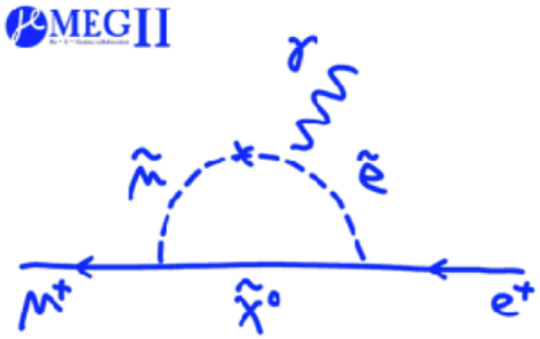
東京大学
素粒子物理国際研究センター
International Center for Elementary Particle Physics
The University of Tokyo

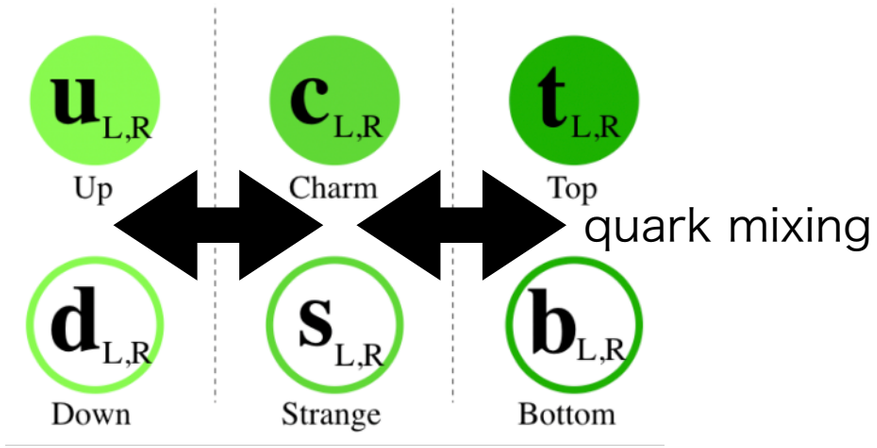


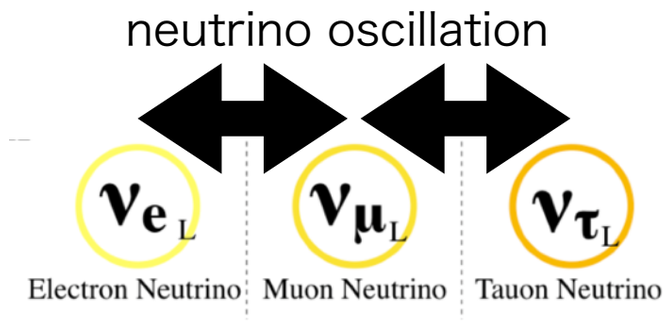
MEG II実験：
2023年データのガンマ線解析状況およびMPPCの非線形応答の補正による性能向上の研究

Sei Ban (ICEPP), for the MEG II collaboration
17th Mar. 2025, JPS 第80回年次大会@広島大学

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)

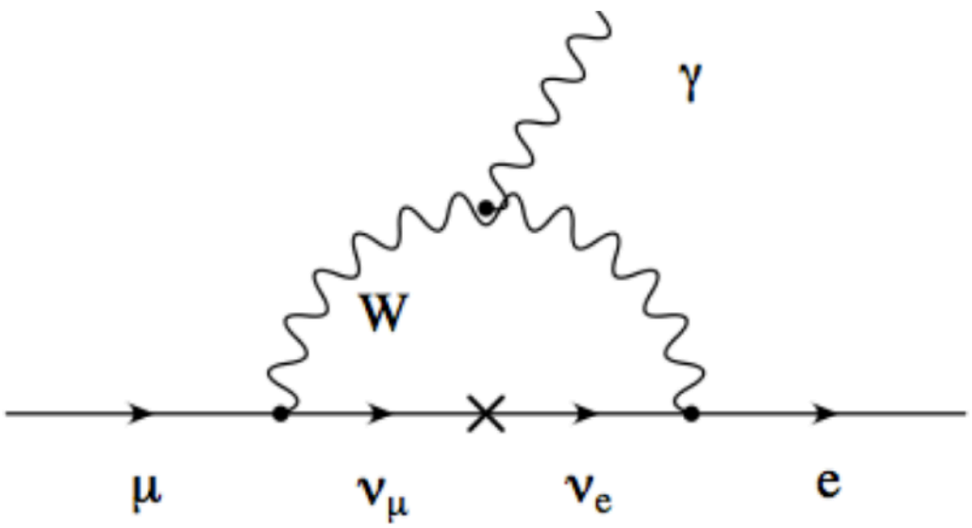
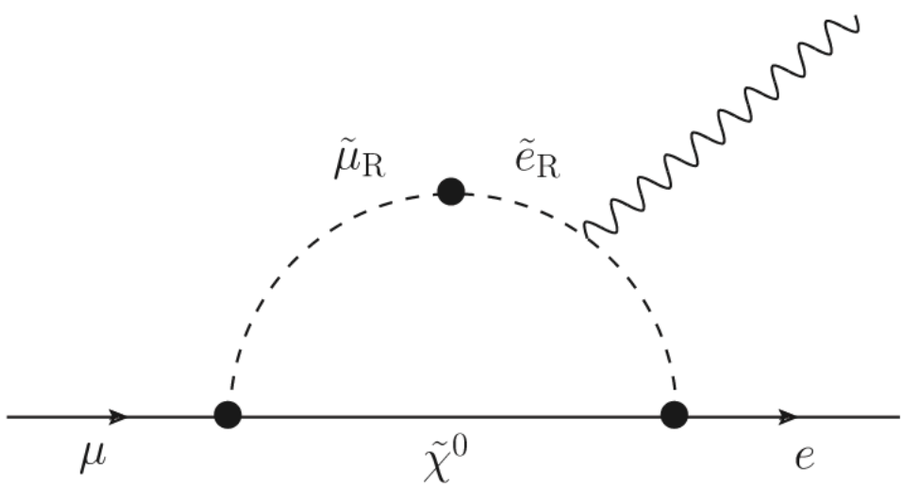


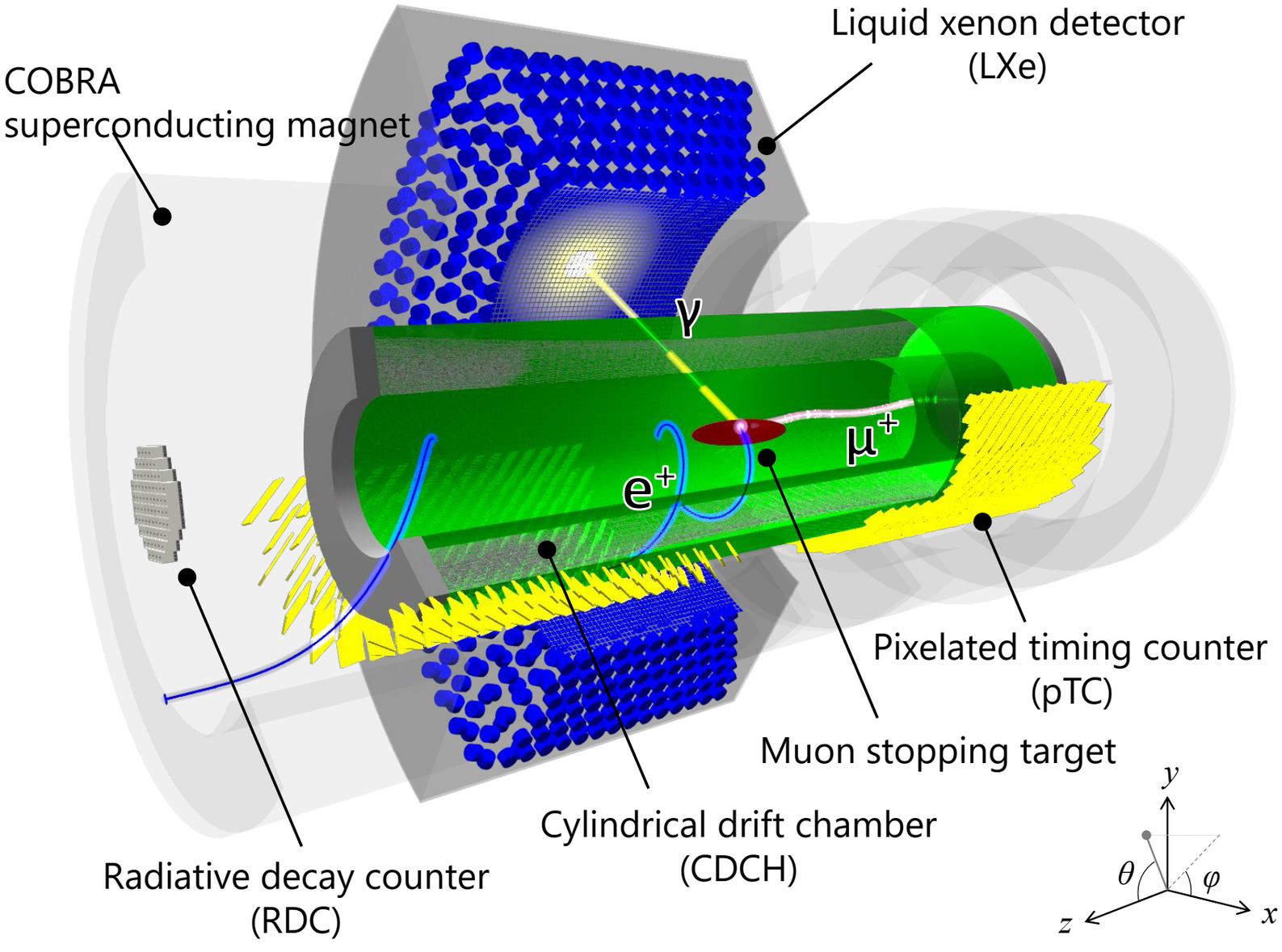
Diagram in the SM + neutrino oscillation

