Liquid xenon detector with highly granular scintillation readout to search for $\mu^+ \rightarrow e^+\gamma$ with sensitivity of 5×10^{-14} in MEG II experiment

MEG II 実験における感度 5×10^{-14} での $\mu^+ \rightarrow e^+\gamma$ 探索のためのシンチレーション光を高精細に読み出す液体キセノン検出器

Shinji Ogawa
@ PhD defense, 2020/11/17

Abstract

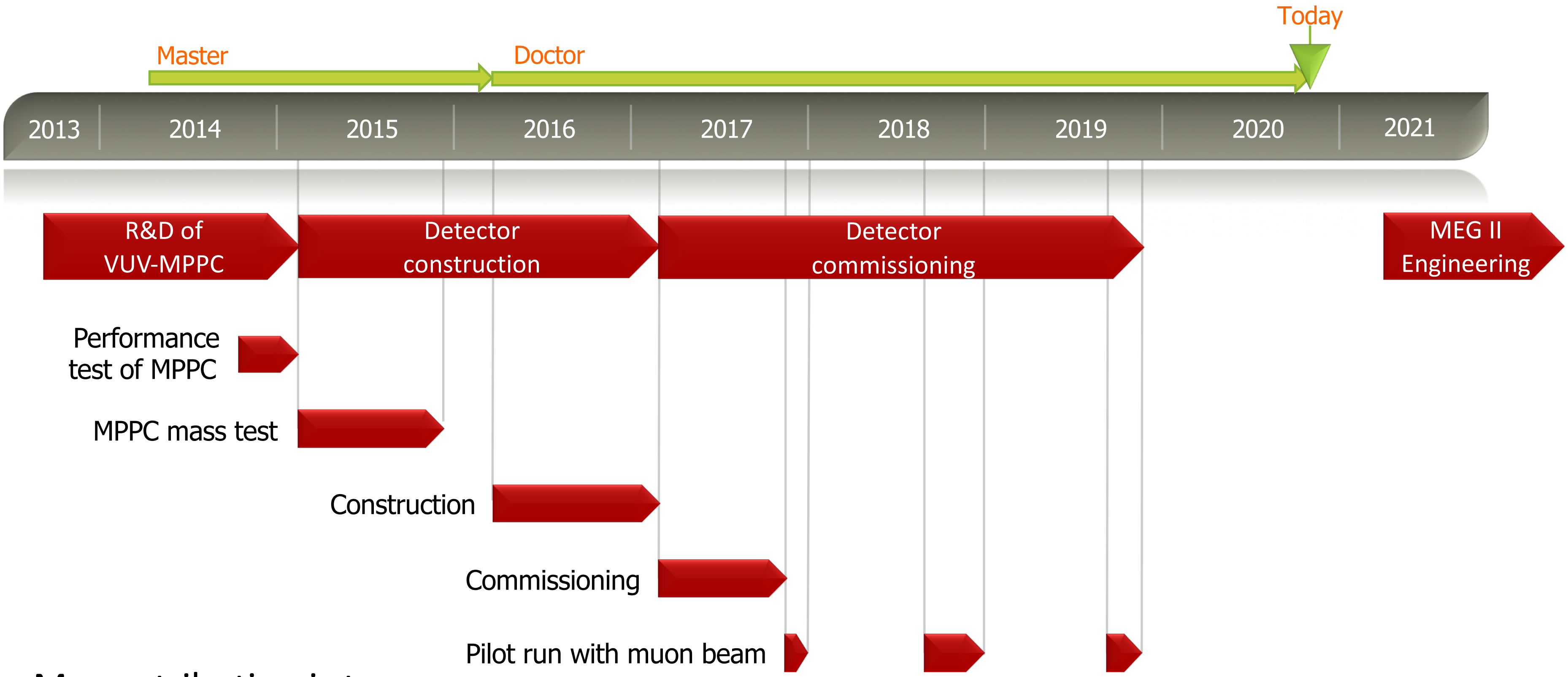
- To search for a charged lepton flavor violating decay, $\mu^+ \rightarrow e^+\gamma$, a new liquid xenon γ-ray detector has been developed.
  - This detector utilizes a VUV-sensitive MPPC newly developed for this purpose.

- 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 $5\mathrm{x}10^{-14}$.

Timeline of LXe detector /my contribution



My contribution is to

- Finalize R&D of MPPC
- Join detector construction
- Lead the detector commissioning & pilot runs for detector performance evaluation.
- Develop and improve the reconstruction algorithm.

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Charged lepton flavor violation

- The Standard Model (SM) in the particle physics are a successful model.
- However, it is though to be a low energy approximation of more fundamental physics.
  - Hierarchy problem.
  - Dark matter.
  - etc...

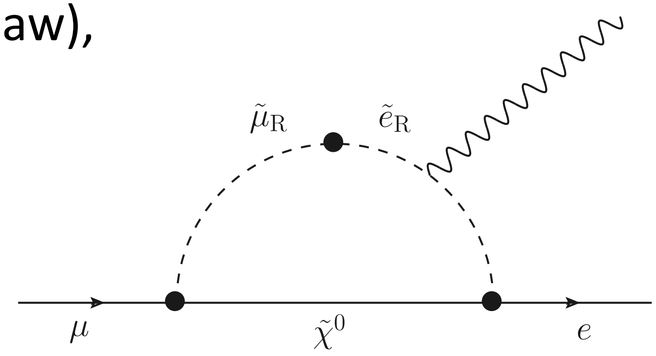
→ Physics beyond the Standard Model (BSM) is actively searched.

- A charged lepton flavor violating (CLFV) decay of a muon, $\mu \to e\gamma$, is an interesting probe in the search of BSM.
- Never been observed, and prohibited in SM by charged lepton flavor conservation.
- It can occur if we take neutrino oscillation into account, but its branching ratio is too small to be detected ($Br(\mu \to e\gamma) \sim 10^{-55}$), due to small mass difference of neutrinos.

→ Discovery of CLFV would be a clear evidence of BSM.

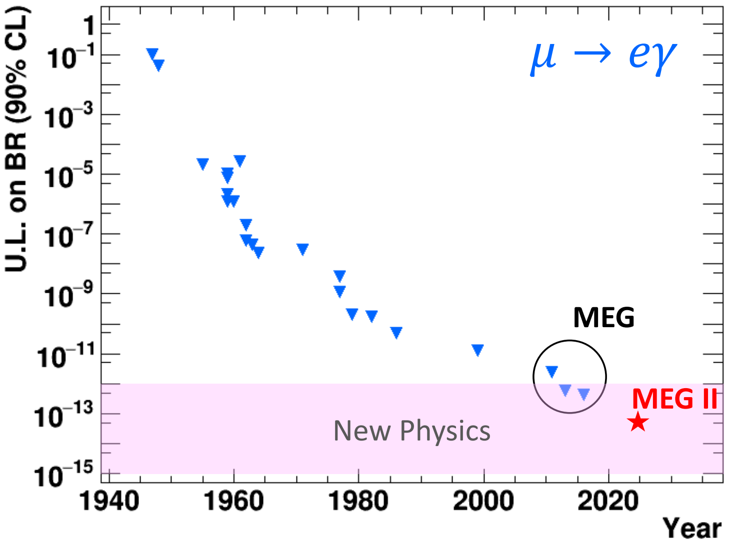
Charged lepton flavor violation (cont’d)

- In some BSM models (e.g. SUSY-GUT, SUSY-Seesaw), $O(10^{-12} \sim 10^{-15})$ branching ratio is predicted.
  - This is experimentally detectable.



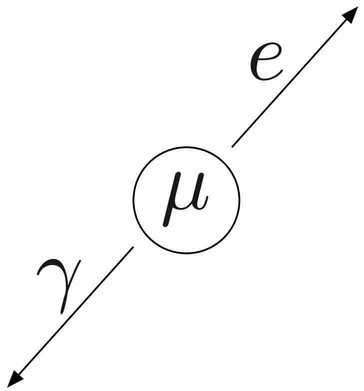
- Current experimental limit: 4.2×10^{-13} (by MEG, 90% C.L.)
- **MEG II searches for μ→eγ with a sensitivity of ~5×10^{-14}.** (one order of magnitude imporvement)

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



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

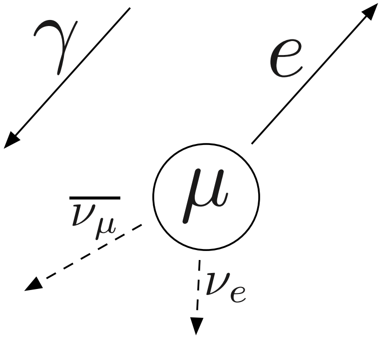
- $E_e = E_\gamma = 52.8\mathrm{MeV}(= m_\mu/2)$
- back-to-back
- coincident

- 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

$$N_{\mathrm{acc}} \propto R_{\mu^+}^2 \times \underbrace{\Delta E_\gamma{}^2 \times \Delta p_{\mathrm{e}^+} \times \Delta\Theta_{\mathrm{e}^+\gamma}^2 \times \Delta t_{\mathrm{e}^+\gamma}}_{\text{detector resolutions}} \times T.$$

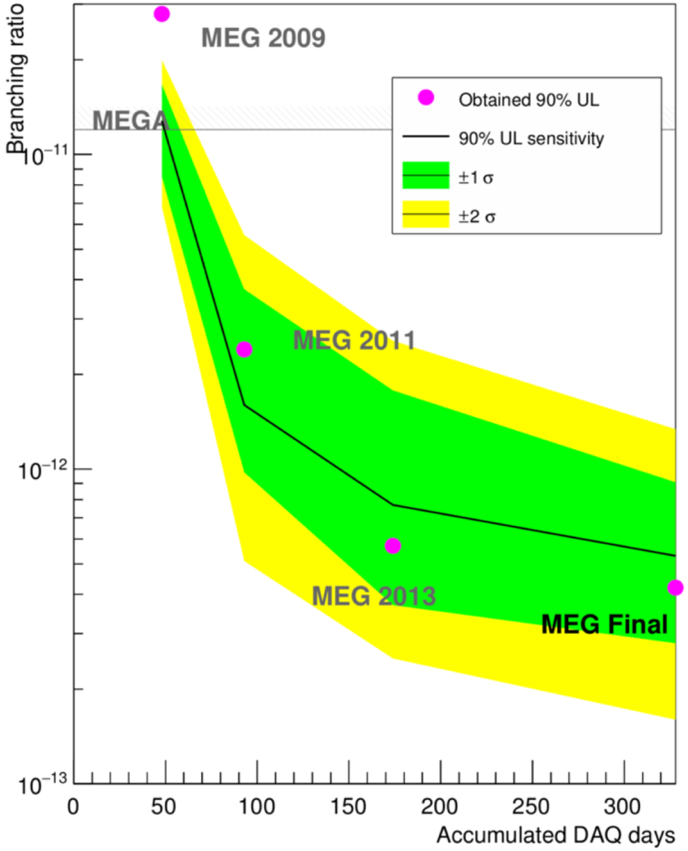
MEG experiment

- 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 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.

Sensitivity of MEG vs DAQ time



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.

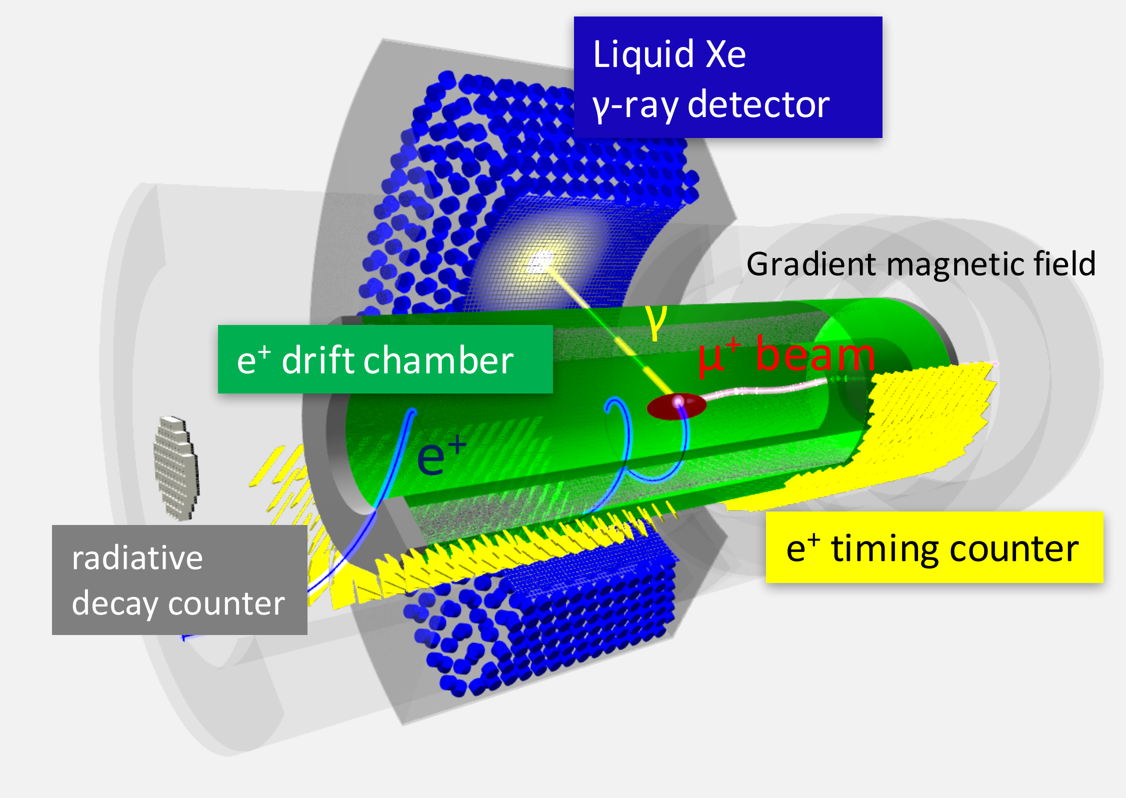
- x2 for all detector resolutions

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

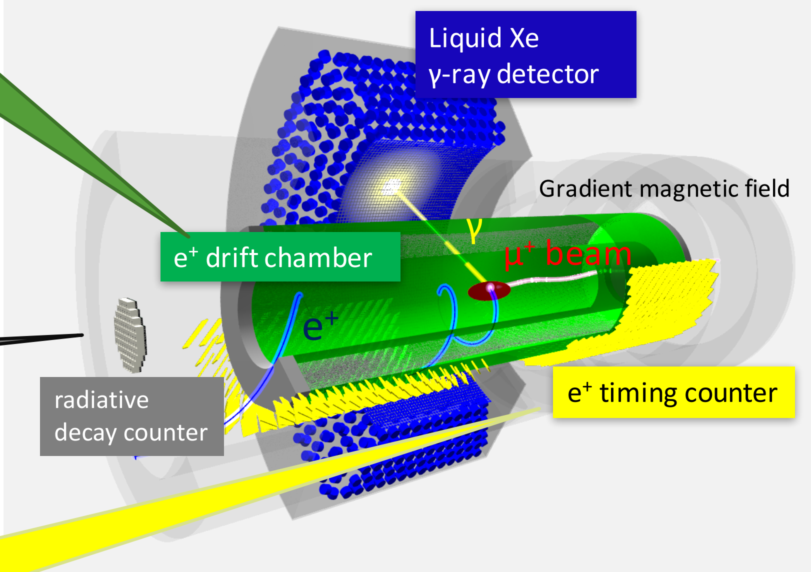


MEG II experiment

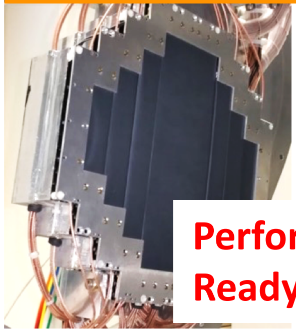
Drift chamber

Constructed. Commissioning ongoing.

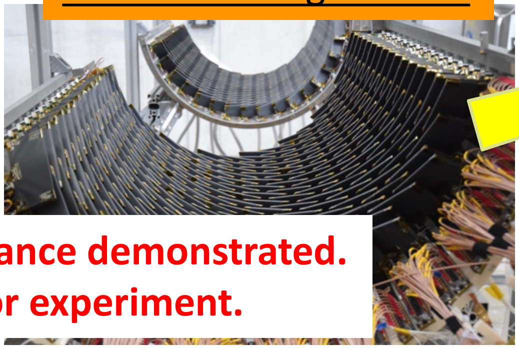
MEG II detectors



Radiative decay counter

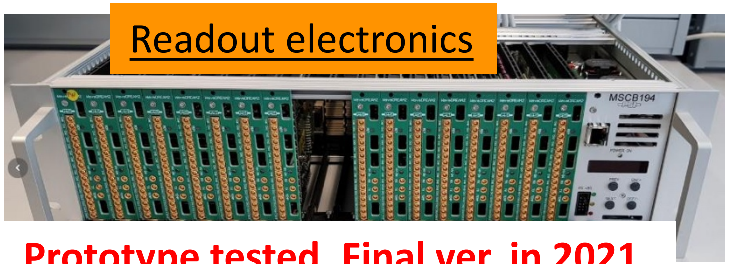


Positron timing counter



**Performance demonstrated.
Ready for experiment.**

Readout electronics



Prototype tested. Final ver. in 2021.

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

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

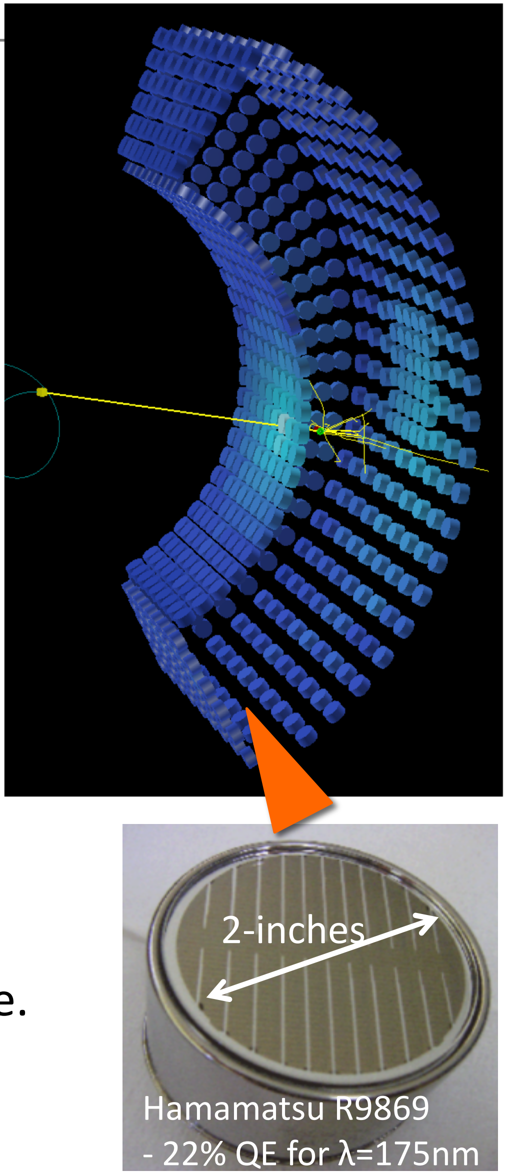
- 900 ℓ LXe detector
- Scintillation light readout by 846 PMTs（Photomultiplier Tube）

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.

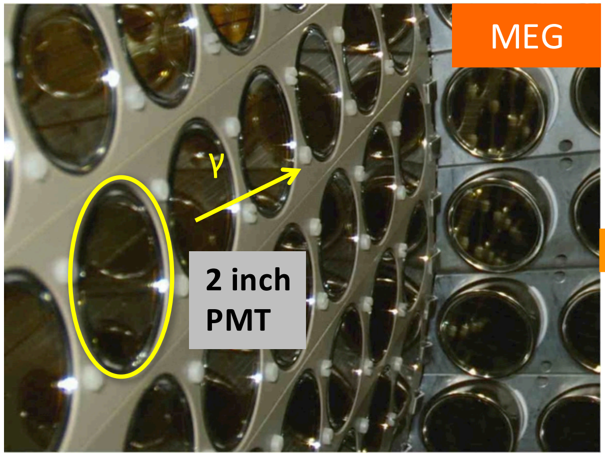


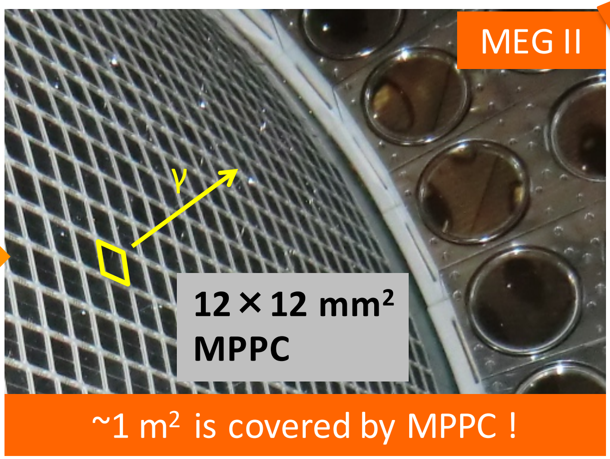
Hamamatsu R9869
- 22% QE for λ=175nm

LXe γ-ray detector in MEG II

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

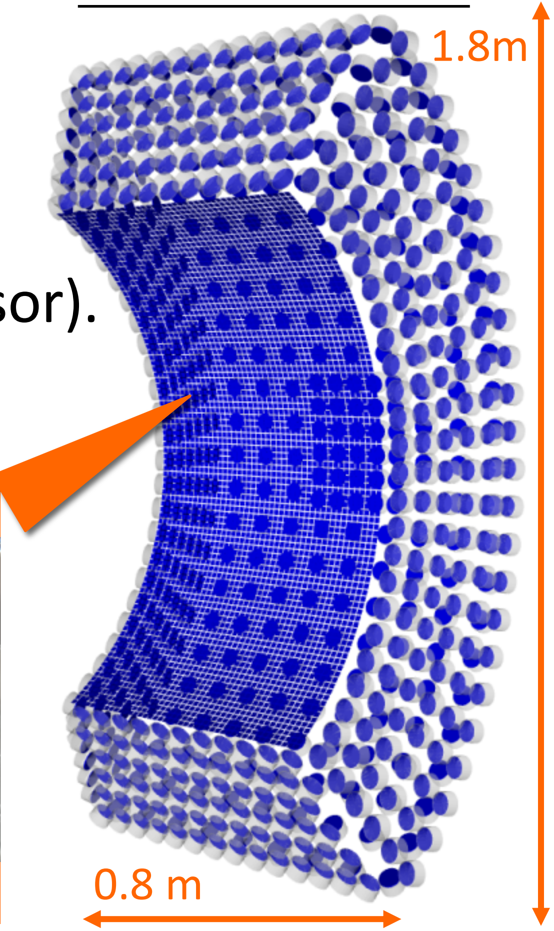
Major upgrade:
Replacing **216 PMTs** on the γ-entrance face
with 4092 MPPCs (new type of silicon photosensor).





~1 m² is covered by MPPC !

MEG II LXe detector



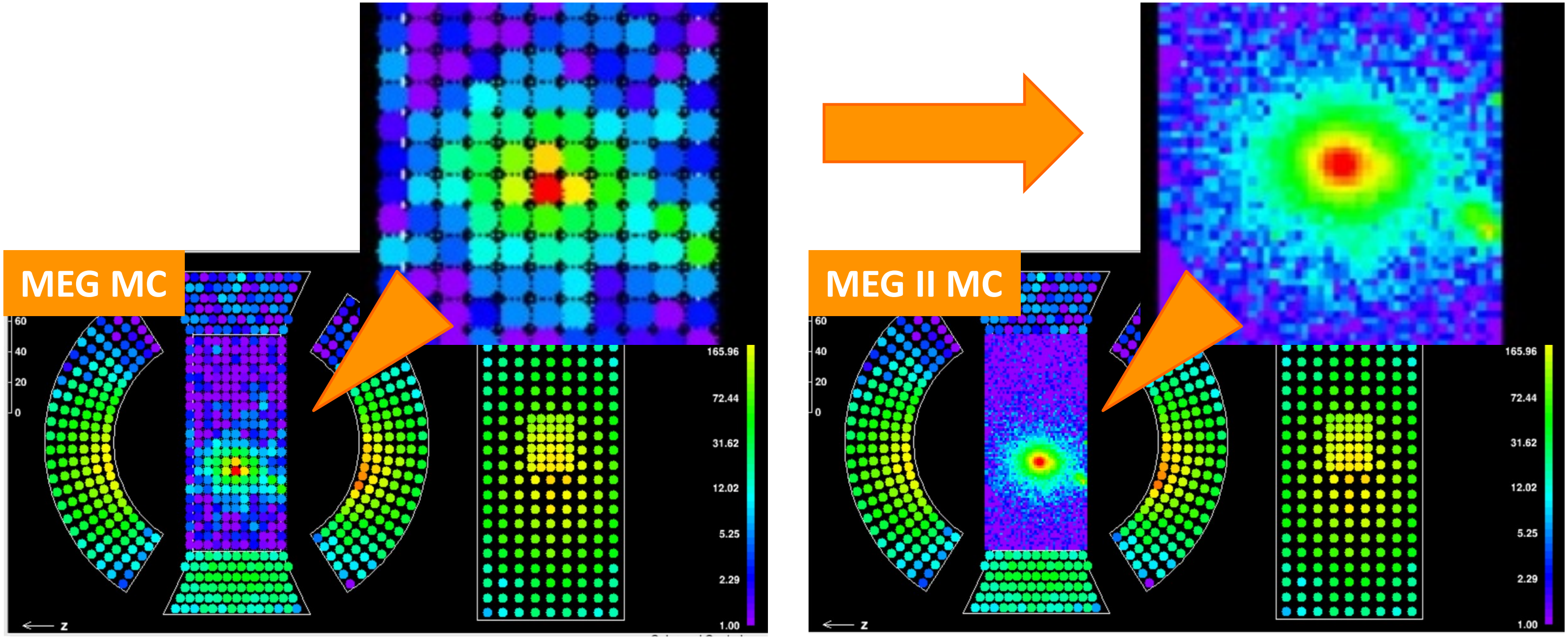
LXe γ-ray detector in MEG II (cont’d)

1. Better position resolution

Higher granularity of the readout

→ Better position resolution for shallow event.

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

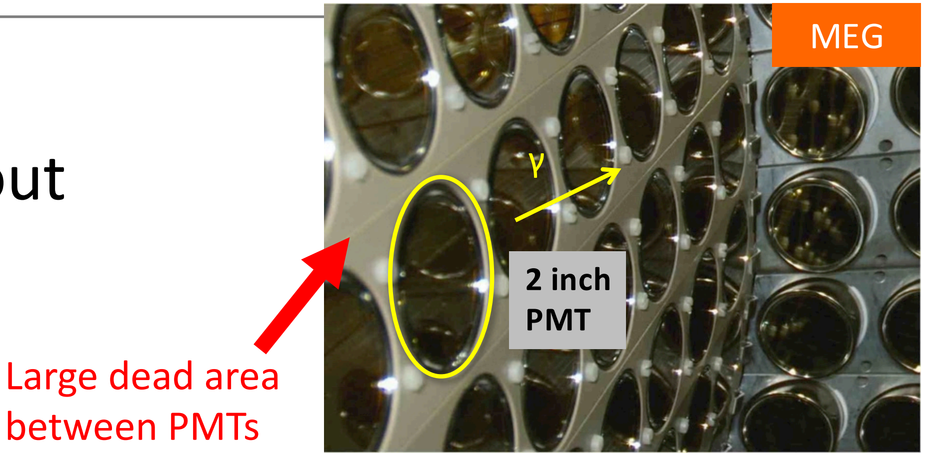


LXe γ-ray detector in MEG II (cont’d)

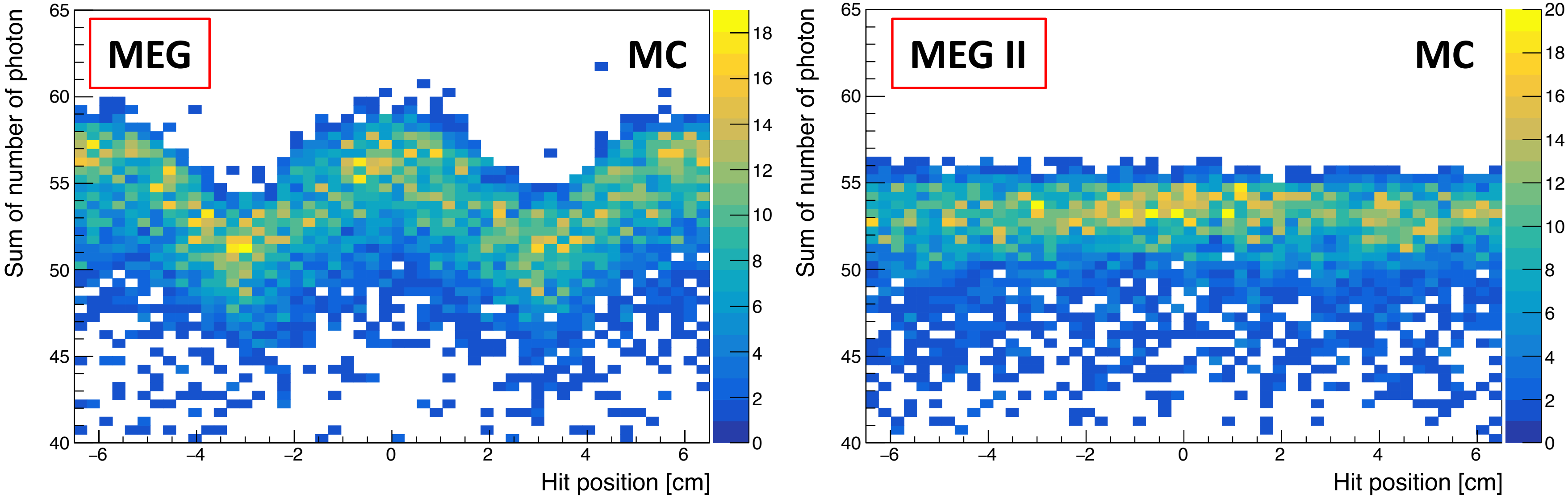
2. Better energy resolution

Better uniformity of the readout

→ Better energy resolution
for shallow event



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



LXe γ-ray detector in MEG II (cont’d)

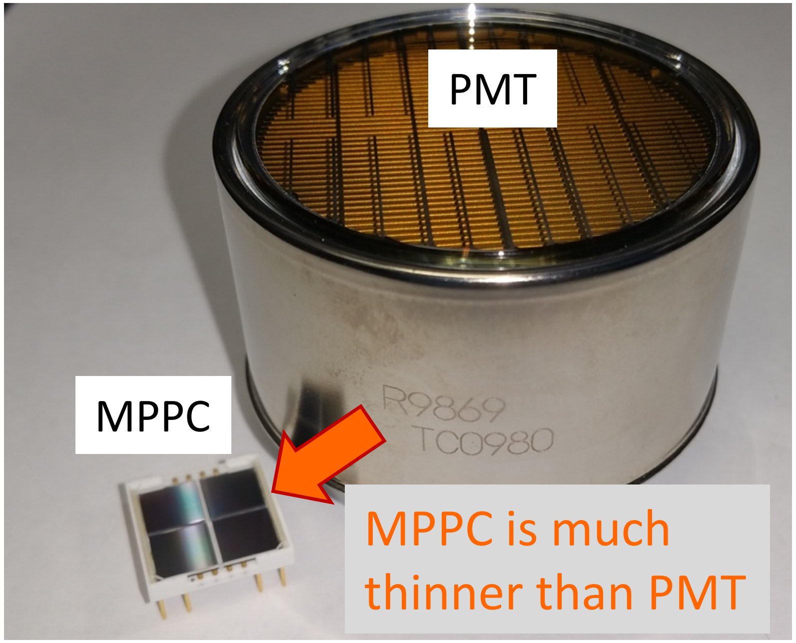
3. Better detection efficiency

Reduced material budget of the photosensors

(0.183 X_0 for PMT -> 0.029 X_0 for MPPC)

→ Better detection efficiency
(63% in MEG -> 69% in MEG II)

- γ-rays losing its energy before entering LXe cannot be used in the μ→eγ search.



MPPC is much thinner than PMT

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VUV-sensitive MPPC

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

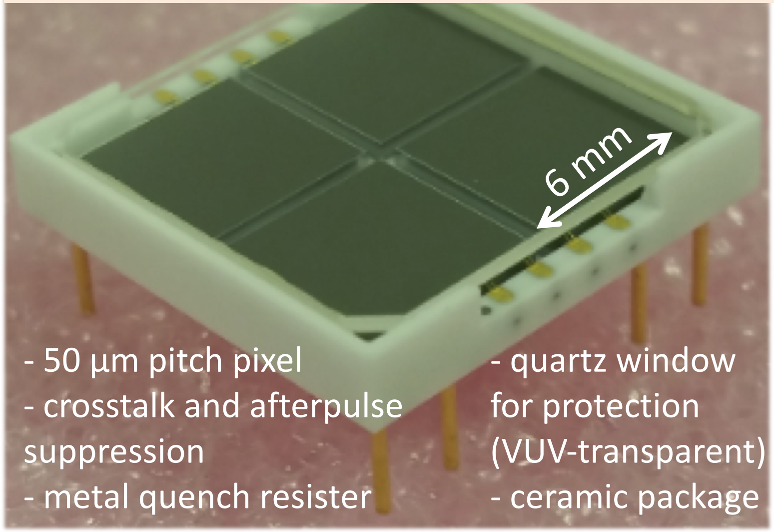
VUV-sensitive (PDE (λ=175nm) > 15%)

- Normal MPPCs are insensitive to the xenon scintillation light in VUV range.

→

- VUV-sensitive MPPC newly developed.

Hamamatsu S10943-4372



- 50 µm pitch pixel
- crosstalk and afterpulse suppression
- metal quench resister

- quartz window for protection (VUV-transparent)
- ceramic package

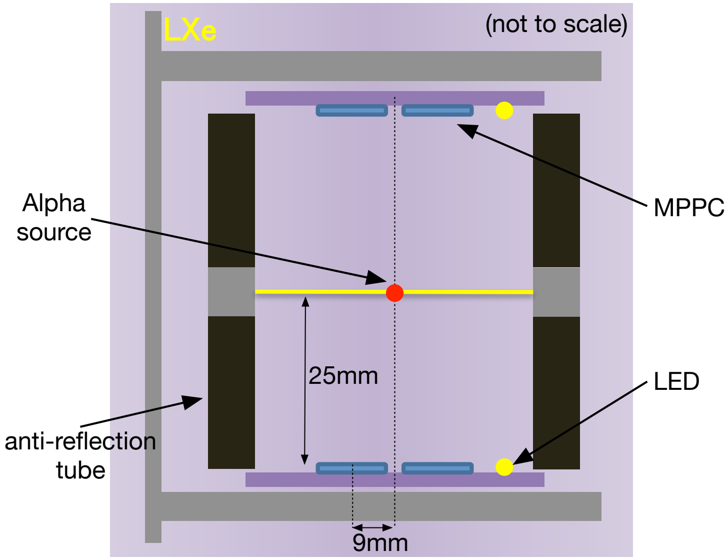
Large sensitive area (12 × 12 mm^2)

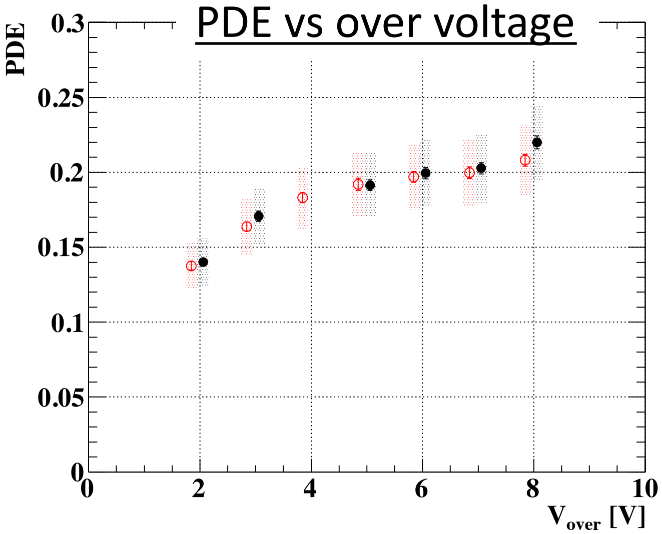
- To keep the number of readout channels manageable.
- Discrete array of four 6 × 6 mm^2 chips.
- Four chips connected in series at readout PCB to reduce the sensor capacitance and the long time constant.

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.



