Liquid xenon gamma-ray detector for MEG II experiment

MEGII実験にむけた液体キセノンガンマ線検出器の開発

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@ Flavor physics workshop, 2020/11/26

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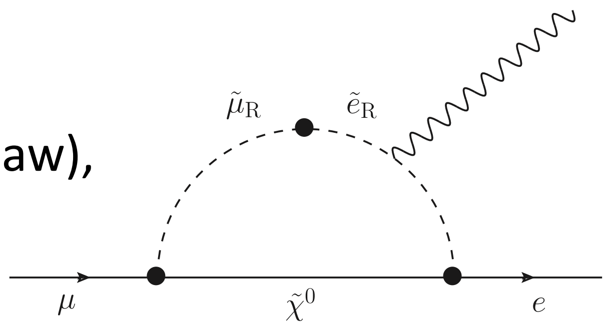
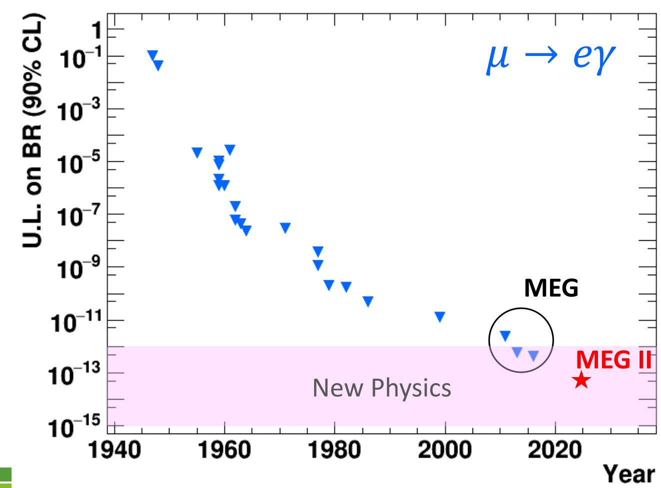
Charged lepton flavor violation

- MEG II experiment searches for a charged lepton flavor violating (CLFV) decay of a muon, μ→eγ.
  - Never been observed, and prohibited in SM by charged lepton flavor conservation.
  - In some BSM models (e.g. SUSY-GUT, SUSY-Seesaw), $O(10^{-12} \sim 10^{-15})$ branching ratio is predicted.



- Current experimental limit: 4.2×10^{-13} (by MEG, 90% C.L.)
- **MEG II searches for μ→eγ with a sensitivity of ~5×10^{-14}.** (one order of magnitude imporvement)

- Complementary with other CLFV searches in the next decade.
  - MEG II (μ→eγ) : This talk
  - Mu2e, COMET (μN→eN)
  - Mu3e (μ→eee)

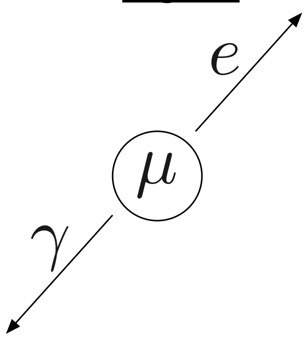


How to search for μ→eγ

- Signal event is identified from many other background events with its kinetics.
  - Energy, direction, and timing of the e & γ are measured.

- A good detector resolution is a key to achieve a good sensitivity in μ→eγ search.
  - Good detector resolution
    → Better separation of signal event from background
    → Better sensitivity.

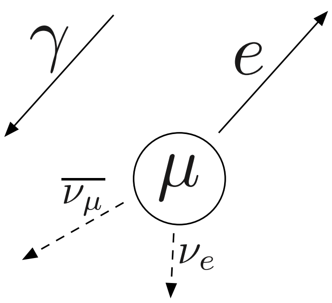
Signal



2-body decay to nearly massless particles

- $E_e = E_\gamma = 52.8\text{MeV}(= m_\mu/2)$
- back-to-back
- coincident

Dominant Background (BG): accidental considence



e & γ: originating from different muons.

- having nearly 52.8MeV,
- emitted nearly back-to-back
- emitted at the nearly same timing

MEG II experiment

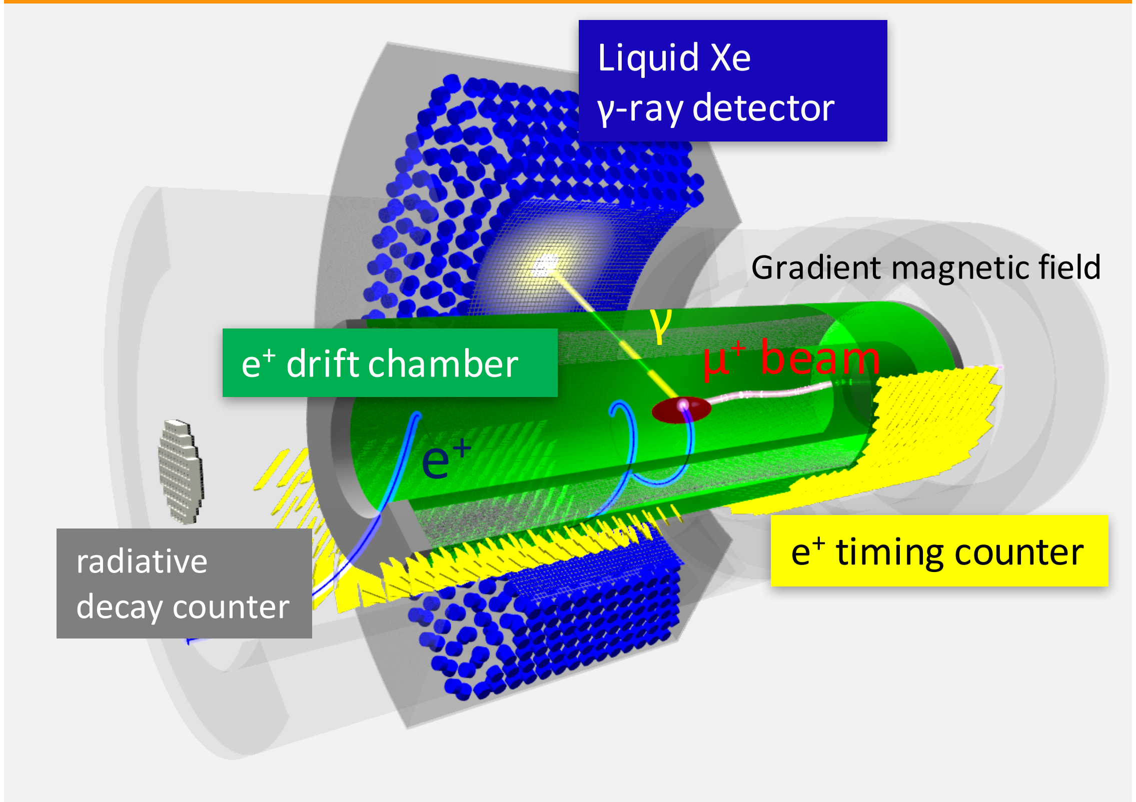
An upgrade experiment called MEG II is planned,
to improve the sensitivity of MEG by another one order of magnitude.

Better detector resolutions.
- x2 for all detector resolutions

More muon statistics.
- x2.3 muon beam rate
  $(3 \times 10^7 \rightarrow 7 \times 10^7\ \mu/s)$
- x2.3 positron efficiency
  (30% -> 70%)

A new detector for background tagging.

MEG II detectors

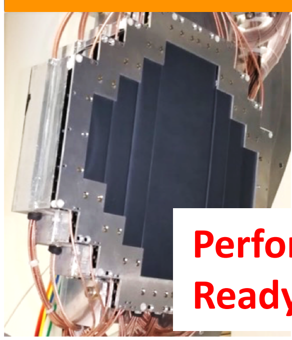


MEG II experiment

Drift chamber

Constructed. Commissioning ongoing.

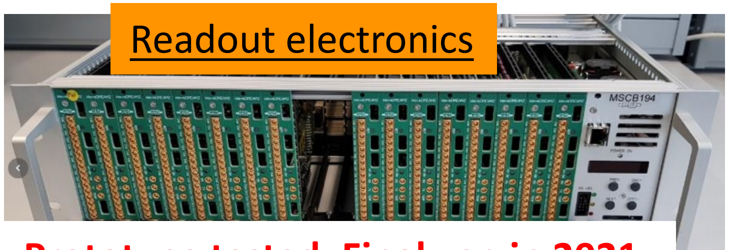
Radiative decay counter



Positron timing counter

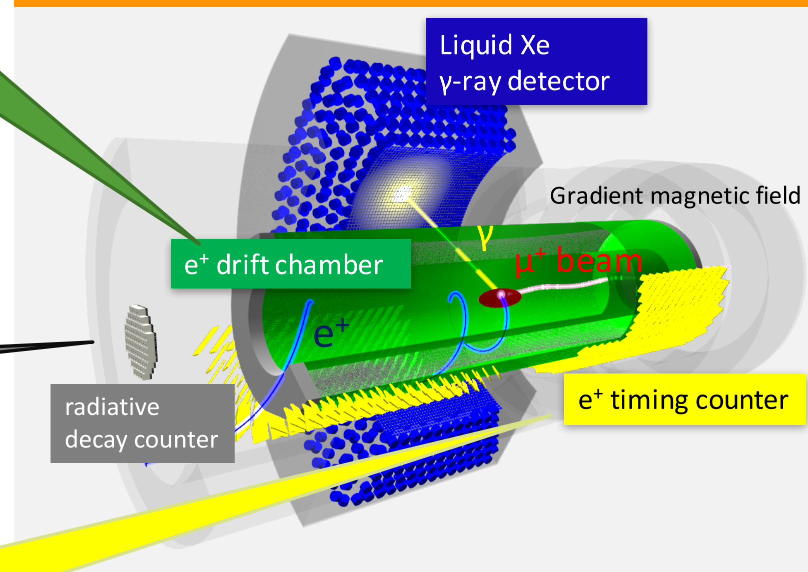
Performance demonstrated. Ready for experiment.

Readout electronics



Prototype tested. Final ver. in 2021.

MEG II detectors



MEG II detectors and electronics are being prepared.

Aiming to start data-taking in 2021.

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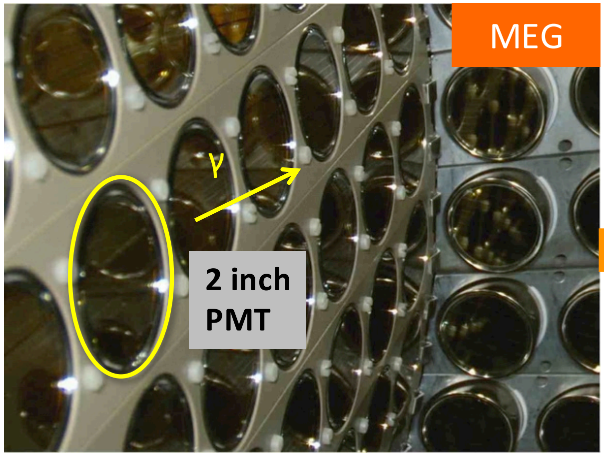
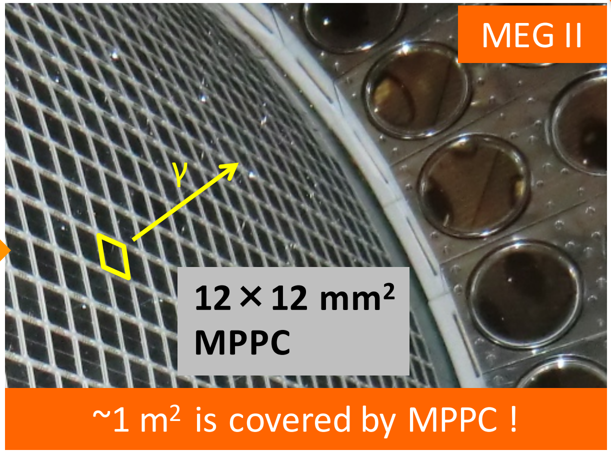
LXe γ-ray detector in MEG II

LXe detector has been upgraded to MEG II
to significantly improve performance.

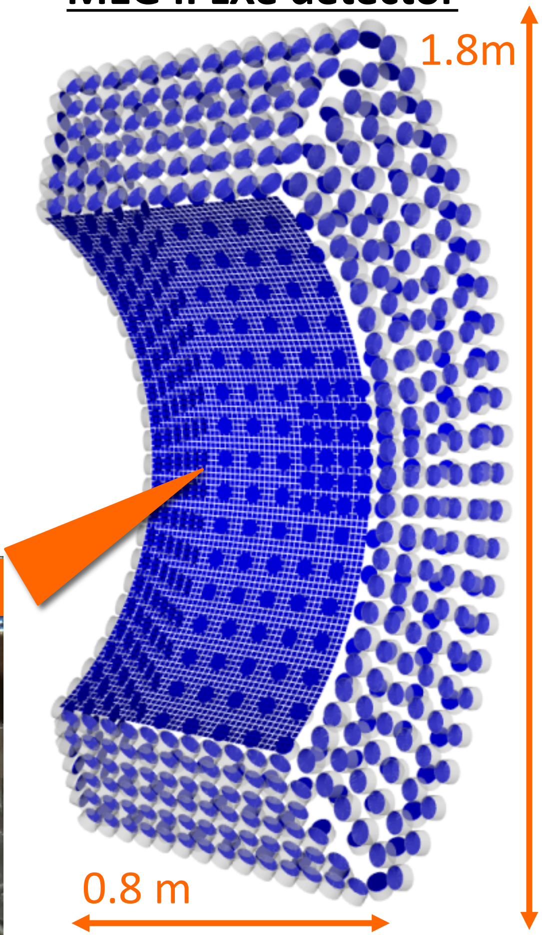
- Scintillation light from LXe (λ=175nm) detected by photosensors.

216 2-inch PMTs on the γ-entrance face has been replaced with **4092 12×12 mm^2 MPPCs.**



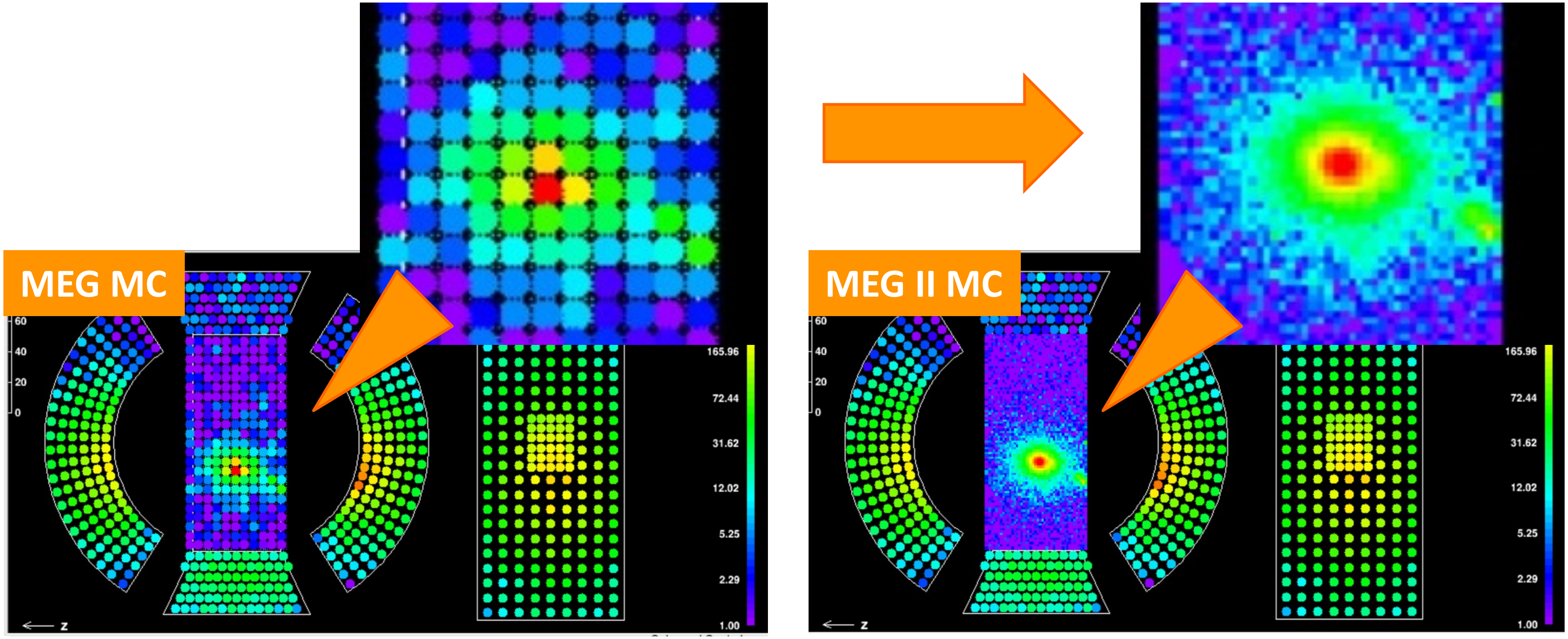


MEG II LXe detector



LXe γ-ray detector in MEG II (cont'd)

1. **Better position resolution** from higher granularity.
2. **Improved energy resolution**
   from better uniformity of scintillation readout.
3. **Increased detection efficiency**
   from reduced material of the γ-entrance face.



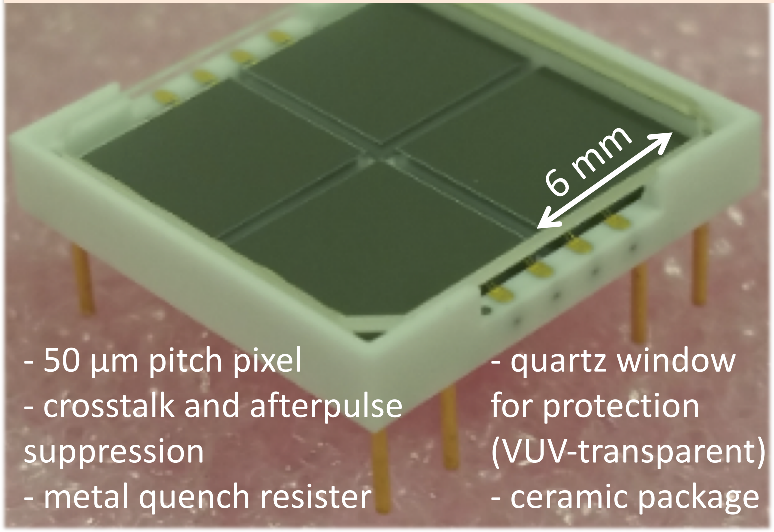
VUV-sensitive MPPC

MPPC for MEG II LXe detector has been developed in collaboration with Hamamatsu Photonics K.K.

VUV-sensitive (PDE (λ=175nm) > 15%)

- Normal MPPCs are insensitive to the xenon scintillation light in VUV range.
  →
- VUV-sensitive MPPC newly developed.

Hamamatsu S10943-4372



Large sensitive area (12 × 12 mm^2)

- To keep the number of readout channels manageable.
- Discrete array of four 6 × 6 mm^2 chips.
- Four chips connected in series at readout PCB to reduce the sensor capacitance and the long time constant.

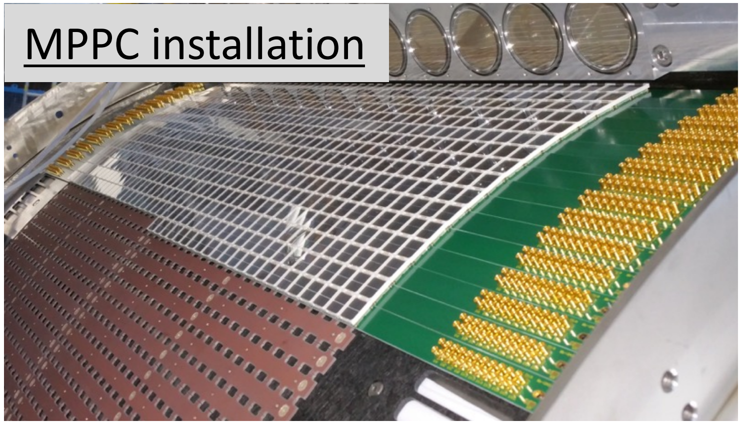
Detector construction & commissioning

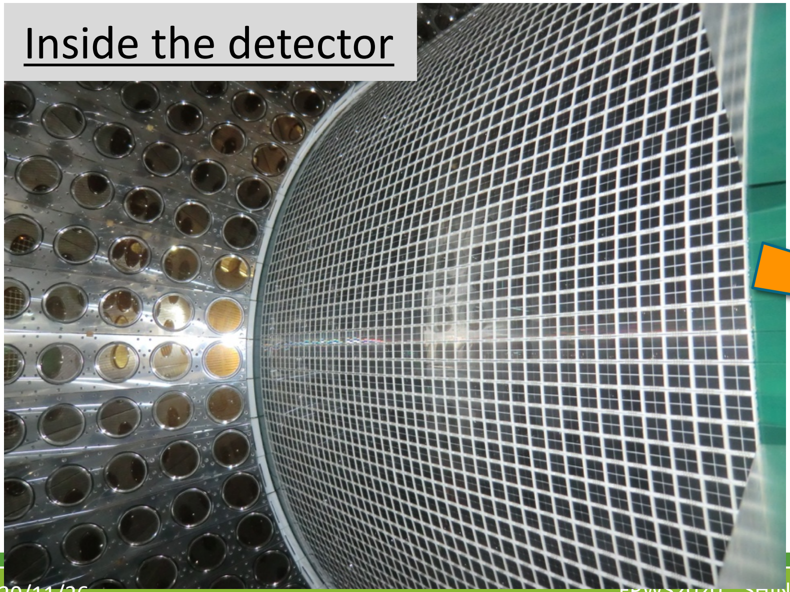
2015
MPPC mass production & Test of all MPPC

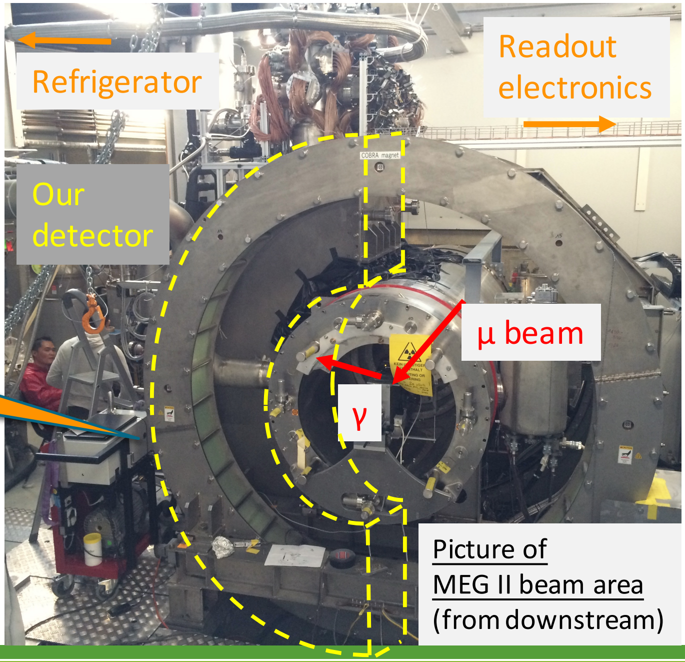
2016
MPPC & PMT installation

2017 Apr.
Construction completed.

2017-2019
Beam test to demonstrate performance.







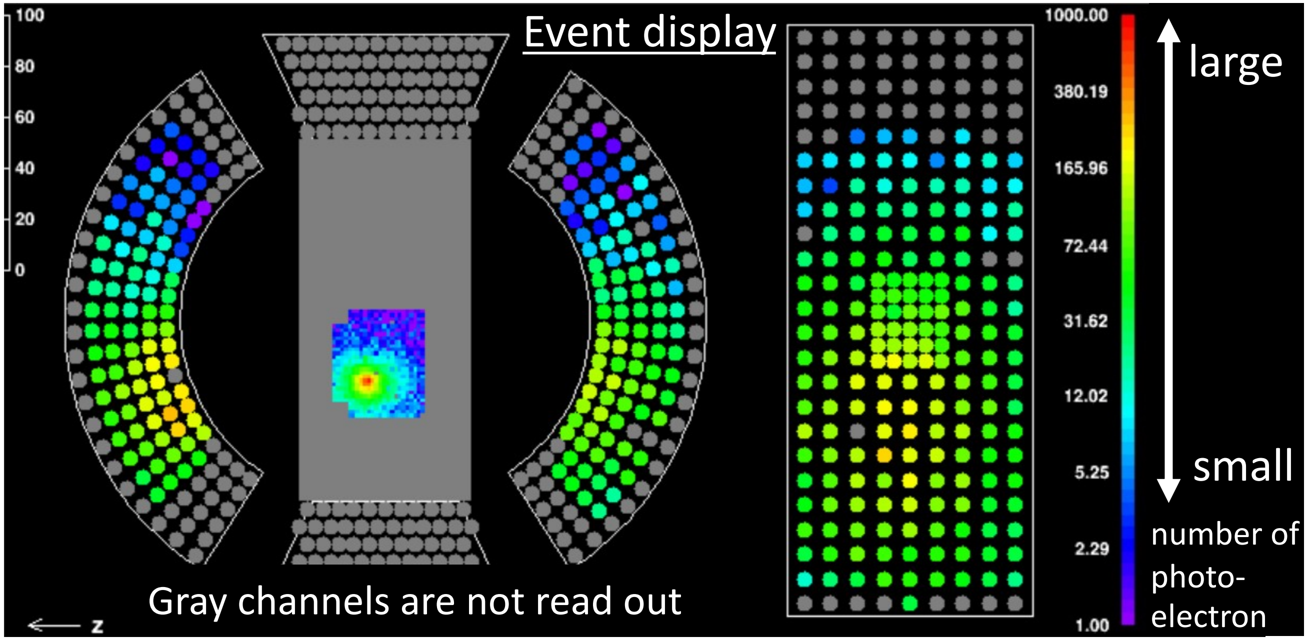
Beam test

A series of beam test was carried out to evaluate detector performance.

- Use a prototype of WaveDREAM (electronics for MEG II) for data acquisition.
  - Only a quarter of the detector was read out,
    due to the limited number of readout channel.
    → Use γ-rays hitting the center of the readout area to evaluate resolutions.

