MEG II実験における、背景事象削減に向けたガンマ線再構成手法の開発

Development of gamma-ray reconstruction algorithm towards the reduction of background events in MEG II experiment

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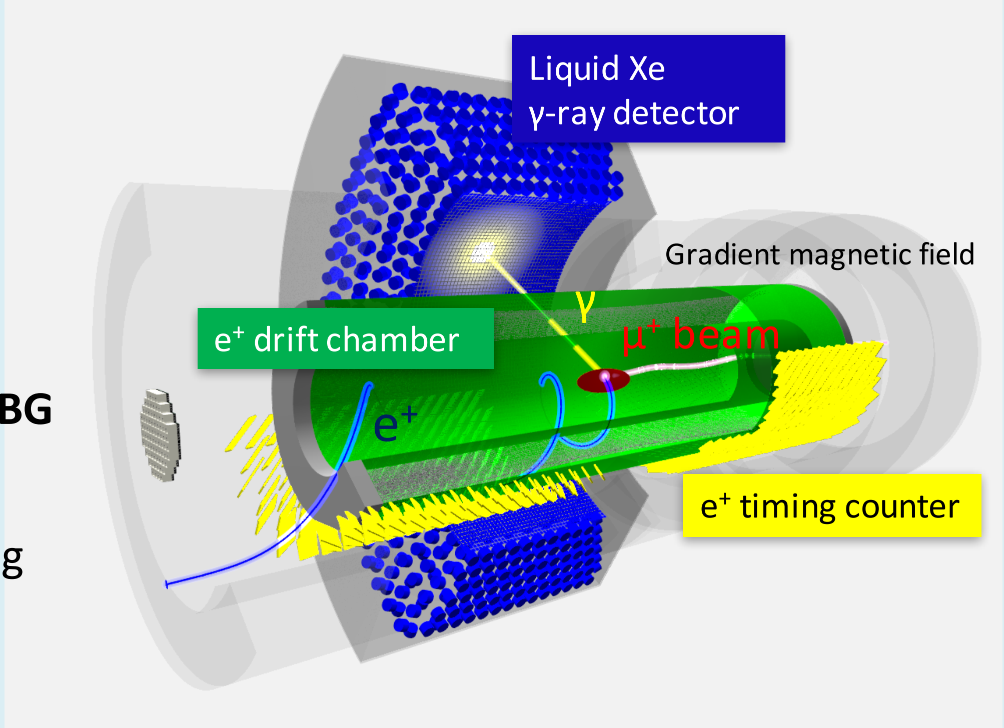
MEG II experiment

Upgrade of MEG experiment

- Searches for $\mu \to e\gamma$.
- Dominant BG : accidental BG
- **More statistics**
  - x2.3 muon beam rate
  - x2 positron efficiency
- **Better separation of signal event from BG**
  - x2 for all detector resolutions
  - New detector for background tagging will be introduced



Expected sensitivity: 6×10^{-14}

- One order of magnitude better than MEG

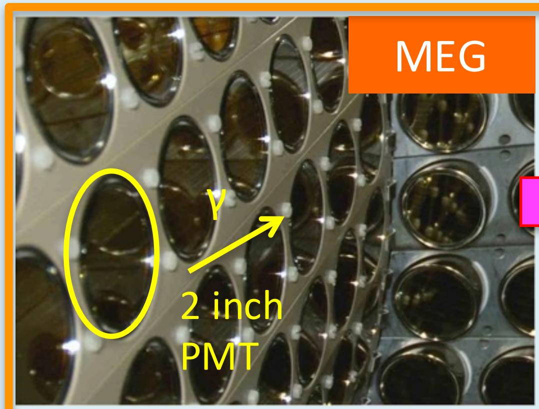
Engineering run from 2019

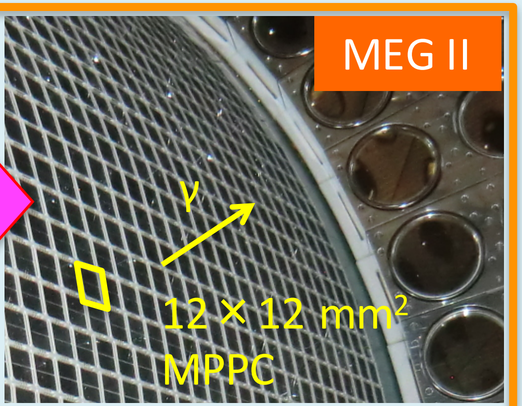
- Followed by physics data taking.

Reference :
"The design of the MEG II experiment", Eur. Phys. J. C (2018) 78:38

LXe detector upgrade

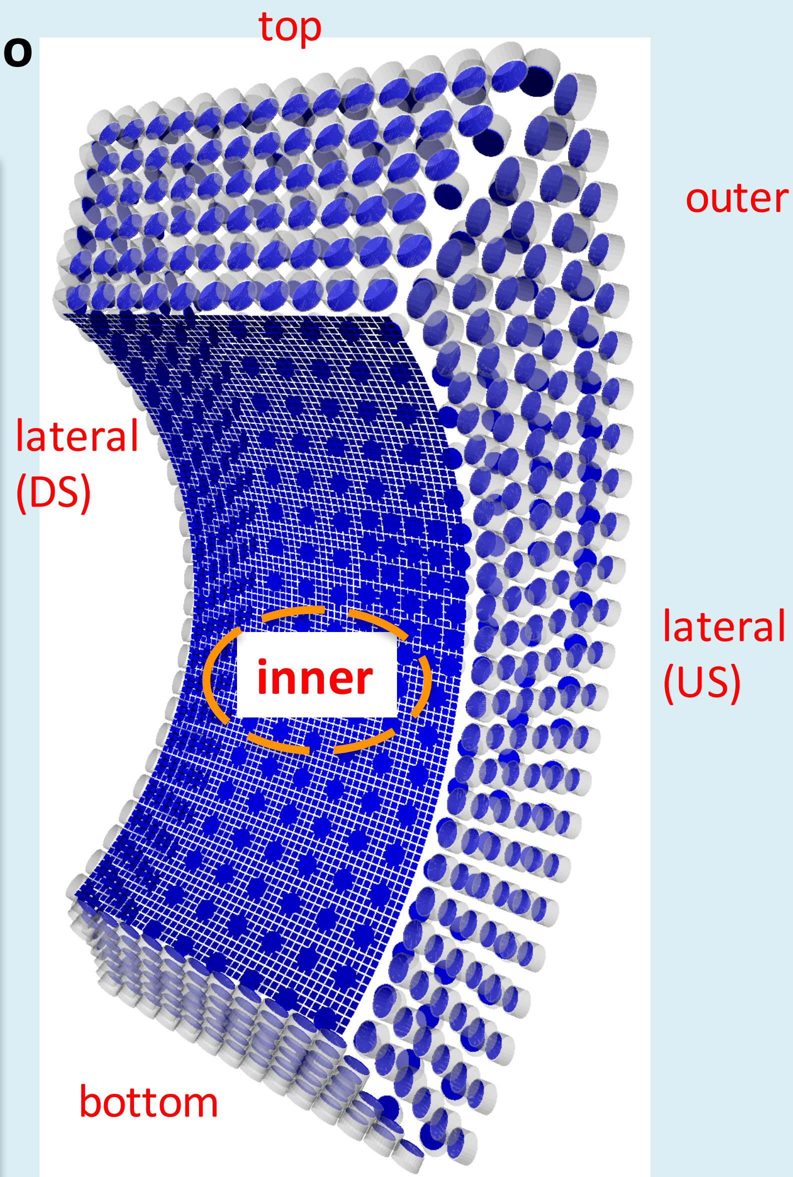
We have upgraded LXe detector for MEG II to significantly improve the performance.





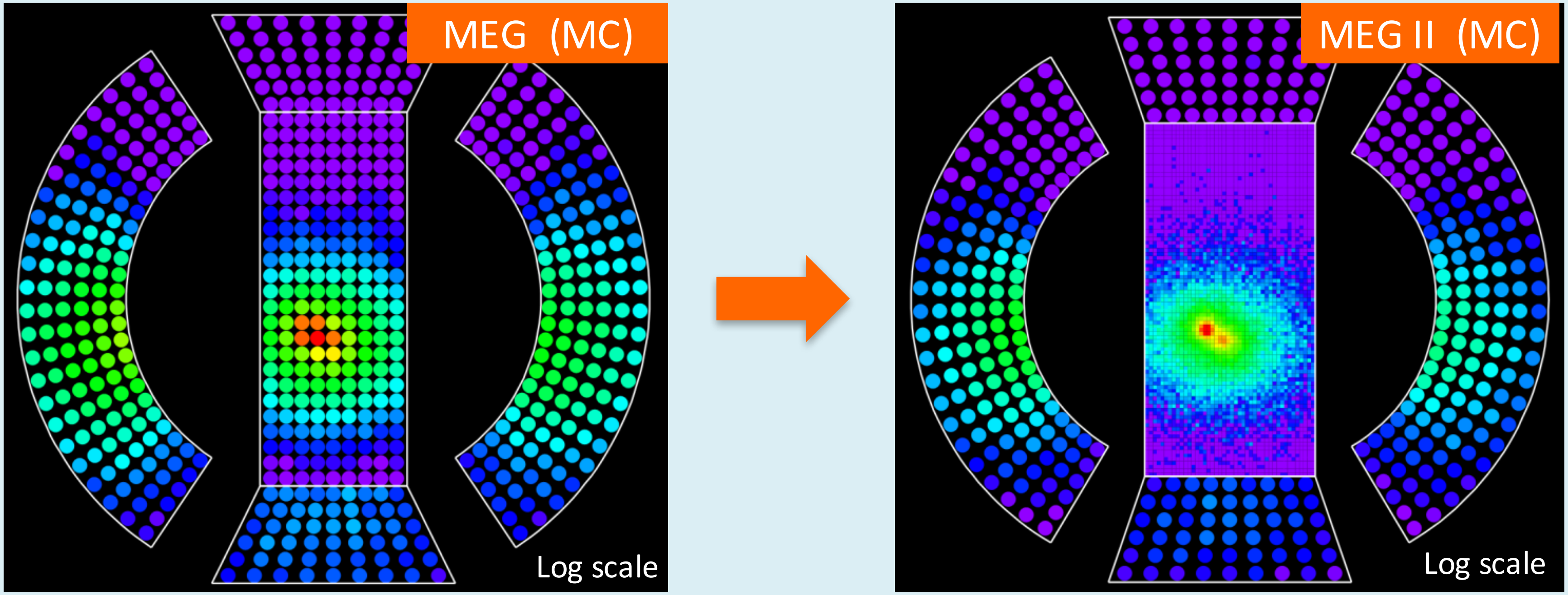
We have replaced 216 2-inch PMTs on the γ-entrance face with 4092 12 × 12 mm² MPPCs.

