Core-to-Core Program

Pileup Analysis for the Liquid Xenon Detector of the MEG II experiment

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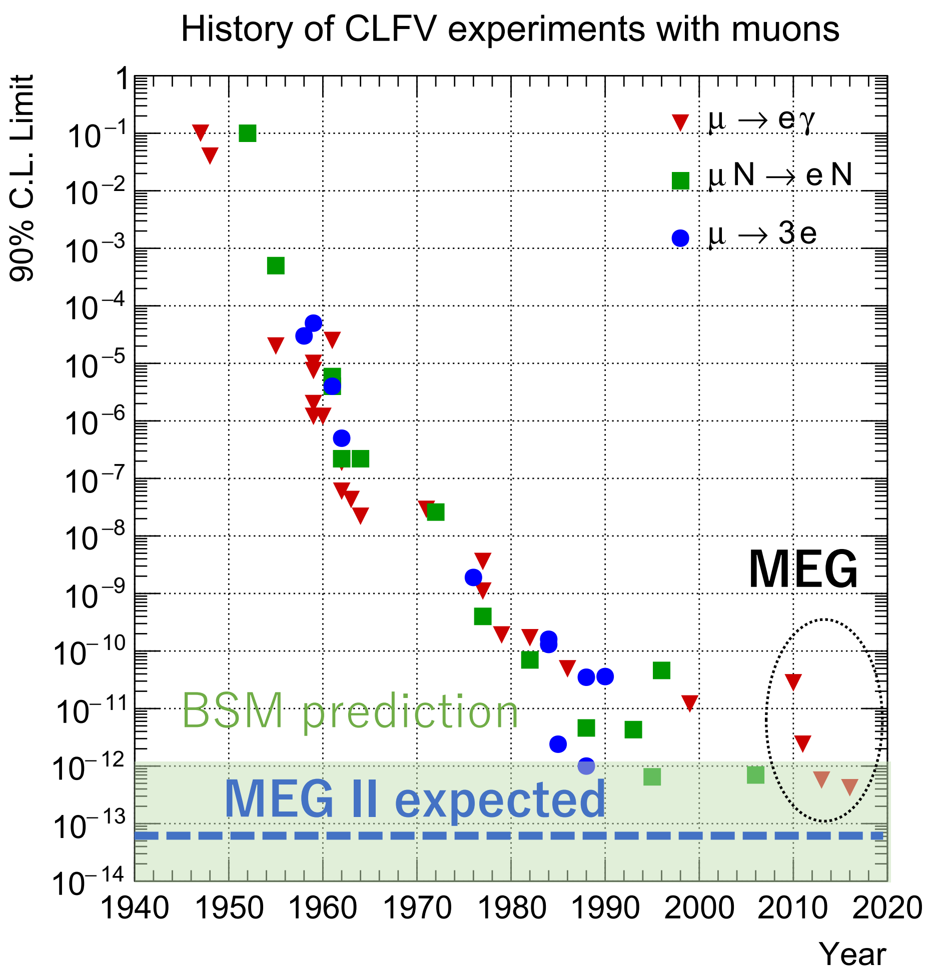
MEG II Experiment

- The MEG II experiment searches for a charged lepton flavor violating (cLFV) decay of a muon, μ→eγ.
- In the SM, the branching ratio of the decay is too small to be detected: Br(μ→eγ) ~ 10^{-54}.
- Many BSM models predict experimentally detectable branching ratios for the decay: Br(μ→eγ) ~ 10^{-14}-10^{-12}.
  - SUSY-GUT
  - SUSY-seesaw
- The MEG experiment gives the most stringent upper limit of 4.2×10^{-13}.
- The MEG II experiment plans to search for the decay with the higher sensitivity by one order of magnitude than MEG.

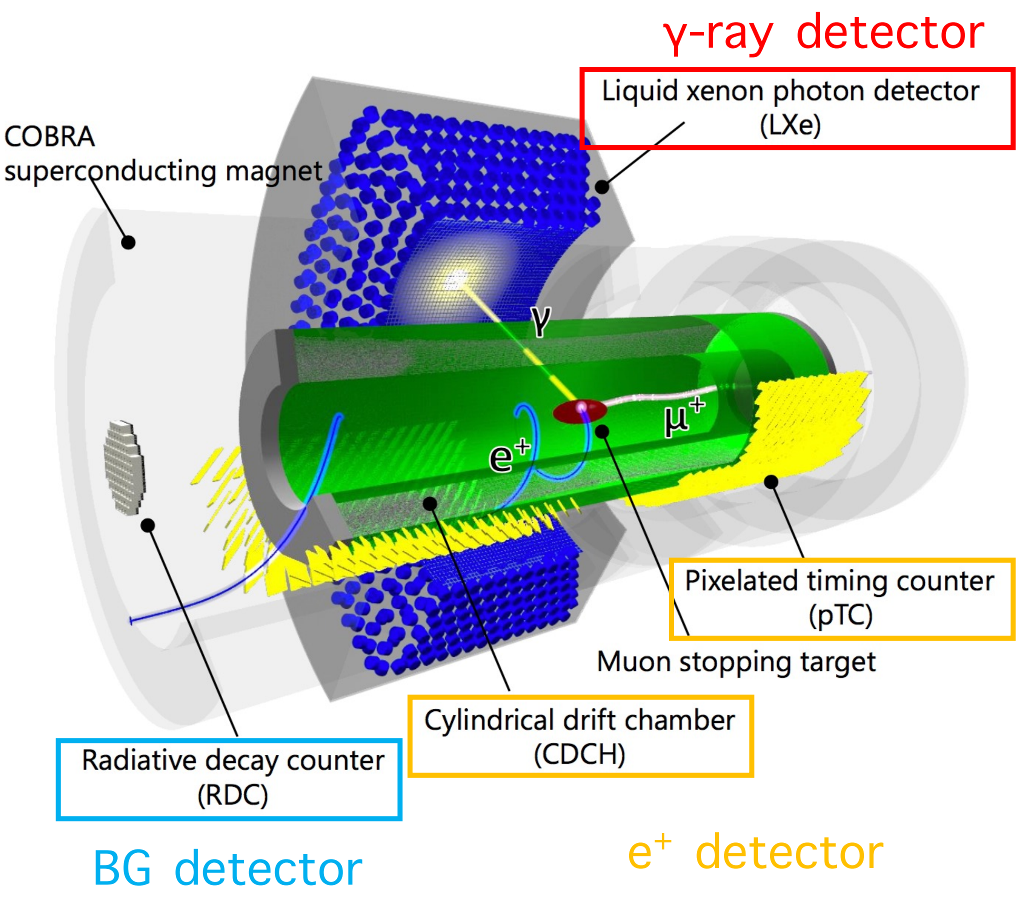


* Ratio of Br is predicted to be

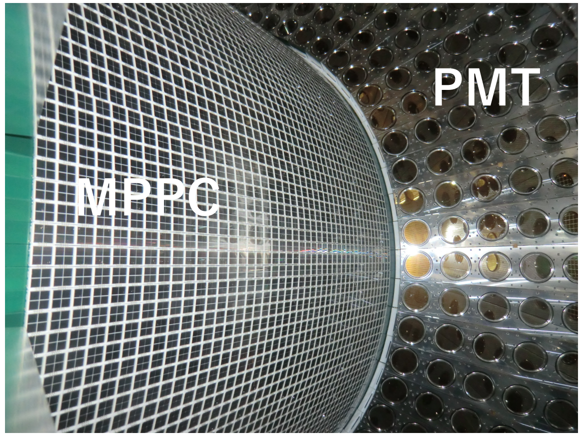
$$\frac{\mathcal{B}(\mu \to \mathrm{eee})}{\mathcal{B}(\mu^+ \to \mathrm{e}^+\gamma)} \approx 6 \times 10^{-3},$$

$$\frac{\mathcal{B}(\mu^- N \to \mathrm{e}^- N)}{\mathcal{B}(\mu^+ \to \mathrm{e}^+\gamma)} \approx 2.6 \times 10^{-3} \ (\text{for N} = \text{Al}).$$

γ-ray Detector of MEG II Experiment

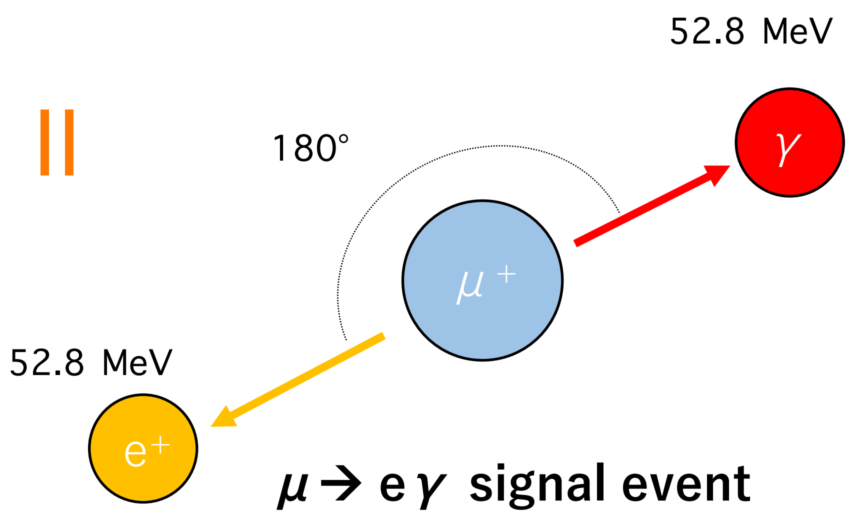


Inside LXe



- Liquid xenon photon detector (LXe) detects energy, position and timing of a γ-ray.
- Scintillation lights from liquid xenon are detected with PMTs and MPPCs.
- In this talk, the pileup analysis for the LXe detector will be reported.

Signal & BG in MEG II

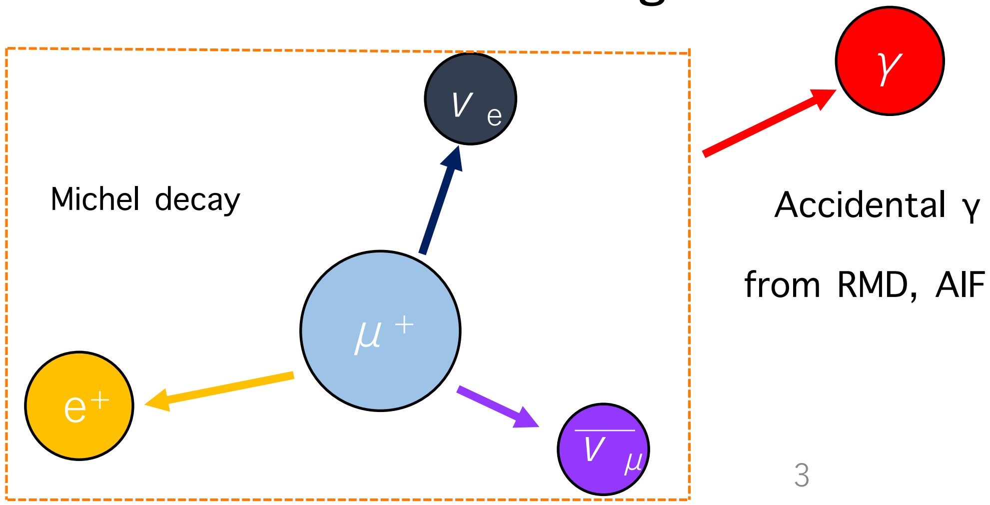


$\mu \to e\gamma$ signal event

- $\mu \to e\gamma$ signal event can be characterized by
  - $E_e = E_\gamma = 52.8$ MeV
  - back to back
  - coincident in time
- **The dominant background derives from the accidental coincidence of e^+ and γ-ray from different μ decays.**
- The number of the accidental background is proportional to the square of the beam rate R_μ:

  $N_{bg} \propto R_\mu^2$

Dominant Background



Source of γ-ray Pileups

- The pileup γ-rays can **greatly affect the energy reconstruction** since it uses information of all channels.

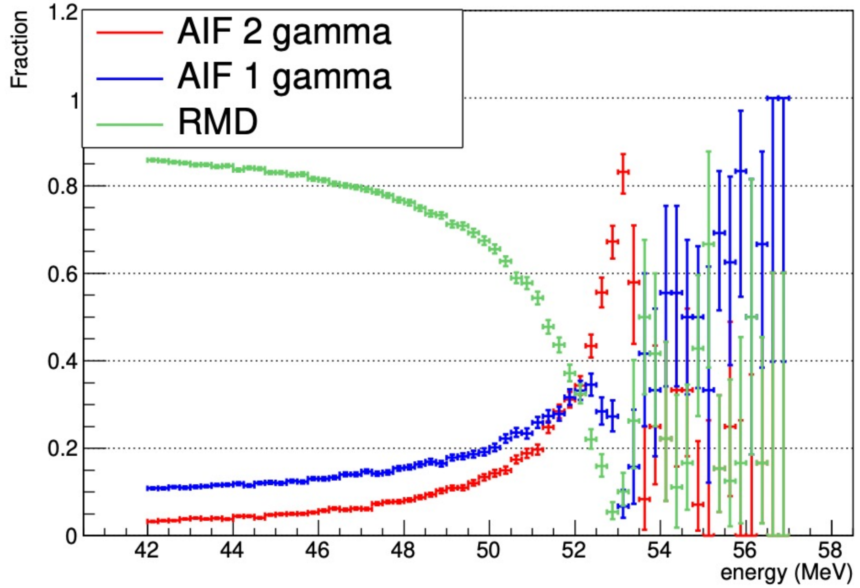
  ↔ The effects on the position and the timing are limited since they are reconstructed using local information.

- The existence of the pileups **increases the number of background events** in the signal region.

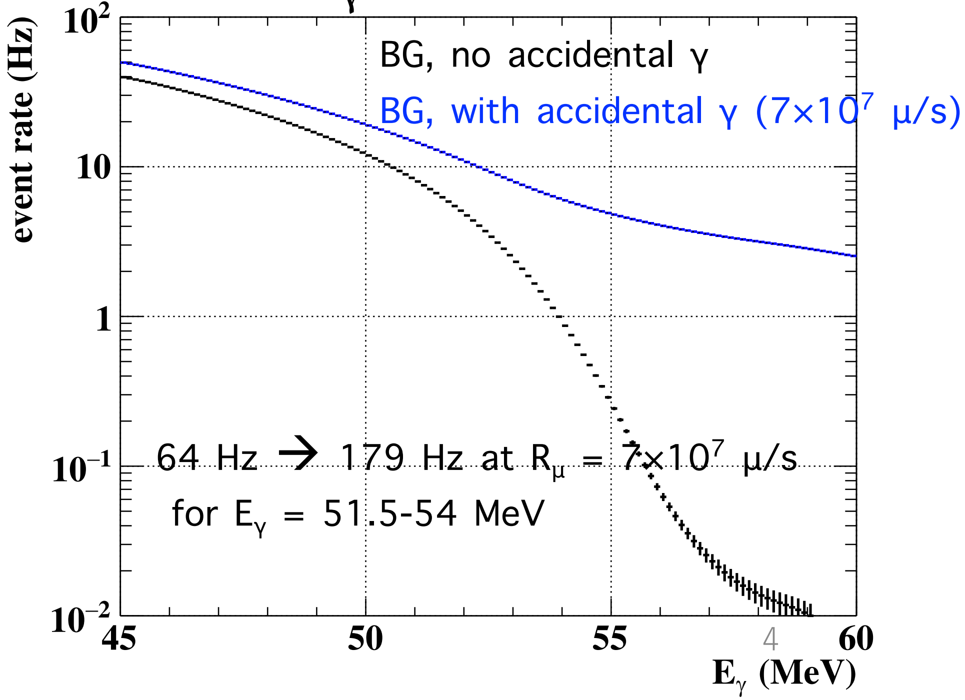
  1. **γ-ray from the same μ decay** → On-timing pileup
     - AIF 2γ: 34% ($\sigma_{E\gamma}$ = 1.7%)
  2. **γ-ray from different μ decays** → Off-timing pileup
     - RMD γ + accidental pileup γ
     - AIF 1γ + accidental pileup γ

- Therefore, the pileup elimination is crucial for the better sensitivity.

Fraction of Background γ-rays



E_γ distribution

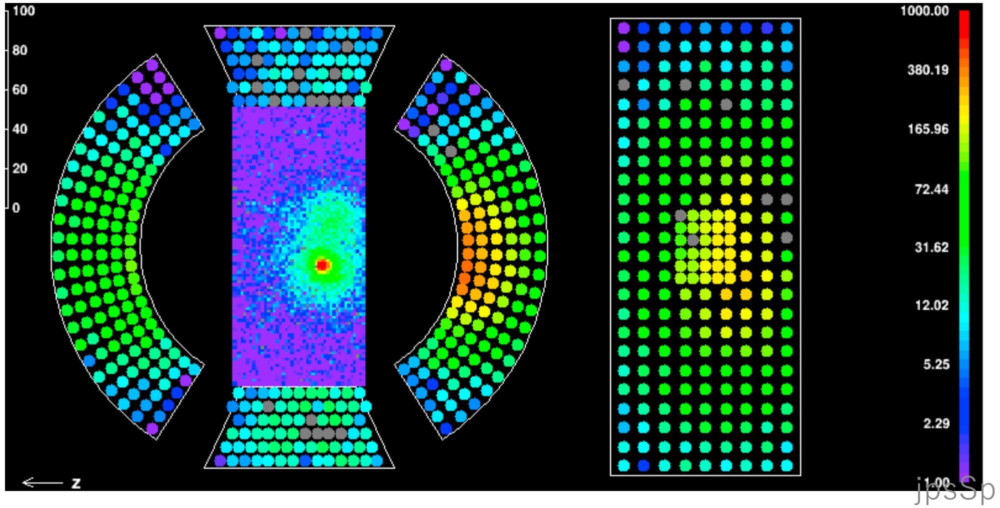


Strategy for Pileup Elimination

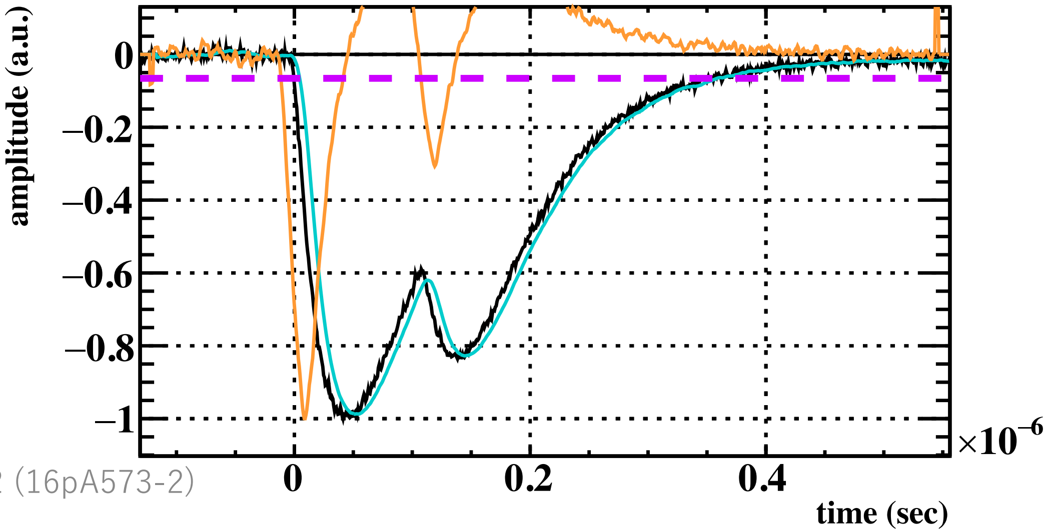
The pileup γ-rays are spatially or temporally detectable.

- **On-timing pileup:** spatial search and event rejection
- **Off-timing pileup:** temporal search and unfolding of waveform

On-timing Pileup

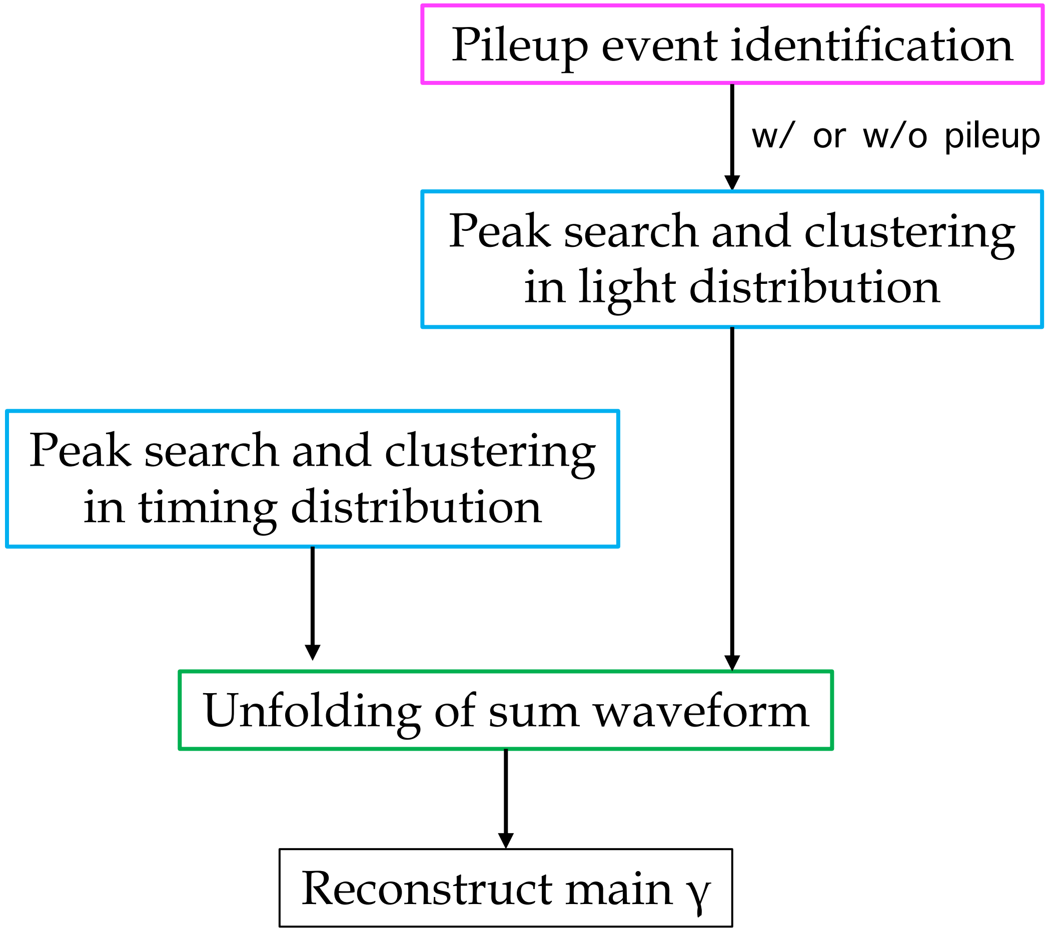


Off-timing Pileup



Pileup Elimination Algorithm

- A series of algorithms was developed for the pileup elimination.
- It consists of three steps:
  1. Pileup event identification with DL-based algorithm
  2. Peak search and clustering of channels in light and timing distributions
  3. Unfolding of sum waveform
- Detailed algorithm was reported in the Autumn meeting of 2021 (15pT3-7).