<u>Operation conditions</u>

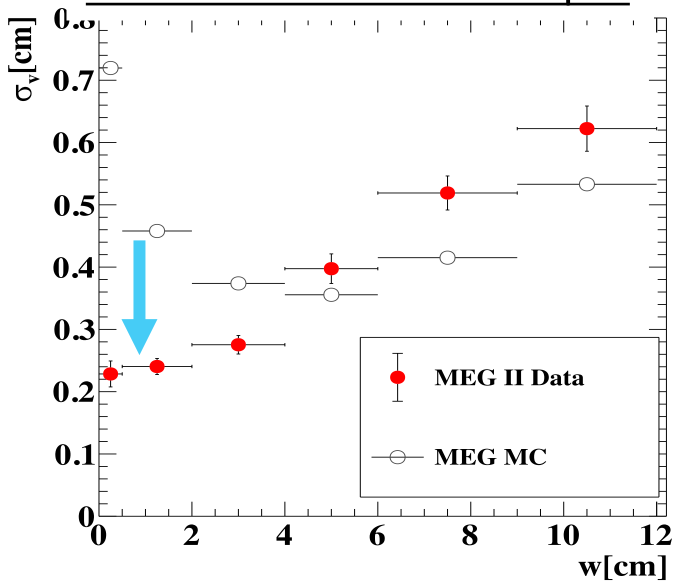
- MPPC @ over voltage ~7V
- PMT@ gain ~ 8x10^5
- Signal amplification by a factor of 2.5
- Waveform digitization by 1.2GHz sampling



Resolution improvement for shallow events

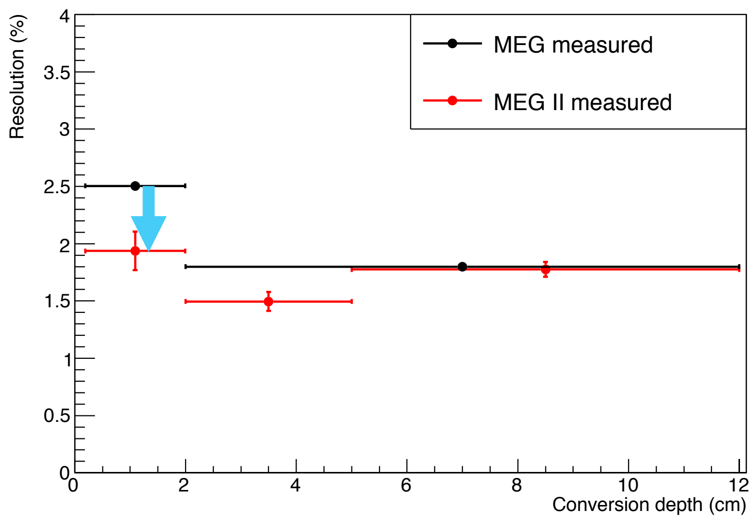
- Detector resolutions are measured in the beam time.
- Position and energy resolution for shallow events are improved from MEG, thanks to the replacement from PMT to MPPC.

Position resolution vs depth



Measured from a reconstructed position distribution by a collimator placed in front of the detector

Energy resolution (for 53MeV γ) vs depth



Estimated by fitting the γ-ray spectrum from muon beam (radiative muon decay & annihilation of Michel positron)

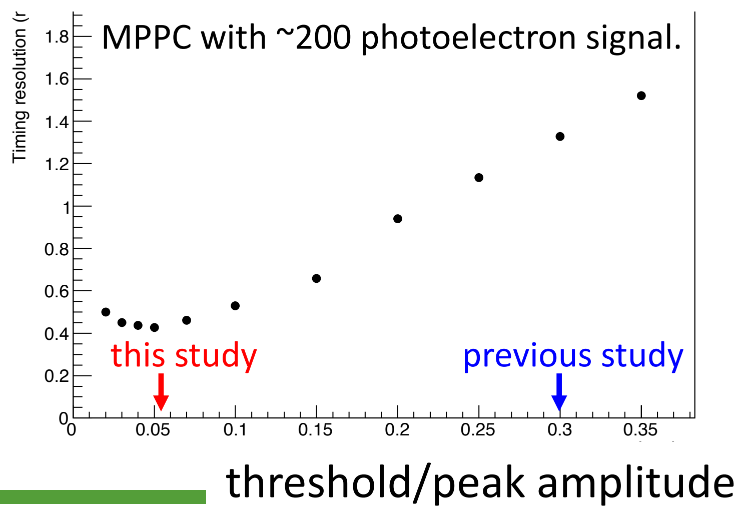
Improvement in the analysis

- Further performance improvement achieved in the offline analysis.

Timing resolution

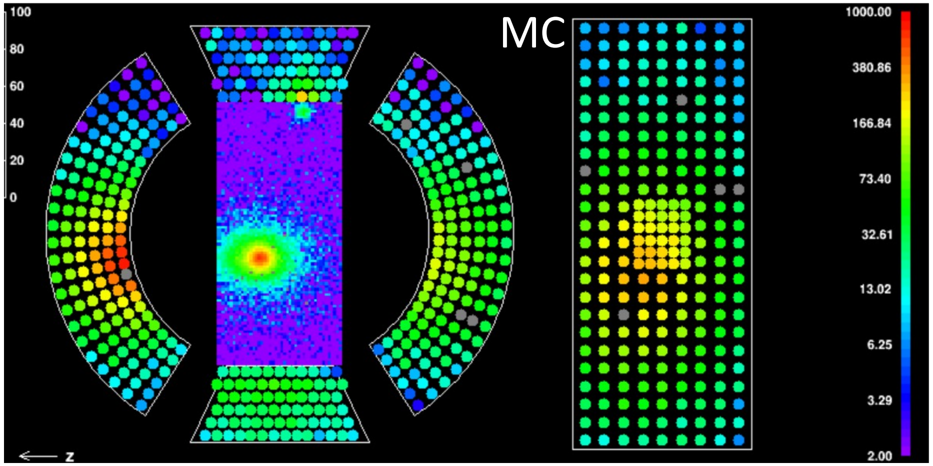
Better timing resolution by optimized threshold in the timing extraction from photosensor waveform.
→
Timing resolution improved
from 76ps (design) to 55ps (this study).

Timing resolution of a MPPC waveform



Two gamma-ray BG event identification

Some of the BG events come from annihilation of Michel positron.
→
Identify two γ event to reduce background.
→
~20% reduction of BG event.



Branching ratio sensitivity of MEG II

- These resolution improvement of the LXe γ-ray detector leads to an improvement of branching ratio sensitivity of MEG II.

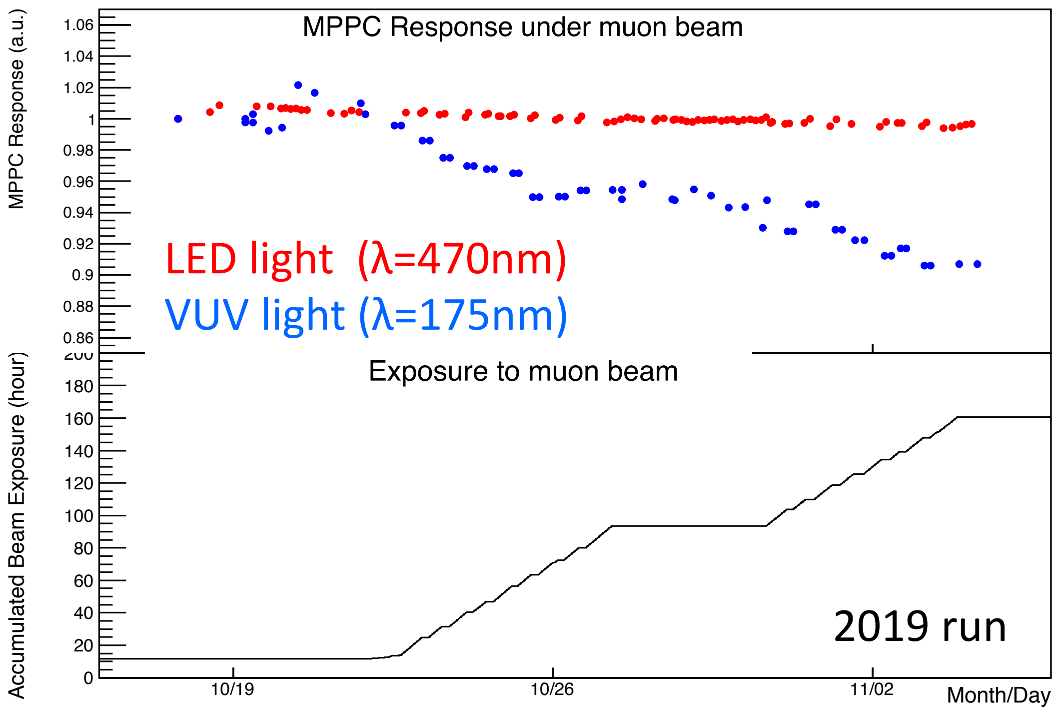
- In total, -40% improvement of sensitivity by the LXe detector upgrade.
- Together with the upgrade of other detectors, $Br(\mu \to e\gamma) = \mathbf{6{\times}10^{-14}}$ will be achievable with three years DAQ.

	MEG	**MEG II**	**Sensitivity improvement from MEG to MEG II**
Position resolution (shallow/deep)	4.1/3.8 mm	2.4/4.8 mm	-20%
Energy resolution (shallow/deep)	2.5/1.8%	1.8/1.8%	-13%
Timing resolution	62 ps	55 ps	-3%
Two γ event identification (MC)	without identification	with identification	-12%

MPPC VUV PDE degradation

A degradation of MPPC PDE for VUV light is found.

- Correlated with the beam usage
  -> Should be a kind of radiation damage.
- Obvious only for VUV light.
- -9(2)% only by 160 hours MEG II beam usage.



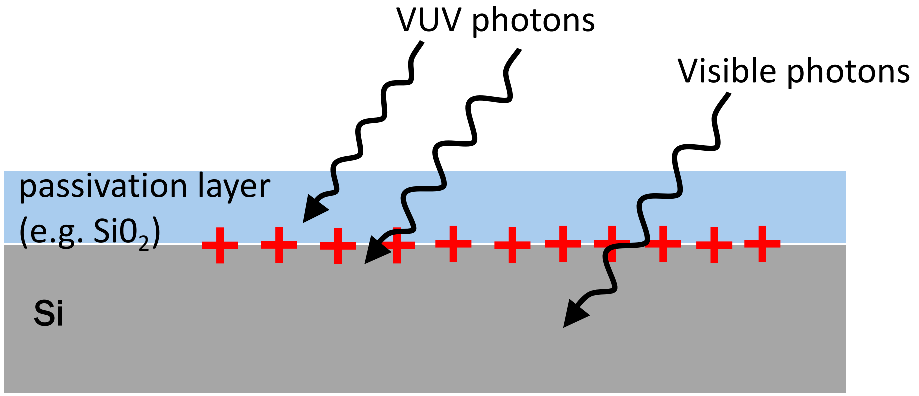
Cause of PDE degradation

This kind of radiation damage was neither reported nor expected.

- The radiation level of our experiment should be sufficiently small.
- Degradation of PDE was not reported.

→ Specific to our special MPPC sensitive to VUV light.

- VUV photons convert very near the surface of the MPPC.
- One hypothesis: Surface damage by VUV irradiation.
  - Accumulated stationary charges near the sensor surface can distort the nearby electric field, and can affect the PDE only for VUV light.



Recovery of damage by annealing

Annealing is known to be useful for radiation damage of MPPCs.

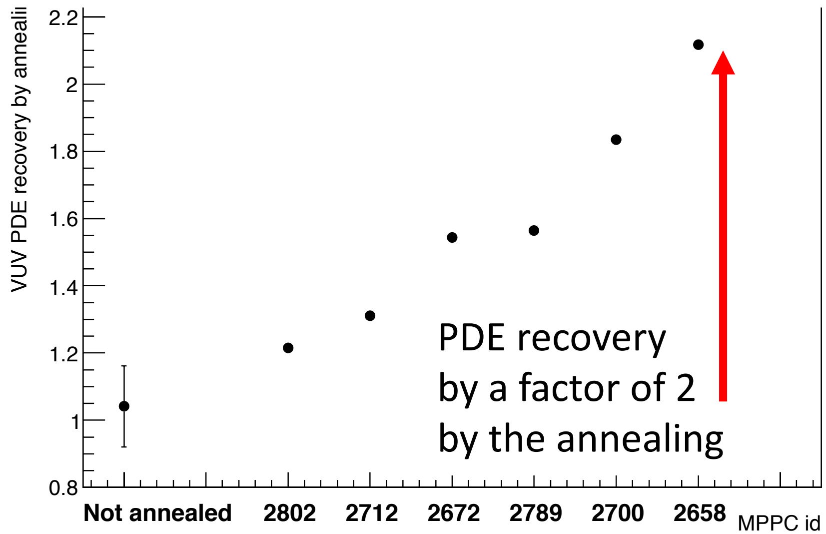
- By keeping MPPC at higher temperature,
accumulated charges can be de-trapped by thermal excitation.

→ Tested also for our MPPC.
(for small number of MPPCs in the detector)

Recovery of the damage
by the annealing is confirmed.

- MPPCs are heated to ~ 70℃
by a Joule heat for 1-2 days.

PDE(after annealing) / PDE(before annealing)
vs. annealing strength (duration & temperature)



Effect of PDE degradation on MEG II sensitivity

- The PDE degradation will affect the branching ratio sensitivity of MEG II.
  - PDE gets below 2% after 60 days MEG II beam usage.
- All MPPCs are annealed during annual accelerator shutdown period (Jan-May).
- Reduction of the beam rate leads to the reduction of accidental background and can minimize the degradation on the sensitivity.

Original Plan

- **120 days DAQ**/year
  @ beam rate: $\mathbf{7\times10^{7}\,\mu/sec}$
- $Br(\mu\rightarrow e\gamma)=\mathbf{6\times10^{-14}}$ (3 year DAQ)

Reduction of beam time

- Annealing during annual accelerator shutdown period.
- **60 days DAQ**/year
  @ beam rate: $\mathbf{7\times10^{7}\,\mu/sec}$
- $Br(\mu\rightarrow e\gamma)=\mathbf{9.4\times10^{-14}}$ (3 year DAQ)

Reduction at reduced beam rate

- Annealing during annual accelerator shutdown period.
- **120 days DAQ**/year
  @ beam rate: $\mathbf{3.5\times10^{7}\,\mu/sec}$
- $Br(\mu\rightarrow e\gamma)=\mathbf{6.6\times10^{-14}}$ (3 year DAQ)

Summary

- MEG II experiment searches for a charged lepton flavor violating decay, $\mu^+ \rightarrow e^+\gamma$.
  - Current upper limit by MEG: 4.2×10^{-13} (90% C.L.)
- A new liquid xenon γ-ray detector has been developed which utilizes a VUV-sensitive MPPC newly developed for this purpose.

- Good performance of this detector has been demonstrated.
- An unexpected radiation damage on the MPPCs was found.
  - Effect on the sensitivity can be minimized by the annealing of the MPPCs, and reduction of the beam rate.

- Together with other MEG II detectors, $Br(\mu \rightarrow e\gamma) = \mathbf{6.6{\times}10^{-14}}$ is expected by three years of DAQ.
- MEG II data-taking will start in 2021.

backup

Abstract

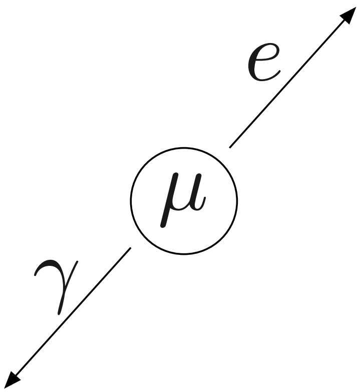
- To search for a charged lepton flavor violating decay, $\mu^+ \rightarrow e^+\gamma$, a new liquid xenon γ-ray detector has been developed.
  - This detector utilizes a VUV-sensitive MPPC newly developed for this purpose.

- The detector construction and commissioning was conducted, and the performances have been measured.
  - Resolution improvements realized by the MPPCs have been demonstrated.
  - An unexpected radiation damage on the MPPCs was found.

- The expected sensitivity with this detector is estimated.
  This detector is confirmed to have a sufficient performance to search for $\mu^+ \rightarrow e^+\gamma$ with a sensitivity of $5\text{x}10^{-14}$.

How to search for μ→eγ

- An event signature of μ→eγ is utilized to distinguish signal event from many other background events by SM muon decays.



Signal

2-body decay to nearly massless particles

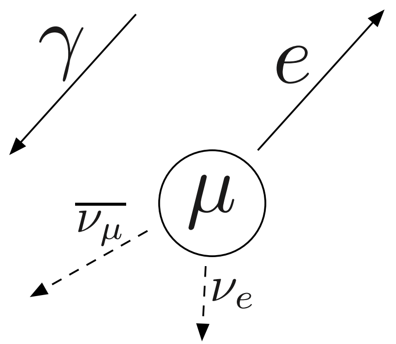
- $E_e = E_\gamma = 52.8\text{MeV}(= m_\mu/2)$
- back-to-back
- coincident

- To identify signal event, we will measure
  - γ-ray hit position, energy, and timing.
  - positron momentum and timing.

How to search for μ→eγ (cont'd)

- Dominant background is an accidental coincidence of e and γ.

Dominant Background(BG): accidental considence



e & γ: originating from different muons.

- having nearly 52.8MeV,
- emitted nearly back-to-back
- emitted at the nearly same timing

- A good detector resolution is the key to achieve a good sensitivity in μ→eγ search.
  - Good detector resolution
    → Better separation of signal event from background
    → Better sensitivity.

The number of background events in signal region

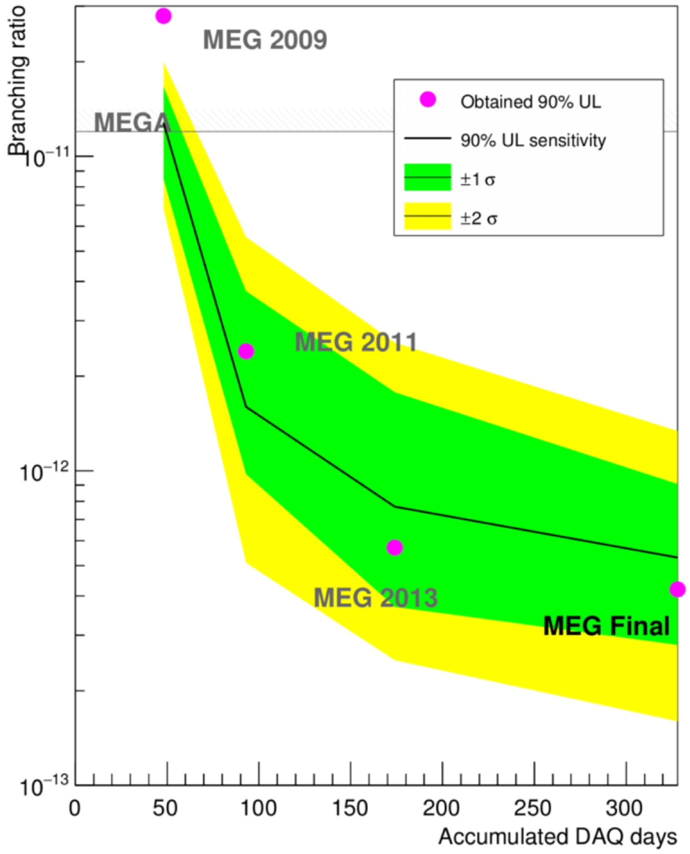
$$N_{\mathrm{acc}} \propto R_{\mu^+}^2 \times \underline{\Delta E_\gamma{}^2 \times \Delta p_{\mathrm{e}^+} \times \Delta\Theta_{\mathrm{e}^+\gamma}^2 \times \Delta t_{\mathrm{e}^+\gamma}} \times T.$$

detector resolutions

MEG experiment

- MEG experiment searched for μ→eγ.
  - Utilized world most DC intense available at Paul Scherrer Institute (PSI).
  - Data-taking time : 4.5 years (2009-2013)

Sensitivity of MEG vs DAQ time



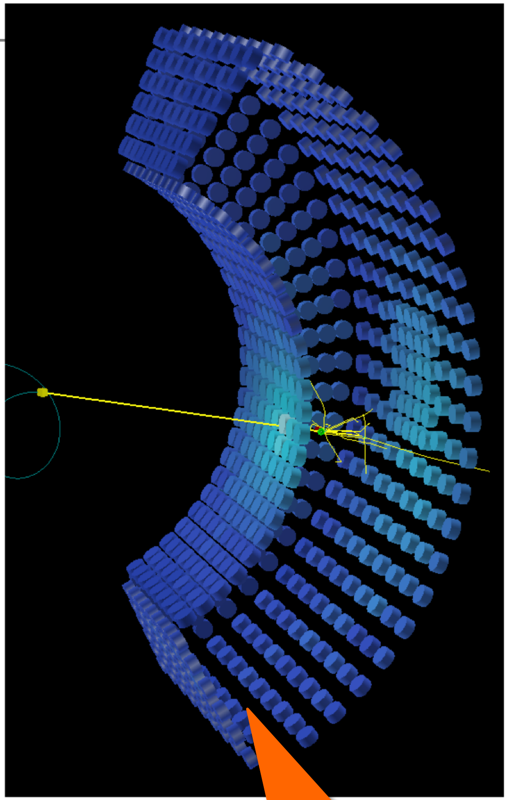
- Sensitivity improvement by another one order of magnitude is not possible by a simple extension of MEG.
  - The sensitivity improves only by a factor of $\sqrt{\text{DAQ time}}$.

→ It will take O(100) years to achieve $5\text{x}10^{-14}$ with MEG detectors.

LXe γ-ray detector in MEG

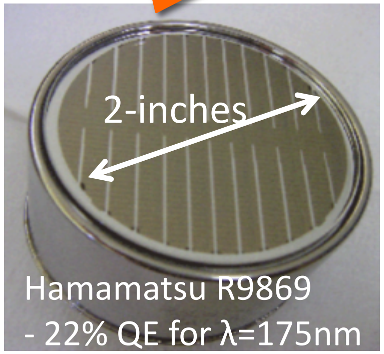
Liquid xenon (LXe) γ-ray detector was used in MEG.

- 900 ℓ LXe detector
- Scintillation light readout by 846 PMTs（Photomultiplier Tube）



Advantages of LXe

- High stopping power (X_0=2.8cm)
  → A rather compact detector with a reasonable efficiency.
- Sufficient light yield (~75% of NaI)
  → Good resolution by large photoelectron statistics.
- Fast decay time of scintillation (τ_{decay} = 45ns for γ)
  → Suitable for an operation in high pileup environment.
- Liquid
  → Uniform response can be achieved easier than crystals.



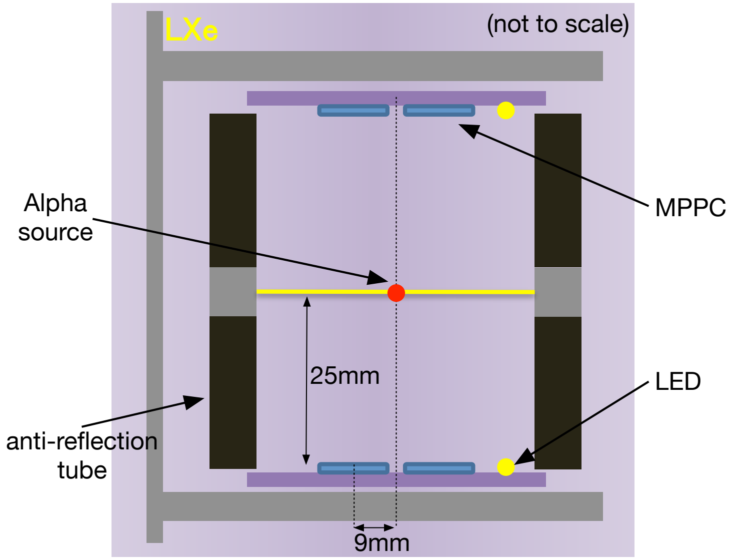
Disadvantages of LXe

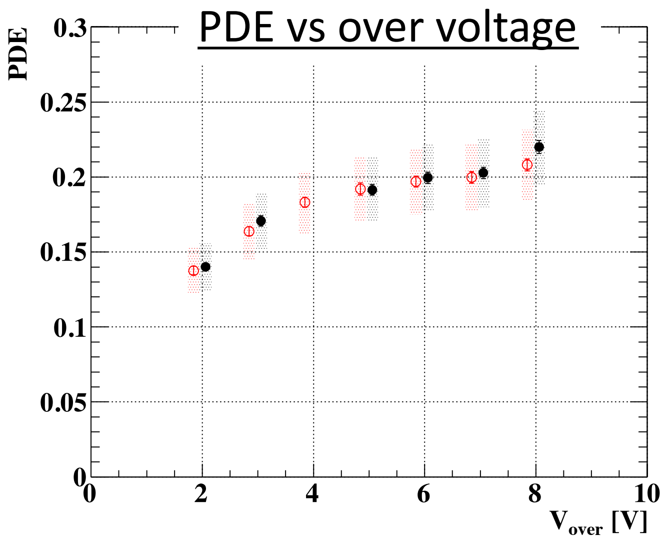
- Scintillation light (λ=175nm) in VUV (vacuum ultraviolet) range.
- Low temperature (165K) is required
- High purity is required.

VUV-sensitive MPPC (cont'd)

- In the Normal MPPCs, protection layer of resin at the surface absorbs VUV.
  → Protection layer removed. Another VUV-transparent quartz window for protection.
- Attenuation length of VUV light in silicon is only 5 nm, and VUV photons cannot directly reach the sensitive region (as for visible light).
  → Thinner contact layer & non-zero electric field at contact layer.

- Sufficient PDE (Photon detection efficiency, 光子検出効率) above ~20% is demonstrated for xenon scintillation light in lab test.



