MEG II実験液体キセノン検出器のビーム環境下での性能評価

In-beam performance of MEG II liquid Xe detector

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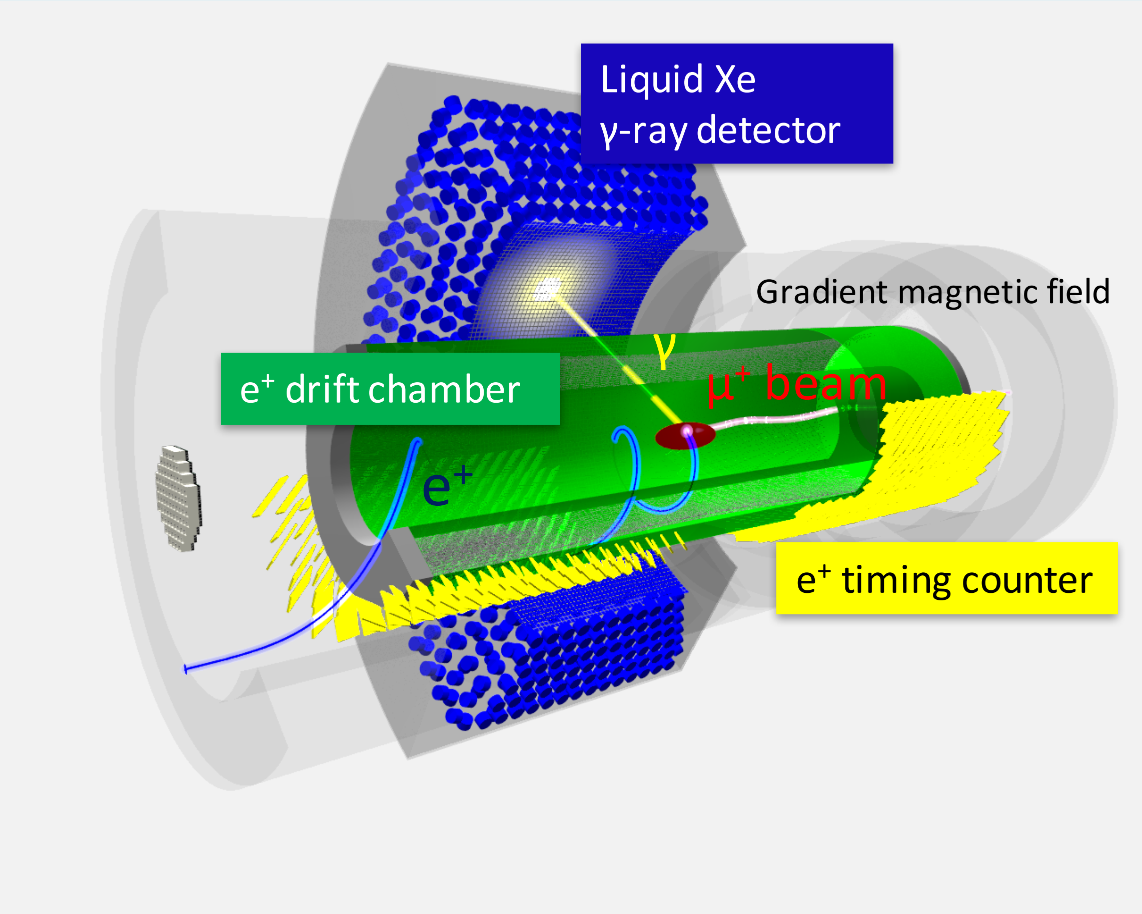
MEG II experiment

Upgrade of MEG experiment

- Searches for $\mu \rightarrow e\gamma$.
- μ^+ stopping rate will be doubled
  - 3×10^7 μ/s → 7×10^7 μ/s
- Detection efficiency will improve.
- Resolutions of all detectors will become half.
- New detector for background tagging will be introduced



Expected sensitivity: 6×10^{-14}

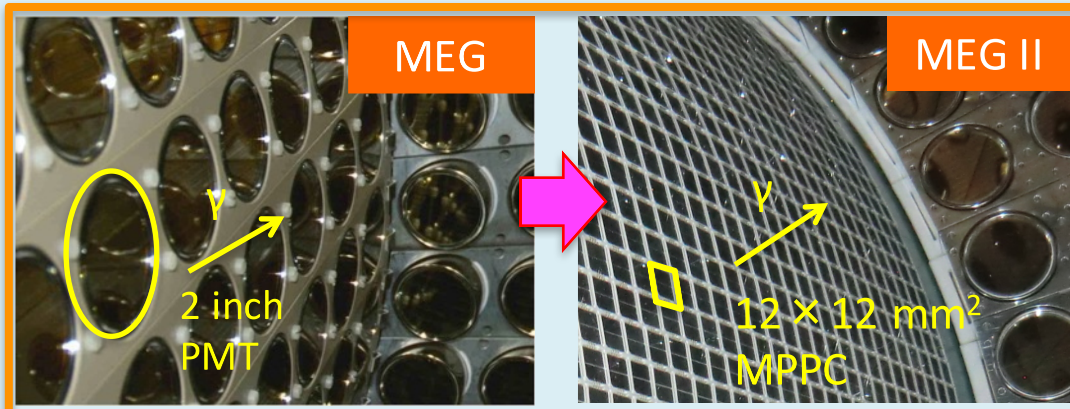
- One order of magnitude better than MEG

2017	2018
Pilot run with muon beam	Engineering run

Reference :
“The design of the MEG II experiment” , arXiv:1801.04688

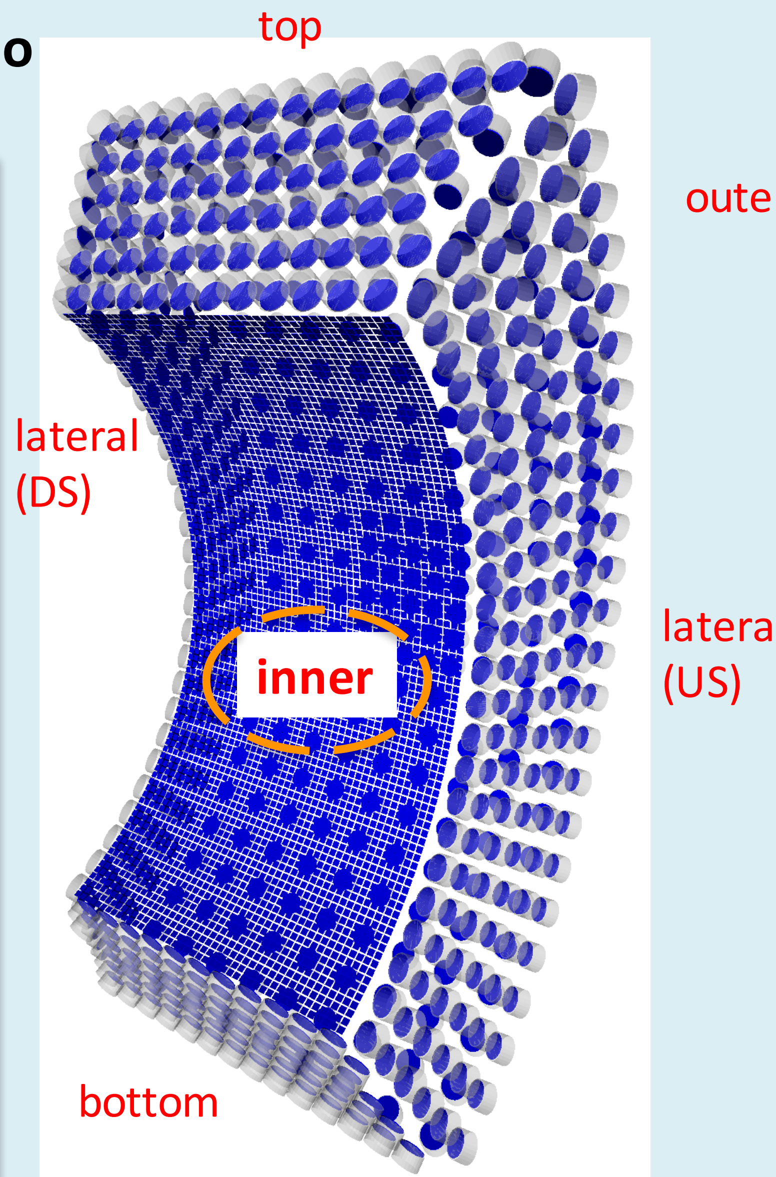
LXe detector upgrade

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

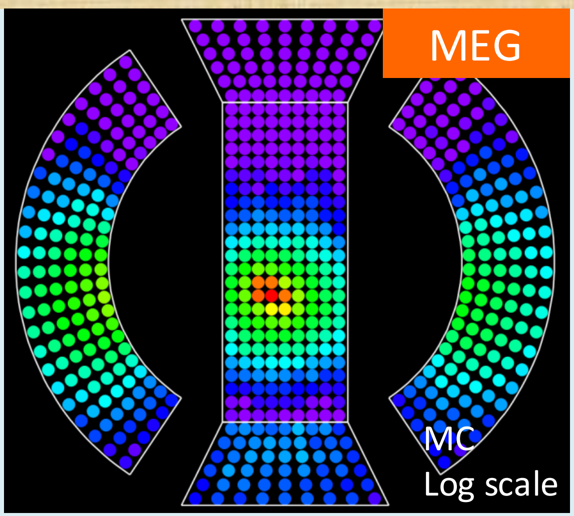


Expected performance

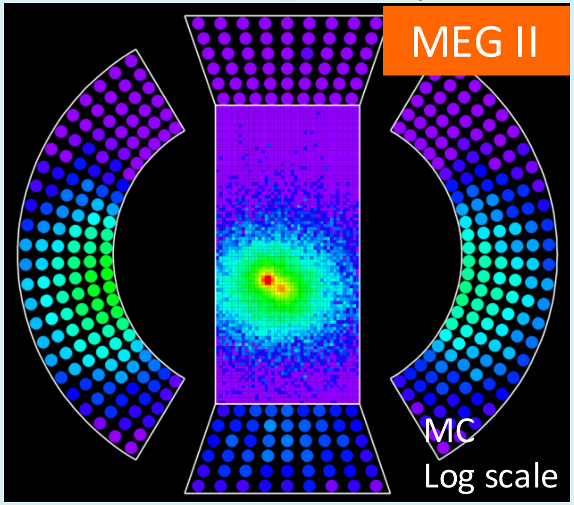
- Significant improvement of all resolutions and efficiency are expected.

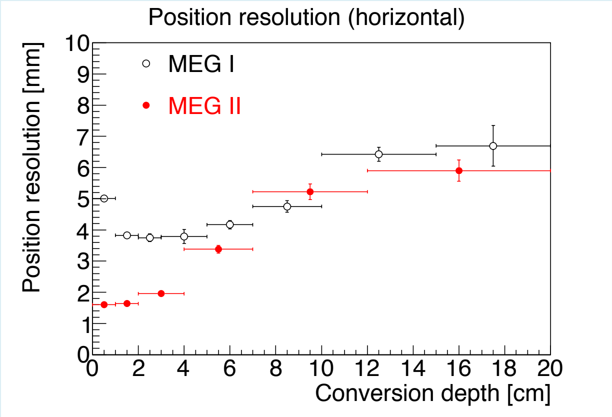
Detector performance for signal γ-ray

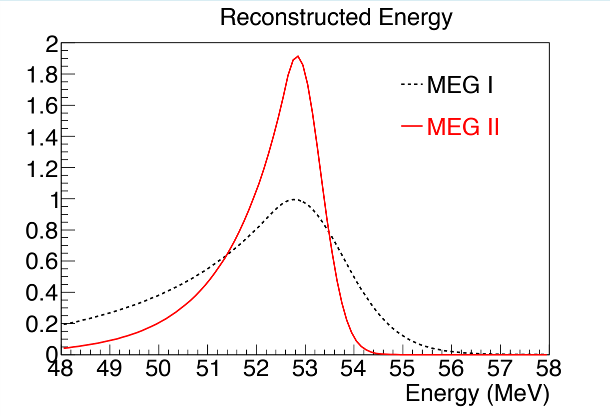
	MEG (measured)	MEG II (simulated)
Position	~5 mm	~2.5 mm
Energy	~2%	0.7 - 1.5%
Timing	62 ps	40 - 70 ps
Efficiency	65%	70%



Imaging power improves







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LXe detector in 2017

- LXe detector in 2017
  - Detector commissioning
    - LXe control & purification. Performance measurement of all sensors. etc...
    - Reference : "Commissioning of all MPPCs for MEG II LXe detector" at "JPS. 2017年秋季大会"
  - **Pilot run with muon beam. : This talk**
    - ~Two week beam time at the End of 2017 Dec.
    - γ-ray DAQ from radiative muon decay and Michel positron annihilation.

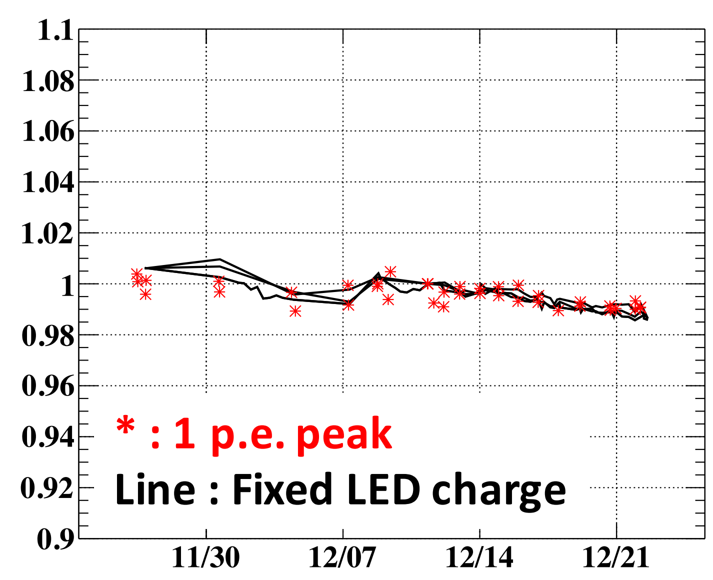
- In-beam performance estimation of detector.
  - **Detector stability : OK**
  - **Gamma-ray DAQ : OK**
  - Detector performance estimation
    - Position resolution : Ongoing. → ***25aK206-3***
    - **Timing resolution : OK**
    - **Energy resolution : Noise problem found**

Detector stability

- Detector stability is successfully monitored.
  - **MPPC gain**
  - PMT Gain : 4% gain decrease by aging effect.
  - Light yield : Stable at 4% precision.
  - etc...

Similar method with MEG.