Topics of This Talk

- The performance of the algorithm was evaluated with MC.
  ← The assumption was too ideal.

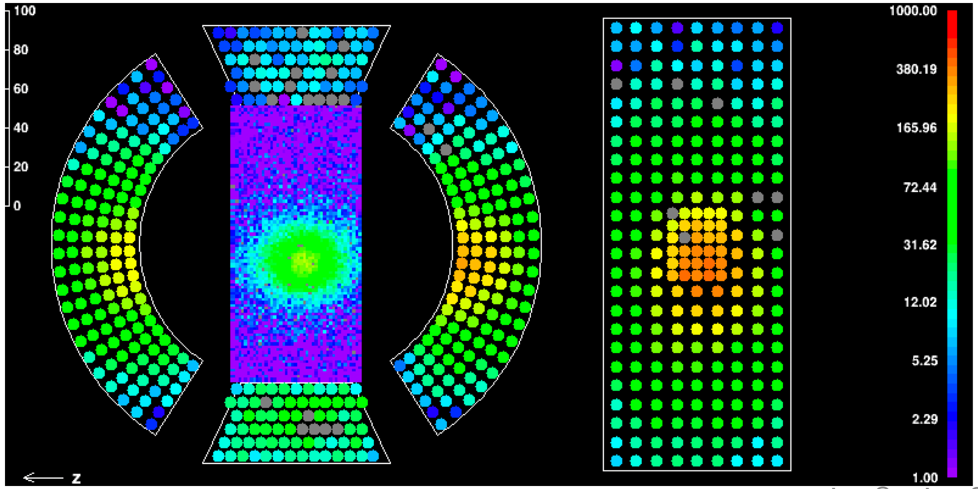
- This talk focuses on the performance evaluation in more realistic situation.
  - Noise
  - Dead channel
  - PDE decrease of the MPPCs
  - Calibration precision

Noise/Dead Channel

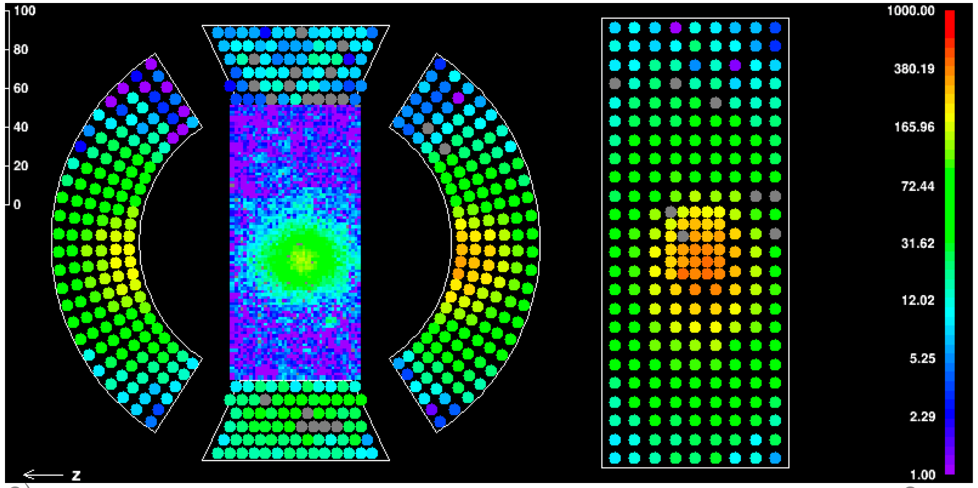
For the realistic simulation, the effects of noise and dead channels were introduced.

- Noise: **mixing noise data** taken in 2021 to simulated waveforms. ← Coherent noise
- Dead channels: **masking information of dead channels** observed in 2021 (30 MPPCs + 28 PMTs).

Simulated Noise (Gaussian White Noise)

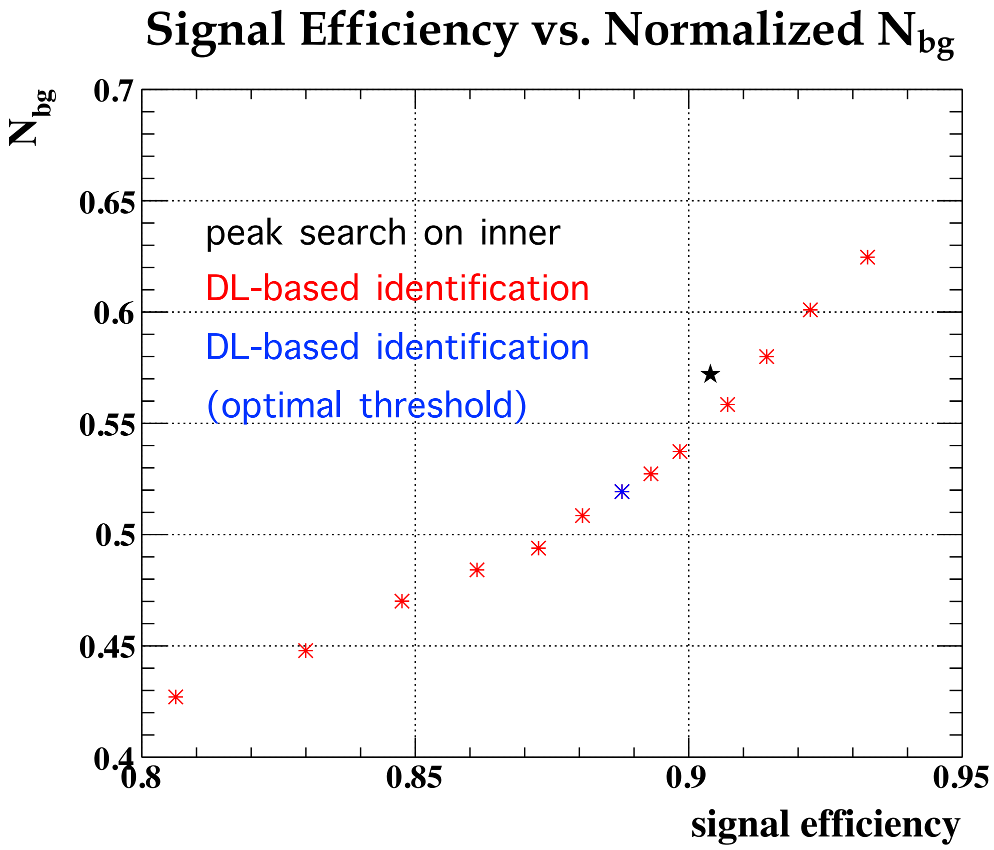


Real Noise



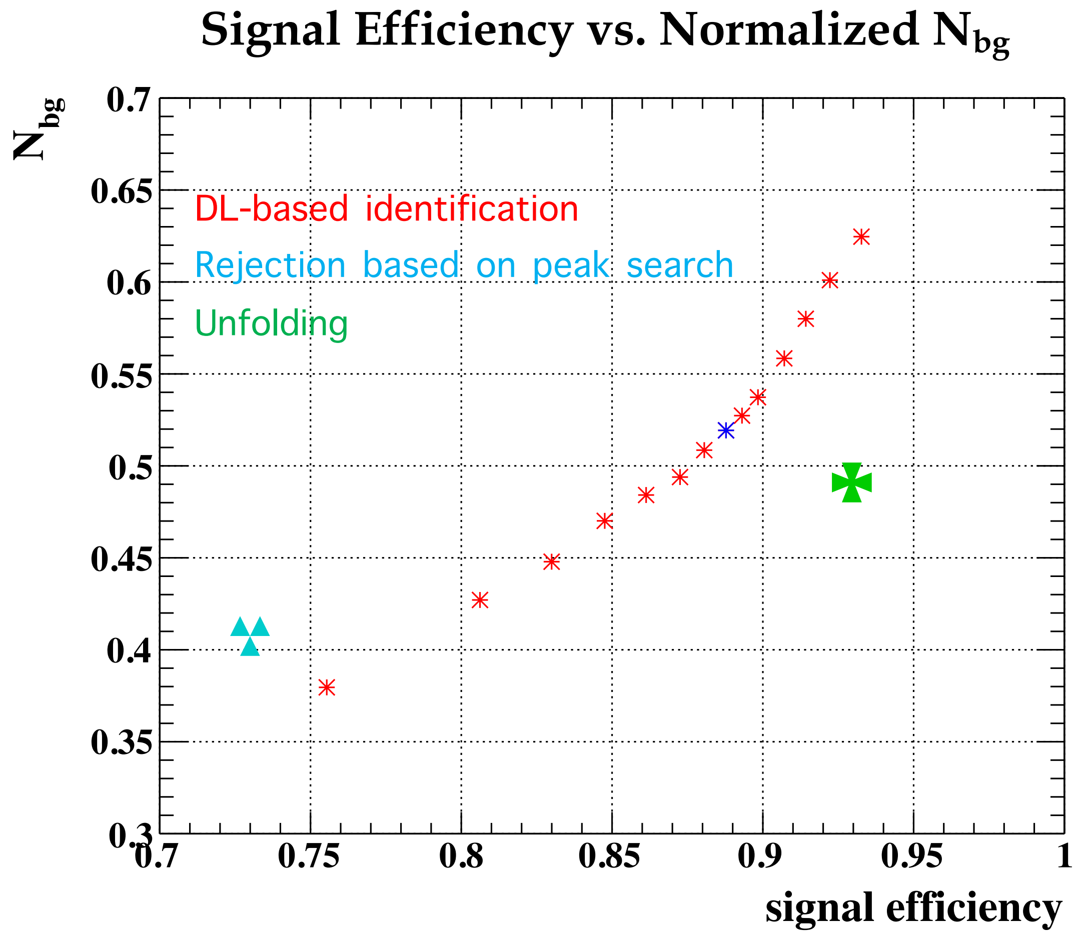
Performance – DL-based Pileup Identification –

- Less background at the same signal efficiency was achieved.
  - Higher detection efficiency especially at deep region
  - Tolerance to the fake peak
- The DL model is superior in terms of **optimized filtering and threshold.**
  ↔ The re-binning and low-pass filter are applied for the peak search to avoid picking up fake peaks, and threshold is set by hand.
- The threshold was optimized to maximize the signal-to-background ratio.



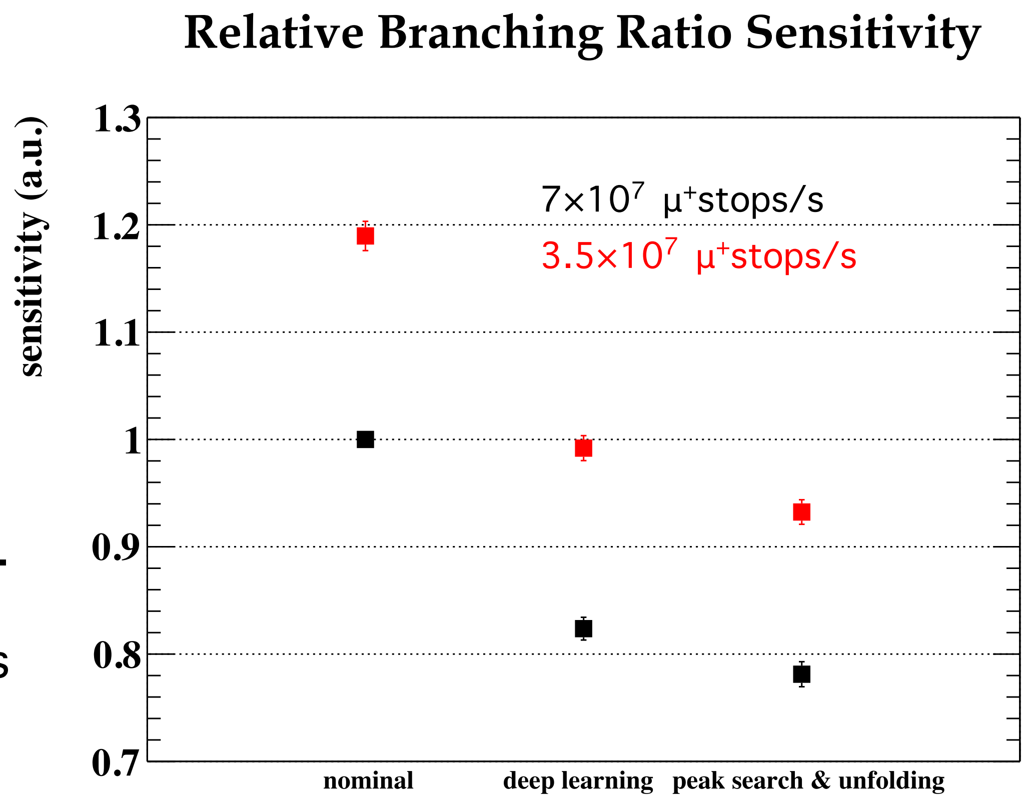
Performance
– Peak Search and Unfolding of Sum Waveform –

- The peak search finds more pileup events.
    - The background events are reduced by 59%.
    - The signal efficiency is also decreased by 27%.
- The unfolding recovers the signal efficiency by 19%.
  ↔ The increase of the backgrounds is only 8%.
- In total, **the backgrounds are reduced by 51%** keeping **the signal efficiency of 93%.**



Effect on Sensitivity

- The DL-based event rejection improves the sensitivity by 18%.
  ← Reduction of on-timing pileups.
- The peak search and the unfolding improves it by 4%.
  ← Less backgrounds and recovery of the signal efficiency.
- In total, **22% improvement** is achieved at 7×10^7 μ^+stops/s and 26% at 3.5×10^7 μ^+stops/s.

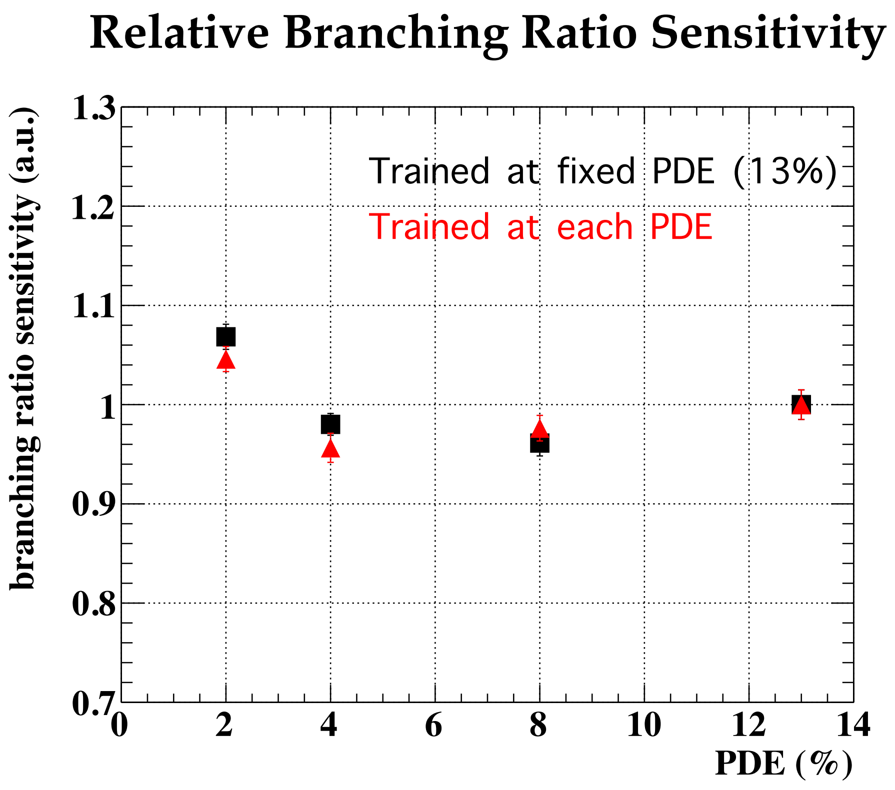


Effect of PDE Degradation

- The PDEs of the MPPCs were found to be degraded probably due to the radiation damage.
- The sensitivity was evaluated assuming different PDEs.
- No tendency due to the PDE degradation.
- Fluctuation from -4% to +7%.
  ← Given by the balance between N_{bg} and signal efficiency
- The performance does not depend on the PDE at training of DL.

Table 5.4 Number of backgrounds and signal efficiency for different MPPC PDEs ($E_\gamma =$ 51.5–54 MeV) when the deep learning model is trained at a fixed PDE of 13% or each PDE.

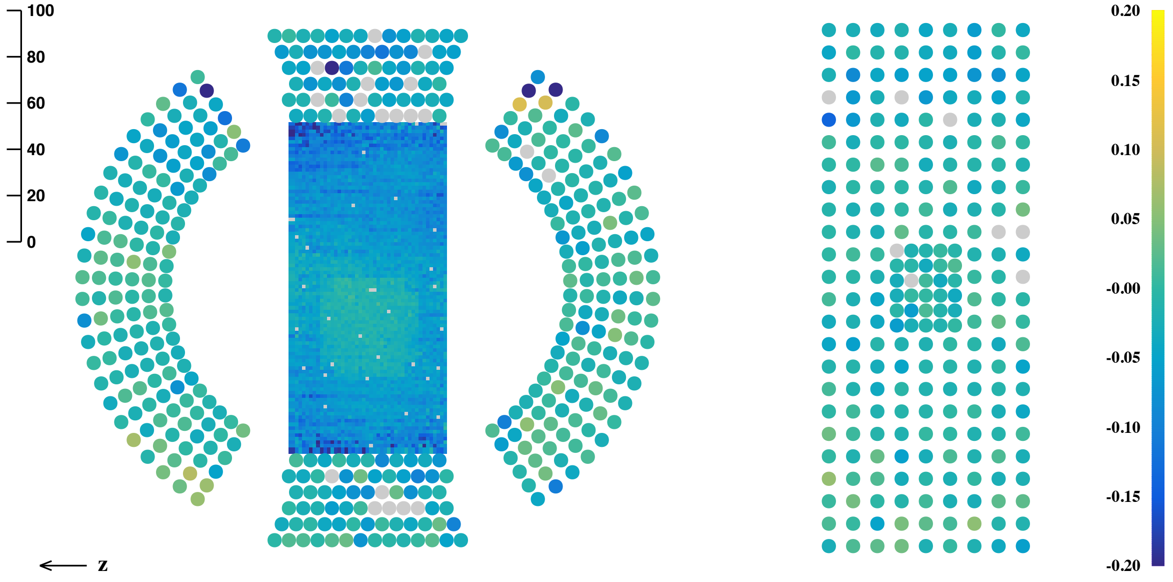
PDE	Trained at PDE 13%		Trained at each PDE	
	N_{bg}	signal efficiency	N_{bg}	signal efficiency
13%	0.491	0.930	0.491	0.930
8%	0.468	0.950	0.486	0.956
4%	0.489	0.944	0.485	0.942
2%	0.584	0.962	0.576	0.962



Effect of Calibration Precision

- The number of photons can fluctuate and be biased due to the statistical and systematic uncertainties of the calibration.
- The performance was evaluated including the statistical uncertainty up to 10% and the systematic uncertainty.
  ← The statistical uncertainty was estimated to be 4% for the calibration.
- **No degradation was observed.**

Systematic Uncertainty of Calibration



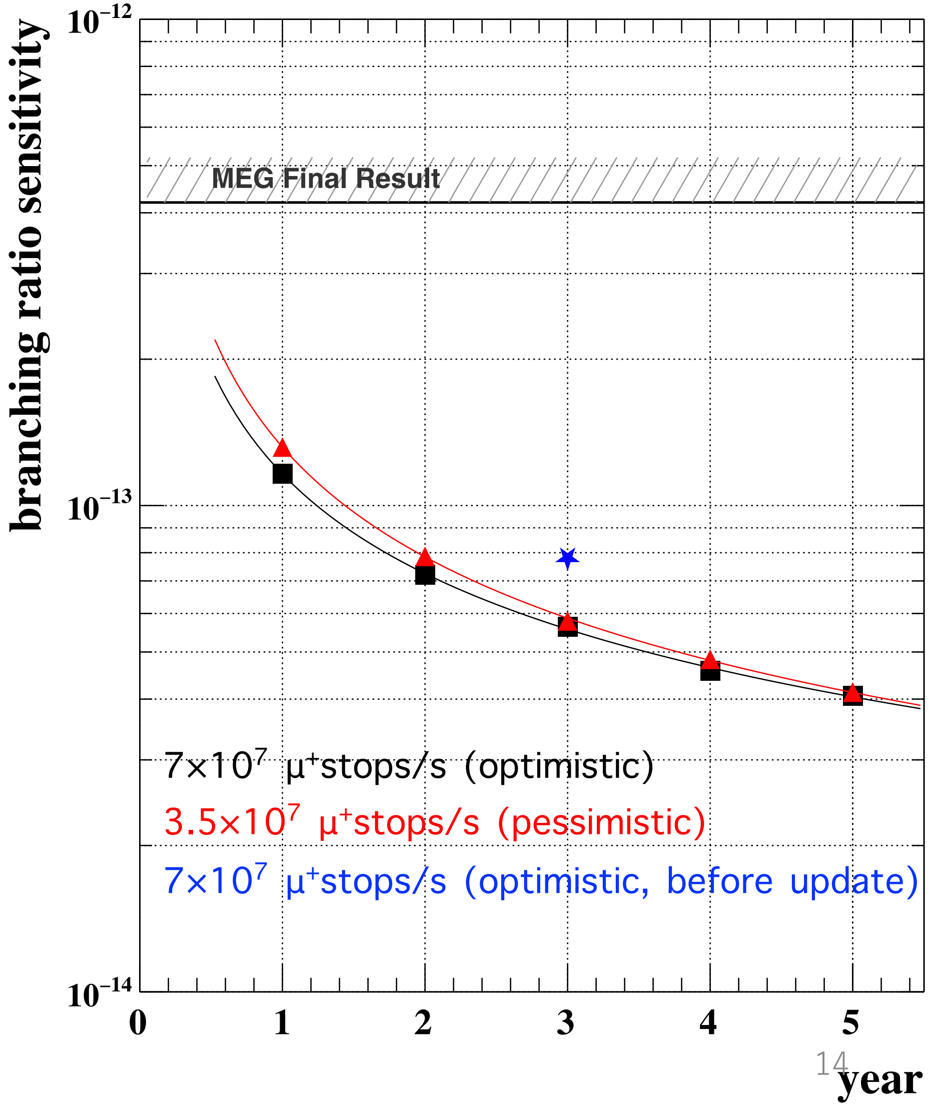
Systematic uncertainty estimated by two different calibration methods

MEG II Projected Sensitivity

- The branching ratio sensitivity was calculated assuming two scenarios for PDE degradation:
  - Optimistic: 7×10^{7} μ^{+}stops/s, PDE saturation at 2%
  - Pessimistic: 3.5×10^{7} μ^{+}stops/s, No PDE saturation
- The sensitivity was estimated to be
  - 5.6×10^{-14} at 7×10^{7} μ^{+}stops/s
  - 5.8×10^{-14} at 3.5×10^{7} μ^{+}stops/s

  ← Equivalent even with halved statistics mainly due to better position efficiency (65% → 74%) and less backgrounds.