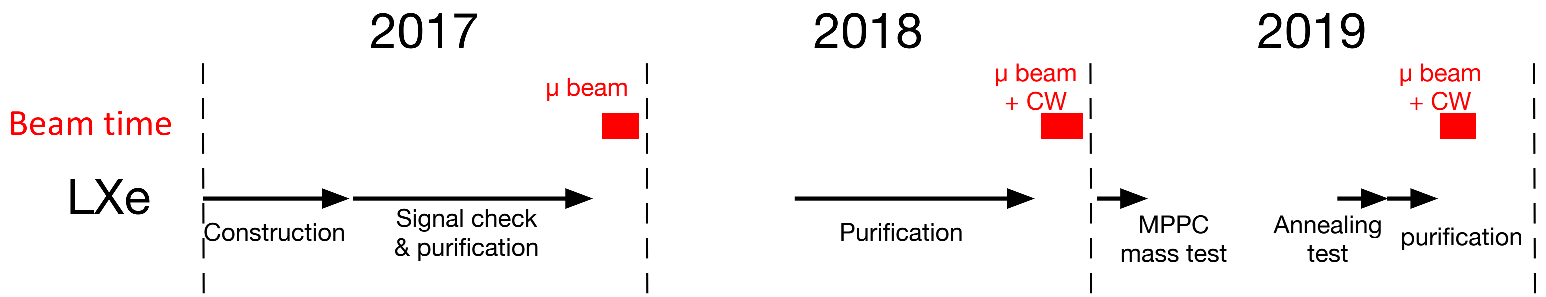


Beam test

A series of beam test was carried out to evaluate detector performance.

List of obtained data

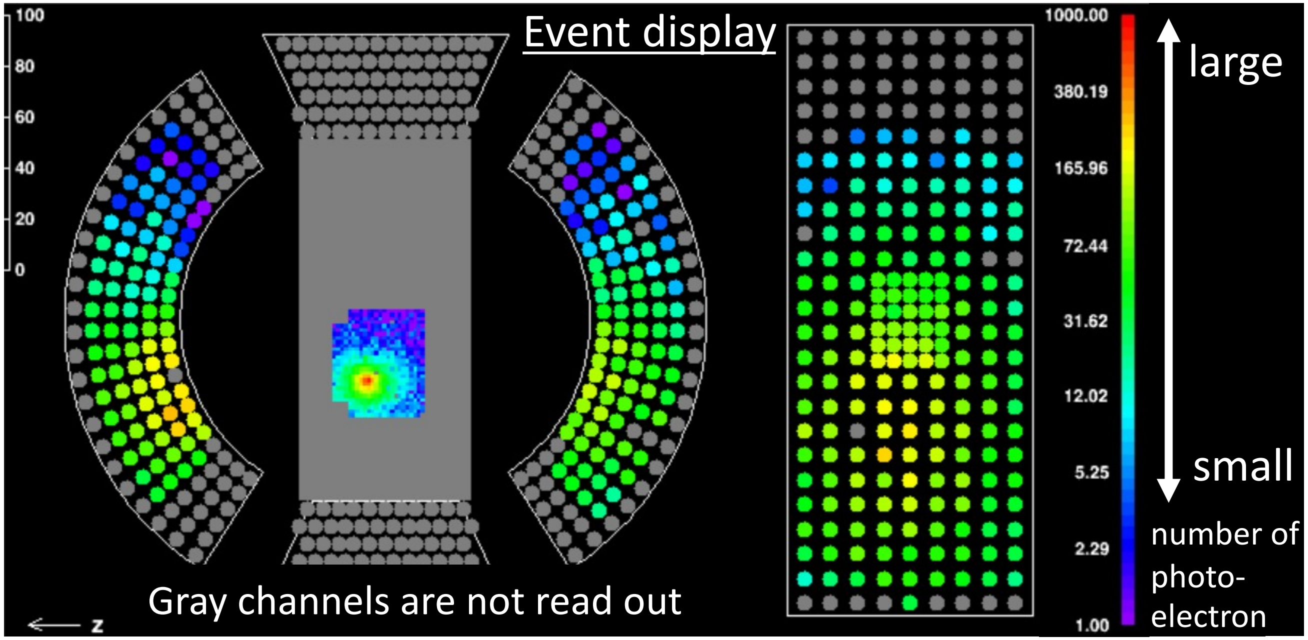
- BG γ : γ-rays from muon beam (background in μ→eγ search).
  - Mainly from radiative muon decay (RMD) on target.
  - Gamma-ray energy up to 52.8MeV.
- CW Li : 17.6 MeV monochromatic γ-ray from ${}^{7}_{3}\mathrm{Li}(\mathrm{p},\gamma){}^{8}_{4}\mathrm{Be}$.
- Calibration data : LED for gain calibration, alpha for PDE calibration, etc...



Beam test (cont'd)

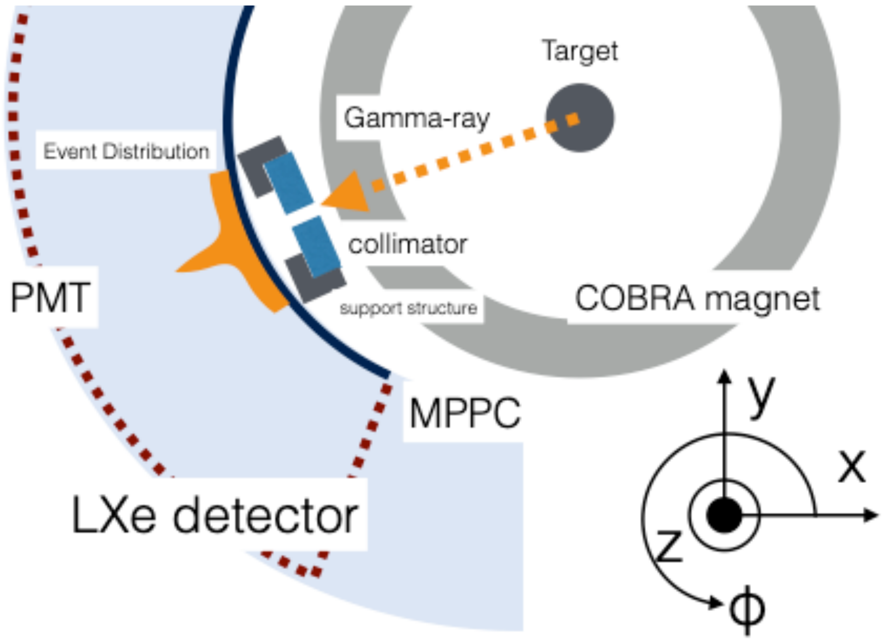
- Use a prototype of WaveDREAM (electronics for MEG II) for data acquisition.
  - Only a quarter of the detector was read out.
    due to the limited number of readout channel.
    → Use γ-rays hitting the center of the readout area to evaluate resolutions.
  - Waveforms from each photosensor are recorded.

- Operation conditions
  - MPPC
    @ over voltage ~7V
  - PMT
    @ gain ~ $8x10^5$
  - Signal amplification
    by a factor of 2.5
  - waveform digitization
    by 1.2GHz sampling

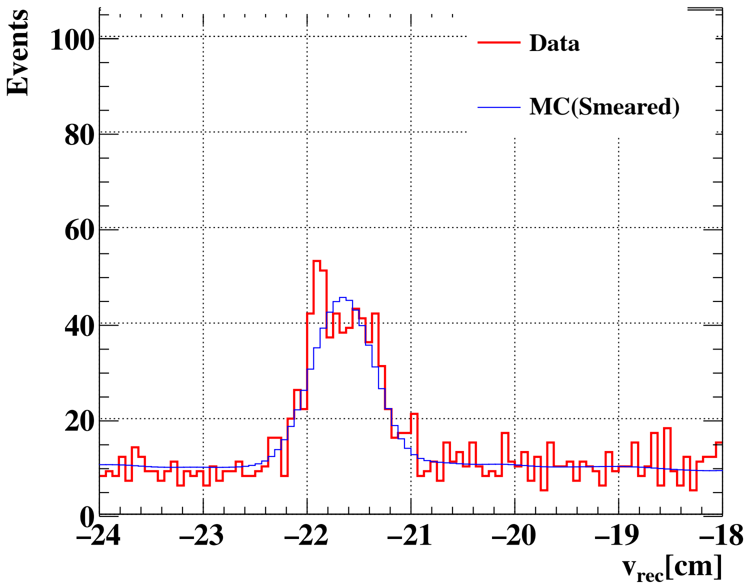


Position resolution

- Position resolution was measured by placing a lead collimator in front of the detector.
- 17.6MeV γ-ray from CW-Li was used because of its smallness of the γ generation vertex.
- The resolution is evaluated by fitting the peak by a true hit position distribution convoluted by gaussian.



Event Rate (with collimator) vs. γ-ray hit position



Position resolution

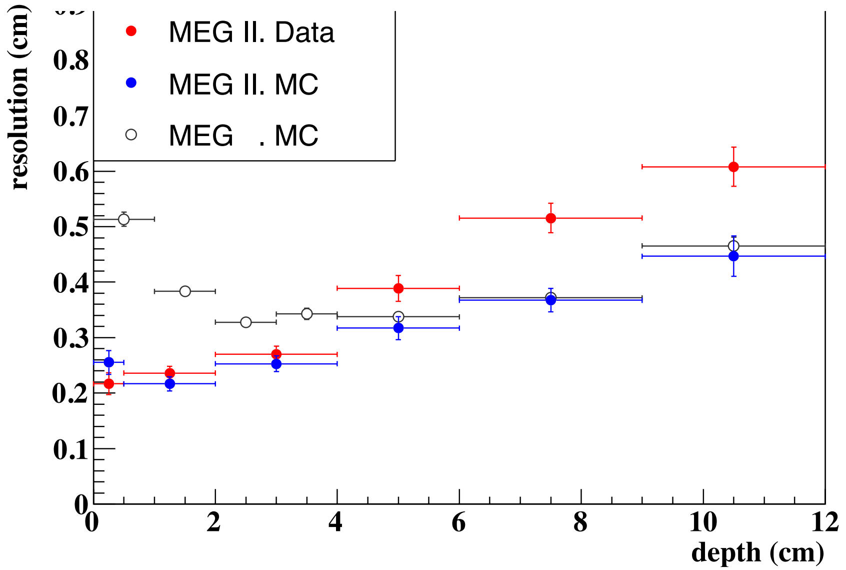
- Resolution improvement for shallow events is demonstrated.

→ 30 % sensitivity improvement

- Worse resolution for deep events than expected.
  - Reason is not understood yet.

→ 4% sensitivity degradation
(effect limited thanks to the small number of deep events)

<u>Position resolution vs γ conversion depth</u>

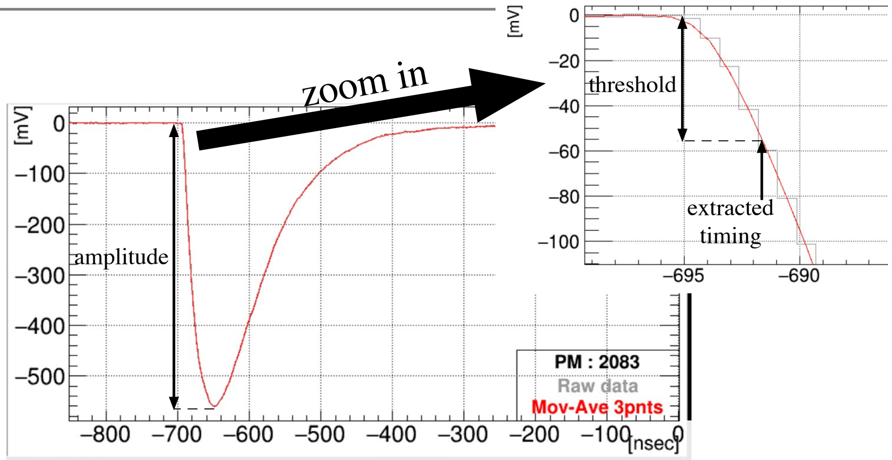


config	Sensitivity (relative to MEG II MC)
MEG	1.30(2)
MEG II MC	1
MEG II Data	1.04(1)

Timing resolution

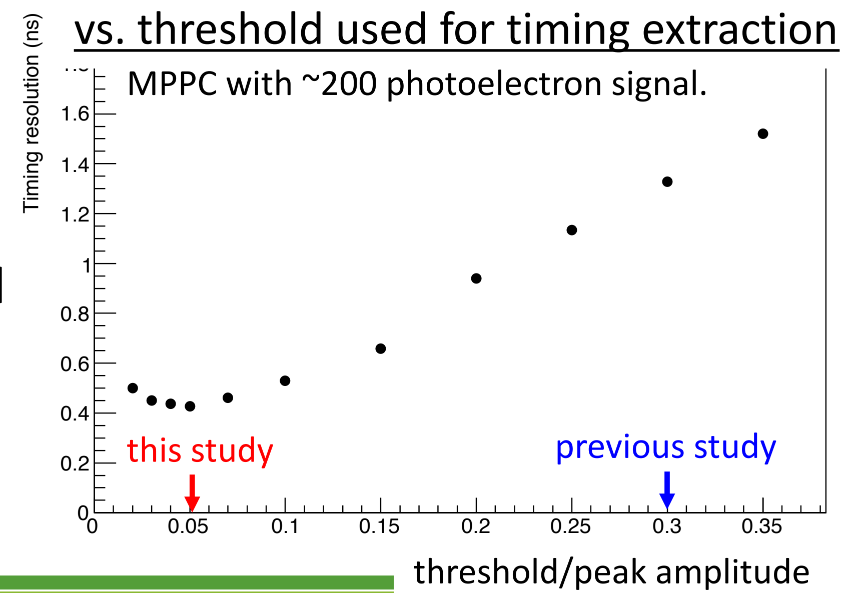
Timing resolution is improved thanks to a analysis parameter optimization.

- Timing of each channel is extracted from each photosensor waveform.
  - Crossing point of a given threshold.
- Timing of γ-ray is reconstructed from a weighted average of timing of each channel.



- Threshold used for the timing extraction is optimized in this study, to have as good resolution as possible.
  - Better timing resolution of each channel → Better γ-ray timing resolution.

Timing resolution of a MPPC waveform vs. threshold used for timing extraction



Timing resolution

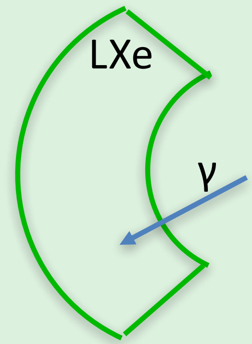
Timing resolution is estimated for BG γ-rays.

- Intrinsic timing resolution from an "even-odd" analysis is adopted.

Intrinsic resolution of 40 ps is achieved.

- It was 56 ps before parameter optimization.

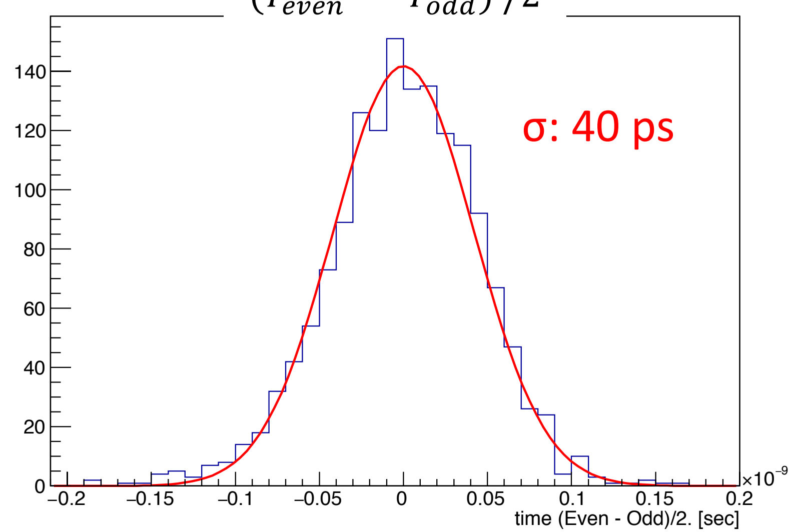
Even-odd resolution



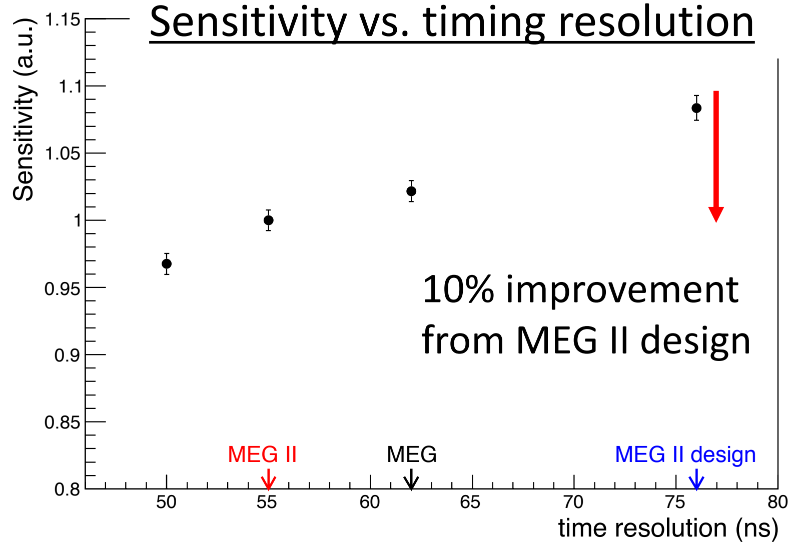
- Reconstruct Tγ from even/odd ch separately.
- $\sigma(T_\gamma) = \sigma(T_{EVEN} - T_{odd})/2$

Sensitivity improved by 10% from MEG II design.

$(T_{even} - T_{odd})/2$



Sensitivity vs. timing resolution



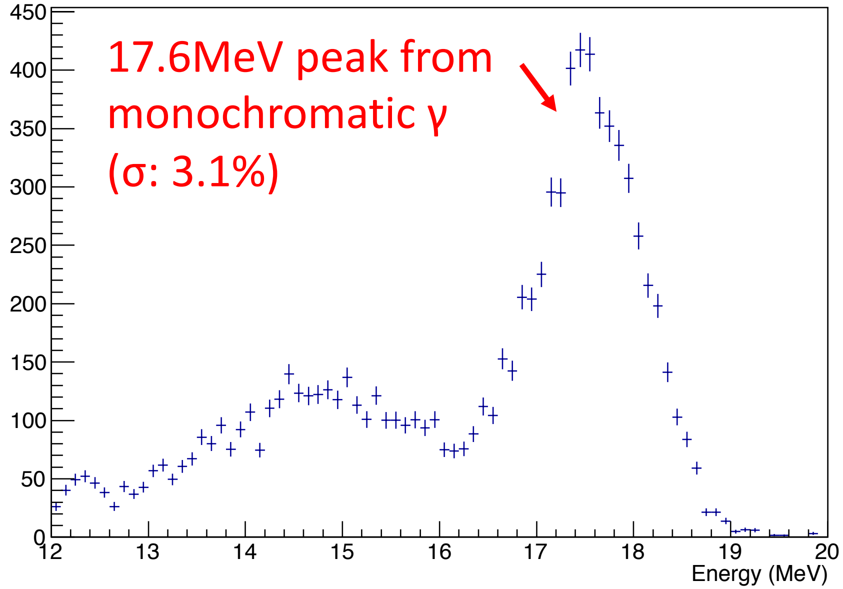
Energy resolution

γ-ray energy is reconstructed from the sum of the number of detected photons.

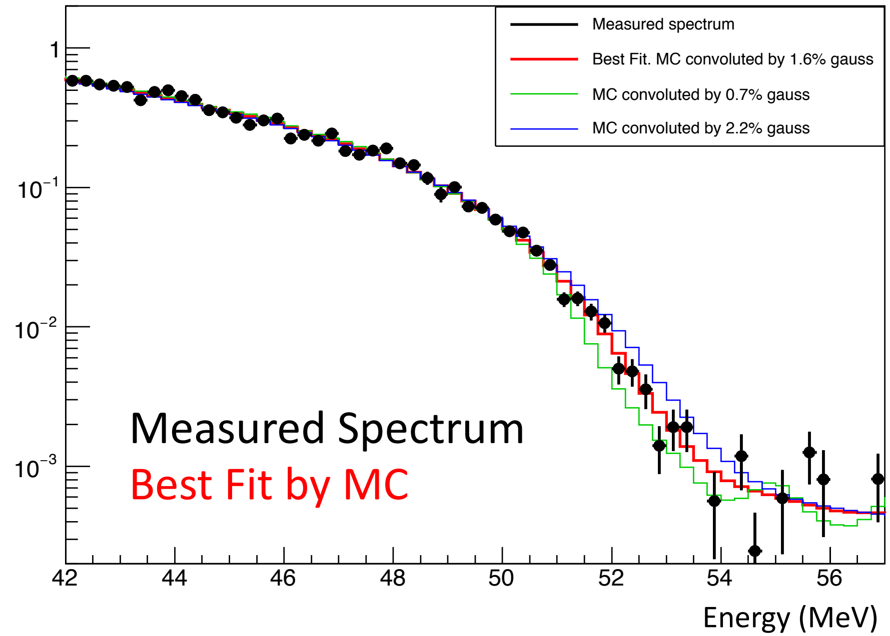
resolution estimated for 17.6 & 52.8 MeV γ-ray.

- 17.6 MeV : From monochromatic γ source (CW Li).
- 52.8 MeV : By fitting γ-ray spectrum from muon beam (mainly from RMD).

Energy spectrum of CW Li γ



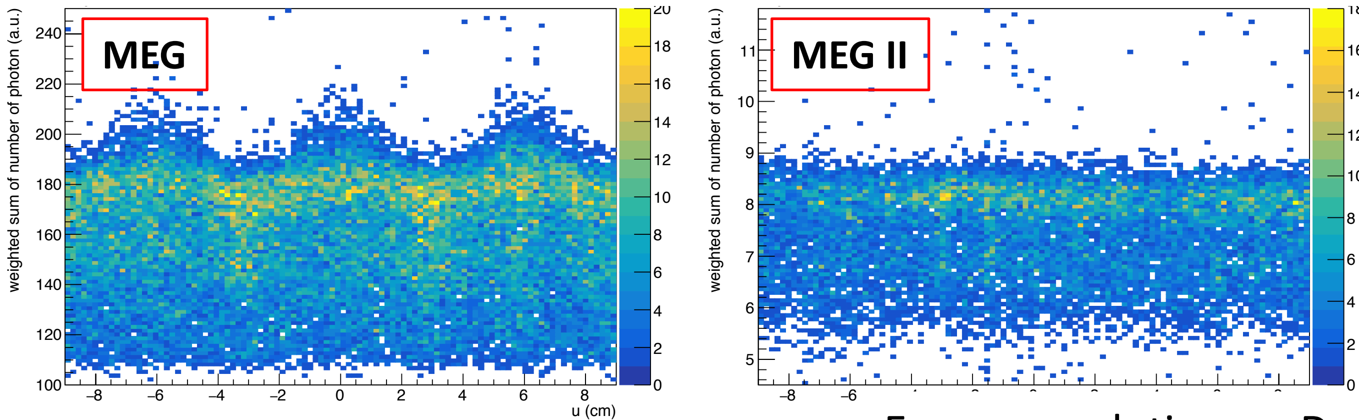
Energy spectrum of BG γ (mainly RMD)



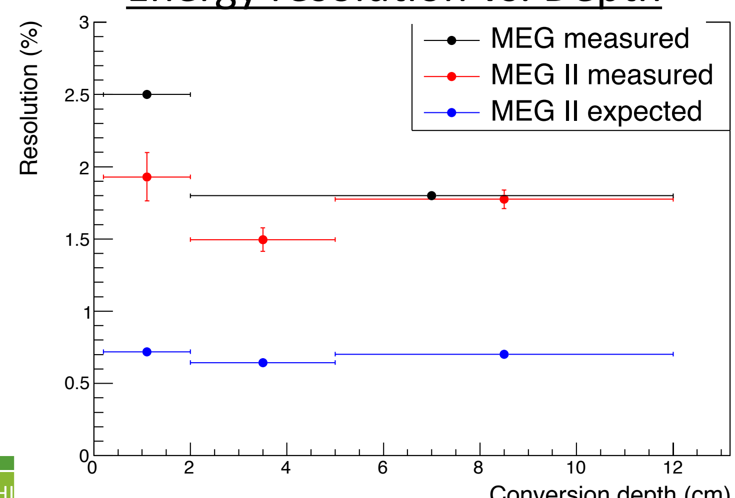
Energy resolution - for shallow events-

- Uniformity of the readout for the shallow events improved.
  - Thanks to the replacement to MPPC.

Detected number of photons vs. γ hit position (horizontal) (depth < 1.5cm)



Energy resolution vs. Depth



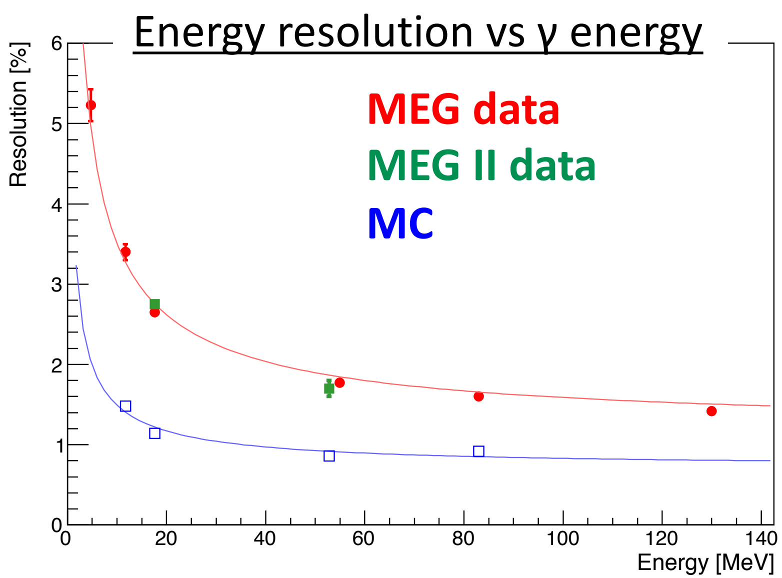
- Resolution for the shallow events improved from MEG.
  - Demonstrated for 52.8MeV γ-ray.