MPPC Gain History (All channel average)

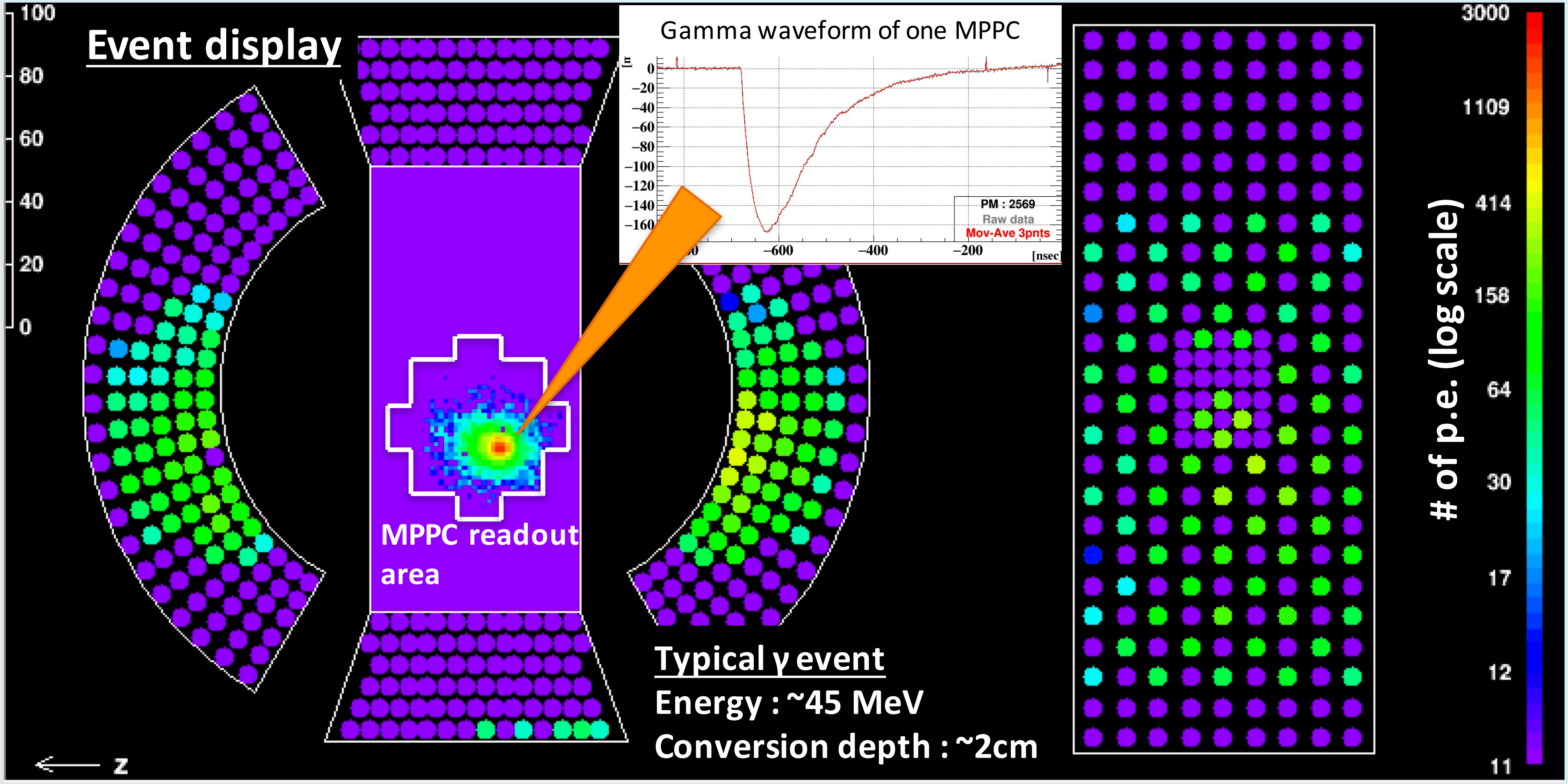


MPPC Gain

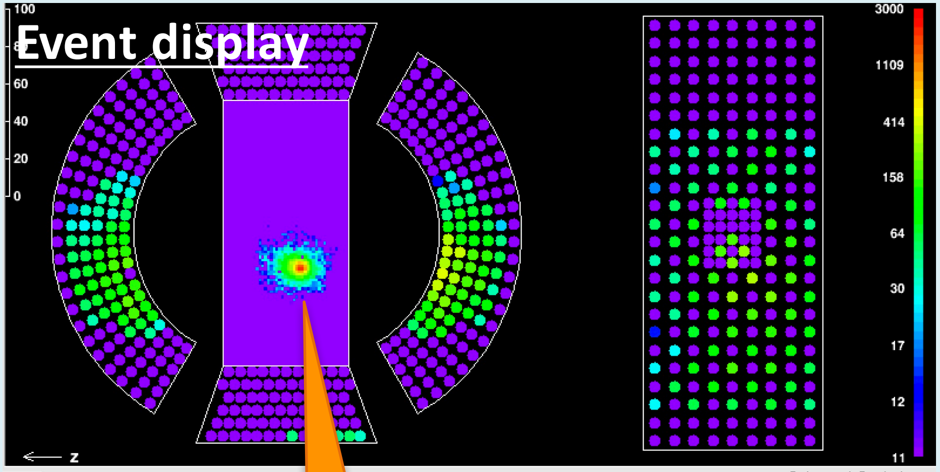
- ~1000 MPPCs operated in LXe.
- Monitored by two methods.
  1. By MPPC 1 p.e. charge.
     (Absolute meas. of gain.)
  2. By LED charge at fixed light intensity.
     (Relative meas. of gain change.)
- Gradual change of gain in both methods.
  - correlated with LXe temperature.

Gamma-ray DAQ

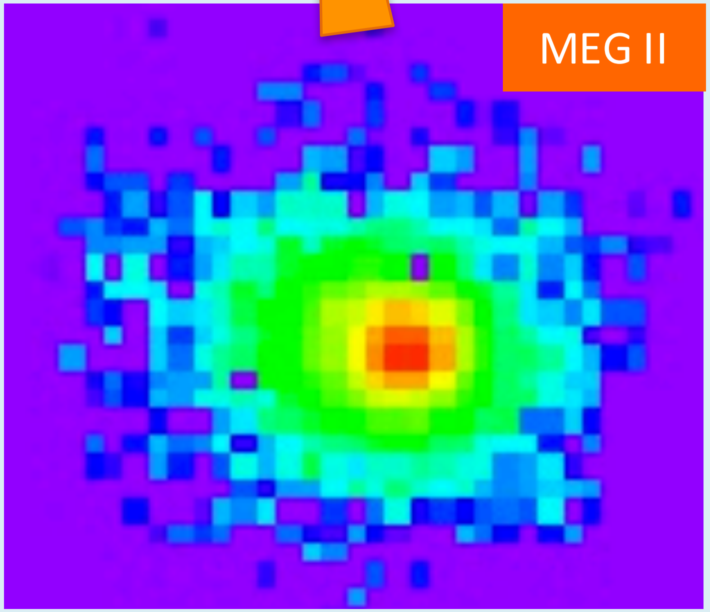
- Gamma-ray data taking was successfully performed.
  - Trigger on sum of MPPC waveform. (threshold: 30-45 MeV)
- Use WaveDREAM (electronics developed for MEG II) for readout.
  - Read out 25% of detector. (960 MPPCs + 192 PMTs)



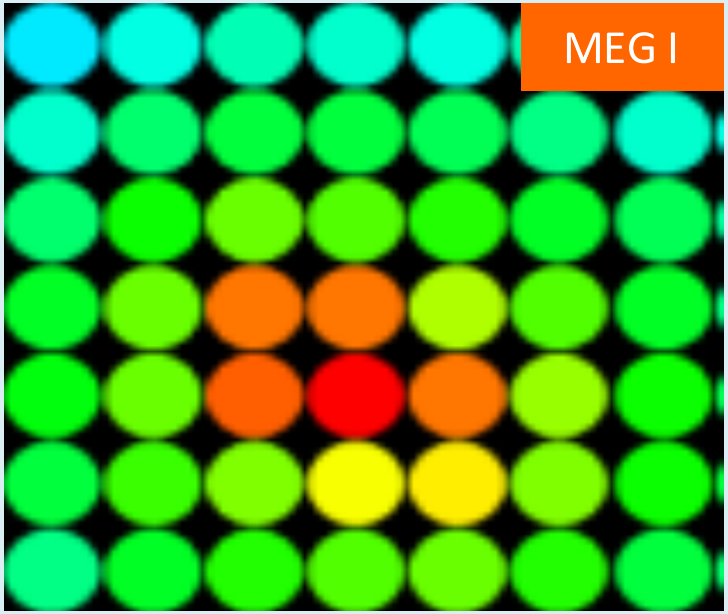
Gamma-ray DAQ



Zoom in



Granularity improvement by MPPC

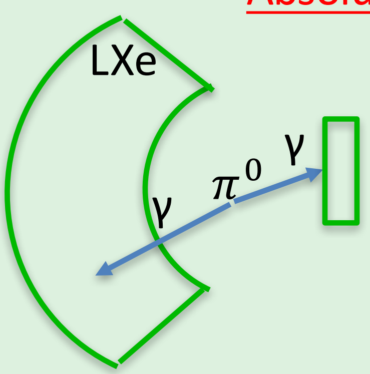


Gamma timing resolution in MEG II

- Background
  - In the previous MC study,
    MEG II timing resolution can be 40-70 ps depending on the noise level.
  - Reference : "Improvement of the event reconstruction method
    for the MEG II liquid xenon detector" at "JPS. 2016年年次大会"

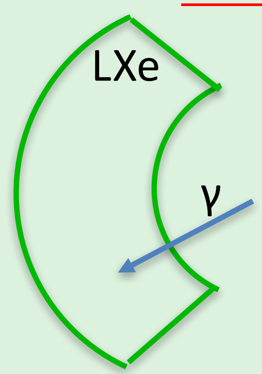
- Goal : Check timing resolution in real noise environment.
  →Perform even-odd analysis.

Absolute resolution



- Use coincident 2γ & reference counter.
- $\sigma(T_\gamma) =$
  $\sigma(T_\gamma - T_{ref}) \ominus \sigma(T_{ref})$

Even-odd resolution



- Reconstruct Tγ from even/odd ch separately.
- $\sigma(T_\gamma) =$
  $\sigma(T_{EVEN} - T_{odd})/2$

※"$\sigma_{absolute}(T_\gamma)$" is a part of "$\sigma_{even-odd}(T_\gamma)$".
Difference is "TOF uncertainty of hit position" etc...

How to reconstruct gamma timing

- Gamma timing is reconstructed from timing from MPPC & PMT waveforms.
  - Timing extraction by waveform analysis
    + χ^2 min fit of time information from all ch.

Waveform Analysis

Noise subtraction

↓

Timing extraction

Robust analysis to high-frequency noise

- Optimal threshold for timing extraction.
- Subtraction of noise coming from system clocks.
- Application of low-pass filter.

↓

Timing reconstruction

Apply time calibration

↓

χ^2 minimization fit

χ^2 minimization fit of all ch time information

$$\chi^2 = \sum_{MPPC,PMT} \left(\frac{t_{pm} - t_{walk} - t_{prop} - t_{offset} - t_{\gamma}}{\sigma} \right)^2$$

Time info from each MPPC, PMT with time calibration

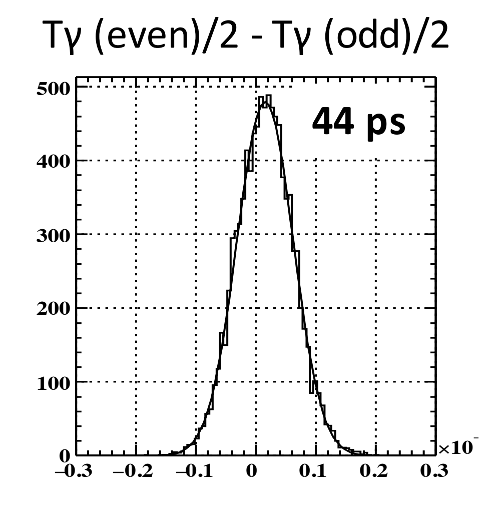
Gamma hit timing (fitting parameter)

Calibration parameters : extracted from data

- Time walk
- Propagation time of scintillation light.
- Time offset of each channel

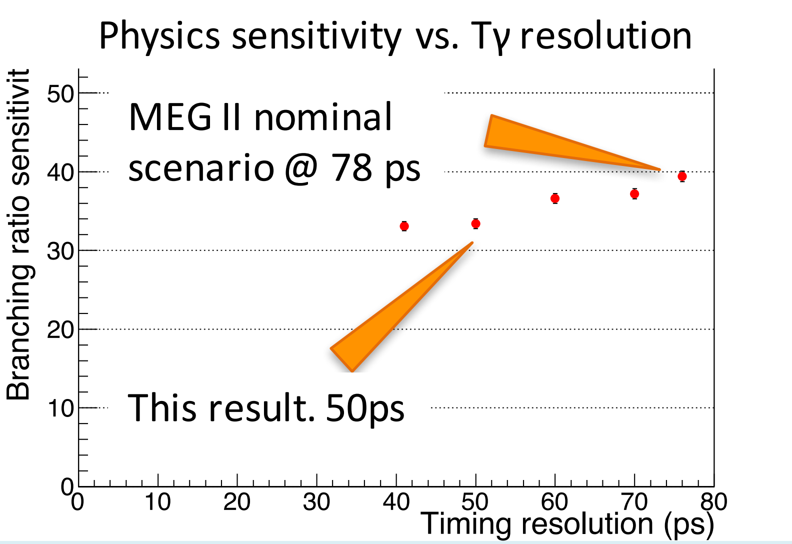
Timing resolution

- **Even-odd timing resolution is 44 ps @ 50MeV.**
- MC is consistent with data.
  - same readout ch, p.e. statistics, same noise level



- 50 ps absolute resolution can be expected in the final configuration.
  →**Indicates ~15% sensitivity improvement**
  from MEG II nominal scenario.

Tγ resolution	Even-odd	absolute
Data	44 ps	???
MC w/ noise	44 ps	50-52 ps

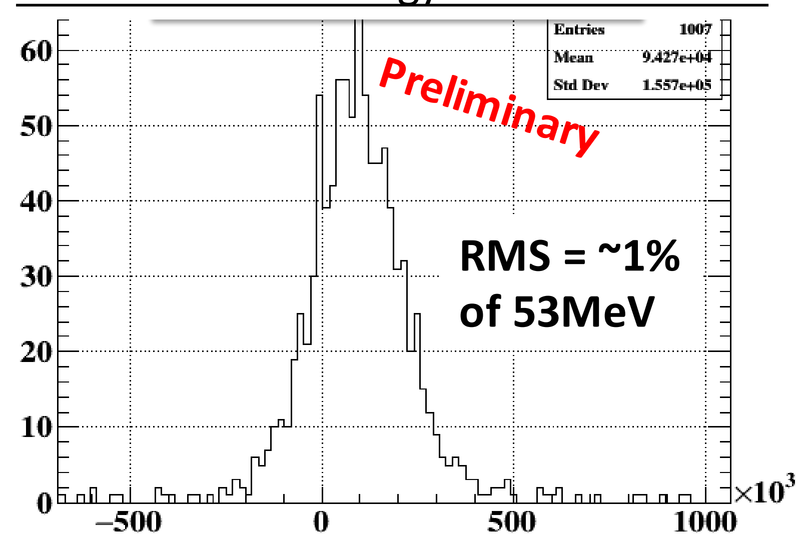


- Next step is to measure the absolute resolution. -> Planned in 2018.
  - TOF uncertainty (position resolution).
  - Effect from coherent noise.

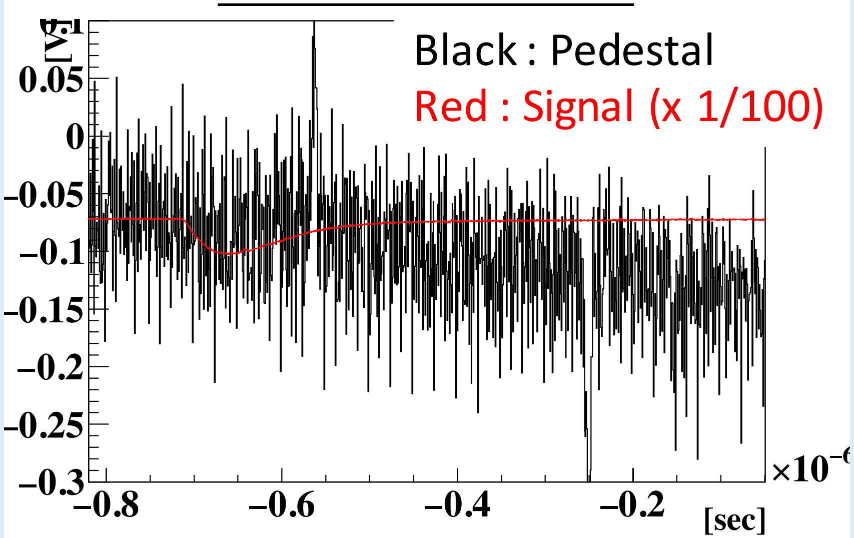
Energy resolution & noise problem

- Energy of γ : reconstructed from sum of charge of all MPPCs and PMTs. → Easily affected by coherent noise.
- **Large low-frequency coherent noise was observed.**
  - ~ 1% of signal γ. (1/4 of detector) → 2-4% by read out whole detector.
  - Our goal of Eγ resolution is 1%. **→Needs to be reduced by factor of 2-4**.
- Effort to reduce it is ongoing both from hardware and software.

Reconstructed energy of Pedestal data



MPPC sum waveform



Summary

- As a final phase of detector commissioning, pilot run of LXe detector was carried out. Detector performance is being estimated.

- Detector stability was successfully monitored.
- Data taking of gamma-ray from muon decay was carried out.

※Position reconstruction : ***25aK206-3***

- Timing resolution by even-odd analysis is estimated to be 44 ps in real noise environment.
  →Absolute timing resolution is expected to be 50ps, which indicates 15% sensitivity improvement from nominal scenario.
- Low frequency coherent noise was found and it affects energy resolution.
  →Needs to be reduced by factor 2-4. Investigation ongoing.

Prospect -Plan in 2018-

- Electronics to read out all channels
  + monochromatic gamma-ray source will be available.
  → Energy resolution measurement.

