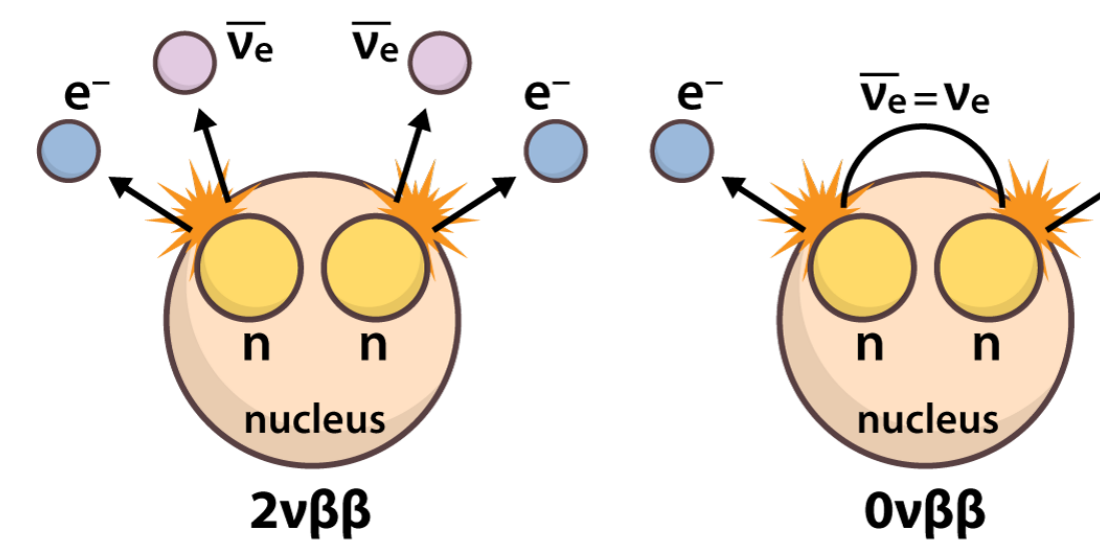


AXEL Experiment : High-Precision Correction of MPPC Nonlinearity Using Signal Waveform Deconvolution

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Neutrinoless double beta decay ($0\nu\beta\beta$)



The Majorana nature of neutrinos is key for ...

- Why is neutrinos extremely light?
- Why is the universe matter-dominated?

Feature of $0\nu\beta\beta$

- very rare event (half-life of ^{136}Xe : 3.8×10^{26} year ^[1])
- The sum of the electrons' kinetic energies is constant.



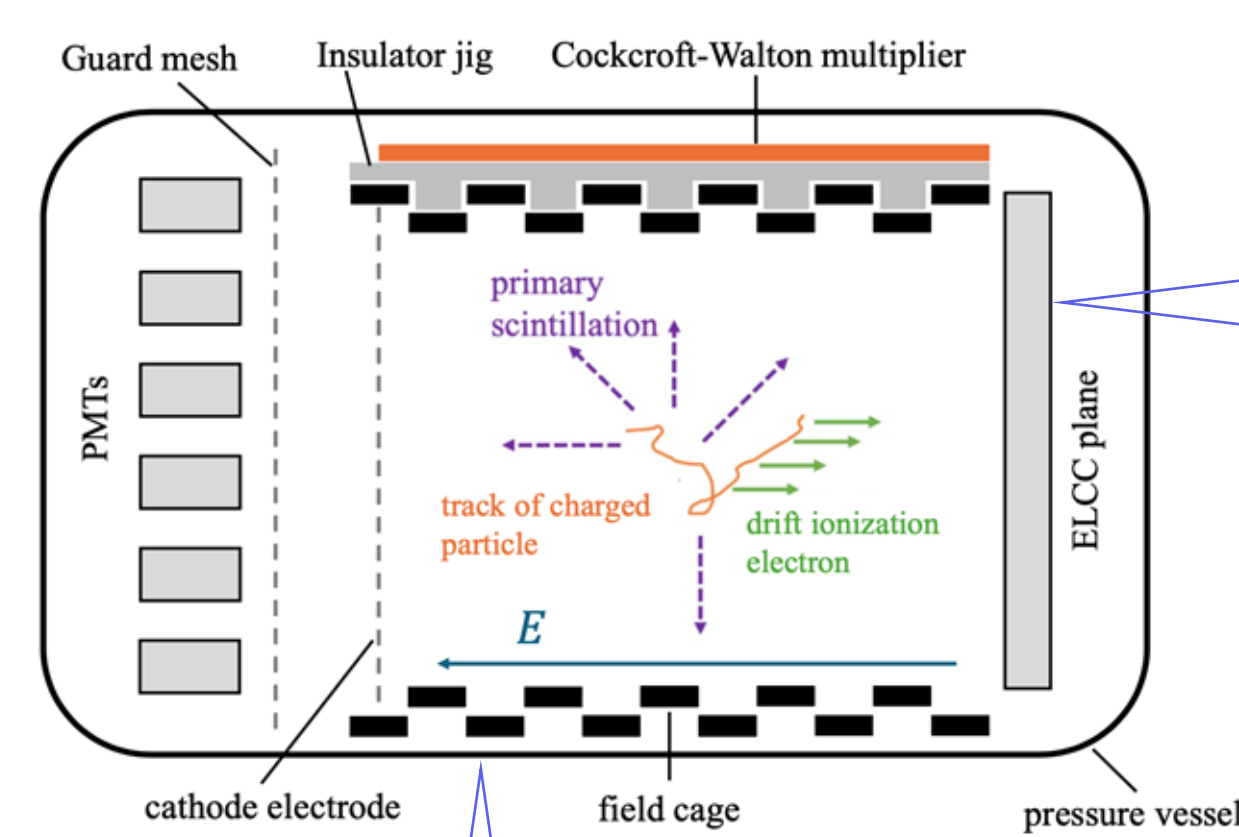
In $0\nu\beta\beta$ search,

Large Mass • Excellent BG rejection capability • High Energy Resolution are needed.

