MEG II実験陽電子タイミングカウンターの長期運用へ向けた運用・解析パラメータの最適化

-Optimization of the Operation & Analysis Parameters of the MEG II Pixelated Timing Counter for Long-term Operation-

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Outline

$\mu \to e\gamma$ search

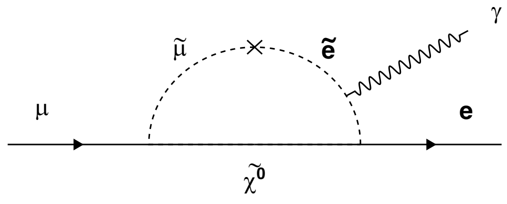
➢ Physics motivation

- Lepton flavor violation (LFV) is strictly forbidden in standard model (SM)
- Neutrino oscillation

= LFV in neutral lepton sector

→ Possibility of charged LFV (cLFV)

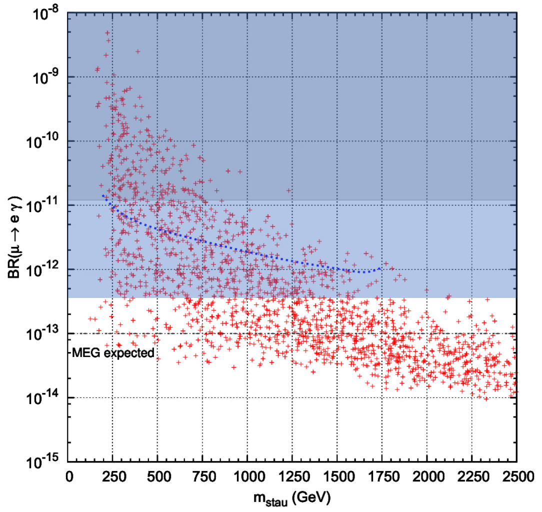
- SM + neutrino oscillation
  - $\mathcal{B}r(\mu \to e\gamma) \sim \mathcal{O}(10^{-54})$ ⟺ clean channel
- Predicted in many new physics models
  - $\mathcal{B}r(\mu \to e\gamma) \sim \mathcal{O}(10^{-15}\text{- }10^{-11})$



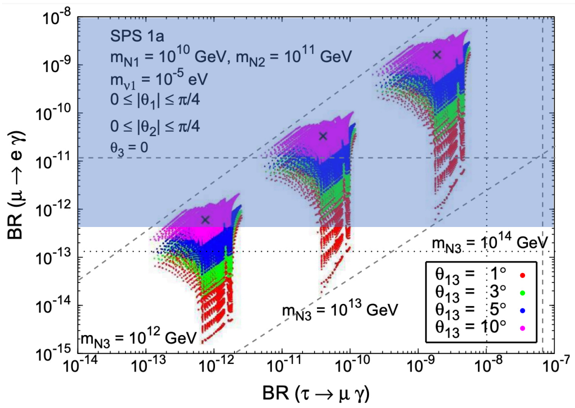
SUSY model

➢ Status of $\mu \to e\gamma$ search

- Upper limit obtained by MEG experiment
  - $\mathcal{B}r(\mu \to e\gamma) \sim 4.2 \times 10^{-13}$ (90 % C.L.)
- MEG II aims for one order higher sensitivity
  - $\mathcal{B}r(\mu \to e\gamma) \sim 6 \times 10^{-14}$

