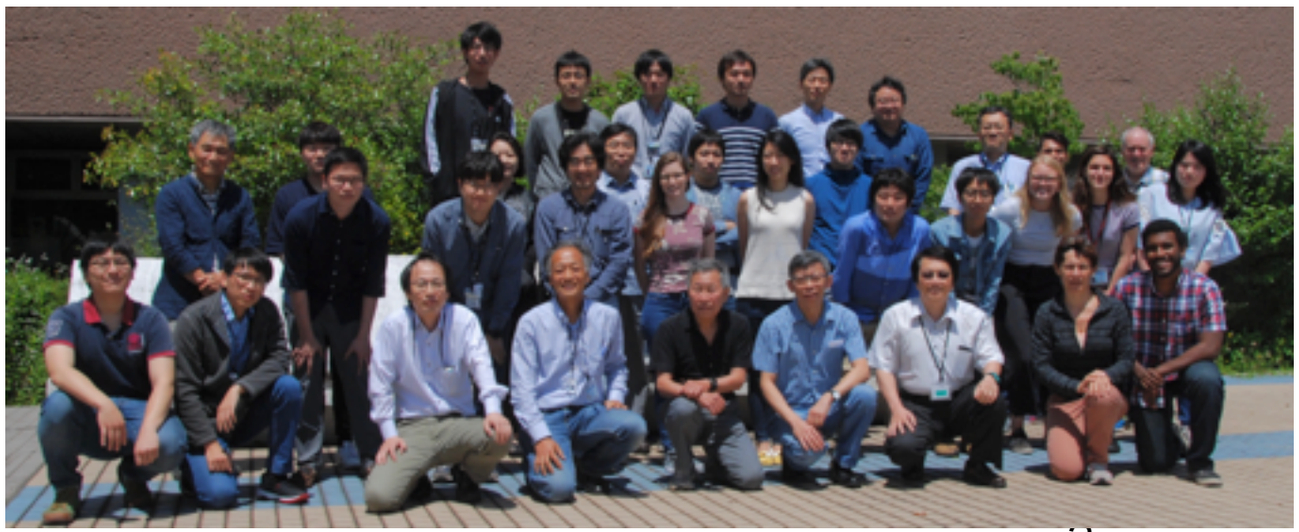
-> Sensitive to New Physics

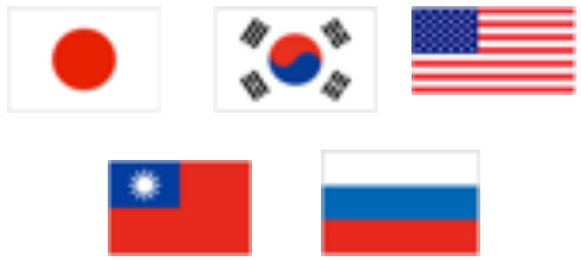


# KOTO experiment

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

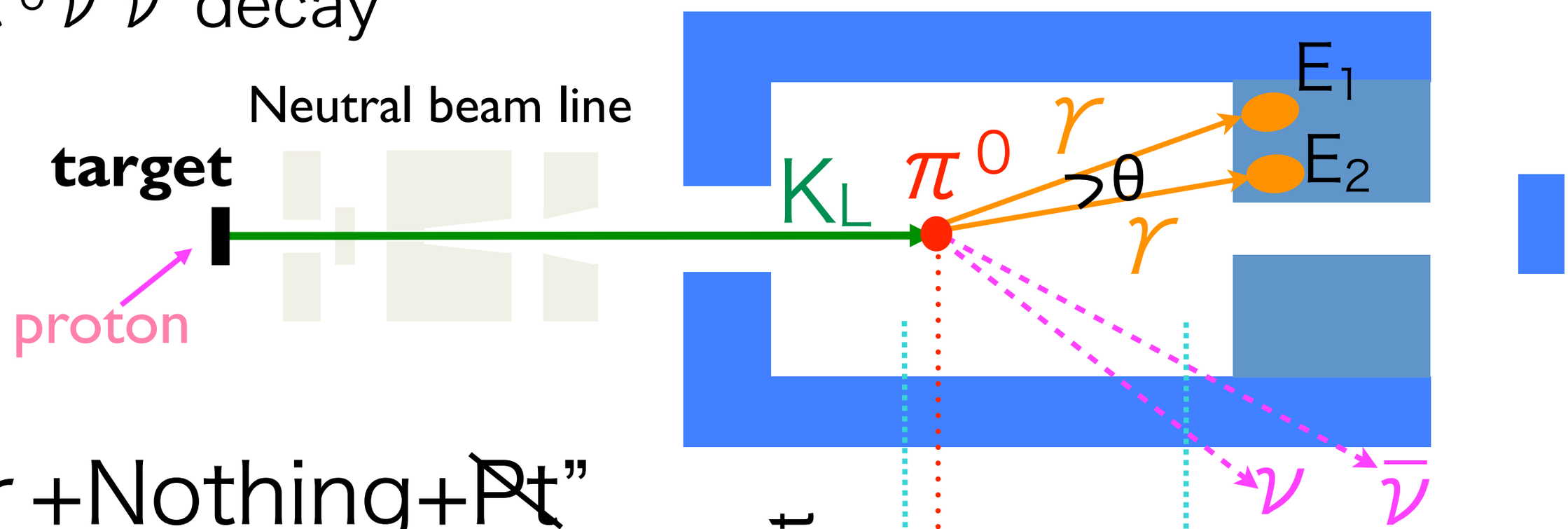





Collaboration photo
at J-PARC(June. 2018)

# Experimental principle

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



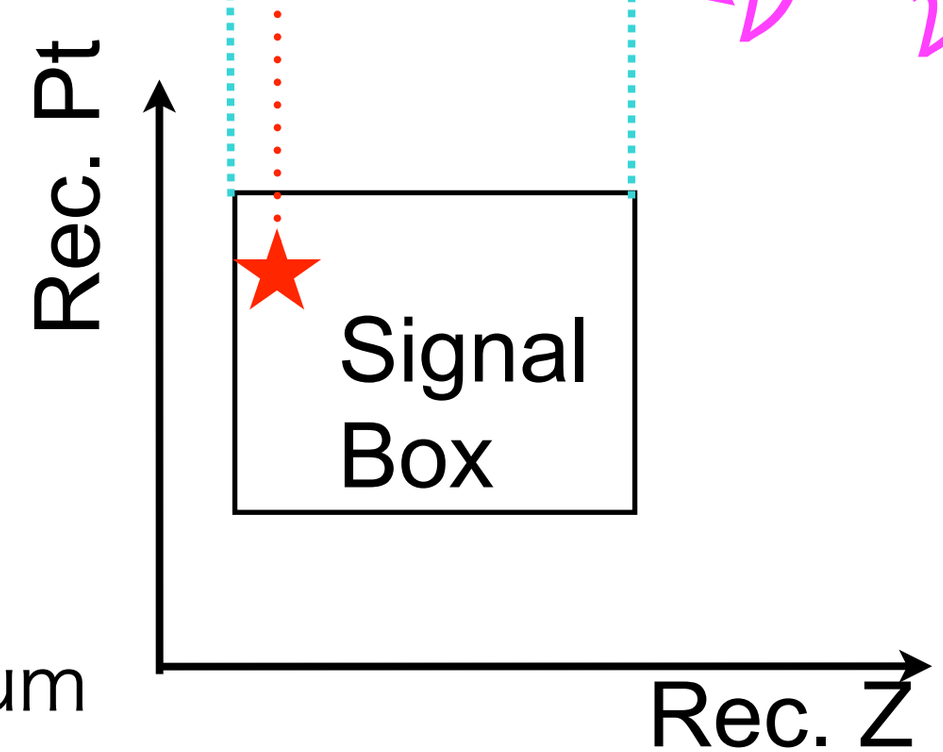

"$2\gamma$+Nothing+$\not{P}t$"

Assuming $2\gamma$ from $\pi^0$,

Calculate z vertex.

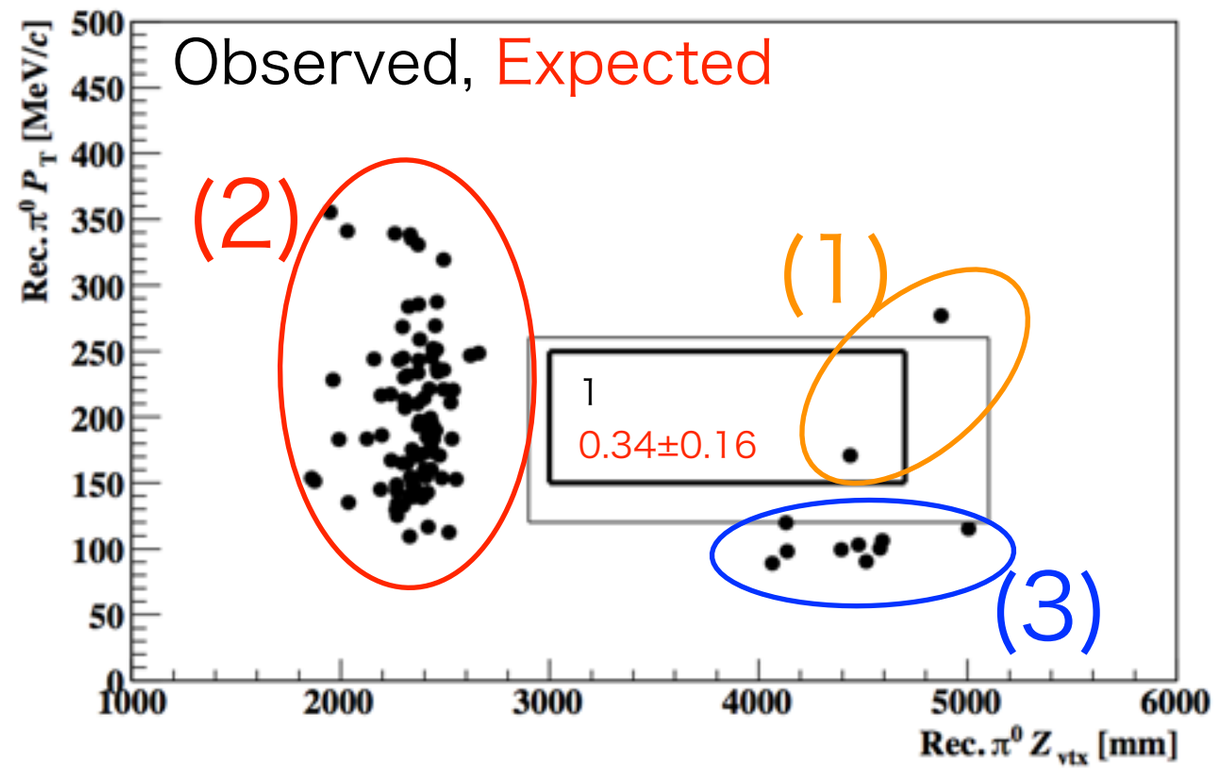
$$M^2(\pi^0)=2E_1E_2(1-\cos\theta)$$

Calculate $\pi^0$ transverse momentum



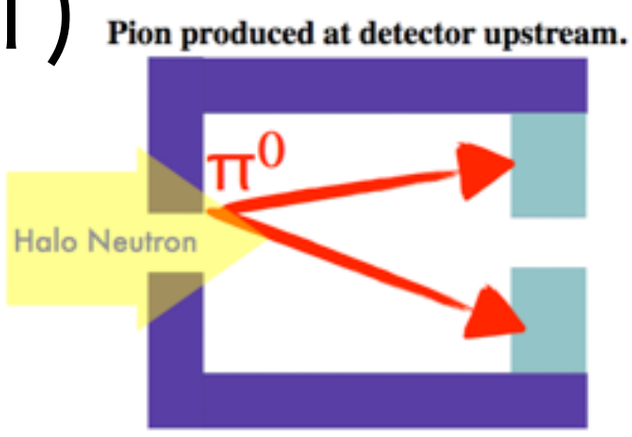
# Results of first physics run

- 2013 100h data
  (PTEP 2017 021C01)
- Observed/Expected=1/0.34
- BR($K_L \to \pi^0 \nu \nu$)<$5.1\times10^{-8}$
  (90% C.L.)

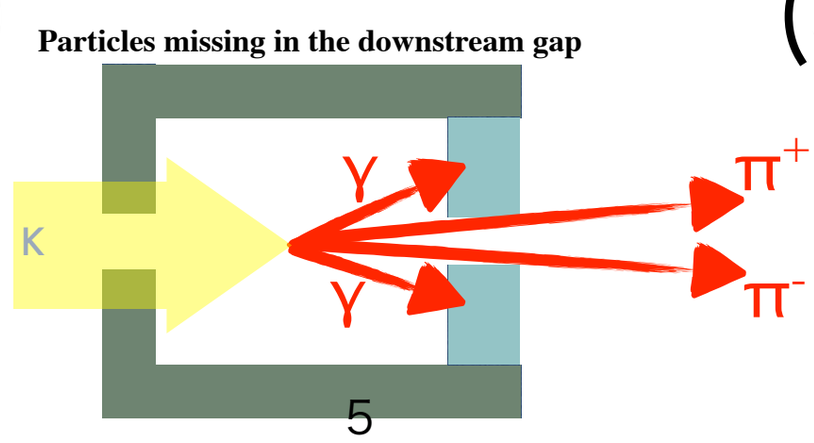



Largest background

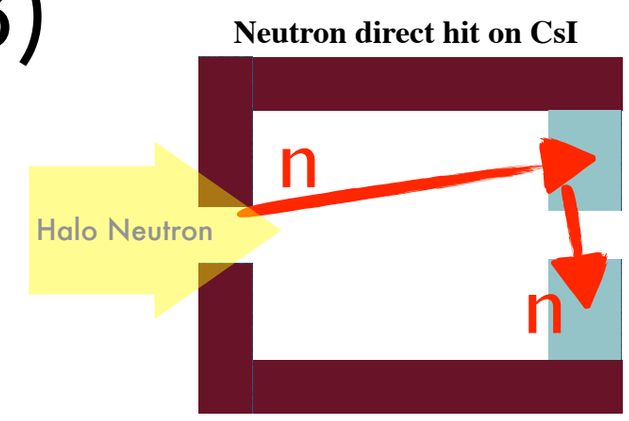
(1)