  ~10 times higher sensitivity than that of MEG



Summary

- The MEG II experiment searches $\mu \rightarrow e\gamma$ decay.
- The pileup analysis for the LXe detector is important to reduce the γ-ray background events in the signal region.
- The new algorithm for the pileup elimination was developed.
- It consists of three steps:
    1. Pileup event identification with DL-based algorithm
    2. Peak search and clustering of channels in charge and timing distributions
    3. Unfolding of sum waveform

Summary

- The performance of the new algorithm was evaluated in more realistic situation.
  - **Sensitivity improvement by 22-26%** compared to the previous algorithm.
  - No effect from PDE decrease and calibration uncertainty

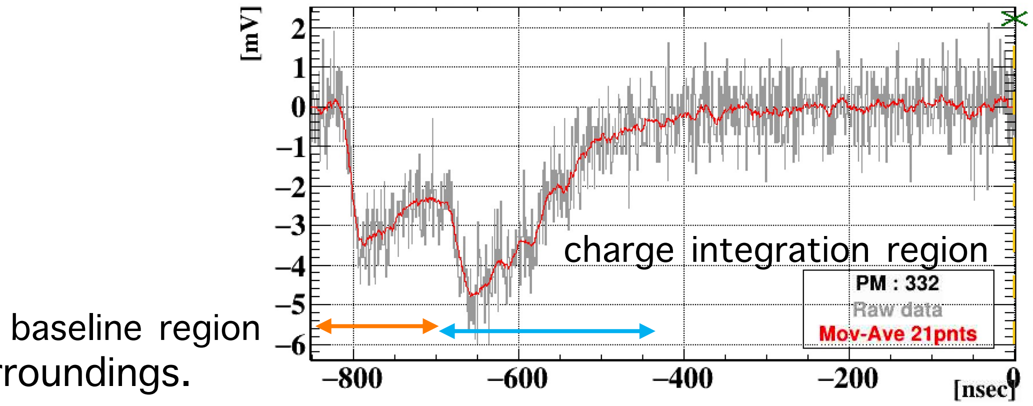
- The branching ratio sensitivity of the MEG II experiment was evaluated with the updates.
  - 5.6×10^{-14} at 7×10^{7} μ^{+}stops/s for three years
  - 5.8×10^{-14} at 3.5×10^{7} μ^{+}stops/s for three years

  ~10 times higher sensitivity than that of MEG

- The performance will be evaluated using data in 2021.

Backup Slides

Step1: DL-based Pileup Identification



Pre-processing is applied for the inputs.

- **Dead channel recovery**

  Values of dead channels are estimated by the mean of surroundings.
  ← Tolerance to the effect of dead channels

- **Normalization**

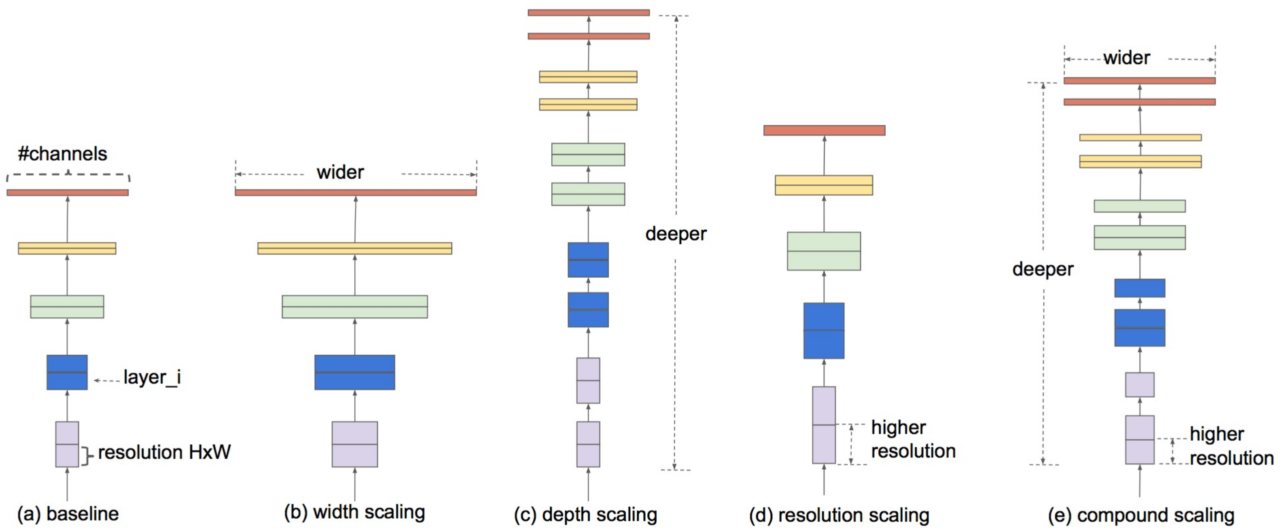
  Normalized by the maximum value, i.e. all input values are no more than 1.
  ← Suppress the energy dependence

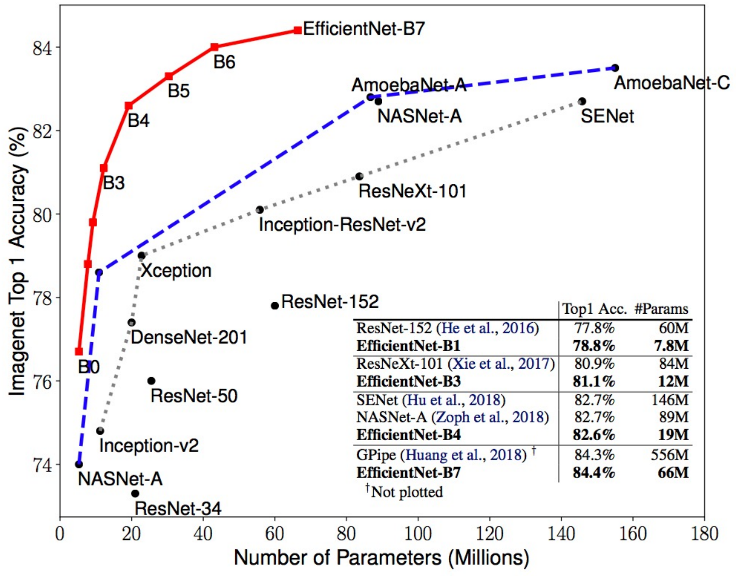
- **Cut off**

  Negative charges are set to 0, i.e. all input values are no less than 0.
  ← Due to a failure of the baseline calculation

EfficientNet

- A type of CNN
- https://arxiv.org/pdf/1905.11946.pdf
- The performance of DL models can be improved by scaling up the original model.
- The optimal scaling method was investigated, and they introduced the efficiently scaled models.
  → A better performance with less parameters was achieved compared to other models.





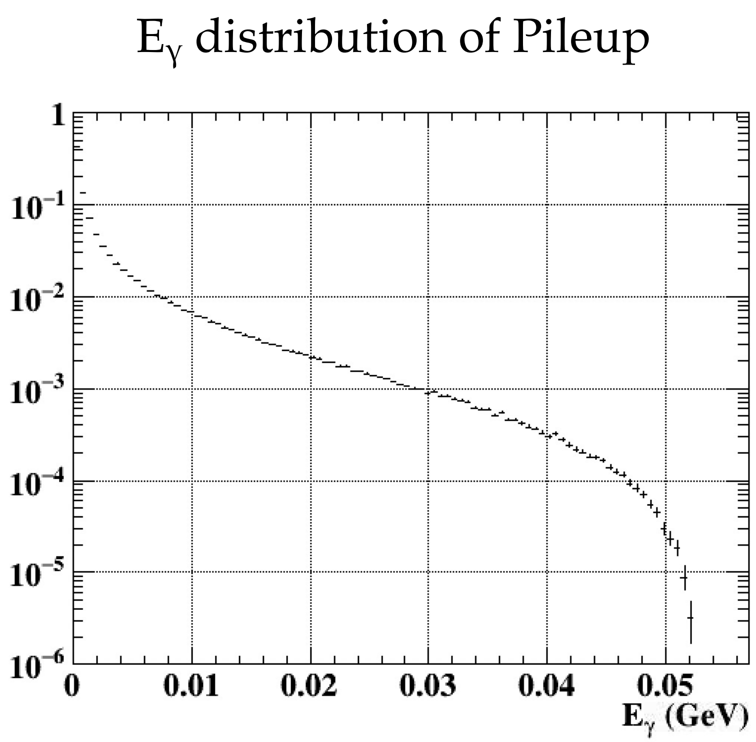
	Top1 Acc.	#Params
ResNet-152 (He et al., 2016)	77.8%	60M
EfficientNet-B1	**78.8%**	**7.8M**
ResNeXt-101 (Xie et al., 2017)	80.9%	84M
EfficientNet-B3	**81.1%**	**12M**
SENet (Hu et al., 2018)	82.7%	146M
NASNet-A (Zoph et al., 2018)	82.7%	89M
EfficientNet-B4	**82.6%**	**19M**
GPipe (Huang et al., 2018) †	84.3%	556M
EfficientNet-B7	**84.4%**	**66M**

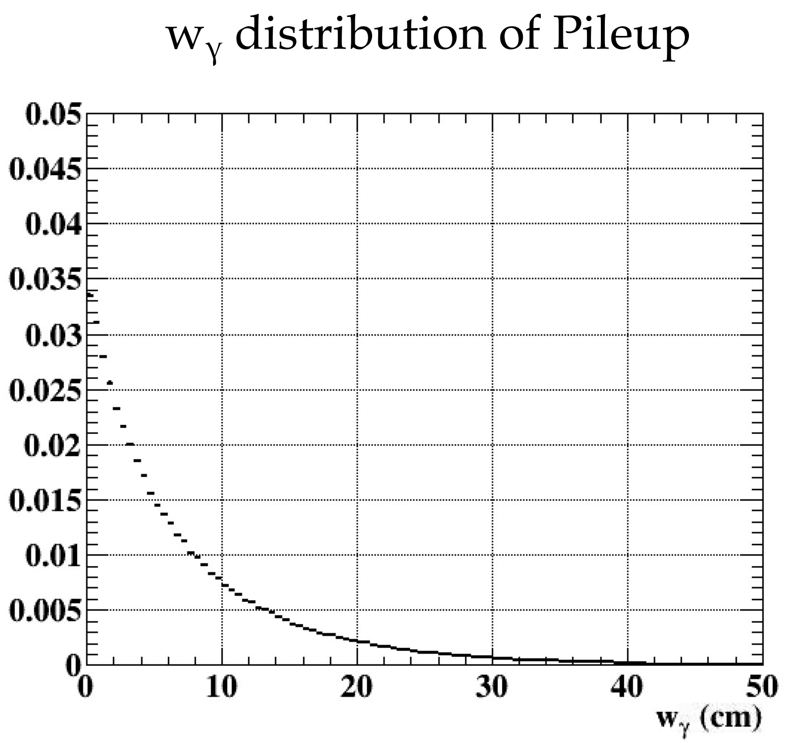
† Not plotted

Model Architecture

```
==========================================================================================================================================
Layer (type:depth-idx)                                        Input Shape               Output Shape              Kernel Shape
==========================================================================================================================================
Model                                                         --                        --                        --
├─EfficientNet: 1-1                                           [1, 1, 93, 44]            [1, 1280]                 --
│    └─Sequential: 2-1                                        [1, 1, 93, 44]            [1, 1280, 3, 2]           --
│    │    └─ConvBN: 3-1                                       [1, 1, 93, 44]            [1, 32, 46, 21]           --
│    │    └─Swish: 3-2                                        [1, 32, 46, 21]           [1, 32, 46, 21]           --
│    │    └─BMConvBlock: 3-3                                  [1, 32, 46, 21]           [1, 16, 46, 21]           --
│    │    └─BMConvBlock: 3-4                                  [1, 16, 46, 21]           [1, 24, 23, 11]           --
│    │    └─BMConvBlock: 3-5                                  [1, 24, 23, 11]           [1, 24, 23, 11]           --
│    │    └─BMConvBlock: 3-6                                  [1, 24, 23, 11]           [1, 40, 12, 6]            --
│    │    └─BMConvBlock: 3-7                                  [1, 40, 12, 6]            [1, 40, 12, 6]            --
│    │    └─BMConvBlock: 3-8                                  [1, 40, 12, 6]            [1, 80, 6, 3]             --
│    │    └─BMConvBlock: 3-9                                  [1, 80, 6, 3]             [1, 80, 6, 3]             --
│    │    └─BMConvBlock: 3-10                                 [1, 80, 6, 3]             [1, 80, 6, 3]             --
│    │    └─BMConvBlock: 3-11                                 [1, 80, 6, 3]             [1, 112, 6, 3]            --
│    │    └─BMConvBlock: 3-12                                 [1, 112, 6, 3]            [1, 112, 6, 3]            --
│    │    └─BMConvBlock: 3-13                                 [1, 112, 6, 3]            [1, 112, 6, 3]            --
│    │    └─BMConvBlock: 3-14                                 [1, 112, 6, 3]            [1, 192, 3, 2]            --
│    │    └─BMConvBlock: 3-15                                 [1, 192, 3, 2]            [1, 192, 3, 2]            --
│    │    └─BMConvBlock: 3-16                                 [1, 192, 3, 2]            [1, 192, 3, 2]            --
│    │    └─BMConvBlock: 3-17                                 [1, 192, 3, 2]            [1, 192, 3, 2]            --
│    │    └─BMConvBlock: 3-18                                 [1, 192, 3, 2]            [1, 320, 3, 2]            --
│    │    └─ConvBN: 3-19                                      [1, 320, 3, 2]            [1, 1280, 3, 2]           --
│    │    └─Swish: 3-20                                       [1, 1280, 3, 2]           [1, 1280, 3, 2]           --
│    └─Sequential: 2-2                                        [1, 1280, 3, 2]           [1, 1280]                 --
│    │    └─AdaptiveAvgPool2d: 3-21                           [1, 1280, 3, 2]           [1, 1280, 1, 1]           --
│    │    └─Flatten: 3-22                                     [1, 1280, 1, 1]           [1, 1280]                 --
├─Sequential: 1-2                                             [1, 1280]                 [1, 1]                    --
│    └─Dropout: 2-3                                           [1, 1280]                 [1, 1280]                 --
│    └─Linear: 2-4                                            [1, 1280]                 [1, 256]                  [1280, 256]
│    └─ReLU: 2-5                                              [1, 256]                  [1, 256]                  --
│    └─Linear: 2-6                                            [1, 256]                  [1, 1]                    [256, 1]
│    └─Sigmoid: 2-7                                           [1, 1]                    [1, 1]                    --
==========================================================================================================================================
Total params: 4,335,165
Trainable params: 4,335,165
Non-trainable params: 0
Total mult-adds (M): 38.45
==========================================================================================================================================
Input size (MB): 0.02
Forward/backward pass size (MB): 9.42
Params size (MB): 17.34
Estimated Total Size (MB): 26.78
==========================================================================================================================================
```

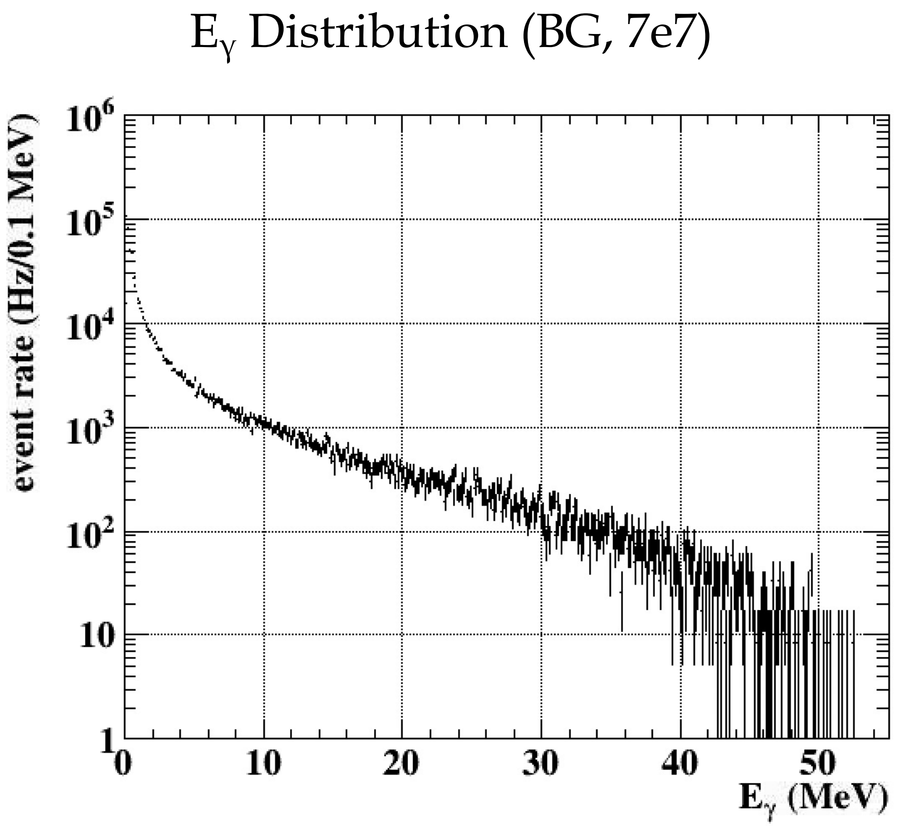
Pileup γ-rays

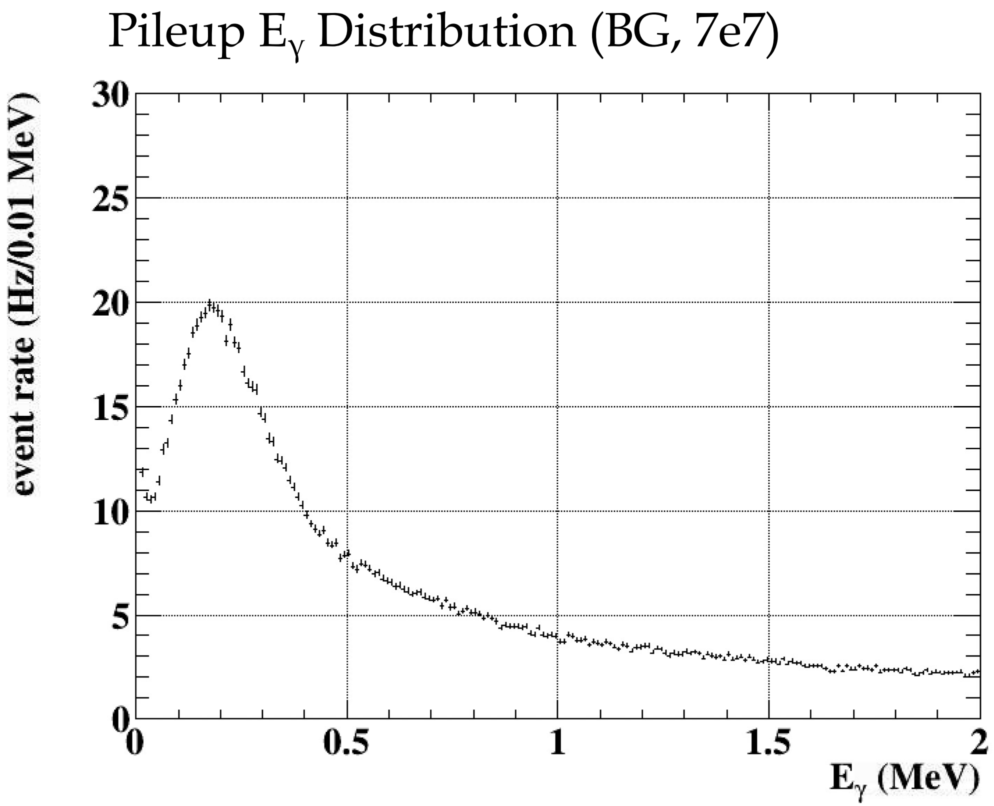




- A small energy and a shallow conversion point are dominant.

