東京大学
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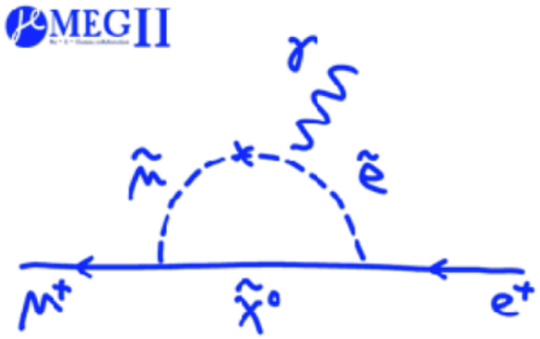
International Center for Elementary Particle Physics
The University of Tokyo



MEG II実験の2023年データにおけるガンマ線解析の現状

Sei Ban (ICEPP), for the MEG II collaboration

19th Mar. 2025, JPS 2025年春季大会@online：19aT2-8

Outline

Introduction : cLFV and MEG II experiment

Reconstruction of gamma-ray event

Correction for non-linear response of SiPMs

Summary & Prospects

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Introduction : cLFV and MEG II experiment

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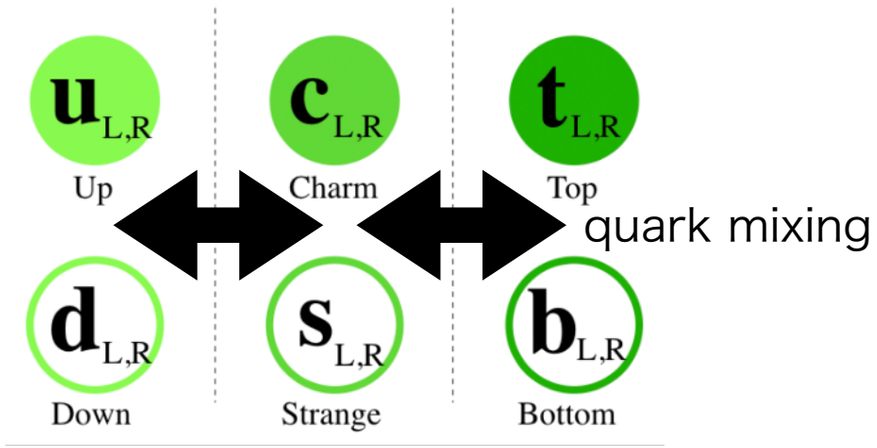
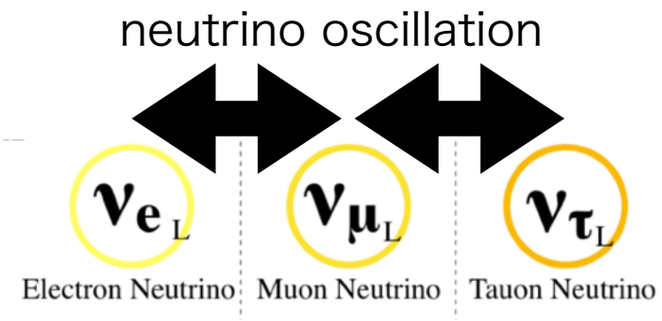
Charged Lepton Flavor Violation

- In quark and neutrino (neutral lepton) sector, the flavor violates in SM





- Some theories BSM predict flavor violation in the charged lepton sector
  - In the Standard Model (+ν osci.), it is practically prohibited : $Br(\mu \to e\gamma) = 10^{-54}$
  - In BSM, $Br(\mu \to e\gamma) \sim O(10^{-14})$ is predicted (not observed yet)

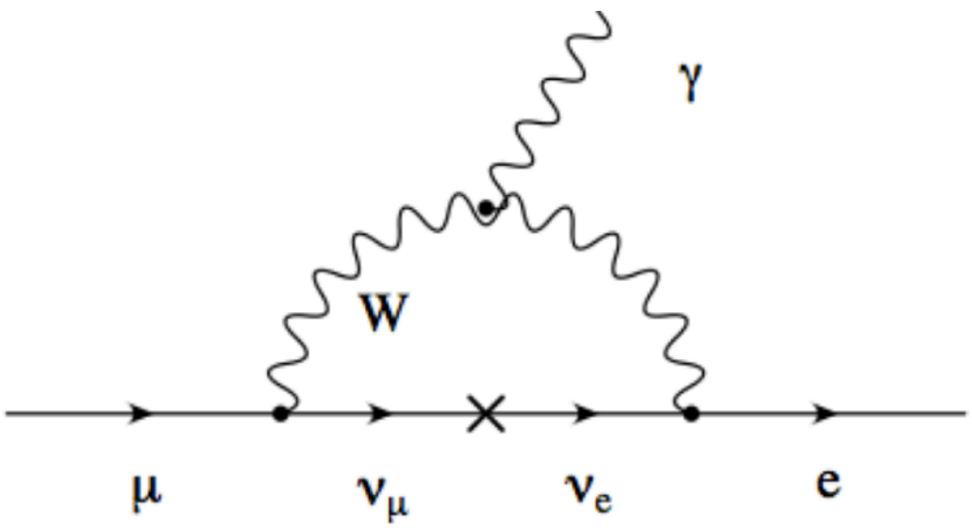
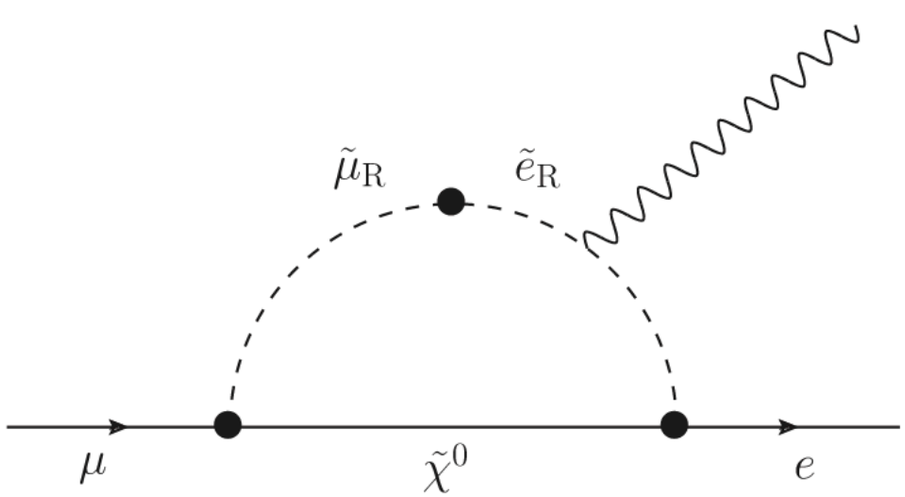


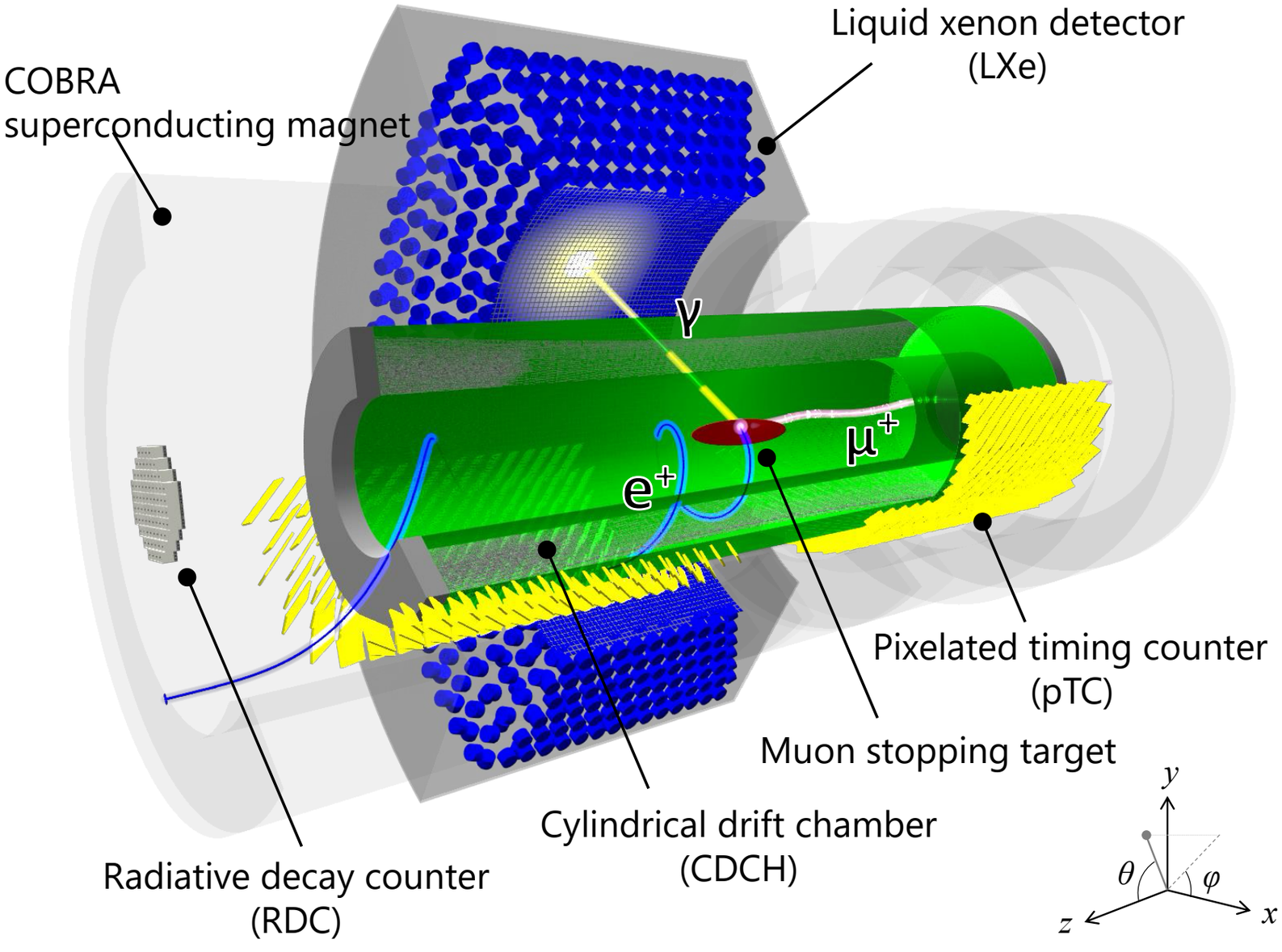
Diagram in the SM + neutrino oscillation