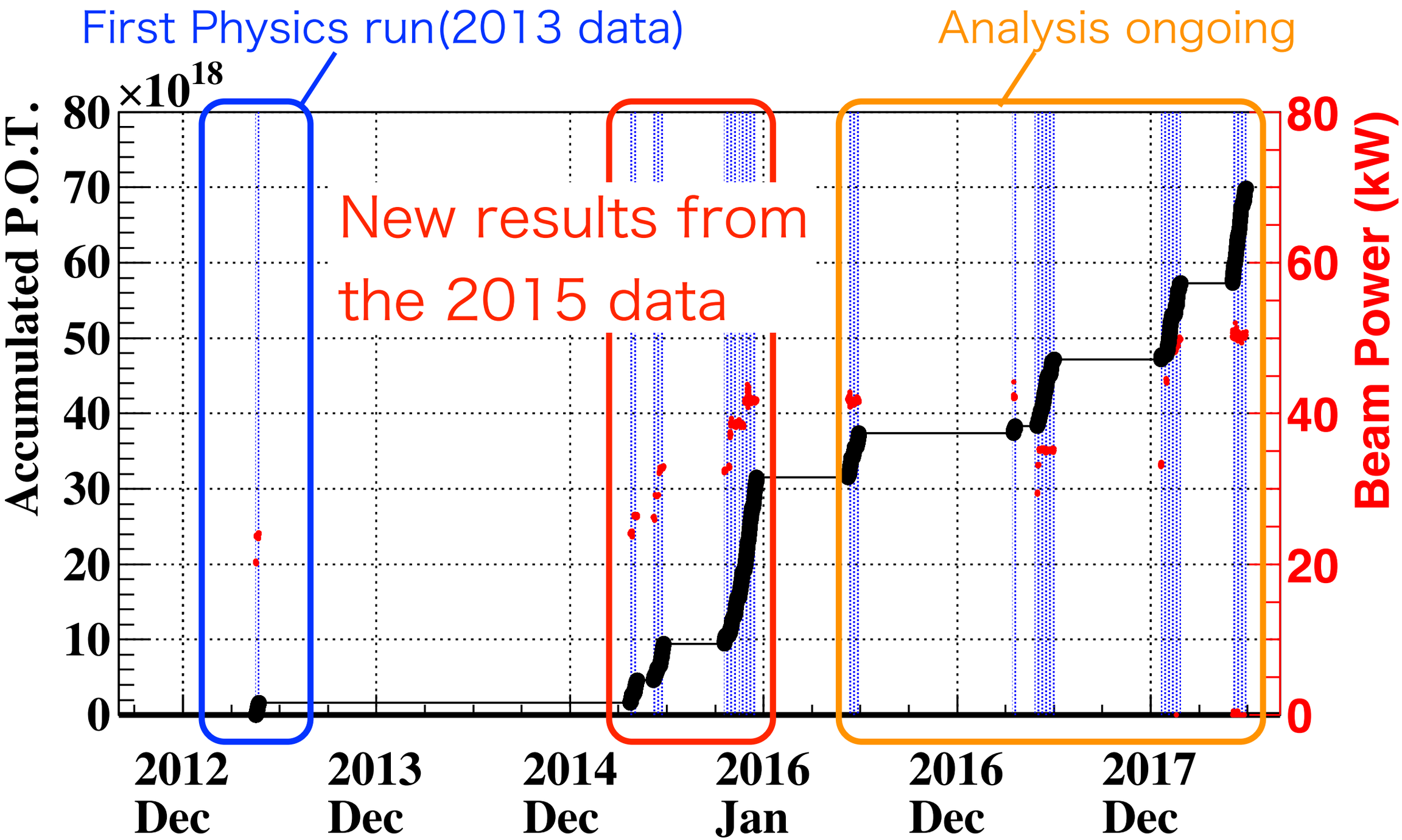

(2)



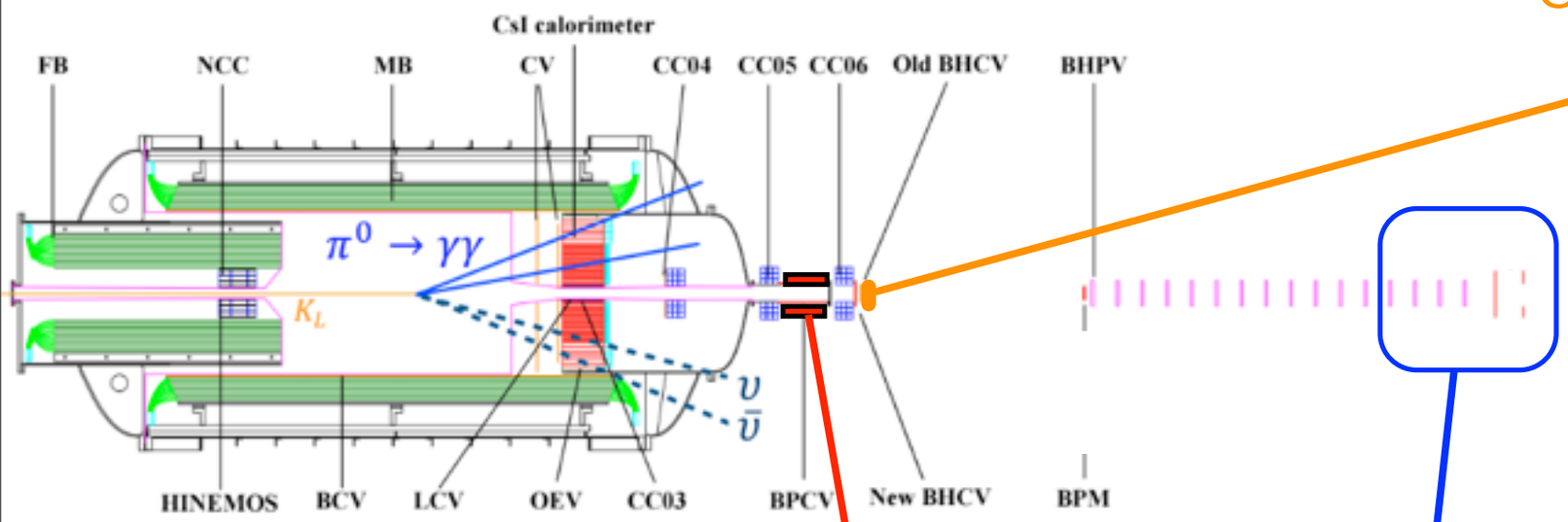

(3)



# Run history

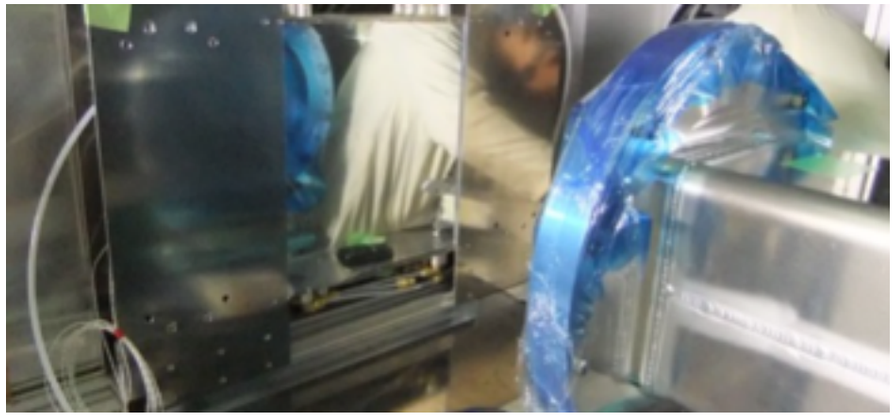

First Physics run(2013 data)
Analysis ongoing
New results from
the 2015 data
Accumulated P.O.T.
×10^18
80
70
60
50
40
30
20
10
0
Beam Power (kW)
80
60
40
20
0
2012
Dec
2013
Dec
2014
Dec
2016
Jan
2016
Dec
2017
Dec

# Detector upgrade after 2013 run




Capable for higher beam power

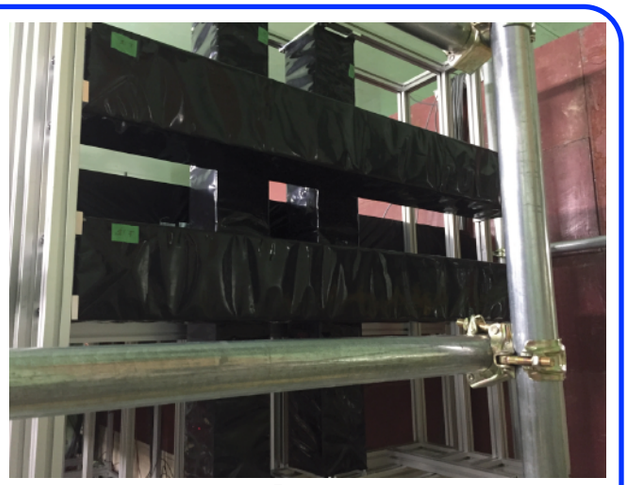
In-beam Charged Veto
(Wire chamber $CF_4$+$C_5H_{12}$ gas)



Increase detection efficiency
for charged particles

Scintillator counters

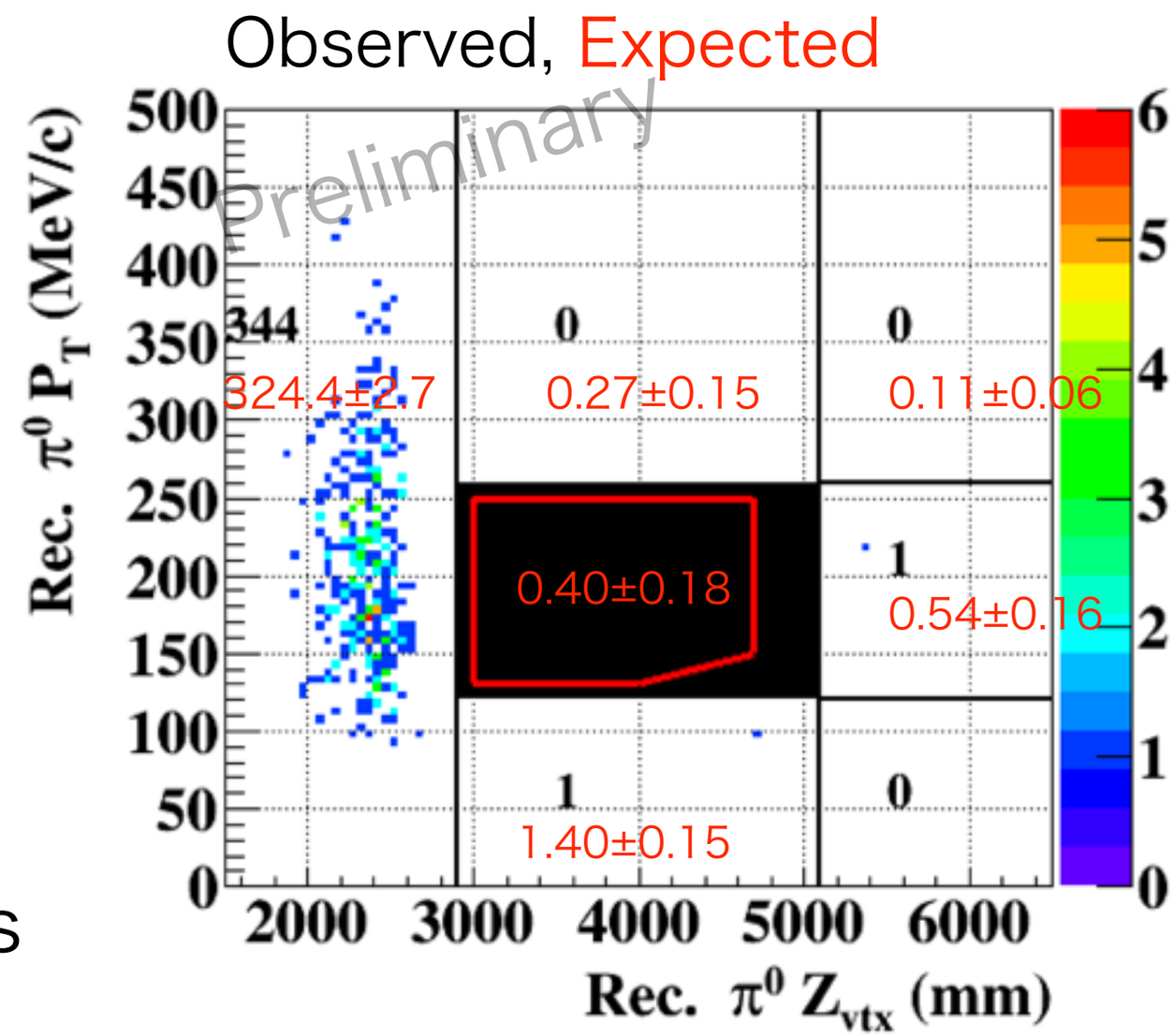
Increase photon detection efficiency



Additional photon counters

# Features of 2015 data analysis

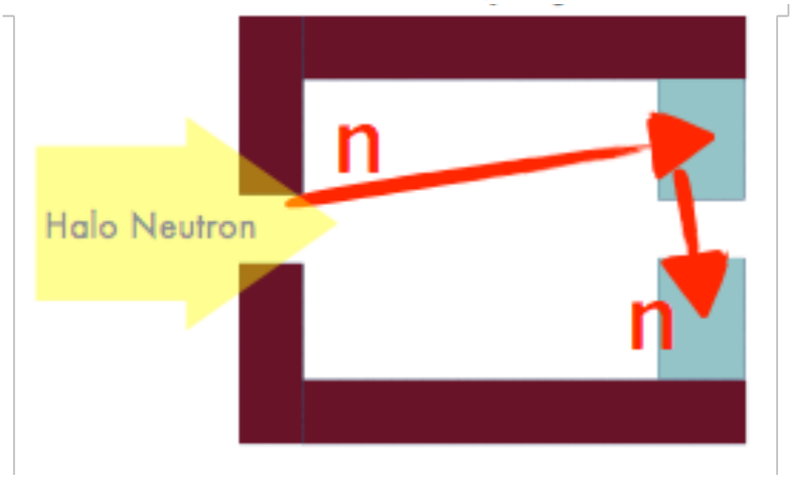
- Larger statistics
  - (First physics run)x20
- Better control samples to study neutron BG
- Detector upgrade
  - Installed several detectors to reduce kaon-decay BG

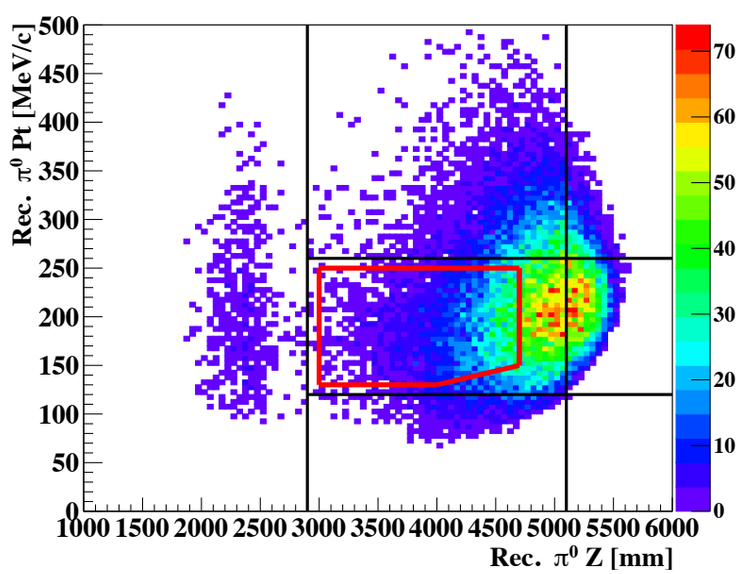


# Halo neutron background

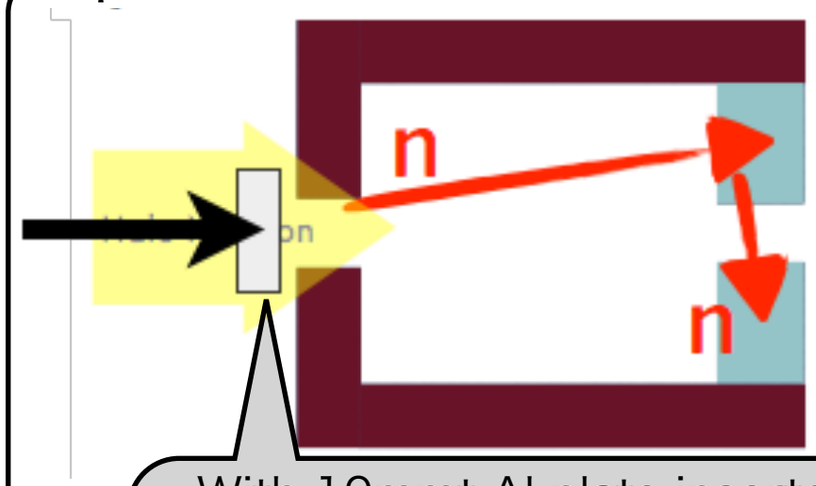
-Collected control samples to study of neutron clusters