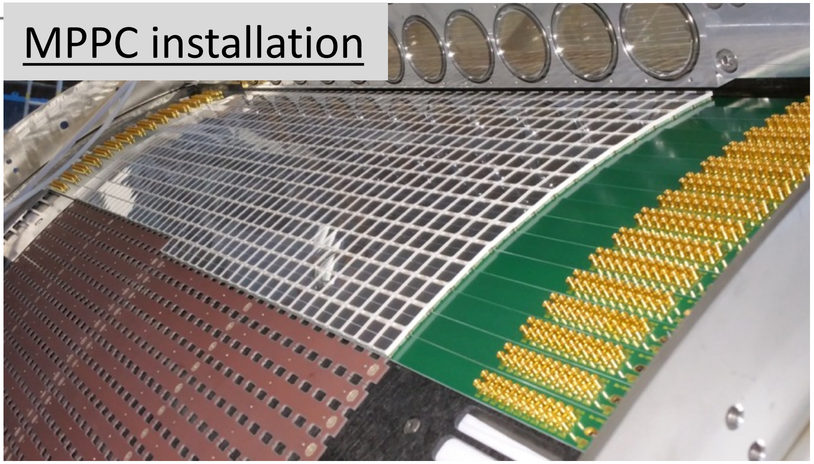


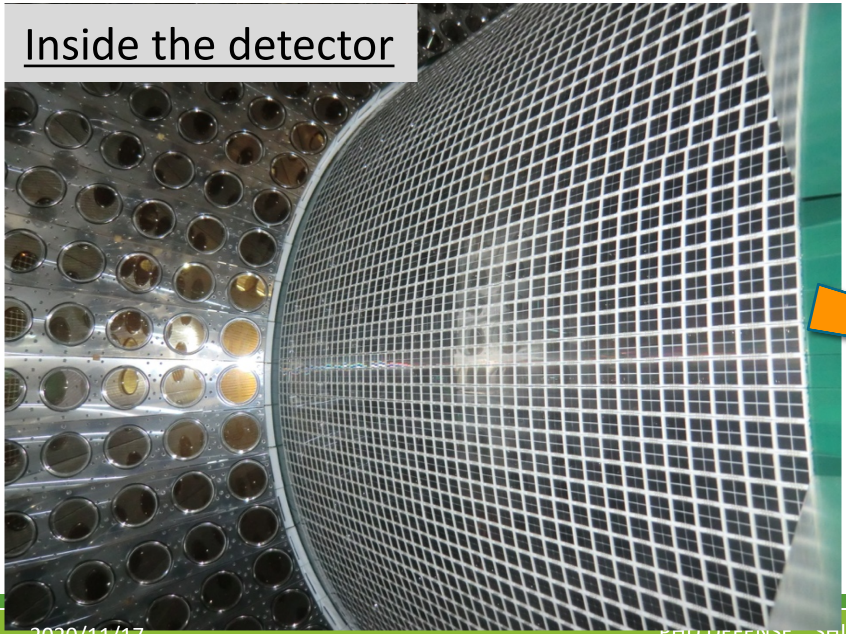
Detector construction

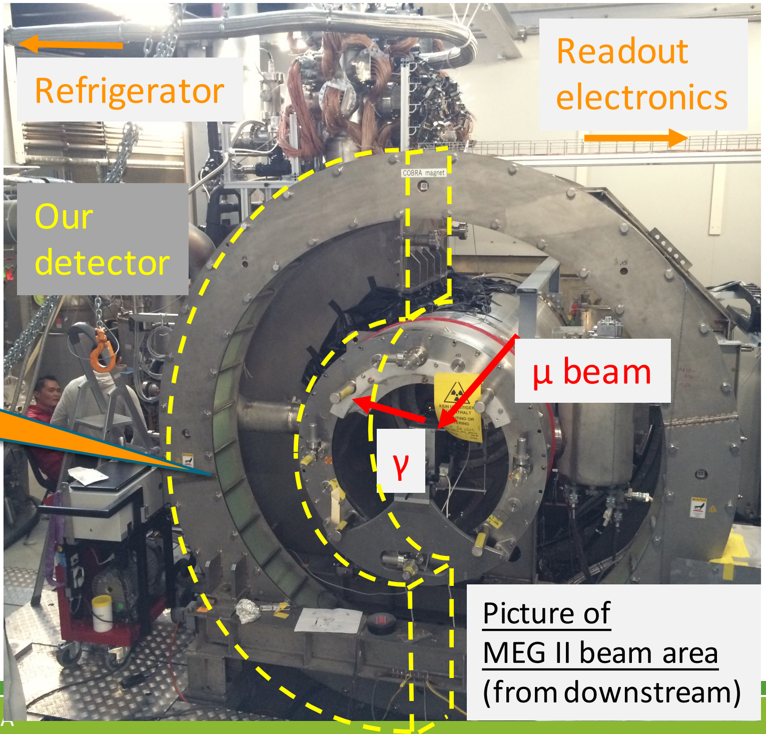
2015
MPPC mass production (by HPK)
& all MPPC test

2016
MPPC & PMT installation

2017 Apr.
Construction completed.


MPPC installation


Inside the detector



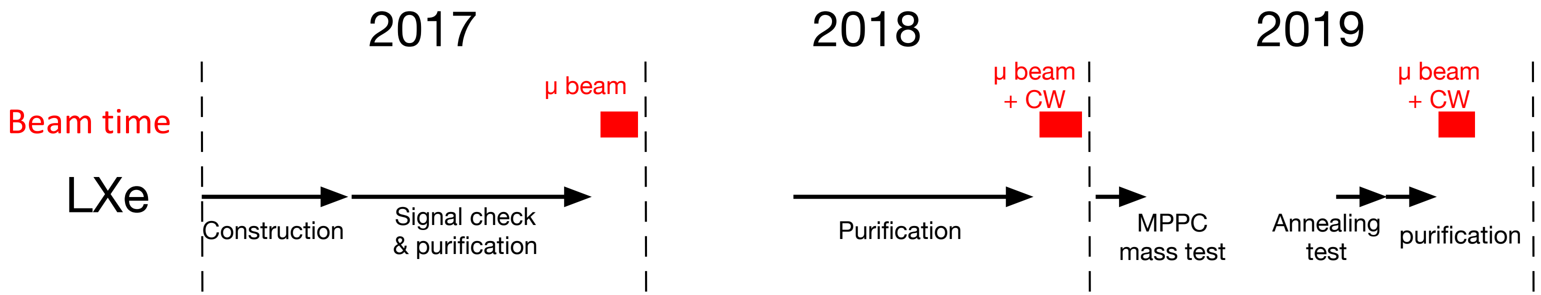
Picture of MEG II beam area
(from downstream)

Beam test

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

List of obtained data

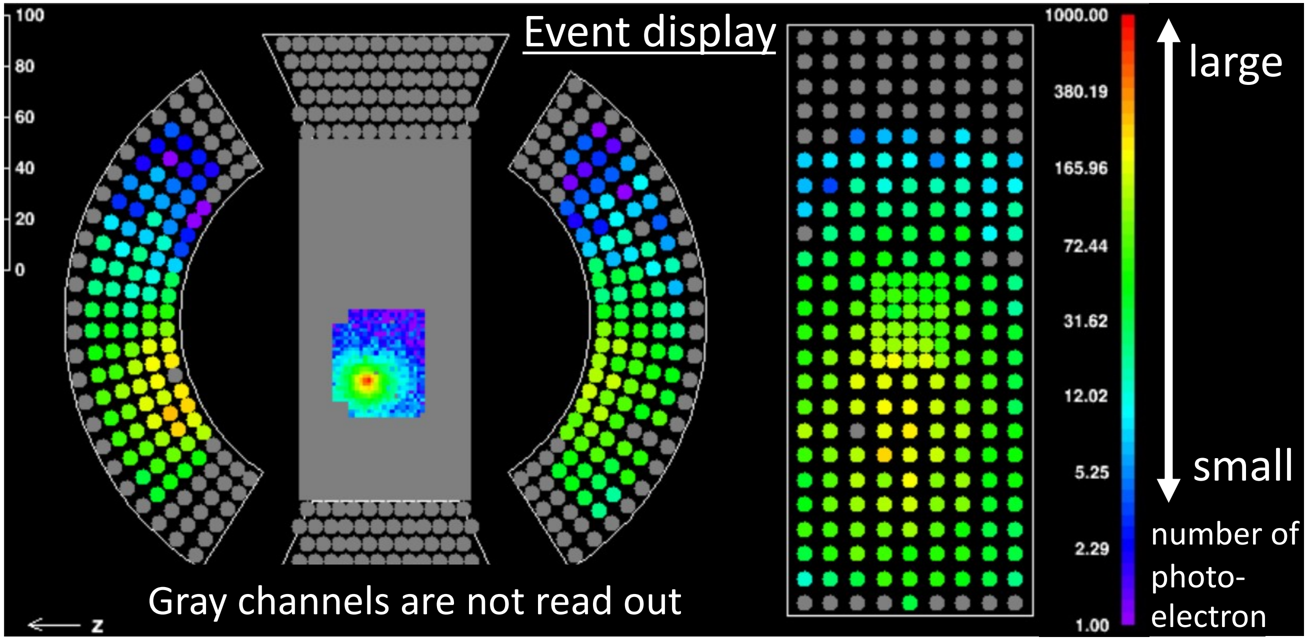
- BG γ : γ-rays from muon beam (background in μ→eγ search).
  - Mainly from radiative muon decay (RMD) on target.
  - Gamma-ray energy up to 52.8MeV.
- CW Li : 17.6 MeV monochromatic γ-ray from ${}^{7}_{3}\mathrm{Li}(\mathrm{p},\gamma){}^{8}_{4}\mathrm{Be}$.
- Calibration data : LED for gain calibration, 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 ~ 8×10^5
  - Signal amplification
    by a factor of 2.5
  - waveform digitization
    by 1.2GHz sampling


Event display

Gray channels are not read out

large

small

number of photo-electron

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Measured performance

Improvements

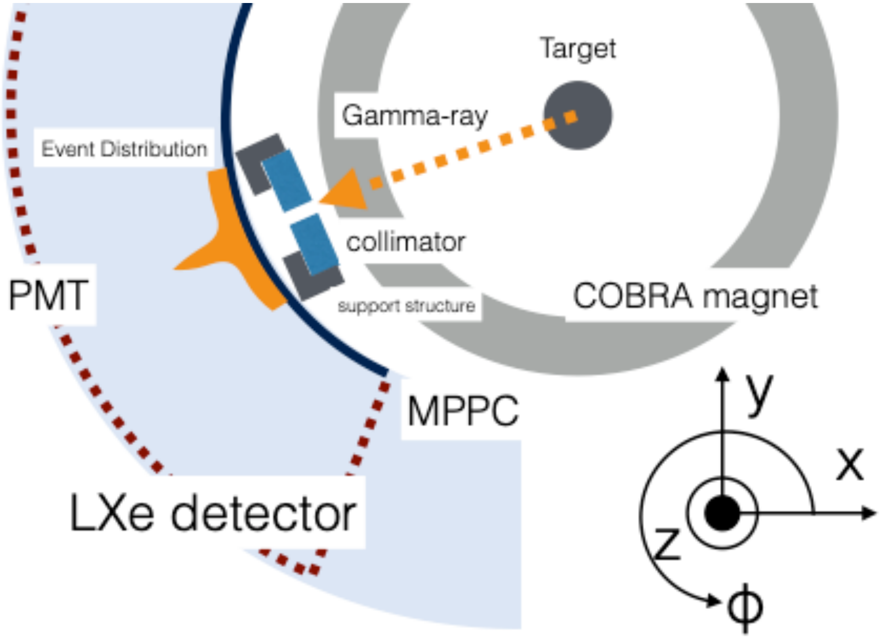
- Position resolution for shallow events
- Energy resolution for shallow events
- Better timing resolution by analysis optimization
- Reduction of background by AIF 2γ events identification

Issues

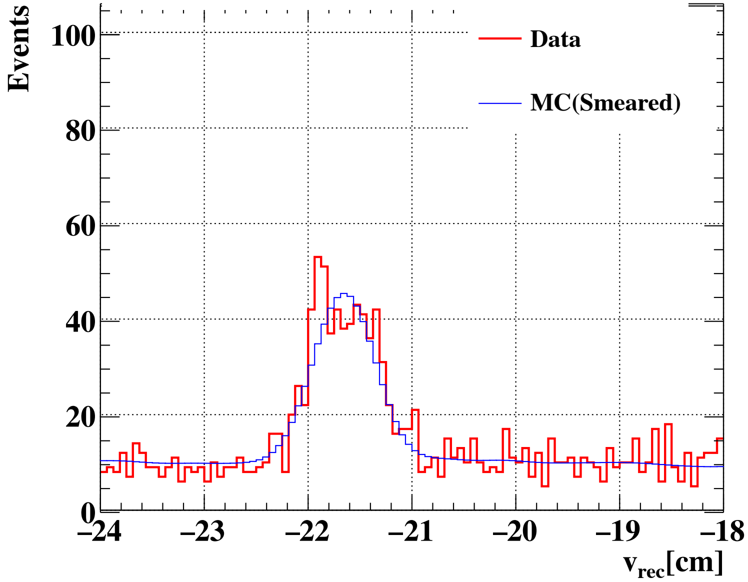
- Unknown contribution on energy resolution
- Faster PMT Gain degradation than expected
- MPPC PDE degradation by beam radiation
- Angular dependence of MPPC PDE

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

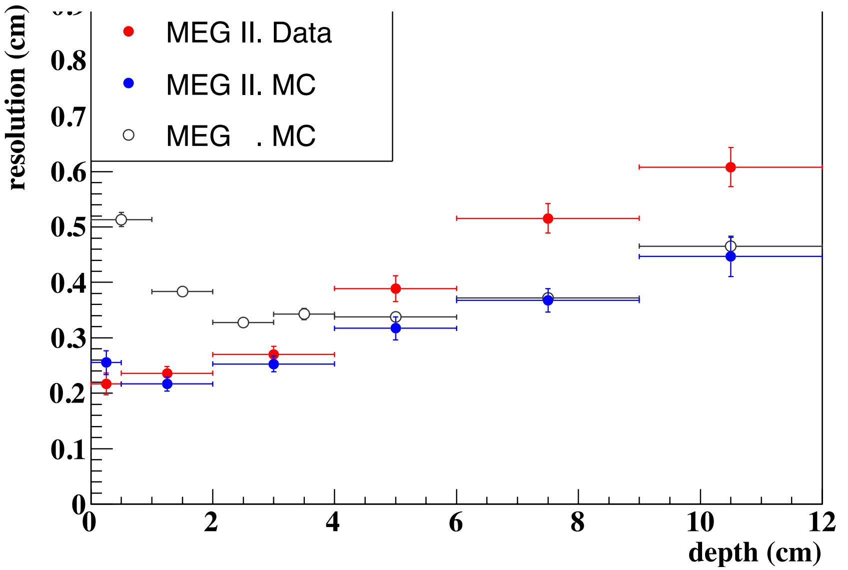
- Resolution improvement for shallow events is demonstrated.

→ 30 % sensitivity improvement

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

→ 5% sensitivity degradation
(effect limited thanks to the small number of deep events)

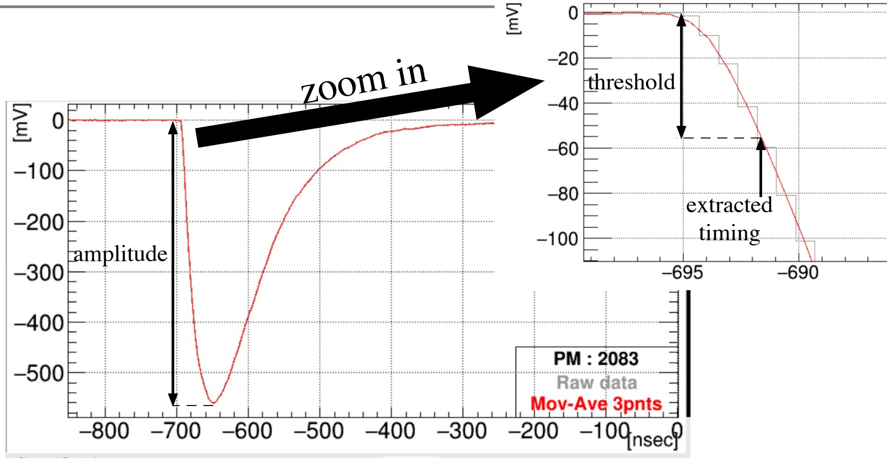
Position resolution vs γ conversion depth



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

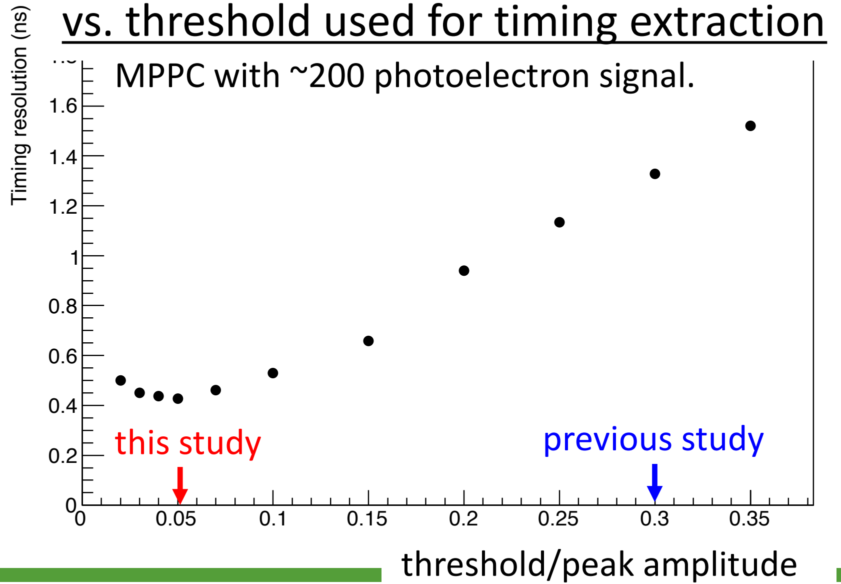
Timing resolution

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.

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



- 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

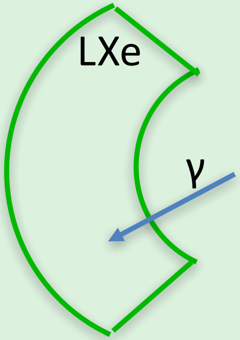
Timing resolution is estimated for BG γ-rays.

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

Intrinsic resolution of 40 ps is achieved.

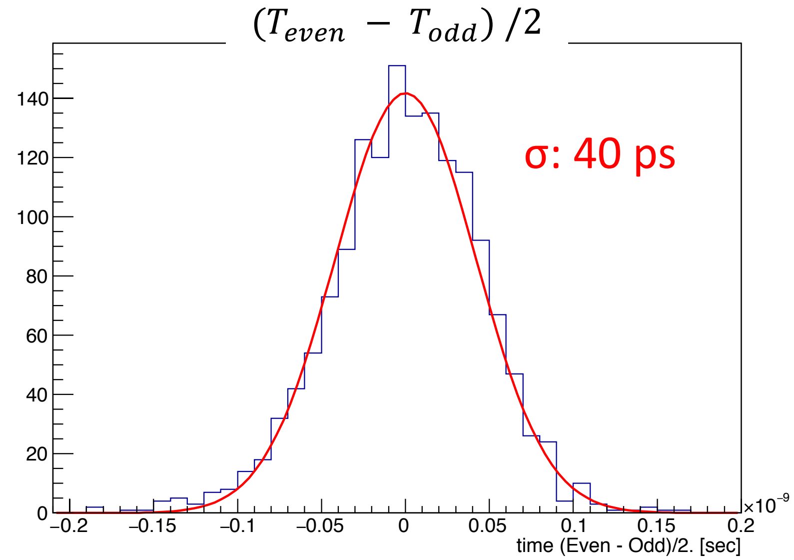
- It was 56 ps before parameter optimization.

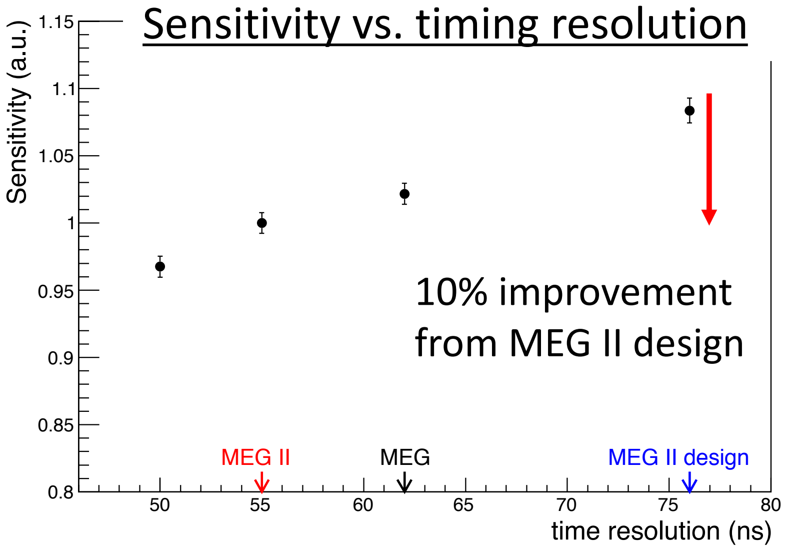
Even-odd resolution



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

Sensitivity improved by 10% from MEG II design.





Sensitivity vs. timing resolution

10% improvement from MEG II design

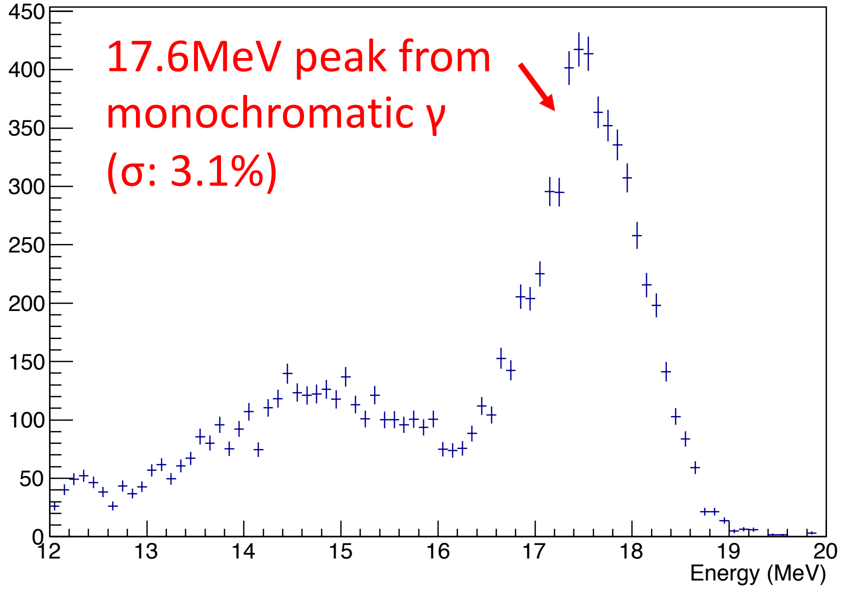
Energy resolution

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

resolution estimated for 17.6 & 52.8 MeV γ-ray.

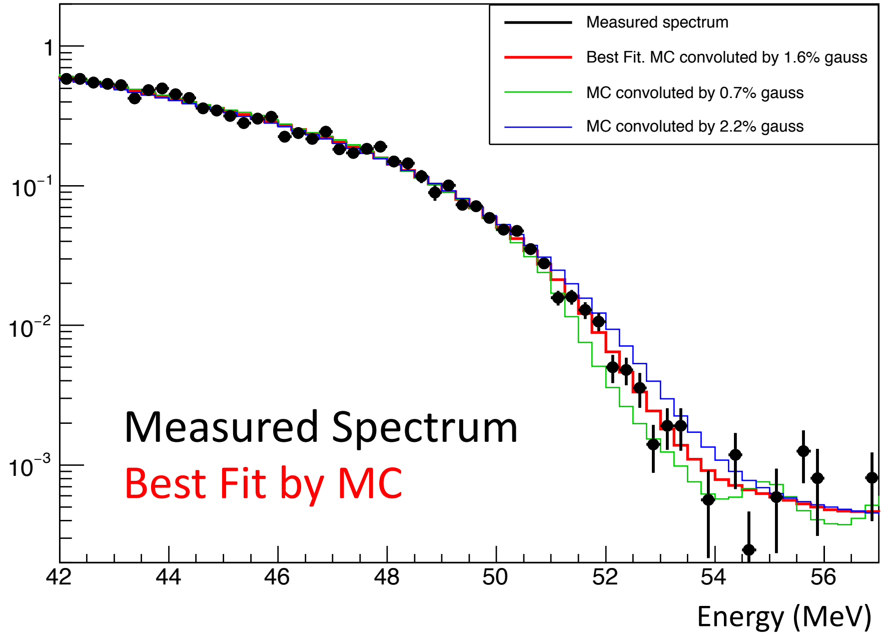
- 17.6 MeV : From monochromatic γ source (CW Li).
- 52.8 MeV : By fitting γ-ray spectrum from muon beam (mainly from RMD).

Energy spectrum of CW Li γ



17.6MeV peak from monochromatic γ (σ: 3.1%)

Energy spectrum of BG γ (mainly RMD)



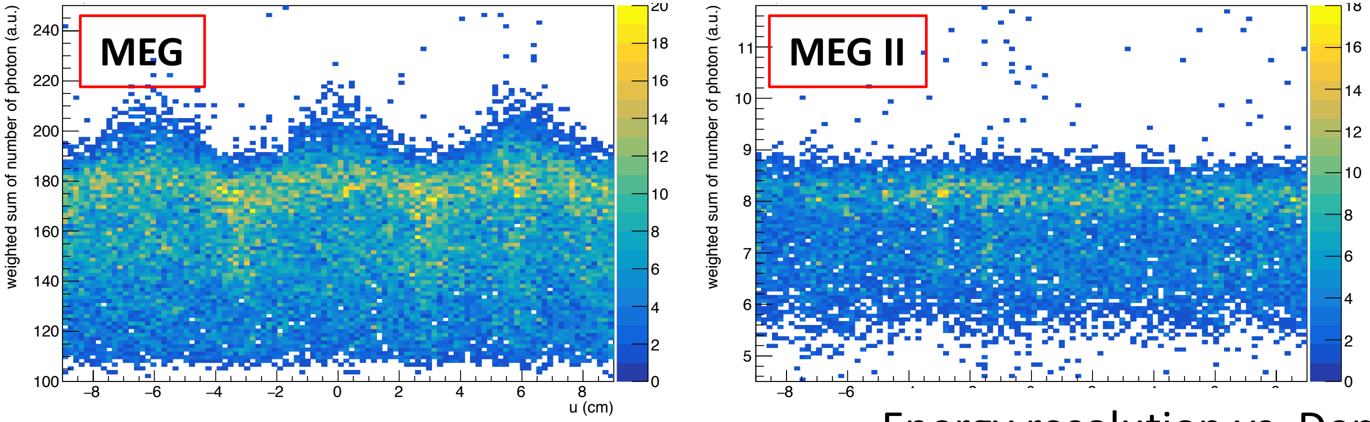
Measured Spectrum

Best Fit by MC

Energy resolution - for shallow events-

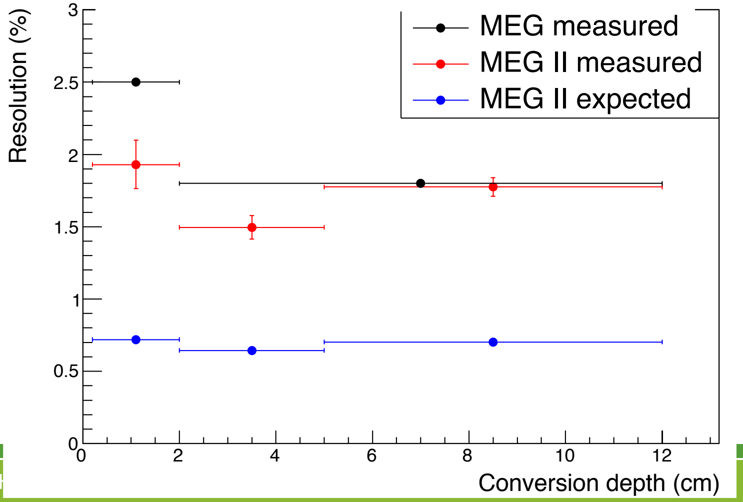
- Uniformity of the readout for the shallow events improved.
  - Thanks to the replacement to MPPC.

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



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

Energy resolution vs. Depth

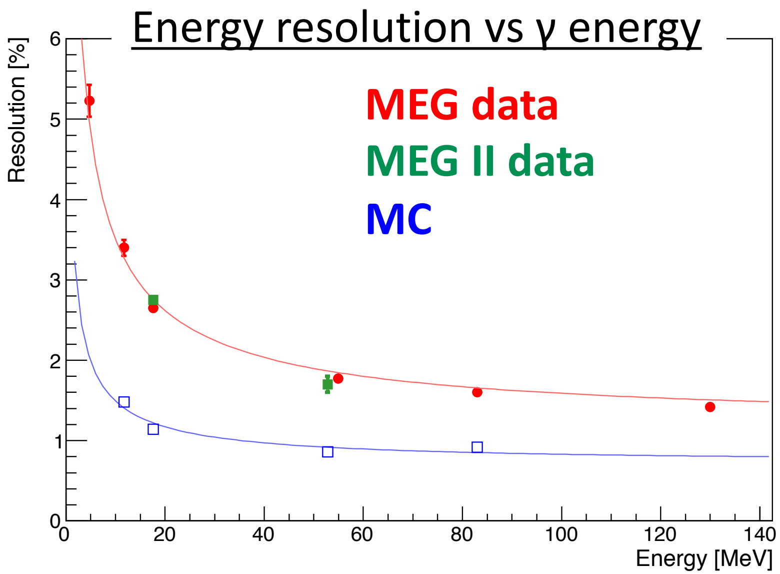


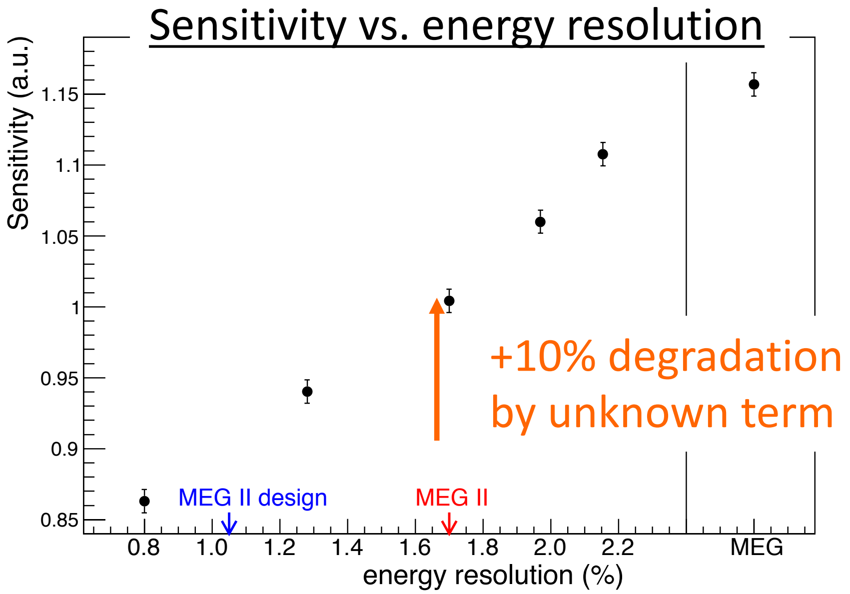
Energy resolution -unknown term-

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 vs γ energy


Sensitivity vs. energy resolution

+10% degradation by 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. $1/\sqrt{\mathrm{Number\ of\ photoelecton}}$).

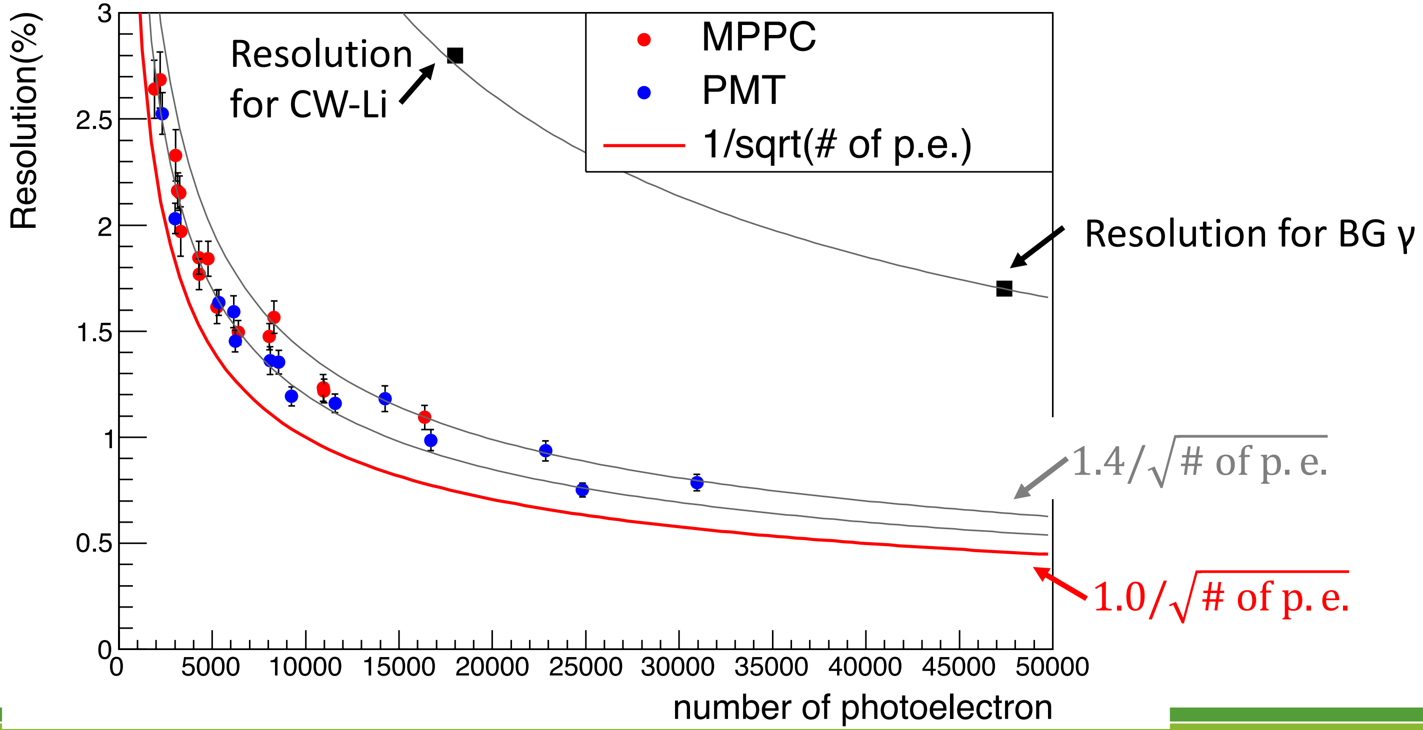
- For the investigation, “even-odd energy resolution” is investigated.
  - Event-by event fluctuation of
    $$E_\gamma\,(\mathrm{all\ ch.}) = E_\gamma\,(\mathrm{even\ ch.}) + E_\gamma\,(\mathrm{odd\ ch.})$$
    is measured to be larger than simulation.
  - By checking the fluctuation of
    $E_\gamma\,(\mathrm{even\ ch.}) - E_\gamma\,(\mathrm{odd\ ch.})$,
    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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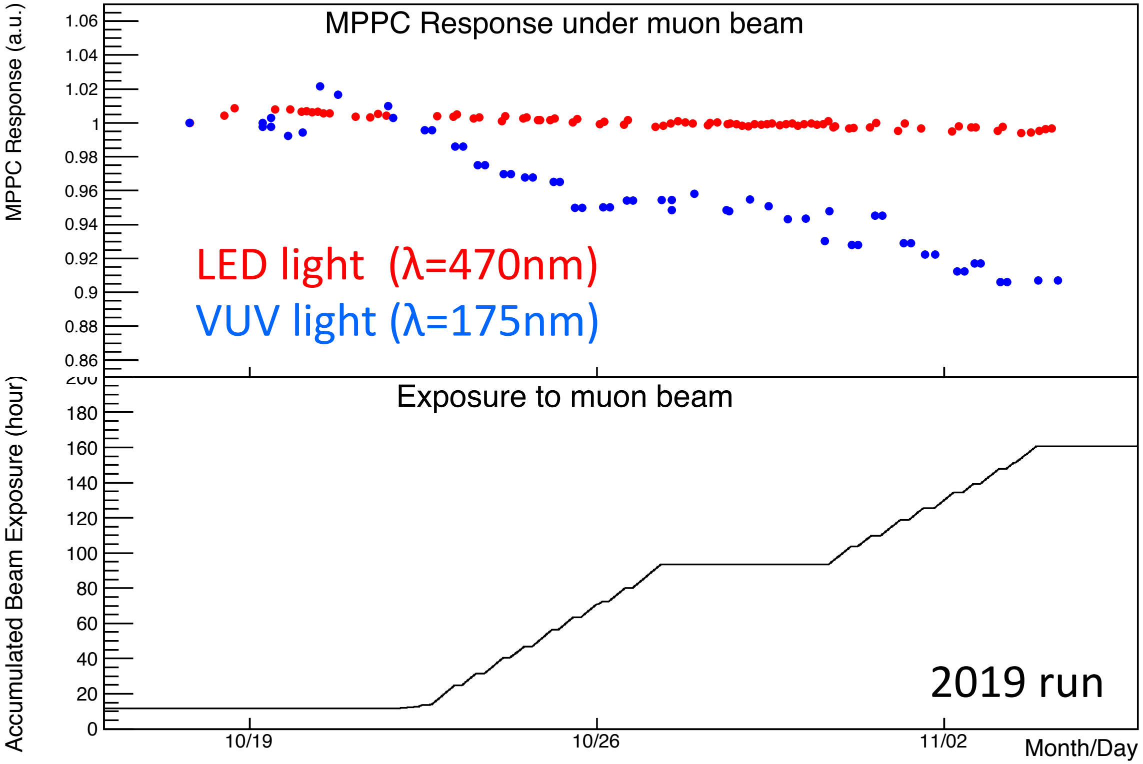
MPPC VUV PDE degradation

A degradation of MPPC PDE (検出効率) for VUV light is found.

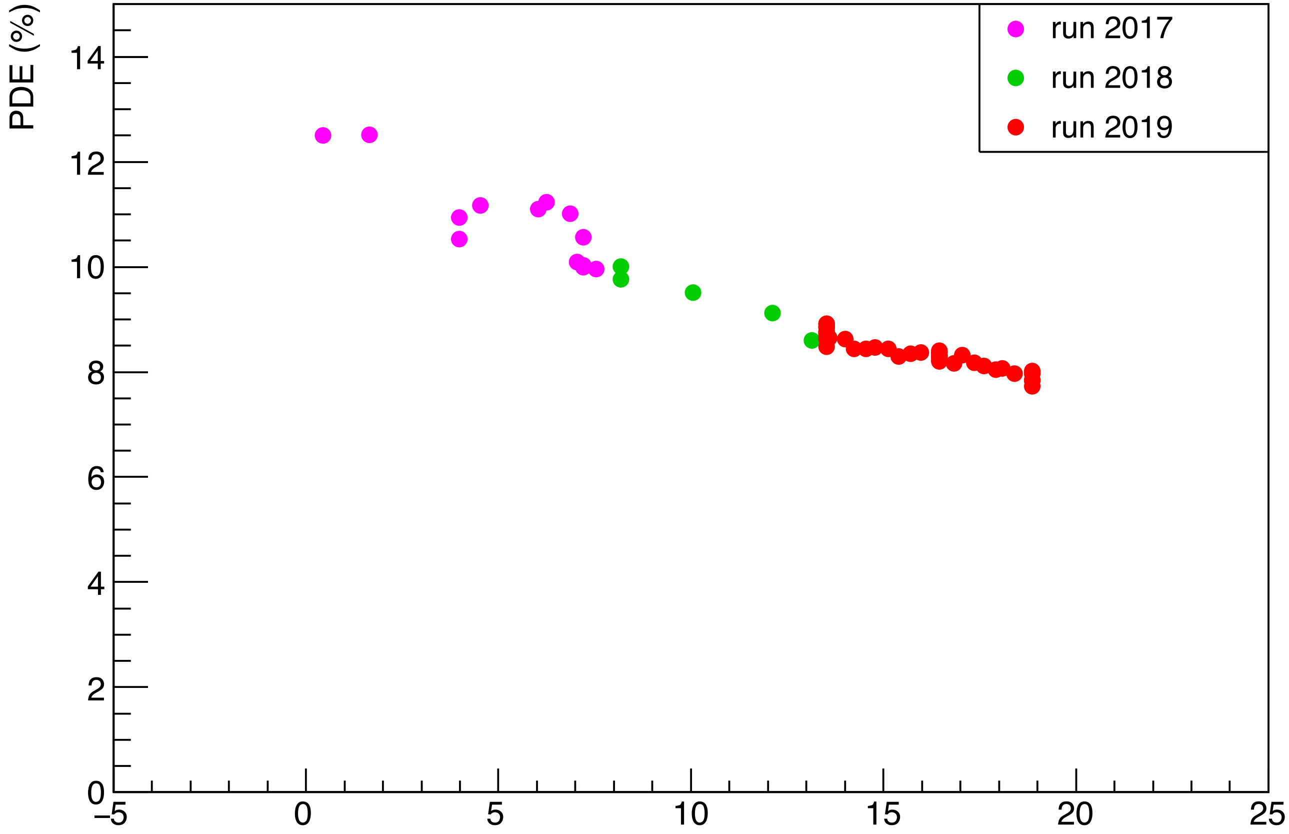
- Correlated with the beam usage -> Should be a kind of radiation damage.
- Obvious for VUV light. -9(2)% by 160 hours MEG II beam usage.



MPPC VUV PDE degradation (cont’d)

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

PDE vs. accumulated beam usage

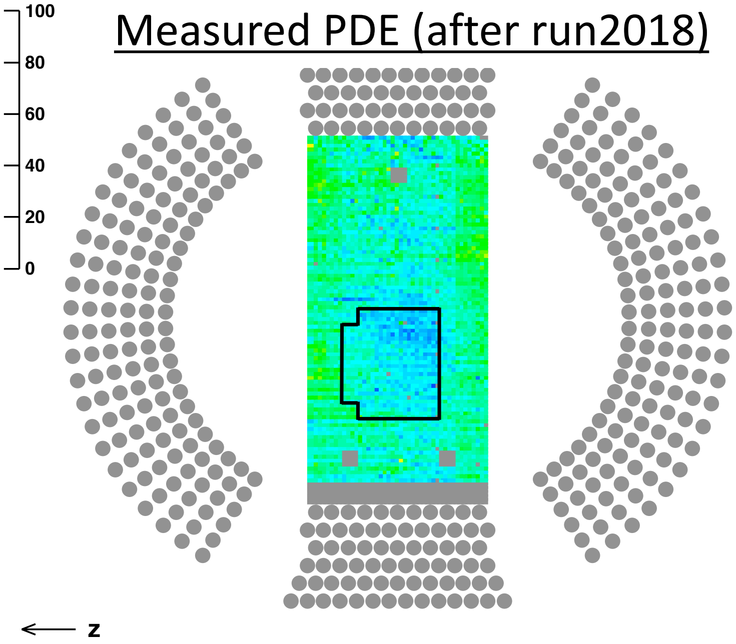


Beam usage [Day]
normalized to MEG II beam

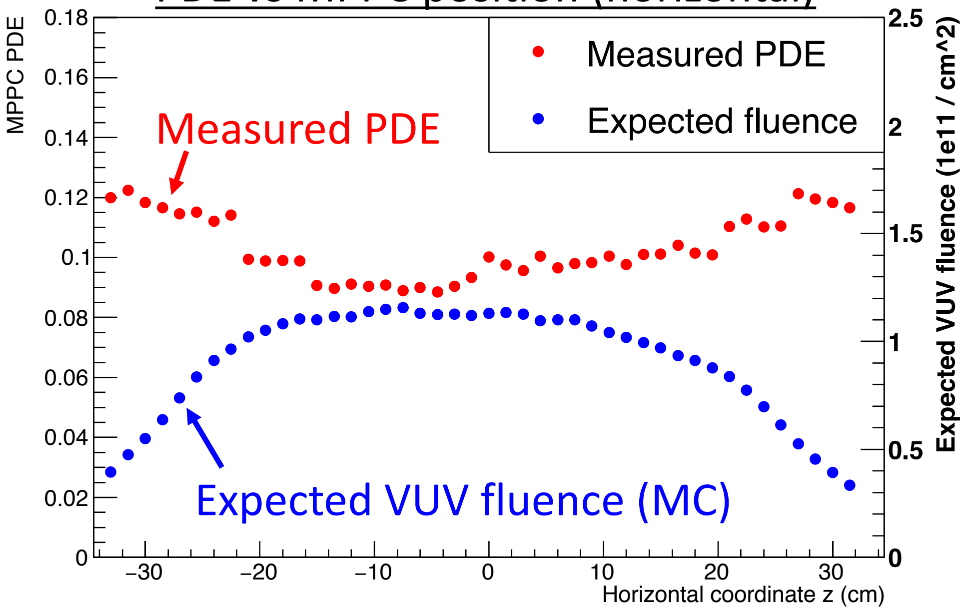
MPPC VUV PDE degradation (cont’d)

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.