Pileup γ-rays





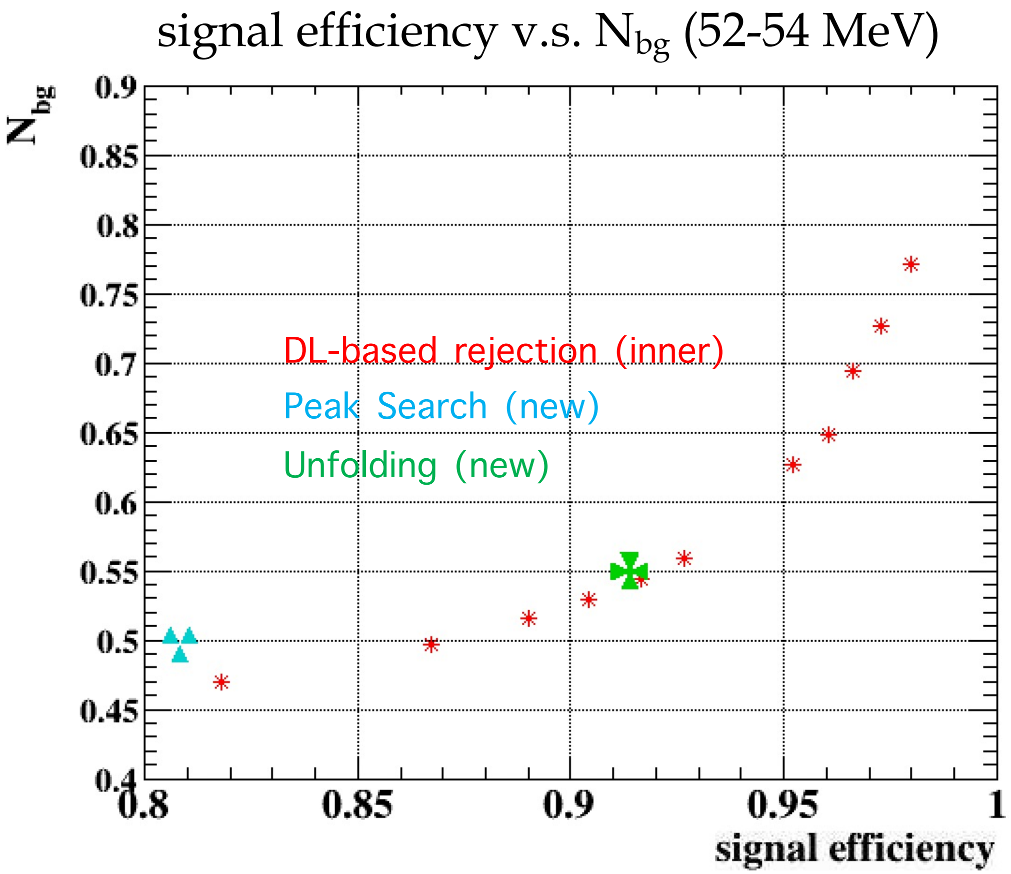
The pileup analysis can find pileups whose energies are more than 0.2 MeV.

The event rate of γ-ray hits for $E_\gamma > 0.2$ MeV is 0.7 MHz.

$(|u| < 25\ \text{cm}) \wedge (|v| < 71\ \text{cm}) \wedge (0 < w < 38.5\ \text{cm})$

Signal Efficiency

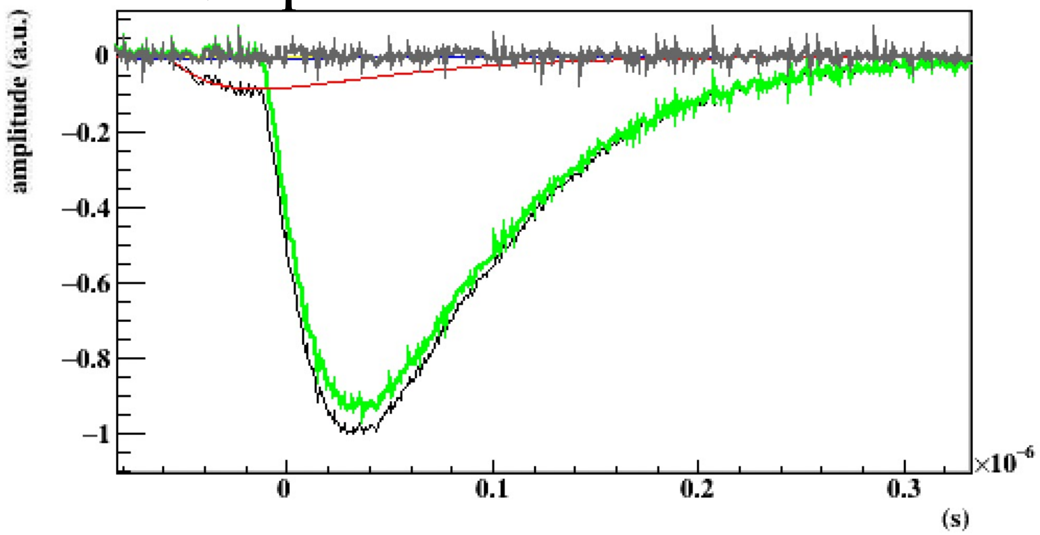
- The number of backgrounds for the new unfolding method is equivalent to the DL-based rejection at the same signal efficiency.



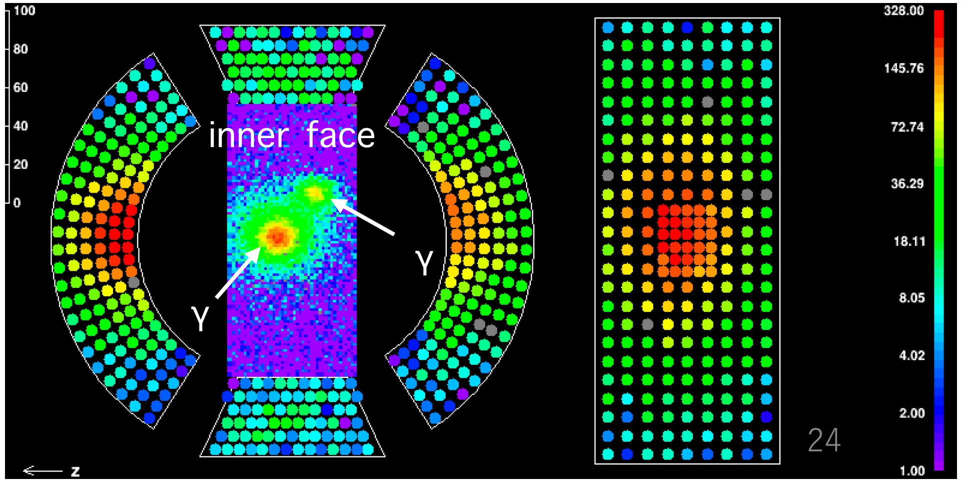
Previous Algorithm for Pileup Elimination

- There were algorithms already implemented.
- It consists of two steps:
  1. **Unfolding with sum waveform fitting**
     - Take sums of MPPC and PMT channels
     - Fit a template waveform
     - The waveforms are unfolded.
     - Sensitive to off-timing pileups
  2. **Rejection with peak search in charge distribution**
     - Search peaks whose charges are larger than a threshold on inner face.
     - The events with pileups are rejected.
     - Sensitive to on-timing pileups
- They are processed independently.

Example of MPPC Sum Waveform

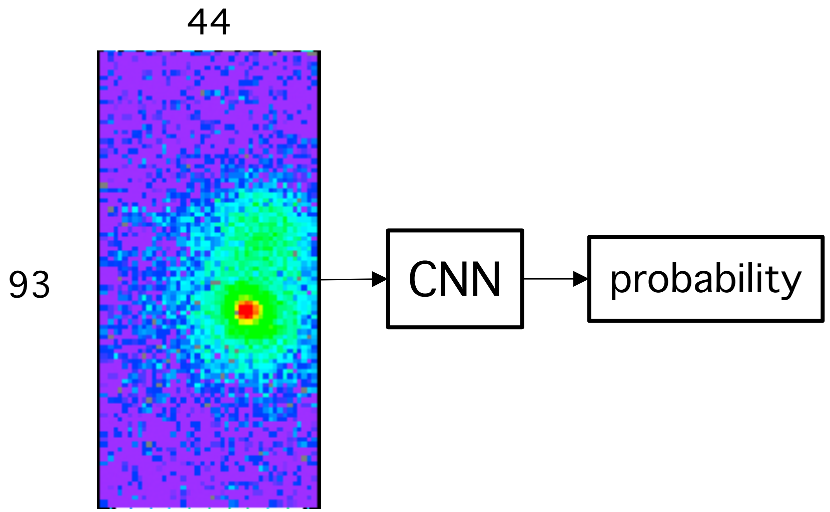


Example of Charge Distribution



Step1: DL-based Pileup Identification

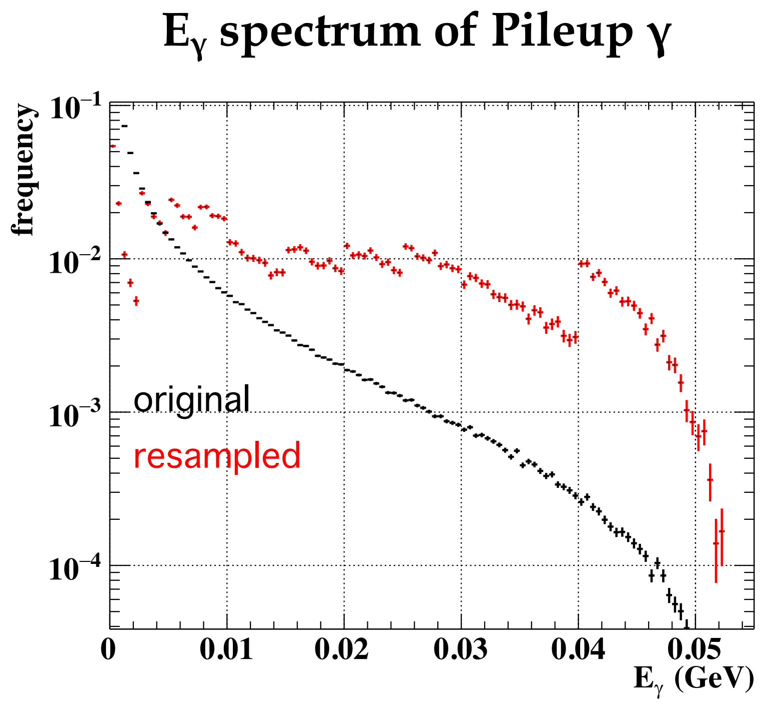
- The deep learning-based pileup identification method was implemented.
- The DL model judge whether the event likely has pileup γ-rays.
- Model architecture
  - Based on Convolutional Neural Network
  - Input: light distribution on inner face (93 × 44 pixels)
  - Output: Probability to include pileup γ-rays

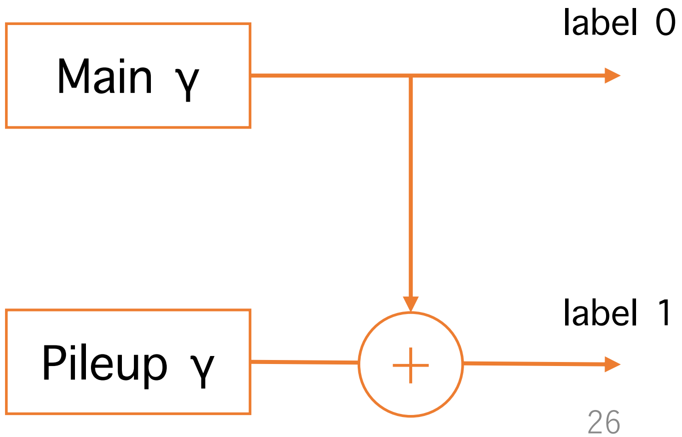


Step1: DL-based Pileup Identification

Dataset

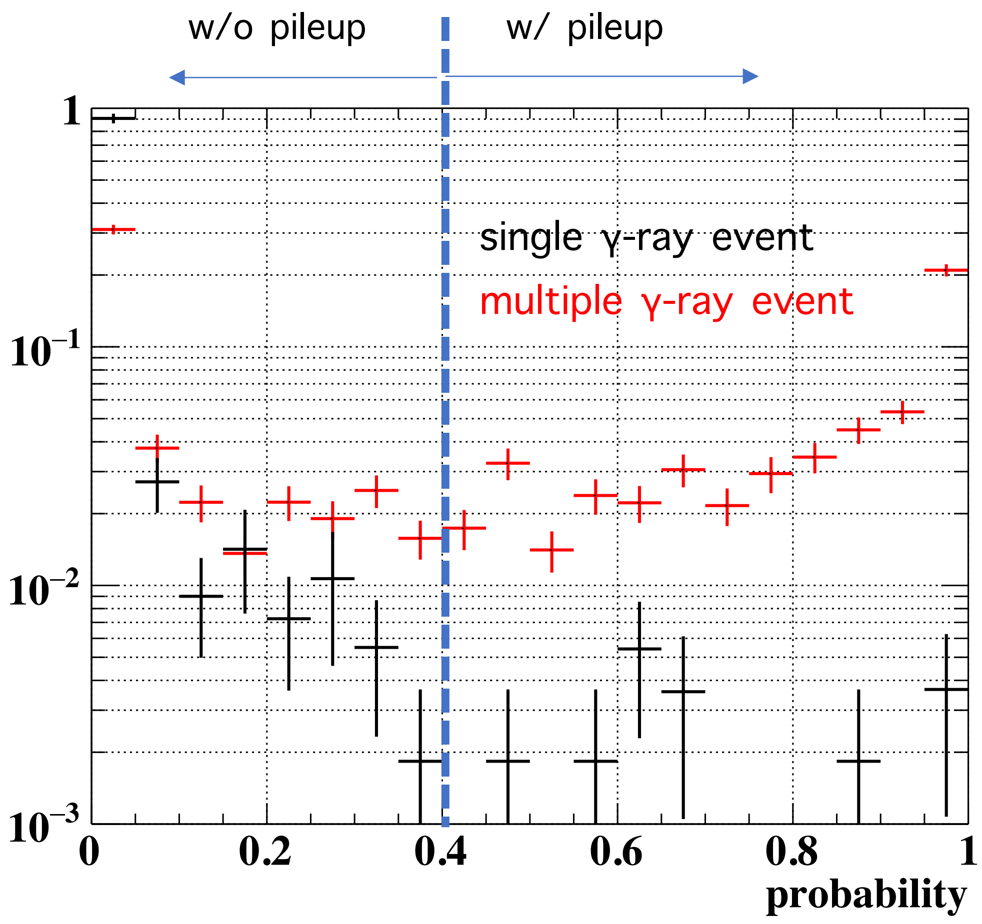
- Generated with MC
  - Main γ (uniform energy in 20-100 MeV, 1.6×10^5 events)
    ← Suppress the energy dependence
  - Pileup γ (resampled from the original pileup γ, 1.2×10^5 events)
- Two types of data are prepared by mixing them.
  - Only main γ : labeled as “0”
  - Main and pileup γ : labeled as “1”





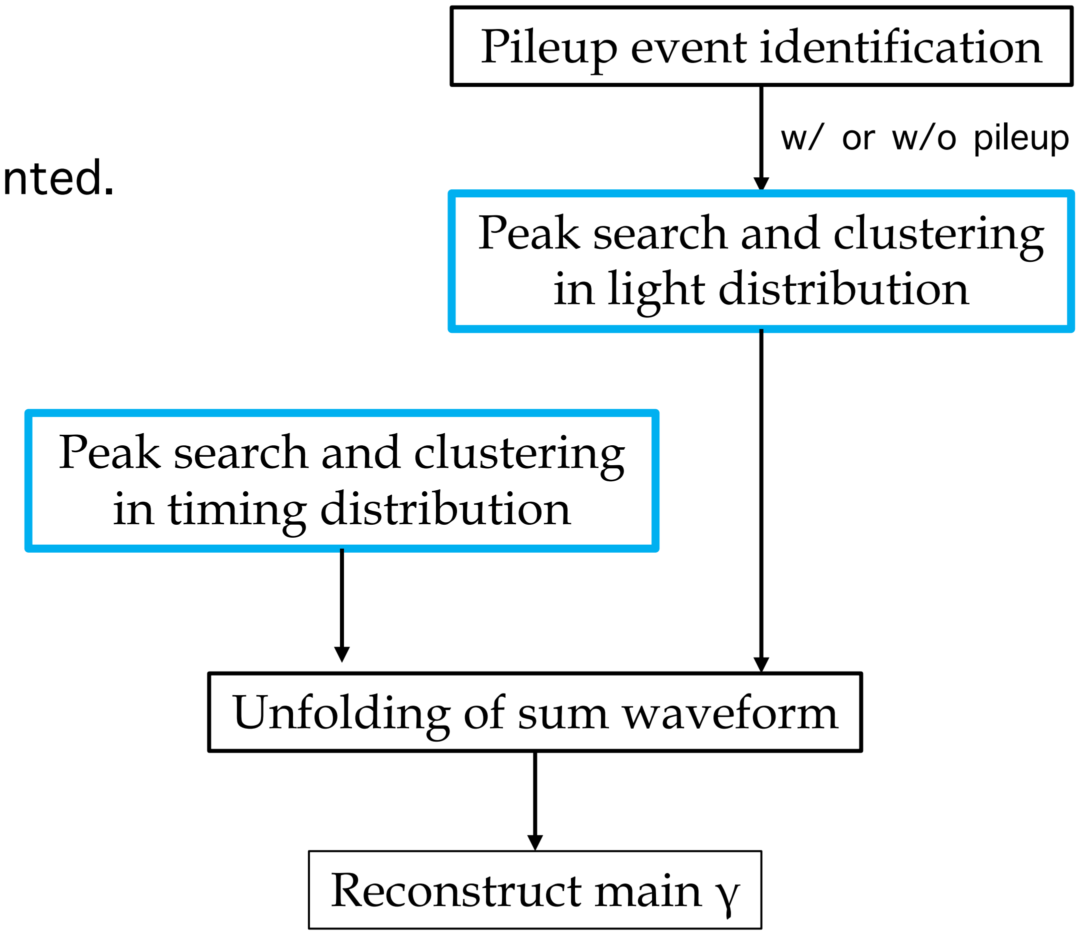
Step1: DL-based Pileup Identification

- The DL model was trained to predict
  - Single γ-ray event: 0
  - Multiple γ-ray event: 1
    ← The peak around 0 is due to low energy pileup γ-rays which are too difficult to be identified.
- The threshold to decide whether an event has pileup γ-rays or not was set to maximize the signal-to-background ratio.



Step2: Peak Search and Clustering

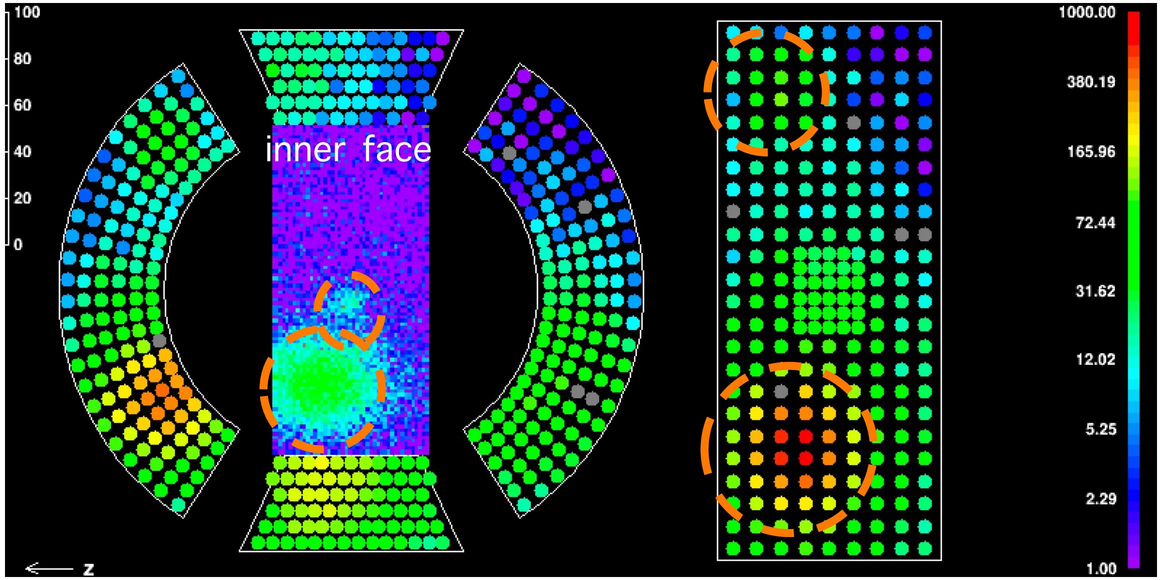
- Two peak search and clustering methods are implemented.
  - **Search in light distribution**
    → search for on-timing pileups
  - **Search in timing distribution**
    → search for off-timing pileups



Step2: Peak Search and Clustering

- Pileups are searched for in the light distribution on the inner and outer faces.
- A peak search is performed and channels whose light yields are larger than a threshold are clustered.
- Sensitive to the on-timing pileups.