- Better granularity
  - Better position resolution
- Better uniformity of scintillation readout
  - Better energy resolution
- Less material of the γ-entrance face
  - Better detection efficiency



Multiple γ identification

- Granularity of γ incident face has been largely improved.
  - 1 PMT replaced with 4 x 4 MPPC. (i.e. factor 16 improvement)
  - Main purpose: Improvement of position/ energy resolution.
- Can we utilize higher granularity for other purpose?
  → ***Identification of multiple γ event.***

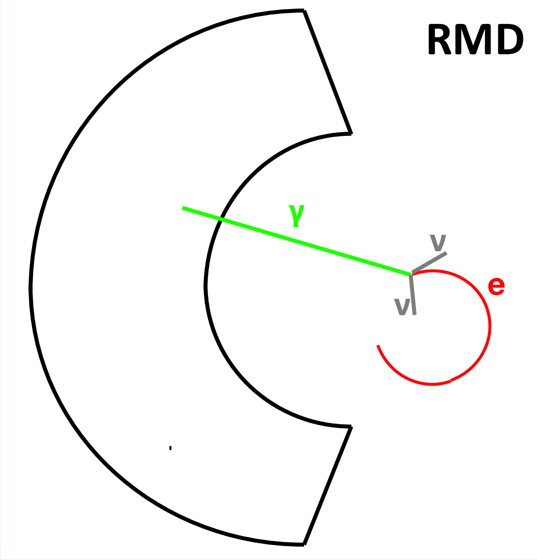


Gamma-ray background in MEG II

- Main BG in MEG II : accidental BG of e & γ . Eγ ~ Eγ of Signal (= 52.8MeV).
- Three types of background γ near signal energy.

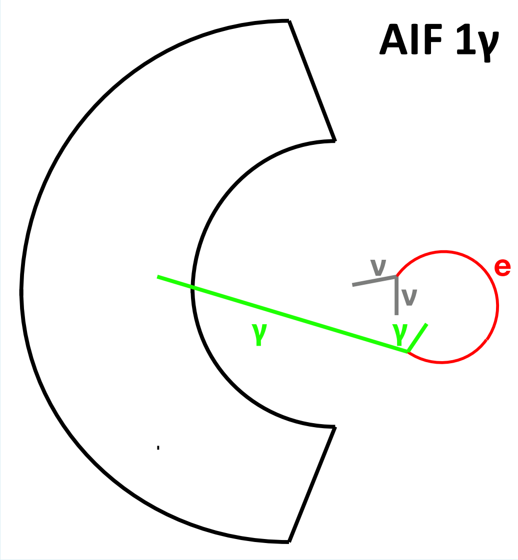
Background γ (Eγ ~ Eγ of Signal)

Radiative decay of muon (RMD)

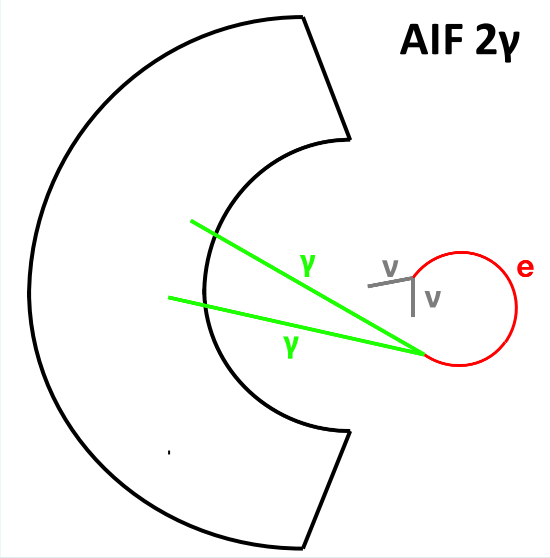


- γ from RMD.

Annihilation in Flight (AIF) of Michel positron



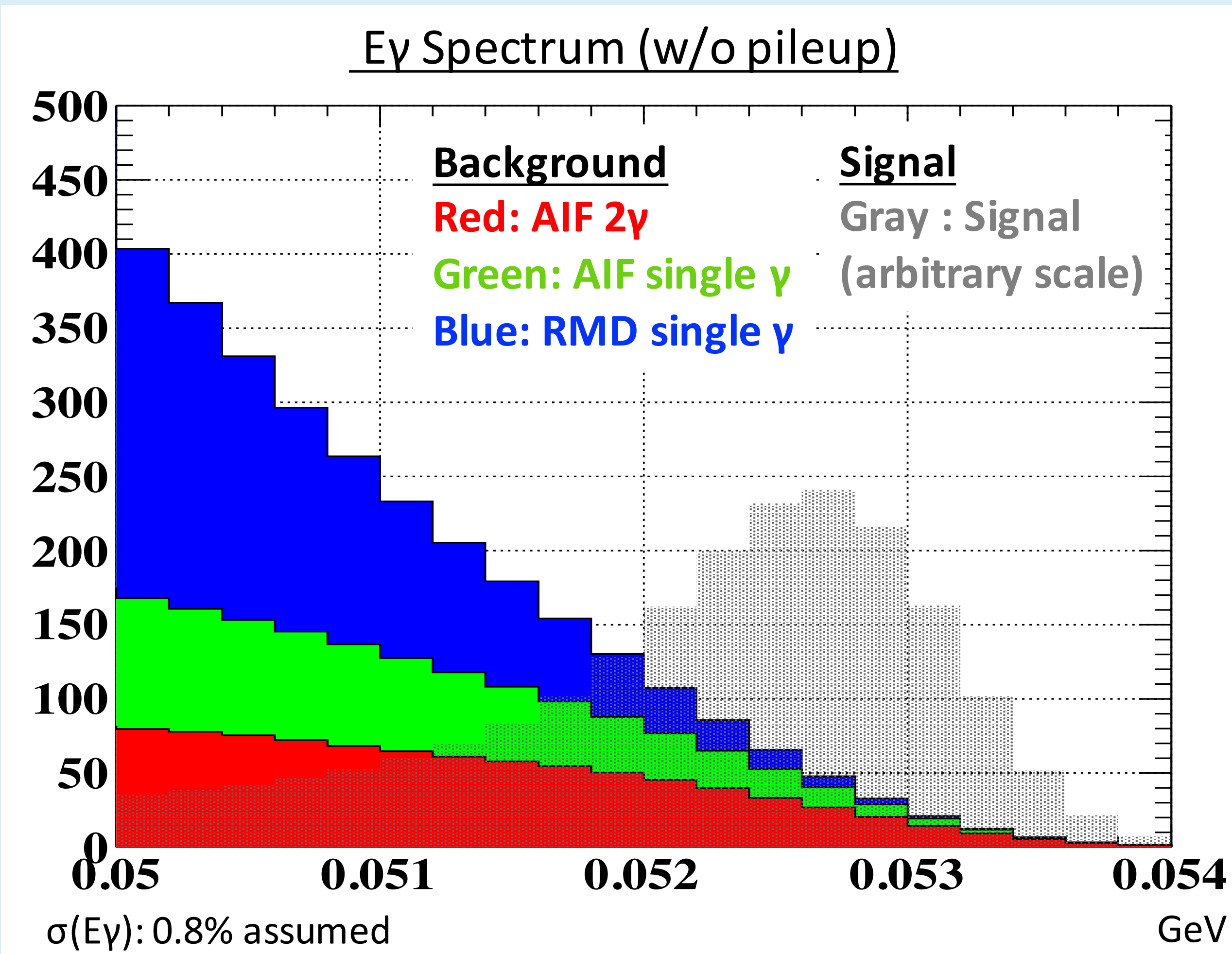
- Large opening angle.
- Single γ goes into LXe.



- Small opening angle.
- Both 2γ go into LXe.

Gamma-ray background in MEG II

- Energy spectrum of BG γ generated by MC (muon decay on target).
- AIF 2γ is dominant (60%) in “signal region”.



Signal region

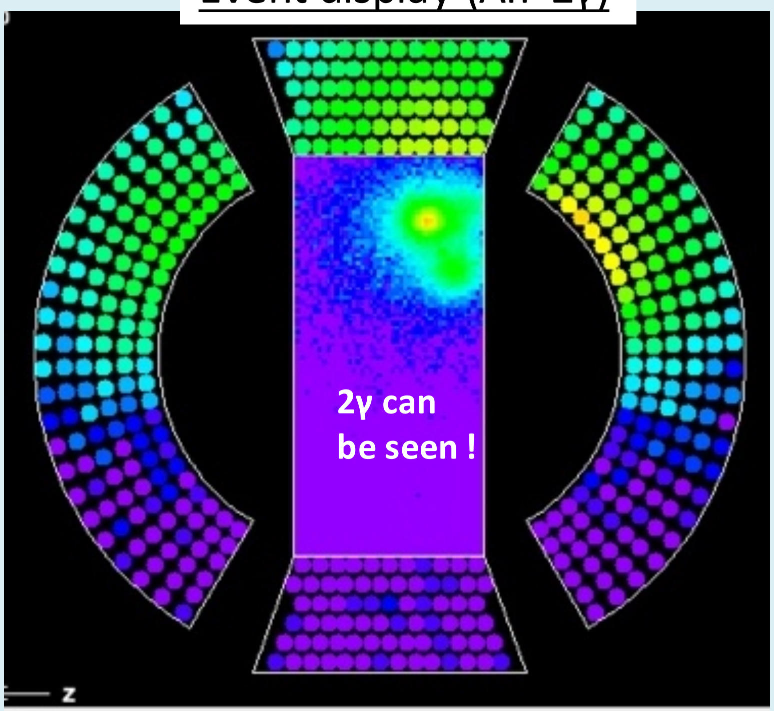
- Defined as 52.4 – 54 MeV in this study.
- Likelihood fit by PDF will be performed in MEG analysis.

Gamma-ray background in MEG II

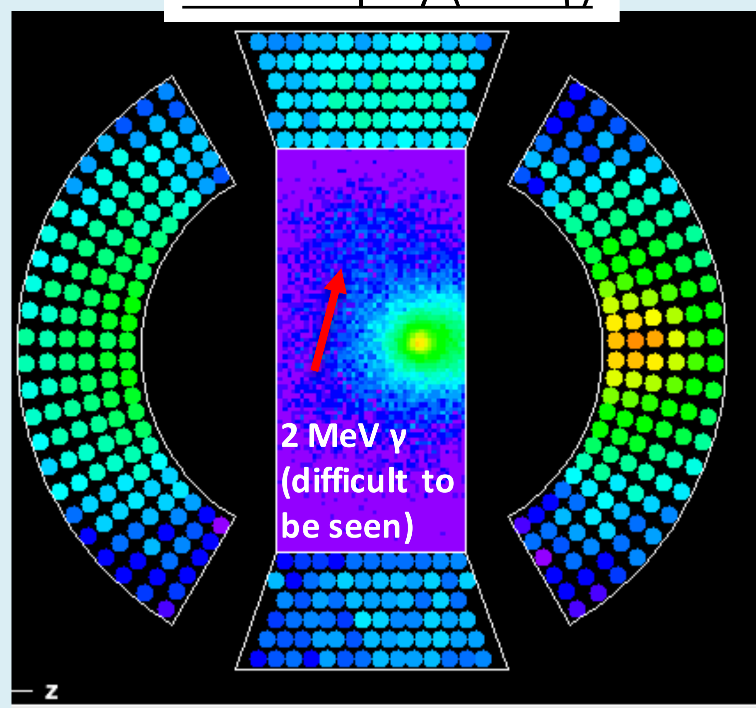
- Energy spectrum of BG γ generated by MC (muon decay on target).
- AIF 2γ is dominant (60%) in “signal region”.