[1] KamLAND-Zen collaboration, Phys. Rev. Lett. 135, 262501 (2025)

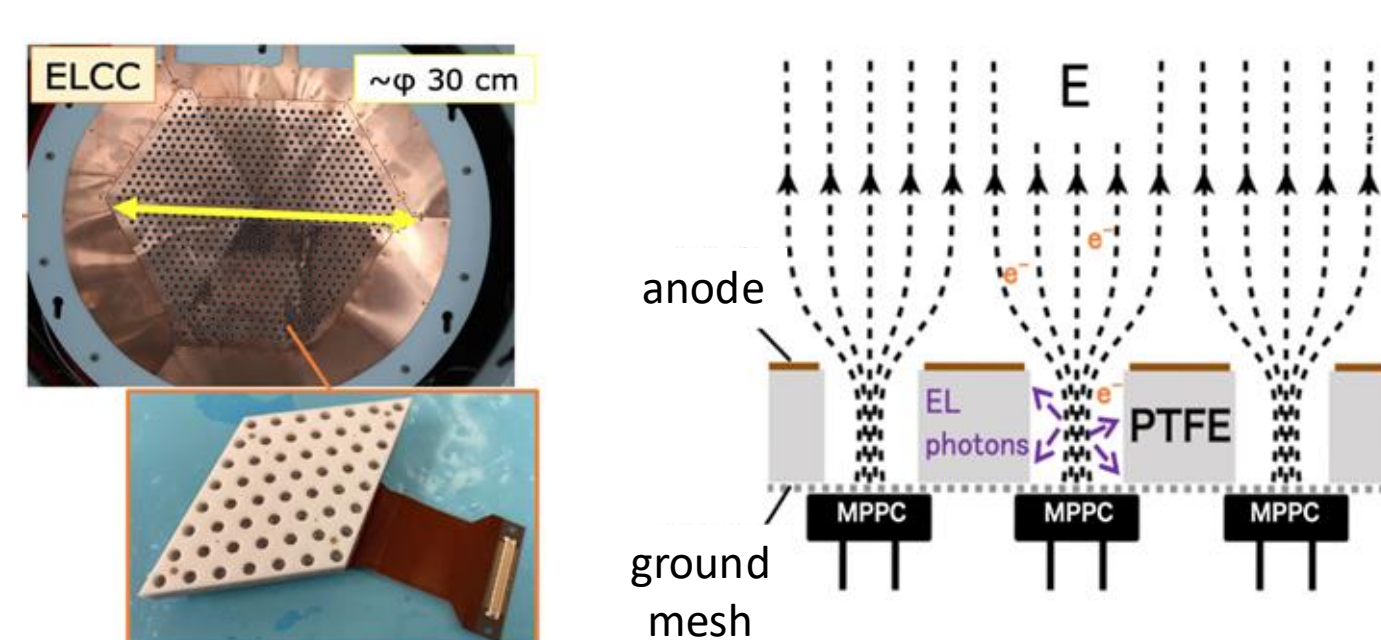
AXEL (A Xenon Electroluminescence Detector)

High-pressure xenon gas time projection chamber with the aim of observing the $0\nu\beta\beta$ of ^{136}Xe .



ELCC (Electroluminescence Light Collection Cell)

AXEL group original ionized electron readout system!

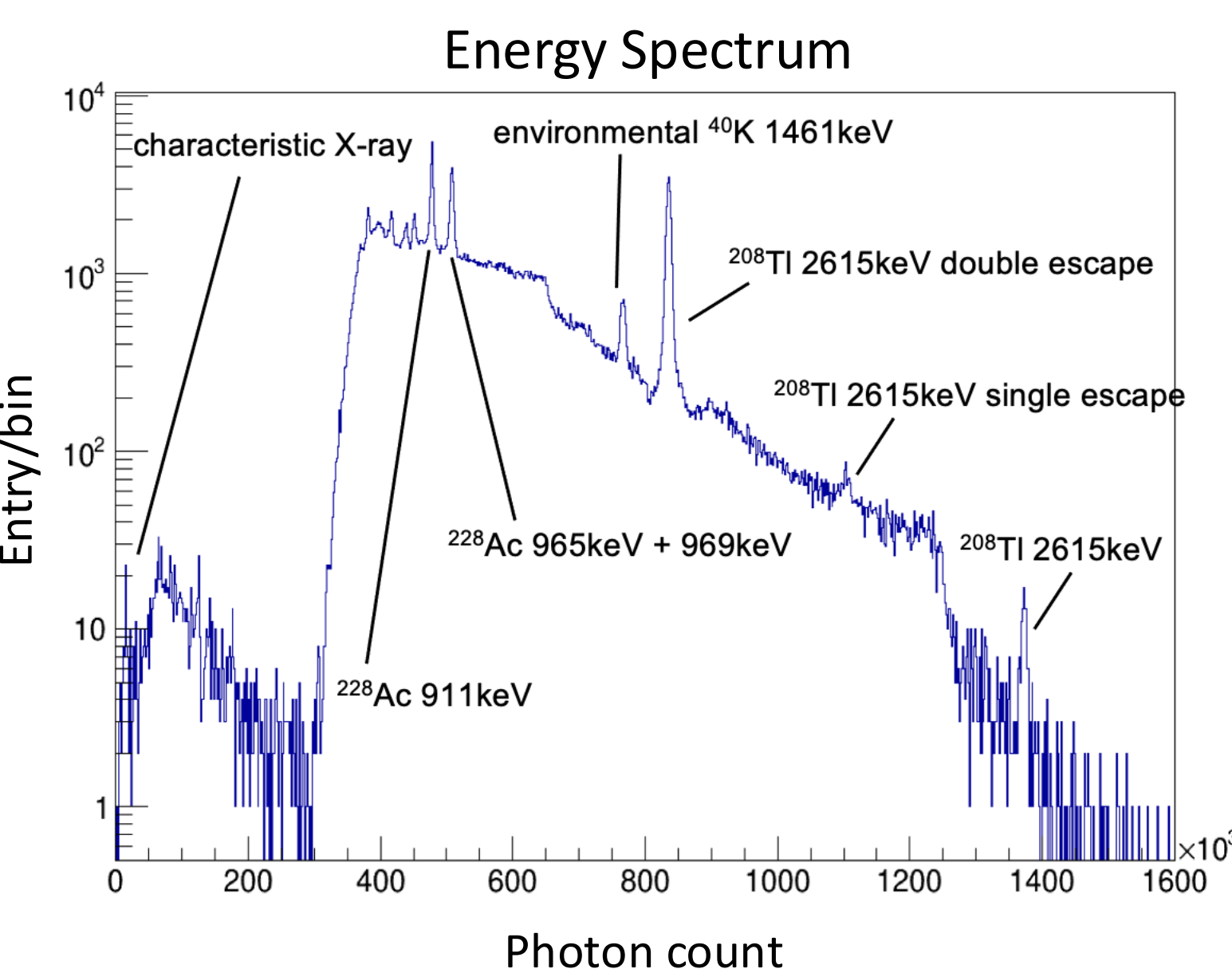


EL process is a linear amplification process

→ **Hight Energy Resolution**

8bar high-pressure gas → **Large Mass**
3D track → **BG rejection**

Evaluation of Energy Resolution Using a ^{208}Tl Source



Breakdown of Energy Resolution
(FWHM @2615keV)