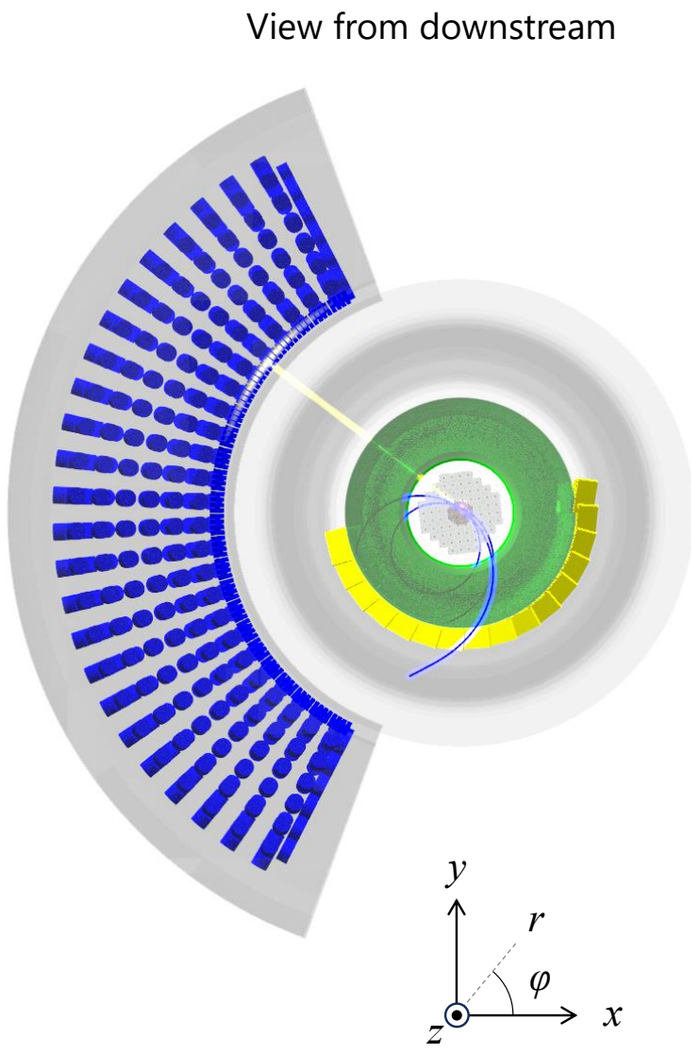


Possible diagram in SUSY-GUT senario

MEG II experiment

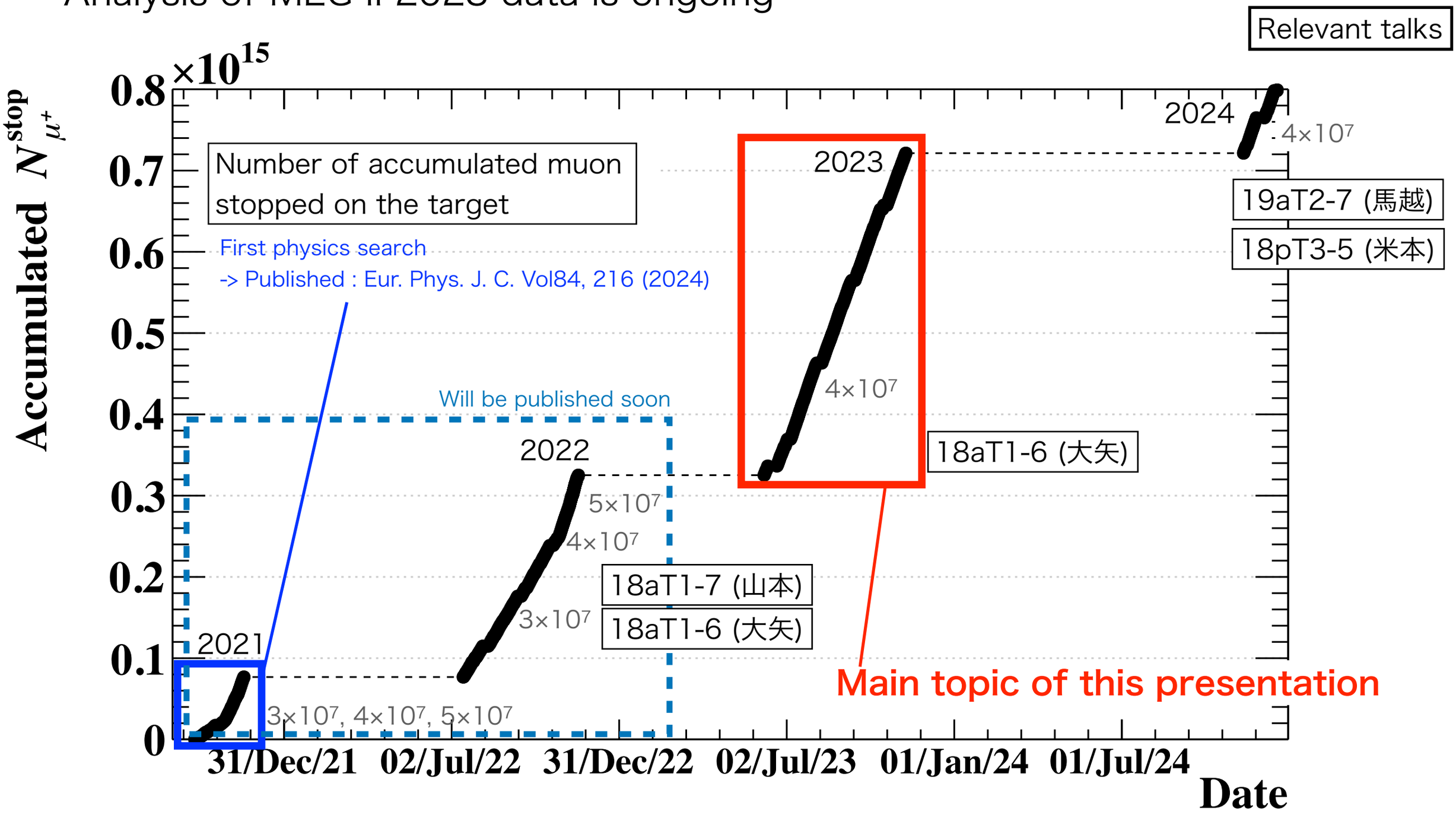
- MEG II experiment aims to search for charged lepton flavor violation : $\mu^+ \rightarrow e^+\gamma$
  - with higher sensitivity by one order of magnitude compared to the MEG
  - Using high intensity continuous muon beam at Paul Scherrer Institut (PSI)
  - Target sensitivity of Br($\mu^+ \rightarrow e^+\gamma$) : 6×10^{-14}





Timeline of the MEG II experiment

- Physics run started since 2021
  - First result was published in 2024
  - MEG II 2021+2022 result will be published soon
  - Analysis of MEG II 2023 data is ongoing



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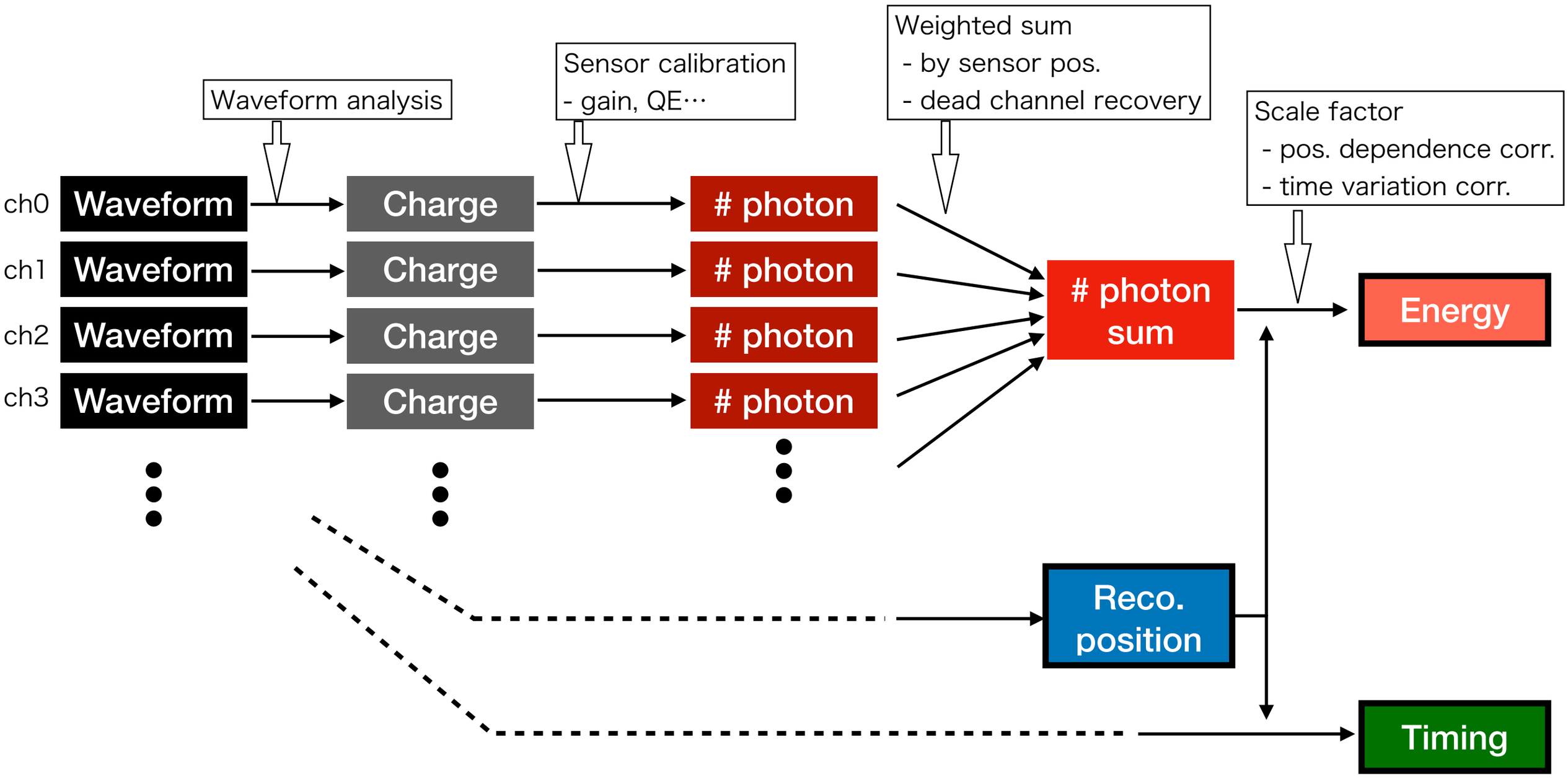
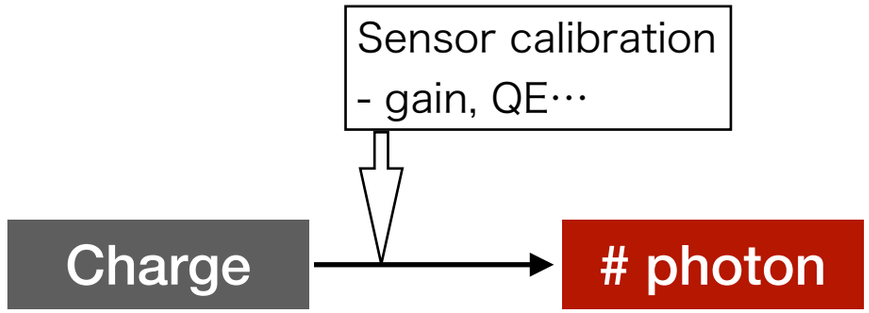
Reconstruction of Gamma-ray

- Reconstruction flow of gamma-ray
  - Energy, timing, and position are reconstructed

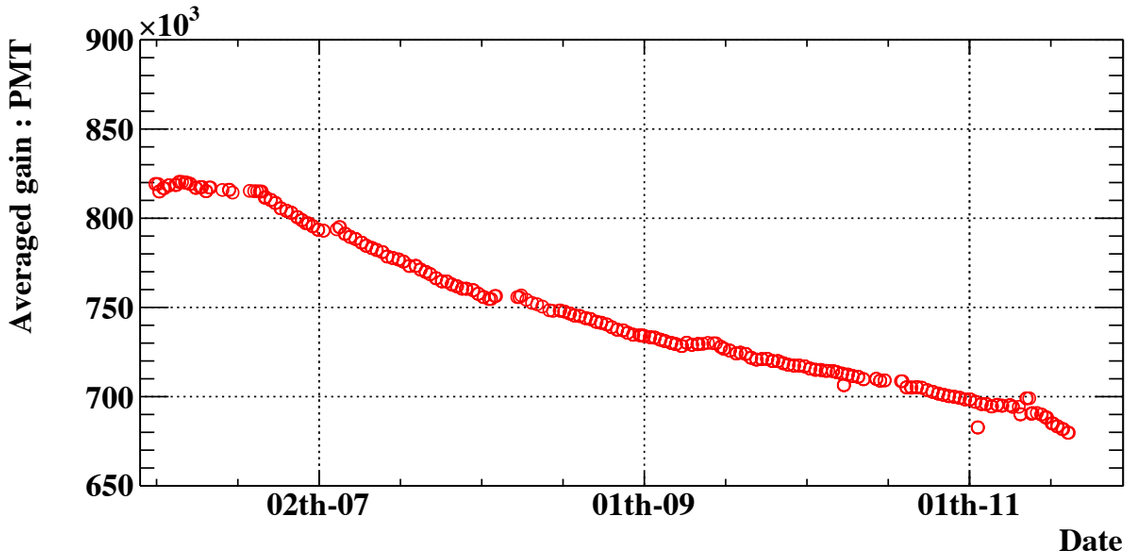


Reconstruction of Gamma-ray : Calibration

- Sensor calibrations were completed

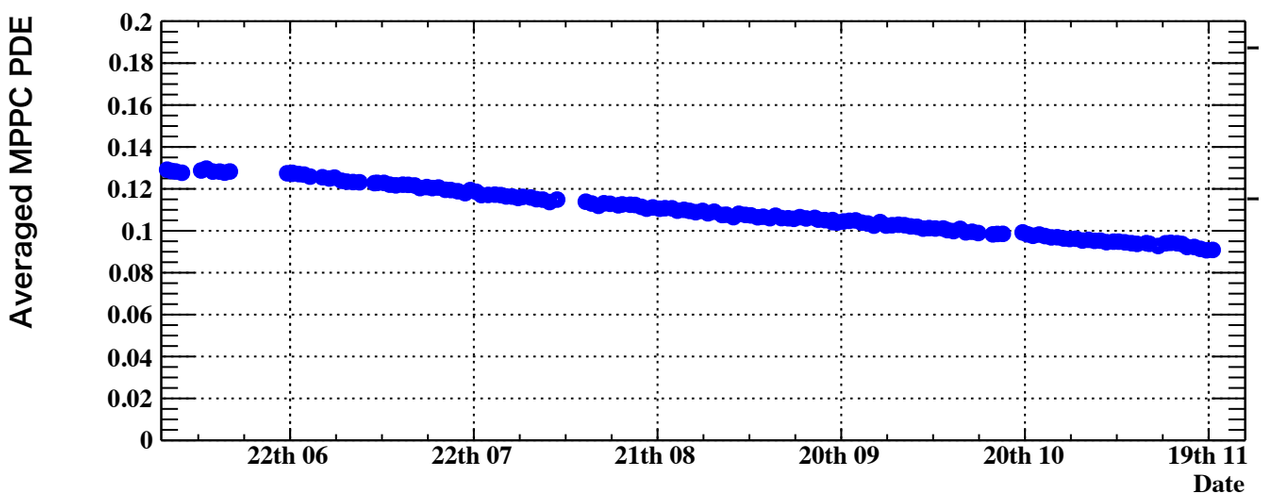


- Gain calibration using LEDs



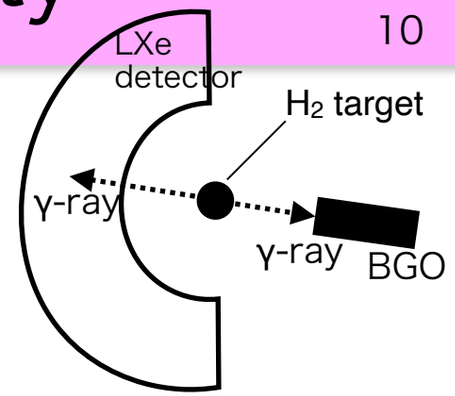
- PMT gain decreased due to UVU-irradiation during beam time (known problem)
- For MPPC, crosstalk&after-pulse probability are also calculated in addition to gain calibration