※R&D of reference counter
: ***25aL401-5***

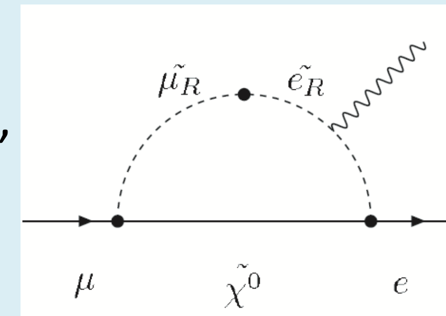
- Reference timing counter
  + coincident two γ from π^0 will be available.
  → Absolute timing resolution measurement.

- Engineering run of all MEG II detectors will be done in 2018, and physics data taking will start from 2019.

BACKUP

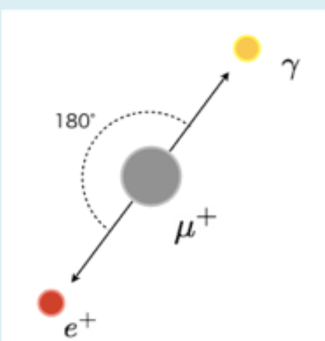
μ→eγ search

- We search for charged **lepton flavor violating decay of muon, μ->eγ.**
- Prohibited in SM, detectable branching ratio in some BSM model
- Main background is the **accidental background**.
- Detector resolutions, **especially energy resolution of γ-ray**, are important to effectively distinguish the signal event from the accidental background.



Signal

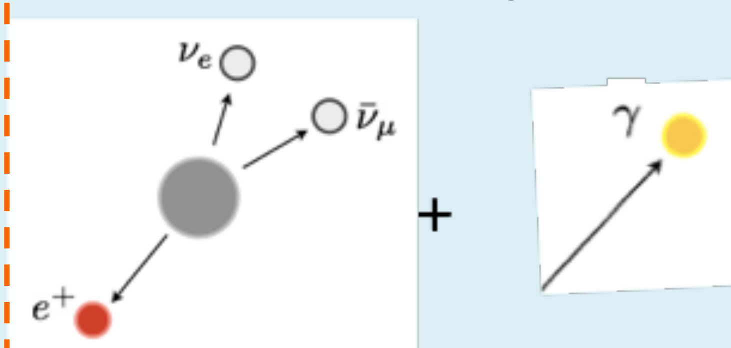
Signal decay



- E=52.8MeV
- back-to-back
- coincident

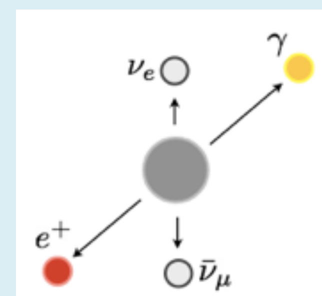
Background

Accidental background



- **Dominant background**
- E < 52.8MeV
- not back-to-back

Radiative muon decay

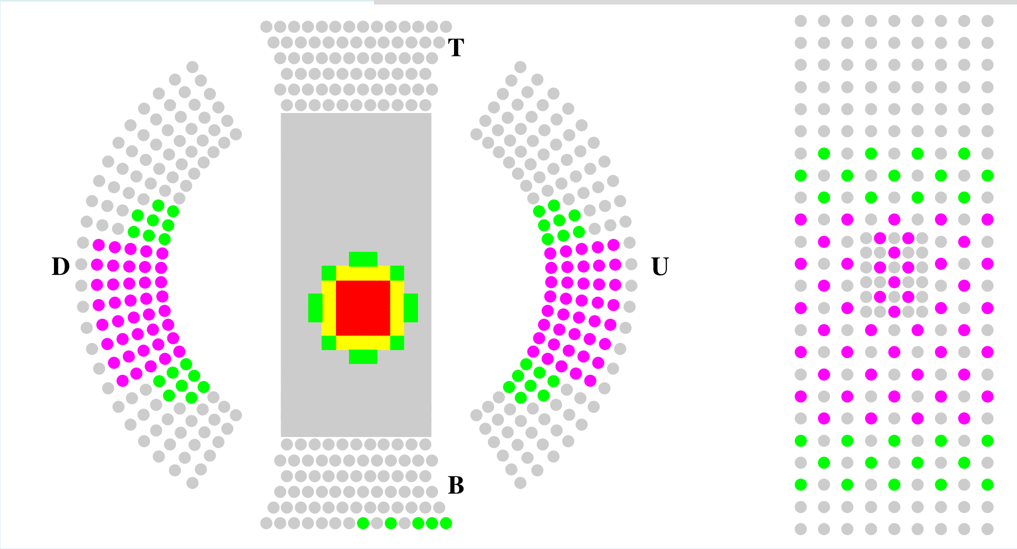


- E<52.8MeV
- not back-to-back
- coincident

Photo sensor used for beam test

- We read out 704 MPPCs + 192 PMTs.
  - Due to the event rate issue, we are reading out 4 crate at the same time.
  - MPPC @ over voltage 7V
  - PMT @ gain 1.6×10^{6} (~ same w/ MEG I)
- Several dead channels found.
  - 8 dead MPPCs
  - 4 dead PMTs

w/ TRG : red, yellow, magenta
w/o TRG : green



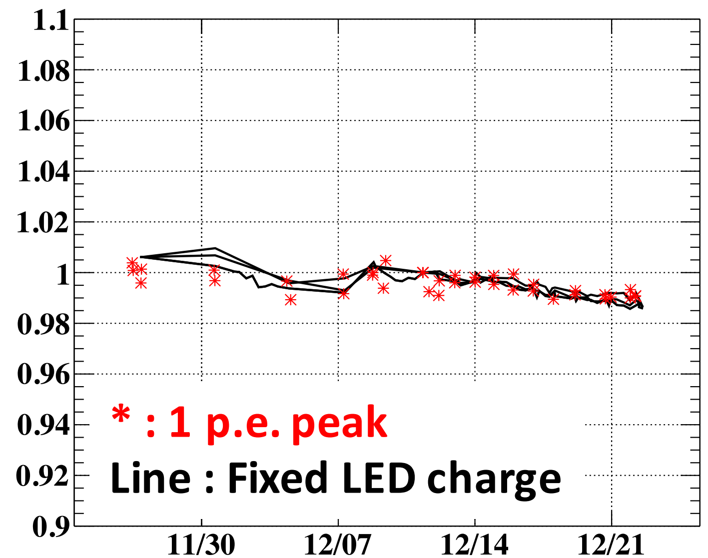
Beam test

					Nov/25 5th crate ready **Sensor calib. commissioning**	26
27 TC run start	28 **periodical monitoring**	29	30	Dec/1	2	3
4	5 **periodical monitoring**	6 CW failure	7	8 6th crate ready	9	10
11 XEC run start	12 **muon beam DAQ**	13 **AmBe**	14	15	16 **AmBe**	17 **AmBe**
18 circuit breaker down **muon DAQ w/ collimator**	19	20 **n generator** **muon beam DAQ**	21	22 Refrigerator stop		

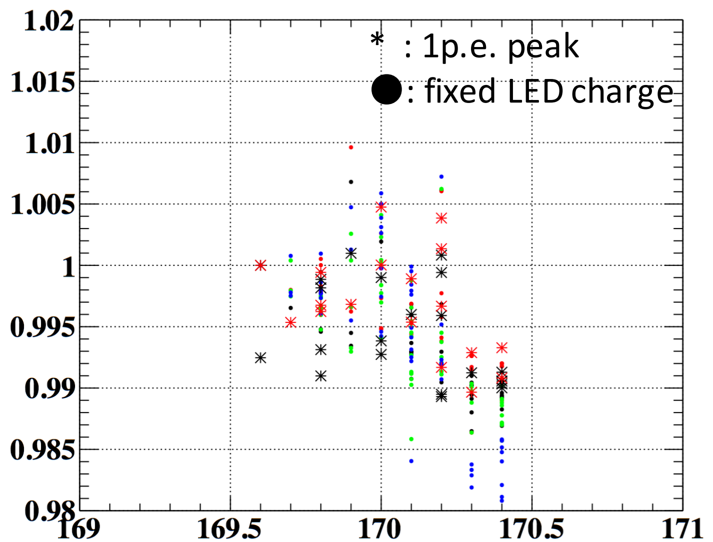
MPPC gain vs temp.

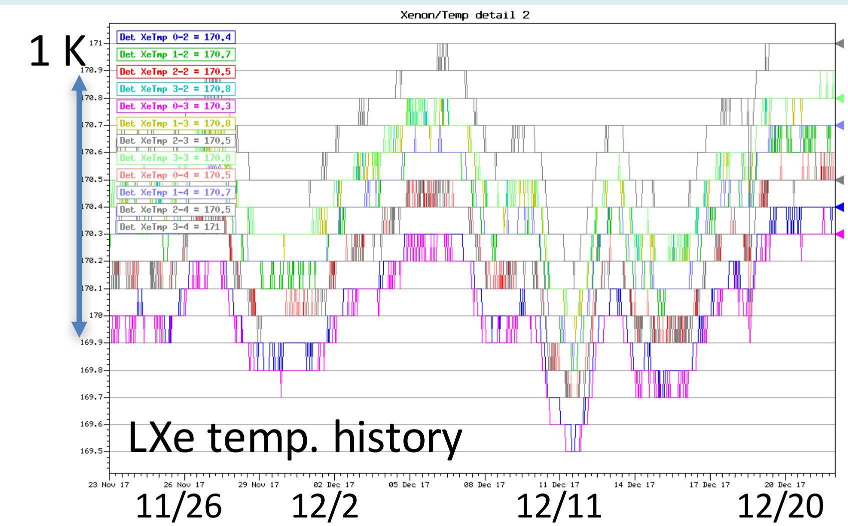
- aa

MPPC Gain History (All channel average)



MPPC gain vs. XEC temp.

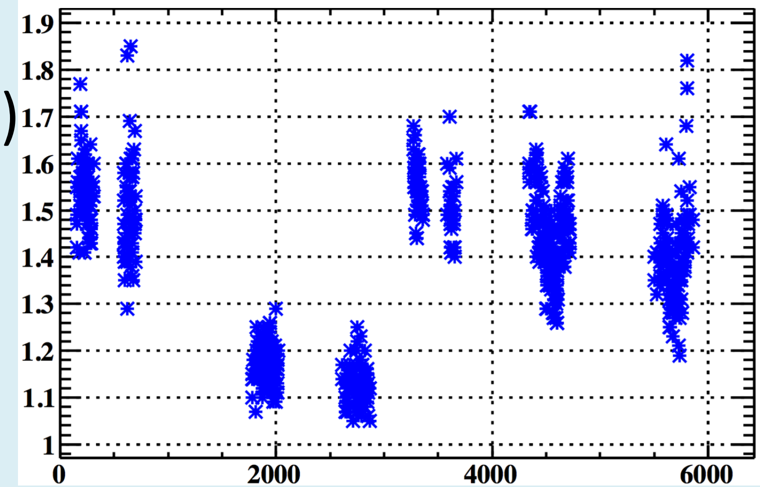




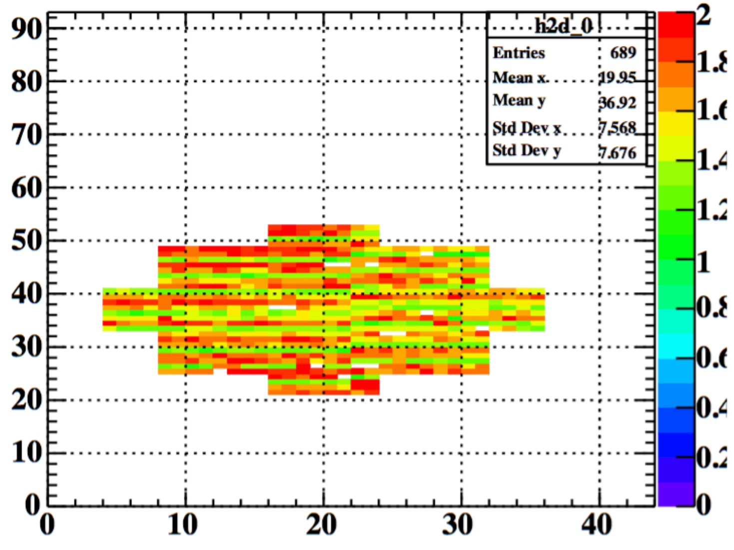
MPPC crosstalk & afterpulse

- Production lot dependence is observed (as is expected from R&D)
- Charge variation b/w production lot is largely suppressed by applying calibration.

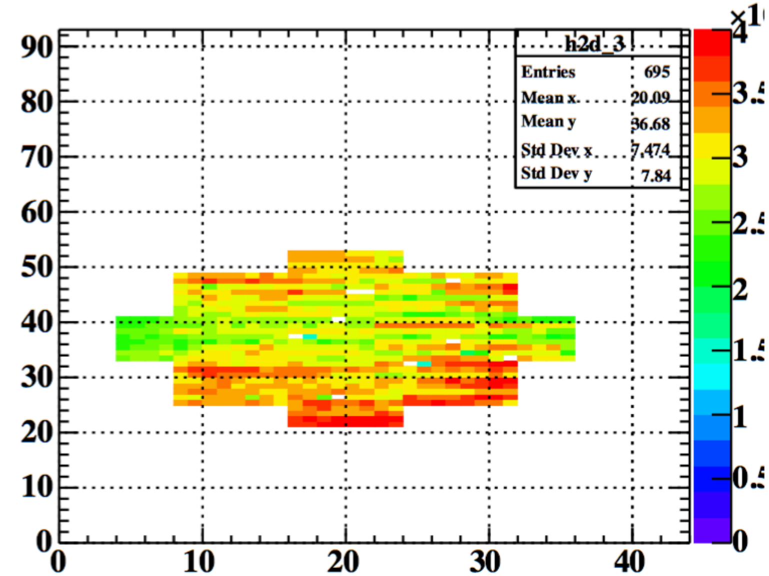
Crosstalk & after pulse vs. MPPC serial



Charge distribution (average) from a LED run



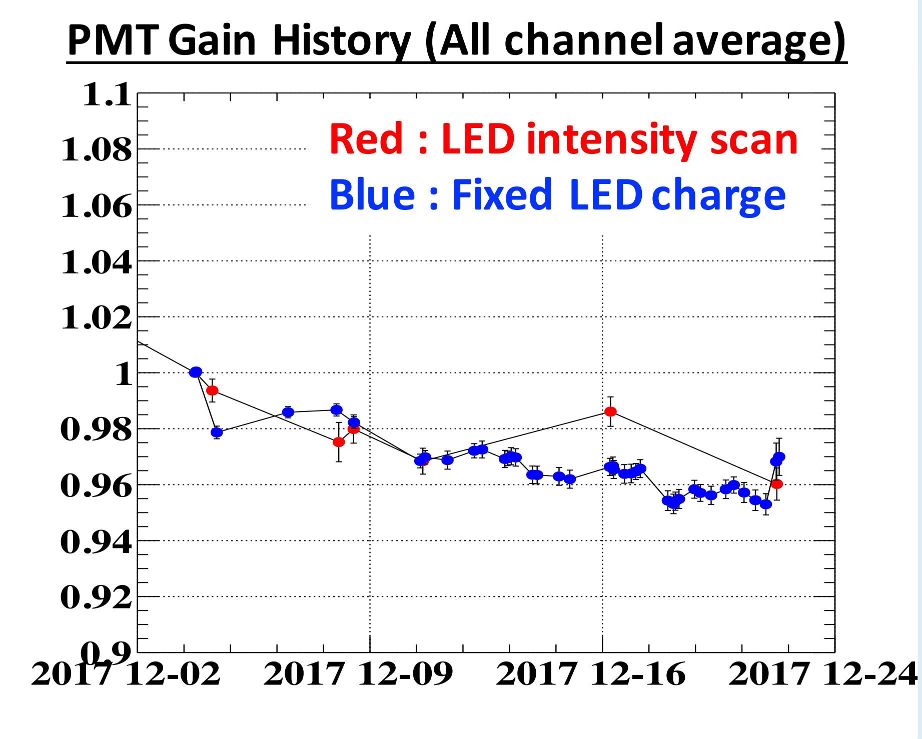
Apply gain, crosstalk, afterpulse calibration



PMT Gain

PMT Gain

- PMT gain was measured by two independent methods.
  1. By LED intensity scan. (Absolute meas. of gain.)
     - Based on Poisson statistics of arrived # of p.e. from LED light.
  2. By charge of LED at fixed light intensity. (Relative meas. of gain change.)
- Those two methods shows consistent behavior with ~2 % precision.
- Gradual decrease of gain is aging of PMT under beam (known from MEG I).

