MEG II experiment: Commissioning of Liquid Xenon Detector towards Start of Physics Run (1)

MEG II 実験：液体キセノン検出器の物理ラン開始に向けたコミッショニング(1)

Kazuki Toyoda on behalf of the MEG II Collaboration

19-Sep-2019

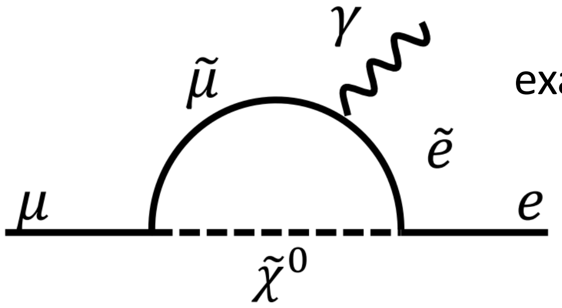
JPS autumn @Yamagata Univ.

Outline

- Introduction
  - $\mu \to e\gamma$
  - MEG II
  - Liquid Xenon Detector
  - pre-Engineering Run
- Photo-Sensor Monitoring
  - MPPC
  - PMT
  - Energy Scale
  - Prospect

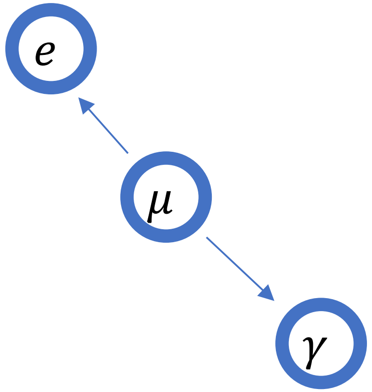
$\mu \to e\gamma$

- Charged Lepton Flavor Violation
  - practically **forbidden** in Standard Model by tiny neutrino mass
  - but many predictions by **new physics** are **within experimental reach**
    - eg. SUSY with GUT/Seesaw



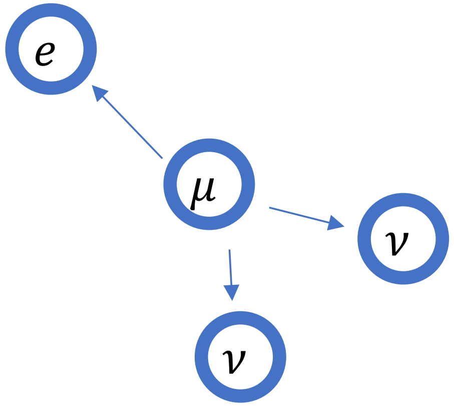
example of $\mu \to e\gamma$ decay

- $\mu \to e\gamma$ search
  - Signal

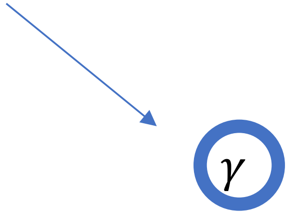


- both 52.8 MeV/c
- back to back
- same timing

  - Dominant Background: Accidental



+



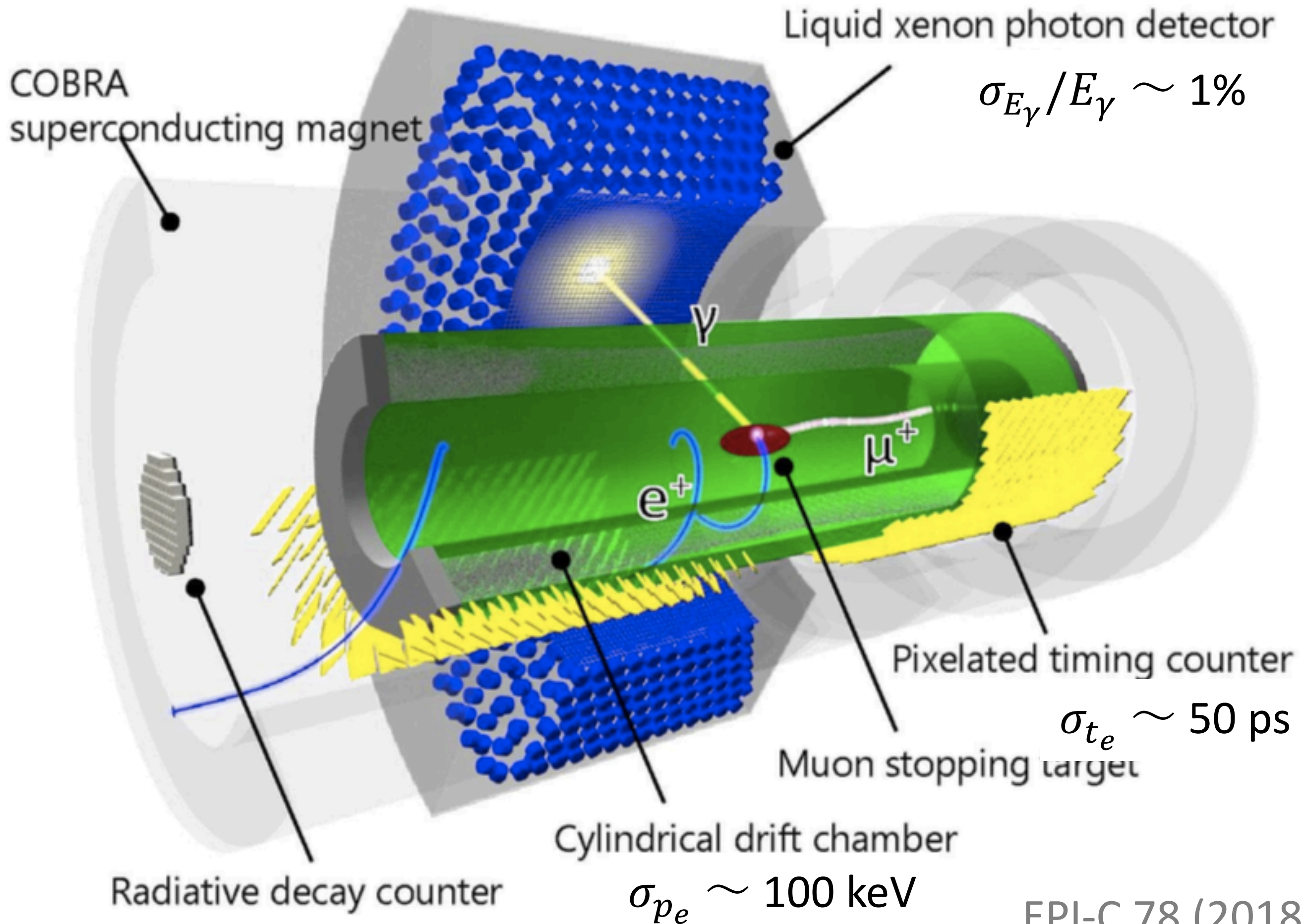
from $\mu \to e\nu\nu\gamma$
$ee \to \gamma\gamma$

MEG II

- goal sensitivity: **6.0×10^{-14} in 60 weeks**
  compared to MEG I result:
  $Br(\mu \to e\gamma) < 4.2\times10^{-13}$
  (sensitivity: 5.3×10^{-13})

- key concept:
  - high μ intensity: $7\times10^{7}\mu/s$ @PSI
  - high resolution detectors

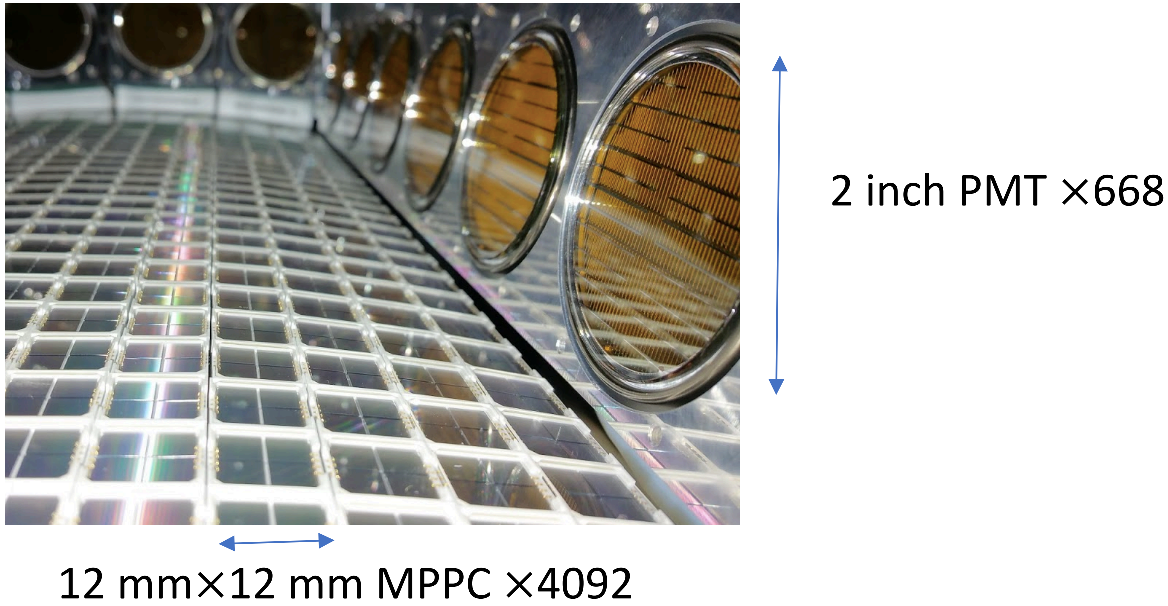
- talks
  - overall status: 19pT22-2
  - timing counter: 17pT12-1,2,3
  - radiative decay counter: 18pT12-1

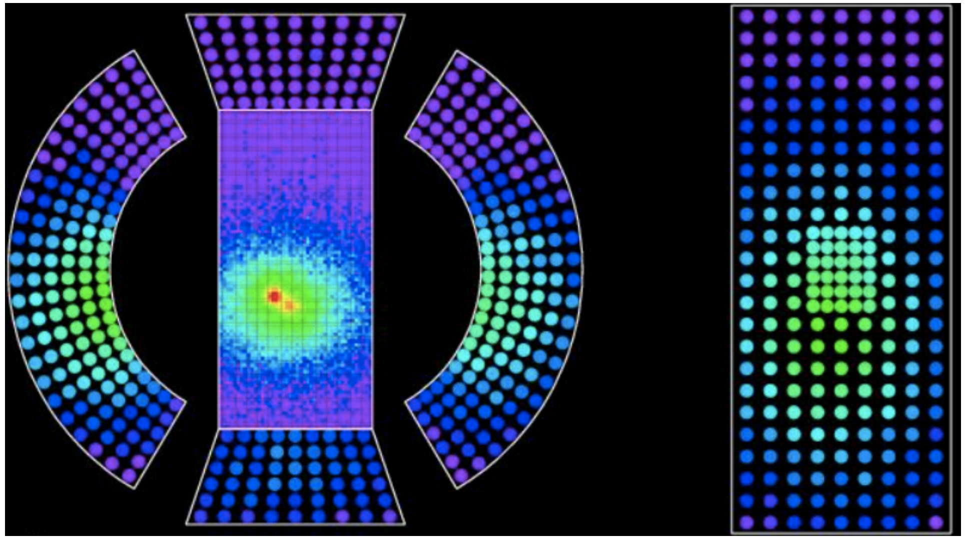


EPJ-C 78 (2018) 380

Liquid Xenon Detector

- 900 L liquid Xe scintillator (VUV-light ~175 nm)
- PMTs on γ incident surface are replaced to MPPCs