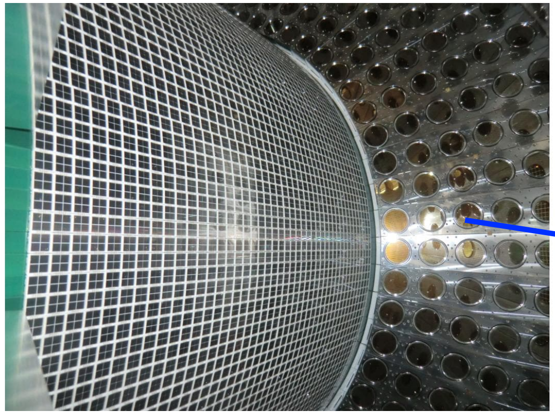


SUSY GUT

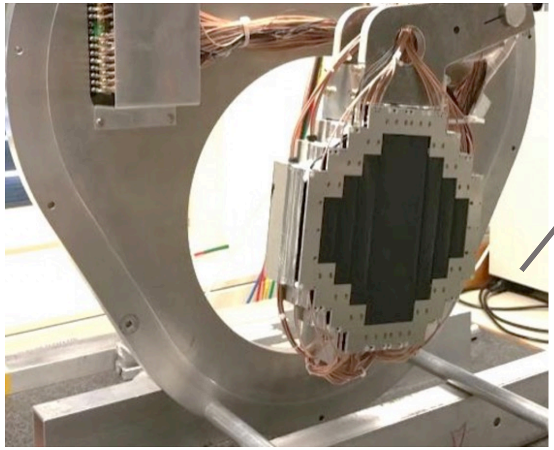


SUSY seesaw

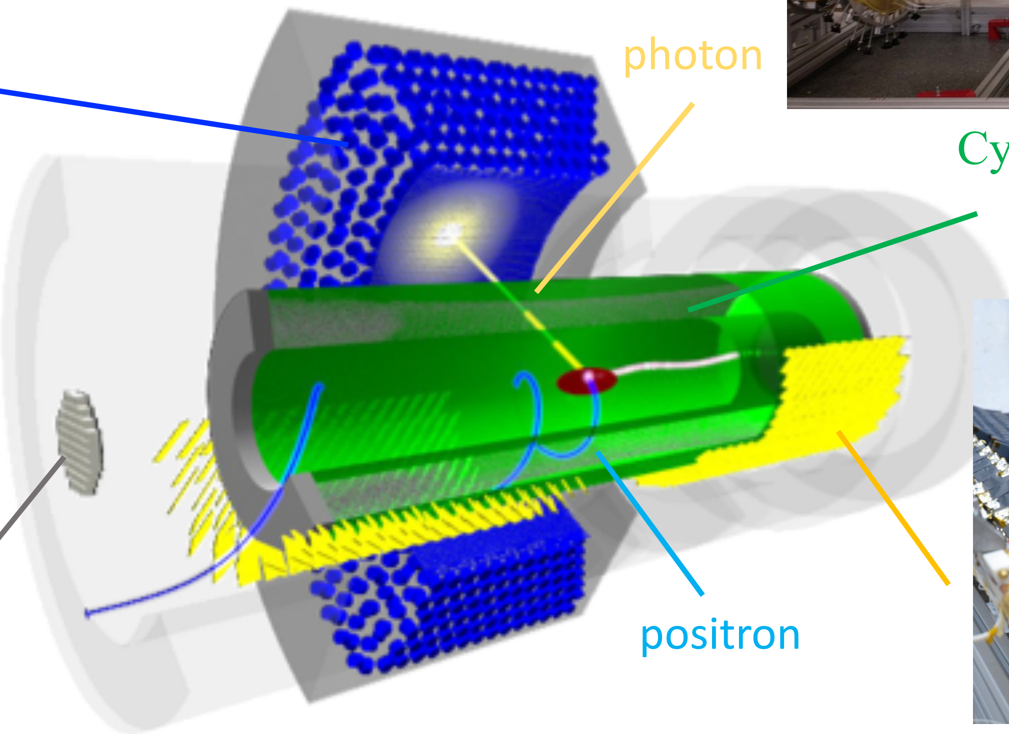
MEG II experiment

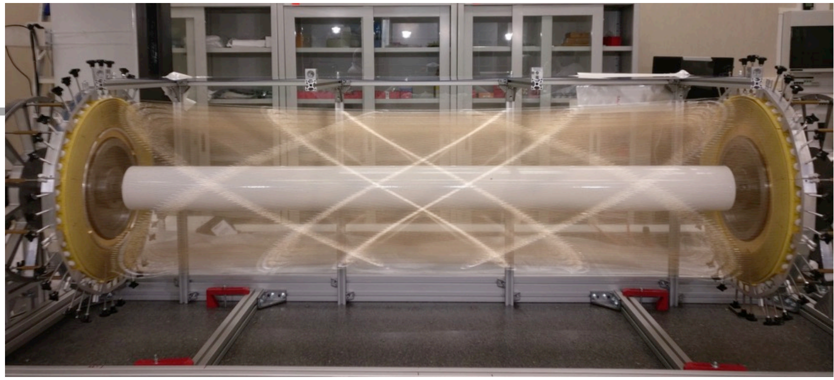


Liquid xenon (LXe) calorimeter

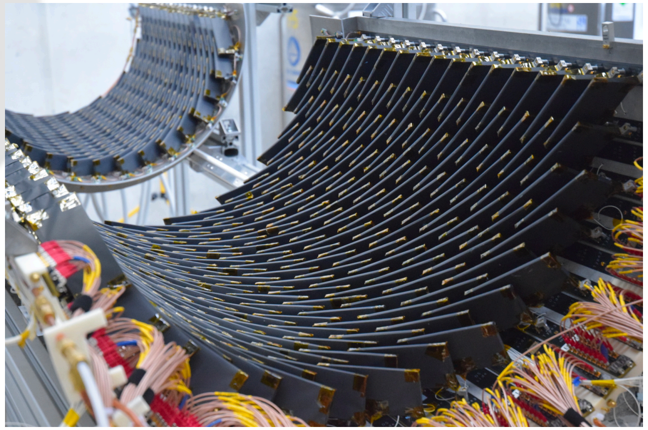


Radiative decay counter (RDC)





Cylindrical drift chamber (CDCH)

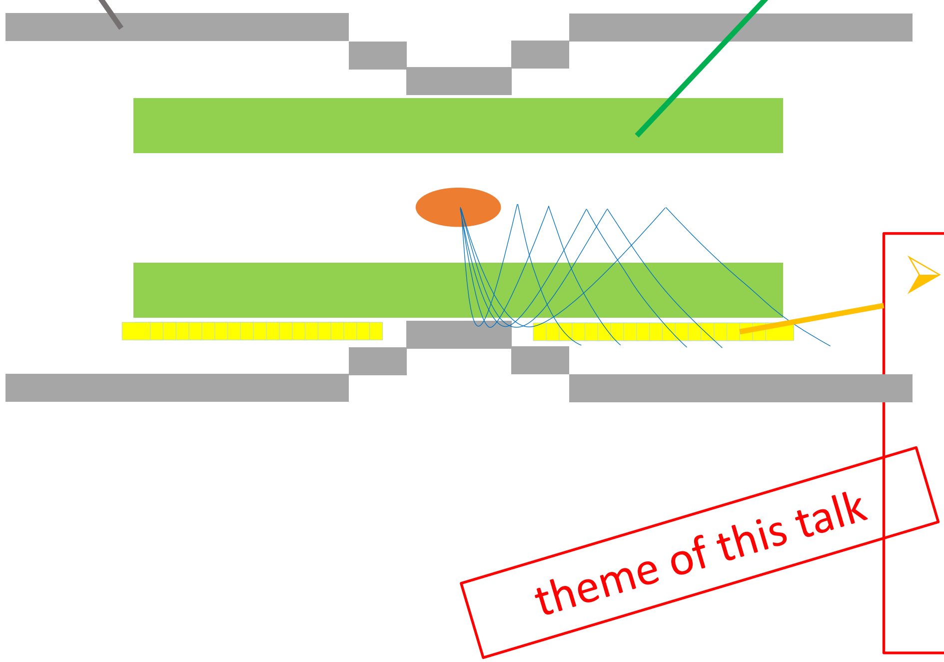


Pixelated timing counter (pTC)

Use most intense DC μ^+ beam at PSI

Positron spectrometer

- Constant bending radius (COBRA) magnet
  - Superconducting solenoid with gradient magnetic field
  - Bends signal positrons with constant radius independent of emission angle
  - Sweeps positrons away from central region

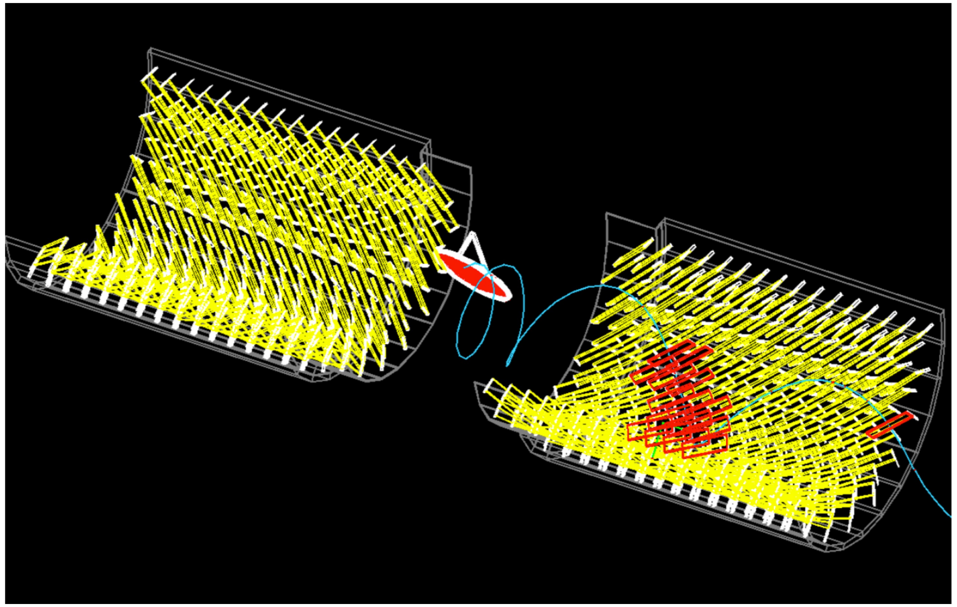


- Cylindrical drift chamber (CDCH)
  - Single-volume, full-stereo, wire chamber
  - Reconstructs positron track (i.e. E_{e^+}, θ_{e^+})
- Pixelated timing counter (pTC)
  - Plastic scintillator + SiPM readout
  - Reconstructs positron time (i.e. t_{e^+})

pTC design

Overall design

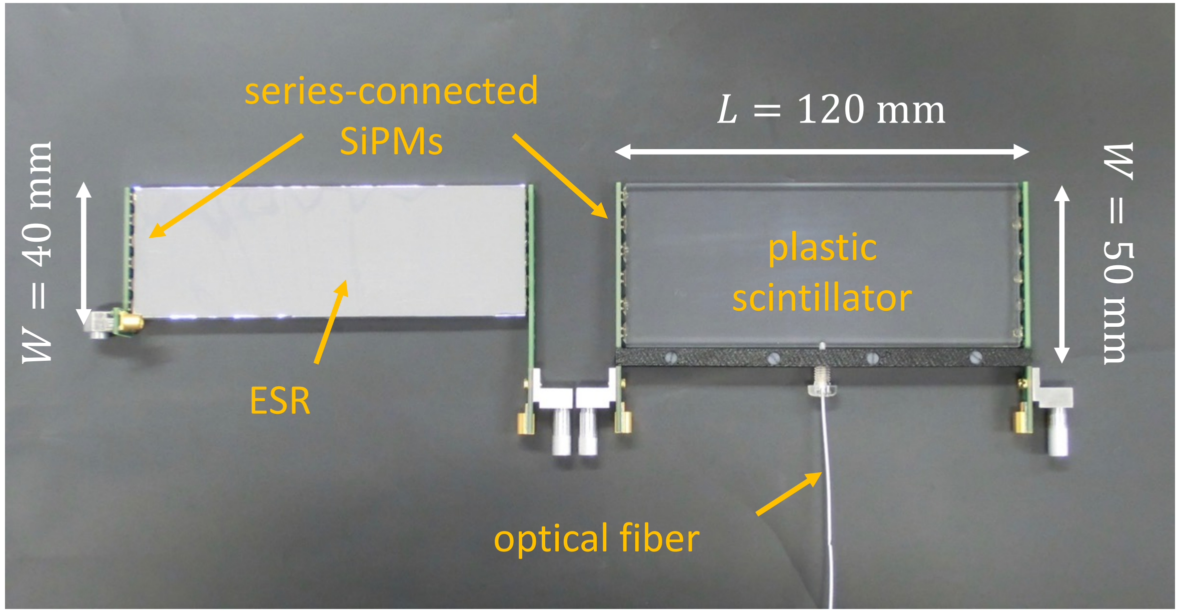
- 512 pixels laid cylindrically upstream & downstream of target



