MEG II実験での$\mu \to e\gamma$探索解析の現状

ーガンマ線再構成の改良と2022年データ解析の見通しー

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他MEG IIコラボレーション

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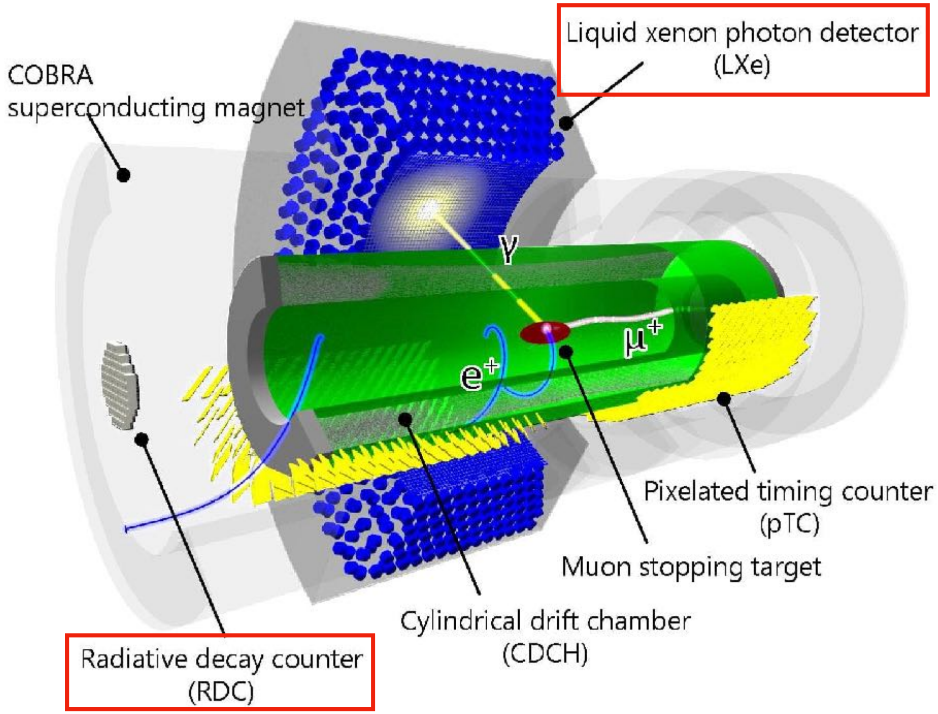
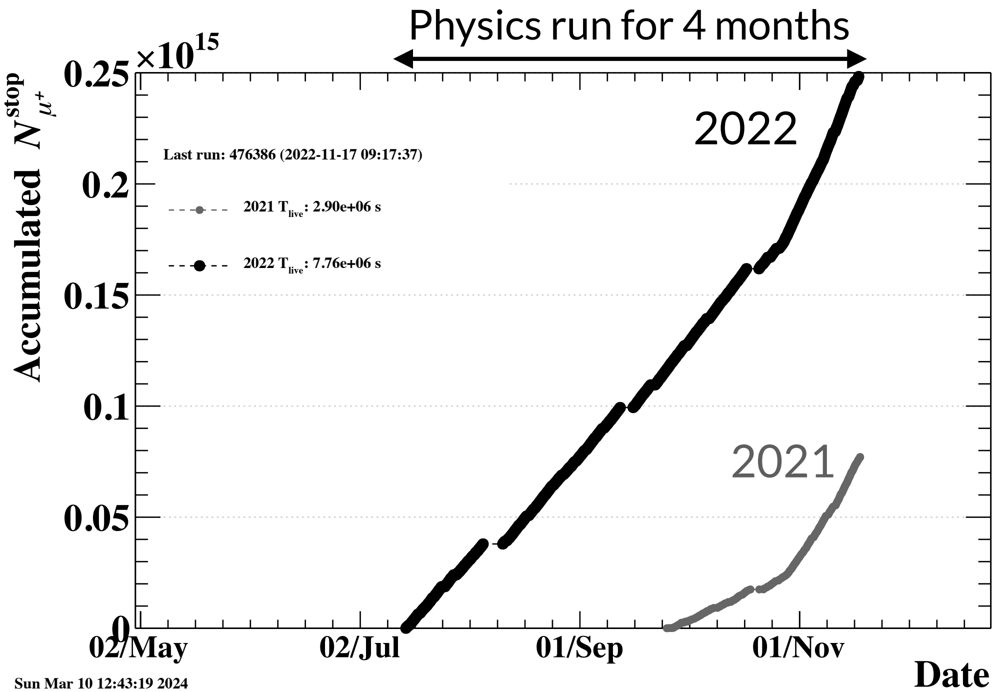
日本物理学会2024年春季大会

18aT2-7

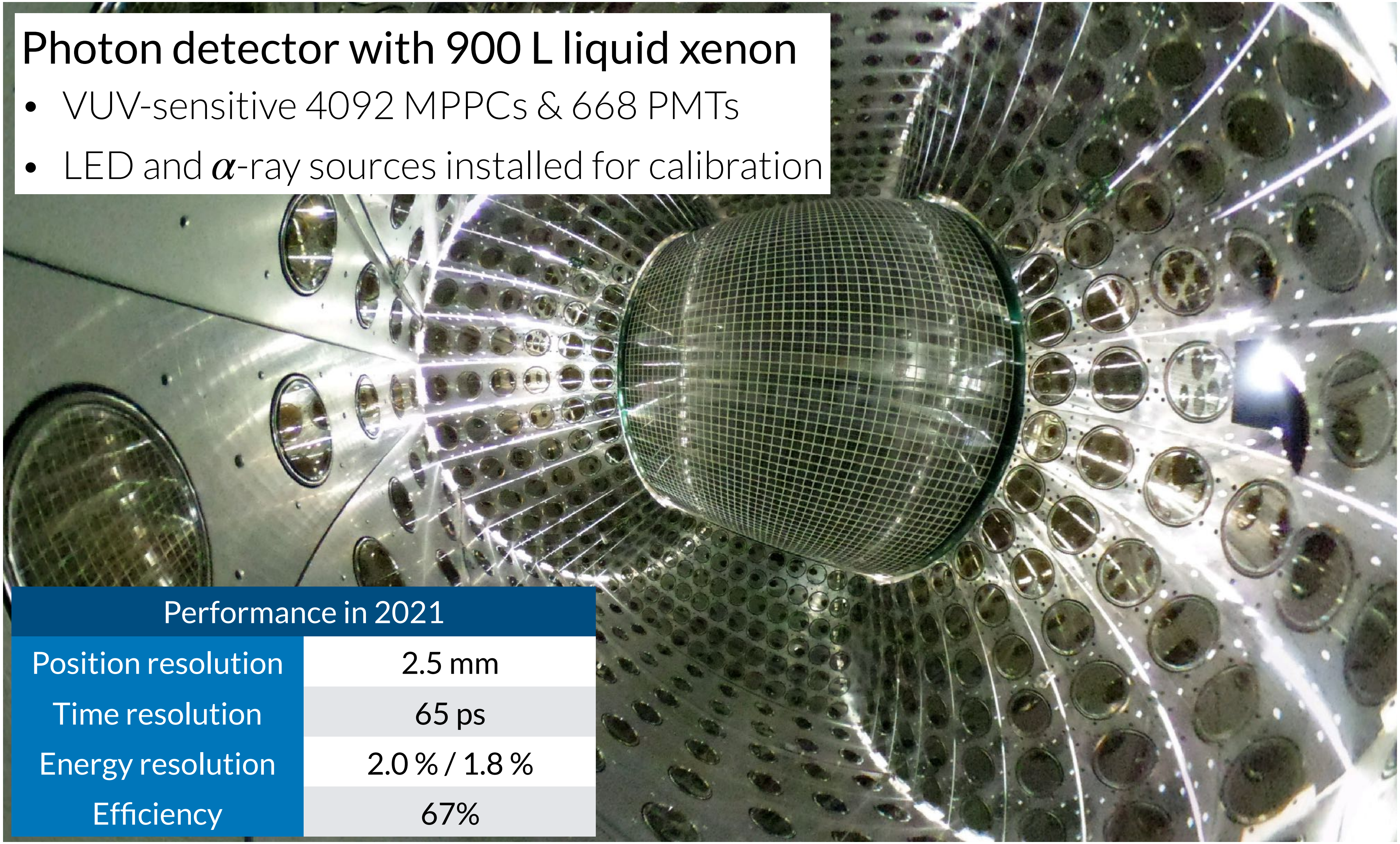
$\mu \to e\gamma$ search in MEG II

- MEG II experiment in a search of $\mu \to e\gamma$ started physics run in 2021
  - $BR < 7.5 \times 10^{-13}$ (90% C.L.) with the 2021 dataset
  - Target sensitivity: 6×10^{-14}





