MEG II 実験における陽電子タイミングカウンターの解析手法の改善

Study on improving the analysis of the pixelated Timing Counter in the MEG II experiment

2019/09/17

日本物理学会 2019年秋季大会

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Core-to-Core Program

Outline

➢Introduction of MEG II
- MEG II experiment
- pTC design
- pTC performance

➢Introduction of this study
- Aim & motivation
- Overview

➢Lab test
- Measurement setup
- Pulse height behavior
- Time center behavior

➢Effect on MEG II
- MC study
- Correction using data

➢Summary & prospect

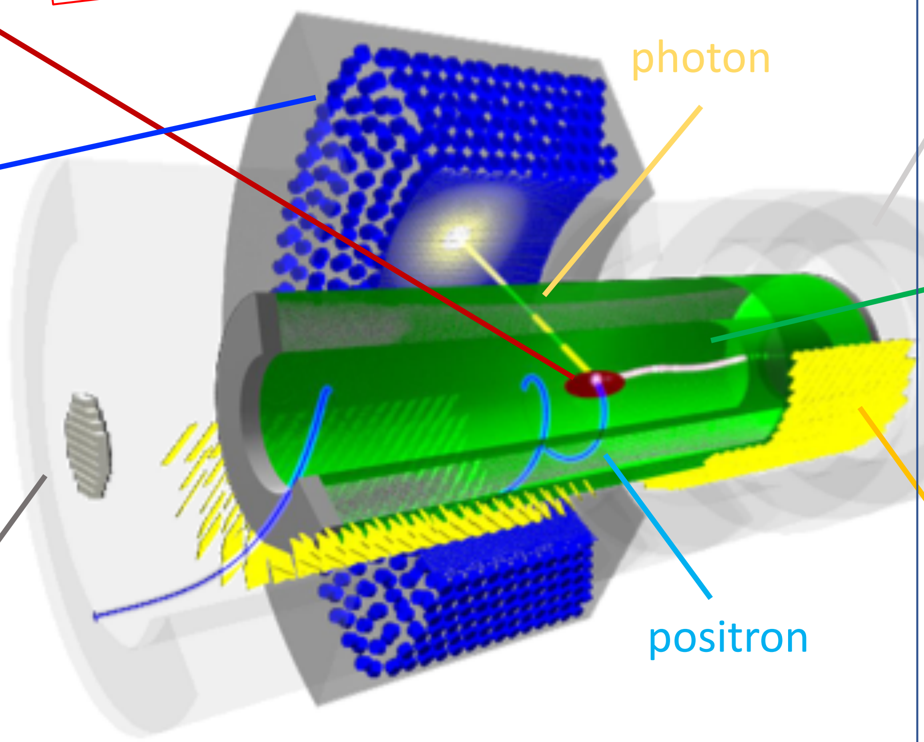
MEG II experiment

- ➢ Target
  - Stops muons inside target
- ➢ Liquid Xenon (LXe) calorimeter
  - Detects signal photons

  c.f. 17aT12 小林、恩田
  19pT14 豊田、小川、家城
- ➢ Radiative decay counter (RDC)
  - Detects background positrons