- Light detection efficiency calibration using alpha-ray source

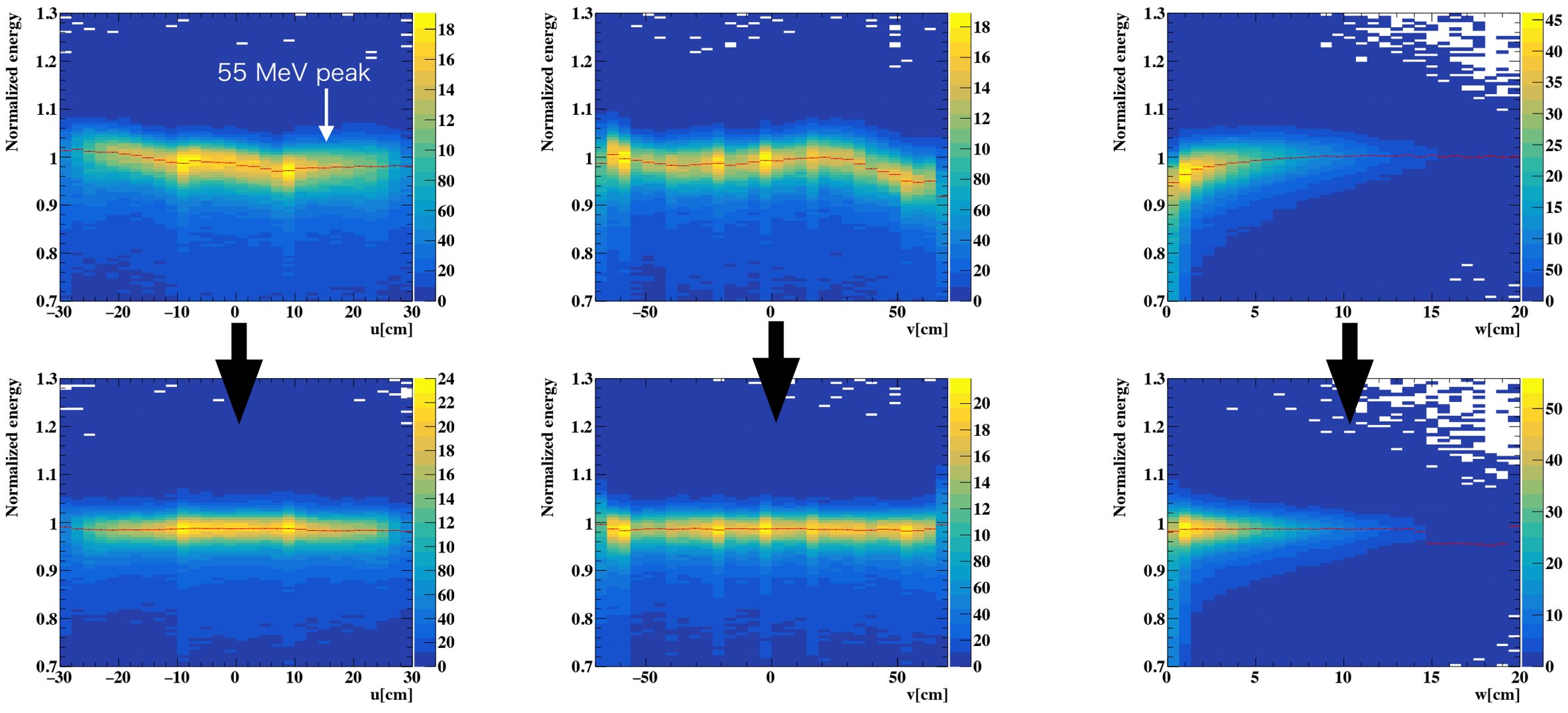


MPPC PDEs were slightly decreasing by radiation damage during beam time (known problem)
-> PDEs are recovered by annealing during shutdown period

Reconstruction of Gamma-ray : Non-uniformity



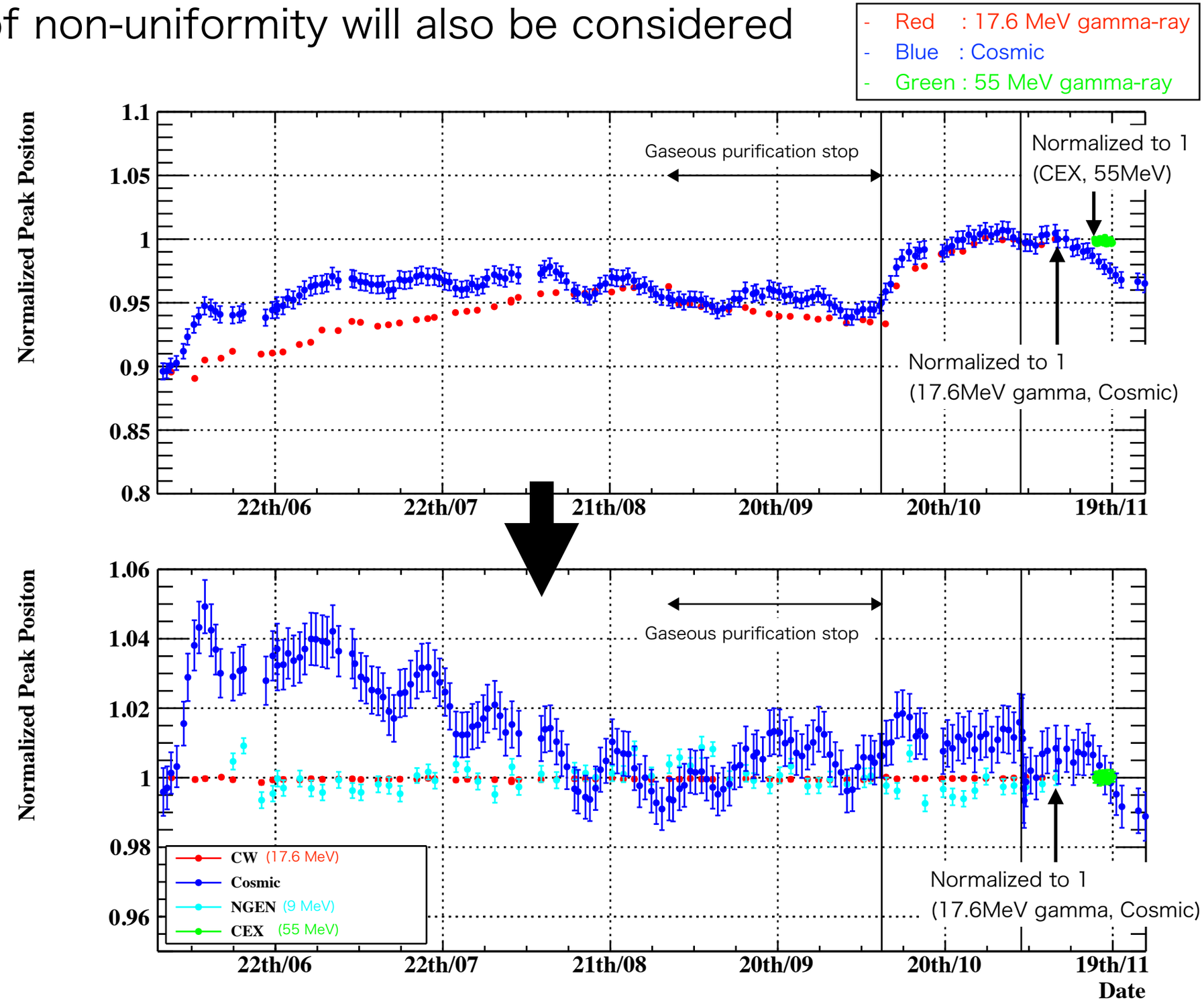
- Non-uniformity correction by 55 MeV gamma-ray
  - π^- beam to H_2 target —(Charge EXchange with p)—> $\pi^0 \rightarrow \gamma\gamma$
    - Dedicated calibration run at the end of 2023 run
    - Tagging the back-to-back γ by BGO crystals, 55 MeV γ-rays are obtained
- Further precise correction will be available using 17.6 MeV γ-ray and BG spectrum



- (In addition to these, 3D-corrections are applied)

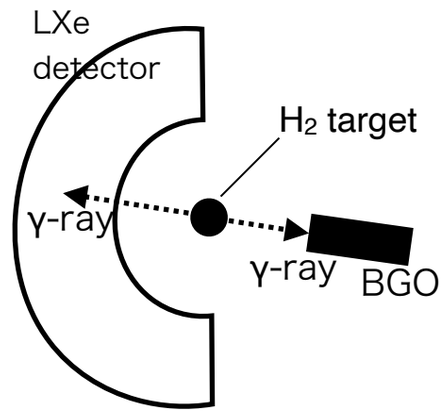
Reconstruction of Gamma-ray : Time variation

- Time variation correction by mono-energetic gamma-ray (17.6 MeV, 55 MeV)
  - This time, only time variation of energy scale is corrected
    - Time variation of non-uniformity will also be considered



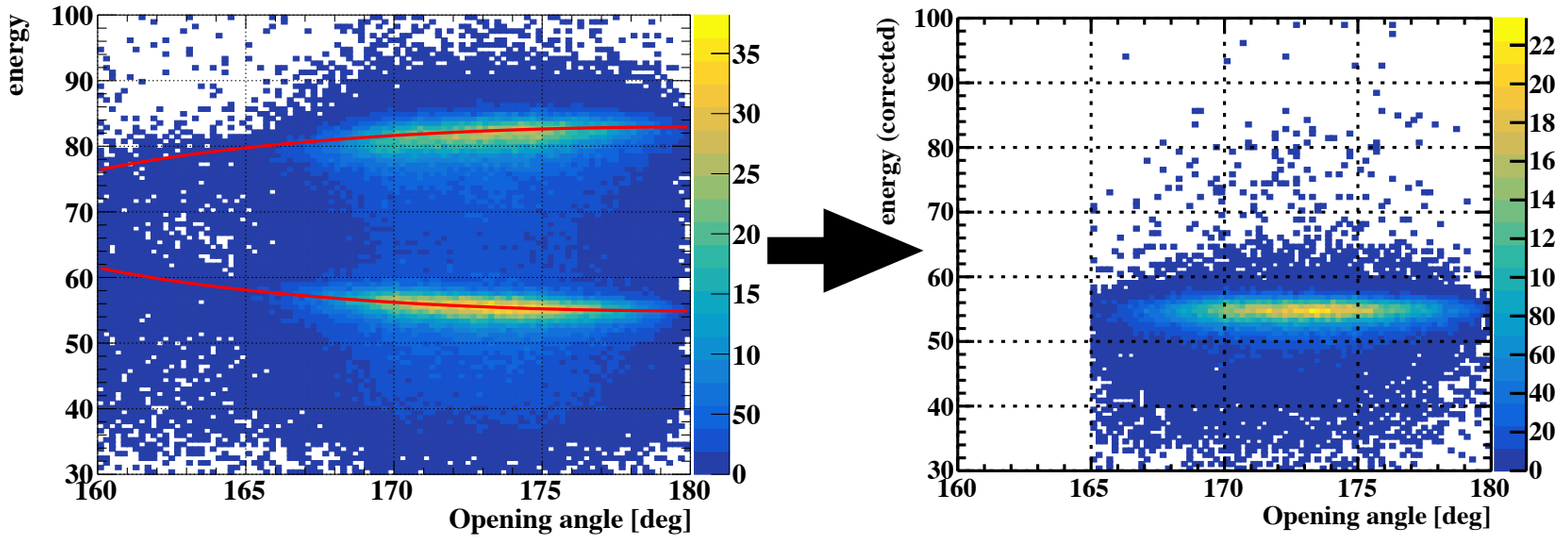
Reconstruction of Gamma-ray : Energy Resolution