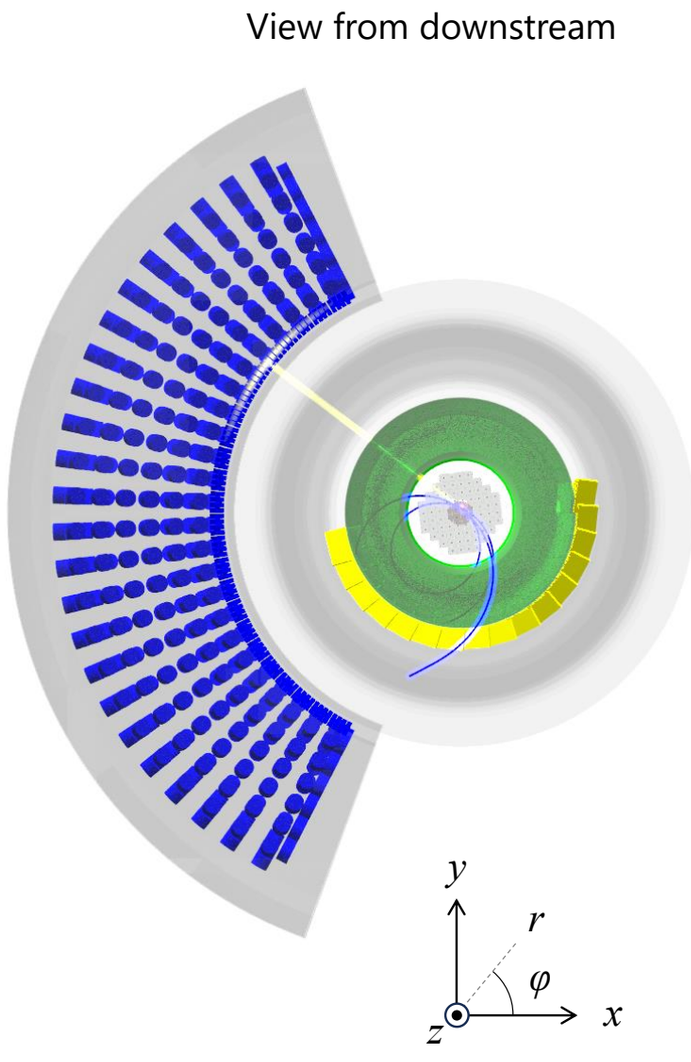


Possible diagram in SUSY-GUT senario

MEG II experiment

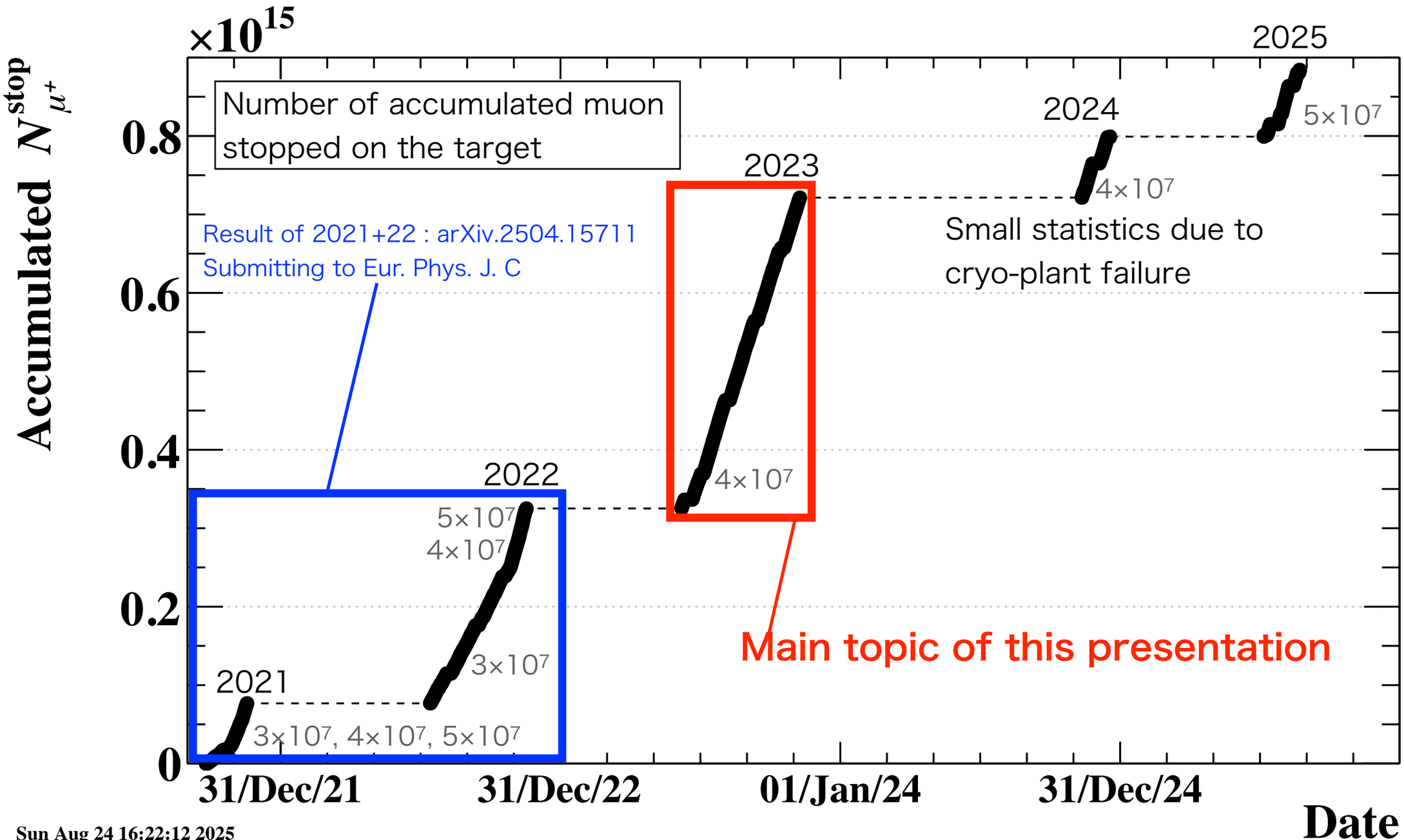
- MEG II experiment aims to search for charged lepton flavor violation : $\mu^+ \rightarrow e^+\gamma$
  - with higher sensitivity by one order of magnitude compared to the MEG
  - Current limit with 2021+2022 data : $Br(\mu^+ \rightarrow e^+\gamma) < 1.5\times10^{-13}$ (90% C.L.)
  - Target sensitivity of $Br(\mu^+ \rightarrow e^+\gamma)$: 6×10^{-14}





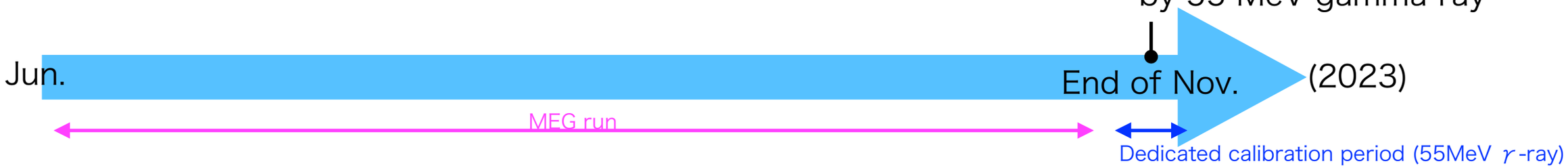
Timeline of the MEG II experiment

- Physics run started since 2021
  - will be continued by the end of 2026
  - Analysis of MEG II 2023+2024 data is ongoing

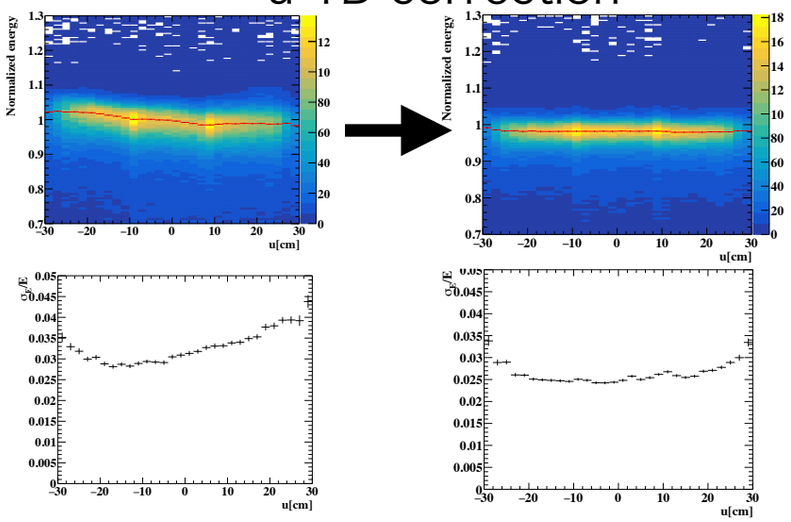


Non-uniformity correction

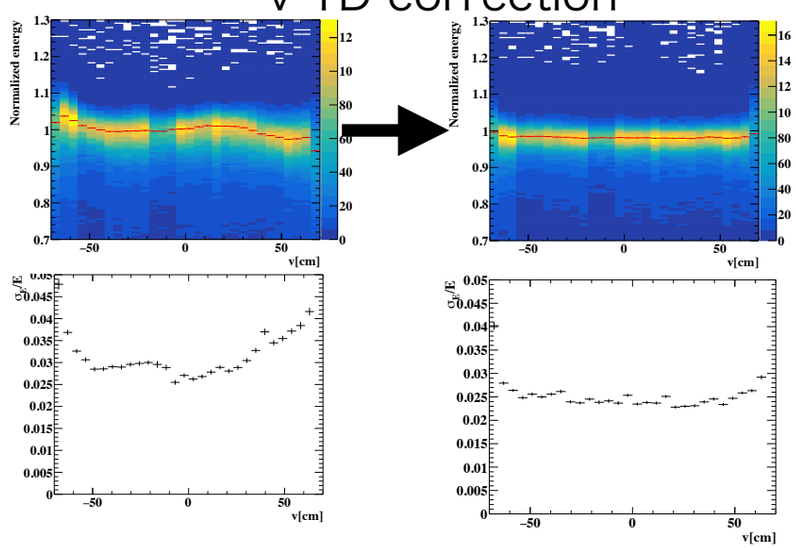
- Correction for non-uniformity by 55 MeV gamma-ray



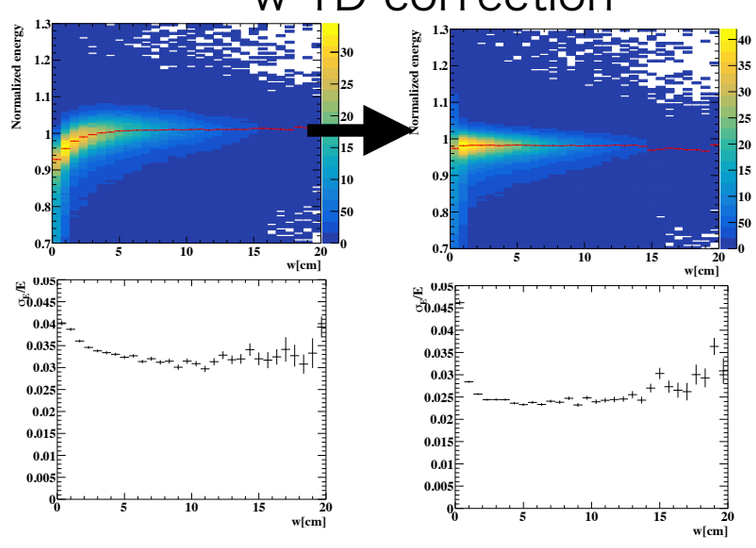
u-1D correction



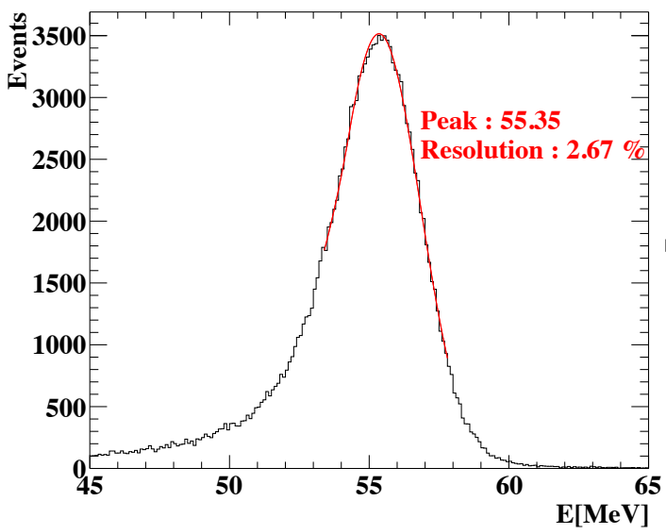
v-1D correction



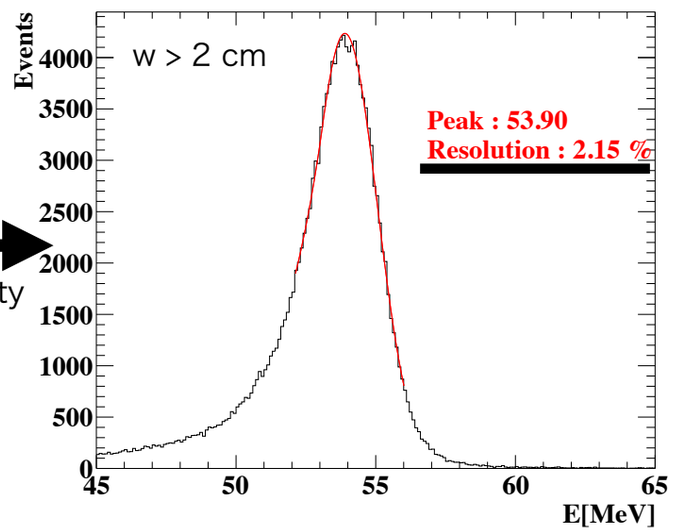
w-1D correction



+ additional correction : (u,v)-2D-correction, (u,v,w)-3D-correction



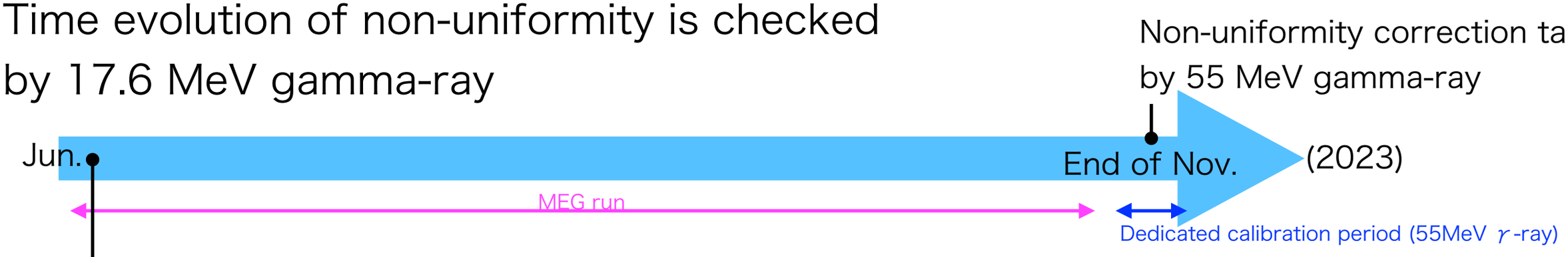
non-uniformity correction

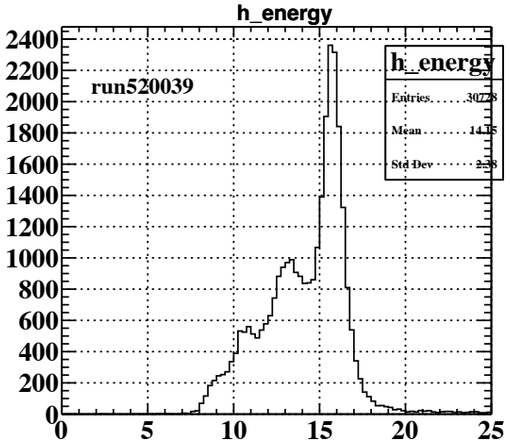


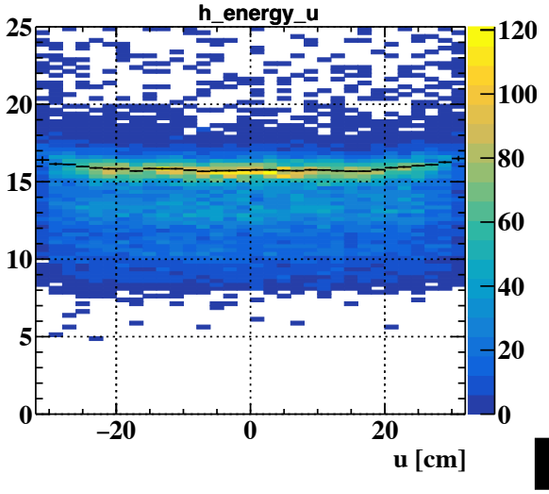
Achieved good energy resolution :
2.15% at 55 MeV
but it is worse than 2021(22) analysis
- it was 1.8(1.9)%
Reason of worse resolution is under investigation
-> Non-linear response of MPPCs may a cause

