*2019.09.25 @ J-PARC Symposium 2019*

# Recent Result on the Measurement of $K_L \rightarrow \pi^0 \nu \nu$ at the J-PARC KOTO Experiment

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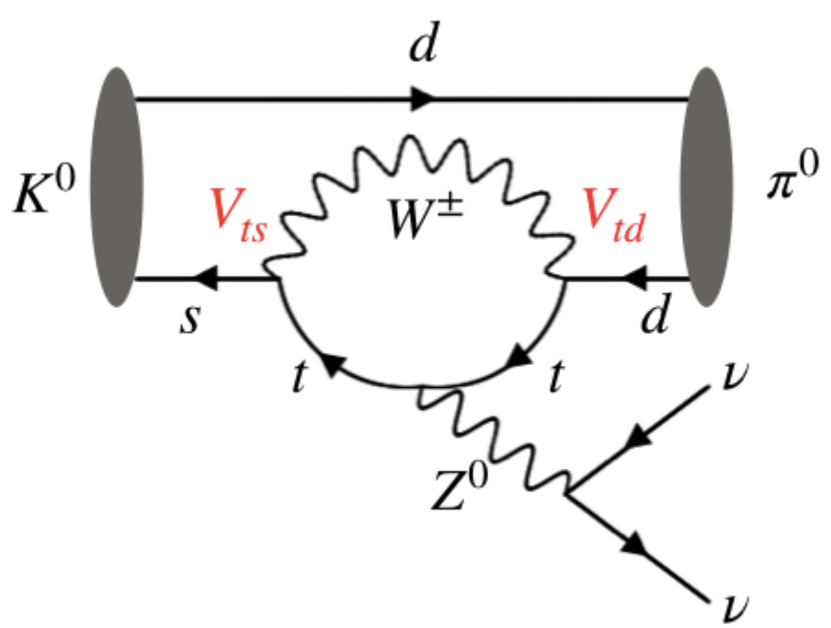
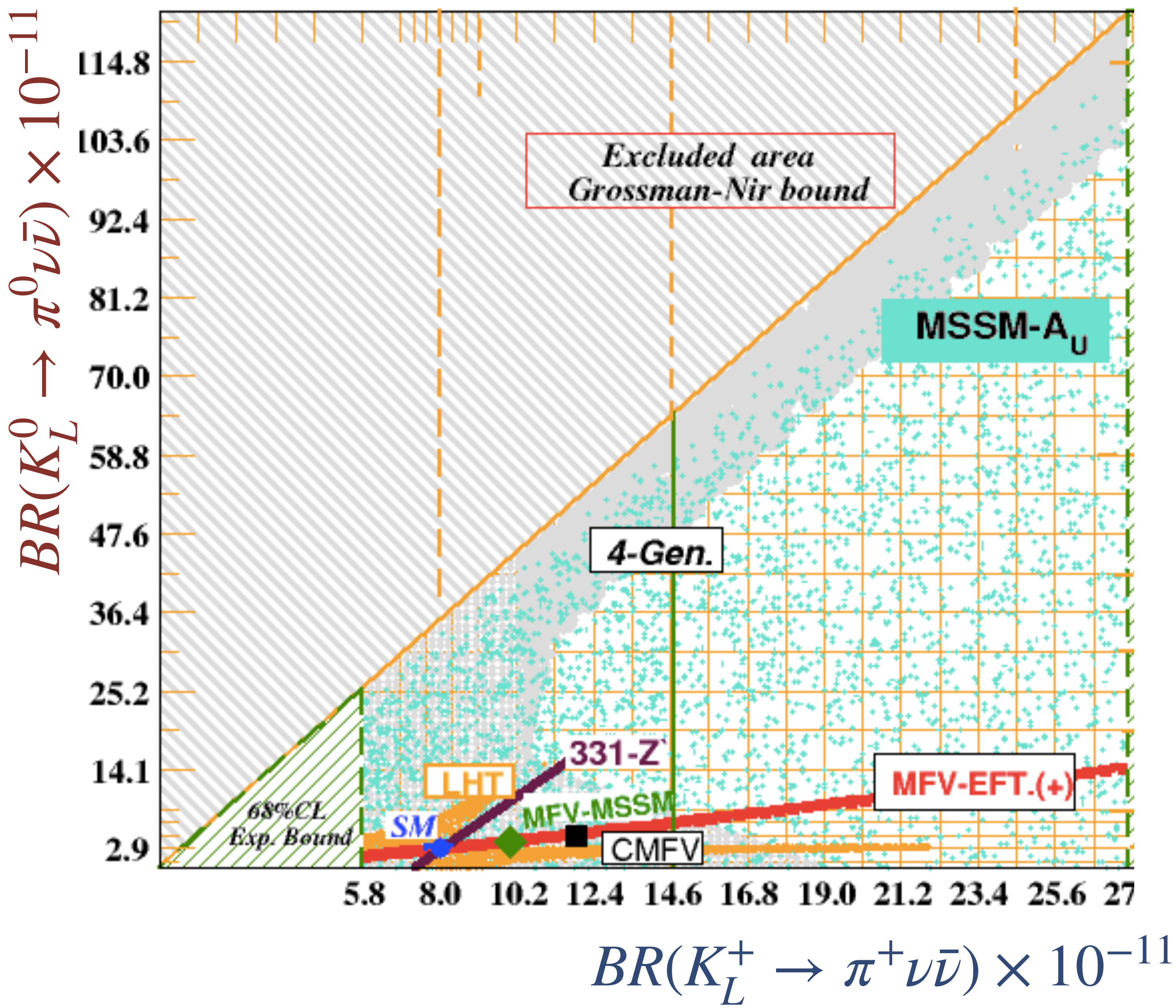
National Taiwan University
(KOTO collaboration)

# Physics in $K_L \to \pi^0 \nu\nu$

- **FCNC + Direct CPV in SM**



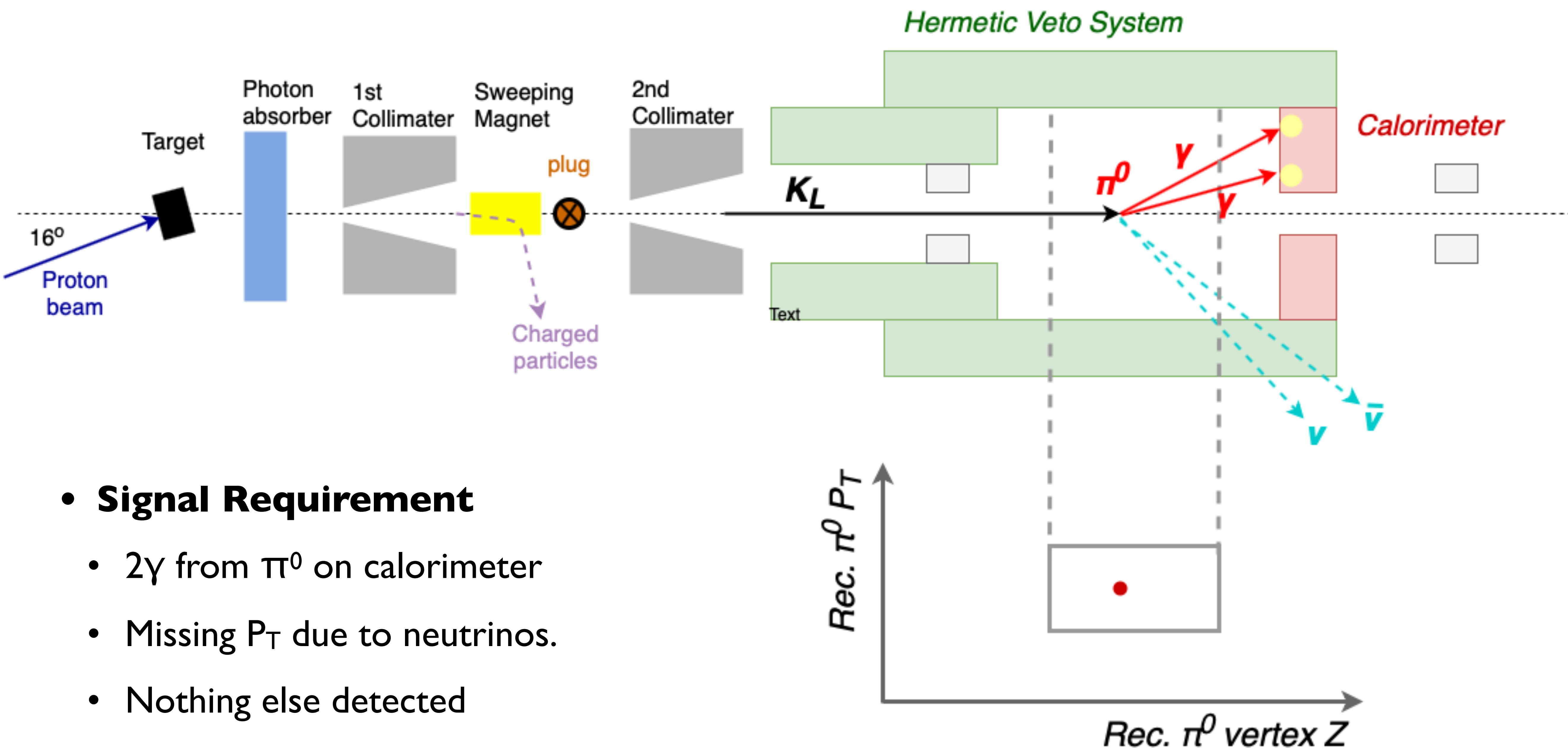




- **Small theoretical uncertainty**

Sensitive to new physics.

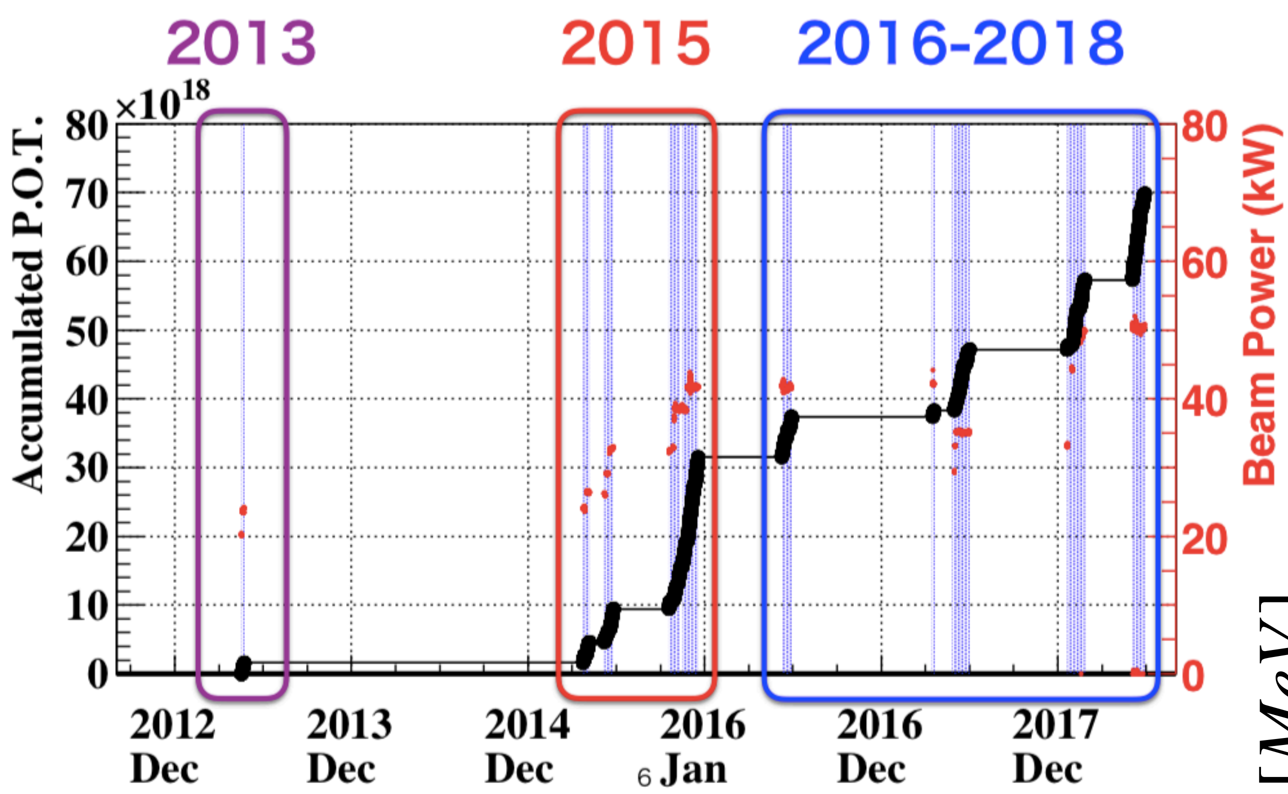
ref: http://www.lnf.infn.it/wg/vus/content/Krare.html

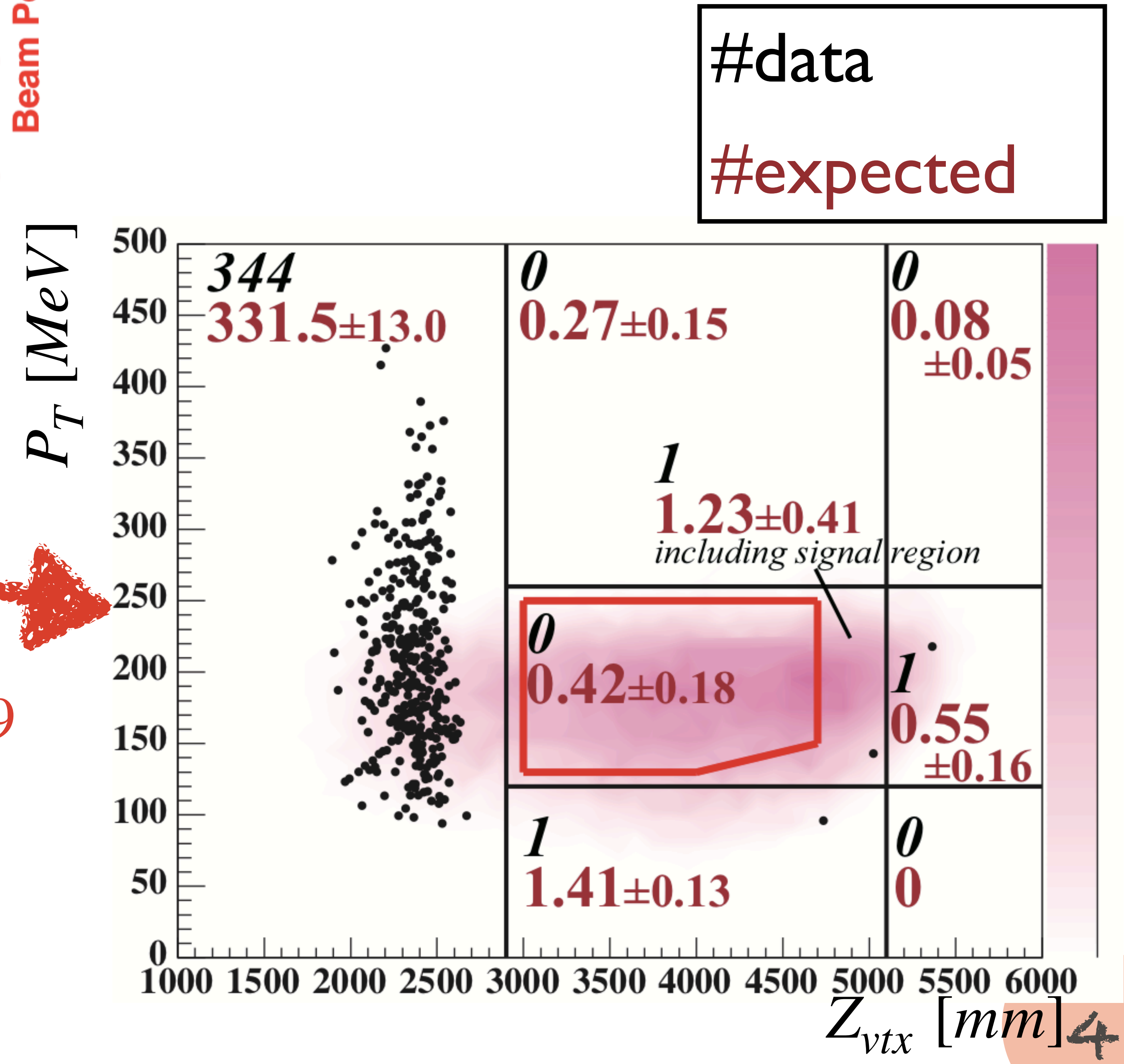
# The KOTO Experiment




- **Signal Requirement**
  - $2\gamma$ from $\pi^0$ on calorimeter
  - Missing $P_T$ due to neutrinos.
  - Nothing else detected
- **Blind Analysis**
  - The distribution in the signal box is inaccessible.

# Result from 2015 Runs




$$BR(K_L^0 \to \pi^0 \nu \bar{\nu}) < 3.0 \times 10^{-9}$$

*(90% C. L.)*

# Probe to Lower Sensitivity

## Single event sensitivity (SES)

$$SES = 1/(N_{K_L} \times A_{sig})$$

Collect more kaons. Enhance the signal acceptance.

## Background Level (BGL)

$$BGL \propto N_{K_L} \times \epsilon_{bg}$$

Suppress BGs more.

# DAQ Upgrades

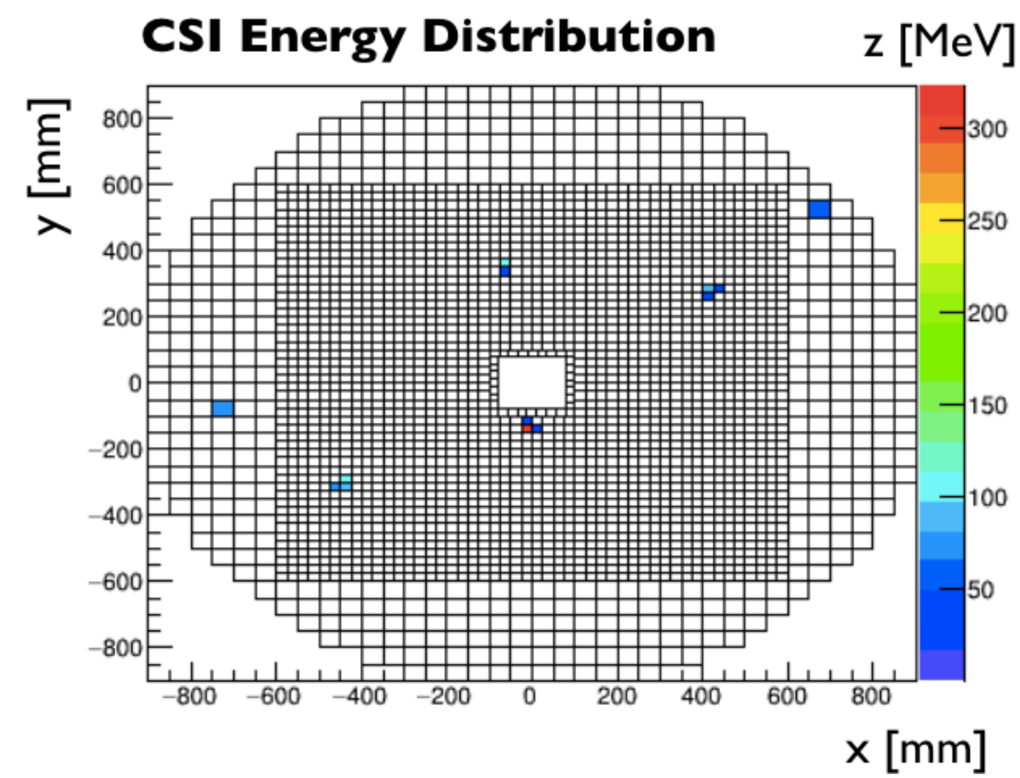
- **New Trigger Based on #cluster**

  Efficiency to collect signal = 99.6%.

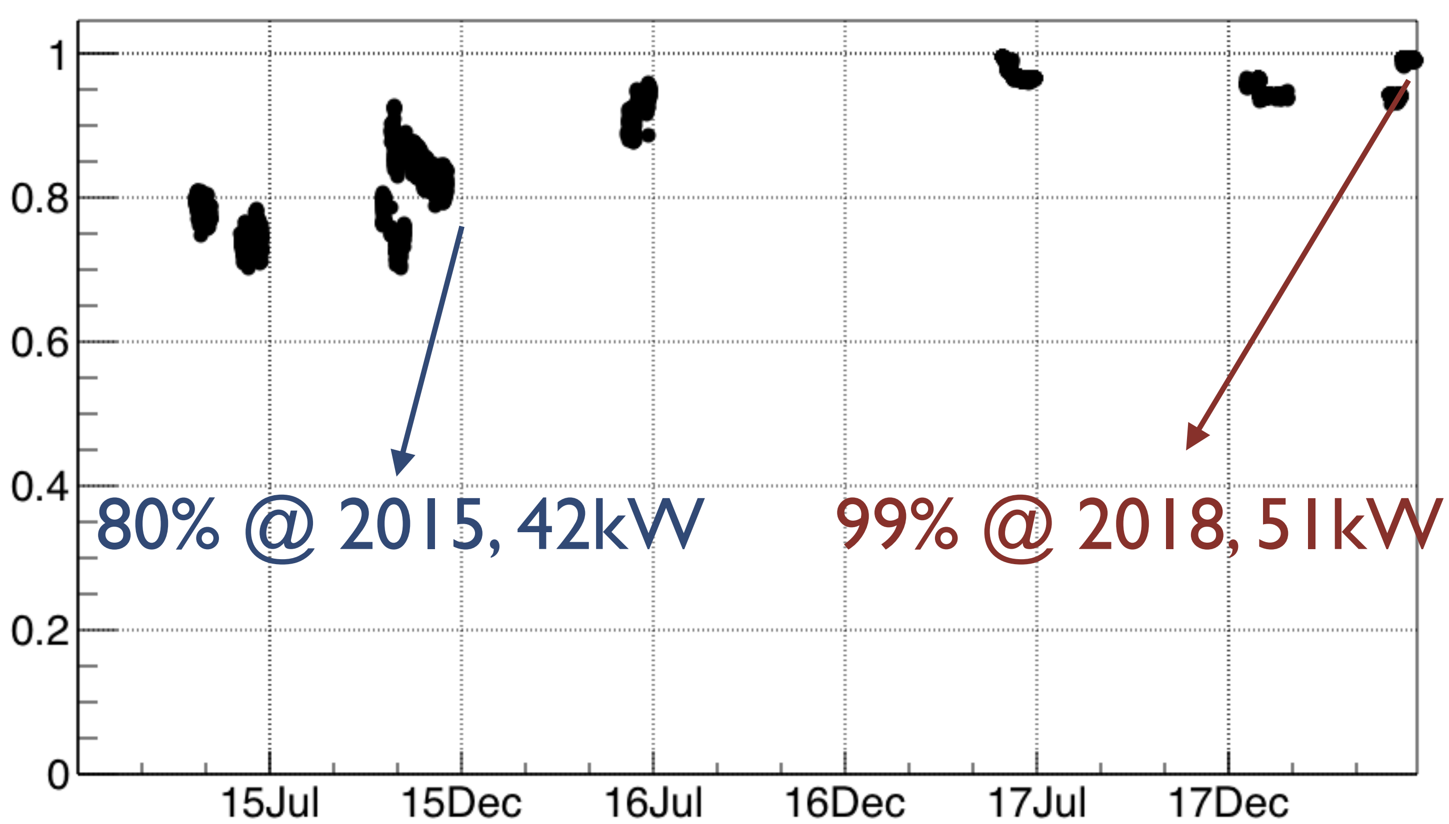
  Neutron BG control sample collection efficiency x 2.

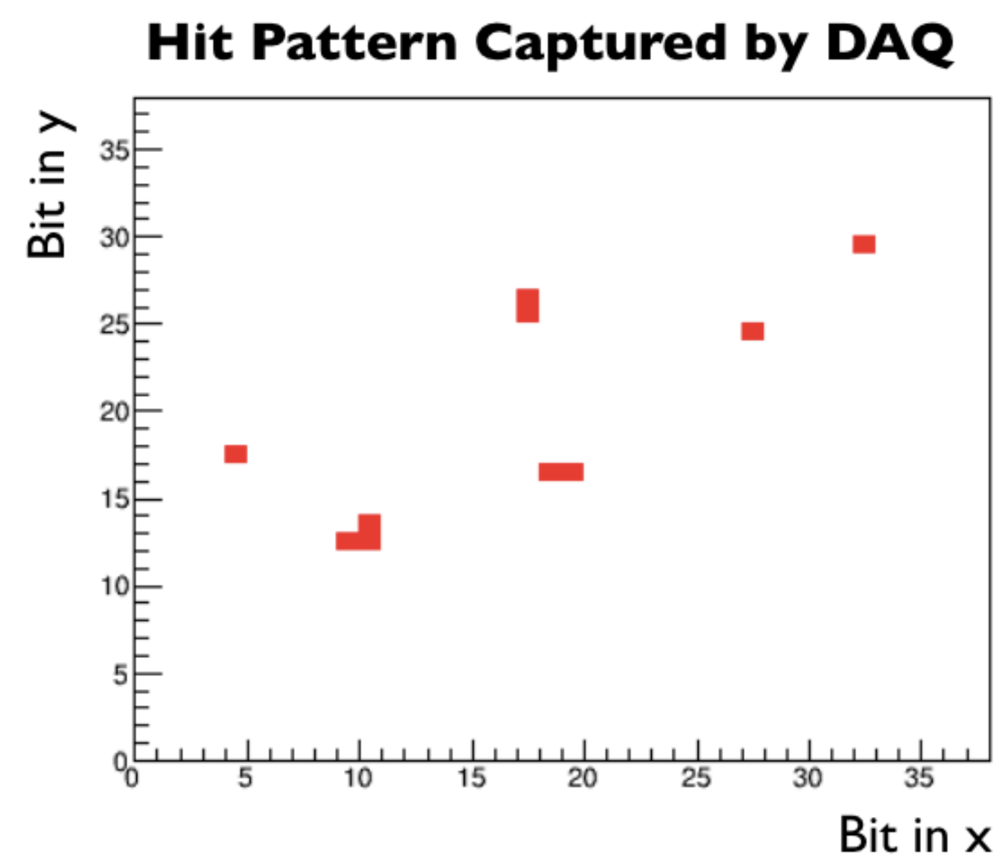
- **High processing speed**

  Loss is reduced from 20% down to 1%.