  c.f. 18pT12 大矢

Use most intense muon beam at PSI



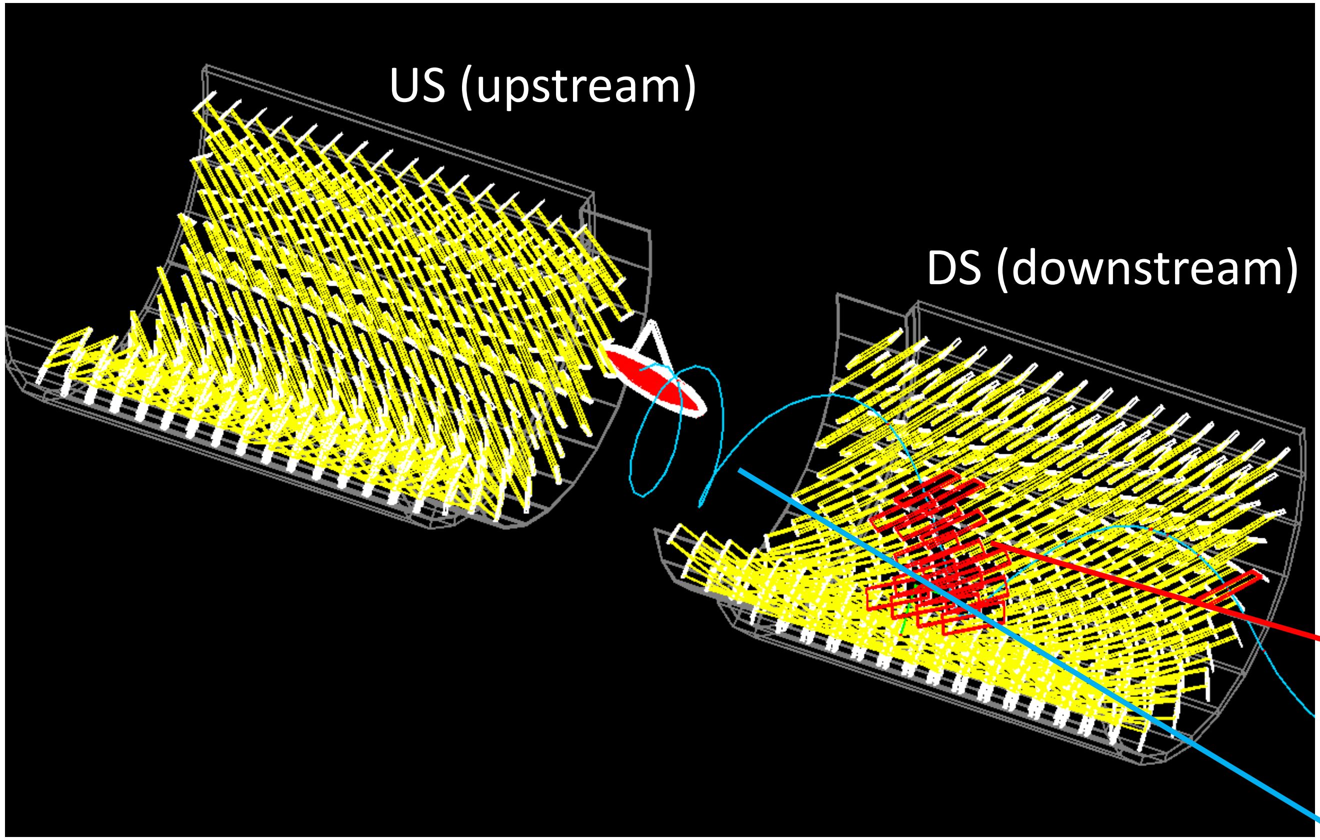
Search for $\mu^+ \rightarrow e^+\gamma$ reaction

Positron spectrometer

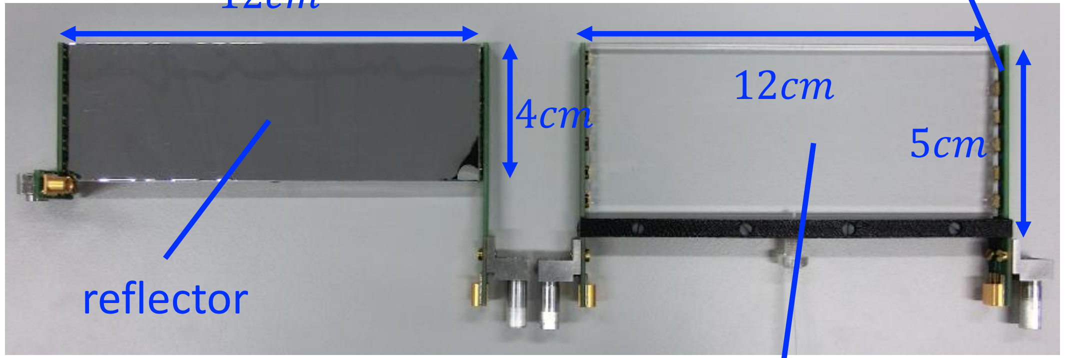
- ➢ Superconducting solenoid magnet (COBRA)
  - Bends signal positrons with constant radius
- ➢ Cylindrical drift chamber (CDCH)
  - Single volume wire chamber with He based gas
  - Reconstructs positron track
- ➢ Pixelated timing counter (pTC)
  - Plastic scintillator + SiPM readout
  - Reconstructs positron time