Measured PDE (after run2018)

PDE vs MPPC position (horizontal)



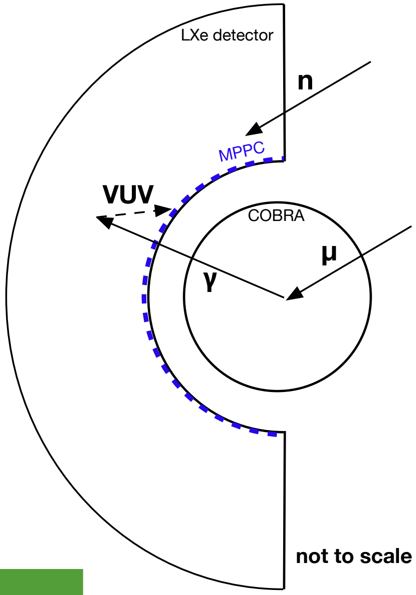
Measured PDE

Expected VUV fluence (MC)

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

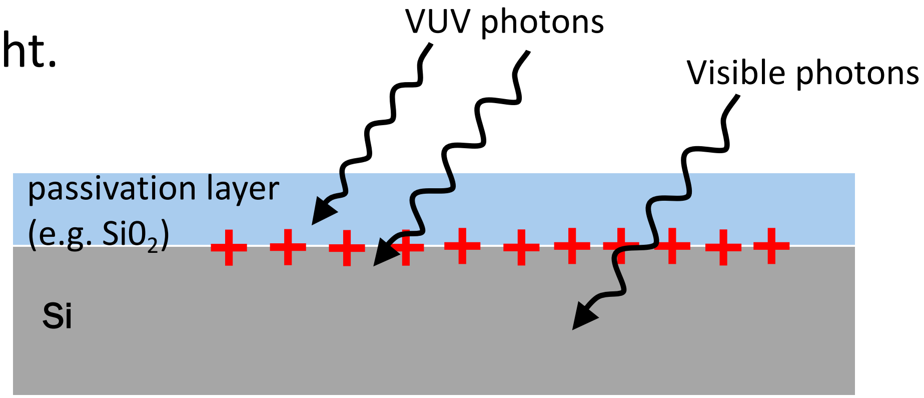
Cause of PDE degradation

Observed degradation may be related to a special detection mechanism of VUV photon in our MPPC.

- Visible photon directly reaches the sensitive region.
- Attenuation length of VUV light in silicon is only 5 nm, and VUV photons cannot directly reach the sensitive region.
  → Convert in shallow region, and drift to the sensitive region.

One hypothesis: Surface damage by VUV irradiation.

VUV irradiation
→ Accumulation of stationary charges near the sensor surface
→ Distortion of the electric field
→ Degradation of PDE only for VUV light.



Recovery of damage by annealing

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

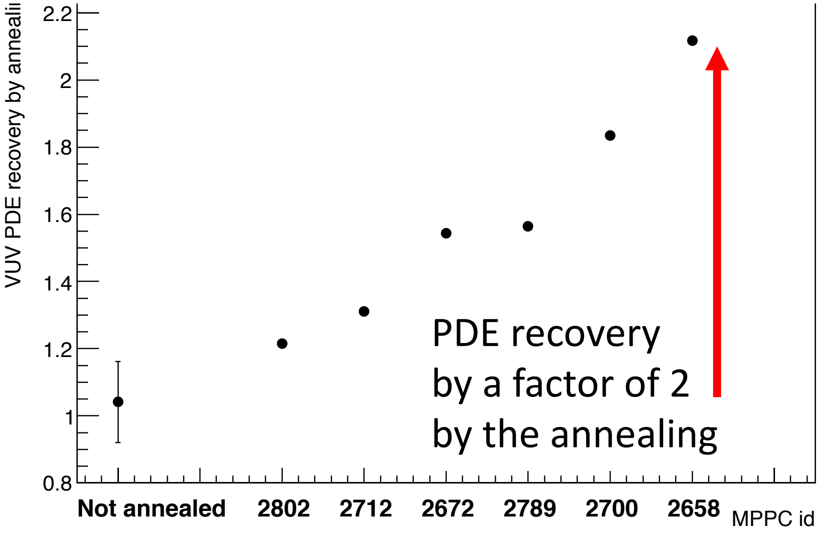
- By keeping MPPC at higher temperature,
accumulated charges can be de-trapped by thermal excitation.

→ 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)



PDE recovery
by a factor of 2
by the annealing

Effect of PDE degradation on sensitivity

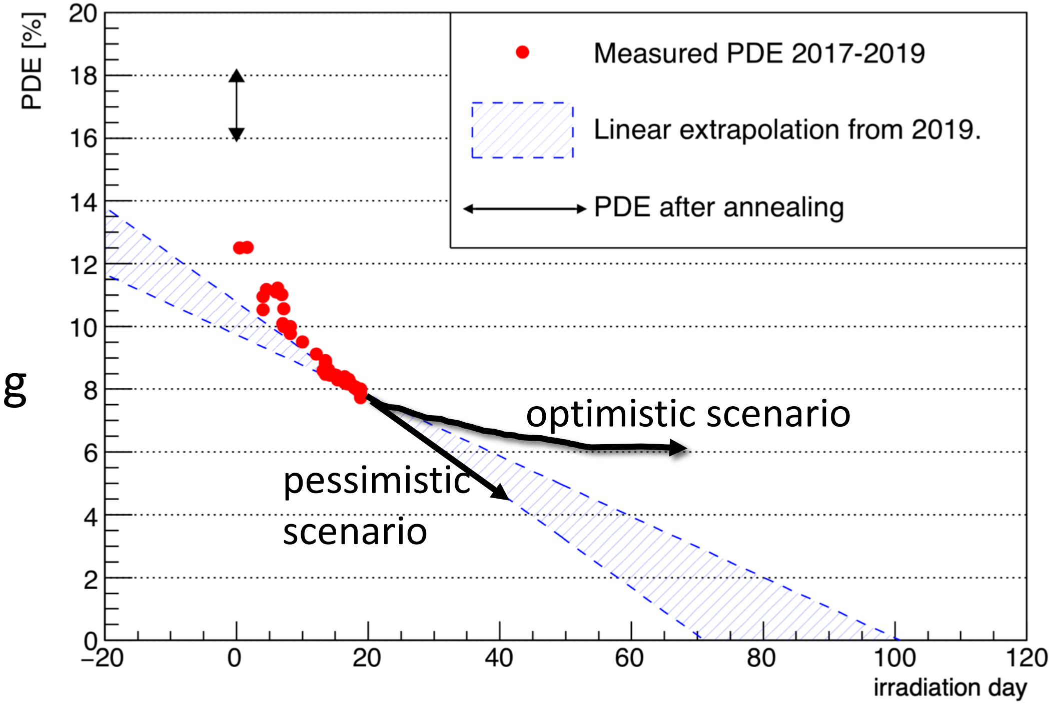
The PDE degradation may affect the sensitivity of MEG II.

- 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. Larger statistical fluctuation
   Should not be a large effect
   because statistical fluctuation of the MPPC signals is not a dominant term in the resolution.

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

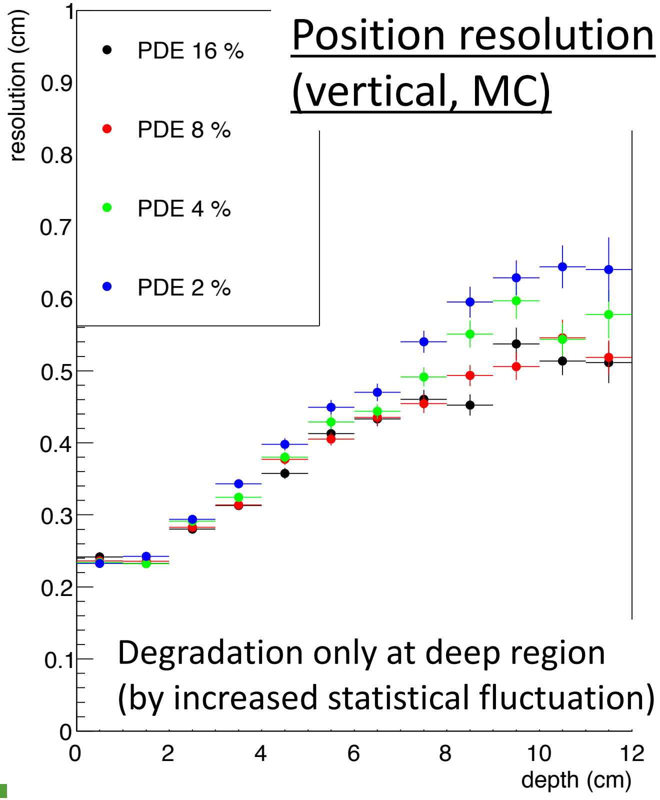
→ No crucial effect is expected on the resolution by the lower PDE.

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

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

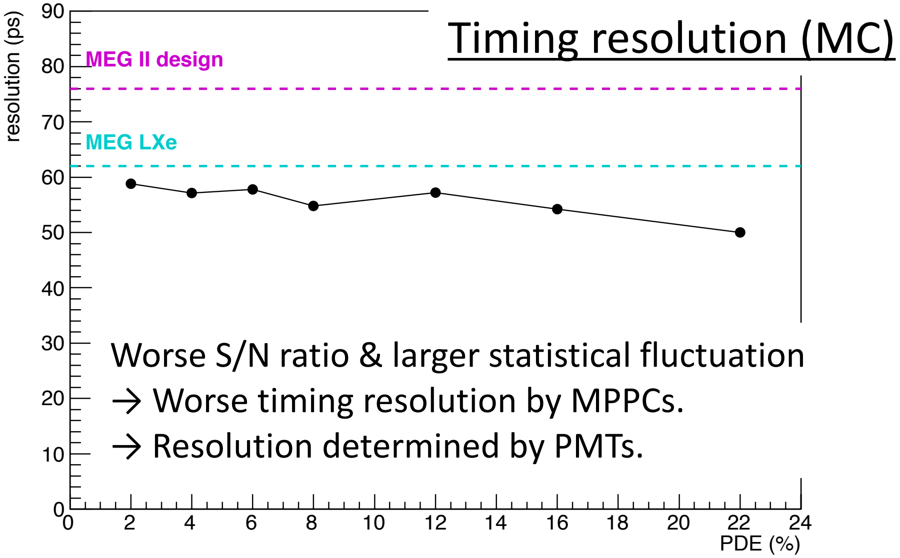
→

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



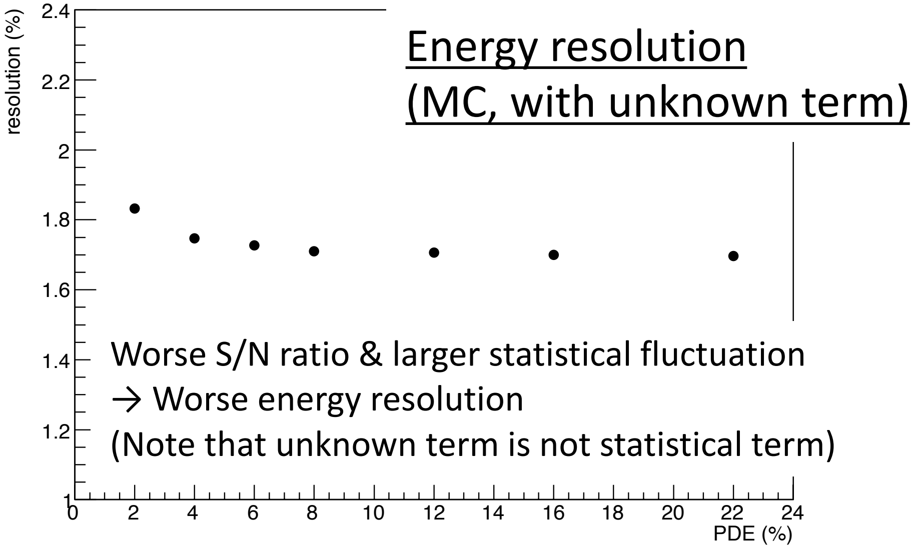
Position resolution (vertical, MC)

Degradation only at deep region
(by increased statistical fluctuation)



Timing resolution (MC)

Worse S/N ratio & larger statistical fluctuation
→ Worse timing resolution by MPPCs.
→ Resolution determined by PMTs.



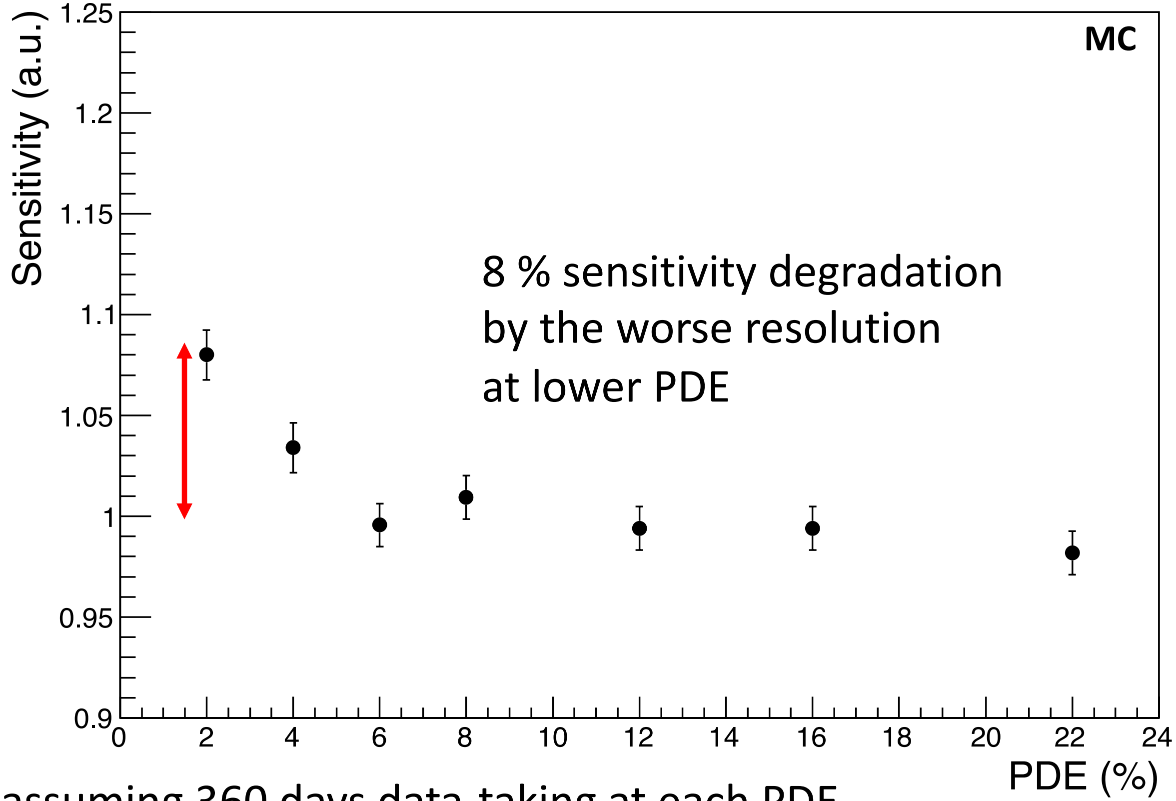
Energy resolution (MC, with unknown term)

Worse S/N ratio & larger statistical fluctuation
→ Worse energy resolution
(Note that unknown term is not statistical term)

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



8 % sensitivity degradation by the worse resolution at lower 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,
  - $Br(\mu \rightarrow e\gamma) = 9.4 \times 10^{-14}$ (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.
  - $Br(\mu \rightarrow e\gamma) = 6.6 \times 10^{-14}$ (90% C.L., by 3 years DAQ)

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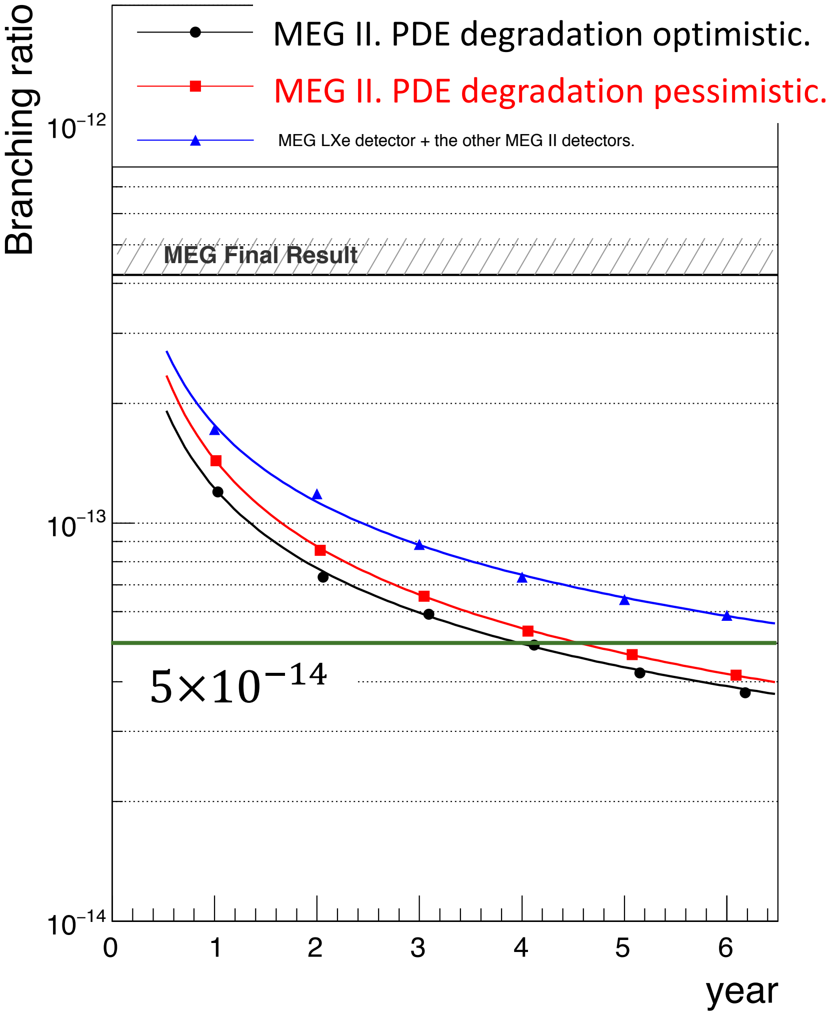
Expected sensitivity

- 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



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Conclusion (same as 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.

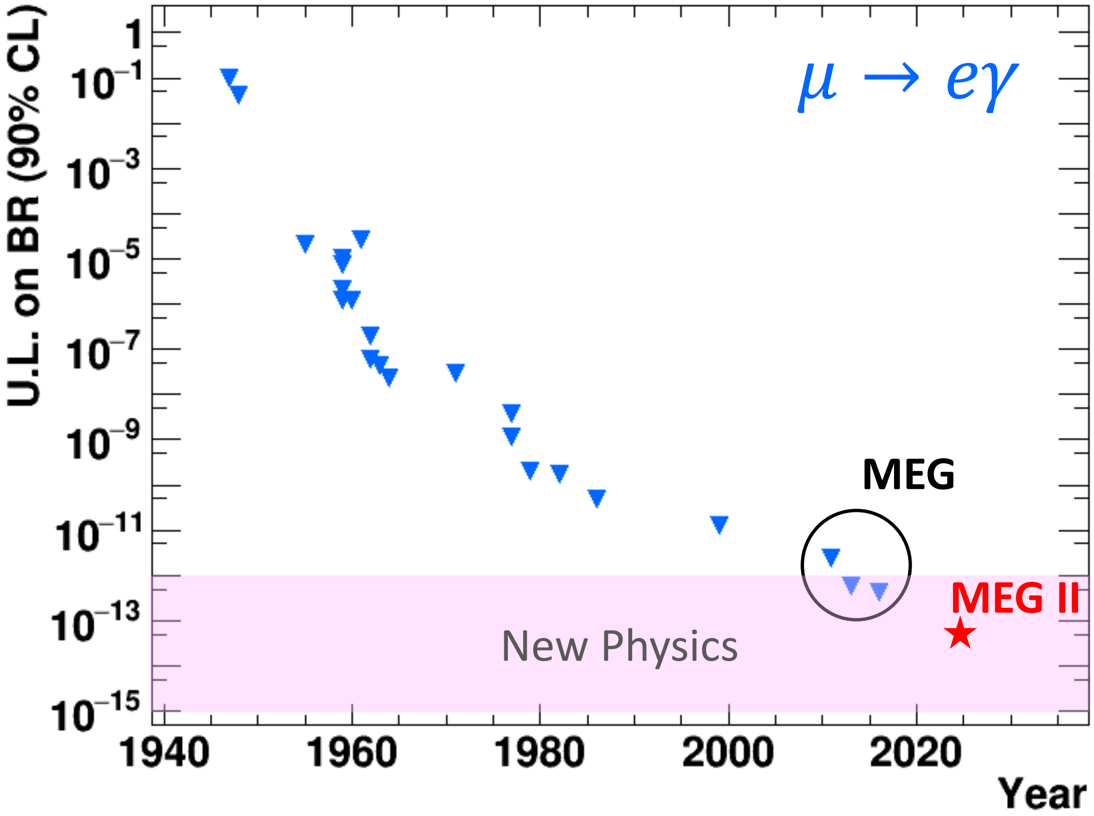
- The detector construction and commissioning was conducted, and the performances have been measured.
  - Resolution improvements realized by the MPPCs have been demonstrated.
  - An unexpected radiation damage on the MPPCs was found.

- 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 5×10^{-14}.

BACKUP
-intro/design-

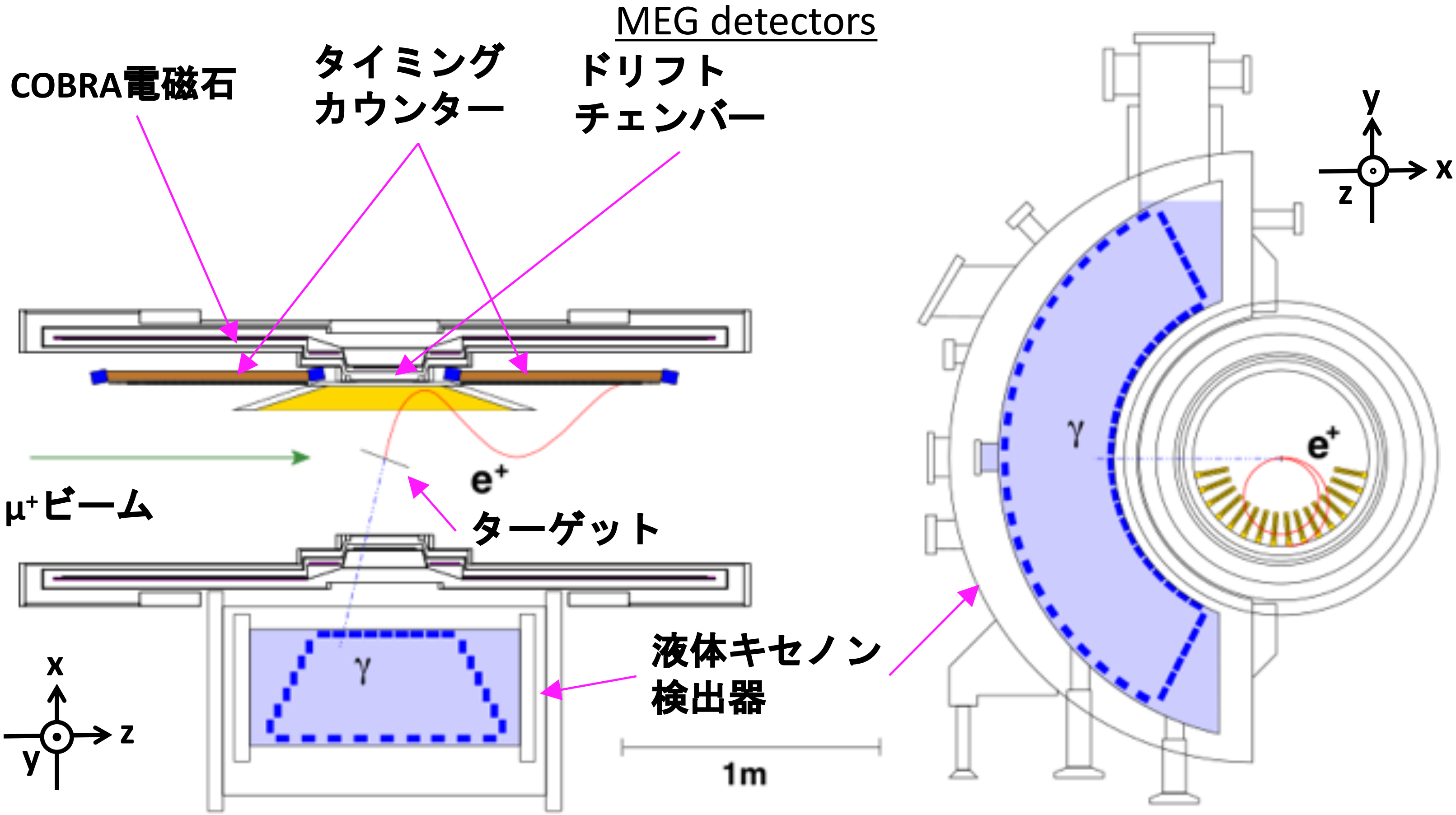
a

a

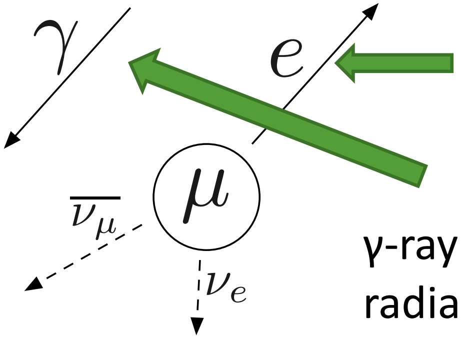

U.L. on BR (90% CL)
1
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
1940
1960
1980
2000
2020
Year
$\mu \rightarrow e\gamma$
MEG
MEG II
New Physics

MEG Detectors

aa

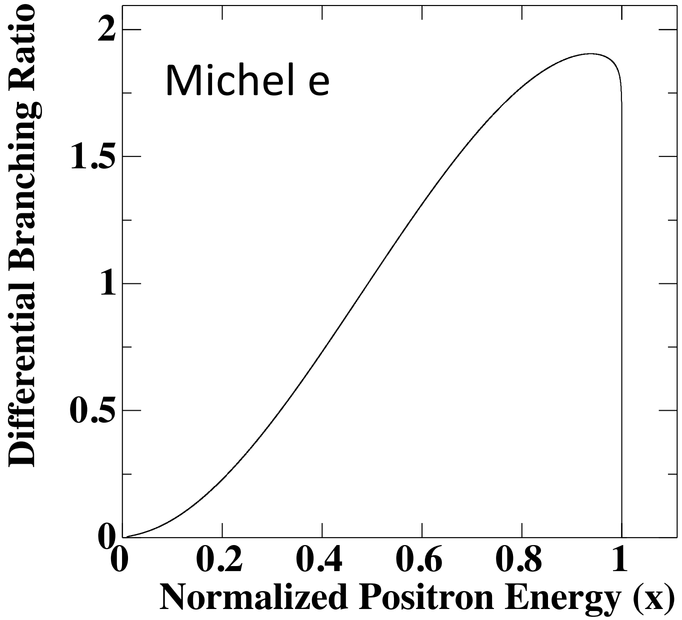


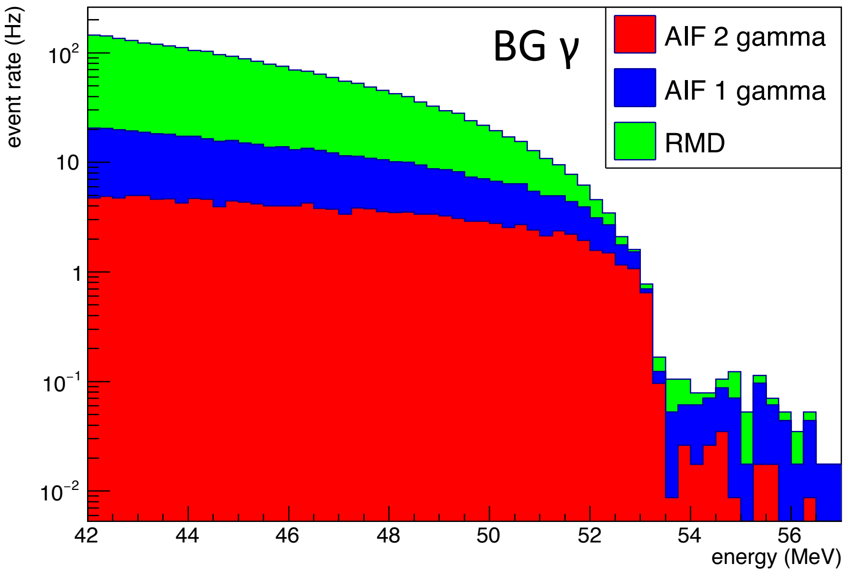
Source of Acc. BG



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





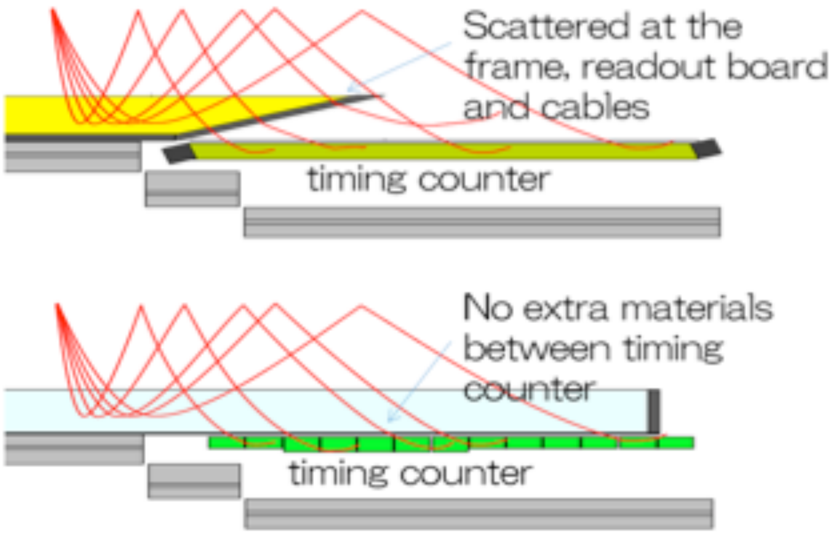
Single event sensitivity

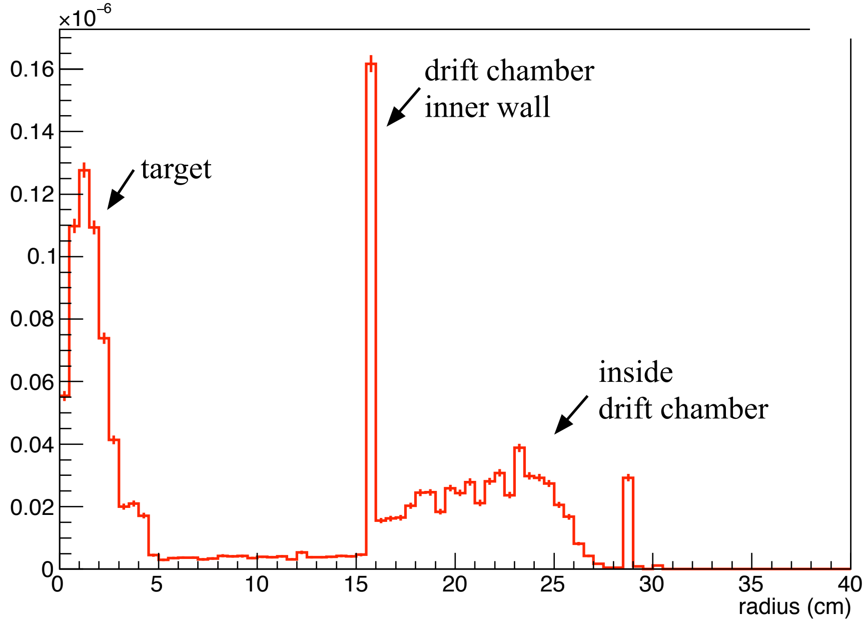
Single event sensitivity = 1/k
k = number of muon decay

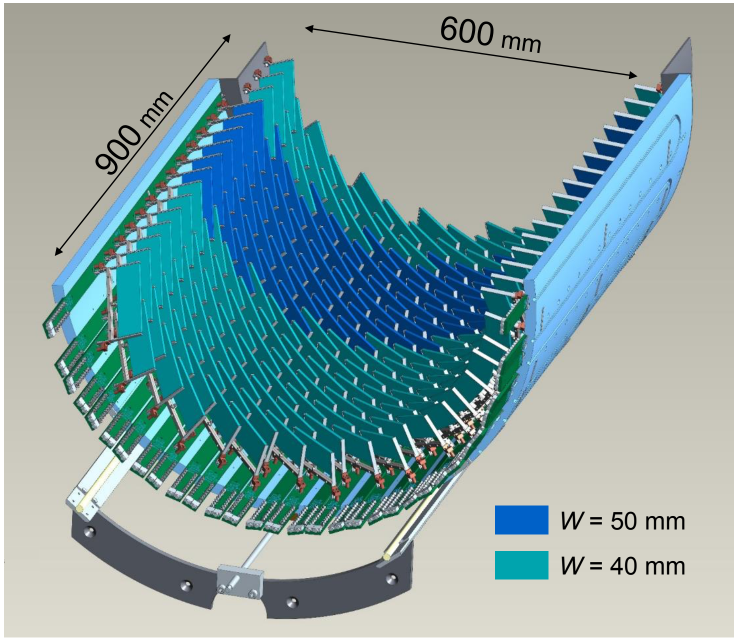
	DAQ	single event sensitivity ($\times10^{-14}$)	sensitivity ($\times10^{-14}$)
MEG	3e7 x 4.5 year	5.8	53
MEG II design	7e7 x 3 year	0.97	5
MEG II plan A	7e7 x 3 year (x0.5)	1.9	9.3
MEG II plan B	3.5e7 x 3 year	1.9	6.6

Positron detectors

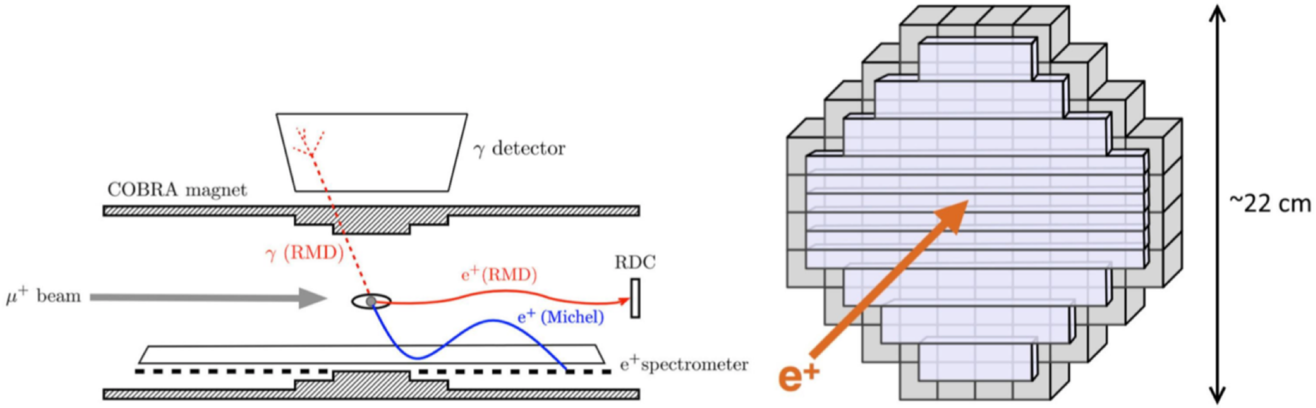
a





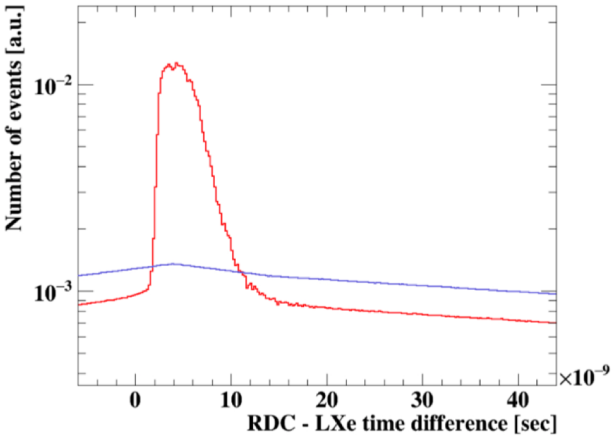


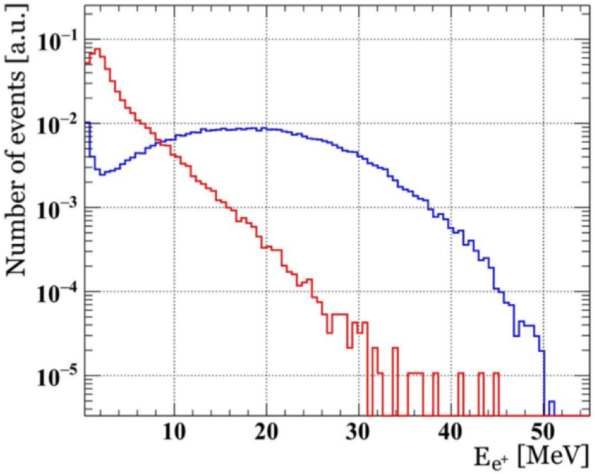
RDC



(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

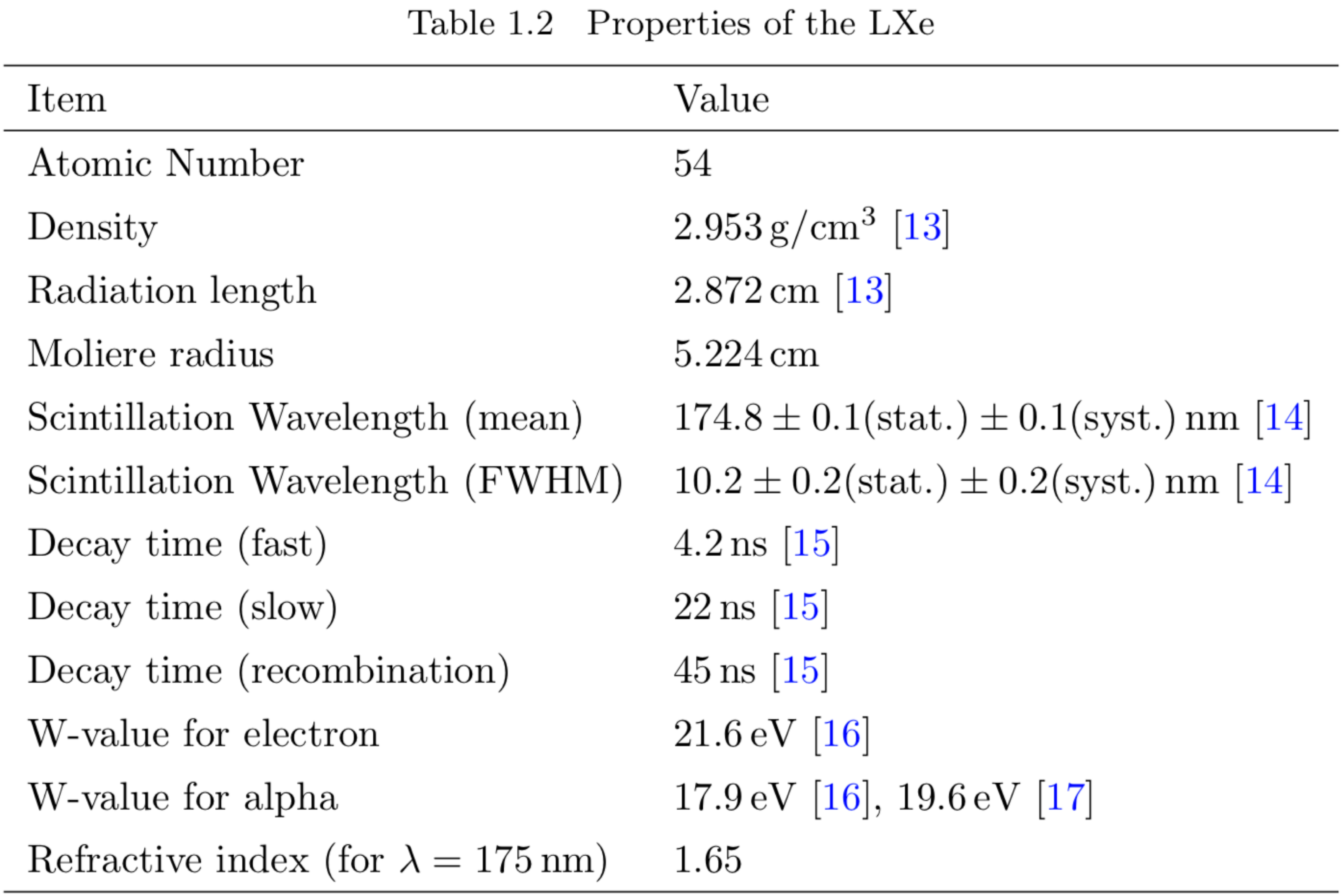


Table 1.2 Properties of the LXe

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

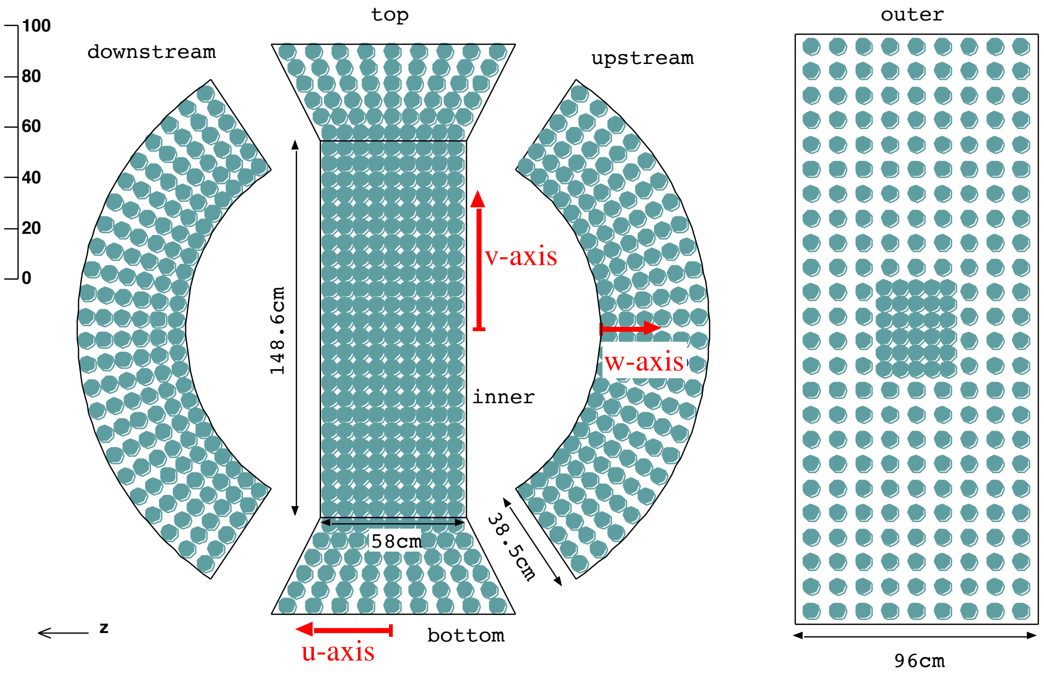
excitation

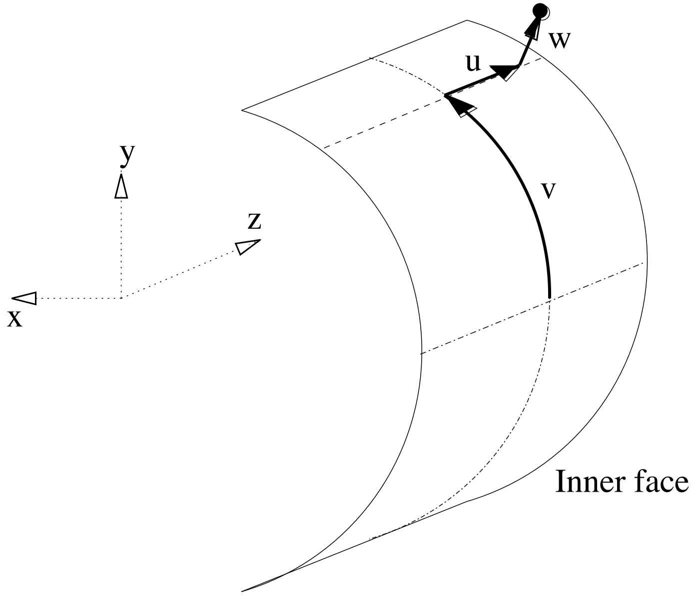
$$\mathrm{Xe}^* + \mathrm{Xe} + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^* + \mathrm{Xe}$$
$$\mathrm{Xe}_2^* \rightarrow 2\mathrm{Xe} + h\nu$$

ionization

$$\mathrm{Xe}^+ + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^+$$
$$\mathrm{Xe}_2^+ + e^- \rightarrow \mathrm{Xe}^{**} + \mathrm{Xe}$$
$$\mathrm{Xe}^{**} \rightarrow \mathrm{Xe}^* + \mathrm{heat}$$
$$\mathrm{Xe}^* + \mathrm{Xe} + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^* + \mathrm{Xe}$$
$$\mathrm{Xe}_2^* \rightarrow 2\mathrm{Xe} + h\nu$$