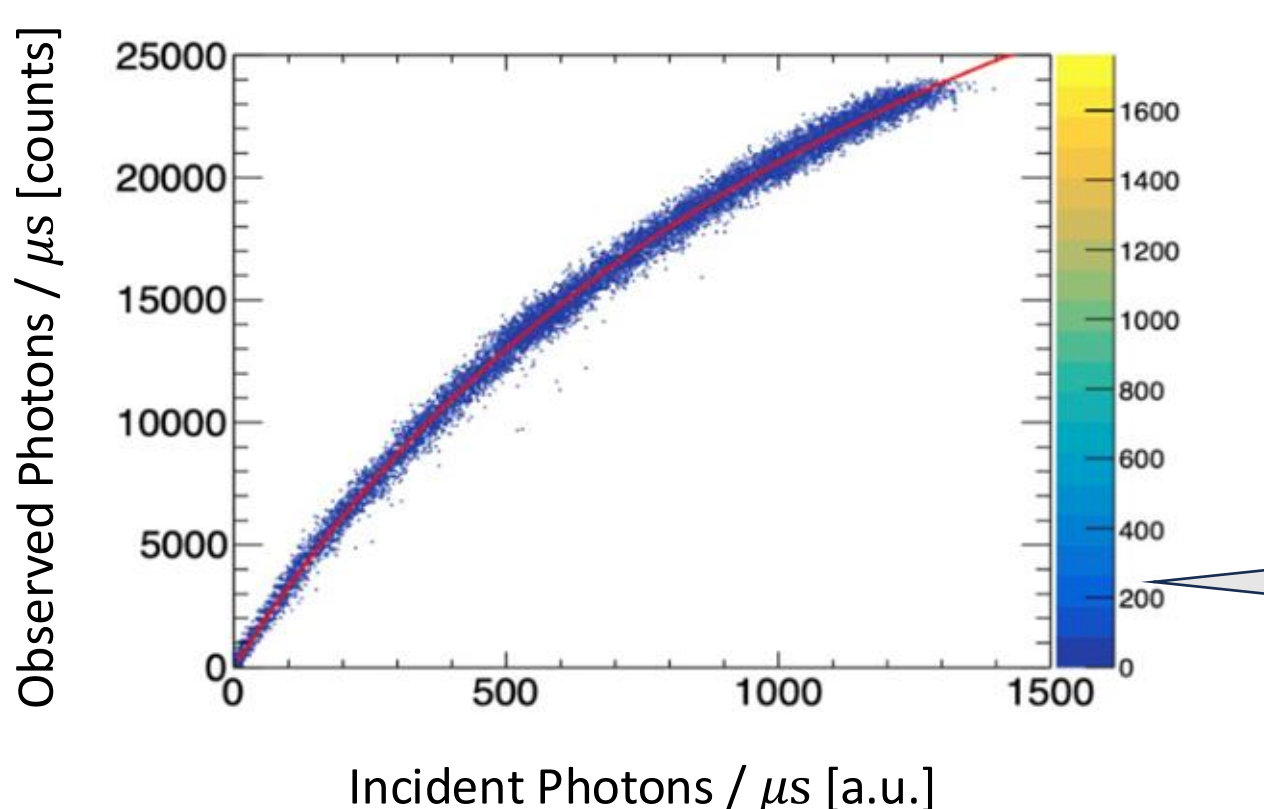
Fluctuation of the number of initial ionization electrons	0.25 %
Mis-reconstruction of z-position	0.24 %
Fluctuation of the EL generation and detection	0.20 %
Error in time dependence correction	0.18 %
Recombination	0.17 %
Variation in time bin of time variation correction	0.12 %
Estimation total	0.52 % to 0.54 %
Data total	(0.67 ± 0.08) %

* only major contribution

We are advancing R&D toward 0.5%.

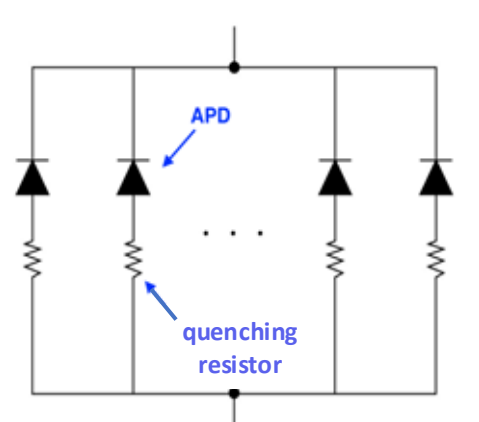
MPPC (Multi-Pixel Photon Counter)

Nonlinear response by MPPC saturation

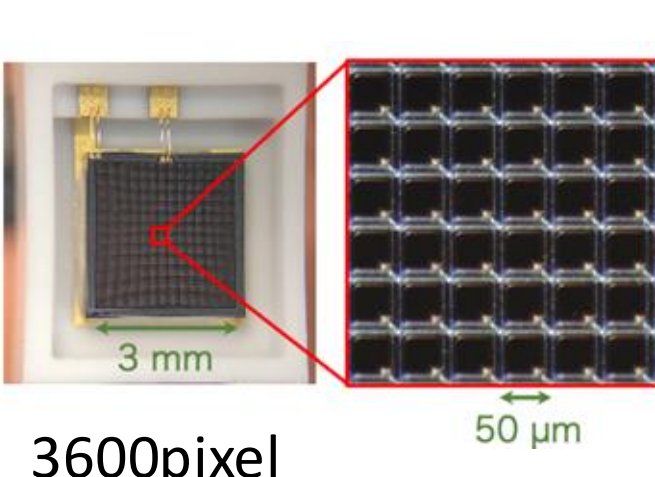


Recovery time $\tau \sim 70\text{ns}$ @50Ω
In $0\nu\beta\beta$, the maximum ~ 1400 photons/(MPPC · 70 ns)
→ Not negligible