Introduction

➢pTC design



Positron event display



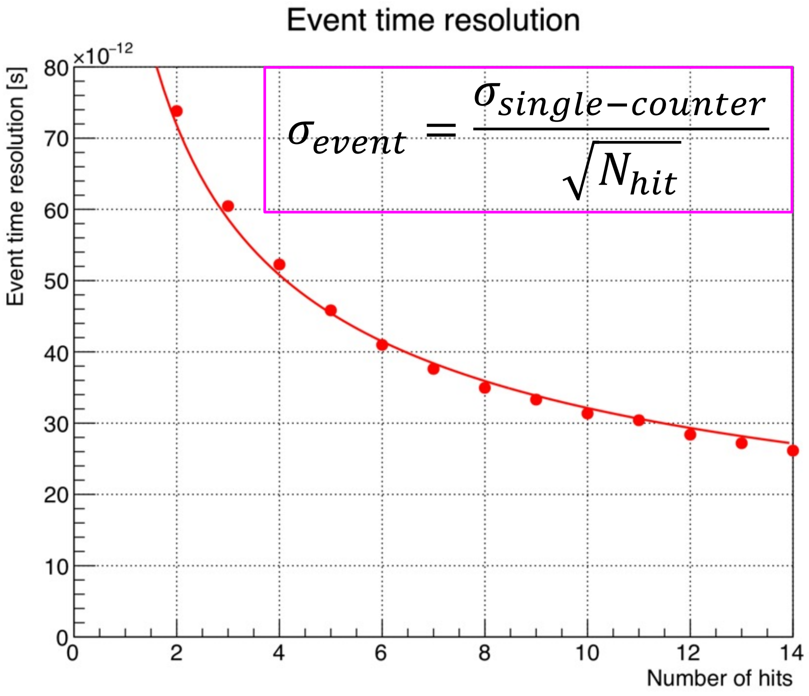
Single counter design

Pixelated design of pTC allows multiple-hits for signal positron event

Introduction

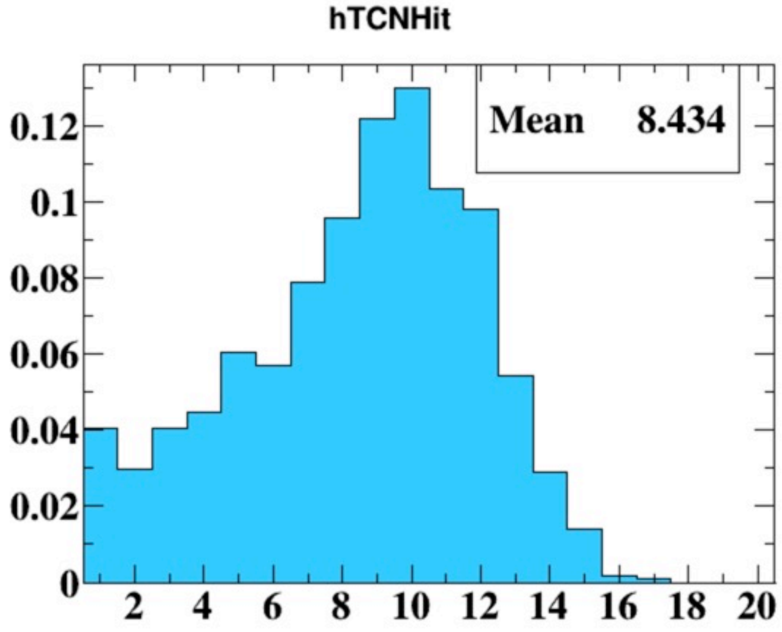
➢pTC performance

- Pixelated design allows N_{hit}~8 for signal event
- High time resolution can be achieved for multiple-hit events