MC event display
example of pile up

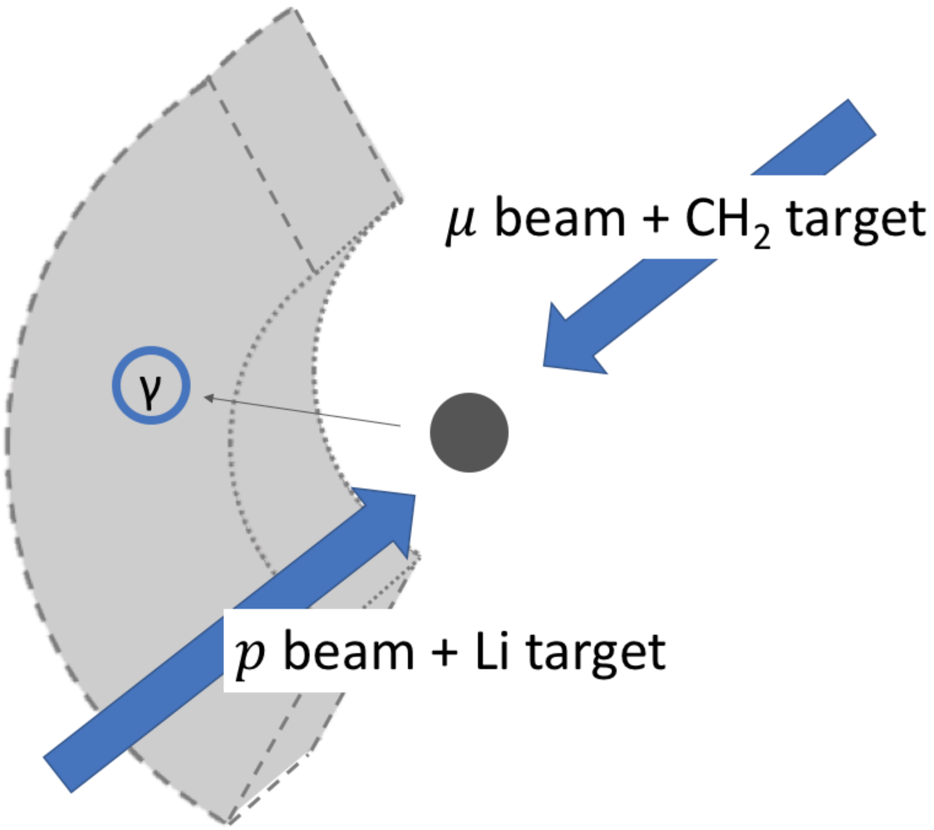
→ improved uniformity and granularity

- energy resolution : **2%** @MEG I → **1%** @MEG II (expected)
- position resolution: **5 mm** @MEG I → **2.5 mm** @MEG II (expected)

Commissioning of Xe Detector

- pre-Engineering Run 2018
  - sensor calibration by LED, ^{241}Am α source
  - 17.6 MeV γ from p-Li reaction
  - background γ from μ beam ($\mu \rightarrow e\nu\nu\gamma,\ \ ee \rightarrow \gamma\gamma$)
  - limited to ¼ of full readout electronics

- talks
  - MPPC PDE issue: 17aT12-4,5
  - energy resolution:
    - sensor monitoring: 19pT14-6 (this talk)
    - background spectrum: 19pT14-7
    - p-Li reaction: 19pT14-8



Outline

- Introduction
  - $\mu \rightarrow e\gamma$
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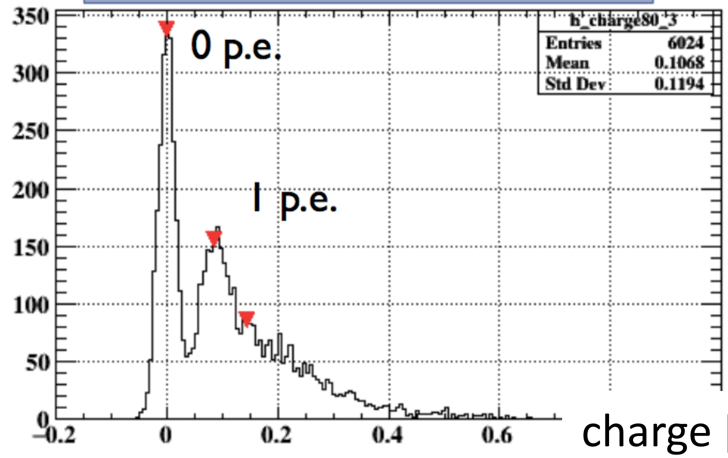
  - Liquid Xenon Detector
  - pre-Engineering Run
- Monitoring of Photo-Sensor
  - MPPC
  - PMT
  - Energy Scale
  - Prospect

MPPC

- $charge = N_{photon} \cdot PDE_\lambda \cdot gain \cdot ECF$
  - weak LED

PDE : Photon Detection Efficiency (depend on wavelength)
gain : charge from 1 pixel
ECF : Excess Charge Factor (= crosstalk + afterpulsing)

Example of charge distribution



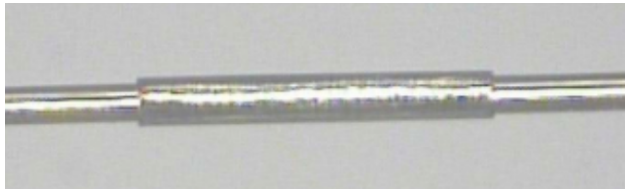
Charge follows "Poisson + correlated noise" distribution

$$gain \cdot ECF = \frac{mean}{\mu\ (expected\ \#\ of\ primary\ discharge)}$$

estimated from pedestal fraction:
$P(0\,pe) = e^{-\mu}$

  - Strong LED: response for visible light
  - charge from scintillation by α from ^{241}Am
  - current from scintillation by γ from μ


LED

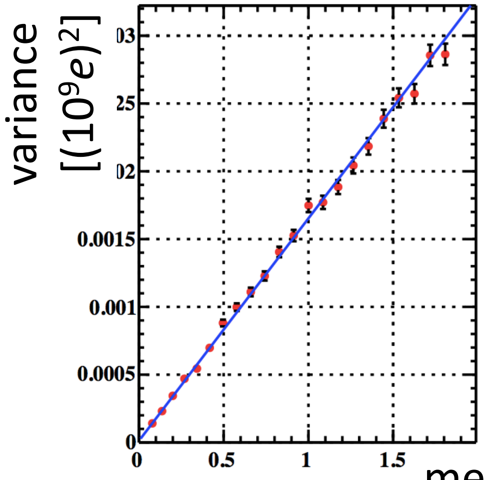

^{241}Am α source

PMT

- $charge = N_{photon} \cdot QE \cdot CE \cdot gain$
  - LED of different intensity

QE : Quantum Efficiency
CE : Collection Efficiency
gain : charge from 1 photoelectron

depend on B-field



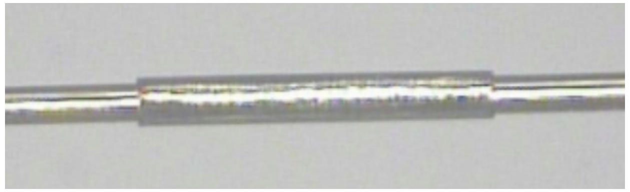
slope = gain

Charge follows Poisson distribution

$$gain = \frac{variance}{mean}$$

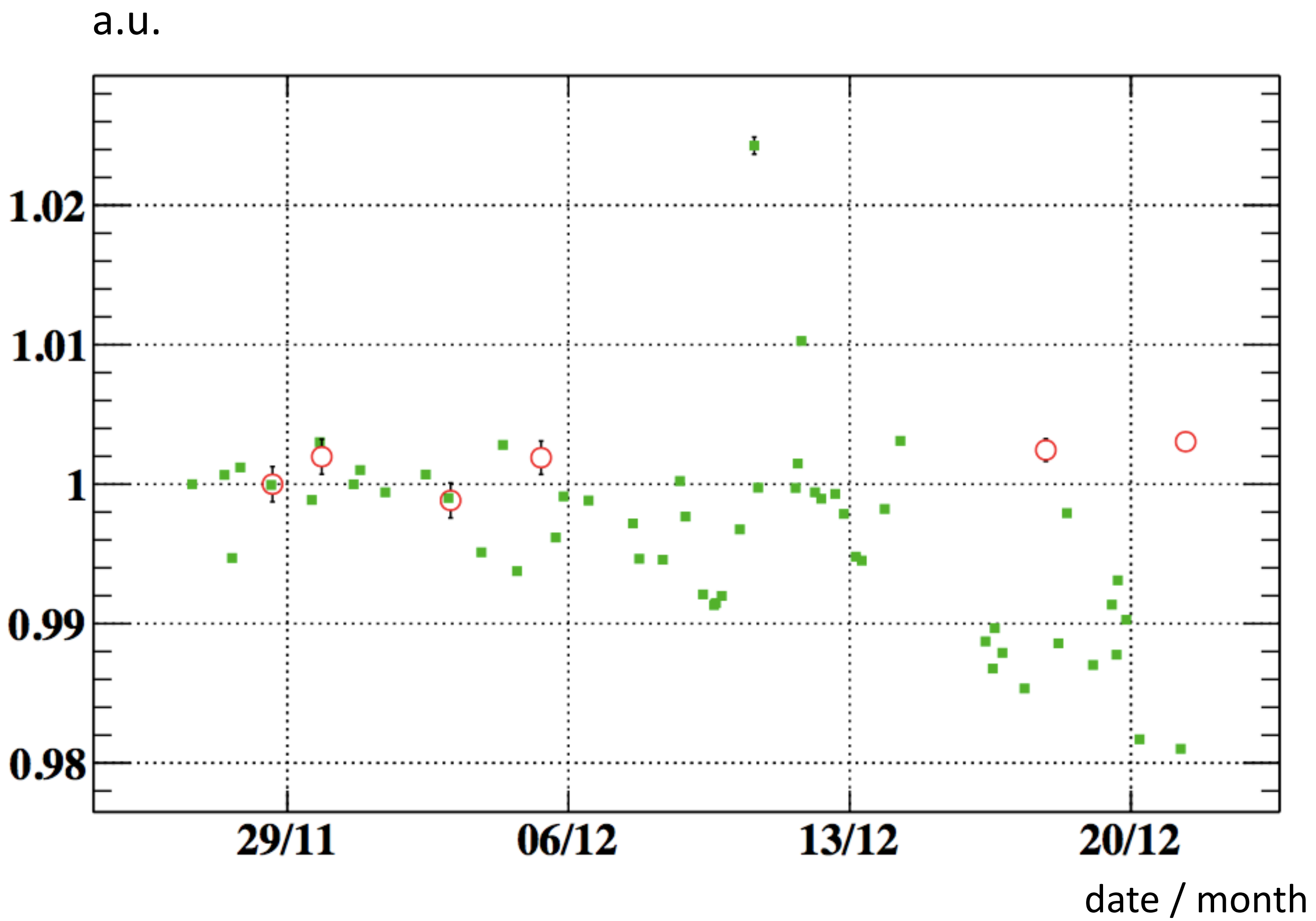
- Strong LED: response for visible light
- charge from scintillation by α from ^{241}Am
- current cannot be read out