Light Distribution



outer face

Step2: Peak Search and Clustering

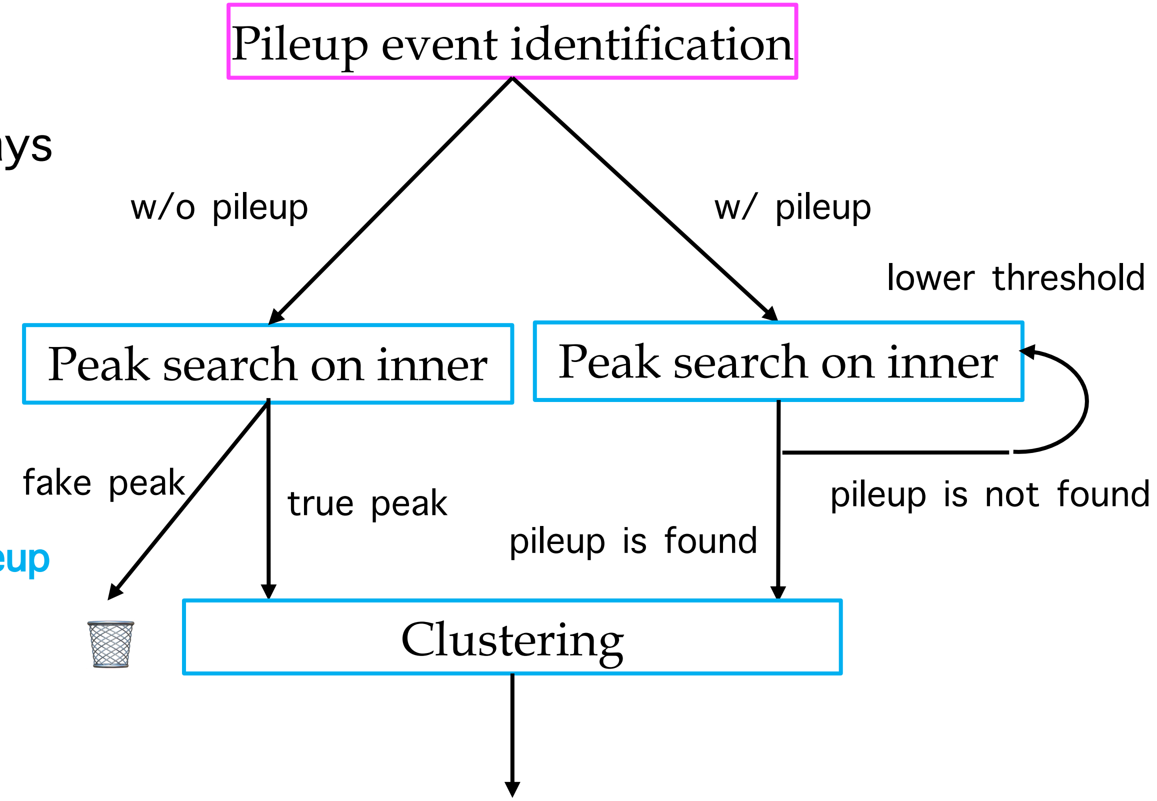
The information whether the event likely has pileup γ-rays from the DL model is used to **select the peak search method** in the light distribution on the inner face.

- **"w/o pileup"**: peak search with the nominal threshold, and **peaks with small energies are discarded.**

← Tolerant to fake peaks.

- **"w/ pileup"**: peak search **reducing the threshold until a pileup γ-ray is found.**

← The deep pileup γ-rays can be found with the lower threshold.



Step2: Peak Search and Clustering

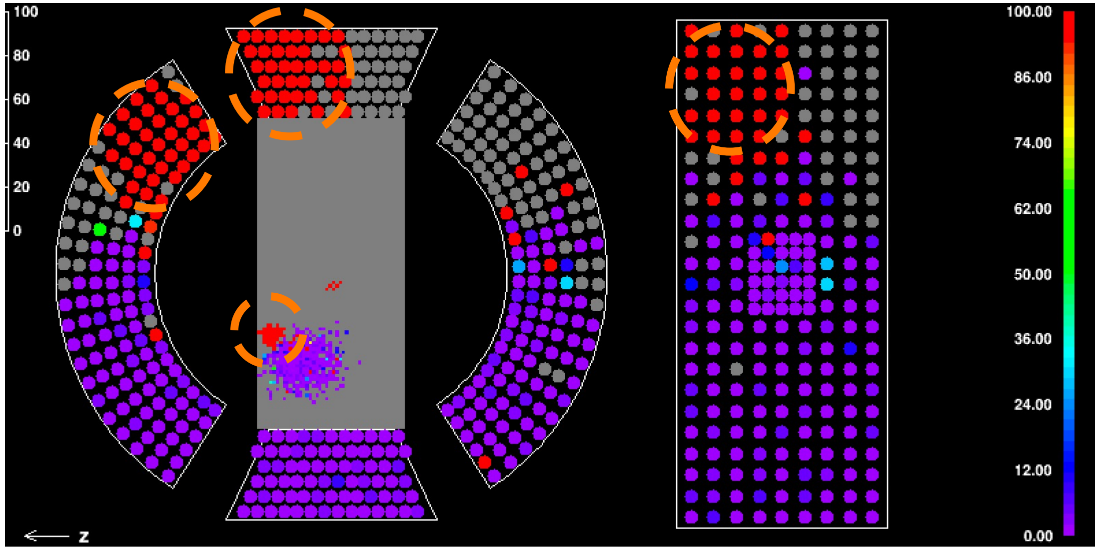
- **Pileups are searched for in the timing χ^2 distribution on all the faces.**
- The χ^2 of i-th channel is defined as

$$\chi_i^2 = \frac{(t_\gamma - t_i)^2}{\sigma_i^2},$$

where t_γ is the reconstructed γ timing, and t_i and σ_i are the timing and its uncertainty of the channel.

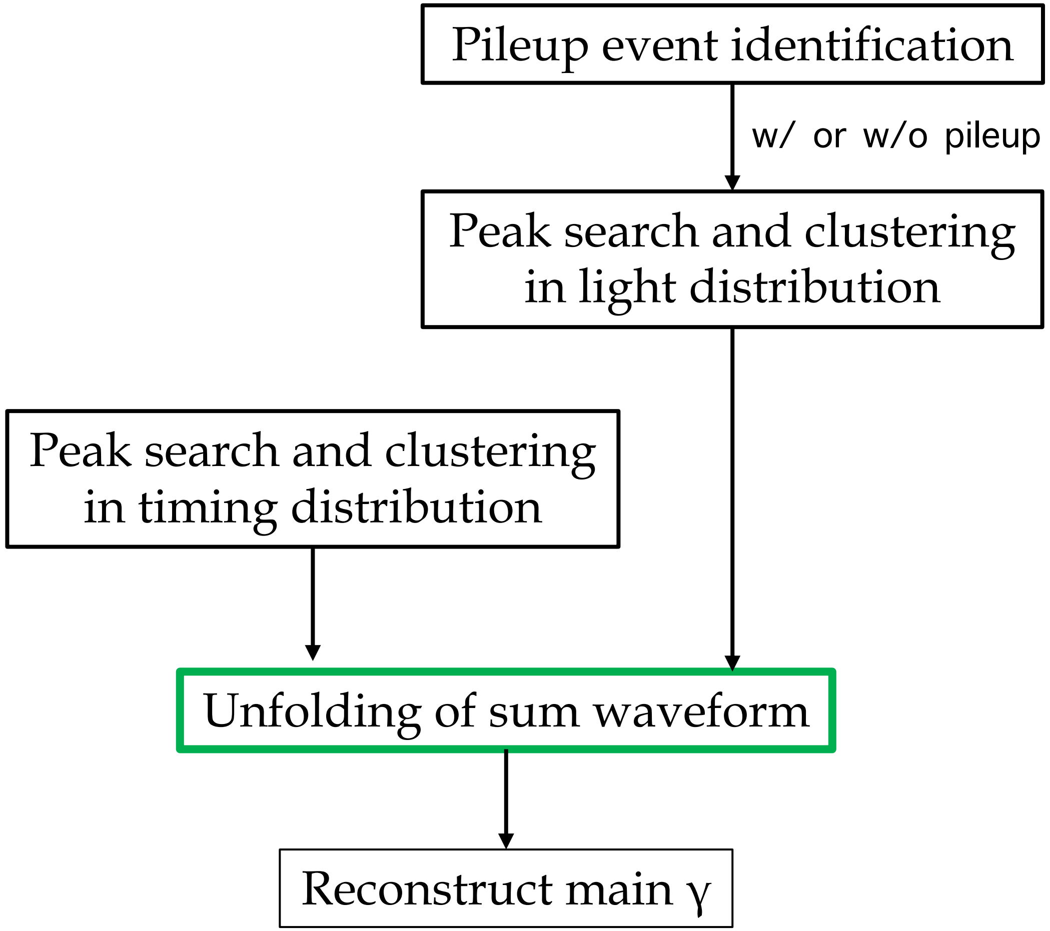
- **Channels whose χ^2 are larger than a threshold are clustered.**
- Sensitive to the off-timing pileups.

Timing χ^2



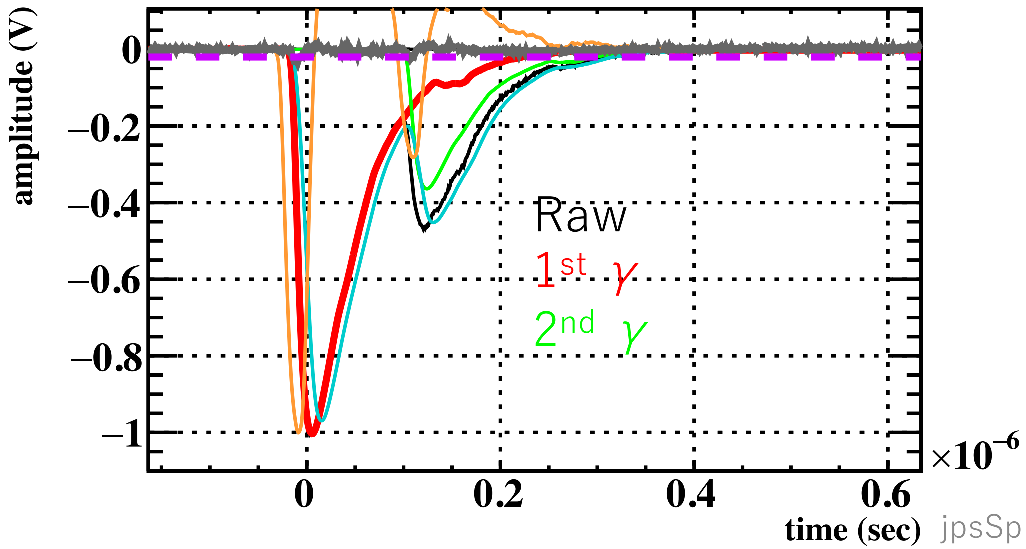
Step3: Unfolding of Sum Waveform

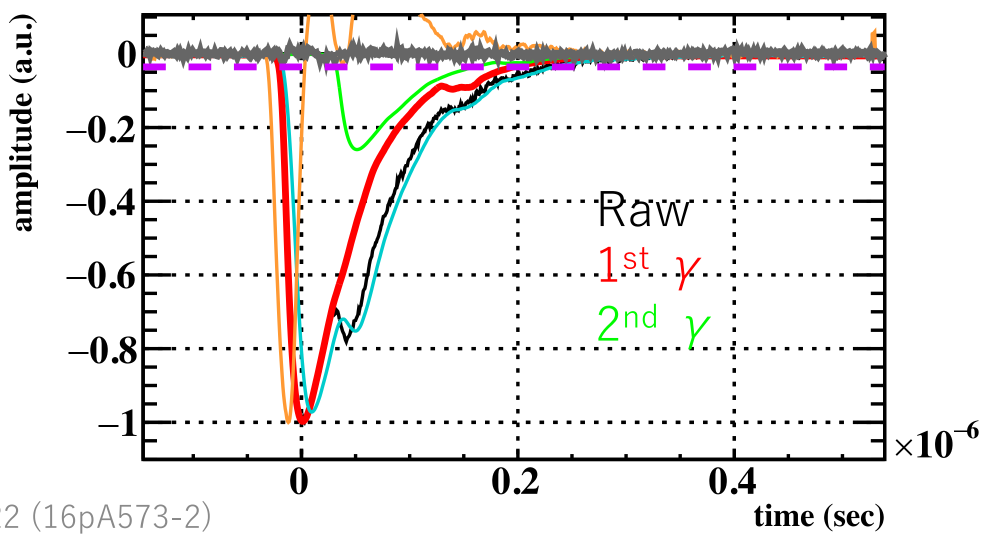
- Sum waveforms are unfolded based on the information of the found pileups.
- Two types of sum waveforms are generated:
  - **Total sum waveform:** All MPPCs/PMTs
  - **Cluster sum waveform:** MPPCs/PMTs belonging to each cluster
- **Pulse timings and energies are extracted from the sum waveforms.**



Step3: Unfolding of Sum Waveform

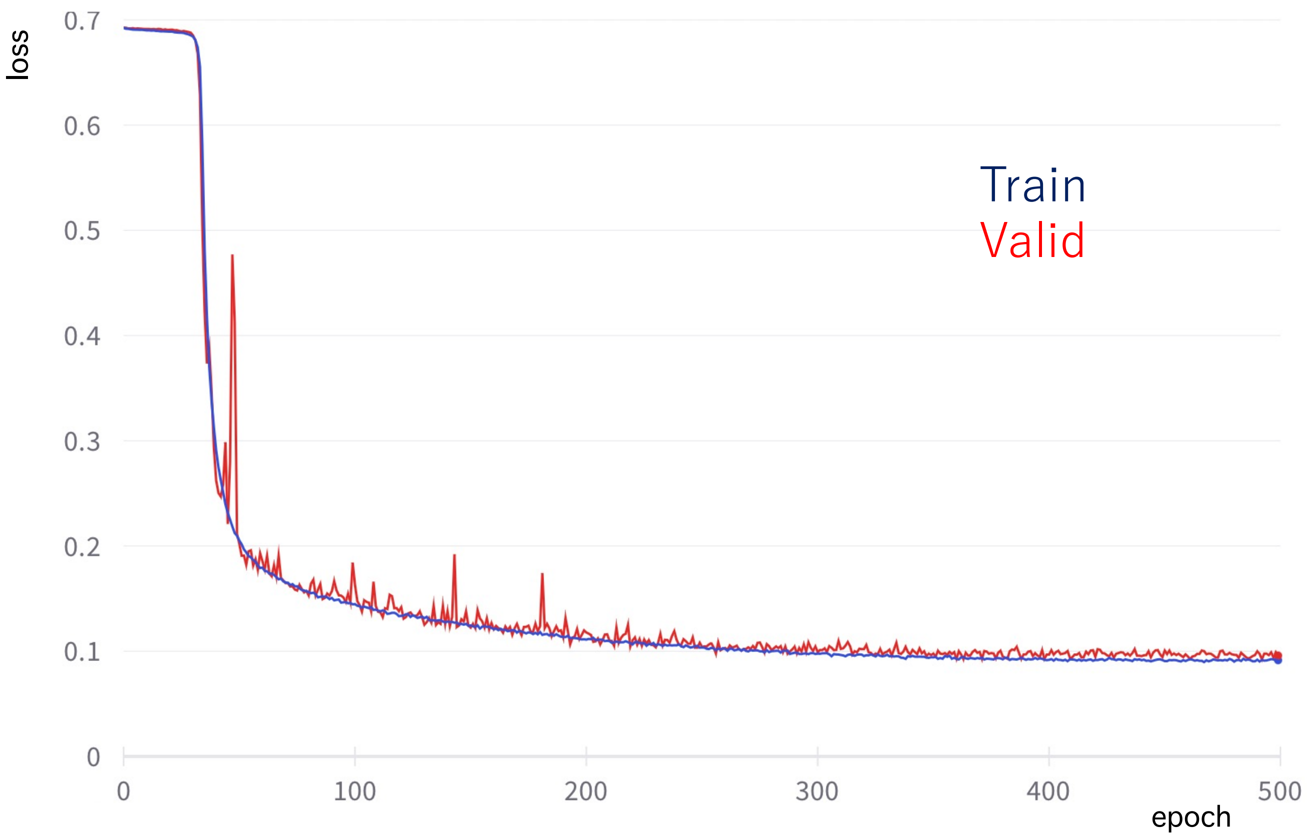
- **Template waveforms are fit to the total sum waveforms** using the extracted timings and energies as initial values.
- The energy of the main γ-ray is reconstructed from the fitting result.
- Finally, an event status is assigned for each event depending on the unfolding results.





Training

- Optimizer: SGD, lr=0.01
- Loss: Binary cross entropy
- Scheduler: CosineAnnealing(max_T=500)
- Batch size: 200
- The number of epochs: 500

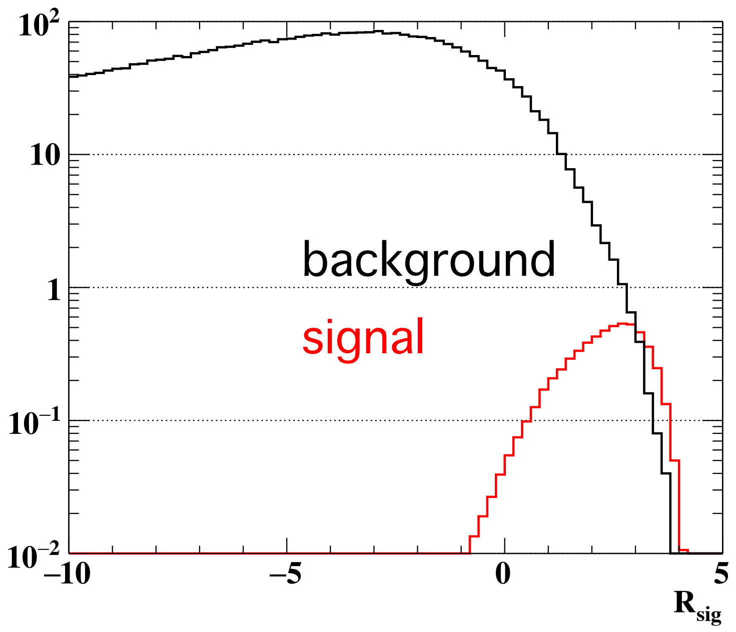


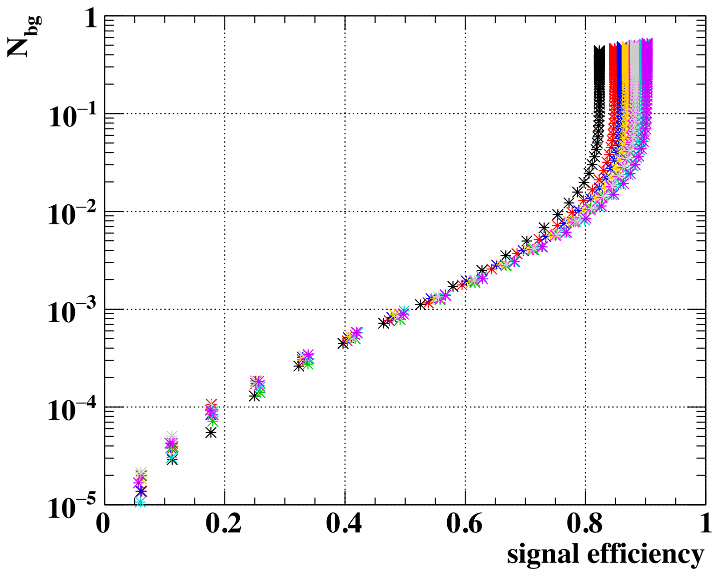
Threshold Scan

- The probability given by the model is translated to a binary flag by setting a certain threshold.
- The threshold was set to maximize the signal-to-background ratio of the relative signal likelihood as

$$R_{\mathrm{sig}} = \log_{10}\left(\frac{S(x_i)}{f_R R(x_i) + f_A A(x_i)}\right)$$

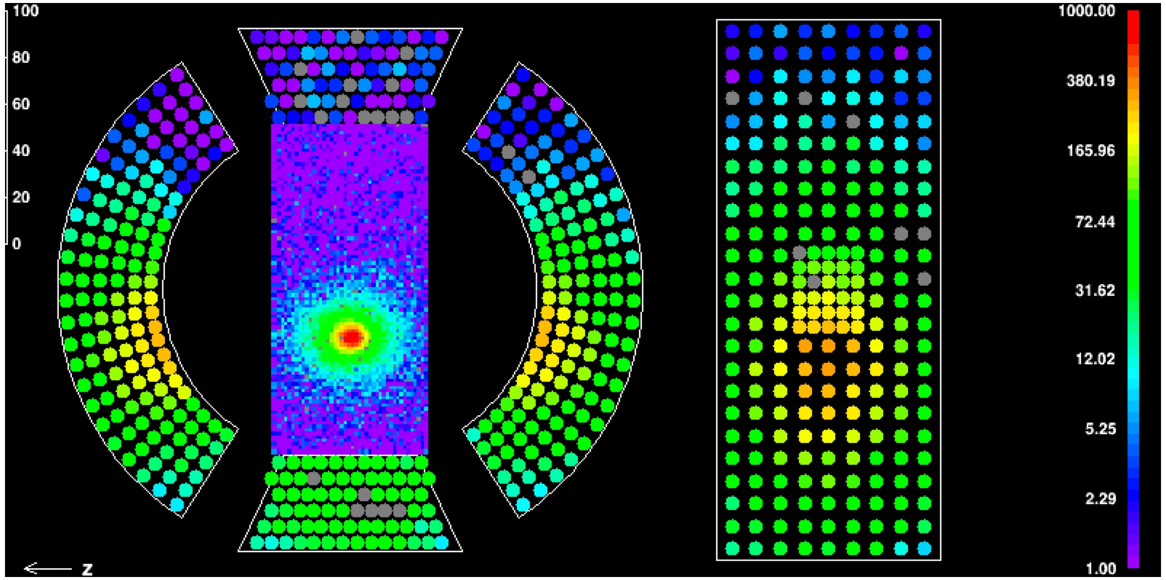
- The threshold was set to be 0.40.