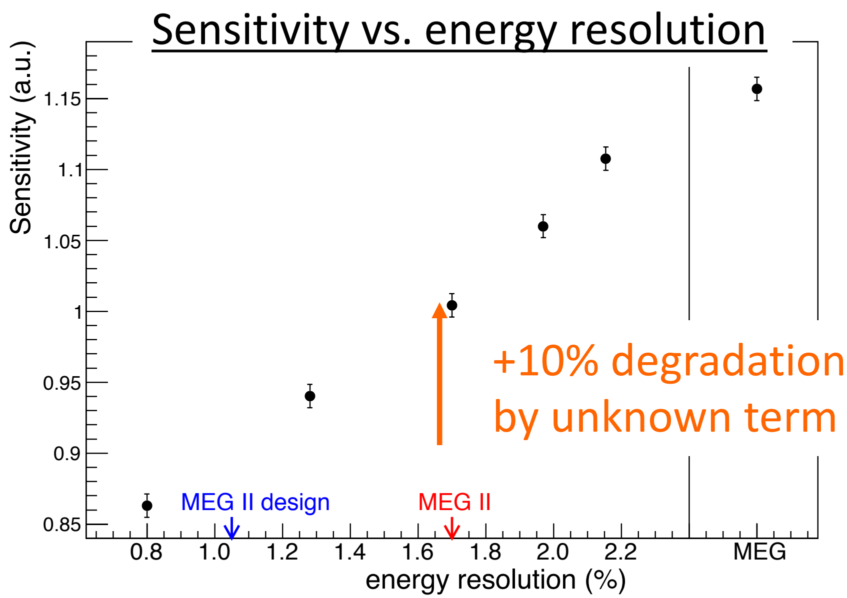
Energy resolution -unknown term-

Measured energy resolution is worse than MC. (1.6% degradation for 52.8MeV γ-ray.)

- It is not due to a noise or an instability of the energy scale.
- Similar degradation also observed in MEG.
- Should be caused by the same reason in MEG & MEG II, but the reason is not yet identified.
  - Common issue on our detector? Some intrinsic property of LXe?

Sensitivity will deteriorate by 10% due to the unknown term.





Energy resolution -unknown term-

- Is the unknown term due to the statistical fluctuation of number of photon?
  - The detected number of photon on each photosensor may fluctuate larger than the Poisson distribution (i.e. $1/\sqrt{\mathrm{Number\ of\ photoelecton}}$).

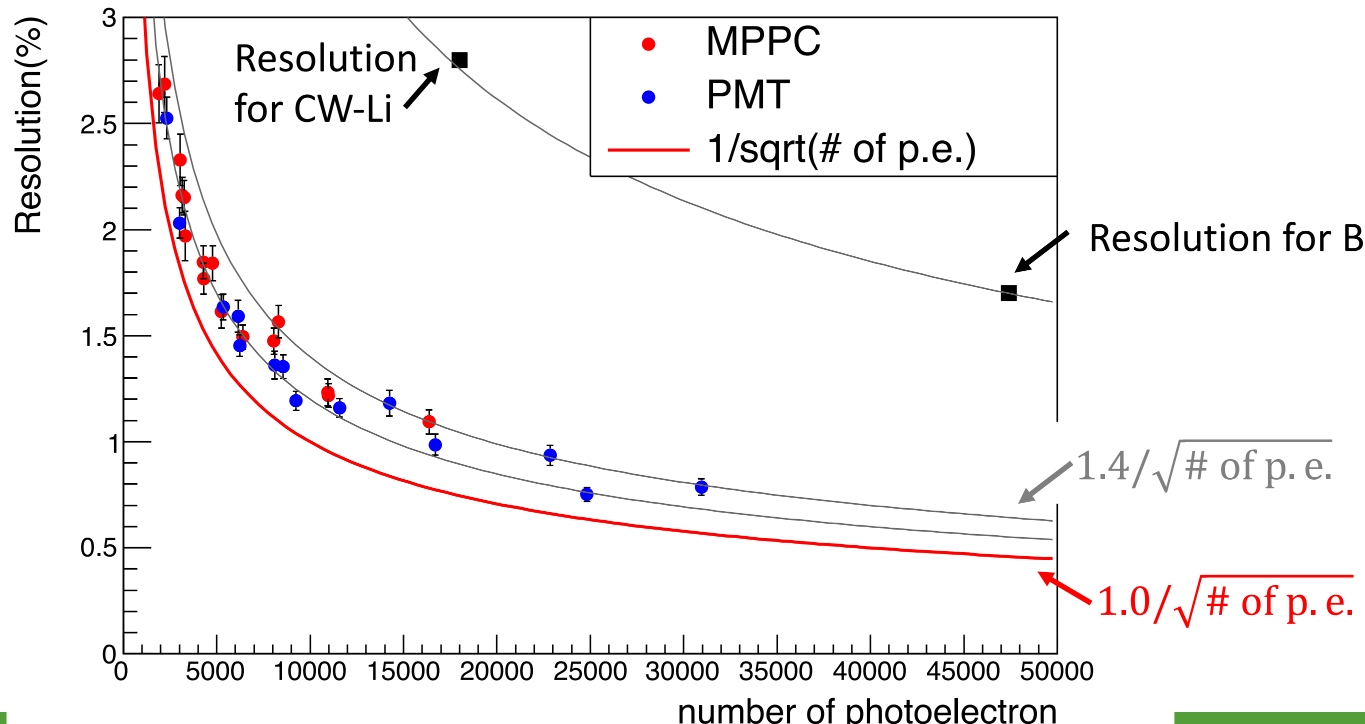
- For the investigation, “even-odd energy resolution” is investigated.
  - Event-by event fluctuation of
    $$E_\gamma\,(\mathrm{all\ ch.}) = E_\gamma\,(\mathrm{even\ ch.}) + E_\gamma\,(\mathrm{odd\ ch.})$$
    is measured to be larger than simulation.
  - By checking the fluctuation of
    $E_\gamma\,(\mathrm{even\ ch.}) - E_\gamma\,(\mathrm{odd\ ch.})$,
    we can know whether the unknown term is coherent on $E_\gamma\,(\mathrm{even\ ch.})$ and $E_\gamma\,(\mathrm{odd\ ch.})$ or not.
  - Statistical fluctuation will appear as independent fluctuation on $E_\gamma\,(\mathrm{even\ ch.})$ and $E_\gamma\,(\mathrm{odd\ ch.})$.

Energy resolution -unknown term-

- No large excess of the "even-odd resolution" is observed.
  - Estimated for MPPC and PMT.
  - Many combination of the partial sums are checked.

→ The unknown term is not due to a statistical fluctuation.

"Even-odd energy resolution" vs. number of photoelectron



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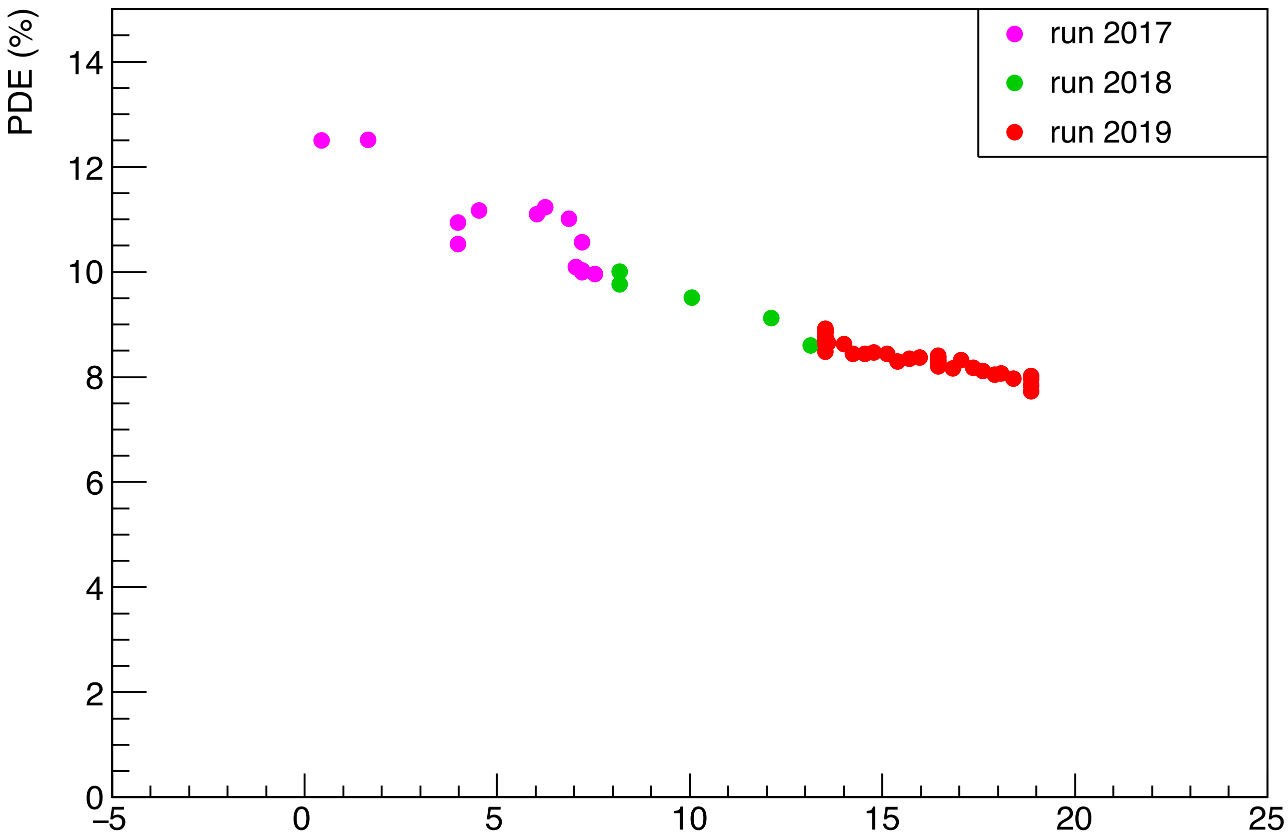
MPPC VUV PDE degradation (cont’d)

Degradation of PDE is also observed from the beginning of the beam time.

PDE vs. accumulated beam usage

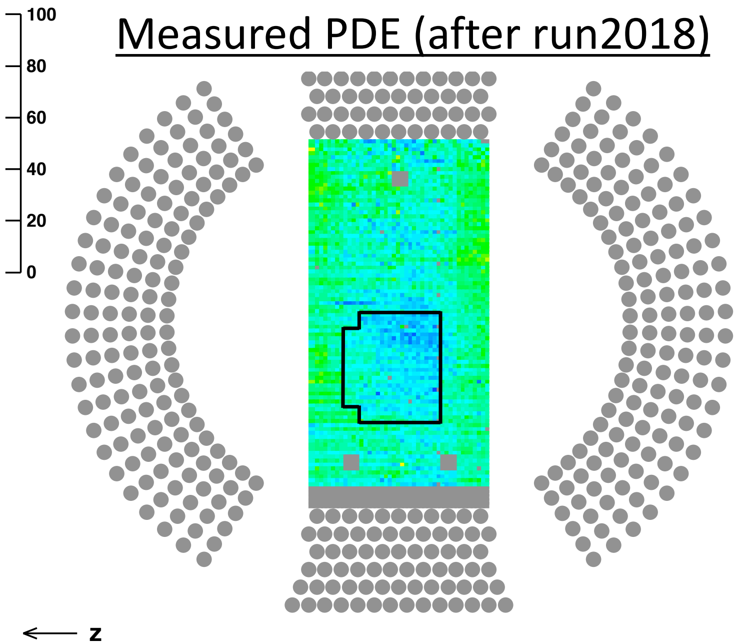


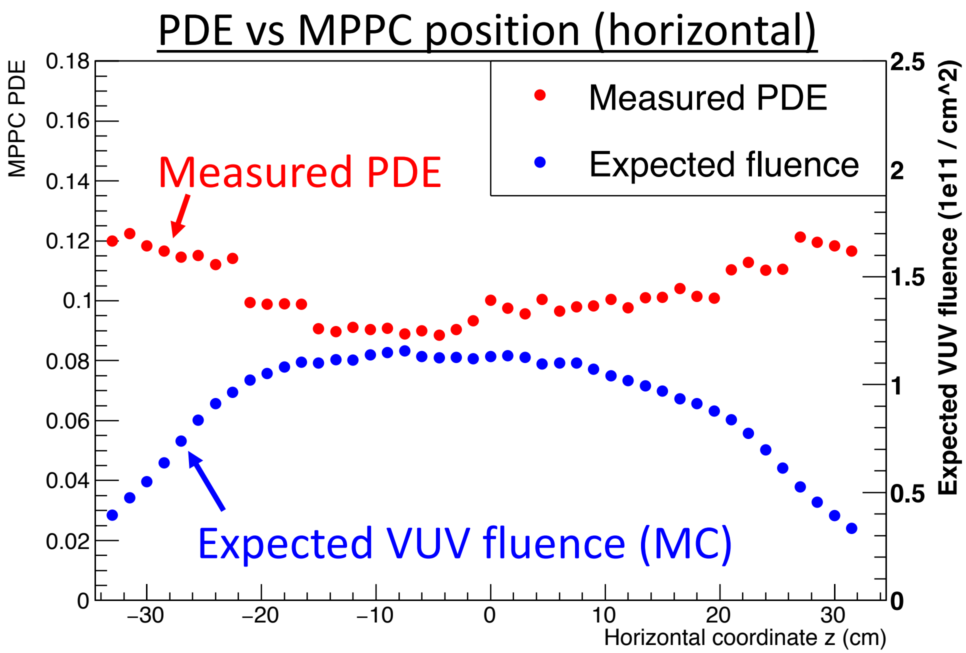
Beam usage [Day]
normalized to MEG II beam

MPPC VUV PDE degradation (cont'd)

Another (indirect) evidence of degradation
: PDE of the MPPCs located at the edge (horizontal direction) is lower.

- Material budget of the magnet and the LXe detector are suppressed only in the acceptance region.
→ Smaller radiation fluence at the edge. → Higher PDE of the MPPCs at the edge.

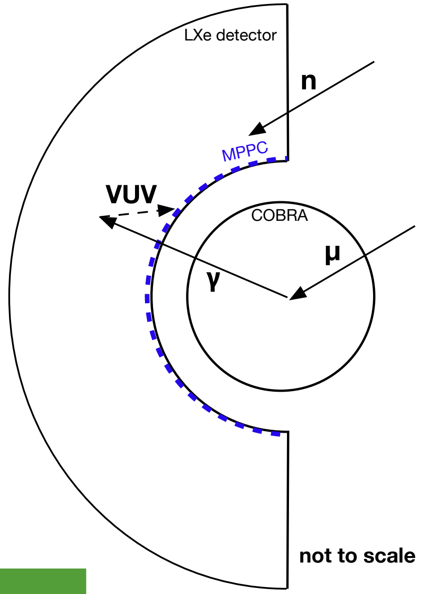




Cause of PDE degradation

This kind of radiation damage
was neither reported nor expected.

- The radiation level of our experiment should be sufficiently small.
- Degradation of PDE was not reported.



	dose/fluence (in 2019 run)	reported damage
γ-ray (IEL)	0.01 Gy	large dark noise rate @>10^2 Gy
neutron (NIEL)	3×10^6 n/cm^2 (MeV equiv.)	large dark noise rate @>10^8 n/cm^2
VUV photon	4.6-5.8 $\times 10^{10}$/mm^2	not reported

Effect of PDE degradation on sensitivity

The PDE degradation may affect the sensitivity of MEG II.

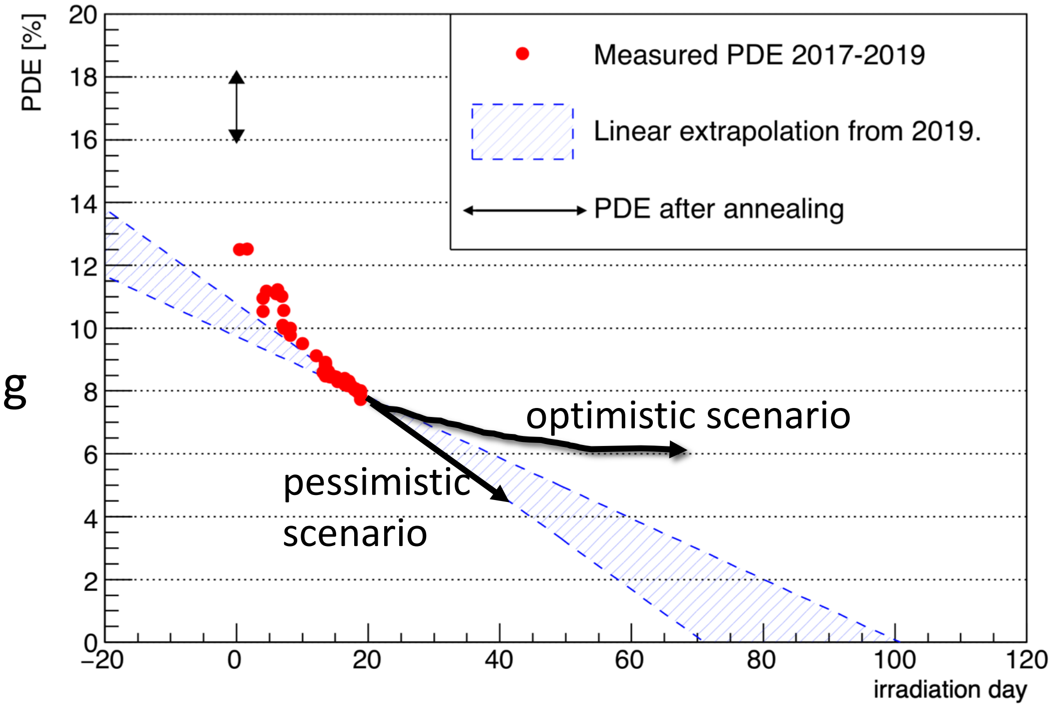
- The degradation speed is getting lower.
  → The degradation speed in the future is not clear.

Effect on the sensitivity.

1. Resolution may deteriorate at lower MPPC PDE.

2. MEG II data-taking plan has to be modified.
   (maximal continues data-taking time will be limited.)

MPPC PDE vs. accumulated beam usage



γ-ray resolution at lower PDE

The γ-ray resolutions may get worse than the measurement at PDE 7% if the MPPC PDE gets lower by the degradation.

1. <u>Larger statistical fluctuation</u>
   Should not be a large effect
   because statistical fluctuation of the MPPC signals is not a dominant term in the resolution.

2. <u>Worse signal to noise ratio</u>
   S/N ratio can be recovered by utilizing an amplifier
   because dominant noise comes from waveform digitizer after amplification.

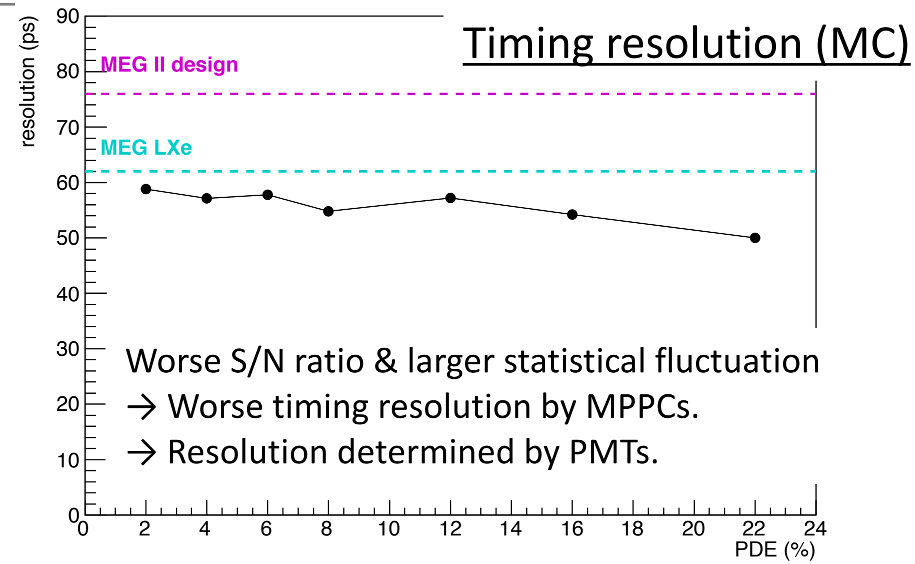
→ No crucial effect is expected on the resolution by the lower PDE.

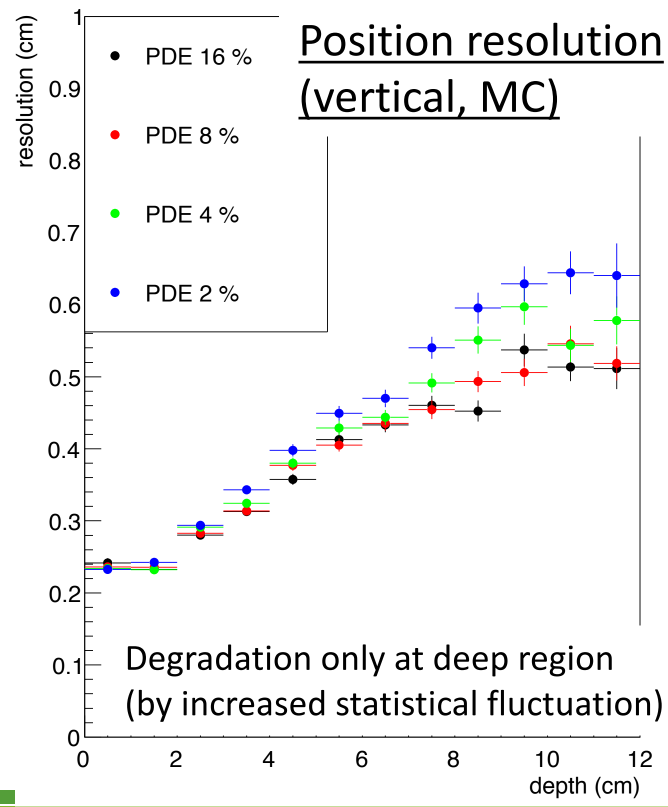
γ-ray resolution at lower PDE (cont'd)

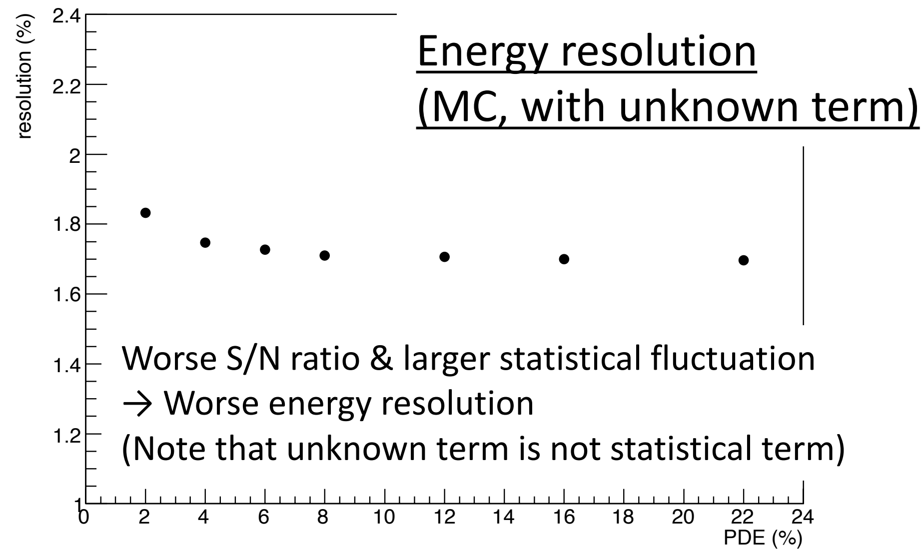
Detector resolution at lower MPPC PDE is estimated by the simulation.

→

No large resolution degradations are expected down to PDE of 2%.



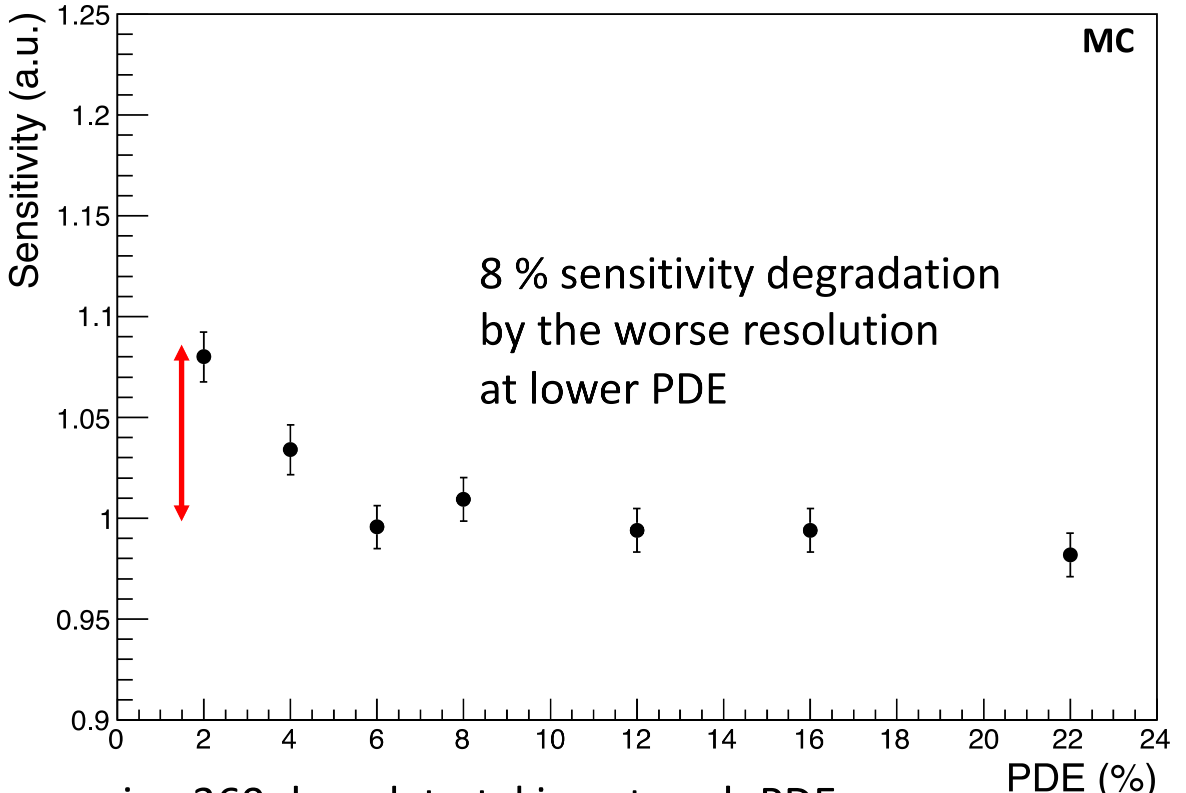




γ-ray resolution at lower PDE (cont'd)

The degradation of the MEG II sensitivity by the resolution degradation at lower MPPC PDE is limited.