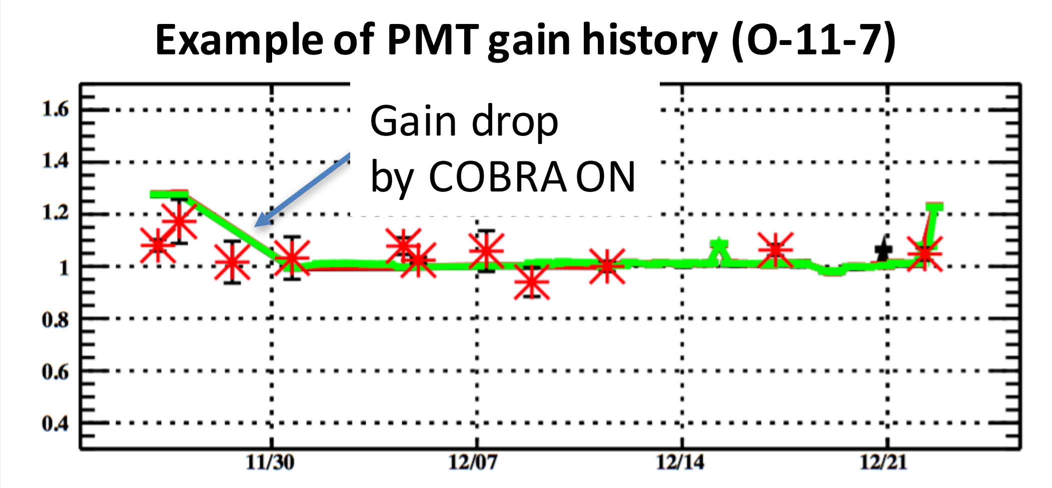


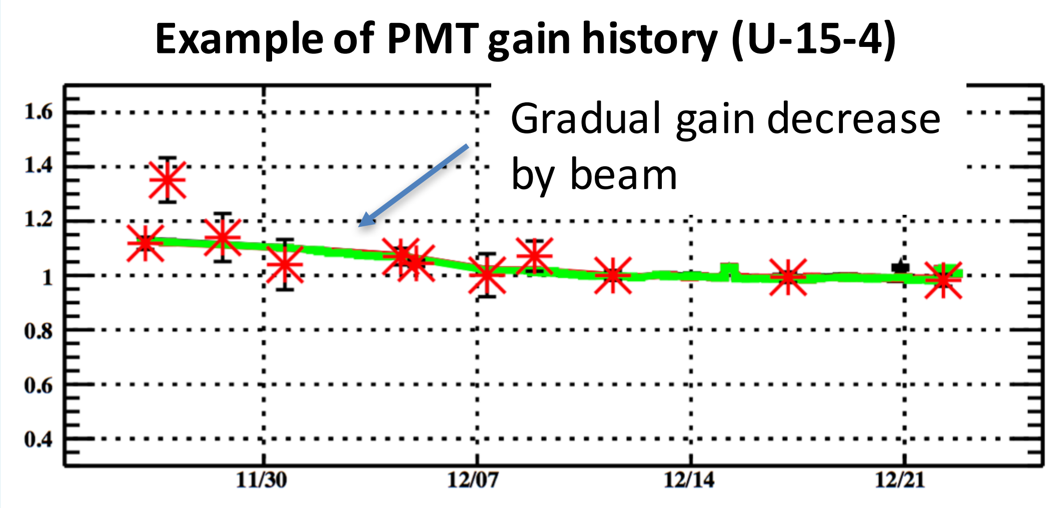
LXe light yield

- aa

PMT gain history

- PMT gain calibration by intensity scan
  + relative gain monitor by fixed intensity LED .
  - HV is decided to have 1.6×10^{6} w/o COBRA b-field.
- PMT gain is affected by COBRA & beam.
  - The size of effect has individual difference.
- Gain history database will be prepared for each PMT.

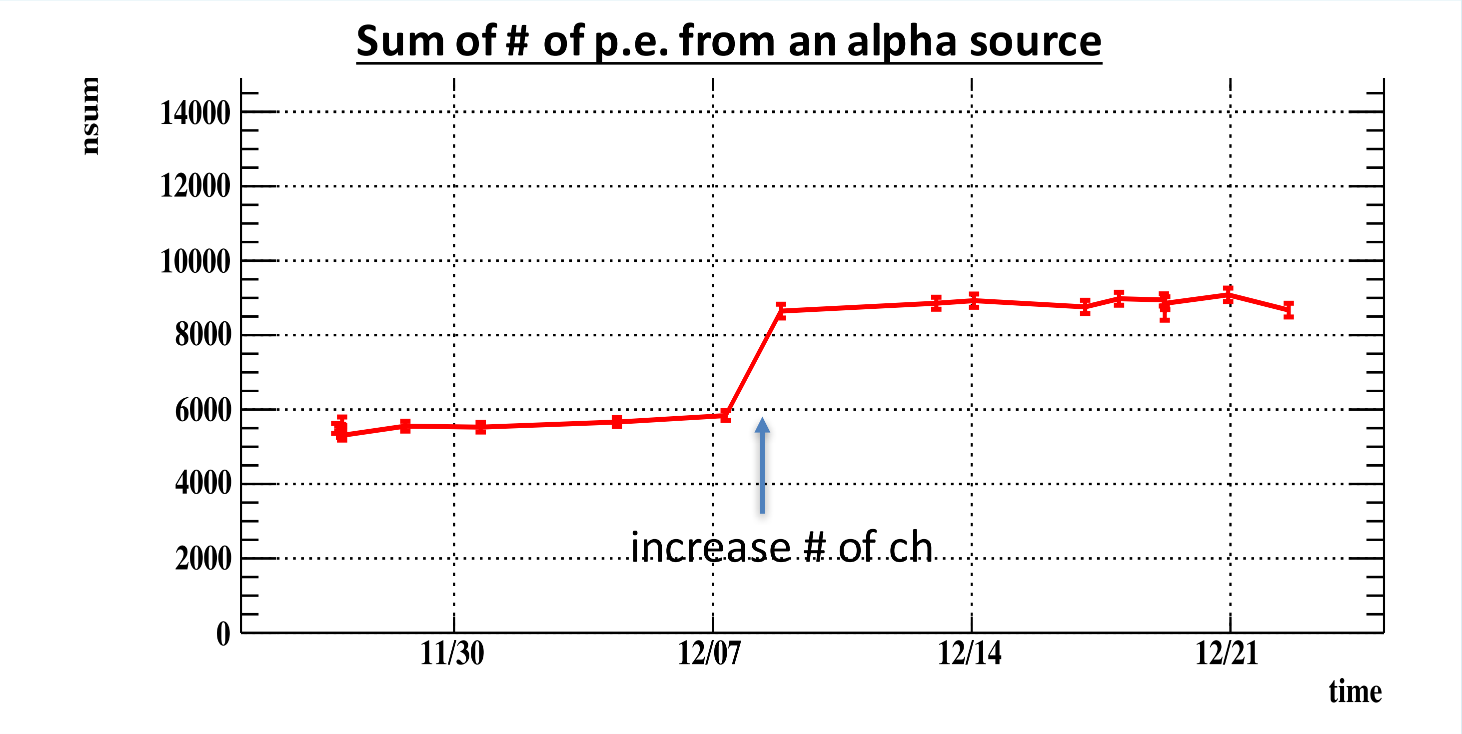




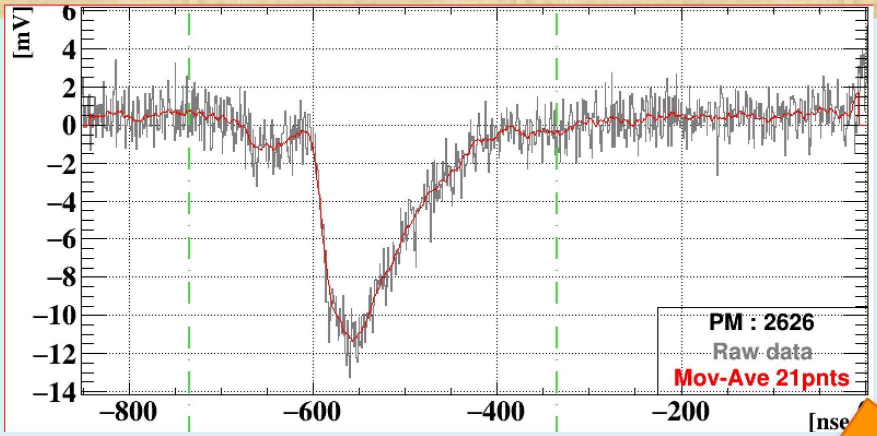
* : Intensity scan
Line : Fixed LED charge

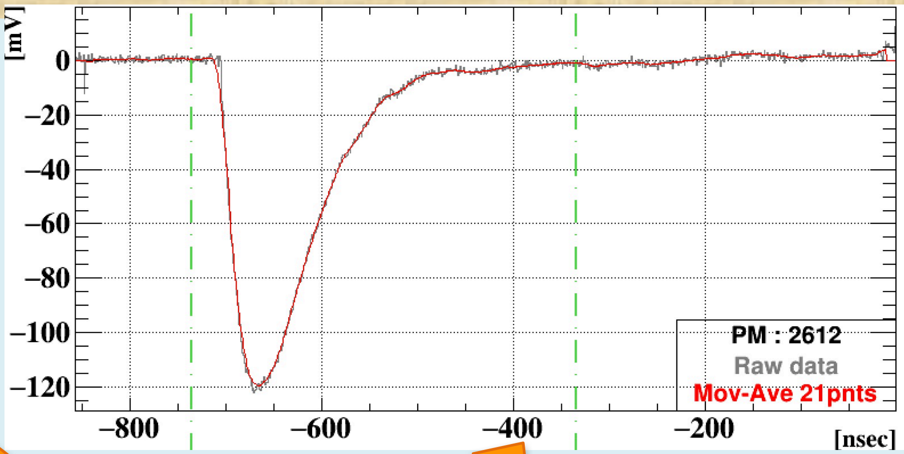
Light yield

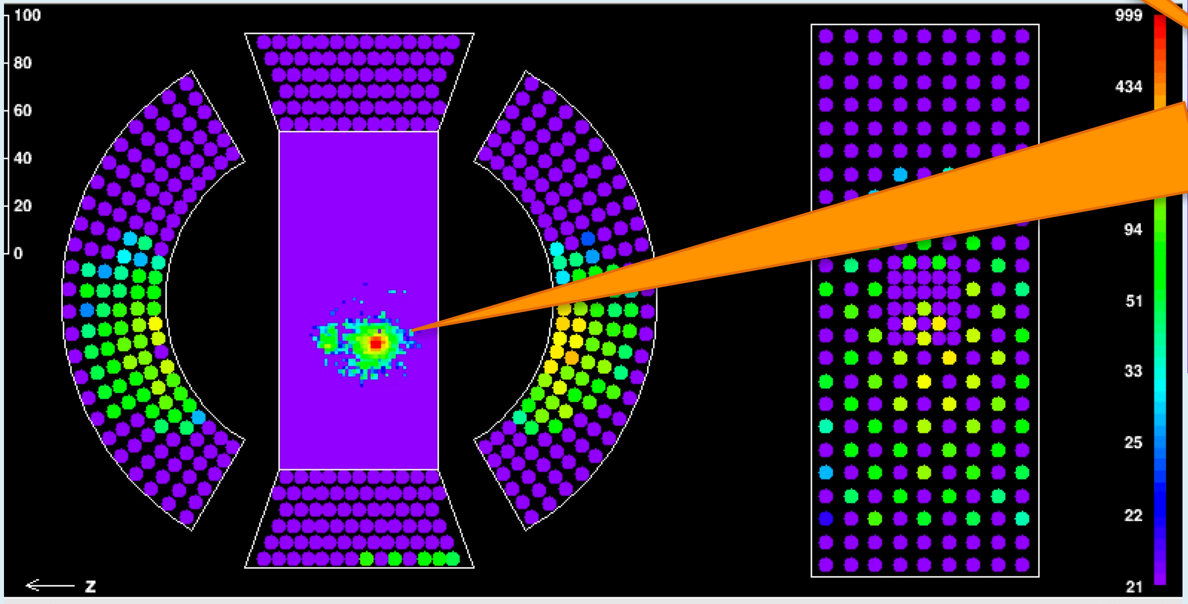
- aa

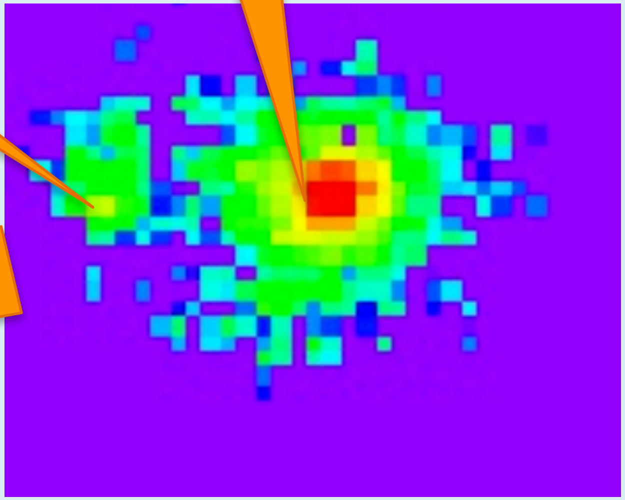


Event display example –pileup event-



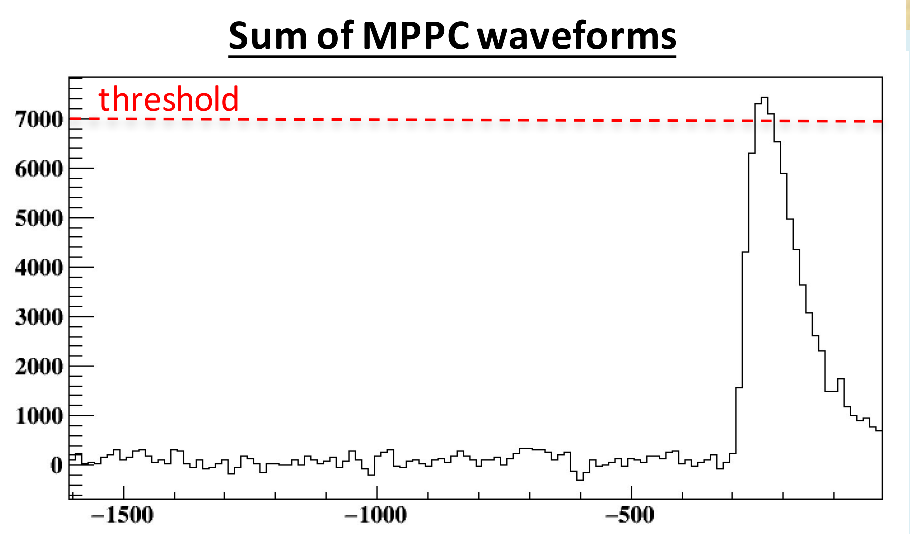




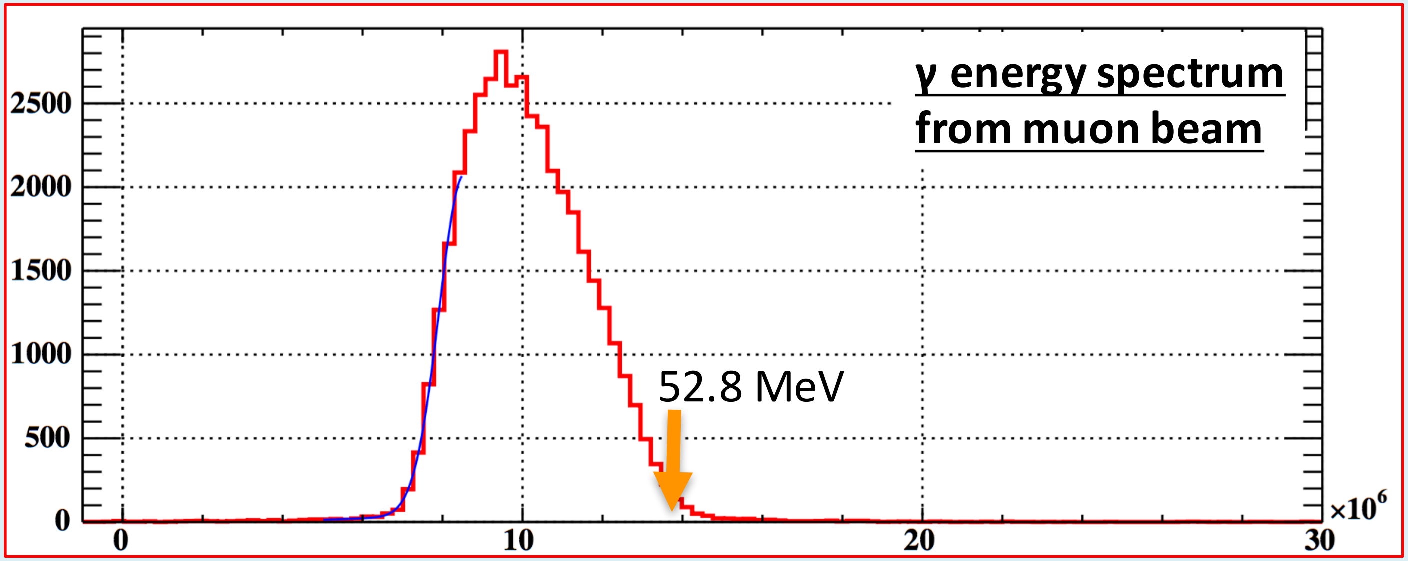


Gamma-ray DAQ

- Trigger for gamma-ray DAQ
  - Trigger is generated **when sum of MPPC waveforms exceeds a given threshold**.
  - Threshold is set to 30-43 MeV.