pTC time resolution obtained from MC

×



Number of hits distribution

$= \sim 36.6ps$

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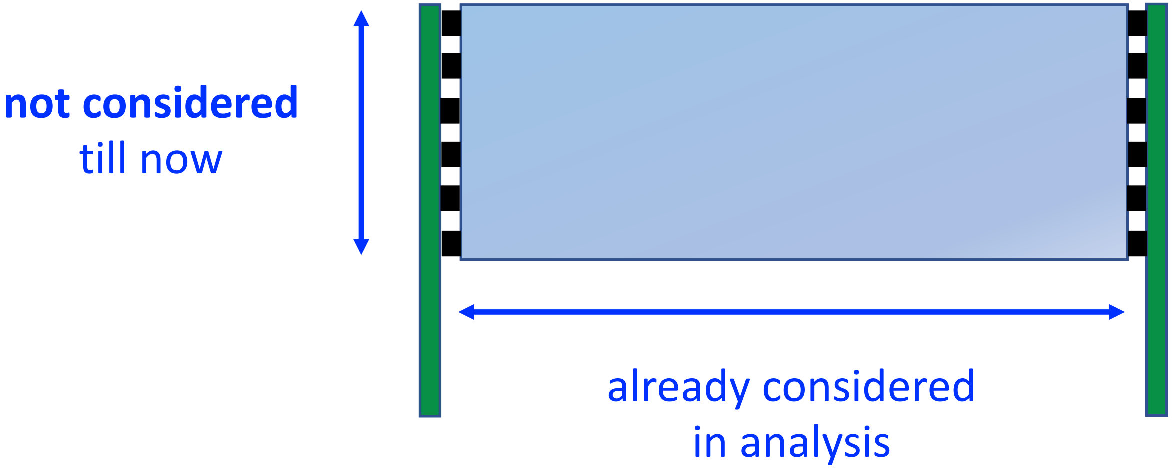
Aim & motivation

➢Aim

- Understand time response of detector & improve analysis algorithm

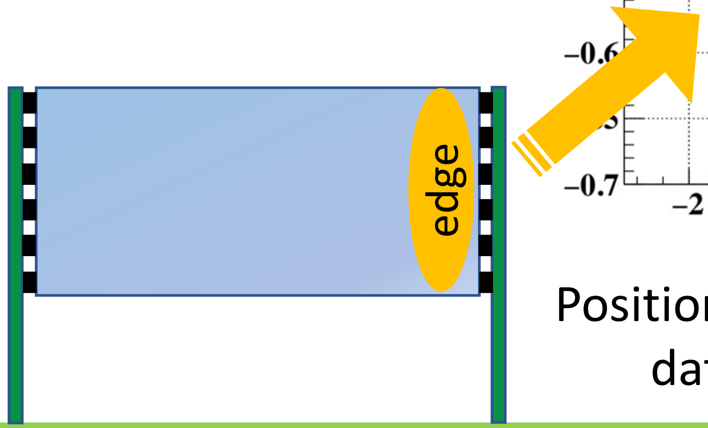
1. Investigate vertical position dependence of reconstructed hit time
2. Investigate how hit time is affected by (non-uniform) radiation damage to SiPMs
3. Attempt some time correction in offline analysis to improve pTC performance

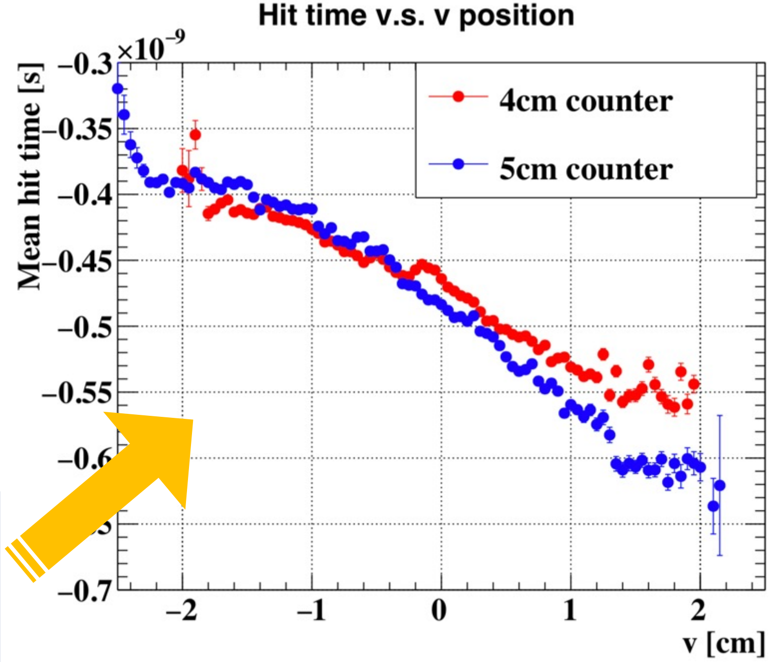


Aim & motivation

➢Motivation (1)