MEG II sensitivity vs. MPPC PDE



※ assuming 360 days data-taking at each PDE

Modification on data-taking plan.

In the pessimistic scenario, PDE gets below 2% after 60 days MEG II beam usage.

- We can anneal all the MPPCs during the annual accelerator shutdown period (Jan-May).
- Original MEG II DAQ plan (120 days/year x 3 years) has to be modified.

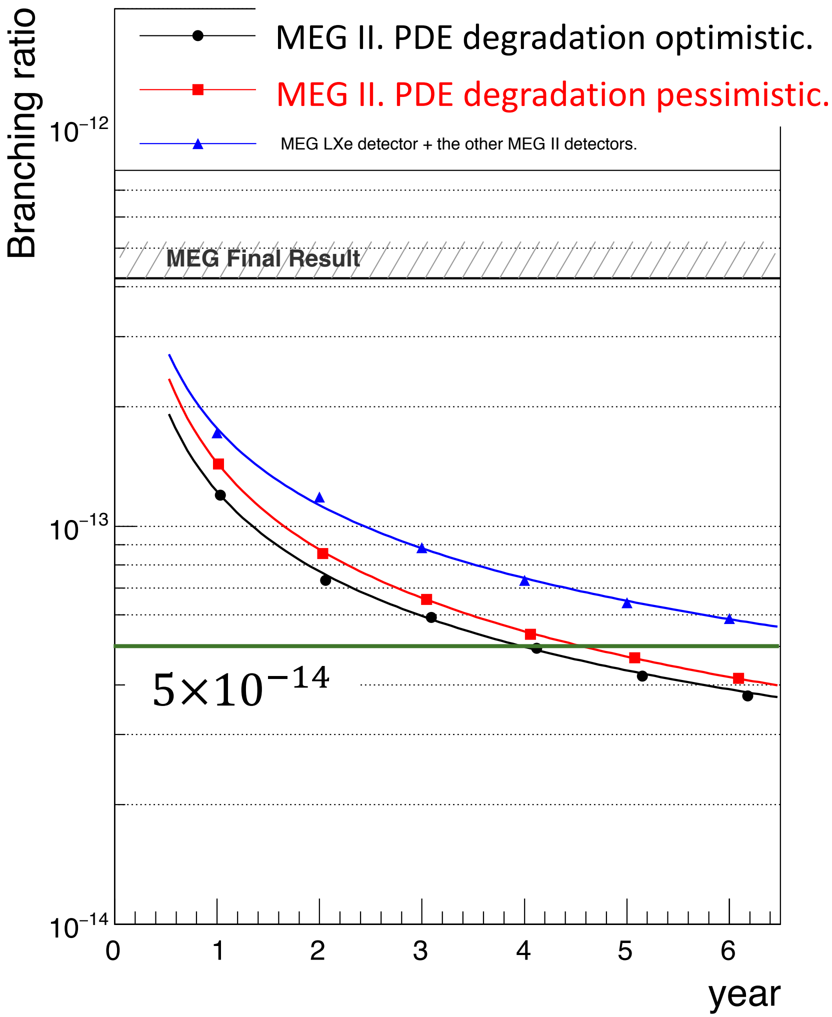
- If we simply carry out 60 days DAQ at MEG II beam intensity for each year,
  - $Br(\mu \to e\gamma) = 9.4 \times 10^{-14}$ (90% C.L., by 3 years DAQ)

- A reduction of the beam rate (not beam time) is proposed in this study to suppress the degradation as much as possible.
  - The number of accidental backgrounds can be reduced (∝(Beam Rate)^2).
  - This will also improve pileup environment.
  - $Br(\mu \to e\gamma) = 6.6 \times 10^{-14}$ (90% C.L., by 3 years DAQ)

Expected sensitivity

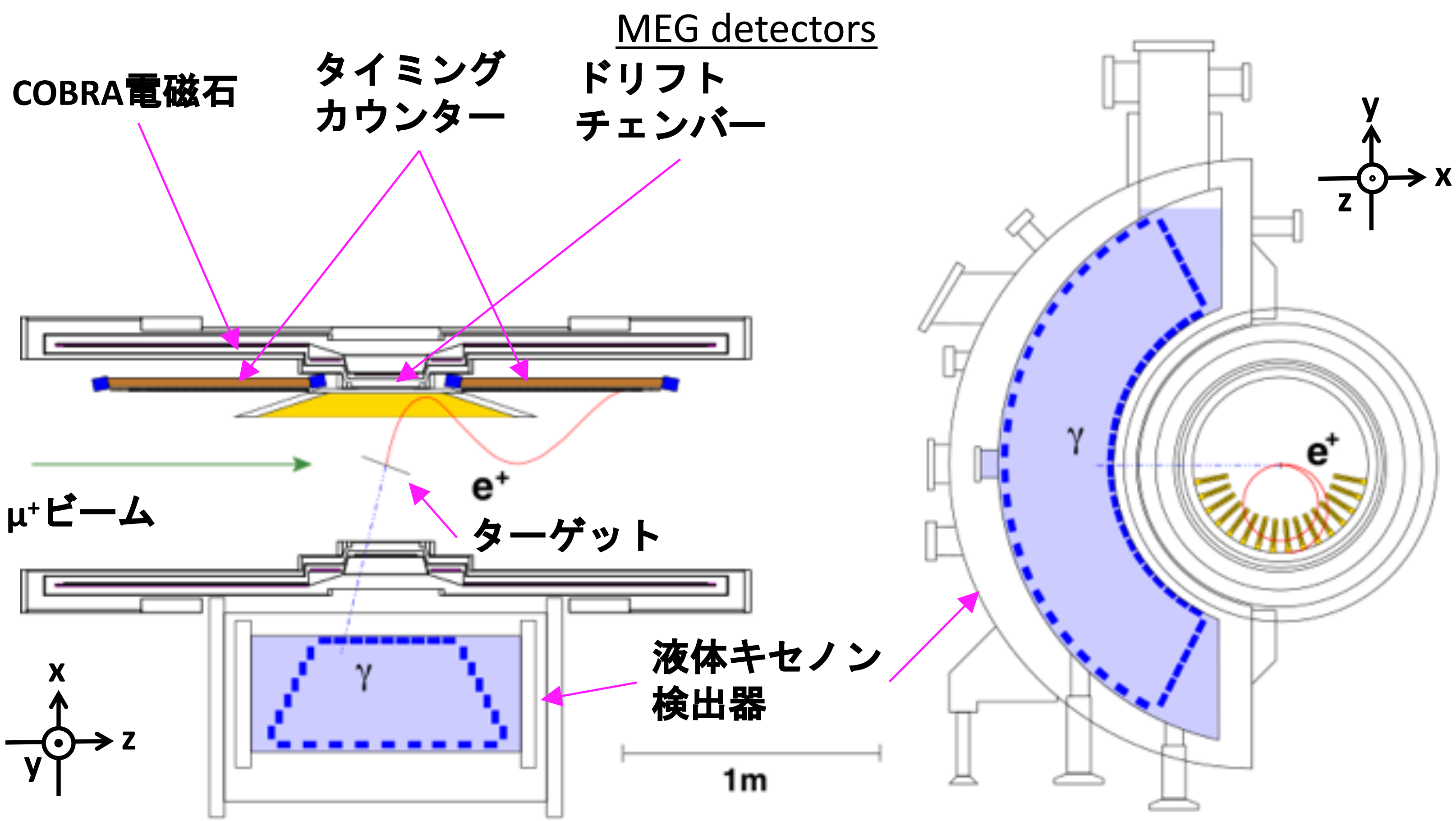
- Sensitivity of MEG II experiment is estimated based on the measured detector resolutions.
  - Including all the measured resolutions discussed above.
- Calculated for the pessimistic scenario and the optimistic scenario on the PDE degradation speed in the future.
- The sensitivity of 5×10^{-14} can be achieved by a reasonable amount of the beam time (4.0-4.6 years).

MEG II sensitivity vs. DAQ time

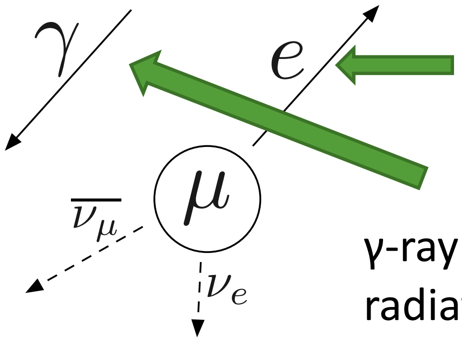


MEG Detectors

aa

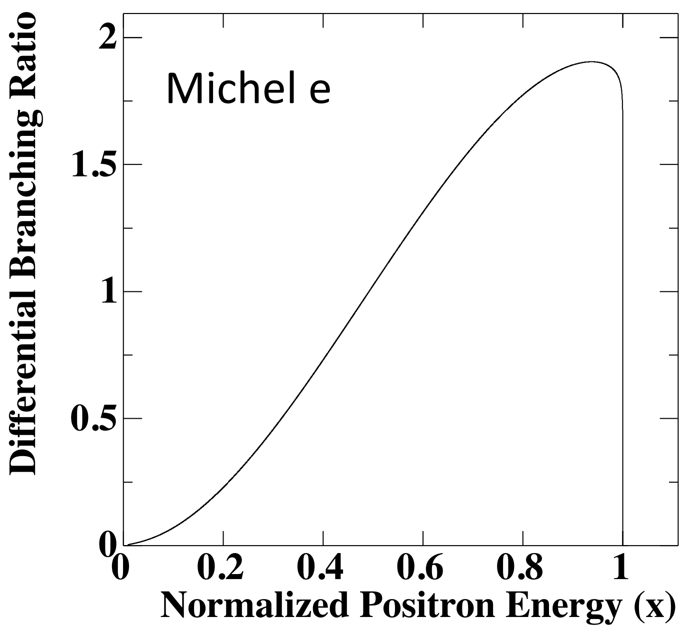


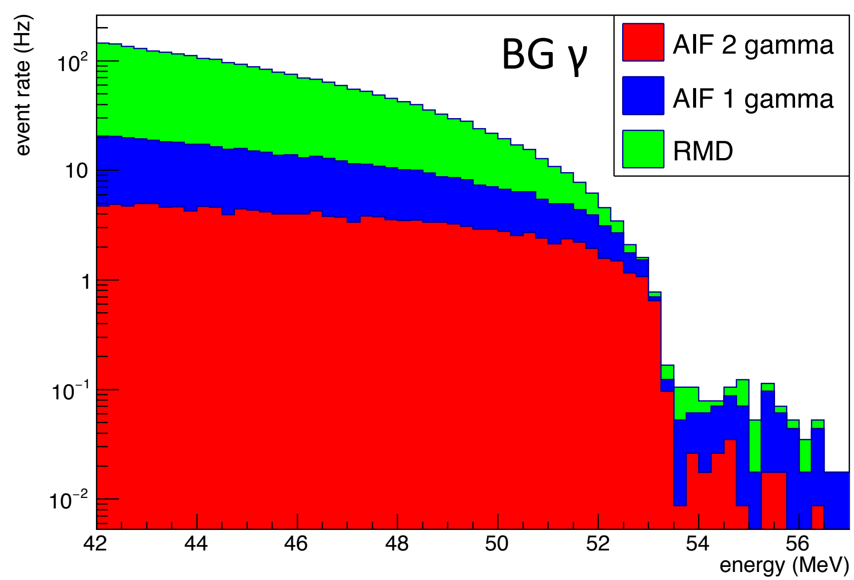
Source of Acc. BG



positron from Michel decay ($\mu \rightarrow e\nu\bar{\nu}$)

γ-ray from
radiative muon decay (RMD, $\mu \rightarrow e\nu\bar{\nu}\gamma$),
and annihilation of Michel positron in flight





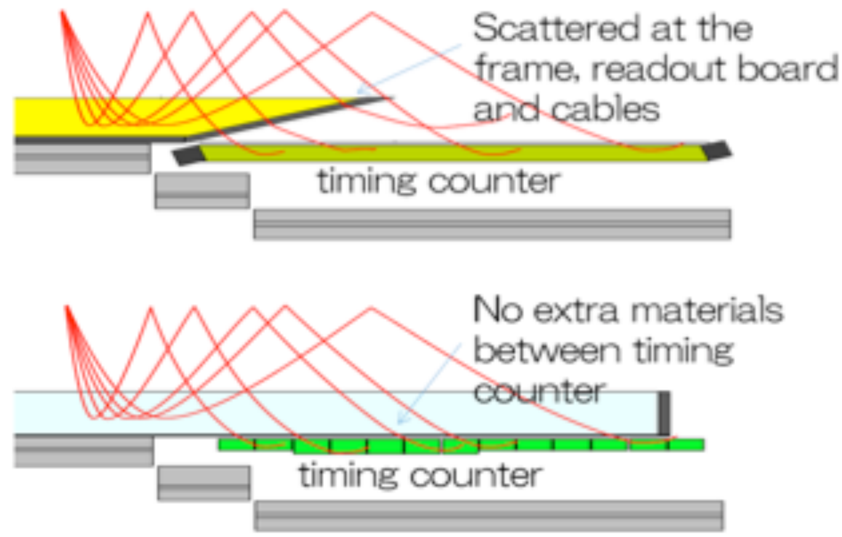
Single event sensitivity

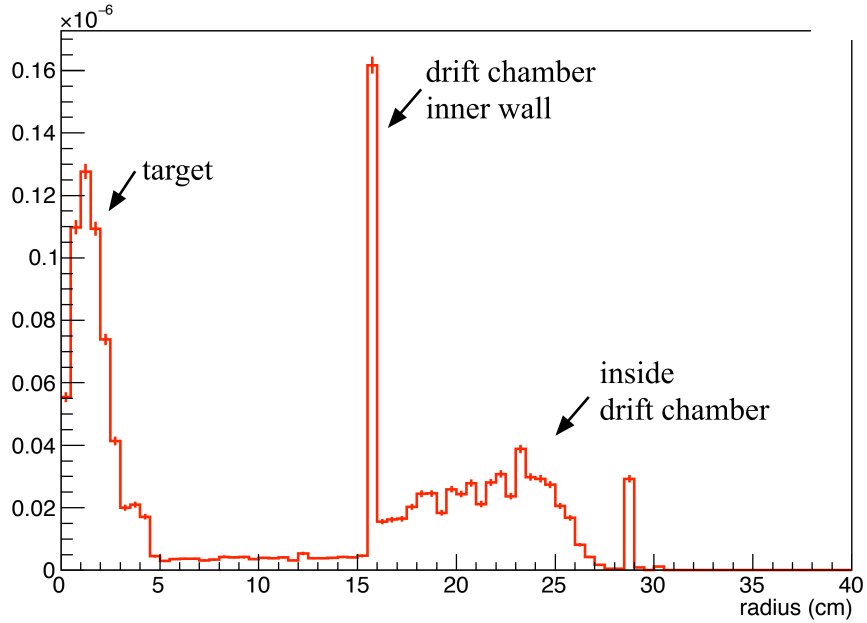
Single event sensitivity = 1/k
k = number of muon decay

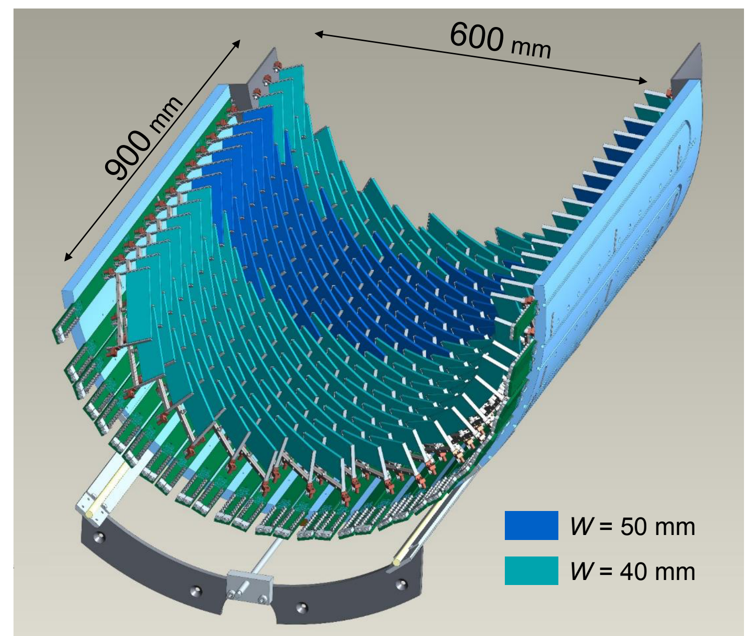
	DAQ	single event sensitivity (x10^{-14})	sensitivity (x10^{-14})
MEG	3e7 x 4.5 year	5.8	53
MEG II design	7e7 x 3 year	0.97	5
MEG II plan A	7e7 x 3 year (x0.5)	1.9	9.3
MEG II plan B	3.5e7 x 3 year	1.9	6.6

Positron detectors

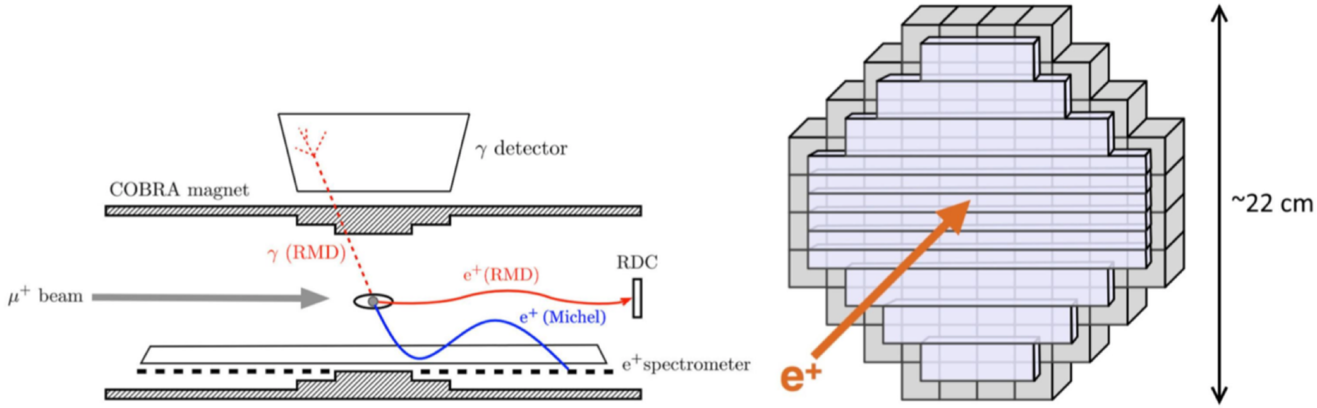
a





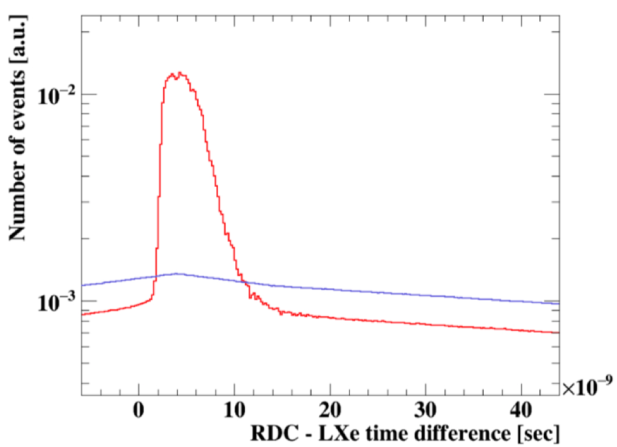


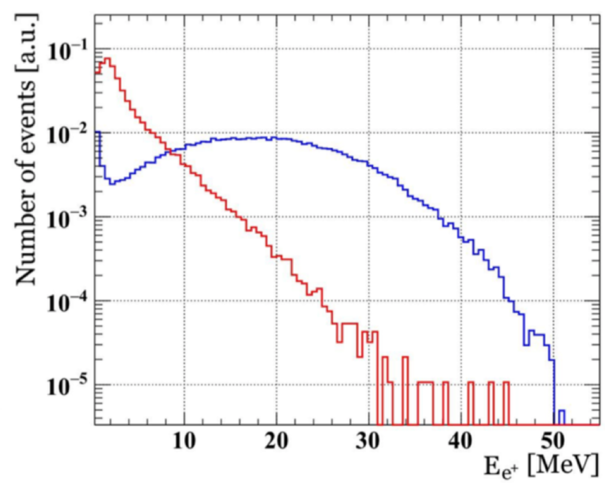
RDC



(a) (b)

Figure 1.28 (a) Concept of the RDC [7]. (b) Design of the RDC. It consists of a timing counter (plastic scintillators) and a calorimeter (LYSO crystals) [7].





LXe as scintillator

Table 1.2 Properties of the LXe

Item	Value
Atomic Number	54
Density	$2.953\,\mathrm{g/cm^3}$ [13]
Radiation length	$2.872\,\mathrm{cm}$ [13]
Moliere radius	$5.224\,\mathrm{cm}$
Scintillation Wavelength (mean)	$174.8 \pm 0.1(\mathrm{stat.}) \pm 0.1(\mathrm{syst.})\,\mathrm{nm}$ [14]
Scintillation Wavelength (FWHM)	$10.2 \pm 0.2(\mathrm{stat.}) \pm 0.2(\mathrm{syst.})\,\mathrm{nm}$ [14]
Decay time (fast)	$4.2\,\mathrm{ns}$ [15]
Decay time (slow)	$22\,\mathrm{ns}$ [15]
Decay time (recombination)	$45\,\mathrm{ns}$ [15]
W-value for electron	$21.6\,\mathrm{eV}$ [16]
W-value for alpha	$17.9\,\mathrm{eV}$ [16], $19.6\,\mathrm{eV}$ [17]
Refractive index (for $\lambda = 175\,\mathrm{nm}$)	1.65

LXe as scintillator

excitation

$$\mathrm{Xe}^* + \mathrm{Xe} + \mathrm{Xe} \to \mathrm{Xe}_2^* + \mathrm{Xe}$$

$$\mathrm{Xe}_2^* \to 2\mathrm{Xe} + h\nu$$

ionization

$$\mathrm{Xe}^+ + \mathrm{Xe} \to \mathrm{Xe}_2^+$$

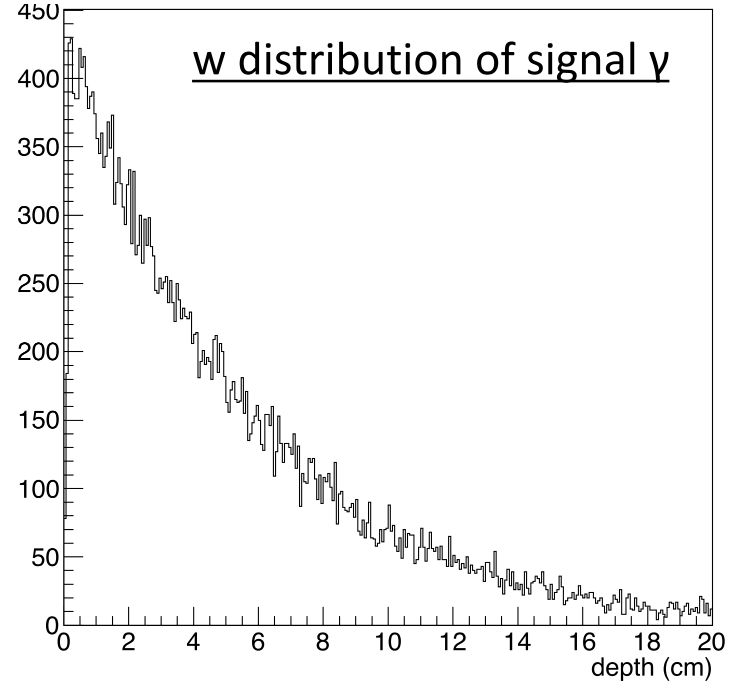
$$\mathrm{Xe}_2^+ + e^- \to \mathrm{Xe}^{**} + \mathrm{Xe}$$

$$\mathrm{Xe}^{**} \to \mathrm{Xe}^* + \mathrm{heat}$$

$$\mathrm{Xe}^* + \mathrm{Xe} + \mathrm{Xe} \to \mathrm{Xe}_2^* + \mathrm{Xe}$$

$$\mathrm{Xe}_2^* \to 2\mathrm{Xe} + h\nu$$

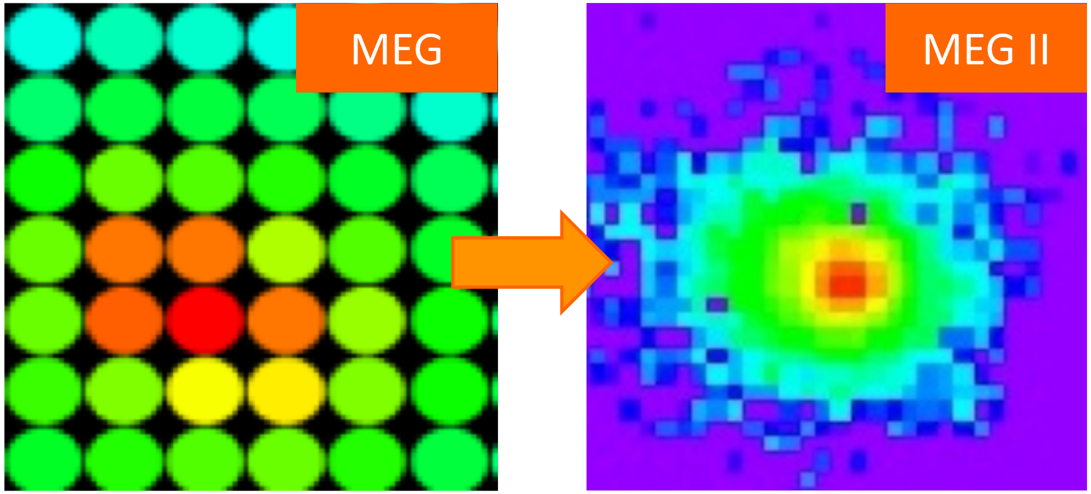
LXe γ-ray detector in MEG II

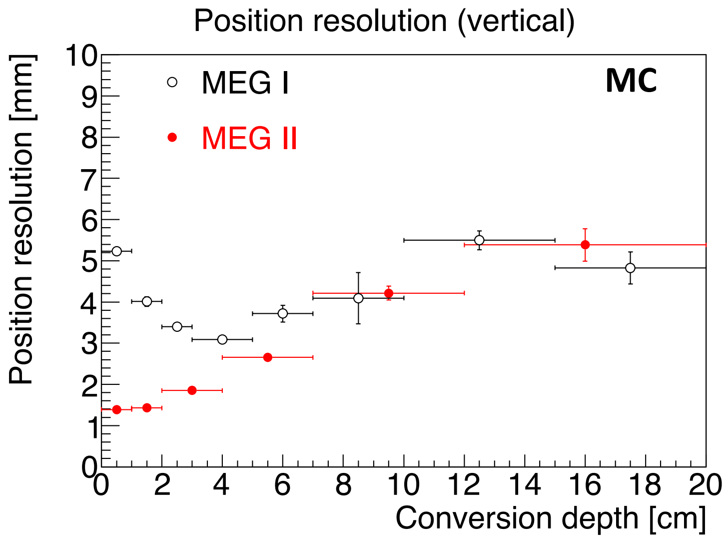


1. Better position resolution

Higher granularity of the readout
→ Better position resolution
for shallow event.