Positron event display

Single-pixel design

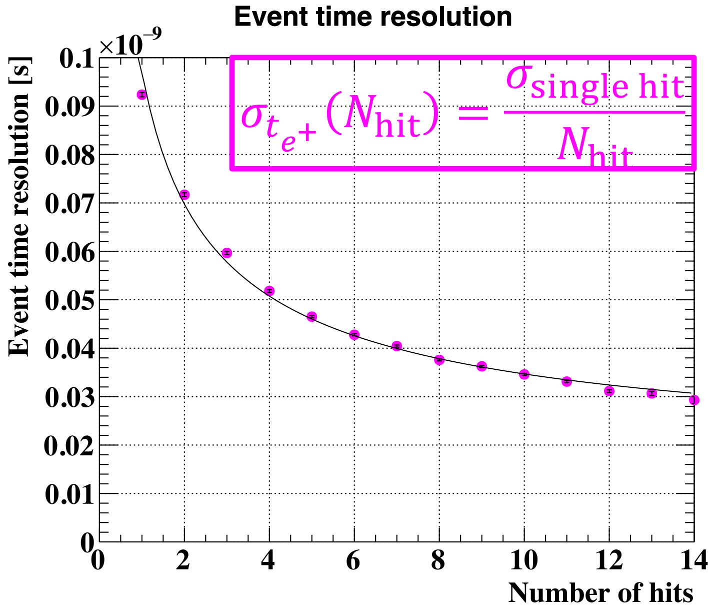
- 40/50 mm×120 mm×5 mm plastic scintillator + 6 series-connected SiPMs × 2
- Laser light can be inserted from fiber below



pTC performance

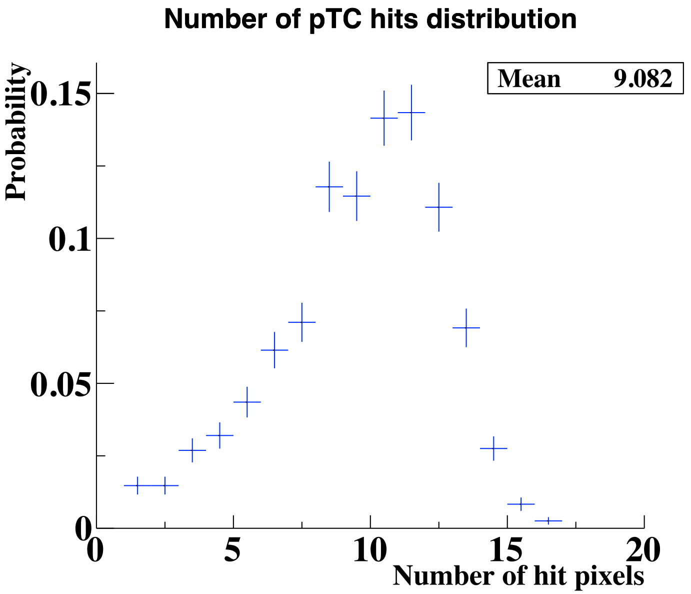
➢ Multiple pixel hit scheme

- Average number of pixel hits: ~9
- Single-pixel resolution: ~80-100 ps
- Overall resolution improves with $^{1}/_{\sqrt{N_{\mathrm{hit}}}}$ → ~38 ps



pTC time resolution

×



Number of hits distribution

= ~38 ps

pTC status

General status

- pTC has already been operated in past 5 years

What is already achieved

- Detector construction
- Basic operation methods
  - Insertion & extraction, cooling system, ...
- Calibration methods
  - Energy deposit, position, time, ...
- Analysis
  - Waveform analysis, hit reconstruction, clustering, tracking
- Performance evaluation

Tasks for pTC

- Detailed study on effect of radiation damage to SiPMs revealed that pTC resolution can degrade by ~20 % in 3 years' data taking (c.f. backup slide)
- pTC must be operated at high performace in long term

Motivation of this study

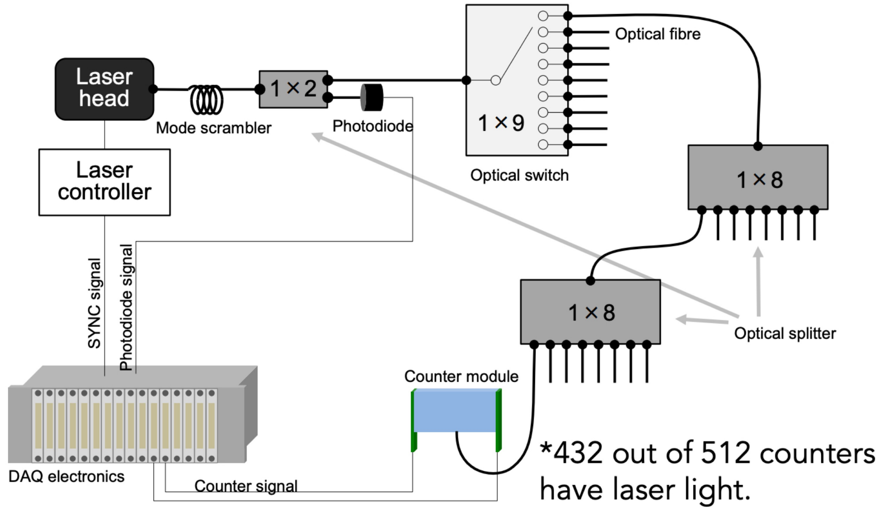
- Develop methods to bring out maximum performance of pTC in long term
  - Optimize bias voltage to SiPMs
  - Optimize constant fraction (CF) parameter in waveform analysis

Outline

Upgrade concept

Conventional optimization scheme

1. Perform overvoltage scan w/ laser system (c.f. backup slide)
2. Choose overvoltage (common to all channels) which yields best time resolution



pTC laser system

What is known so far

- Time resolution depends strongly on signal-to-noise ratio (S/N)
- Radiation damage to SiPMs can moderately increase dark noise
- Dose level depends on global pixel position