LXe photon detector

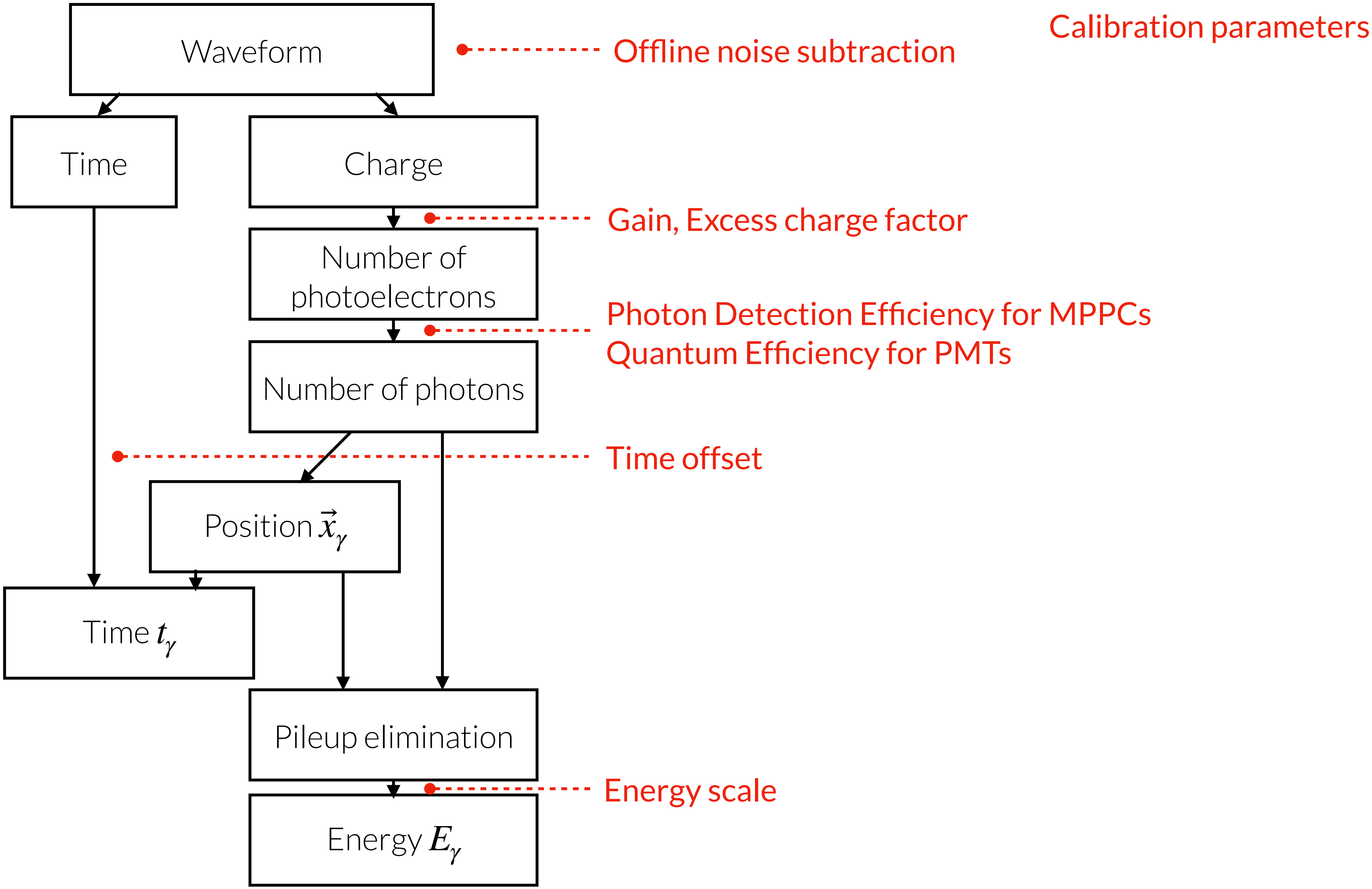


Photon detector with 900 L liquid xenon

- VUV-sensitive 4092 MPPCs & 668 PMTs
- LED and α-ray sources installed for calibration

Performance in 2021	
Position resolution	2.5 mm
Time resolution	65 ps
Energy resolution	2.0 % / 1.8 %
Efficiency	67%

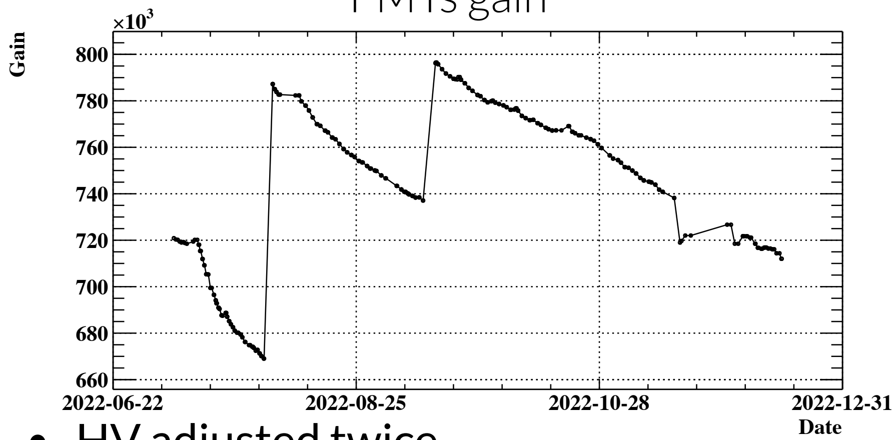
Photon reconstruction in LXe



LXe photosensor calibration

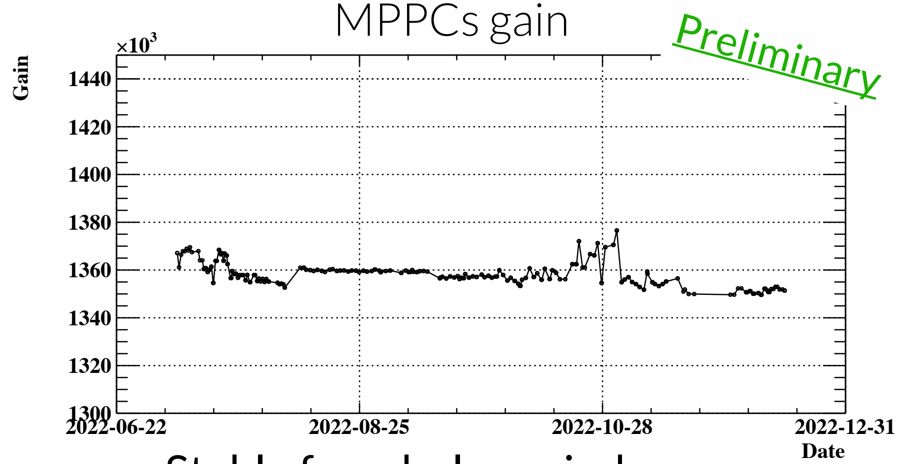
- WIP; To be completed in a month

PMTs gain



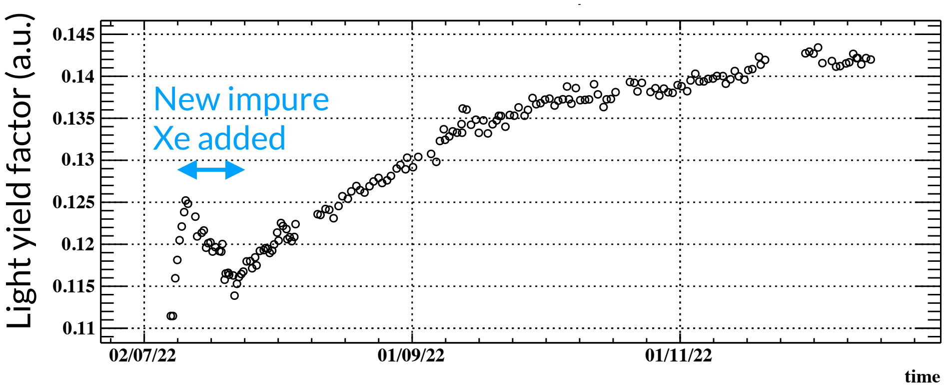
- HV adjusted twice
- Gain decreased due to radiation damage

MPPCs gain



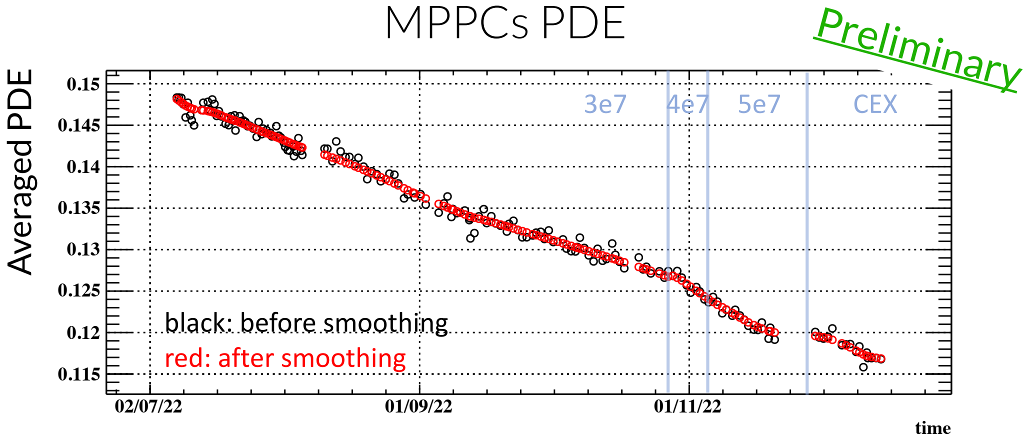
- Stable for whole period

Light yield



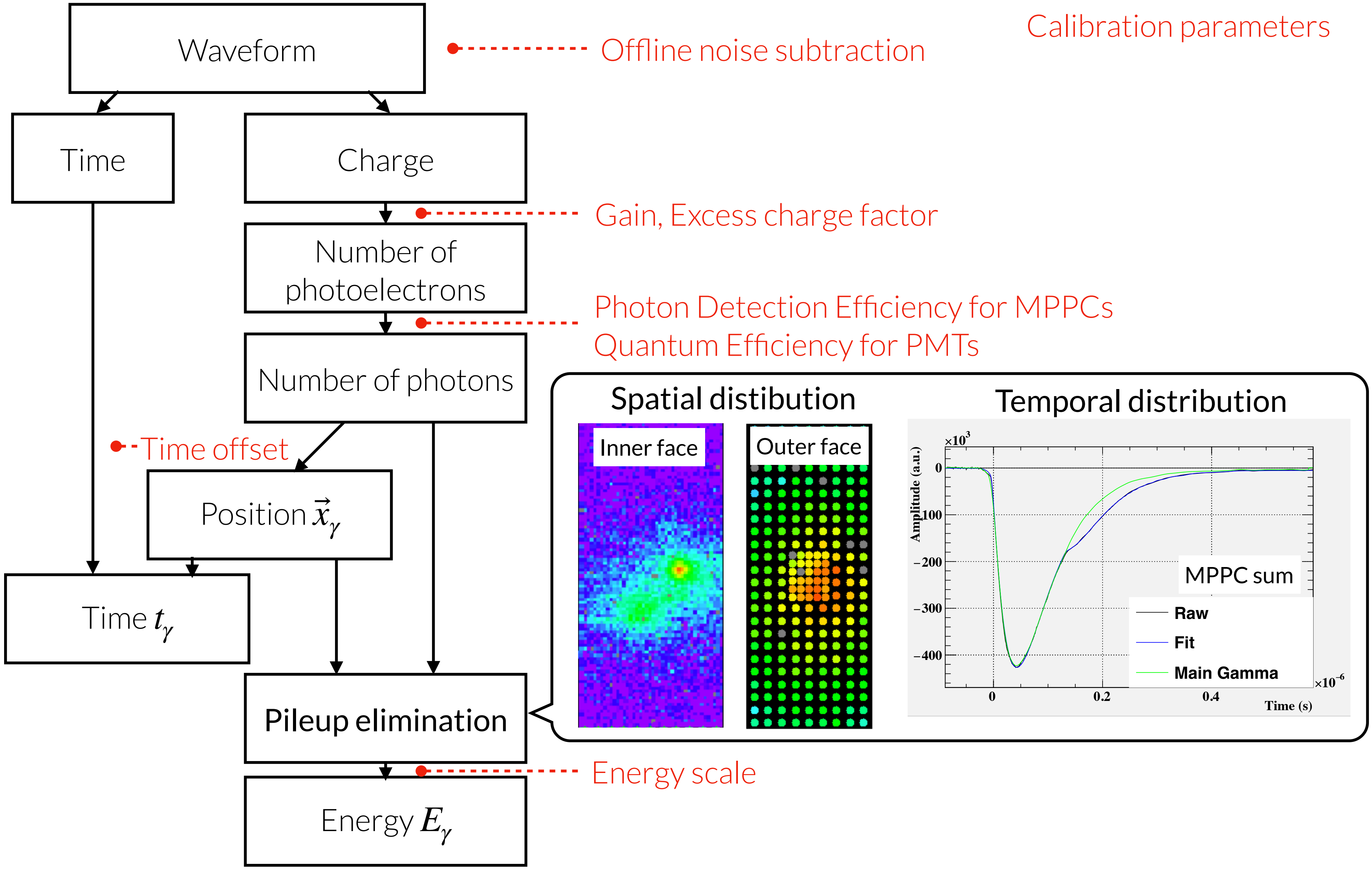
- LXe purification in parallel with DAQ

MPPCs PDE



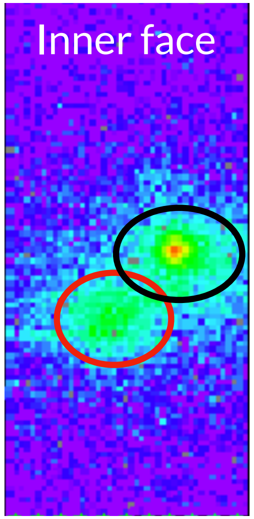
- PDE decreased due to radiation damage
  - Lab. test to be presented by R. Umakoshi (18pT3-7)