(roughly half of signal γ-ray hits
"depth < 4cm")

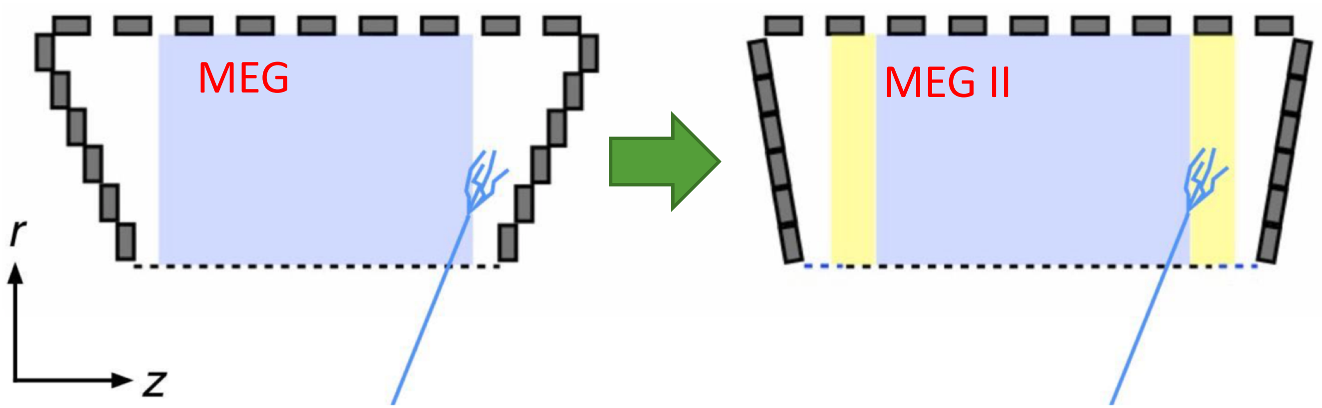




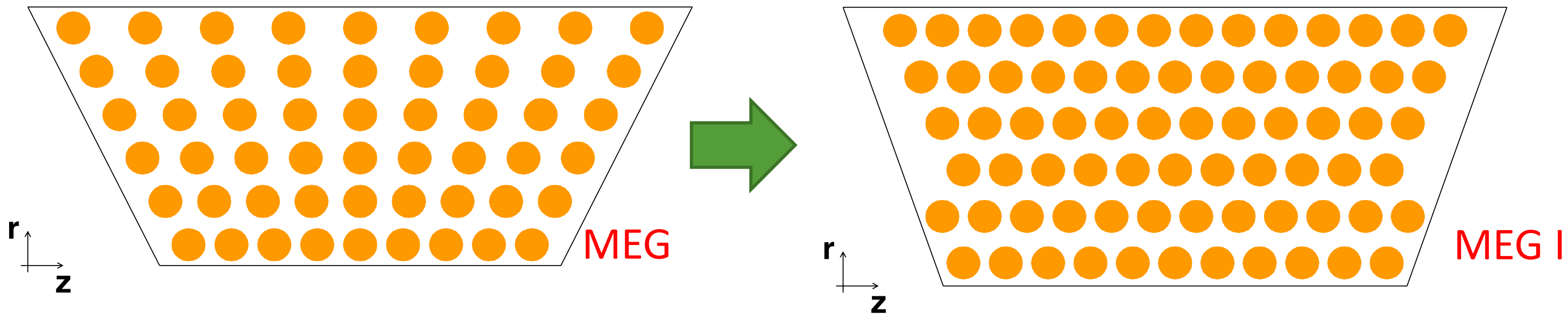
PMT layout

Layout of the PMTs are also improved.

1. LXe fiducial volume extended by 10% to reduce energy leakage
2. PMT surface are on the holder surface to improve uniformity



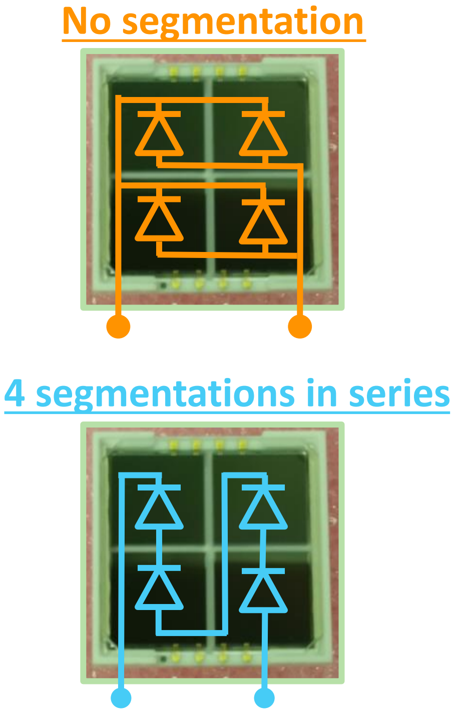
3. More PMTs on the top/bottom face to improve uniformity.

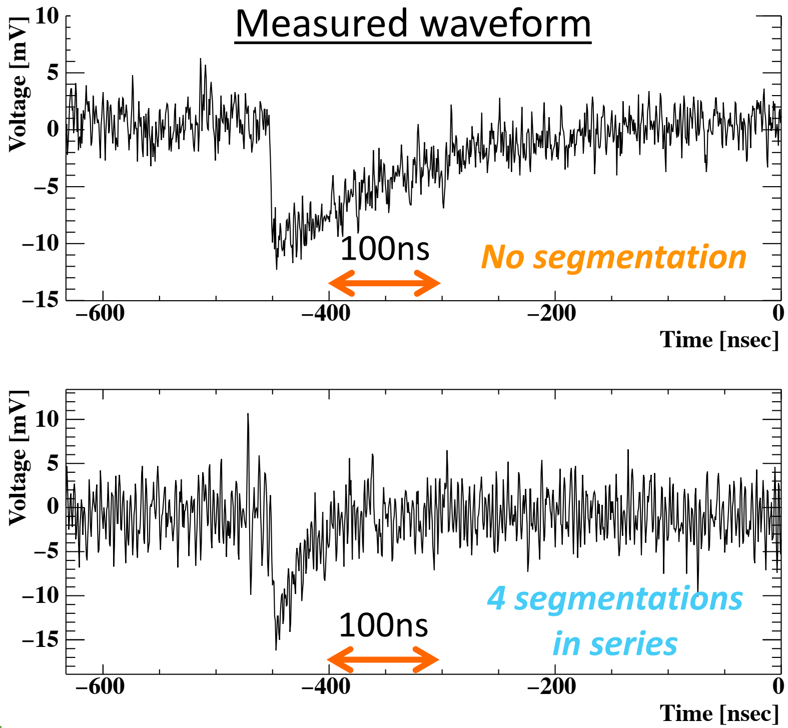


Series readout of MPPC

Large readout are can lead to
- Larger dark noise rate (not problematic when used at LXe temperature).
- Longer time constant by larger sensor capacitance.

Sensor capacitance are reduced by a series connection.
Sufficiently short timing constant has been achieved.



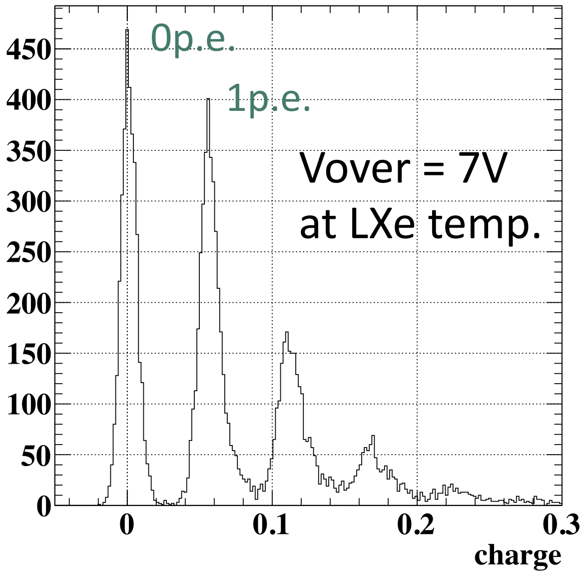


MPPC performance

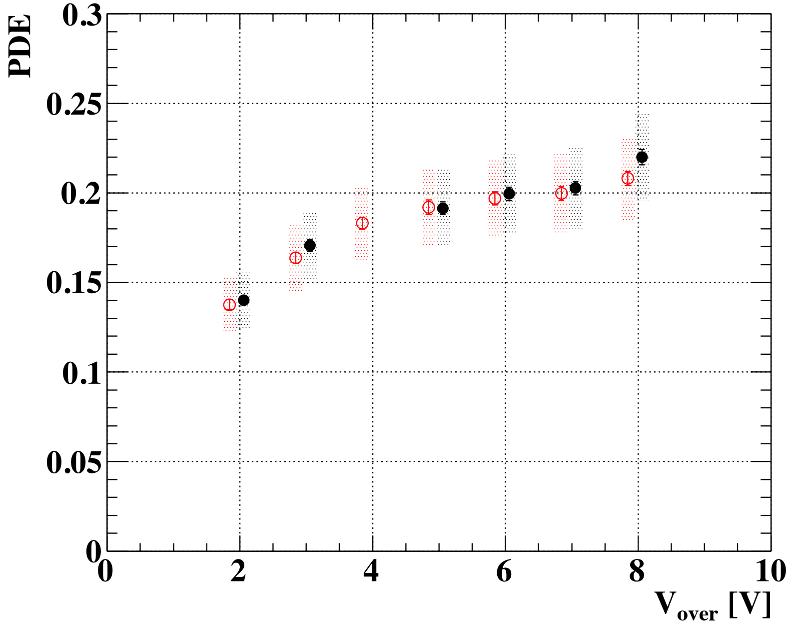
We have tested MPPC in LXe, and **an excellent performance has been confirmed.**

- **Single p.e. peak is clearly resolved** for large sensitive area.
- Gain: 8.0×10^5 (@ Vover=7V, series connection)
- Low crosstalk & after pulse probability (~15% each@ Vover = 7V)
- Sufficient photon detection efficiency (>15%) for xenon scintillation light.

Charge distribution using LED

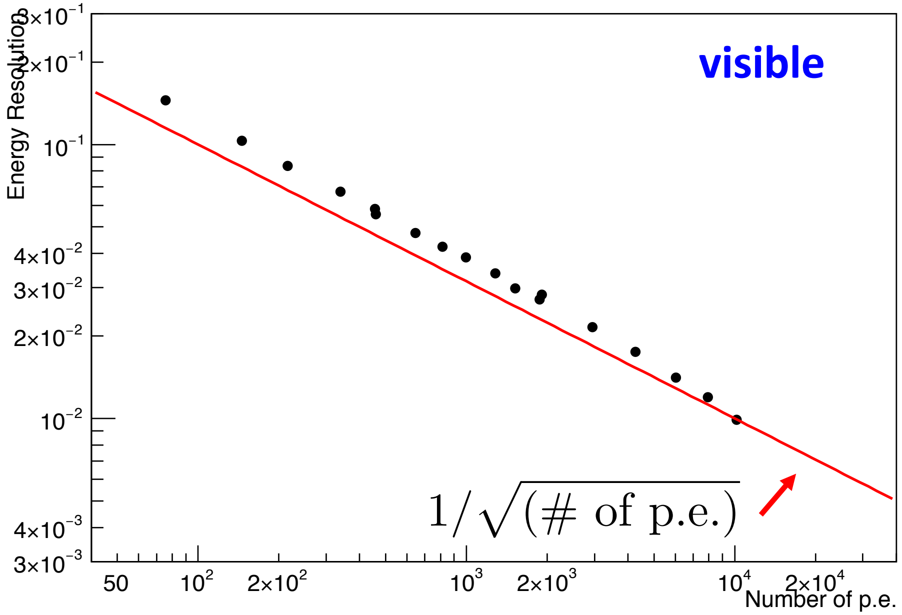


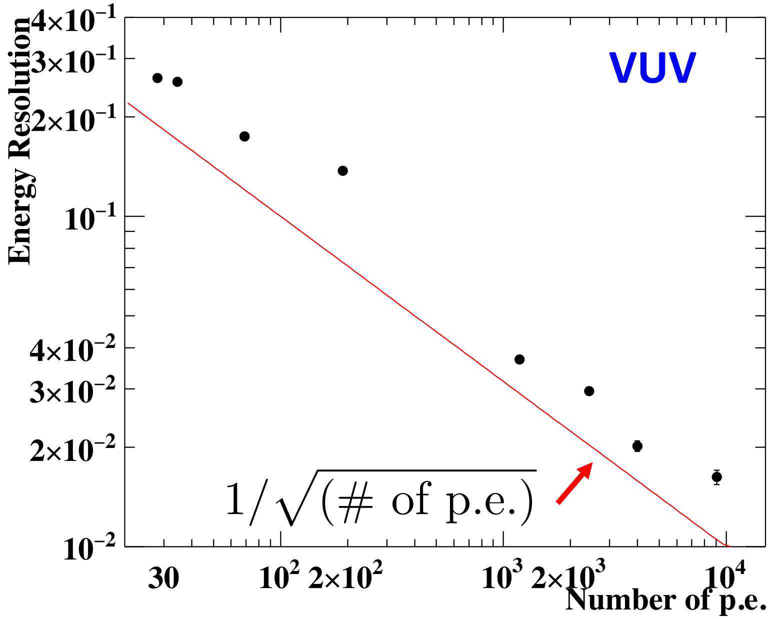
PDE vs. Over voltage



Energy resolution

- Energy resolution for VUV light has been measured as a function of # of p.e
  - using a scintillation light from α source.
  - by changing geometrical acceptance with several setups.
- Energy resolution improves as $1/\sqrt{(\# \text{ of p.e.})}$
  - at least down to ~10^4 p.e.
  - excess noise factor: 1.2 - 1.3

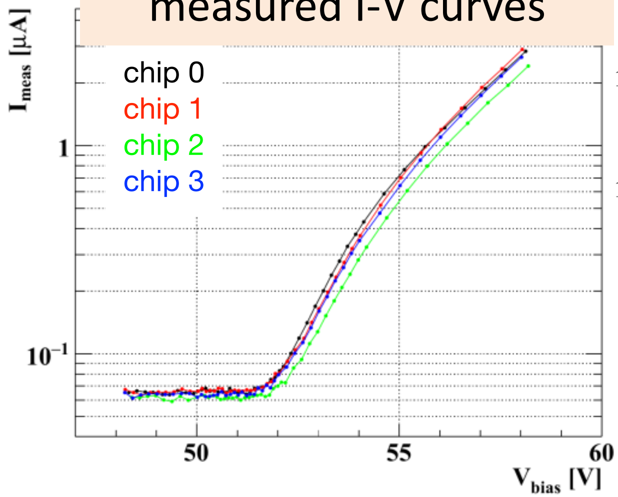




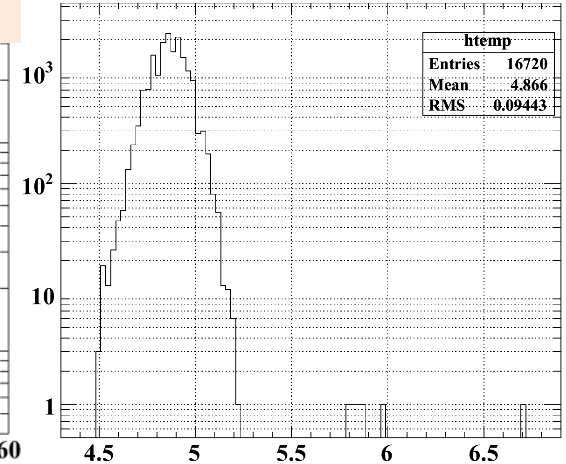
Result of the mass test

We confirmed the normal I-V curves and breakdown voltages for most of the channels.

Example of measured I-V curves



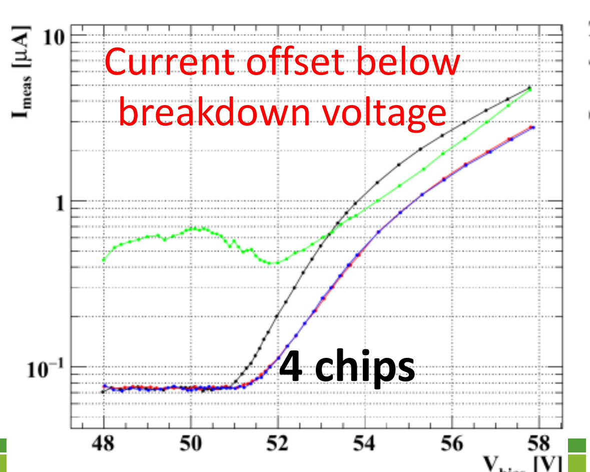
Breakdown voltage

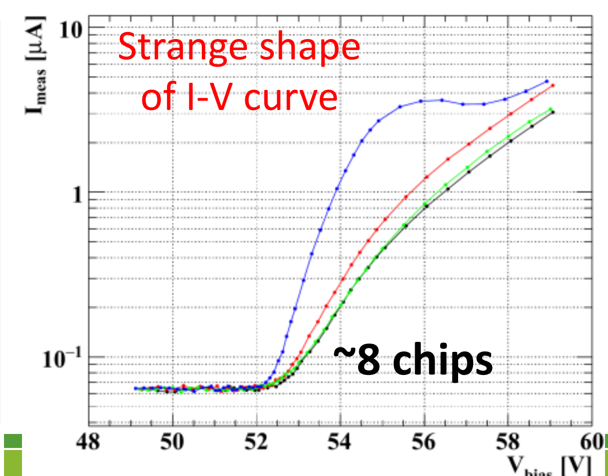


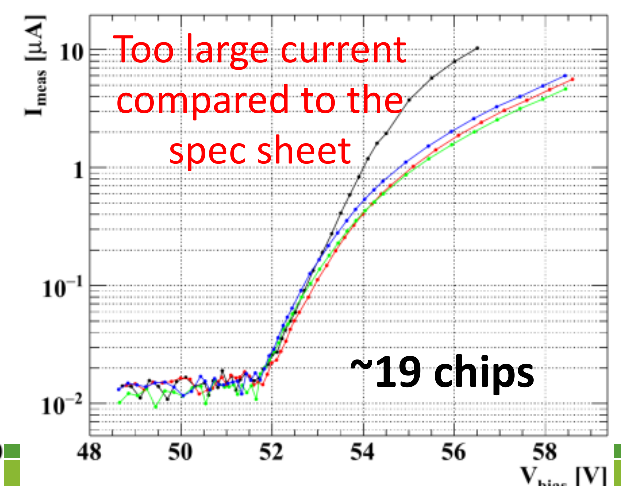
V(breakdown) - V(recommended by HPK)

We found 31 bad chips (0.2% of all MPPC chips).

- There are three kinds of bad chips.
- Bad chips will not be used in the final detector.



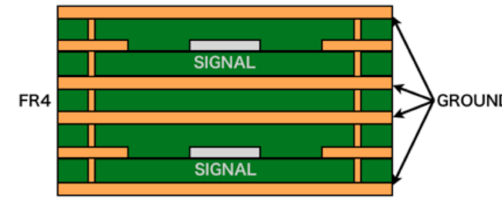




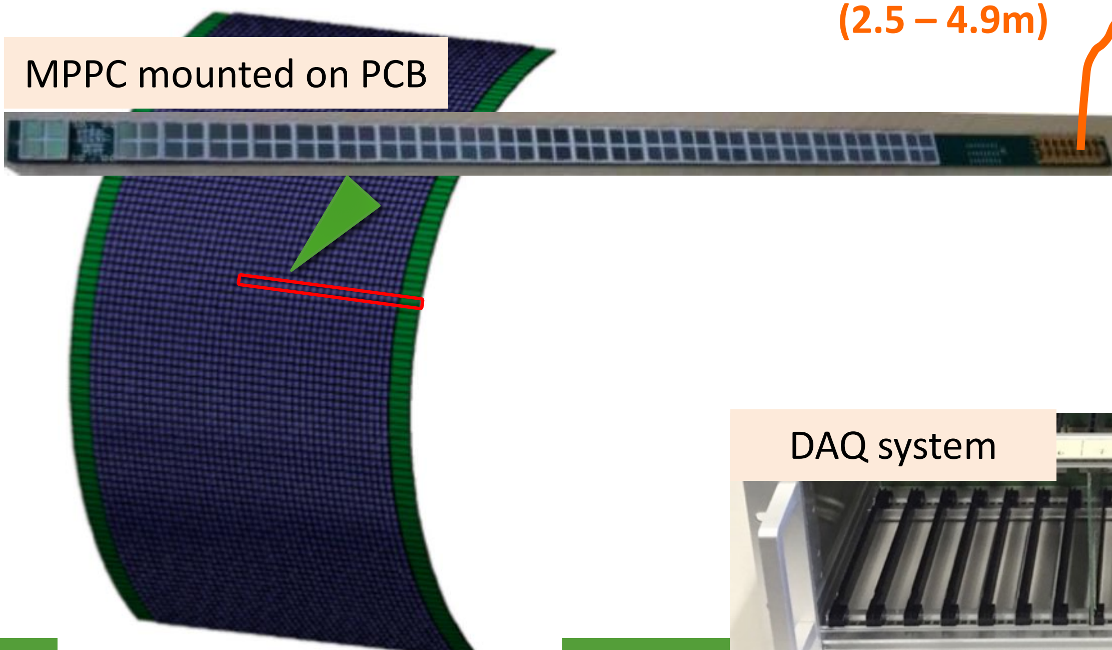
Signal transmission system

- We have developed signal transmission system.
  - It can transmit ~5000 ch signals.
  - Long cable (~12m) before signal amplification.
  - PCB has coaxial-like structure for impedance matching (50Ω), good shielding from external noise, high bandwidth, and low crosstalk.
  - Feedthrough is based on PCB to realize high density transmission.
- This system has been tested in LXe for 600 ch, and confirmed to work properly.