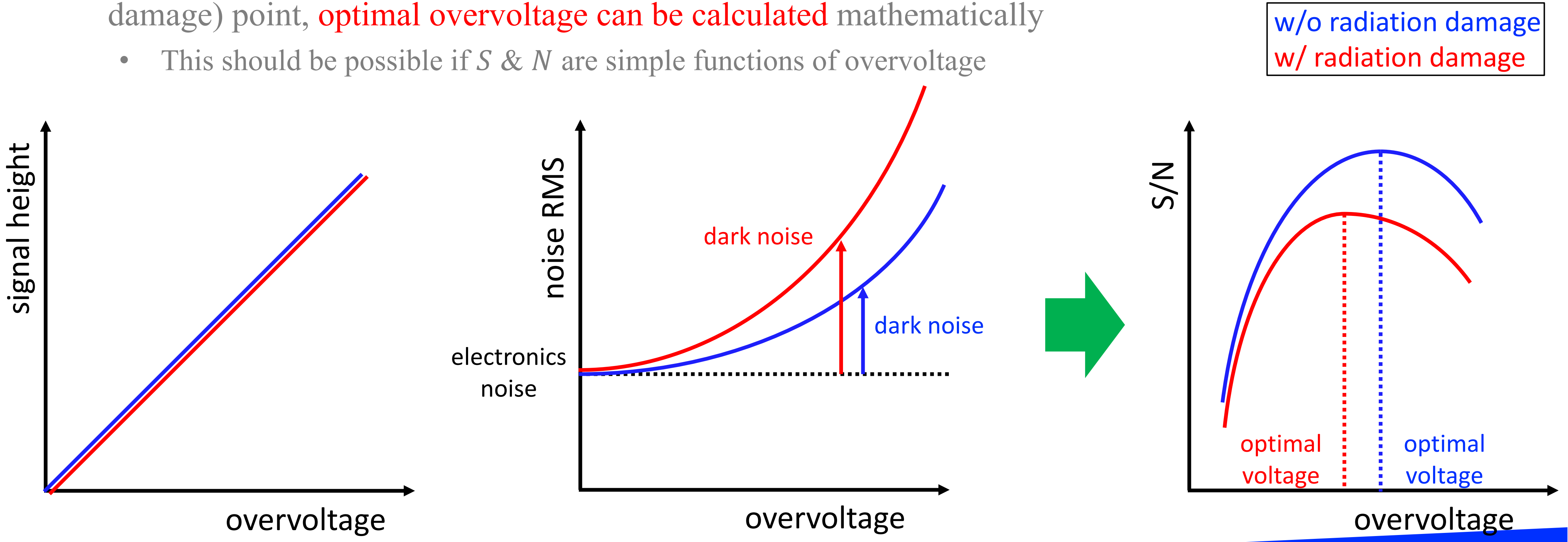
Possible improvements for long-term operation

- Channel-by-channel optimization (Dark noise increase rate differs from channel to channel)
- Online optimization using observed S/N (Conventional scheme requires dedicated DAQ)

New optimization scheme

➢ General idea

- Best time resolution should be achieved when S/N is maximized
- If we can estimate overvoltage dependence of S & N at each time (radiation damage) point, optimal overvoltage can be calculated mathematically
  - This should be possible if S & N are simple functions of overvoltage



Lab test

Measurement

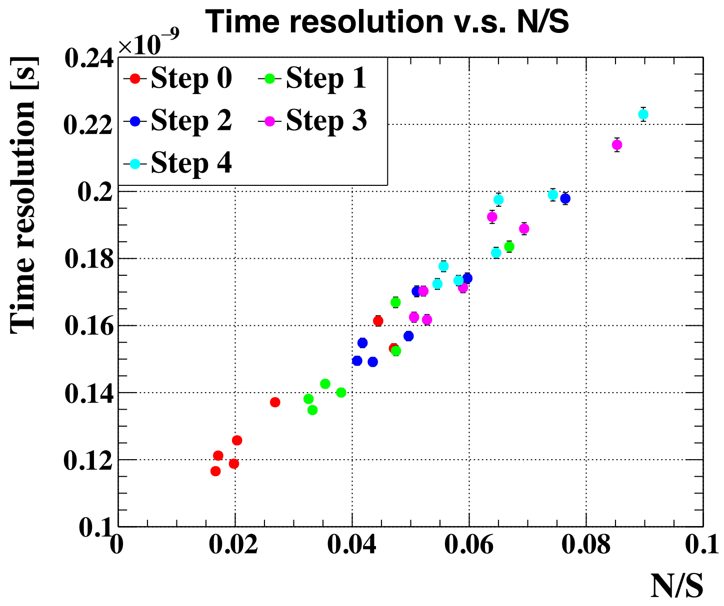
- To see effect of radiation damage, SiPMs were irradiated w/ ^{90}Sr source in 4 steps
- Bias voltage scan was performed at each damage step

Damage step	Irradiation time	Dose level
0	0 hours	$0\ n_{1\ \mathrm{MeV}}/\mathrm{cm}^2$
1	70 hours	$7.5\times10^8\ n_{1\ \mathrm{MeV}}/\mathrm{cm}^2$
2	140 hours	$1.5\times10^9\ n_{1\ \mathrm{MeV}}/\mathrm{cm}^2$
3	210 hours	$2.25\times10^9\ n_{1\ \mathrm{MeV}}/\mathrm{cm}^2$
4	280 hours	$3\times10^9\ n_{1\ \mathrm{MeV}}/\mathrm{cm}^2$

Time resolution & S/N

- Time resolution has linear correlation w/ N/S (inverse of S/N)

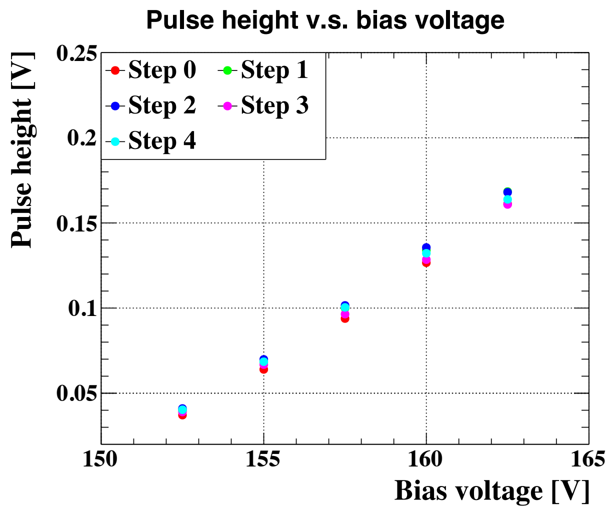
→ Find overvoltage to maximize S/N



Lab test

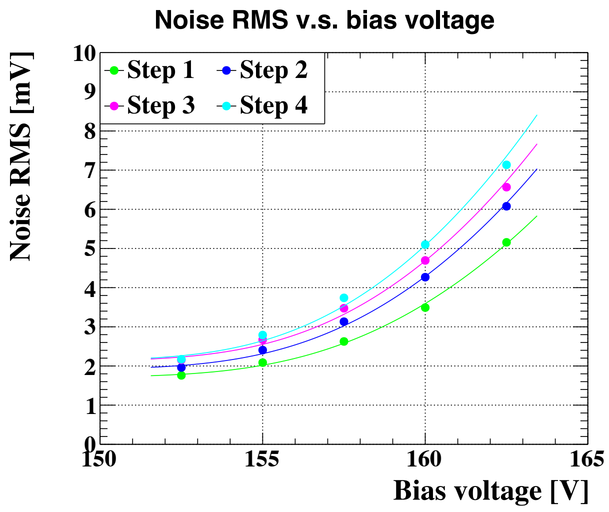
➢ S dependence

- S clearly has linear relation w/ overvoltage
- Radiation damage does not affect S