LED



^{241}Am α source

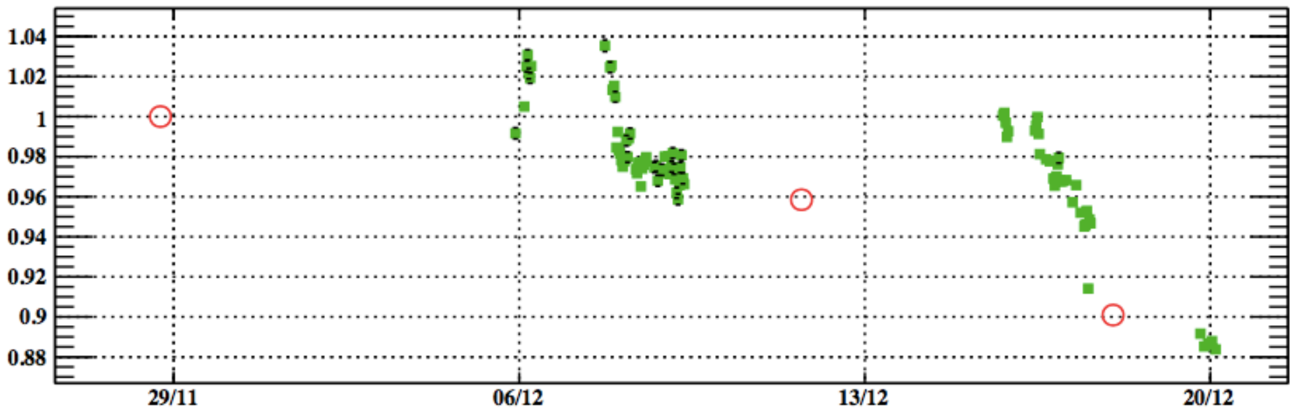
MPPC: Visible Light



- gain looks stable < 0.5%
- LED response decrease ~ 1-2%

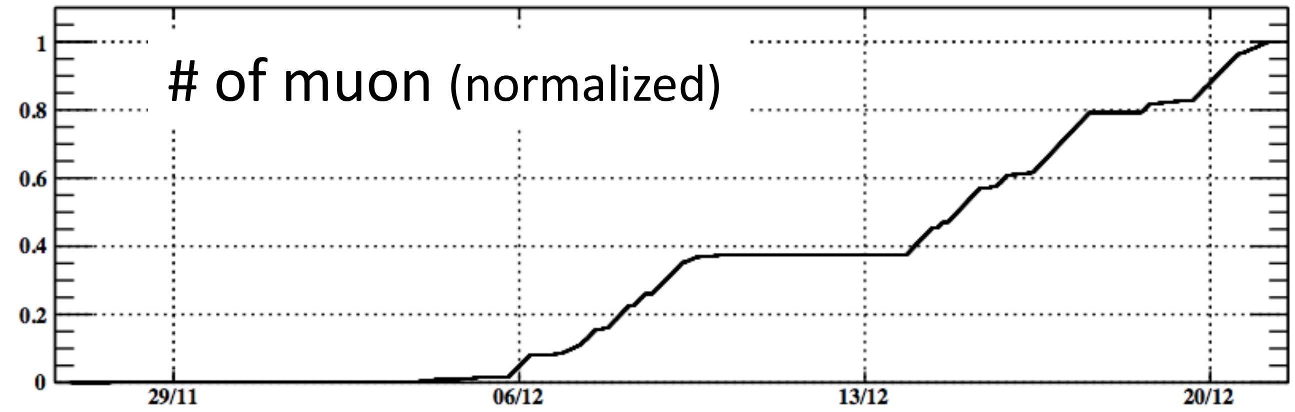
MPPC: VUV Light

a.u.



current from γ (from μ)

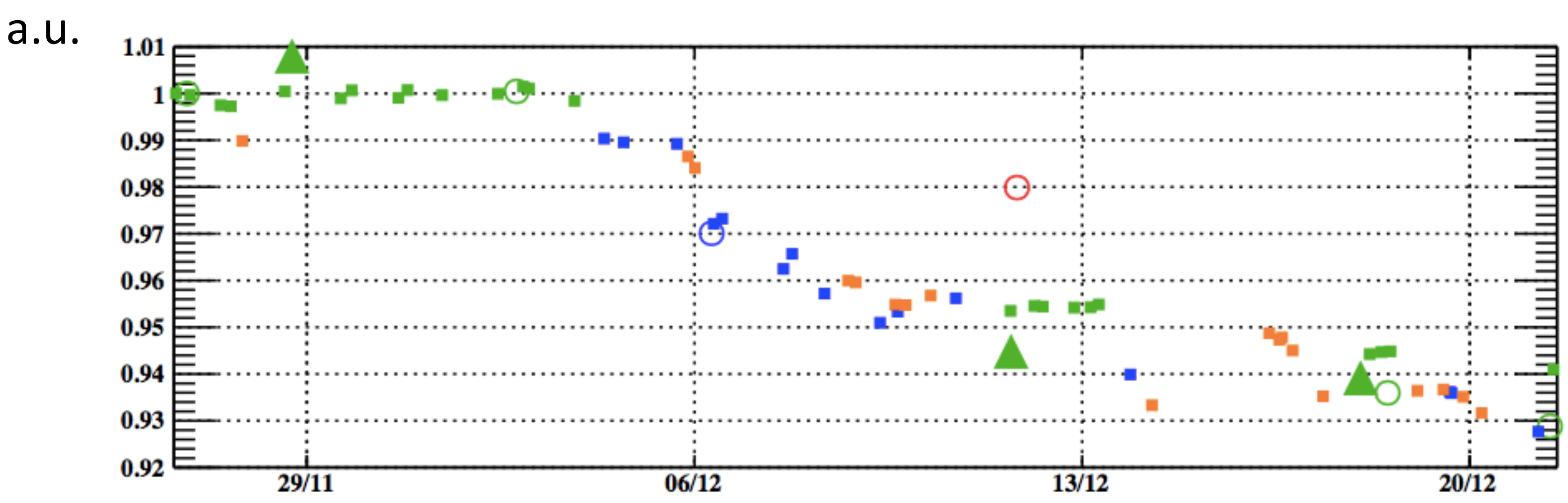
charge from α



- current behavior is not simple
- indicates ~10% decrease of PDE for VUV in ~150 h @MEG II intensity
- response for VUV light is decreasing much faster than for visible light

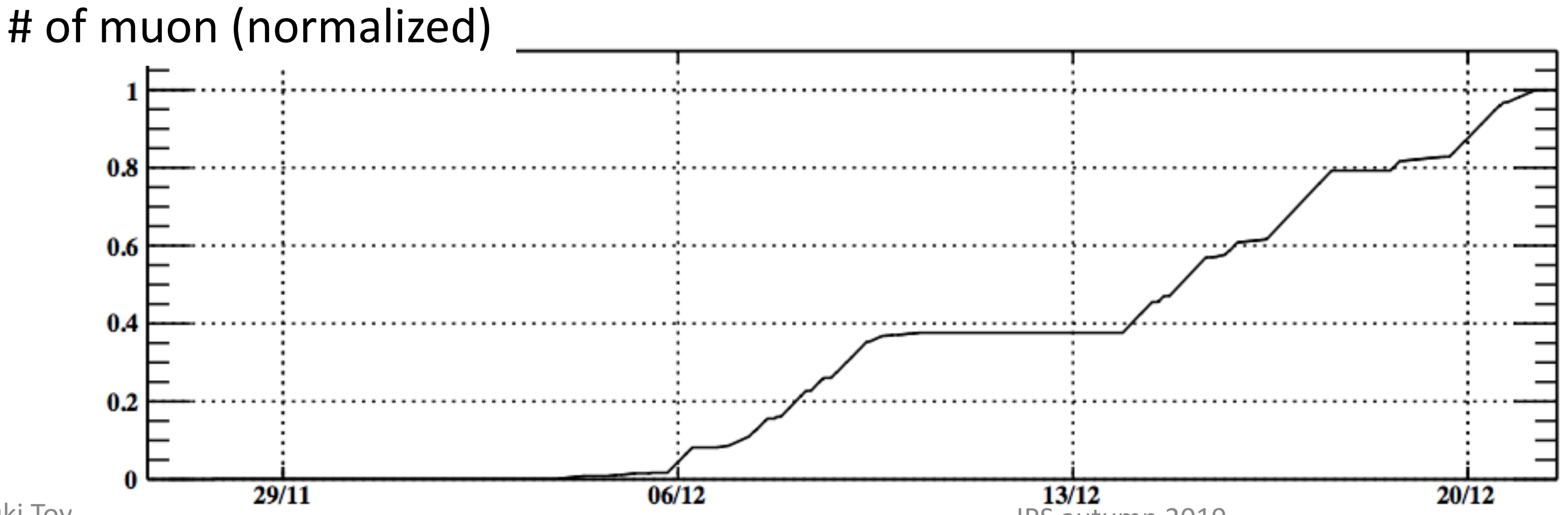
date / month

PMT



gain
LED
alpha

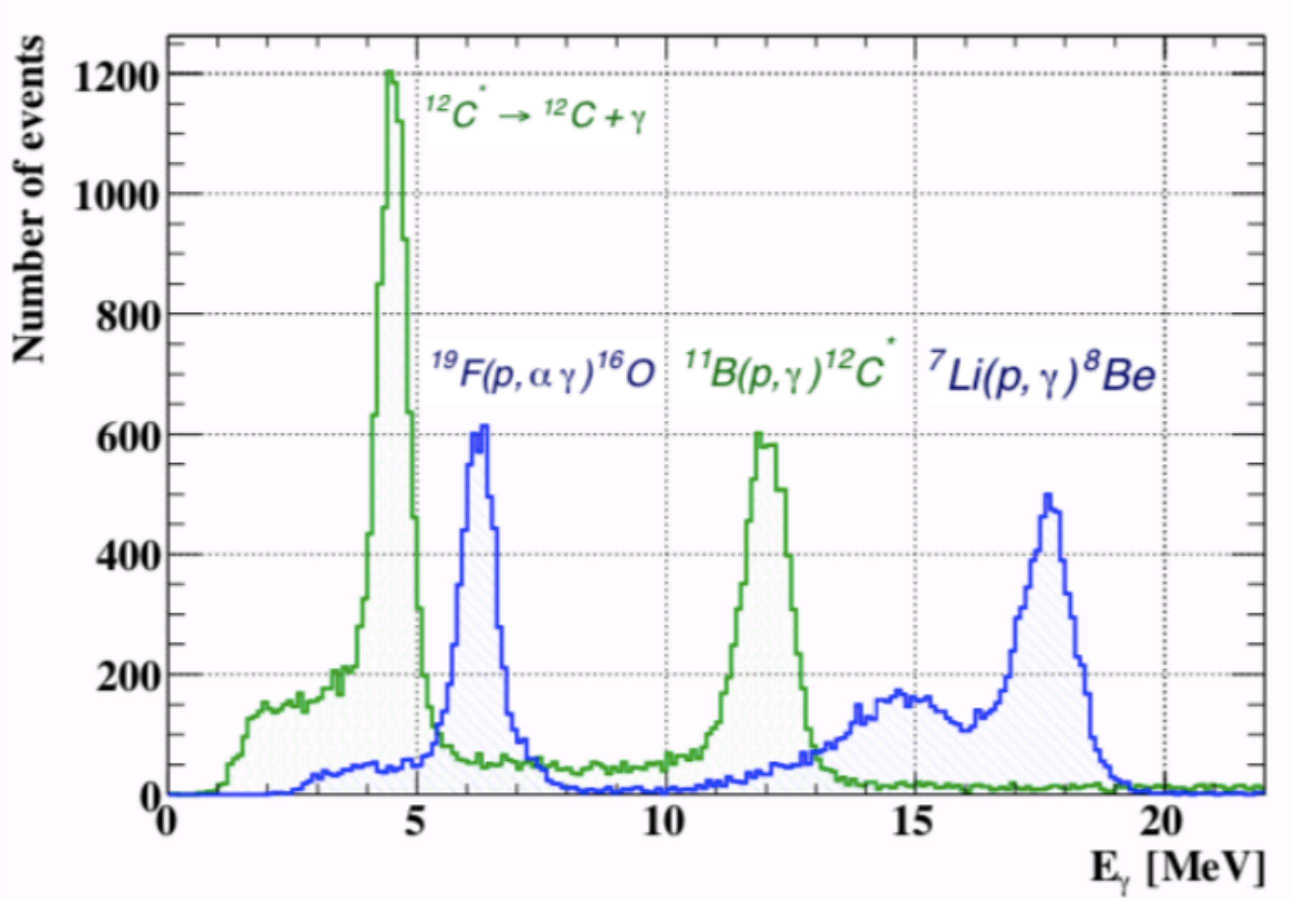
no B-field
B-field config. 1
B-field config. 2
during μ beam