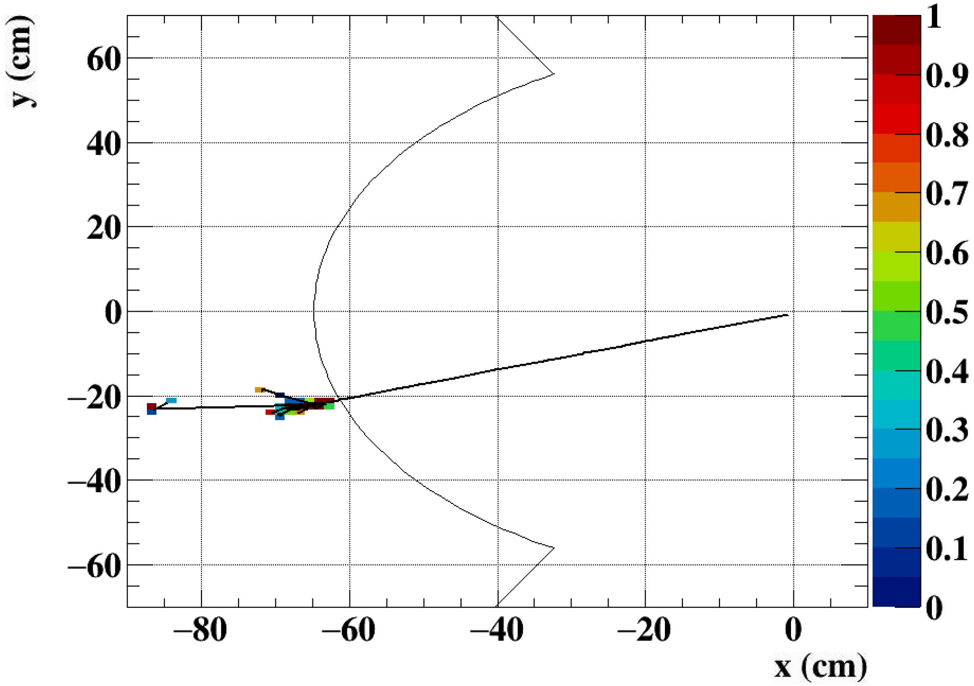




Example of Event

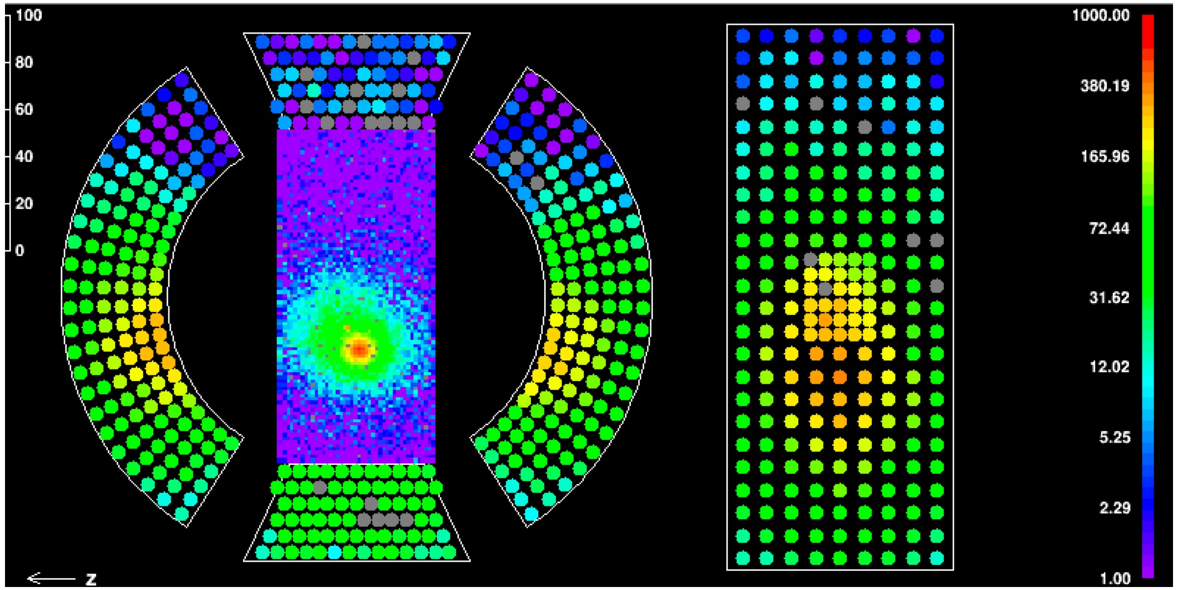
- Single γ-ray event
- Typical light distribution
- Pileup probability: 0.01

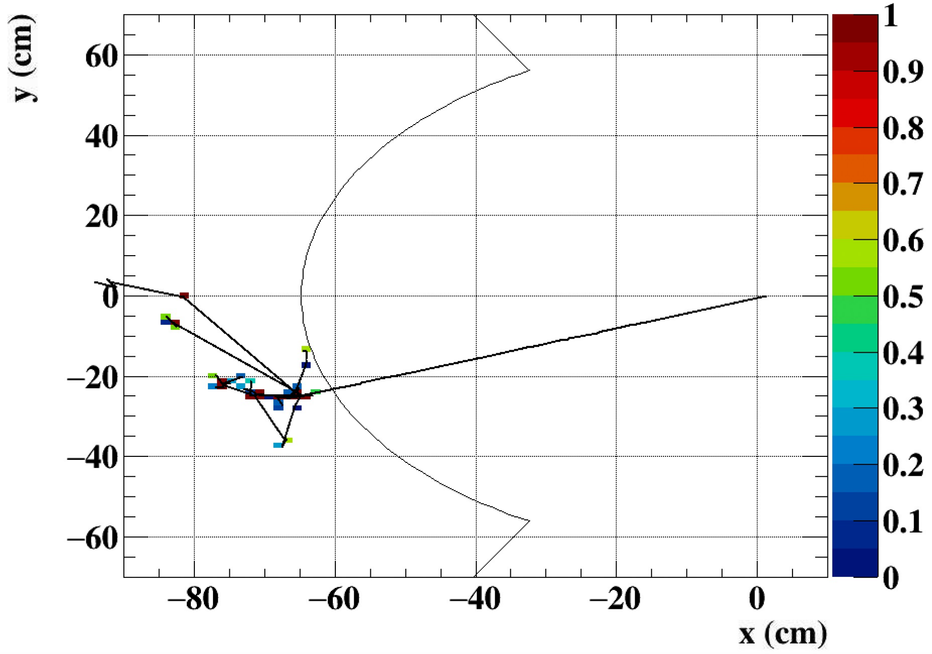




Example of Event

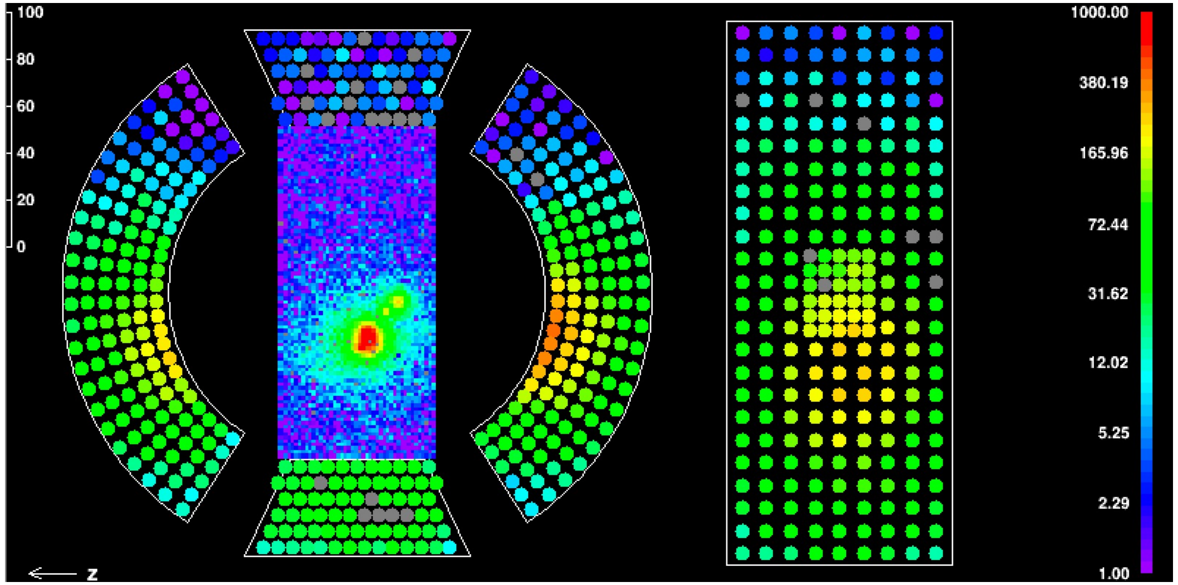
- Single γ-ray event
- Spread due to escaped γ-rays
- Pileup probability: 0.31

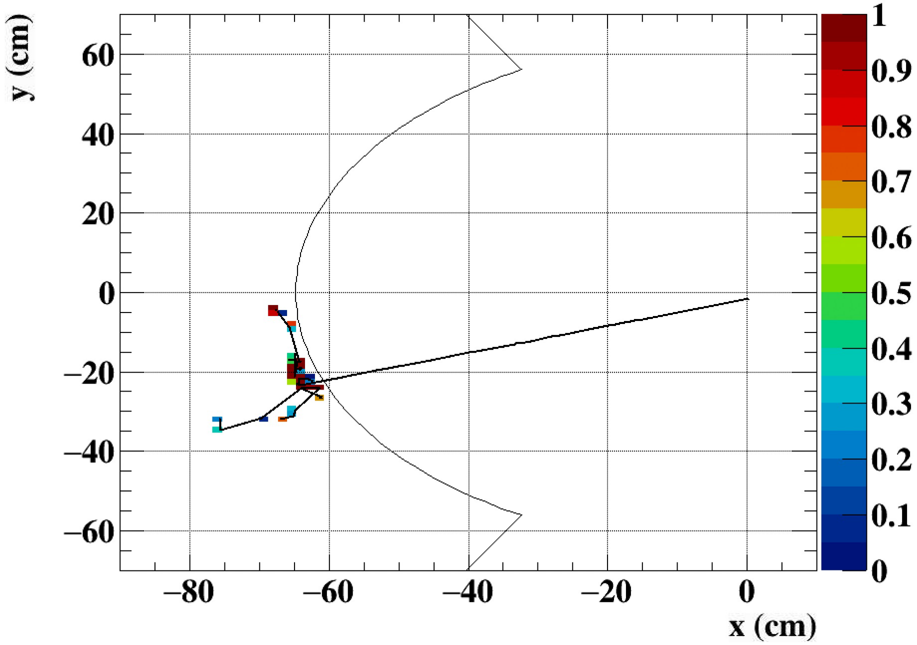




Example of Events

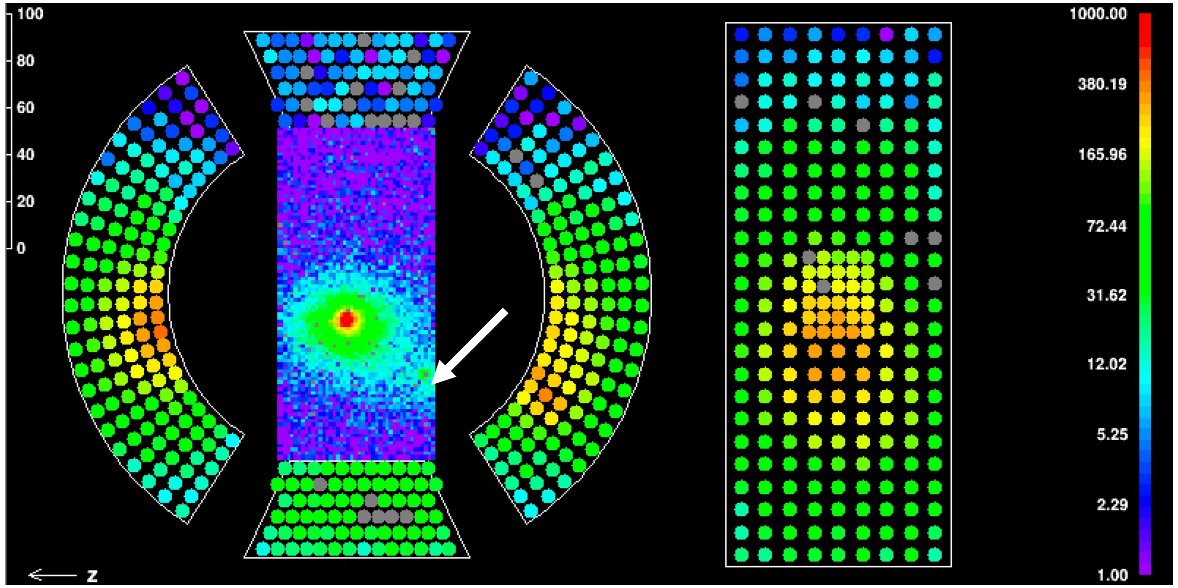
- Single γ-ray event
- Fake peaks from escaped γ-rays
- Pileup probability: 0.99

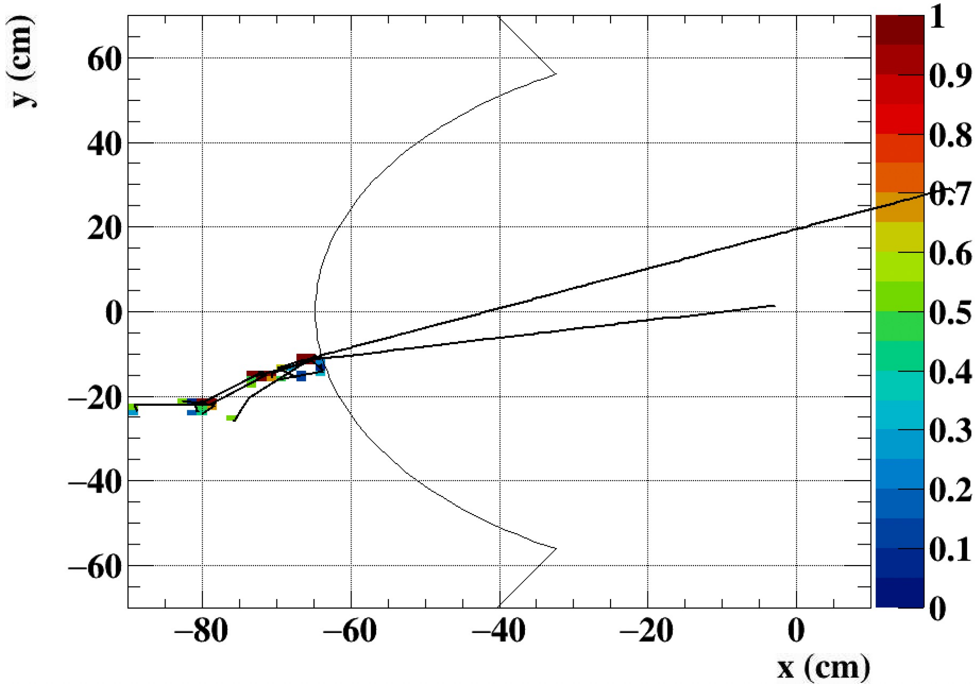




Example of Event

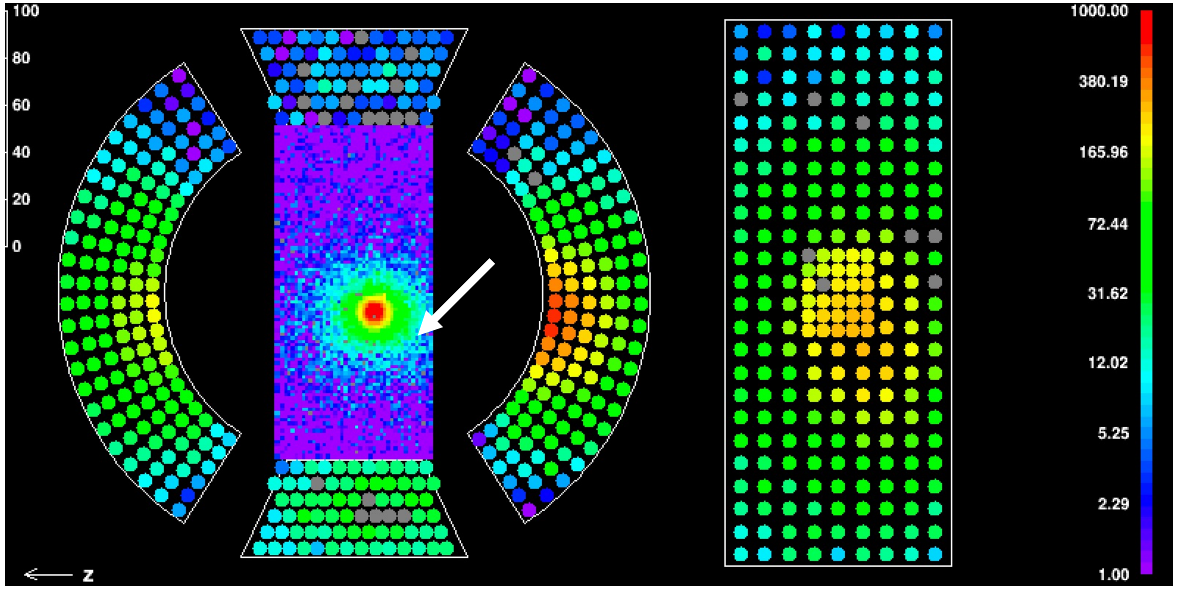
- Two γ-ray event
- Pileup γ-ray in deep region
  - depth: 16 cm
  - energy: 4.51 MeV
- Pileup probability: 0.65

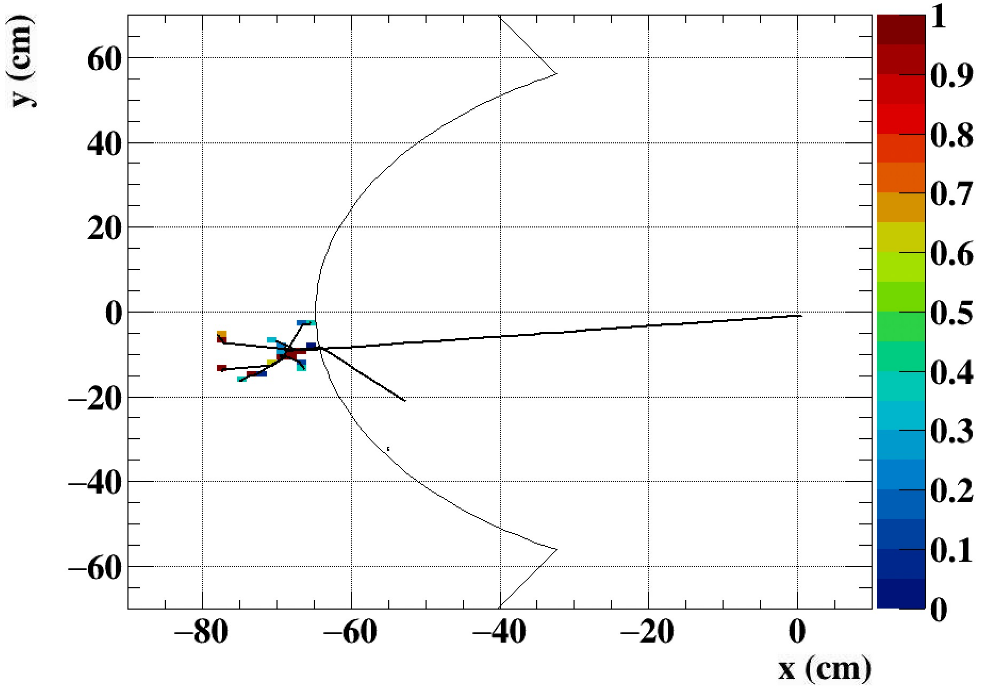




Example of Event

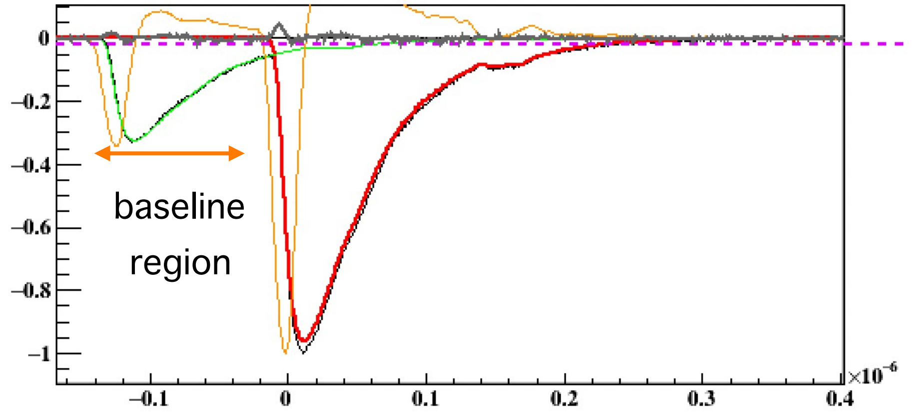
- Two γ-ray event
- Pileup γ-ray in deep region
  - depth: 22 cm
  - energy: 1.80 MeV
- Pileup probability: 0.02