➢ N dependence

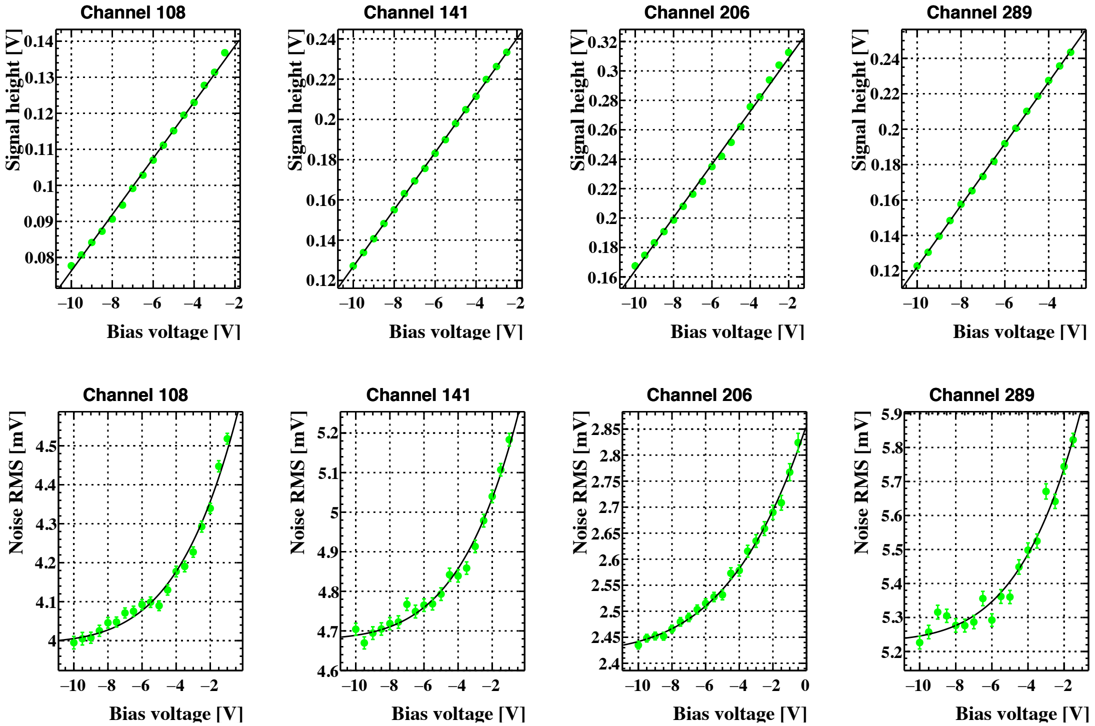
- Overvoltage dependence of $N = \sqrt{N_{\mathrm{SiPM}}^2 + N_{\mathrm{elec}}^2}$ can be described well by assuming
  - $N_{\mathrm{SiPM}} = C(V - V_{\mathrm{breakdown}})^3$
  - $N_{\mathrm{elec}} =$ constant.
- All curves can be fitted solely by changing C



Application to pTC data

➢ pTC laser data

- Linearity of S was verified
- Overvoltage dependence of N can also be fitted well w/ assumed function



➢ Application to beam data

1. Obtain $V_{\mathrm{breakdown}}$ from I-V data
2. Obtain overvoltage dependence of S & N from laser bias voltage scan
3. Convert overvoltage dependence of S for beam data
4. Calculate optimal overvoltage

➢ Verification of new scheme

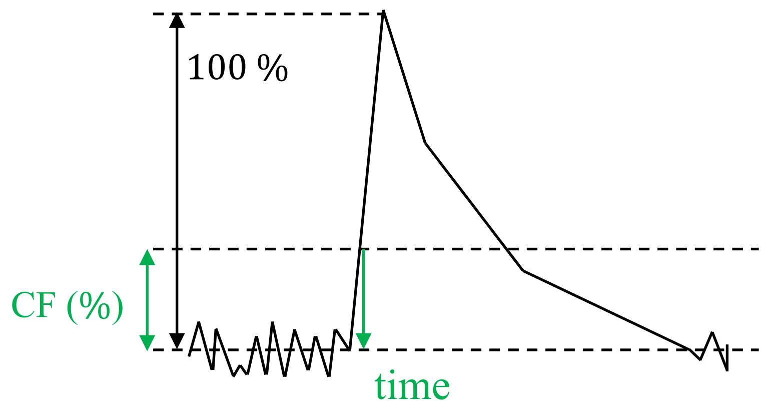
- We did not have time for beam data
- Effect of this scheme has not been verified

Outline

Upgrade concept

➢ pTC analysis

- Constant fraction (CF) method is used to obtain signal time in waveform analysis



➢ Conventional optimization scheme

1. Perform CF scan using beam data
2. Choose CF value (common to all channels) which yields best time resolution

➢ What is known so far

- Optimal CF value strongly depends on noise level
- Radiation damage to SiPMs can moderately increase dark noise
- Dose level depends on global pixel position

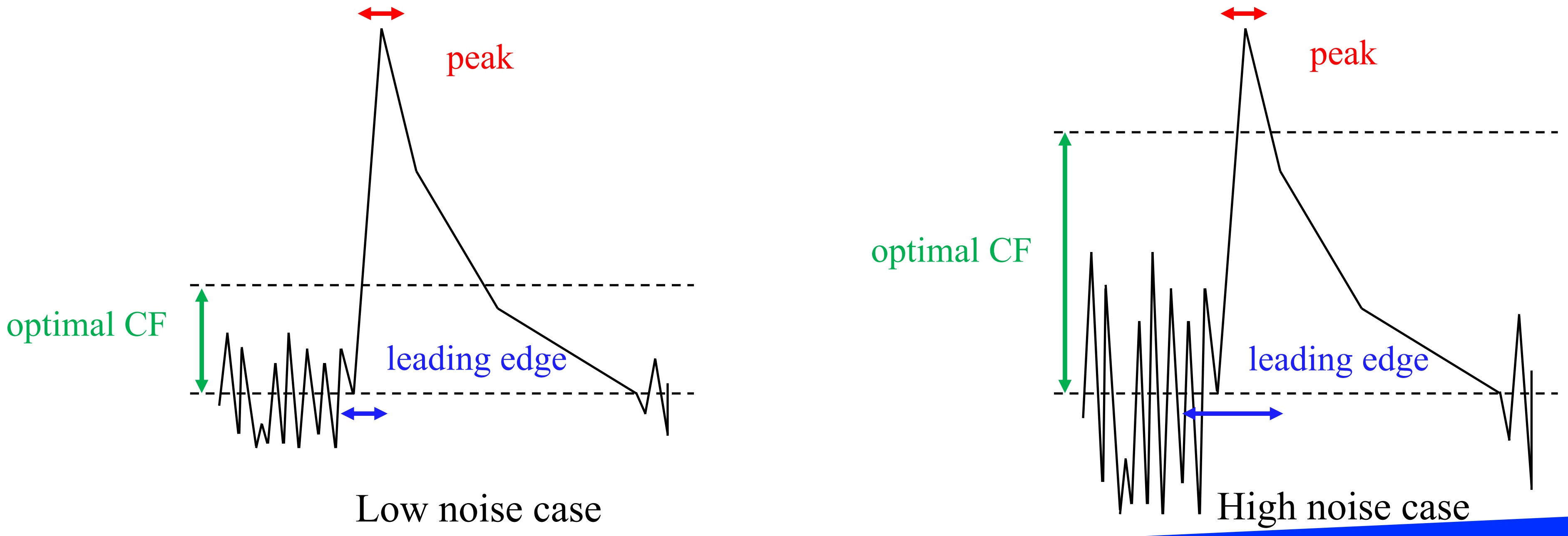
➢ Possible improvements for long-term operation

- Channel-by-channel optimization
(Dark noise increase rate differs from channel to channel)

New optimization scheme

➢ General idea

- Optimal CF should be determined by balance between fluctuation of leading edge & peak time (i.e. S/N)
  - Low noise = small baseline fluctuation = small leading edge fluctuation = lower CF preferred
  - High noise = large baseline fluctuation = large leading edge fluctuation = higher CF preferred
- S/N may be used to determine optimal CF



Lab test

➢ Measurement

- To see effect of radiation damage, SiPMs were irradiated w/ ^{90}Sr source in 4 steps
- Bias voltage scan was performed at each damage step