- **Roughly half of them can be identified by MEG II readout granularity**.
- New in this study.

Event display (AIF 2γ)



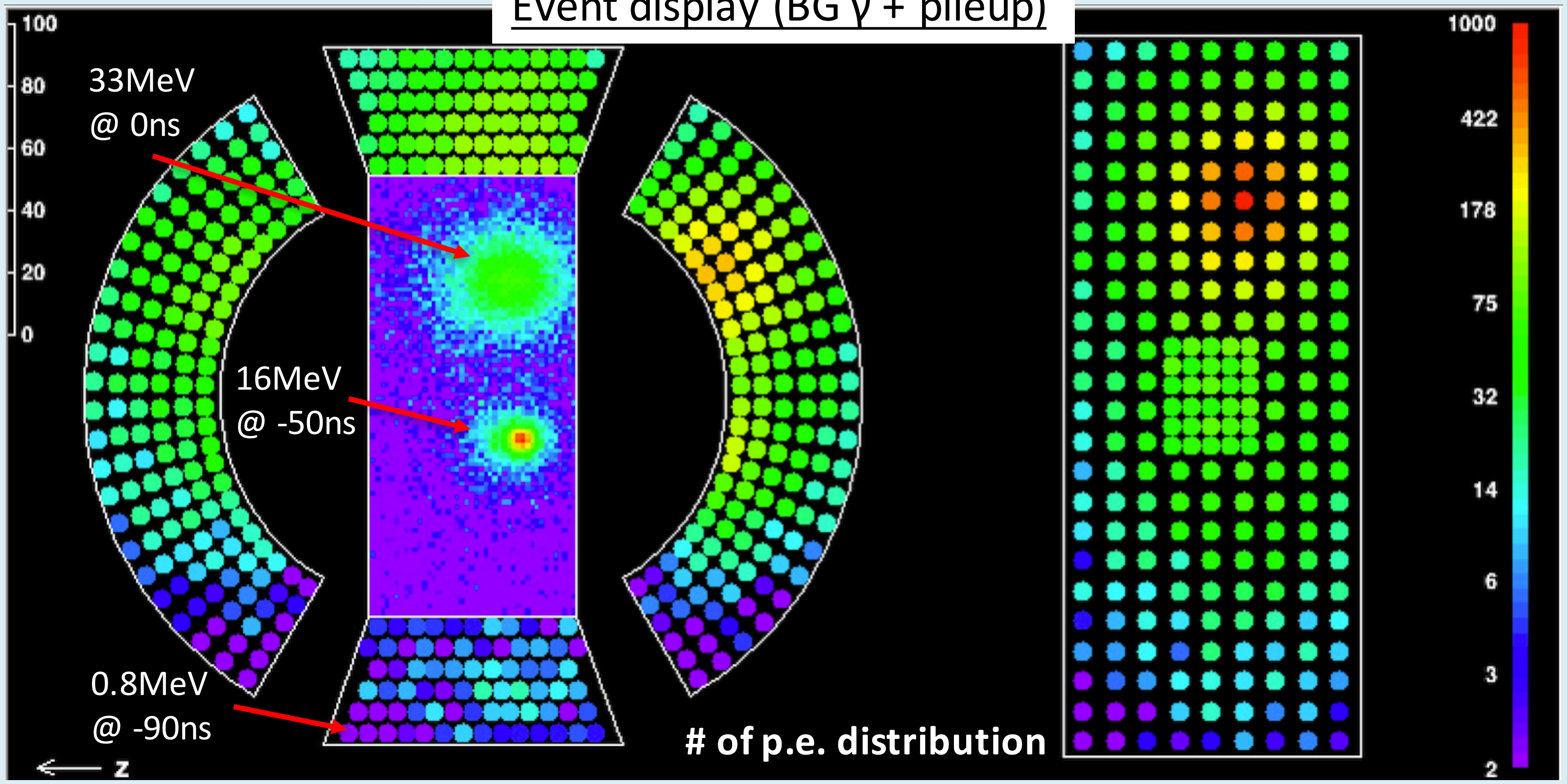
Event display (AIF 2γ)



Pileup gamma

- Many pileup events due to higher beam rate in MEG II
  - 2.3 times higher beam rate than MEG.
  - Rate of pileup γ: 1MHz → Half of events have some pileup hit.
- Energy deposit of pileup γ has to be subtracted.
- Effect on BG spectrum in MEG II has not yet estimated.

Event display (BG γ + pileup)

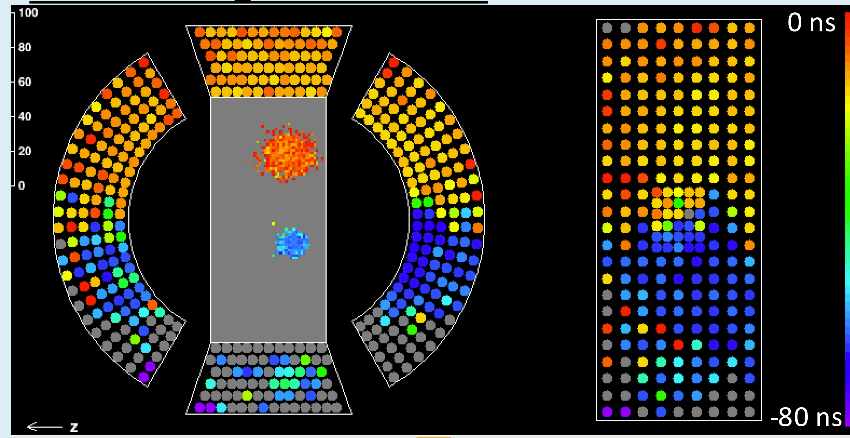


Multiple γ reconstruction algorithm

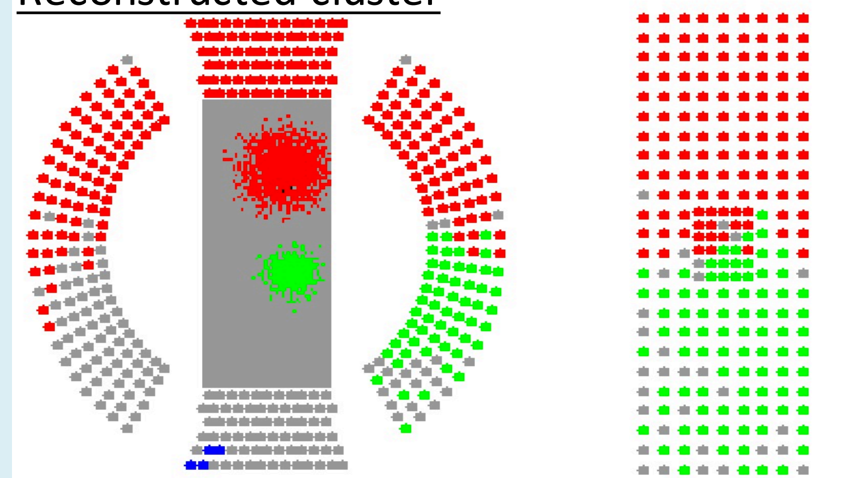
- Reconstruction for multiple γ has been implemented.

1. Multiple hit identification
    1. Waveform Analysis:
        - Extract peak amplitude and timing.
    2. Clustering:
        - Cluster adjacent channel which has similar timing.
        - New cluster is generated from local peak of amplitude.
    3. Quality cut of found clusters.
2. Waveform unfolding

Peak timing distribution



Reconstructed cluster

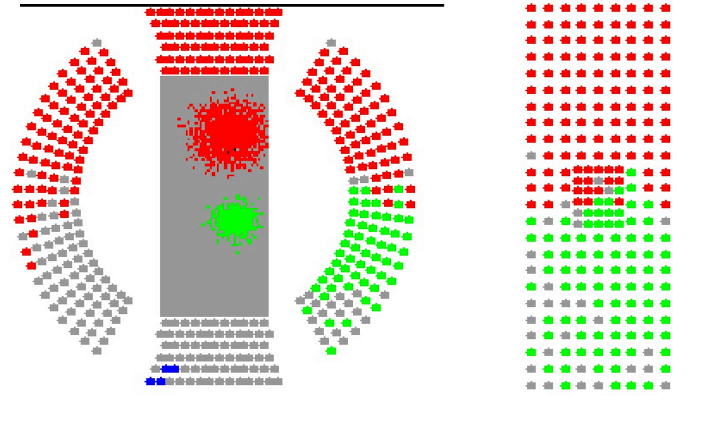


each color corresponds to each cluster

Multiple γ reconstruction algorithm

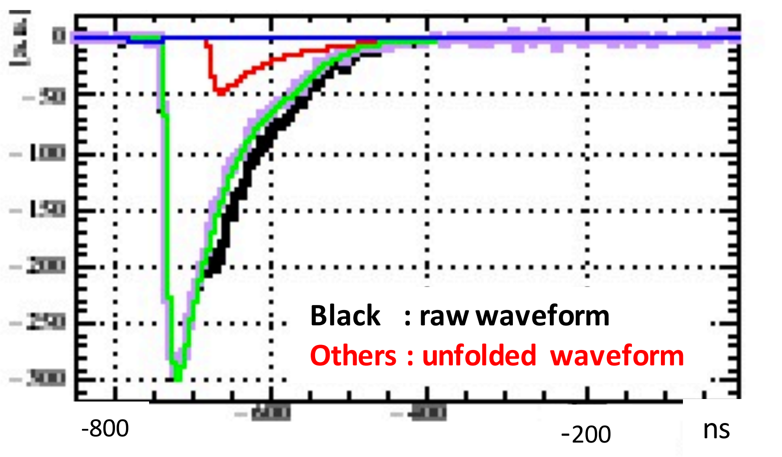
- Reconstruction for multiple γ has been implemented.

Reconstructed cluster

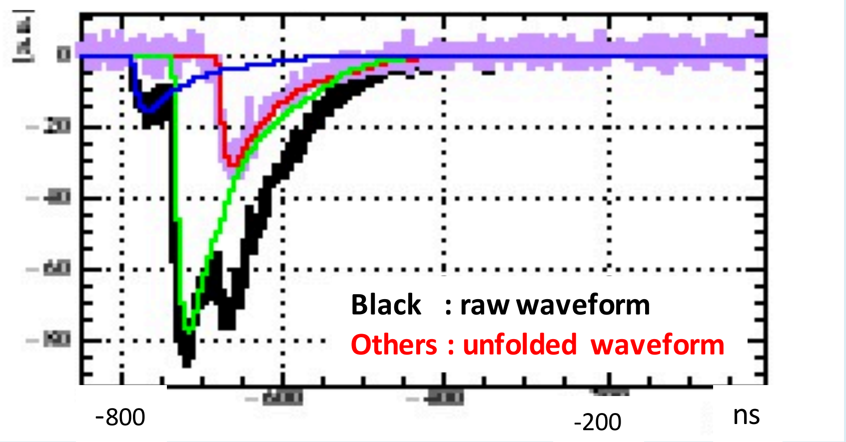


1. Multiple hit identification
2. Waveform unfolding
    1. Make sum waveform for each found cluster.
    2. Fit each waveform to unfold it.