DAQ Live Ratio

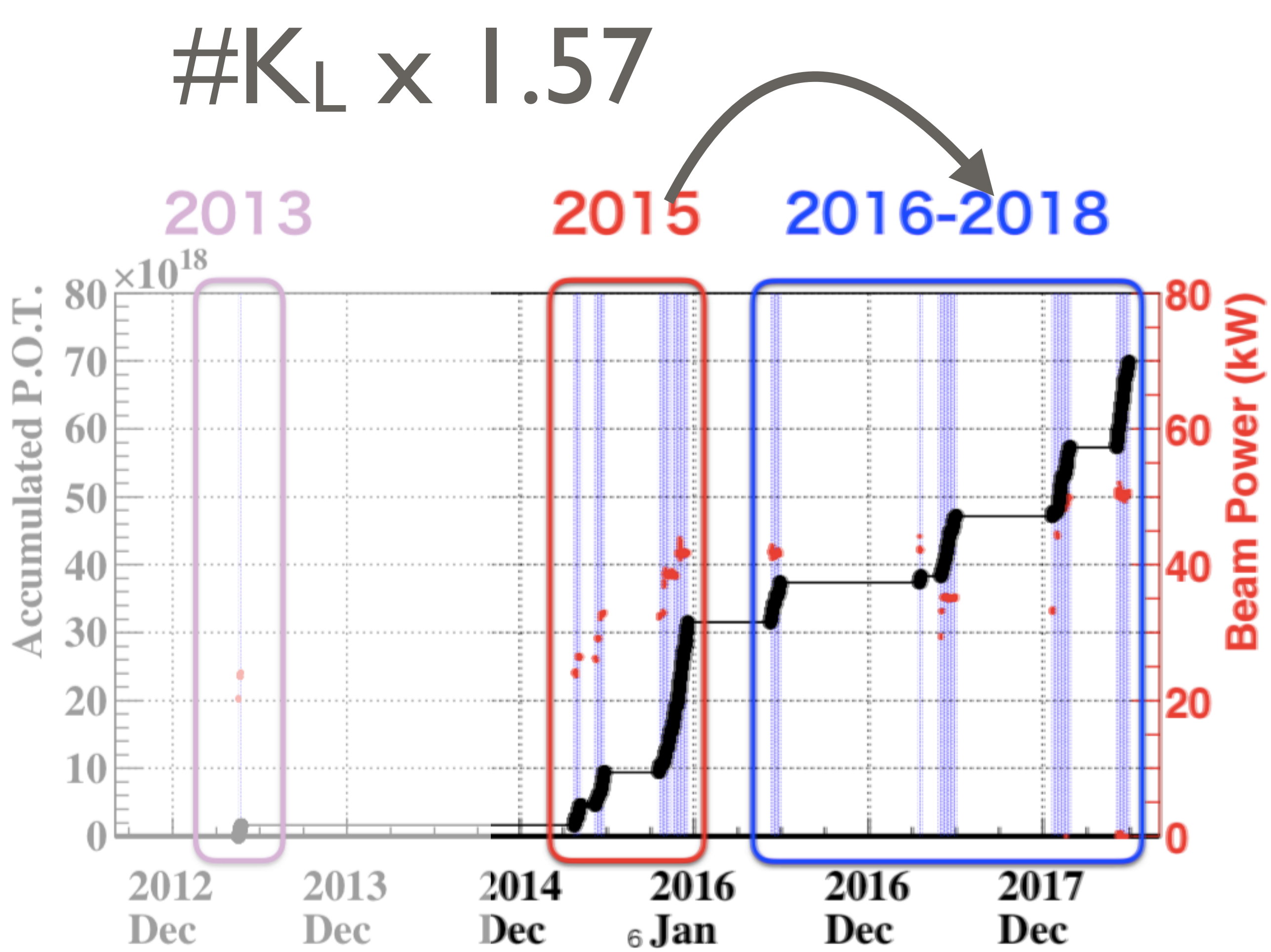


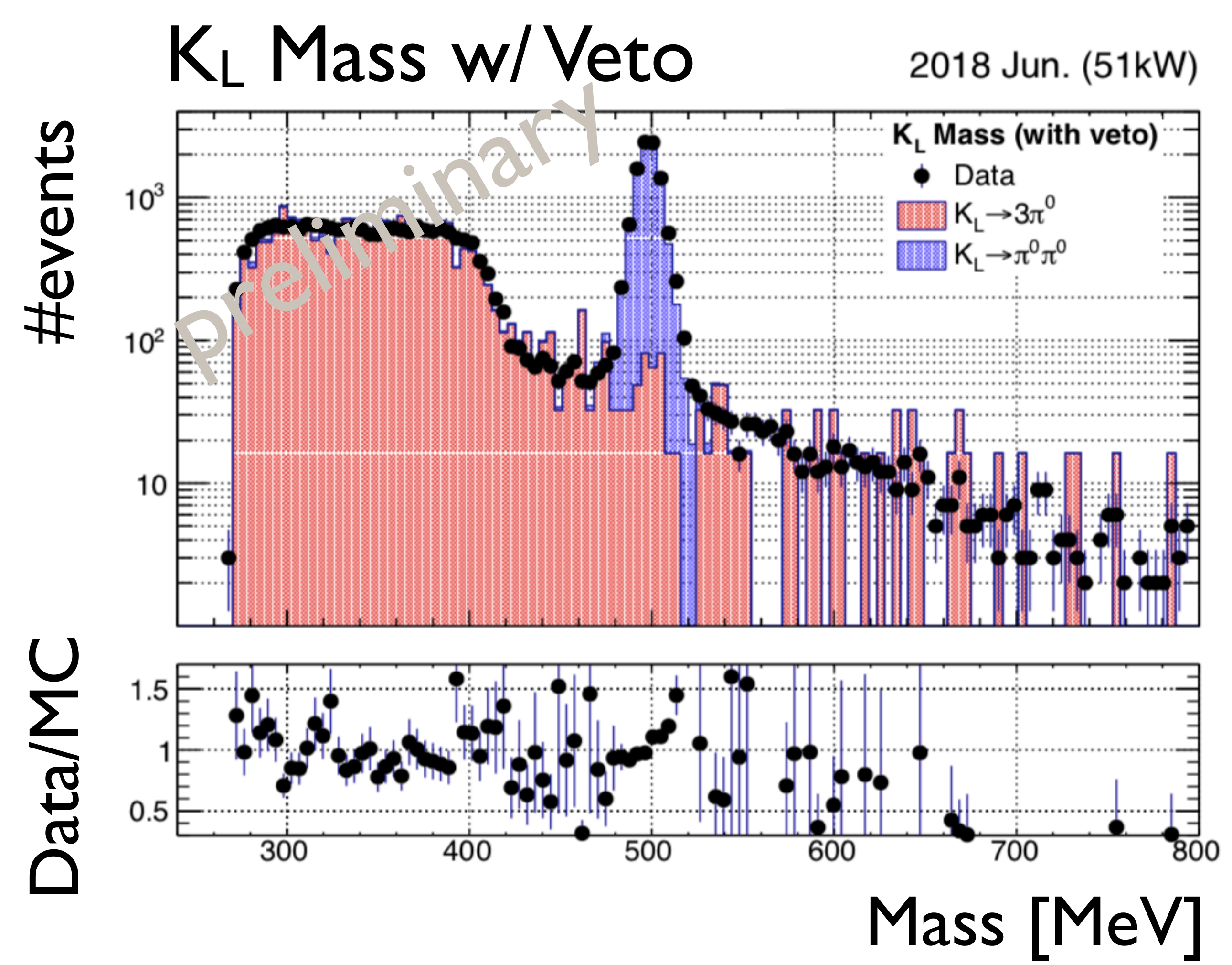



# Number of Kaons

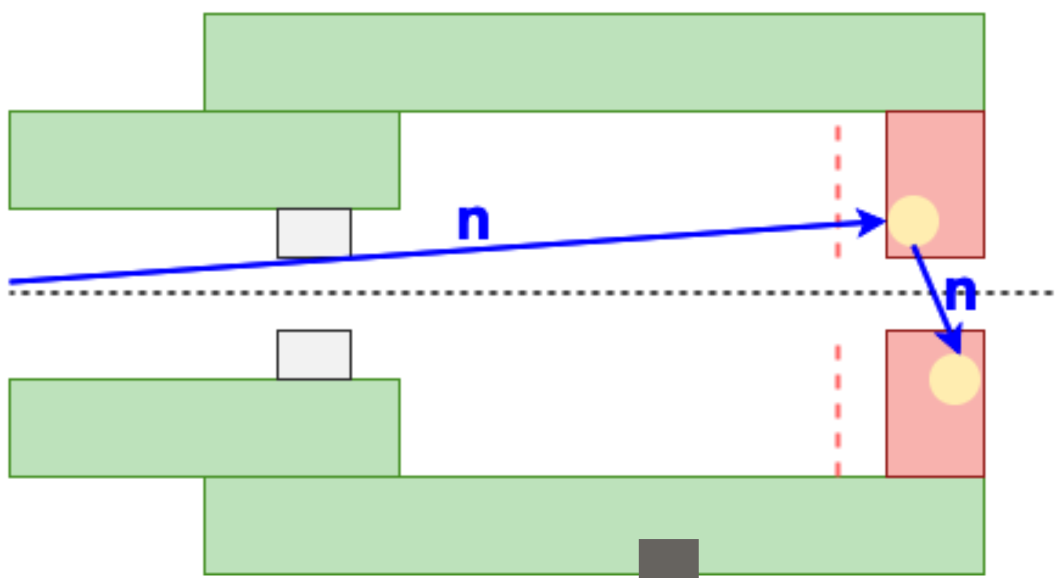
- **Reconstruct $K_L \to 2\pi$ events to extrapolate kaon yield:**

$\#K_L = 7.1 \times 10^{12}$ @ beam exit (preliminary)

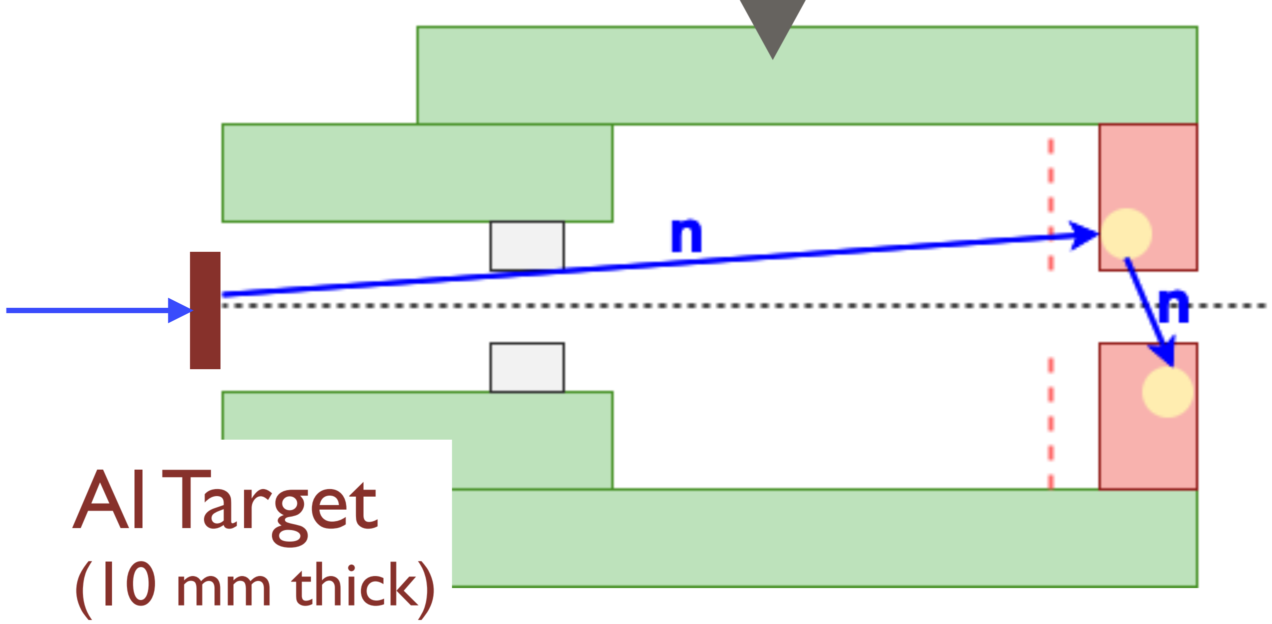


# Neutron-Induced Cluster Backgrounds

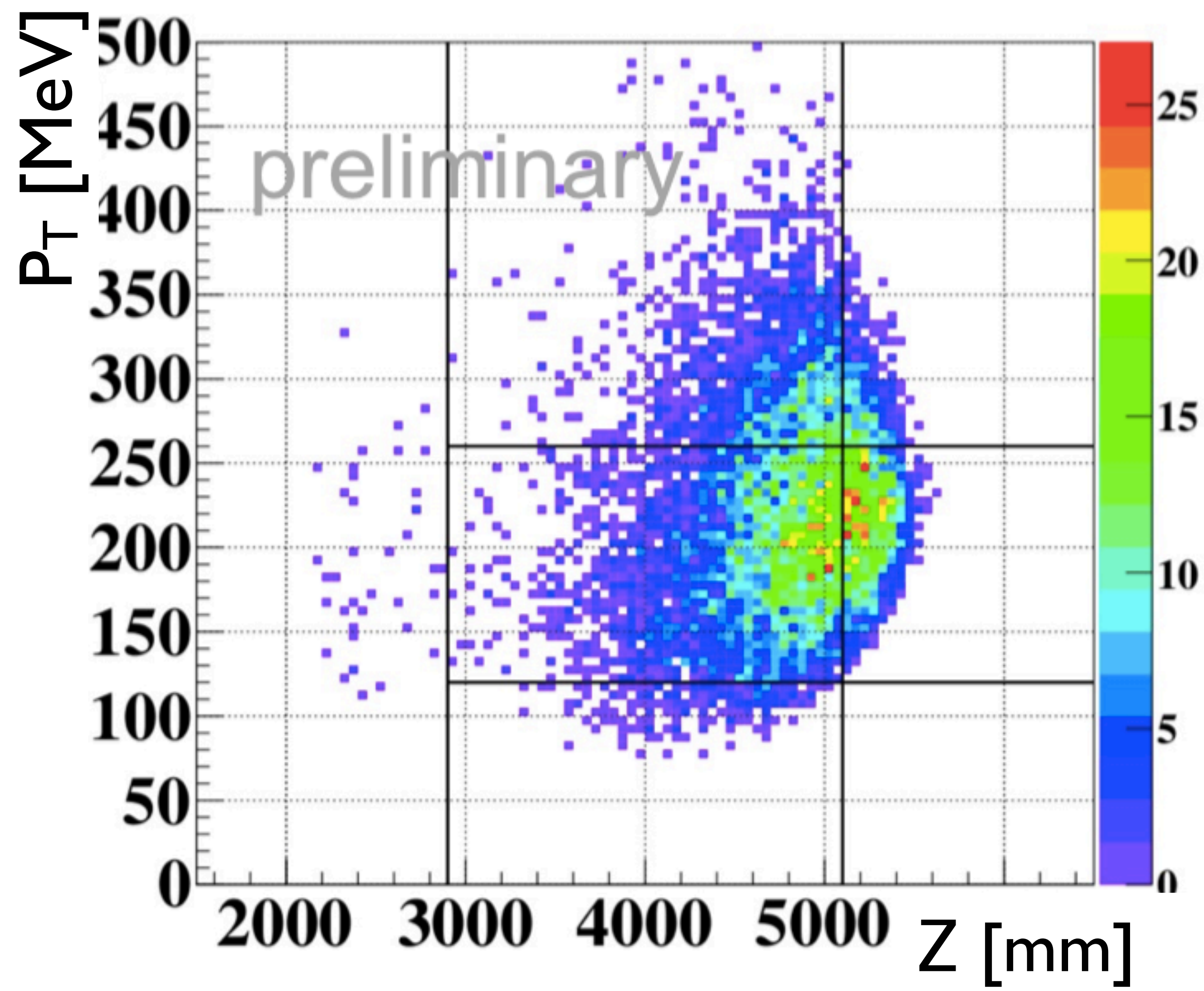



Mimicked by




Neutron Control Samples

(~ x 9 of 2015 runs)

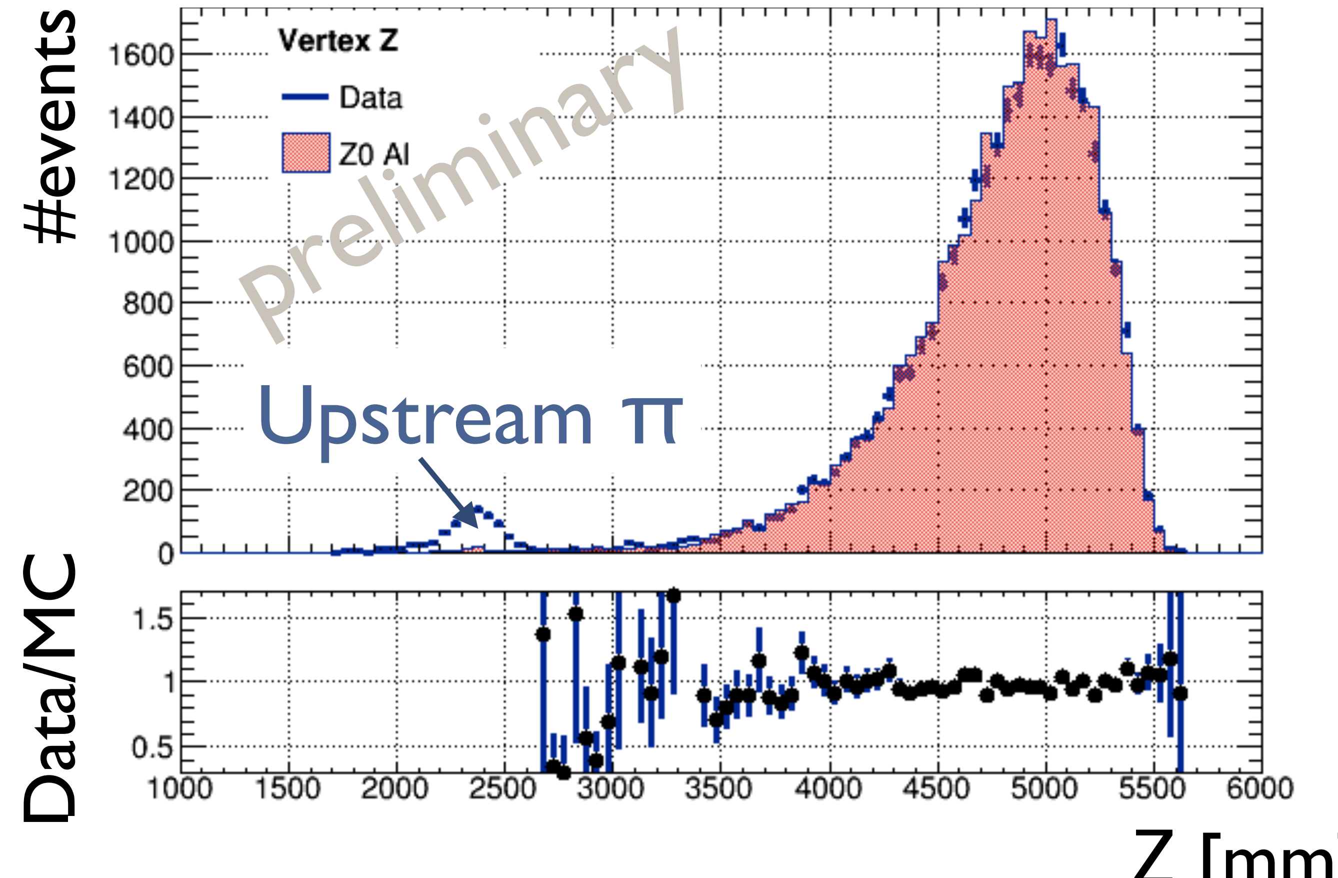


Physics (loose selection criteria)

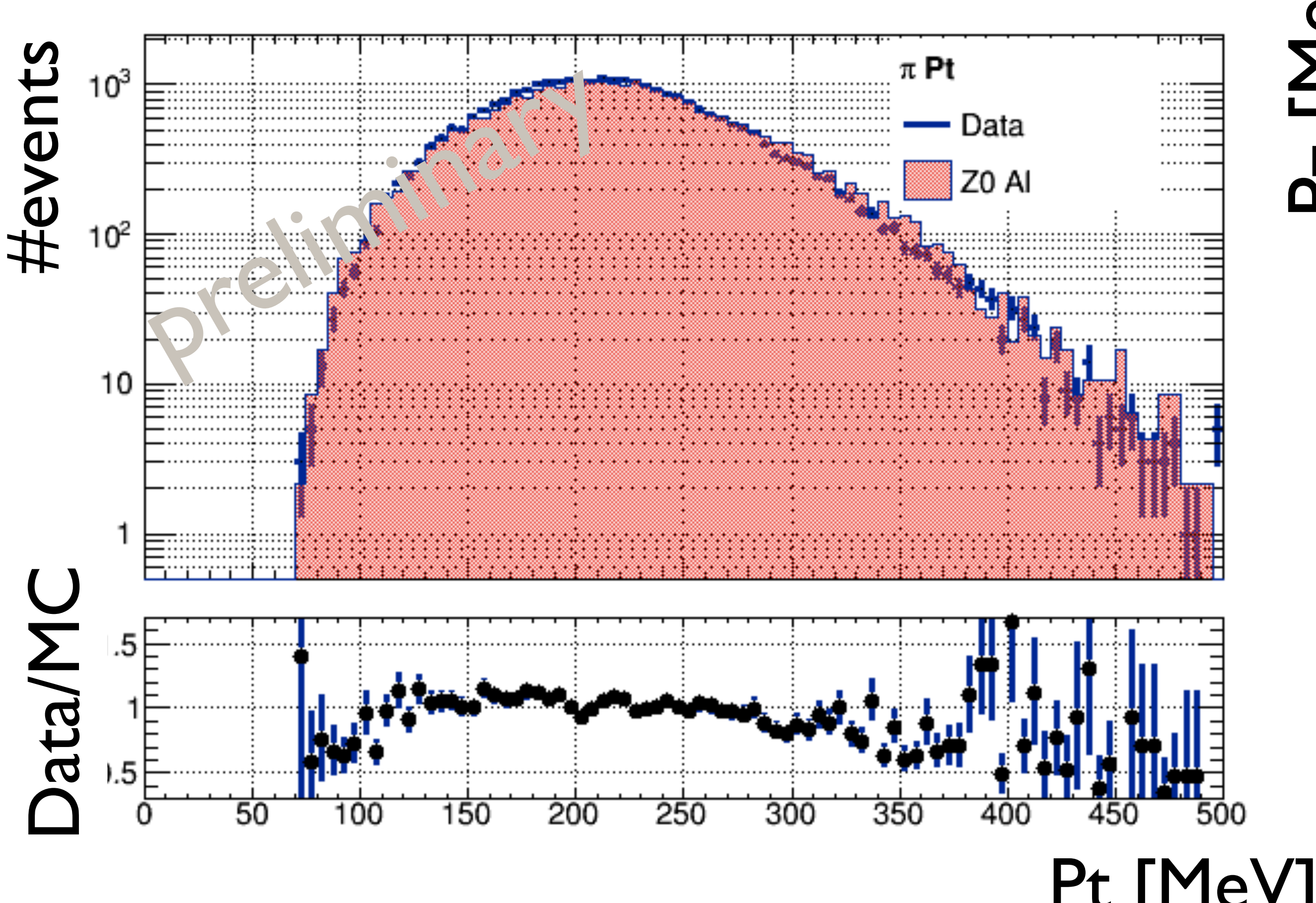
vs.