➢ Analysis

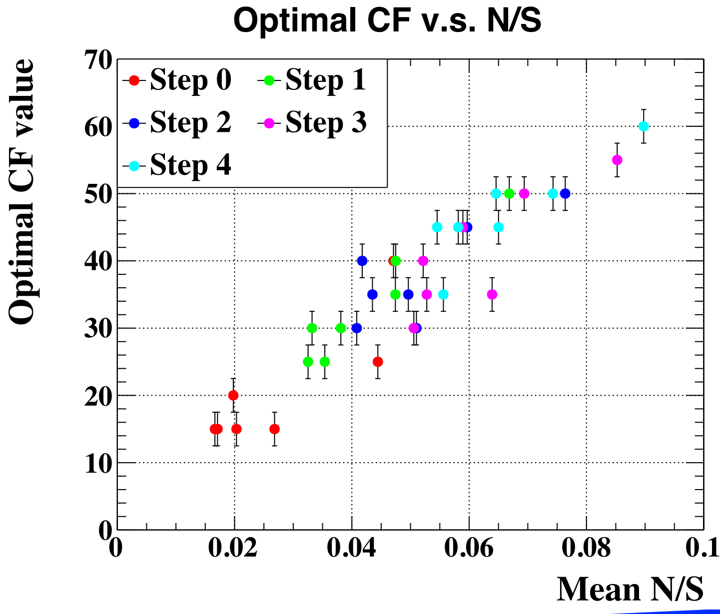
- CF scan was performed in steps of 0.05 from 0.1 to 0.6 for each dataset

→ Optimal CF value (i.e. w/ best time resolution) was obtained for each dataset

➢ Optimal CF & S/N

- Optimal CF has linear correlation w/ N/S (inverse of S/N)

→ Optimal CF can be determined simply from observed S/N

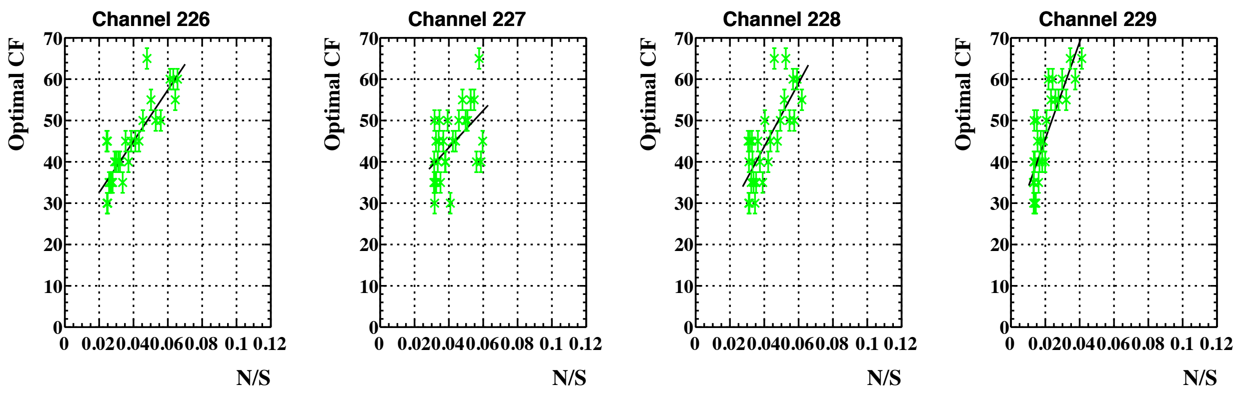


Application to pTC data

➢ pTC laser data

- Linear correlation between optimal CF & N/S was verified for all channels
- Channel individuality seems pretty large

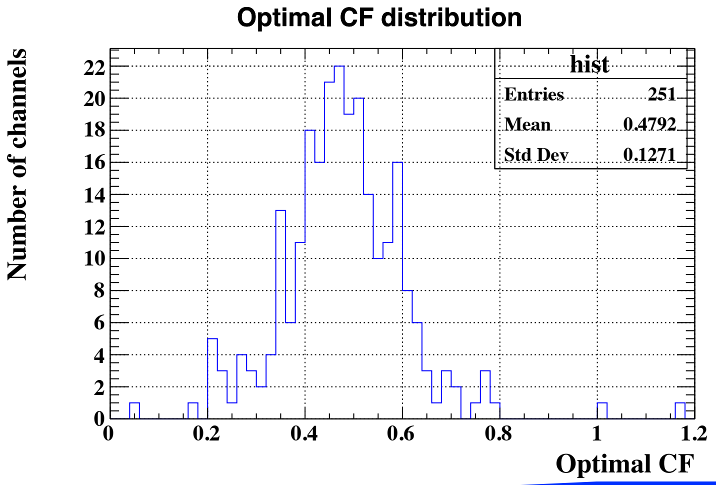
→ Channel-by-channel optimization should be effective



➢ Application to beam data

1. Obtain relation between optimal CF v.s. N/S
2. Obtain N/S in beam data
3. Calculated optimal CF from 1. & 2.

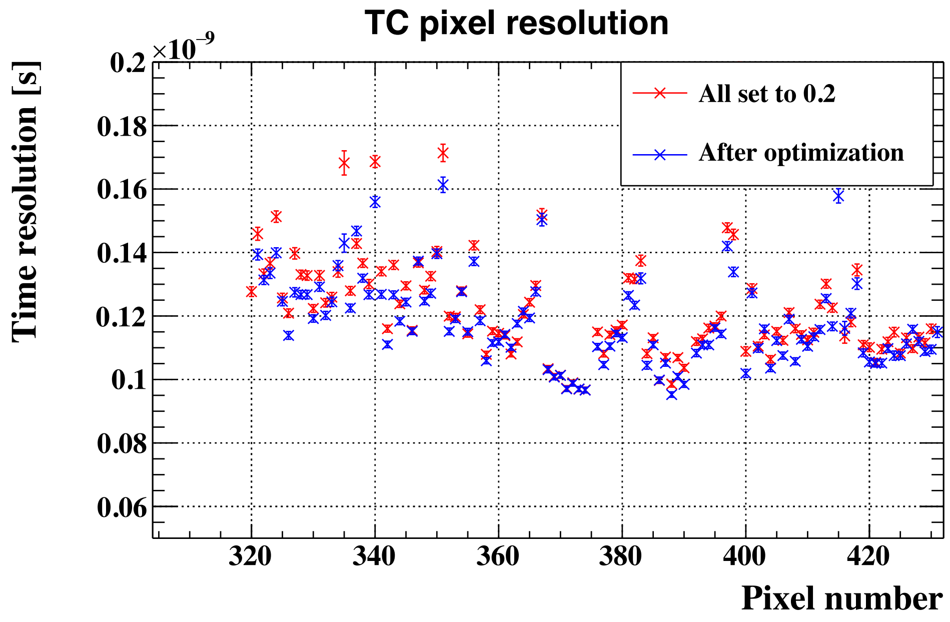
- Optimal CF has wide distribution



Application to pTC data

➢ Verification of new scheme

- Each pixel time resolution was evaluated (w/ 2-hit analysis) using beam data
- Pixel time resolution improved for all channels & by ~3 % on average



Effect of new optimization scheme

Outline

Summary & prospect

➢ Summary

- MEG II pTC measures positron time w/ ~38 ps resolution
- Considering effect of radiation damage to SiPMs, effective optimization of operation & analysis parameters is needed to bring out maximum performance of pTC in long term
- New optimization scheme of bias voltage was developed, which allows online, channel-by-channel optimization w/o dedicated DAQ
- New optimization scheme of CF was developed, which allows channel-by-channel optimization

→ This improved pTC resolution by ~3 %, even w/o radiation damage

➢ Prospect

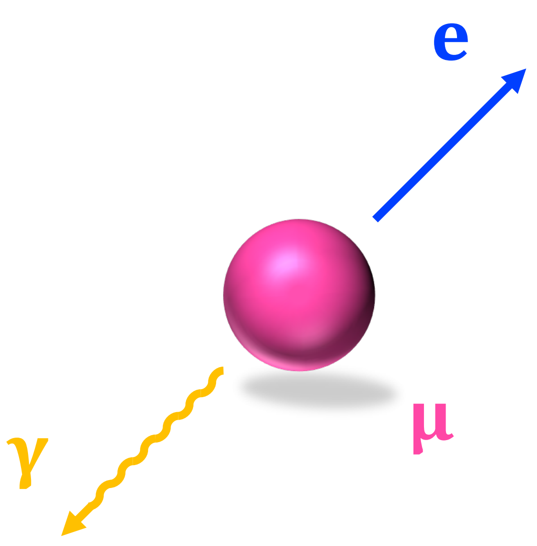
- Attempt new bias voltage optimization
- Evaluate its effect on pTC resolution using beam data