- gain & CE depends on B-field configuration
- all behavior is consistent within ~ 1%
- gain decrease ~ 7%

Validation by γ from *p*-Li Reaction

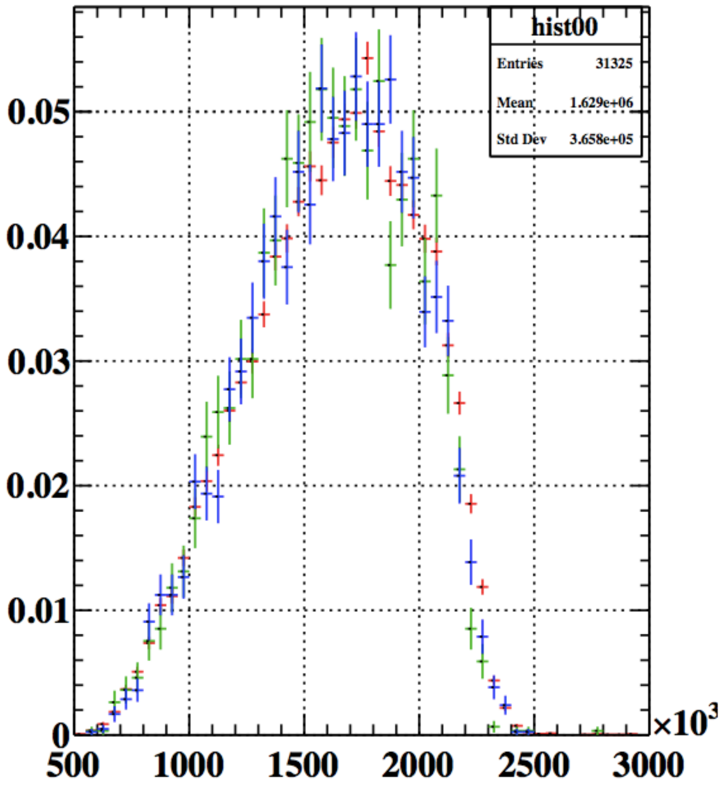
- 0.4-1 MeV *p* by Cockcroft-Walton accelerator
- $Li_2B_4O_7$ target
- 17.6 MeV γ from $^{7}Li(p, \gamma)^{8}Be$
- first time in MEG II
  → detail in following talk
- 3 runs
  - 30th Nov
  - 10th Dec
  - 17th Dec



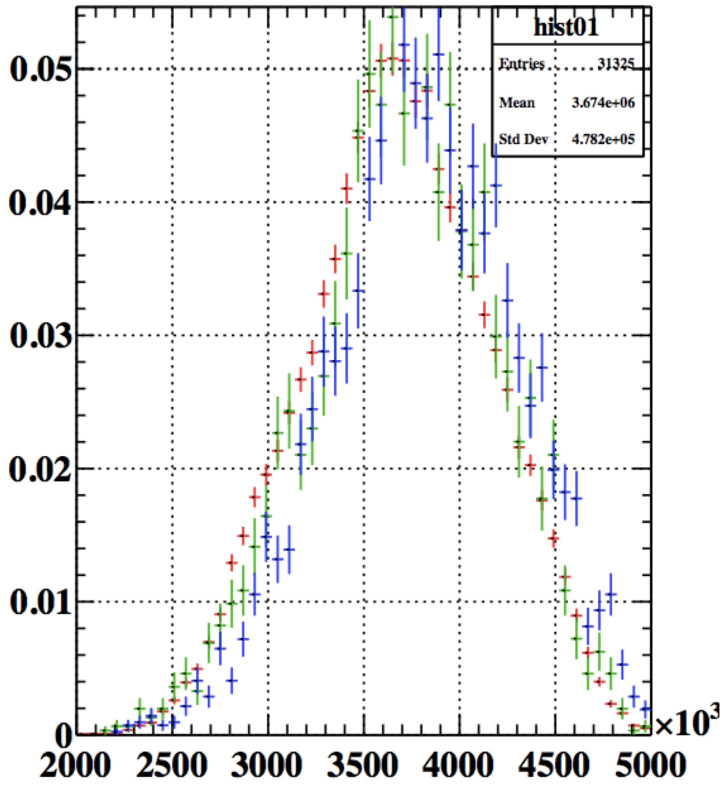
Validation by γ from p-Li Reaction

- 3 runs (30 Nov, 10 Dec, 17 Dec)

MPPC



PMT



energy (a.u.)

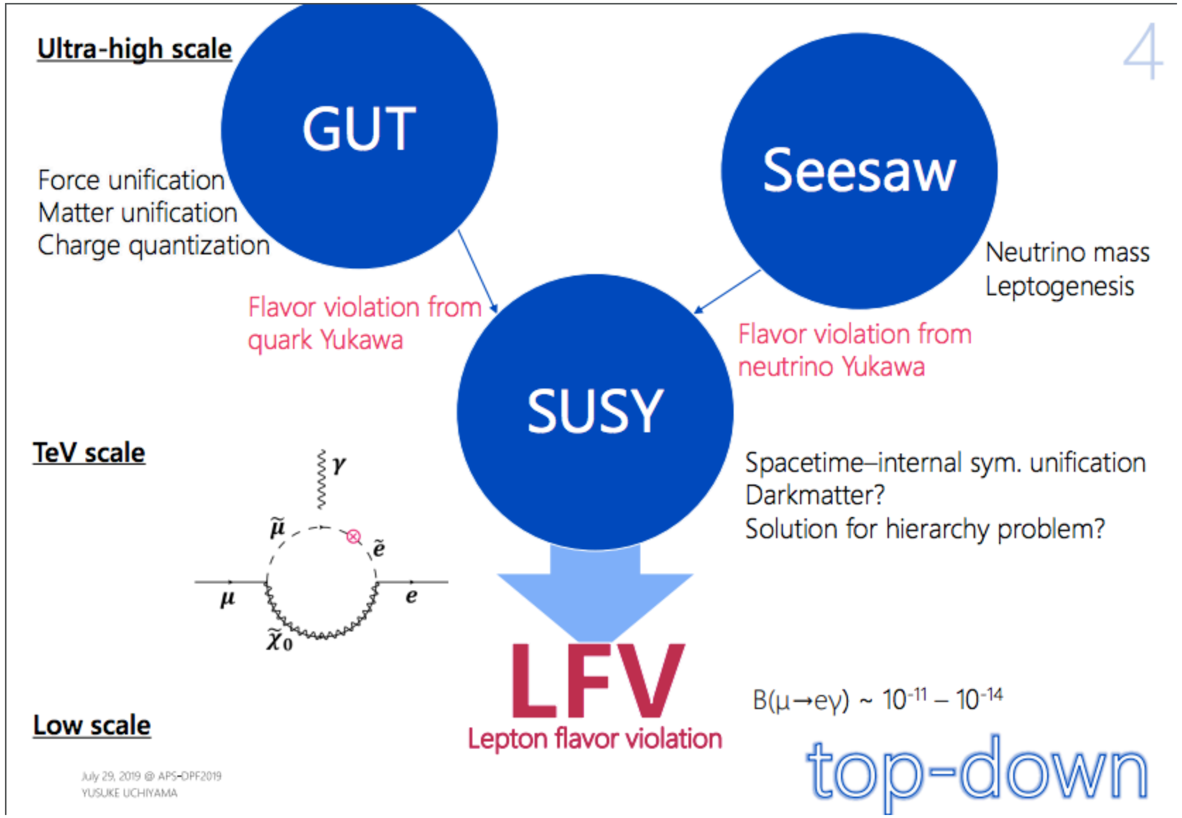
- energy scale shift ~ 5%
- should be within 1%
- should be checked more frequently

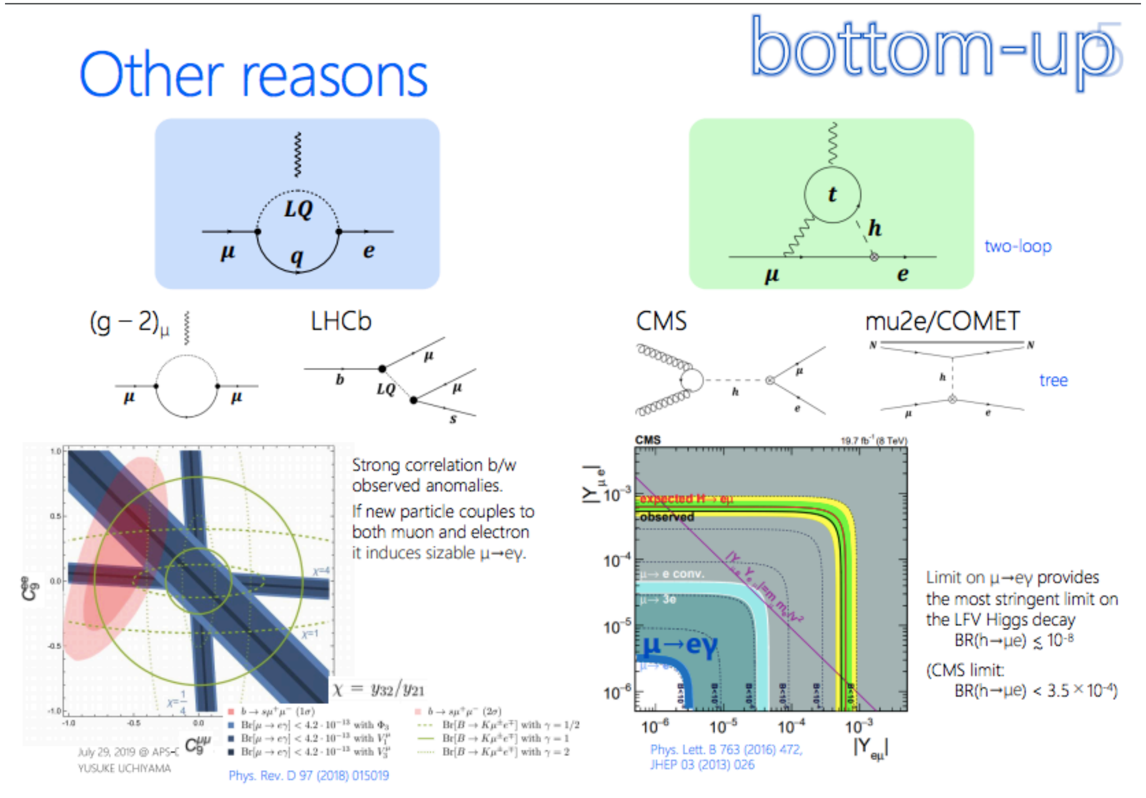
Summary & Prospect

- MPPC
  - PDE for VUV light looks decreasing
    - under investigation (17aT12-4,5)
  - cannot follow the change by frequent LED calibration
- PMT
  - gain seems decreasing although it can be recovered by increasing HV
  - but faster than expected → lab. test is going on
- Engineering Run 2019
  - more stable long-term beam irradiation
  - frequent α calibration (thanks to improve of DAQ speed)
  - frequent p-Li runs to firmly confirm monitoring precision