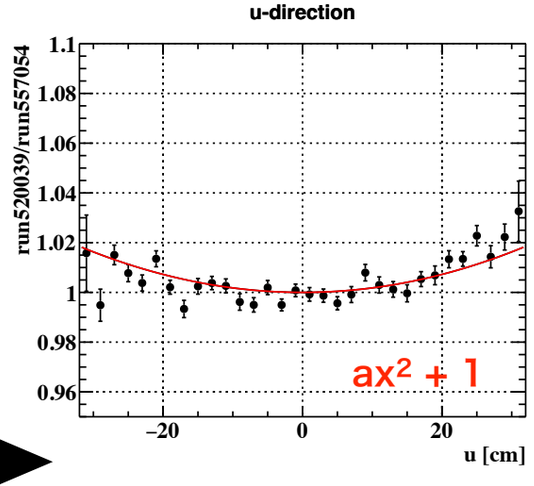
Non-uniformity correction : temporal evolution

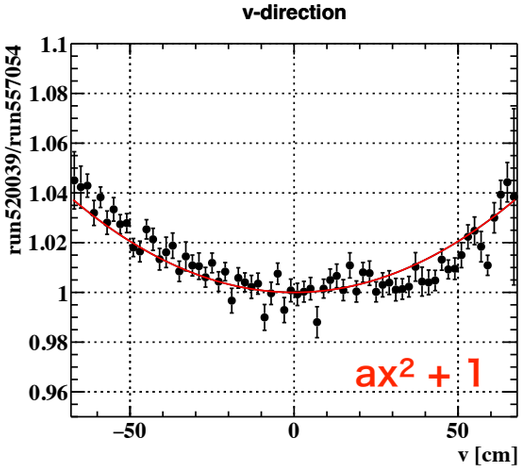
- Time evolution of non-uniformity is checked by 17.6 MeV gamma-ray

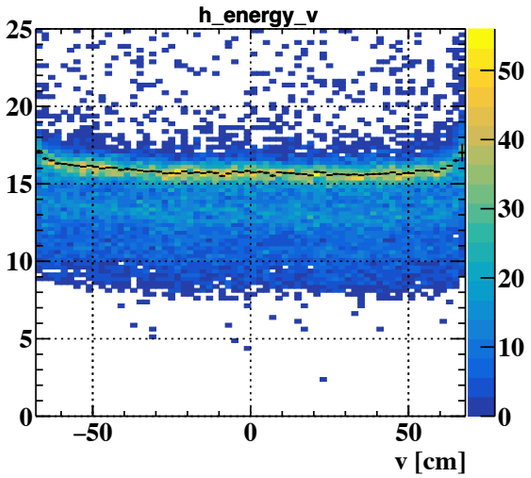


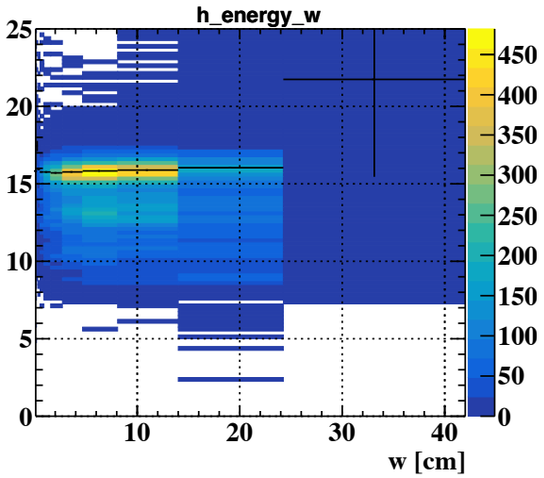


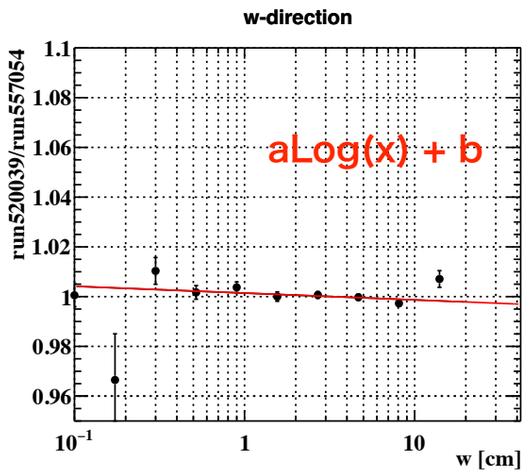






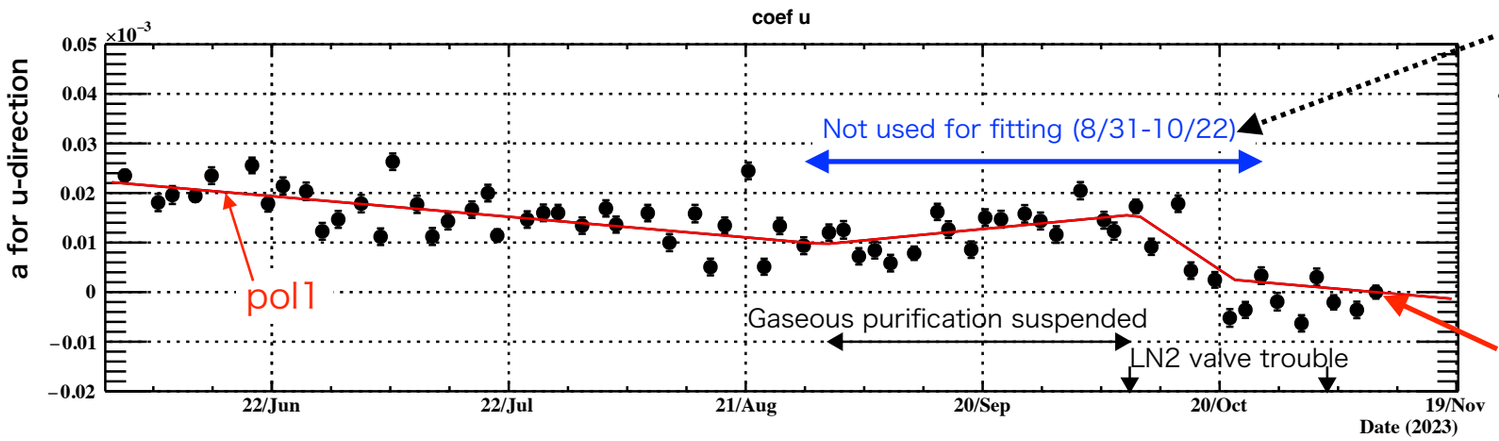






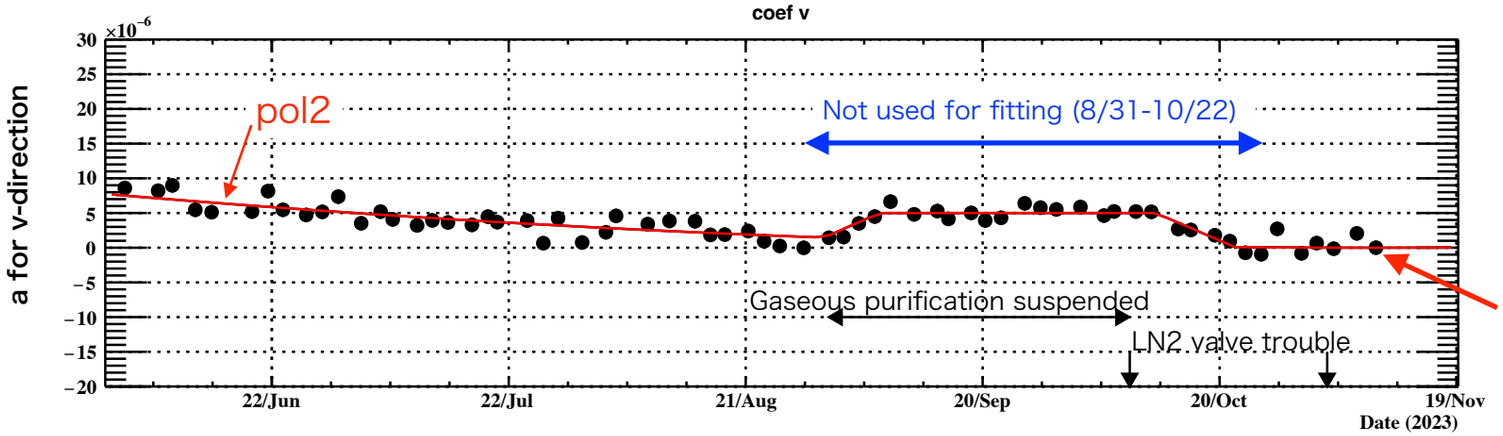
Temporal variation of non-uniformity by 17.6 MeV γ

- Temporal evolution of the coefficient of u,v,w-direction non-uniformity correction by 17.6 MeV gamma-ray

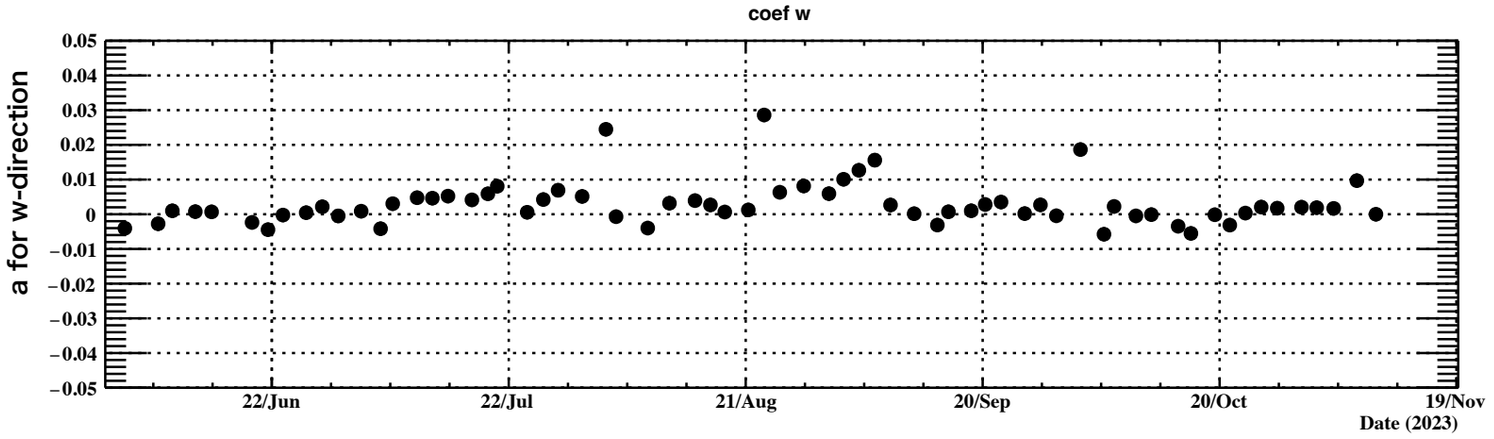


Stopping gaseous purification affects the situation of non-uniformity significantly