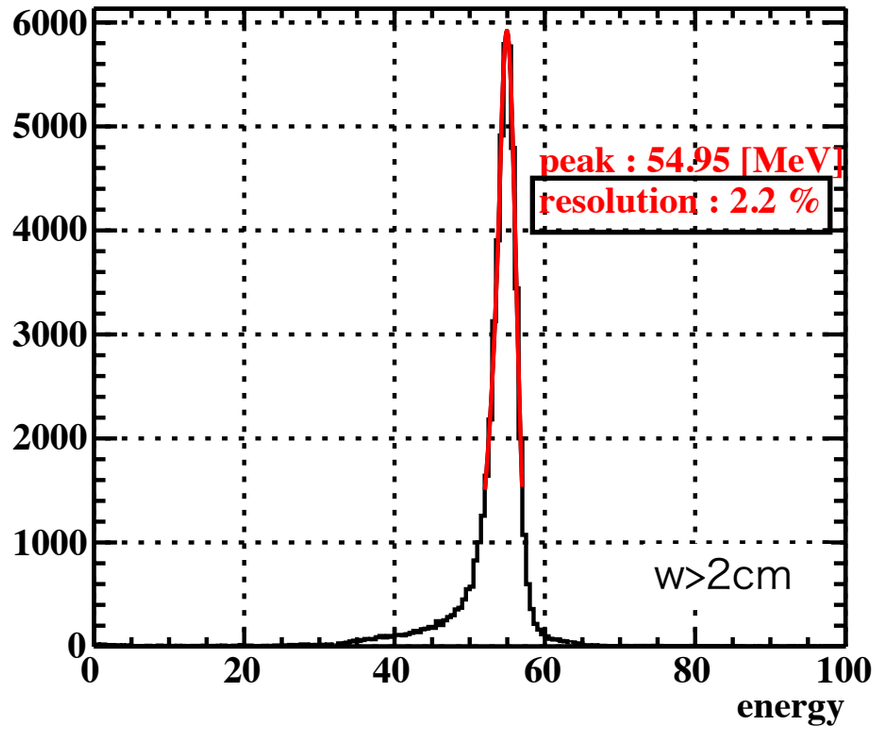
- Energy resolution evaluated with 55 MeV gamma-ray
  - BGO energy cut to select 55 MeV peak
  - Opening angle between two gammas (to the LXe detector and the BGO)
    - -> Correlation is corrected



- Worse energy resolution (σ/E = 2.2% @55MeV) than 2021 data
  - cf) σ/E = 1.8% @55MeV[1] for 2021 data

- To improve the energy resolution, reconstruction scheme is reviewed
  - Non-linear response of SiPMs





- [1] Eur.Phys.J.C 84 (2024) 2, 190

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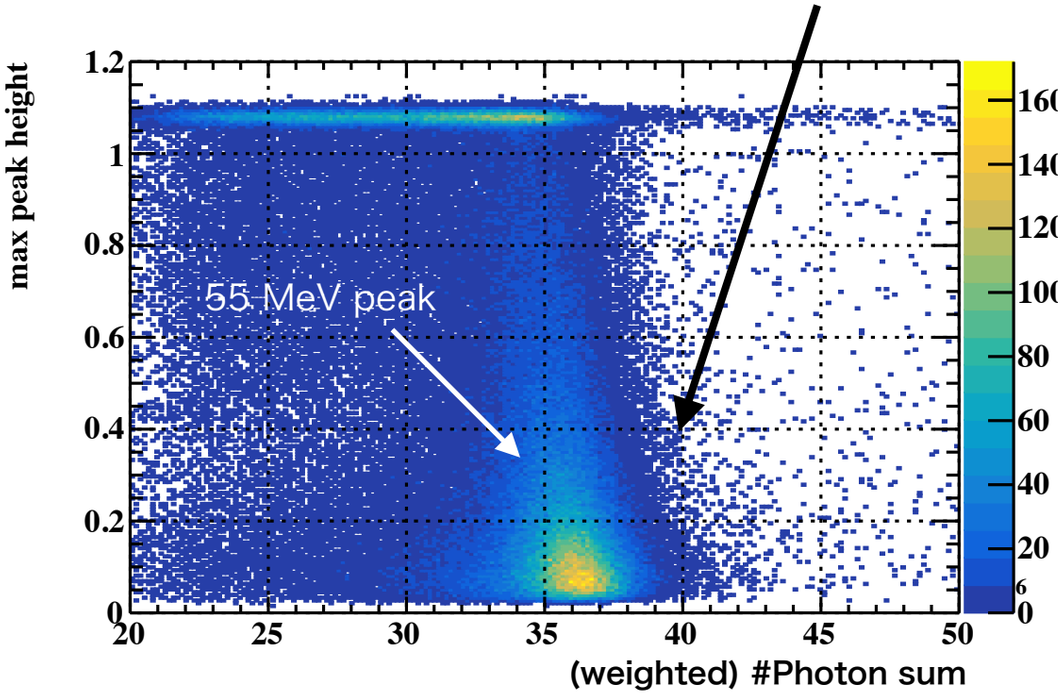
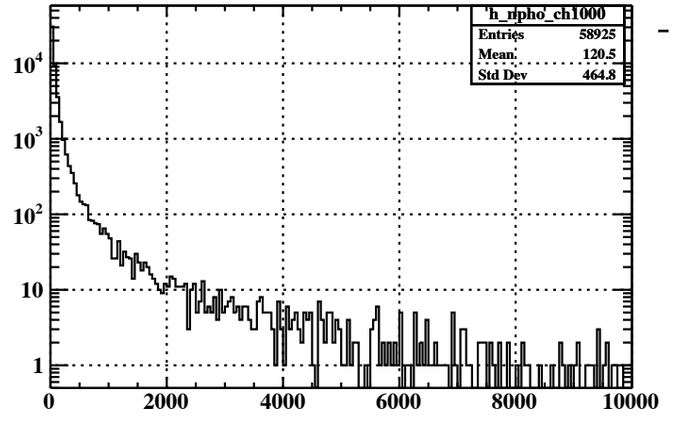
Improvement of #photon reconstruction

- Suspicious MPPC non-linear response
  - smaller #photon reconstruction with larger wave height (larger #photon)
- -> Correct it by modeled saturation curve (model : NIM A Volume 1064, July 2024, 169431)

Negative correlation
- perhaps due to MPPC non-linearity?

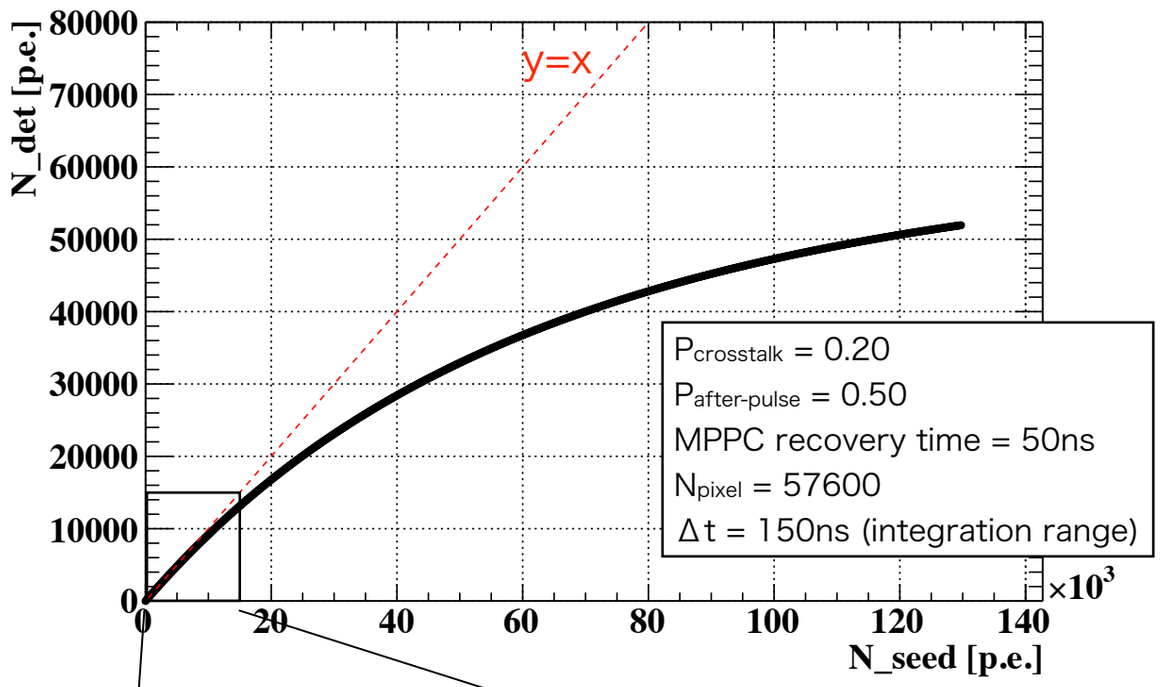


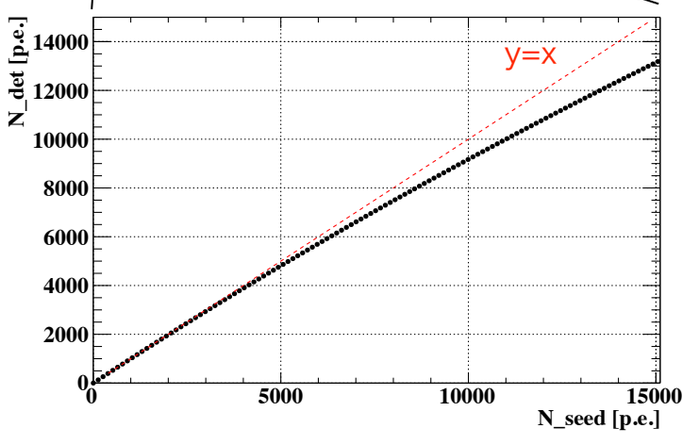
- Distribution of #photon in a single channel



- reach to ~10,000 ph.