Backup

Physics Background





About XEC

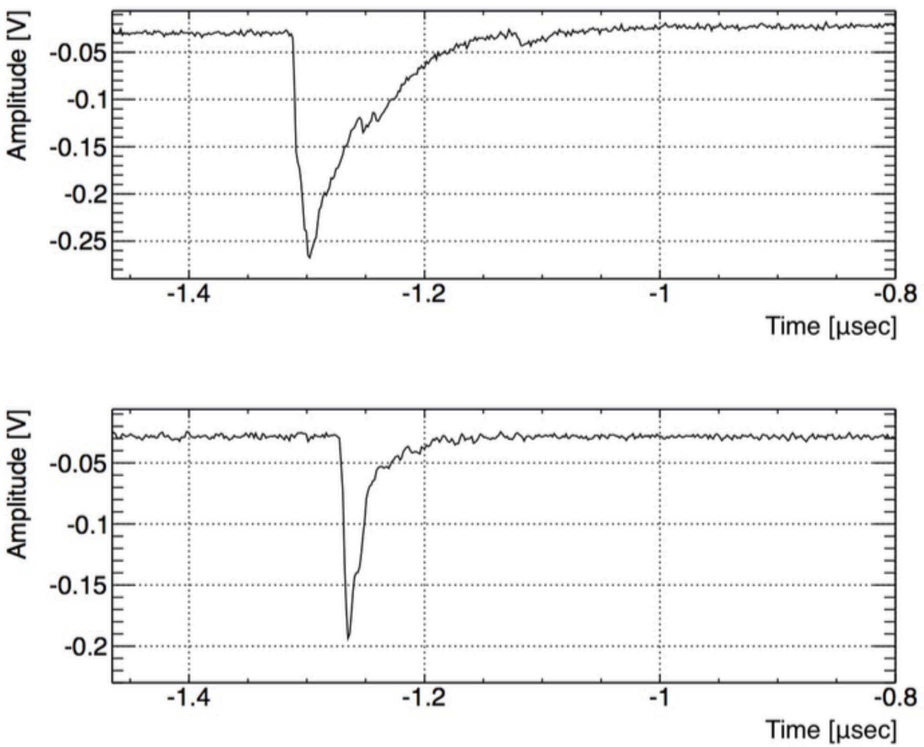


Figure 59 An MPPC signal waveform (upper) and a PMT signal waveform (lower) for the same α-event digitised at a sampling frequency of 700 MSPS.

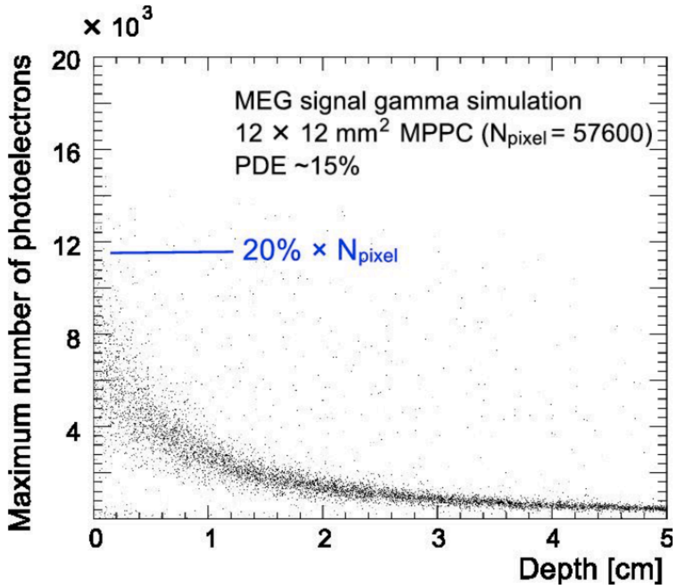


Figure 62 (Top) Response functions for the SiPMs with different total pixel numbers measured for a 40 ps laser pulses [135]. (Bottom) The number of photoelectrons expected from a $12 \times 12\,\mathrm{mm}^2$ MPPC versus conversion depth in the MEG II MC simulation.

XEC Performance (1)

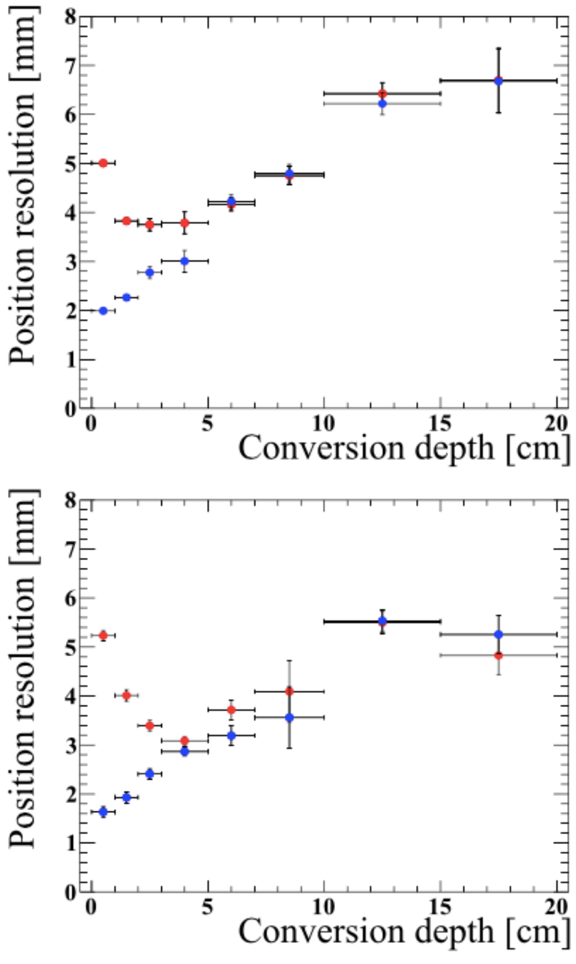


Figure 71 Position resolution in the horizontal (top) and vertical (bottom) directions as a function of the first conversion depth. The resolutions in MEG are shown with red markers, and those in MEG II are shown with blue markers.

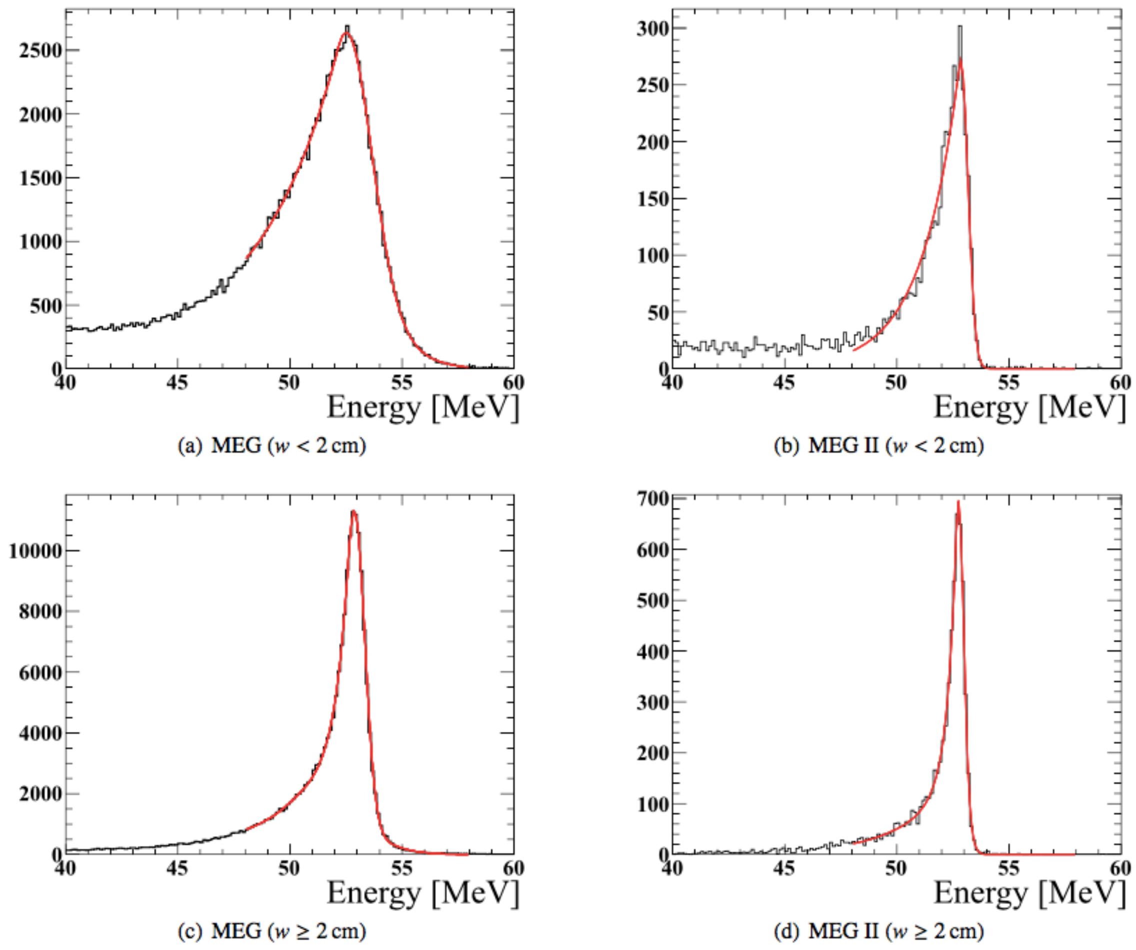
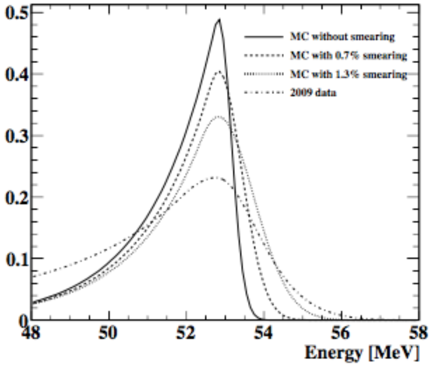
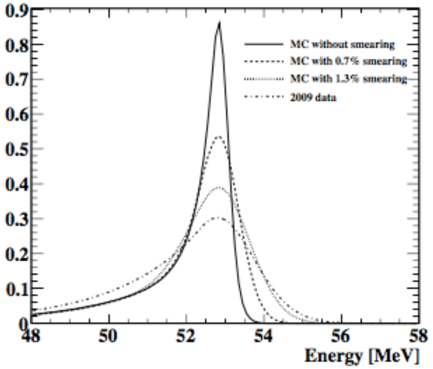


Figure 73 Energy PDFs for $E_\gamma = 52.83$ MeV photons converting in the MEG (left) and the MEG II (right) LXe photon detectors. The response to shallow (top) and deep (bottom) events are shown separately.