Photon reconstruction in LXe

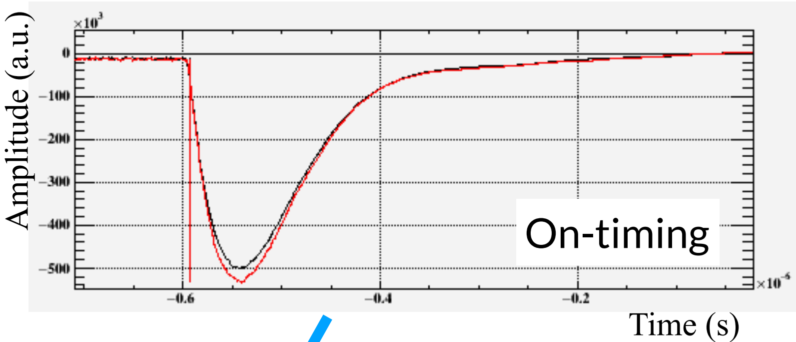


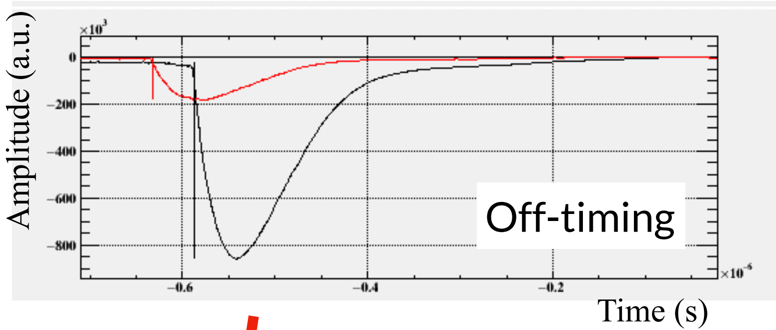
BG γ source & pileup analysis

Spatial distribution

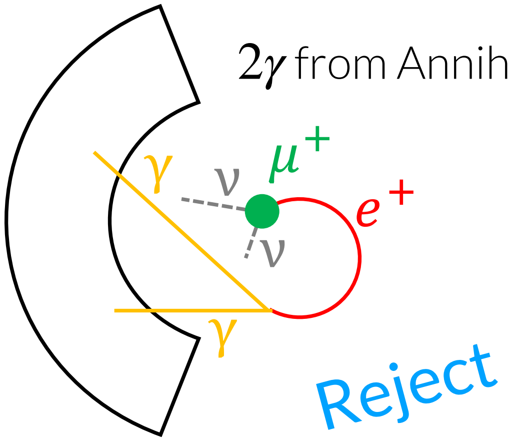


Temporal distribution

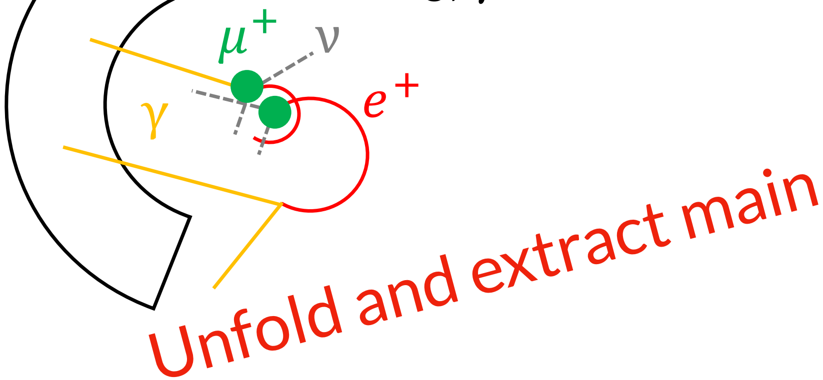




2γ from Annihilation In Flight



AIF 1γ / Radiative decay / Signal
+ low-energy γ

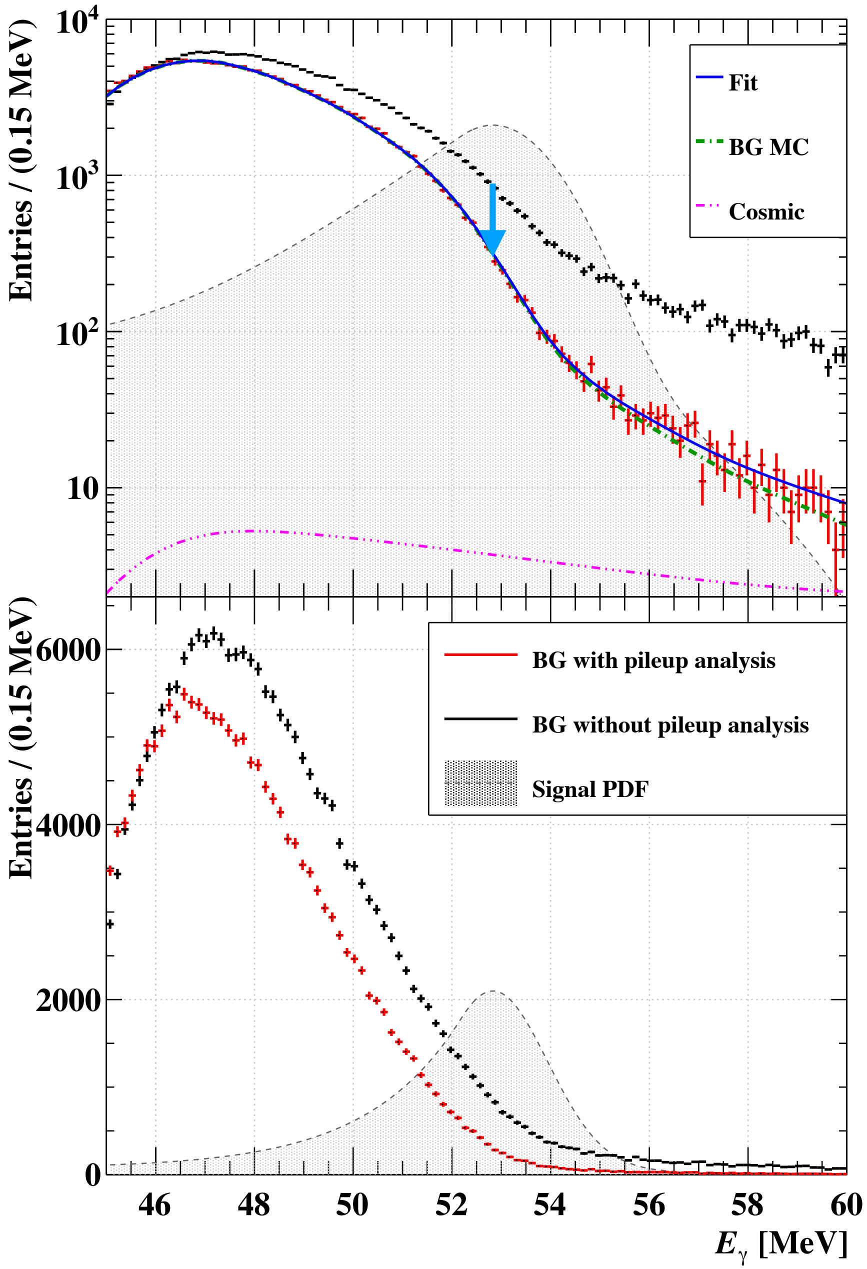


Pileup analysis in 2021

- Performance in 2021
  - 35% BG reduction at $5 \times 10^7\ \mu/s$
  - 92% signal efficiency
    - Inefficiency comes from
      - Fake peak in spatial distribution
      - **Waveform fitting failure**

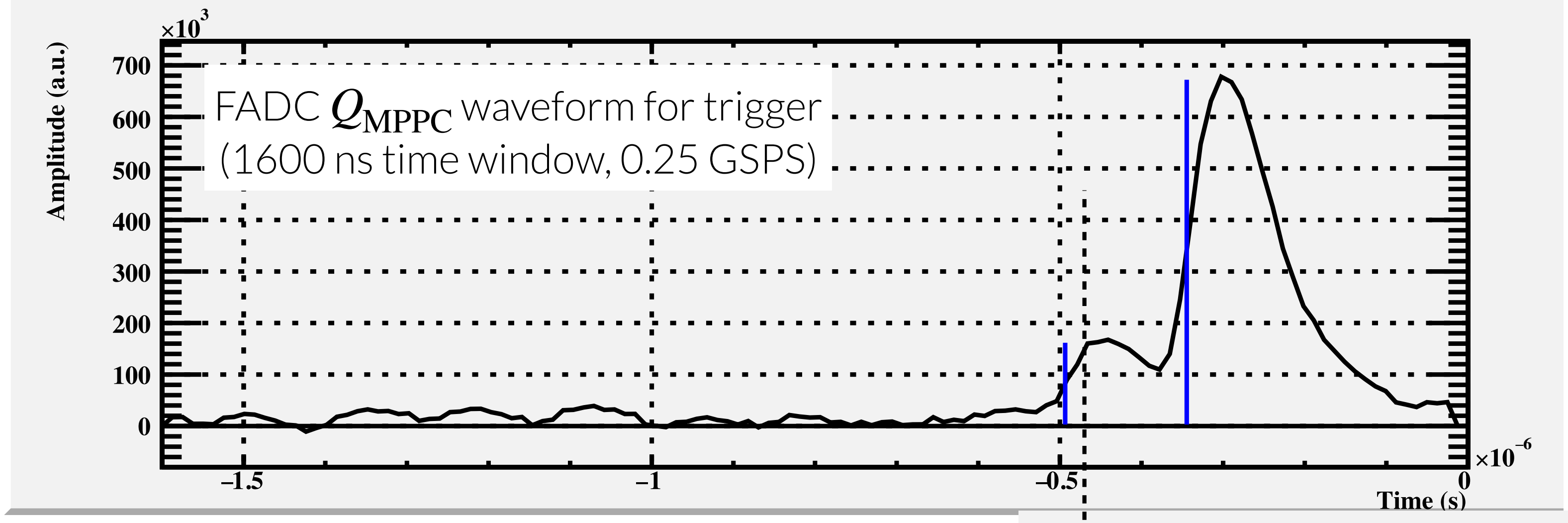
- Before unblinding, **some pileup-missed events found**