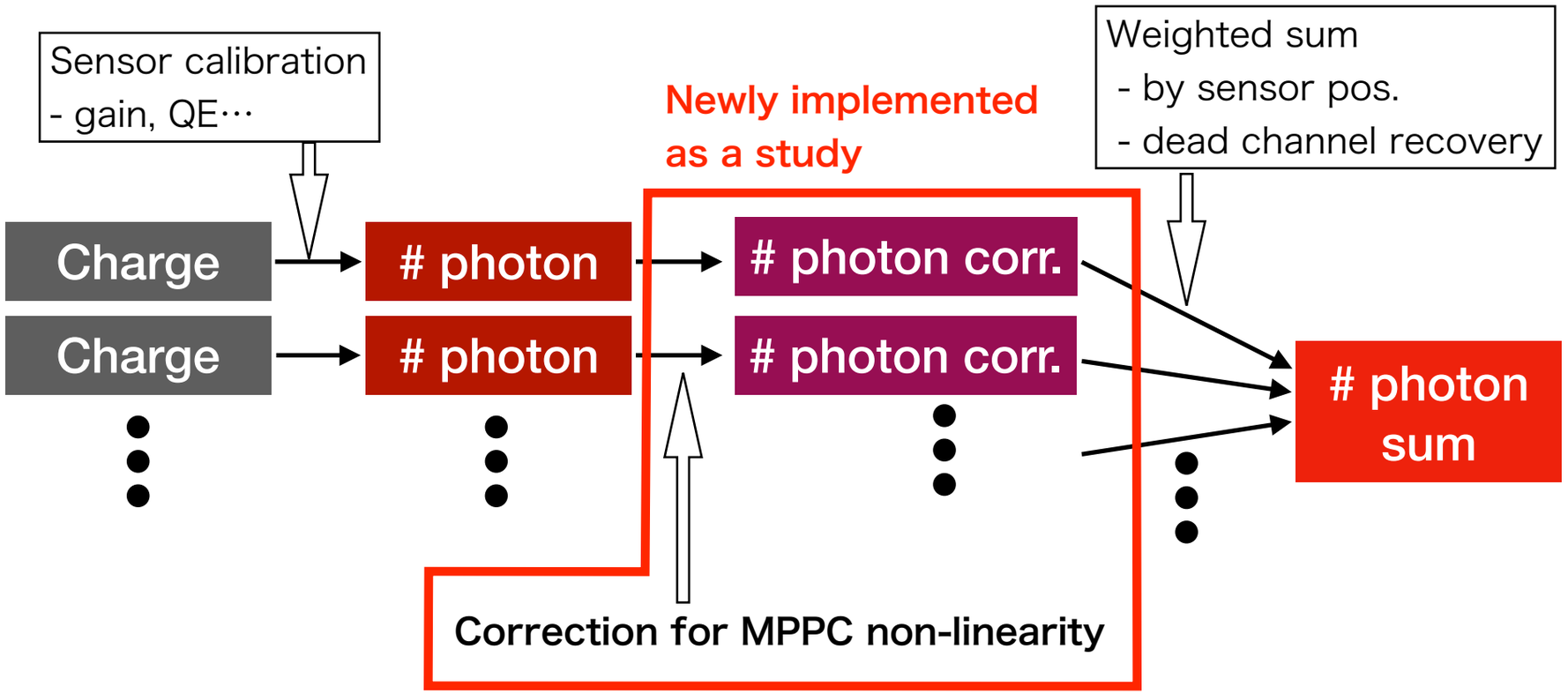
Example of saturation curve

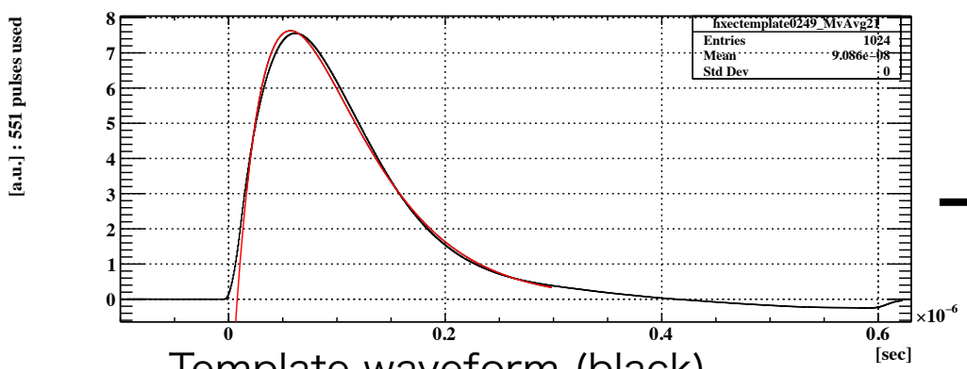




Improvement of #photon reconstruction

- Implementation of correction for MPPC non-linear response





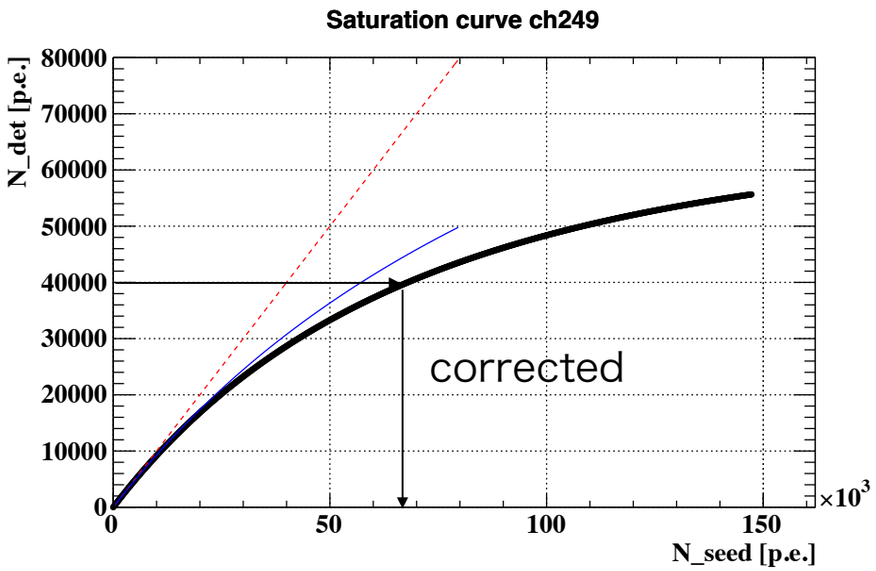
Template waveform (black)

-> Fit to extract recovery time (red)

Crosstalk and after-pulse probability calibrated by LED run

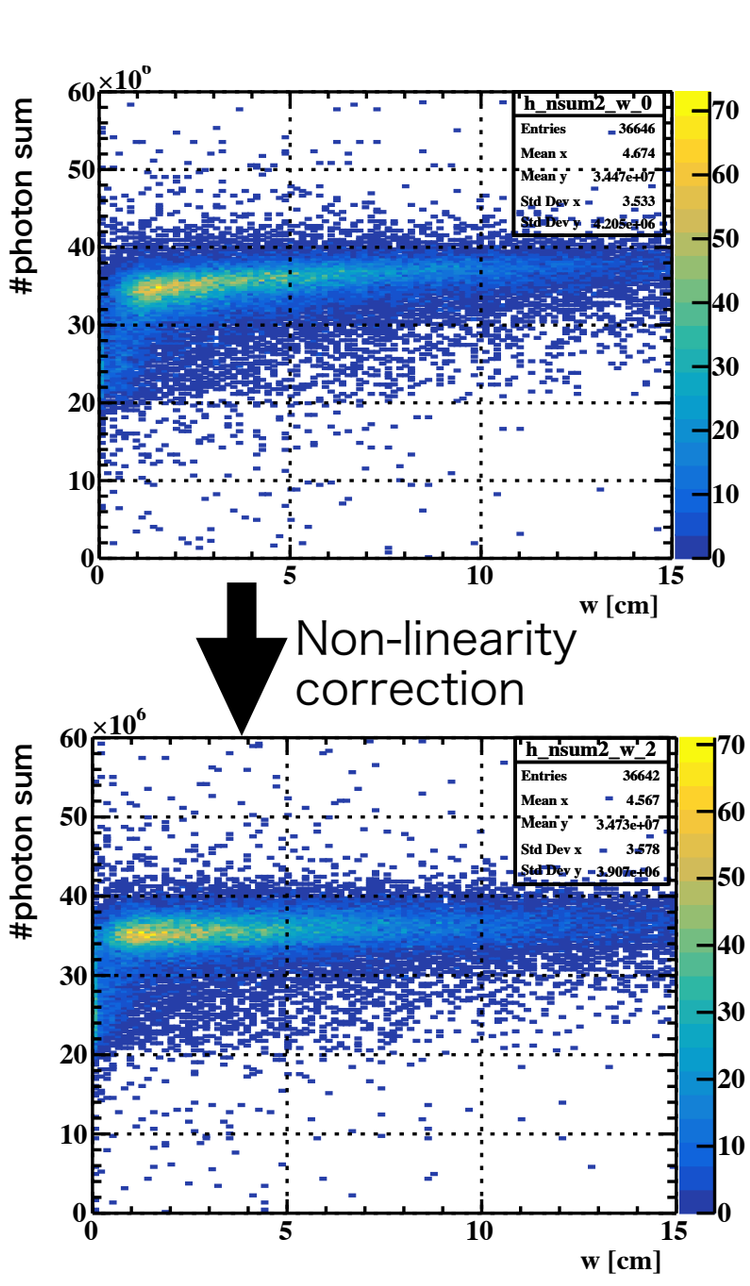
Inputs for saturation curve

Saturation curve is calculated for **each sensor**

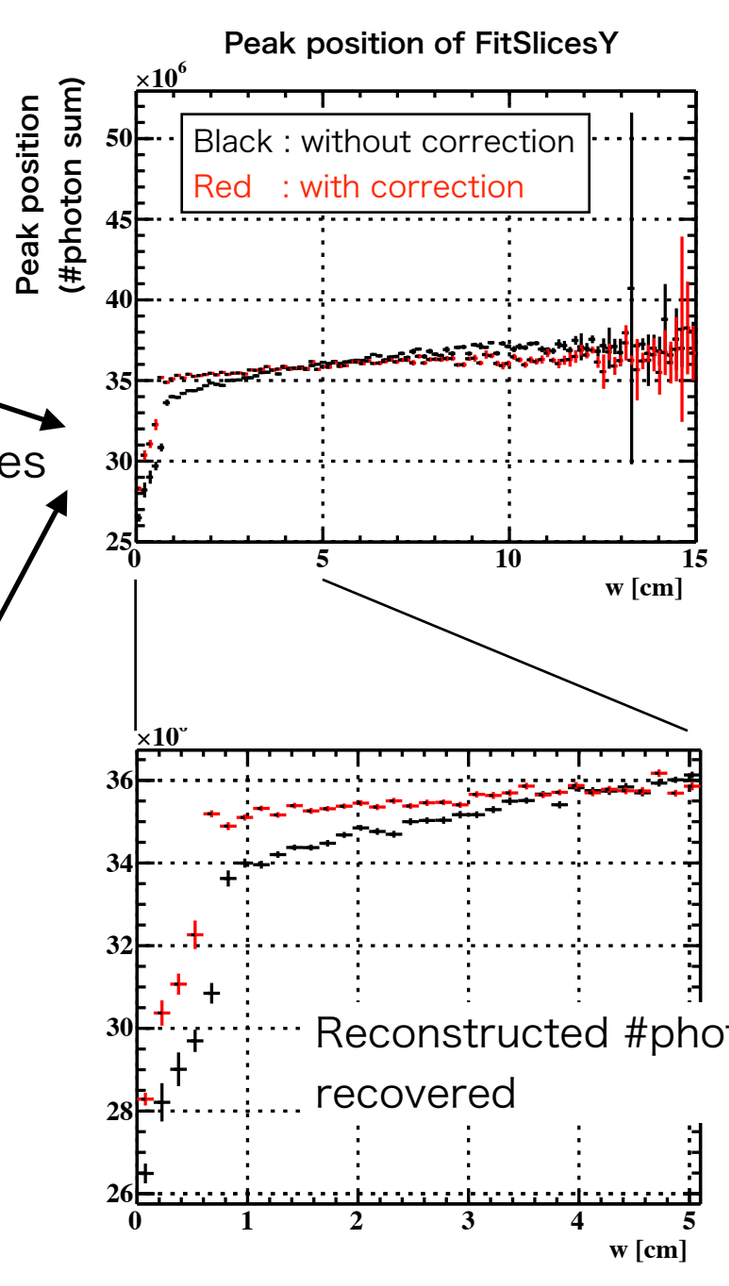


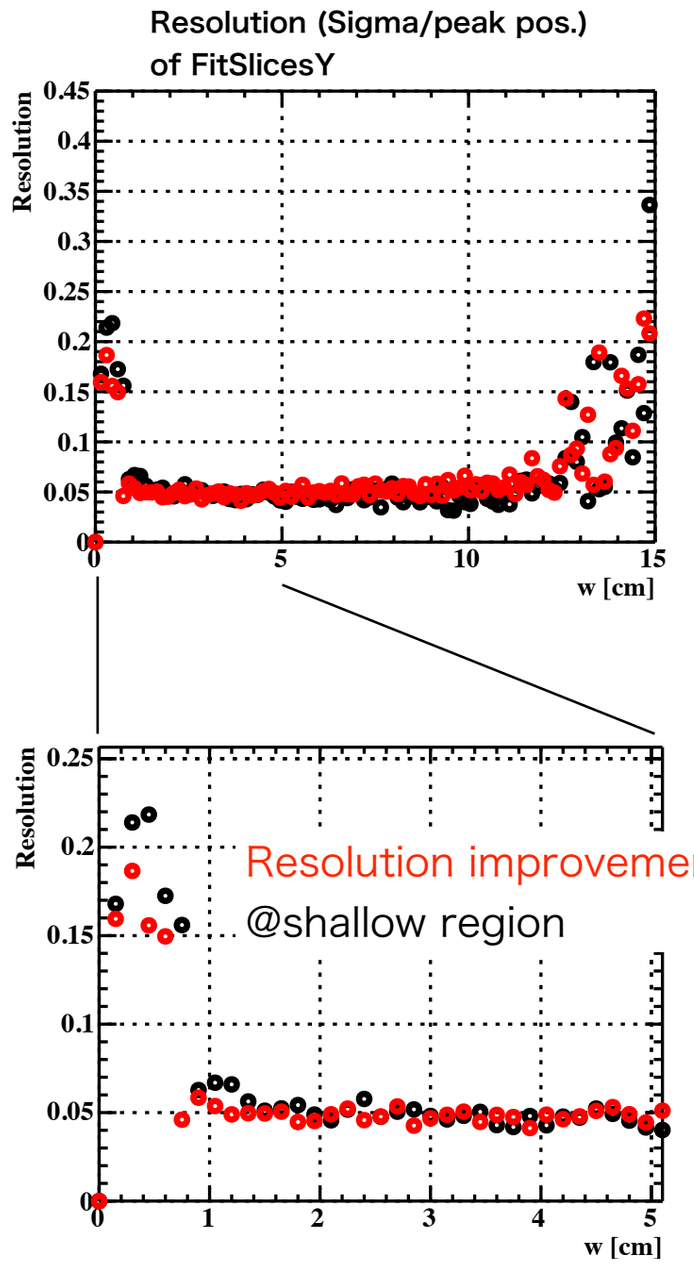
Improvement of #photon reconstruction

- Evaluation of the improvement by non-linearity correction
  - At shallow region, the resolution (σ/peak) is improved
  - But for the other region, improvement is not observed
    - Still have some room to optimize parameters of this correction