LXe detector local coordinate





def

$$u = z$$

$$v = \tan\left(-y/x\right) \times R_{in}$$

$$w = \sqrt{x^2 + y^2} - R_{in}.$$

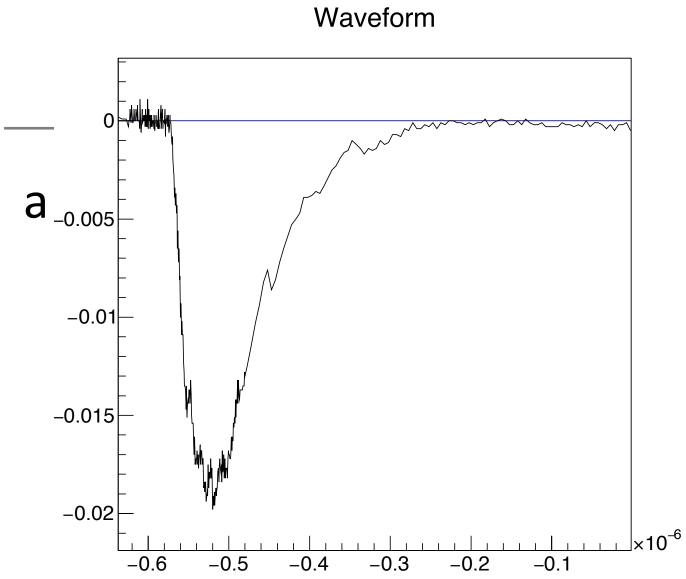
fiducial

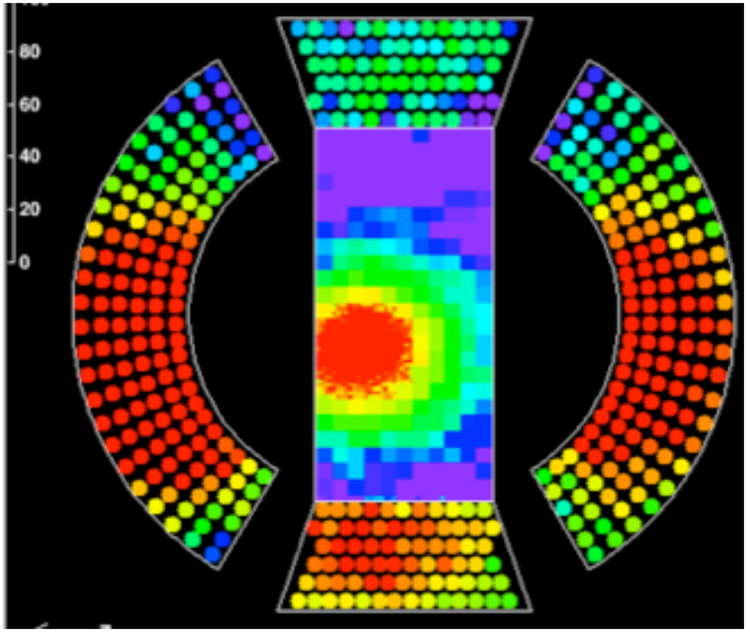
$$|u| < 23.9 \text{ cm}$$

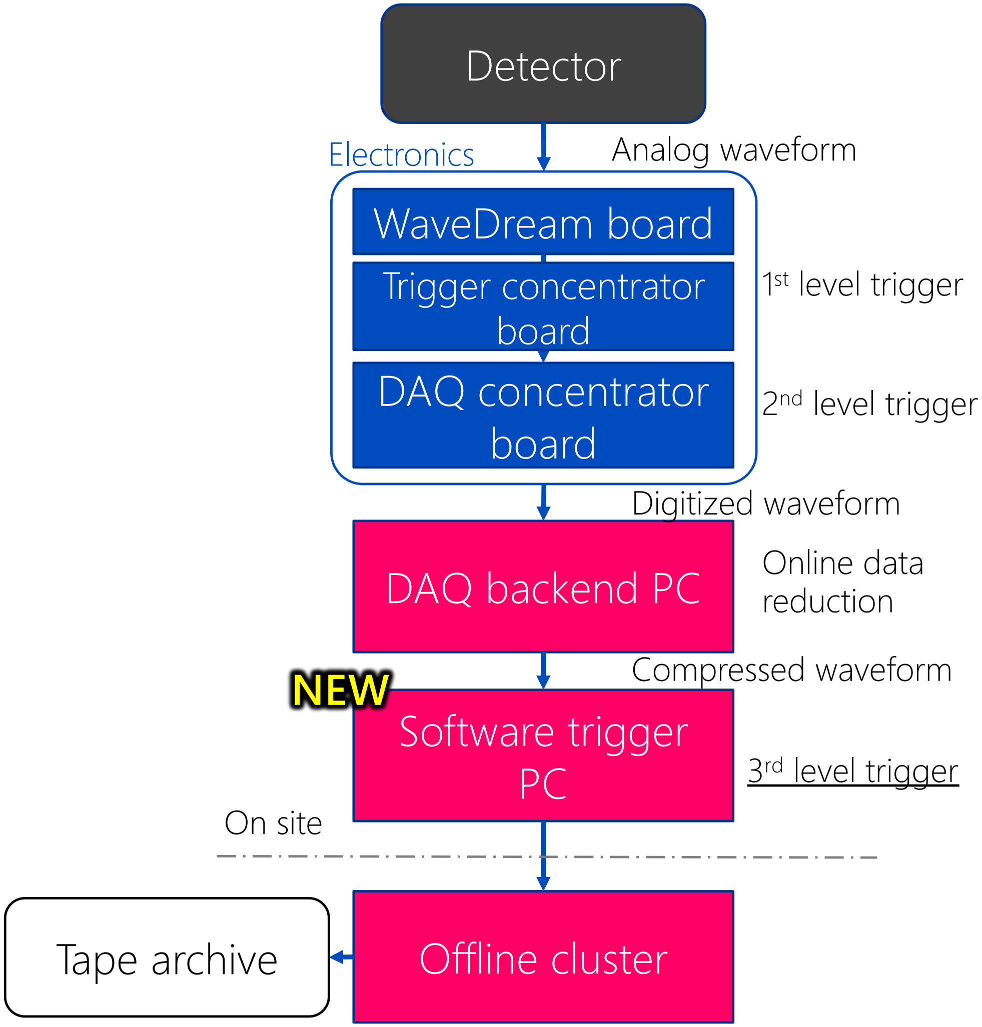
$$|v| < 67.9 \text{ cm}$$

$$0 < w < 38.5 \text{ cm}.$$

Data reduction







Detector

Electronics

Analog waveform

WaveDream board

Trigger concentrator board

DAQ concentrator board

1st level trigger

2nd level trigger

Digitized waveform

DAQ backend PC

Online data reduction

Compressed waveform

NEW

Software trigger PC

3rd level trigger

On site

Tape archive

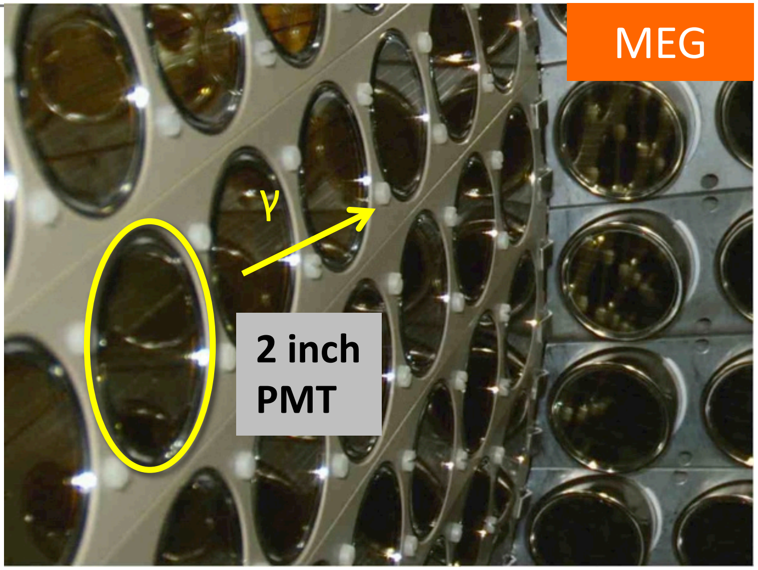
Offline cluster

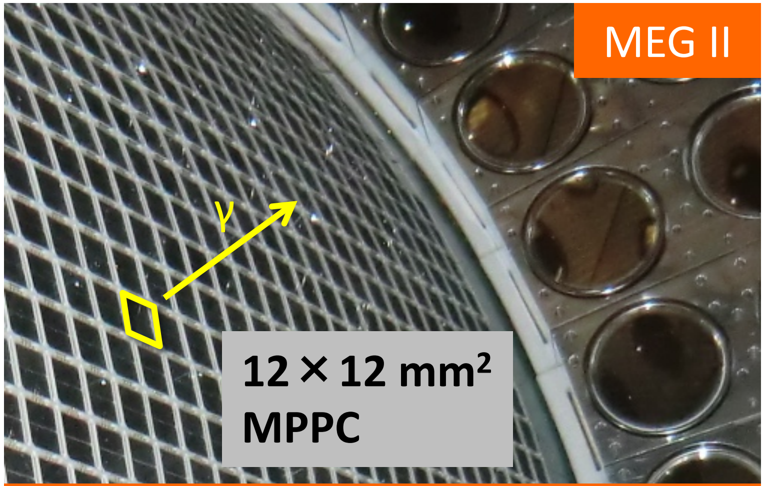
LXe γ-ray detector in MEG II

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 mm^2 MPPCs.**

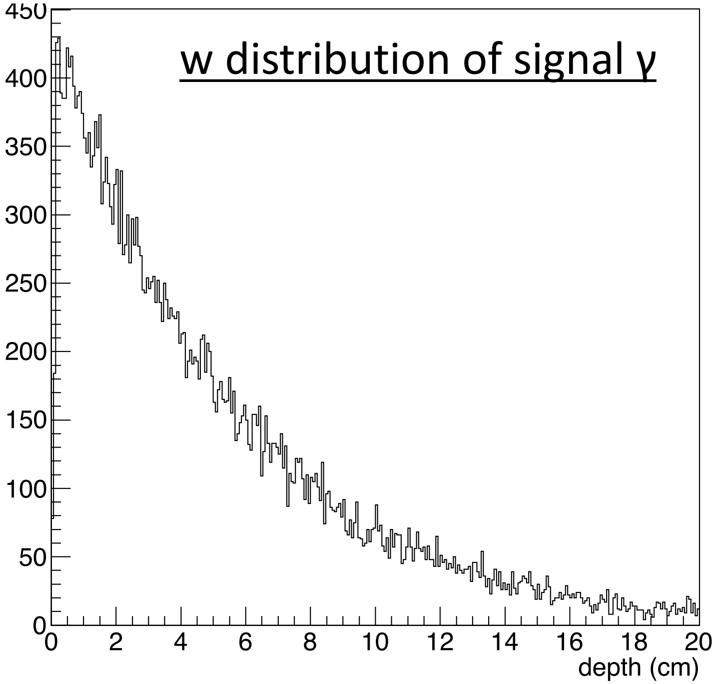
- **Better position resolution** from higher granularity.
- **Improved energy resolution** from better uniformity of scintillation readout.
- **Increased detection efficiency** from reduced material of the γ-entrance face.





~1 m^2 is covered by MPPC !

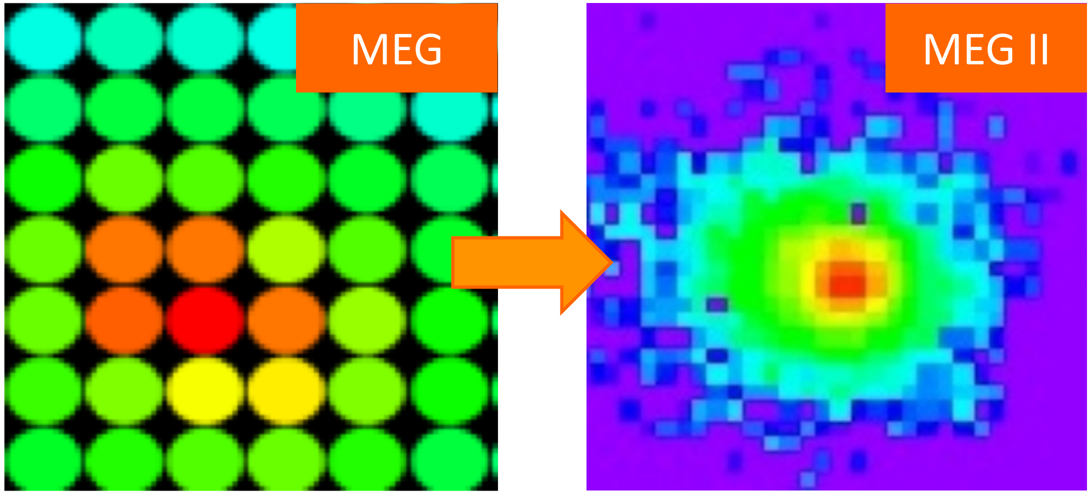
LXe γ-ray detector in MEG II

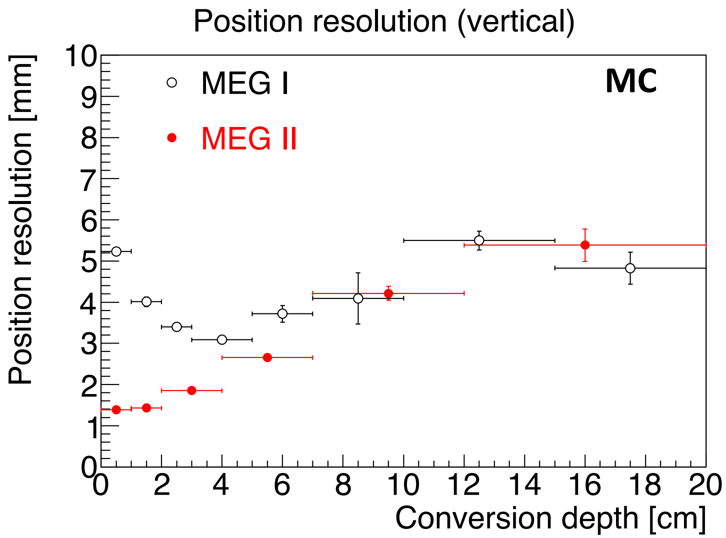


1. Better position resolution

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

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

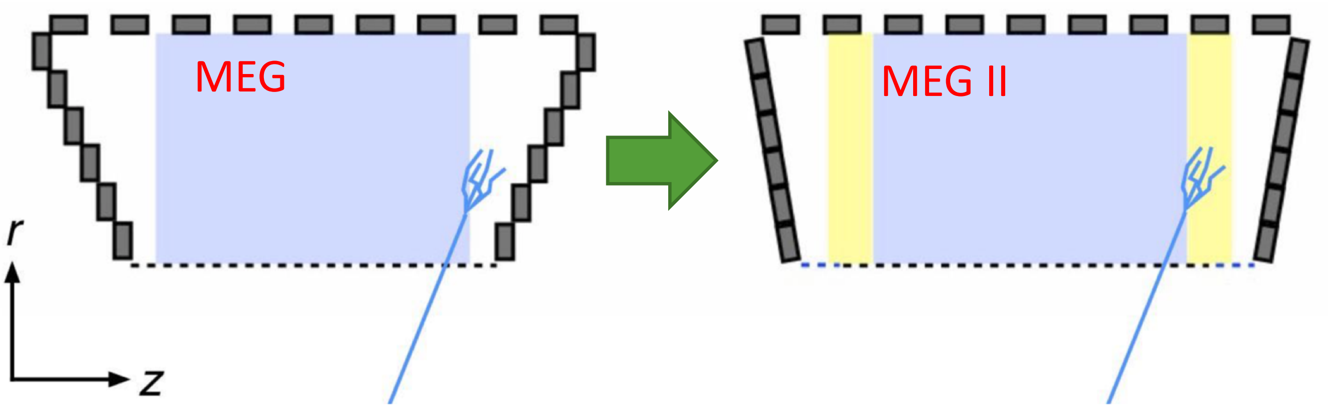




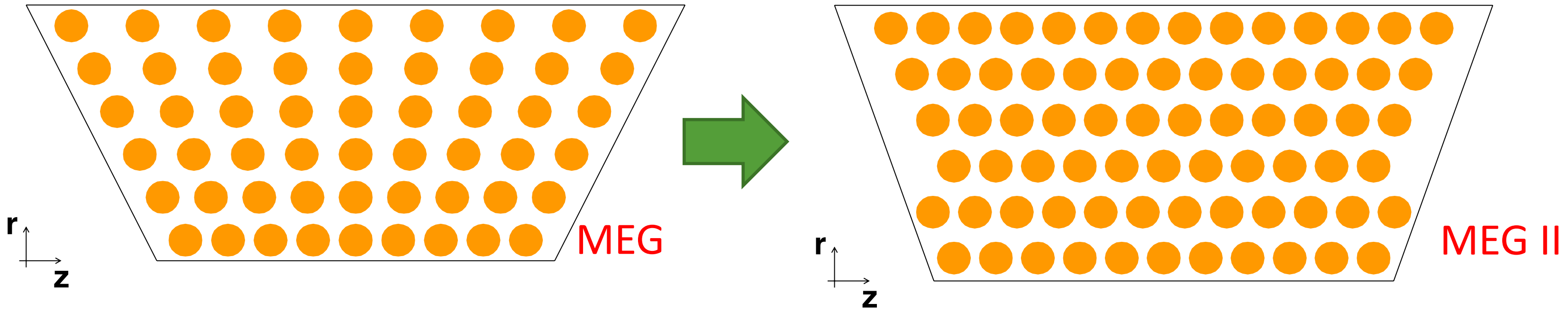
PMT layout

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.



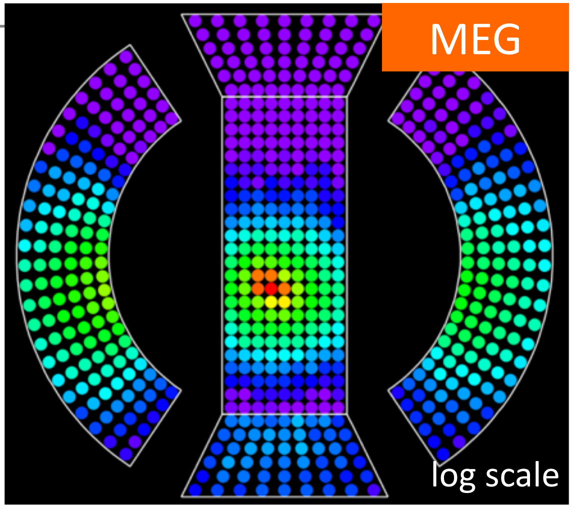
Expected performance

Significant improvement is expected for resolutions and efficiency.

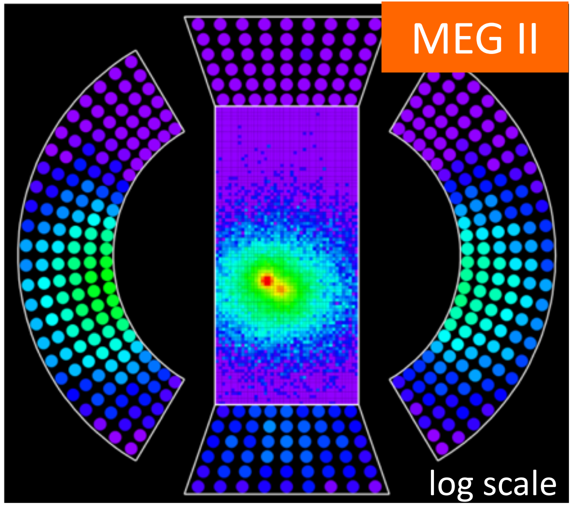
Detector performance for signal γ-ray

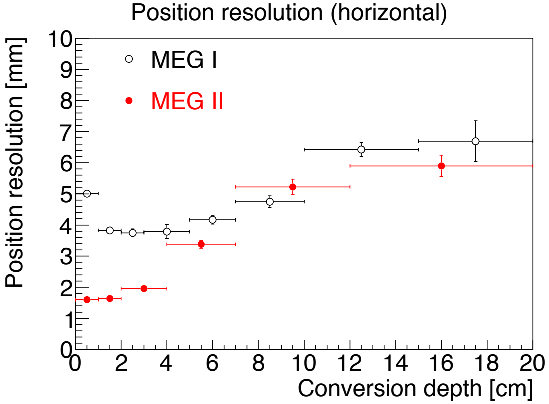
	MEG (measured)	**MEG II (simulated)**
σ (position)	~5 mm	~2.5 mm
σ (energy)	~2%	0.7 - 1.5%
σ (timing)	67 ps	50 - 70 ps
Efficiency	65%	70%

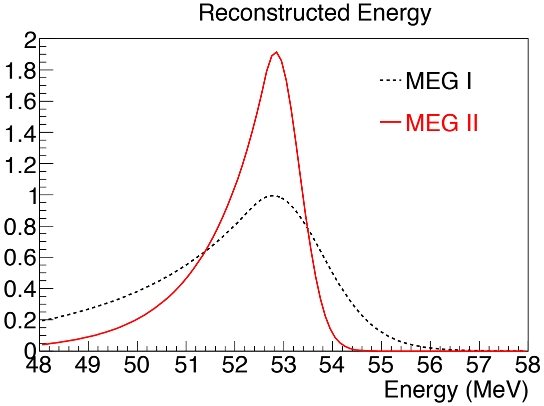
improve by a factor of **2**!



Imaging power improves

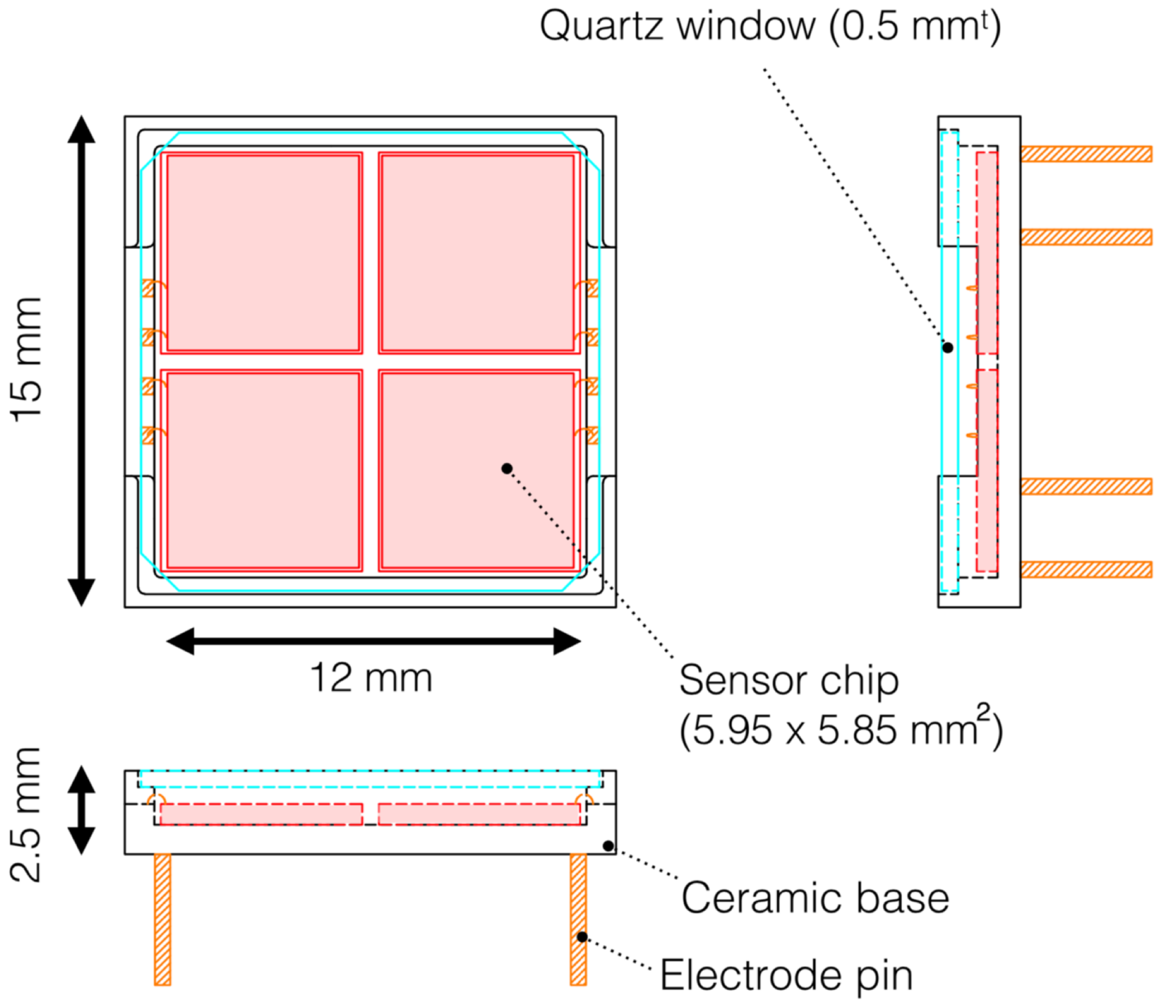






BACKUP
-const.-

MPPC


Quartz window (0.5 mm^t)
15 mm
12 mm
Sensor chip
(5.95 x 5.85 mm^2)
2.5 mm
Ceramic base
Electrode pin

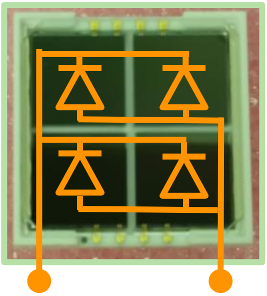
Series readout of MPPC

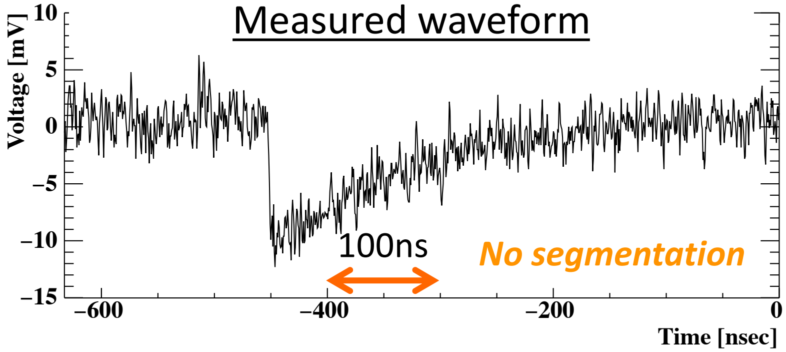
Large readout are can lead to

- Larger dark noise rate (not problematic when used at LXe temperature).
- Longer time constant by larger sensor capacitance.

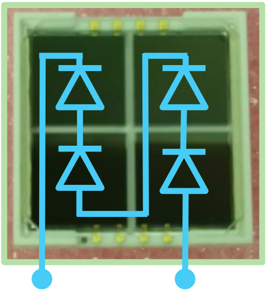
Sensor capacitance are reduced by a series connection.
Sufficiently short timing constant has been achieved.

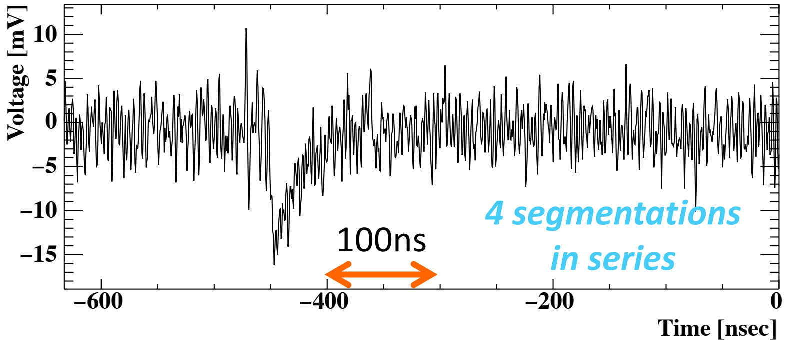
No segmentation





4 segmentations in series



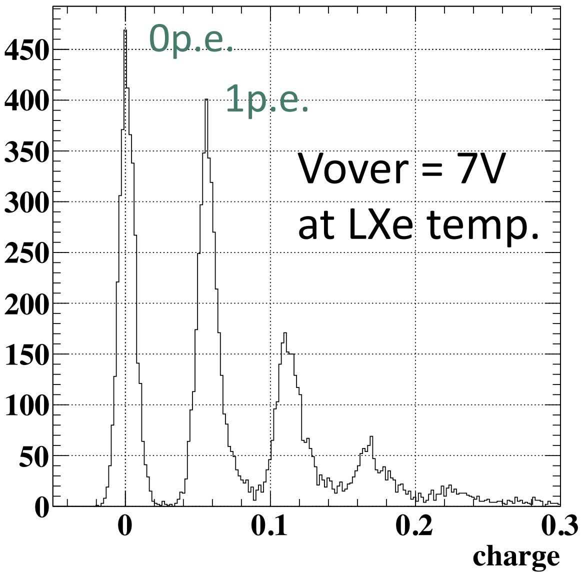


MPPC performance

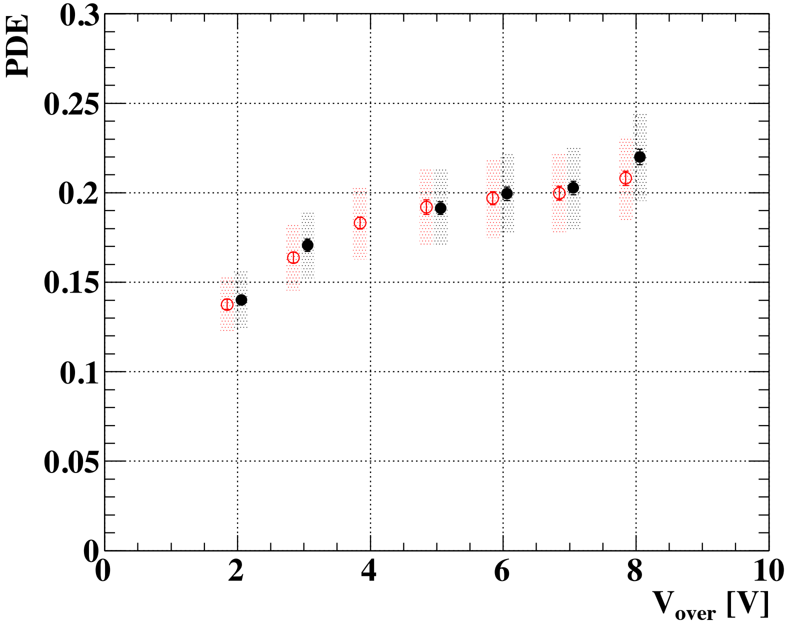
We have tested MPPC in LXe, and **an excellent performance has been confirmed.**

- **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

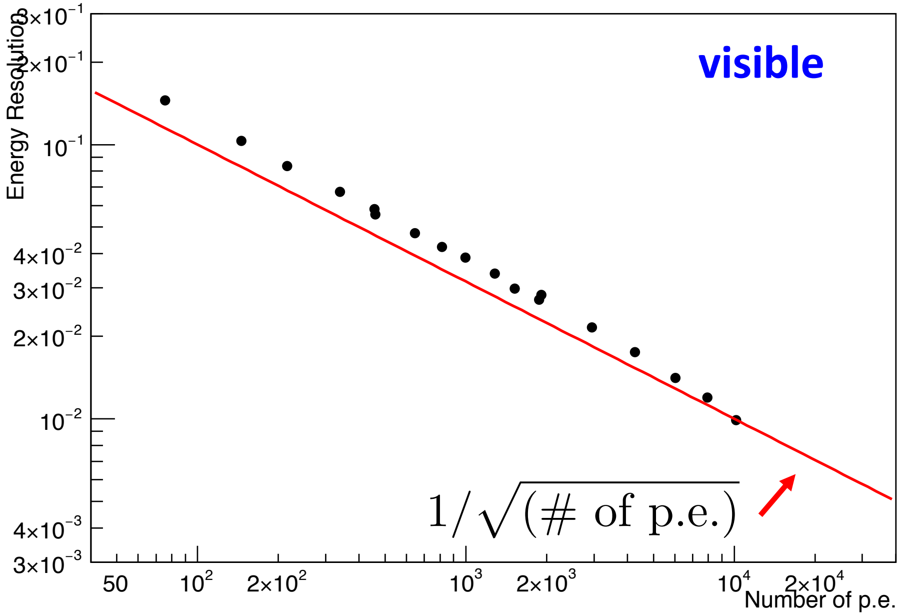


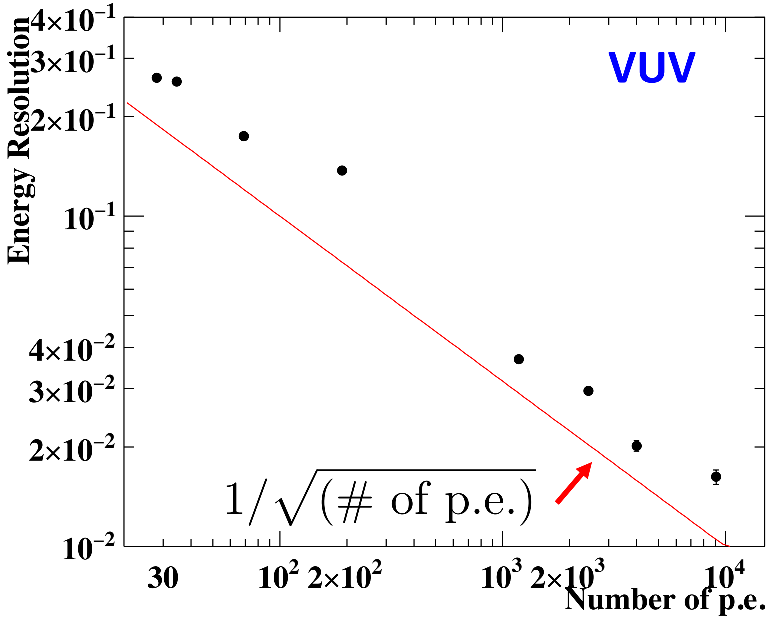
PDE vs. Over voltage



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

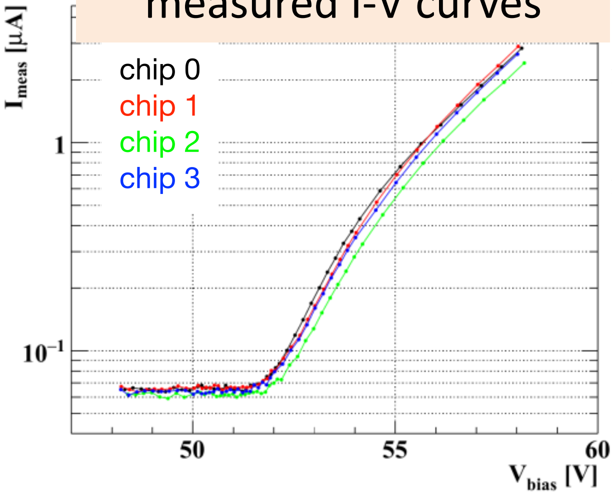




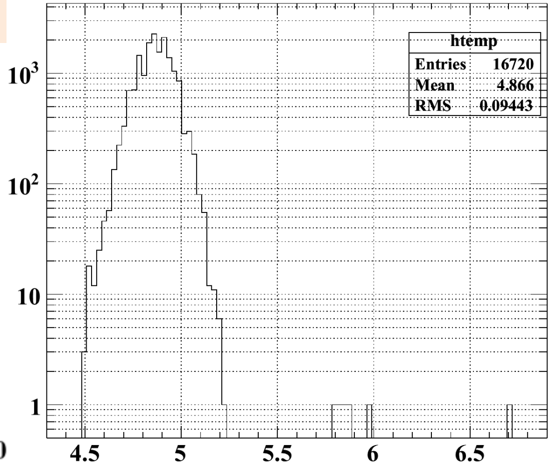
Result of the mass test

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

Example of measured I-V curves



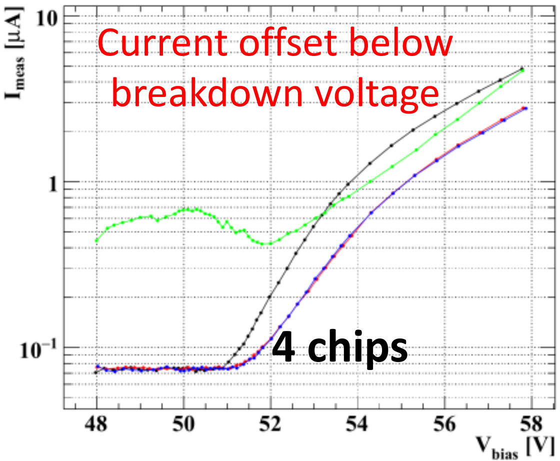
Breakdown voltage



V(breakdown) - V(recommended by HPK)

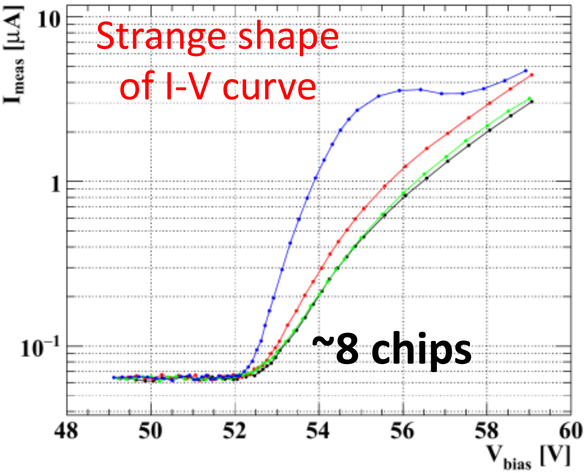
We found 31 bad chips (0.2% of all MPPC chips).