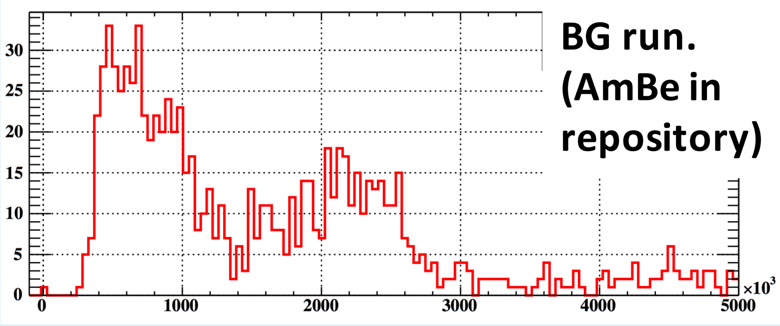
- Energy spectrum
  - Energy scale calibrated at low energy (4.4, 9 MeV)gamma source.



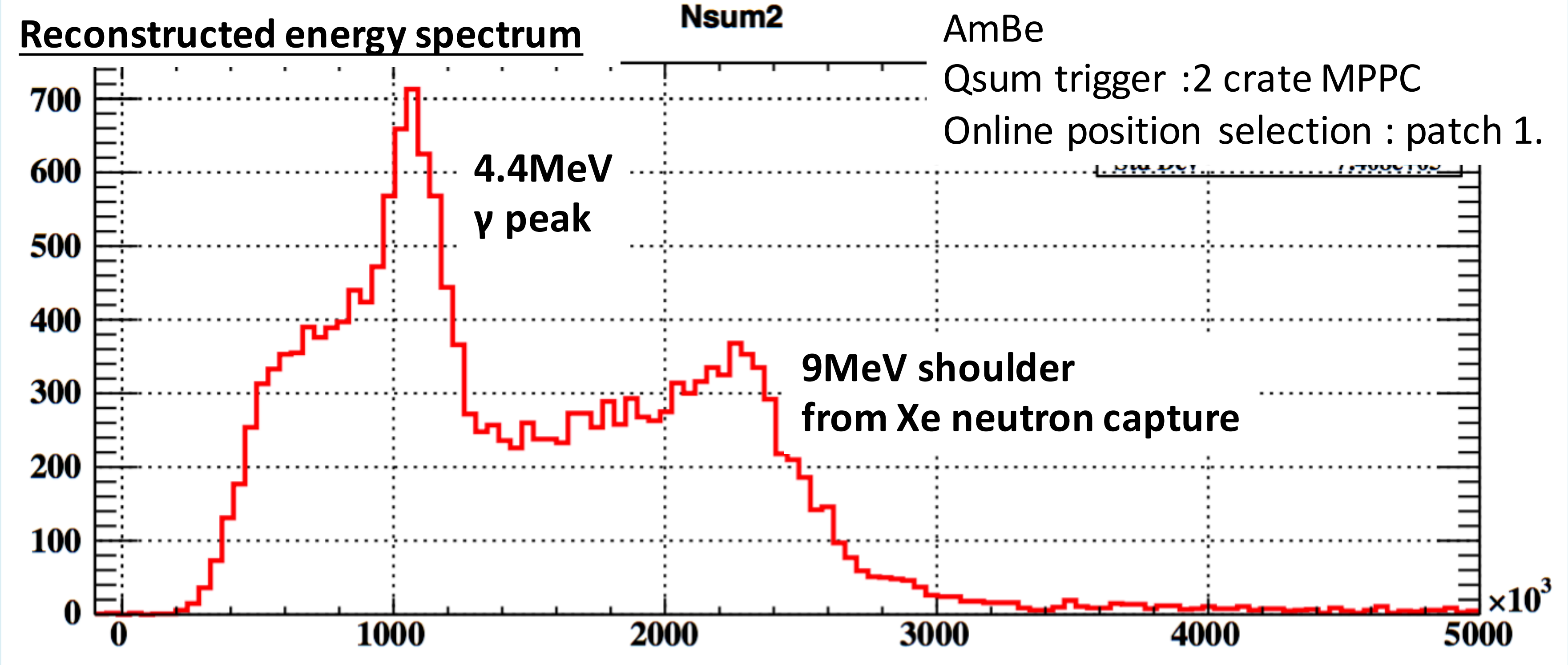
Energy spectrum -AmBe-

Very Preliminary

- We took 4.4MeV γ from AmBe.
- DAQ by self-trigger. Use WDB gain 5.
  - At WDB gain 1 (same config w/ signal), S/N ratio was too bad to trigger 4.4MeV.
- Offline event selection by Q/A of waveform to reject alpha event.



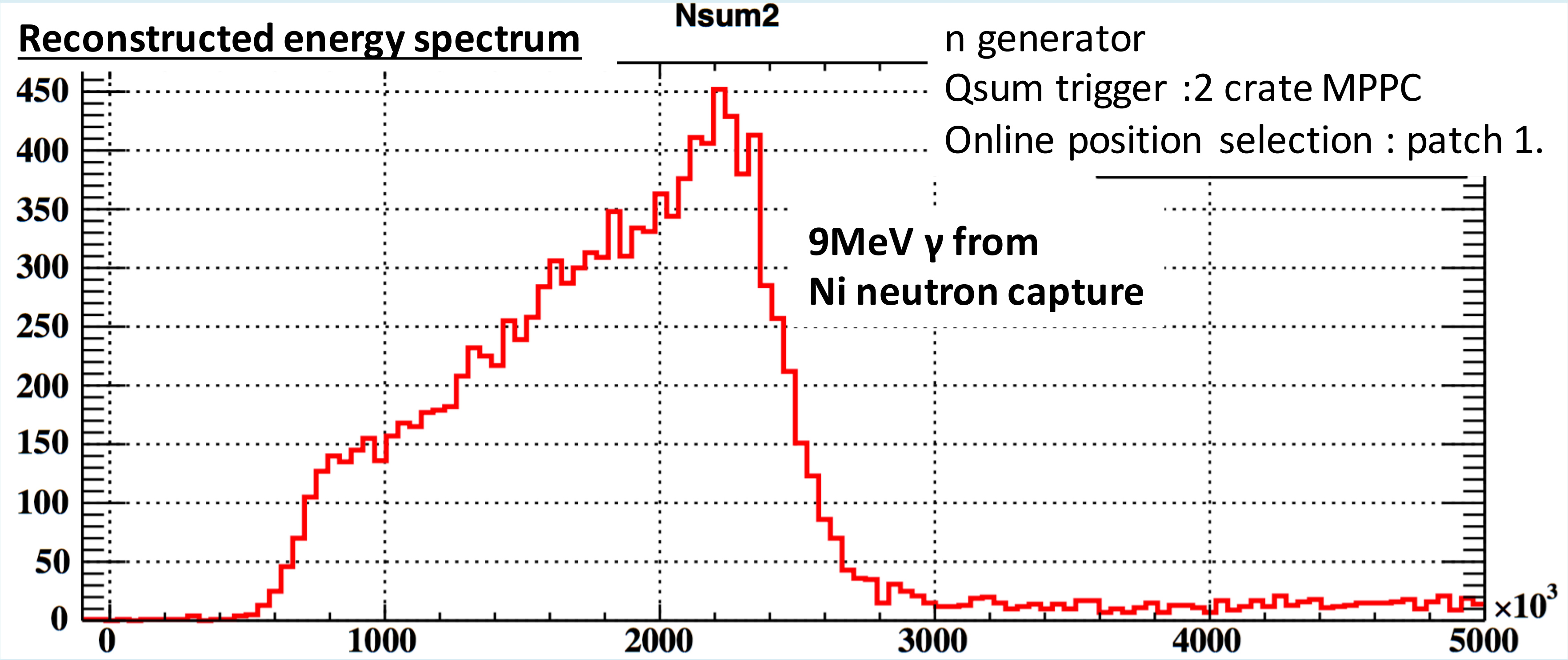
Reconstructed energy spectrum



Energy spectrum -n generator-

Very Preliminary

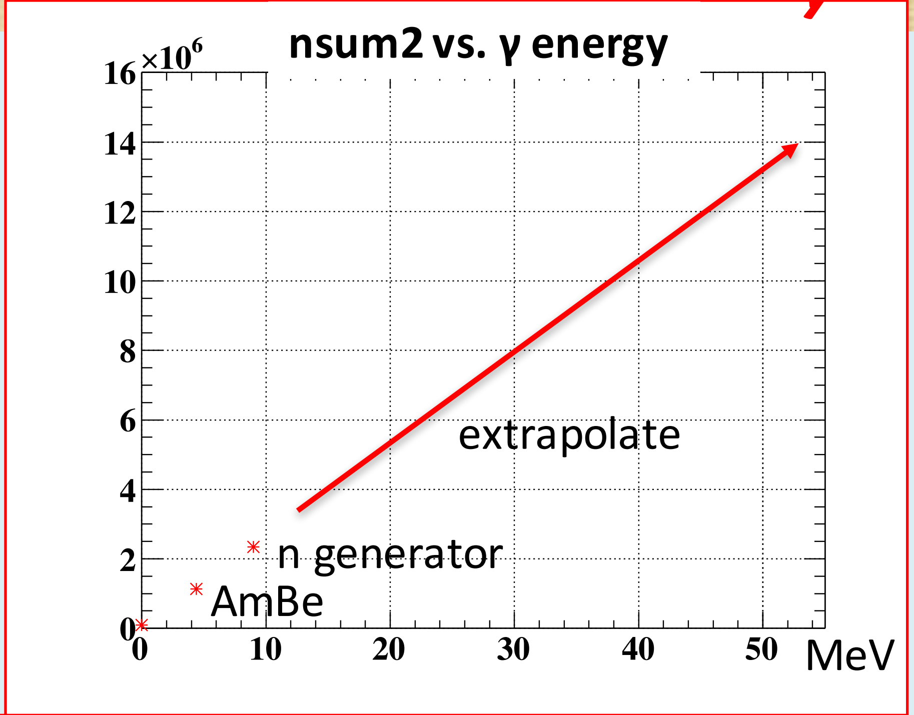
- We took 9MeV γ from neutron generator.
- DAQ by self-trigger. Use WDB gain 5.

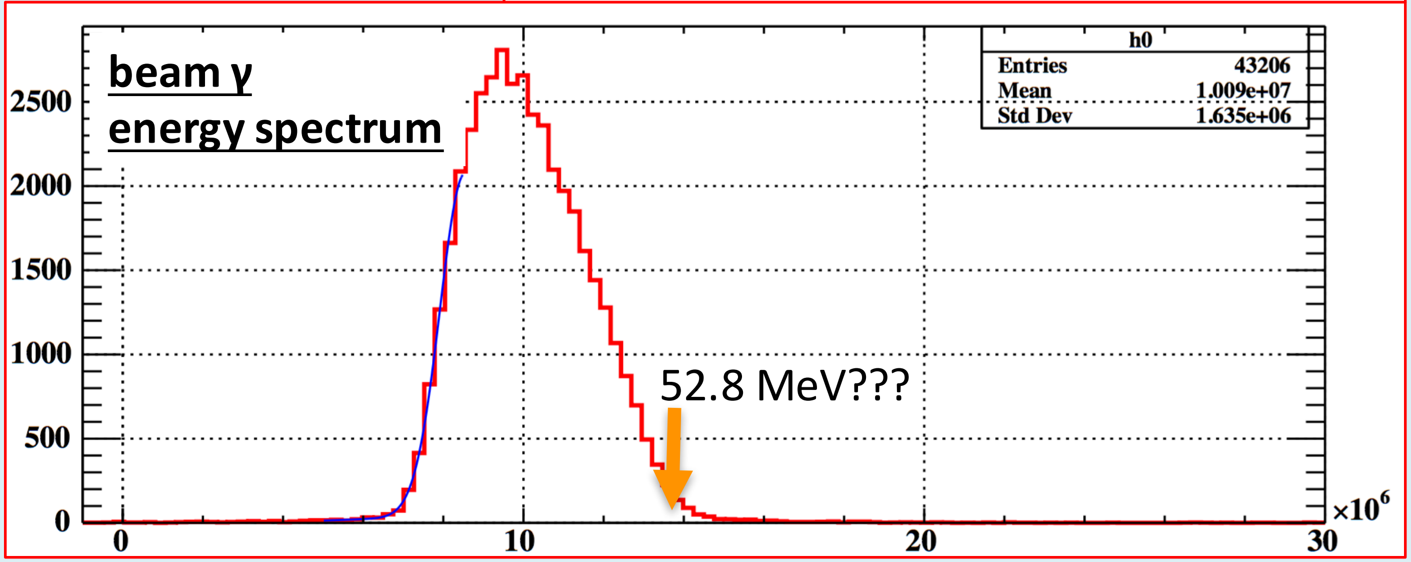


Rough estimate of energy scale

Preliminary

- AmBe & n generator is consistent w/ 1% precision.
- From AmBe and n generator, 52.8MeV is estimated to be corresponding to "nsum2 = 13.7x10^6"
- This is roughly consistent w/ beam γ spectrum.