Fixed to 0



Fixed to 0



- For w-direction, temporal evolution is not observed

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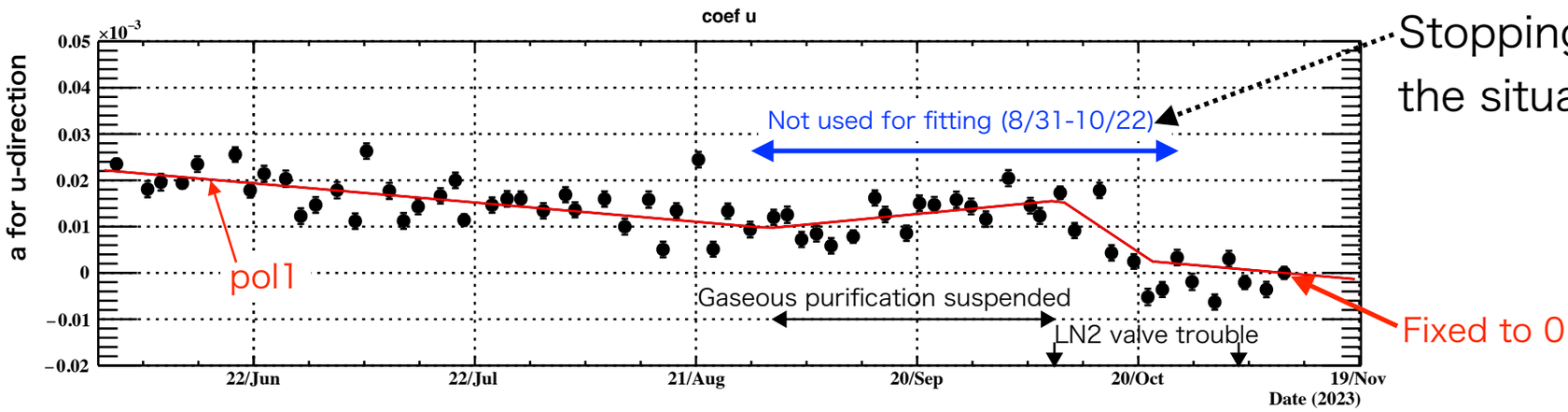

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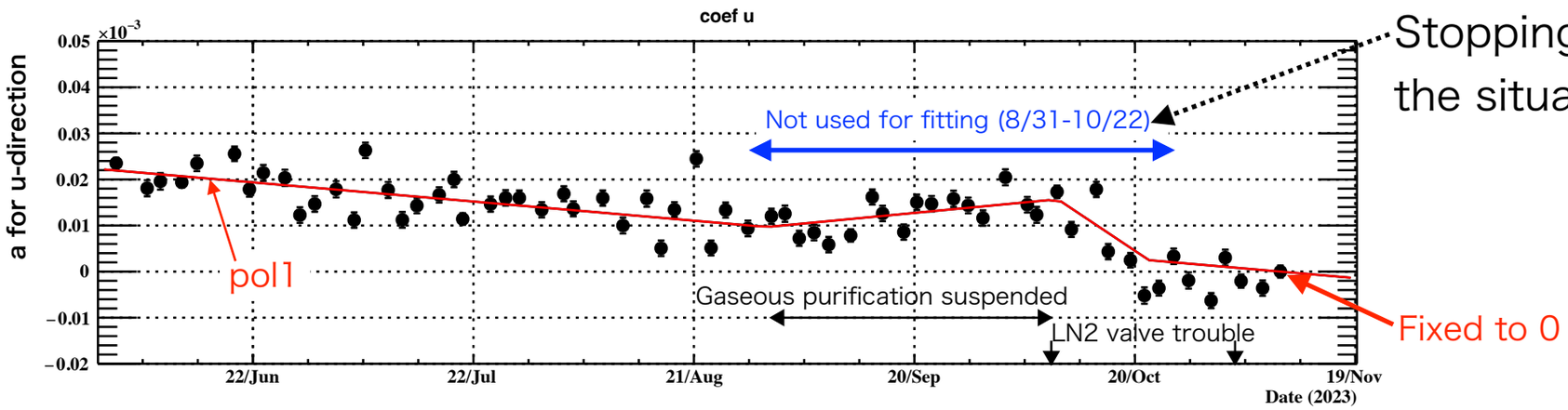

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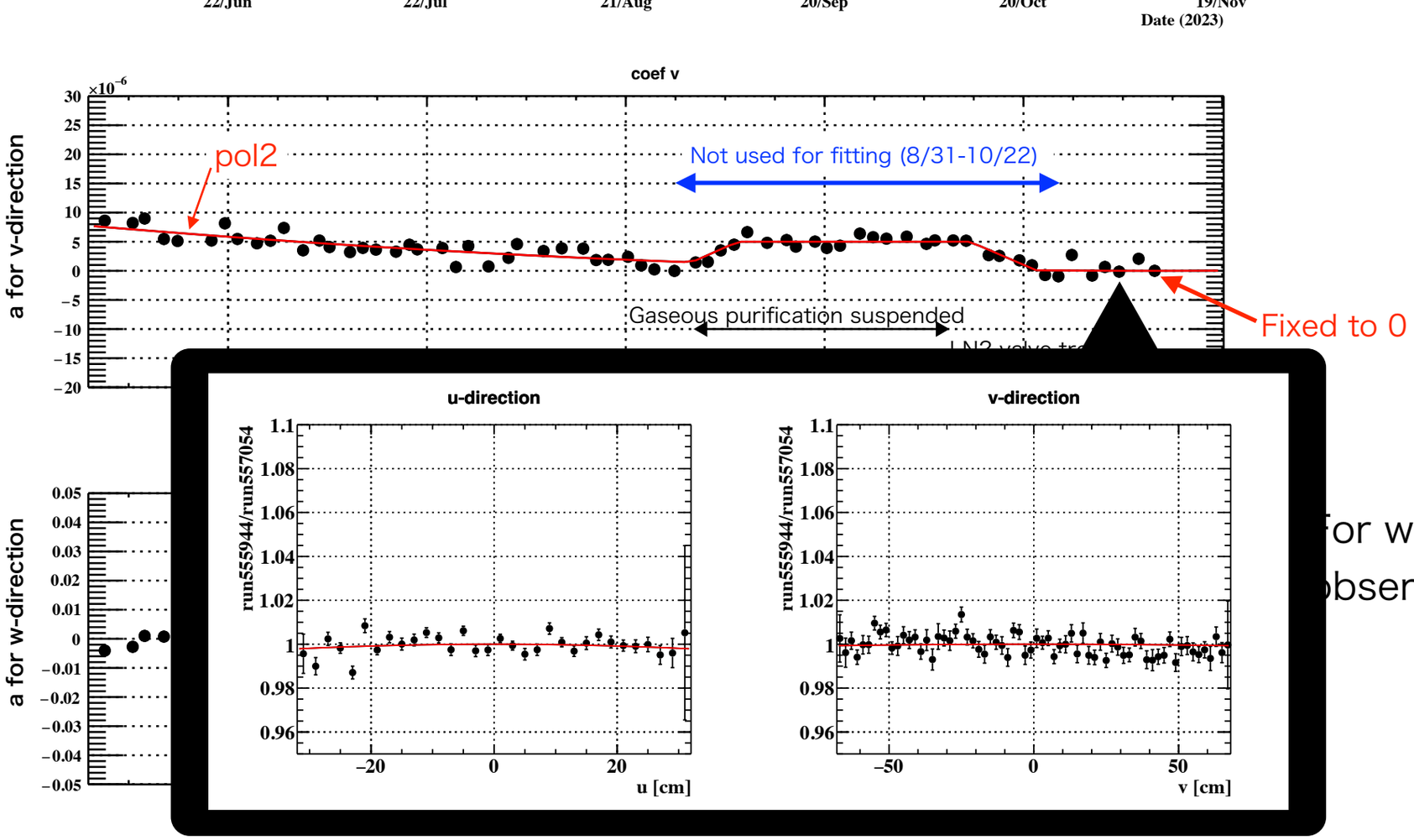
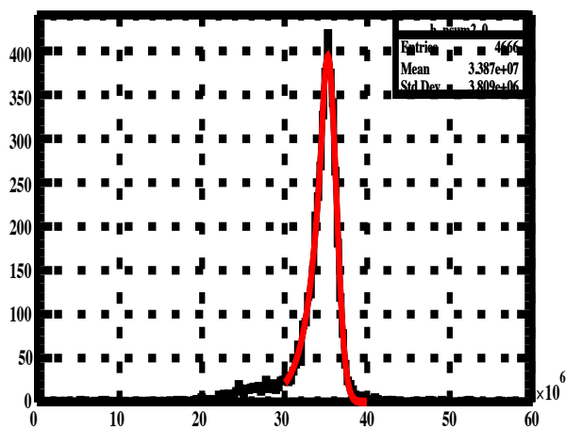


for w-direction, temporal evolution is not observed

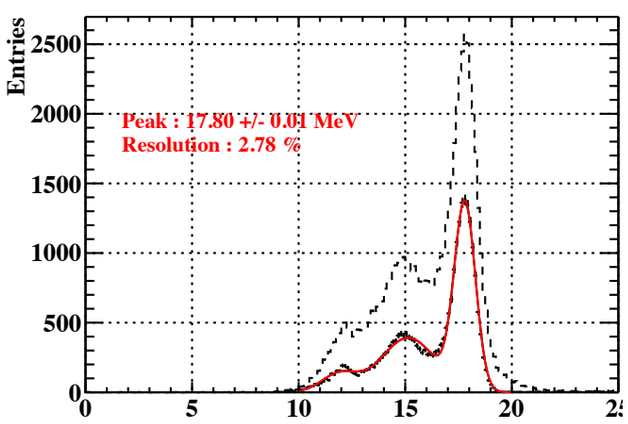
Energy scale calibration

- Temporal evolution of energy scale is calibrated using 4 kind of peaks
  - Gamma-rays with 9, 17.6, 55 MeV and Cosmic-ray
- Weighted average of these peaks are used as energy scale history

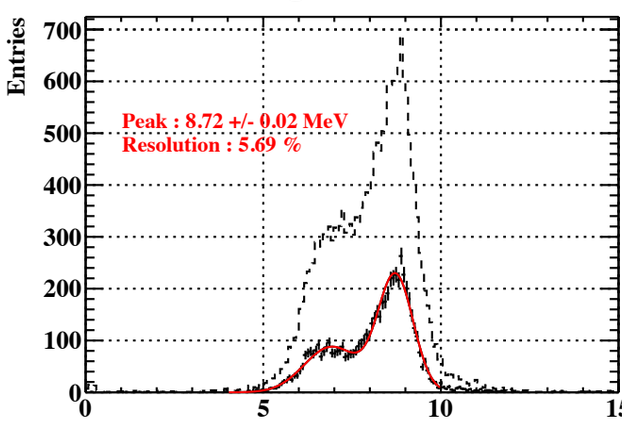
55 MeV gamma-ray by CEX



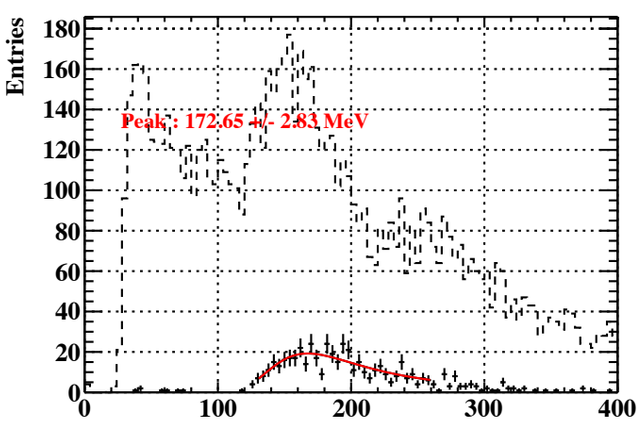
17.6 MeV gamma-ray (CW)