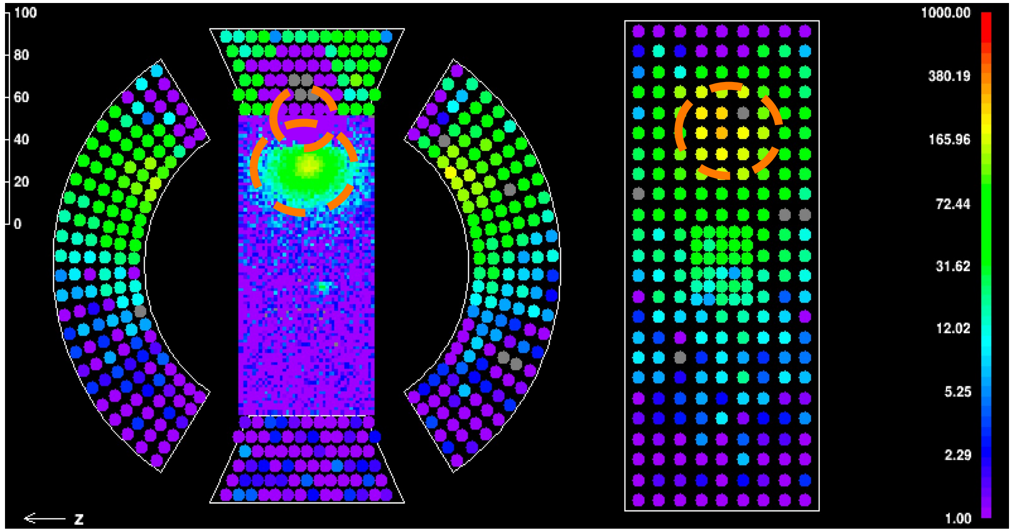




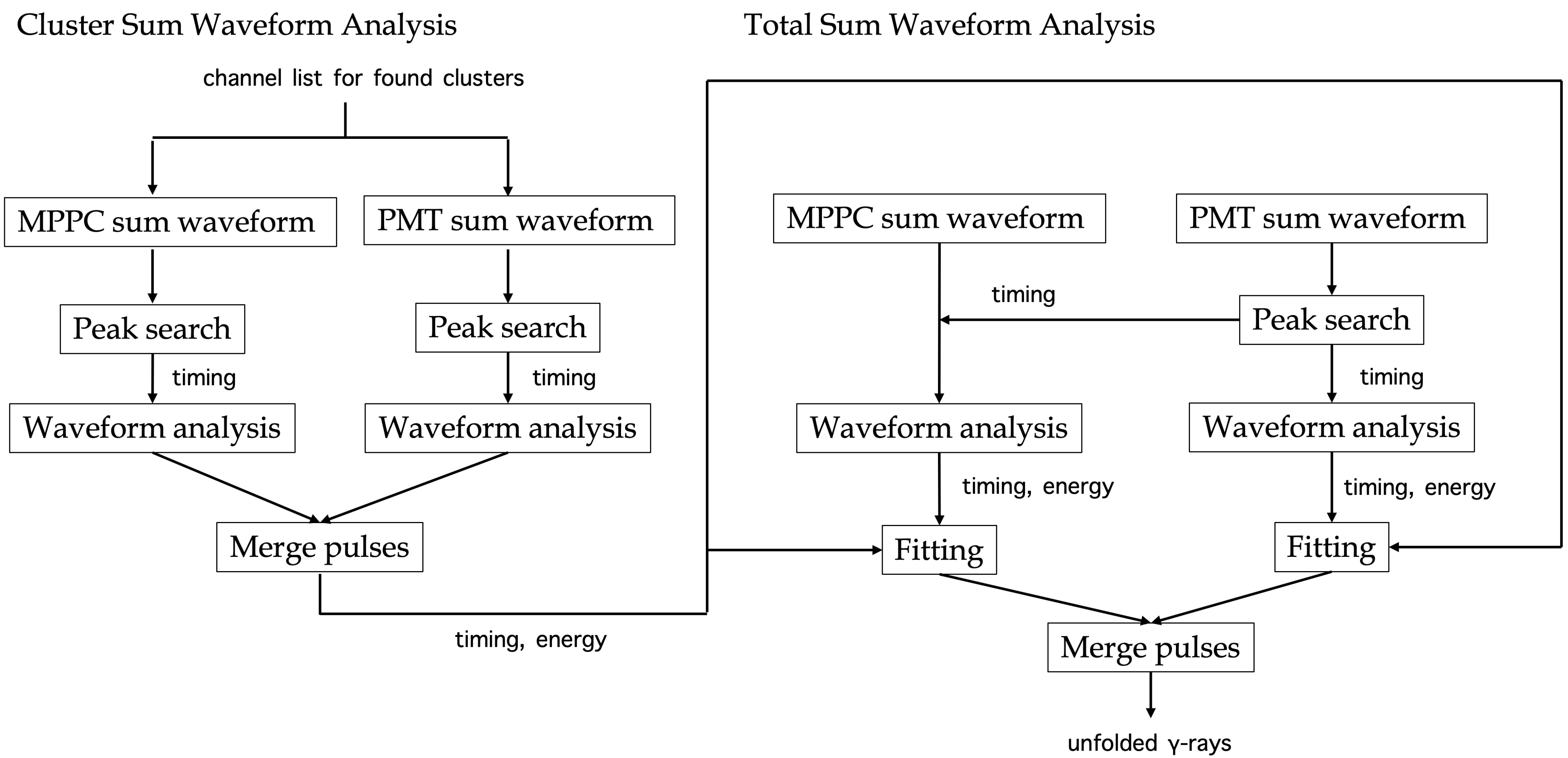
Step2: Peak Search & Clustering

- The peak search in “inverted” light distribution is also implemented.
  ← Light yields are calculated to be negative if there is a pileup in the baseline region.
- The peak search is performed at the same way after multiplying -1.





Step3: Unfolding of Sum Waveform

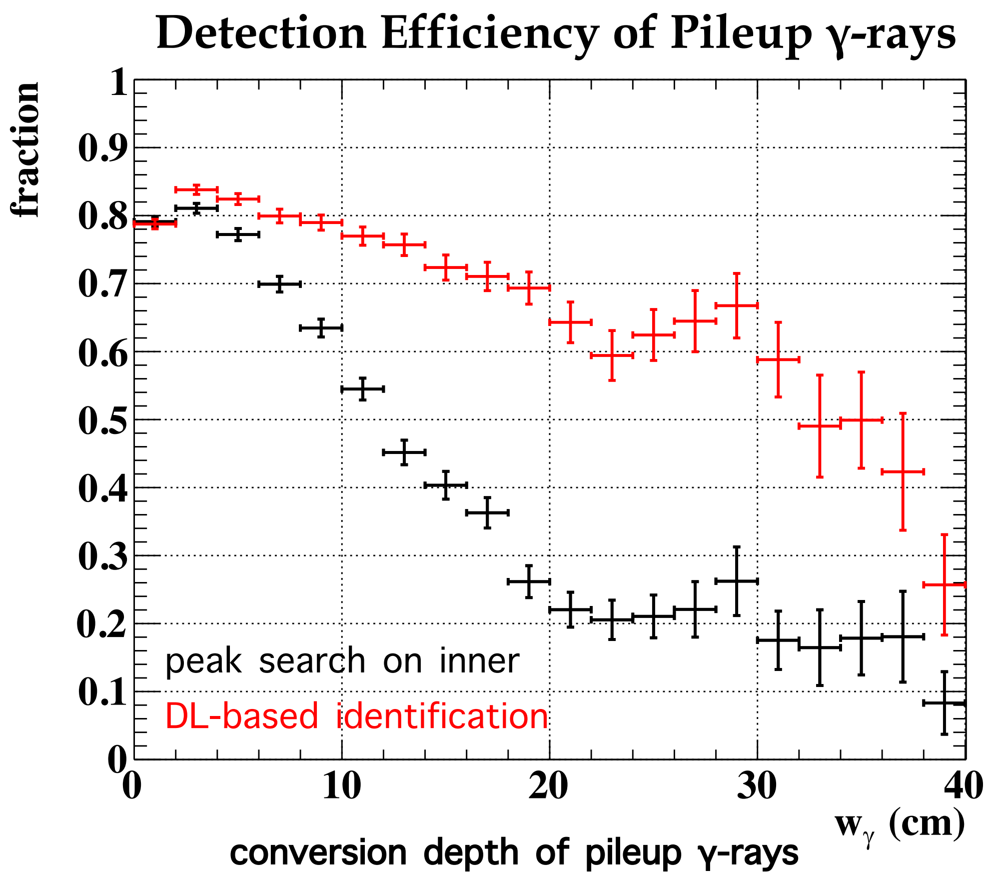


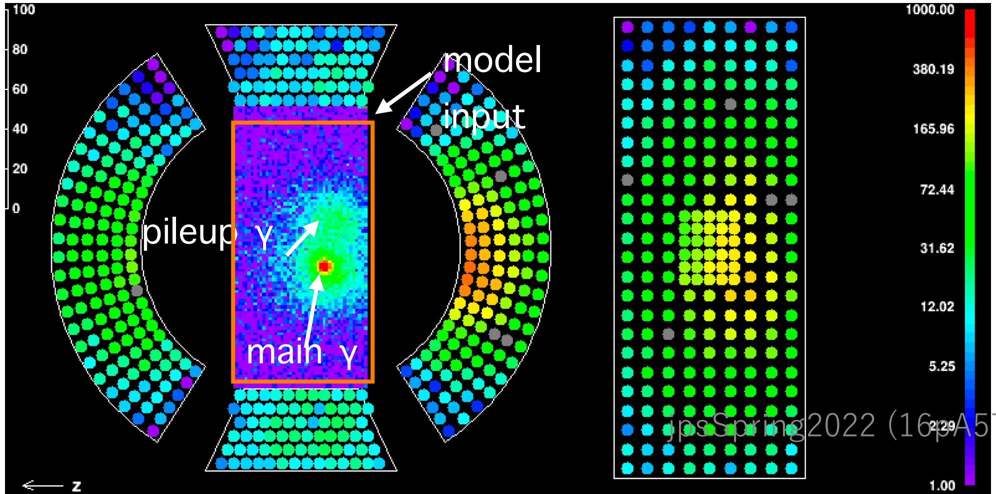
Assignment of Event Status

- Finally, an event status is assigned for each event depending on the unfolding results.
    - **NoPileup:** Only main γ-ray is found by all the algorithms.
    - **Unfolded:** Pileup γ-rays are found, and they are successfully unfolded.
    - **Coincidence:** On-timing pileup γ-rays are found, which cannot be unfolded.
    - **DLRejected:** DL model identifies pileups, but no pileup γ-ray is found with the others.
    - **NotConverged:** Fitting fails to converge.
- Events with Coincidence, DLRejected or NotConverged are rejected.

Performance - DL-based Pileup Identification -

- The performance of the DL algorithm was compared to that of peak search in the light distribution on the inner face.
  ← The same inputs are used.
- **The DL model outperforms the peak search in the deep region.**
  ← A peak structure is not required by utilizing the global distribution.

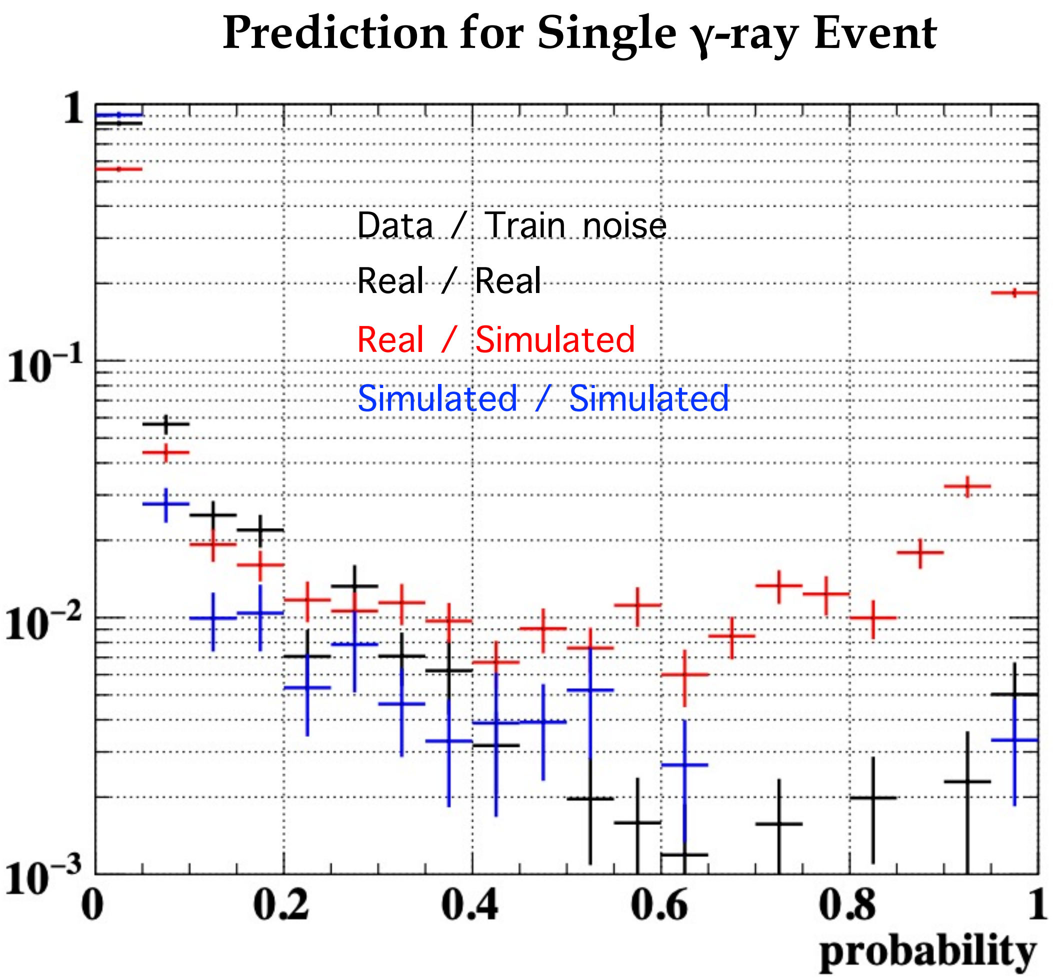




Main γ
+ 1 pileup γ (w_γ ~ 20 cm)

Effect of Noise

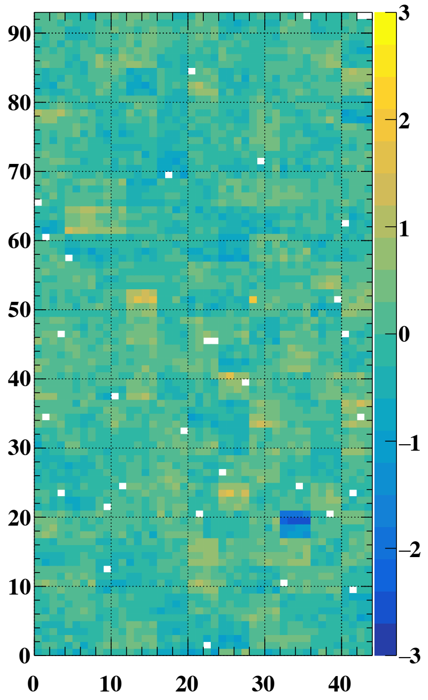
- The noise situation greatly affects the prediction.
- The model trained with simulated noise misidentifies the single γ-ray events as pileup events.



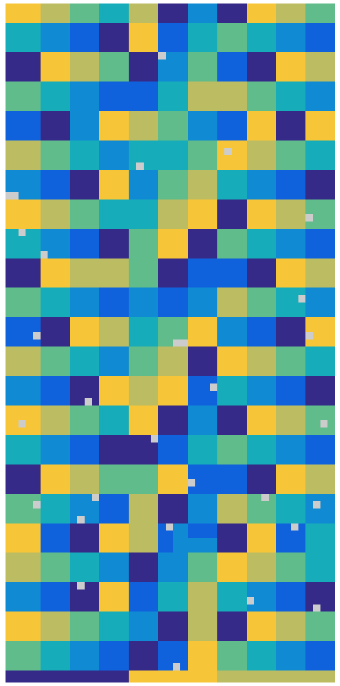
Effect of Noise

- One possible reason is the coherent noise.
  ← Not included in simulated noise.
- Noise coherently arises in the same WDB.

Noise RMS



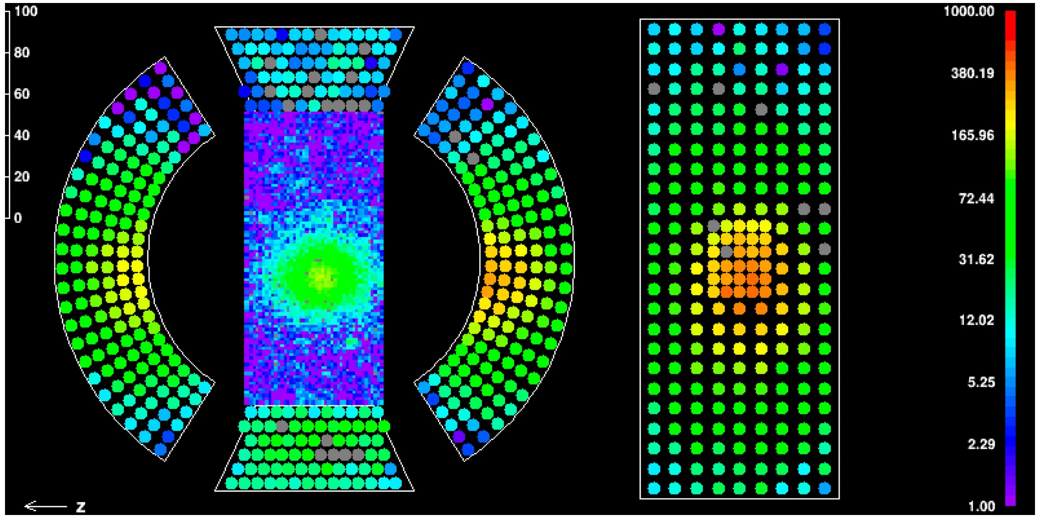
Channel Map



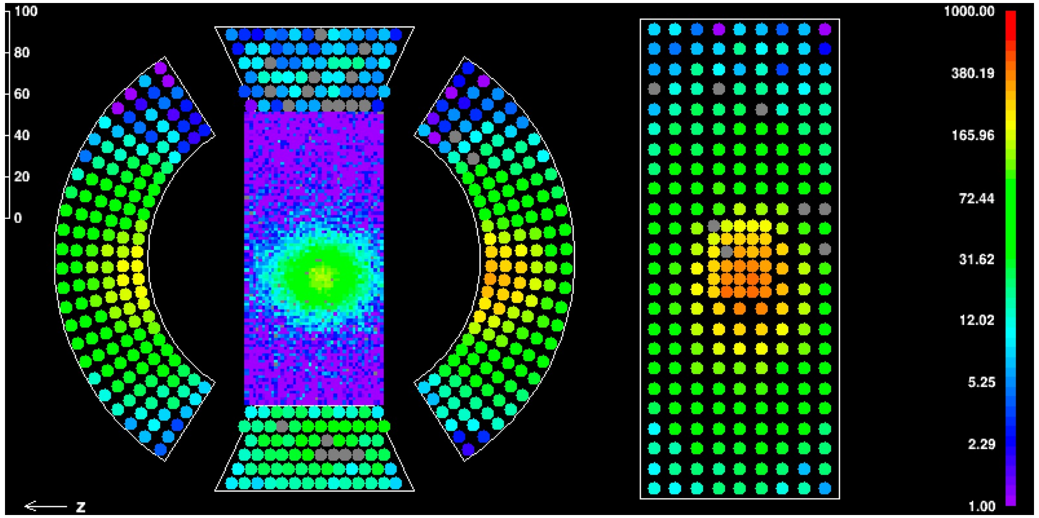
Effect of Noise

- The cluster-like structures in the light distribution derive from the coherent noise.
  → Can be erased by shuffling the channel assignment.

Real Noise



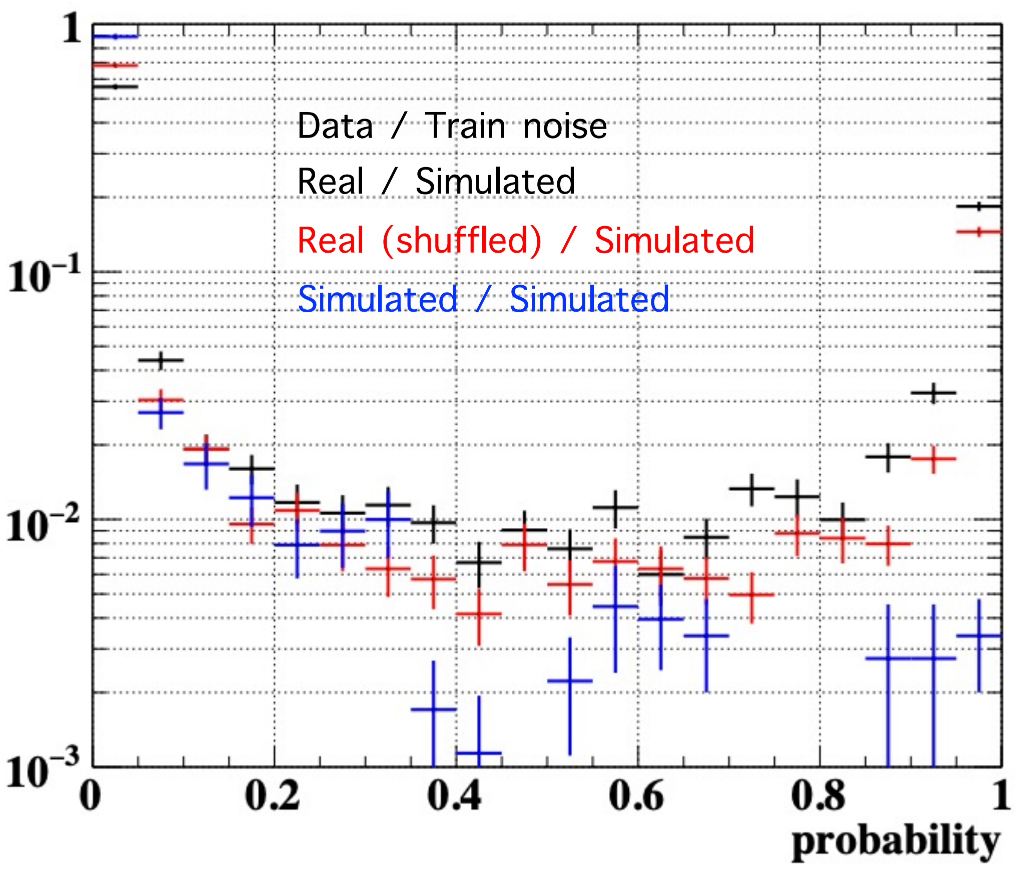
Real Noise (Shuffled)



Effect of Noise

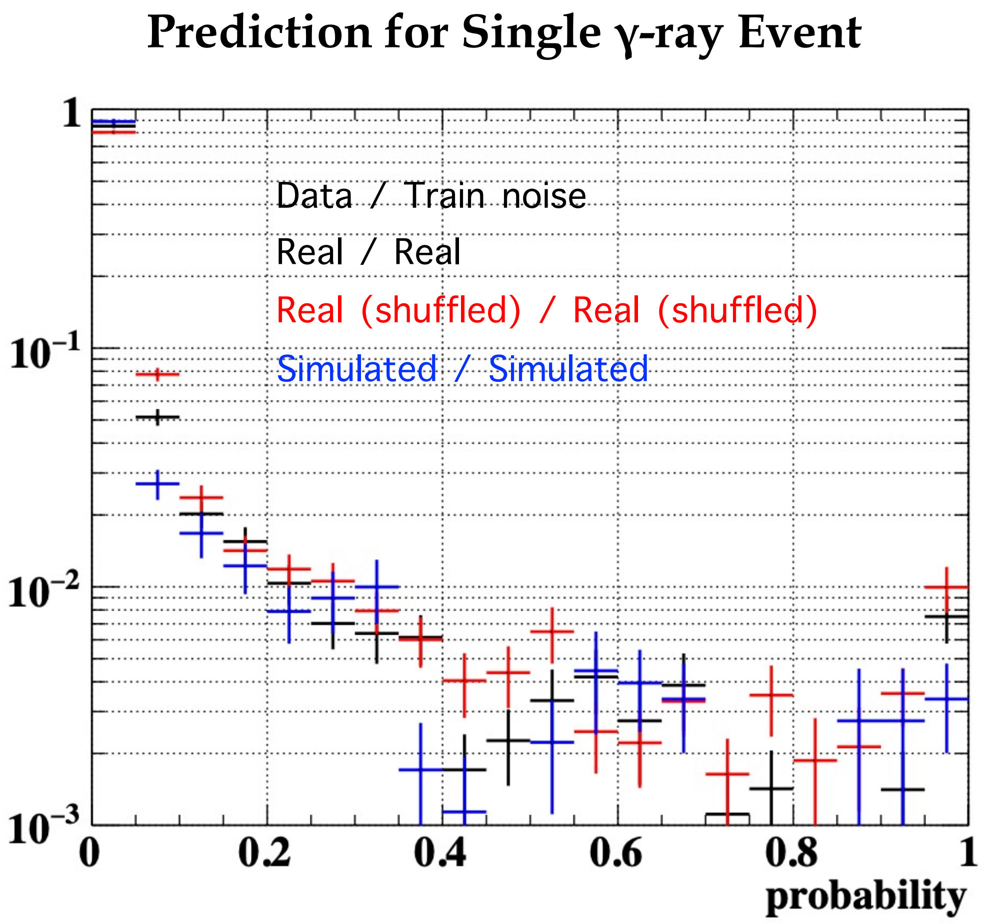
- The shuffling of the channel assignment slightly decreases the entries in the misidentification peak.
  → Partly contributes, but not explained completely.