- Vertical position dependence is seen for "edge hits" in 2017 data

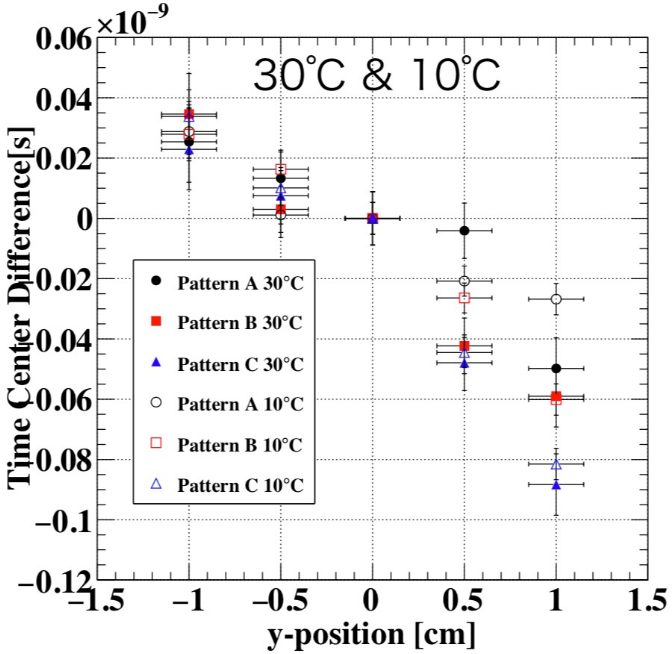




Position dependence from 2017 data using pTC tracking

➢Motivation (2)

- 宇佐見's previous study suggest that radiation damage can affect time center behavior



Position Scan at x=-4.25

宇佐見正志「SiPM直列接続読み出しにおけるシンチレーション時間検出器の放射線損傷による影響の評価」日本物理学会第74回年次大会

Overview

➢Lab test

- Position scan to check intrinsic vertical position dependence of hit time
- Position scan using SiPMs with different radiation damage patterns

➢Effect on MEG II pTC

- Reproduction of data with MC simulation
- Study effect of vertical time offset on pTC performance
- Time correction using MC simulation
- Time correction using pTC data