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



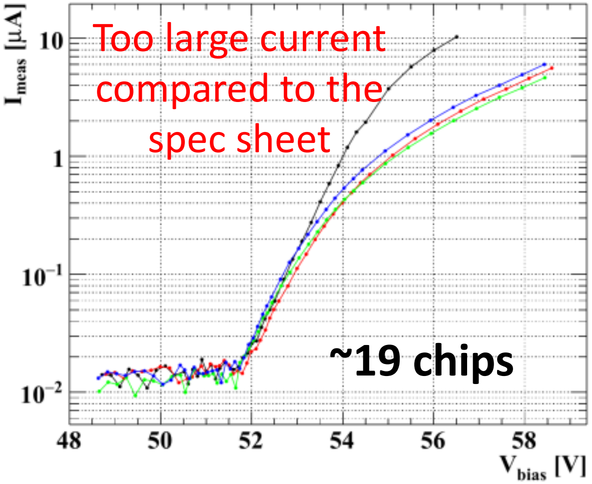
Current offset below breakdown voltage

4 chips



Strange shape of I-V curve

~8 chips

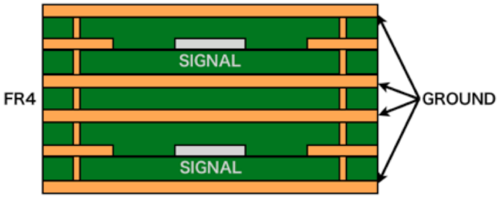


Too large current compared to the spec sheet

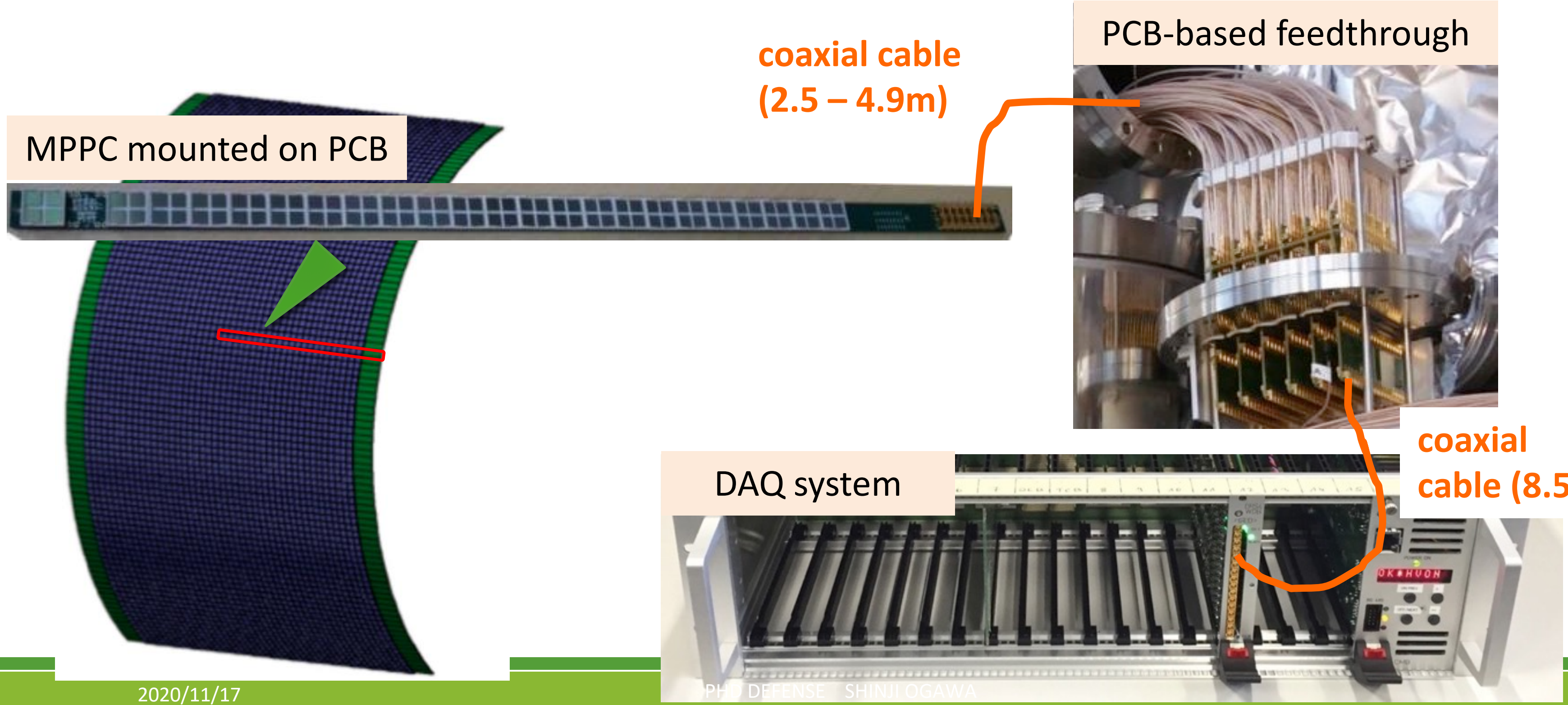
~19 chips

Signal transmission system

“Coaxial-like structure” PCB



- 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.



PCB-based feedthrough

coaxial cable (2.5 – 4.9m)

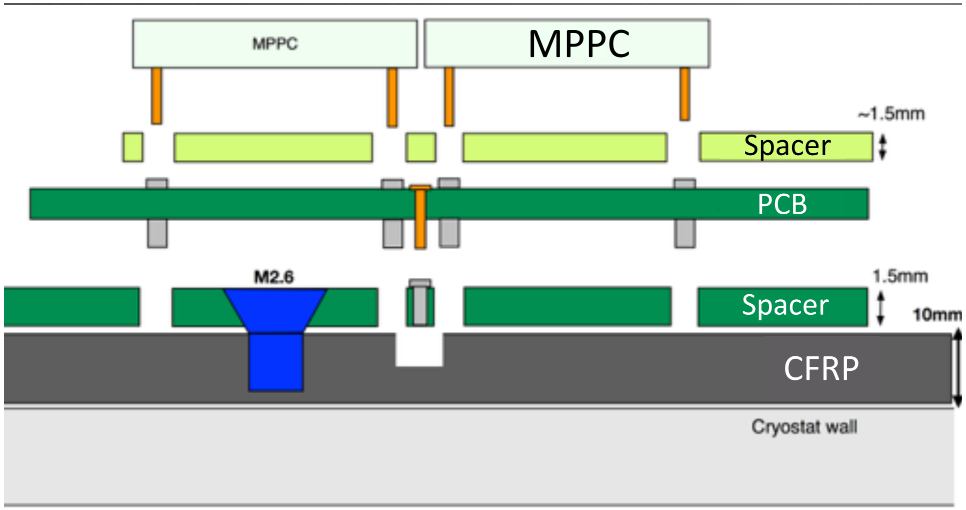
MPPC mounted on PCB

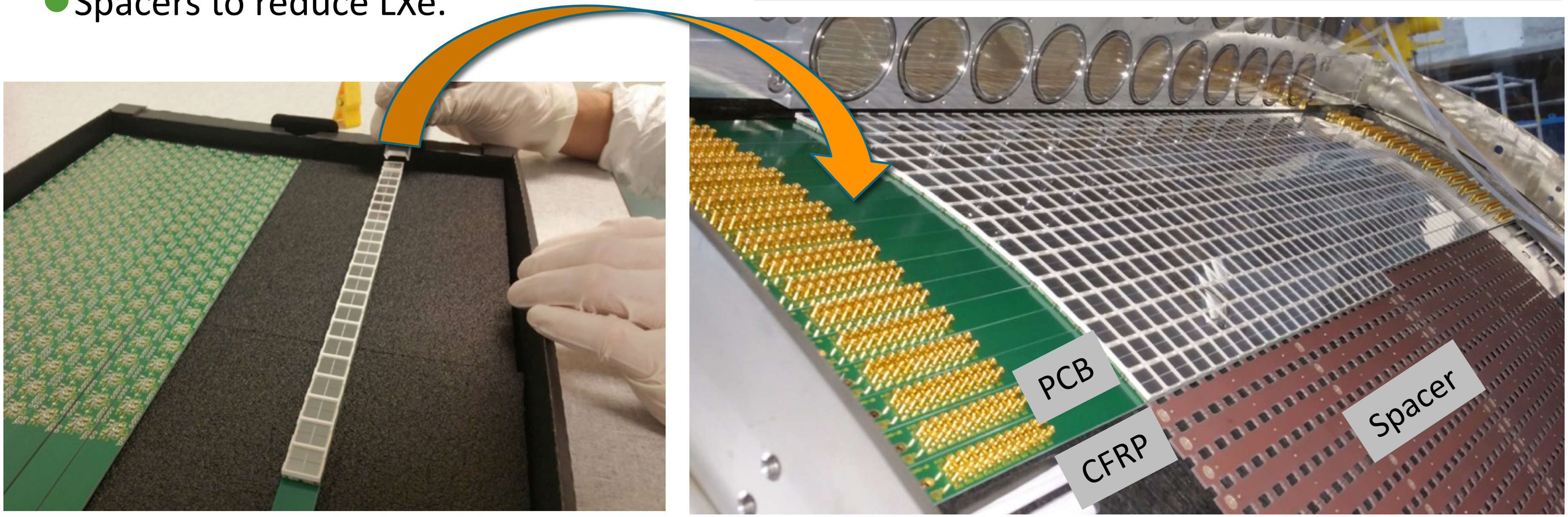
coaxial cable (8.5m)

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

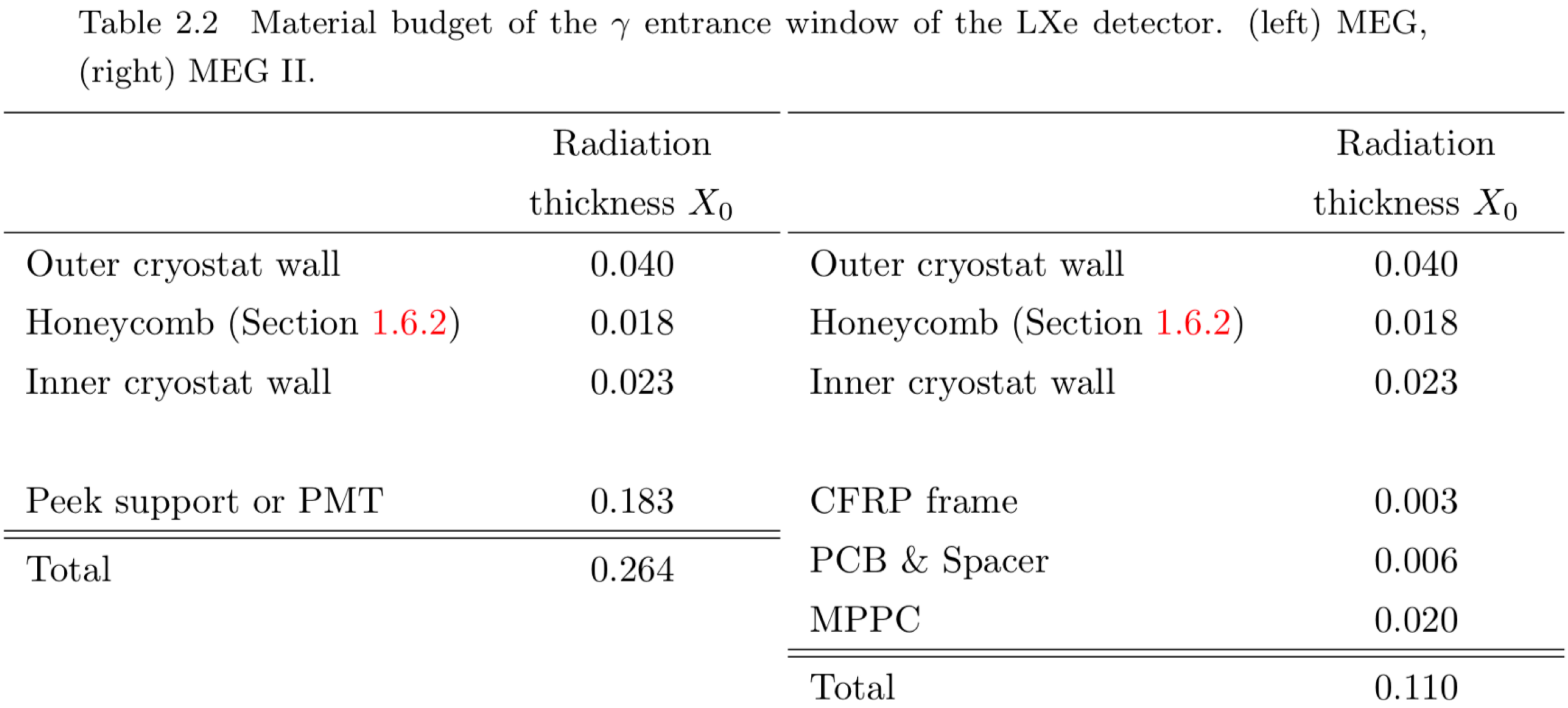


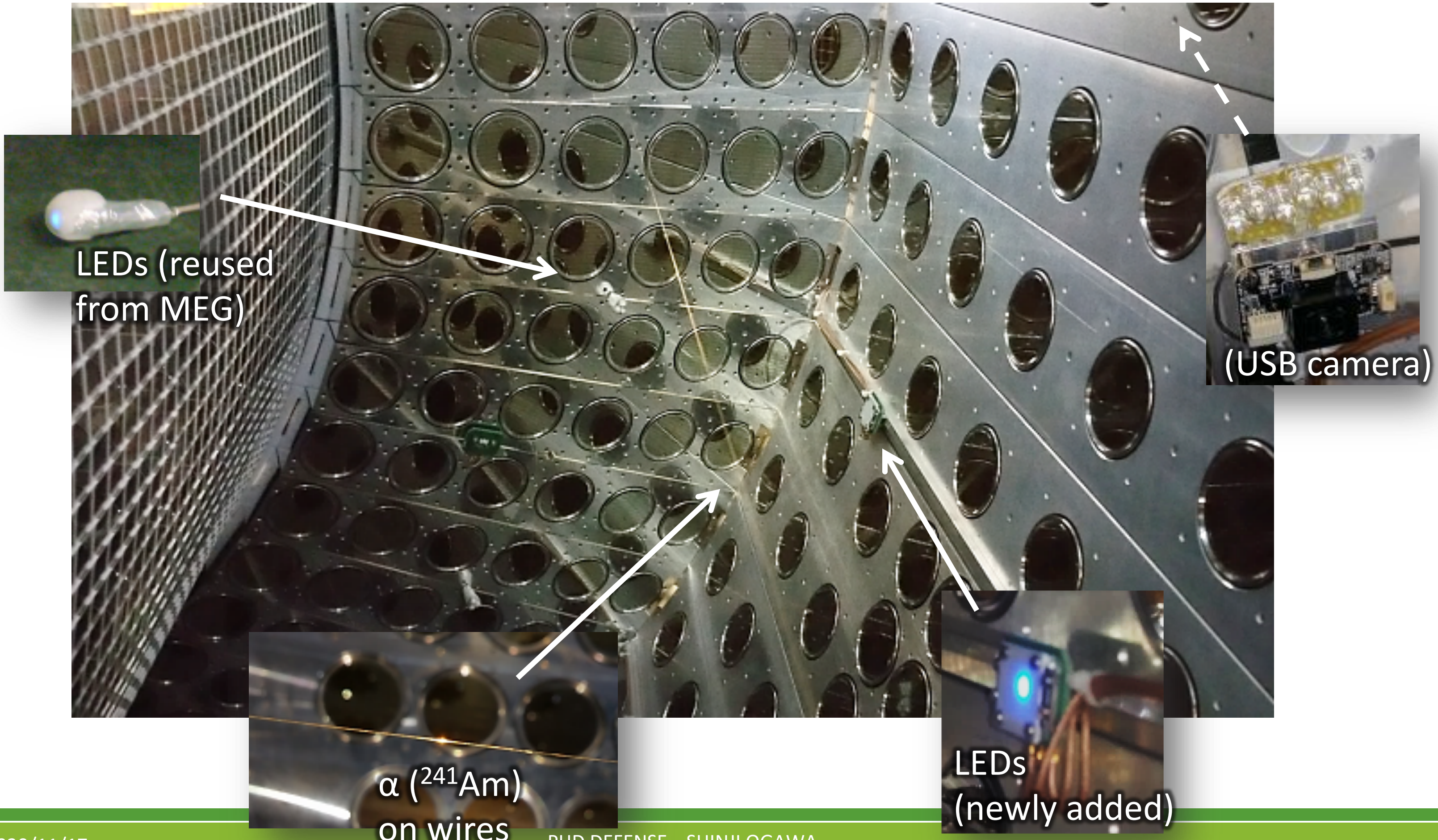
Table 2.2 Material budget of the γ entrance window of the LXe detector. (left) MEG, (right) MEG II.

	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

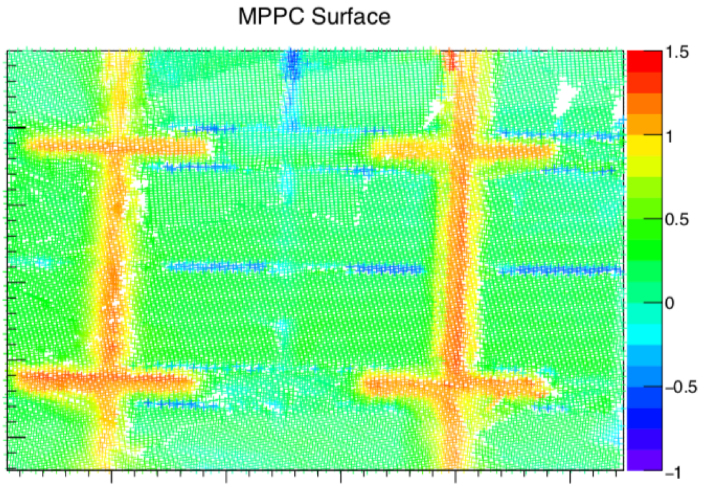
Calibration & monitoring tools

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.)

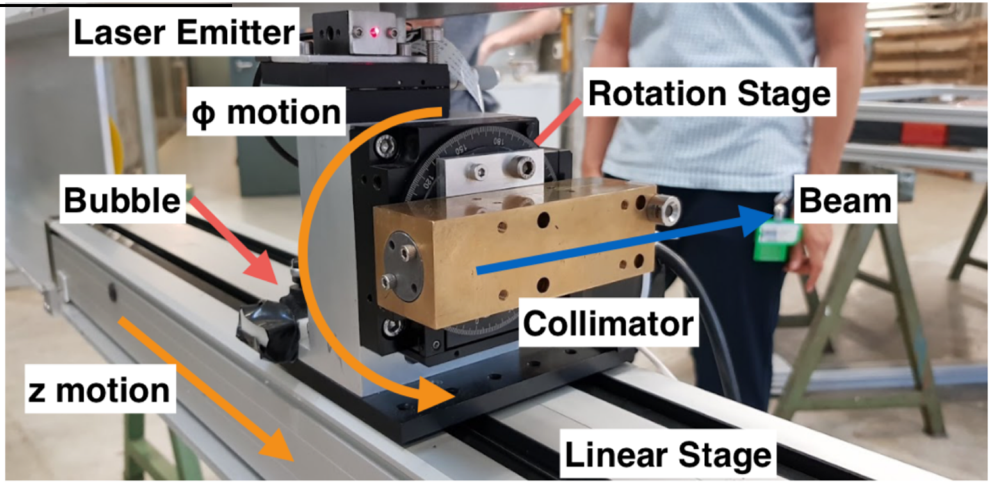


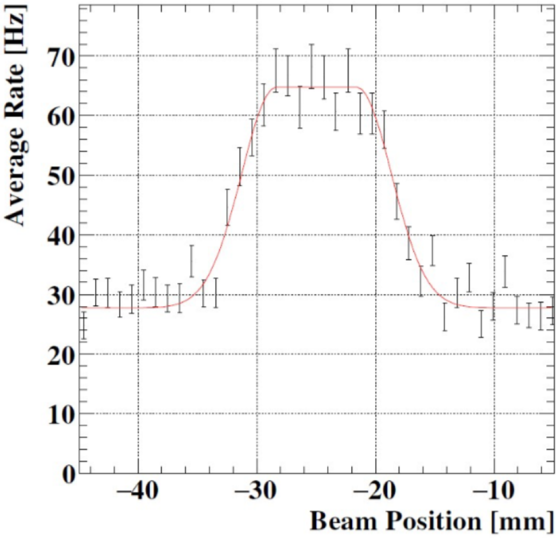
MPPC alignment

laser scanner

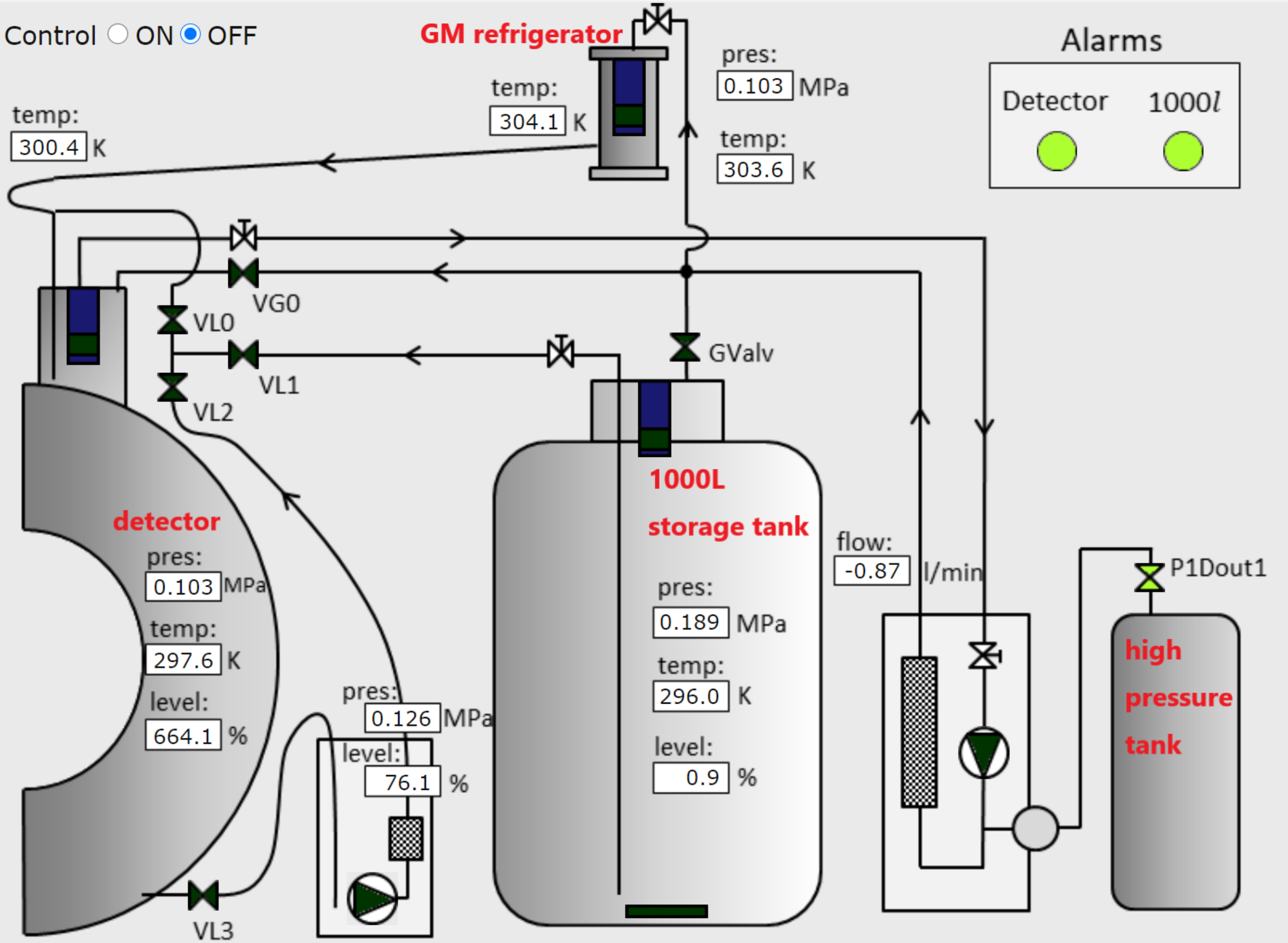


γ-ray measurement





LXe control system



Control ○ ON ● OFF

temp: 300.4 K

temp: 304.1 K

pres: 0.103 MPa

temp: 303.6 K

detector pres: 0.103 MPa

temp: 297.6 K

level: 664.1 %

pres: 0.126 MPa

level: 76.1 %

1000L storage tank pres: 0.189 MPa

temp: 296.0 K

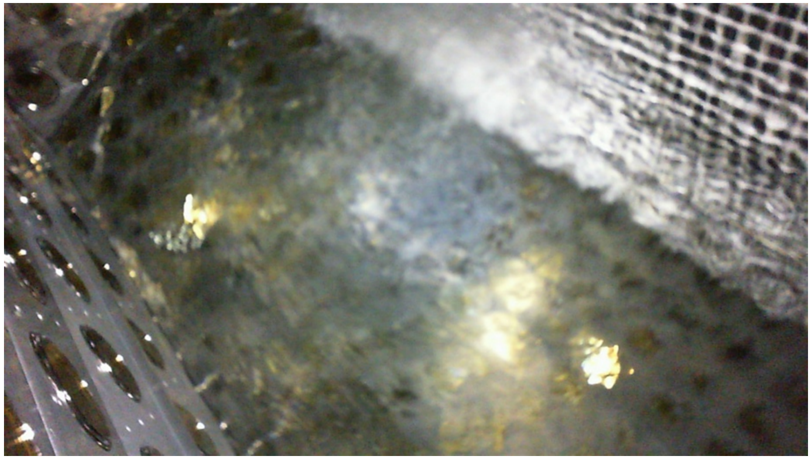
level: 0.9 %

flow: -0.87 l/min

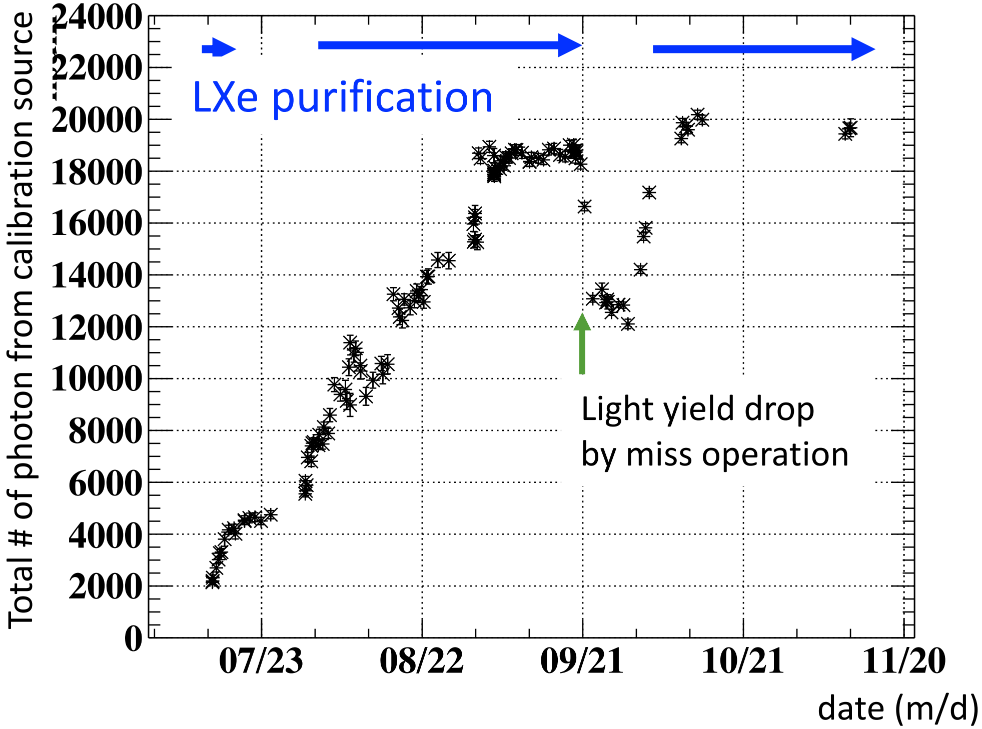
LXe transfer & purification

- LXe has been transferred to the detector.
- After the purification of a few month, sufficient light yield of LXe has been achieved by the purification.
  - Molecular sieves (LXe circulation) + getter (gXe circulation)

Inside the detector during LXe transfer



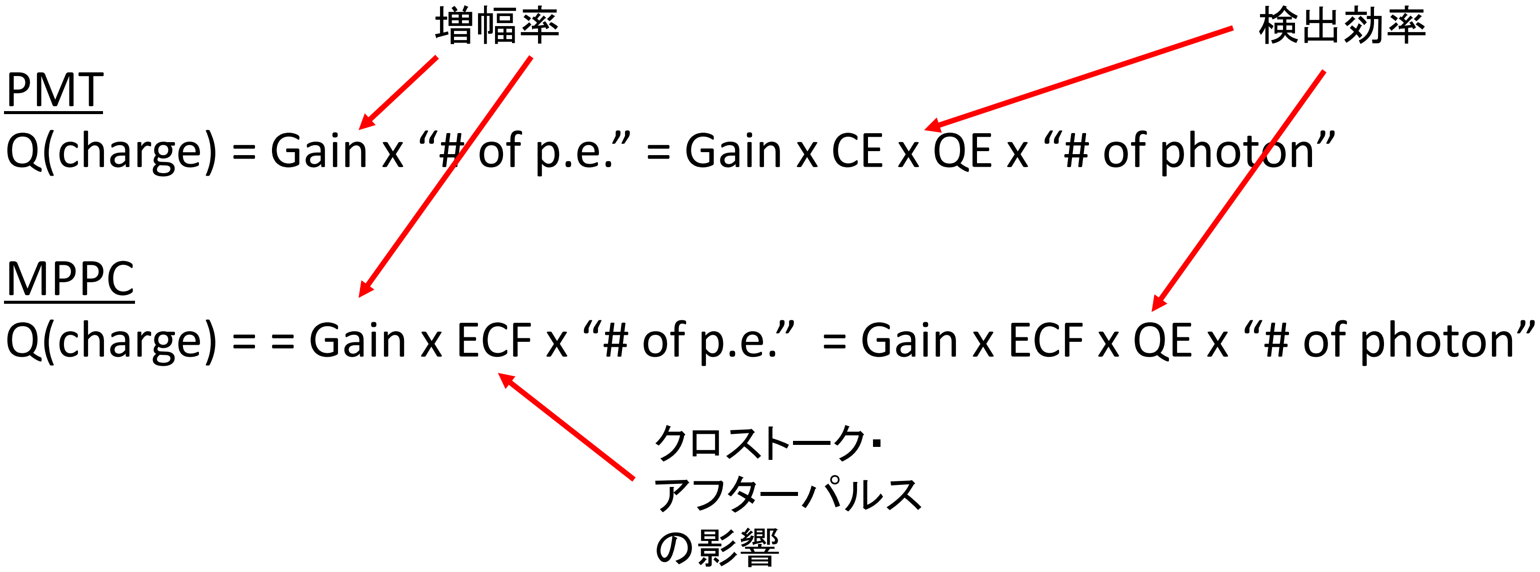
LXe Light yield



BACKUP
-res-

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”

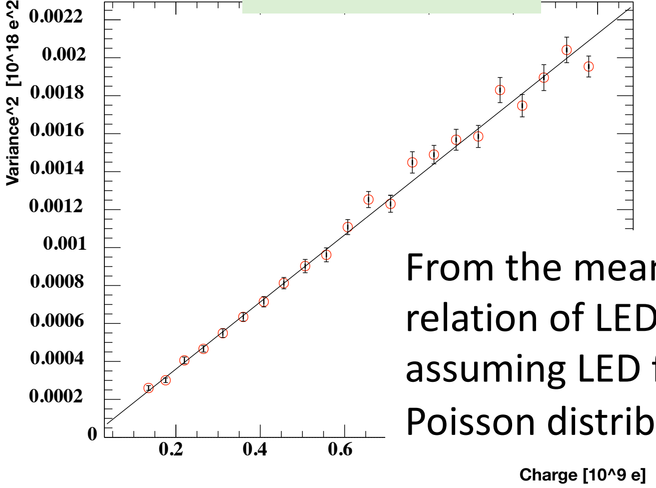
クロストーク・
アフターパルス
の影響

Calibration parameters are measured beforehand.

sensor calibration (cont’d)

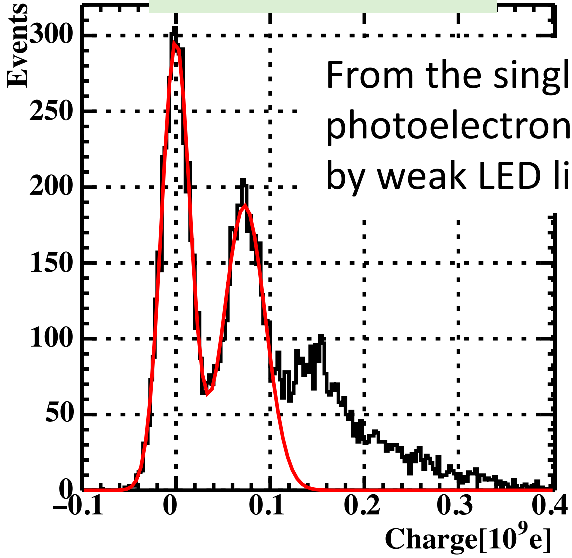
Calibration parameters are measured beforehand.

PMT Gain/CE



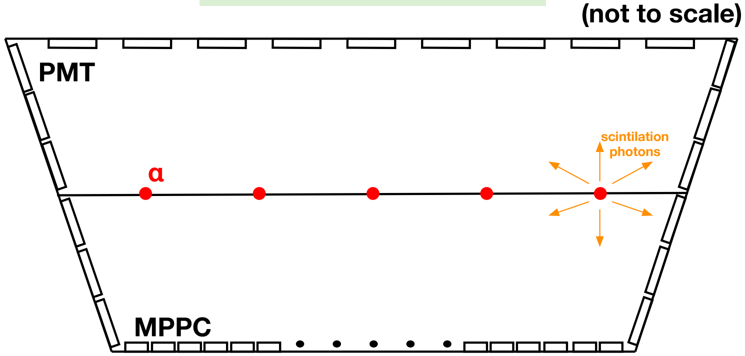
From the mean vs. variance relation of LED charge, assuming LED follows Poisson distribution.

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.

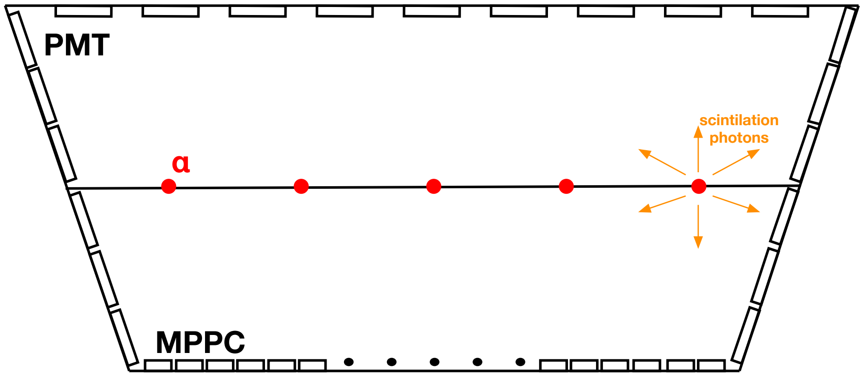
Alpha DAQ

Alpha event trigger by lateral PMT.

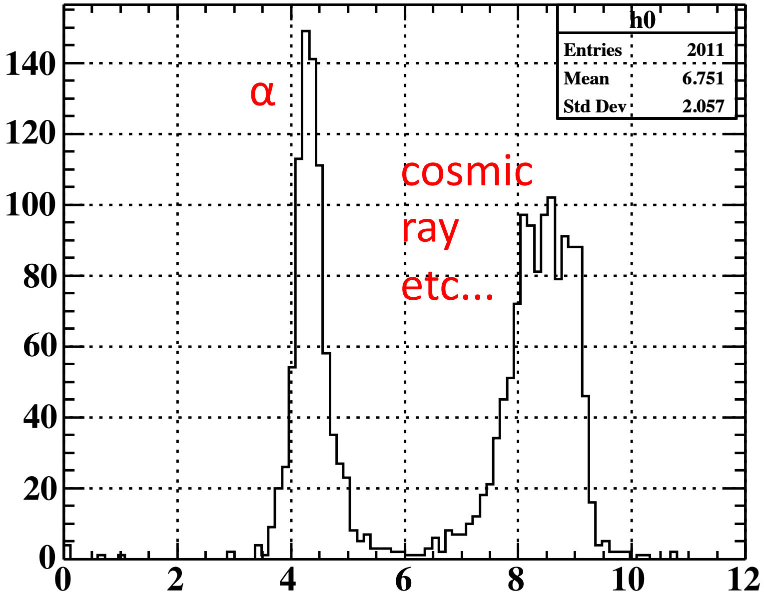
Event selection

- Separate alpha and others by pulse shape discrimination
- Select events from each alpha source by position reconstruction.

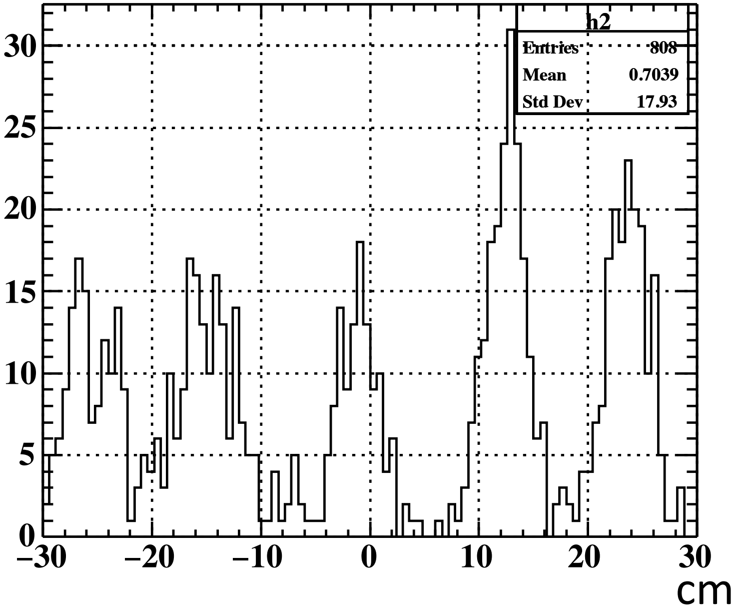
(not to scale)



charge / height



Reconstructed position (α event)



Position reconstruction

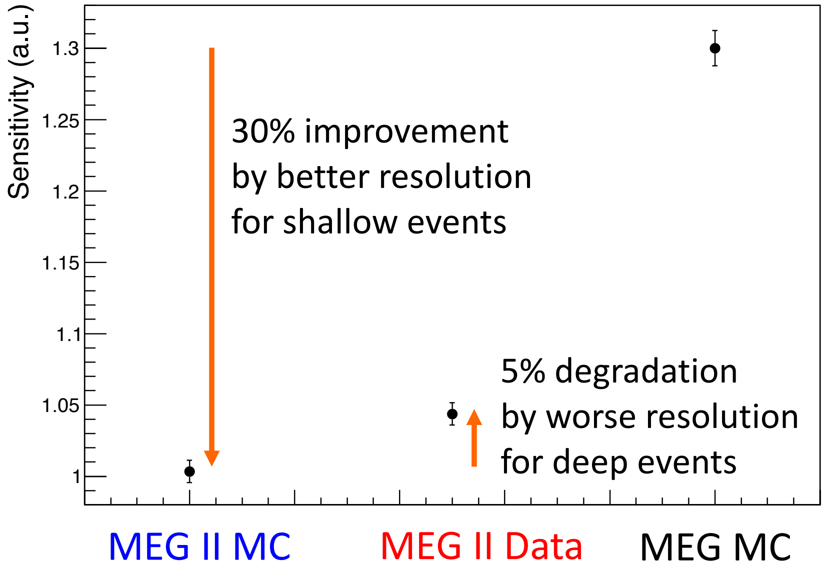
- Reconstructed from light distribution on the inner face (i.e. MPPCs).
- Naively speaking:
  - u/v: Peak position on u/v plane.
  - w: Width of the peak. (deeper event -> wider peak)
- Implemented as a chi-2 minimization defined as:

$$\chi^2 := \sum_{\mathrm{MPPC}} \left(\frac{N_{\mathrm{pho}} - C \times \Omega(\vec{x})}{\sigma(N_{\mathrm{pho}})} \right)^2 .$$

  - Only the MPPC around the peak is used to suppress bias from shower direction.
  - Several corrections are applied to correct the bias.