Sum waveform (PMT in Green cluster)



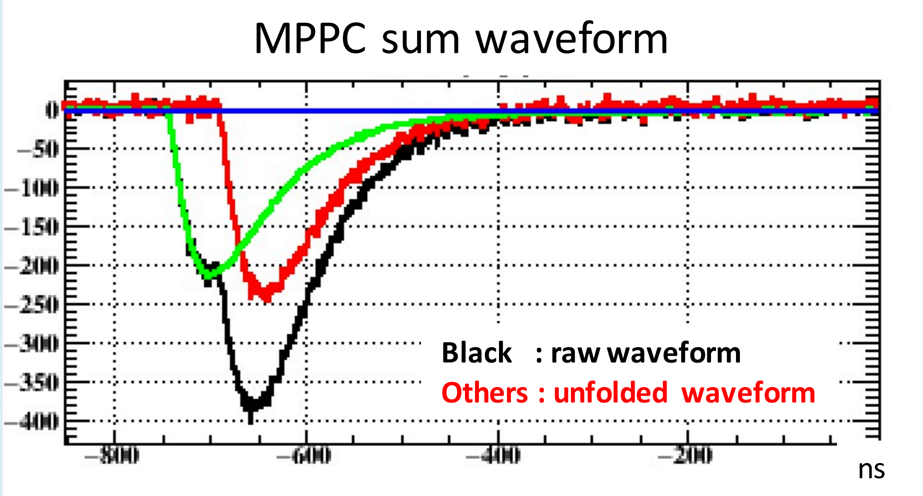
Sum waveform (PMT in Gray cluster)

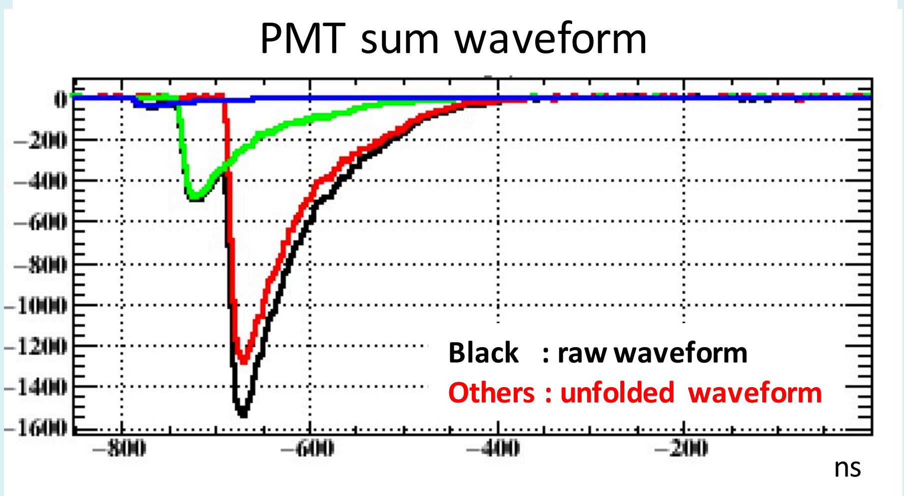


Multiple γ reconstruction algorithm

- Reconstruction for multiple γ has been implemented.

1. Multiple hit identification
2. Waveform unfolding





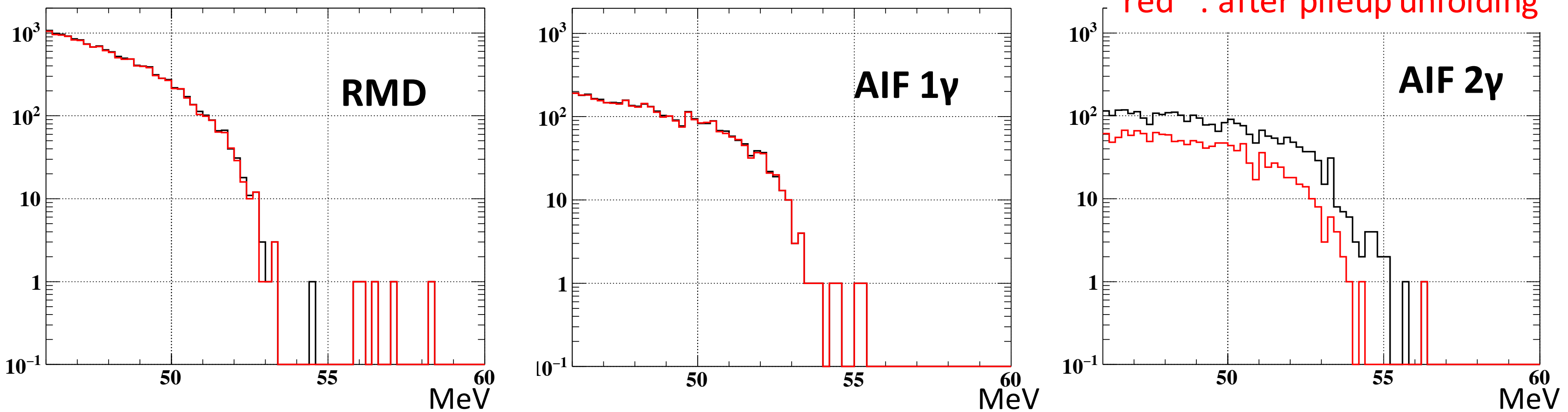
Pulses from each γ are correctly unfolded.

Performance - AIF 2γ identification -

- To estimate analysis performance,
  reconstructed Eγ spectrum has been checked.

Reconstructed Eγ (BG γ, no pileup)

black: before pileup unfolding
red : after pileup unfolding



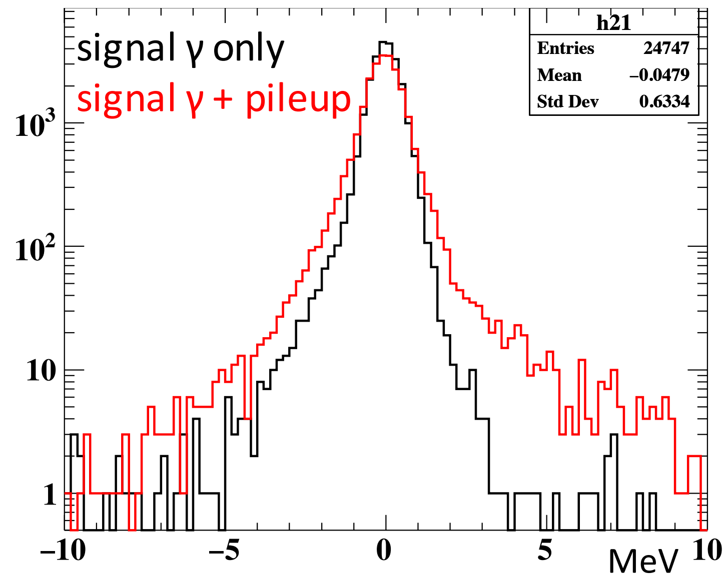
58% reduction of AIF 2γ BG
(being identified as multiple-γ event)

34% of reduction of BG in "signal region".

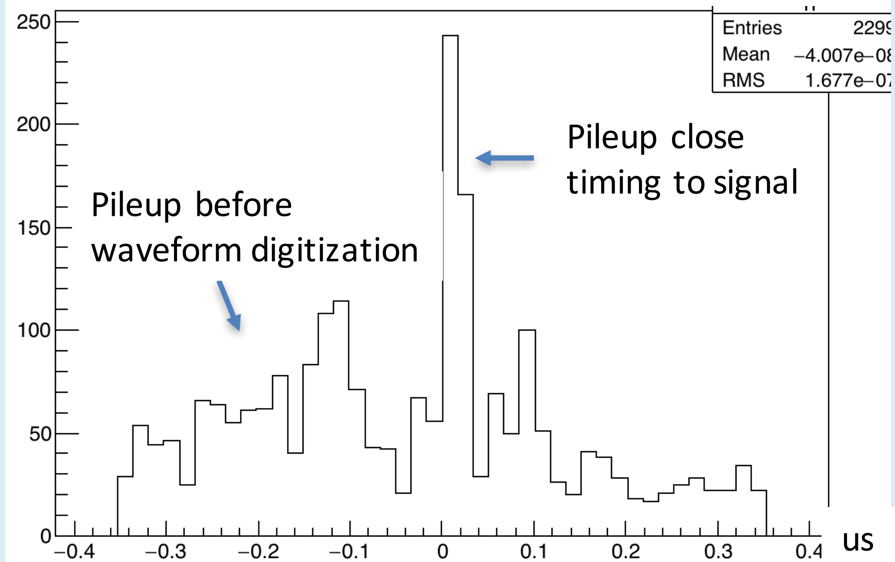
Performance - Pileup elimination (Signal γ)-

- Performance for pileup elimination is also checked.

<u>Eγ (reconstructed) – Eγ (MC truth)</u>
(Signal γ MC)



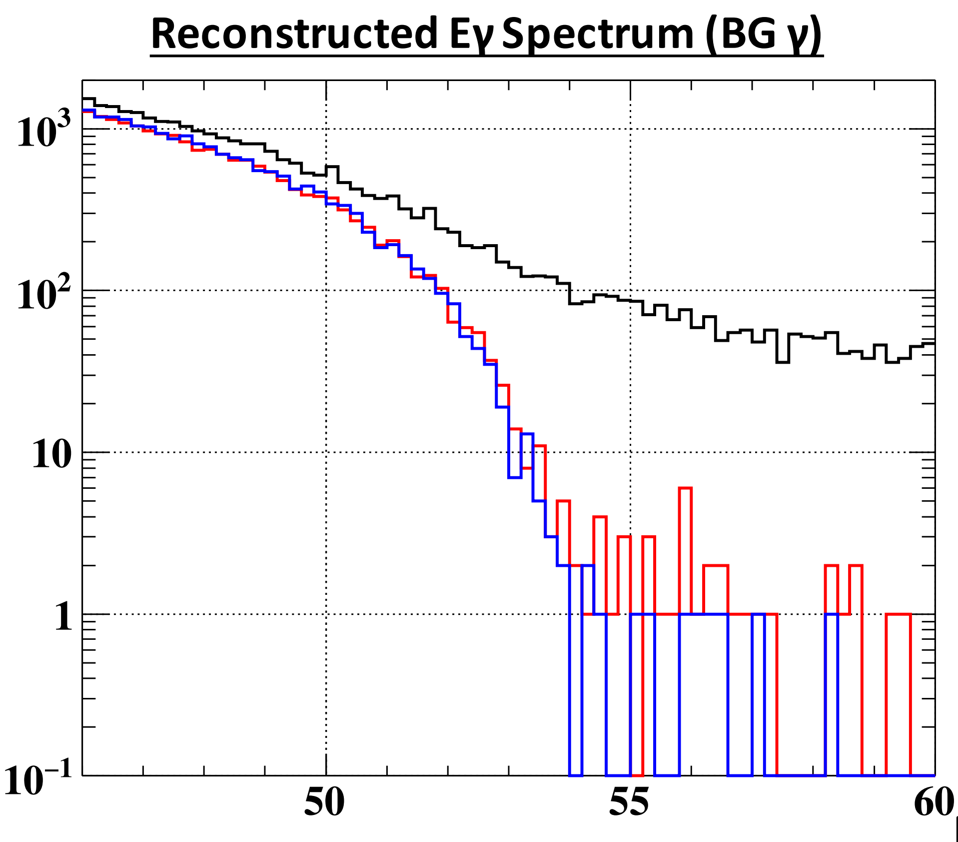
<u>Timing (pileup γ) – Timing (signal γ)</u>
| E(reconstructed) – E(MC truth) | > 3σ



- Tail in reconstructed Eγ caused by misidentified pileup.
  - **6% reconstruction inefficiency to signal event** (out of 3σ from true Eγ).
  - Especially, small energy at same timing pileup.
    → Needs dedicated algorithm (as is in MEG I).