BG mechanism in physics run

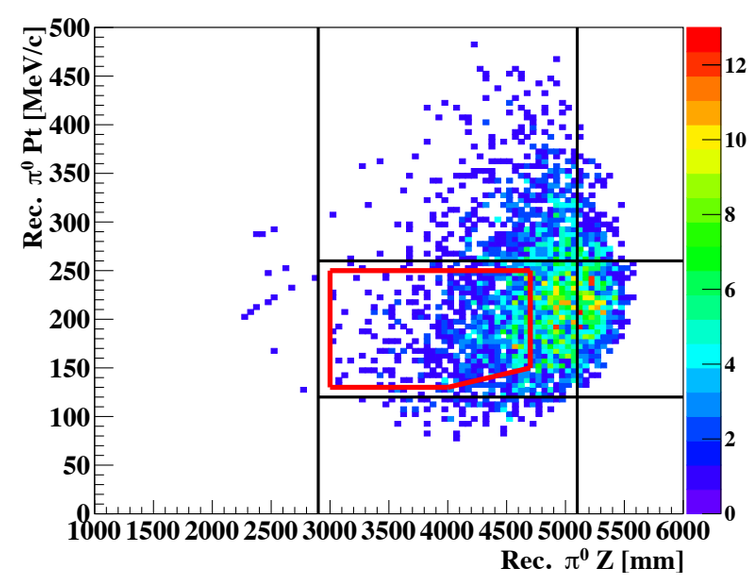



Special run to take control sample

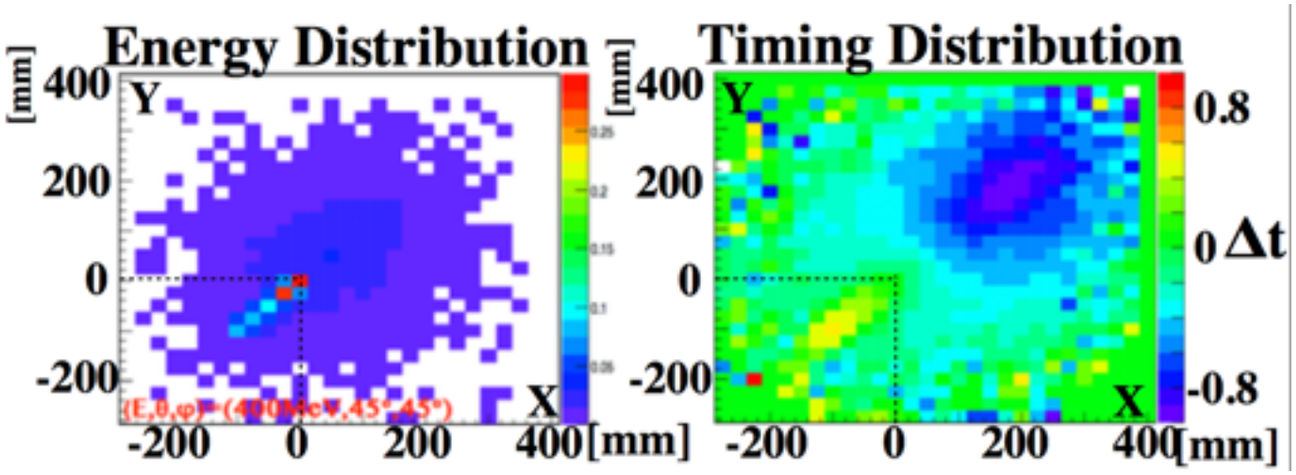



With 10mmt Al plate inserted in the neural beam



# New methods for rejecting neutron Background

Cluster Shape Discrimination

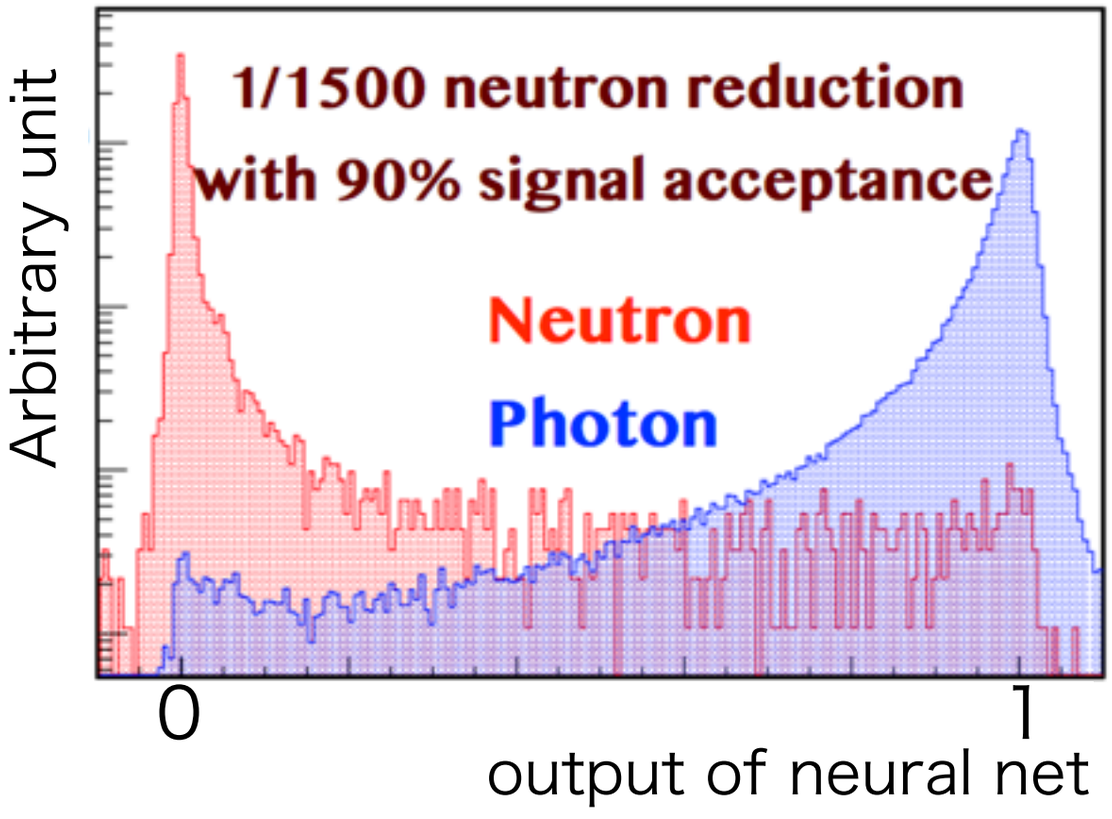



-Use cluster energy and timing information as inputs of neural net

-Training samples

Signal:Signal MC

BG :Special run data

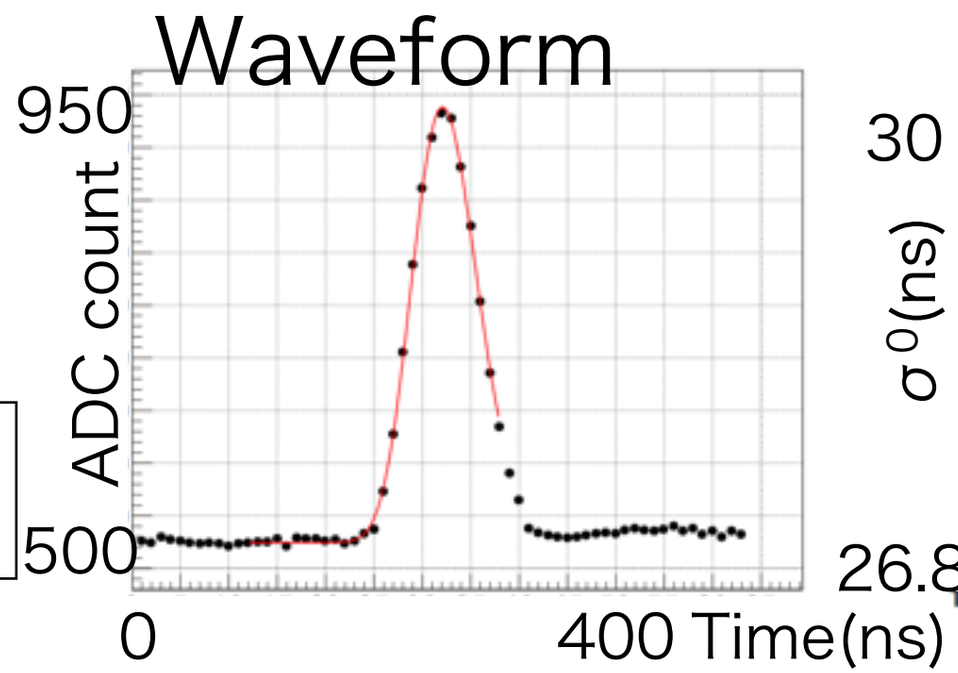


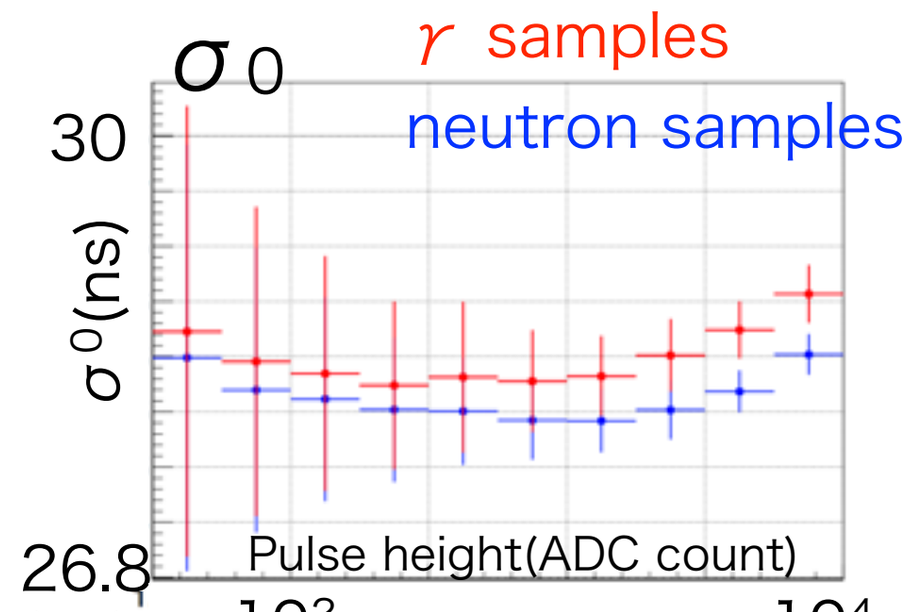
# New methods for rejecting neutron Background

## Pulse Shape Discrimination

$$|A| \exp\left(-\frac{(t-t_0)^2}{2(a(t-t_0)+\sigma_0)^2}\right)$$

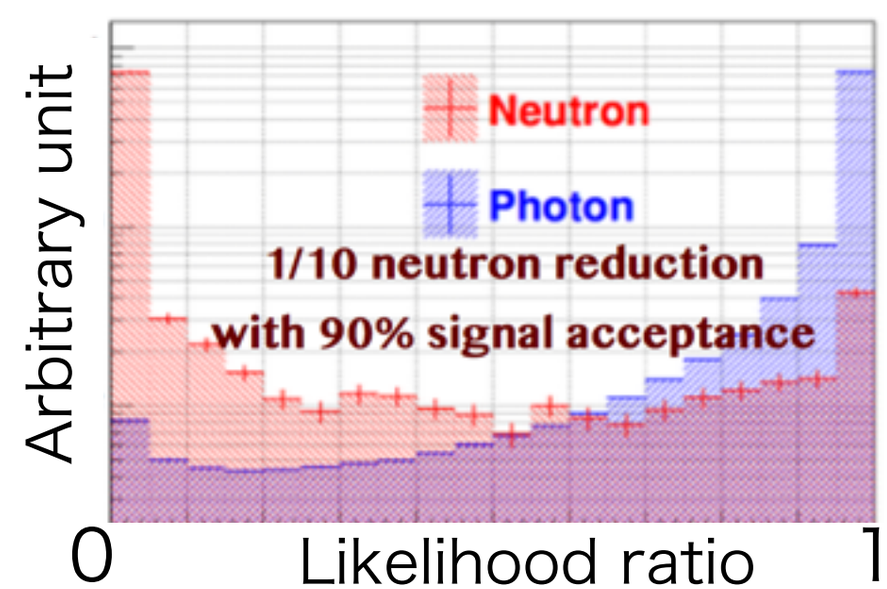
Neutron has wider pulse from hadronic shower



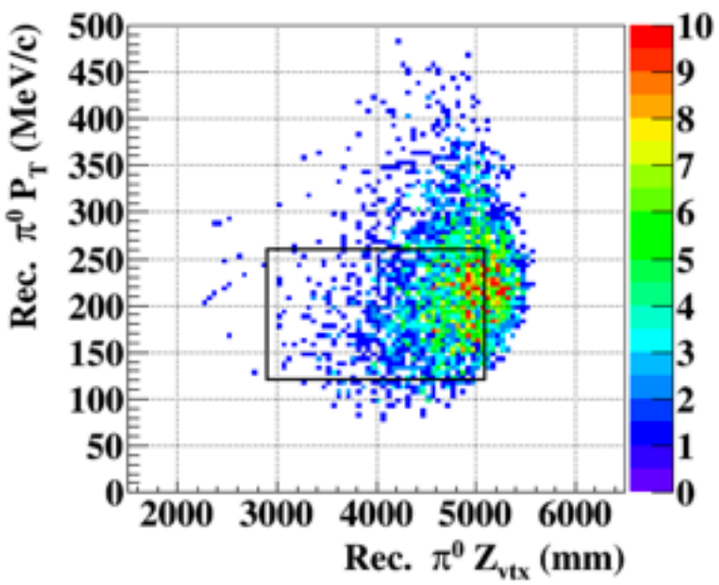

-Make templates. ($\gamma$ and neutron)