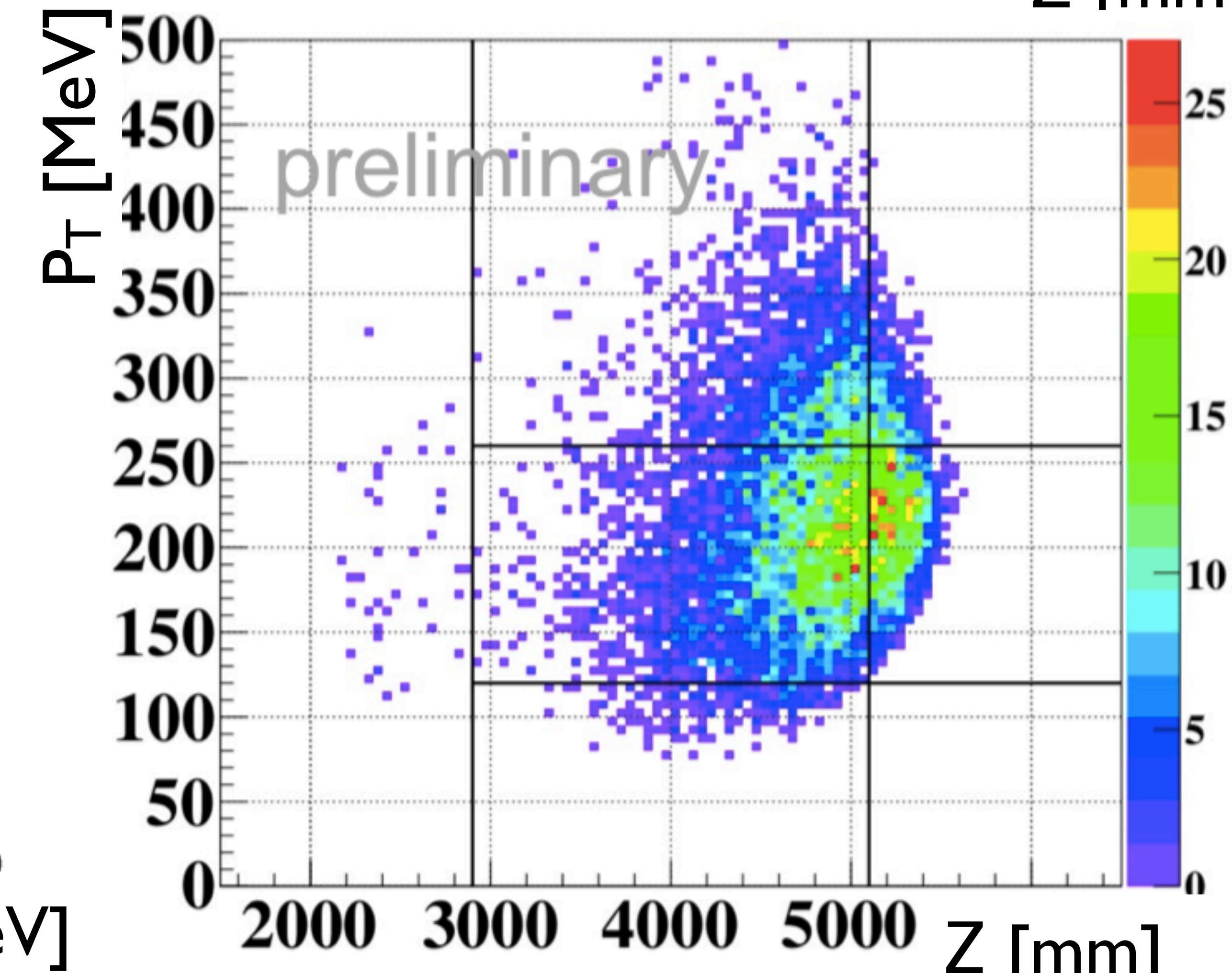
Neutron samples (Al run data)

## Vertex Z

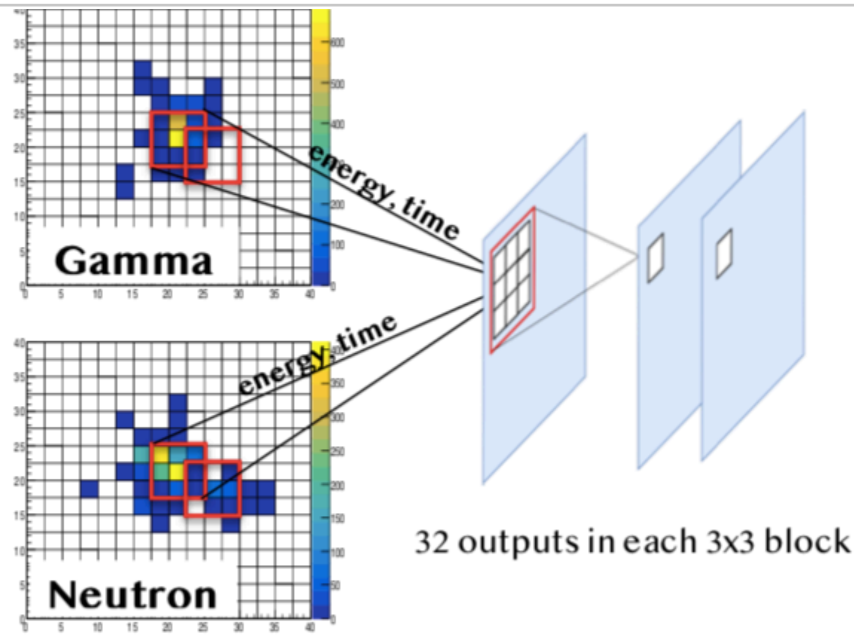



## π Pt



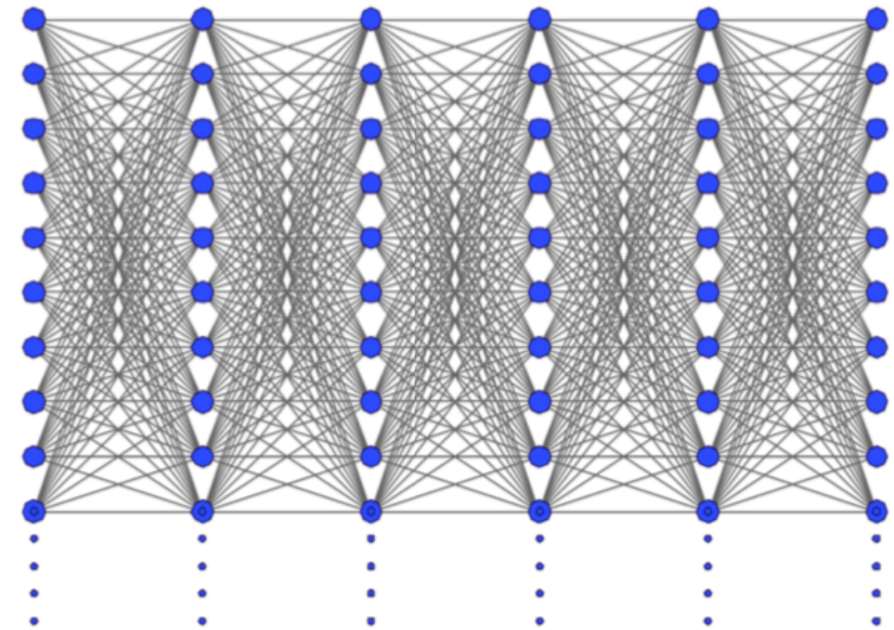



# Cluster Shape Discrimination (CSD)



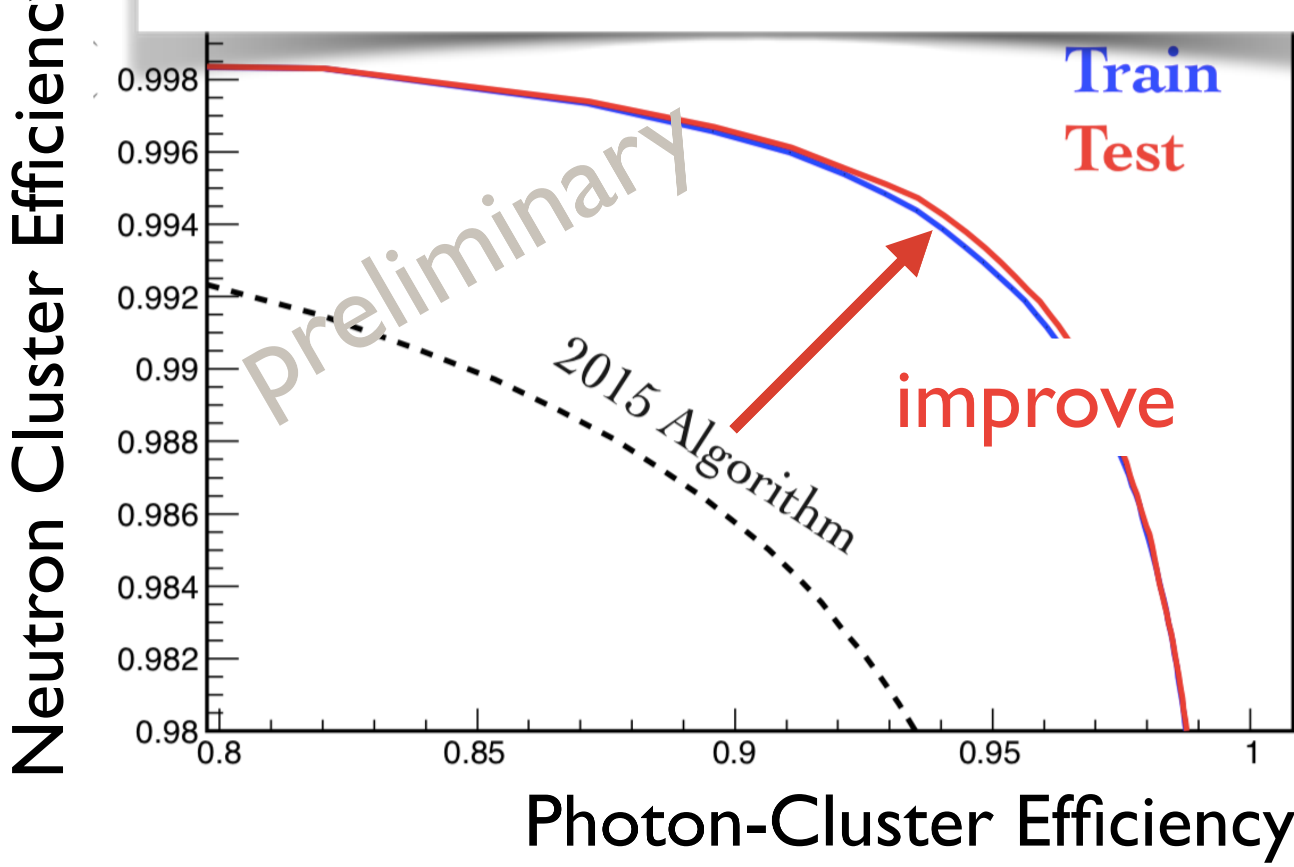

32 outputs in each 3x3 block

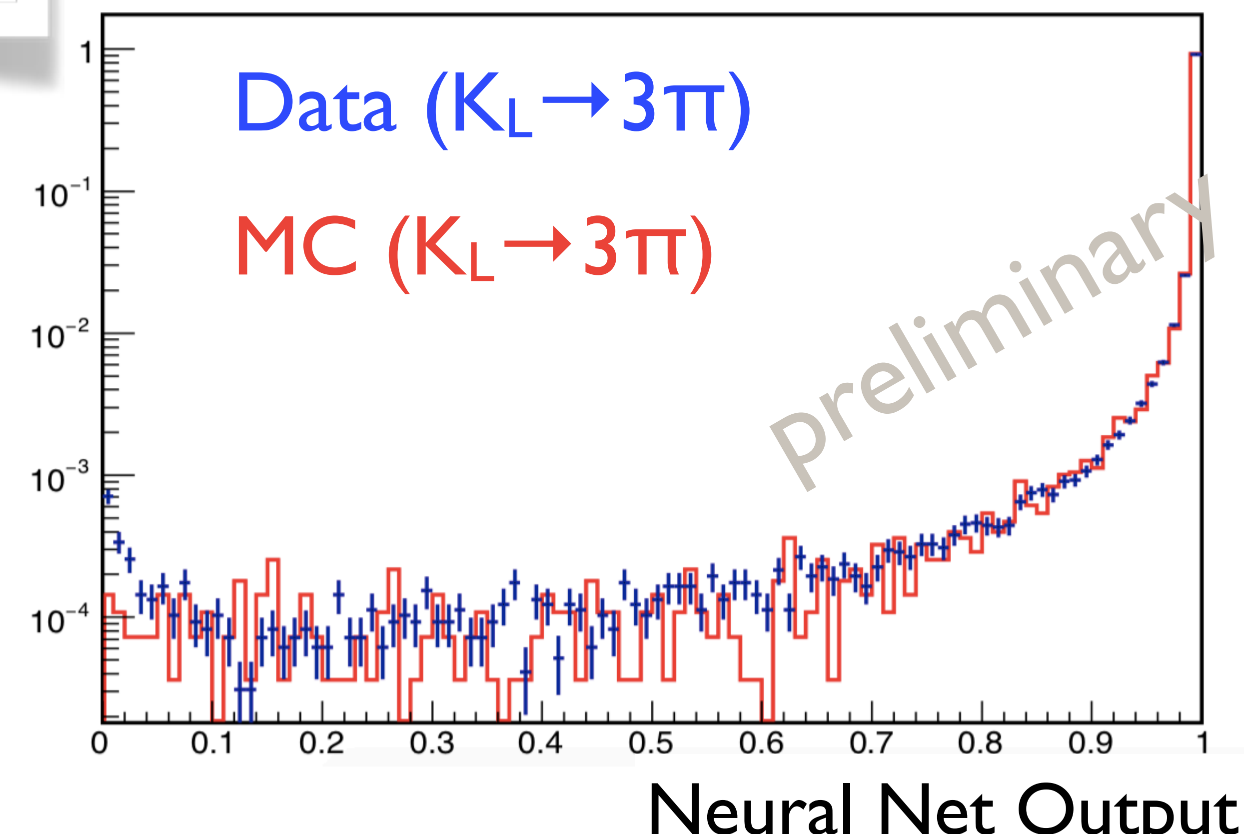
+



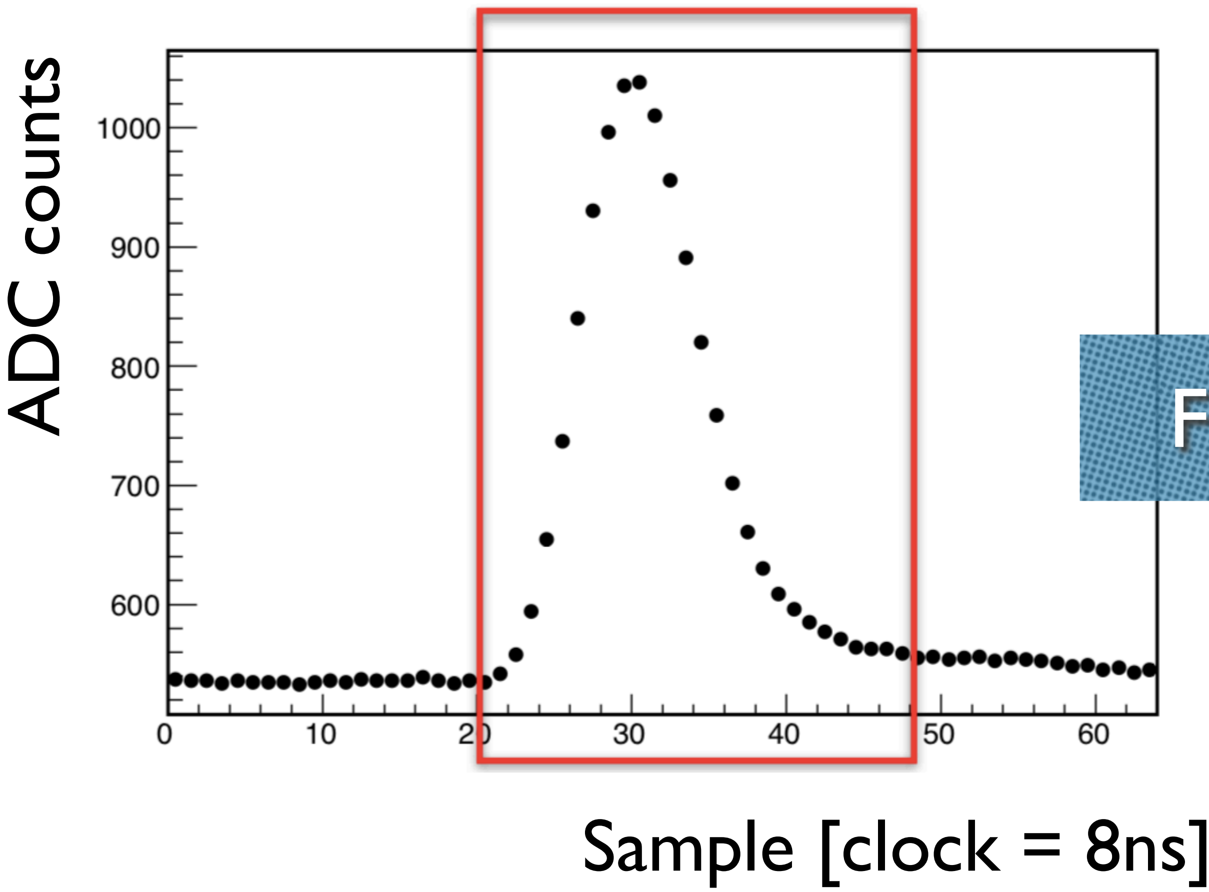
2048 neurons in each layer

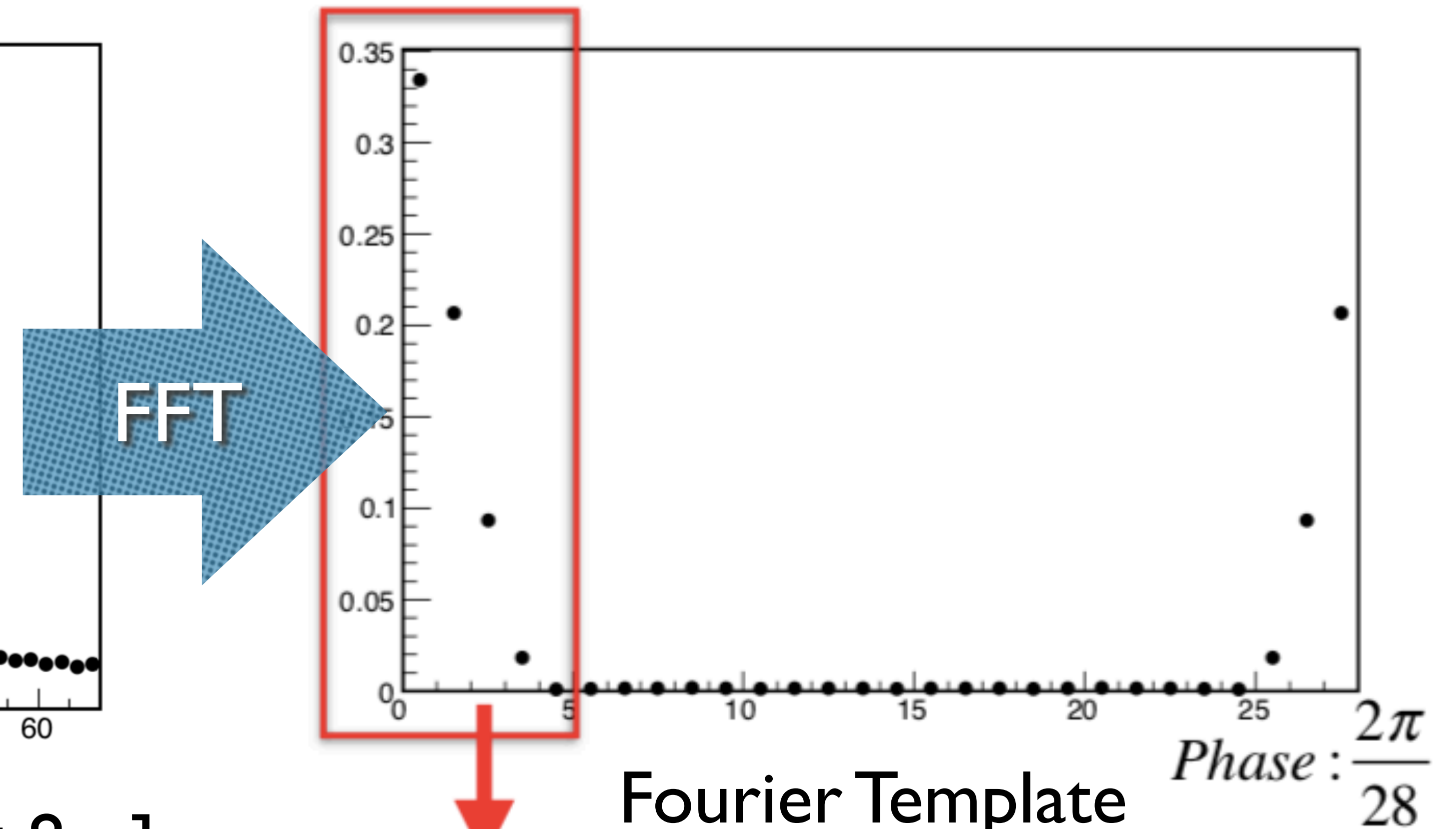
**Neutron Reduction ~ O($10^{-5}$)**

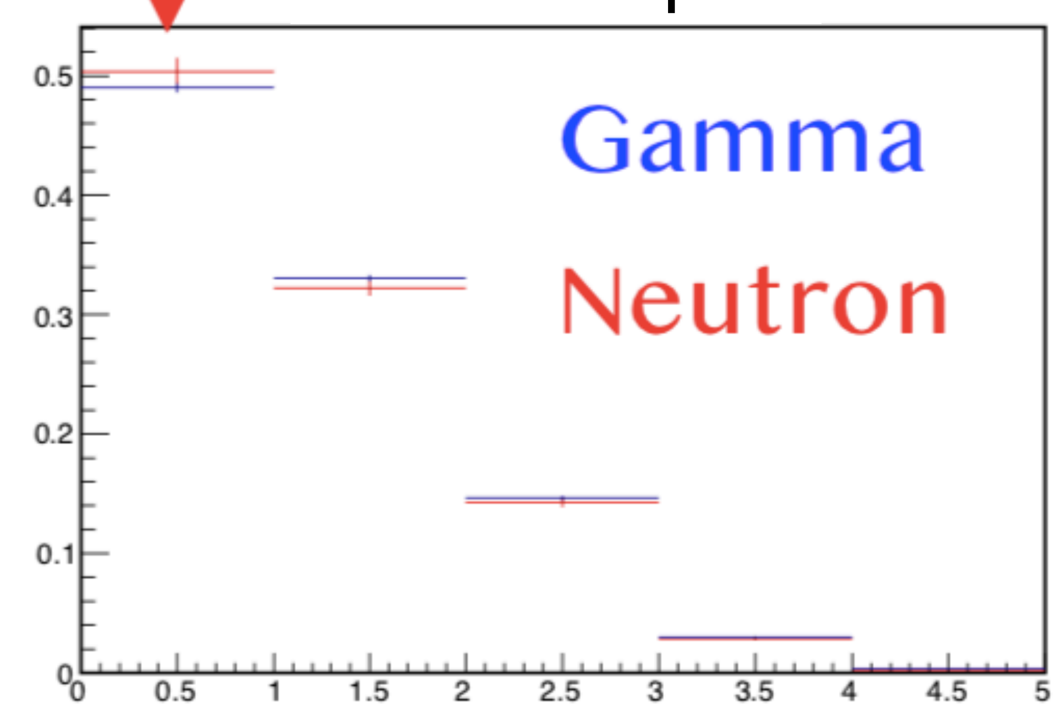


# Pulse Shape Method



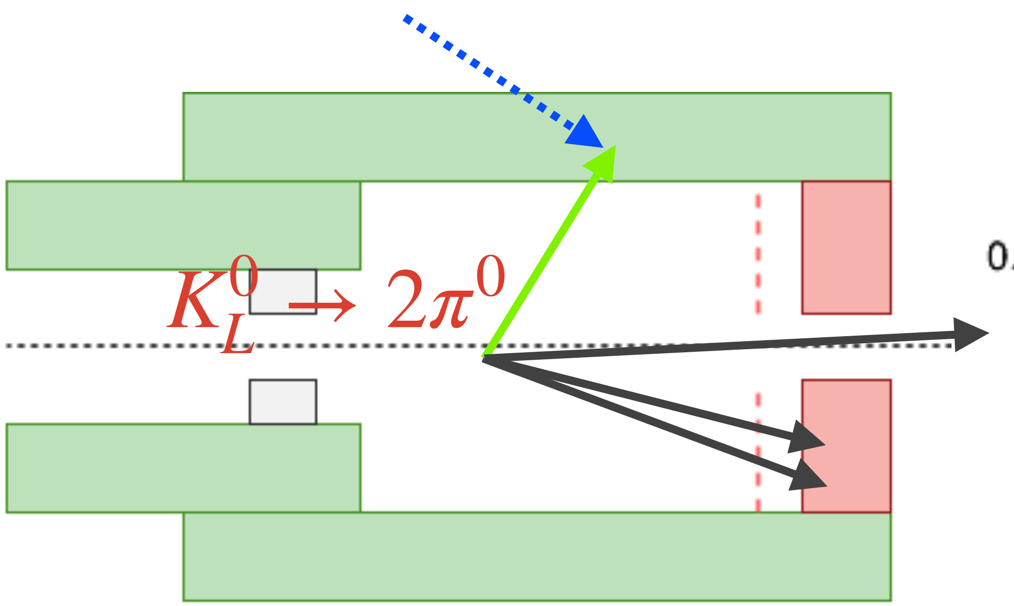



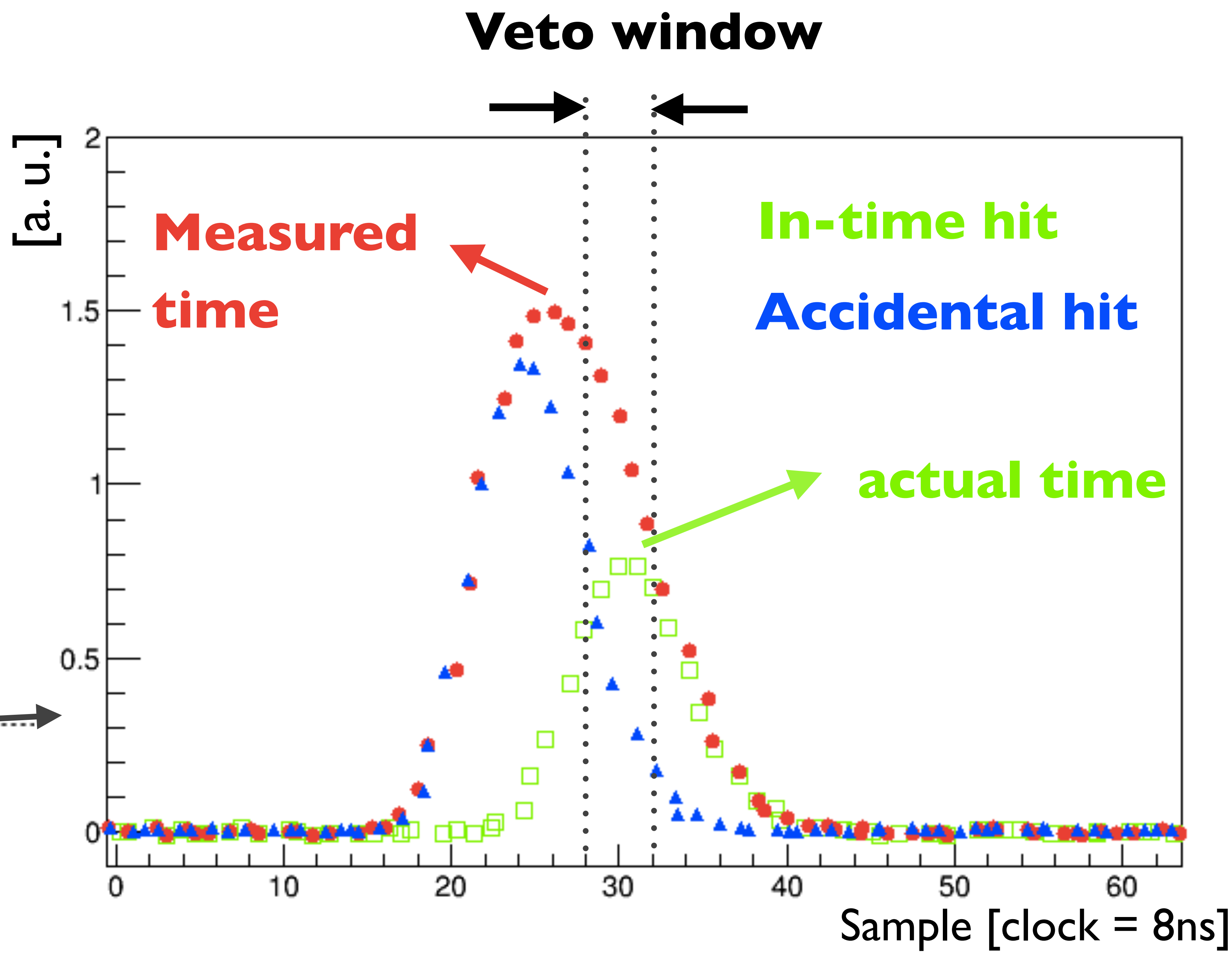




- Neutron pulses tend to be wider.
- Combined reduction with CSD : O($10^{-6}$)
- BGL(hadron cluster) = 0.02 ± 0.00