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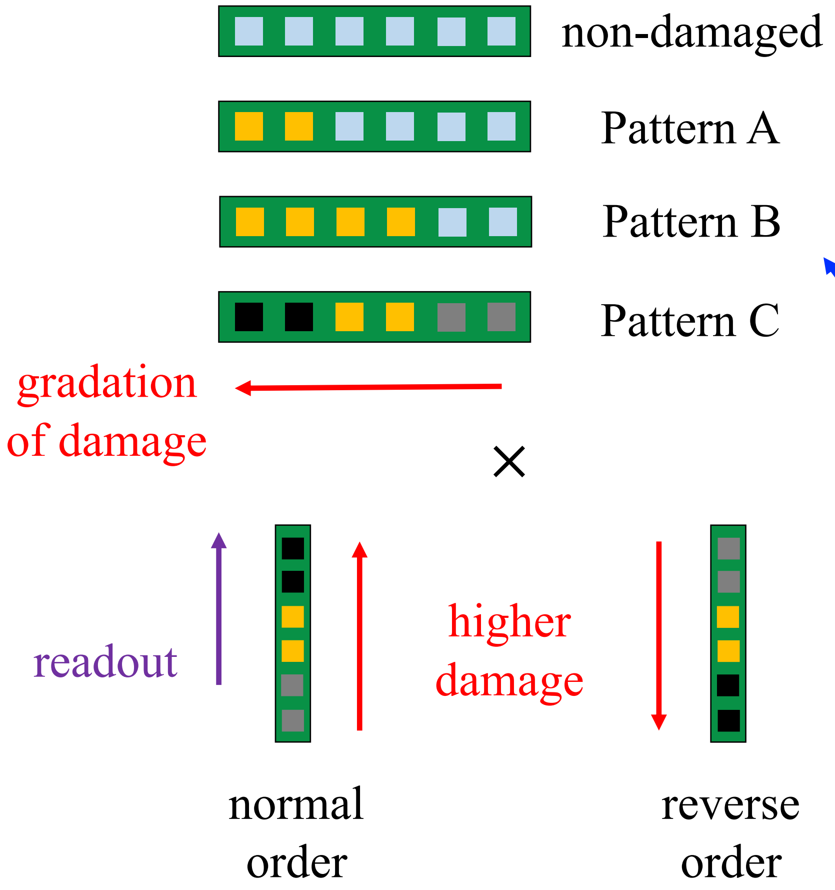
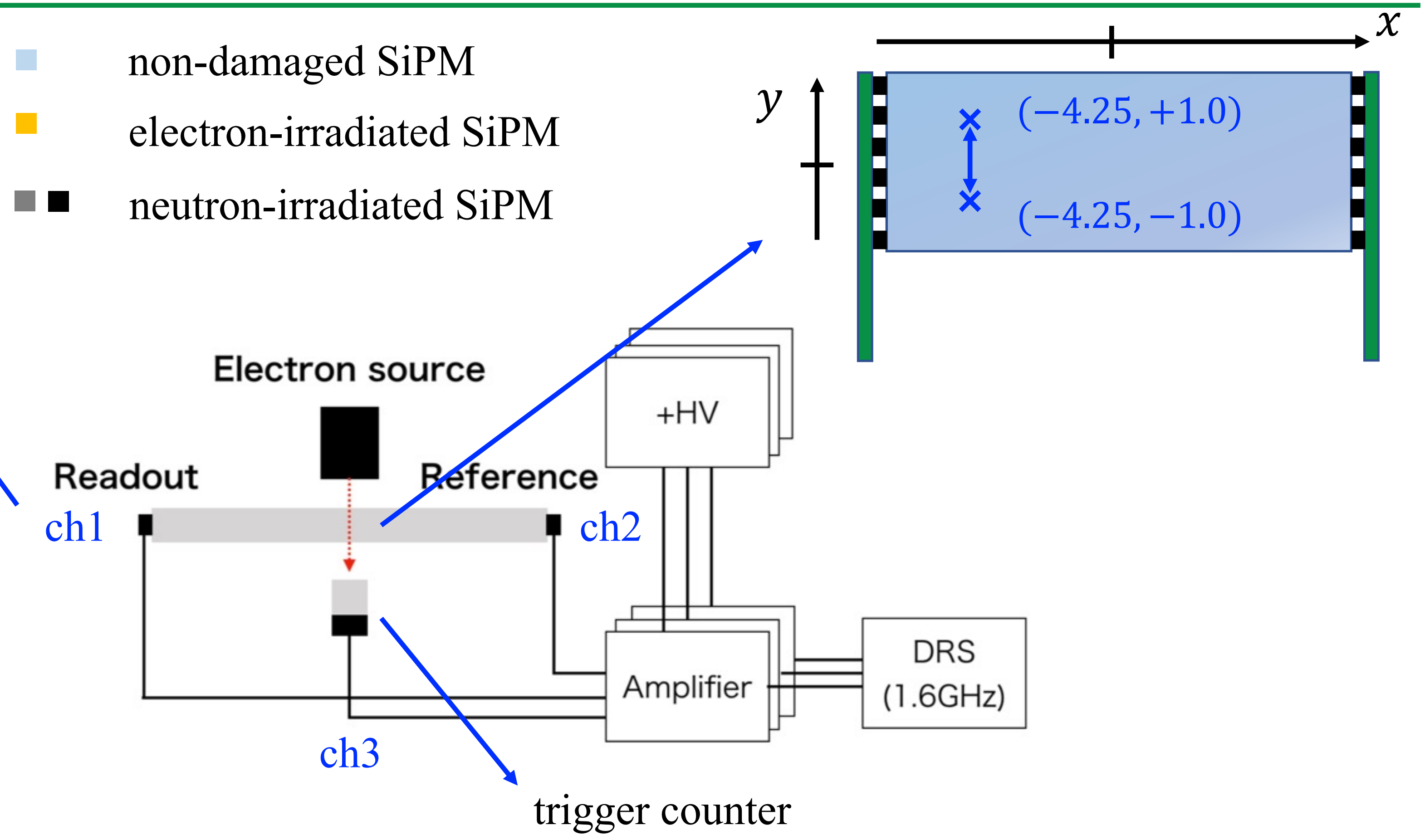
Measurement setup (1/2)