Equivalent circuit



MPPC used in AXEL



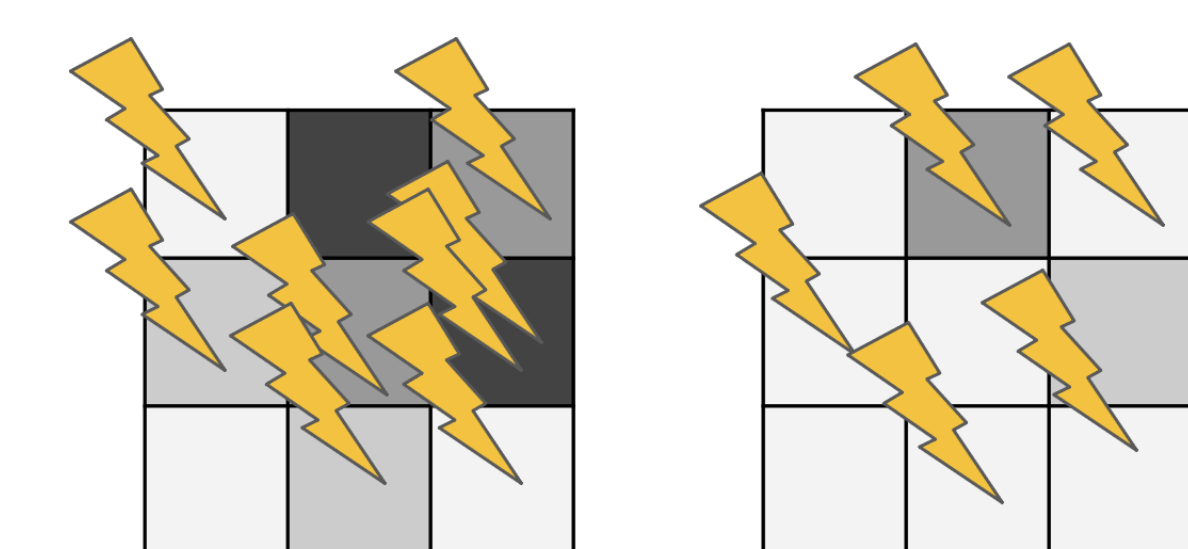
Correction Methods of MPPC Nonlinearity

Average Correction

Measure nonlinearity curves and correct using them directly.

Conventional Method

For example, observed photon count is 4,



$N_{\text{true}} : 8 / \text{gain} : 0.5$ $N_{\text{true}} : 5 / \text{gain} : 0.8$ etc...

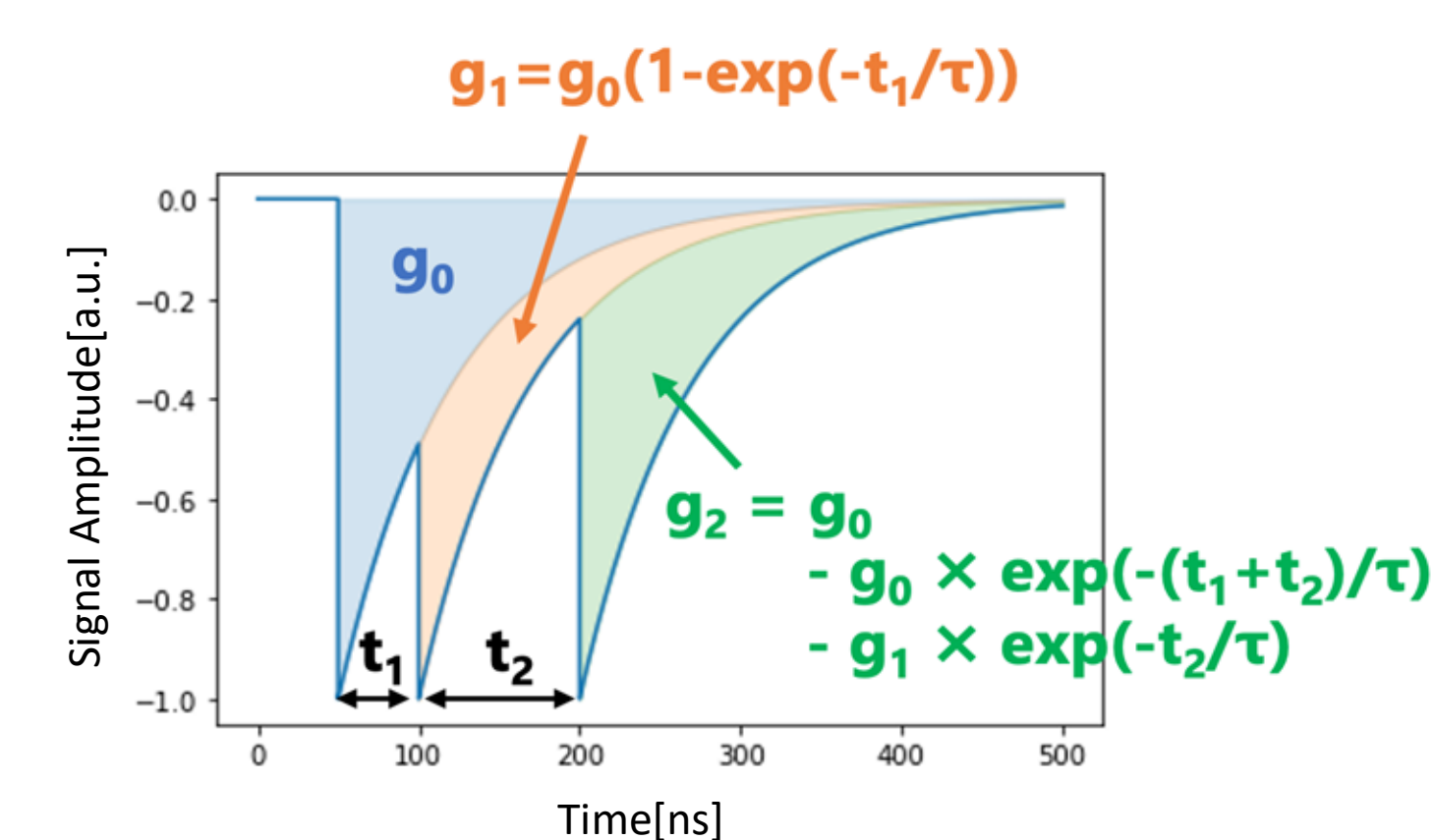
This is equivalent to using the gain averaged over all cases.

→ Correction precision is not very good.

Strict Correction

Estimate the gains more precisely using past signal values.