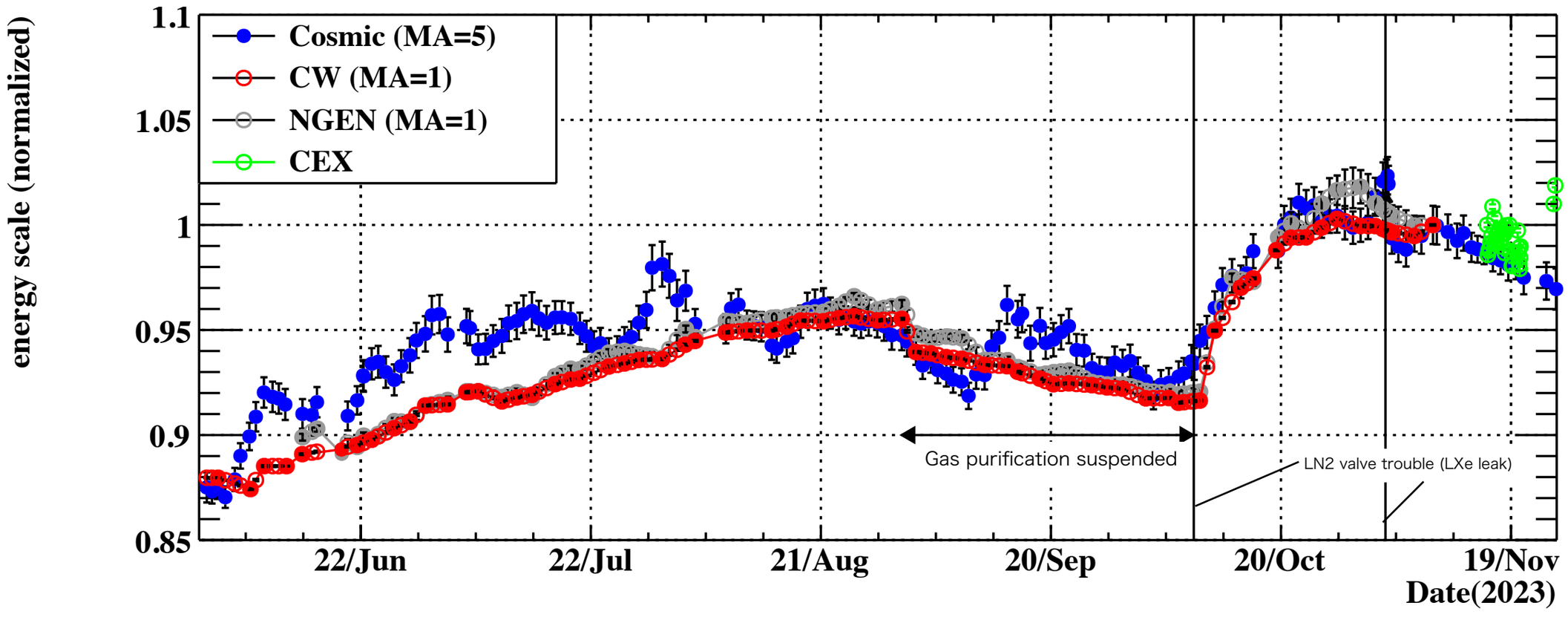


9 MeV gamma-ray
(Neutron generator)



Cosmic-ray





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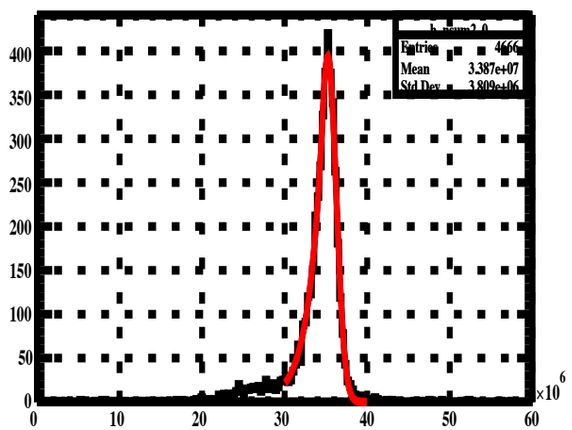
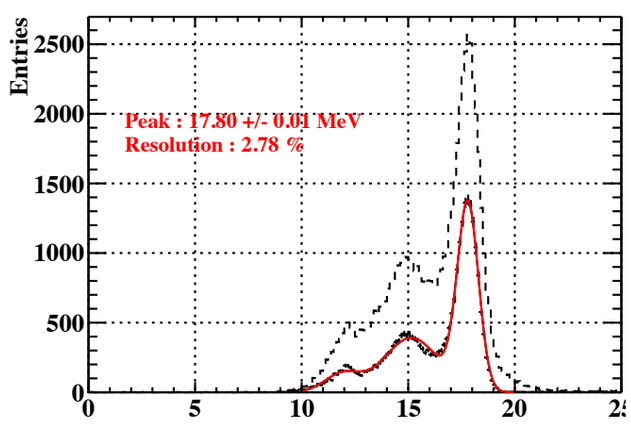


17.6 MeV gamma-ray (CW)



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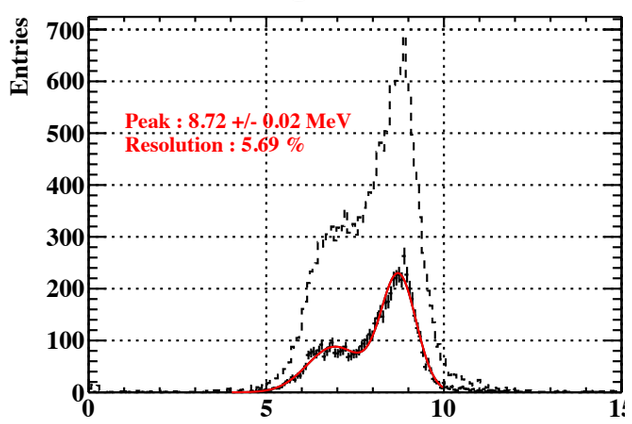
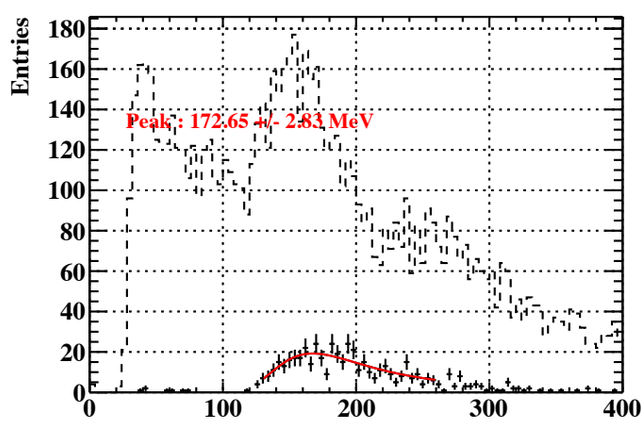
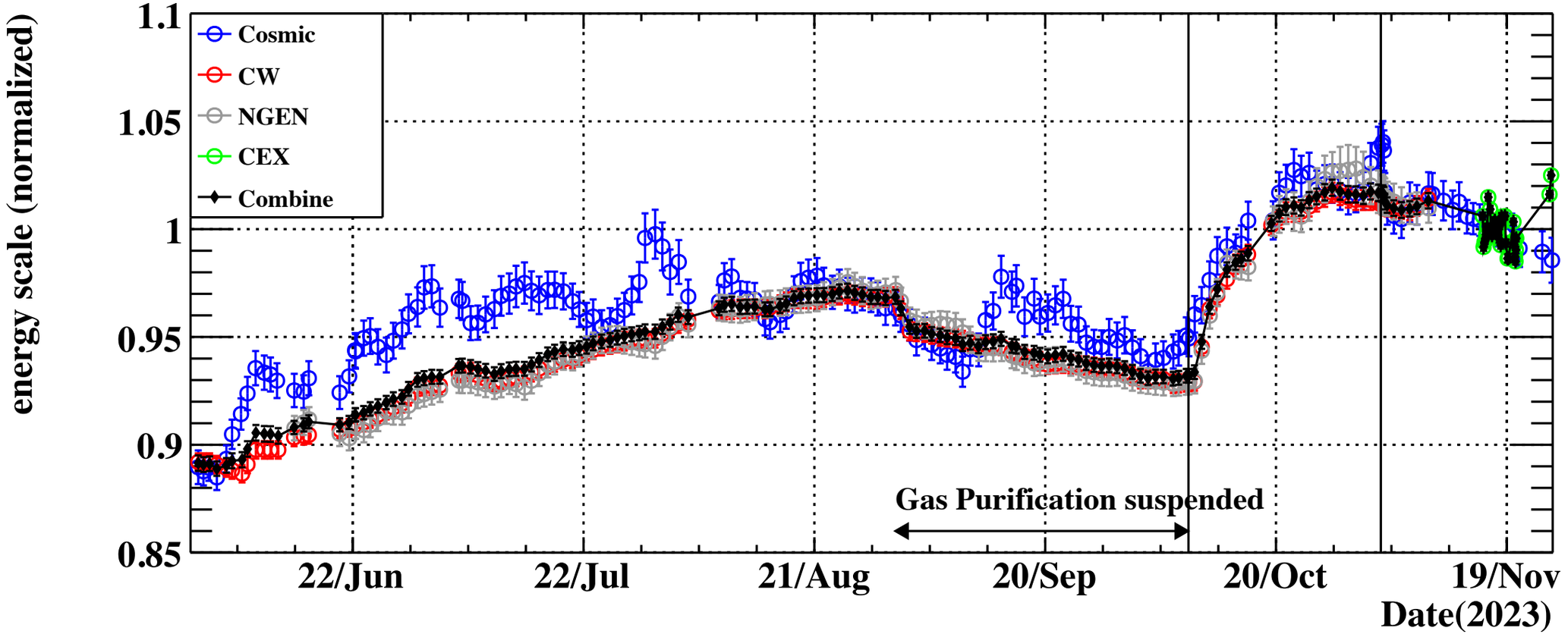


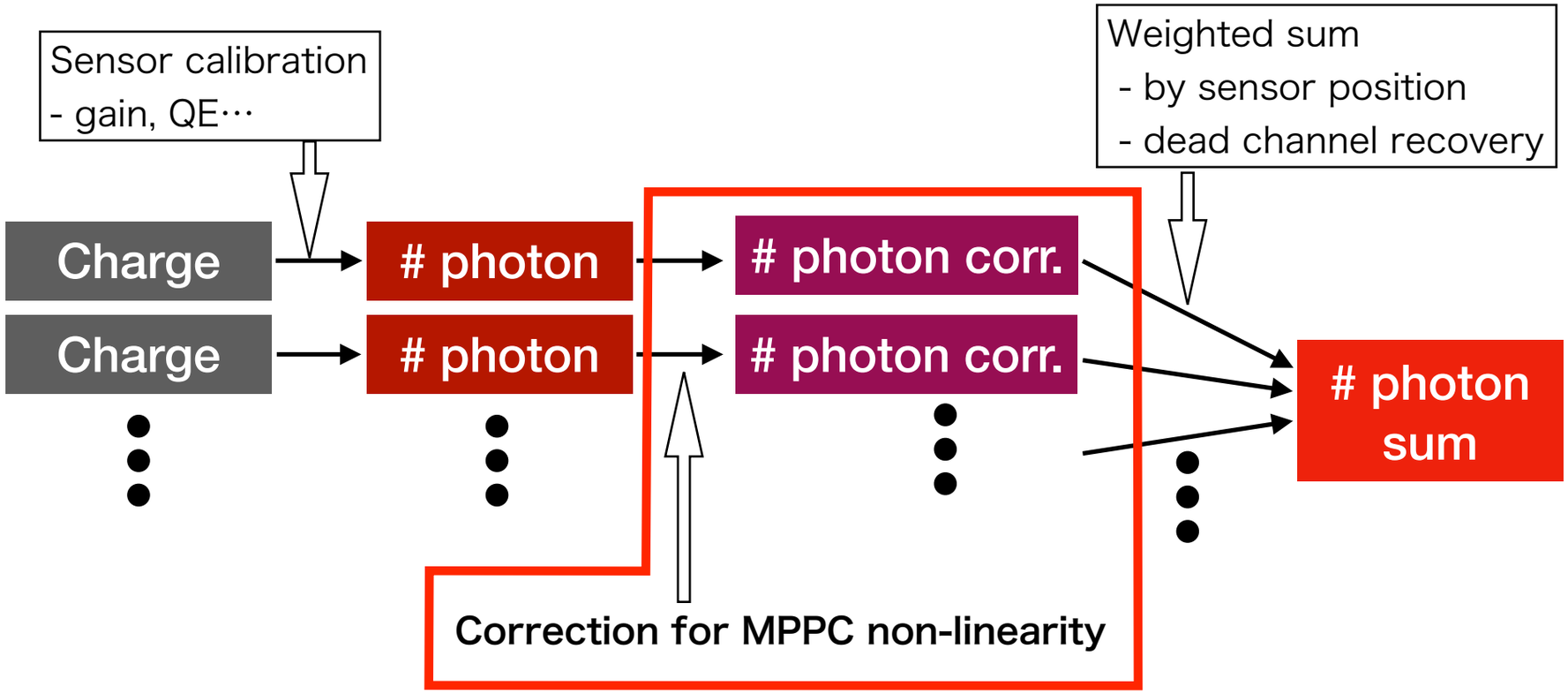
Cosmic-ray



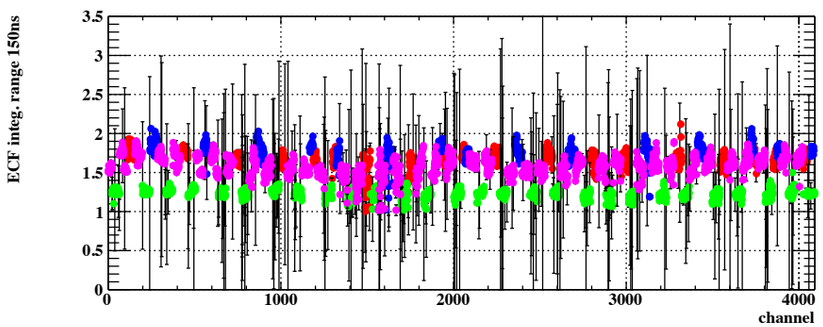


Improvement of #photon reconstruction

- Implementation of correction for MPPC non-linear response
  - Large #photons incident will cause saturation of MPPC signal