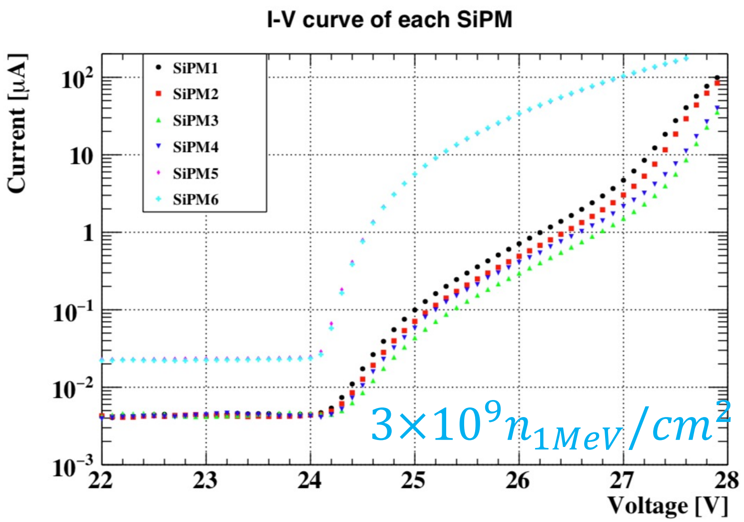


$$(Pulse\ height) = height_{ch1}$$
$$(Time\ center) = cftime_{ch1} - cftime_{ch3}$$

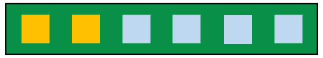
Measurement setup (2/2)

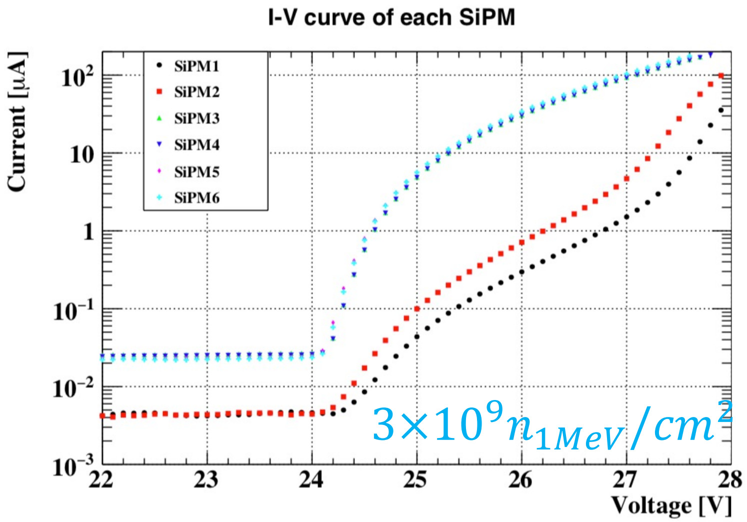
➢IV curves of used SiPMs

- Damage level of each SiPM is apparent from IV curves
- Damage level of pattern C is comparable to that expected in MEG II ($\sim 5\times10^{9} n_{1MeV}/cm^{2}$)