XEC Performance (2)

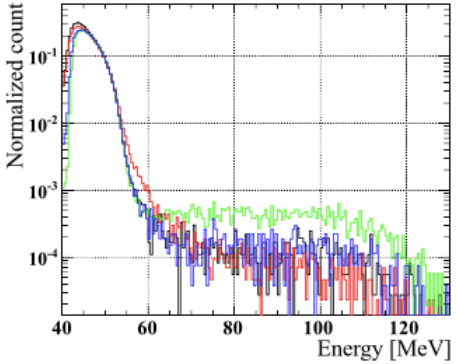


(a) $w < 2\,\mathrm{cm}$

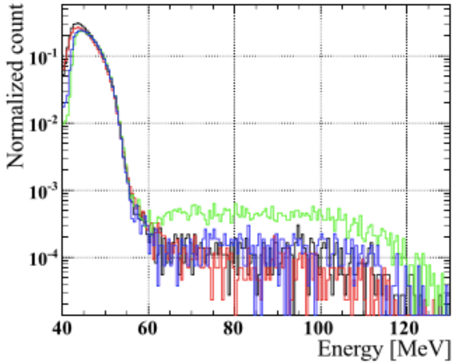


(b) $w \geq 2\,\mathrm{cm}$

Figure 74 Energy response functions with various assumptions of additional fluctuation (0, 0.7 and 1.3%) and that of the 2009 data.



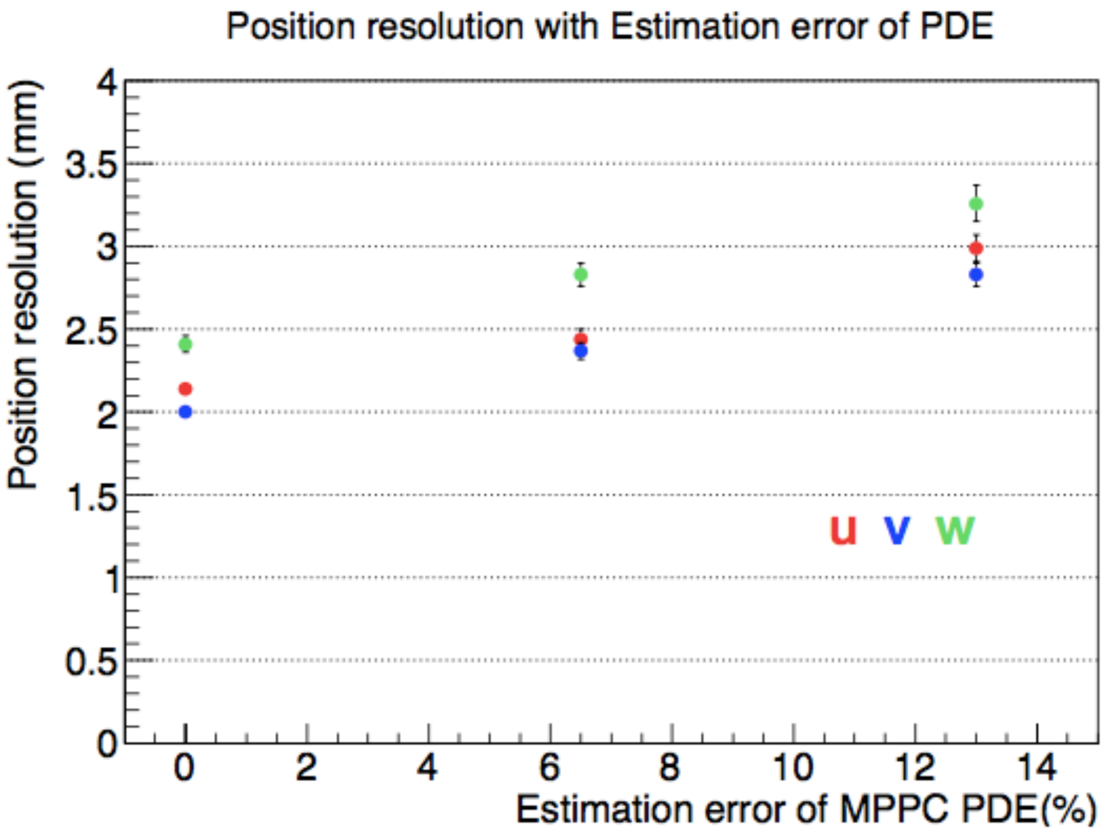
(a) Before unfolding pile-up photons



(b) After unfolding pile-up photons

Figure 75 Reconstructed energy spectrum obtained for different beam intensities. The horizontal axis shows energies in GeV without unfolding pile-up photons (a) and the same after unfolding and subtracting the energy of pile-up photons (b). Green, black, blue and red lines show the spectrum at muon stopping rates of 1.0, 3.0, 3.3 and $8 \times 10^7\ \mu^+/\mathrm{s}$, respectively. The spectra are normalised by the number of events in the range 48–58 MeV; the scaling factors are consistent with the muon stopping rate on the target. A difference in the low energy part below 45 MeV is due to different effective trigger thresholds; a difference in the high energy part is due to the different ratio between the photons backgrounds and the cosmic ray background.

Requirement for Sensor Calibration



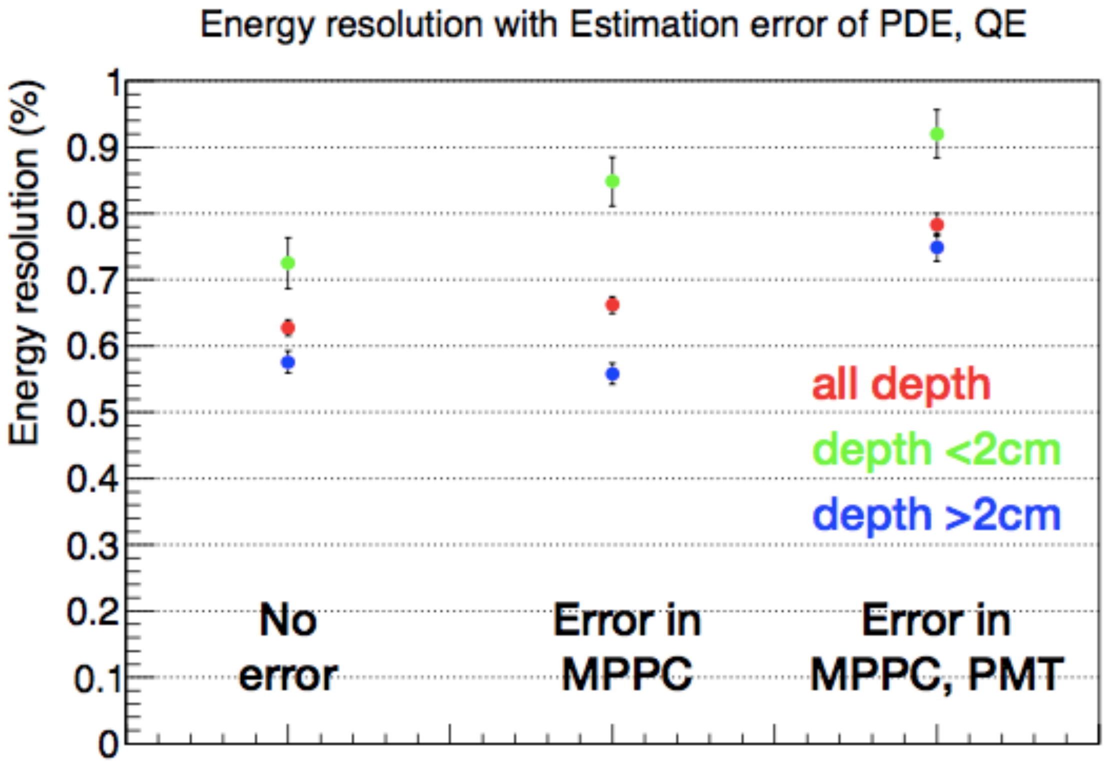


図 5.11　MPPC の PDE の測定誤差と位置・エネルギー分解能の関係 [37]。(左)MPPC の PDE の測定誤差の増加に伴って位置分解能が悪化する。(右)MPPC,PMT の PDE の測定誤差の増加によってエネルギー分解能が悪化する。

Estimation of Radiation

推定radiation	推定量	根拠
γ	1×10^{-2}Gy	シミュレーション
neutron	2.7×10^{6} n/cm^{2}	実験ホールにおける過去の測定
photon (Xe scintillation)	~10^{15} photon ($10^{13\text{-}14}$ p.e.)	シミュレーション : 1e6 p.e. /s 電流の実測値: 1e7 p.e. /s ビーム期間: 150時間