➡ Update pileup analysis

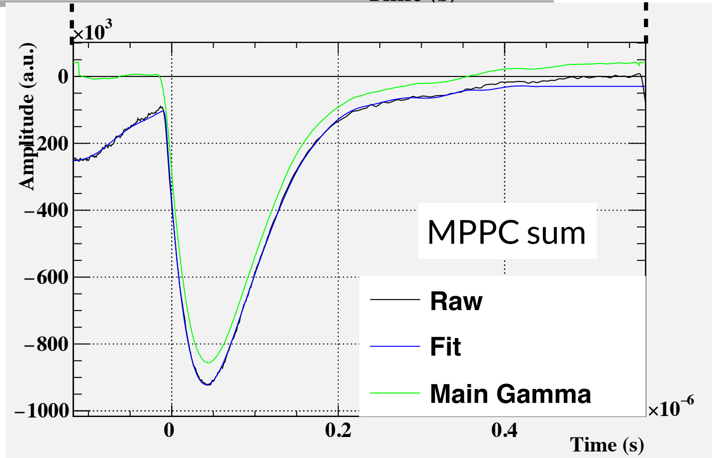


Pre-timing pulse detection

- **FADC waveform for trigger newly introduced to detect pre-timing pulse**
  - 1600 ns time window



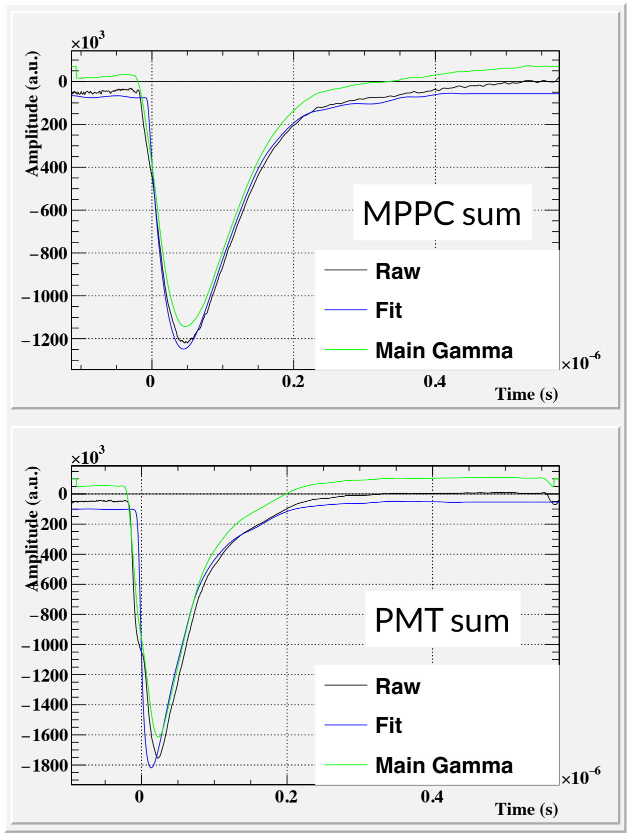
DRS waveform
(~700 ns time window, 1.4 GSPS)

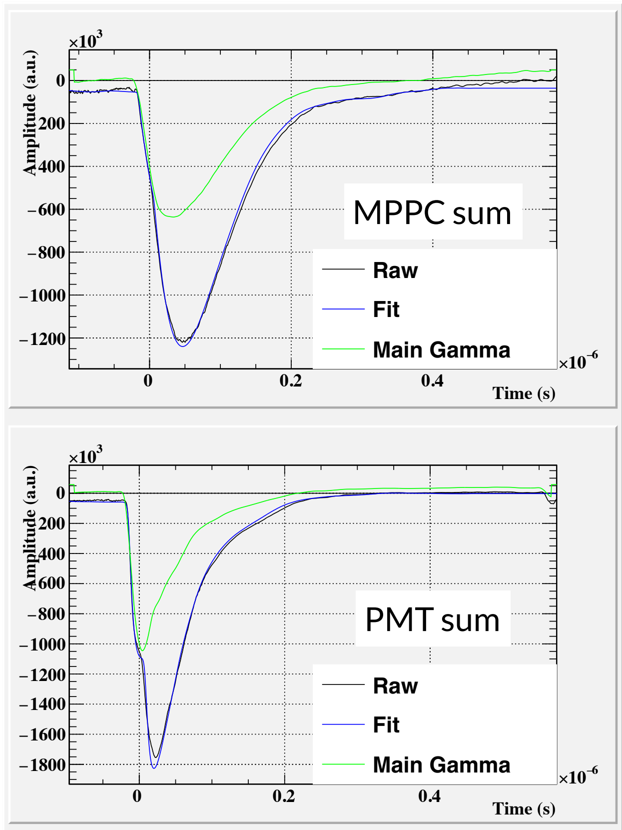


Simultaneous fit with MPPC and PMT

- MPPC and PMT summed waveforms fitted independently so far
- PMT waveform sharper than that of MPPC

➡ **Better time determination by simultaneous fit**





Pileup analysis performance

- **Minimise both signal inefficiency and # background events**
- No clear performance improvement observed with 2021 data & MC
  - (Analysis reliability improved)

➡ **Further data-driven studies planned**

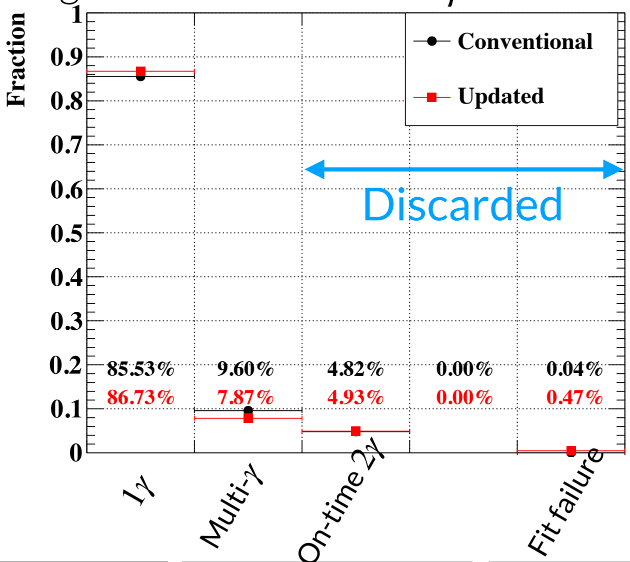
Signal inefficiency

- 4.9% vs 5.3%
- χ^2 underestimated in conventional method

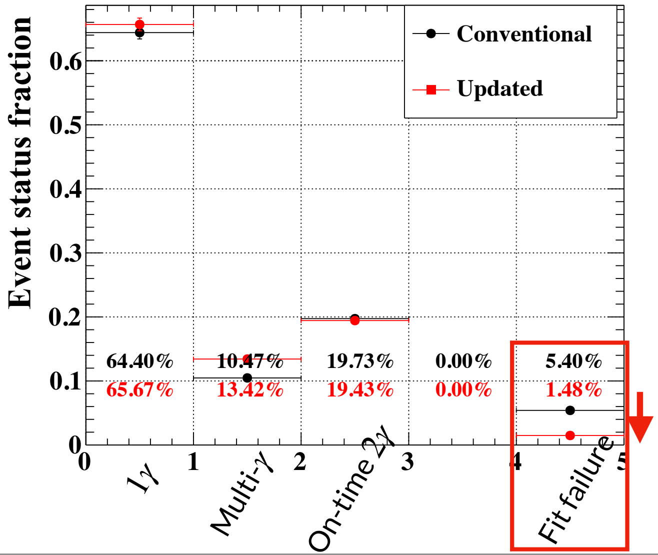
Background reduction

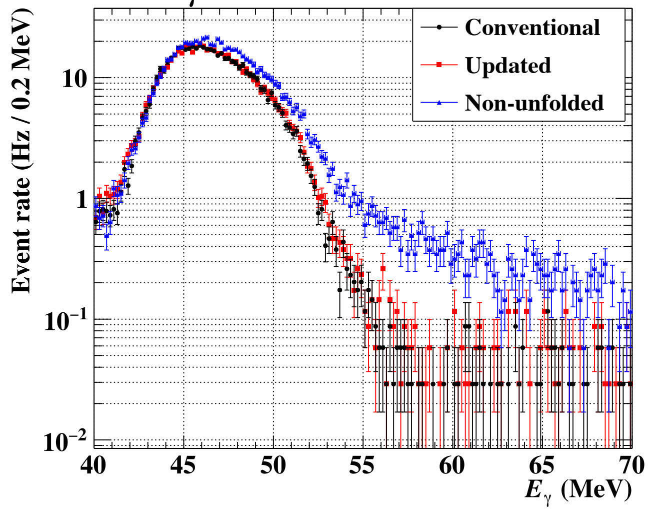
- Fitting-failed events reduced
- But, BG reduction (35%) and E_γ spectrum not improved
  - Main γ in fitting-failed events might have smaller energy than analysis region (48 MeV)