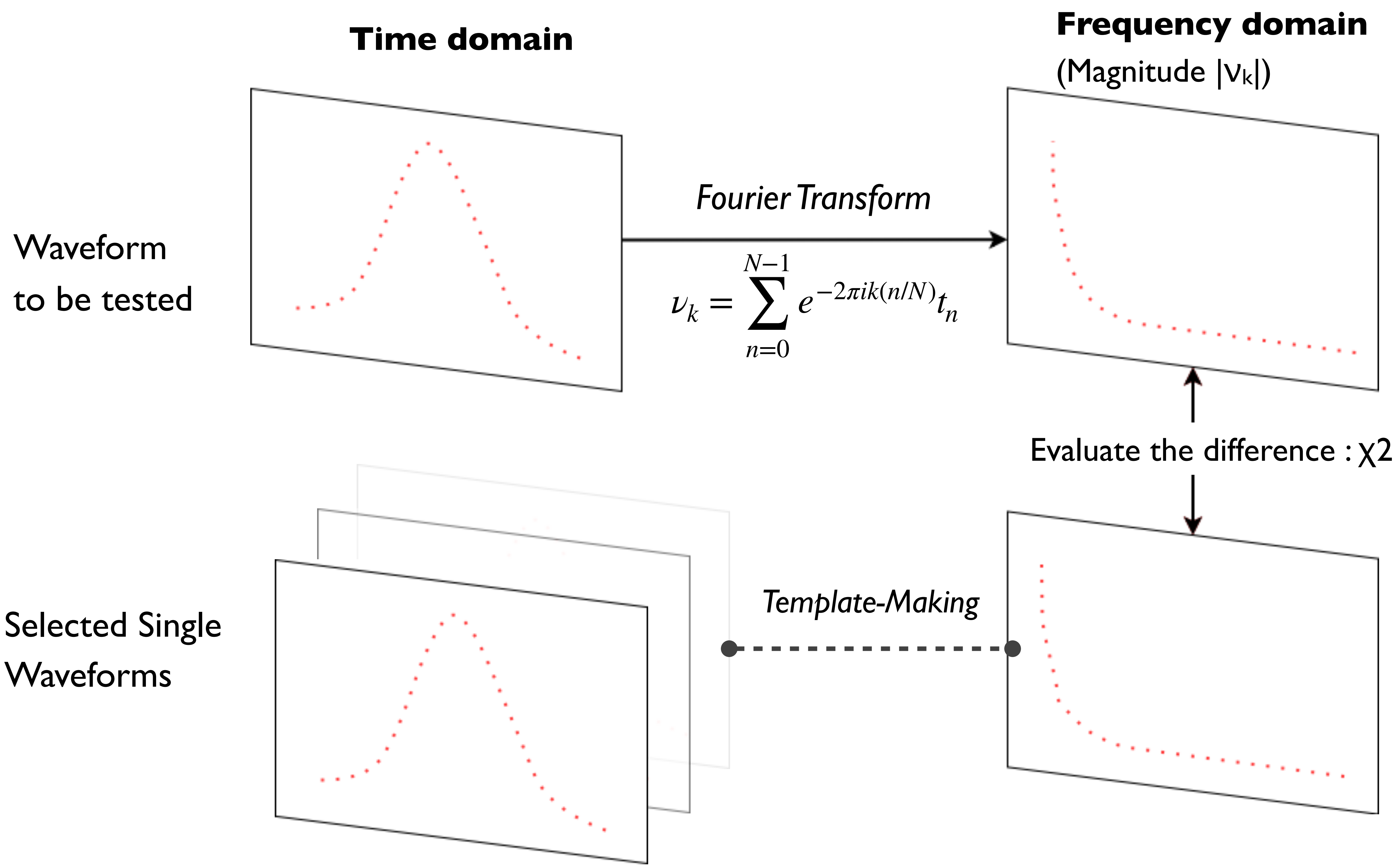
# Overlapped Pulse Background Mechanism

- Accidental hit deviates the timing and thus weakens the veto power.



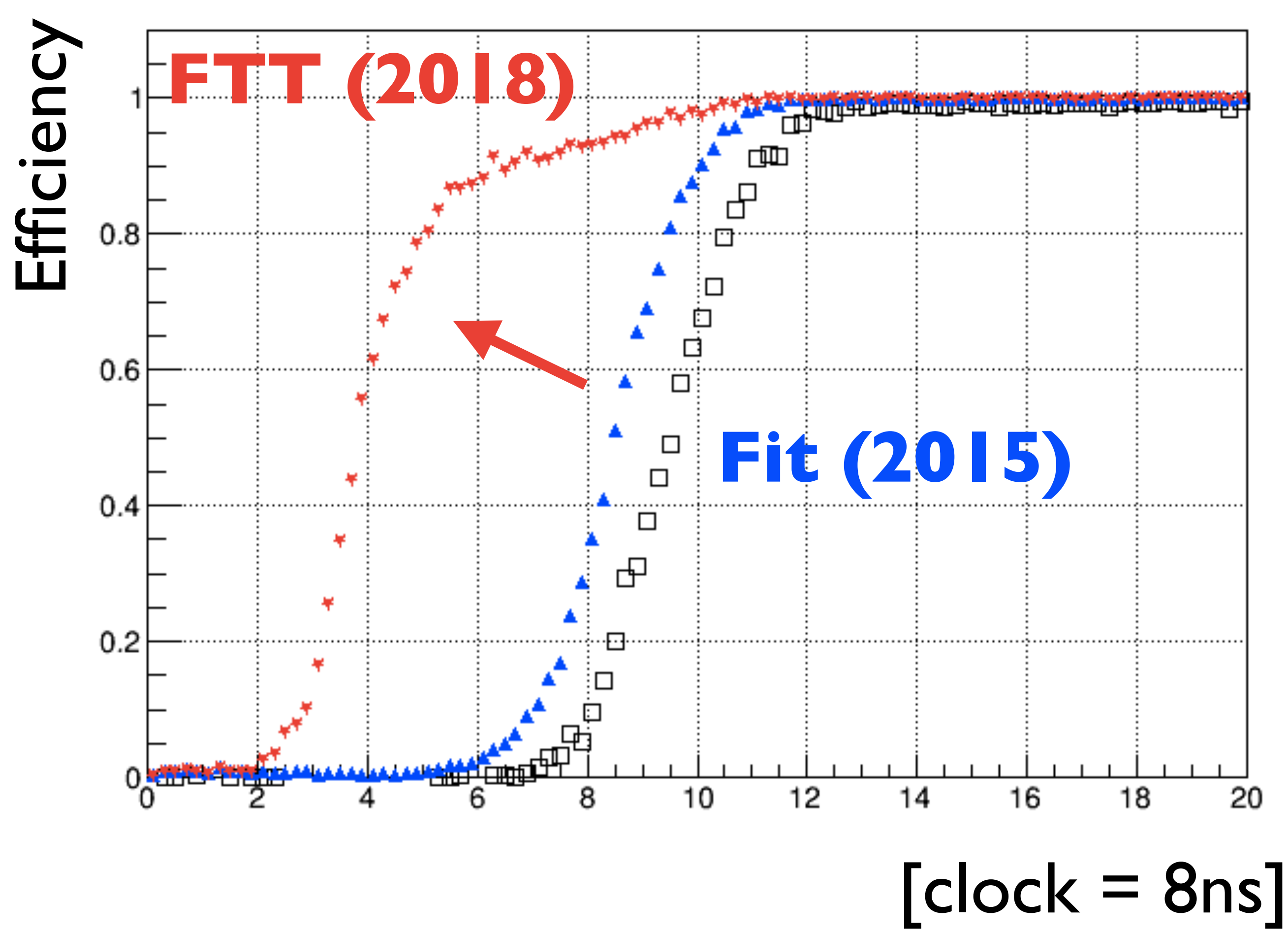
# Fourier Transform Template (FTT) Method

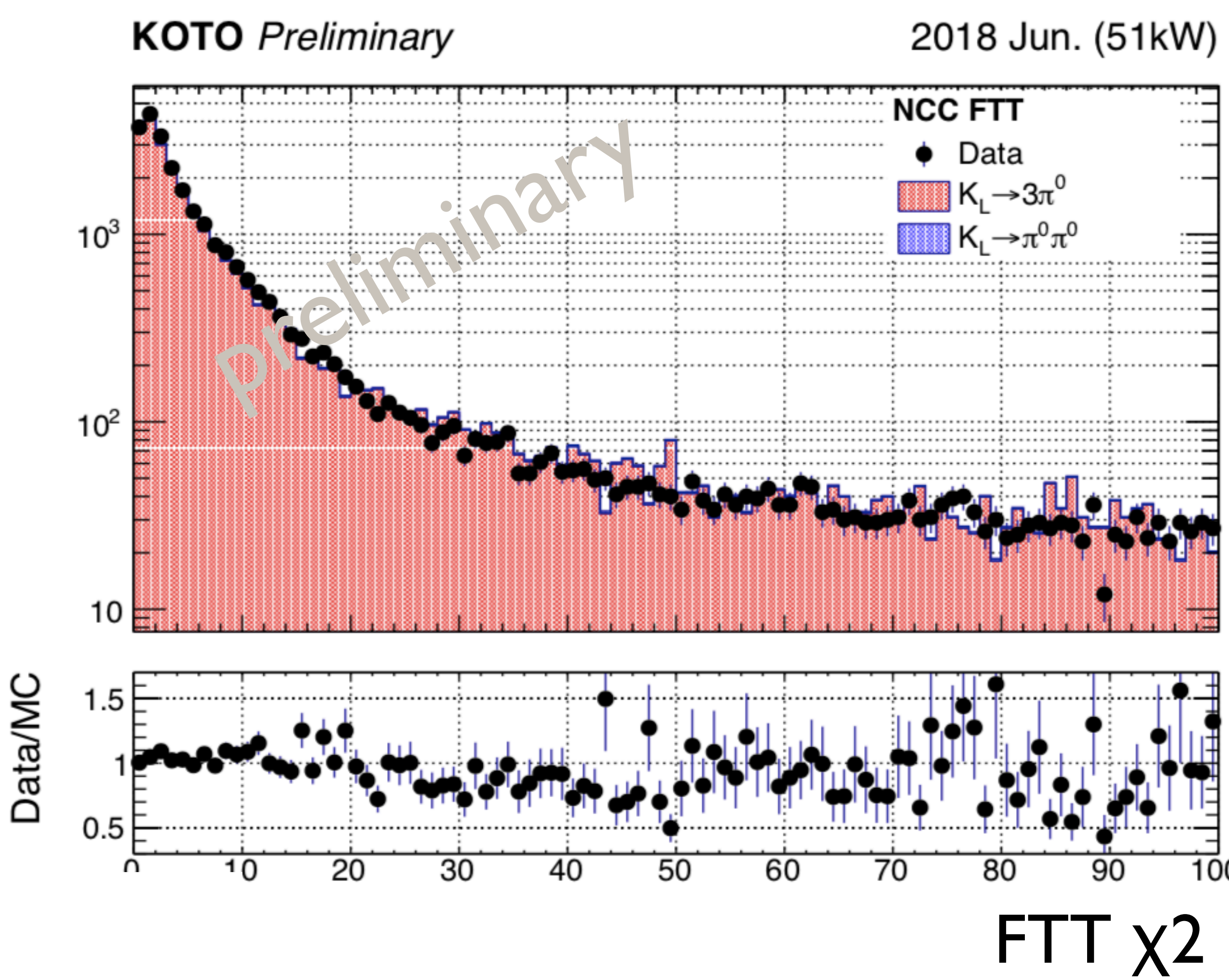


# Suppression of Overlapped Pulse Background

- Strategy:
  - Large FTT χ2 : Wide window.
  - Small FTT χ2 : Narrow window.
- 10% acceptance recovery with the negligible BGL.

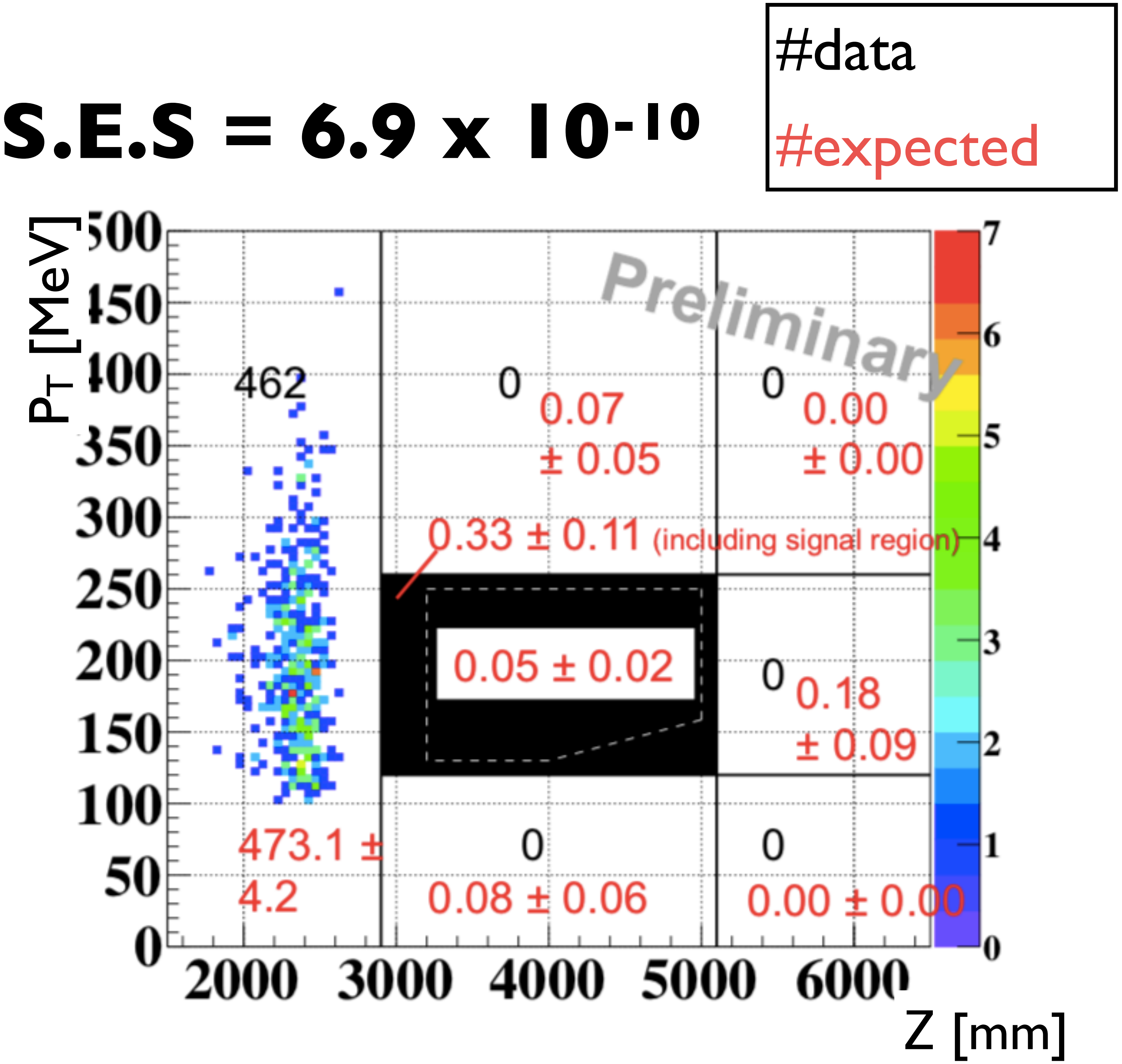
Overlapped Pulse Discrimination



# Final Estimation

**S.E.S = 6.9 x $10^{-10}$**

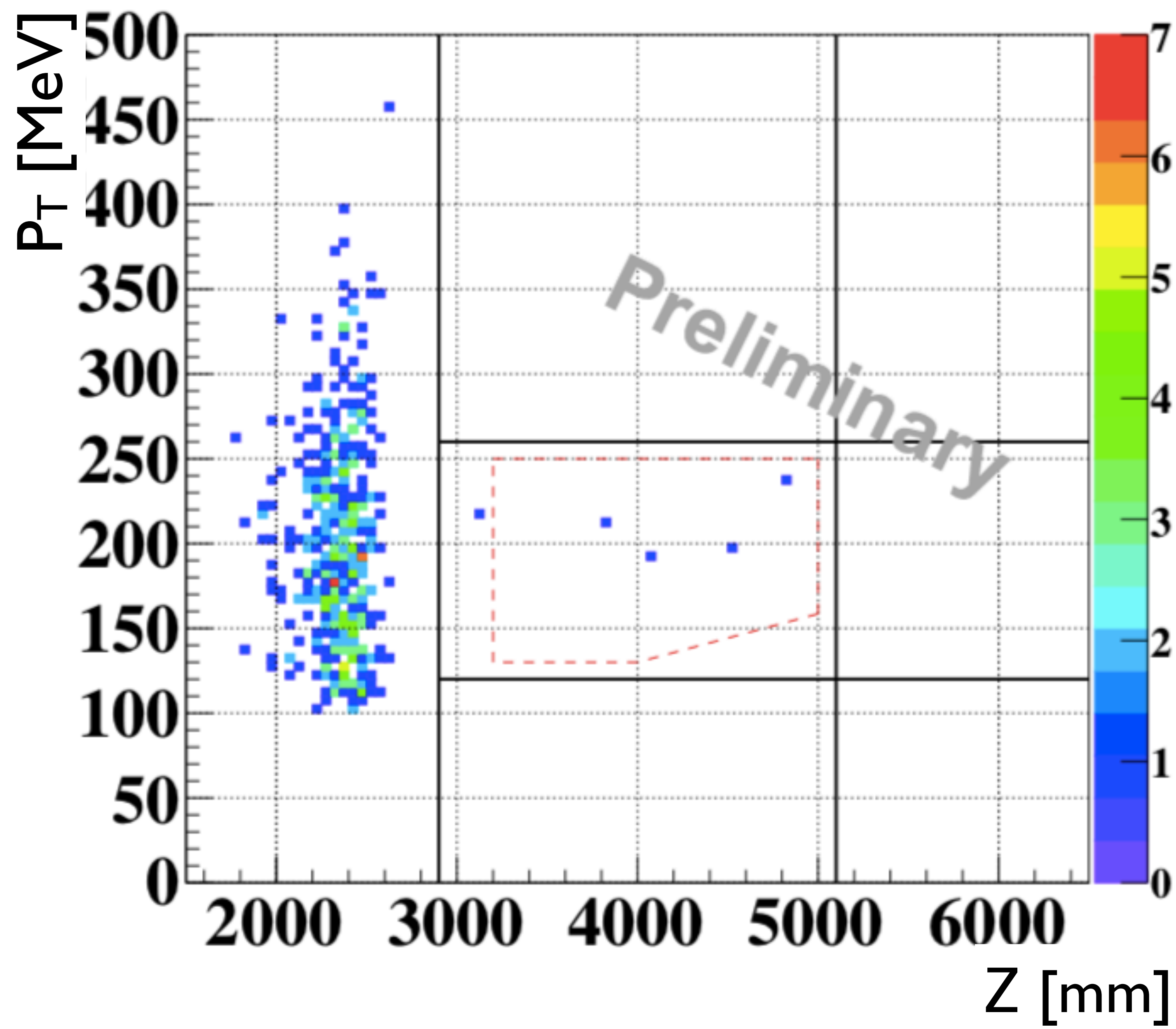



| Method | BGL |
|---|---|
| **$K_L \to 2\pi$** | <0.18 |
| **$K_L \to \pi^0\pi^+\pi^-$** | <0.02 |
| **$K_L \to 3\pi$ (Overlapped)** | <0.04 |
| **$K_L \to \pi e \nu$ (Overlapped)** | <0.09 |
| **Upstream π** | 0.00 ± 0.00 |
| **η from CV** | 0.03 ± 0.01 |
| **Hadronic Cluster** | 0.02 ± 0.00 |
| **Total** | 0.05 ± 0.02 |