Performance - Pileup elimination (BG γ) -

- Pileup identification and unfolding work well for 97% of events.
- Other 3% of pileup event are left in signal energy.
  → Non-negligible number of pileup events.
  - **+24% of BG event in "signal region".**
    - +7% for 52 - 54 MeV. + 37% for 52.8 – 54 MeV.



BG γ + pileup
black: before pileup unfolding
red : after pileup unfolding

BG γ (no pileup)
blue : after pileup unfolding

Black → Red:
- 97% reduction,
- by pileup identification

Blue→ Red:
- +24% BG event,
- BG increase by pileup

Summary & Prospect

- LXe detector in MEG II has been upgraded, and readout granularity has been improved by a factor of 16.
- Reconstruction algorithm of pileup identification and unfolding has been developed, and its performance has been tested by MC.
  - Number of BG event in "signal region" ($52.4 < E\gamma < 54$ MeV) is discussed.

- By utilizing MEG II granularity, **58% of AIF 2γ event is identified**, and this leads to **34% reduction of BG**.
- Due to the **misidentified pileup**, **24% increase of BG, and 6% of signal inefficiency**.

Prospect

- Improvement of identification performance.
- For the precise estimation of those effect,
  physics sensitivity estimation by likelihood fit by PDF is needed.

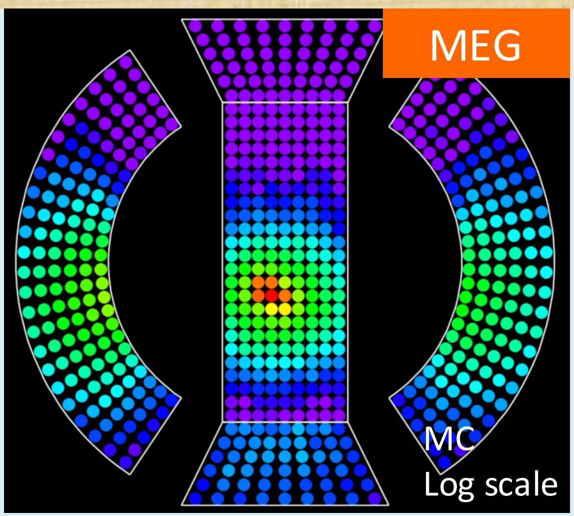
BACKUP

Expected performance

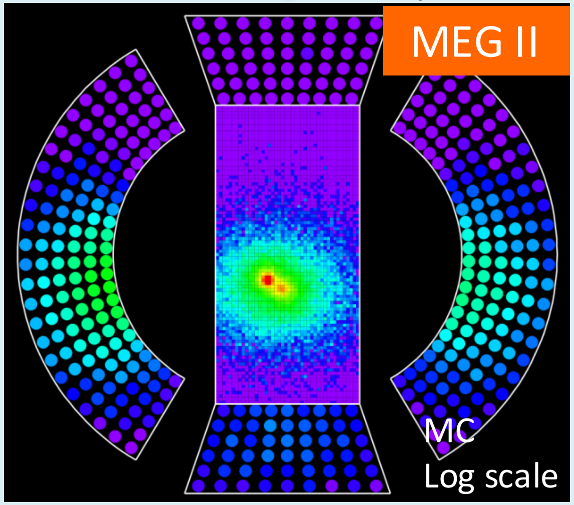
- Significant improvement of all resolutions and efficiency are expected.

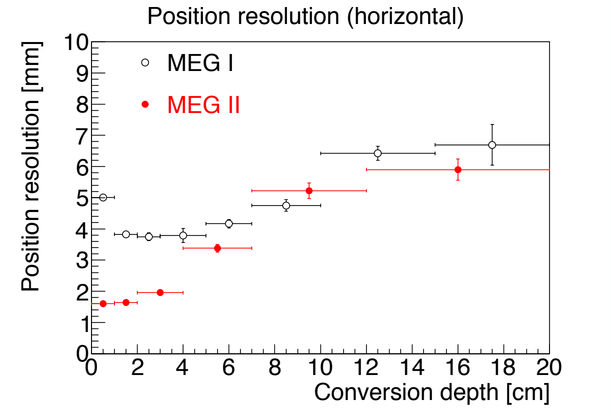
Detector performance for signal γ-ray

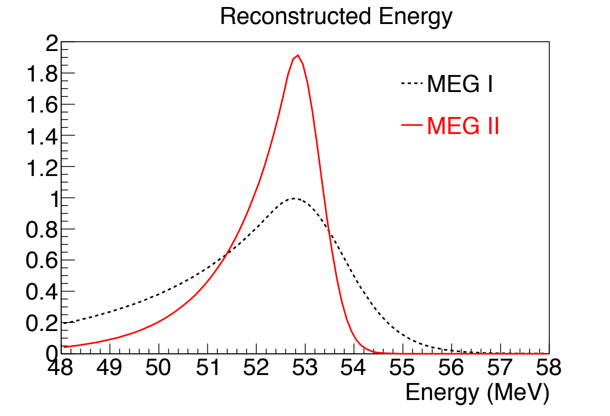
	MEG (measured)	MEG II (simulated)
Position	~5 mm	~2.5 mm
Energy	~2%	0.7 - 1.5%
Timing	62 ps	40 - 70 ps
Efficiency	65%	70%



Imaging power improves



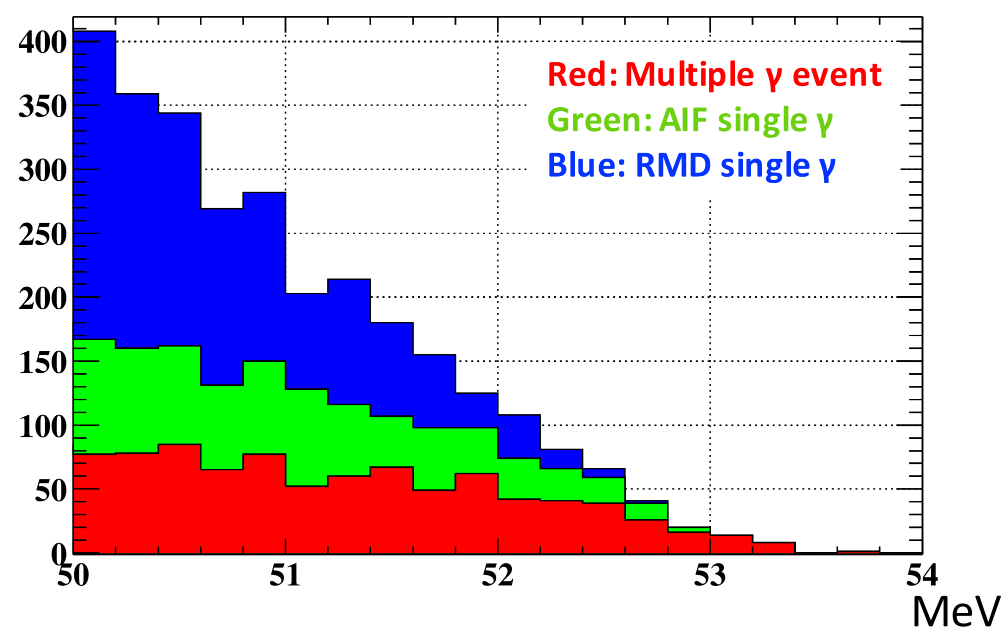




Multiple γ from single muon decay

- I classified high Eγ BG event into three types.
  1. Single γ event from RMD decay. (= “RMD 1γ”)
  2. Single γ event from Michel decay. (= “AIF 1γ”)
  3. Multiple γ event from single muon decay. (= “AIF 2γ” + unusual events)
- High Eγ BG event in signal region is dominated by multiple γ events.

Energy deposit distribution from single muon decay.



eV (i.e. -1σ - +3σ).

60%

True energy deposit

# of event	52.4 < Eγ (MeV) < 54
Multiple γ	104
AIF single γ	37
RMD single γ	9

Multiple γ events

- If we can identify multiple γ events, we can reduce BG event.
  → How multiple γ events look like?

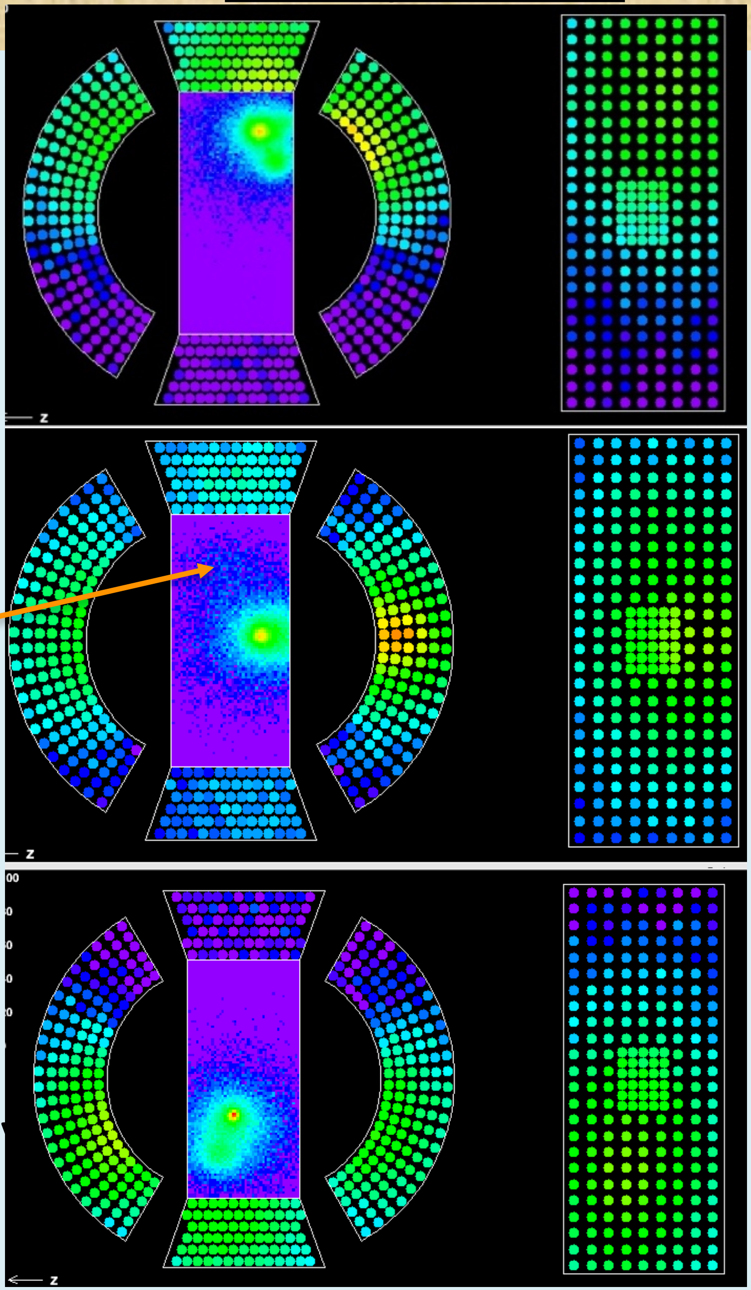
- Most of them 2γ from AIF.
- Whether we can identify them as 2 γ, depends on
  - Energy
  - Hit depth
    (deep events is hard to be found)
  - distance on Inner face

- By my eye, 60-80 % of them can be identified as 2γ event.