-Calculate likelihood ratio

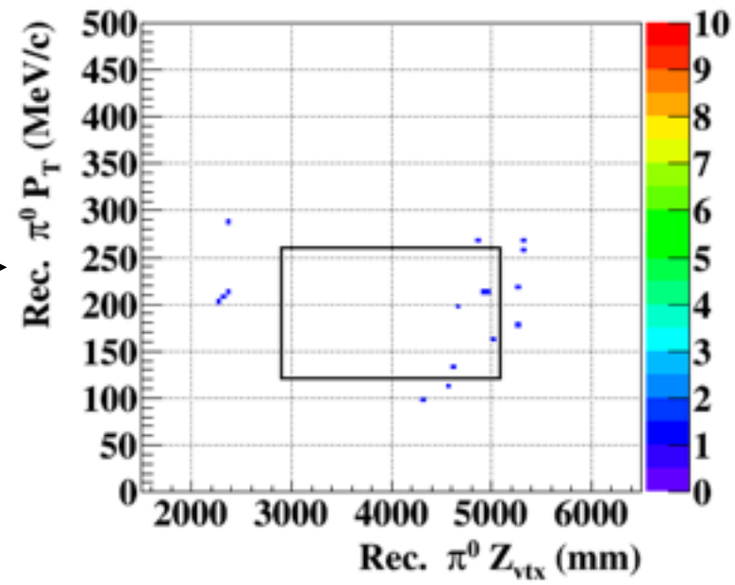


# New methods for rejecting neutron Background

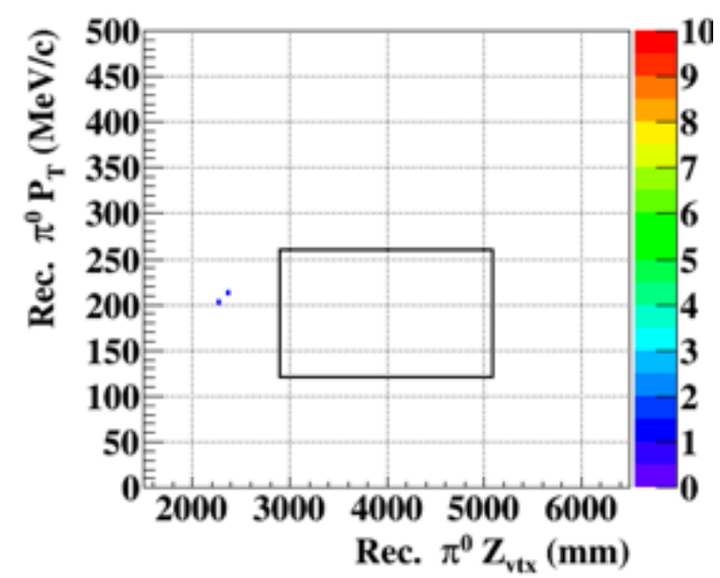
Neutron Sample




2013 selection

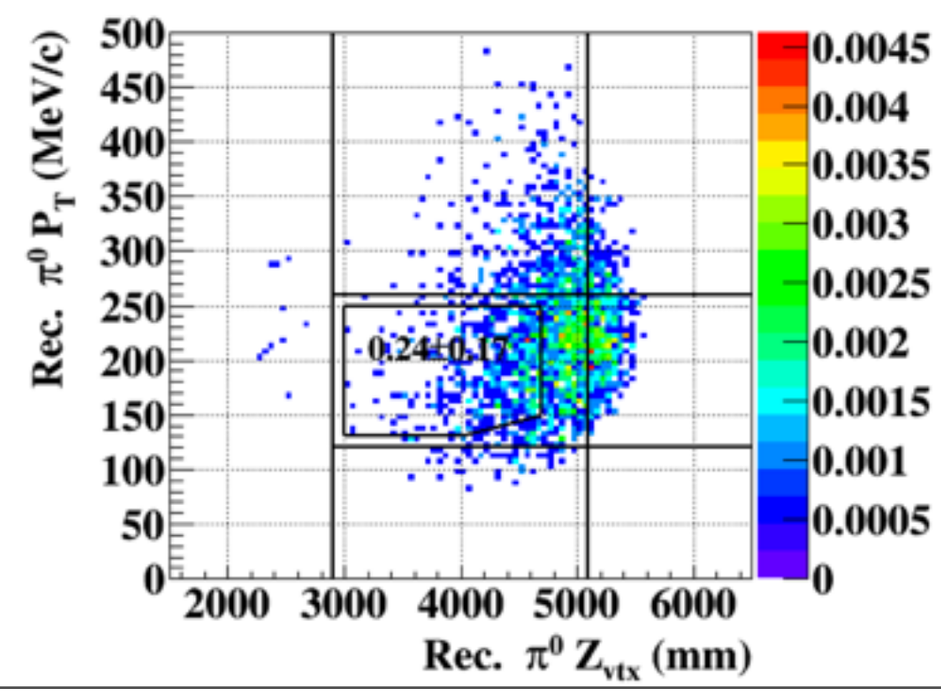



2015 selection

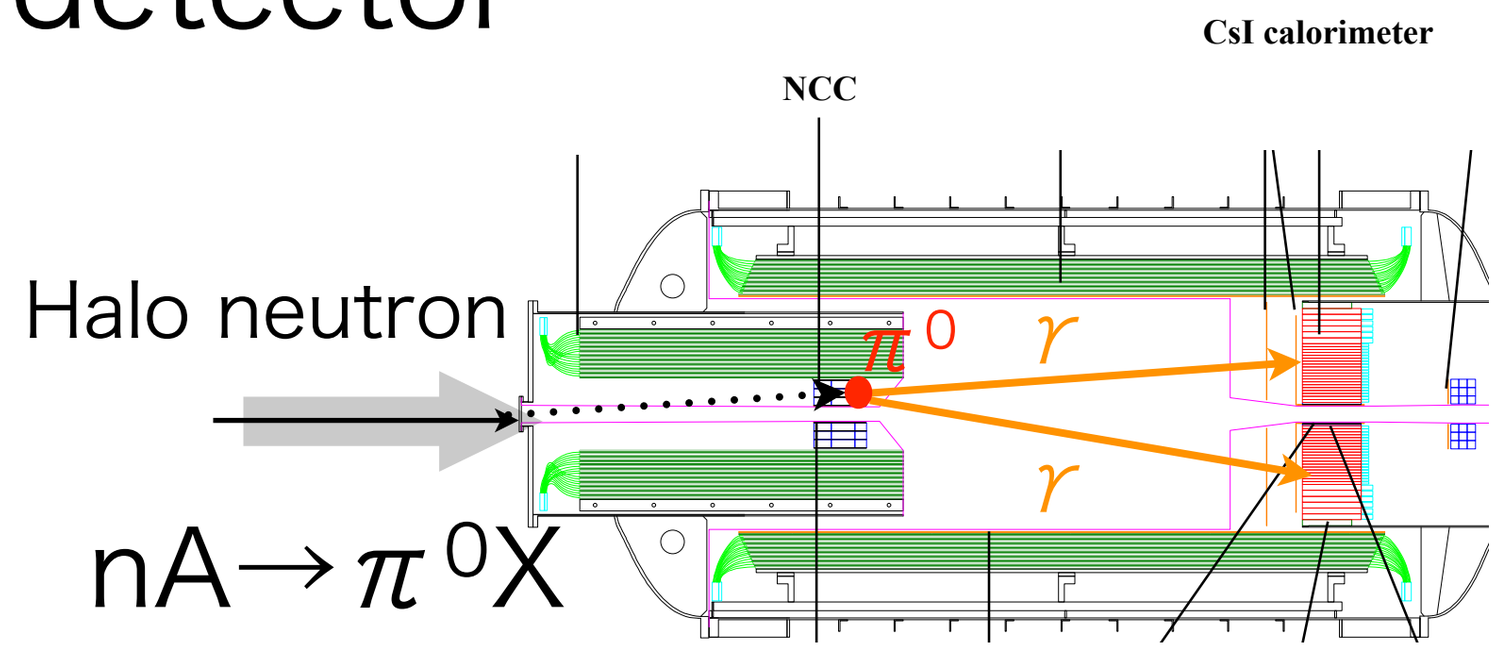


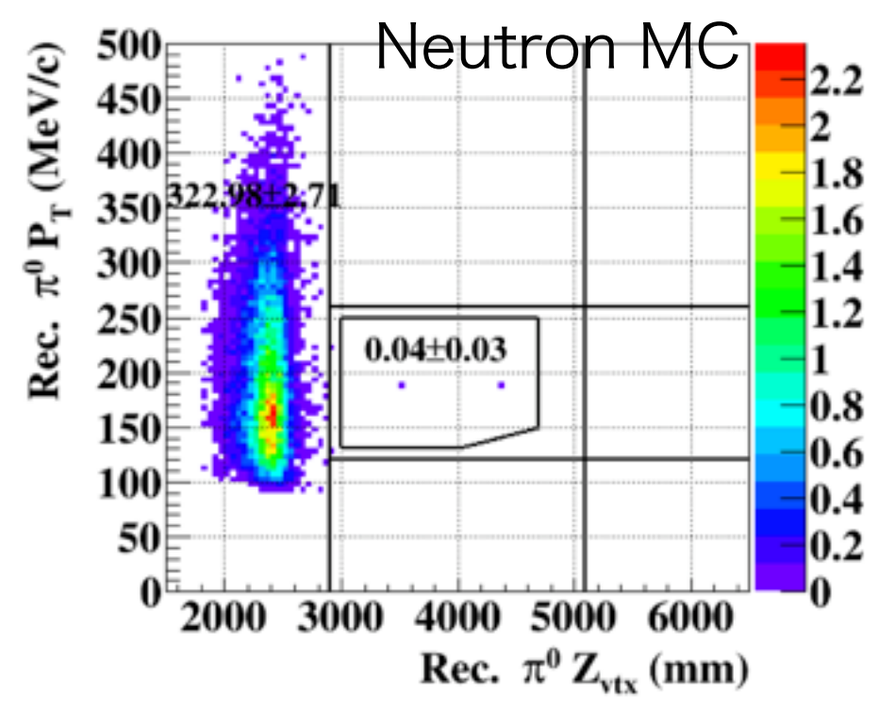

-#(Neutron background) reduced by a factor of 10.

-The number of neutron background in the signal box is 0.24±0.17



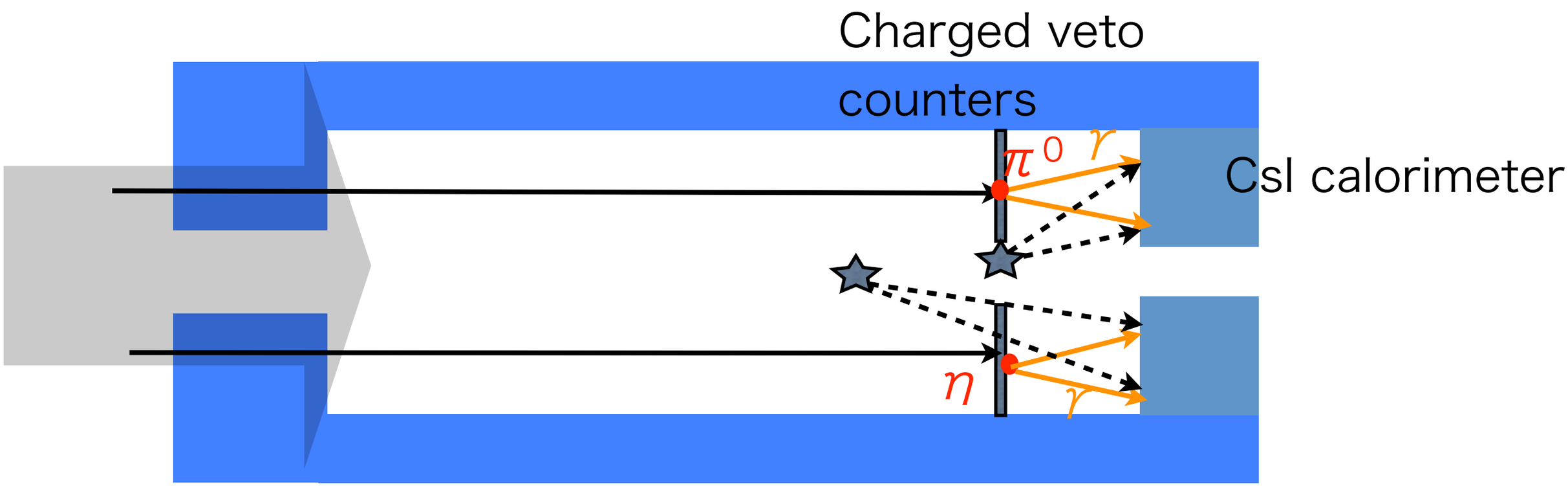
# Halo neutron hitting upstream detector



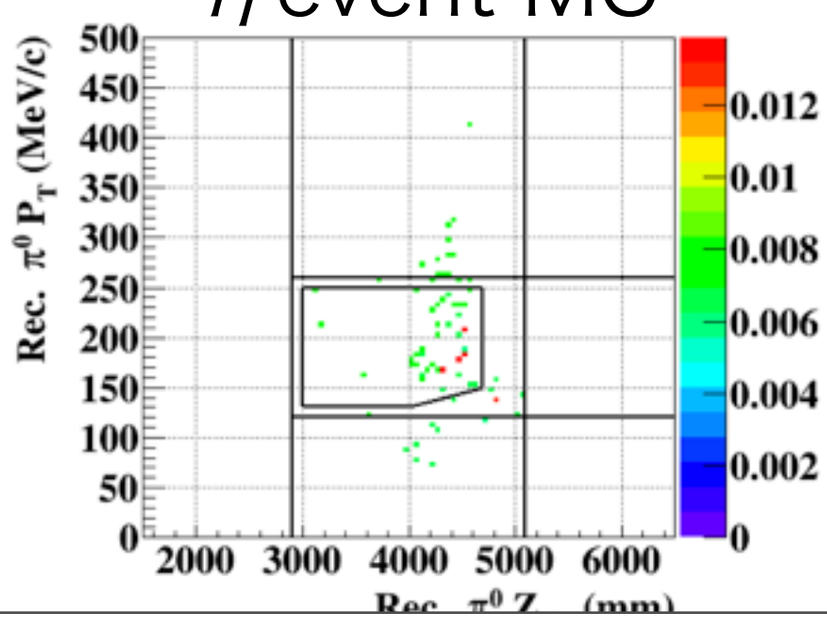




- The number of upstream events expected in the signal box
  - 0.04±0.03

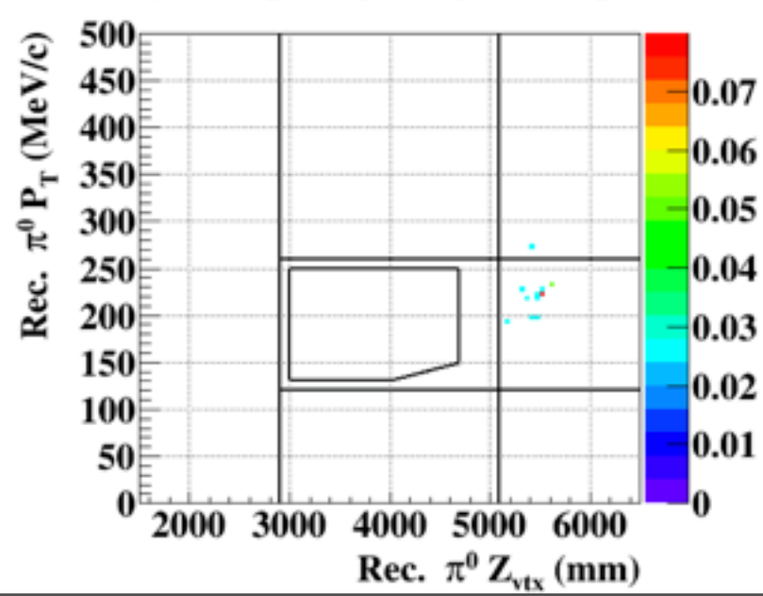
# Halo neutron hitting the materials near the CsI Calorimeter