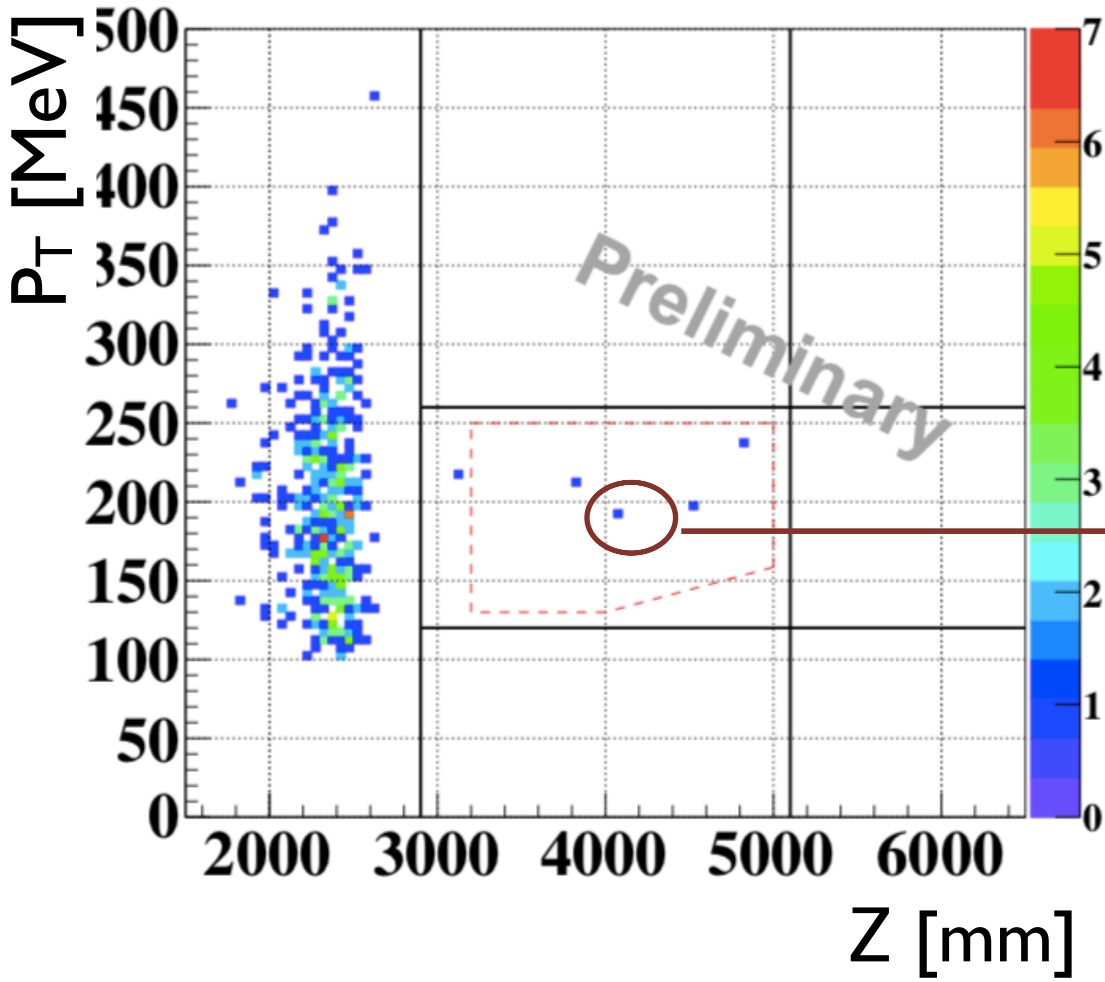
* Acceptance x 1.2 from 2015 analysis

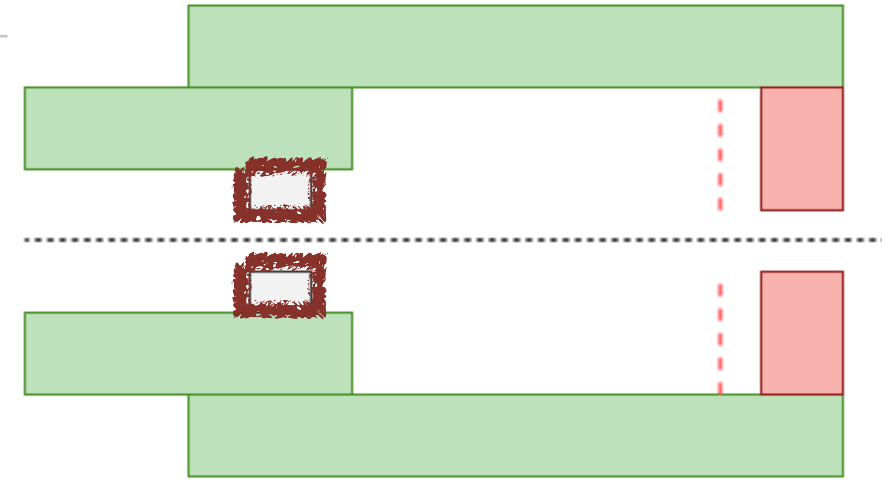
# Plot after Opening the Box

- Open the box at the end of August.
- 4 candidate events

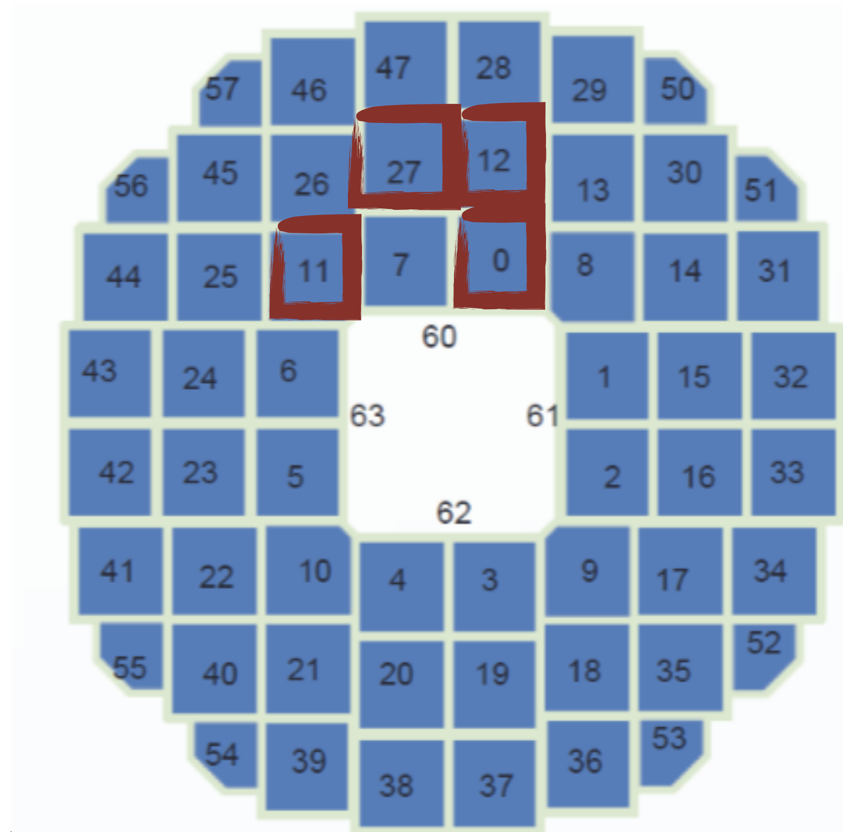


# Event Property

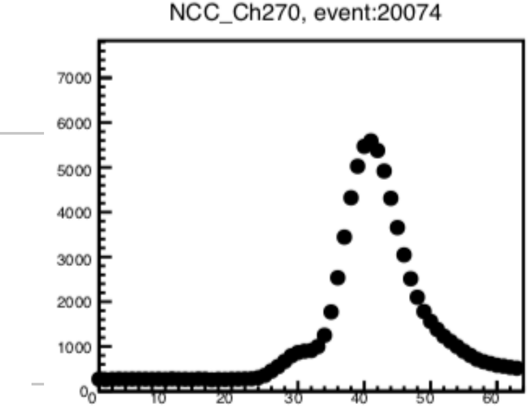


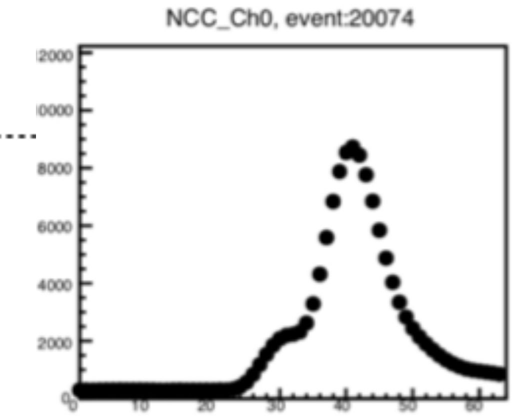



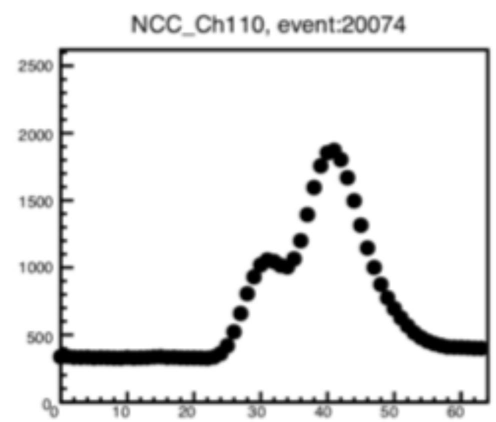
(Upstream collar counter)

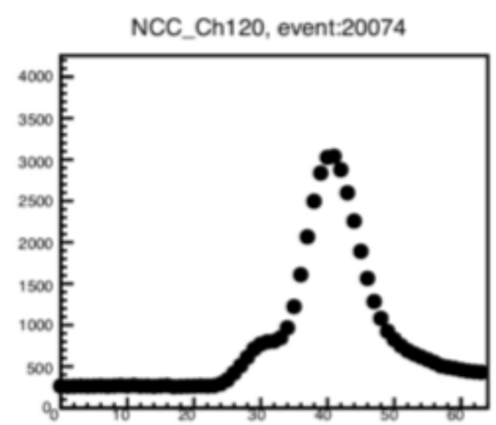


view from upstream




- The double pulse is identified by FTT.
- The deviation is ~70 [ns].

  (wider than WIDE window)
- Also studying other events. Will investigate other background possibilities.

# Summary

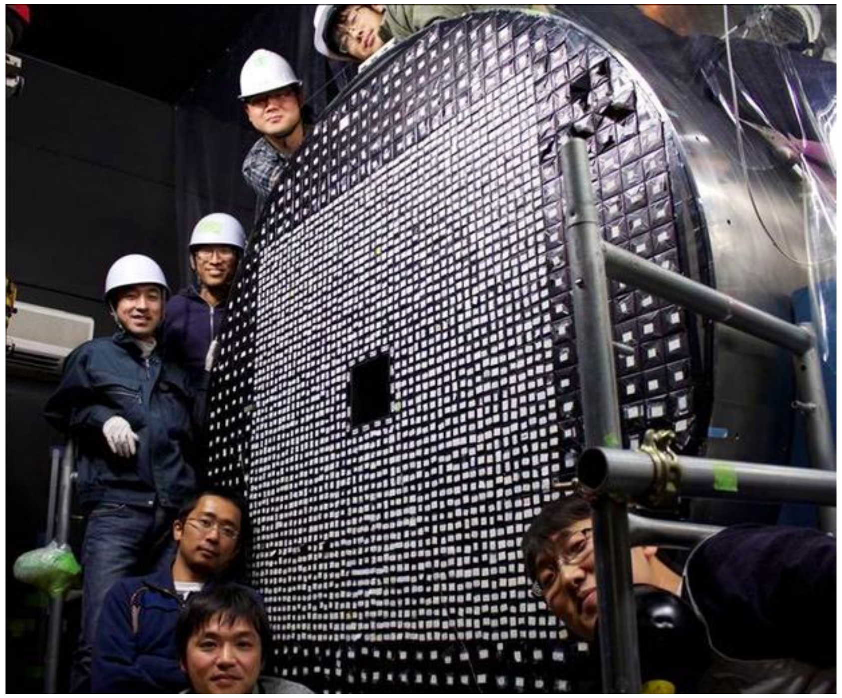
- The data from 2016 to 2018 is analyzed.
  - #Kaon x 1.57 and signal acceptance x 1.2 from 2015 analysis. Single event sensitivity of $6.9 \times 10^{-10}$ is achieved.
  - Background level estimation = $0.05 \pm 0.02$
  - 4 candidate events were observed. Their study is ongoing. We are also investigating other background possibilities.

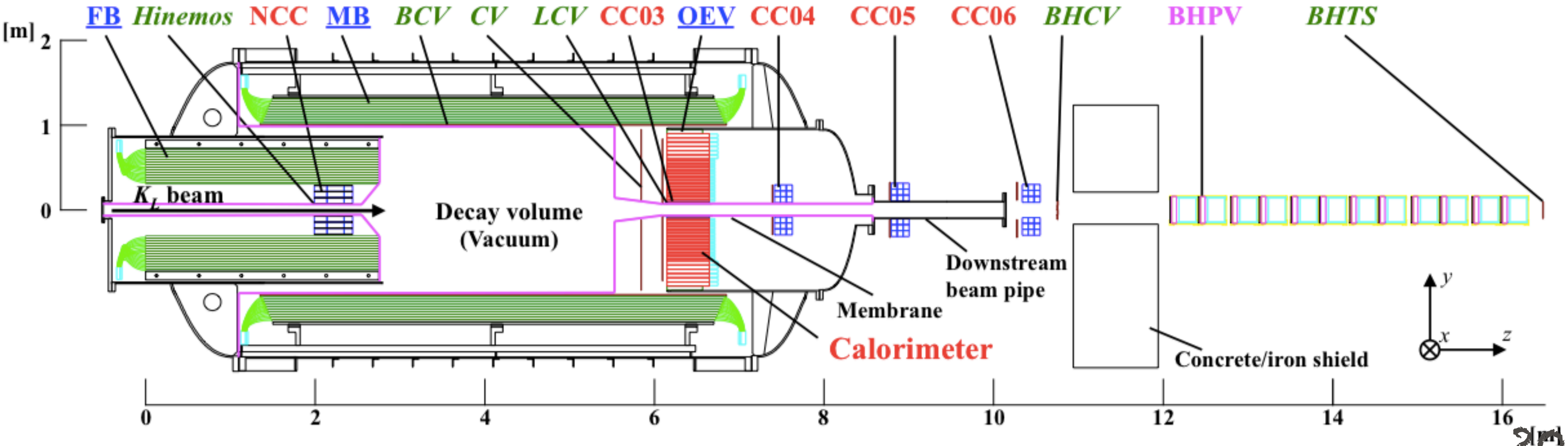
# Backup

# The KOTO Detector

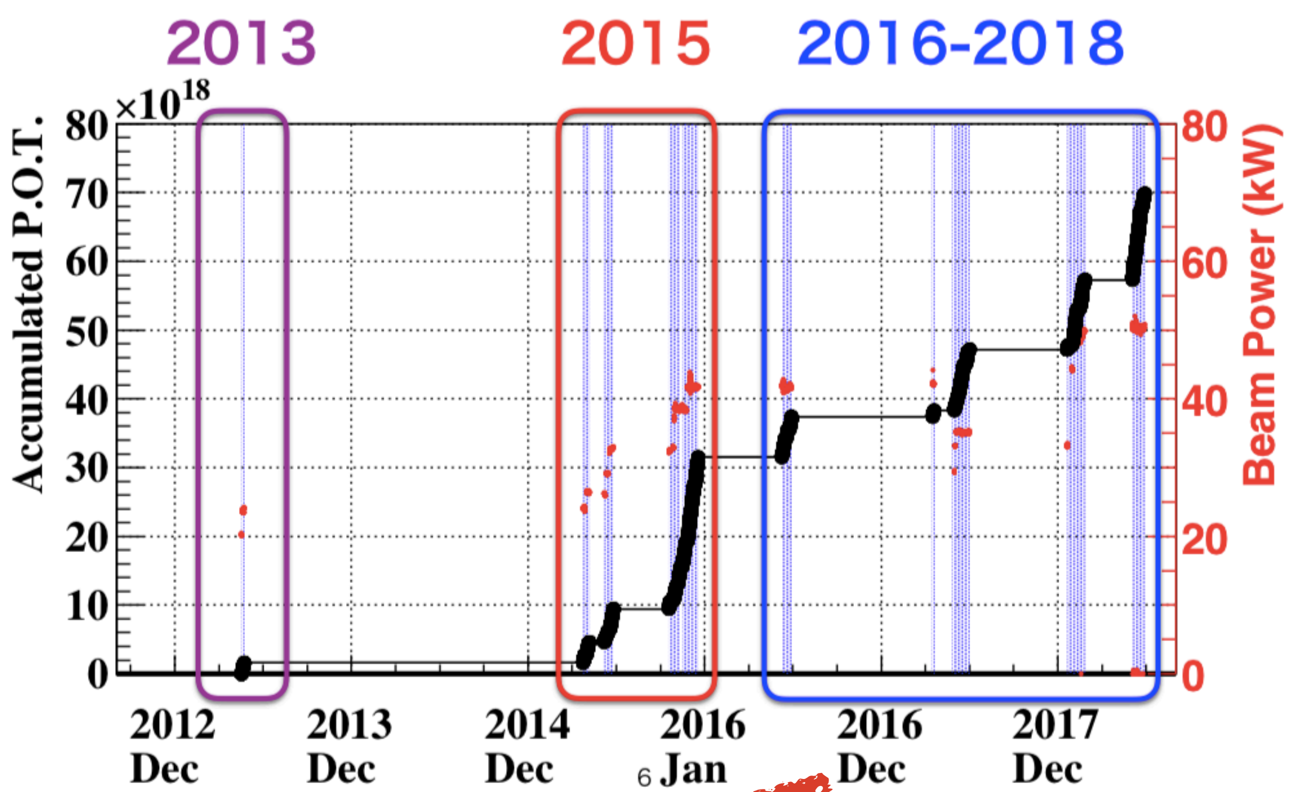
- *CsI Calorimeter*
- *Charged veto*
- *Photon veto*

| Decay Modes | Branching Fraction |
|---|---|
| $K_L \to \pi^{\pm}e^{\mp}\nu$ | $(40.55 \pm 0.11)\%$ |
| $K_L \to \pi^{\pm}\mu^{\mp}\nu$ | $(27.04 \pm 0.07)\%$ |
| $K_L \to 3\pi^0$ | $(19.52 \pm 0.12)\%$ |
| $K_L \to \pi^0\pi^+\pi^-$ | $(12.54 \pm 0.05)\%$ |
| $K_L \to \pi^0\pi^0$ | $(8.64 \pm 0.06) \times 10^{-4}$ |
| $K_L \to 2\gamma$ | $(5.47 \pm 0.04) \times 10^{-4}$ |



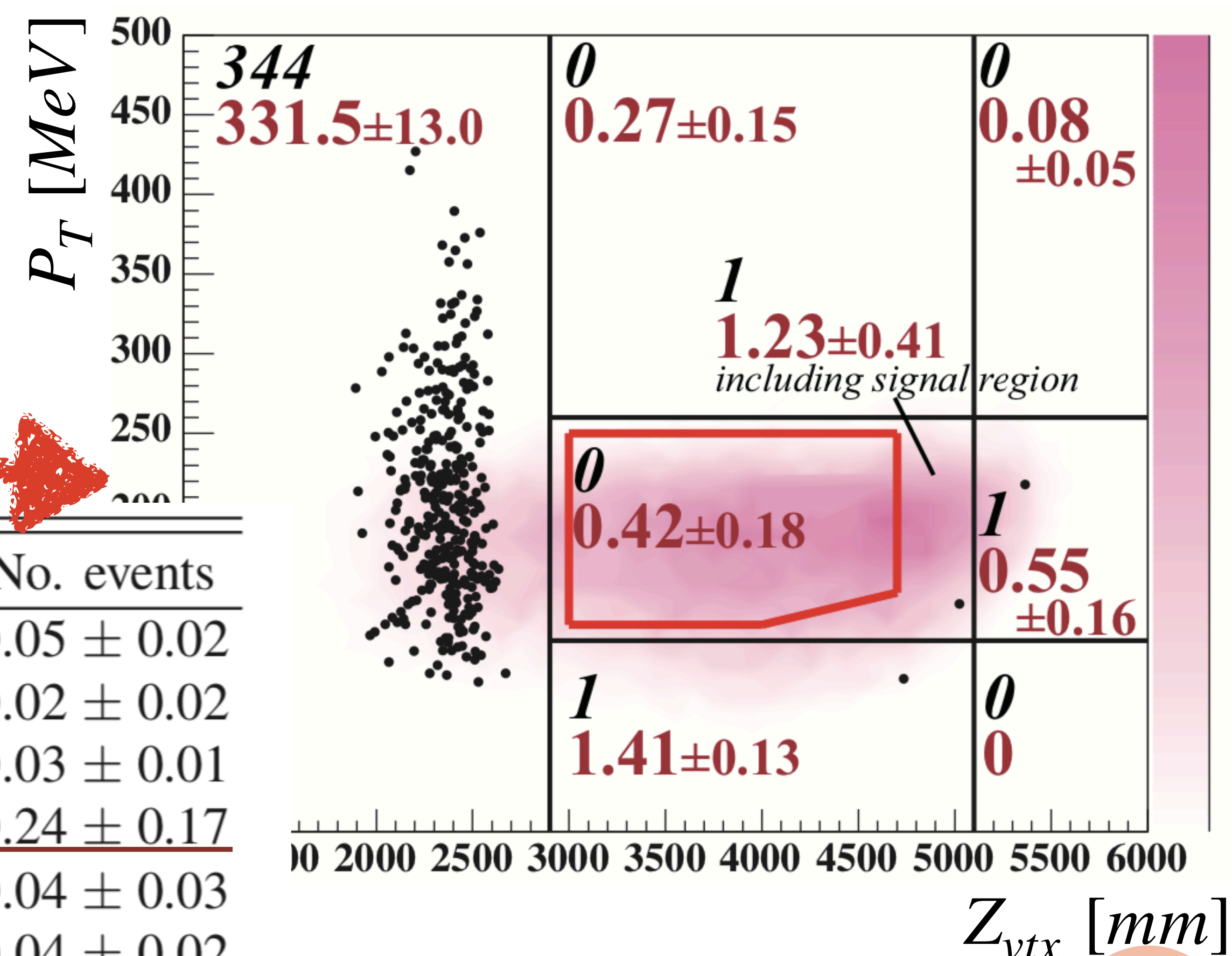


# Result from 2015 Runs




$BR(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) < 3.0 \times 10^{11}$

(90% C. L.)

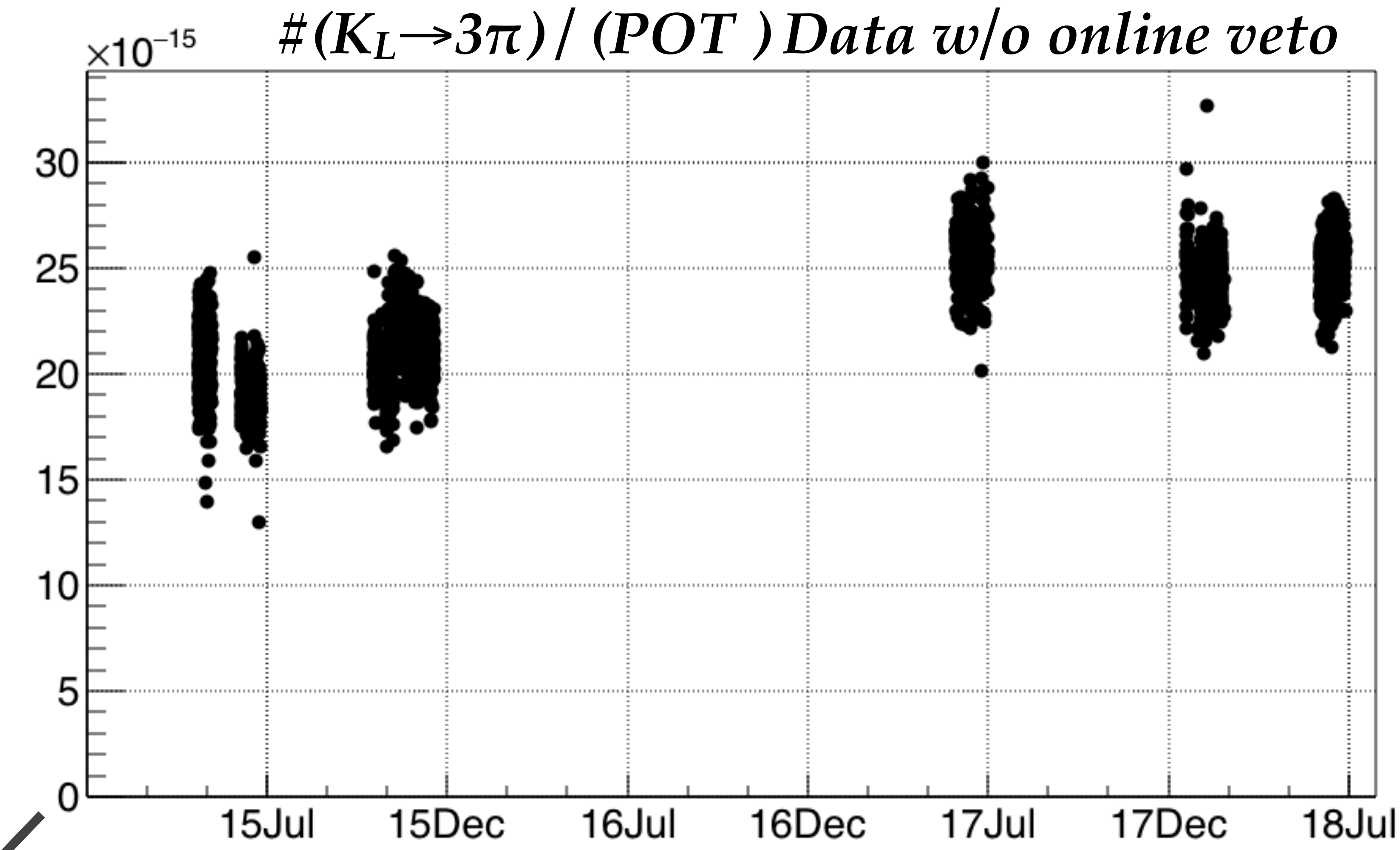



## Background Level

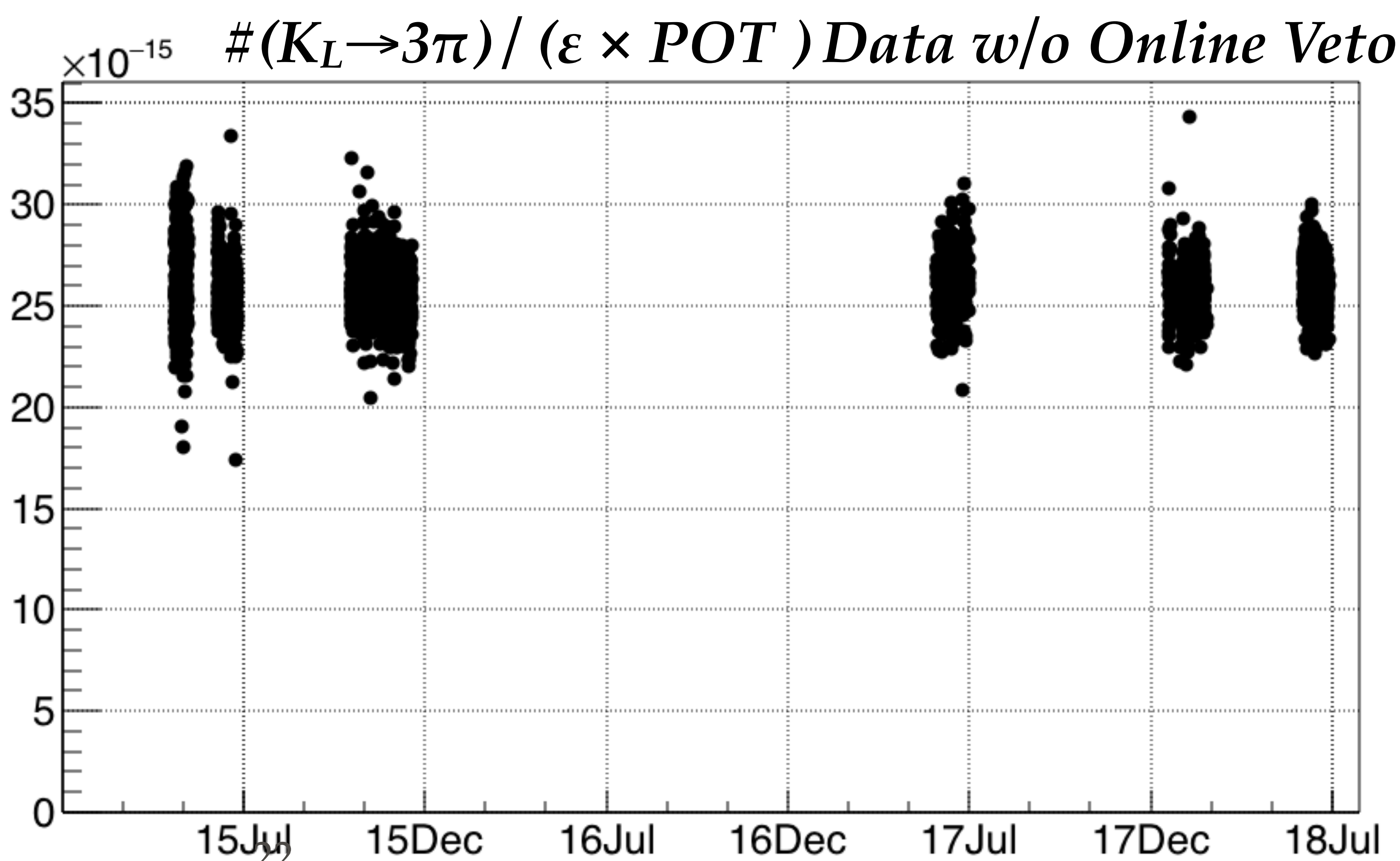
| Source | | No. events |
|---|---|---|
| $K_L$ decay | $K_L \rightarrow \pi^+\pi^-\pi^0$ | $0.05 \pm 0.02$ |
| | $K_L \rightarrow 2\pi^0$ | $0.02 \pm 0.02$ |
| | Other $K_L$ decays | $0.03 \pm 0.01$ |
| Neutron induced | Hadron cluster | $0.24 \pm 0.17$ |
| | Upstream $\pi^0$ | $0.04 \pm 0.03$ |
| | CV $\eta$ | $0.04 \pm 0.02$ |
| Total | | $0.42 \pm 0.18$ |

# $\#K_L \rightarrow 3\pi$ Live Ratio Effect

- The min. bias data is used to minimize the effect of accidental hits in veto counters.
- The gain in number of kaons benefit from the improvement of live ratio.