  → **Those can be identified by pileup anal**

3 example events.

2 MeV γ
at w = 15cm



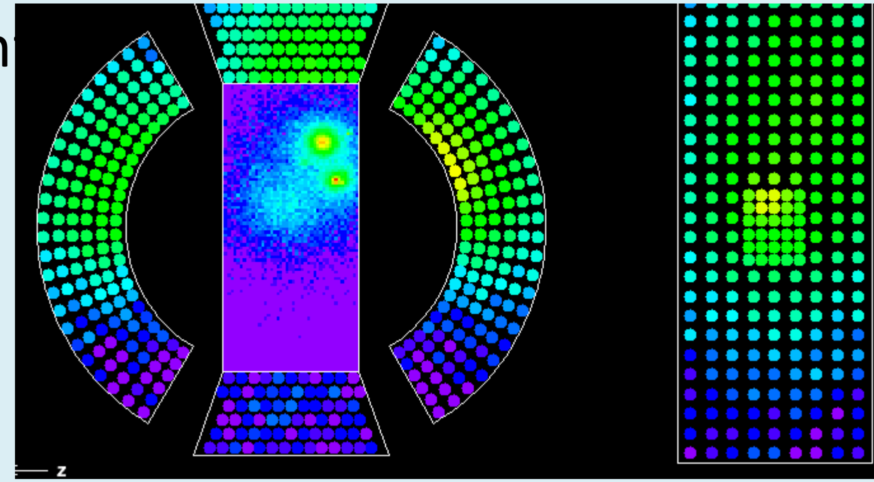
Multiple γ events

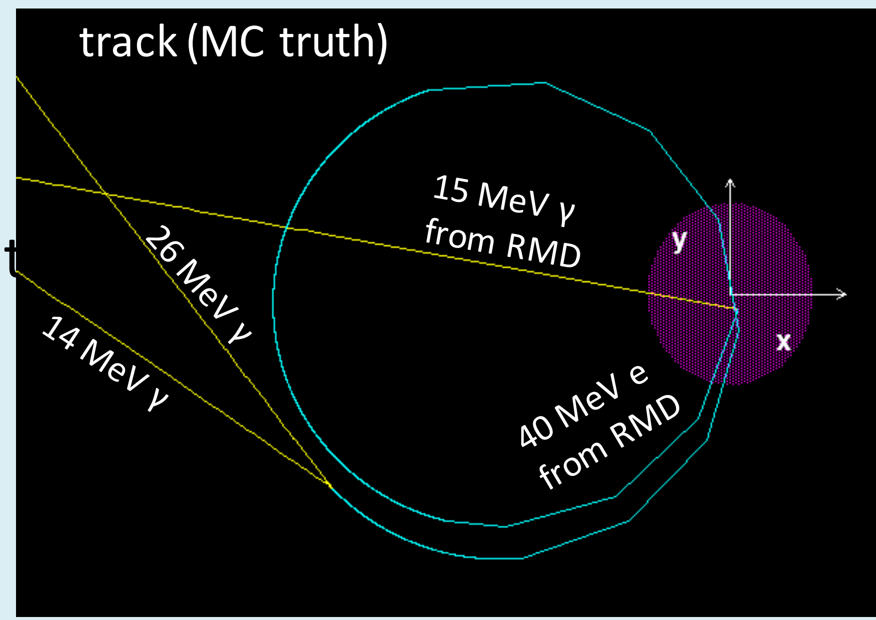
- Another type of multiple γ even
combination of RMD and AIF.

- In this event
  - 15MeV γ + 40MeV e from RMD.
  - Positron cause pair creation.
Both 14 & 26 MeV γ goes to XEC.

- Many of those events can also be identified as multiple γ event by my eye.

Example events.





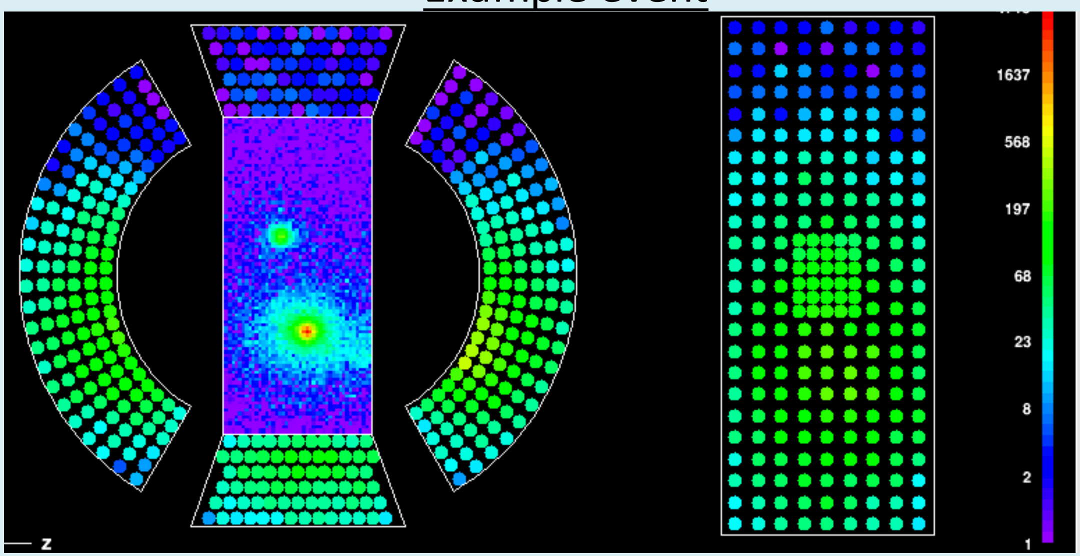
Pileup found, not unfolded.

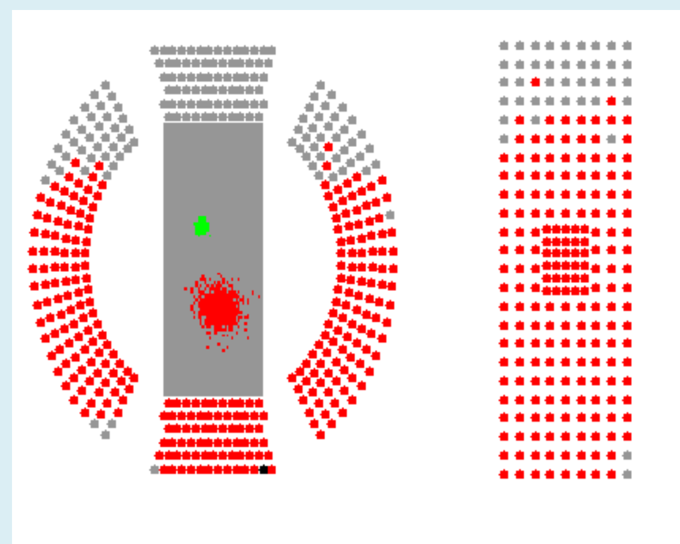
- Sometimes we can find the existence of pileup, but cannot be unfolded.
- Typical example : Pileup at the same timing.
  - Assignment of PMT Charge for each cluster is not correct.
    (No local peak of pileup γ on PMT faces.)

→ For now, those event (large energy pileup at same timing on inner face) is flagged to reject them in the physics analysis.

- In MEG I, EneTotalSumRec task performed template fit of light distribution for those events.

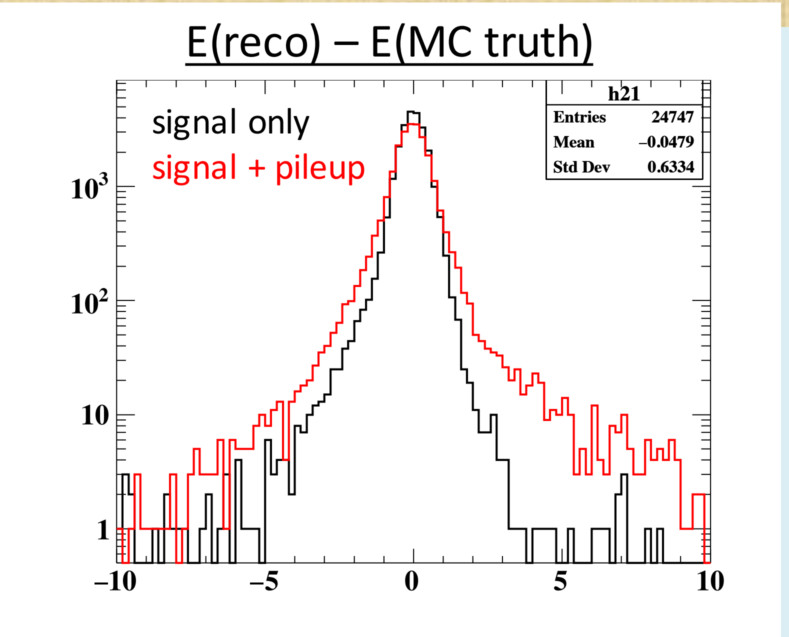
Example event





Performance -signal γ + pileup -

- Performance for Signal γ + pileup.
  - Half of events has pileup γ.
- Two source of inefficiency for signal.
  1. Event selection in pileup analysis.
  2. Tail events in reconstructed energy
- In total, 6% inefficiency.