Prediction for Single γ-ray Event



Effect of Noise

- The training with the appropriate noise can vanish the difference of the prediction result.

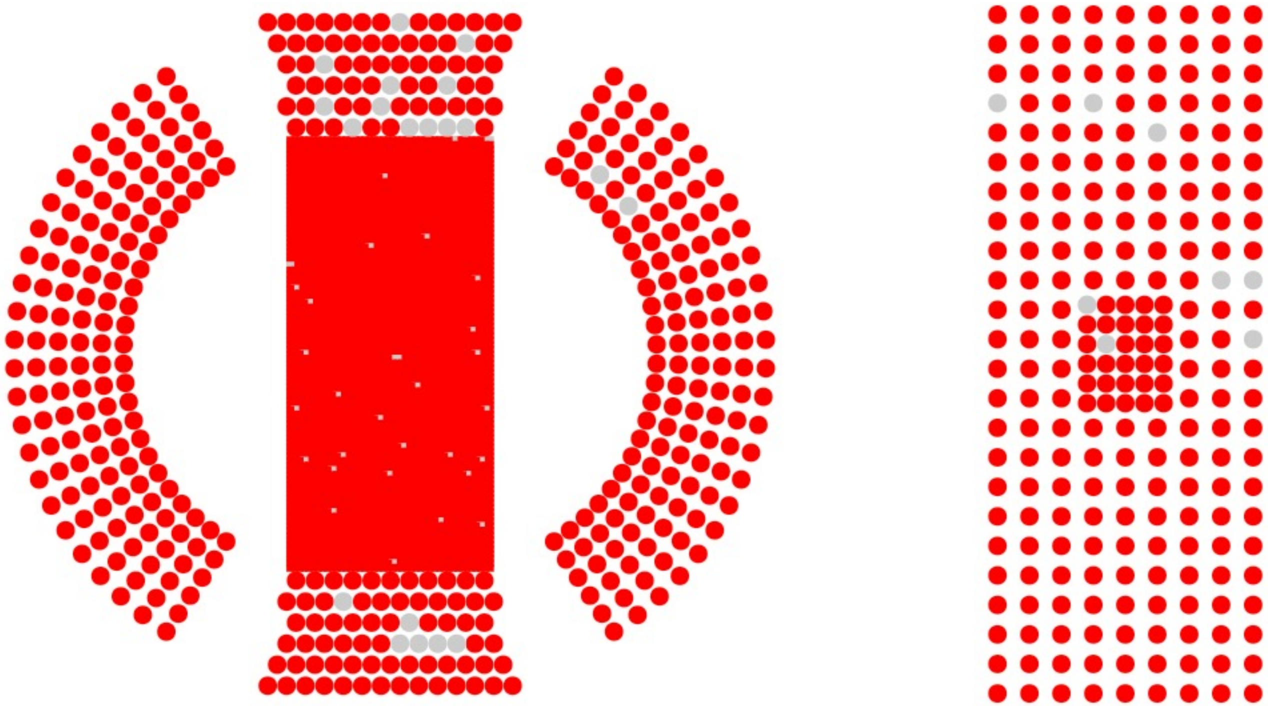


Dead Channel

Dead channels were masked based on the observation in 2021:

- 30 channels for the MPPCs
- 28 channels for the PMTs

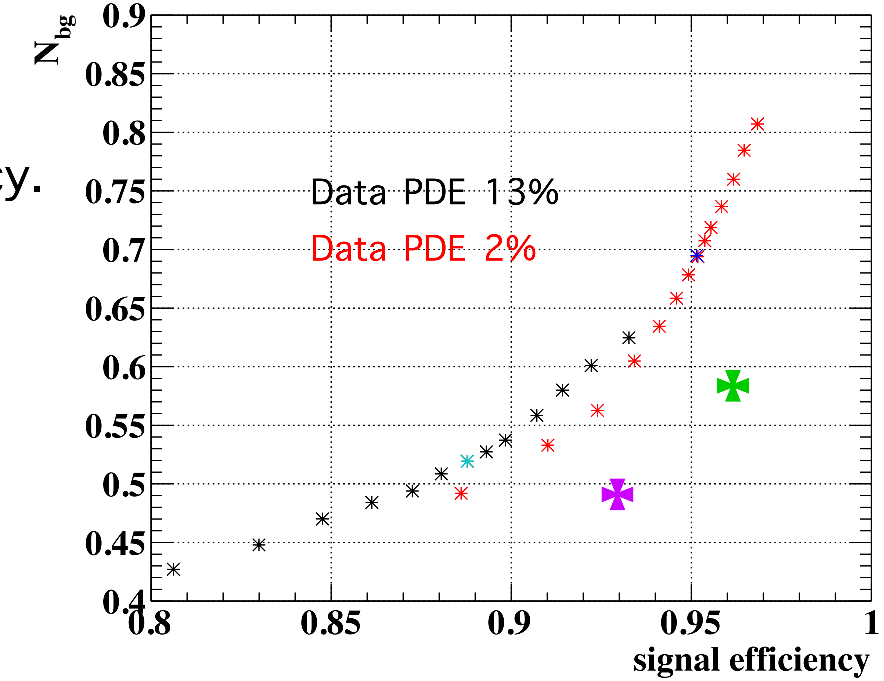
Channel Map



red: alive
grey: dead

Effect of PDE Degradation

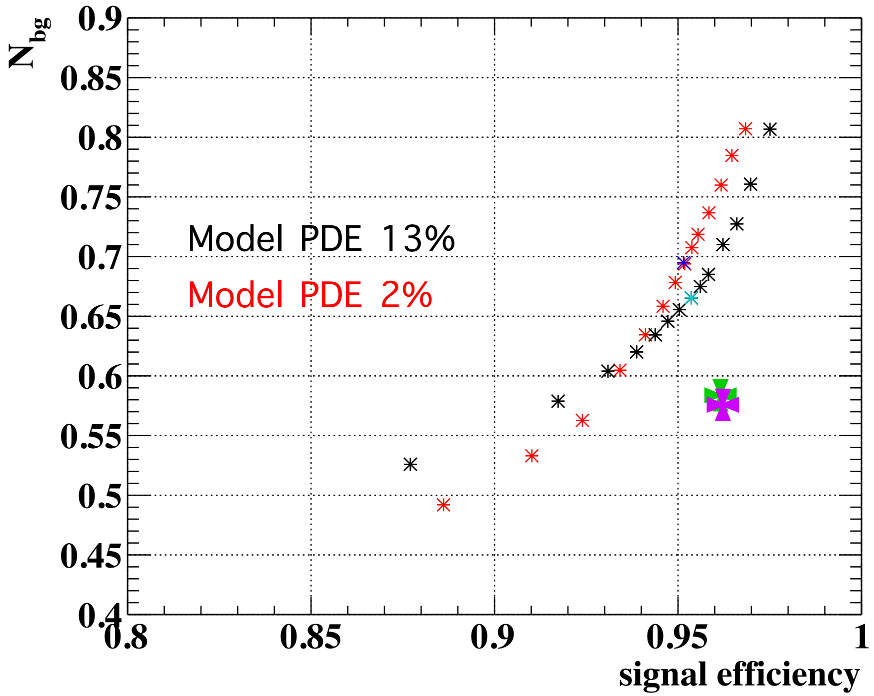
- The PDE decrease can deteriorate the pileup elimination performance.
  ← Low signal-to-noise ratio
- The performance was evaluated assuming lower PDEs.
- At PDE 2%, N_{bg} increases due to the lower detection efficiency.
  ↔ Signal efficiency also gets higher.



*The model is trained at PDE 13%.

Effect of PDE Degradation

- The PDE decrease can deteriorate the pileup elimination performance.
  ← Low signal-to-noise ratio
- The performance was evaluated assuming lower PDEs.
- N_{bg} is slightly less when the model is trained at PDE 2%.
  ↔ Signal efficiency is similar.

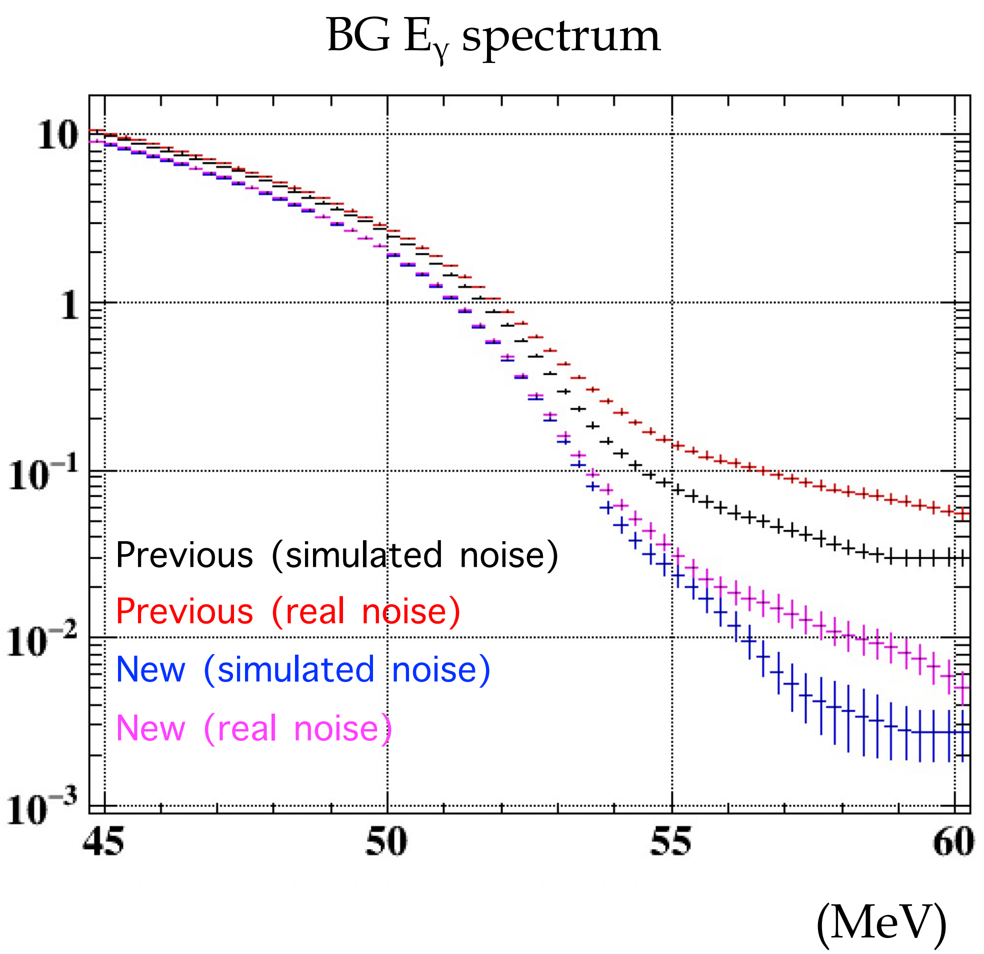


*The data is at PDE 2%.

Effect of Real Noise

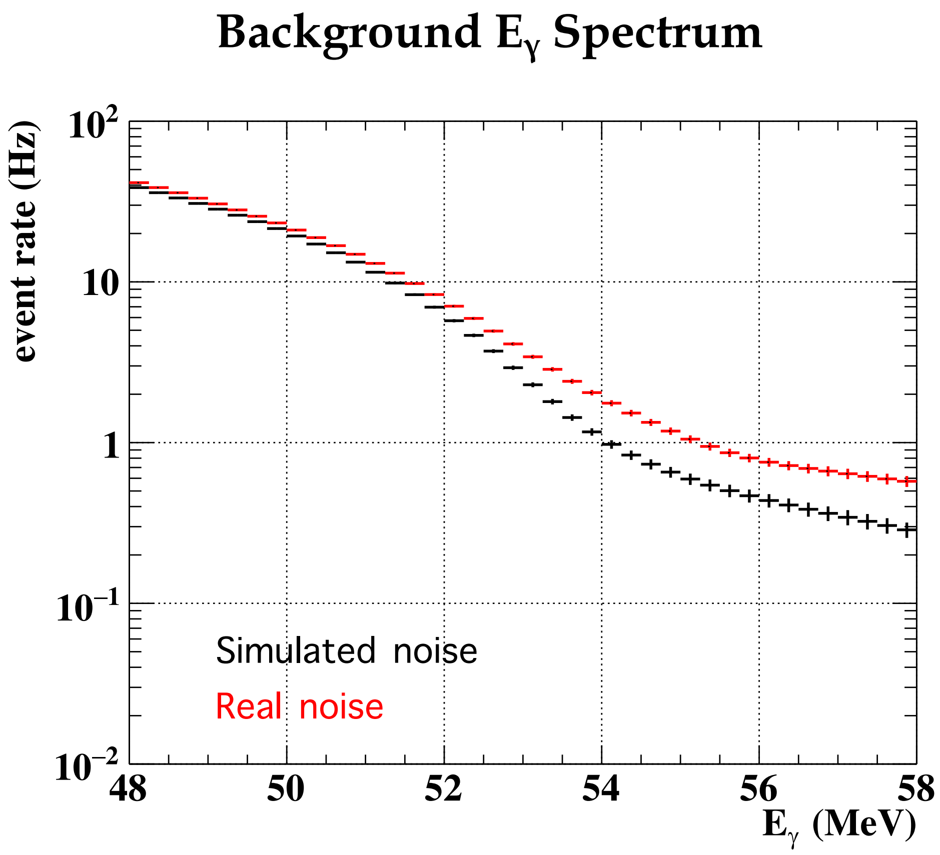
The real noise was found to increase the number of backgrounds in the high energy region.

- Previous algorithm : +11% (48-58 MeV)
  +28% (51.5-54 MeV)
- New algorithm : + 2% (48-58 MeV)
  + 5% (51.5-54 MeV)



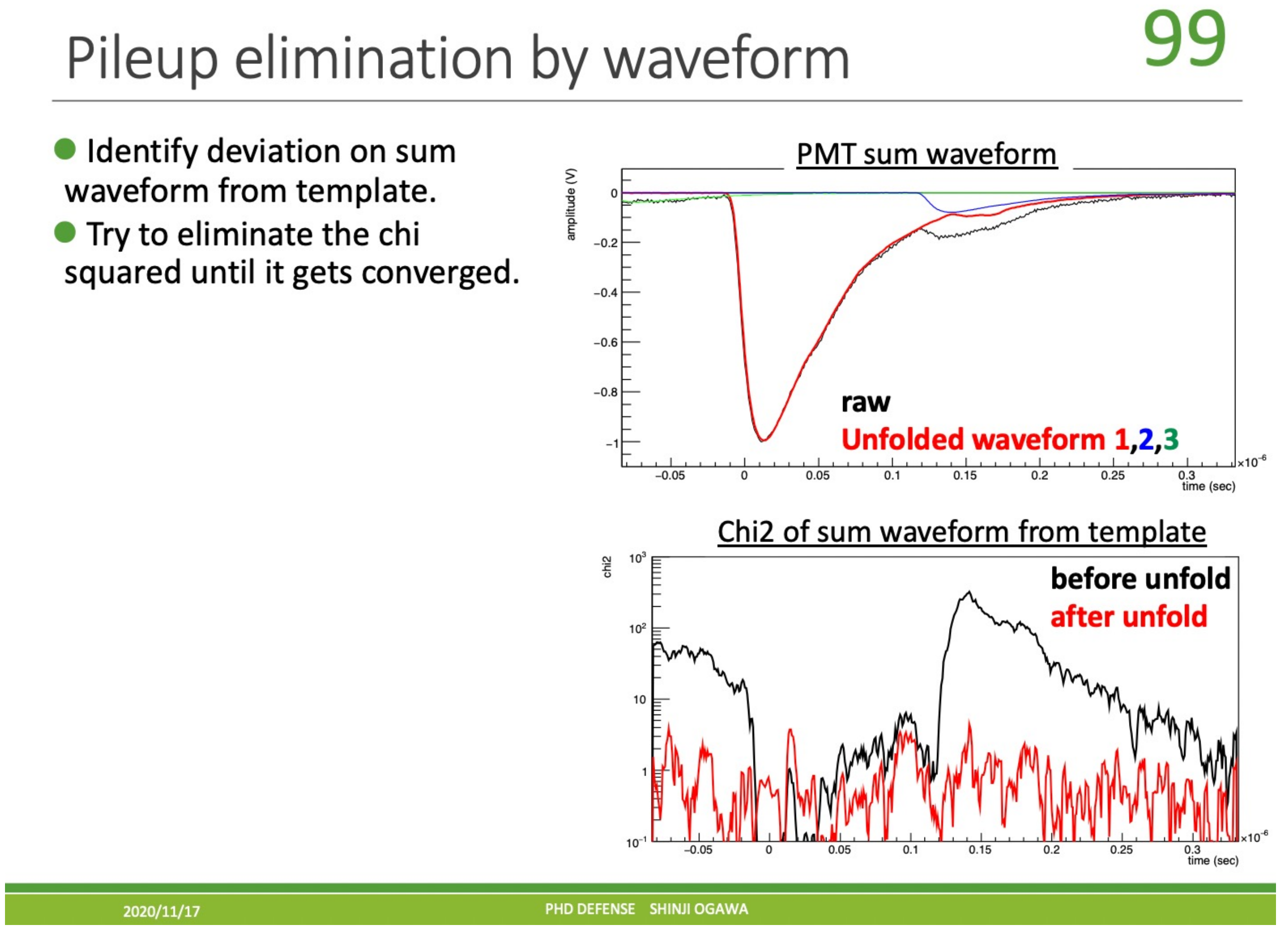
Nominal Branching Ratio before Update

- The previous paper reported the sensitivity of 6×10^{-14} for three years of data-taking.
- The nominal setting of this estimation includes
  - **Positron updates:** $k = 1.03 \times 10^{14} \rightarrow k = 9.38 \times 10^{13}$
  - **Real noise:** increase of the background events by 28% (E_γ = 51.5-54 MeV).
- The nominal value is calculated to be 7.8×10^{-14}.



Previous Algorithm for Pileup Elimination

- Used in “Shinji Ogawa. Liquid xenon detector with highly granular scintillation readout to search for μ+ → e+γ with sensitivity of 5 × 10−14 in the MEG experiment. PhD thesis, The University of Tokyo, 2020. URL: https://meg.web.psi.ch/docs/theses/ogawa_phd. pdf.”
- Pileup elimination with waveform
  - Only off-timing pileups can be detected.
  - Instability of fitting
  - Not tolerant to noise with hard codded parameters



Discussion on Projected Sensitivity

- The sensitivity at the halved intensity was found to be equivalent to the other:
  - 5.6×10^{-14} at 7×10^{7} μ^{+}stops/s
  - 5.8×10^{-14} at 3.5×10^{7} μ^{+}stops/s

← Reduction of accidental backgrounds

Improvement of positron performance* at lower intensity

Table 7.1 Parameters for sensitivity calculation as the nominal setting.

Variables	Values	
	7×10^{7} μ^{+}stops/s	3.5×10^{7} μ^{+}stops/s
$\sigma_{p_{e^+}}$	$100\,\mathrm{keV}/c$	$90\,\mathrm{keV}/c$
$\sigma_{\theta_{e^+}}$	6.7 mrad	6.2 mrad
$\sigma_{\phi_{e^+}}$	4.9 mrad	4.7 mrad
σ_{E_γ}	1.7%	
σ_{u_γ}	2.5–8.1 mm (for different w_γ)	
σ_{v_γ}	2.5–7.4 mm (for different w_γ)	
σ_{w_γ}	2.4–13.9 mm (for different w_γ)	
$\sigma_{t_{e^+\gamma}}$	70 ps	68 ps
ϵ_{e^+}	65%	74%
ϵ_γ	69%	
k	9.38×10^{13} (for three years)	5.34×10^{13} (for three years)

* Without the improvement of the positron performance, the sensitivity at the higher intensity is better thanks to the sufficient reduction power of the γ-ray pileup elimination.

Discovery Sensitivity

- At design stage,
  - 90% C.L. Exclusion: 6×10^{-14} for three years
    ← same as the value of this thesis
  - 3σ Discovery: 1×10^{-13} for three years
  - 5σ Discovery: 2×10^{-13} for three years

MEG II Sensitivity in Design Paper