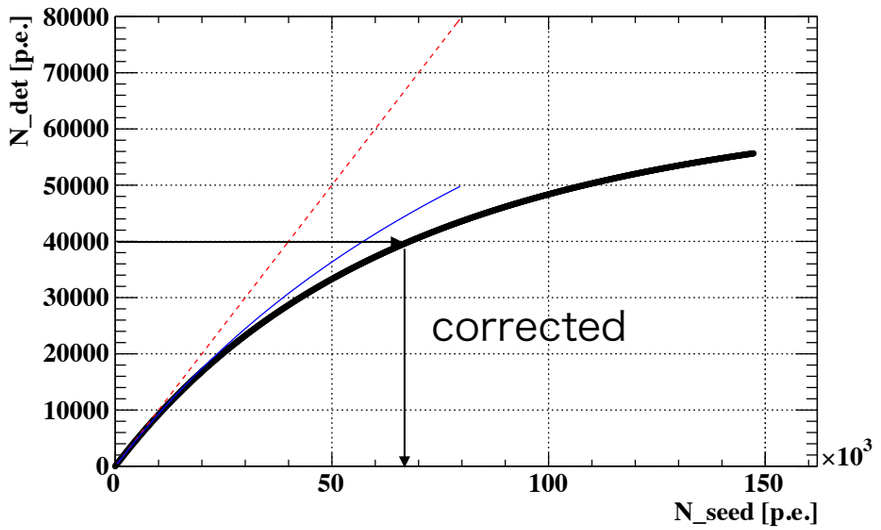
Recovery time of MPPC : 50ns



Crosstalk and after-pulse probability calibrated by LED run

Inputs for saturation curve

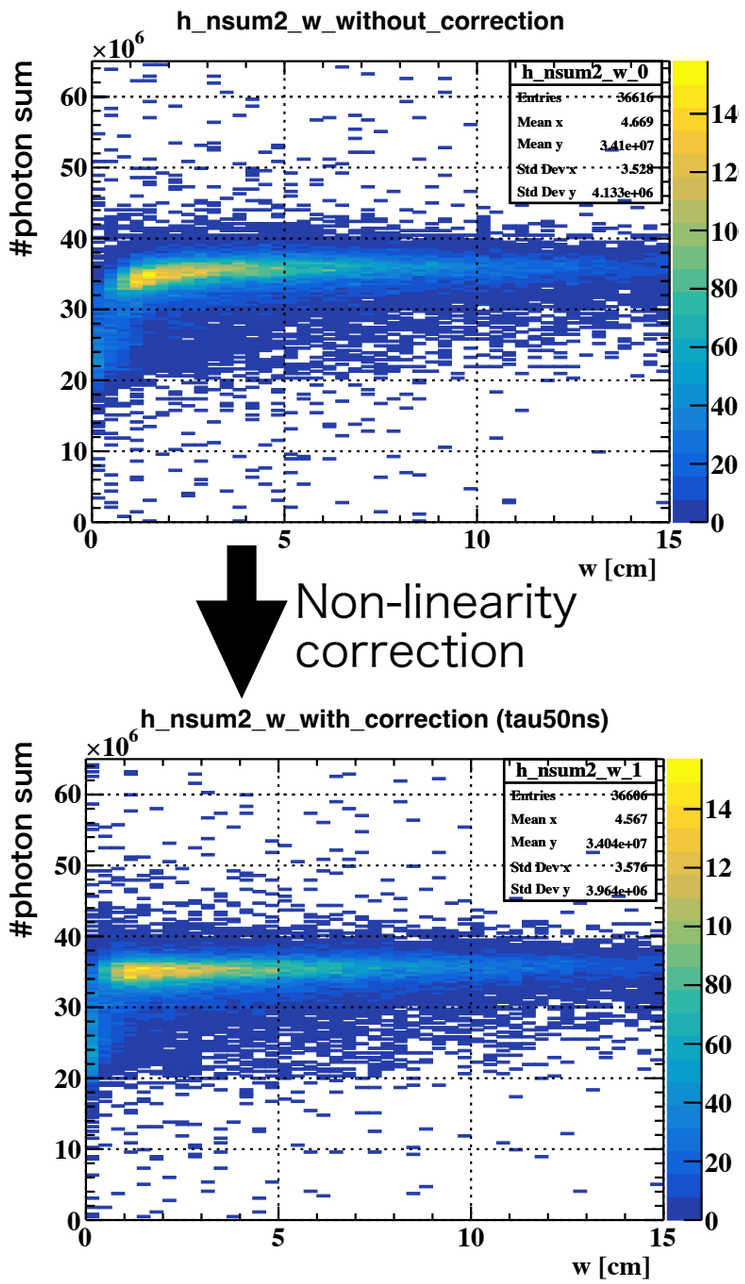
Saturation curve is calculated for **each sensor**



- (model : NIM A Volume 1064, July 2024, 169431)

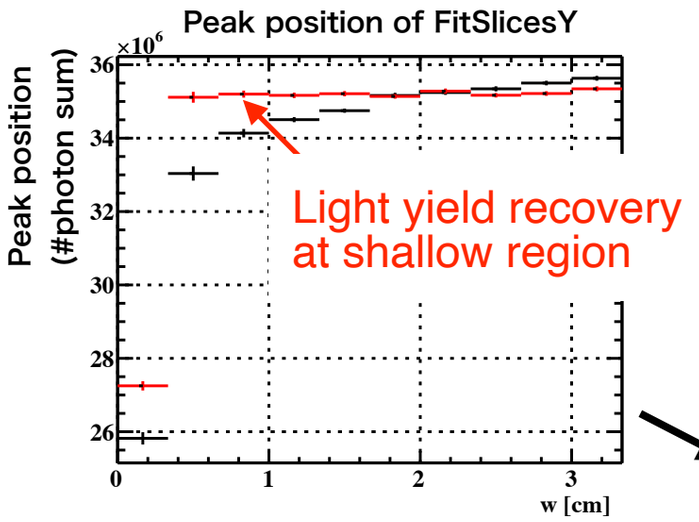
Improvement of #photon reconstruction

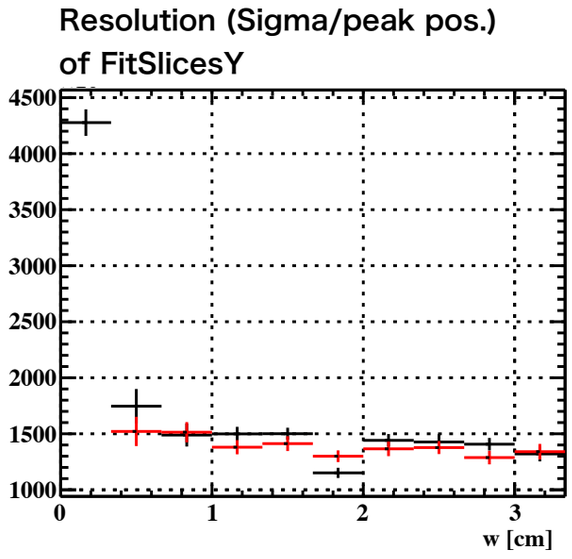
- Evaluation of the improvement by non-linearity correction
  - Light yield recovery at shallow region is seen -> correction works as intended
  - But for resolution improvement is almost not observed
    - Non-linear response may not be a main cause of worse resolution

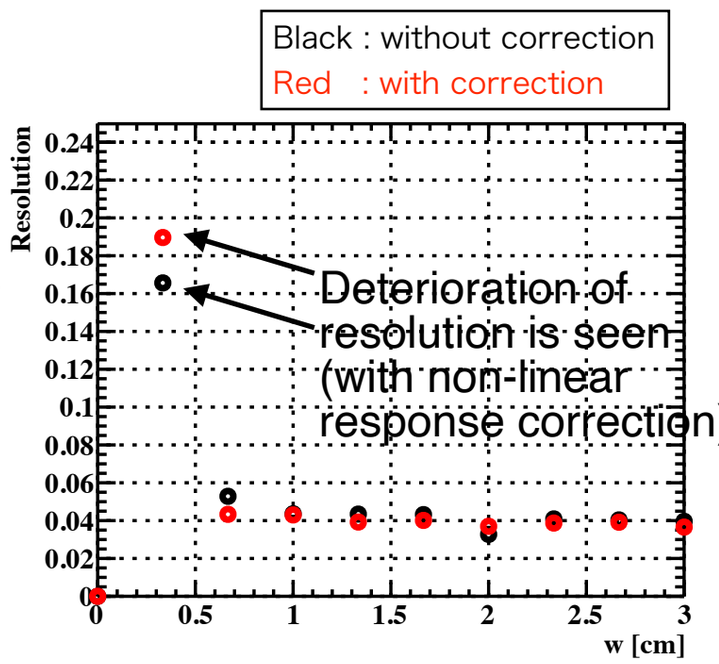


Non-linearity correction

FitSlices







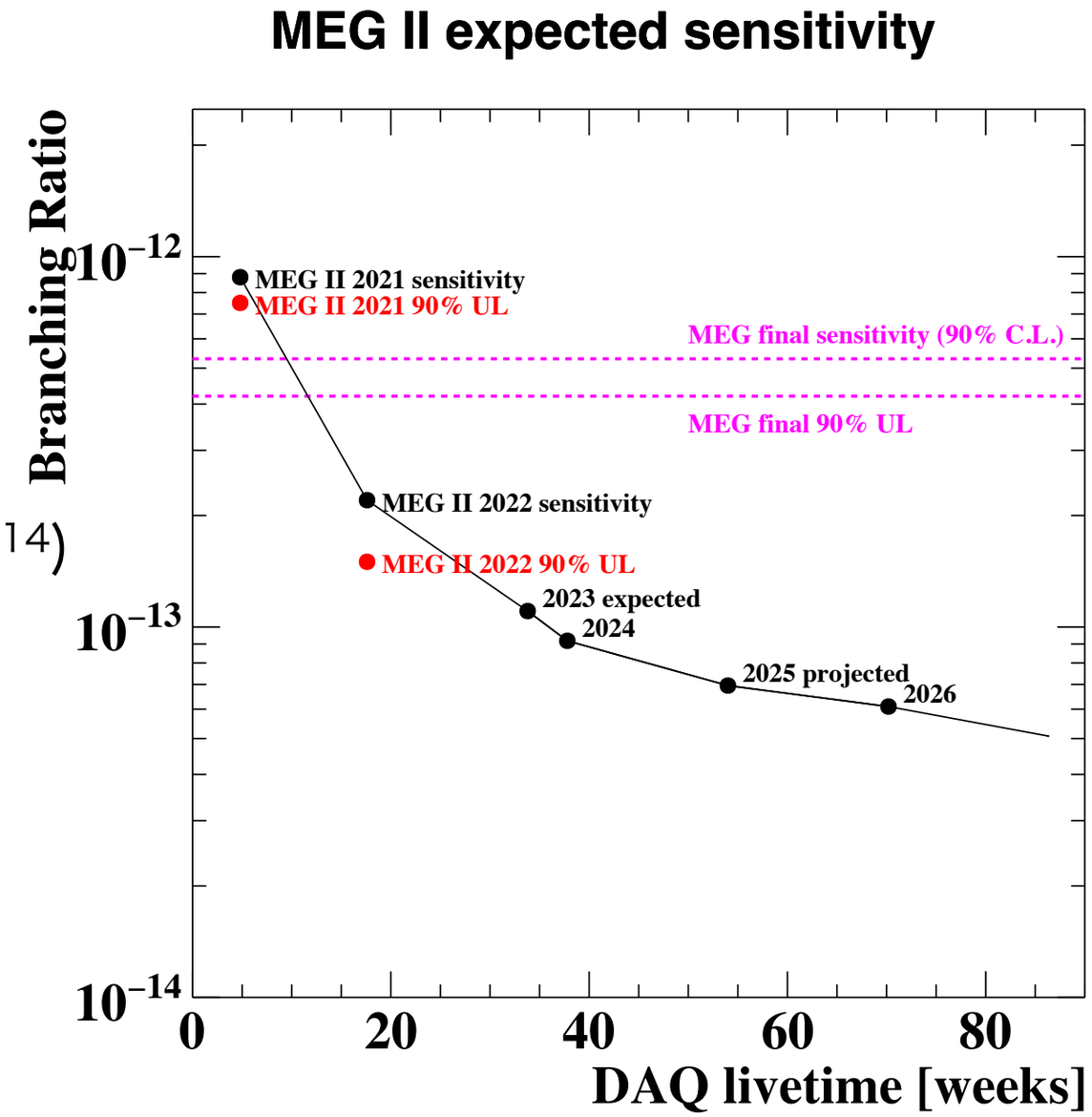
Summary and Prospect of sensitivity

- MEG II experiment started to take physics data since 2021
  - will continue by the end of 2026
- Latest result : Br($\mu^+ \to e^+\gamma$) : 1.5×10^{-13} (90% C.L.) using 2021+2022 data