$\eta$ event MC




$\pi^0$ event MC



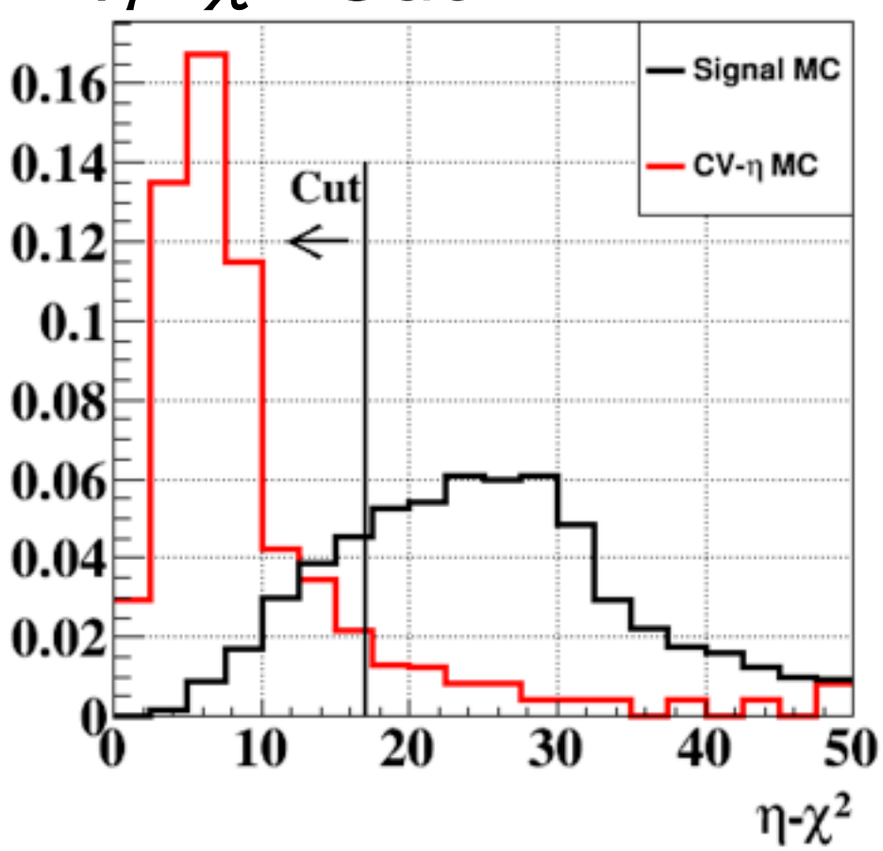
# New cut for BG events caused by $\eta$

-Check cluster shape under the assumptions

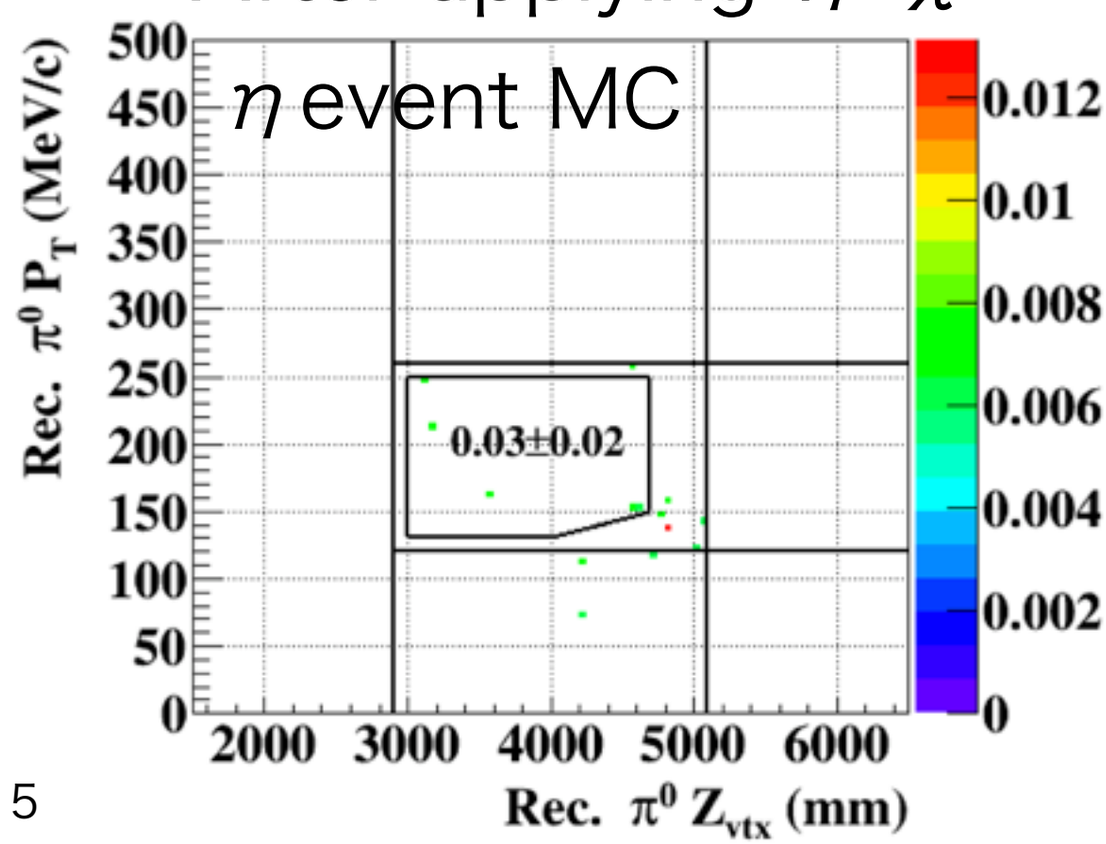
-$\eta$ mass, Vertex position= Charged veto counter(CV)

-After applying $\eta$-$\chi^2$ cut, the number of $\eta$ background events expected in the signal box is 0.03±0.02

$\eta$-$\chi^2$ Cut

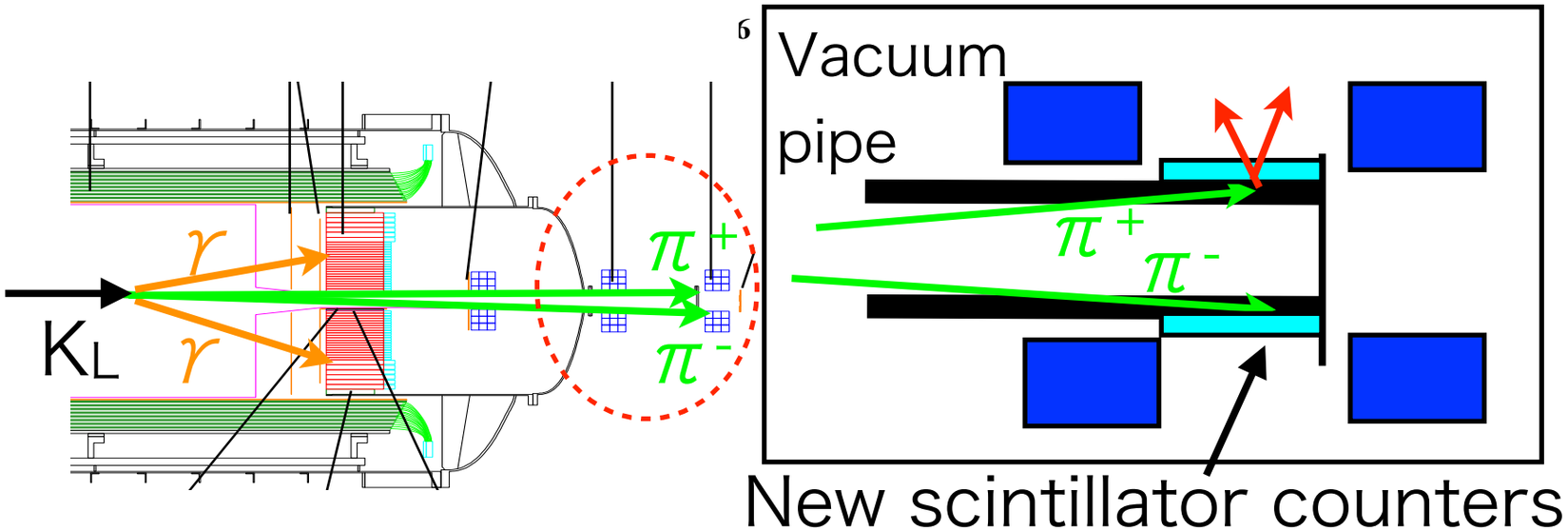



After applying $\eta$-$\chi^2$

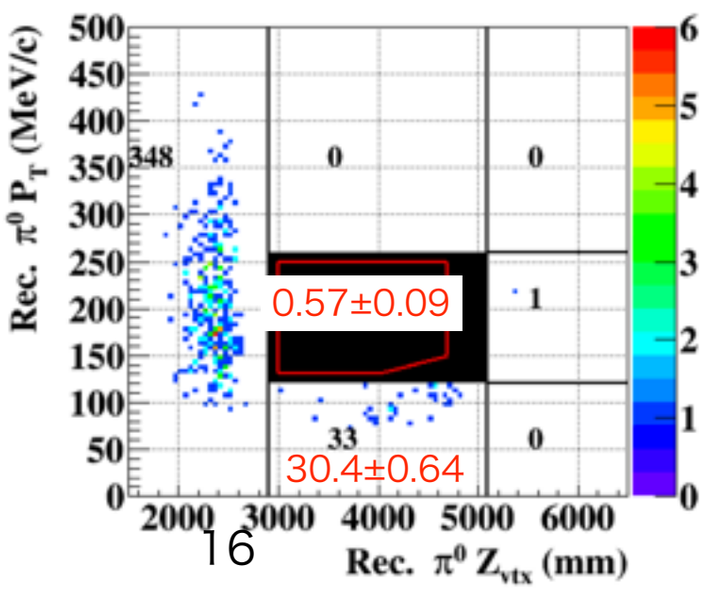


# $K_L \to \pi^+\pi^-\pi^0$ background

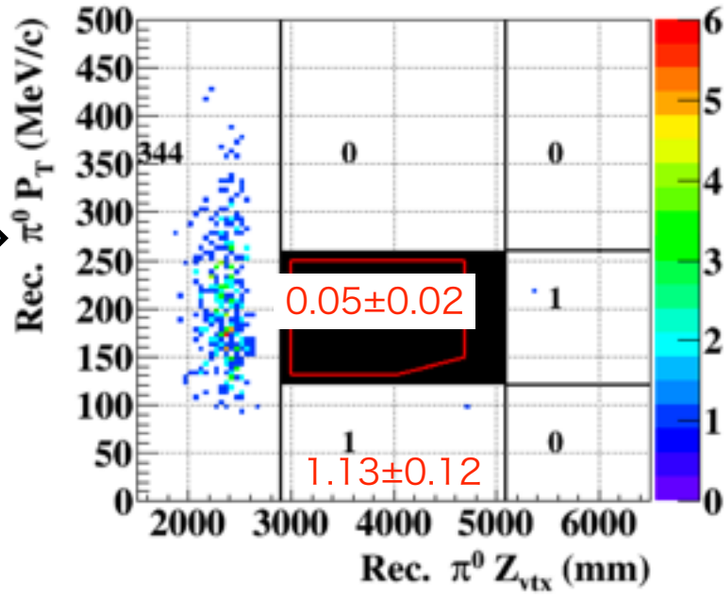
-Thinner vacuum pipe
  ->#(Background)
    became 1/2.
-Installed new scintillator counters
  ->#(Background)
    became 1/10.
    (0.05±0.02)