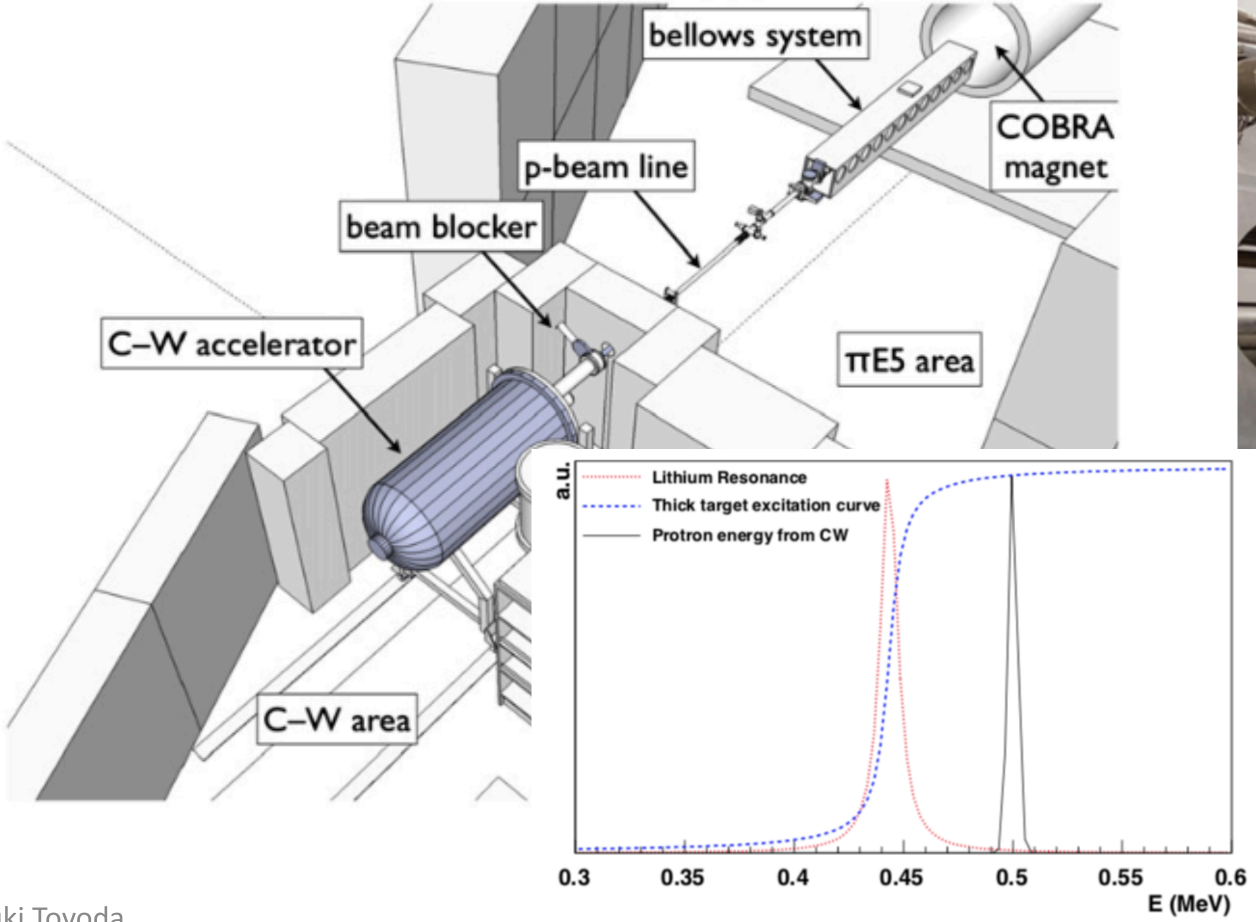
PMT History

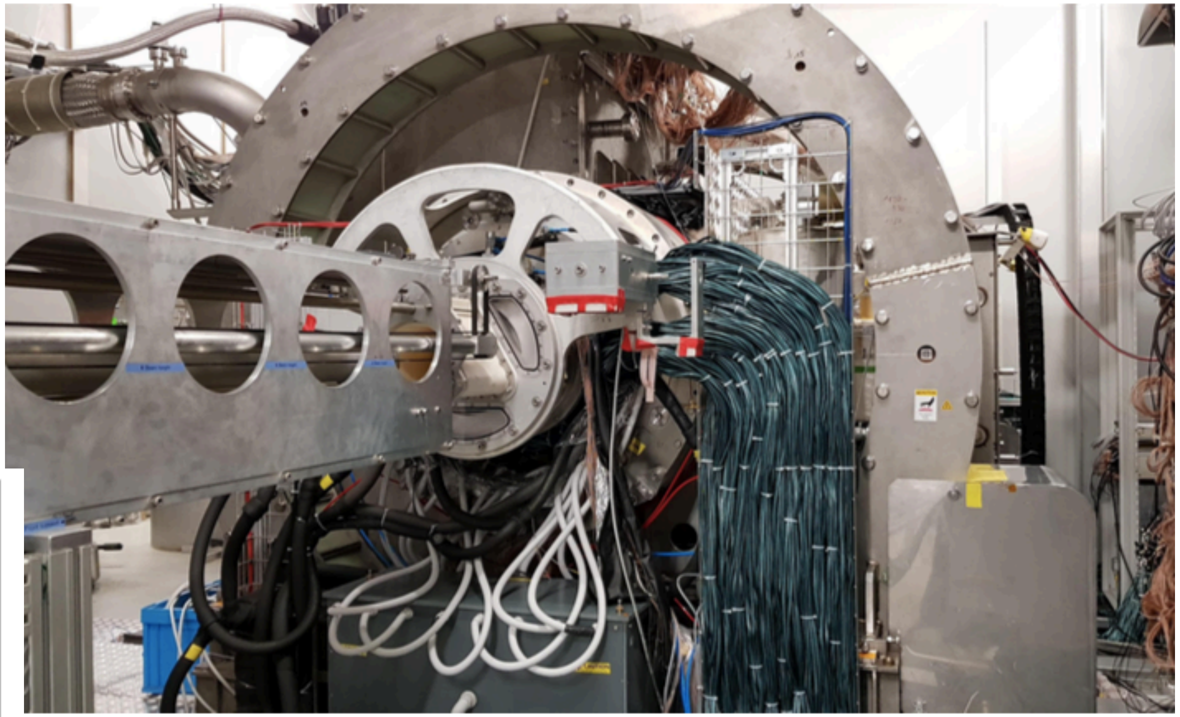
Individual Difference

- Individual difference of measured PDE:
  - MPPC: 1.0%(636 channels)
  - PMT: 5.2%(364 channels)

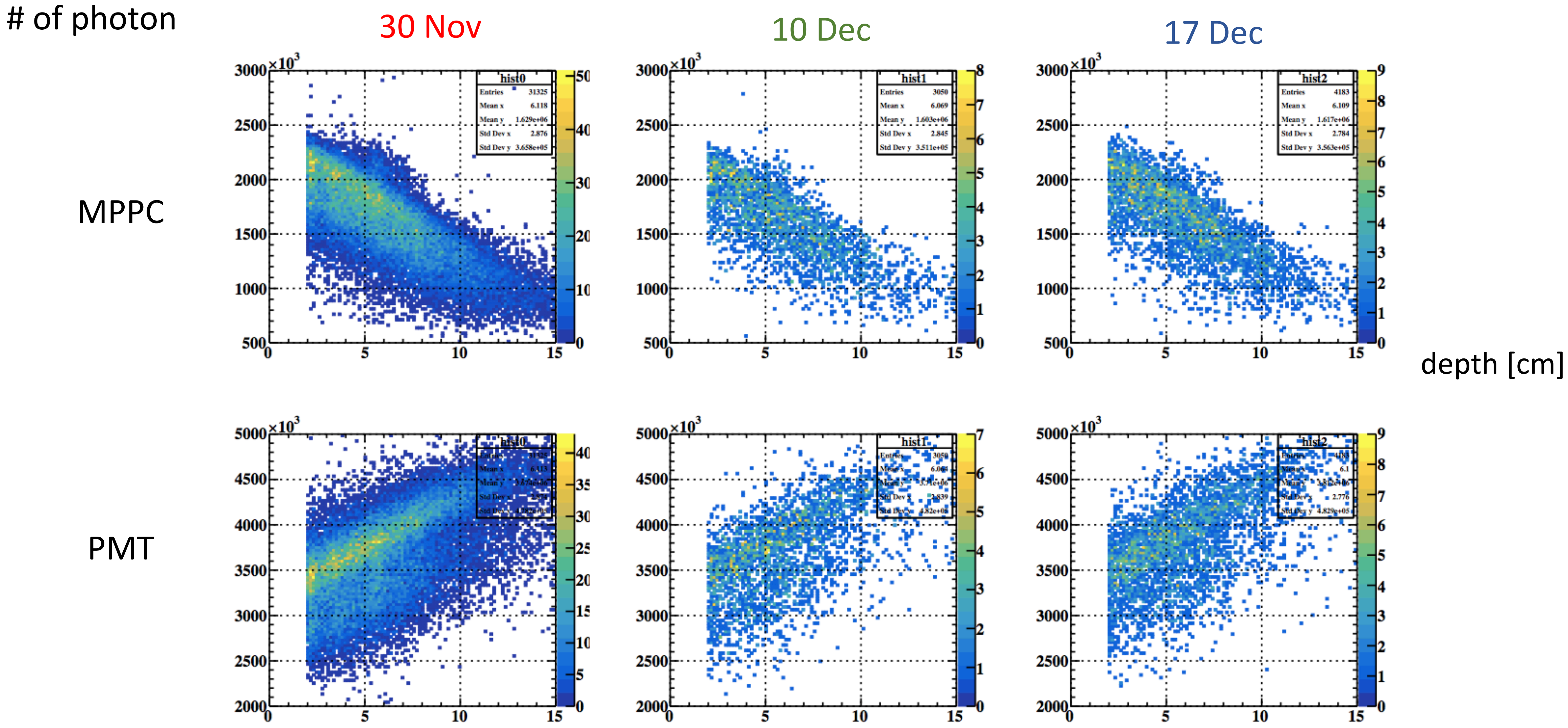
$$\sigma_{obs} \sim \sqrt{\sigma_{true}^2 + \sigma_{resolution}^2}$$

CW

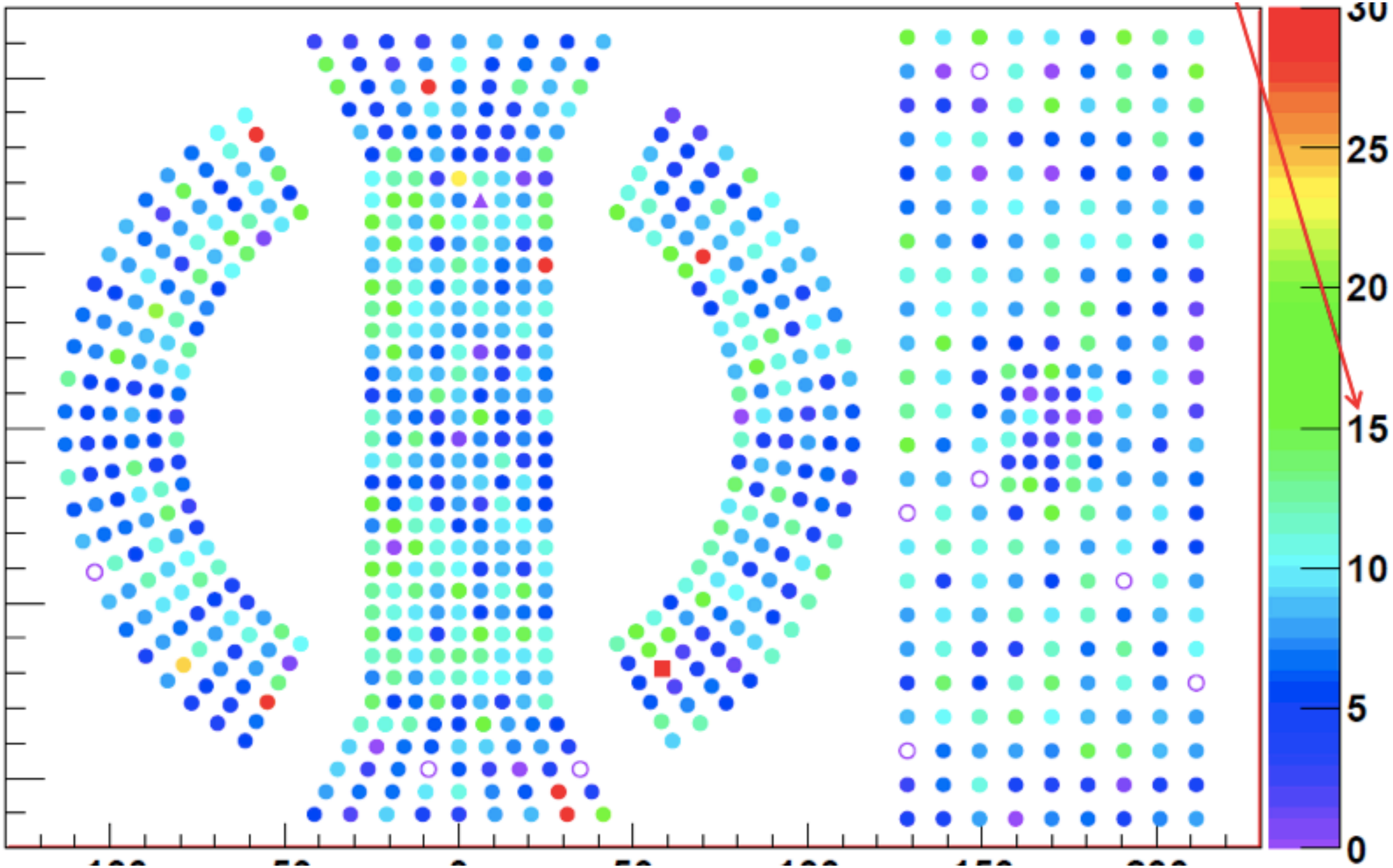

bellows system
COBRA magnet
p-beam line
beam blocker
C–W accelerator
πE5 area
C–W area
a.u.
Lithium Resonance
Thick target excitation curve
Protron energy from CW
0.3
0.35
0.4
0.45
0.5
0.55
0.6
E (MeV)