Position resolution

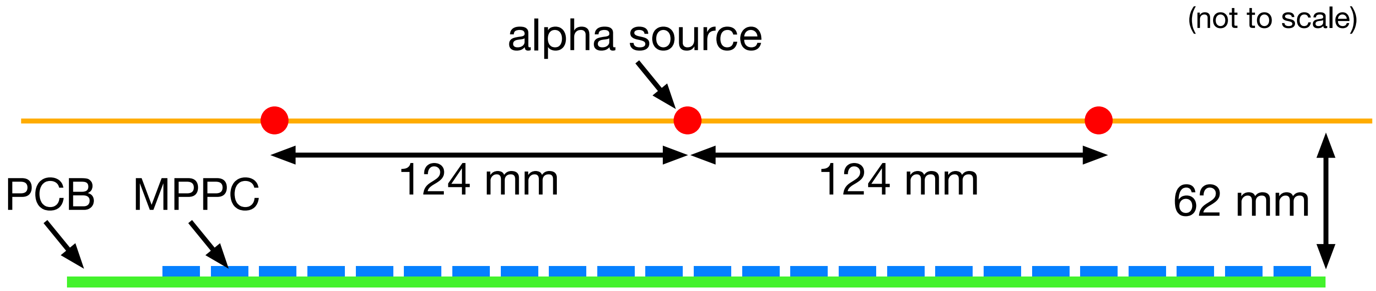
Effect on sensitivity.



30% improvement
by better resolution
for shallow events

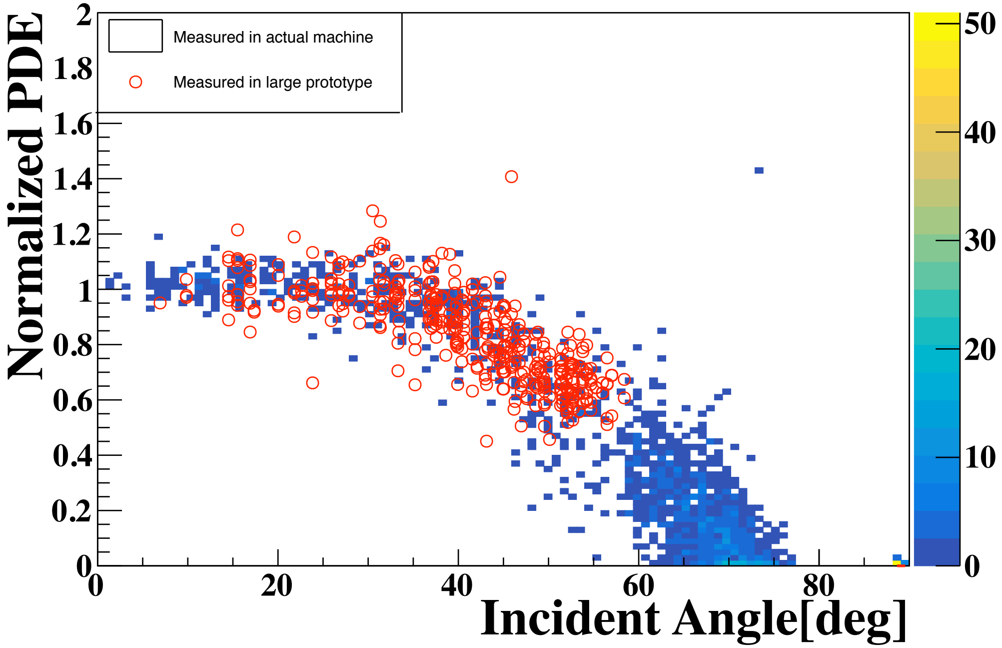
5% degradation
by worse resolution
for deep events

Angular dependence of PDE



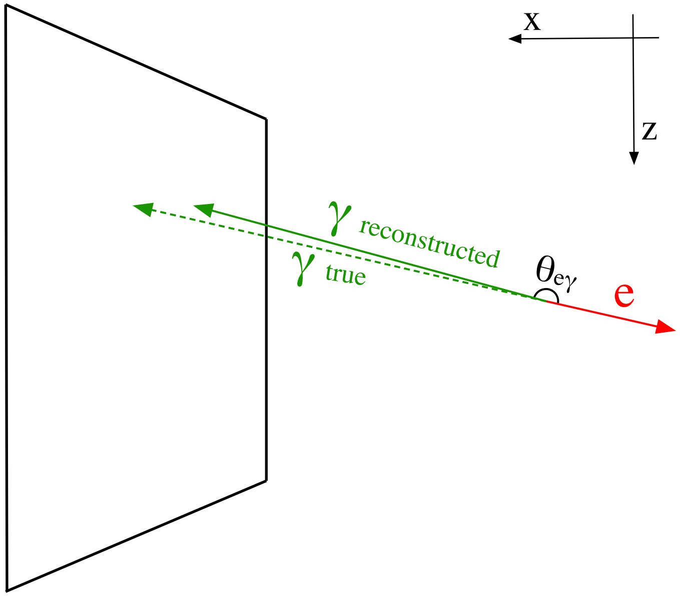
Unexpected angular dependence of VUV PDE was observed.

MPPC PDE vs incident angle

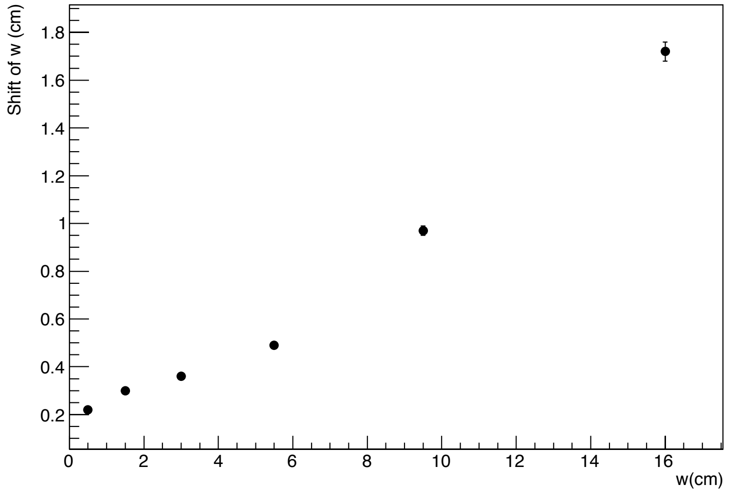


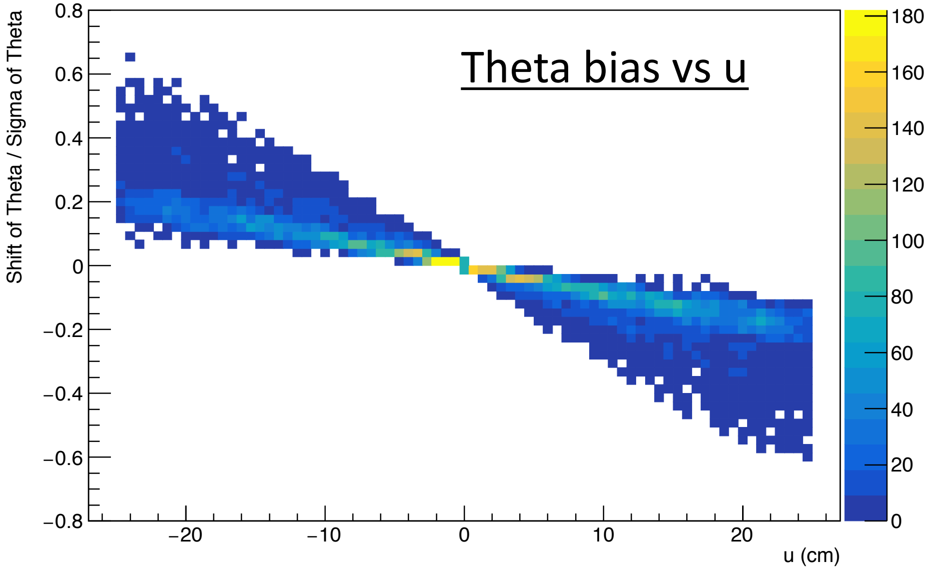
Angular dependence of PDE

Reconstructed shallower
→ Bias in θ_eγ
→ 0.6% sensitivity degradation at most.



W shift vs W (by angular dependence)

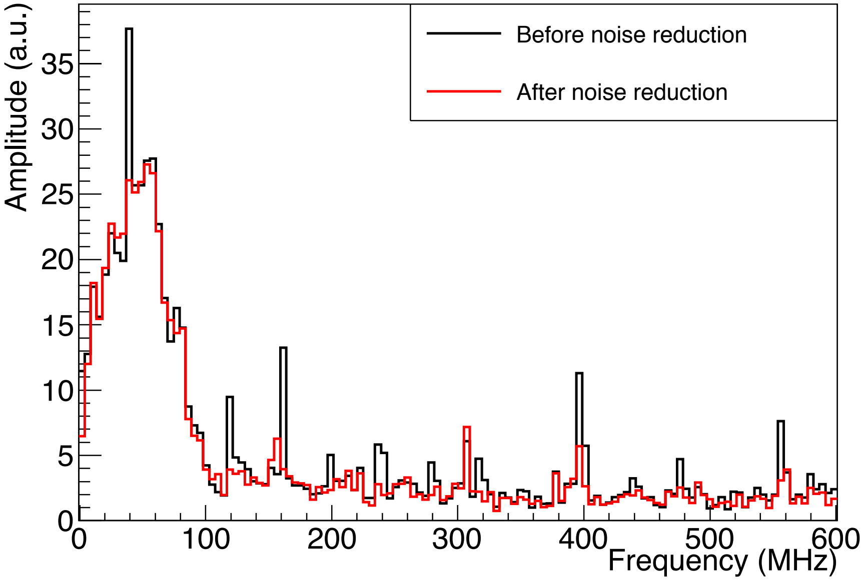



Theta bias vs u

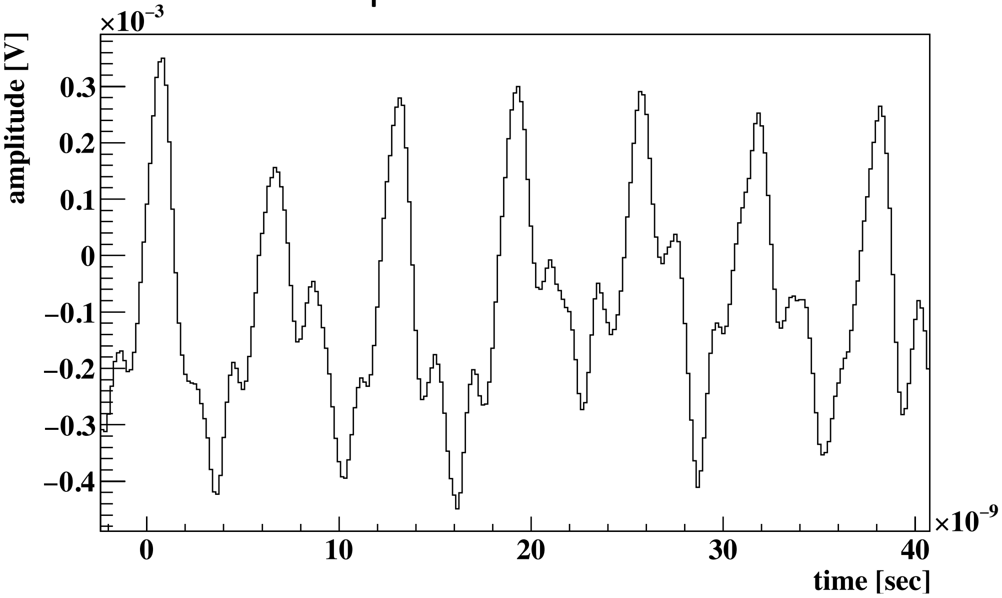
noise reduction

High frequency noise from readout electronics is subtracted.

- 80 * n Hz
- Phase from DRS clock



template to be subtracted



Timing resolution -reconstruction-

Timing of γ-ray is reconstructed from a weighted average of signal timings on each photosensor.

- Minimization of the χ^2 defined as follows:

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

Time info from each MPPC, PMT

Calibration parameters

Timing resolution of each channel

Gamma hit timing
(fitting parameter)

- Weight: timing resolution of each channel.
  - as a function of number of photoelectron.
  - channel with a large number of photoelectrons → better timing resolution.
  - channel with a small number of photoelectrons → worse timing resolution.

- Calibration parameters are evaluated from the residual of the χ^2 minimization.
  → Analyzed iteratively.

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

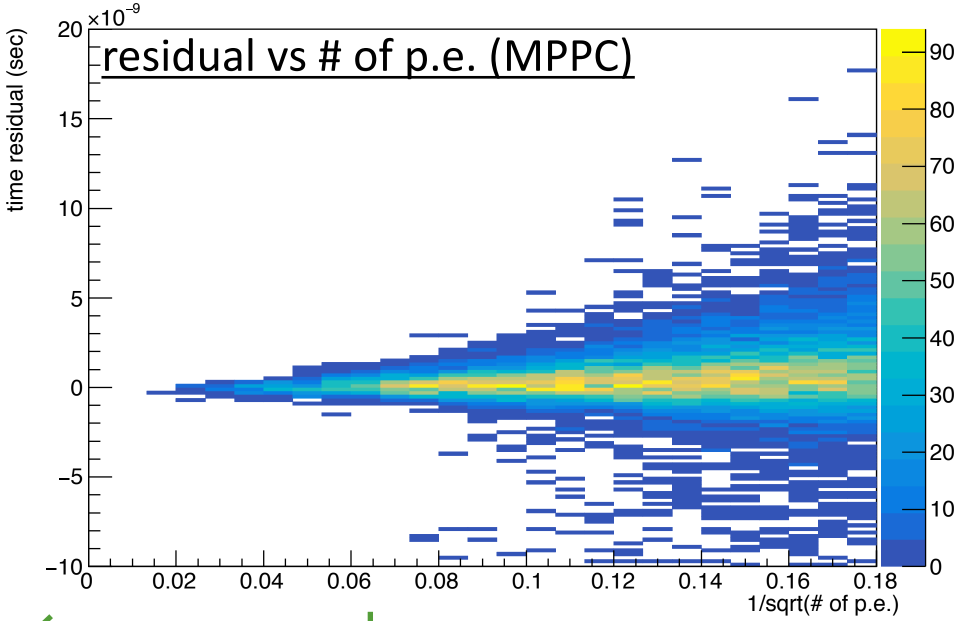
Gamma hit timing (fitting parameter)

Calibration parameters : extracted from data

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

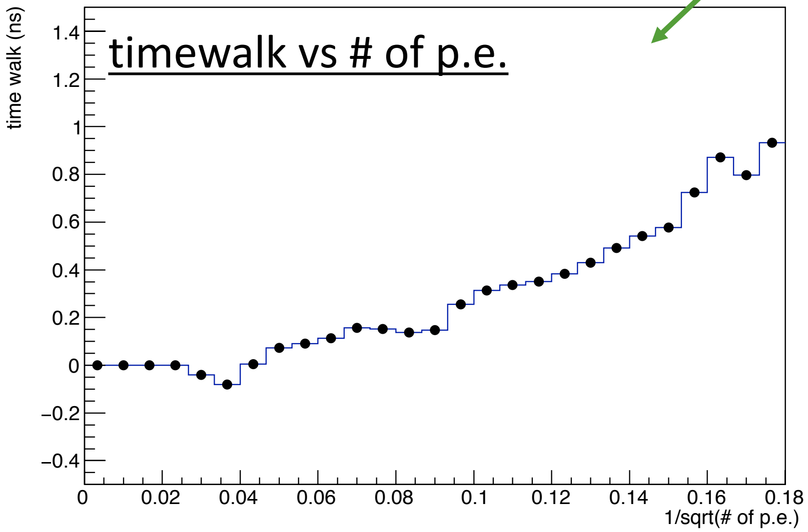
Timing resolution -c

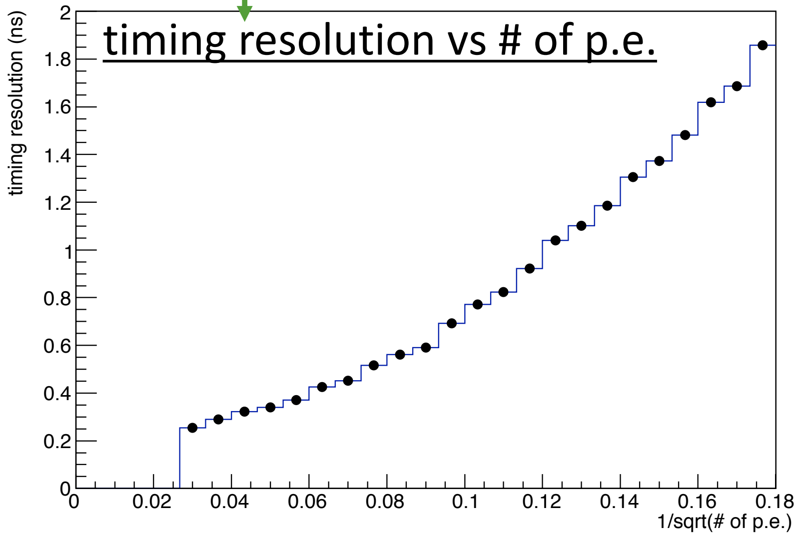
Calibration parameters are extracted from residual in time reconstruction.
→ Extracted iteratively.



mean

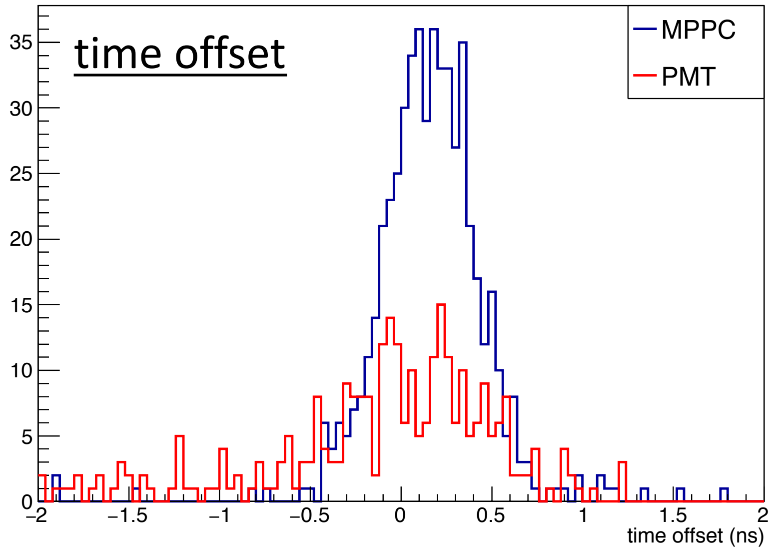
sigma



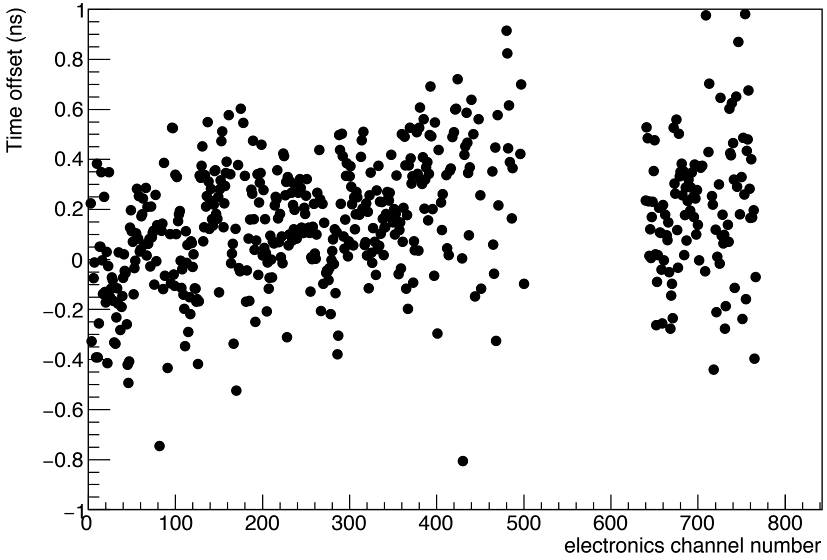


Time offset

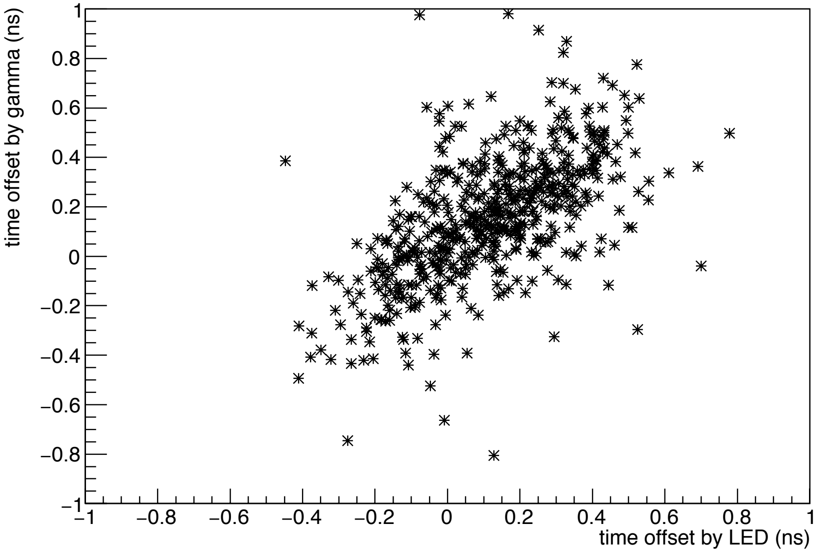
time offset of each channel


time offset

Time offset vs electronics channel



time offset (Gamma) vs time offset (LED)



Timing resolution

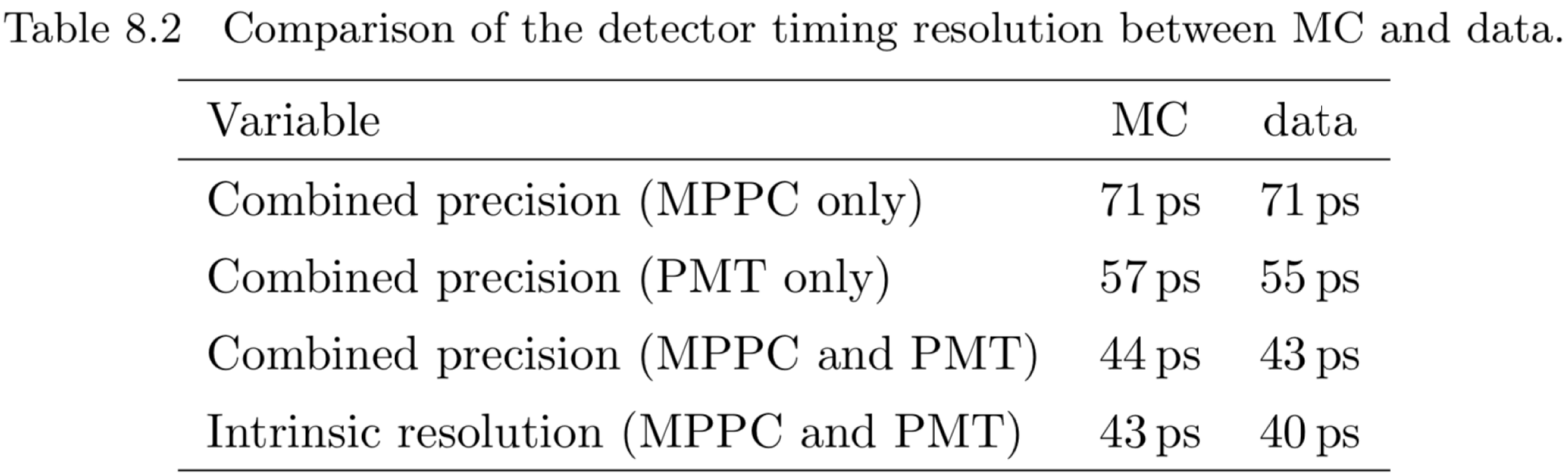


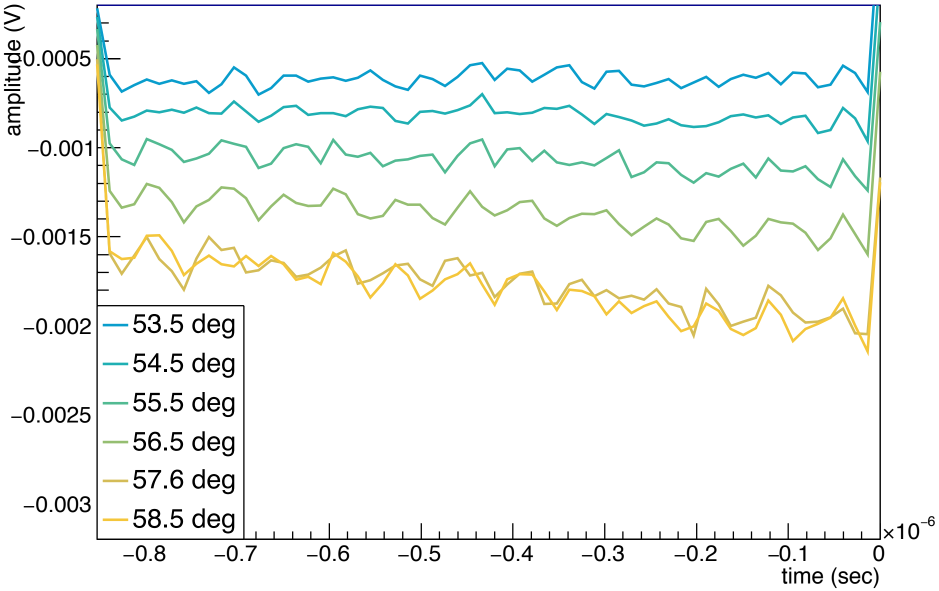
Table 8.2 Comparison of the detector timing resolution between MC and data.

Variable	MC	data
Combined precision (MPPC only)	71 ps	71 ps
Combined precision (PMT only)	57 ps	55 ps
Combined precision (MPPC and PMT)	44 ps	43 ps
Intrinsic resolution (MPPC and PMT)	43 ps	40 ps

Energy offset

Energy offset is monitored independently from Pedestal run.

Dependence on electronics temperature is newly identified and is corrected.



Energy reconstruction w/ limited ch.

aa

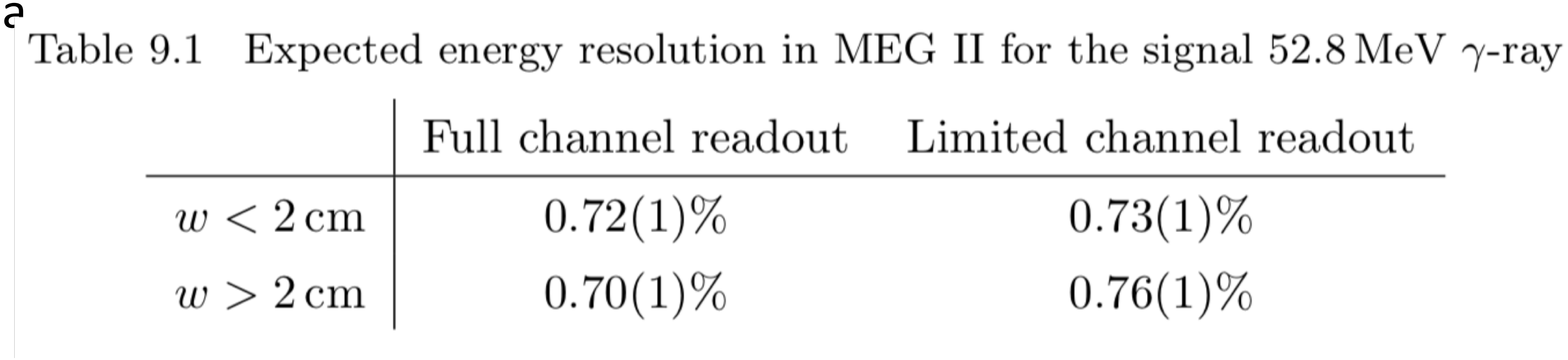
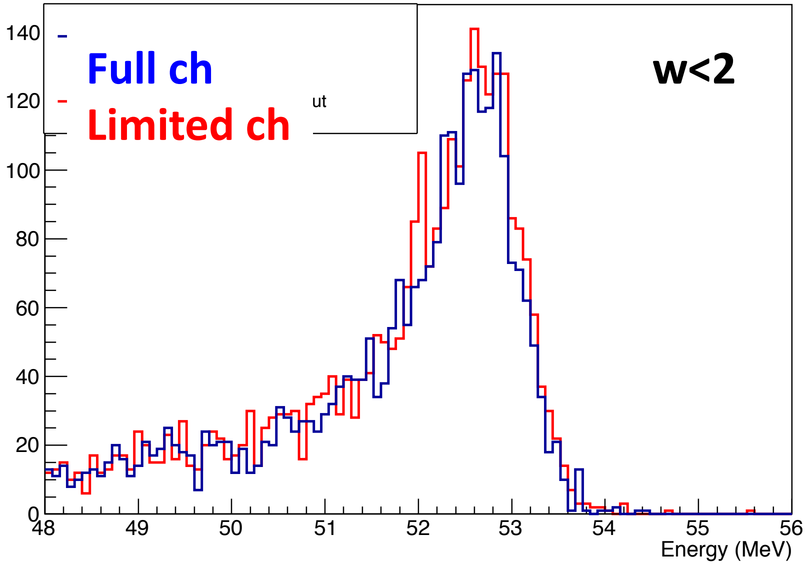
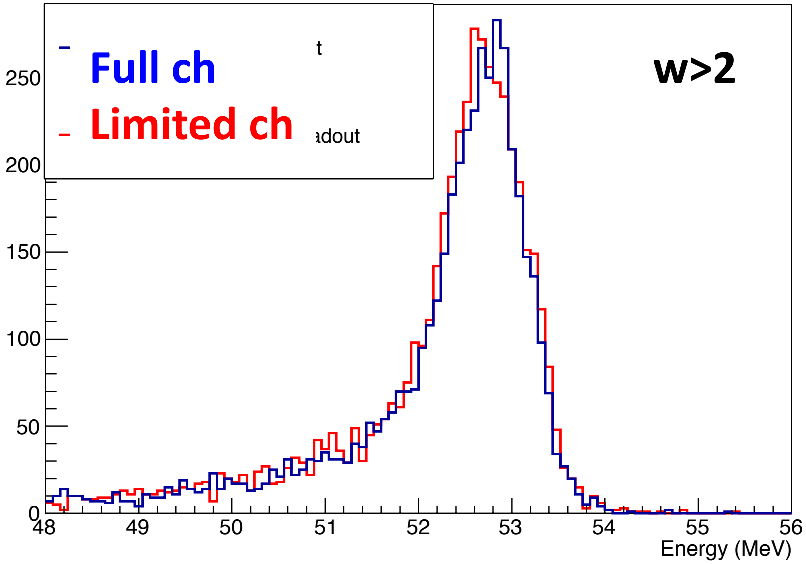


Table 9.1 Expected energy resolution in MEG II for the signal 52.8 MeV γ-ray

	Full channel readout	Limited channel readout
$w < 2\,\mathrm{cm}$	0.72(1)%	0.73(1)%
$w > 2\,\mathrm{cm}$	0.70(1)%	0.76(1)%

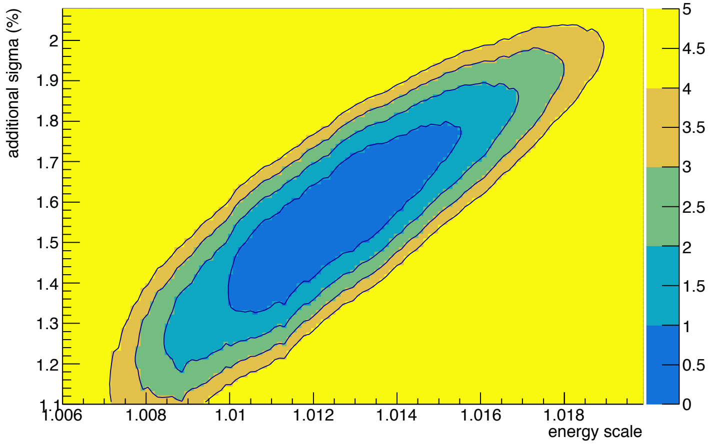


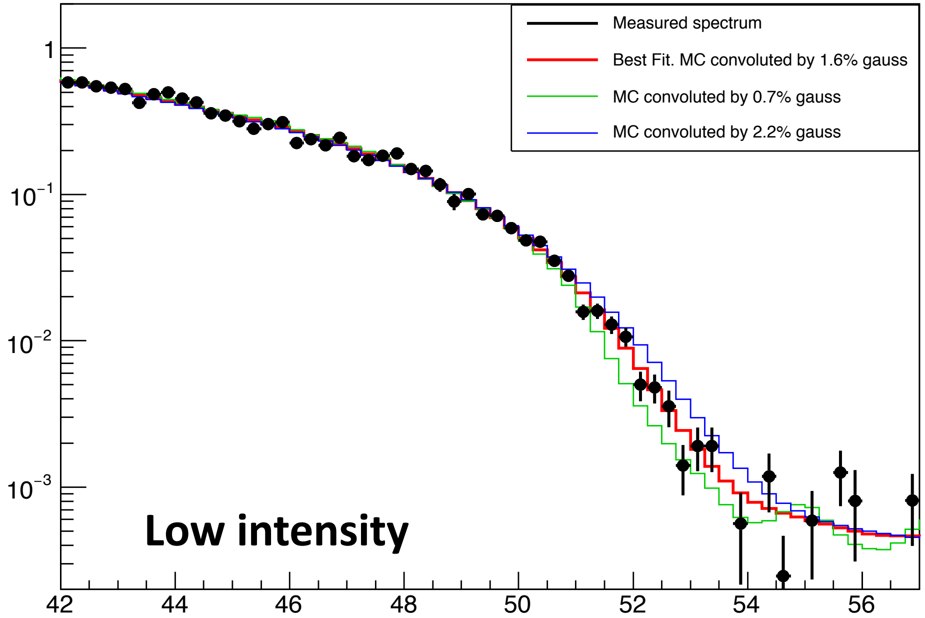


BG gamma fit

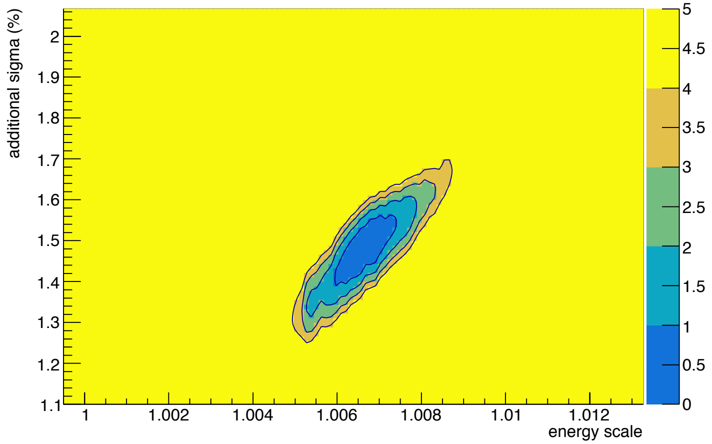
aa

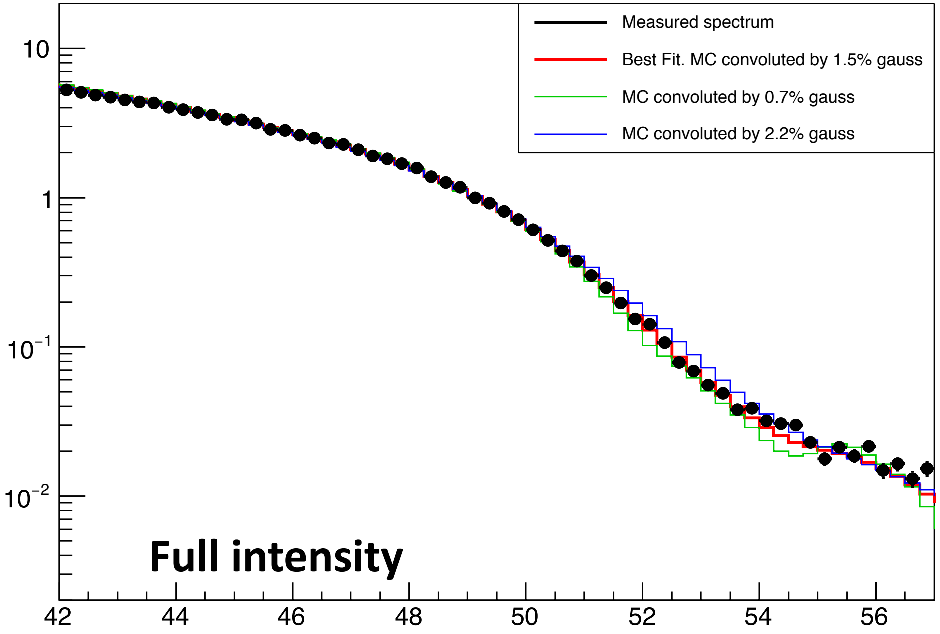
2 x negative log likelihood





2 x negative log likelihood

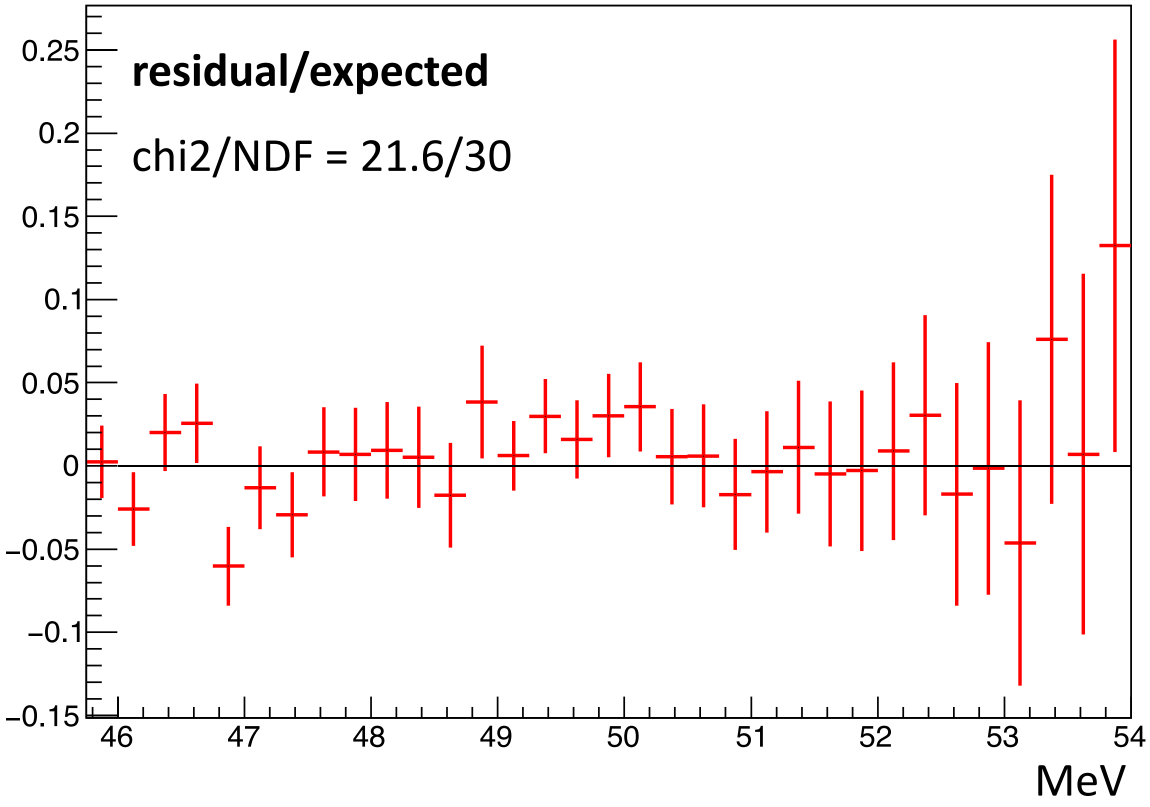




BG gamma fit

aa

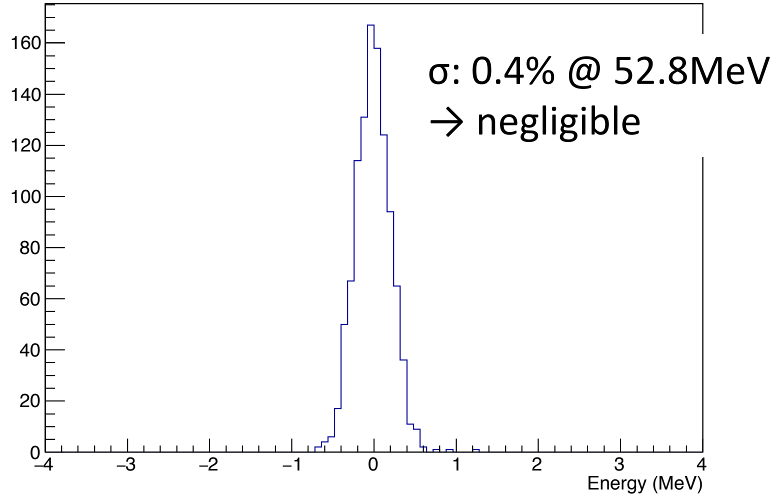
BG γ spectrum. Residual in Best Fit.