"Coaxial-like structure" PCB

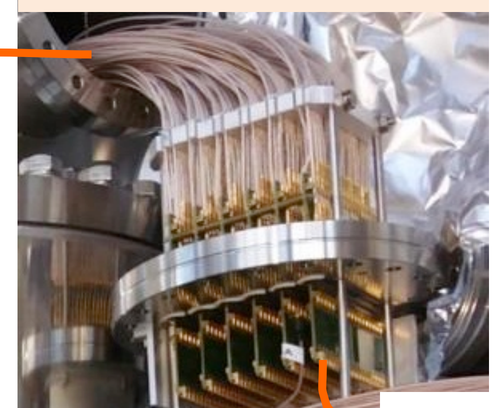


MPPC mounted on PCB



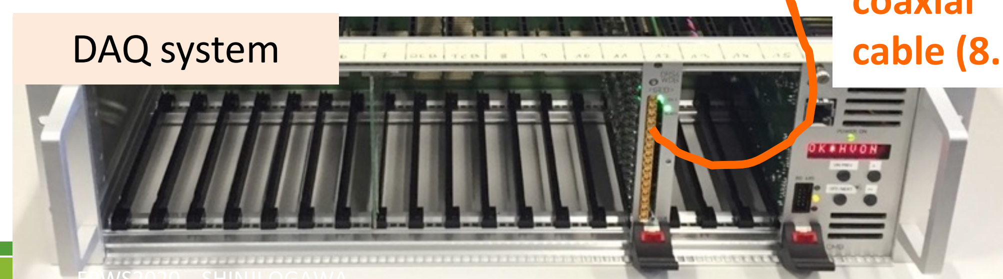
coaxial cable
(2.5 – 4.9m)

PCB-based feedthrough



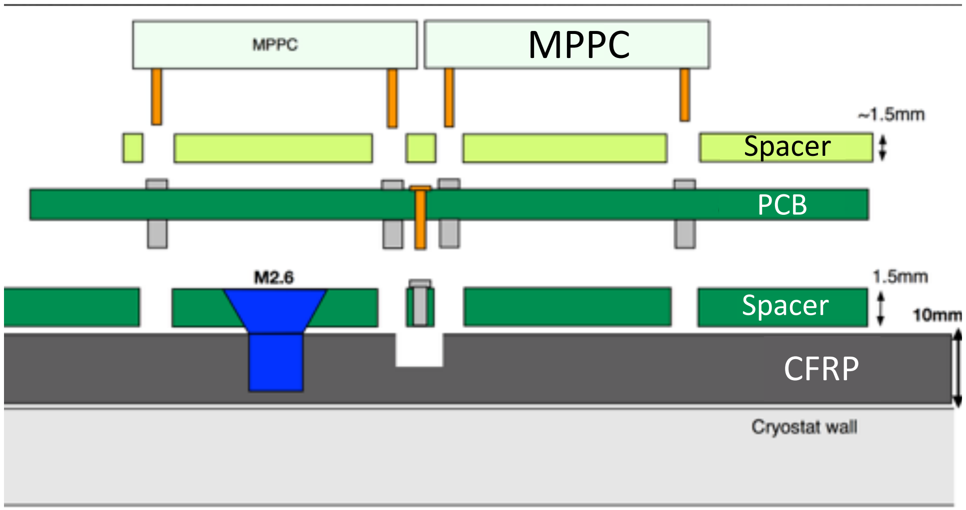
coaxial
cable (8.5m)

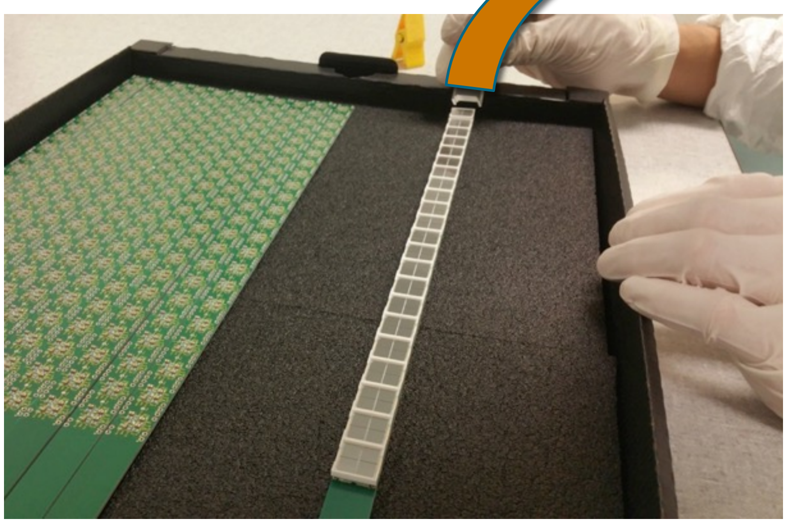
DAQ system

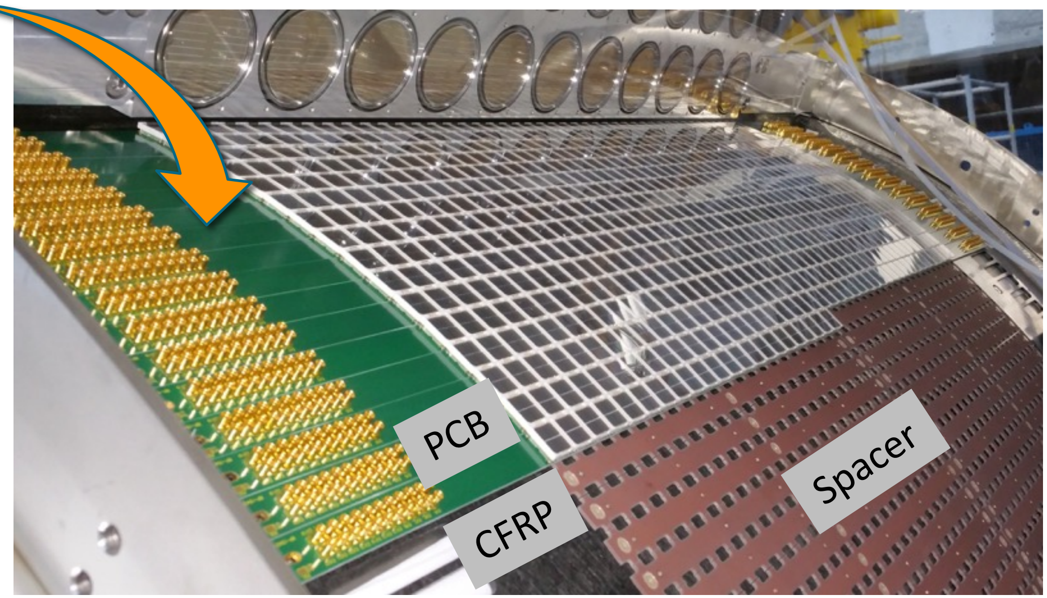


MPPC installation to the cryostat

- MPPCs are mounted on PCBs.
  - for signal readout and alignment.
  - PCBs are fixed on CFRP support structure which is attached on cryostat.
- These support are designed to minimize the material.
  - Thin support structure with low mass material
  - Spacers to reduce LXe.







MPPC installation to the cryostat

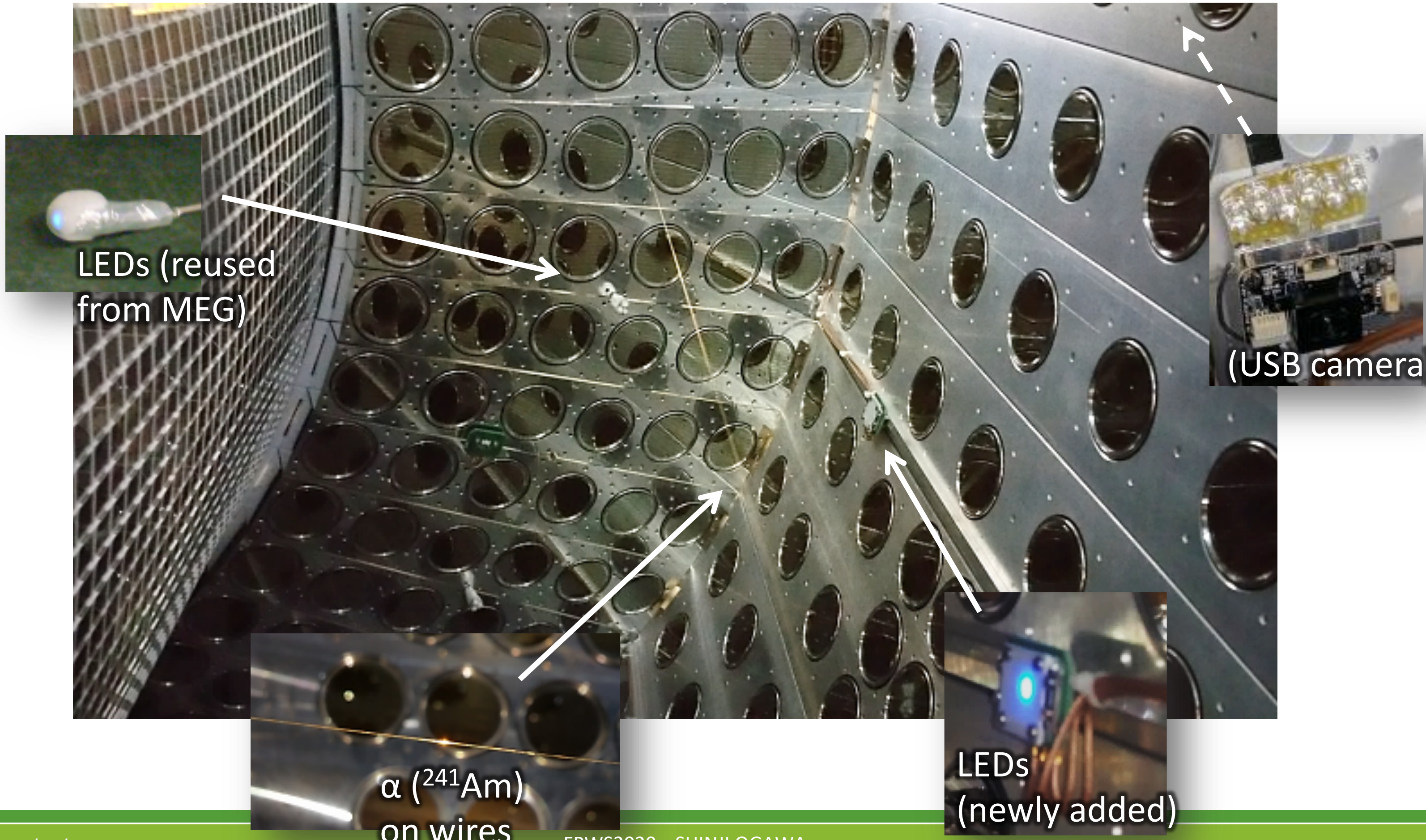
Table 2.2 Material budget of the γ entrance window of the LXe detector. (left) MEG, (right) MEG II.

	Radiation thickness X_0
Outer cryostat wall	0.040
Honeycomb (Section 1.6.2)	0.018
Inner cryostat wall	0.023
Peek support or PMT	0.183
Total	0.264

	Radiation thickness X_0
Outer cryostat wall	0.040
Honeycomb (Section 1.6.2)	0.018
Inner cryostat wall	0.023
CFRP frame	0.003
PCB & Spacer	0.006
MPPC	0.020
Total	0.110

Calibration & monitoring tools

LEDs and α wires are installed as we did in MEG.
Some LEDs are added for calibration of SiPMs.
(Calibration tools with accelerator are not shown here.)



sensor calibration

Reconstruction of gamma-rays utilizes
“detected number of photon” on each photosensor.

増幅率　　　　　　検出効率

PMT
Q(charge) = Gain x “# of p.e.” = Gain x CE x QE x “# of photon”

MPPC
Q(charge) = = Gain x ECF x “# of p.e.” = Gain x ECF x QE x “# of photon”

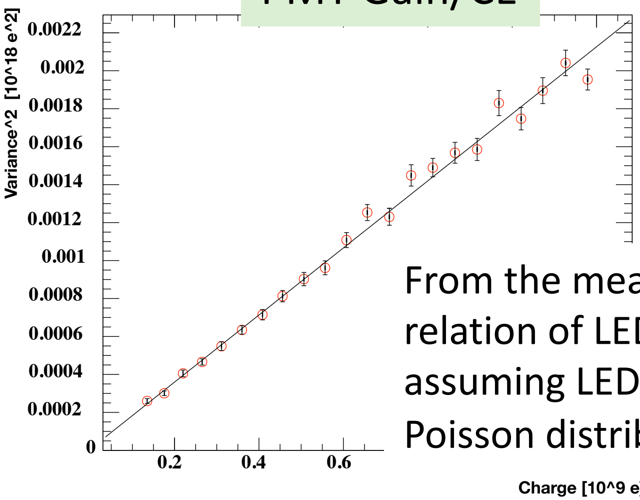
クロストーク・
アフターパルス
の影響

Calibration parameters are measured beforehand.

sensor calibration (cont'd)

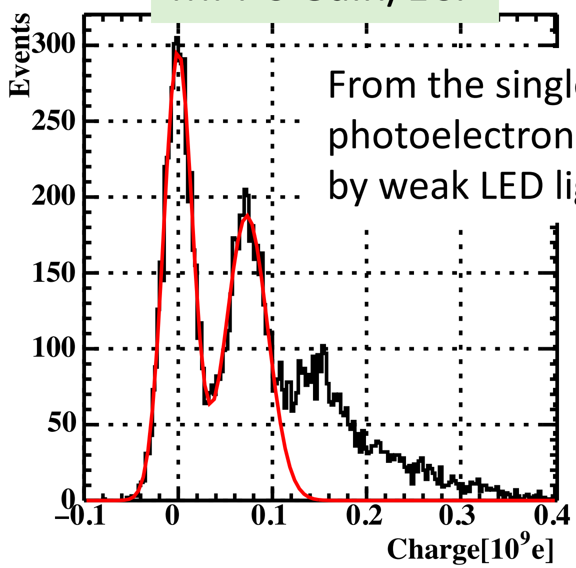
Calibration parameters are measured beforehand.

PMT Gain/CE



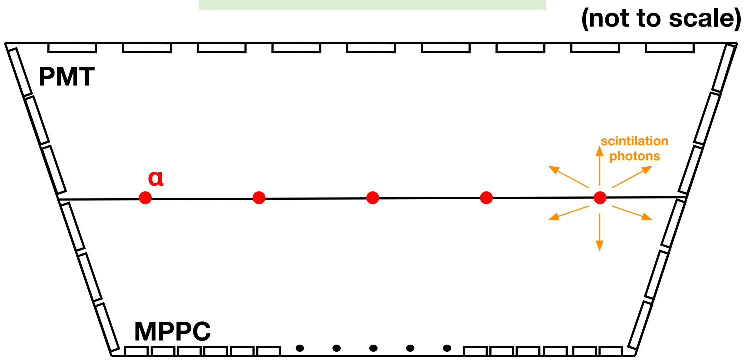
From the mean vs. variance relation of LED charge, assuming LED follows Poisson distribution.

MPPC Gain/ECF



From the single photoelectron peak by weak LED light.

PMT&MPPC QE



By using alpha source inside the detector.
It is regarded as point-like VUV light source thanks to its short path length.

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

↓

Timing reconstruction

Apply time calibration

↓

χ^2 minimization fit

Robust analysis to high-frequency noise

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

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

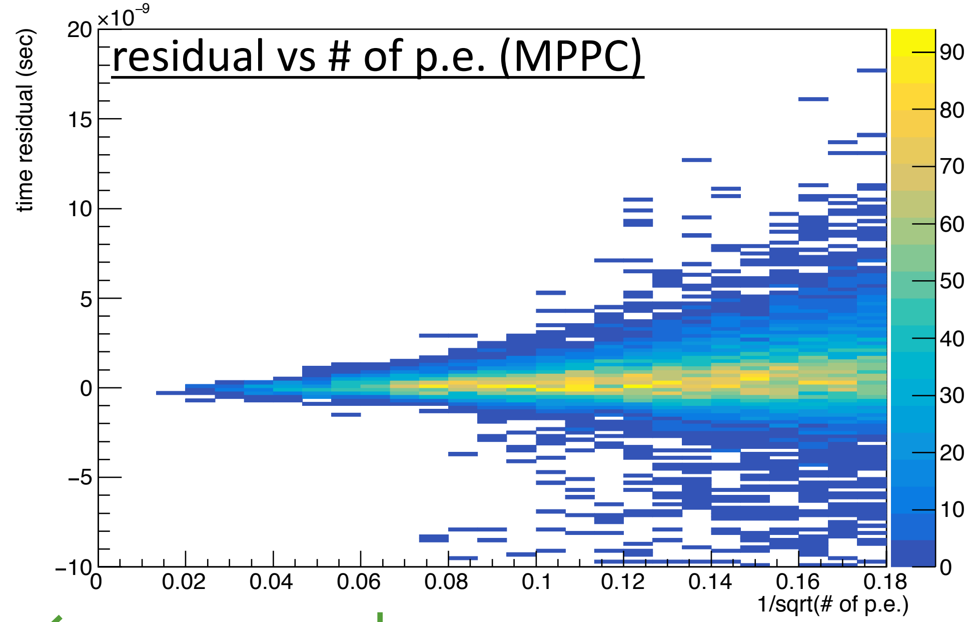
Gamma hit timing
(fitting parameter)

Calibration parameters : extracted from data

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

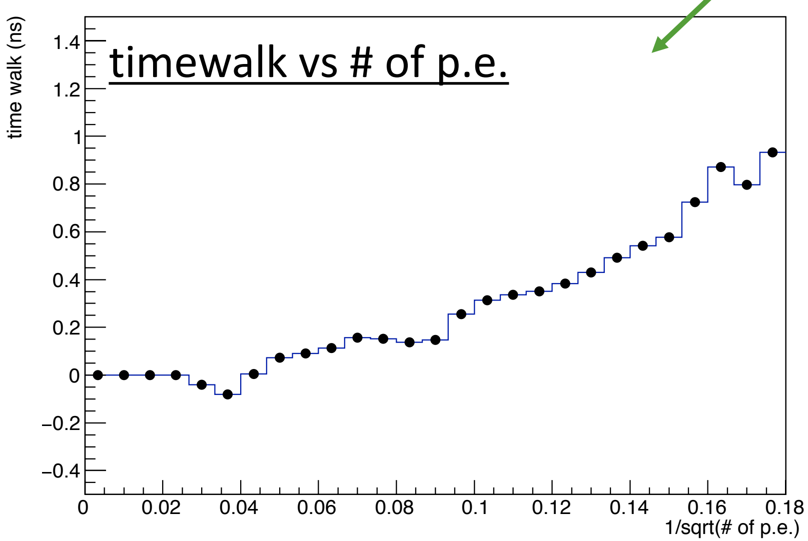
Timing resolution -c

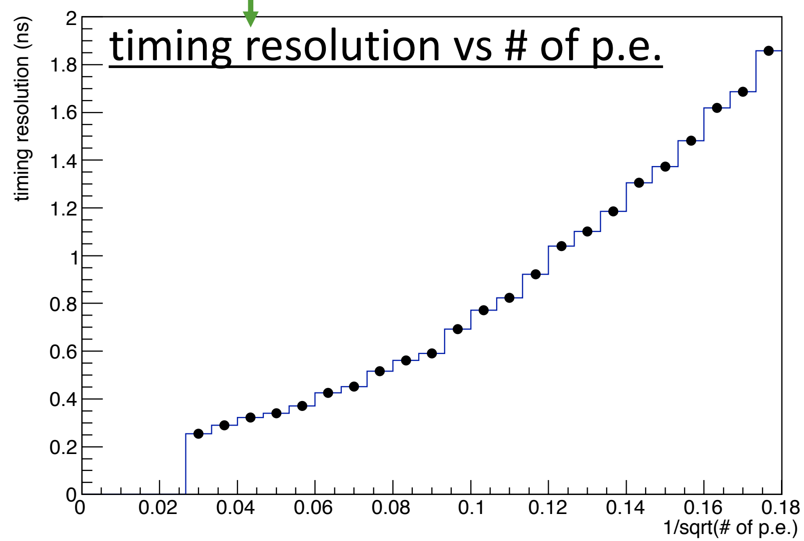
Calibration parameters
are extracted from residual
in time reconstruction.
→ Extracted iteratively.



mean

sigma

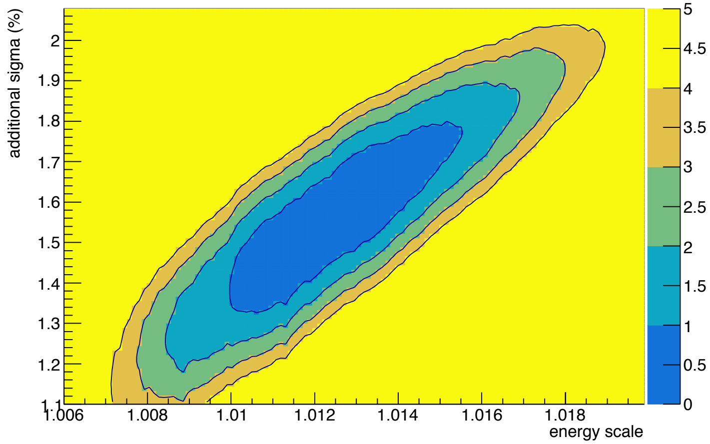


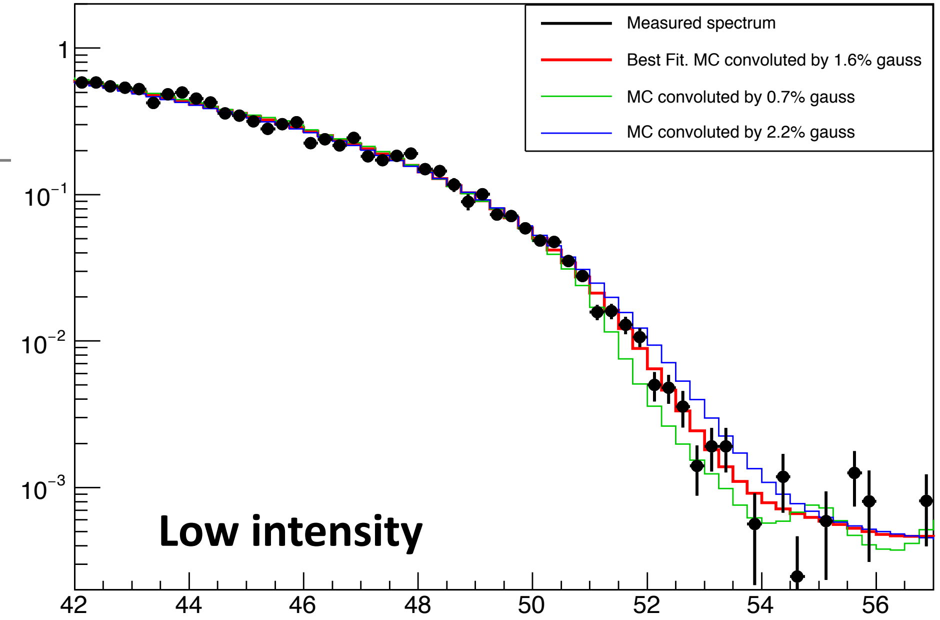


BG gamma fit

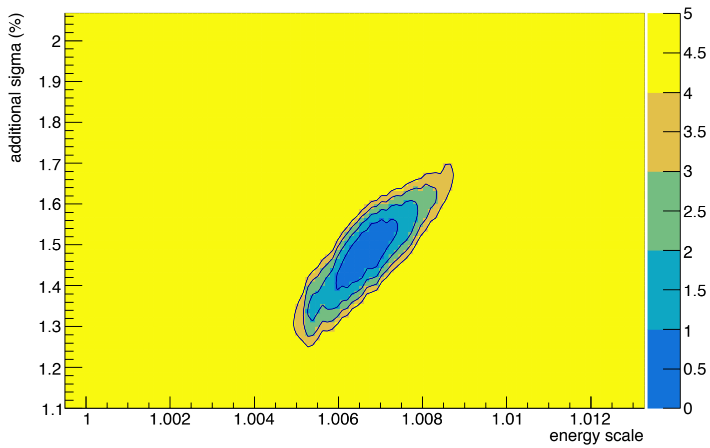
2 x negative log likelihood

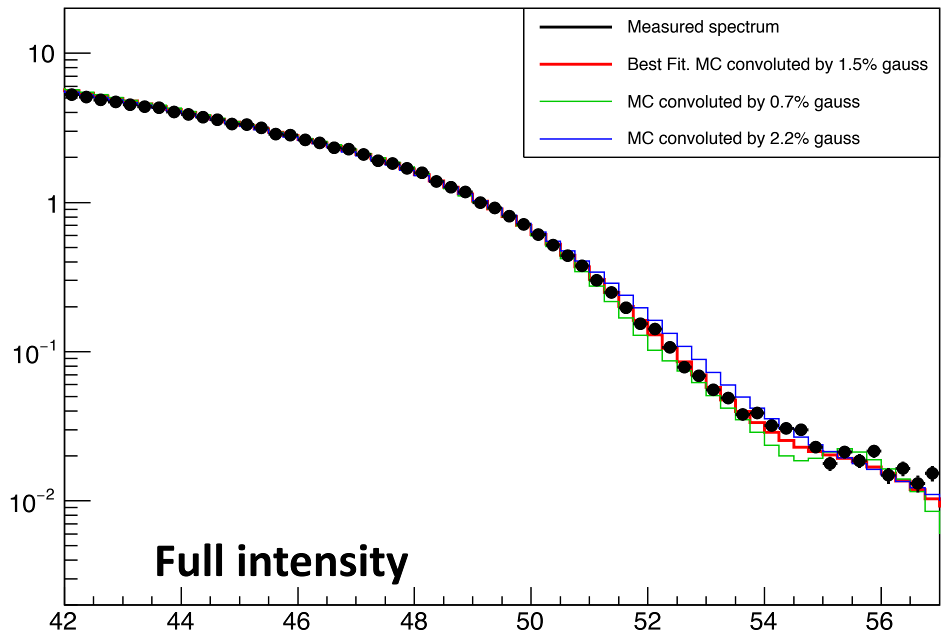
aa





2 x negative log likelihood

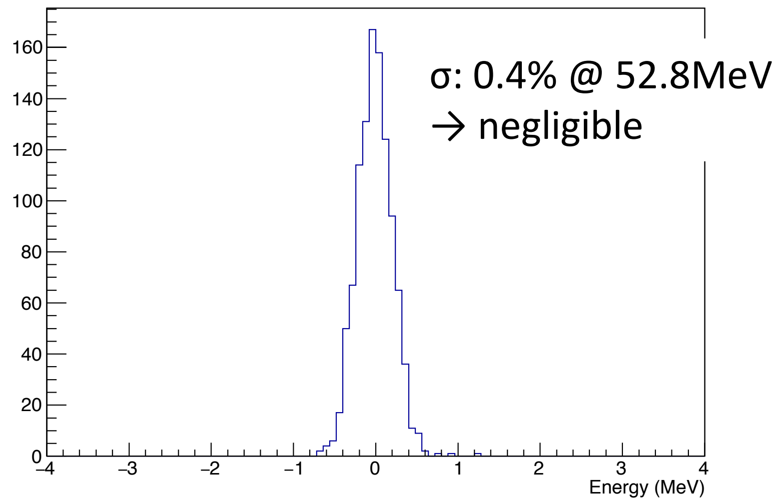




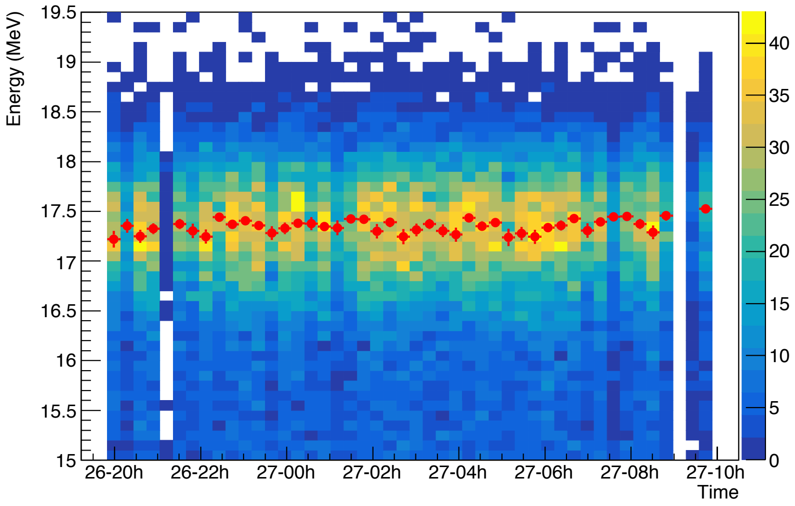
Energy resolution -unknown term-

- The degradation is not due to the noise.
- The degradation is not due to some instability.

Reconstructed energy of pedestal event.