- 2023 data :
  - Analysis is ongoing
    - Energy reconstruction : done
      - Non-uniformity correction
      - Energy scale history
    - + trial to improve the resolution
      - Non-linear response correction
  - sensitivity prospect : almost reach O(10^{-14})

-> aim to reach the final sensitivity :

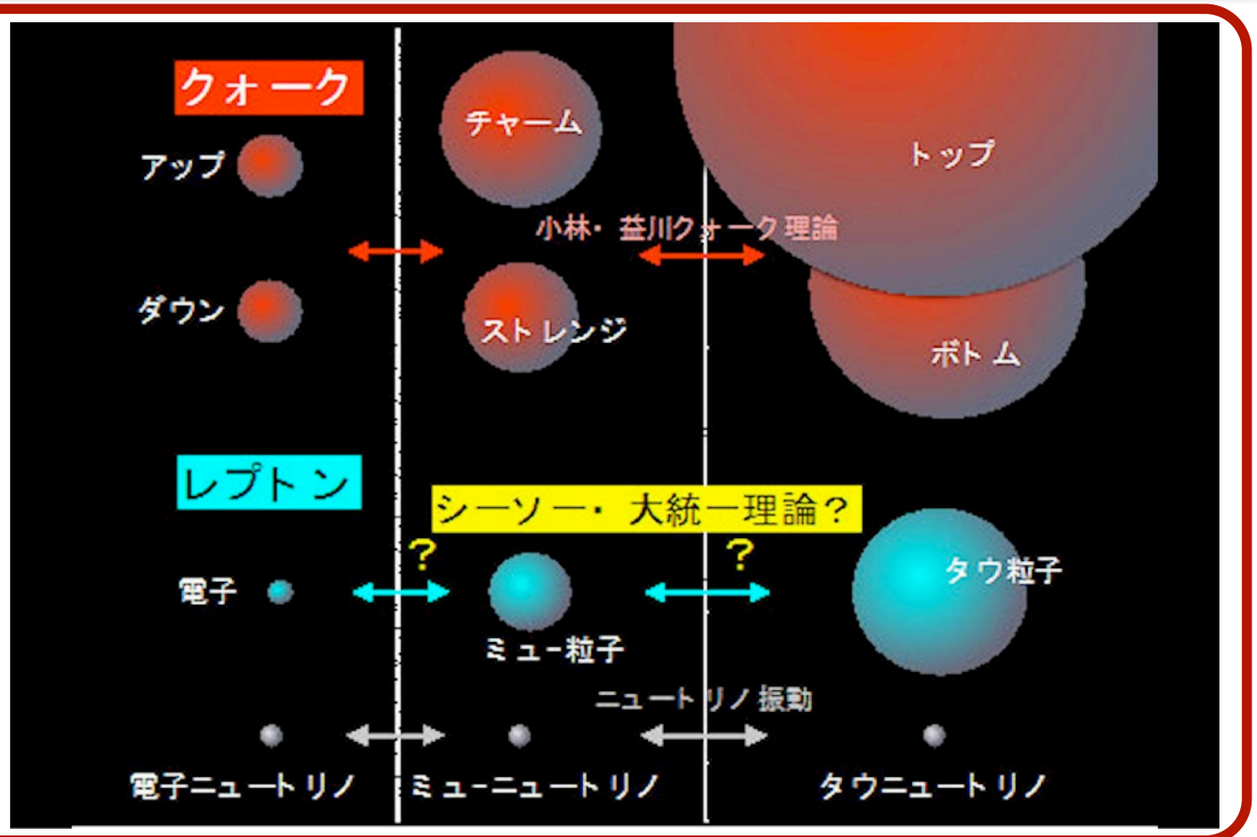
$(5\text{-}6)\times10^{-14}$



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

- In the Standard Model, it is practically prohibited : $Br(\mu \rightarrow e\gamma) = 10^{-54}$
- In BSM, $Br(\mu \rightarrow e\gamma) \sim O(10^{-14})$ is predicted (not observed yet)

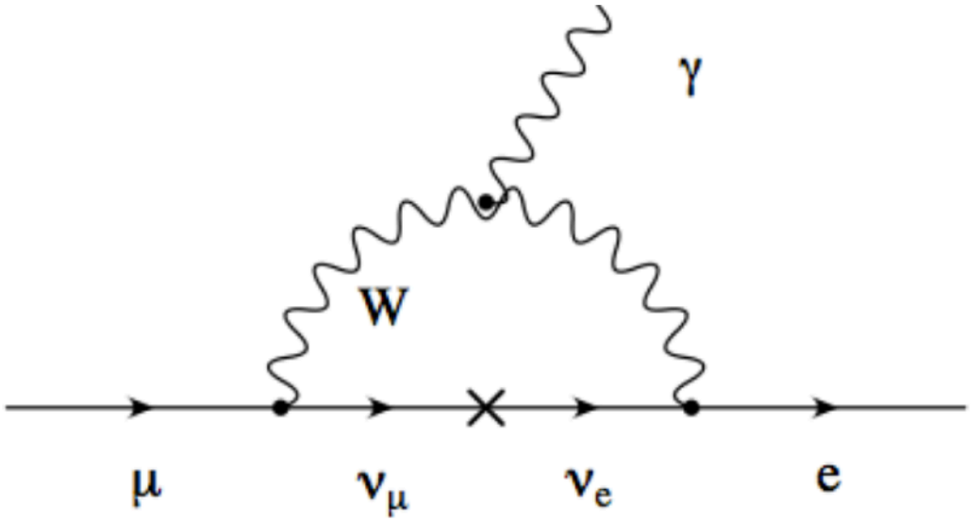
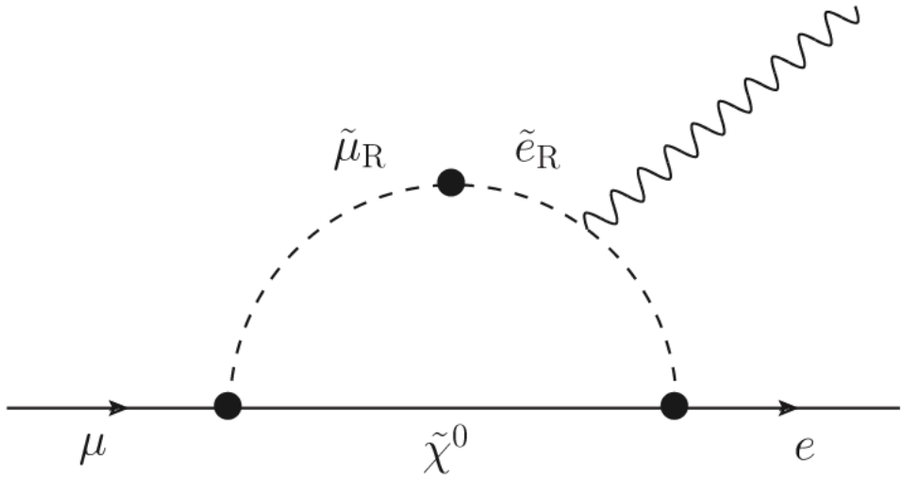


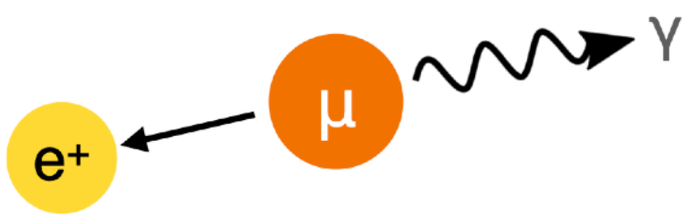
Diagram in the SM + neutrino oscillation



Possible diagram in SUSY-GUT senario

MEG II experiment : signal and background

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

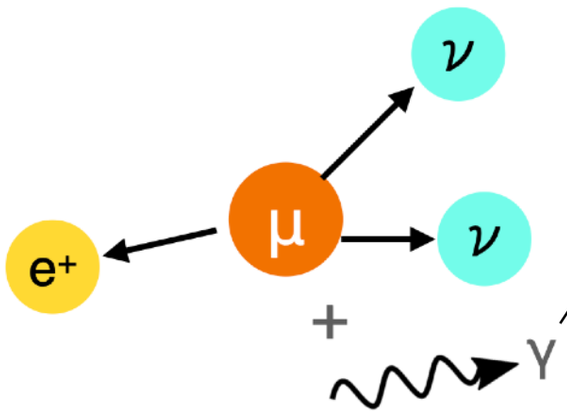


back-to-back

on-timing

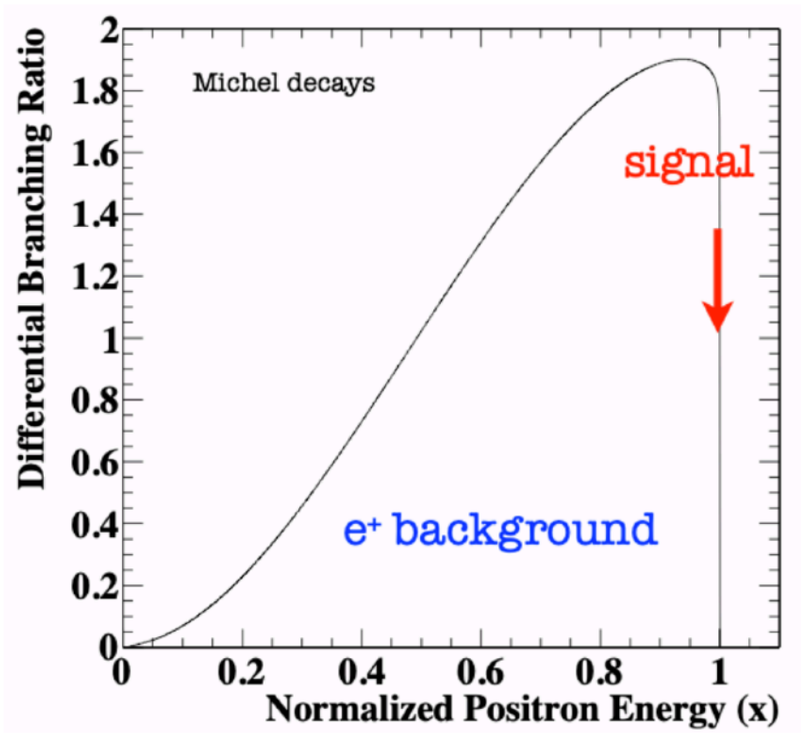
$$N_{sig} \propto R_\mu \times T \times \mathrm{Efficiency}$$

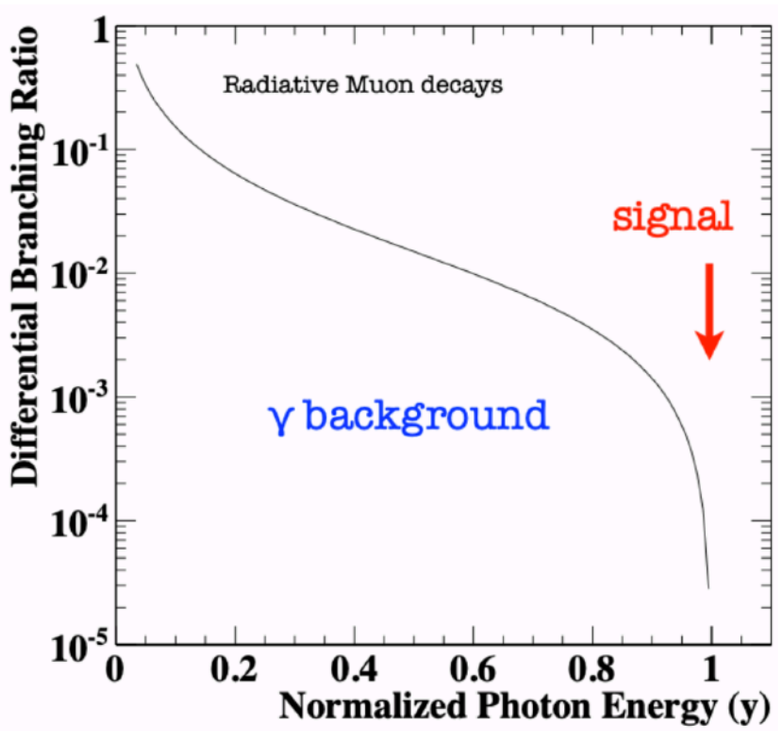
- Dominant background : Accidental coincidence of Michel positron and gamma



Gamma originated from
- Annihilation in flight
- Radiative muon decay

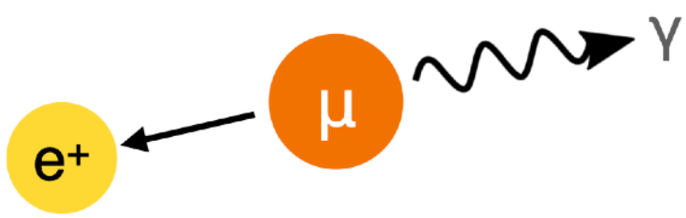
$$N_{acc} \propto \underbrace{R_\mu^2}_{\text{beam rate}} \times \underbrace{T}_{\text{time}} \times \underbrace{\Delta E_\gamma^2 \times \Delta E_e \times \Delta\Theta_{e\gamma}^2 \times \Delta T_{e\gamma}}_{\text{Resolutions}}$$