Backup Slides

Signal & background

➢ Signal

- $E_{e^+} = E_\gamma = \frac{m_\mu}{2} \simeq 52.8\ \mathrm{MeV}$
- $t_{e^+\gamma} = 0$
- $\theta_{e^+\gamma} = 180°$



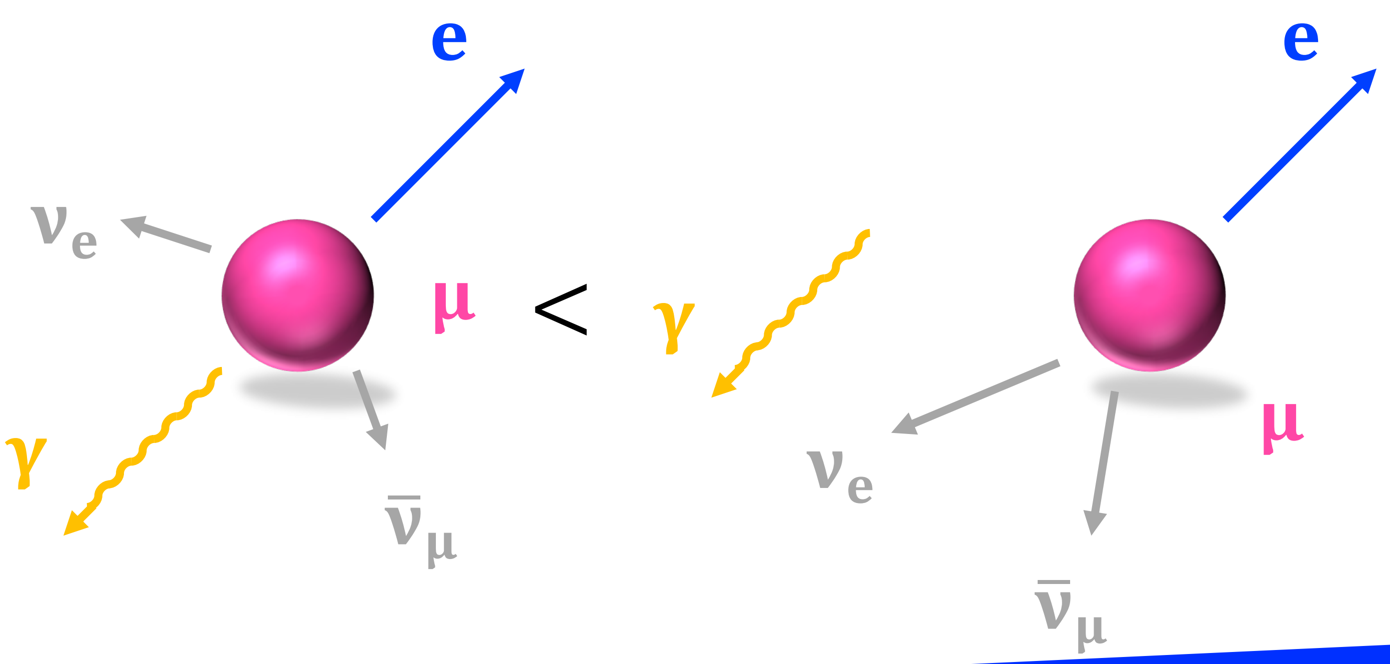
➢ Background

Physics background

- Radiative muon decay (RMD)
- $E_{\nu_e} \simeq 0,\ E_{\bar{\nu}_\mu} \simeq 0$
- $\theta_{e^+\gamma} \simeq 180°$

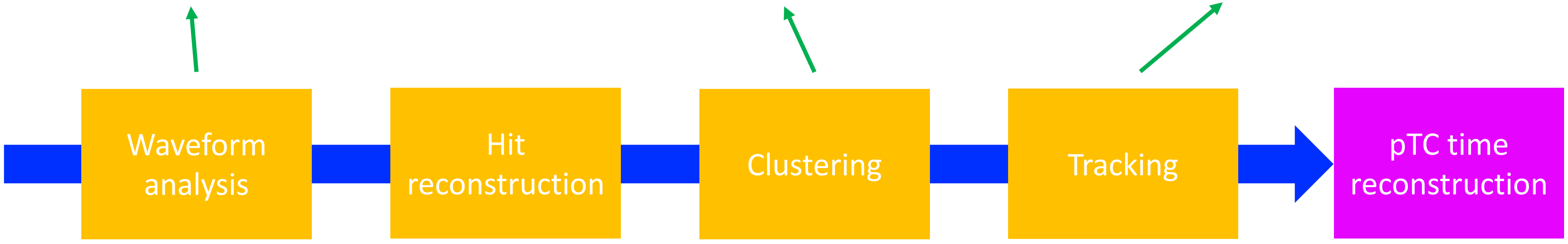
Accidental background

- Michel e^+
- RMD or AIF γ

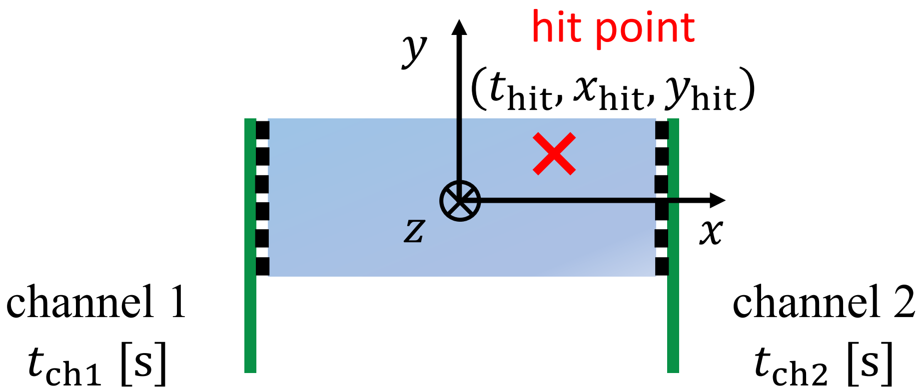


pTC analysis

- **Waveform analysis**
  - Obtain signal time in each channel using CF method
- **Clustering**
  - Group hits from the same positron track
- **Tracking (pTC tracking)**
  - Reconstruct positron track from pTC pixel hits



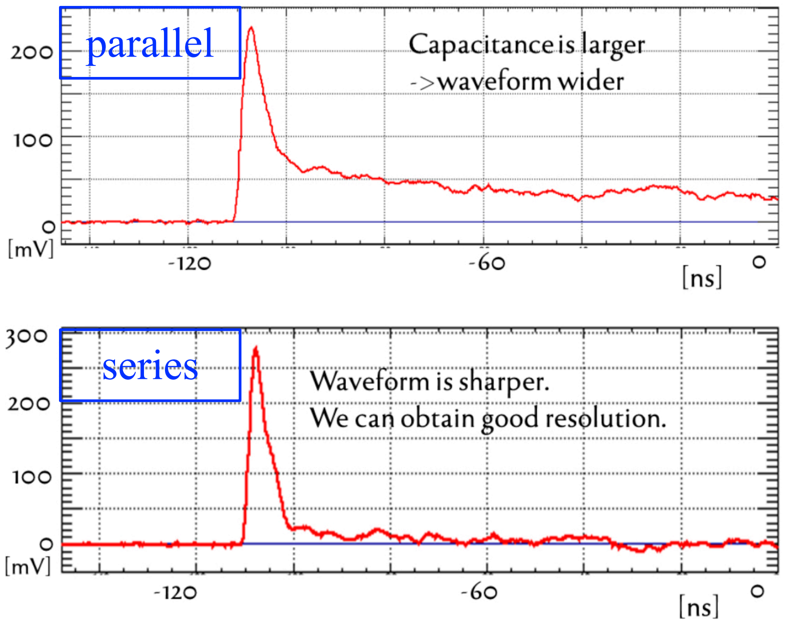
- **Hit reconstruction**
  - Obtain each pixel hit time, x hit position & energy desposit
    - $t_{\mathrm{hit}} = \frac{t_{\mathrm{ch1}}+t_{\mathrm{ch2}}}{2} - \frac{L}{2v_{\mathrm{eff}}} - t_{\mathrm{offset}}$
    - $x_{\mathrm{hit}} = \frac{t_{\mathrm{ch1}}-t_{\mathrm{ch2}}+\delta t}{2} v_{\mathrm{eff}}$
    - $E_{\mathrm{dep}} = C_E\sqrt{Q_{\mathrm{ch1}} \cdot Q_{\mathrm{ch2}}}$