FitSlices





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Summary and Prospect of sensitivity

- MEG II experiment will continue by 2026
  - PSI πE5 beam line update in 2027-28

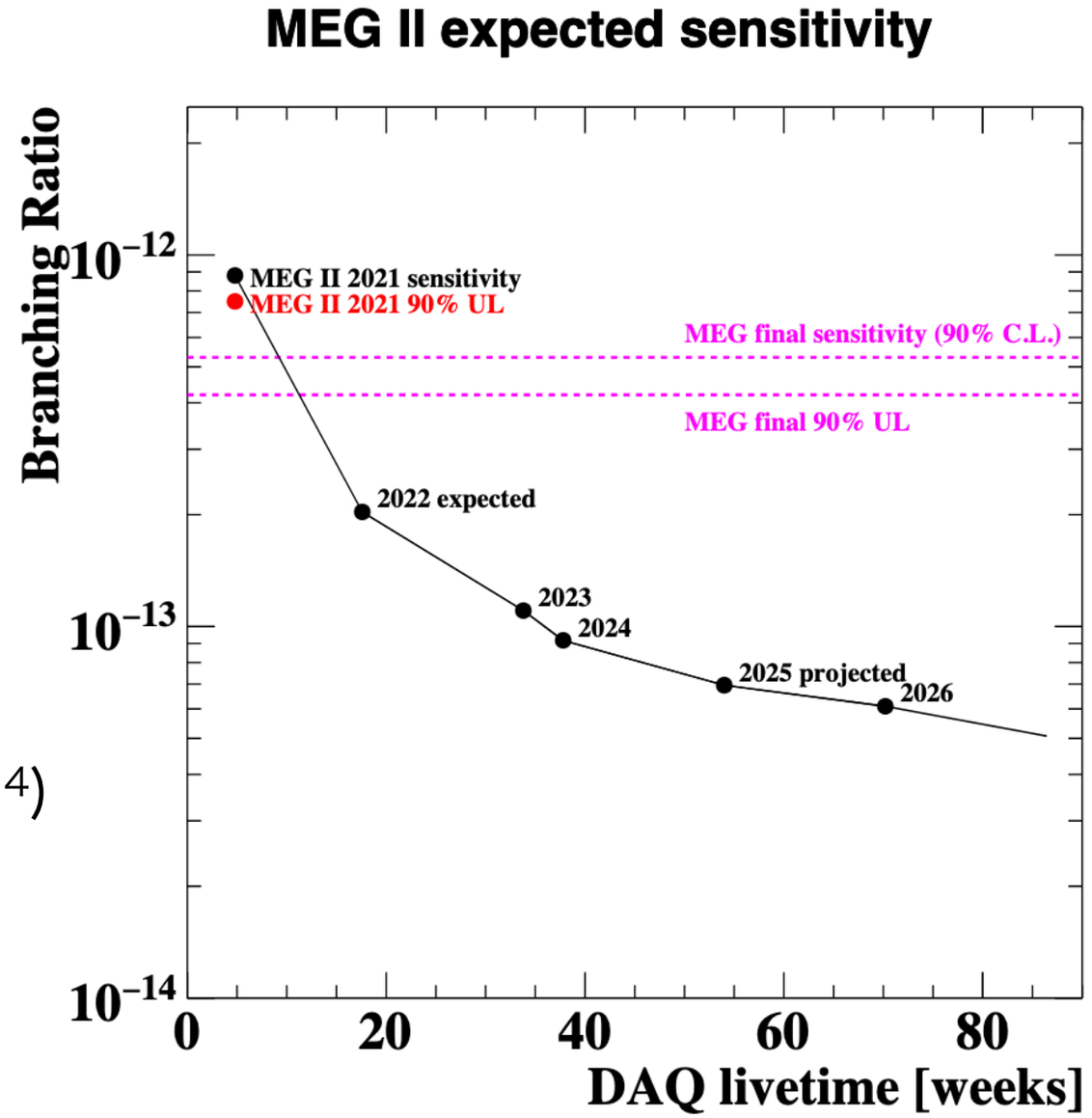
- Prospect of MEG II sensitivity
  - Sensitivity is calculated as 90% C.L. upper limit with BG only hypothesis

- 2021+2022 data : will be published soon !
  - sensitivity : 2.2 ×10^{-13} (preliminary)
    - see the talk : 18aT1-7 (山本)

- 2023 data :
  - Analysis is ongoing
    - Energy reconstruction : ongoing
    - + trial to improve the resolution
  - sensitivity prospect : almost reach O(10^{-14})

-> aim to reach the final sensitivity :

(5-6)×10^{-14}

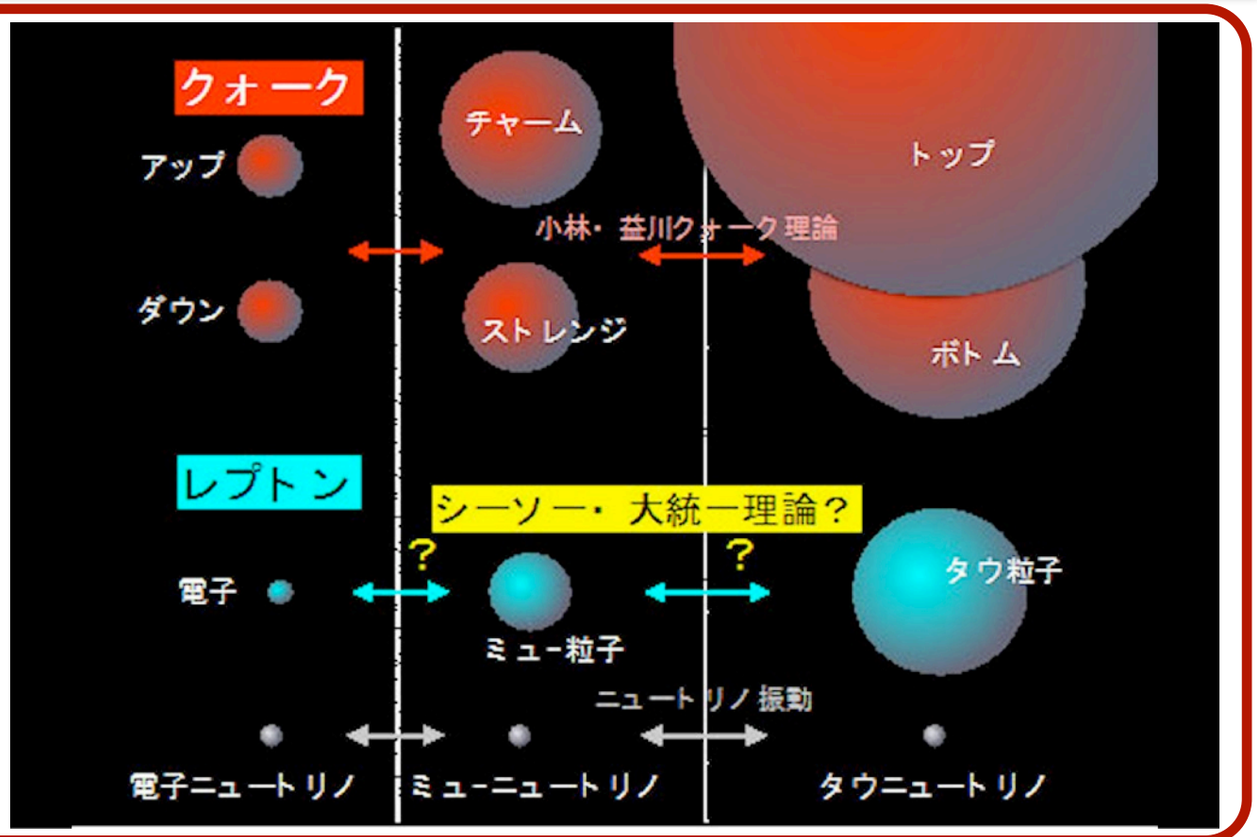


Back up

Charged Lepton Flavor Violation

- **Strong evidence of new physics once it observes**

- Grand Unified Theory predicts cLFV
  - SUSY-GUT, SUSY-seesaw
  - Typical prediction :
    - $Br(\mu \rightarrow e\gamma) \sim O(10^{-14})$
    - Can be observed realistically



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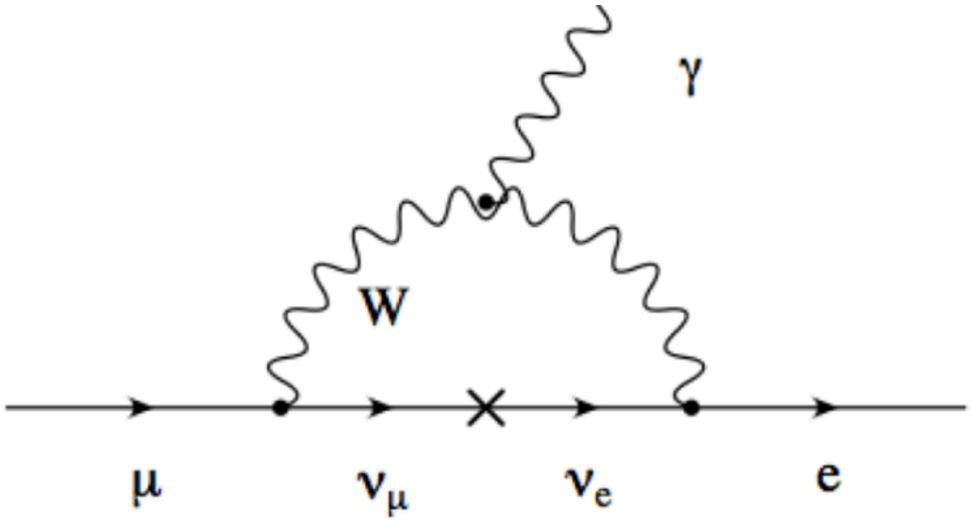
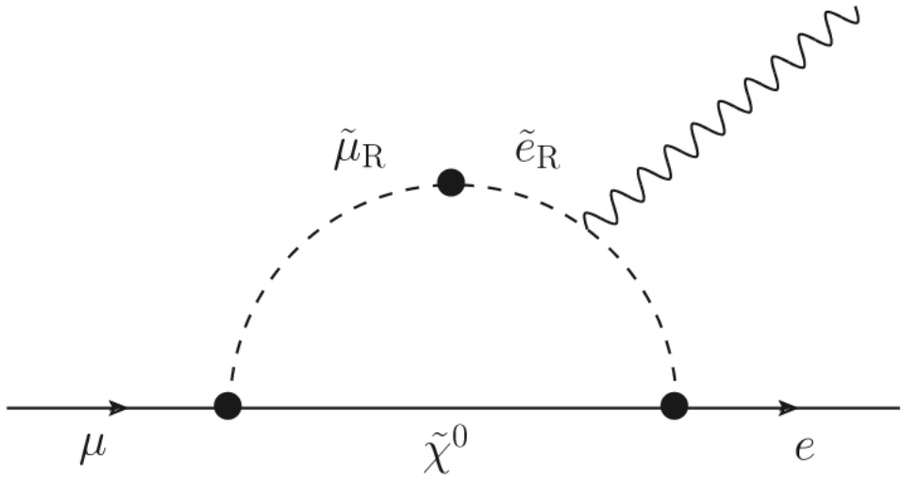