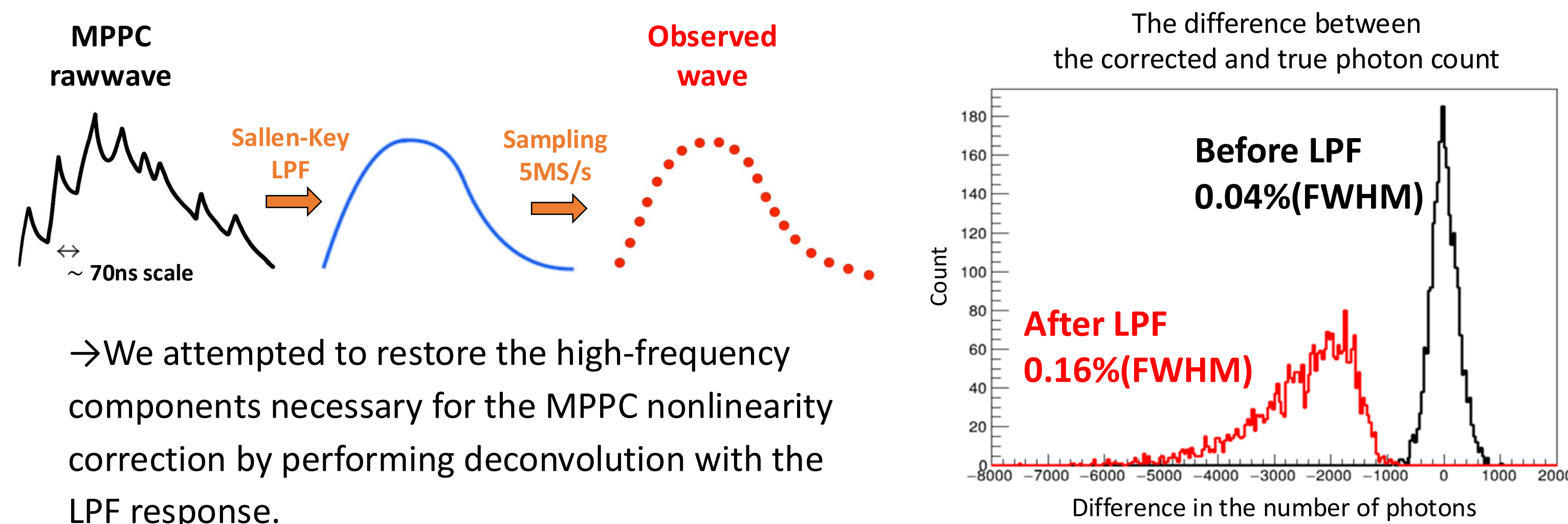
New Method



Use the fact that the gain recovers at $\exp(-t/\tau)$.

→ A structure with a timescale of approximately τ is required.

Background & Motivation of This Study (Effects of LPF)



→ We attempted to restore the high-frequency components necessary for the MPPC nonlinearity correction by performing deconvolution with the LPF response.

Richardson-Lucy deconvolution

Iterative method using the following update equation. Mathematically, it is equivalent to the maximum likelihood method.

$$\phi_i^r = \sum_j \psi_j^r P_{ij}$$
$$\psi_j^{r+1} = \psi_j^r \sum_i \frac{\tilde{\phi}_i}{\phi_i^r} P_{ij}$$

P_{ij} : kernel

ϕ^r : r-th estimated observed waveform

$\tilde{\phi}$: observed waveform(data)

ψ^r : r-th estimated waveform

* ψ^0 is assumed to be a smooth, non-negative function.