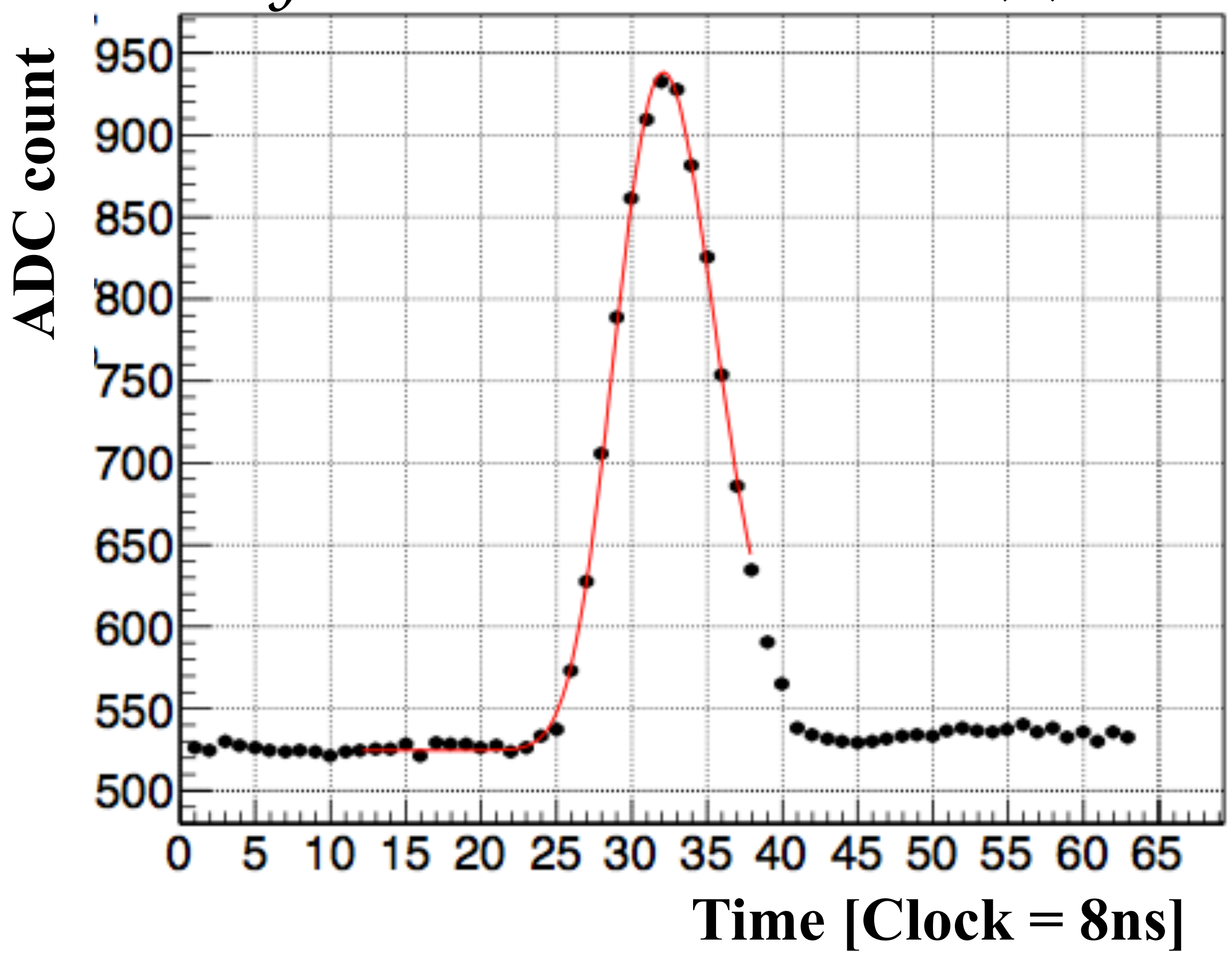

*Add live ratio correction, it is nearly a constant among all runs.*




- Data w/o online veto (min. bias)
  + kin. cuts
  + extra cluster time cut

# 2015 Pulse Shape Method

*Waveform Fitting by an Asymmetric Gaussian AG(x)*

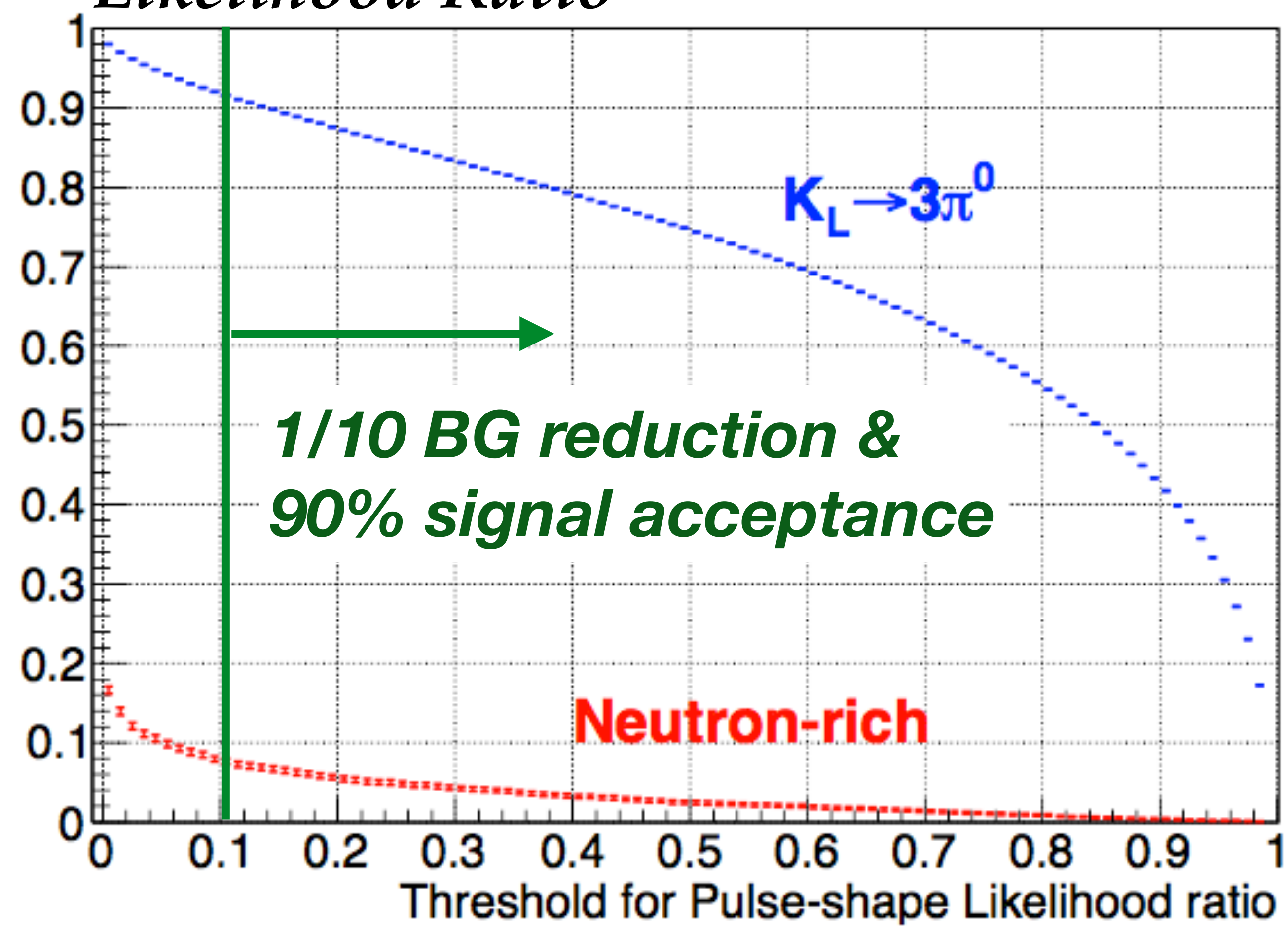



$$AG(x) = A \cdot \exp\left(-\frac{(t-t_0)^2}{2(\sigma_0 + a(t-t_0))^2}\right)$$

*neutron tends to have a longer tail.*

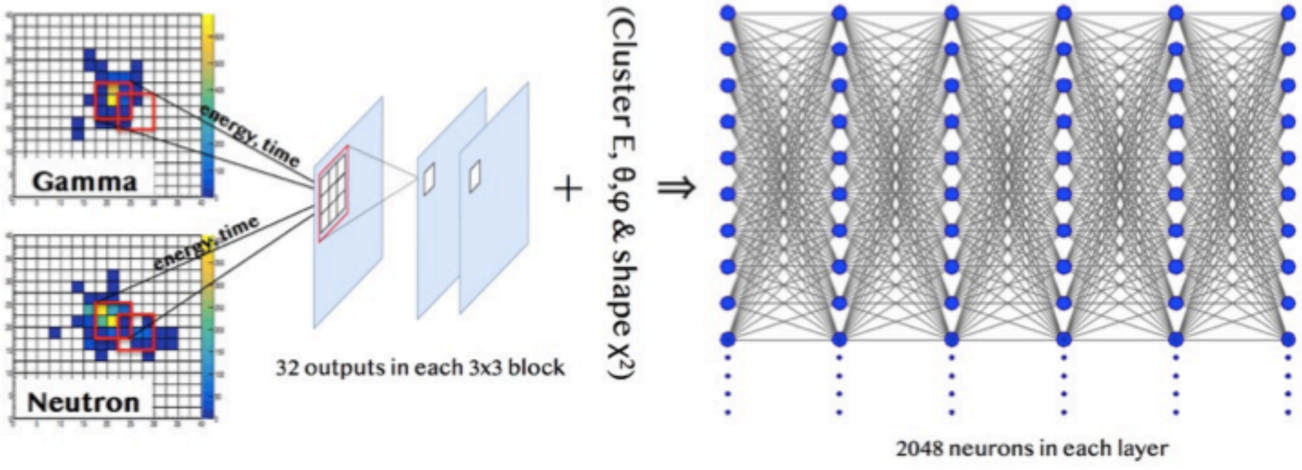
- An 125MHz digitizer is commissioned to store the waveform shape.

*Likelihood Ratio*

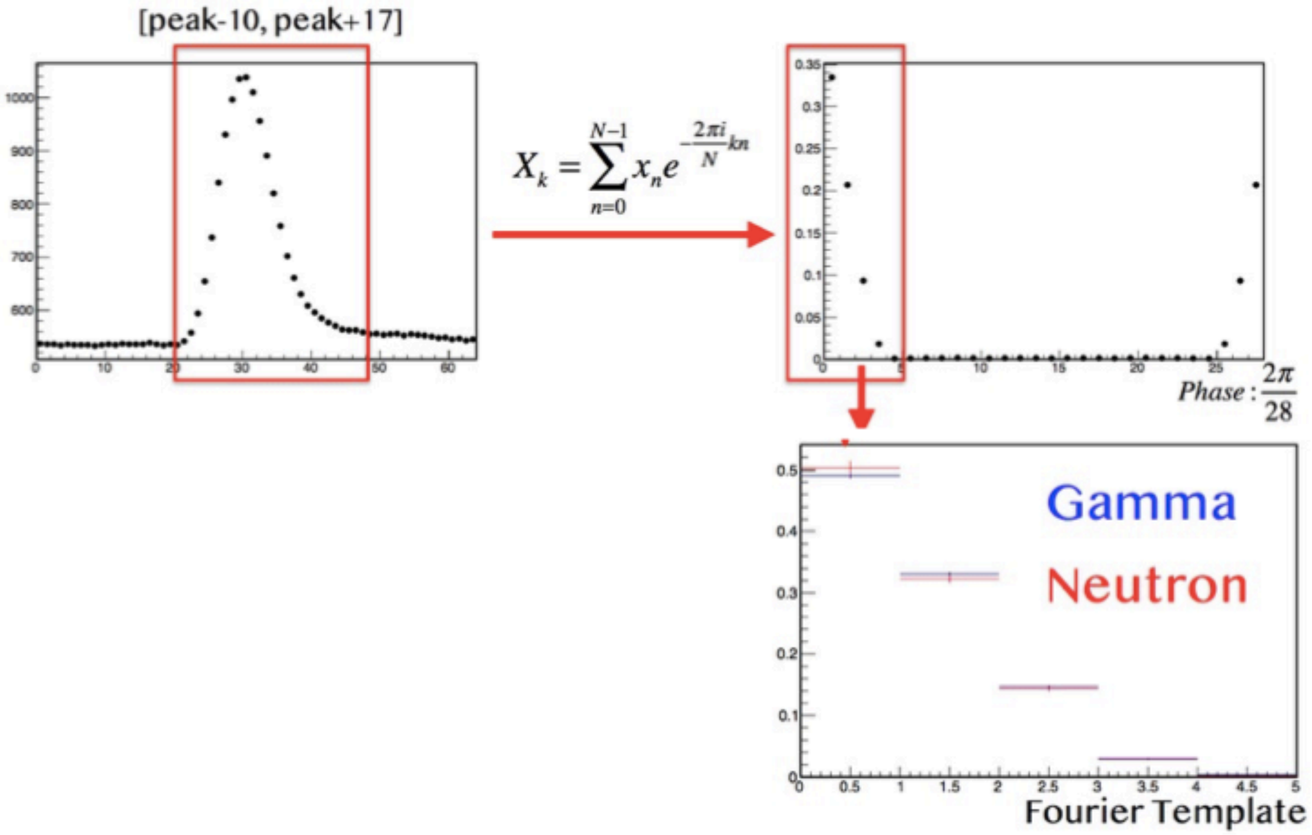


# Improvement from 2015 Method

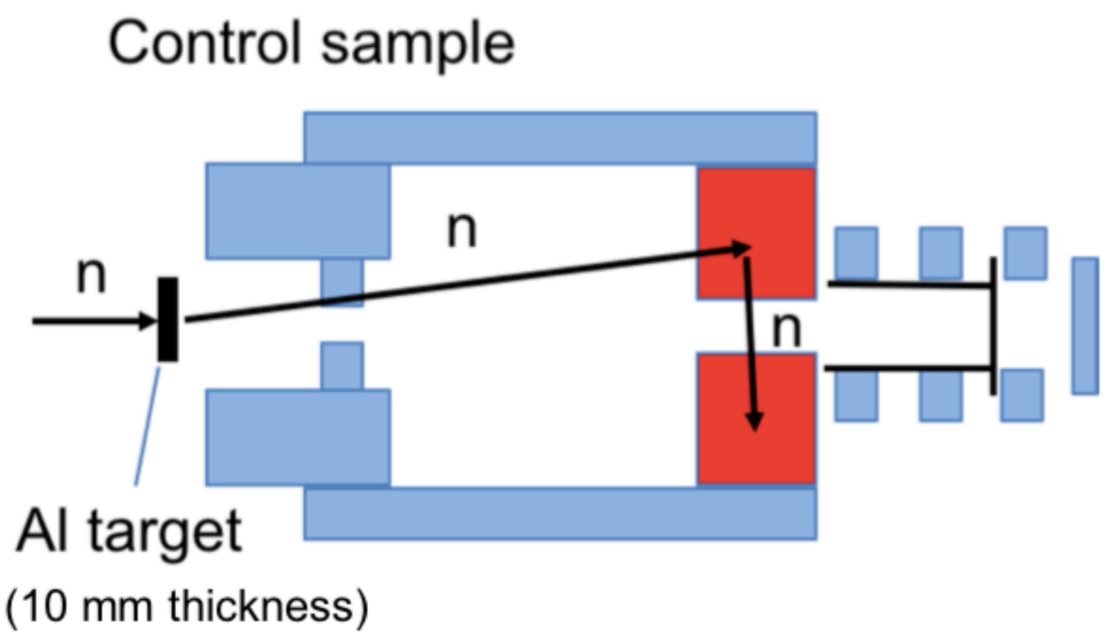
1. Cluster shape cut with deep learning
   – S/N : × ~2 from 2015

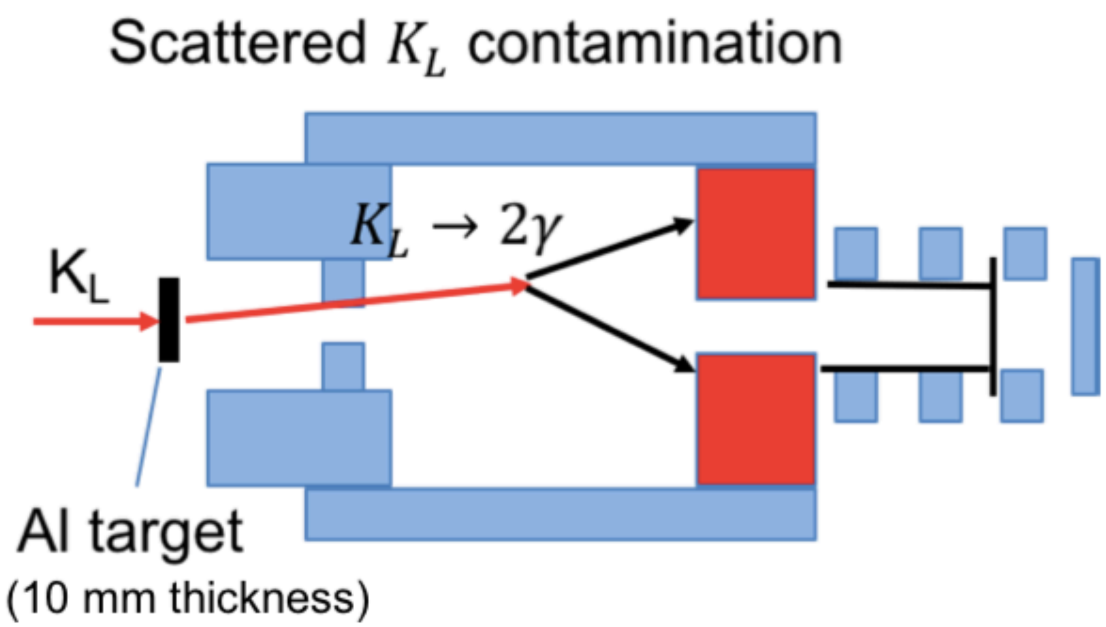



2. Pulse shape discrimination with Fourier transformation
   – S/N : × ~1.8 from 2015



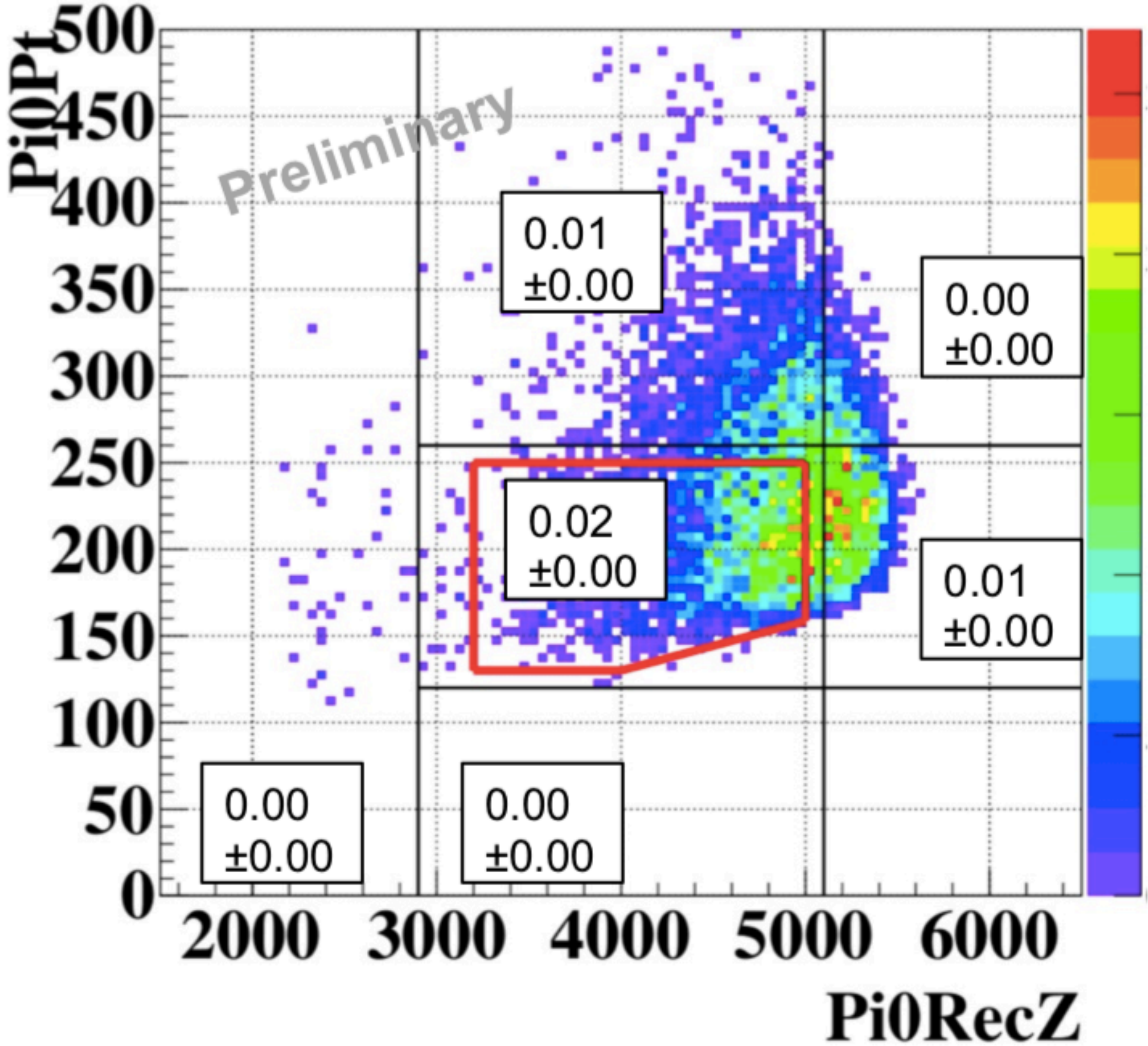
# Kaon Contamination in Neutron Control Samples



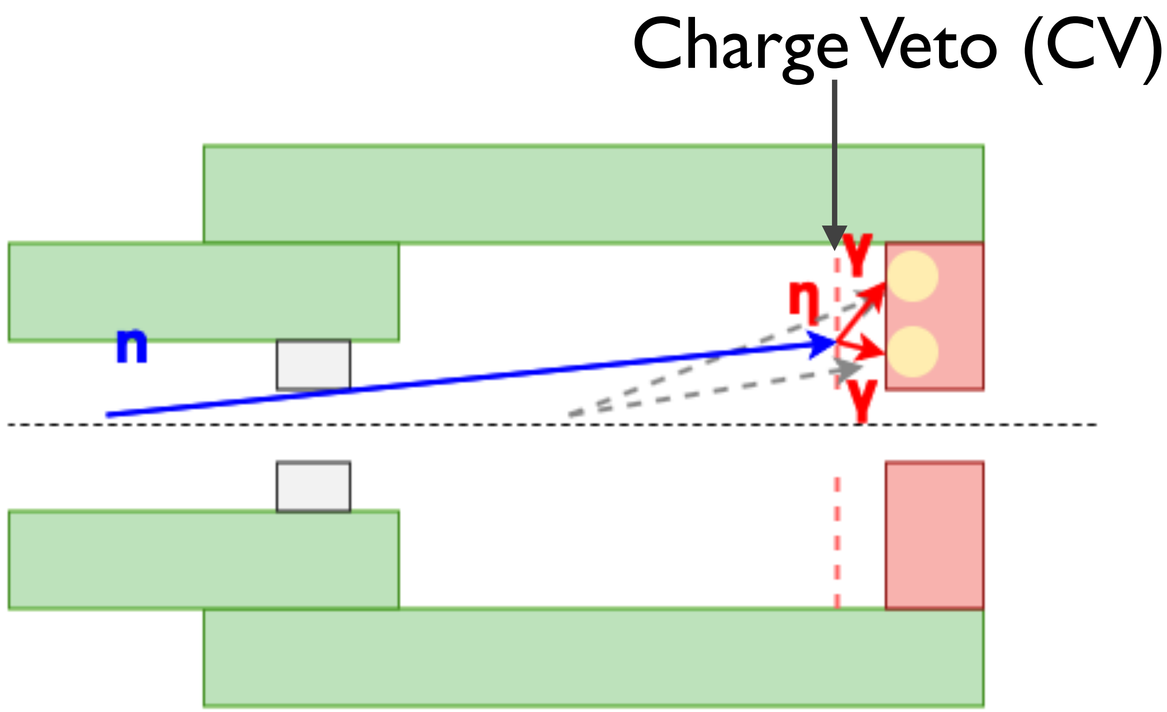

- The neutron control samples is polluted by the kaon decays.
- The neutron-induced cluster BGL in 2015 is likely to be overestimated.