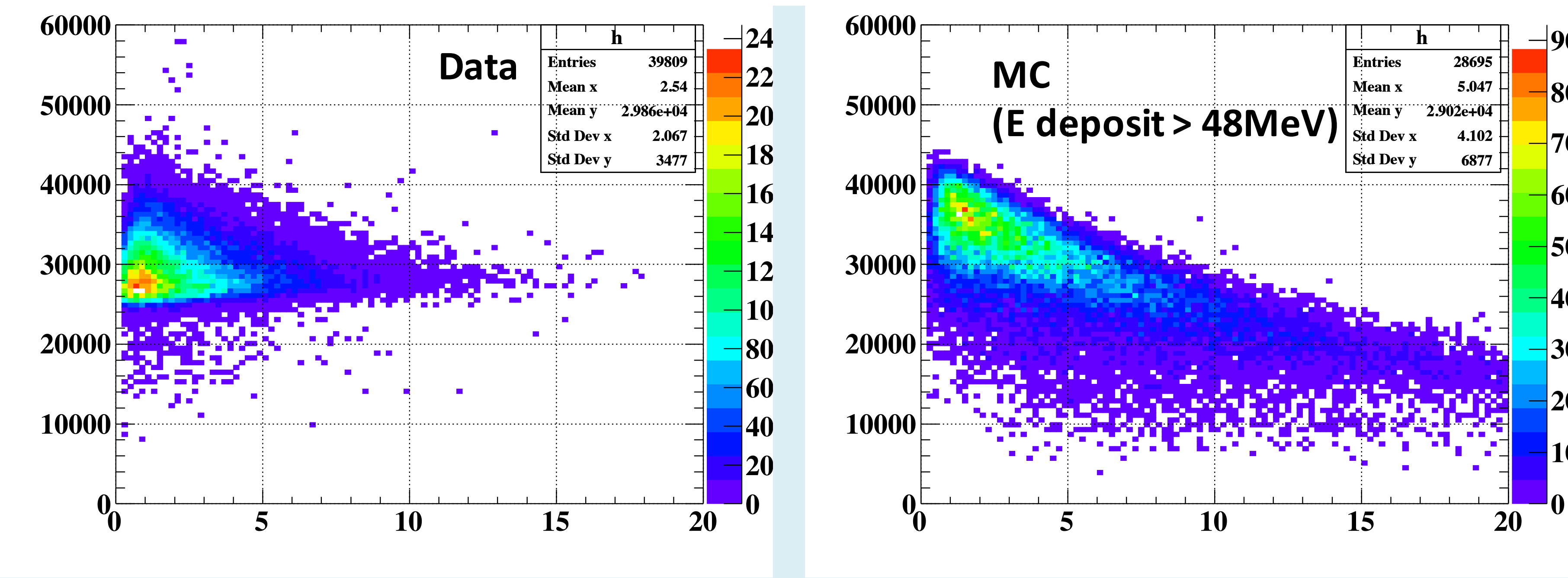




Reconstructed energy in MC

- Energy deposit > 48MeV

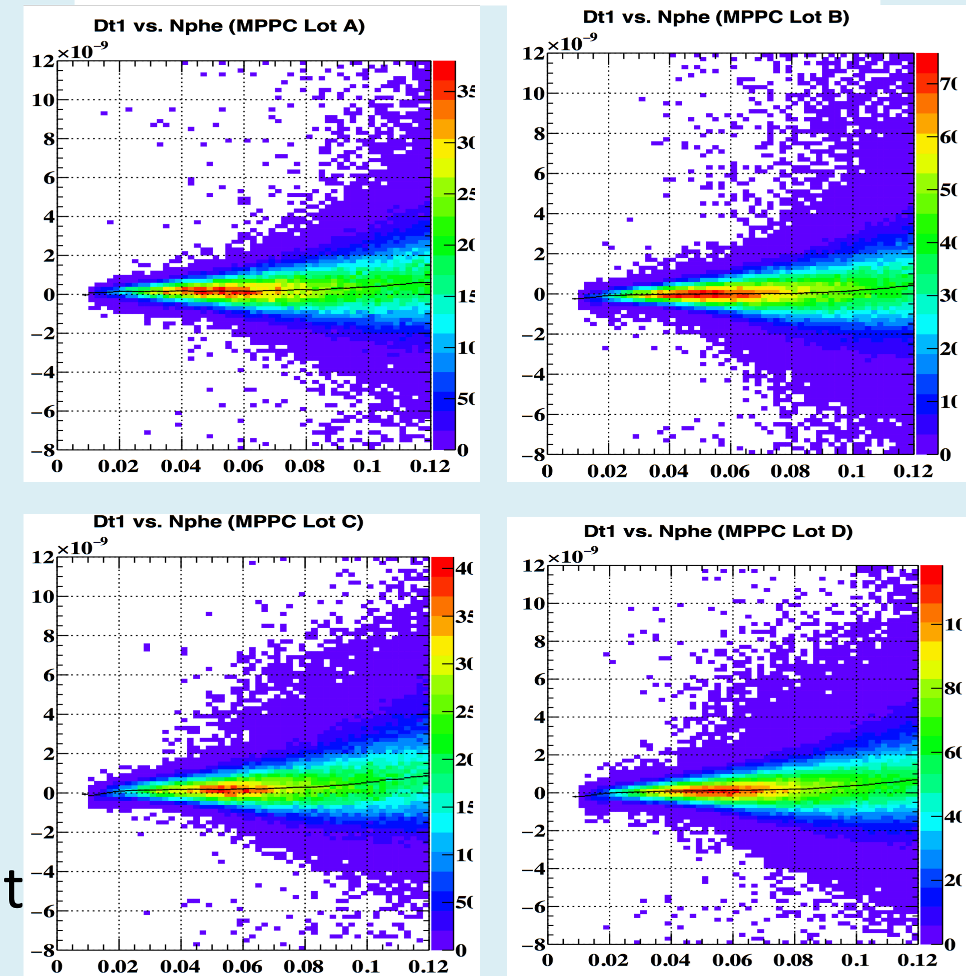
Sum of # of p.e. (MPPC) Vs. w



Time walk calib.

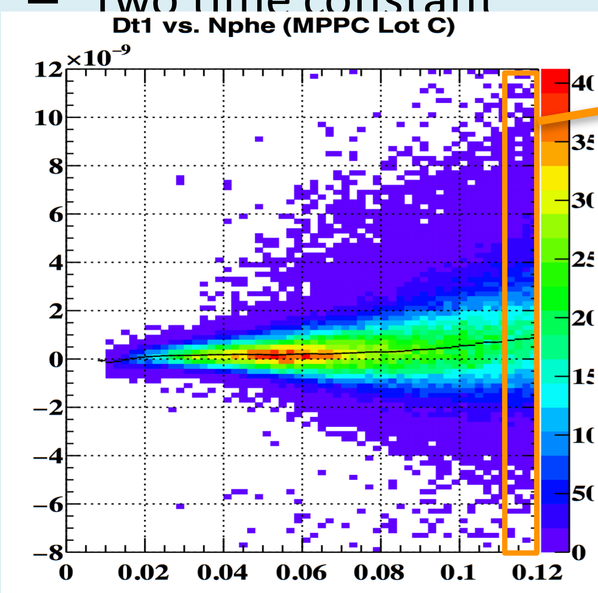
- Photo sensors are divide into 6 groups.
  - MPPC Lot A-D
  - Outer PMT
  - Side PMT.
- Time walk effect even w/ constant fraction.
- Slight difference can be seen at smaller # of p.e. b/w Production Lots. (depends on analysis paramet

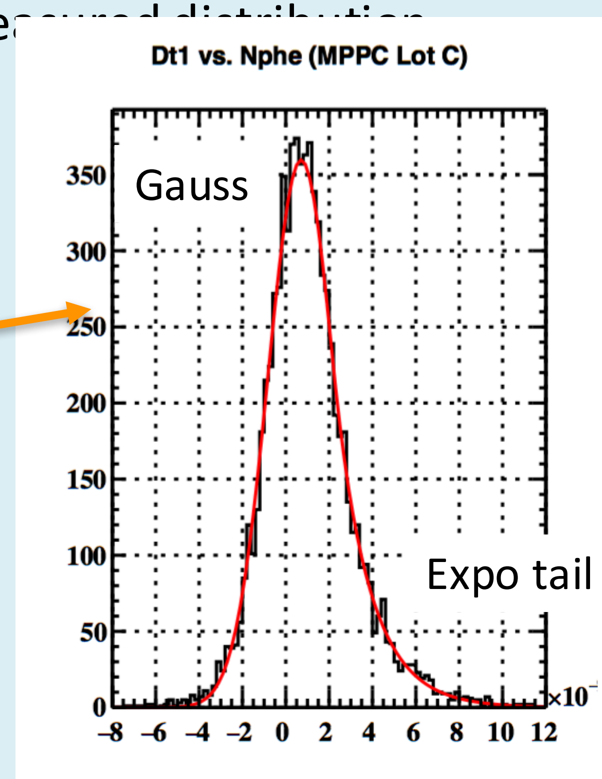
"$t_{pm} - t_{TOF} - t_{\gamma}$" vs. 1/sqrt(#ofp.e.)



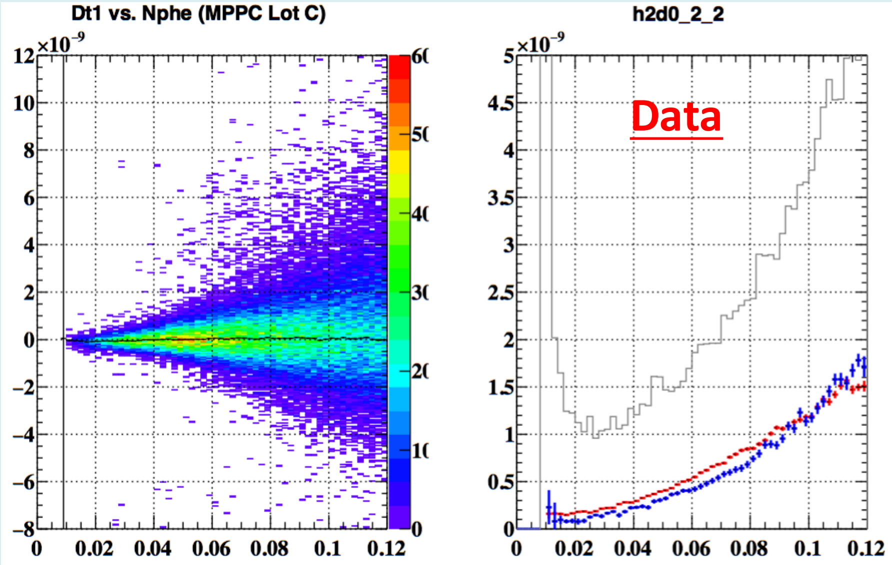
Asymmetric Dt distribution

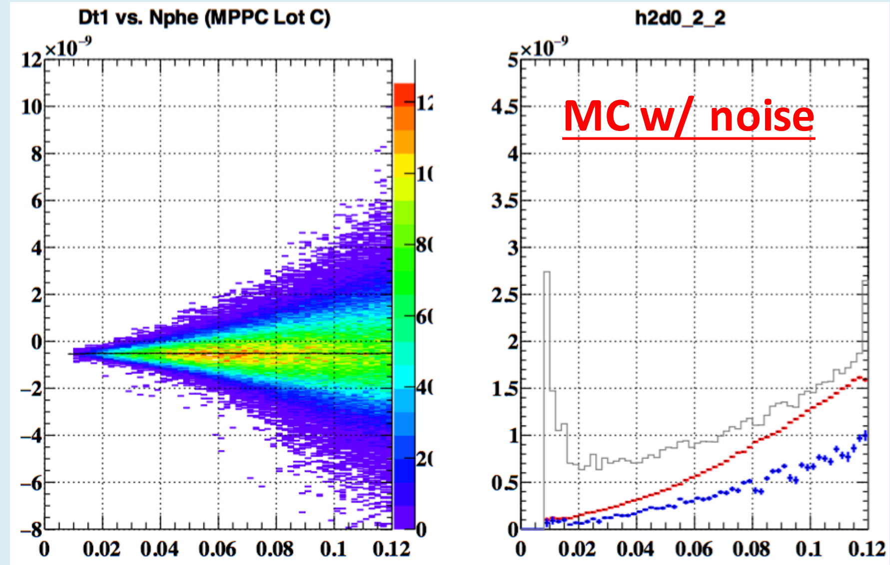
- Asymmetric distribution of "$t_{pm} - t_{walk} - t_{TOF} - t_{\gamma}$" is observed.
  - @small # of p.e. MPPC.
- This asymmetry is taken into account in the Tγ reconstruction.
  - PDF of the fit is generated from this me
- Parametrize by ExpGaus Fit.
  - Gauss + smoothly connected Exp.
  - Two time constant



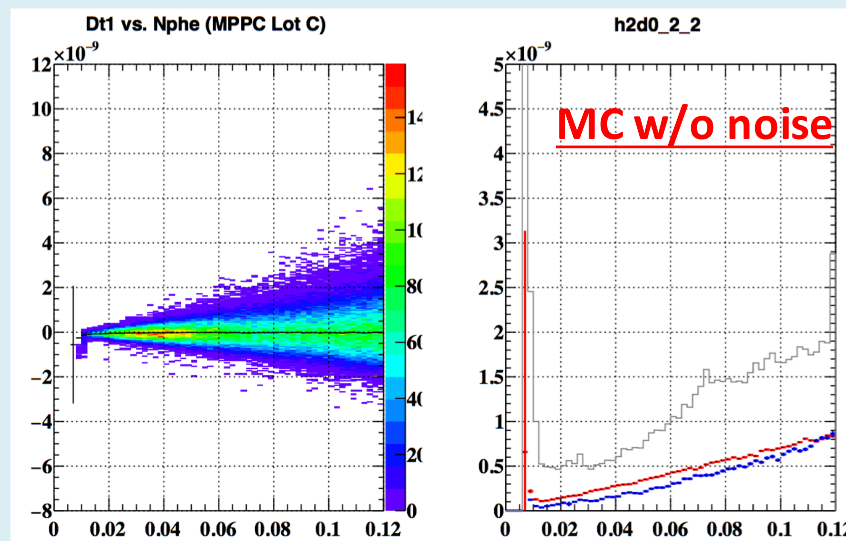


One ch resolution.





Red : sigma of gauss
Blue : decay of expo.

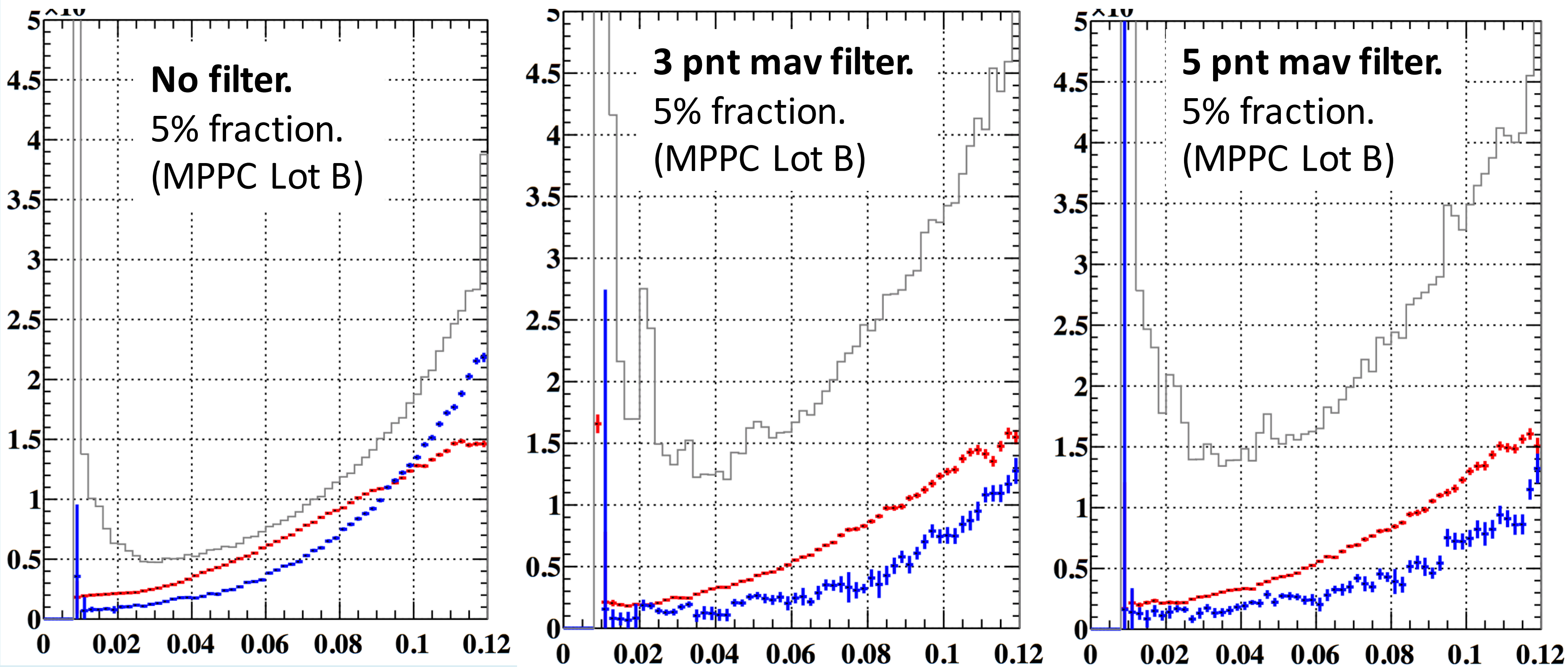


Data & MC w/ noise gets consistent on sigma.

Effect of low-pass filter

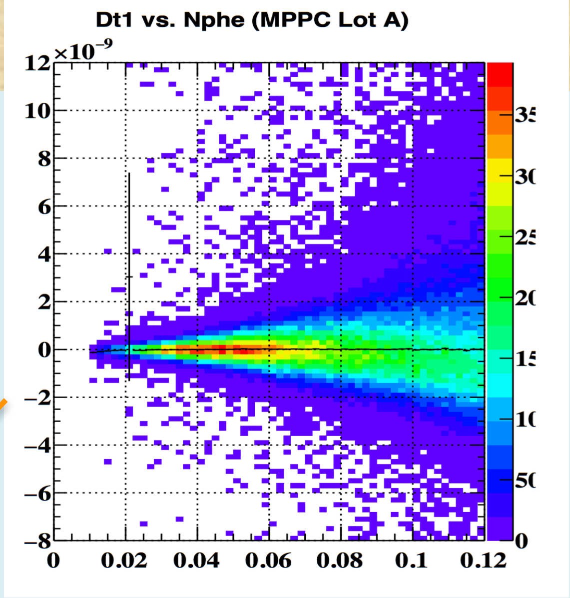
- We can improve one ch timing resolution by using moving average low-pass filter.
- Filter probably eliminates high frequency noise.
- Current best parameter is **5% threshold w/ 3pnt low-pass filter**

“σ” vs. 1/sqrt(#ofp.e.)