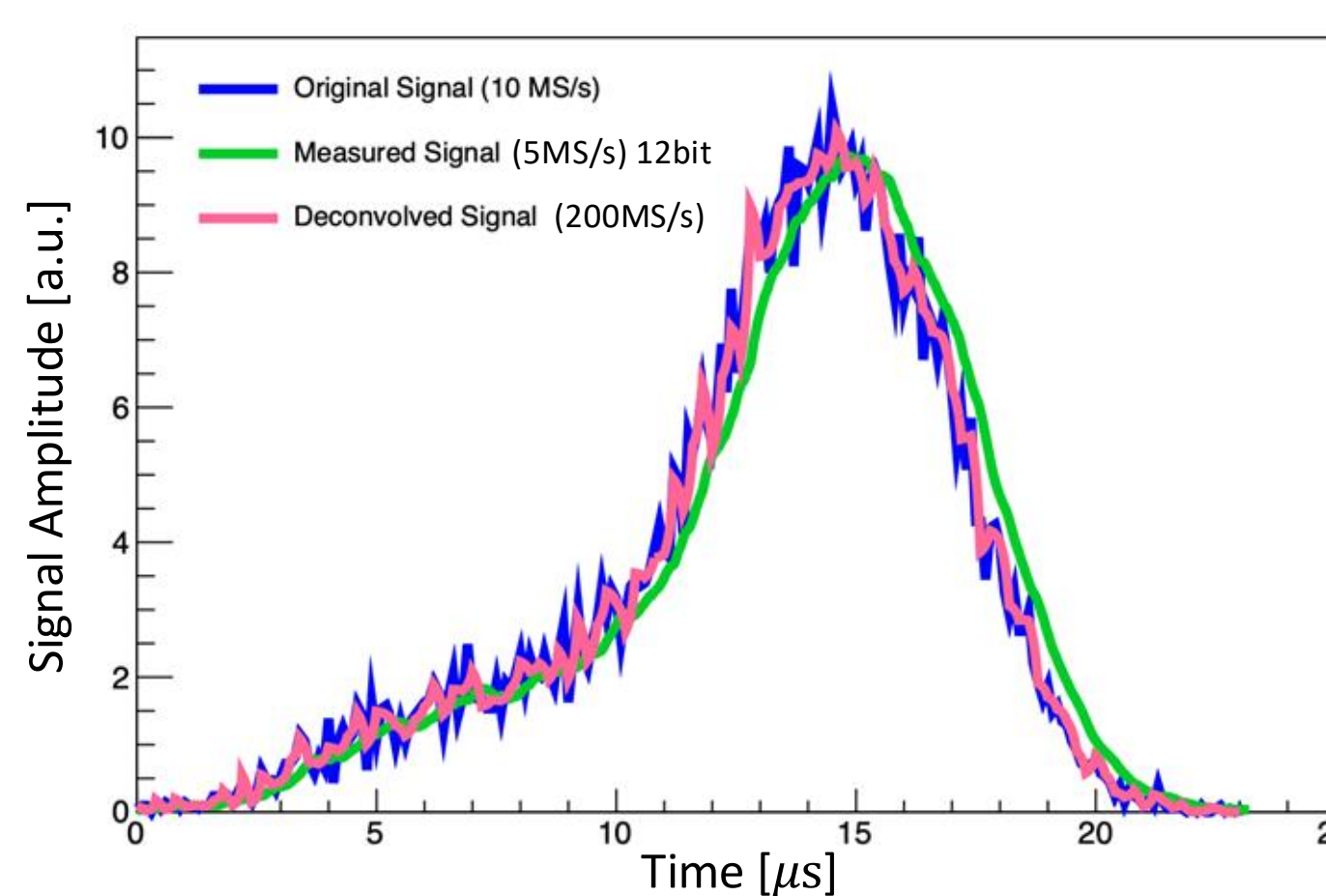
Sallen-Key LPF's impulse response

$$\frac{t}{\tau^2} e^{-\frac{t}{\tau}} \quad (\tau = RC)$$

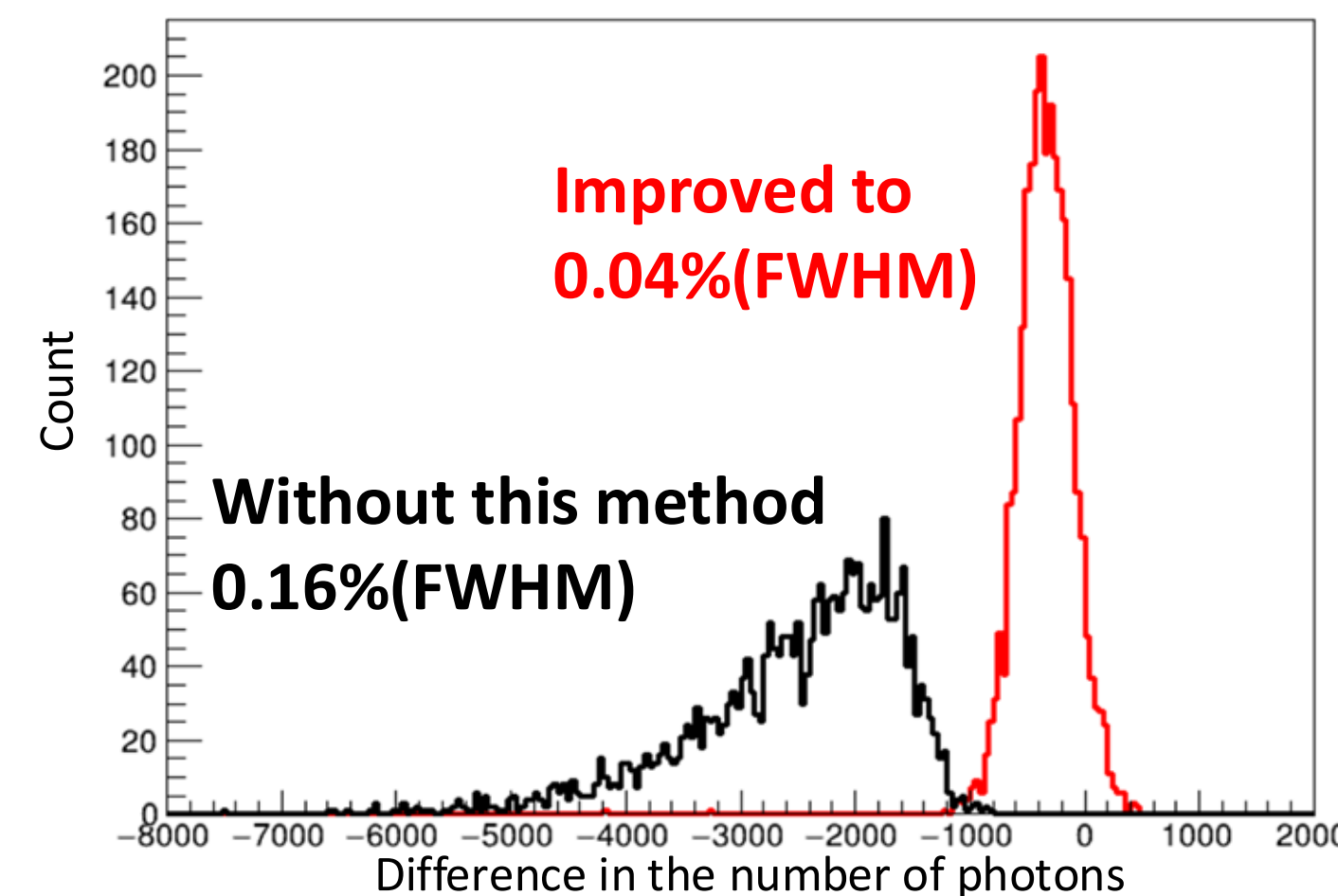
↑ Update using smoothed discrepancy between the estimated and the actual observed value by kernel.

Evaluation Using Simulation Data (2.6MeV electron)

Example of a reconstructed waveform by RL deconvolution (iter=100)