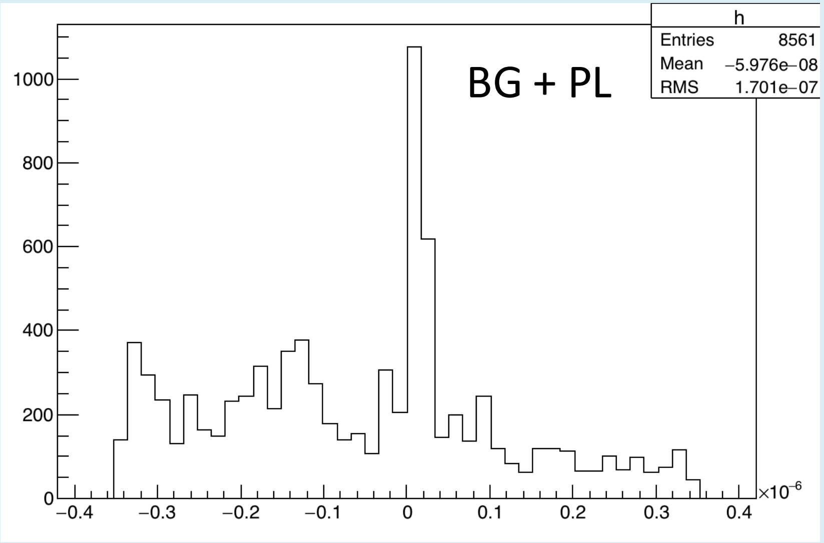
	Signal γ only	Signal γ + pileup	total
Generated in MC	100%	100%	100%
After event selection in pileup analysis	99.5%	96.0%	97.8%
Tail event cut (3σ)	97.5%	90.6%	**94.1%**

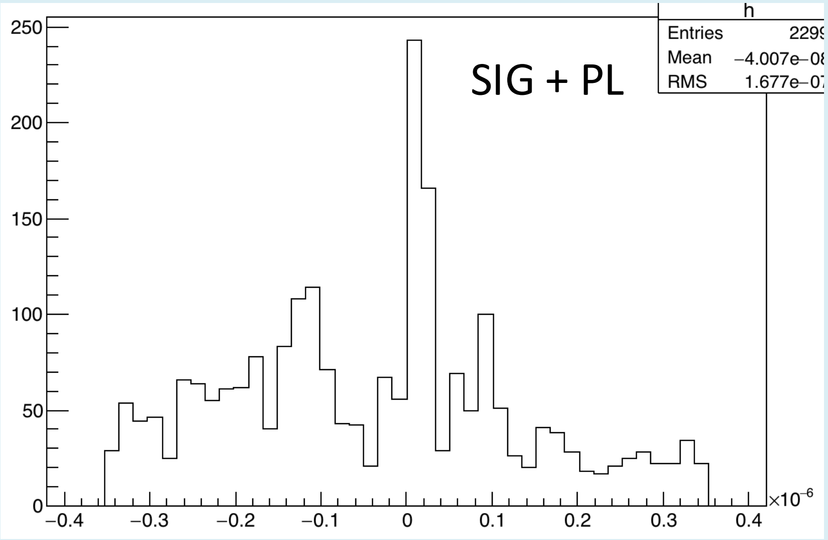
Performance -signal γ + pileup -

- E(reco) – E(MC) > 3σ

<u>time (pileup) – time(main)</u>

(MC truth, |E(reco) – E(MC)| > 3σ, main γ + 1 pileup γ)





event in signal region

# of BG event *in 52 < Eγ < 54*	expected from MC (w/o pileup)	reconstructed (w/o pileup)	reconstructed (w/ pileup)
Multiple γ (+pileup)	200.6	81	81 (80)
AIF single γ (+pileup)	106.5	110	201 (163)
RMD single γ (+pileup)	78.6	72	
Total	385.6	263	282 (243)

52% of BG is AIF 2γ
60% reduction of AIF 2γ
→ 32% reduction of BG

+7% of BG by pileup
-14% by DS RDC

# of BG event *in 52.4 < Eγ < 54*	expected from MC (w/o pileup)	reconstructed (w/o pileup)	reconstructed (w/ pileup)
Multiple γ (+pileup)	115.0	48	54 (54)
AIF single γ (+pileup)	50.2	53	105 (87)
RMD single γ (+pileup)	27.2	27	
Total	192.4	128	159 (141)

60% of BG is AIF 2γ
58% reduction of AIF 2γ
→ 34% reduction of BG

+24% of BG by pileup
-11% by DS RDC

# of BG event *in 52.8 < Eγ < 54*	expected from MC (w/o pileup)	reconstructed (w/o pileup)	reconstructed (w/ pileup)
Multiple γ (+pileup)	54.7	24	27 (27)
AIF single γ (+pileup)	17.6	20	40 (32)
RMD single γ (+pileup)	6.6	5	
Total	78.7	49	67 (59)

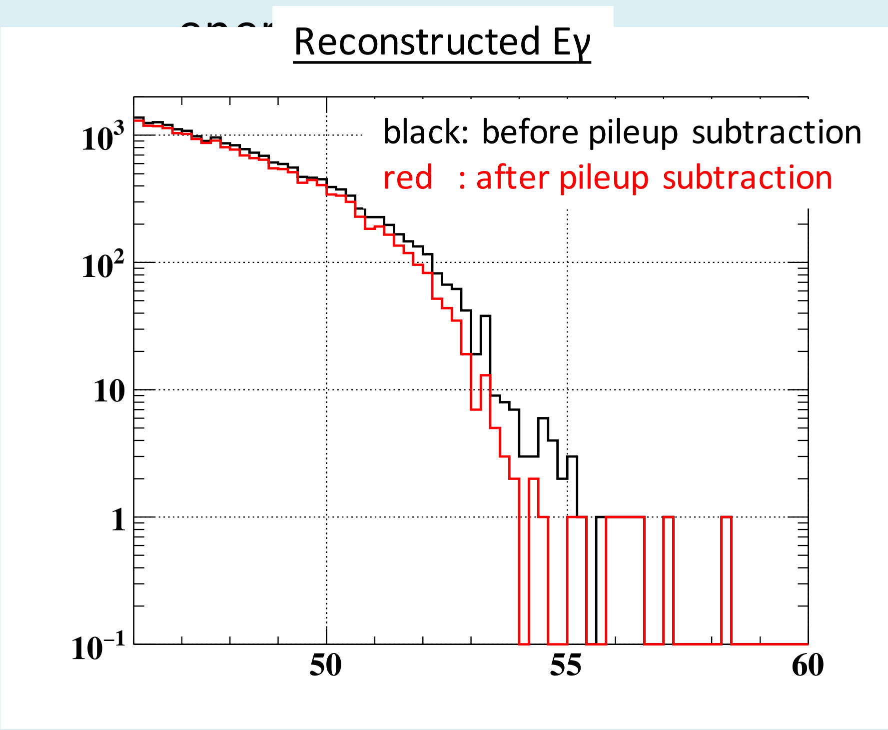
70% of BG is AIF 2γ
56% reduction of AIF 2γ
→ 38% reduction of BG

+37% of BG by pileup
-12% by DS RDC

() : no hit on DS RDC

Performance - BG γ from single muon decay-

- Performance for **single muon decay on target**. (i.e. no pileup event)
- 60% of multiple BG event is identified as multiple γ event and get out of signal Eγ region.
  - Expectation from MC : based on true total energy deposit convoluted by

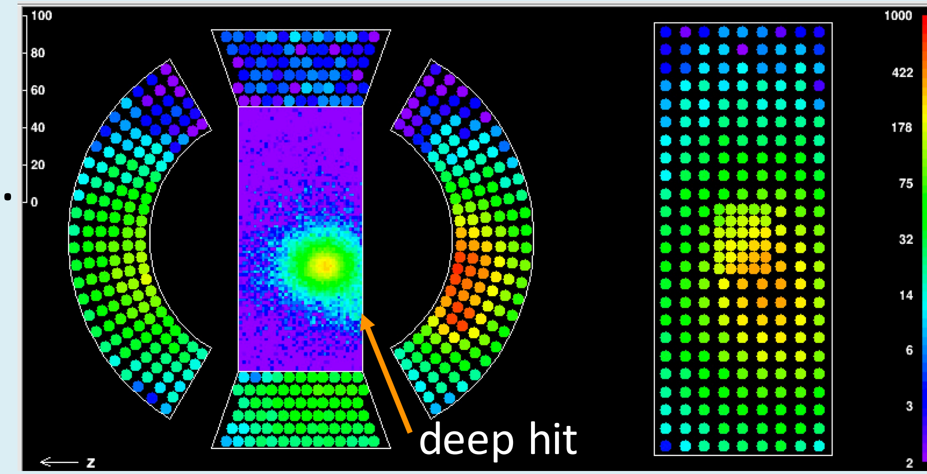


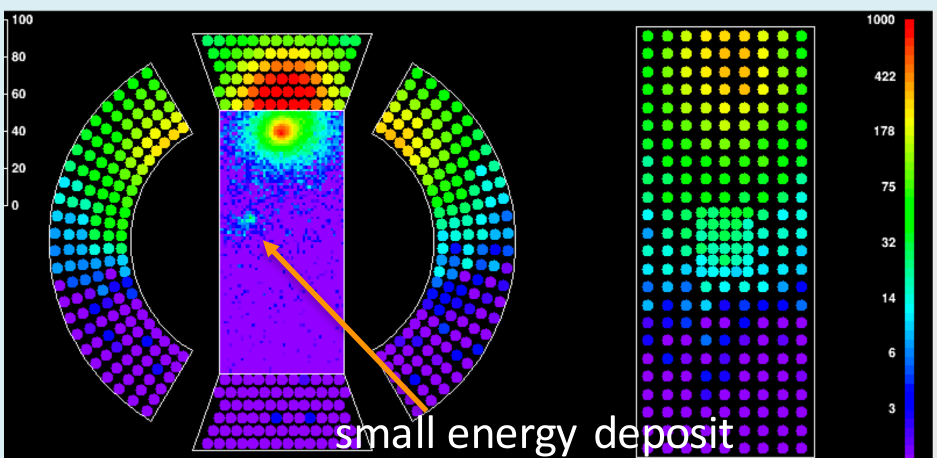
# of BG event in 52.4 < Eγ < 54	expected from MC	reconstructed
Multiple γ	**115.0**	**48**
AIF single γ	50.2	53
RMD single γ	27.2	27
Total	**192.4**	**128**

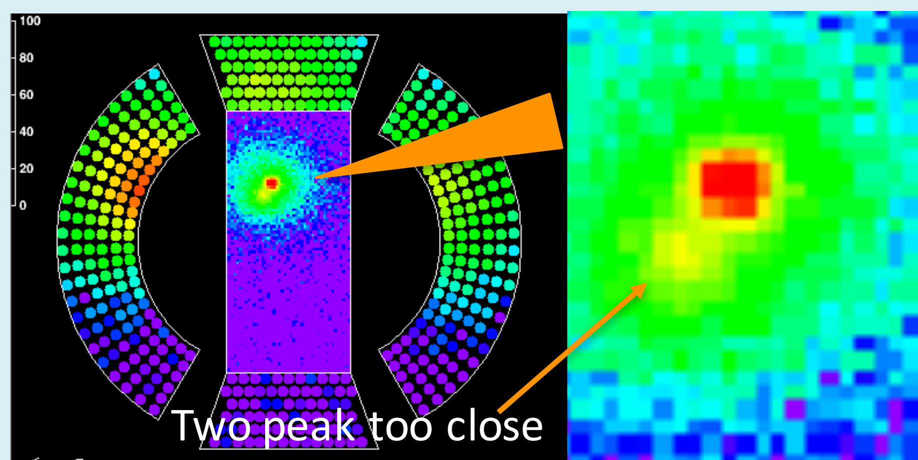
Performance - BG γ from single muon decay-

- 40% of multiple BG event is not identified.
  - Deep hit
  - small energy deposition
  - Too close to find
- It seems not easy to find them.