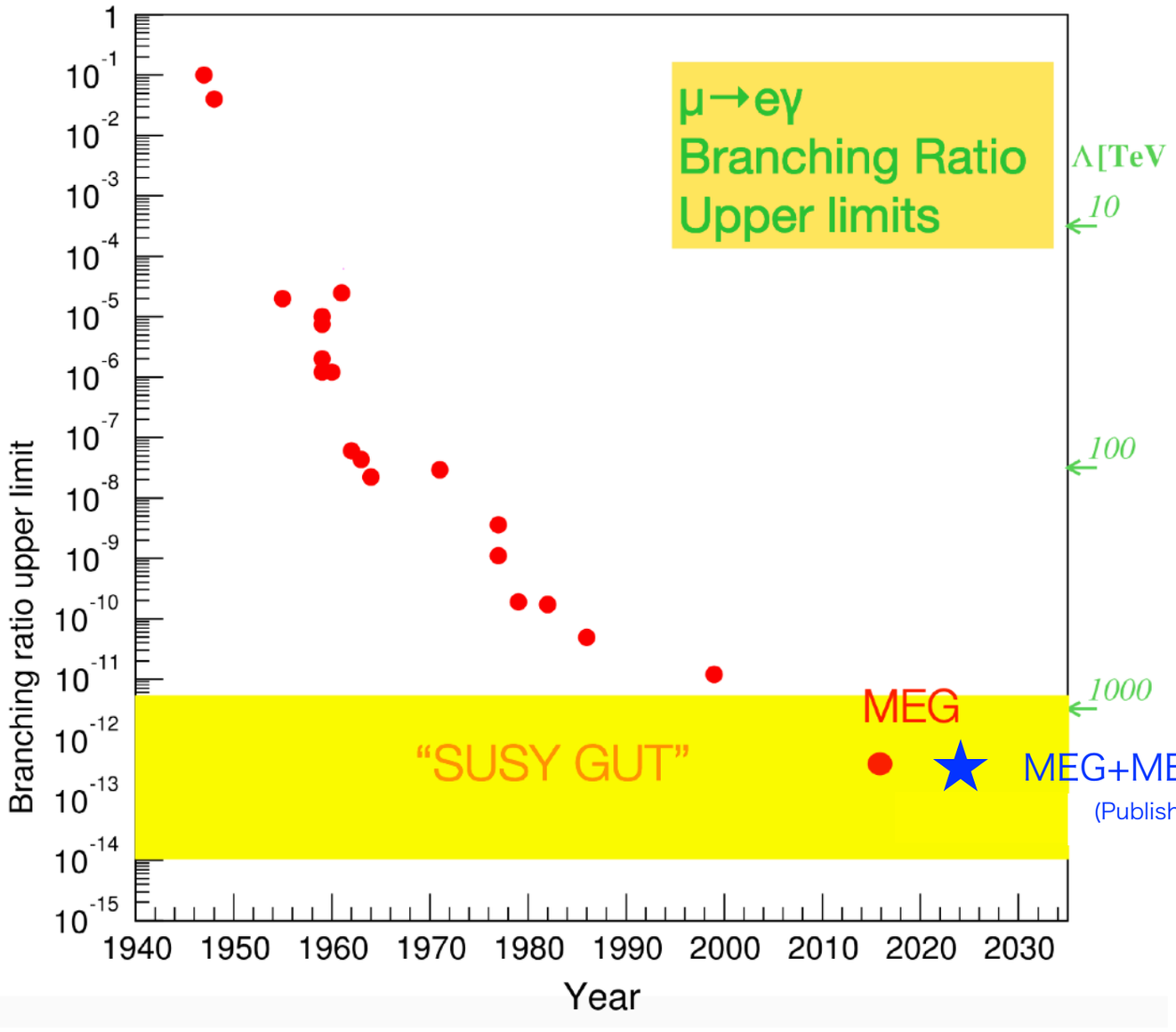
Diagram in the SM + neutrino oscillation



Possible diagram in SUSY-GUT senario

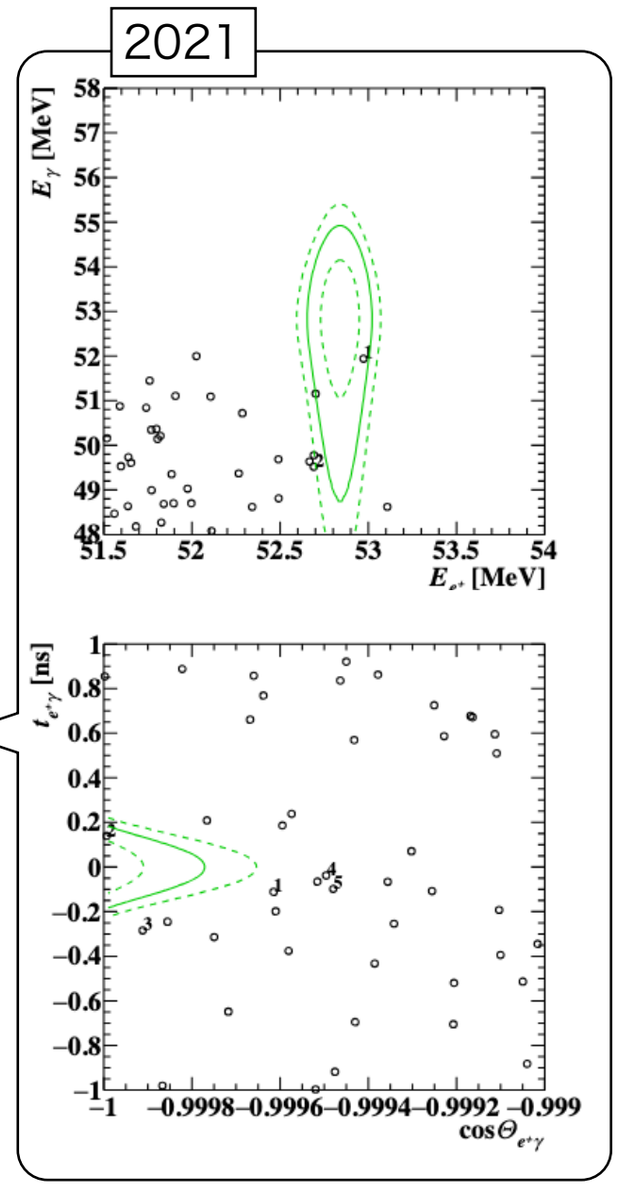
Current status of cLFV (and other experiments)

- Most strict limit for cLFV : Br(μ→eγ) < 3.1×10^{-13} (90% C.L.) by MEG II (+MEG)



MEG+MEG II (2021) : 3.1×10^{-13}

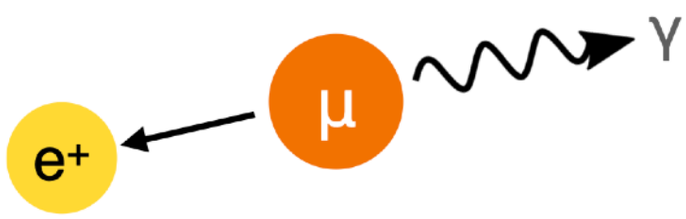
(Published : Eur. Phys. J. C. Vol84, 216 (2024))



- Other channels to search for cLFV
  - $\mu^+\to e^+e^-e^+$: Mu3e
  - $\mu^-N\to e^-N$: COMET, DeeMe, Mu2e
- Still under development/preparation for physics run

MEG II experiment : signal and background

- Signal : Gamma-ray and positron with 52.8 MeV (=$m_\mu/2$)

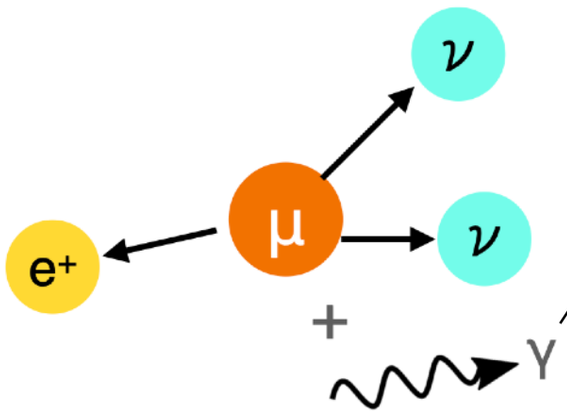


back-to-back

on-timing

$$N_{sig} \propto R_\mu \times T \times \mathrm{Efficiency}$$

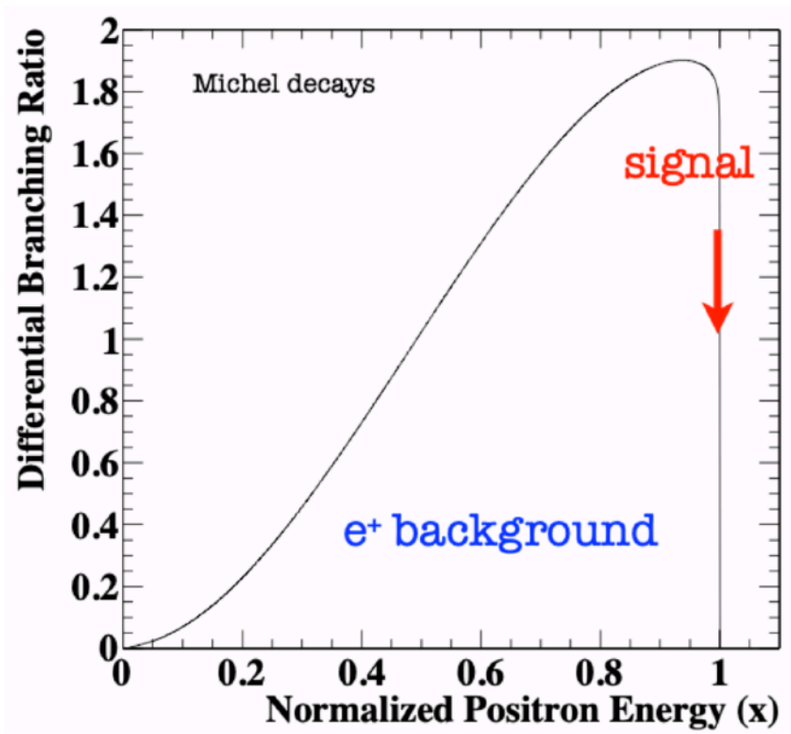
- Dominant background : Accidental coincidence of Michel positron and gamma

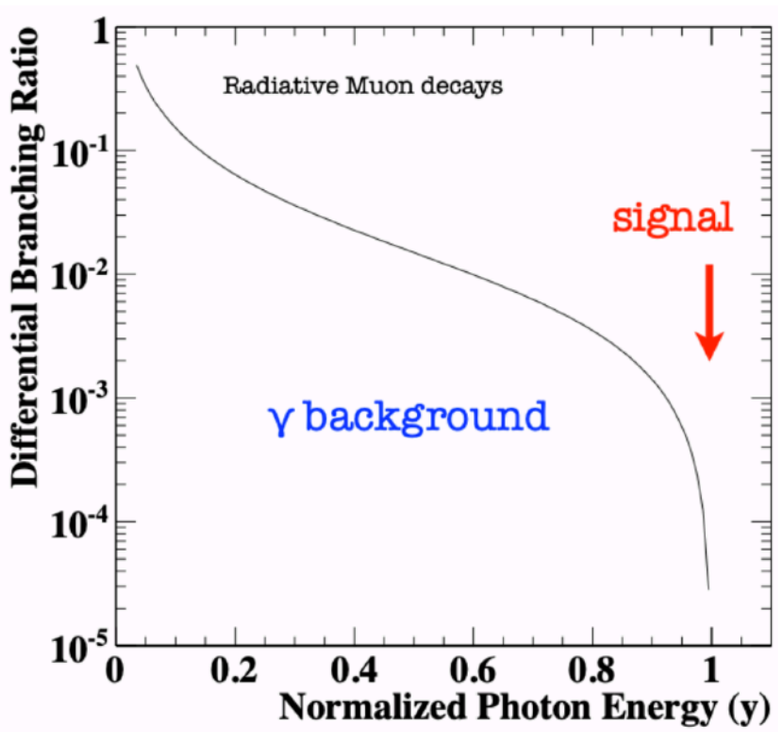


Gamma originated from
- Annihilation in flight
- Radiative muon decay

$$N_{acc} \propto R_\mu^2 \times T \times \Delta E_\gamma^2 \times \Delta E_e \times \Delta\Theta_{e\gamma}^2 \times \Delta T_{e\gamma}$$

beam rate, time, Resolutions





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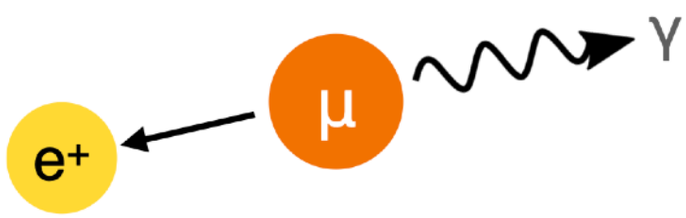