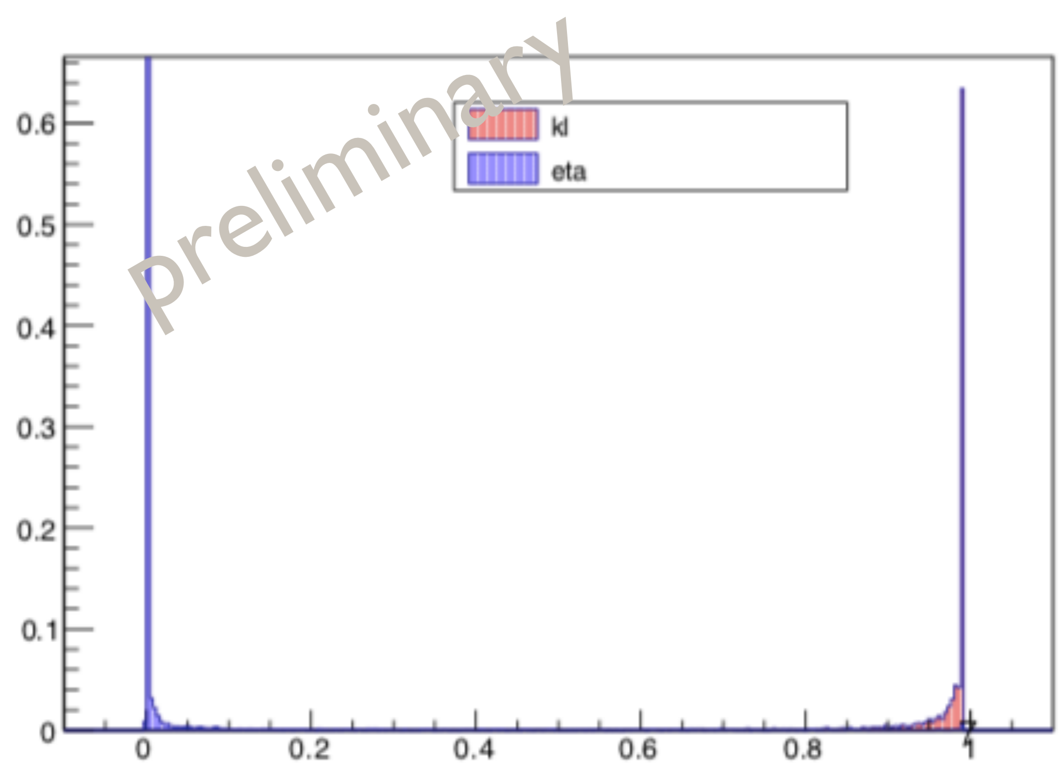
# Final Neutron-Induced Cluster BGL




Extended signal region to downstream from this result

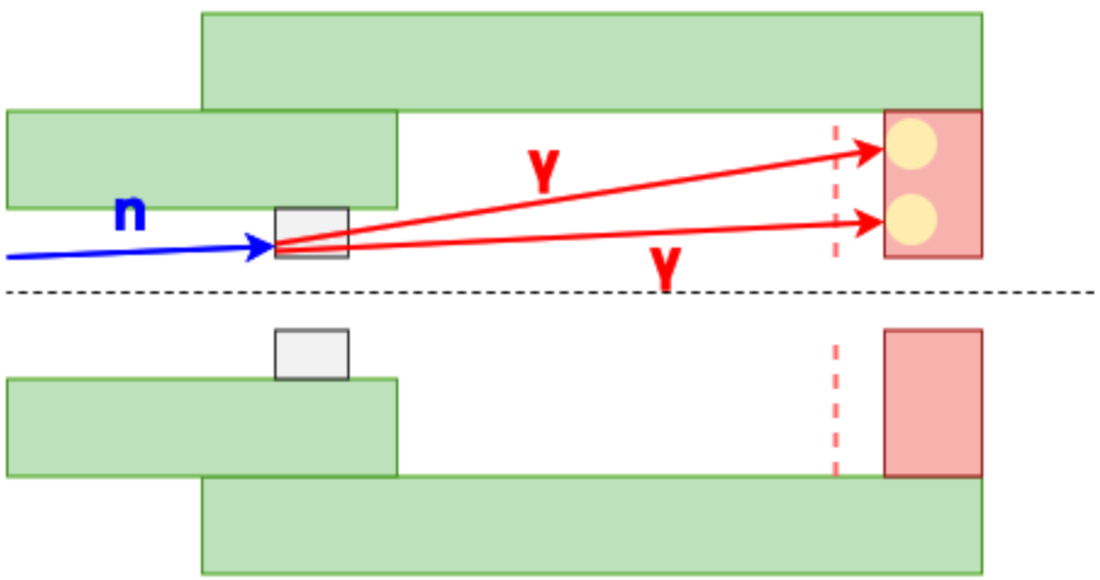
# CV Hadronic Backgrounds



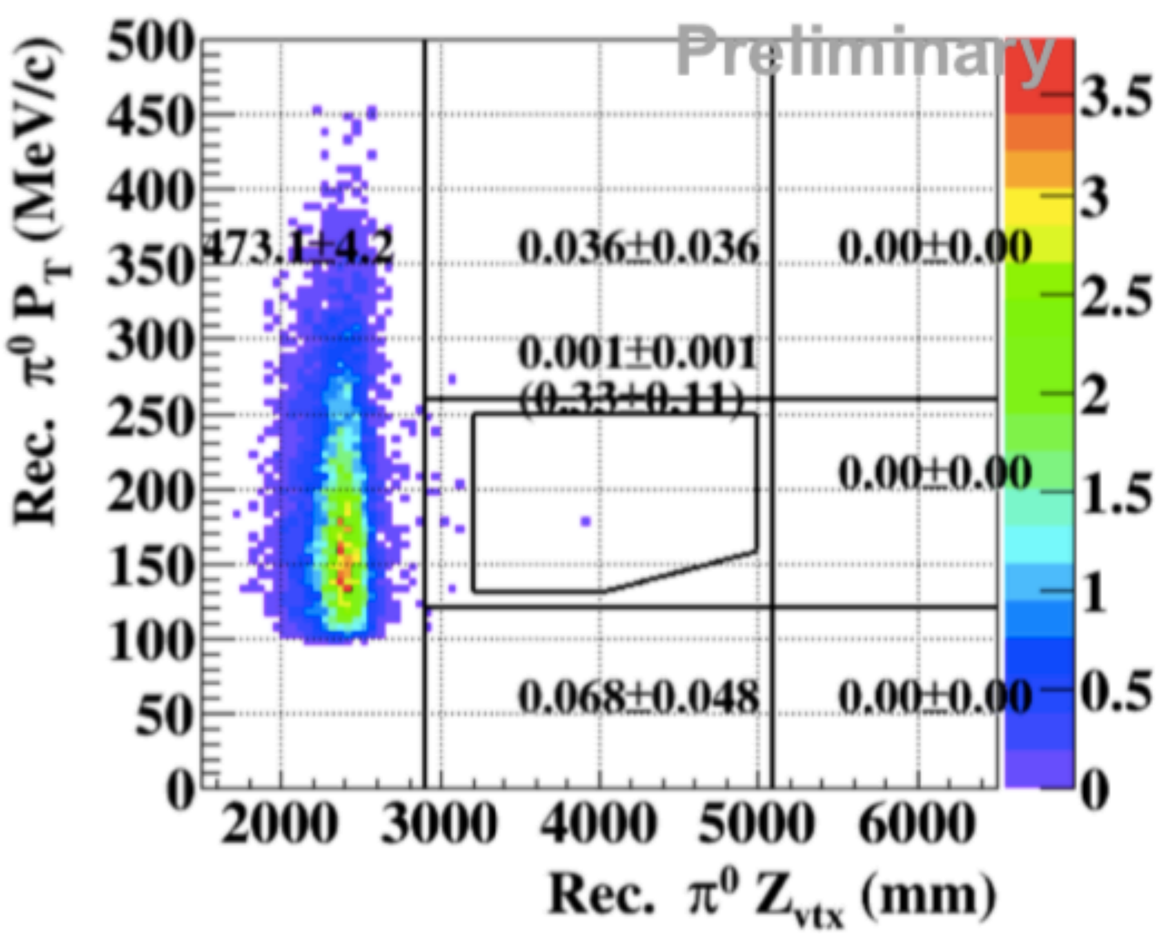



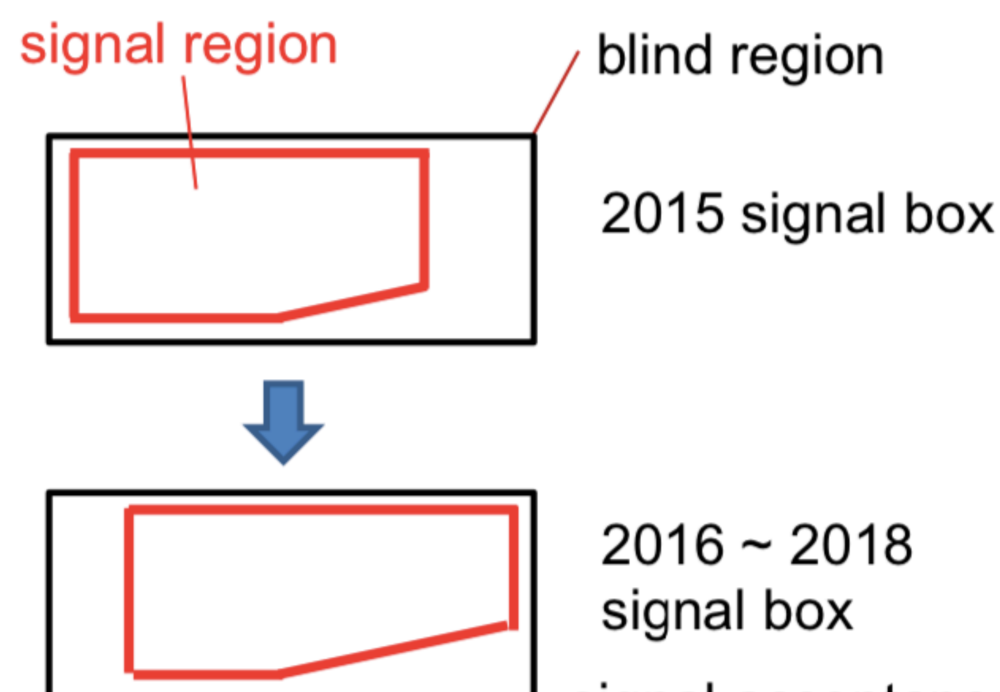

- Use neural network to train.
- Training sample:
  - $K_L \to \pi\nu\nu$ GEANT4-based MC.
  - CV-η GEANT4-based MC.
- Cluster shape information
  - energy / timing
  - BGL = 0.03 ± 0.01

# Upstream Counter Hadronic Backgrounds




- Shrink the upstream edge to suppress NCC BG more.

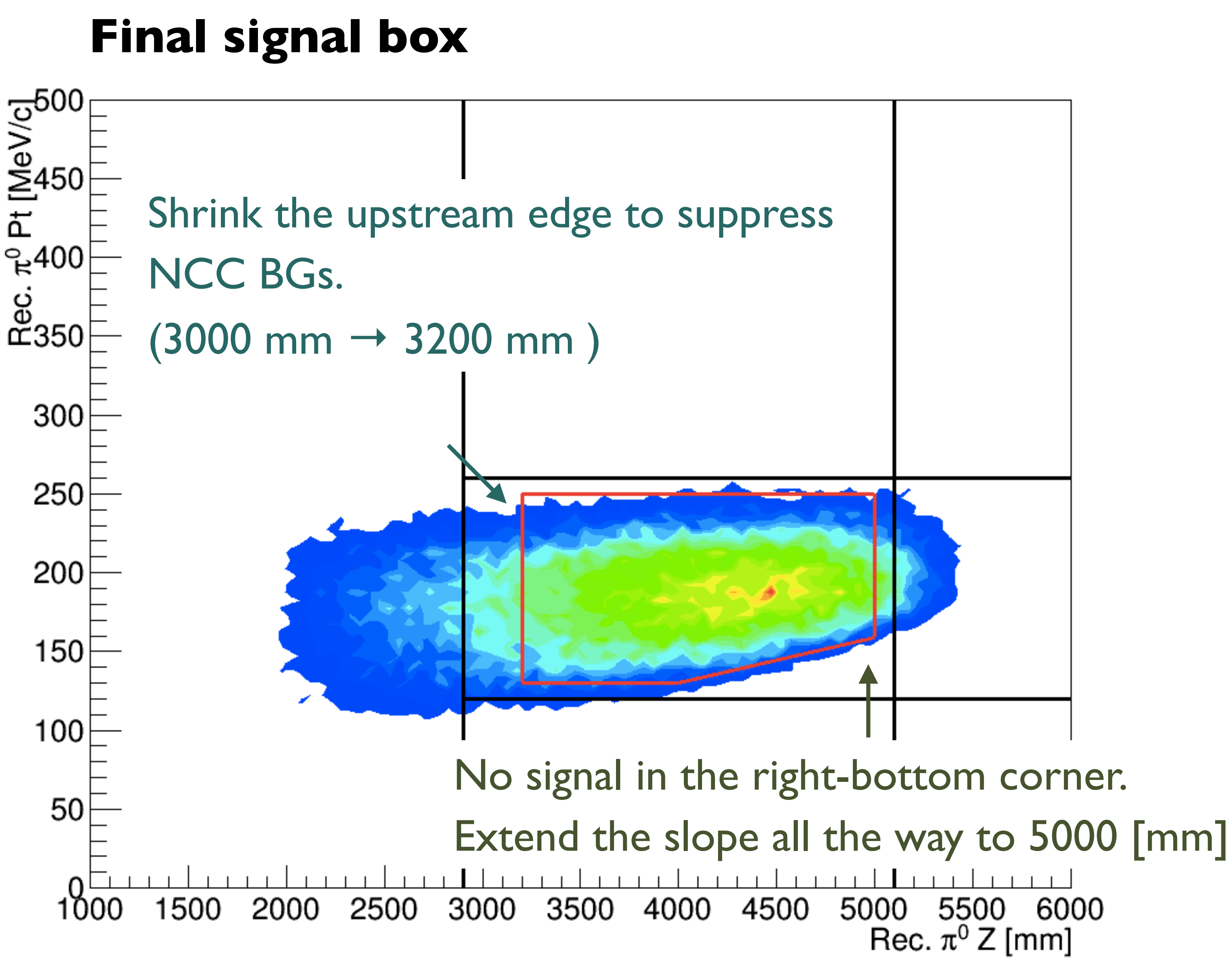



signal acceptance :
+ 6% (from 2015 signal box)

# Final Signal Box Shape

- Thanks for the upgradings on the tool against neutrons. The downstream region is free from the neutron BGs.

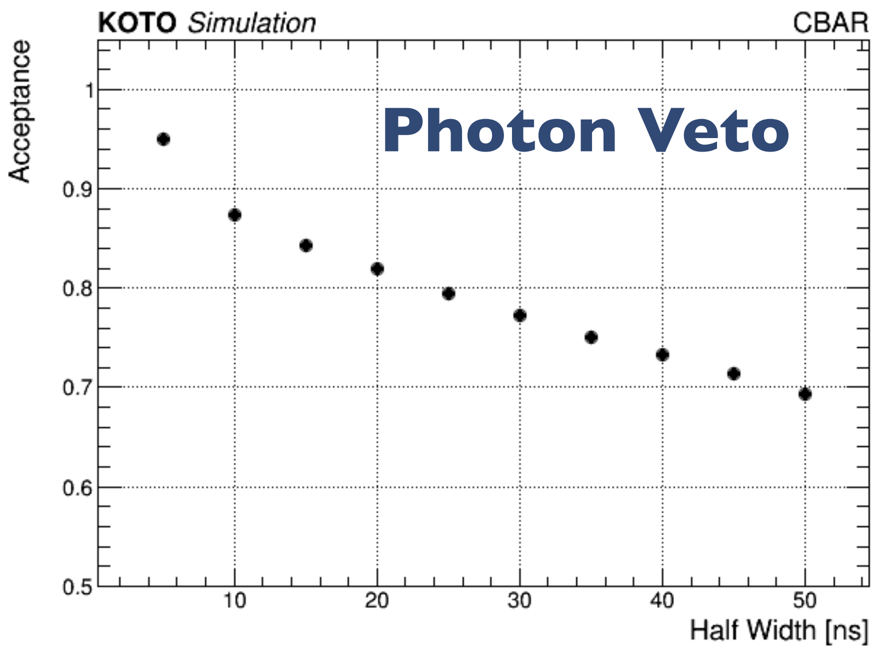


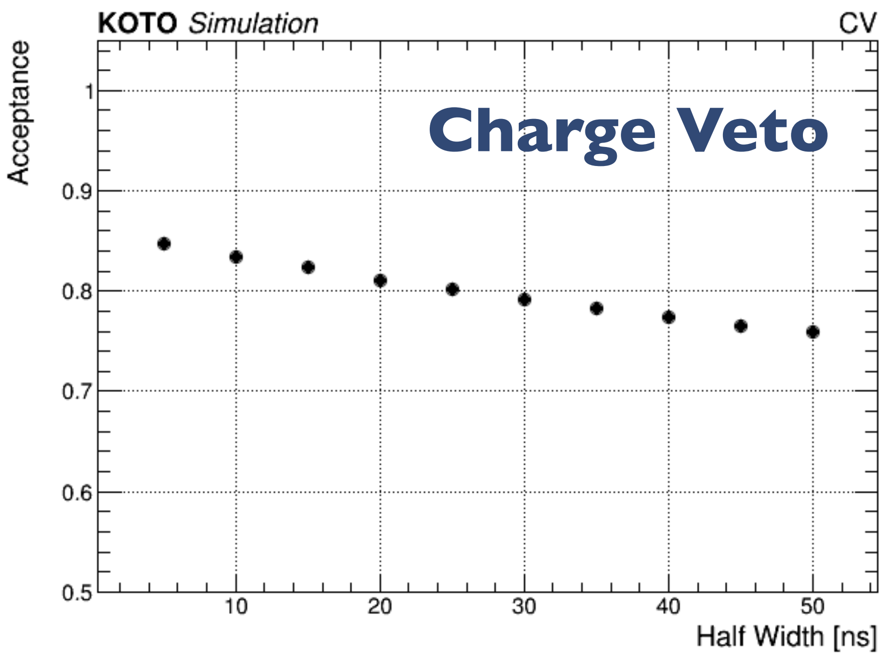
# Veto Window Width vs. Signal Acceptance

**What is the drawback of the wide window ?**

The wider the window is, the larger the acceptance loss is.

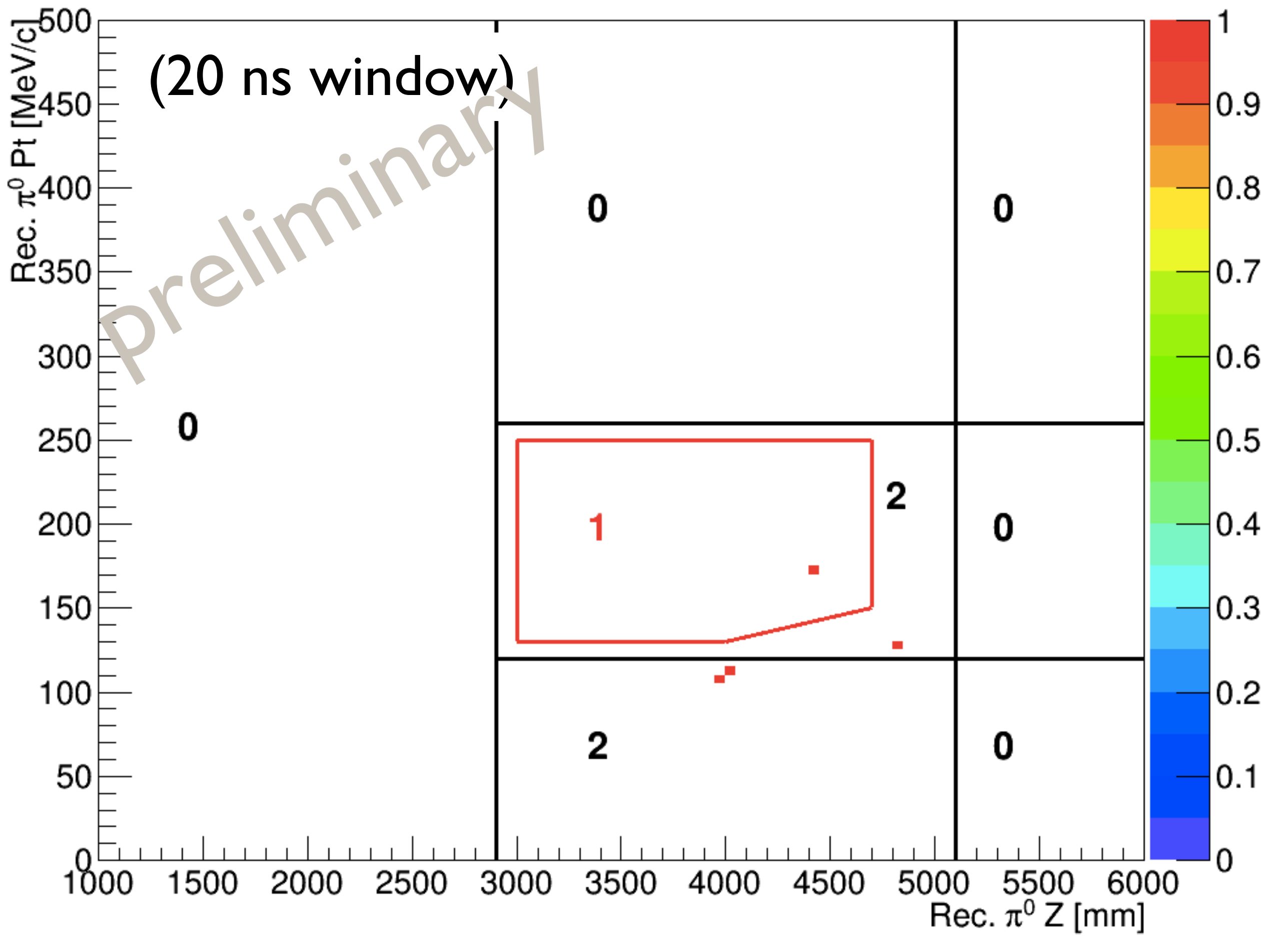
$$Acceptance = \frac{\#\ \text{w/ all kin. cuts + veto}}{\#\ \text{w/ all kin. cuts}}$$