w/o scinti. veto



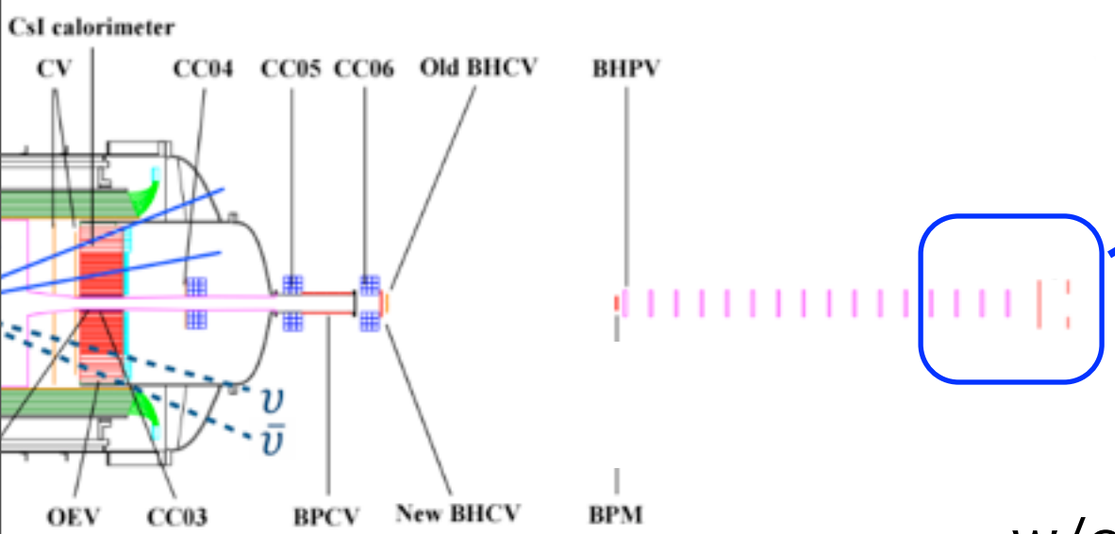

w/ scinti. veto




Observed Expected from $K_L \to \pi^+\pi^-\pi^0$ MC

# $K_L \to 2\pi^0$ background

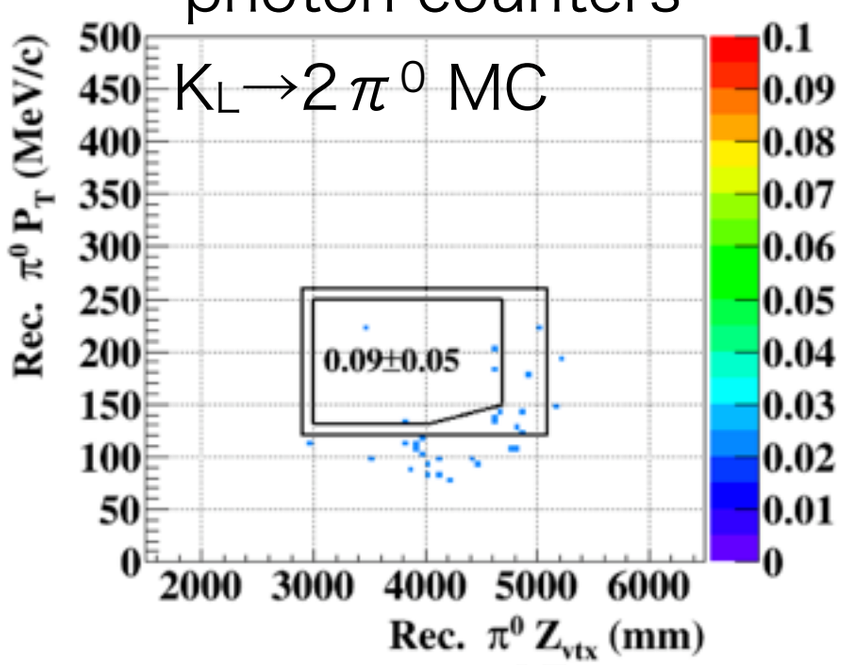
## Installed additional photon counters



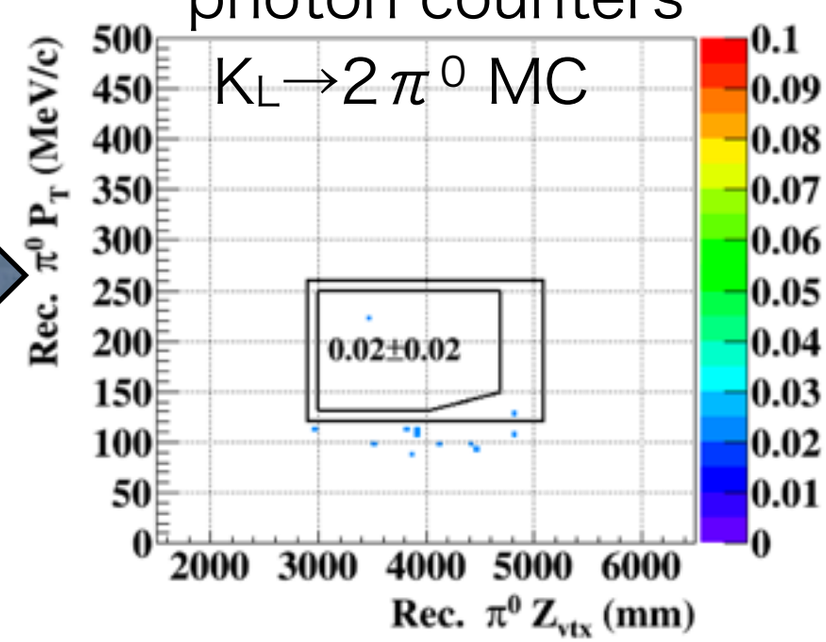


The number of $K_L \to 2\pi^0$ background is -0.02±0.02

w/o additional photon counters




w/ additional photon counters

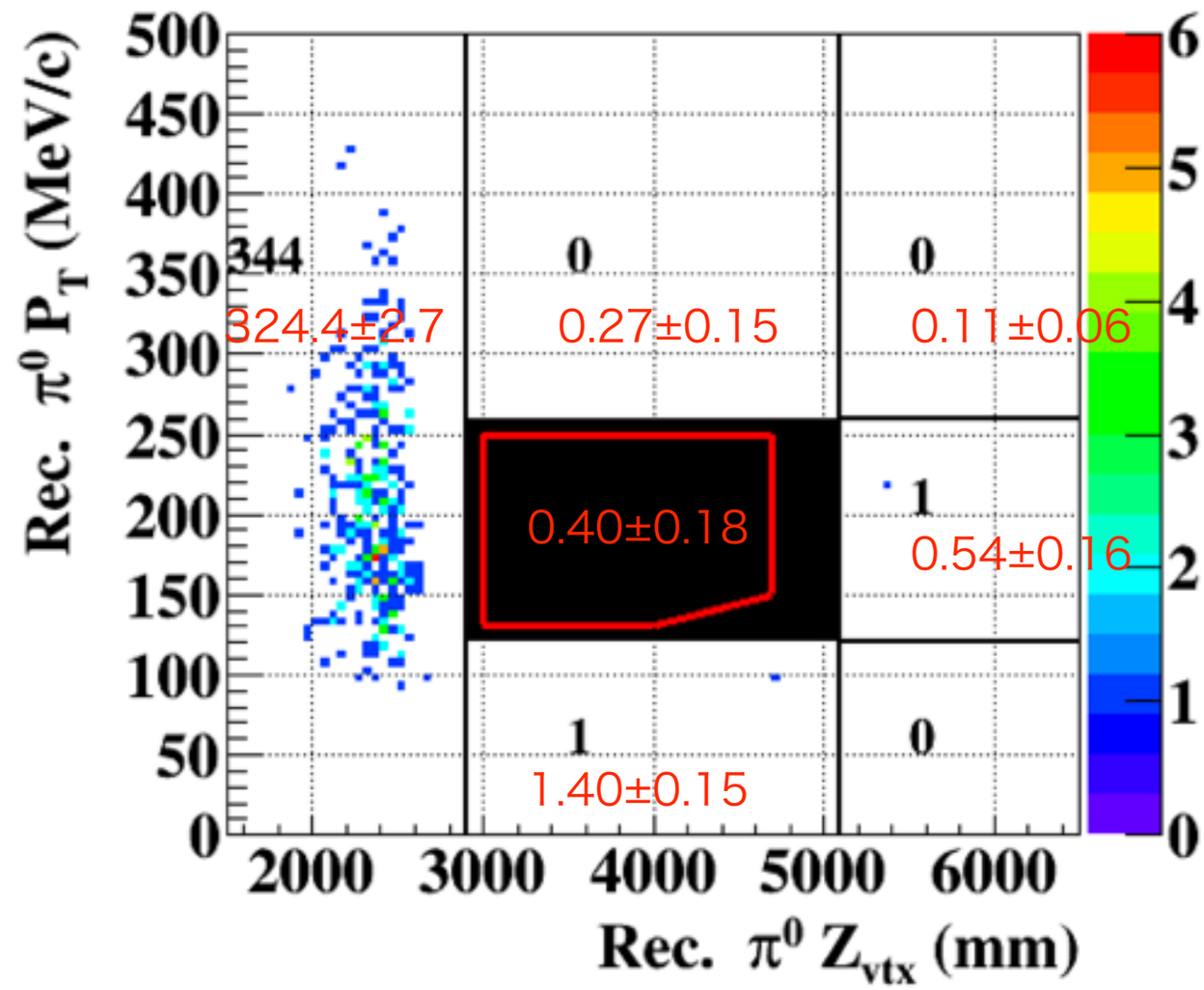


Preliminary

# Results of 2015 analysis

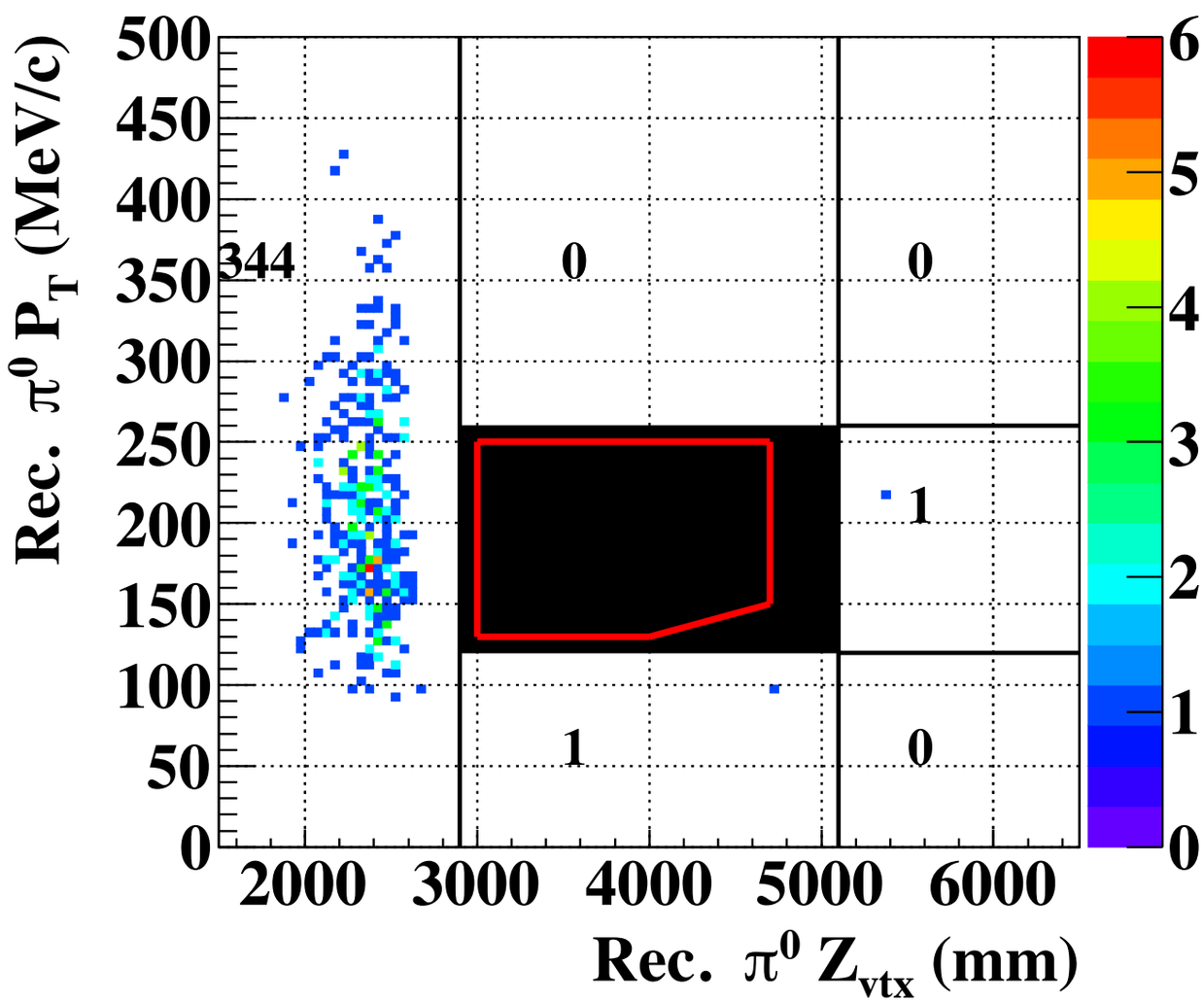
## Summary of background inside the signal box

| background source | #BG |
|---|---|
| Halo neutron hitting CSI | 0.24±0.17 |
| Halo neutron hitting upstream detectors | 0.04±0.03 |
| $\eta$ background | 0.03±0.02 |
| KL->$\pi$+$\pi$-$\pi$0 | 0.05±0.02 |
| KL->2$\pi$0 | 0.02±0.02 |
| other BG sources | 0.02±0.02 |
| Sum | 0.40±0.18 |



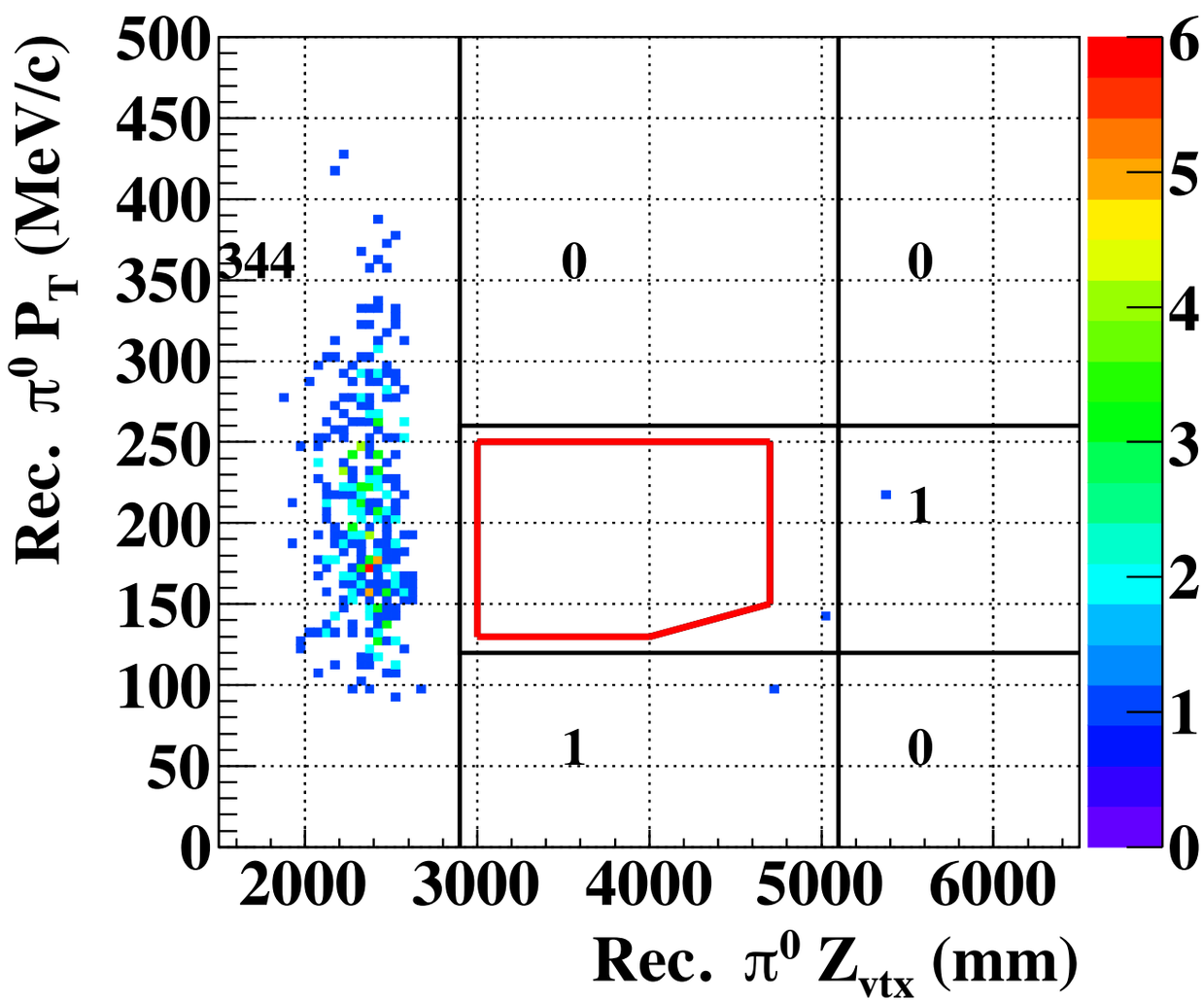

S.E.S: $1.3\times10^{-9}$ cf. Grossman-Nir bound <1.5e-9

# Open the signal box



# Open the signal box

- No signal candidate observed



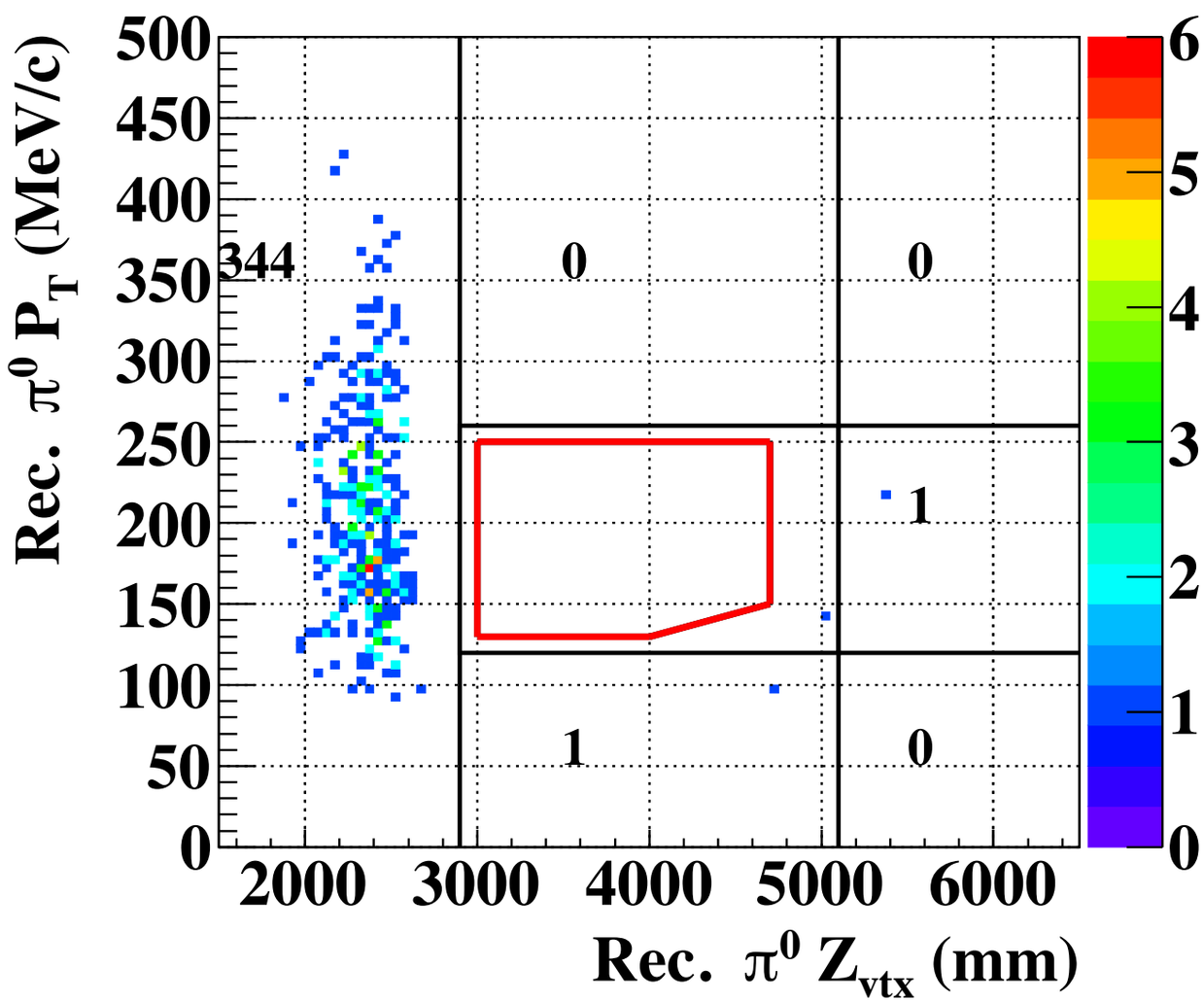
# Open the signal box

- No signal candidate observed

Preliminary

- BR<3.0×10$^{-9}$ @90%C.L.