Energy resolution -unknown term-

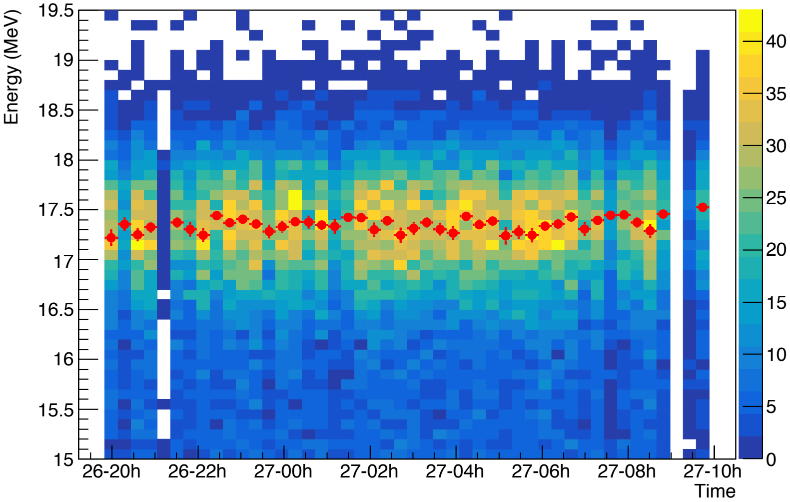
- The degradation is not due to the noise.
- The degradation is not due to some instability.

Reconstructed energy of pedestal event.



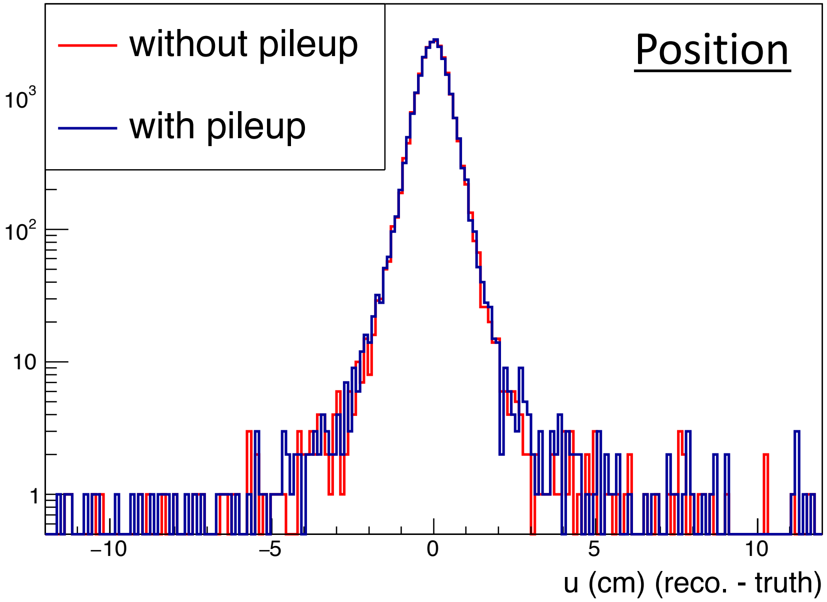
σ: 0.4% @ 52.8MeV
→ negligible

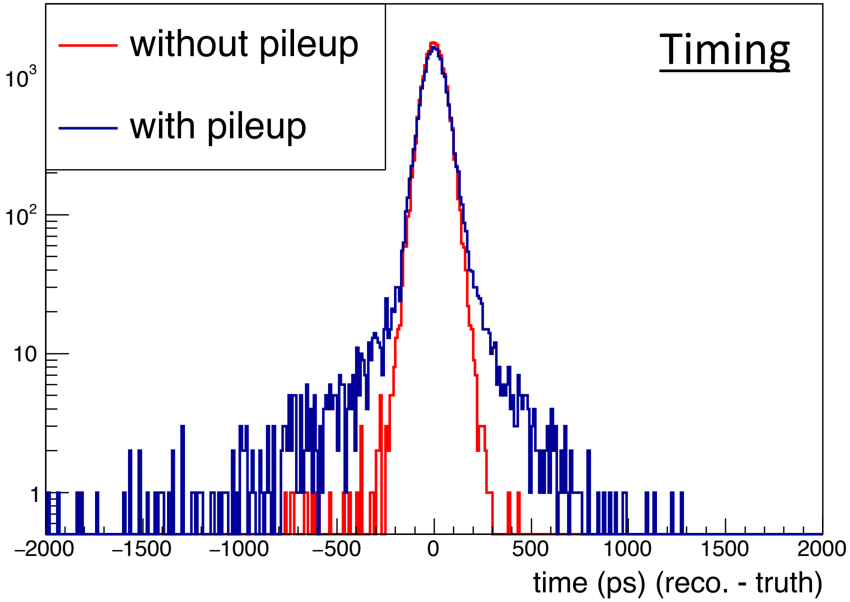
CW Li energy vs Time



Pileup effect on position/timing

- 3% inefficiency to signal events.

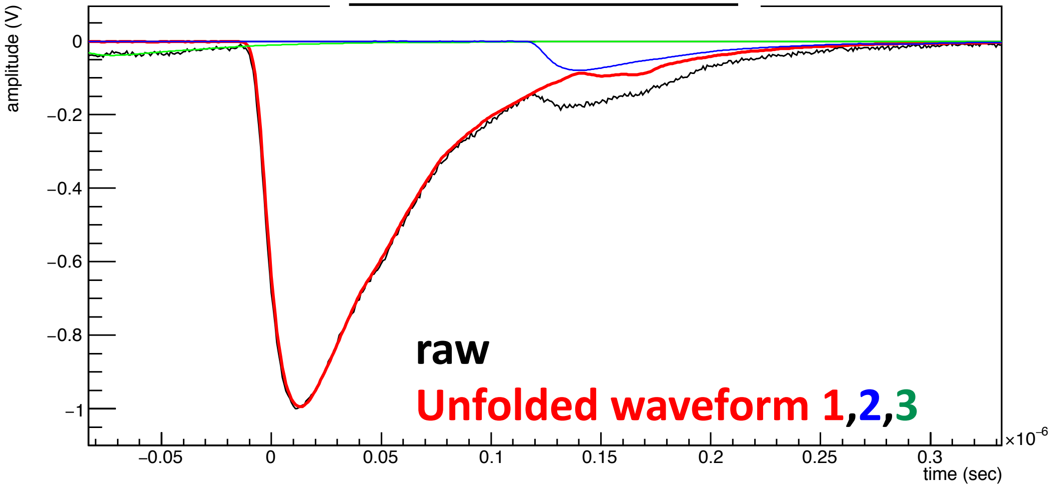




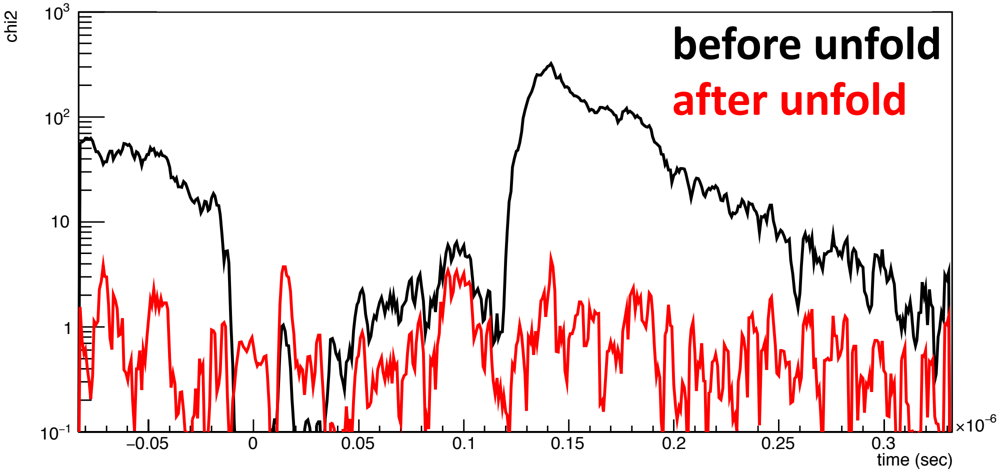
Pileup elimination by waveform

- Identify deviation on sum waveform from template.
- Try to eliminate the chi squared until it gets converged.

PMT sum waveform



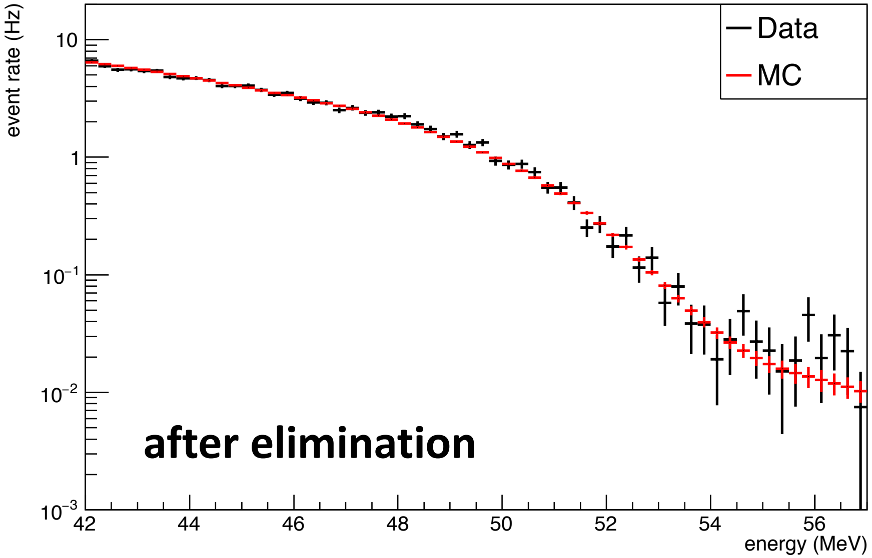
Chi2 of sum waveform from template



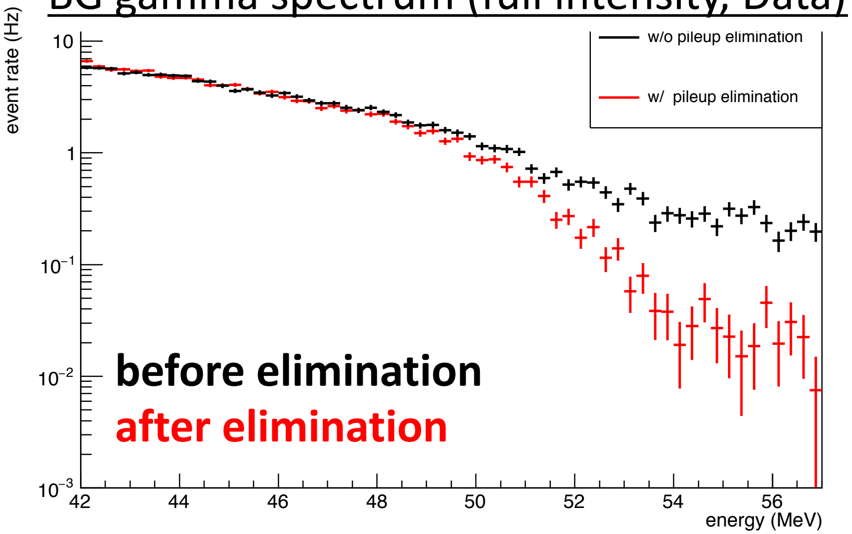
Energy spectrum with WF elimination

a

BG gamma spectrum (full intensity)

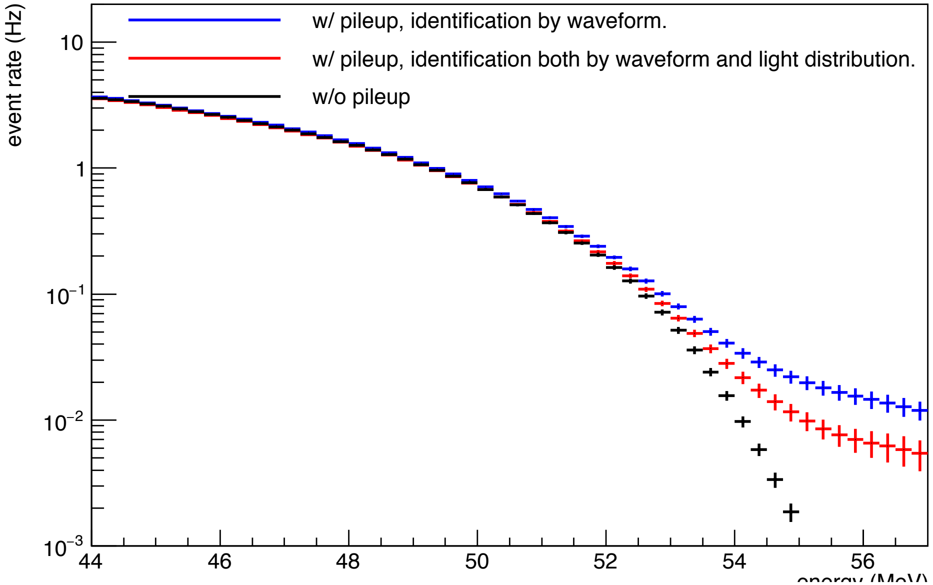


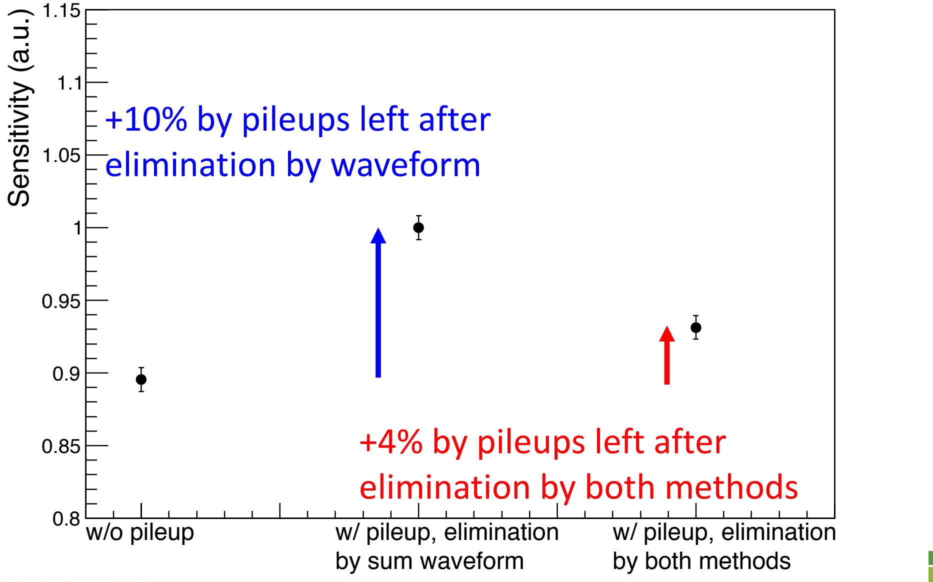
BG gamma spectrum (full intensity, Data)



Energy spectrum wit

Some events left in signal energy region.





+10% by pileups left after elimination by waveform

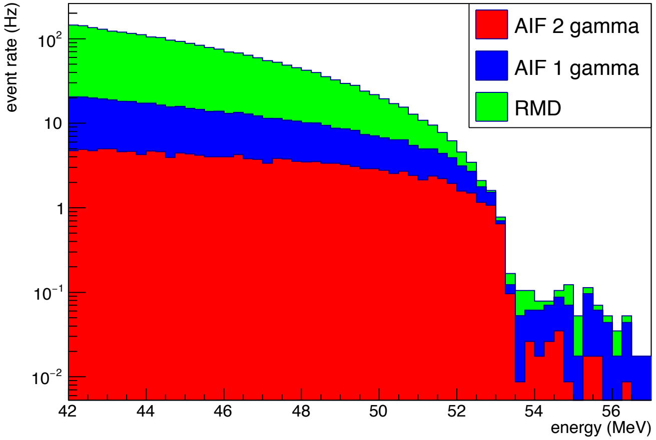
+4% by pileups left after elimination by both methods

AIF2G -motivation-

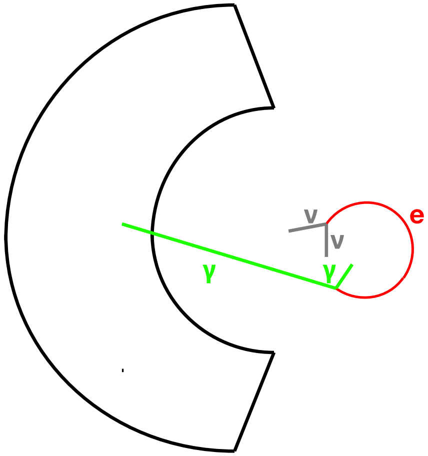
Some of Michel positron annihilate with electron in material.

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

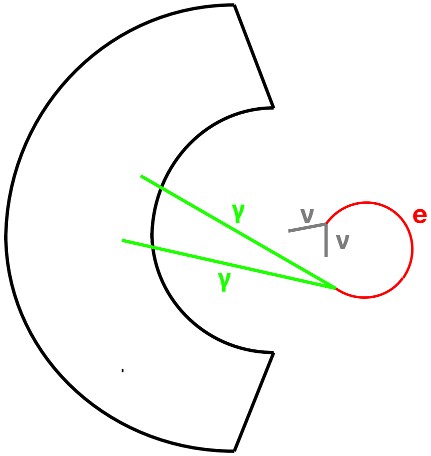
- more dominant near the signal energy.



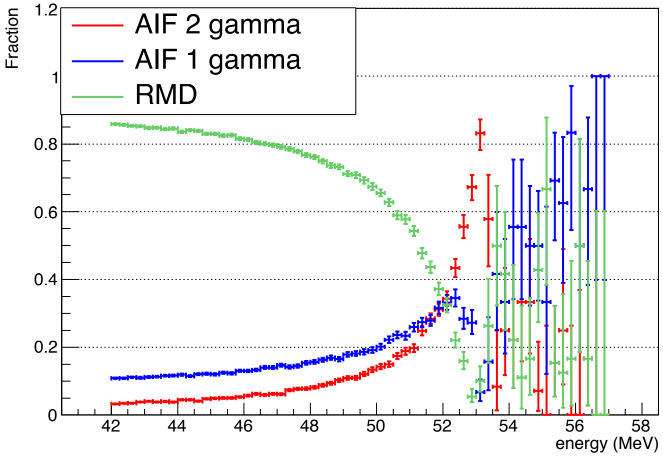
AIF 1γ



AIF 2γ



Fraction of AIF2γ in background γ-rays vs. Energy

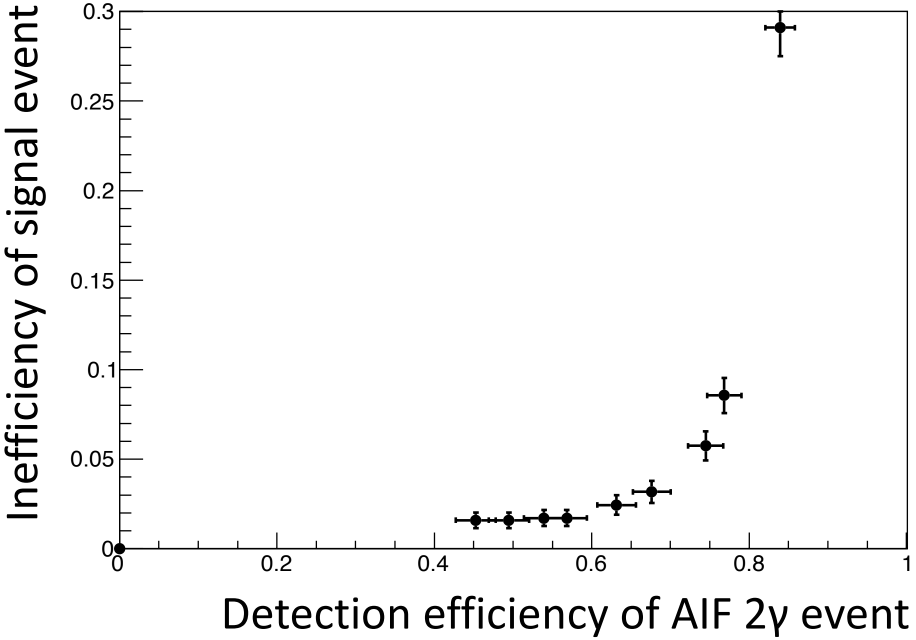


AIF2G -expected performance-

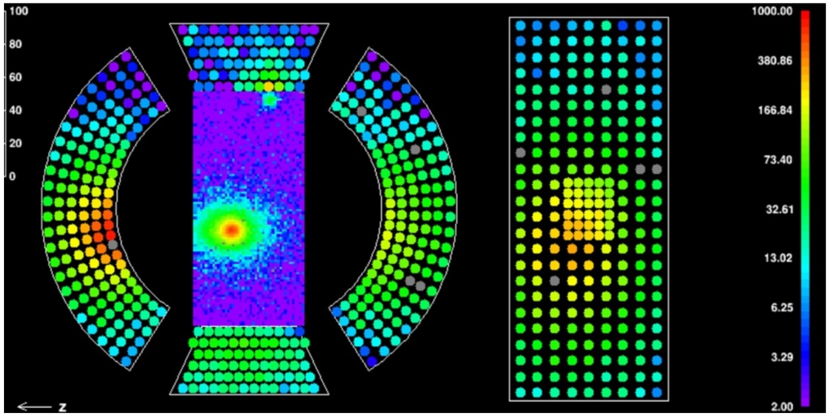
Two peaks on the MPPC light distribution from two gamma-rays are identified.

- ~ 60% of AIF 2γ events can be identified with a few % misidentification of signal event as a background.

→ Lead to 12% sensitivity improvement (in MC.)



<u>Example of two peak event</u>
<u>from single signal γ-ray</u>



γ-ray escaped from EM shower deposit its energy near the inner face.

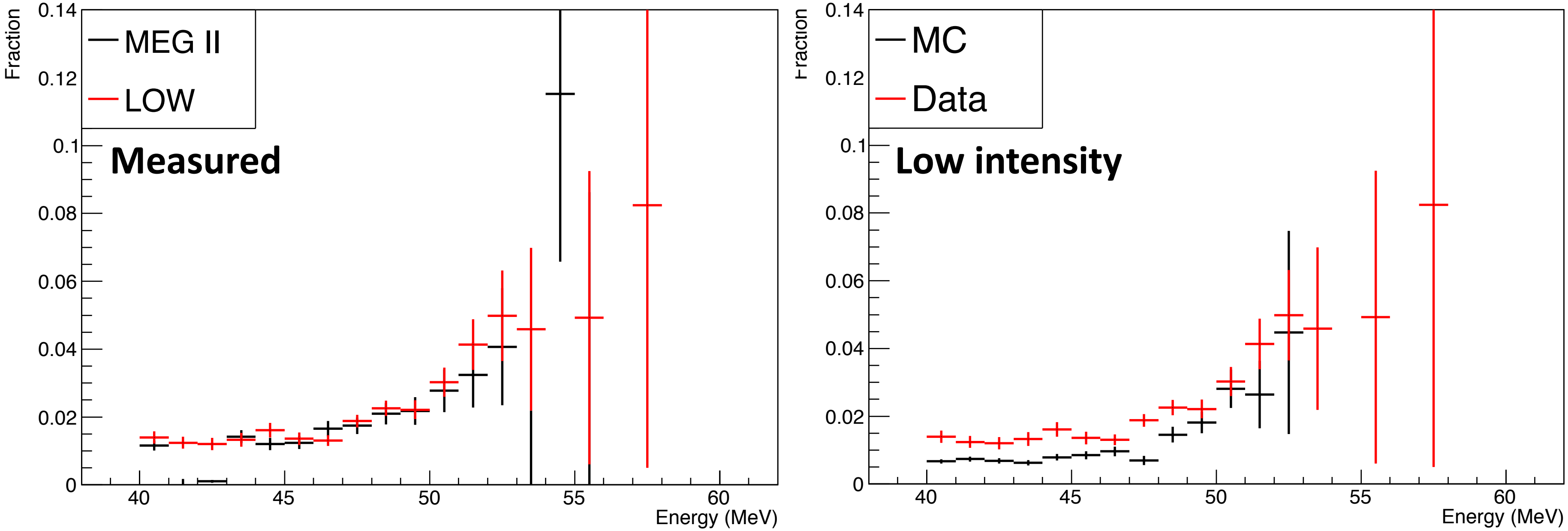
AIF2G -validation in data-

- Validation of the performance with data was failed.
- Fraction of two γ-rays event increased near the 52.8MeV both in MEG II and reduced intensity.

→ AIF 2γ events are identified (not coincident pileup).

- 2γ events in the lower energy are measured to be larger than simulated.
- Inefficiency to signal event with full ch readout may also differ from MC.

Fraction of found 2γ event in background γ-rays in 2019 readout



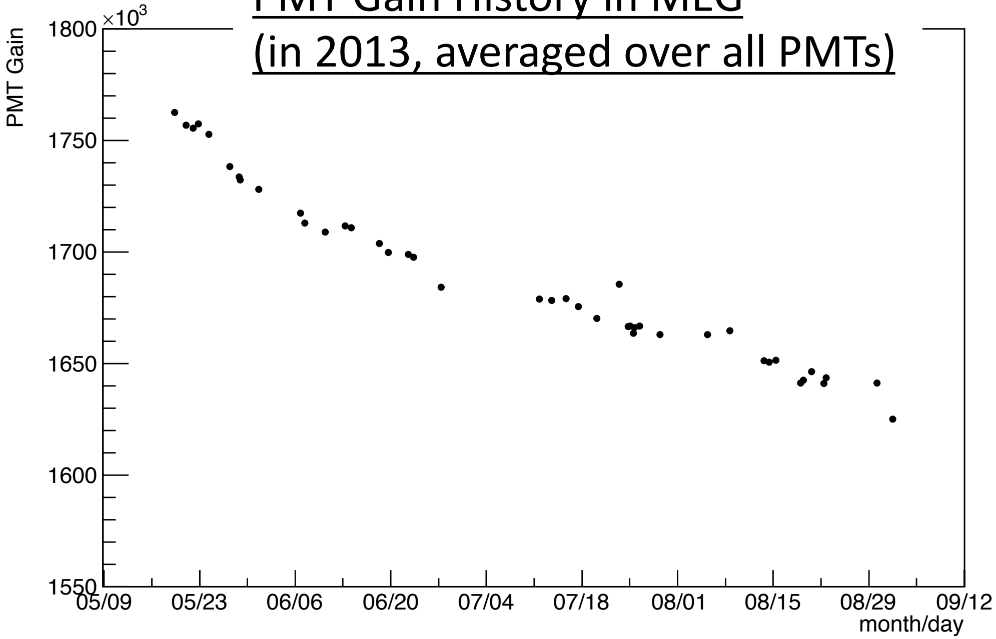
BACKUP
-radiation-

PMT Gain degradation

A gradual decrease of the PMT gain during muon beam usage is known in MEG.

- Probably due to the degradation of the dynode material.
- Degradation was compensated by applying higher voltage to keep the gain of 1.6 × 10^6.
- Degradation by 0.15%/day at 3 × 10^7 [μ/s] beam.

→ 0.35%/day was expected at 7 × 10^7 [μ/s] beam (for MEG II).


PMT Gain History in MEG
(in 2013, averaged over all PMTs)

PMT Gain degradation (cont'd)

Faster gain degradation observed at the beam test with 7×10^7 [μ/s] .

- Measured to be 1%/day at 7×10^7 [μ/s] beam, gain 1.6×10^6 .
- This is probably because the degradation speed is not saturated.

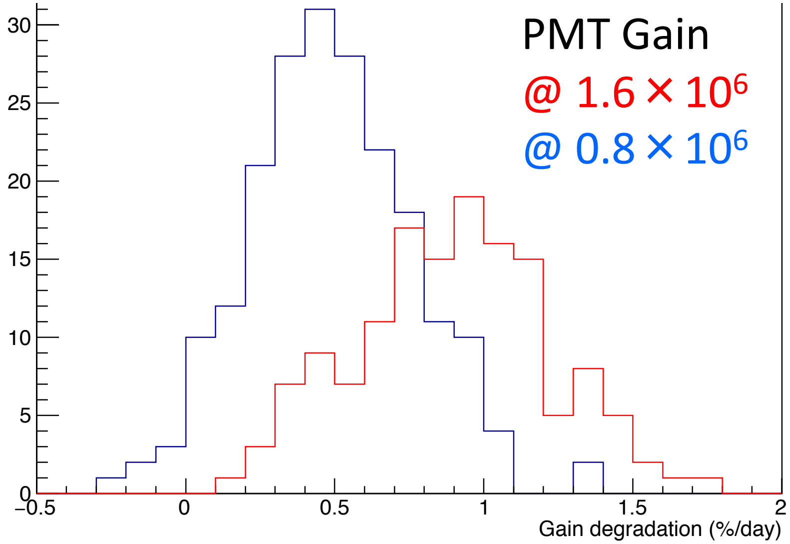
A PMTs operation at reduced gain is tried.

- Degradation speed is halved (0.5%/day), thanks to the reduced dynode current.
- Detector can be operated as long as 5 years if operated at reduced gain.

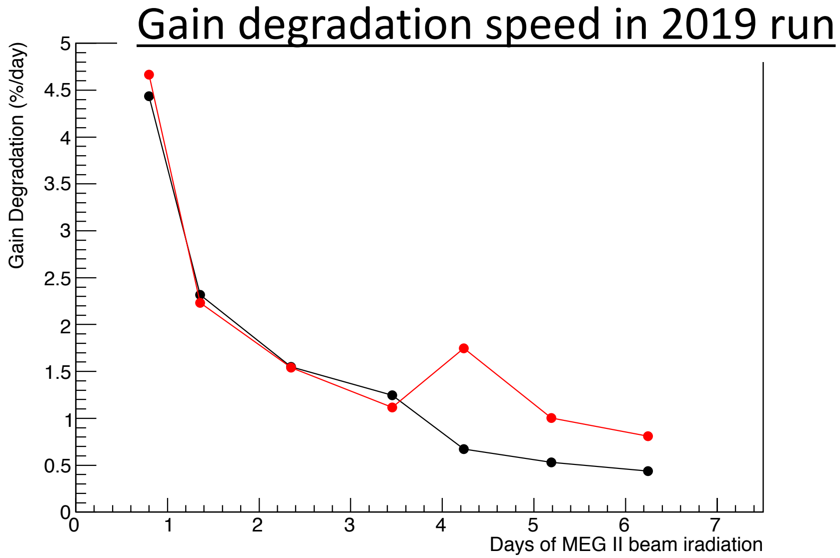
Gain degradation speed of each PMT (under 7×10^7 [μ/s] beam)

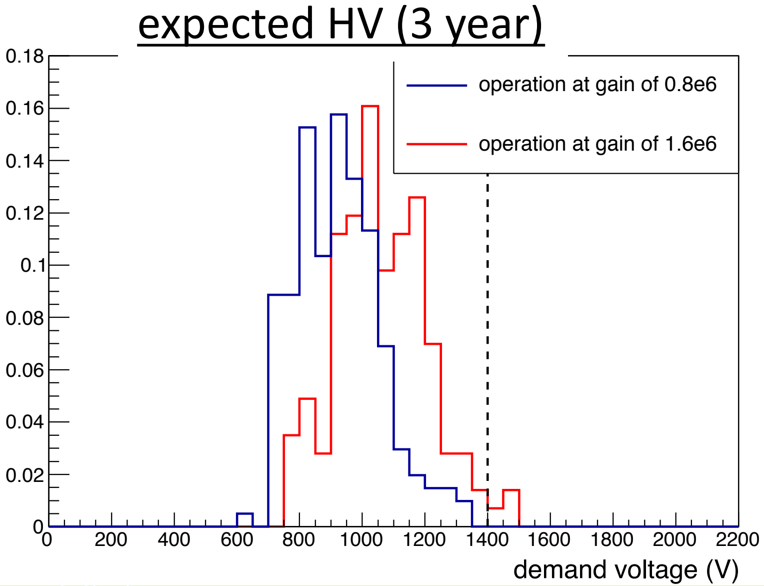
Effects on the resolution should be small.

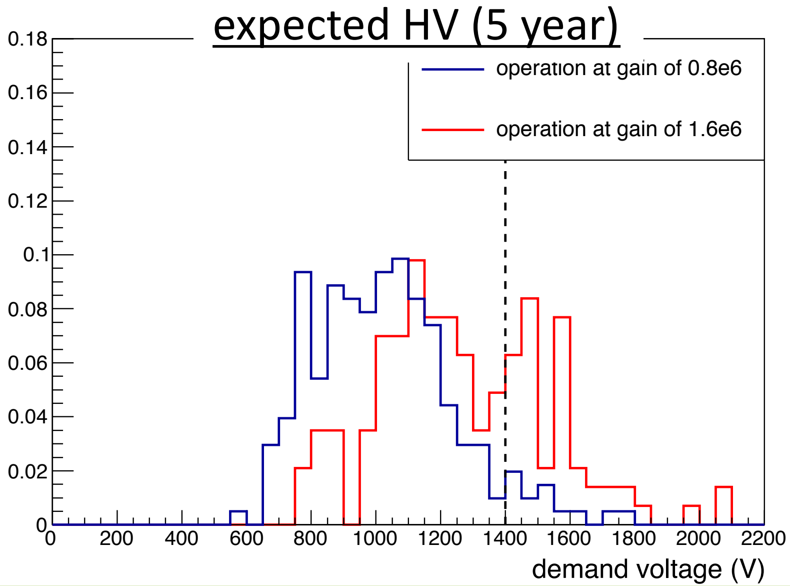
- worse S/N, smaller CE, larger TTS etc...