Signal MC with $3 \times 10^7\ \mu/s$ mixed



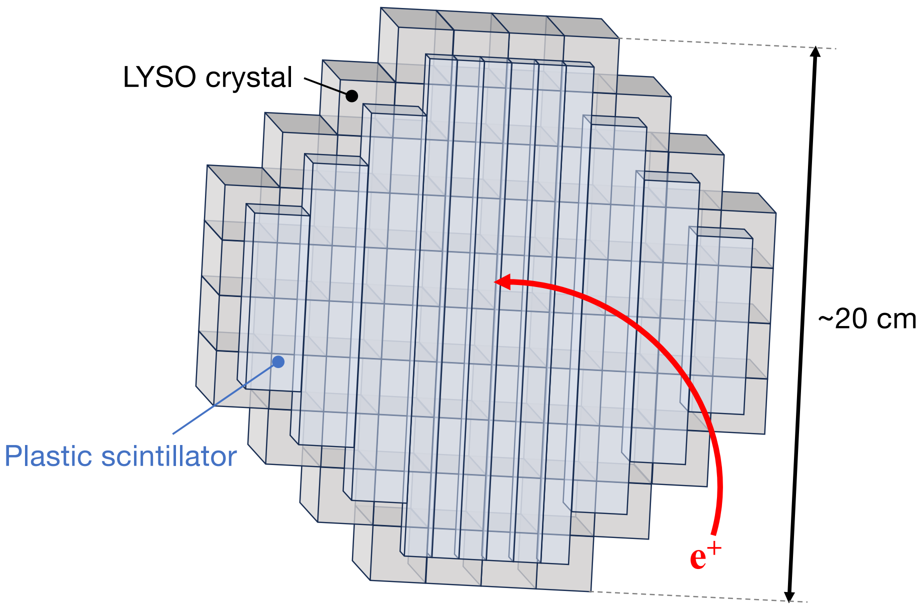
2021 non-physics data with E_γ trigger

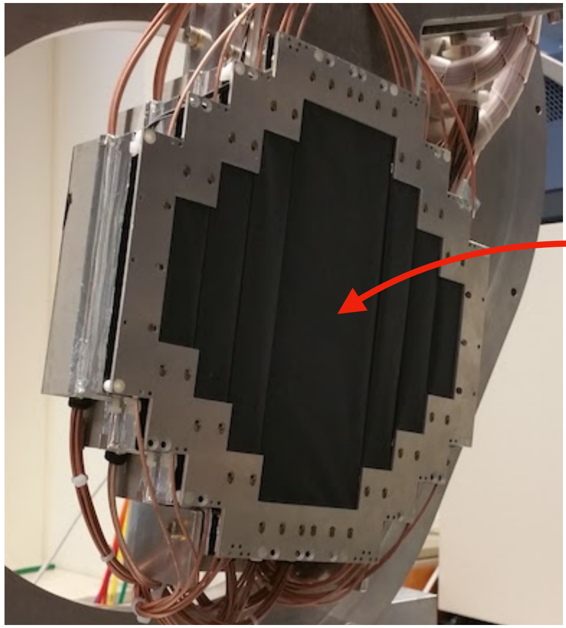


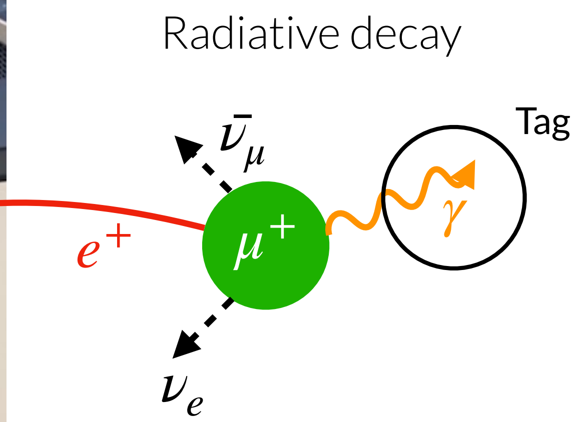


Radiative Decay Counter

- **Detect low-energy e from $\mu \rightarrow e\nu\nu\gamma$ to tag high-energy γ detected in LXe detector**
  - Distribute around beam axis due to magnetic field for spectrometer
- Hit reconstructed by
  - **Pulse detection from waveform**
  - Pulse clustering