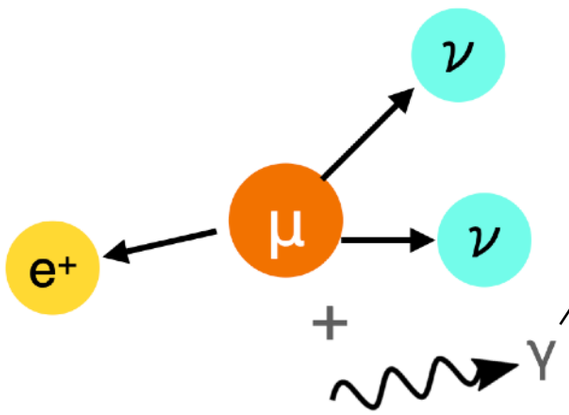
back-to-back

on-timing

$$N_{sig} \propto R_\mu \times T \times \text{Efficiency}$$

High intensity continuous beam is preferred

- Dominant backgrou positron and gamma

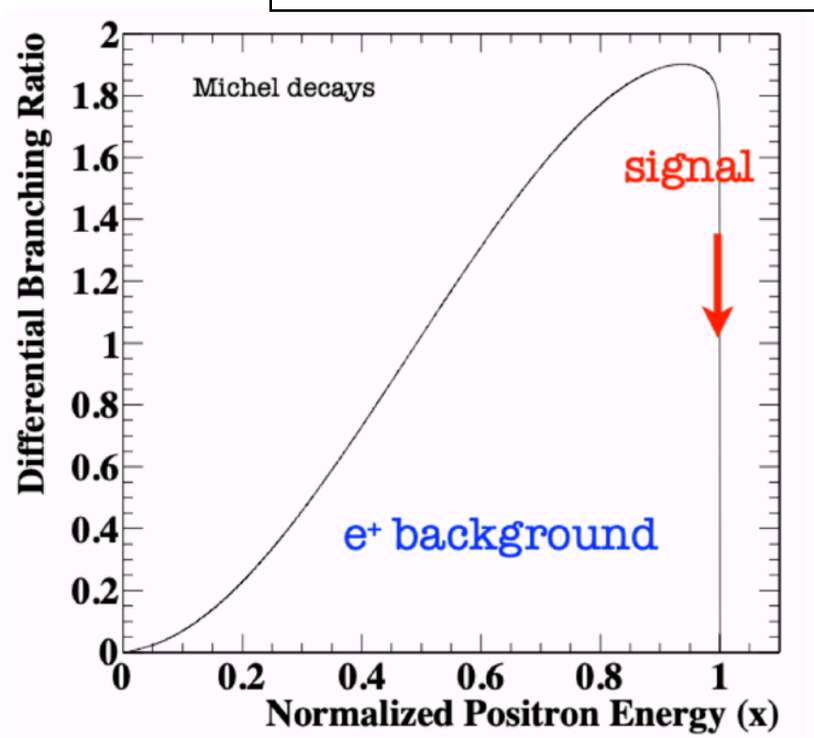


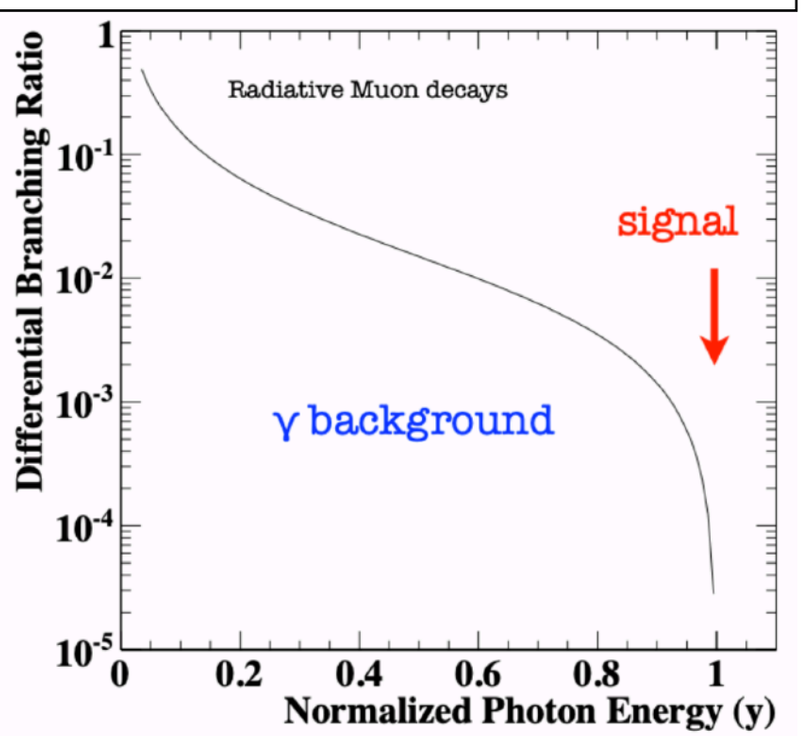
Gamma originated from
- Annihilation in flight
- Radiative muon decay

$$N_{acc} \propto R_\mu^2 \times T \times \Delta E_\gamma^2 \times \Delta E_e \times \Delta\Theta_{e\gamma}^2 \times \Delta T_{e\gamma}$$

beam rate, time, Resolutions

Detector with good resolutions is key to reduce BGs



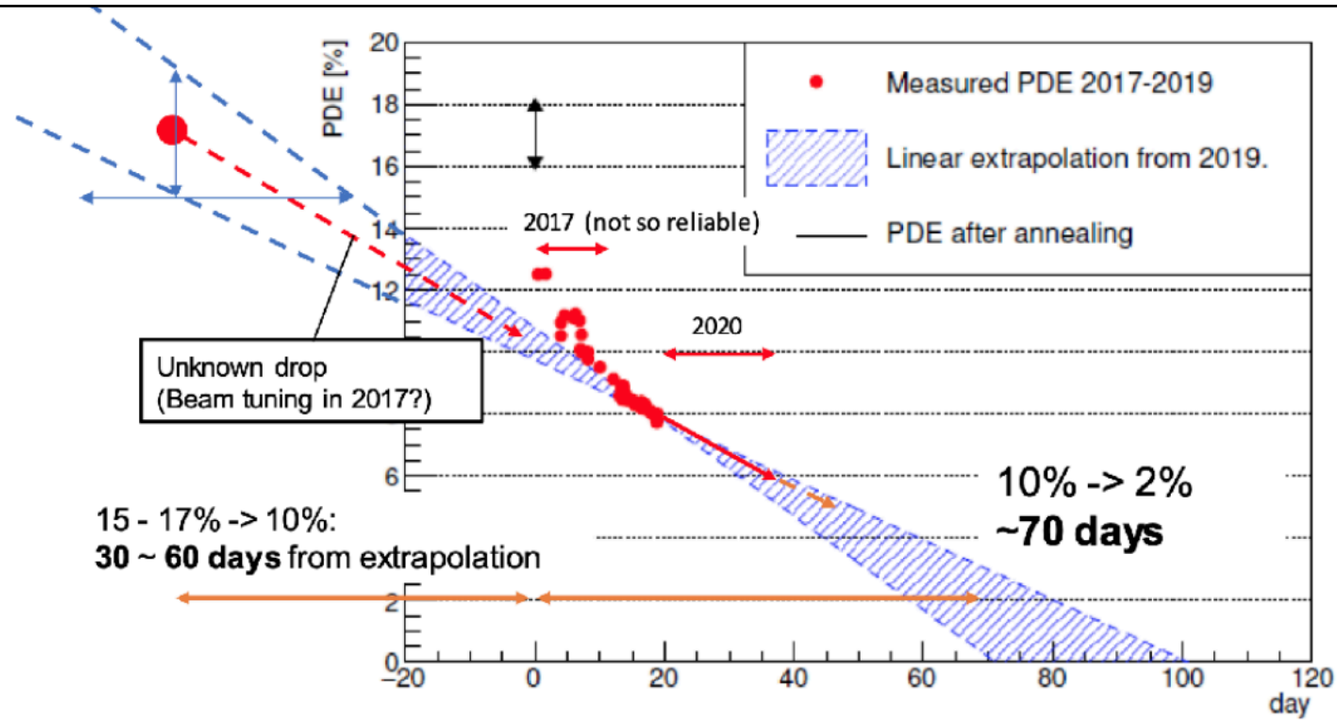


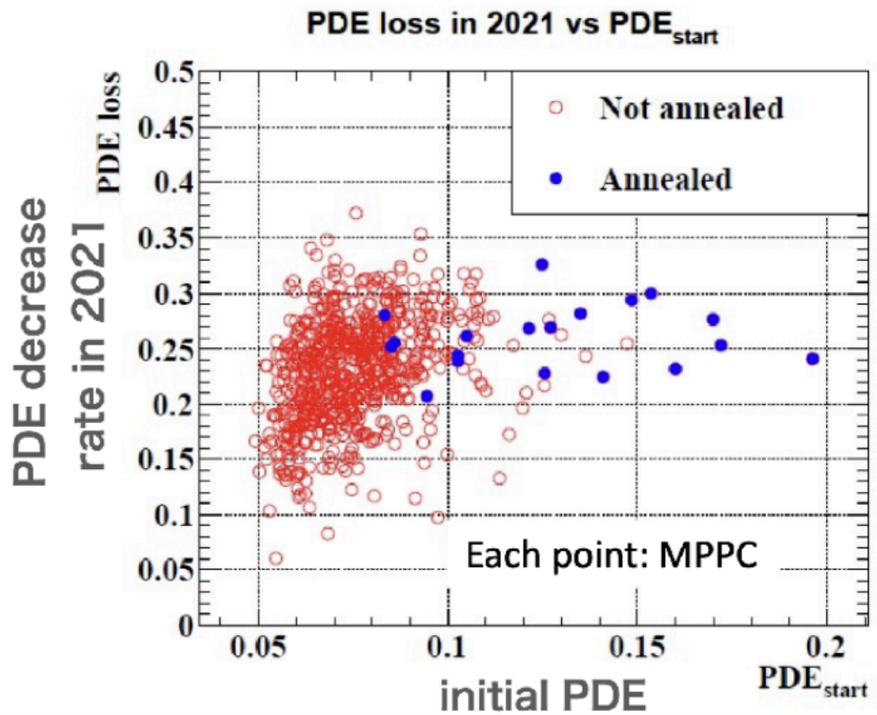
PDE decrease

Slide from T. Iwamoto (15aA562-4)

γ detector (LXe) Issue

- MPPC PDE decrease
  - observed in 2017 under muon beam
  - The cause to be investigated
  - Based on 2021 operation, PDE will change from 16% to 2% in ~100 days MEG II intensity
  - Annealing recovers PDE fully
- Strategy for run 2022
  - LXe MPPC can sustain ~ 120 days with 5×10^7 μ/s
    - Beam intensity optimization necessary
  - Annealing for all MPPCs during accelerator winter shutdown period

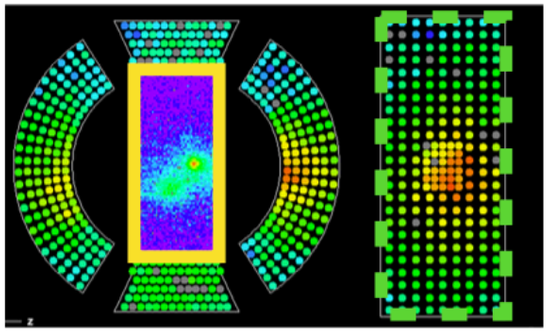




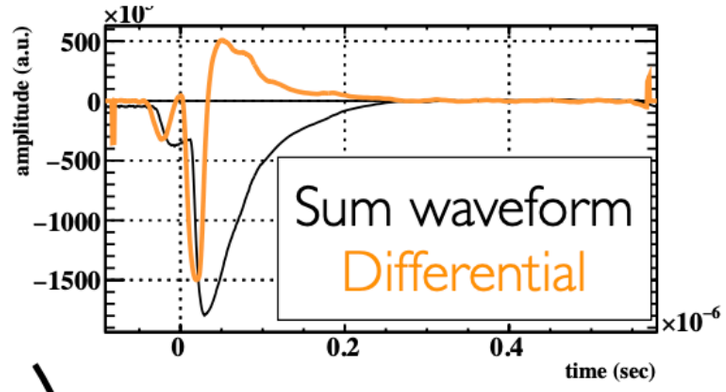
Pileup rejection update in the liquid xenon detector

- Pileup search and unfolding
  - Using information of spacial clustering and #pulses in sum waveform
  - Then unfold the sum waveform by template waveform fit
  - Simultaneous fit between PMT and MPPC sum waveform is performed

Peaks in light distribution

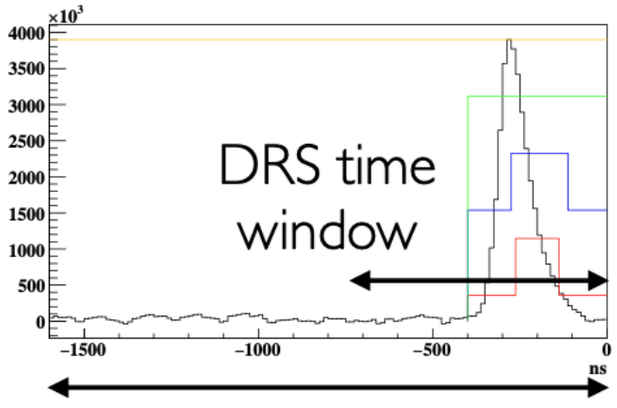


PMT differential waveform



newly implemented

FADC waveform for trigger



Inputs to template fit

Template waveform fit