PMT Gain degradation

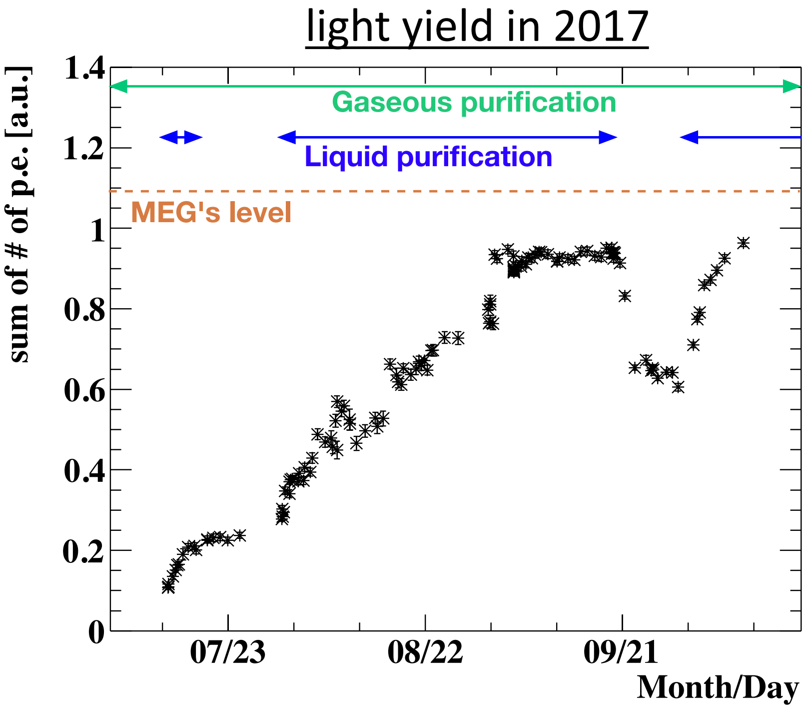

Gain degradation speed in 2019 run

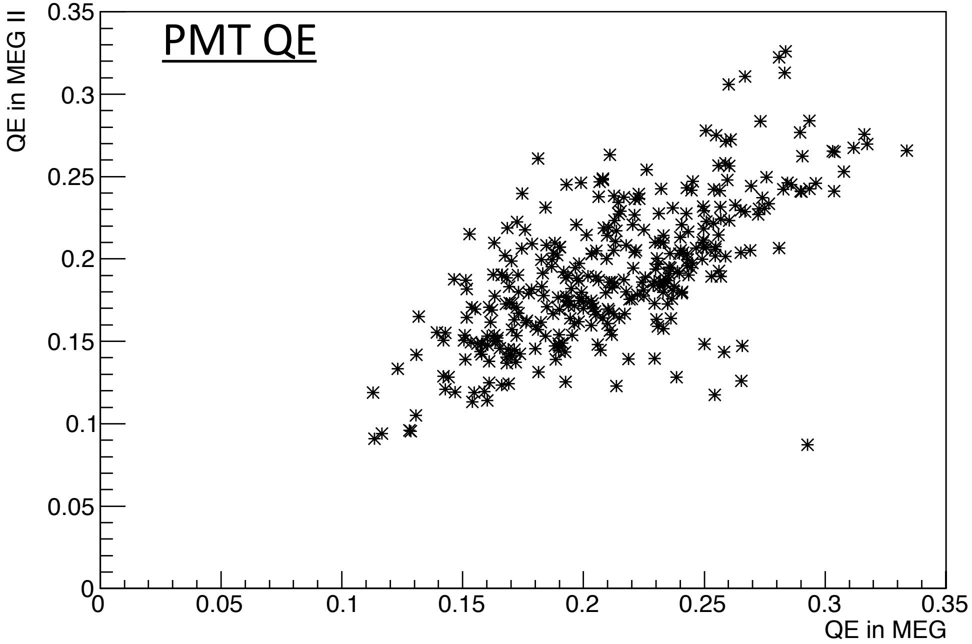

expected HV (3 year)


expected HV (5 year)

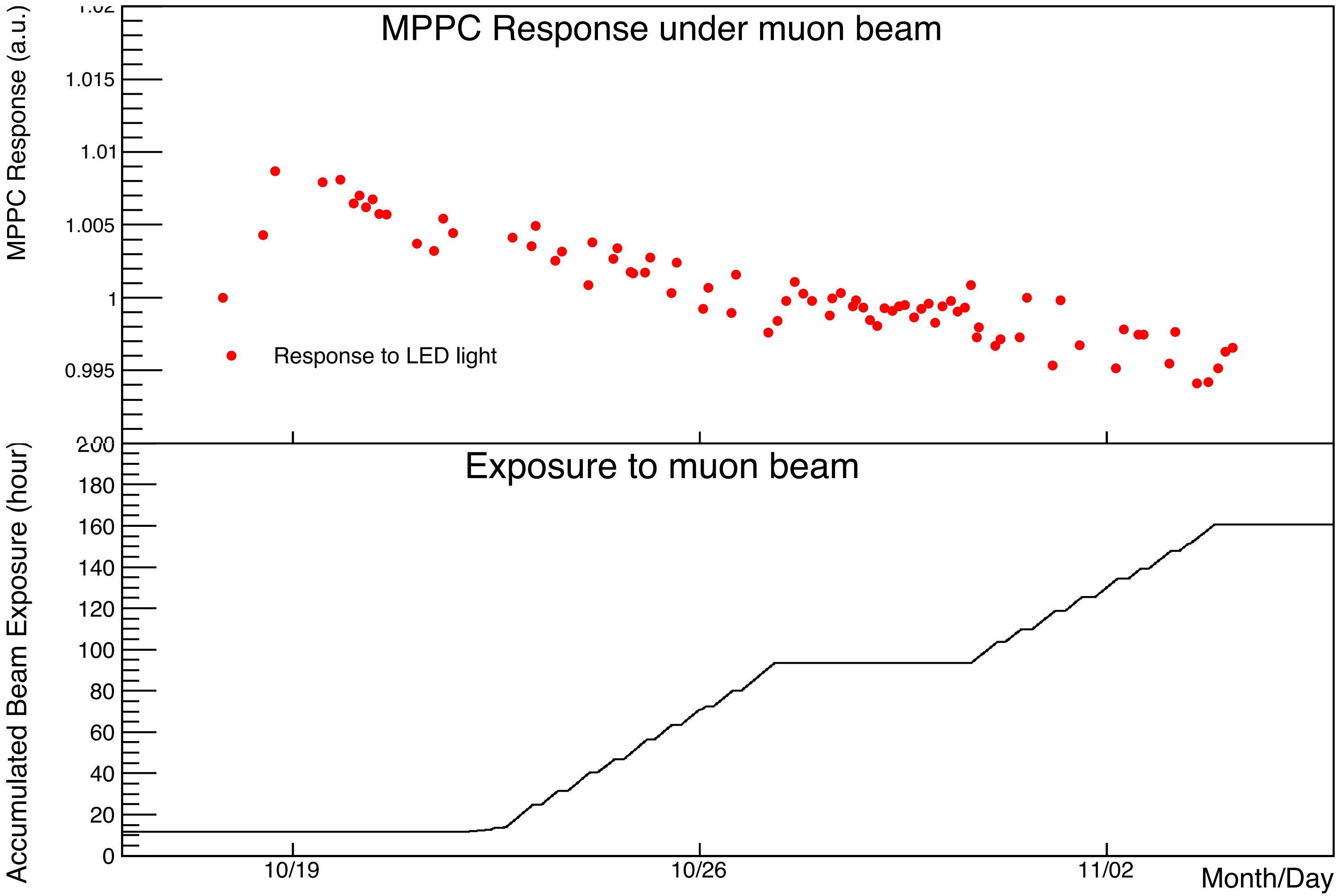
PMT QE

a

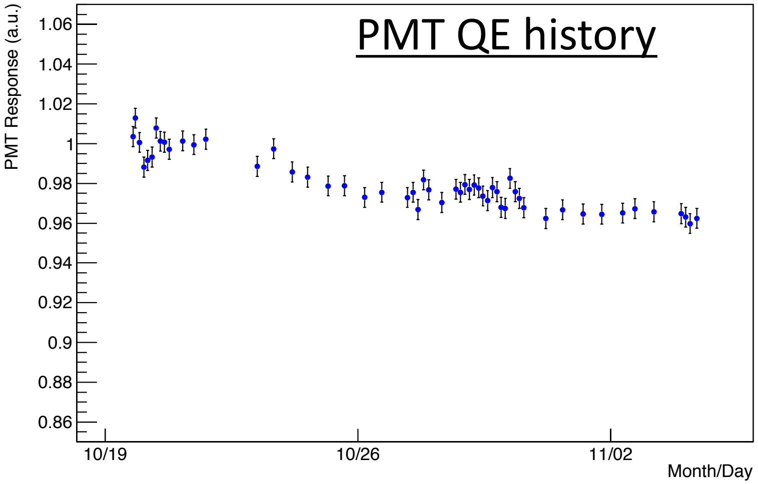

light yield in 2017
sum of # of p.e. [a.u.]
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Gaseous purification
Liquid purification
MEG's level
07/23
08/22
09/21
Month/Day


PMT QE
QE in MEG II
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
QE in MEG

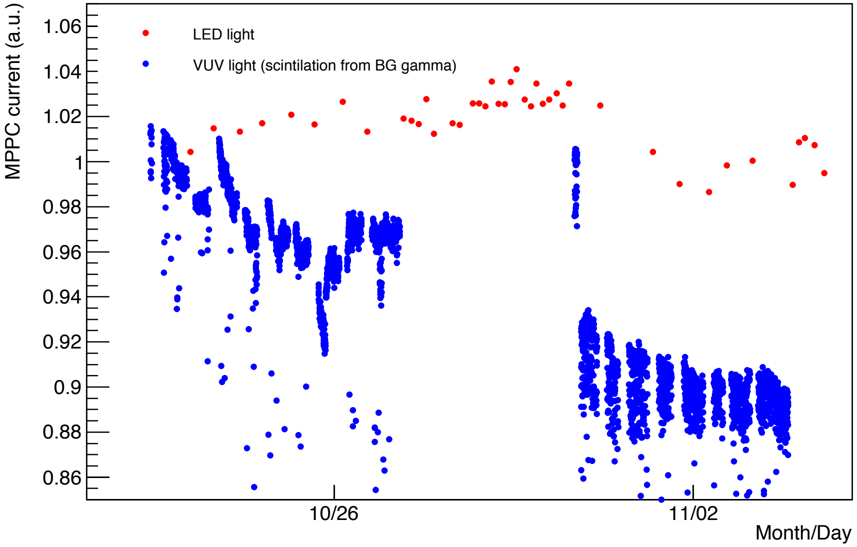
Vis PDE in 2019 run

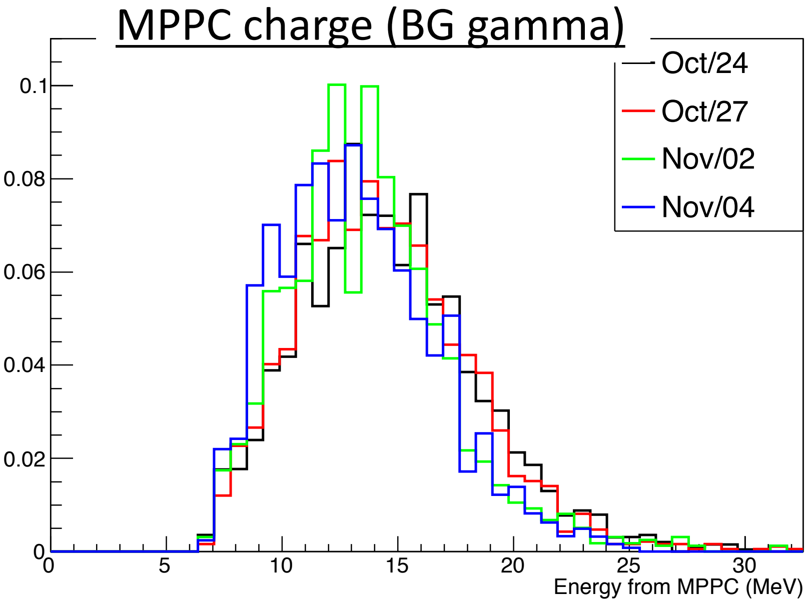


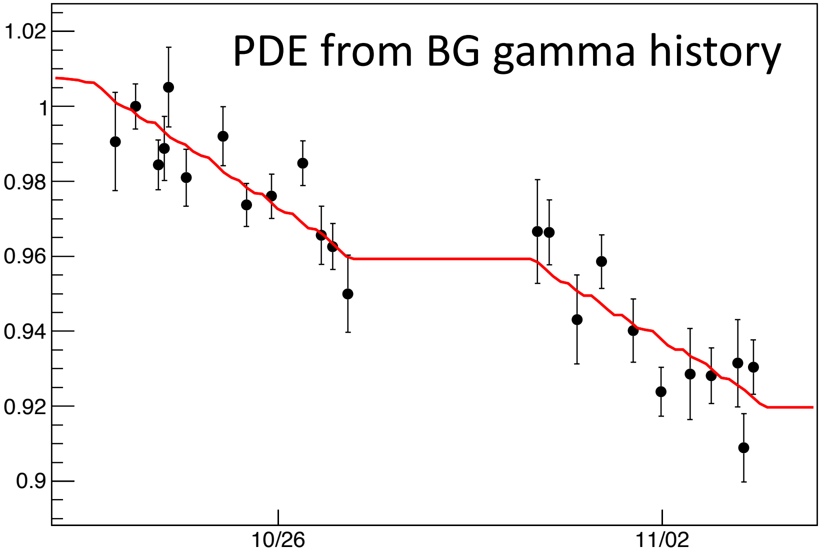
VUV PDE others


PMT QE history

VUV current history




MPPC charge (BG gamma)


PDE from BG gamma history

Annealed MPPC

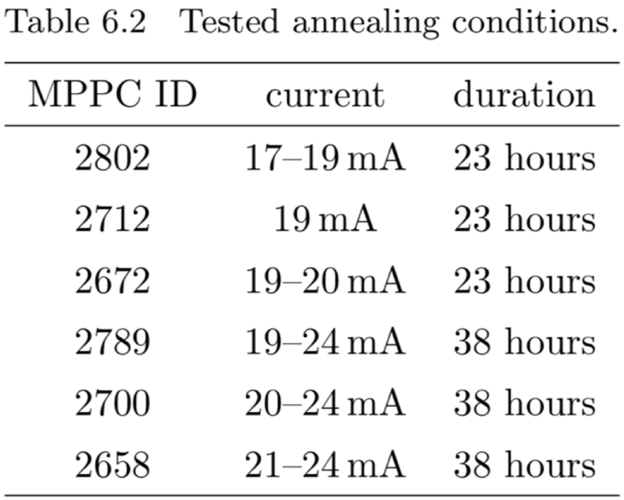
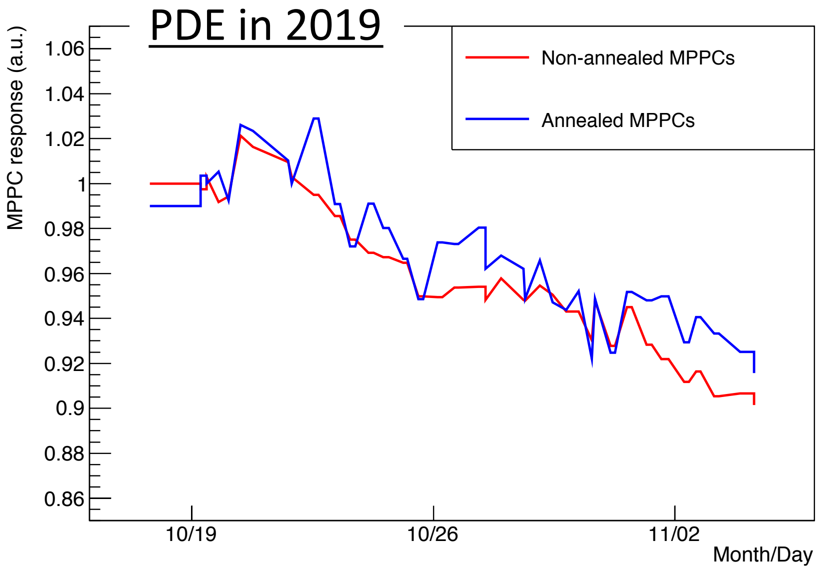
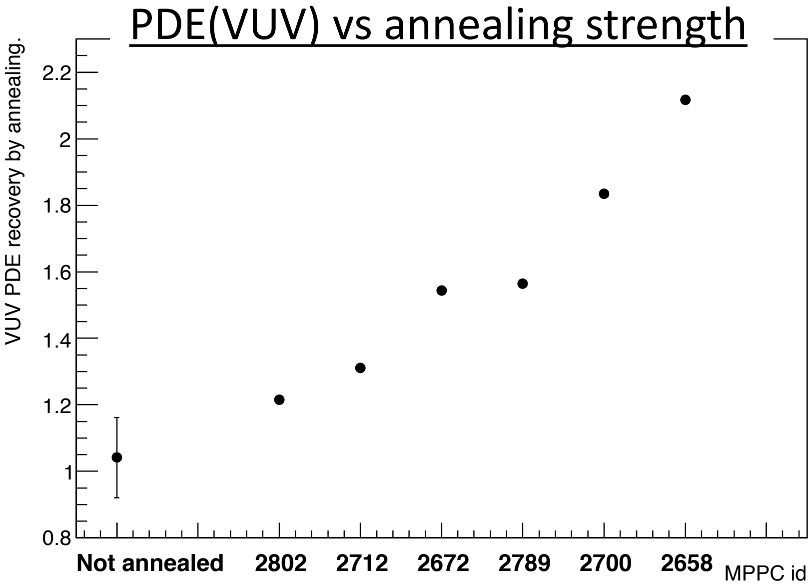


Table 6.2 Tested annealing conditions.

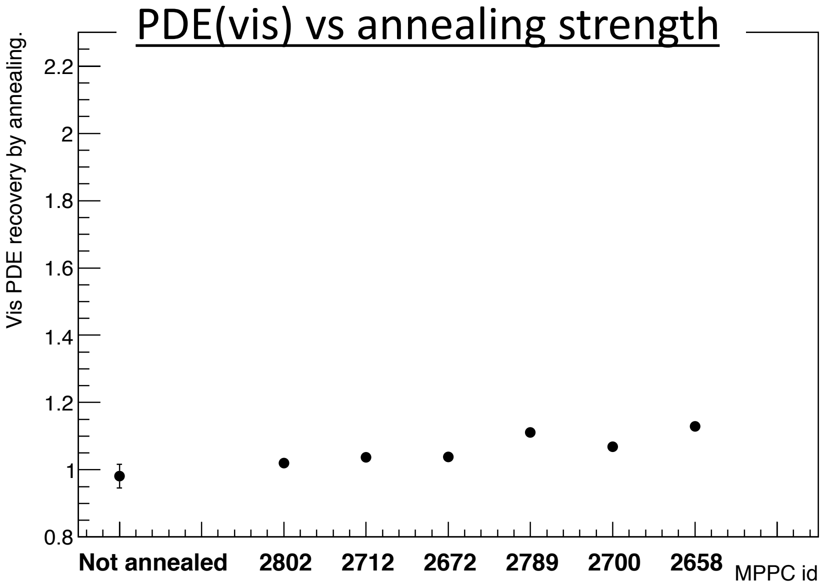
MPPC ID	current	duration
2802	17–19 mA	23 hours
2712	19 mA	23 hours
2672	19–20 mA	23 hours
2789	19–24 mA	38 hours
2700	20–24 mA	38 hours
2658	21–24 mA	38 hours



PDE in 2019



PDE(VUV) vs annealing strength

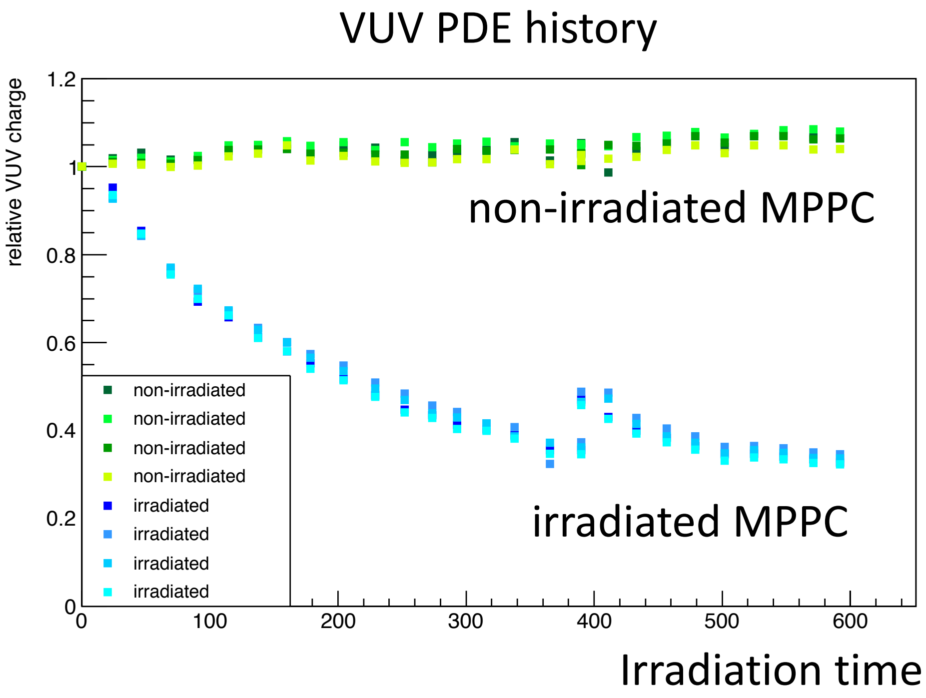


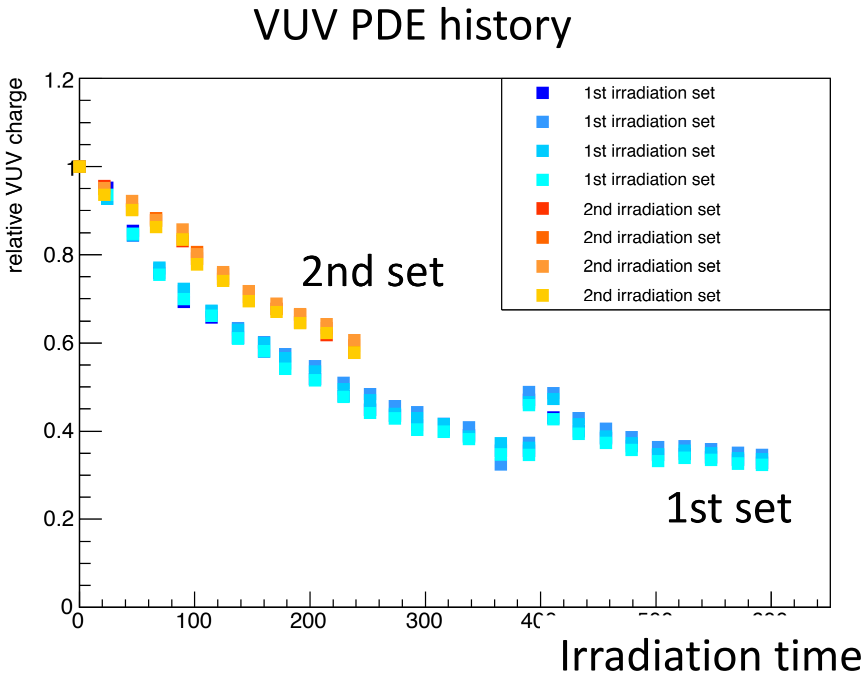
PDE(vis) vs annealing strength

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.





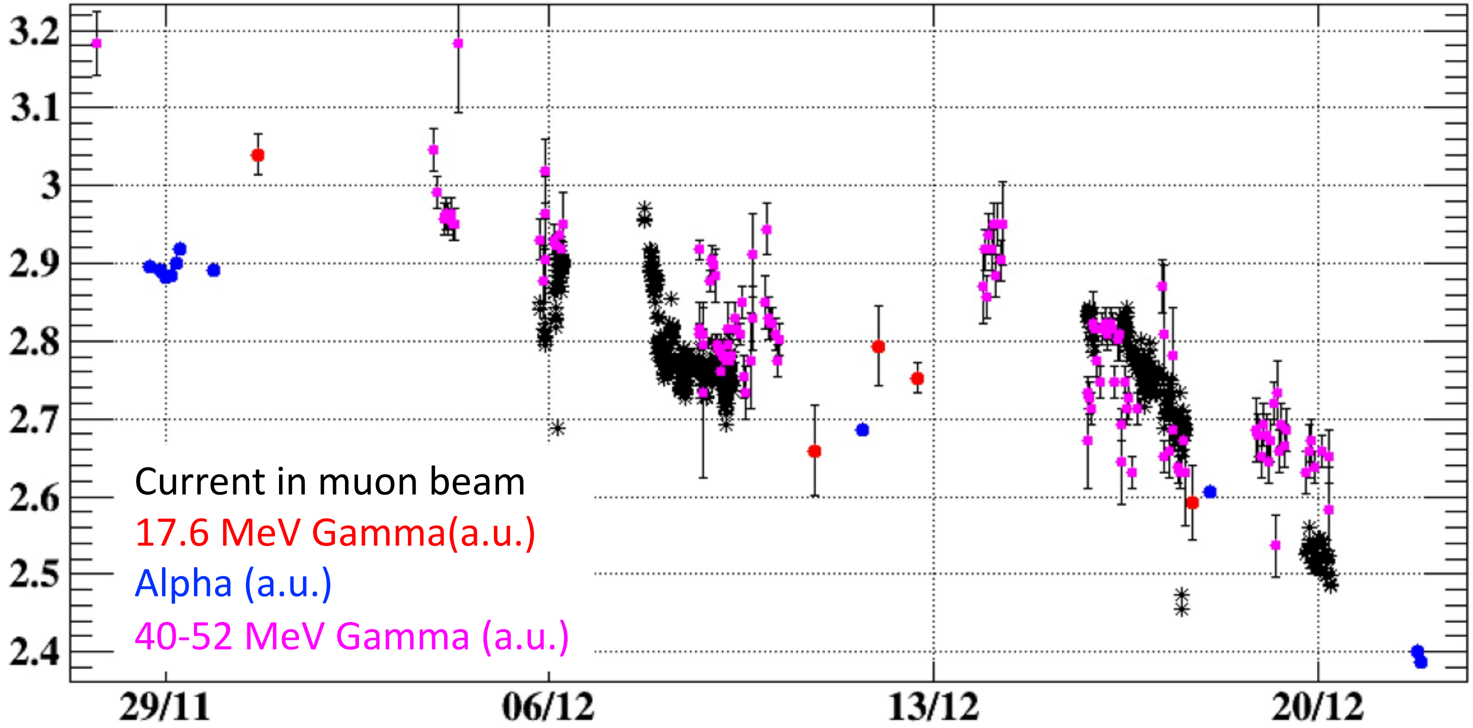
Summary of MPPC PDE (VUV)

以上の重ね書き。

平均10-20%の減少。

- もしbeam rateに比例したradiationだと仮定すると- 0.07~0.13 [%/h]

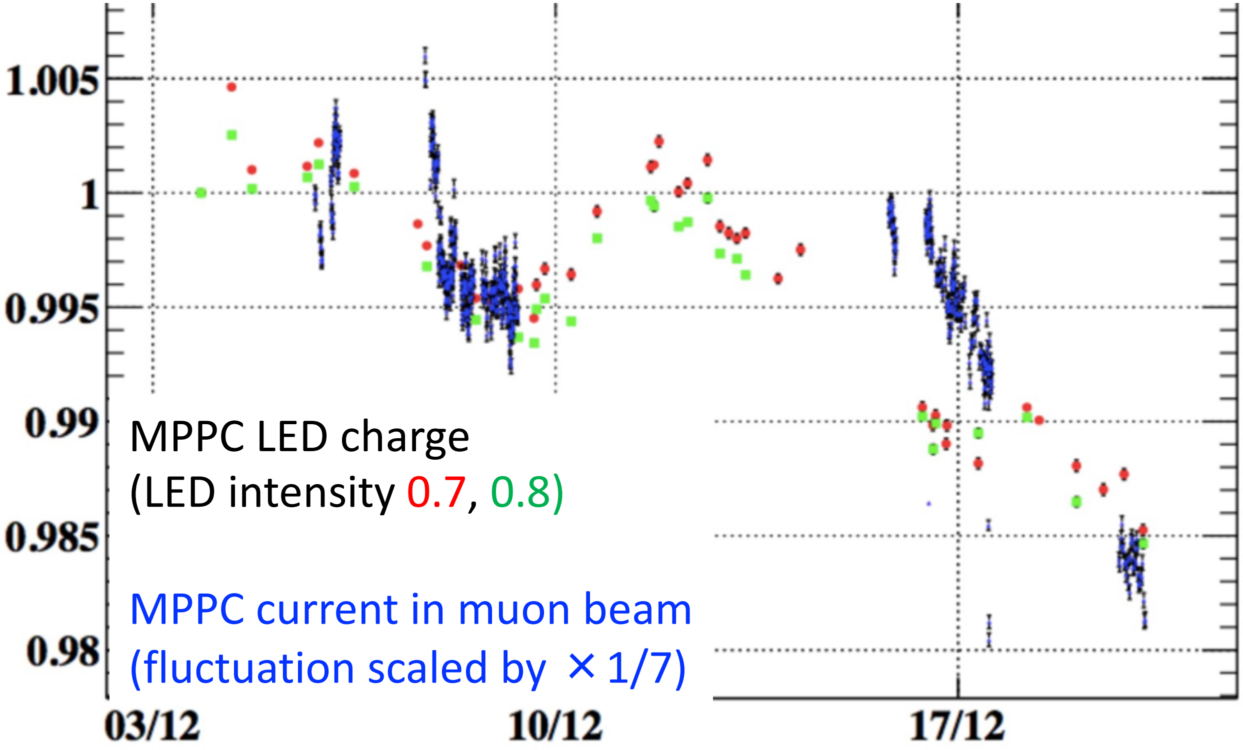
異なる変数同士は、傾向は似ているが一致はしていない。



MPPC PDE (visible light)

青色LEDを同じ電圧で光らせて、MPPCでの電荷を測定。
1p.e. によるGain/EQFを用いることで可視光PDEを評価。
徐々に減少している。
VUV PDE変動を1/7倍したものとcorrelateしているかもしれない。

MPPC charge from fixed intensity blue LED



MPPC LED charge
(LED intensity 0.7, 0.8)

MPPC current in muon beam
(fluctuation scaled by ×1/7)

DAQ at low PDE

<u>Calibration</u>

No problem.

<u>Online resolution</u>

- Online γ-ray resolution should be sufficiently good to keep trigger rate reasonable.
- In principle, the same discussion with offline resolution is applicable.
  - Or even better due to worse resolution (less requirement) than offline resolution.
- Performance of online γ-ray reconstruction has not yet been demonstrated due to noise issue on prototype system etc., and should be checked once we have full channel readout.
- Offline trigger by simple offline reconstruction should be useful to reduce number of recorded event.

EXPECTED SENSITIVITY

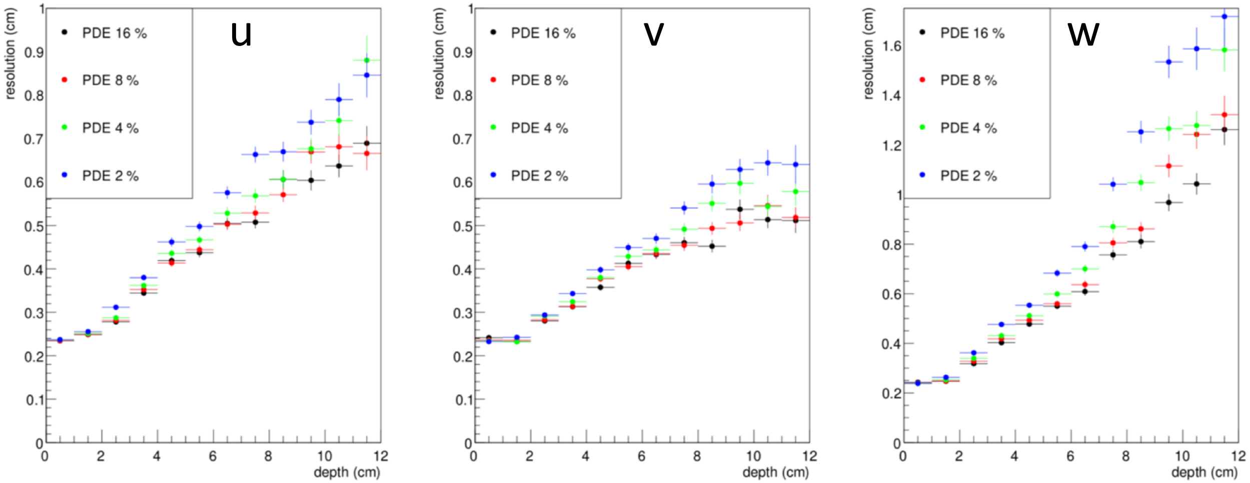
k-factor assumption

- beam rate : 7×10^7 μ/s
- geometrical acceptance : 10.8%
- positron efficiency : 70%
- γ efficiency : 69%
- trigger and analysis efficiency : 91% (same as the first half of MEG)
- DAQ time : Three years. 20 week data-taking per year with 84% live fraction.

→ $k = 1.03 \times 10^{14}$

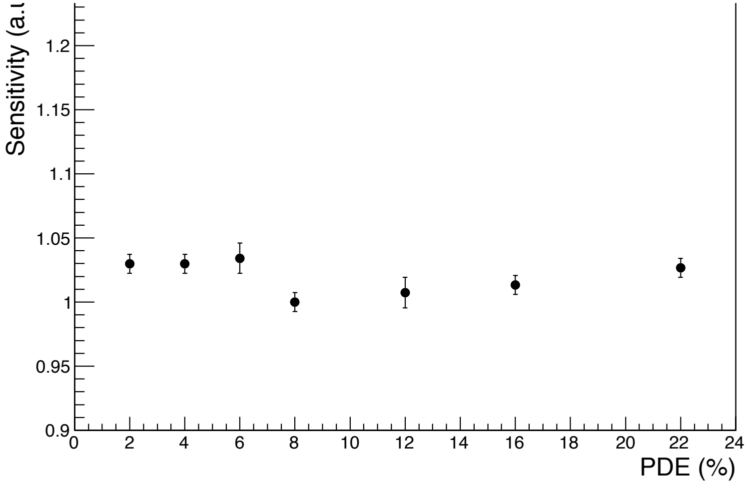
Position resolution at lower PDE

Position resolution of shallow events limited by event-by-event fluctuation of shower development.



Statistical fluctuation on resolution for deep events.

Sensitivity vs PDE (via position resolution)



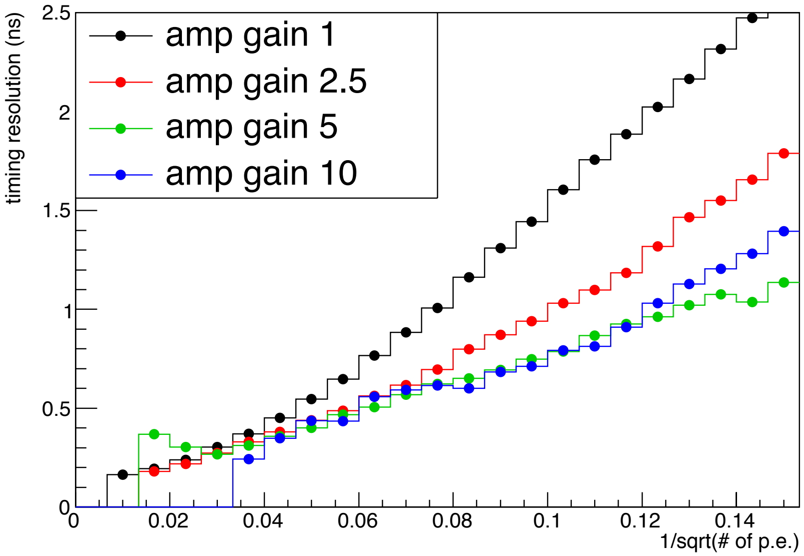
Timing resolution at lower PDE

- Statistical fluctuation and worse S/N deteriorates MPPC timing resolution.
- Usage of larger amplifier gain can suppress the degradation.
- Timing resolution determined by PMTs at lower MPPC PDE.

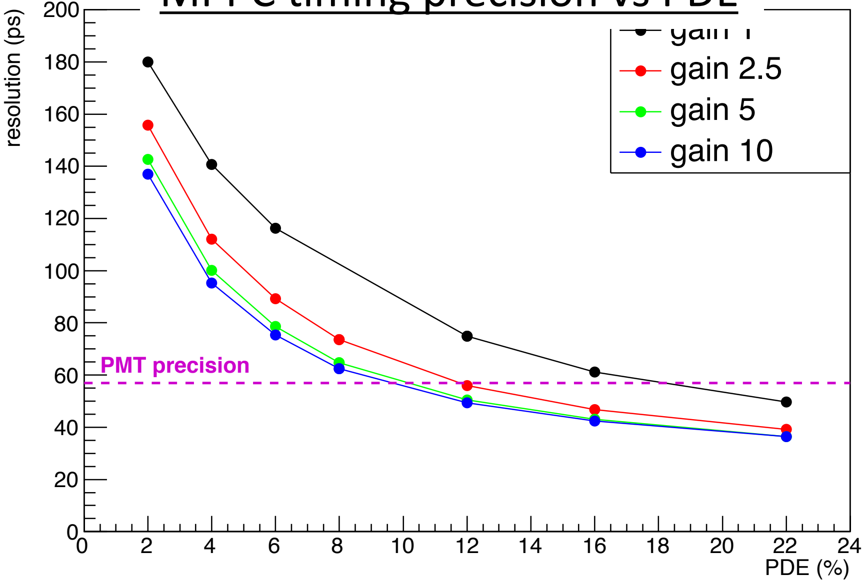
PDE	amplifier gain
$8\% < PDE \leq 22\%$	1
$4\% < PDE \leq 8\%$	2.5
$2\% < PDE \leq 4\%$	5
$0\% < PDE \leq 2\%$	10

amplifier gain	1	2.5	5	10
Noise level	0.7 mV	0.8 mV	0.9 mV	1.3 mV

Timing resolution of a MPPC vs 1/sqrt(# of p.e.)

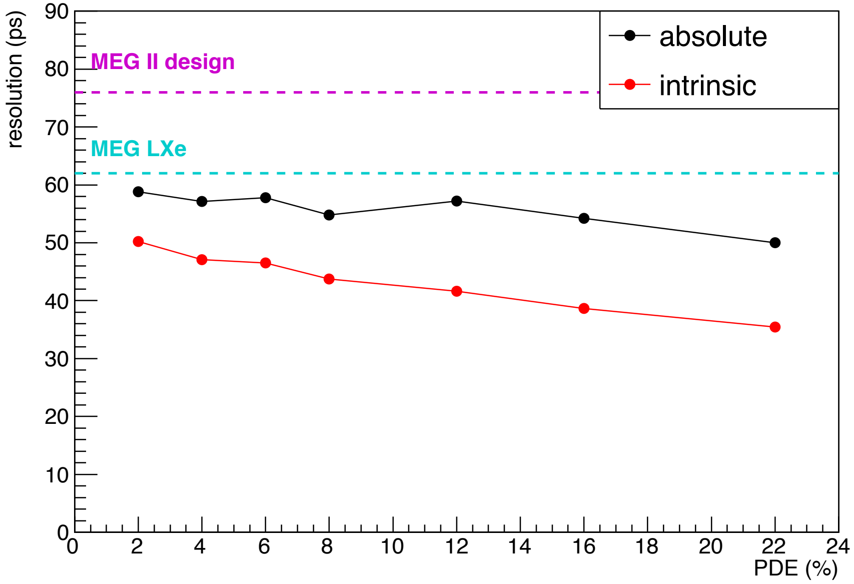


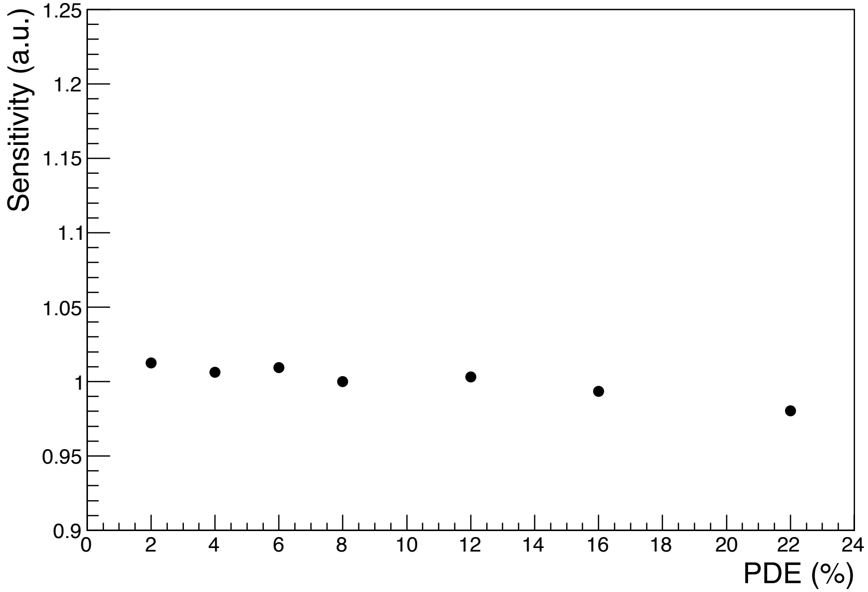
MPPC timing precision vs PDE



Timing resolution at lower PDE

a



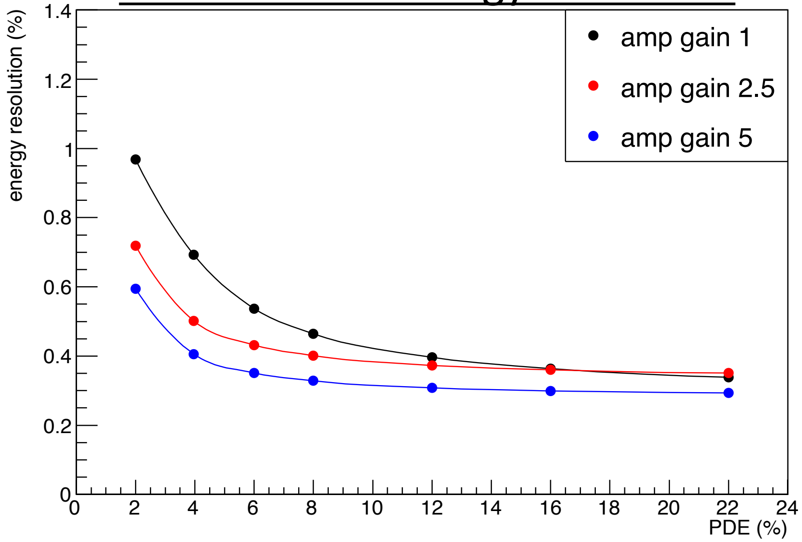


Energy resolution at lower PDE

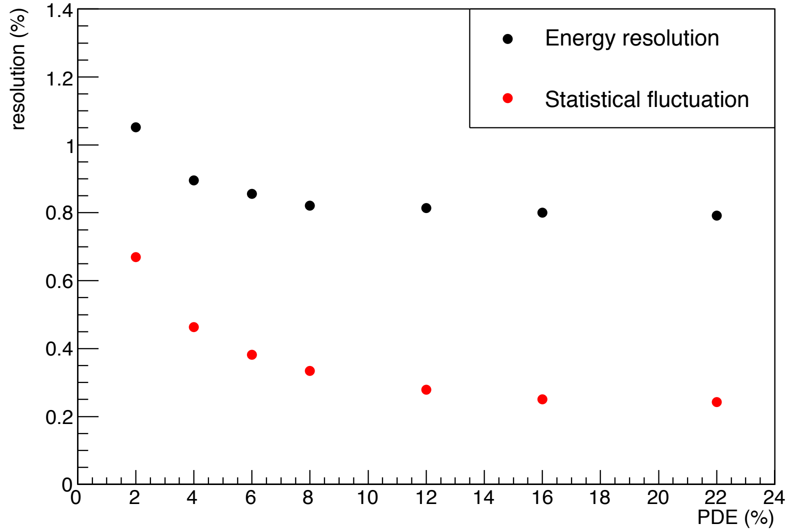
- Statistical fluctuation in energy resolution is not dominant.
- Unknown term is not statistical fluctuation (prev. slide).

- Noise term is not dominant.

Noise term in energy resolution

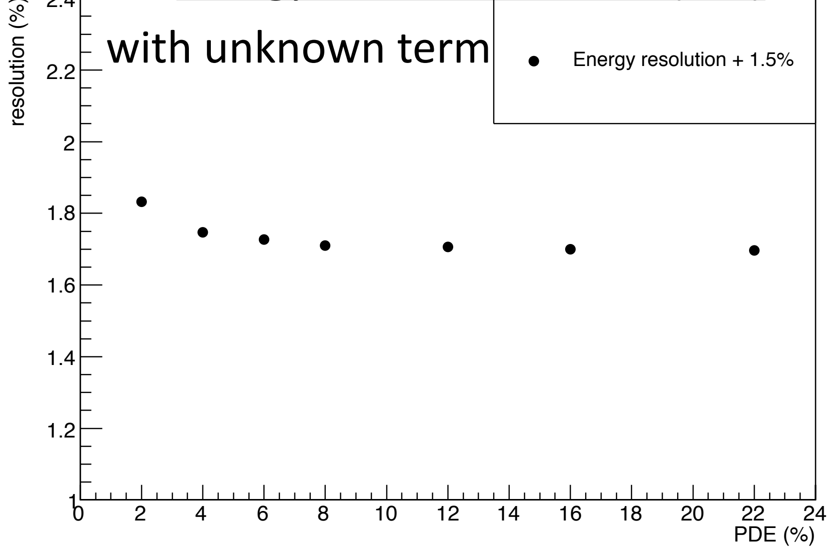


Energy resolution vs PDE (MC)



Energy resolution vs PDE (MC)

with unknown term



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.

Sensitivity of alternative DAQ plans

Plan B has a best sensitivity in these alternative plans.

<u>MEG II sensitivity vs. DAQ year</u>

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