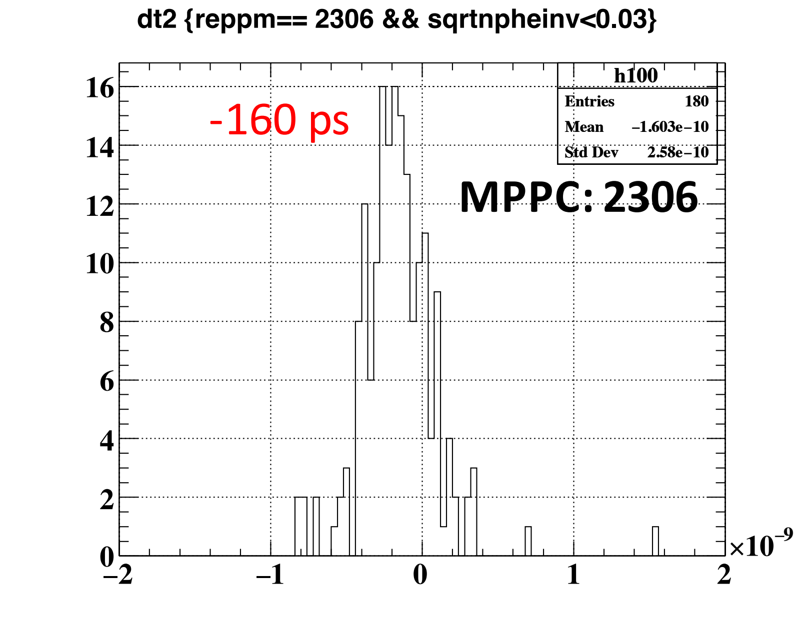
Offset calibration

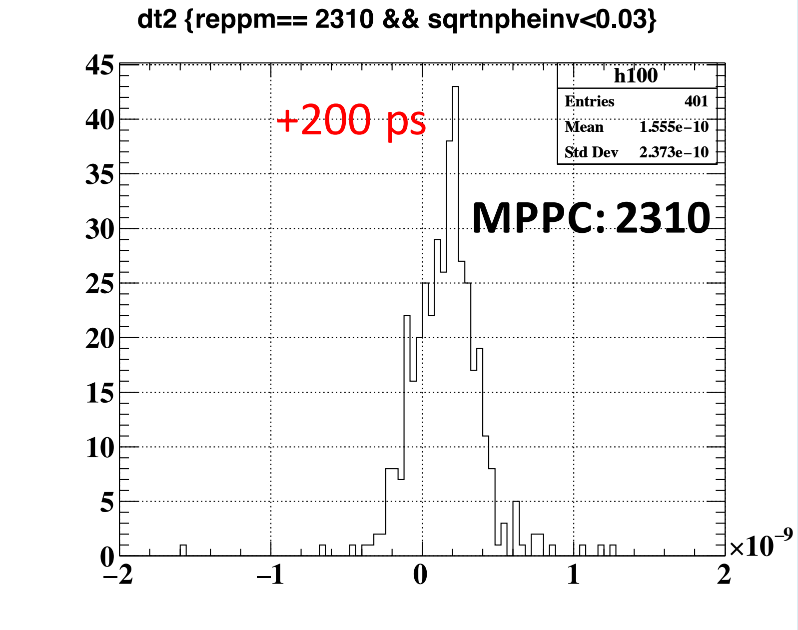
- Ch time offset can be obtained by checking "$t_{pm} - t_{walk} - t_{TOF} - t_{\gamma}$" channel by channel.



- Some offset was observed.

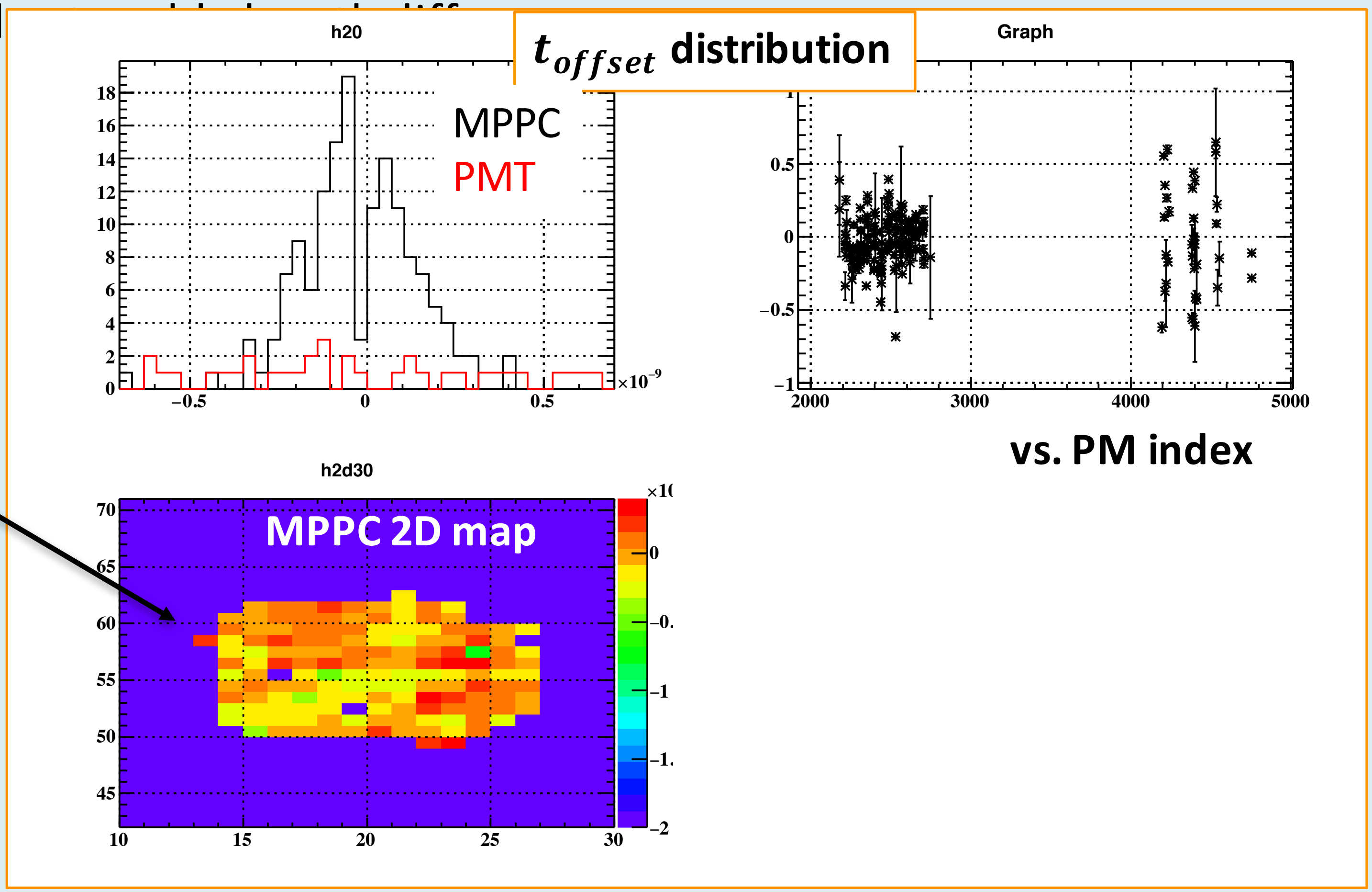
"$t_{pm} - t_{walk} - t_{TOF} - t_{\gamma}$" (ch by ch)





Offset calibration

- RMS of MPPC time offset is ~ 160ps. consistent w/ Mitsutaka & Rina ‘s study.
- PMT is found to have larger distribution.
  - Probably d
    - We cut

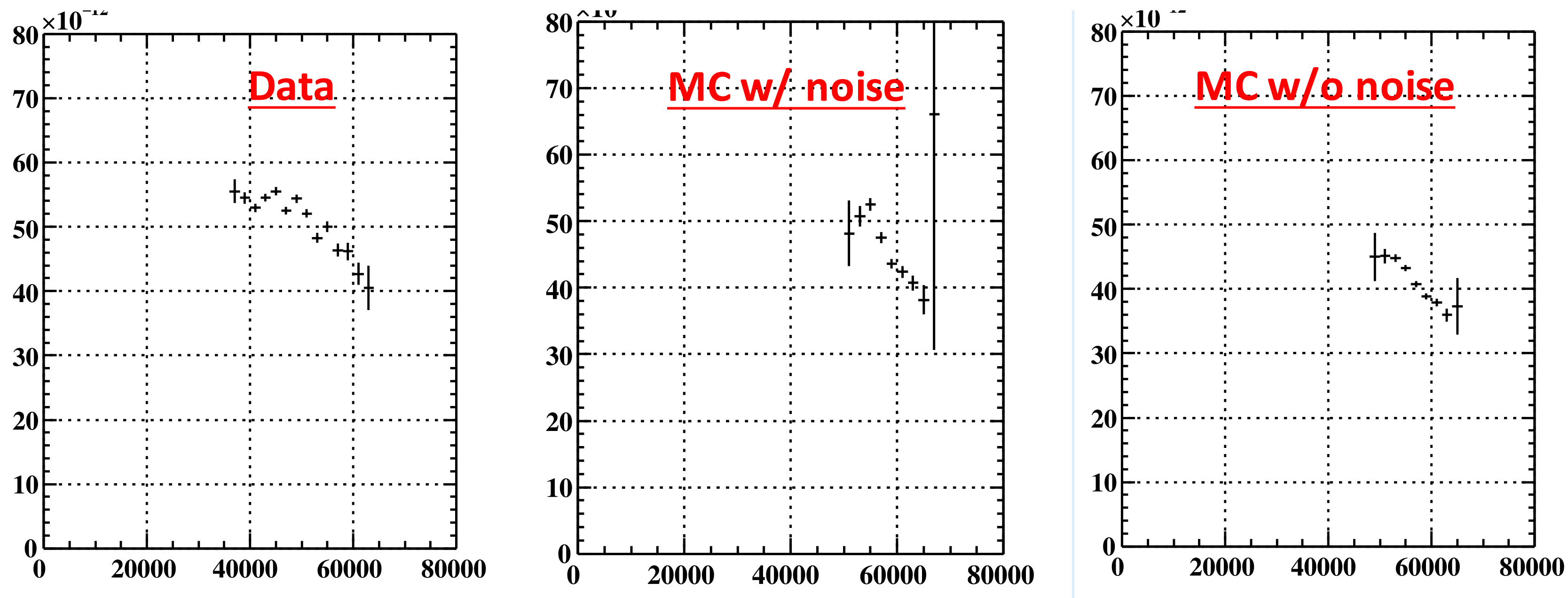


Currently only for ~150MPPC.
Due to online position selection.

Even- odd resolution

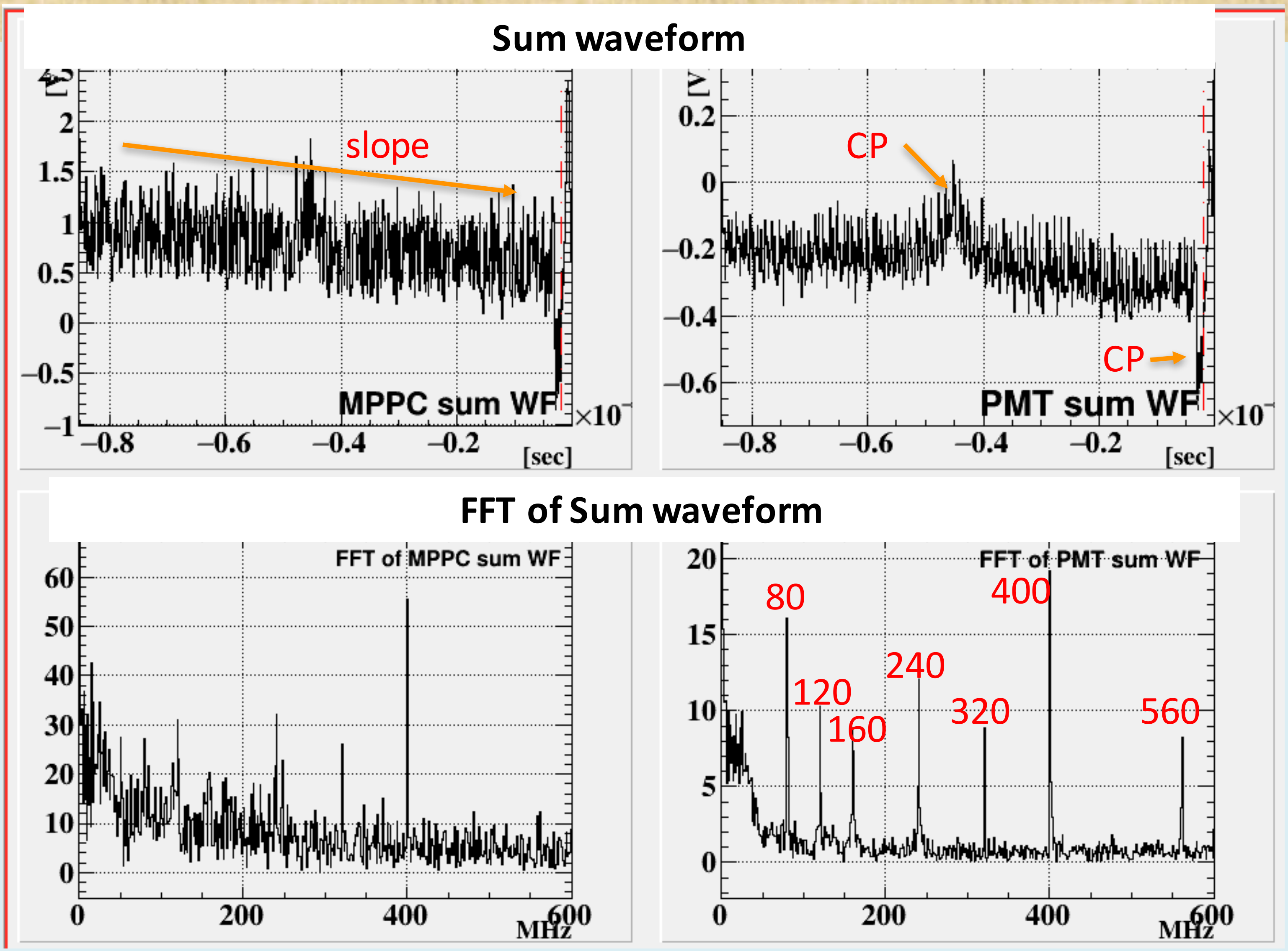
- Data and MC w/ noise gets consistent at end point.
  - Still different at small qsum region.
    - Likely due to conversion depth difference.

Even-odd resolution Vs. Qsum



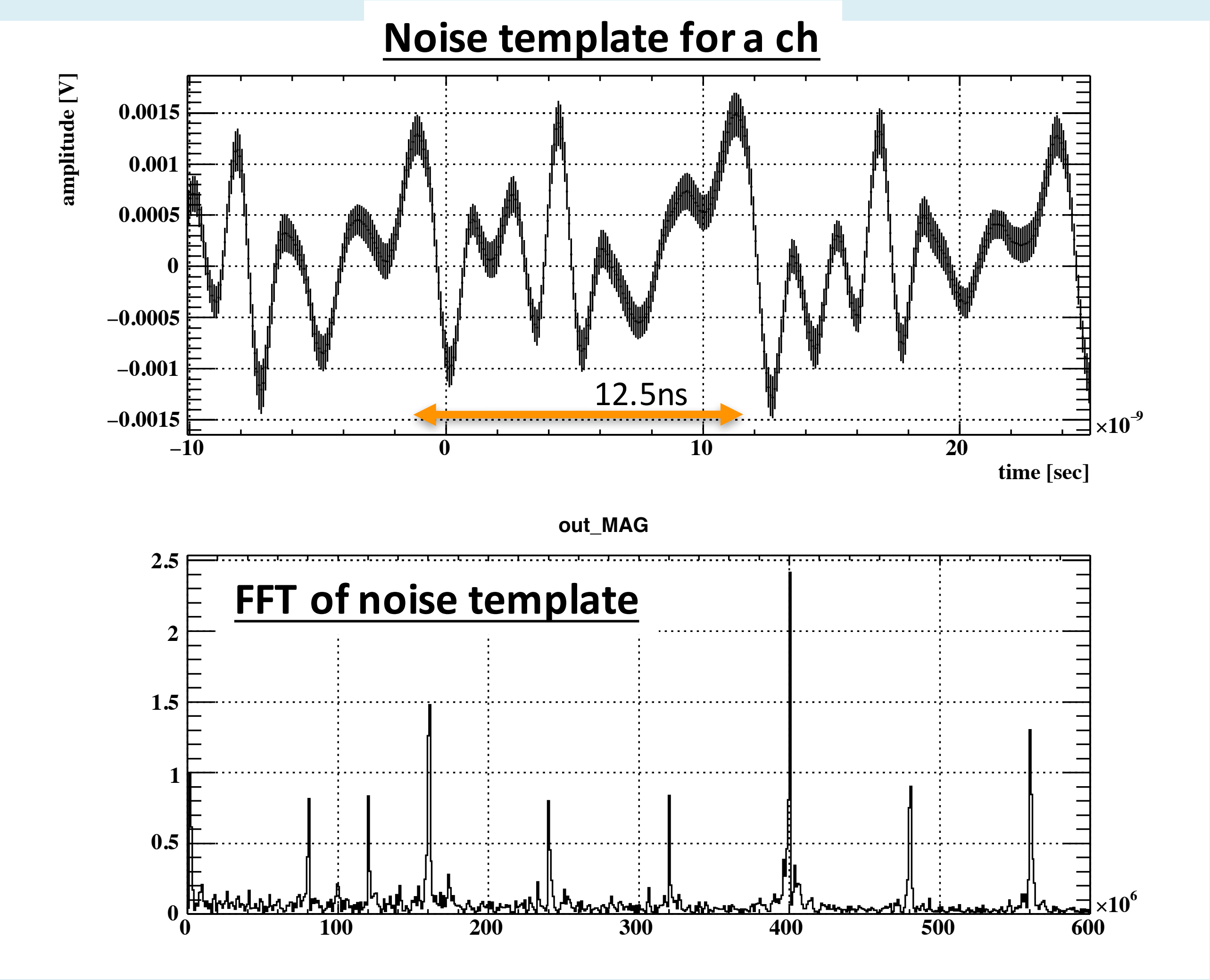
Noise situation

- aa



80 MHz noise template

- 80*n MHz component can be extracted.