MEG II experiment : signal and background

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



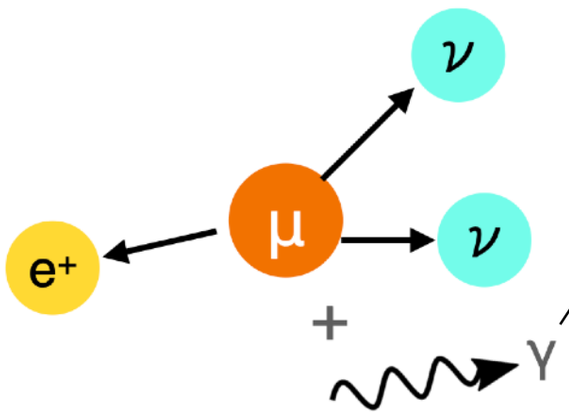
back-to-back

on-timing

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

High intensity continuous beam is preferred

- Dominant backgrou positron and gamma

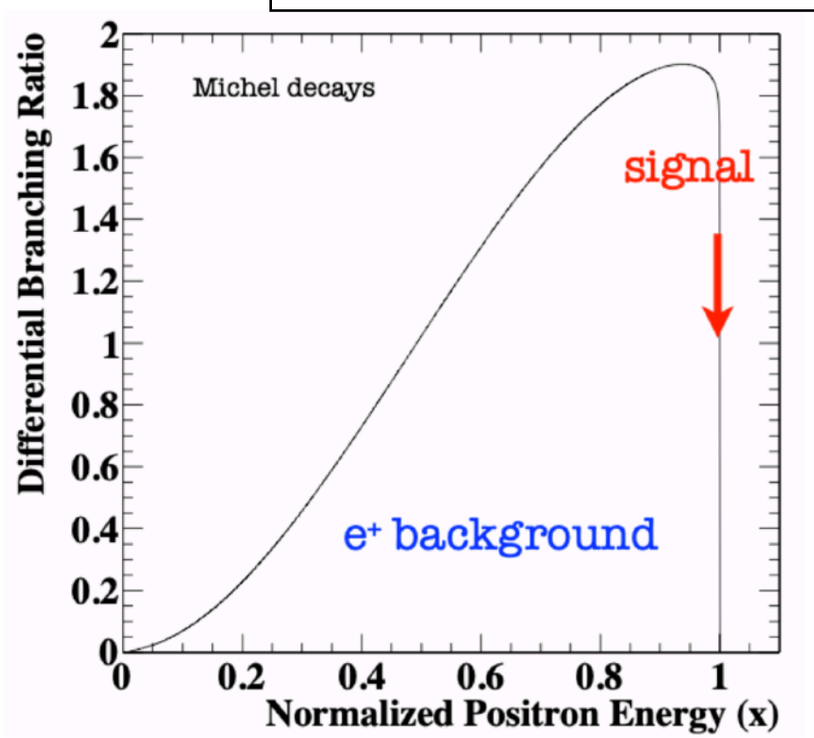


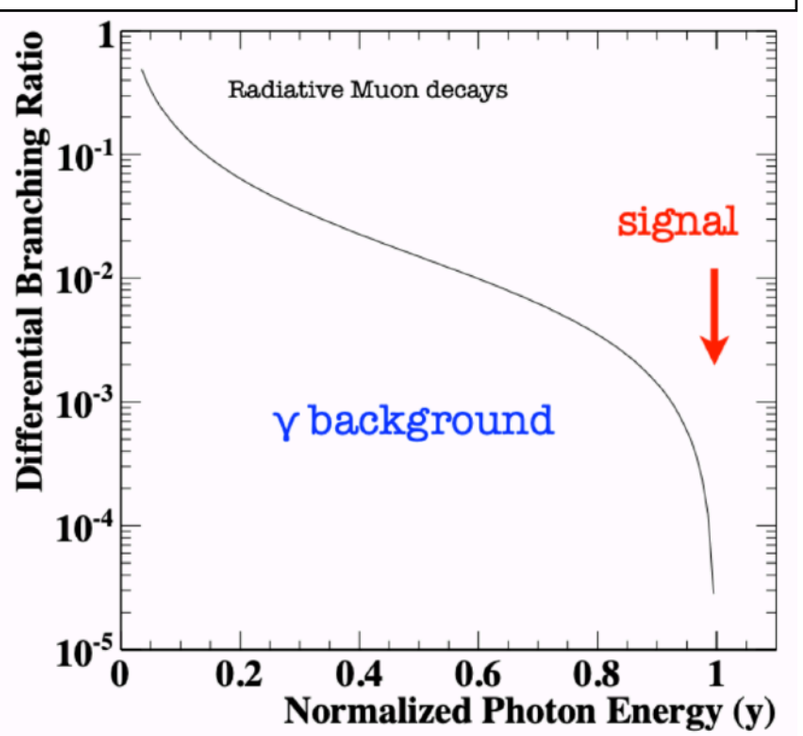
Gamma originated from
- Annihilation in flight
- Radiative muon decay

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

beam rate, time, Resolutions

Detector with good resolutions is key to reduce BGs



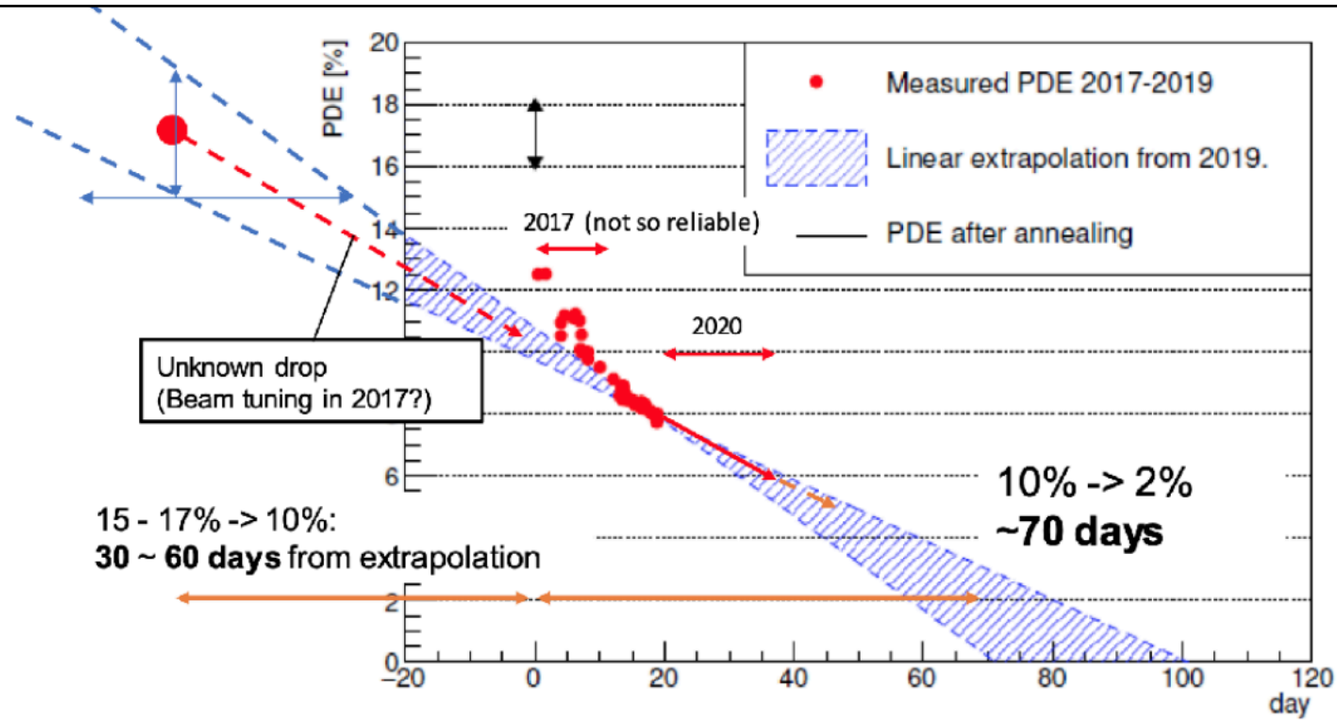


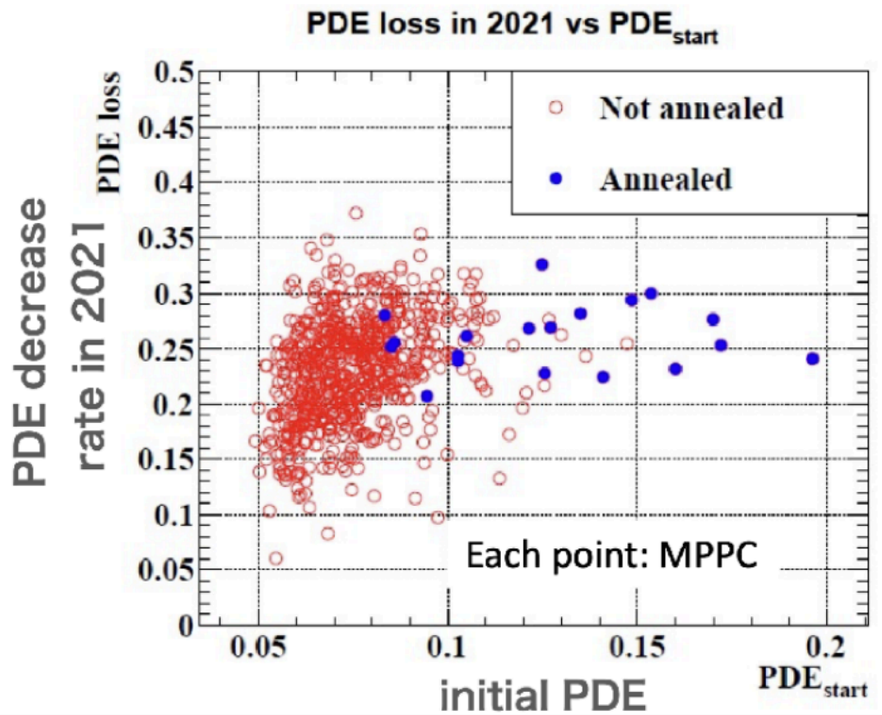
PDE decrease

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

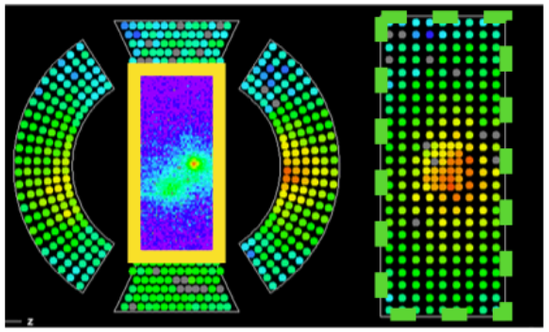




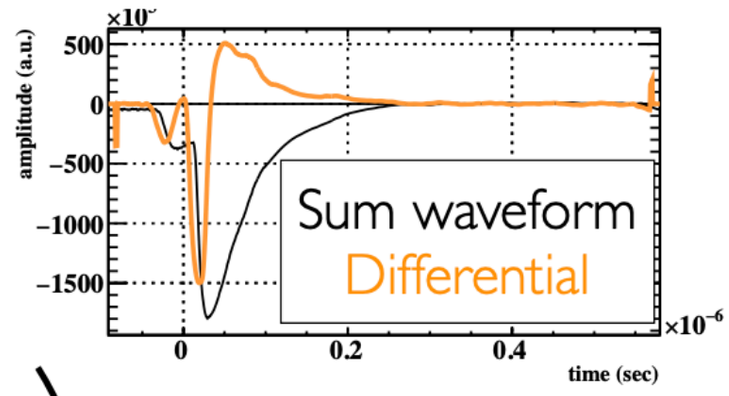
Pileup rejection update in the liquid xenon detector

- 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

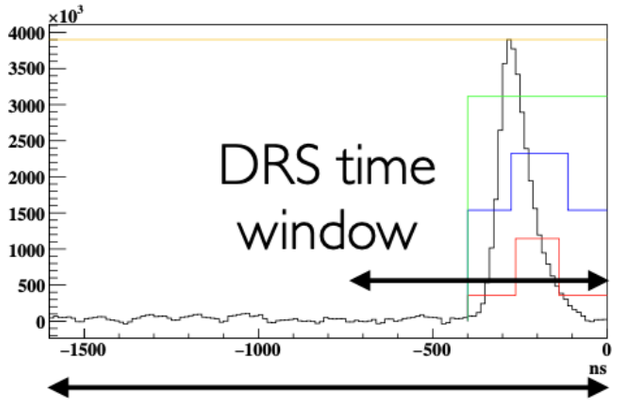


PMT differential waveform



newly implemented

FADC waveform for trigger



Inputs to template fit

Template waveform fit