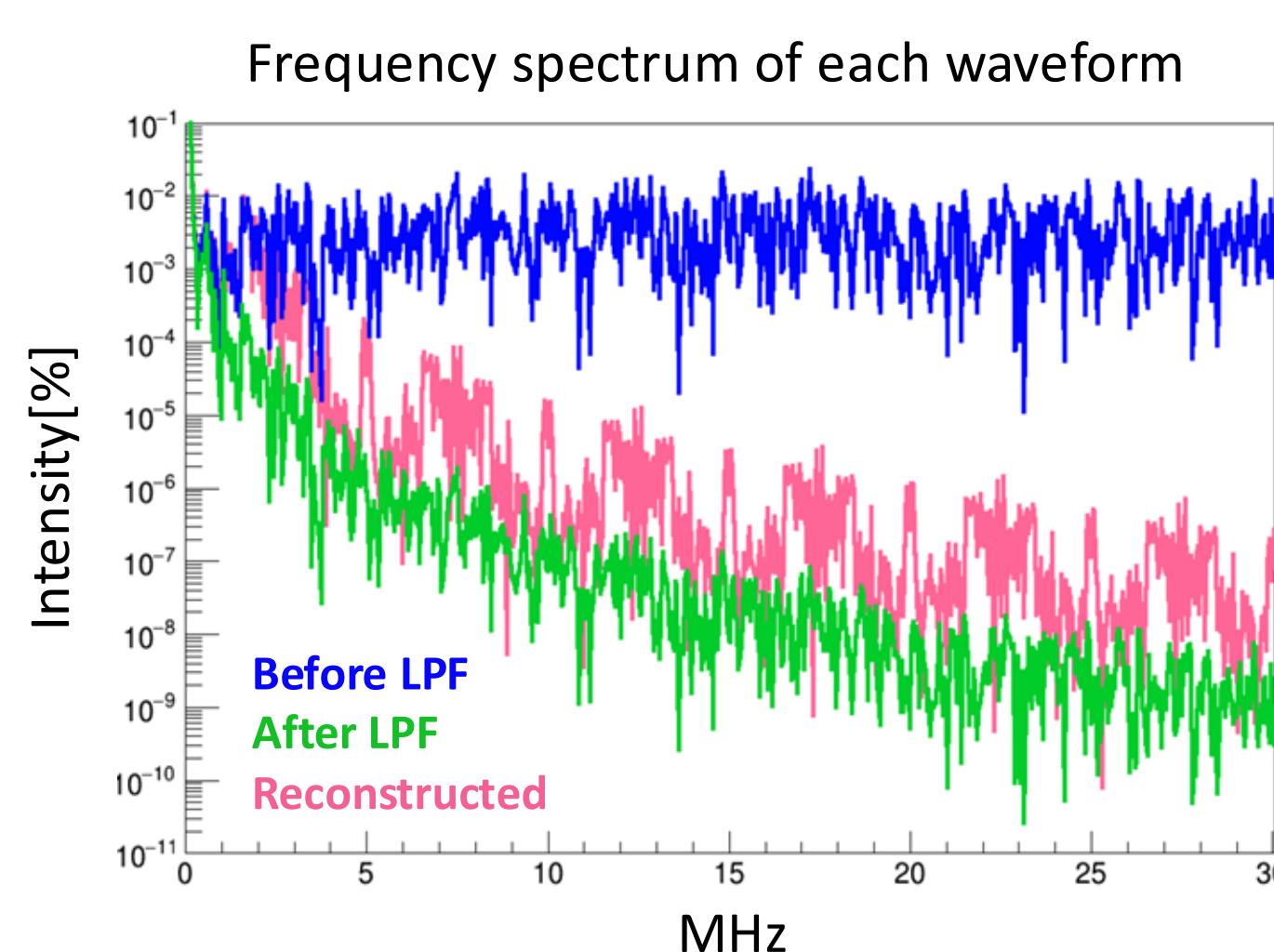


The difference between the corrected and true photon count



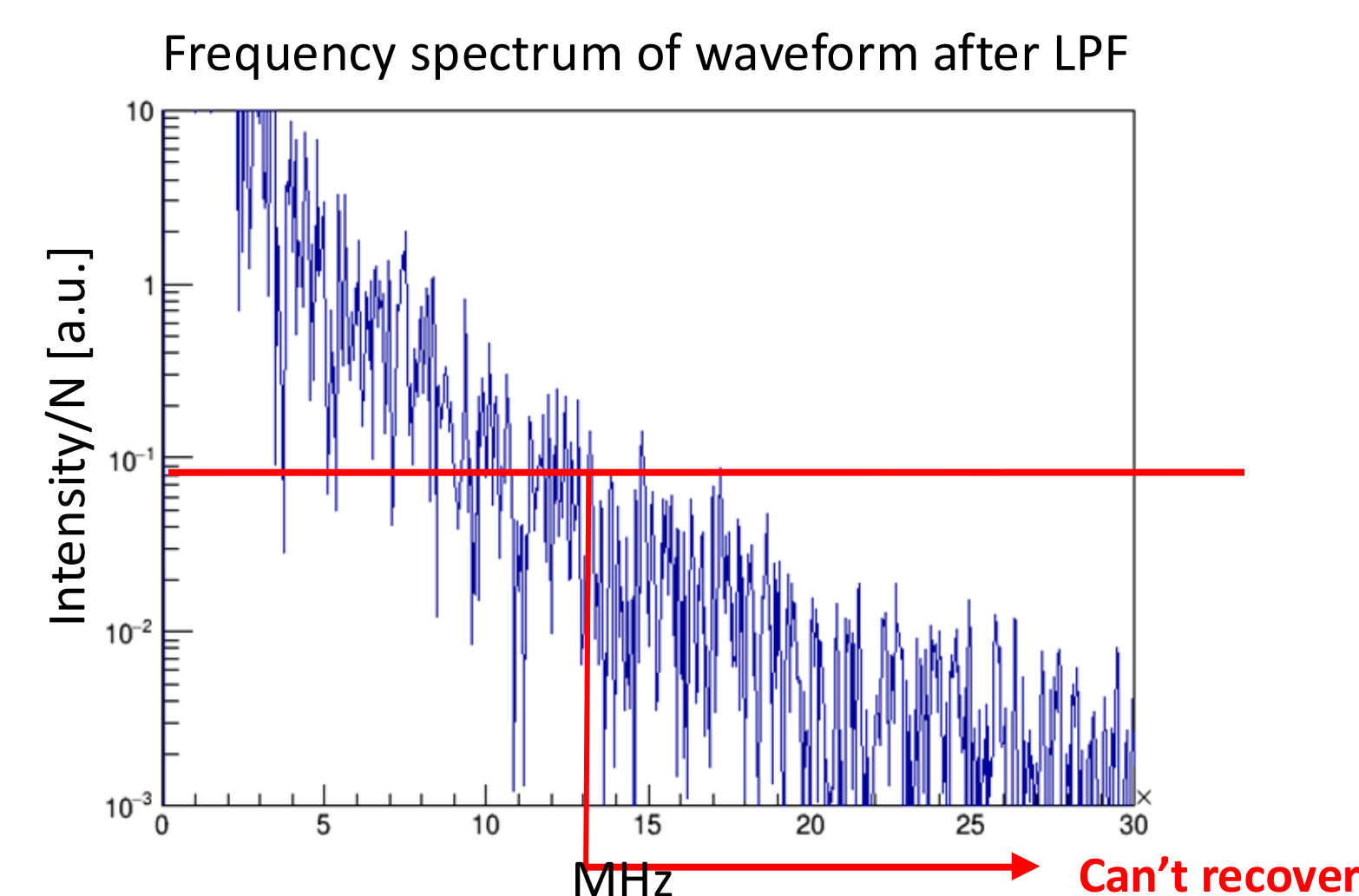
This method completely eliminates energy resolution degradation by the LPF.

Fourier analysis



Despite that the spectrum before the LPF could not be restored much, the energy resolution significantly improved.