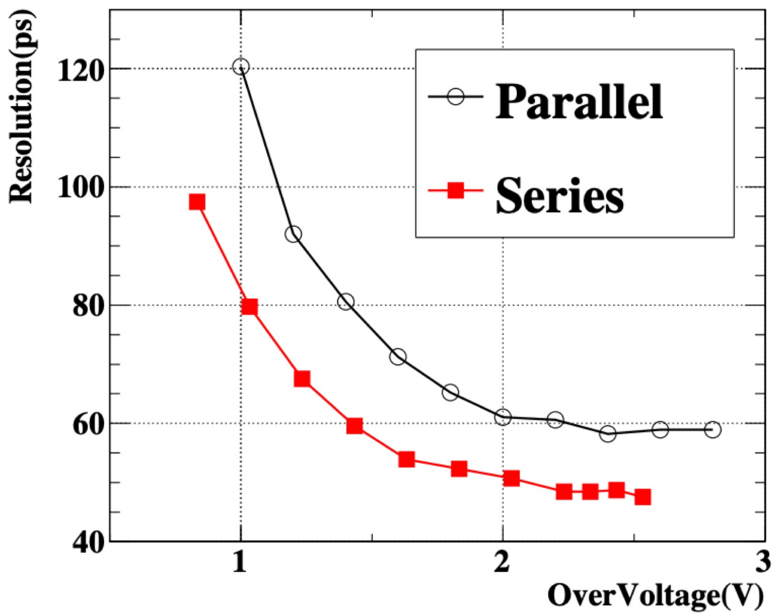
SiPMs in pTC

➢ Connection of SiPMs

- Parallel connection → large capacitance → blunt waveform → bad time resolution
- Series connection → small capacitance → sharp waveform → good time resolution



pTC waveform

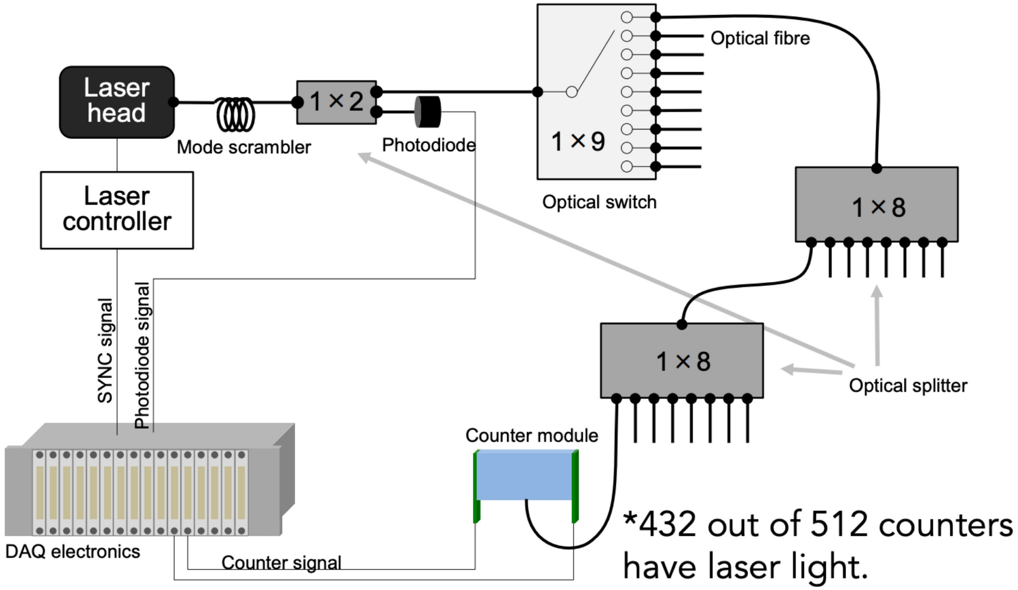


Time resolution

Laser system

➢ System

- Laser light is divided using optical splitters and can be **injected into $^{432}/_{512}$ pixels**
- Can be used for various **DAQ w/o beam**



pTC laser system

➢ Time calibration

- Laser light can be injected into multiple pixels simultaneously
- Optical length of laser components are measured beforehand
- **Time calibration between pixels** can be performed

Radiation damage to SiPMs

➢ Damage type

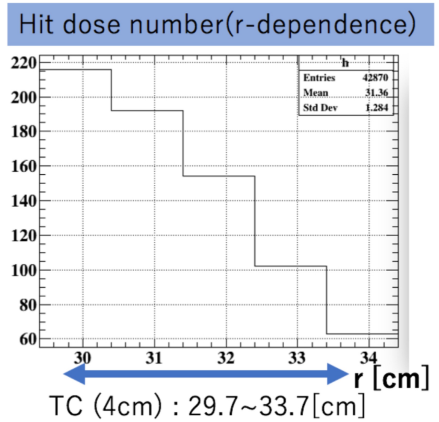
- Bulk damage can be induced by collision of energetic particles
- Result in increase of bulk leakage current
- Dominant damage in MEG II pTC (surface damage is negligible)

➢ Damage level

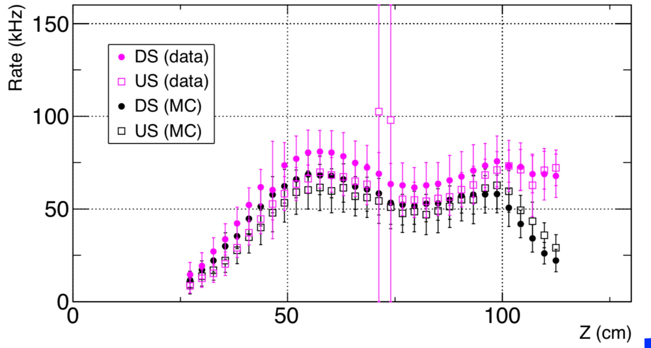
- $\sim 1\times10^{11}\ e^{+}/\mathrm{cm}^2$ exposure of ~50 MeV positrons in 3 years
- Absorbed dose: ~25 Gy
- Current increase: from $\mathcal{O}(1)$ μA to ~100 μA
- Equivalent to $\sim 5\times10^{9}\ n_{1\ \mathrm{MeV}}/\mathrm{cm}^2$

➢ Position dependence of dose level

- Damage level is different within series-connected SiPMs



- Damage level depends on global pixel position



Effect of radiation damage to SiPMs

➢ Dark noise increase

- Radiation damage to SiPMs is known to increase dark noise of SiPMs
- Time resolution is dependent on S/N
- Single-pixel resolution can worsen by ~30 % at 30 ℃
- pTC is planned to be operated at 10 ℃, and resolution deterioration is expected to be suppressed to ~5 %

➢ Hit position dependent time fluctuation

- Vertical hit position dependence of time center exists due to finite signal propagation time
- This can be enhanced by a gradient radiation damage to SiPMs, as in MEG II pTC

→ Resolution deterioration is estimated to be ~15 % in 3 years