Three example events

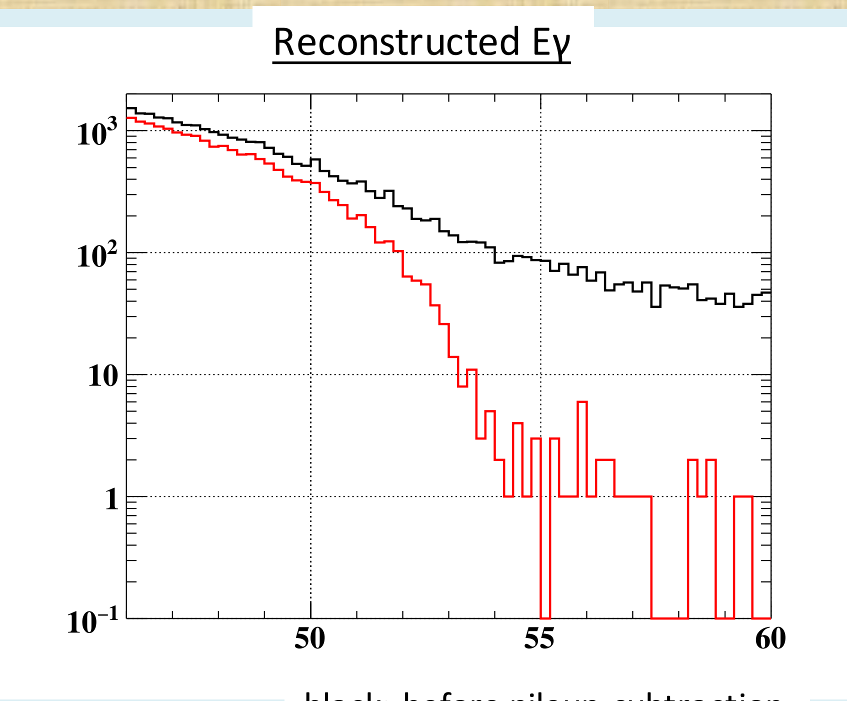






Performance - BG γ + pileup -

- Performance for **BG γ + pileup**.
- Pileup identification and eliminati
  works well for most events,
  but there are several events left
  in the signal region.
- + 24% of BG from pileup.

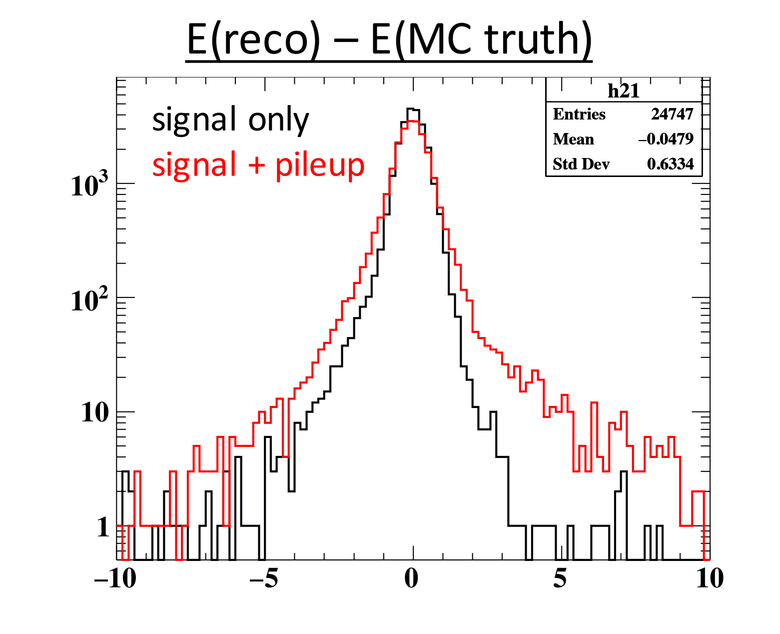


black: before pileup subtraction
red : after pileup subtraction

# of BG event in 52.4 < Eγ < 54	expected from MC (w/o pileup)	reconstructed (w/o pileup)	reconstructed (w/ pileup)
Multiple γ (+pileup)	115.0	48	54
AIF single γ (+pileup)	50.2	53	105
RMD single γ (+pileup)	27.2	27	
Total	192.4	**128**	**159**

Performance -signal γ + pileup -

- Performance for Signal γ + pileup.
  - Half of events has pileup γ.
- Two source of inefficiency for signal.
  1. Event selection in pileup analysis.
  2. Tail events in reconstructed energy
- In total, 6% inefficiency.

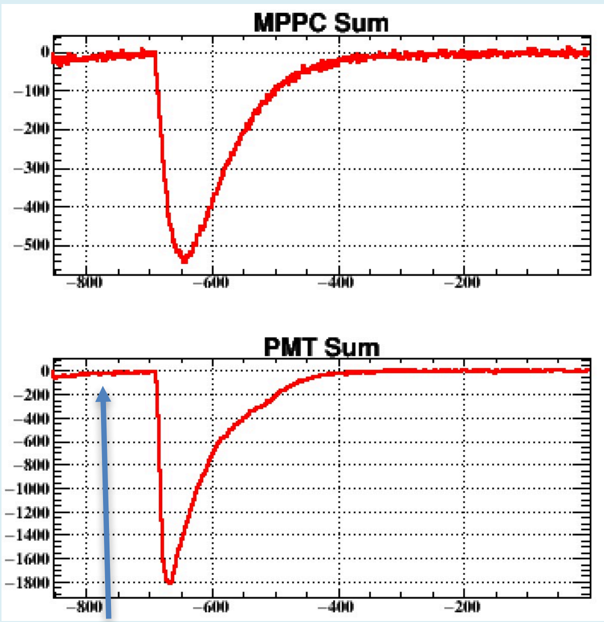


	Signal γ only	Signal γ + pileup	total
Generated in MC	100%	100%	100%
After event selection in pileup analysis	99.5%	96.0%	97.8%
Tail event cut (3σ)	97.5%	90.6%	**94.1%**

Room for improvement of pileup

- There are still room for improvement.
  - Combination with result of other algorithm is promising.

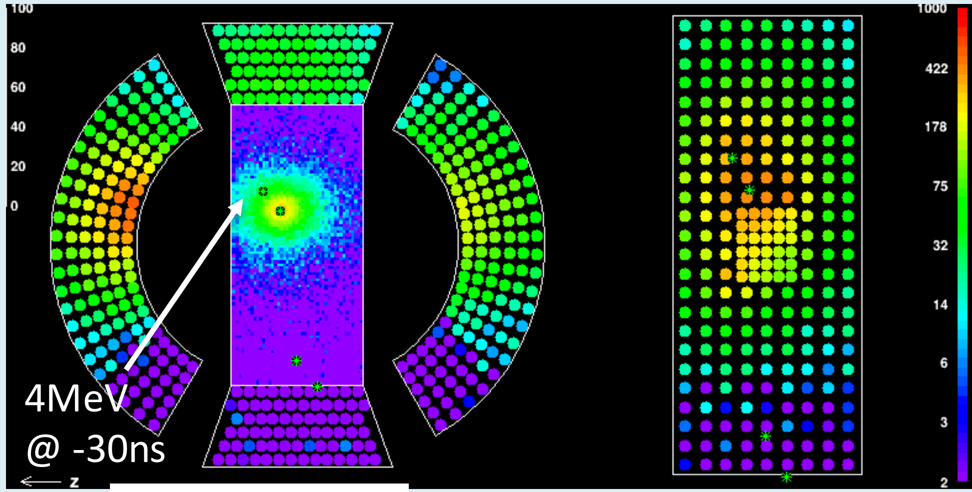
Example No.1 (Out of DRS window)



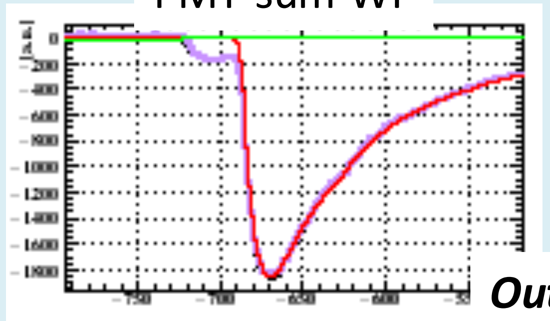
7MeV@-250ns is not found.
Affects -1.6MeV.

Peak search on ADC waveform
should be useful for this

Example No.2 (Small energy , close timing pileup)



PMT sum WF



We can see the sign of pileup in PMT sum WF.

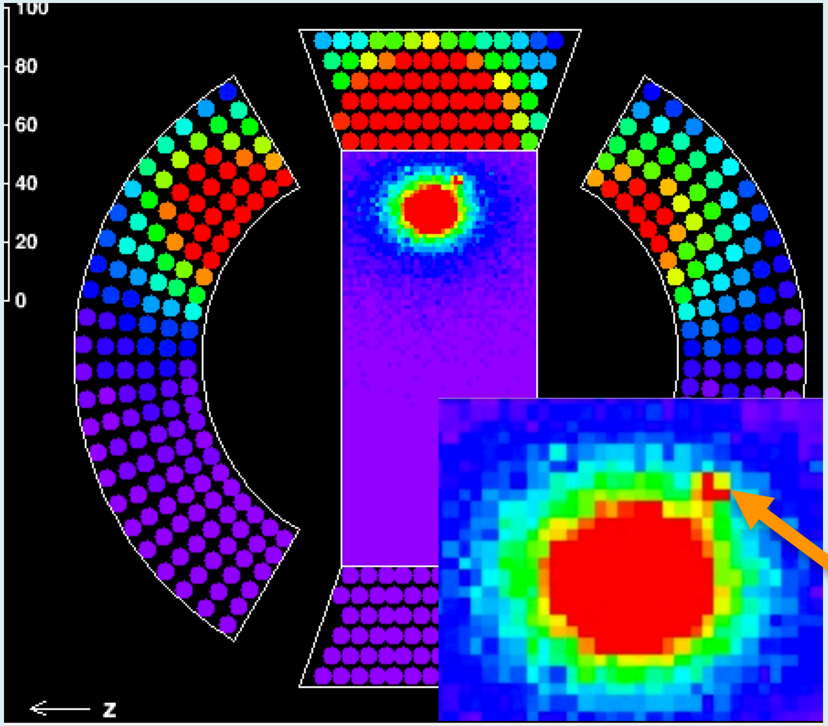
Outlier search in XECTimeFit
should be useful for this

Signal inefficiency by LD

my slide
@collab. Mar/2017

- For some of the signal event, **LD method find multiple peak even for the signal event /o pileup γ.**
  - This is due to the energy deposition just in front of the MPPC caused by the gamma ray escaped from shower.
  - This can lead to the **inefficiency to the signal**, if we eliminate the effect of the pileup based on this kind of false information.

Example : signal event w/o any pileup



second peak in light distribution

Track (MC truth) of this event