Estimate of the Upper Limit for Recoverable Frequencies

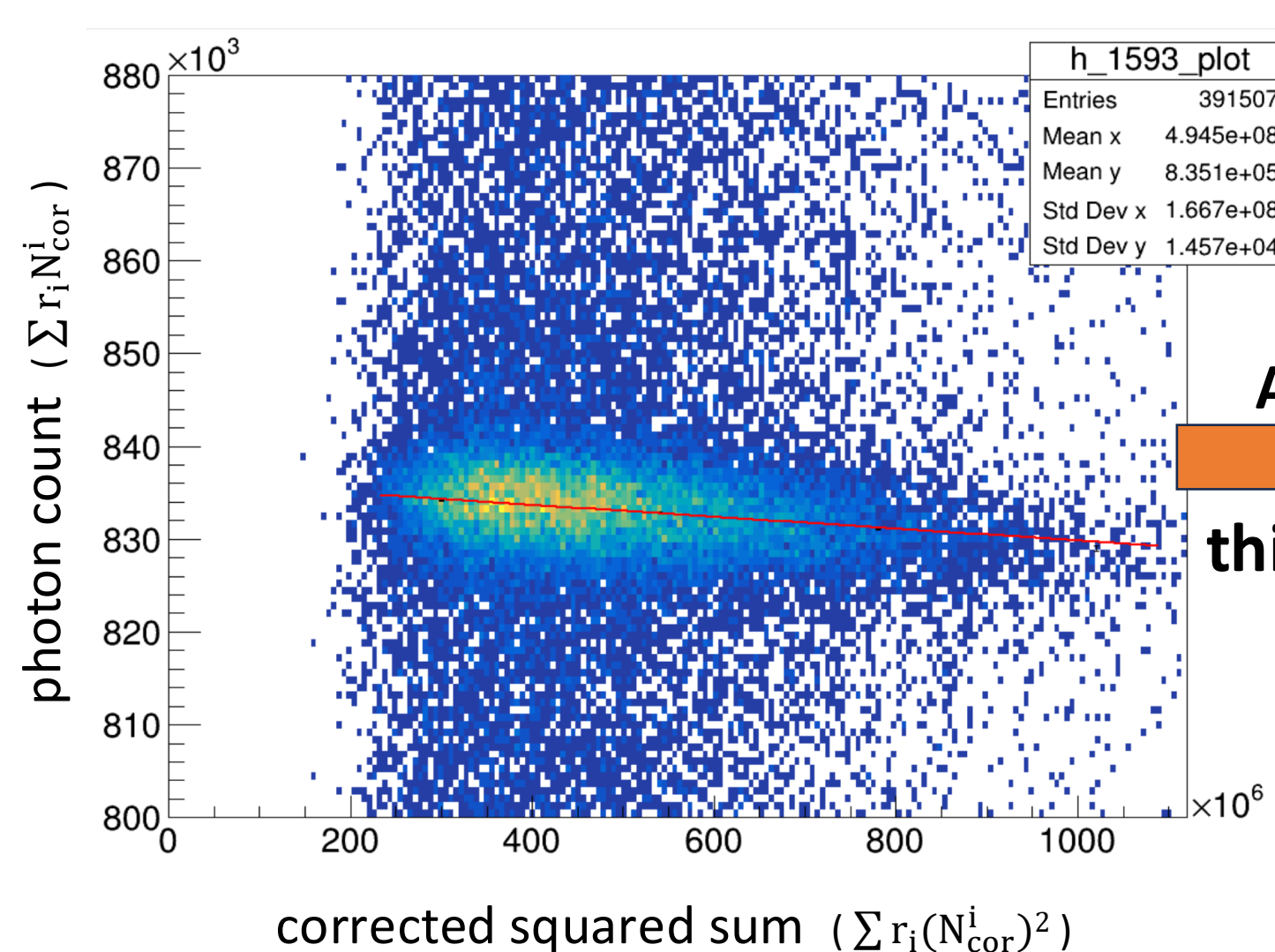


Restorable up to **~13 MHz**
→ Covers the frequency required the correction (~13.7 MHz)

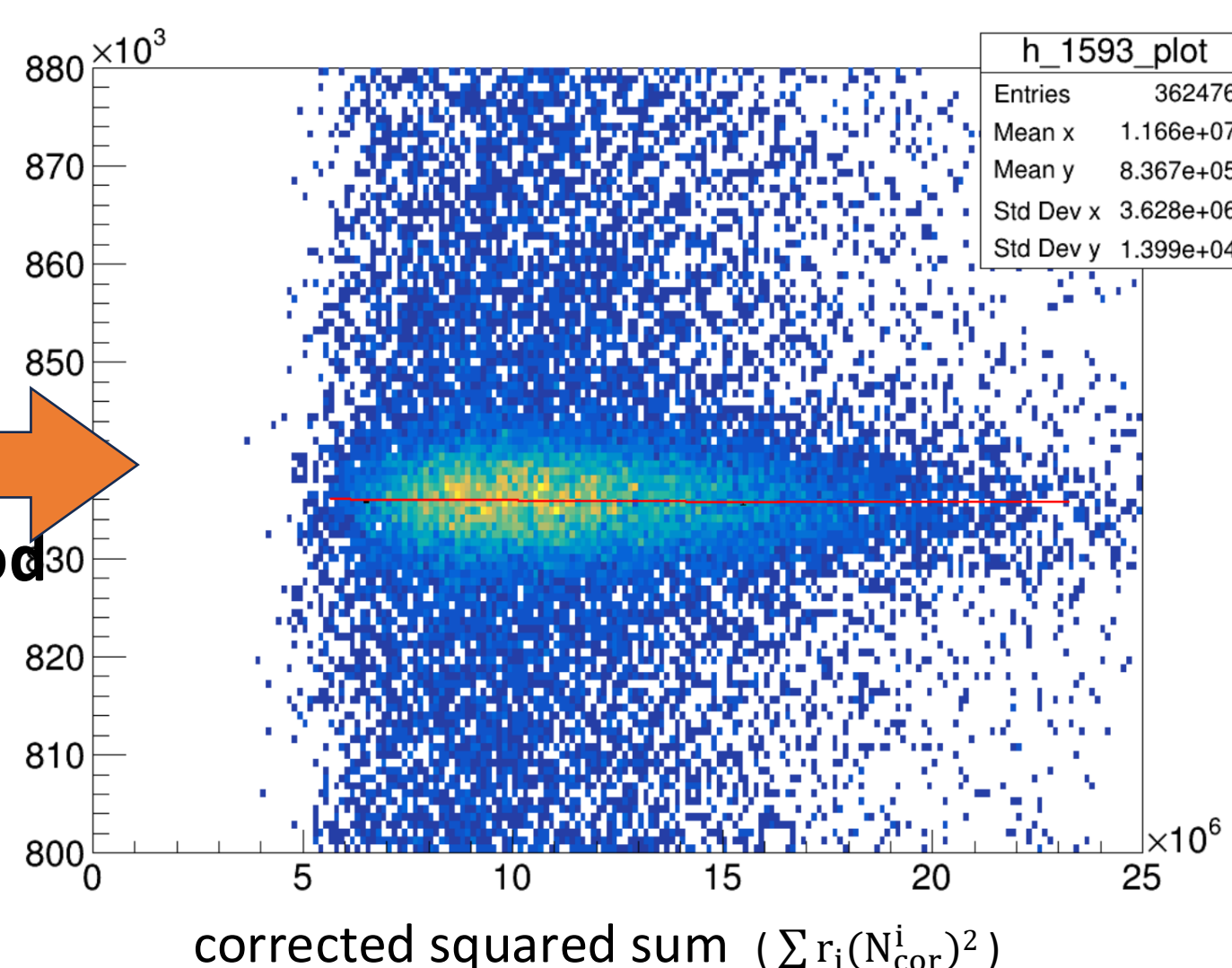
Evaluation Using ^{208}Tl Real Data

By applying this method, the accuracy of nonlinearity correction is improved.

In ^{208}Tl double escape event,



vertical axis : photon count
horizontal axis ~ MPPC saturation level



However, the resolution deteriorated from **0.66%** to **0.70%** (FWHM @ 2458 keV).