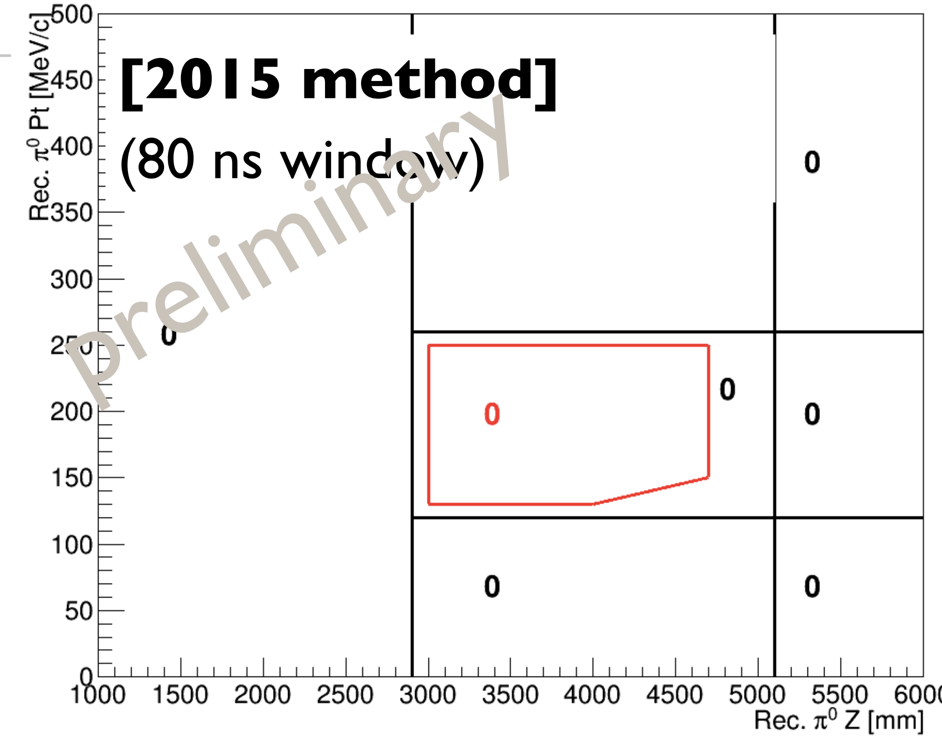


# Ke3 Masking BGL

**#MC ~ #data x 20**

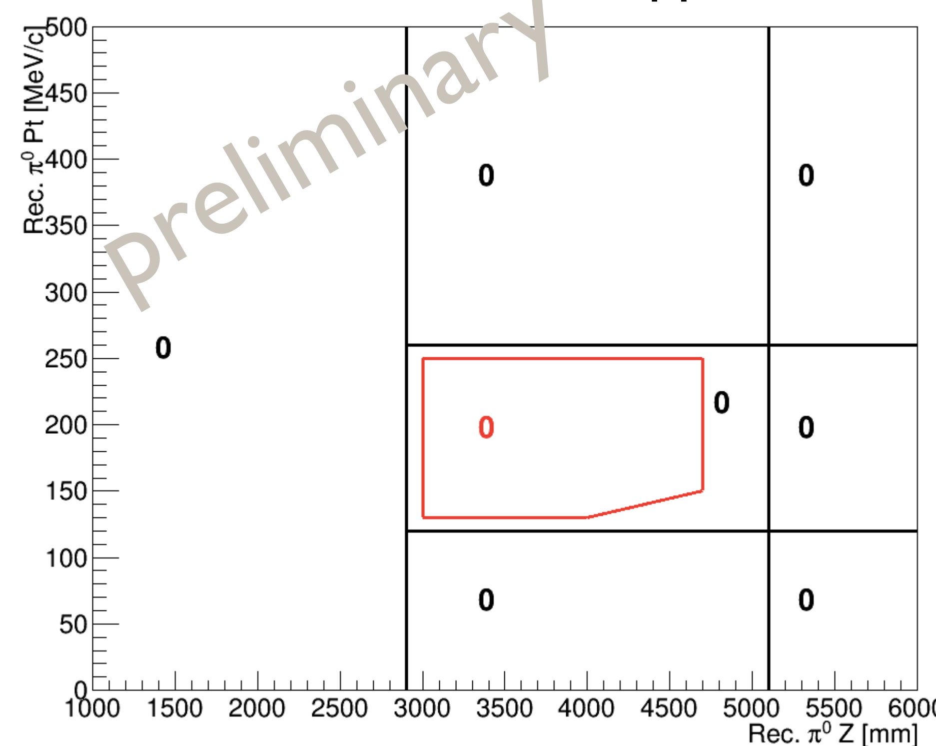


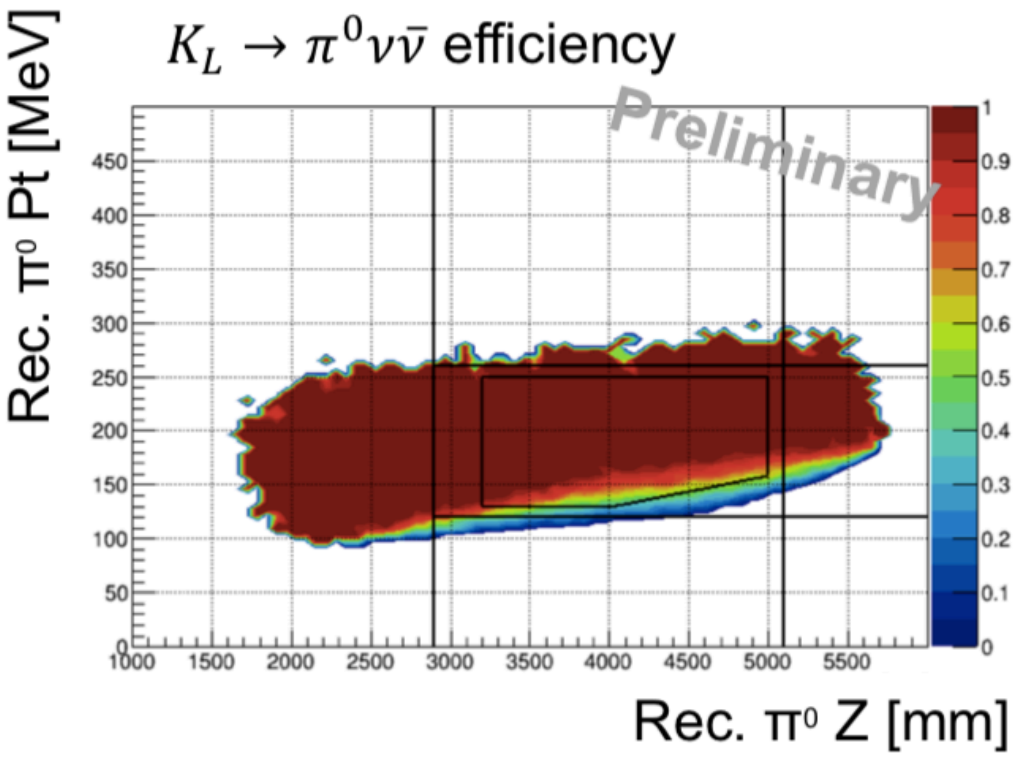

**[2016-2018 method]**

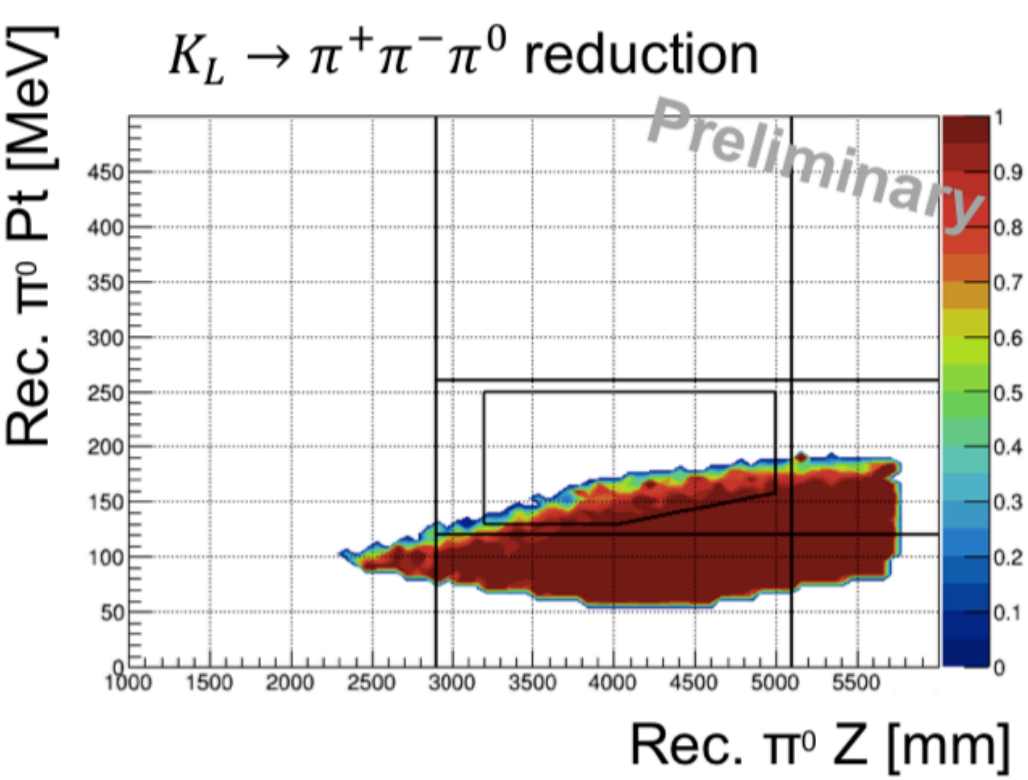
20 ns window if single-hit

150 ns window if overlapped



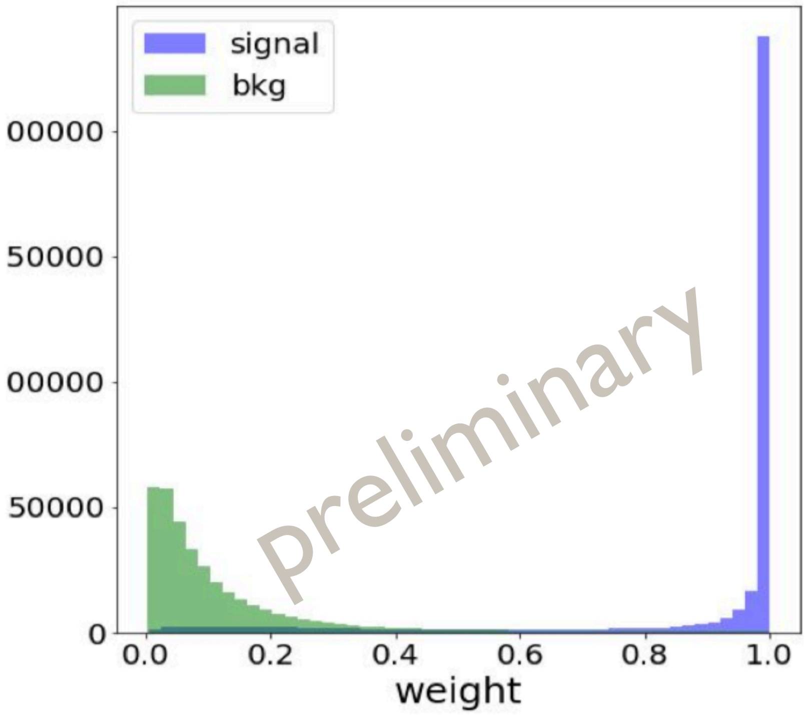
# K→ππ⁺π⁻ DL Cut



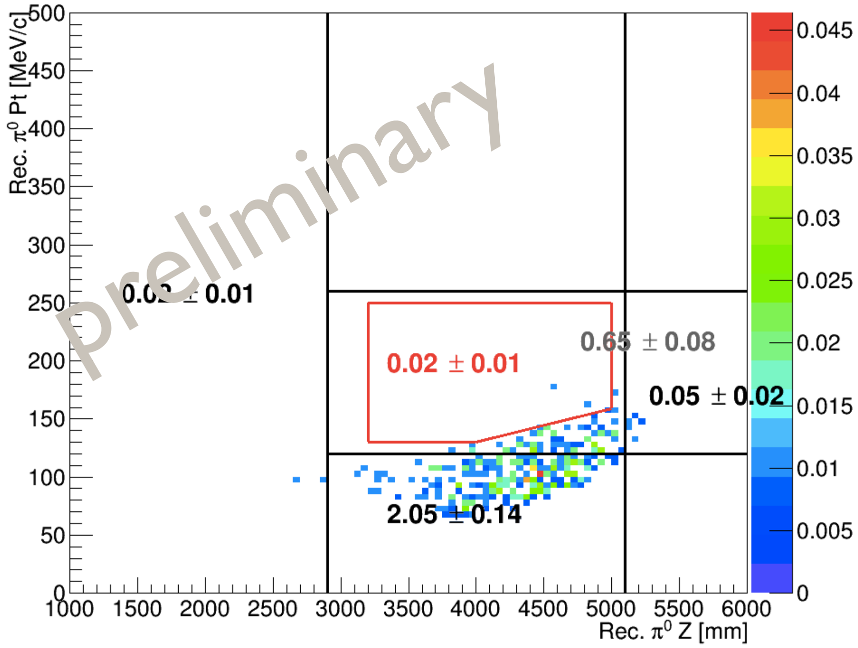

## DNN Cut

- 12 Input Variables:
  - Gamma 1 (higher energy): pt, pz, vr (CsI hit radius), E
  - Gamma 2: pt, pz, vr, E
  - Pi0: pt, pz, E, reconstructed z
- Output Variable:
  - Between 0-1
    - 1 -> Signal
    - 0 -> Background

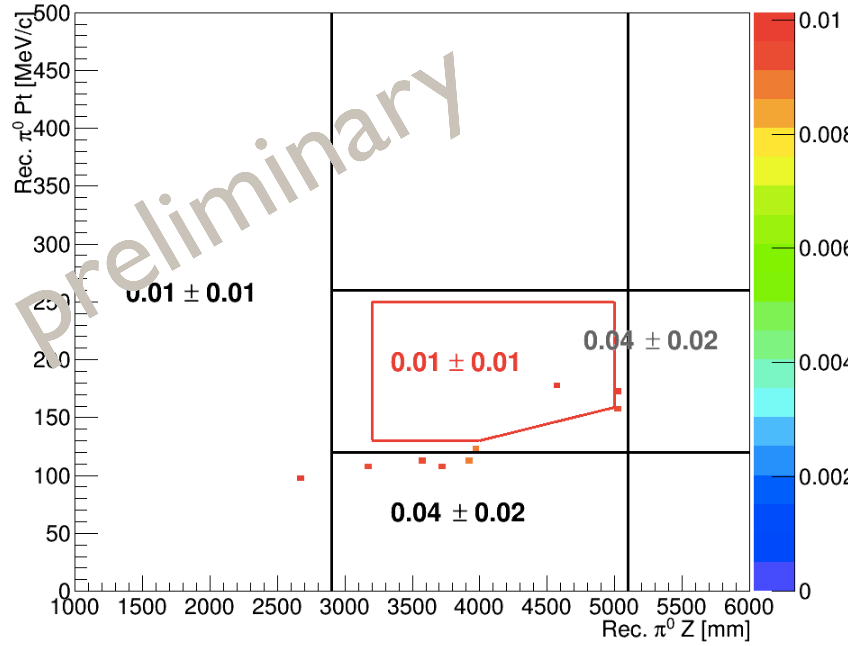


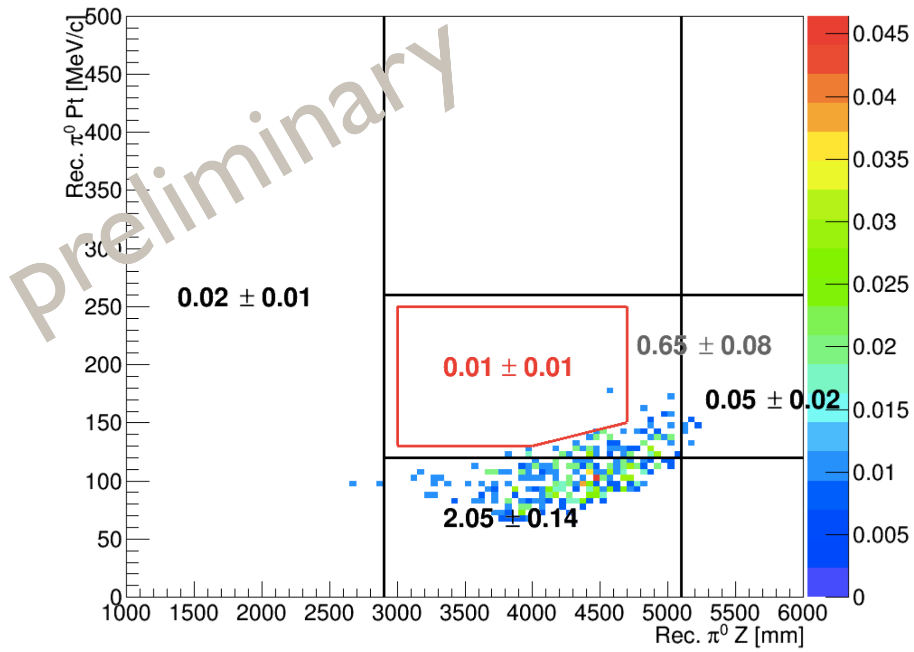
# $K \to \pi\pi^+\pi^-$ BGL with Various Scenarios

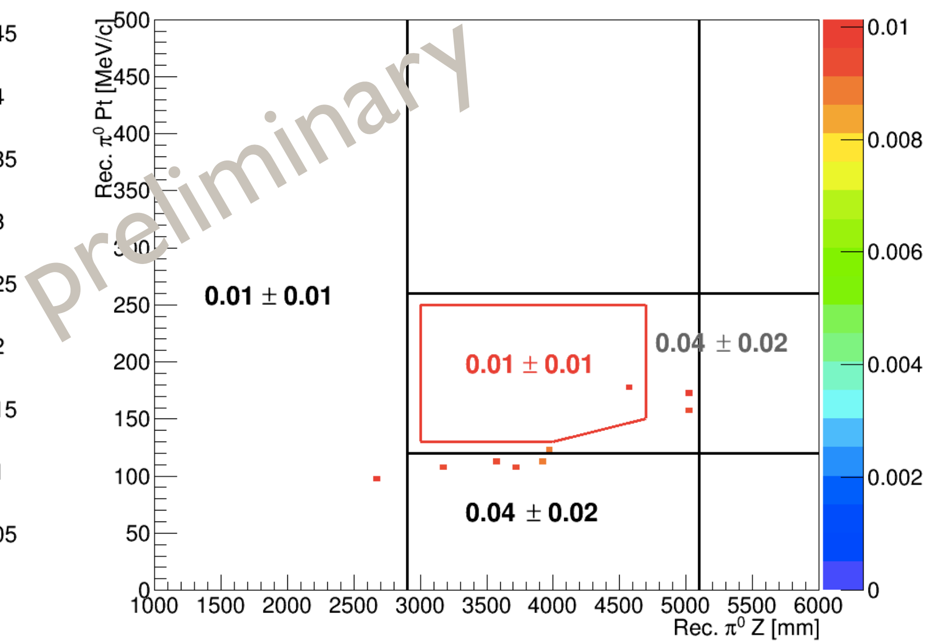
$K \to \pi\pi^+\pi^-$ (Remove DL cut)



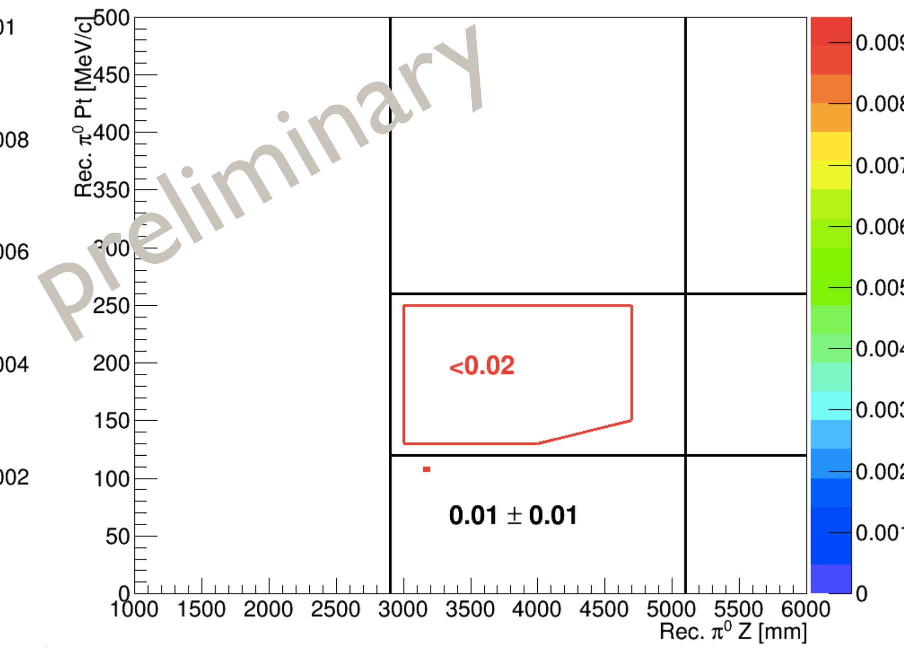

$K \to \pi\pi^+\pi^-$ (Loose DL cut)




$K \to \pi\pi^+\pi^-$ (Tight DL cut)



# Kaon BGL

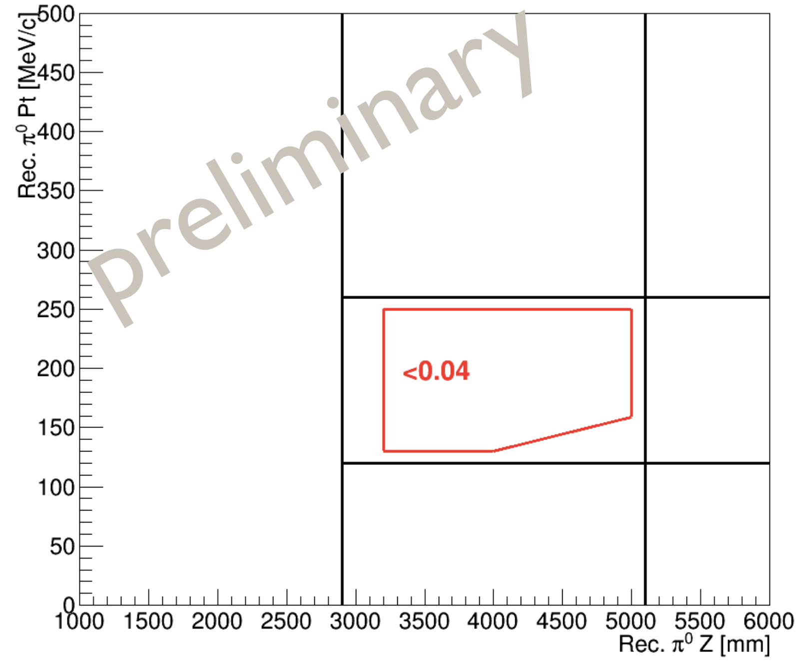
* Remove $K\to\pi\pi^+\pi^-$ DL cut from these 4 plots.

* <u>Masking BGs</u>:
  The entire Pt-Z plot is empty even without $K\to\pi\pi^+\pi^-$ DL cut.

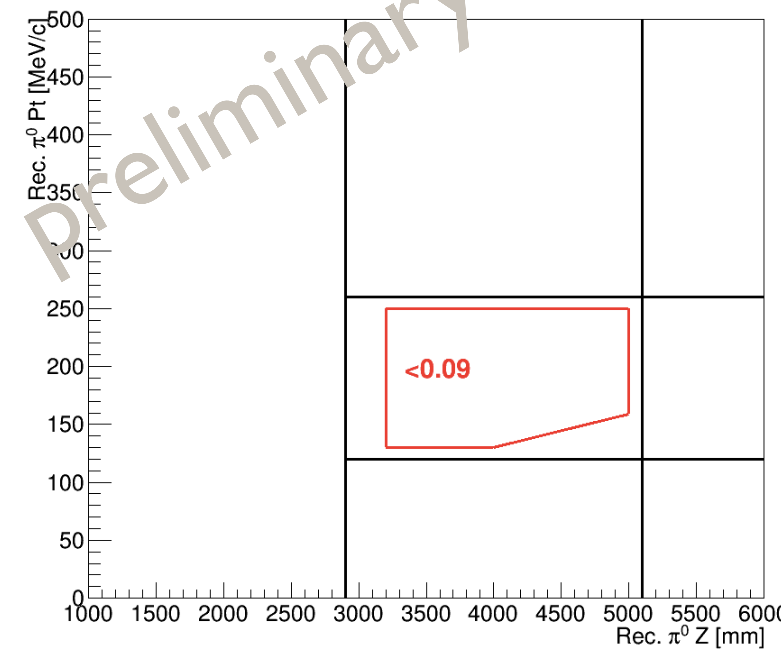
* <u>$K\to2\gamma$ (Scattered)</u>
  The estimated BGL is less than 0.01.

* <u>$K\to2\pi$</u>
  No event in the central box. Upper limit is 0.18. Low-pt event will be killed under loose $K\to\pi\pi^+\pi^-$ DL cut.

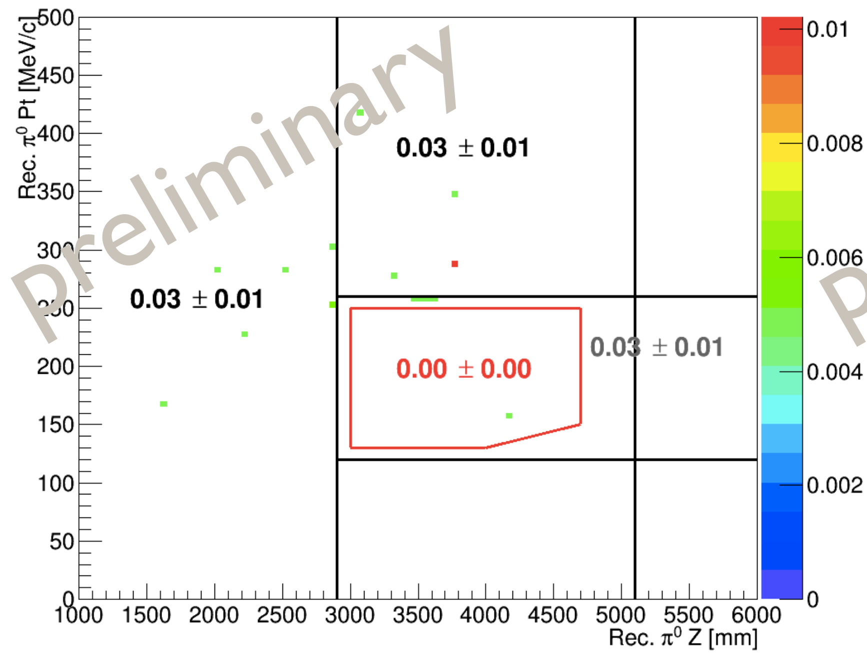
K→3π (Masking)



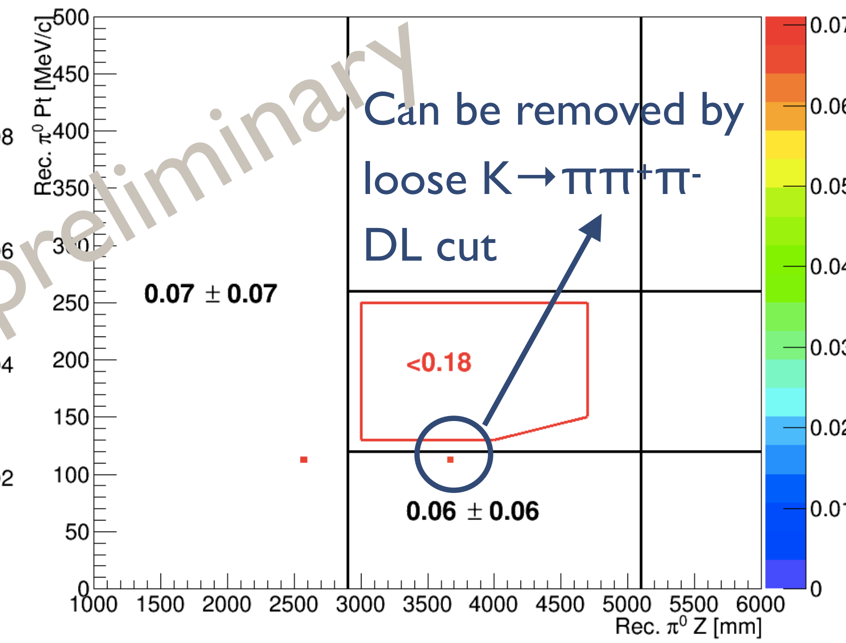

K→πeν (Masking)




K→2γ (Scattered)




K→2π



# Result with Removal of $K \to \pi\pi^+\pi^-$ DL Cut

**S.E.S = 6.48 x $10^{-10}$**