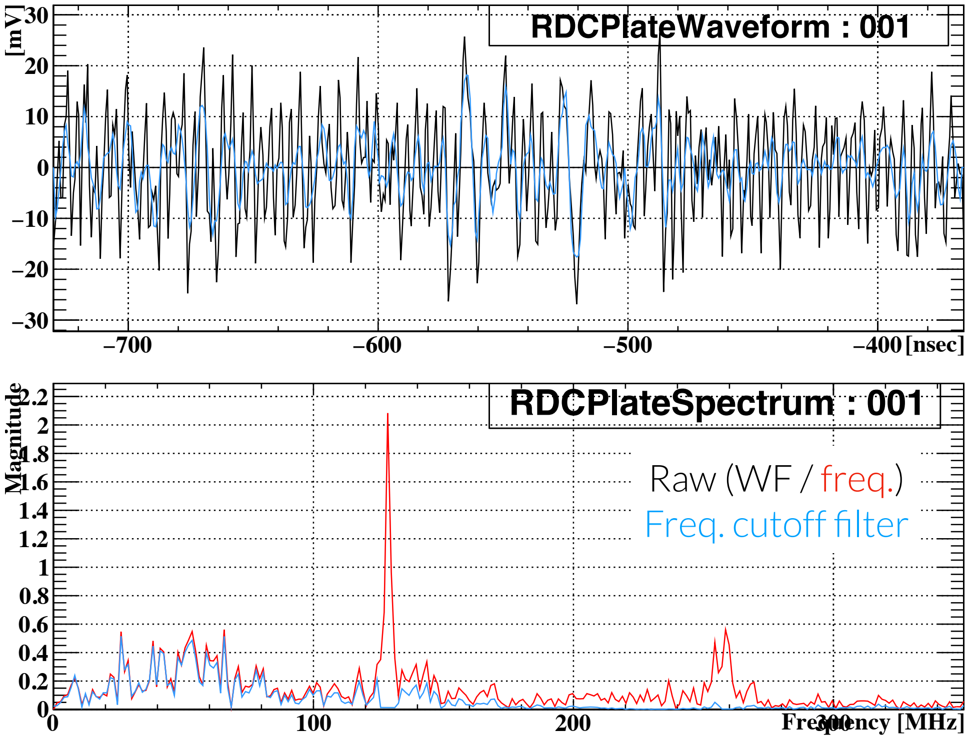


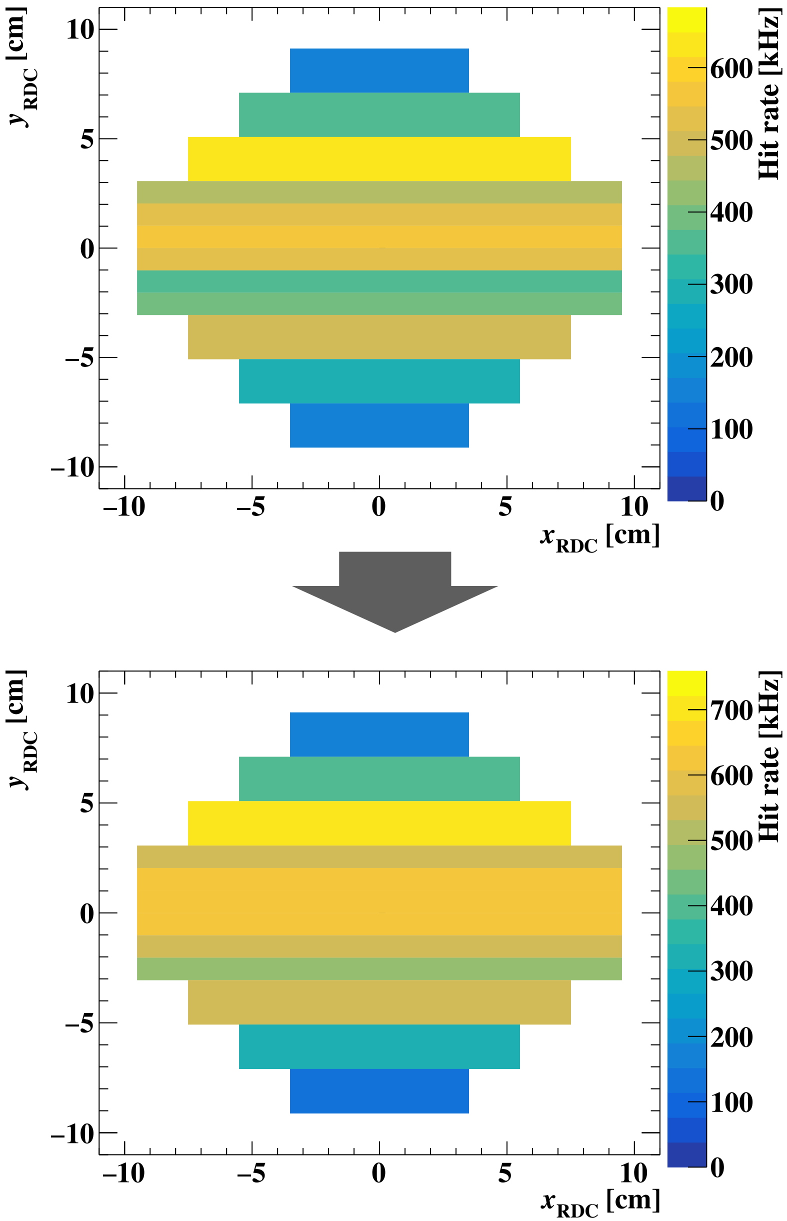
Pulse detection improvement

- Pulse search threshold was high to avoid reconstructing noise as ***e*** hit

➡ **Lower threshold by freq. cutoff filter**

➡ **Efficiency increased by 15%**

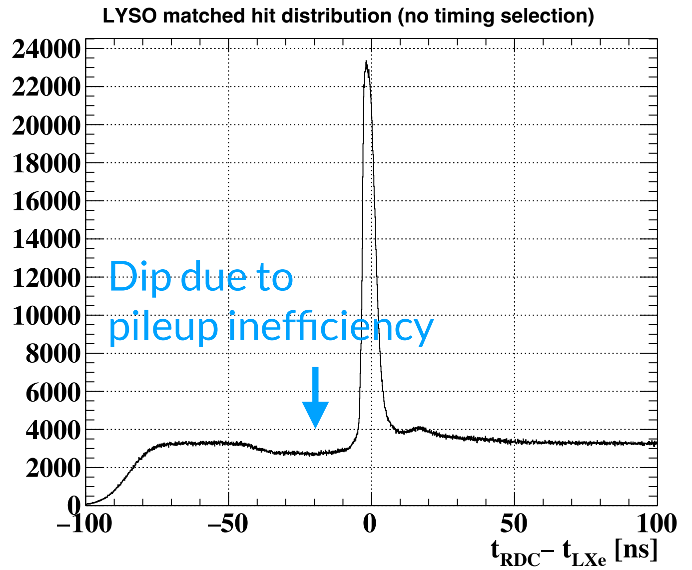


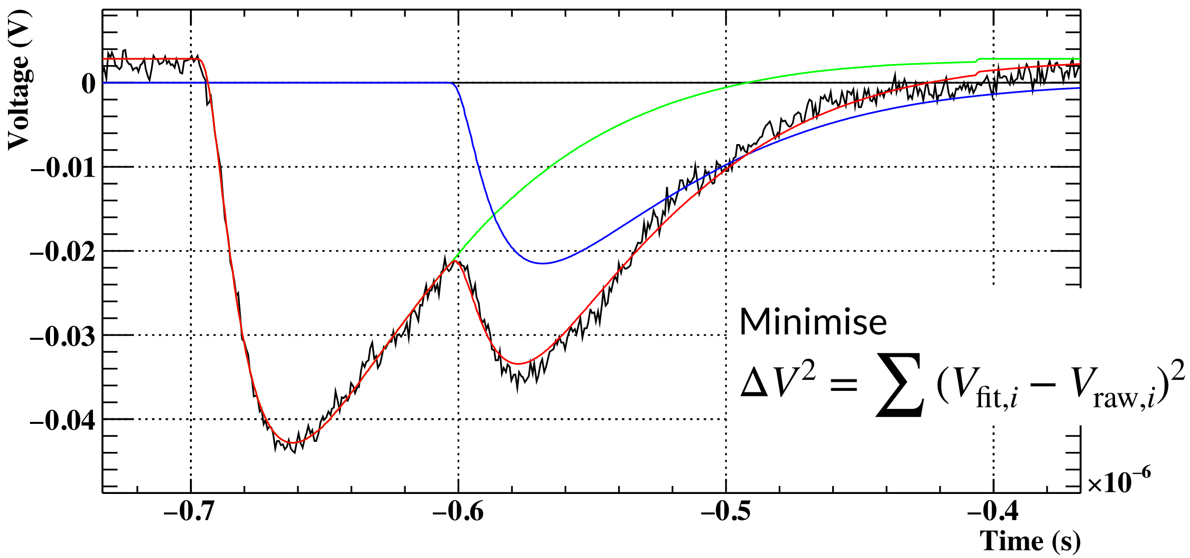


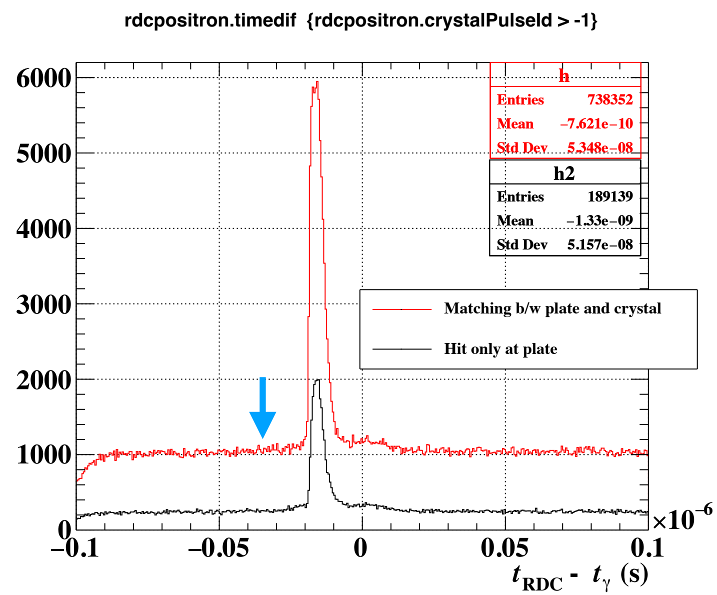
Template waveform fit for unfolding

- Template waveform fit introduced to reduce inefficiency due to pileup

➡ **Dip due to pileup inefficiency disappeared**





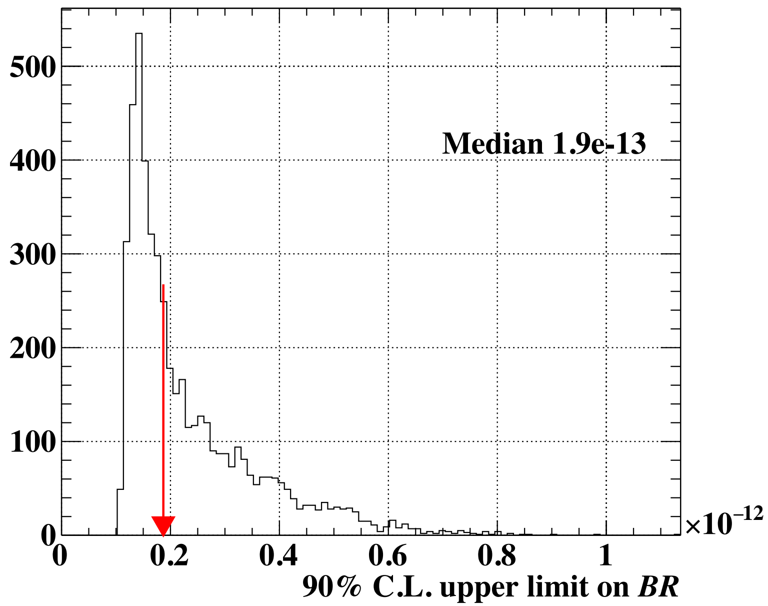


2021+2022 combined sensitivity

- Branching ratio $BR = N_{\mathrm{sig}}/k$
  - # effectively measured μ decays: $k_{2021+22} = 1.32 \times 10^{13}$
- Sensitivity S: Median 90% C.L. upper limits on BR for BG-only hypothesis
  - Median 90% C.L. upper limit on N_{sig}: 2.49

➡ $S_{2021+22} = 1.9 \times 10^{-13}$ (preliminary)

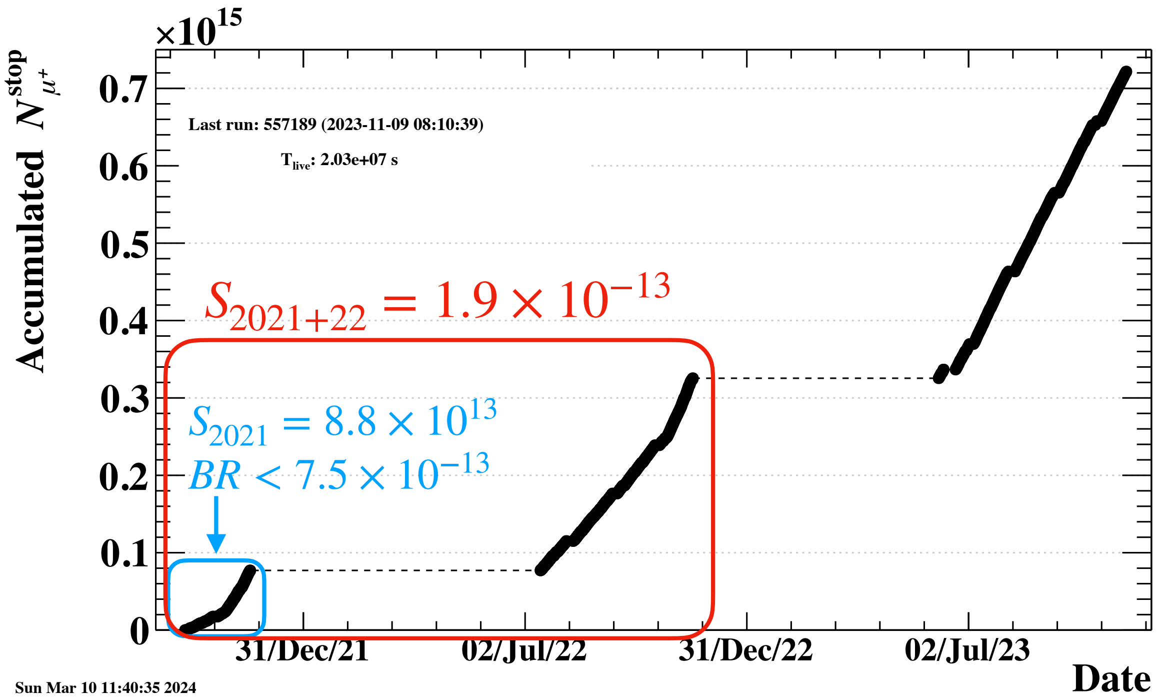
  - c.f. $S_{2021} = 8.8 \times 10^{-13}$
  - c.f. $S_{\mathrm{MEG}} = 5.3 \times 10^{-13}$



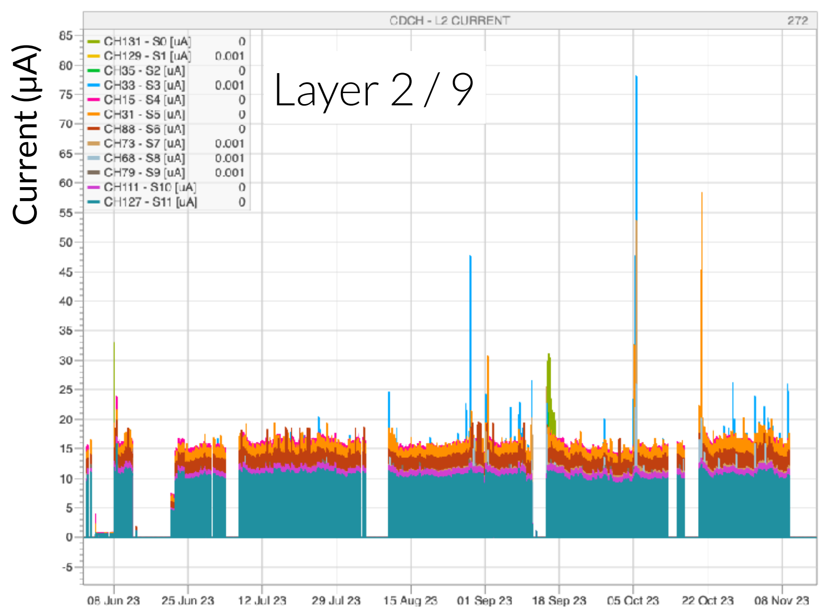
- Assume 2021 detector performance
  - Reconstruction updates not included
  - **Further sensitivity improvement expected**

2023 run

- Most successful physics-data-taking year
  - **1.6 times larger statistics** than the 2022 run
  - **Stable operation for all the detectors and targets**
    - LXe detector operation to be presented by S. Ban (18pT3-6)
  - **Beam intensity optimised to** $4 \times 10^7\ \mathrm{s}^{-1}$ to maximise the sensitivity
- 2023 data analysis gets started