Depth Dependence of Energy

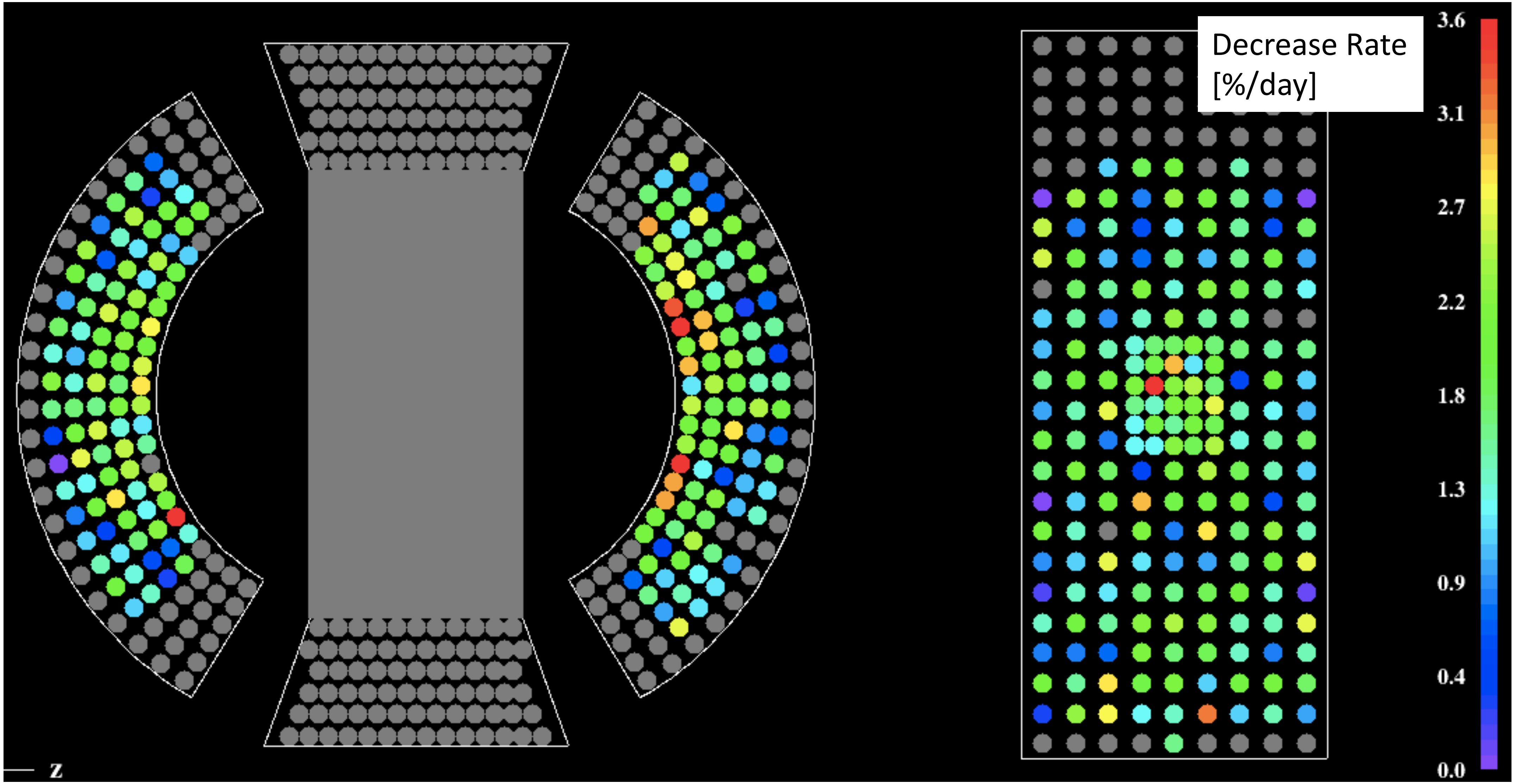


Position Dependence of Decrease @MEG I

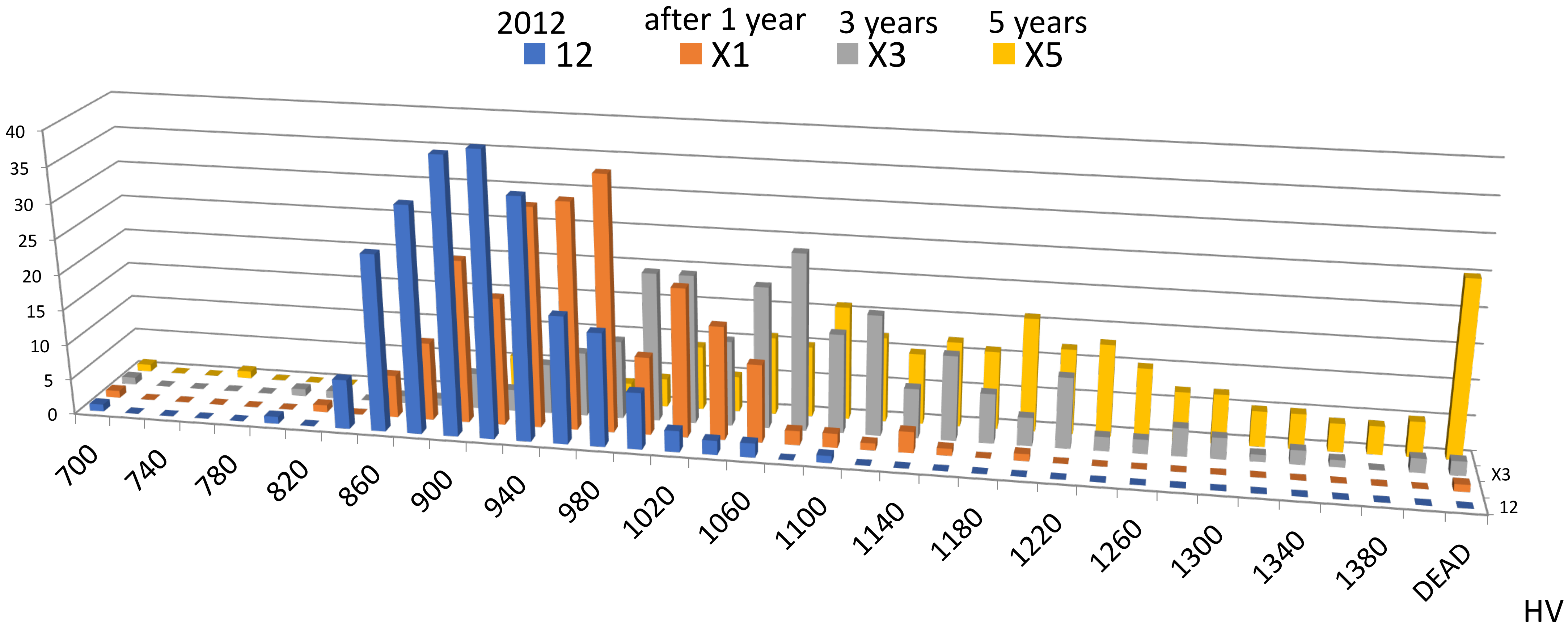


Decrease Rate
[10^{-2}%/day]

Position Dependence of Decrease Rate @ MEG II



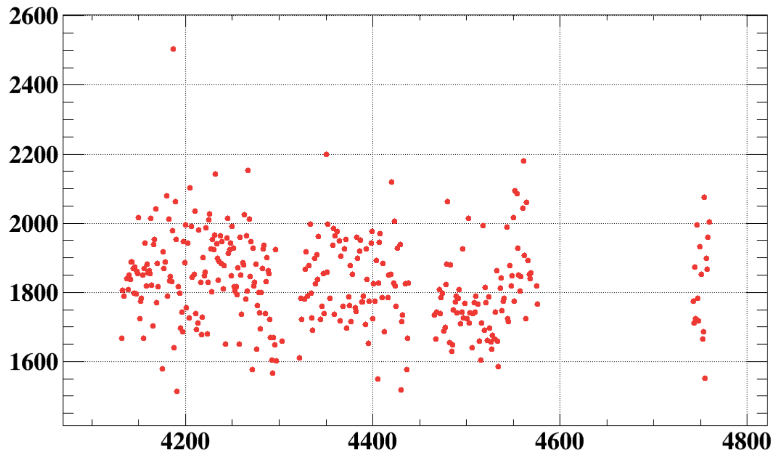
Estimation in 2012



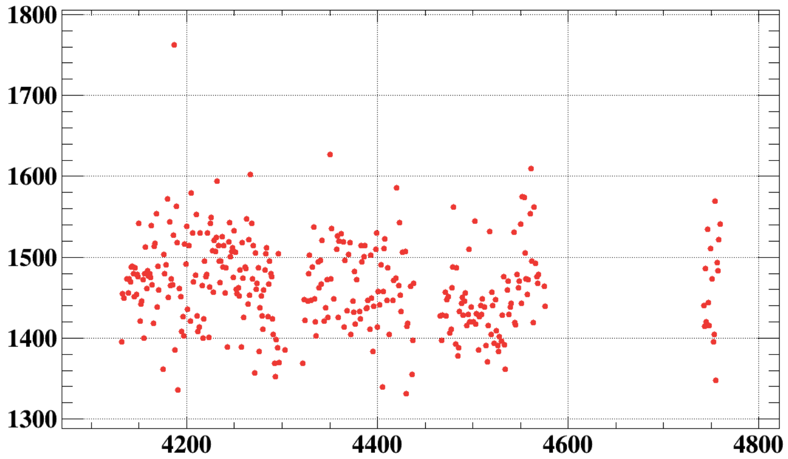
HV Estimation based on Different Models

- $Gain = a(V - V_0)^k$

due to a



due to V0: Zener diodes, cable loss



due to k: dynode material