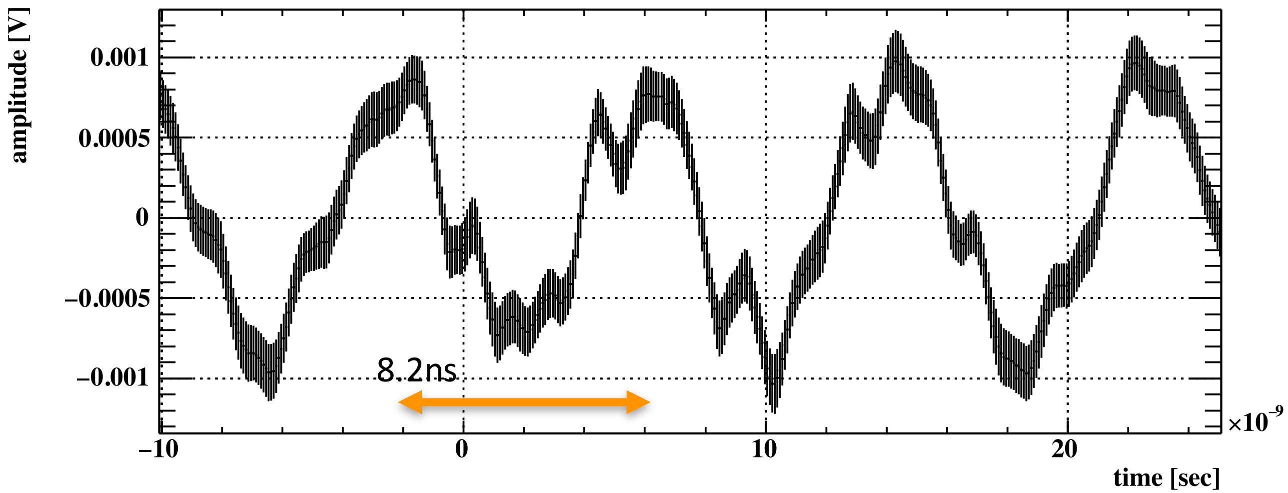


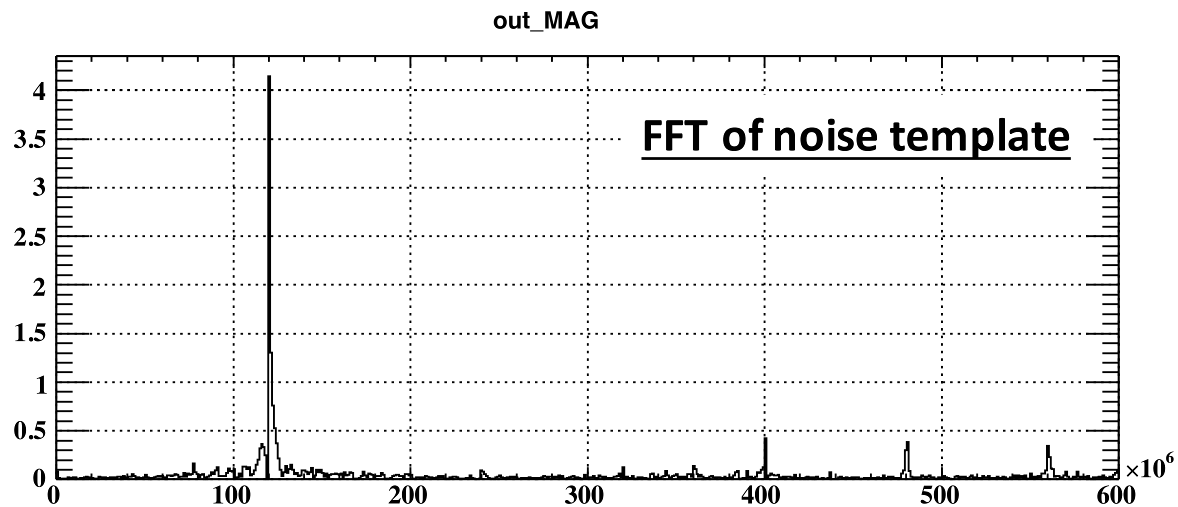
120 MHz noise template

- 120*n MHz component can be extracted.

after extract & subtract 80MHz sync

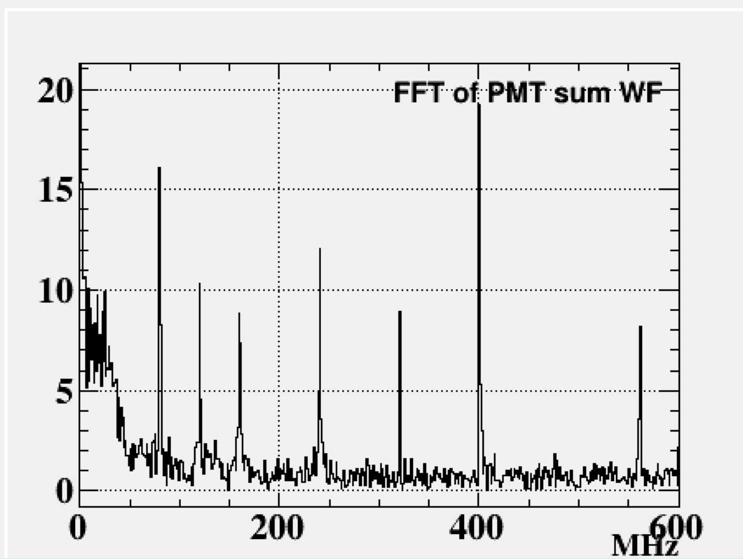
Noise template for a ch



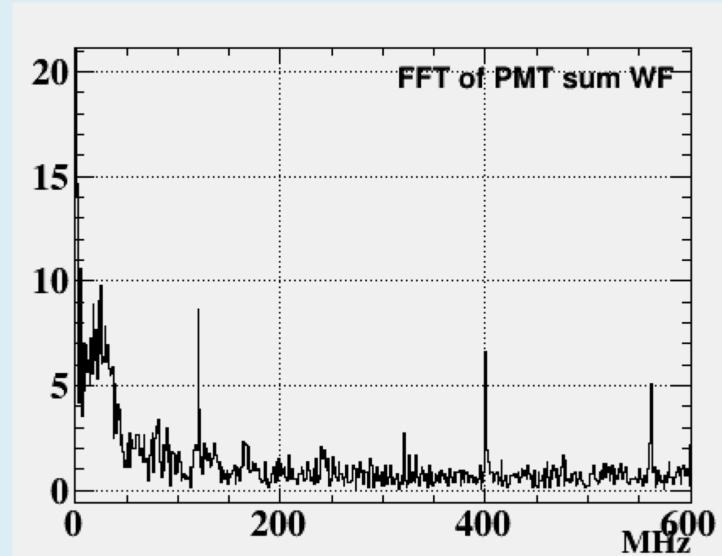


Result -FFT-

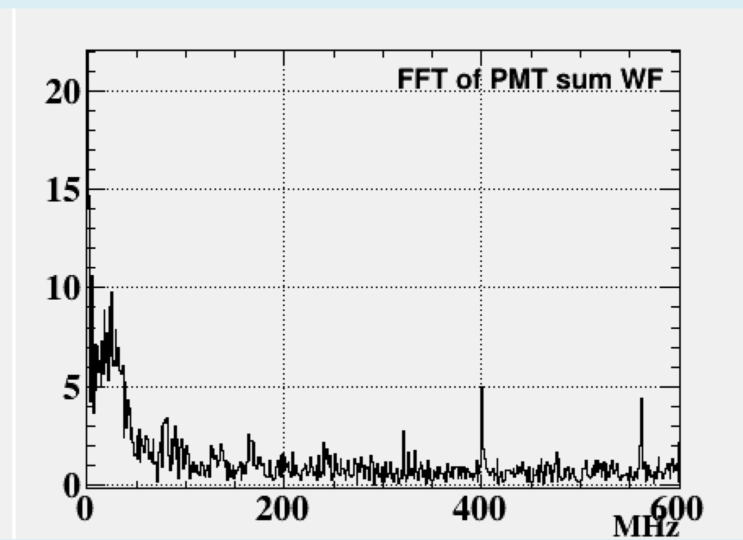
- High frequency noise is subtracted!



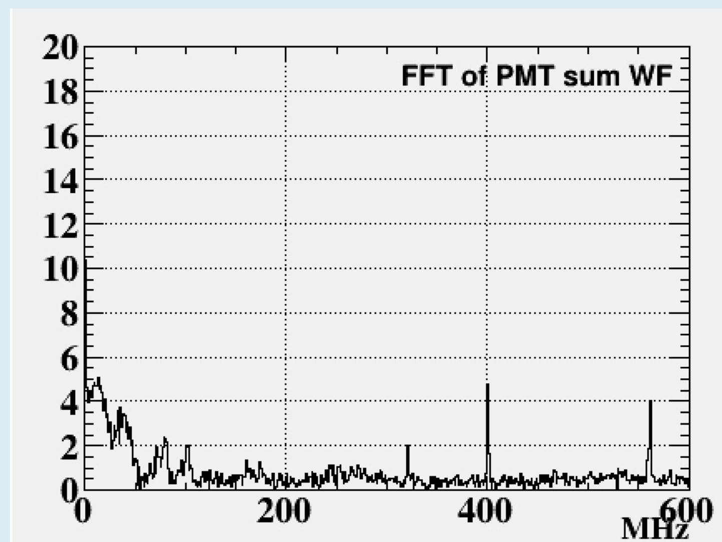
80MHz sync subtraction



120MHz sync subtraction



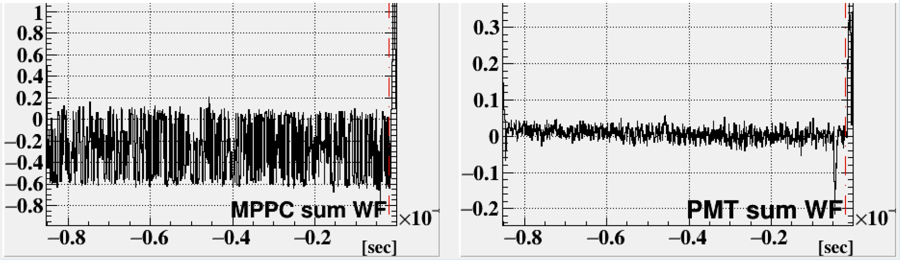
cell pedestal subtraction



80MHz sync noise reduction

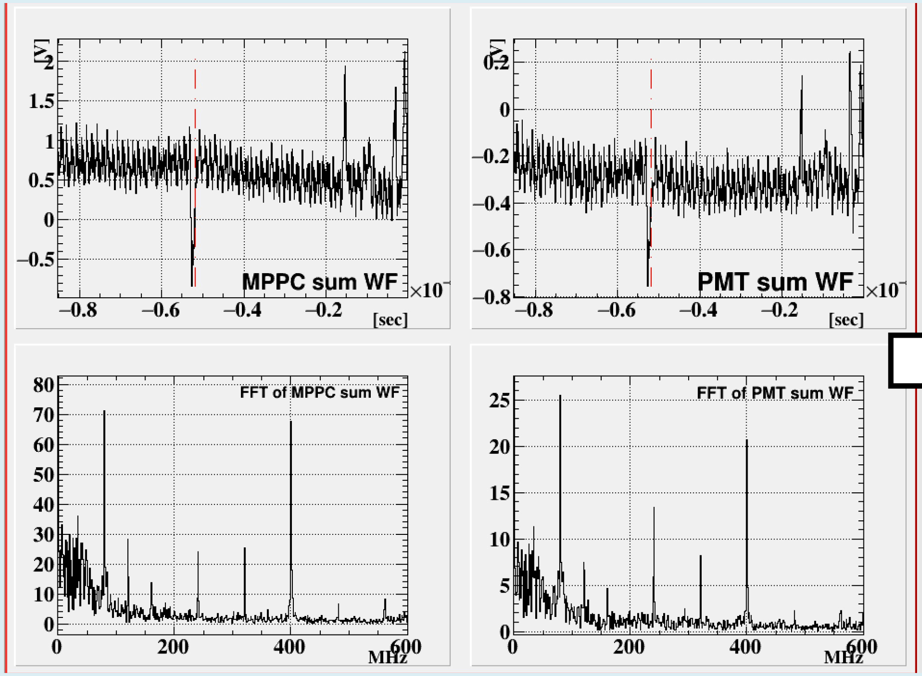
- There was one bad MPPC ch (voltage calib lost???), in the run I used before.

WF on Tuesday.

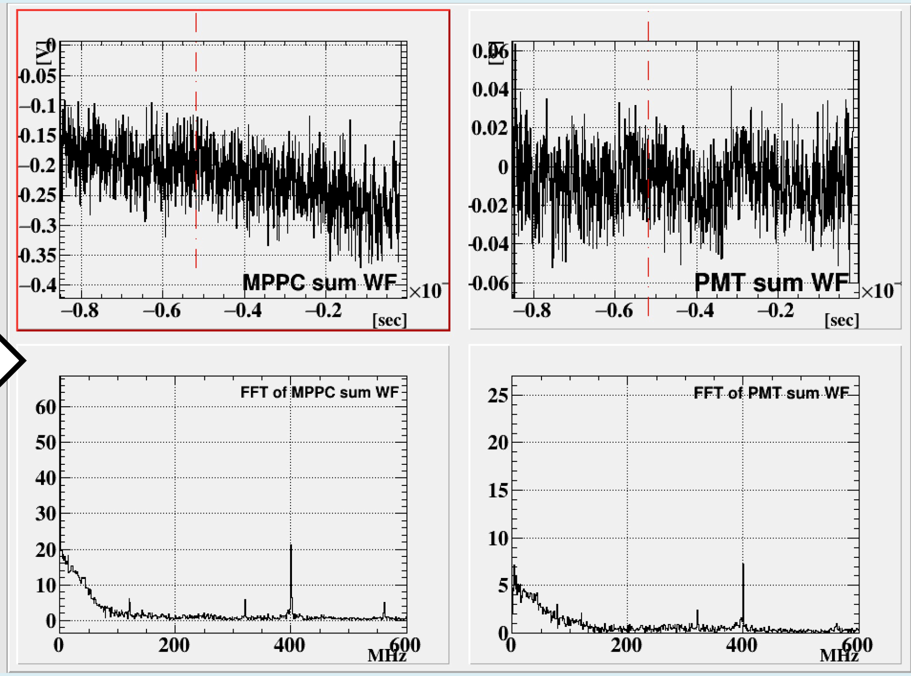


- 80MHz sync noise reduction works well also for MPPC.

Gain 1 (MPPC) Gain 1 (PMT)



Gain 1 (MPPC) Gain 1 (PMT)



Noise rms

- Thanks to the noise reduction, noiserms is improved from 1.7mV to 0.8mV.
- Still larger than MEG I level (~0.4mV).