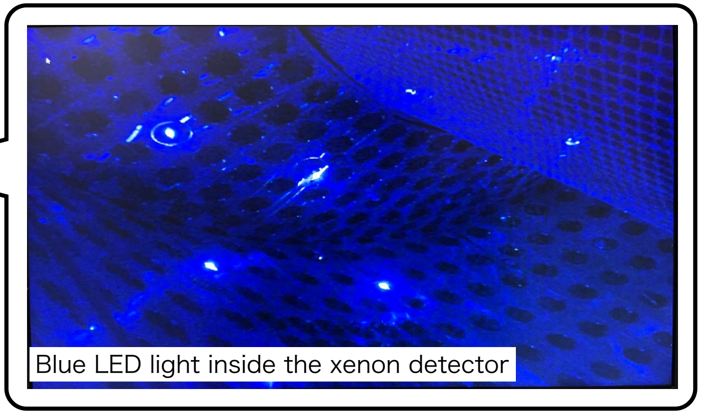


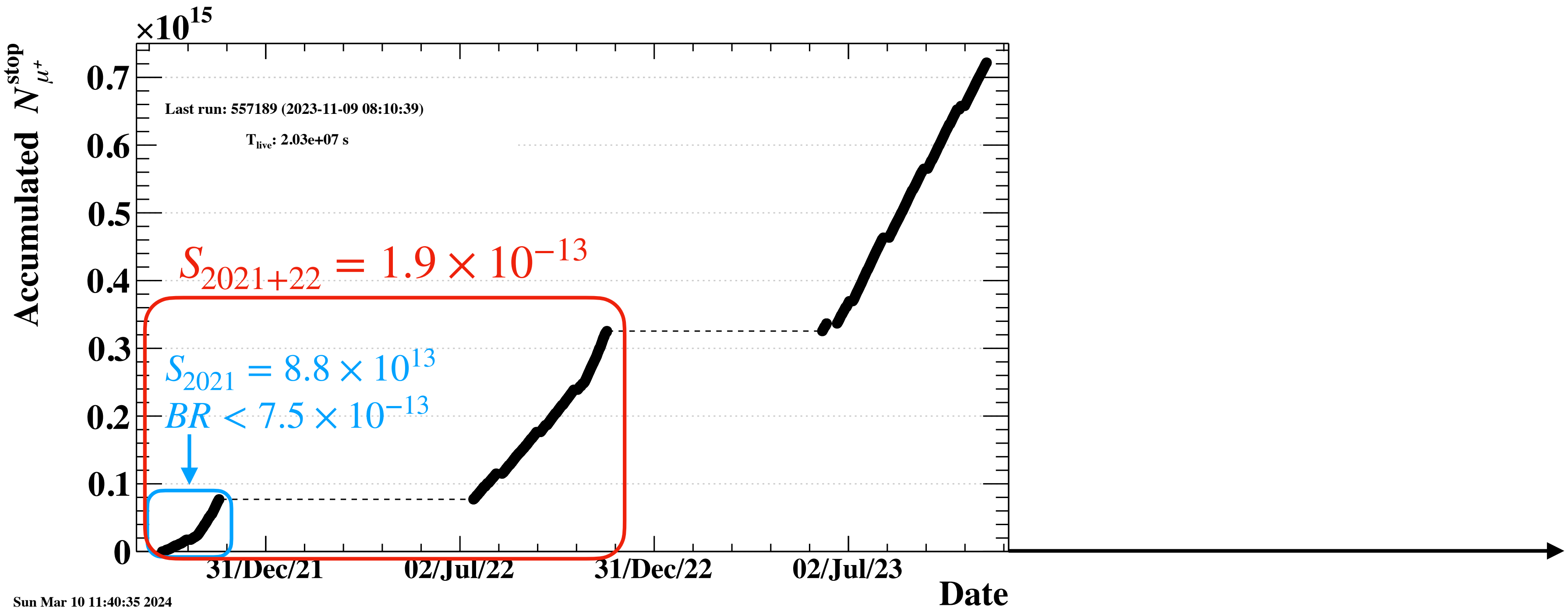
CDCH current; Some spikes due to electonics



Towards 2024 run

- **Detector maintenance in progress**
  - LXe: MPPC annealing for PDE recovery
    - To be presented by S. Ban (18pT3-6)
  - Timing Counter: Pixel counter replacement
    - To be presented by T. Yonemoto (21aT1-1)
  - Cylindrical drift chamber: Electronics maintenance





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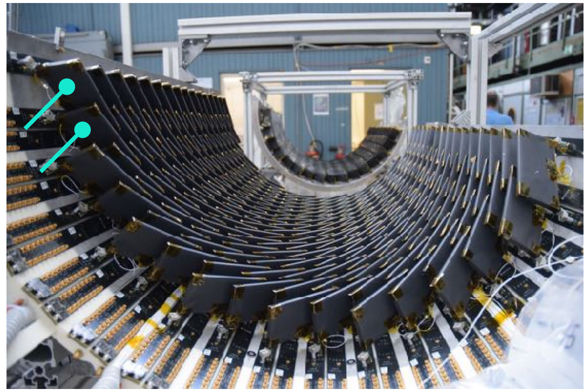

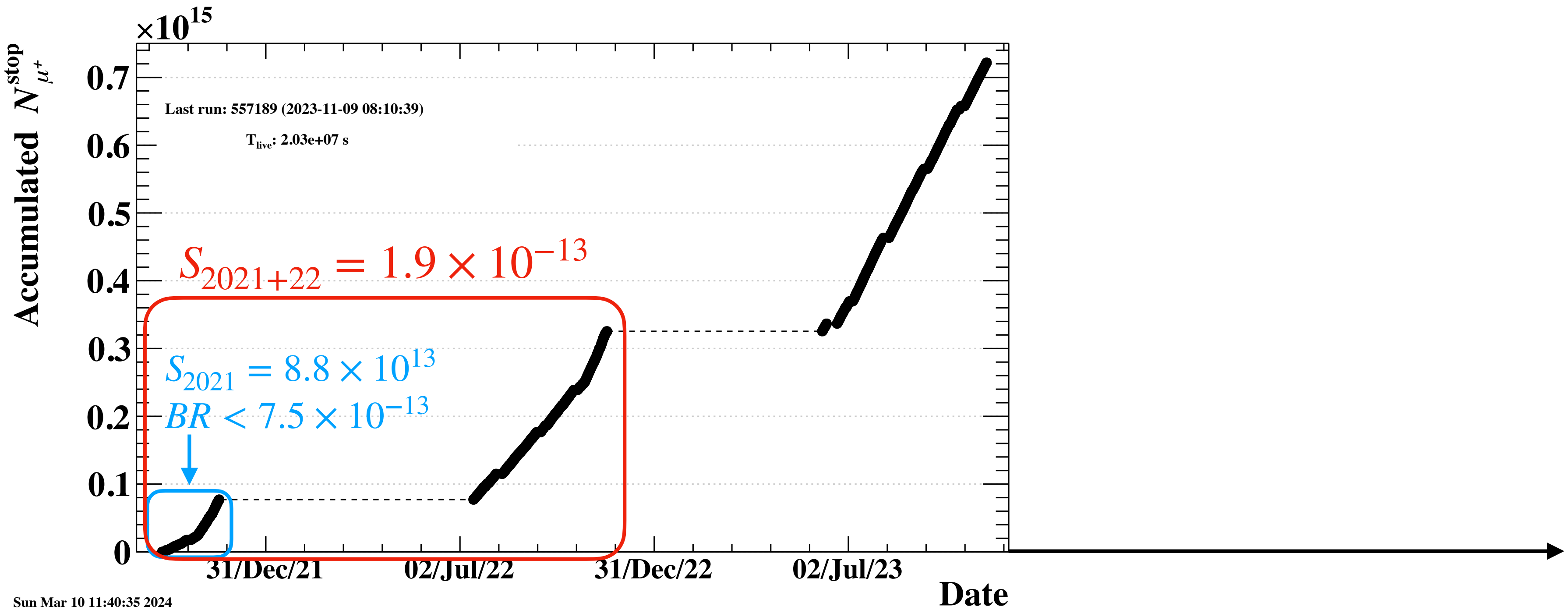

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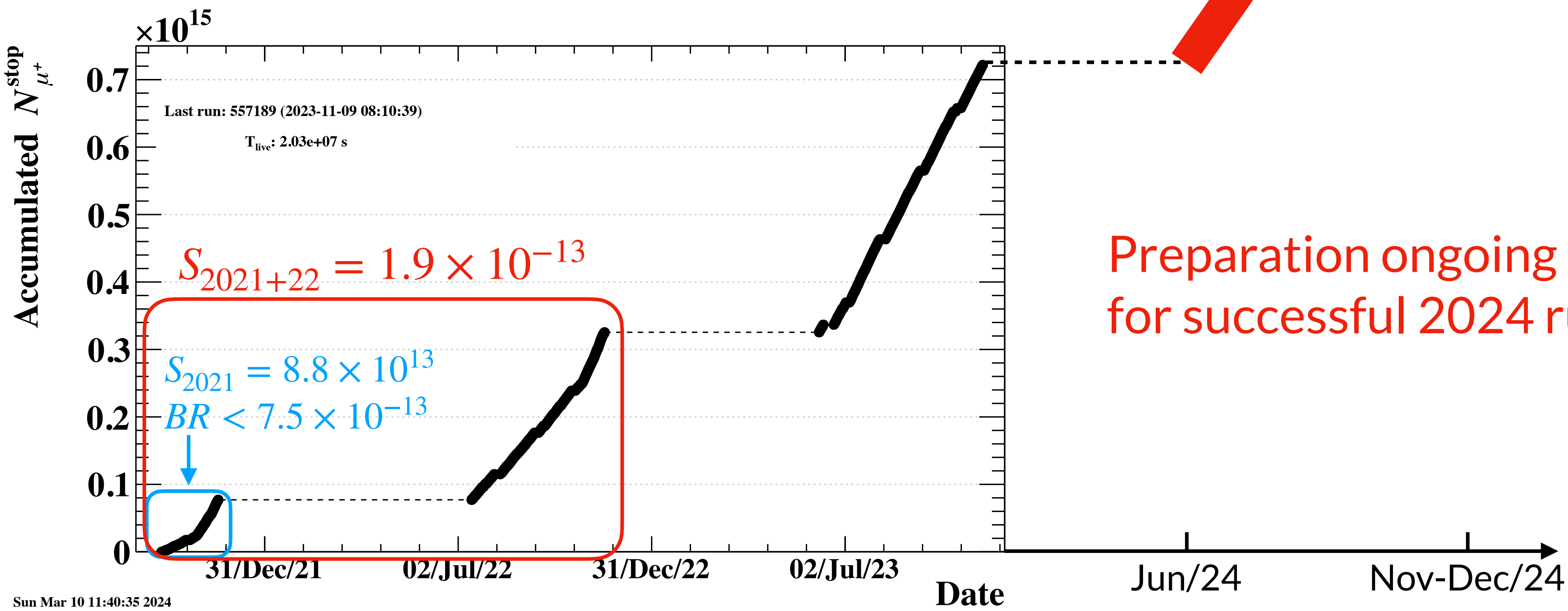


Preparation ongoing
for successful 2024 run!