S.E.Sx 2.3
with Poisson statistics

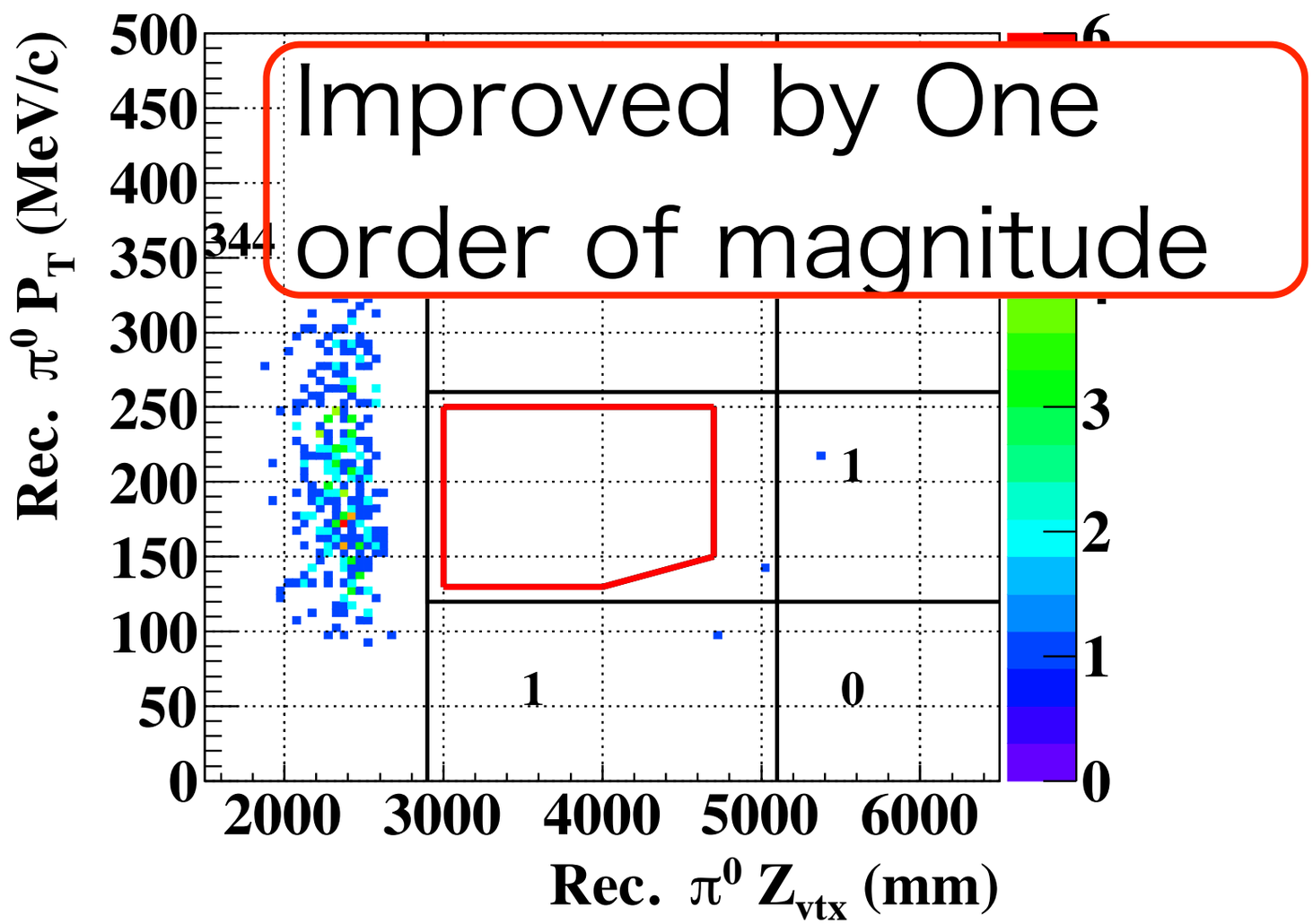


# Open the signal box

- No signal candidate observed
- BR<3.0×10$^{-9}$ @90%C.L.

Preliminary

S.E.Sx 2.3
with Poisson statistics




Improved by One order of magnitude

# Prospect

- 2016-2018 data analysis is ongoing
- 1.5x (physics data),  10x (neutron data)
  ->With 2015-2018 data, we can reach S.E.S of $5\times10^{-10}$
- From this summer
  - We will upgrade detectors to suppress background.
    - Ex. Calorimeter upgrade against neutron BG.

Talk Detector R&D 7/7 14:24 by Kotera
Poster D26 by Mari

  - We will improve analysis to recover acceptance
  - Beam power will increase from 50kW to 90kW gradually, after installing a new production target to the Hadron Hall in 2019.
    ->We aim to go below $10^{-10}$ in a timely manner

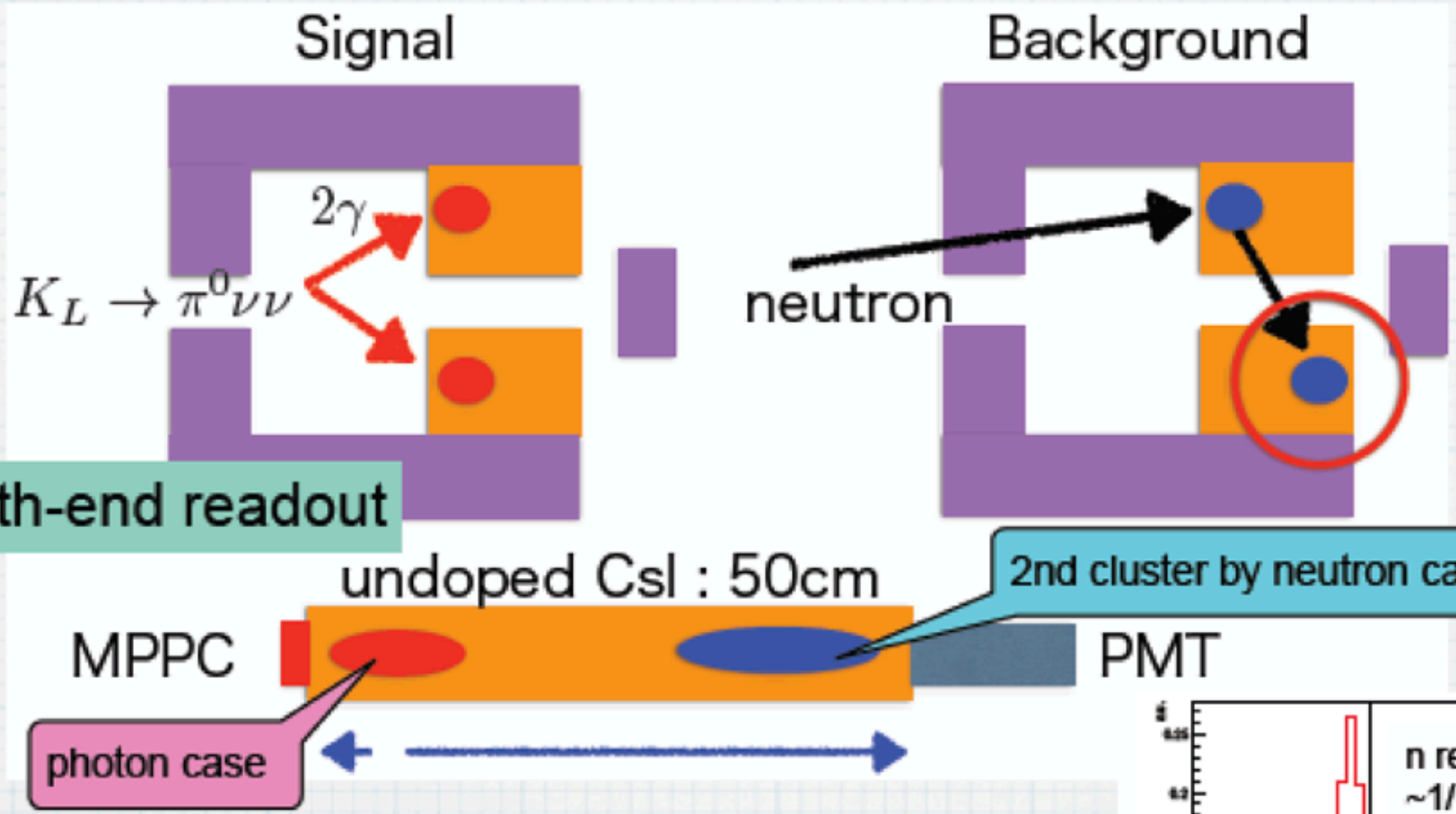
# Summary

- The KOTO experiment studies the $K_L \to \pi^0 \nu \nu$ decay.
- No signal candidate observed in 2015 data.
- BR< $3.0 \times 10^{-9}$ @90% C.L.
  - Improved the current upper limit by one order of magnitude
- 2016-2018 data analysis is ongoing
- We will upgrade detectors and improve analysis to get further sensitivity

Preliminary

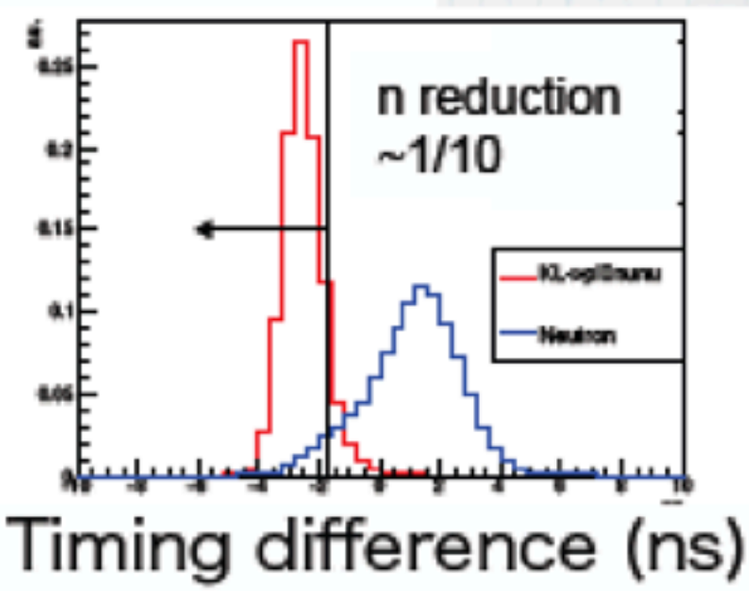
- Back up

# Calorimeter upgrade




Timing Difference ΔT = T(MPPC)-T(PMT)

ΔT (γ) < ΔT (neutron) expected

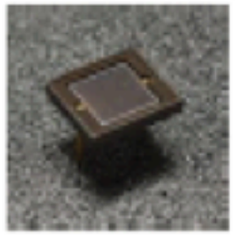



Details in poster presentation by N. Hara (Osaka U)

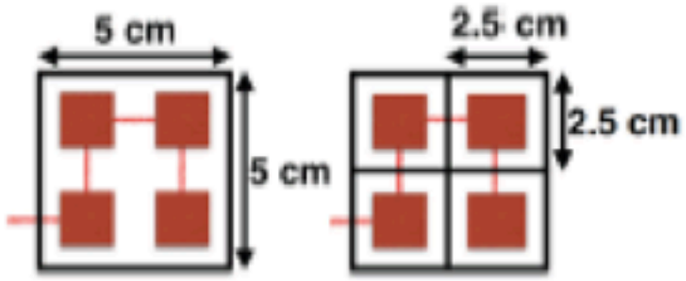
UPGRADE 2018

# Calorimeter upgrade

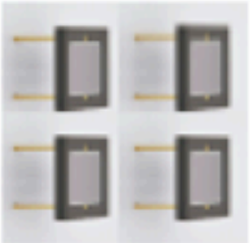
S13360-6050CS (HPK)