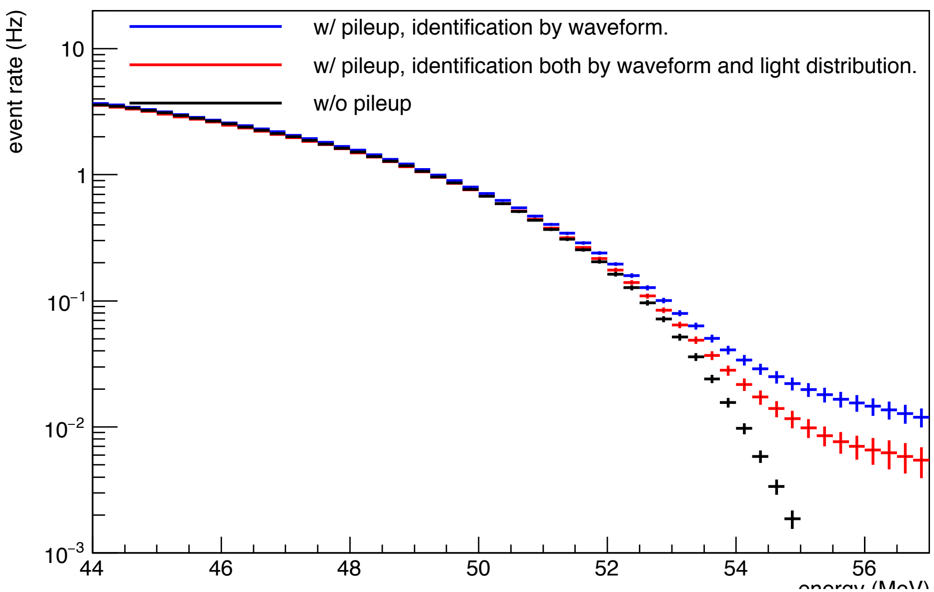


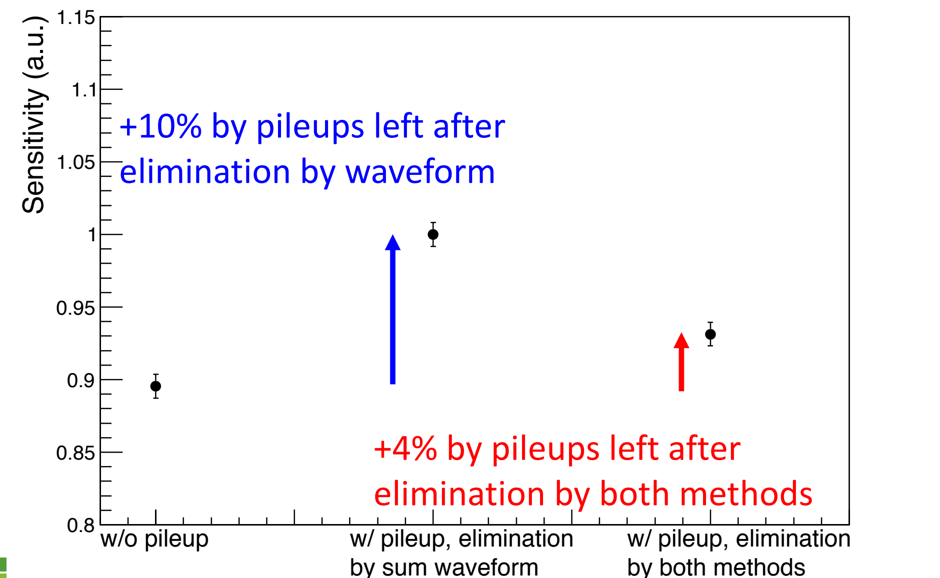
CW Li energy vs Time



Energy spectrum wit

Some events left in signal energy region.



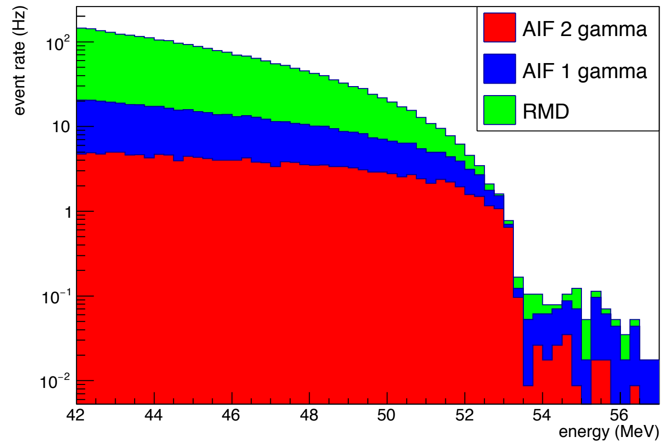


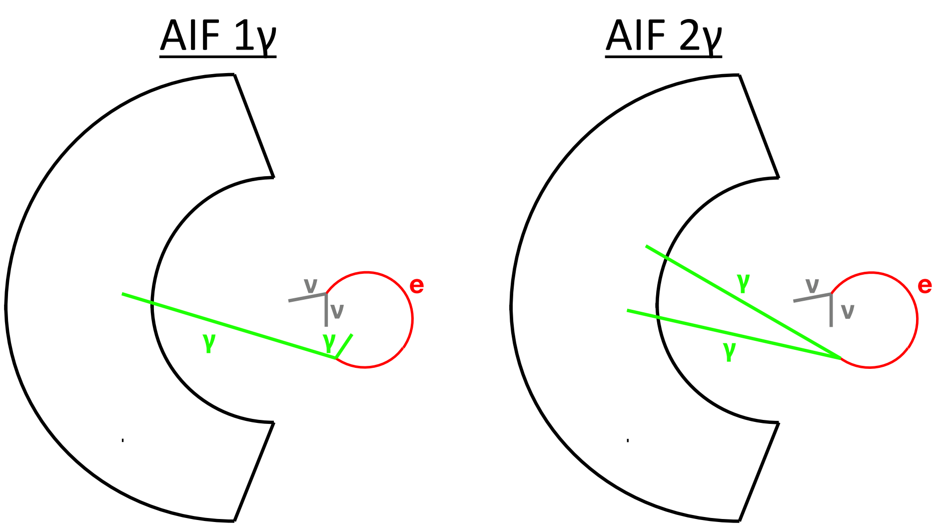
AIF2G -motivation-

Some of Michel positron annihilate with electron in material.

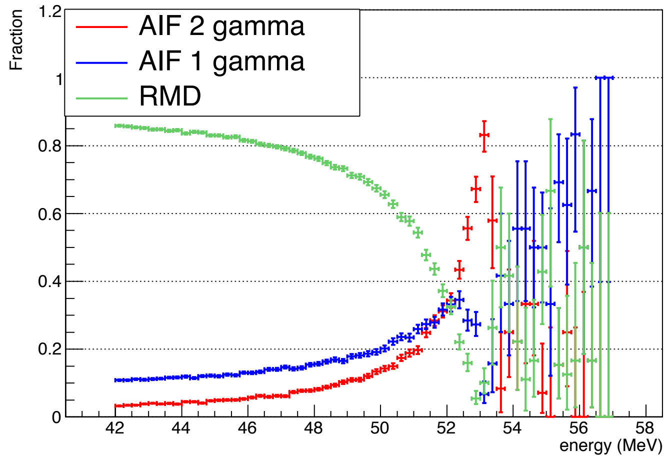
In some of the events, two gamma-rays from annihilation hit the detector.

- more dominant near the signal energy.

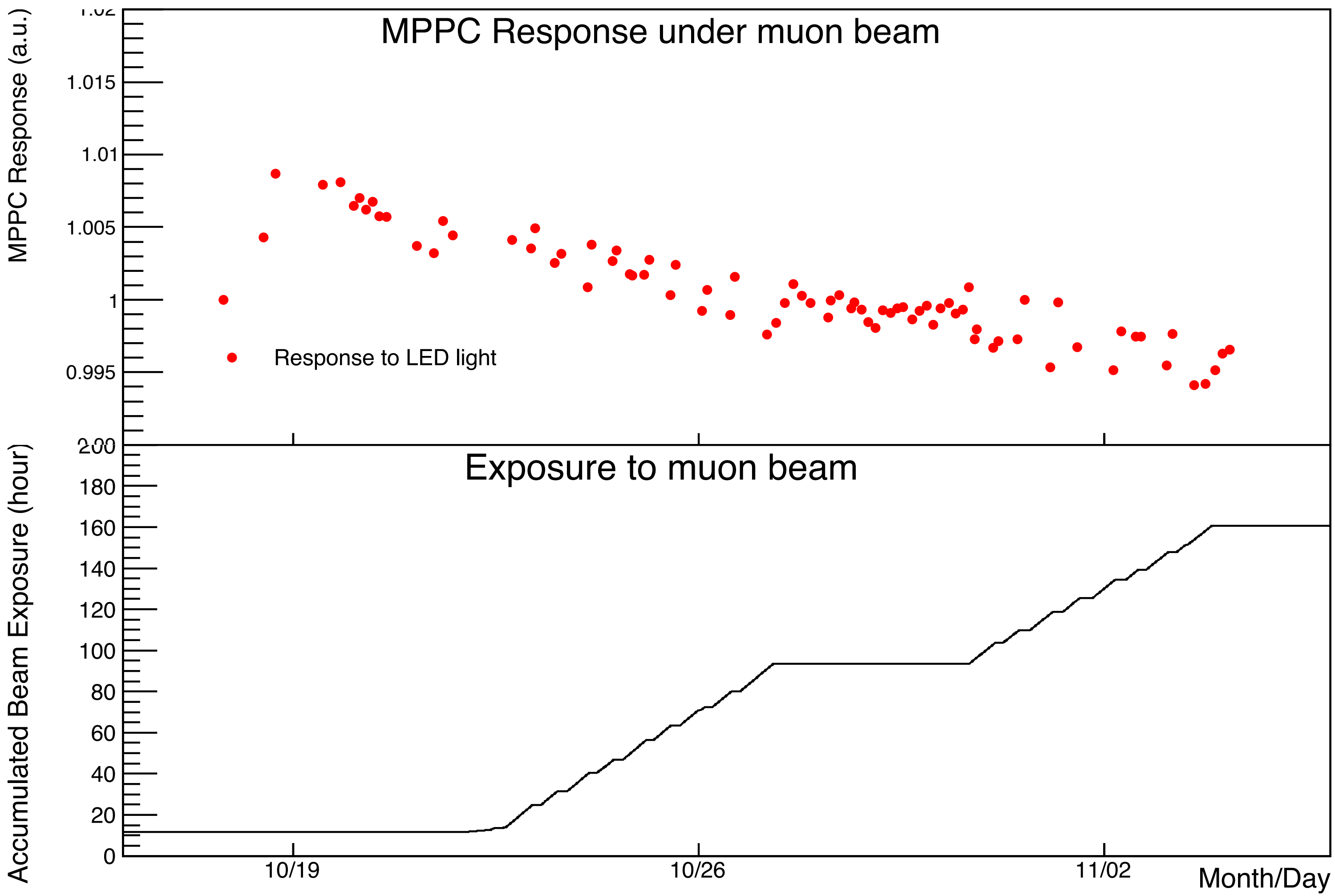




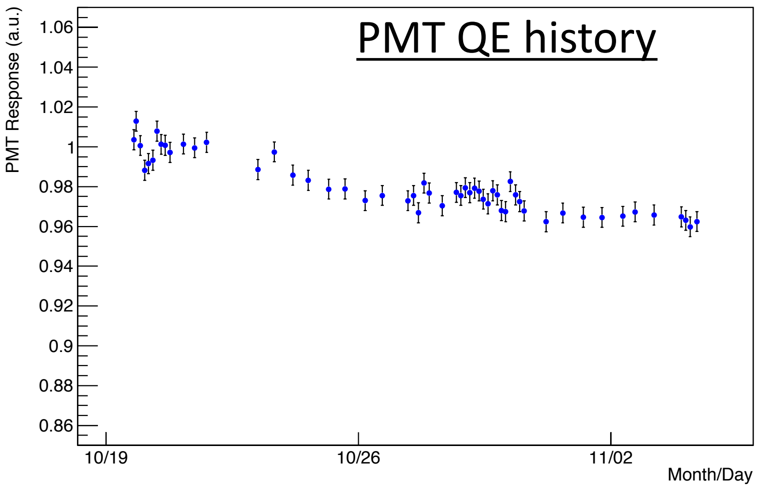
Fraction of AIF2γ in background γ-rays vs. Energy



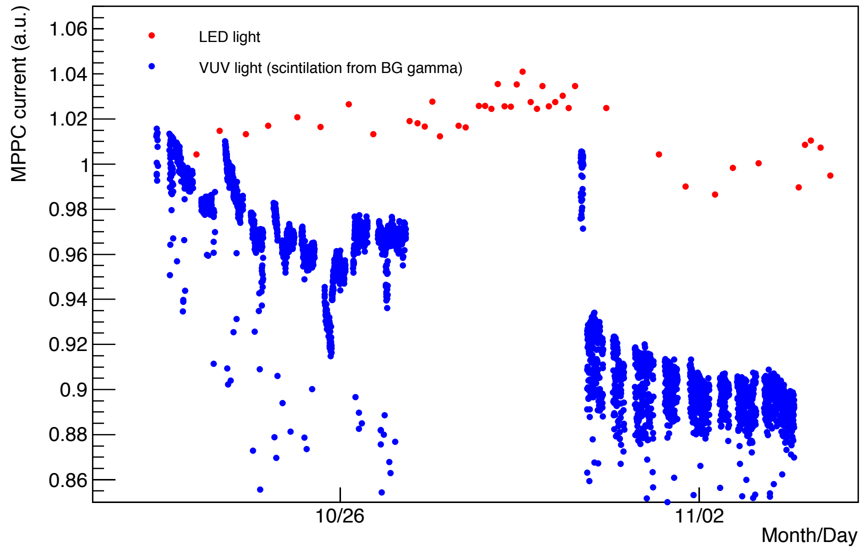
Vis PDE in 2019 run

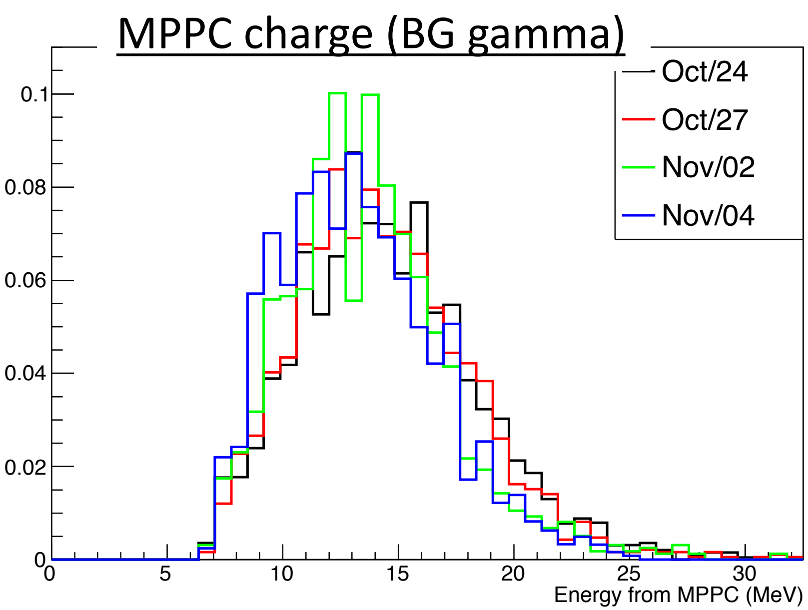


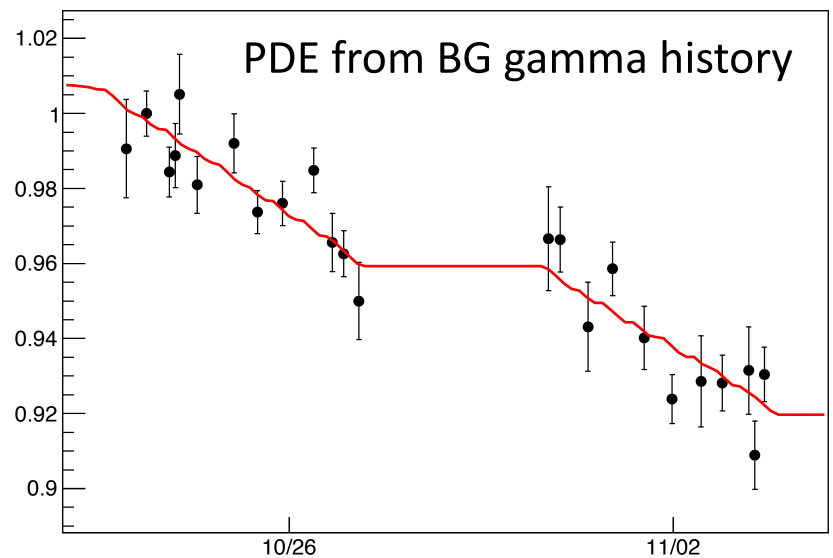
VUV PDE others



VUV current history



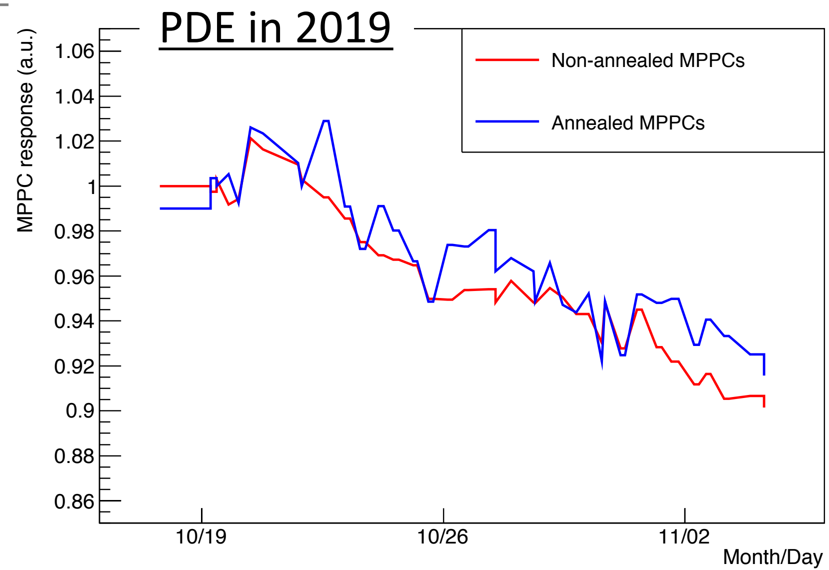


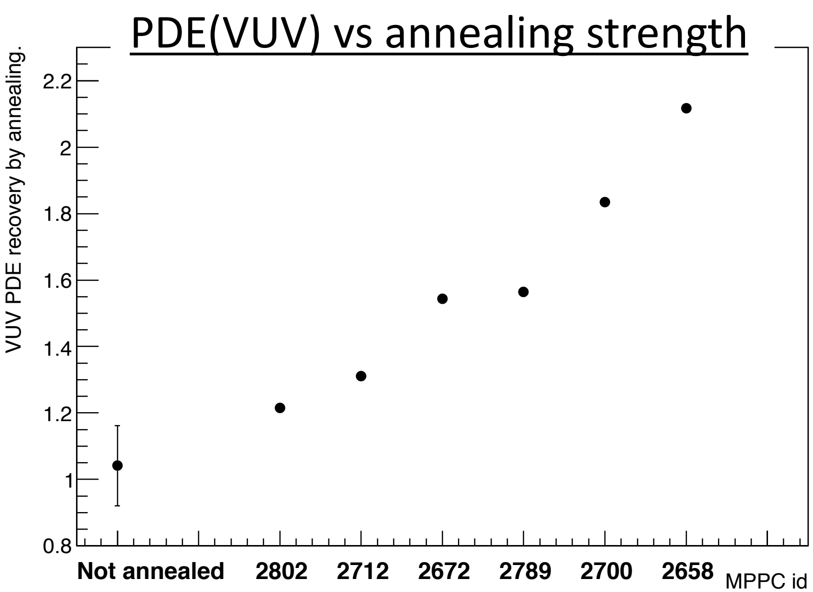


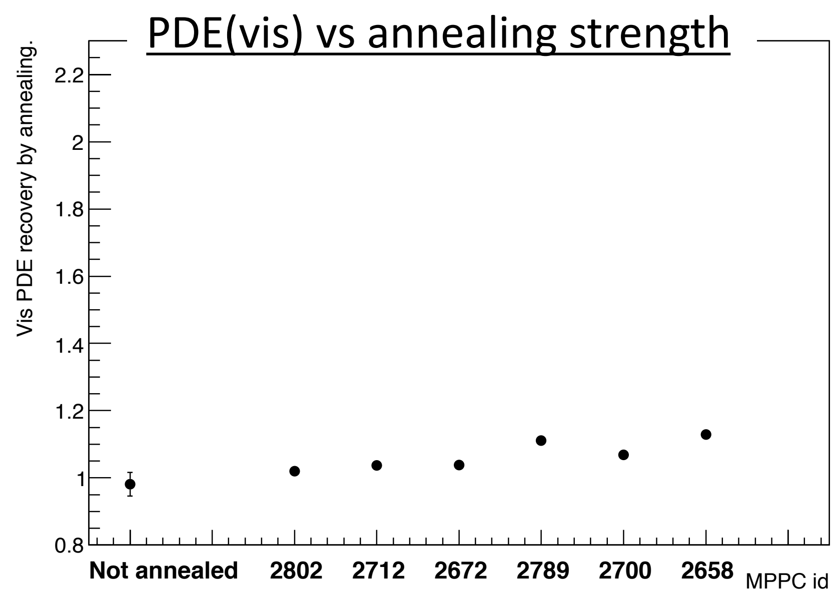
Annealed MPPC

Table 6.2 Tested annealing conditions.

MPPC ID	current	duration
2802	17–19 mA	23 hours
2712	19 mA	23 hours
2672	19–20 mA	23 hours
2789	19–24 mA	38 hours
2700	20–24 mA	38 hours
2658	21–24 mA	38 hours



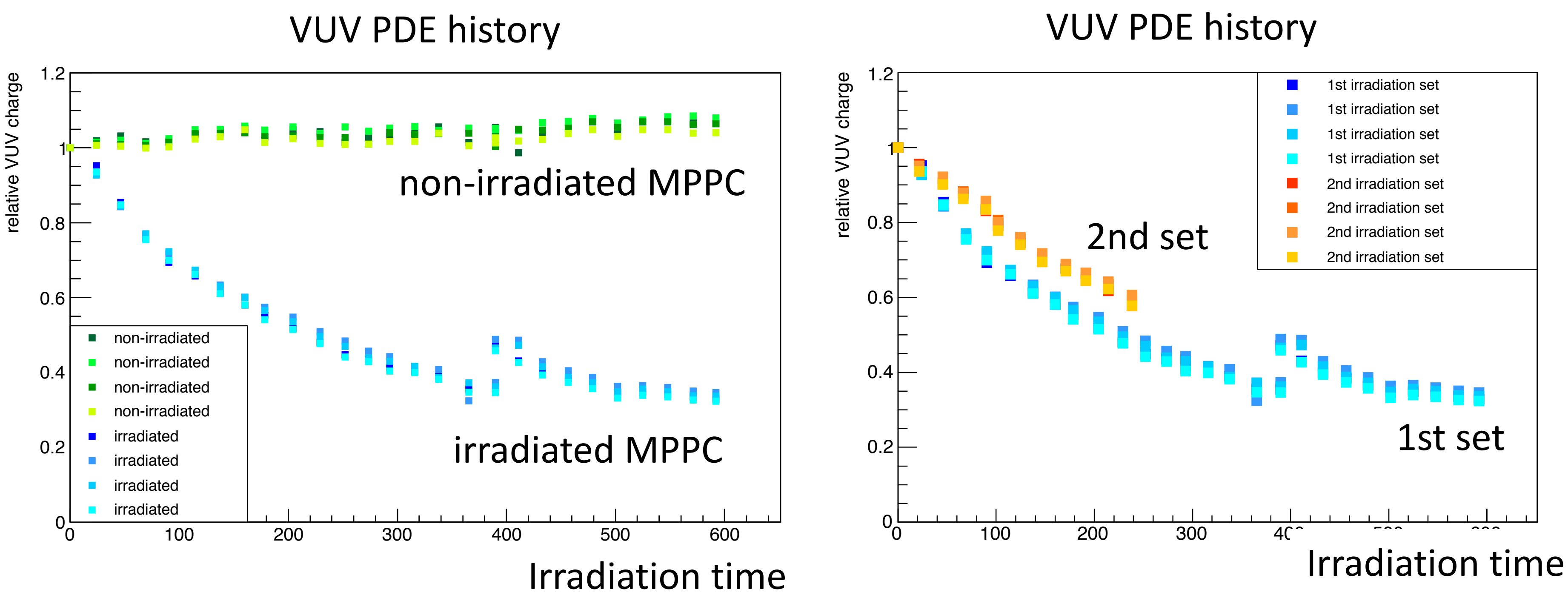




VUV irradiation at room temp.

MPPCs are irradiated by VUV light from xenon lamp.

- Select VUV peaked at 190nm.
- PDE degradation observed at O(1e4) higher irradiation level than run 2019.



Data-taking time

- The data-taking plan of MEG II has to be modified.
- In the worse case, PDE gets below 2% after 60 days MEG II beam usage.
- We can anneal all the MPPCs during the annual accelerator shutdown period (Jan-May).
- Original MEG II plan (120 days beam time/year x 3 years) is not possible.

Three alternative annual DAQ plans are compared.

Plan A: 60 days DAQ at MEG II beam intensity.

Plan B: 120days DAQ at halved beam intensity.

- Pros: Better significance ($N_{SIG}/\sqrt{N_{BG}}$)
  and better pileup environment than plan A.

Plan C: 67 days DAQ at MEG II beam intensity + an annealing in the middle.

- it will take 60 days to anneal all the MPPC
  (current best estimate, may include uncertainty).
- Pros: Larger muon statistics, and higher PDE than plan B.

Data-taking time

Table 11.3 Comparison of the alternative data-taking plans. The number of the signals and the backgrounds is normalized by that in original MEG II plan.

plan	number of signal	number of background	PDE
Plan A	0.5	0.5	2–16%
Plan B	0.5	0.25	2–16%
Plan C	0.57	0.57	5–16%

Sensitivity of alternative DAQ plans

Plan B has a best sensitivity in these alternative plans.

MEG II sensitivity vs. DAQ year

with measured LXe detector performance & PDE degradation (worst case)