Conclusions

- MEG II started physics data-taking in 2021 and operated stably until 2023
  - $BR(\mu \to e\gamma) < 7.5 \times 10^{-13}$ (90% C.L.) only with 2021 dataset
  - $BR(\mu \to e\gamma) < 3.1 \times 10^{-13}$ (90% C.L.) with MEG final + MEG II 2021

- 2021+22 combined analysis ongoing
  - Positron reconstruction performance comparable with 2021
  - LXe detector calibration for 2022 data ongoing
  - Reconstruction algorithm updates
    - Pileup analysis in LXe, Pulse search in RDC
  - Preliminary sensitivity $S_{2021+22} = 1.9 \times 10^{-13}$

- Maintenance work ongoing towards 2024 run

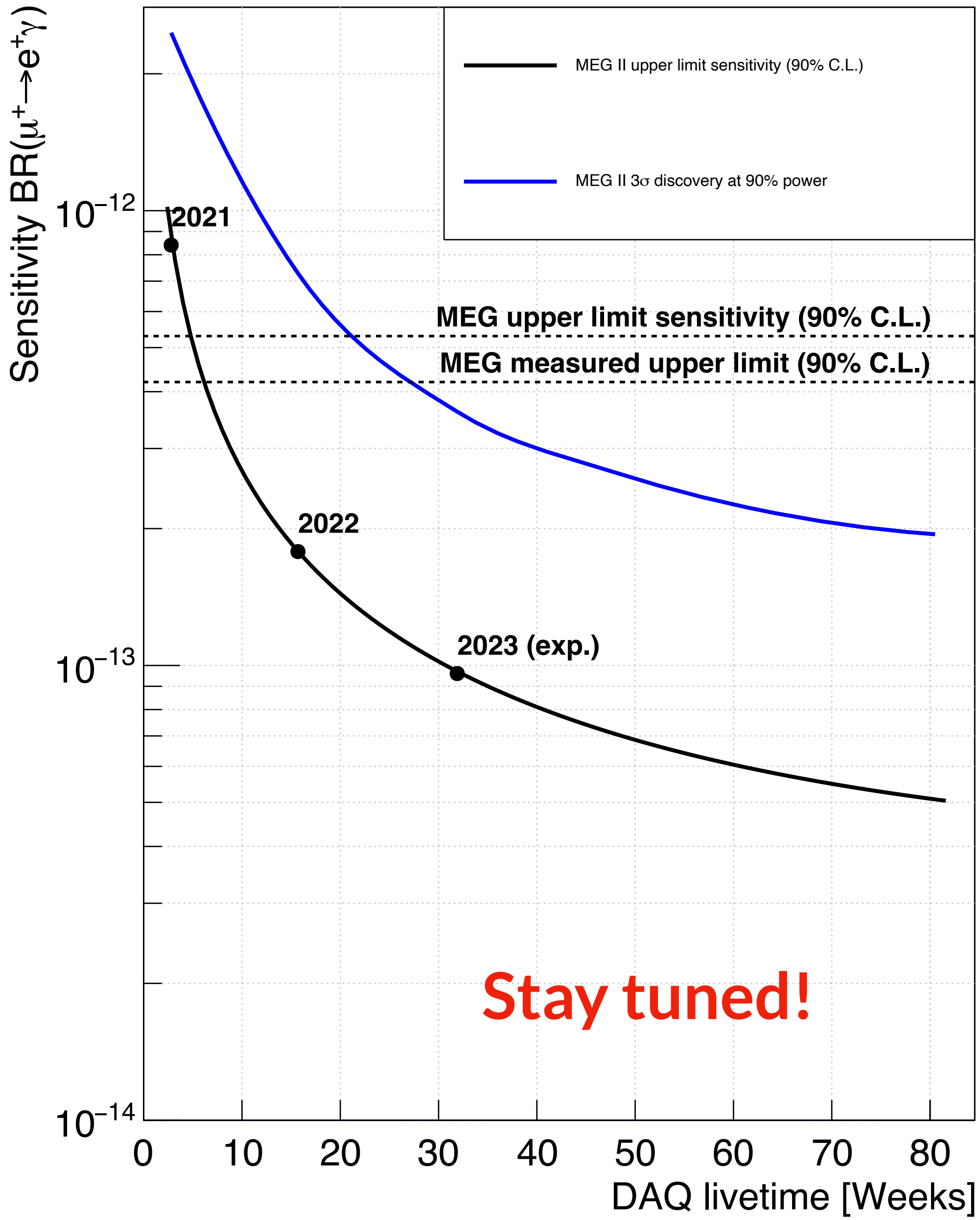
Prospects

- **Aim to publish 2021+22 combined result this summer**

- MEG II prospects
  - Long shutdown at PSI πE5 beamline planned in 2027-28
  - Beamtime to be shared with Mu3e experiment in 2025,26?

➡ Maximise DAQ time and efficiency

➡ $(5-6)\times 10^{-14}$ **sensitivity will be reached**



Backup

PMT gain calibration

A. Matsushita,
78th annual meeting (17aRA81-1)

PMT gain calculation

PMT gain can be calculated from LED intensity scan data.

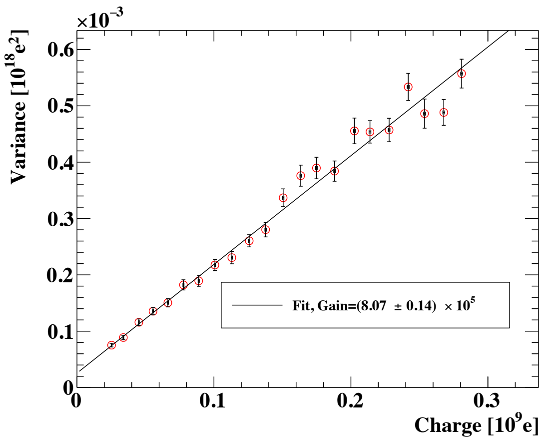
$$\sigma_q^2 = G \times e \times \bar{q} + \sigma_0^2$$

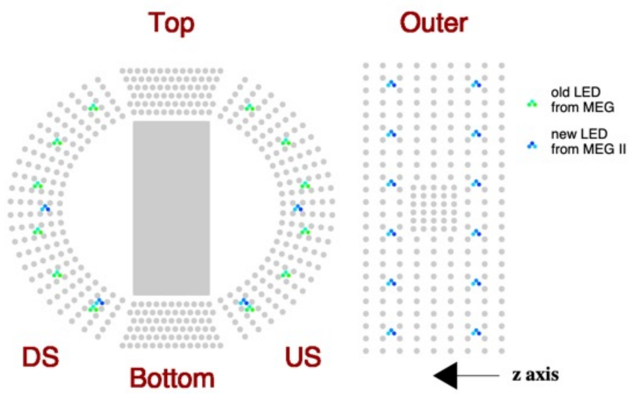
σ_q: spread of integrated charge distribution

G: gain

e: elementary charge

$\bar{q}$: mean of integrated charge





positions of LEDs inside LXe detector

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MPPC gain calibration

A. Matsushita,
78th annual meeting (17aRA81-1)

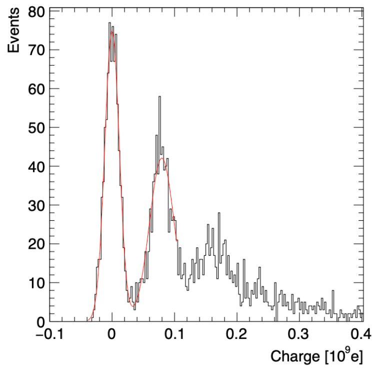
MPPC Gain and ECF calibration

- MPPC gain is calculated from 0 p.e. and 1 p.e. peak using LED data.

  Charge is calculated in multiple integration ranges

$$G(t) = G \times \left(1 - \exp\left(-\frac{t-t_0}{\tau_{\mathrm{fall}}}\right)\right)$$

τ_{fall}: time constant



example of charge distribution
(integration range 70 ns)

- Excess Charge Factor (ECF)

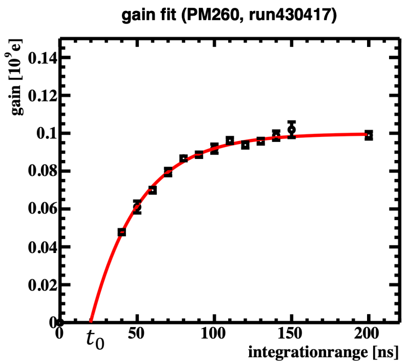
  Charge increase due to cross-talk or after-pulse.

  Calculated assuming the LED light is Poisson light.

$$\mathrm{ECF} = \frac{\mu}{\lambda}$$

$\mu = \frac{\bar{Q}_{measured}}{G}$: Net average number of photoelectrons

$\lambda = -\log \frac{N_{pedestal}}{N_{total}}$: mean of Poisson distribution



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MPPC PDE/PMT QE calibration

- Definition of PDE/QE

$$\epsilon_i = \epsilon_i^{\mathrm{MC}} \times \frac{\bar{N}_{\mathrm{phe},i}}{\bar{N}_{\mathrm{phe},i}^{\mathrm{MC}}} \times F_{\mathrm{LY}}$$

- ϵ_i: PDE/QE of $\boldsymbol{i}$-th sensor
  - ϵ_i^{MC}: 12% PDE, 16% QE
- $\bar{N}_{\mathrm{phe},i}$: mean of the number of photoelectrons
- F_{LY}: Light yield correction

- Calibration source: α-ray from ^{241}Am
  - Comparison b/w MC and data needed
  - Reflectivity of PMT holder in MC is 50% based on absorption curve

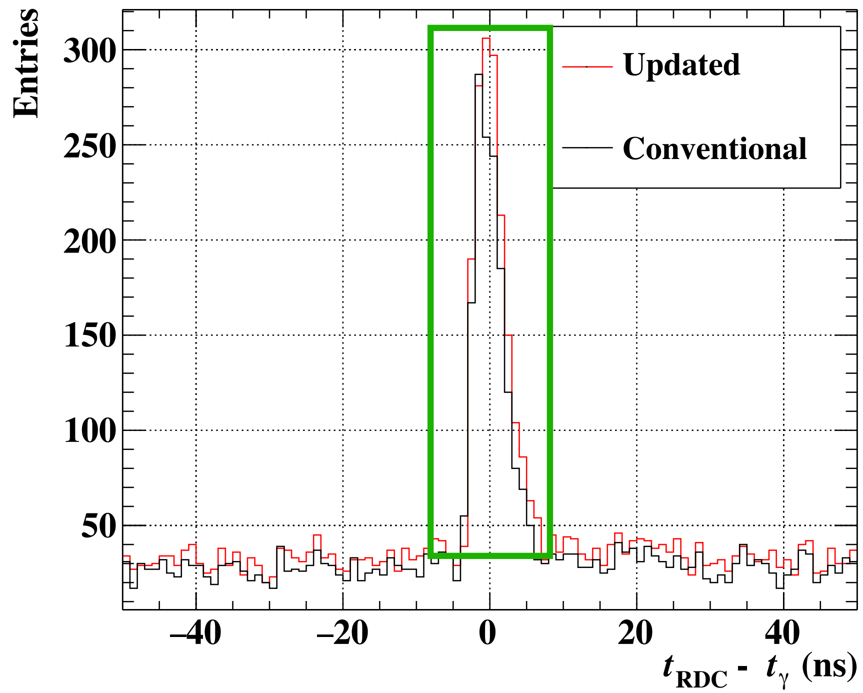
- Averaged PMT QE fixed at 16%
  - Supplied from Hamamatsu
  - ➡ N_{PMT} history interpreted as relative light yield history F_{LY}

RDC performance

- Tagged RMD fraction

$$\frac{\text{\# coincidence positron with } \gamma}{\text{\# background photons in LXe}}$$

- **Efficiency improved**
- But, there is still a discrepancy
  - Under investigation



Tagged RMD fraction with $3 \times 10^7\ \mu/\text{s}$ data in 2021

Conventional	Updated	Expected
21.7(9)%	24.9(9)%	31.9%

+15%

7% discrepancy

$\mu \to e\nu\nu\gamma$ Fraction		Fraction to fly DS		Detection efficiency
76%	×	48%	×	88%