Two types of crystals



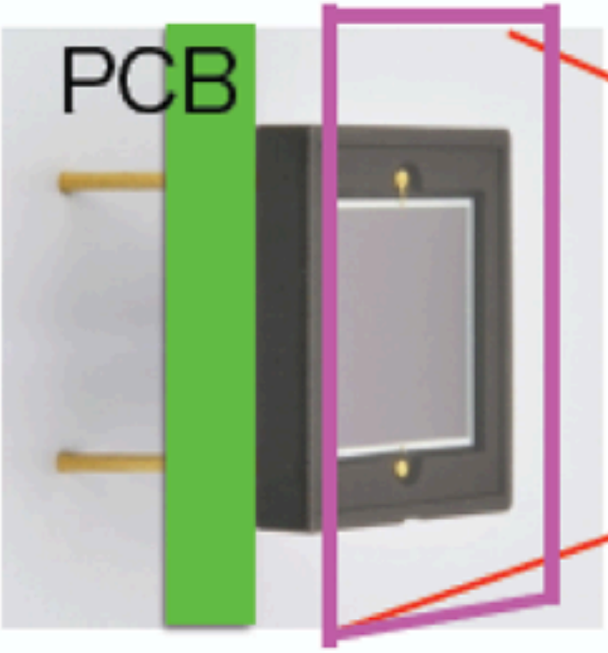

4096 MPPCs 1024 cables

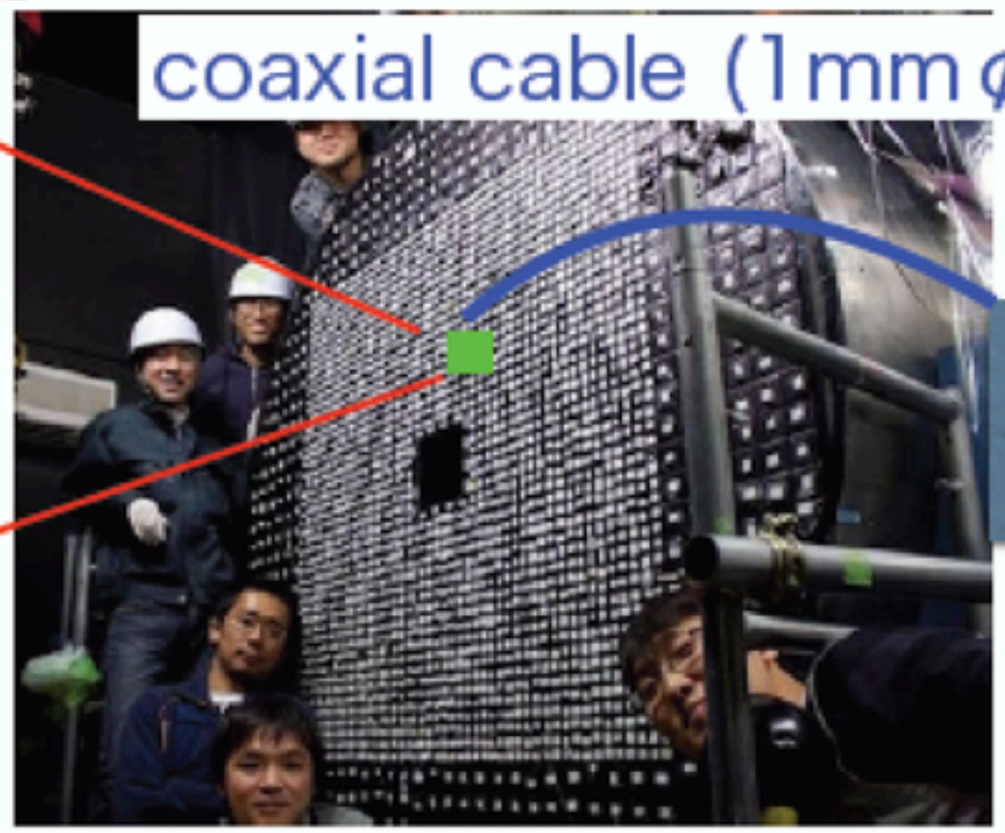


4-MPPC connection

summing up

quartz plate



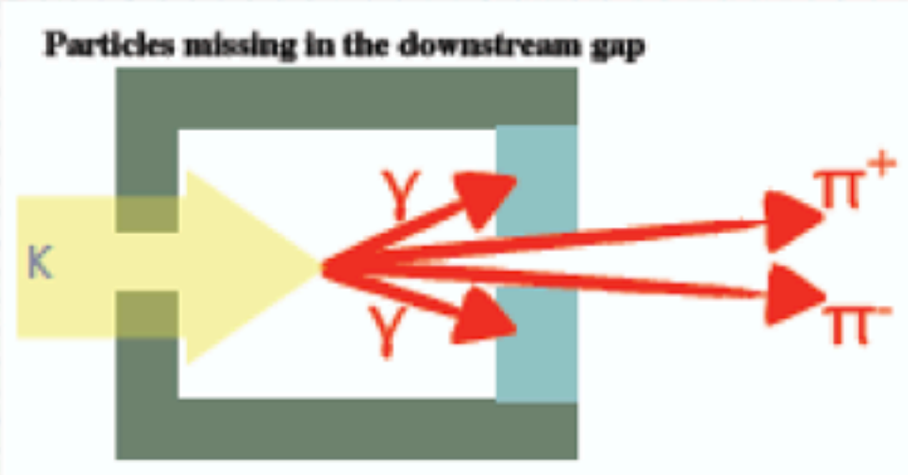




Amp Controller

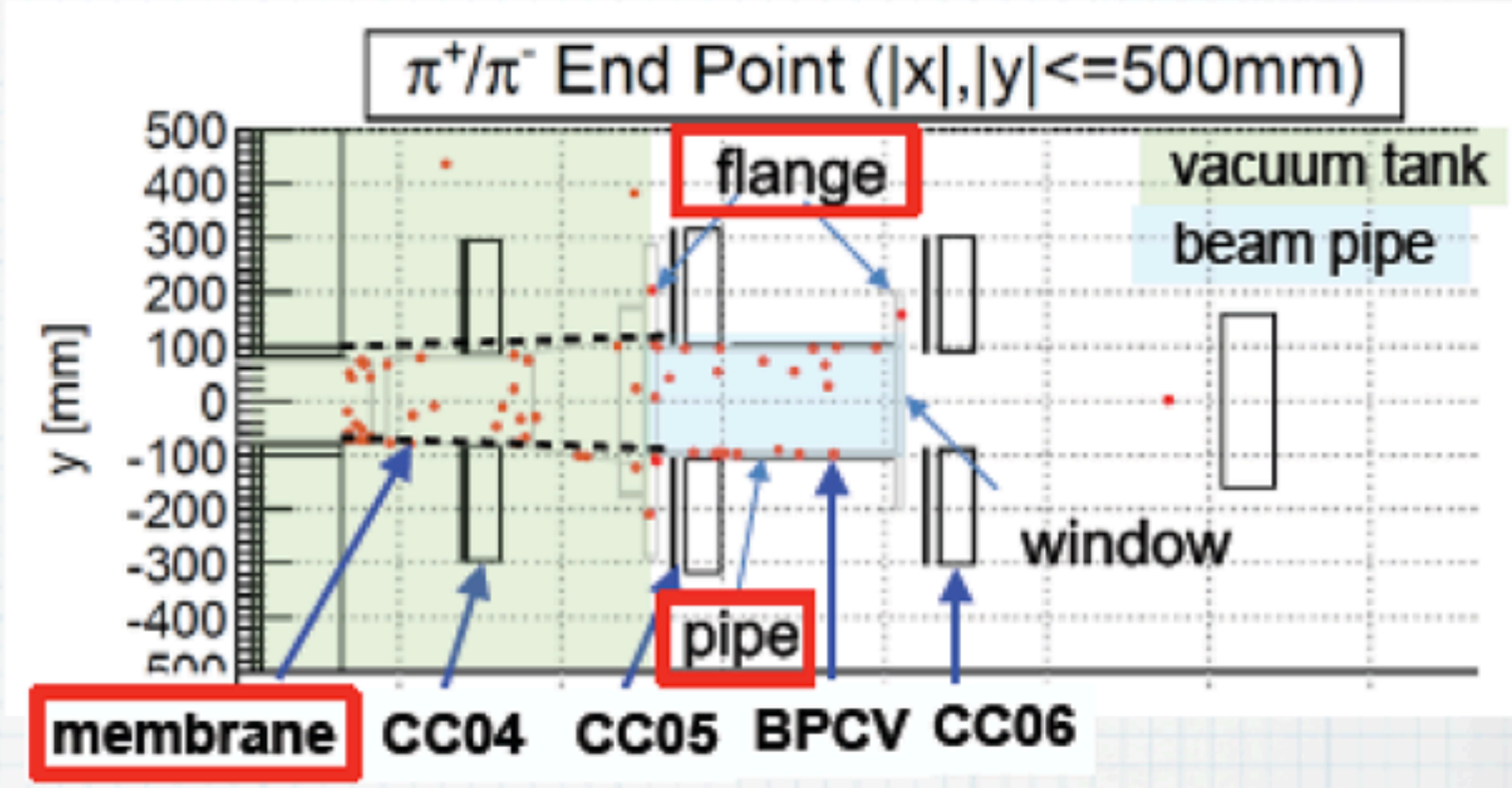
Vacuum

125MHz ADC

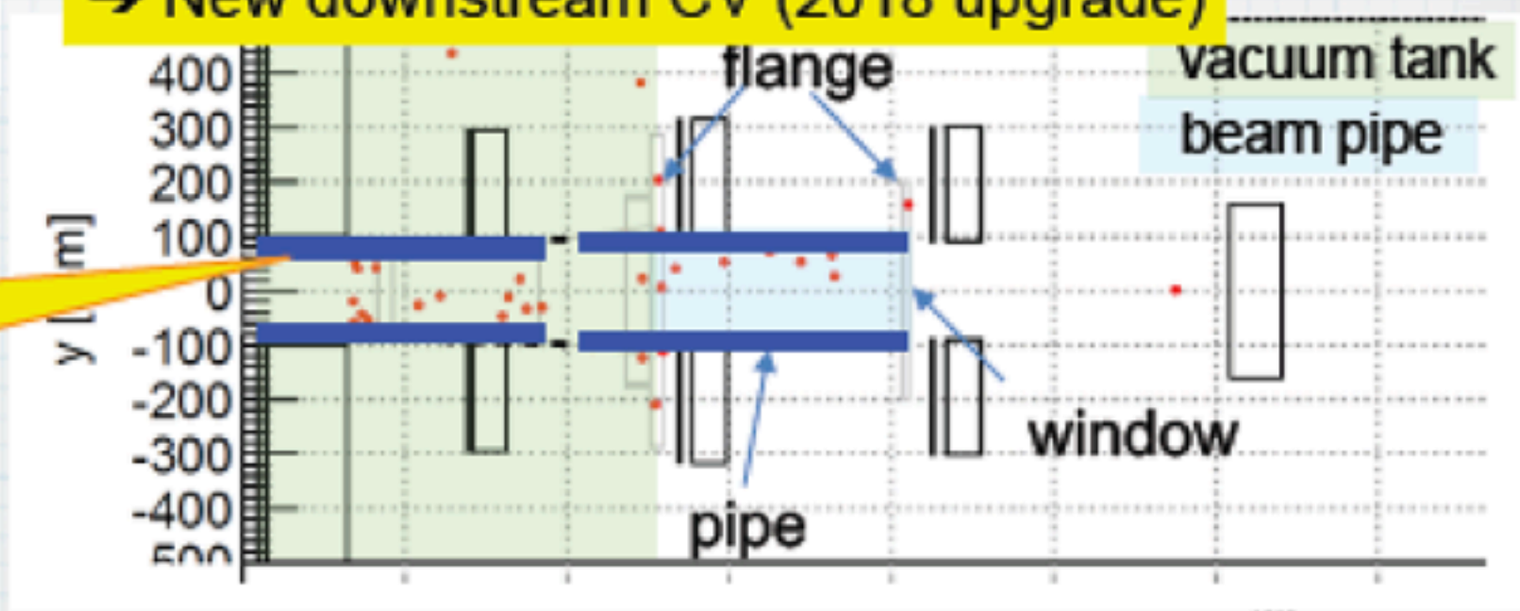
# Remaining $K_L \rightarrow \pi^+\pi^-\pi^0$ in MC




Interaction occurs at
- membrane between low and high vacuum
- G10 support for membrane
- vacuum flanges




➔ New downstream CV (2018 upgrade)




Liner charged veto inside these structures is effective to reduce this background

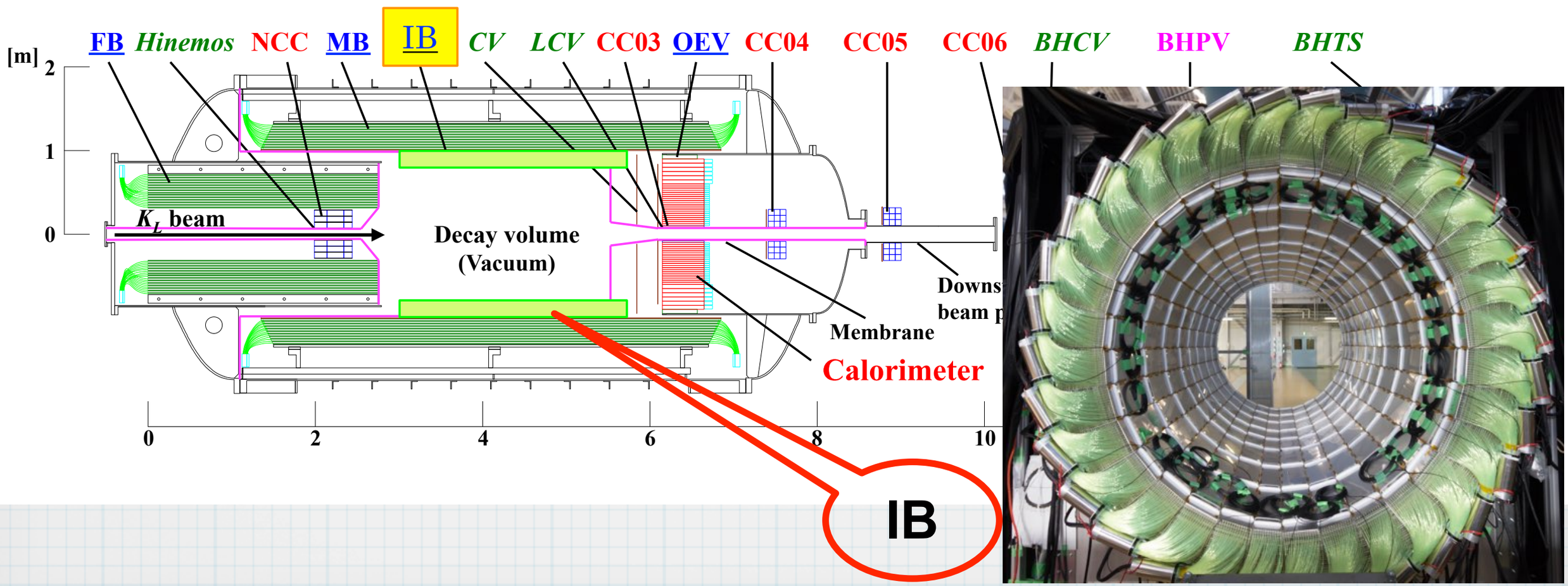
NEXT STEP

# KOTO detector since 2016

* Inner barrel detector (IB) installed

  + several improvements

  - Additional 5 $X_0$ thickness in barrel region
  - fine sampling (sandwich of 1mm lead and 5mm scintillator)



# Improvement against BG

| BG source | #BG 2015 analysis | 2016-2018 data | After 2018 |
|---|---|---|---|
| Halo neutron hitting CSI | 0.24±0.17 | Improve cluster shape discriminant<br>with large amount of neutron samples | Improve cluster shape discriminant<br>Calorimeter upgrade |
| Halo neutron hitting NCC | 0.04±0.03 | Reducing the upstream side of the signal box<br>Consider rejection of neutron cluster by PSLH.<br>Improve cluster shape discriminant | Improve cluster shape discriminant<br>Calorimeter upgrade<br>Neutron detector at downstream* |
| $\eta$ BG | 0.03±0.02 | CSD with deep learning for CV-$\eta$ BG<br>Remove G10 pipe in front of CSI | Neutron detector at downstream*<br>Implement a new Al target in front of CV* |
| KL->$\pi+\pi-\pi0$ | 0.05±0.03 | Use tighter threshold for CC04-CC06<br>(3MeV->1MeV) | install new charged veto counter inside vacuum tank |
| KL->$2\pi0$ | 0.02±0.02 | add additional barrel detector(IB) | add additional barrel detector(IB) |
| Masking KL->3pi0 | 0.01±0.01 | Pulse shape analysis | Pulse shape analysis<br>Install 500MHz FADC for high rate counter like FB |
| Scattered KL->2gamma | 0.01±0.01 | | |

Sentences with asterisk are under discussion.