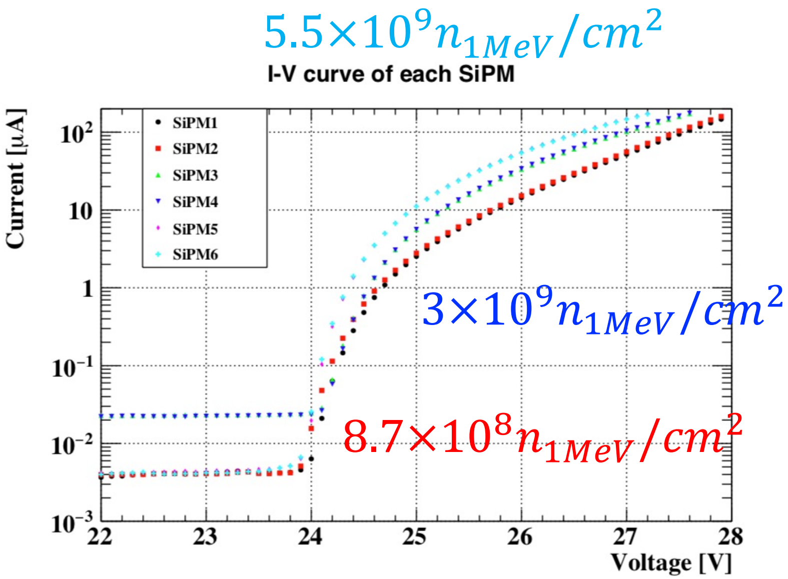


Pattern A





Pattern B

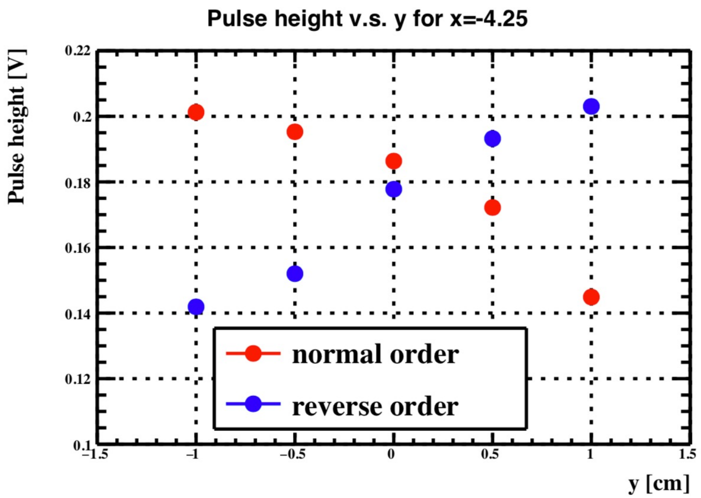


Pattern C

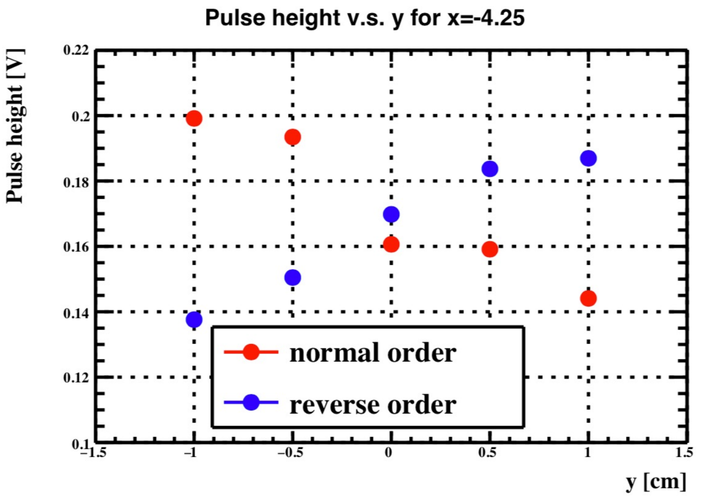
Pulse height behavior (1/2)

➢Result

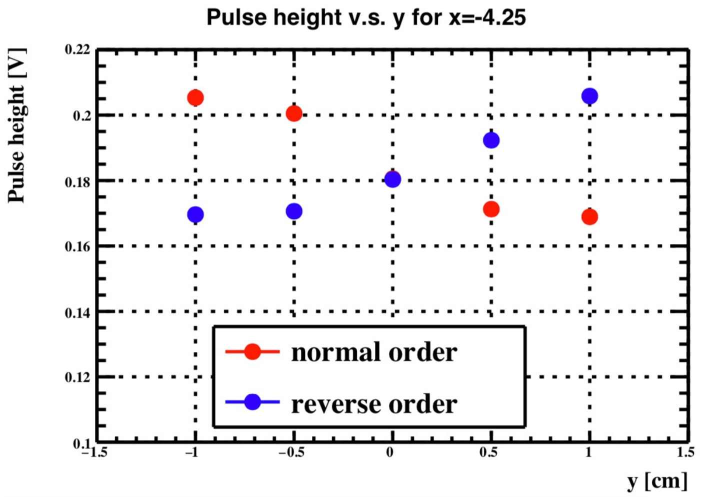
- Opposite behavior for normal & reverse order→ clear effect of radiation damage
- Pulse height is bigger when hit point is closer to less-damaged SiPM



Pattern A



Pattern B

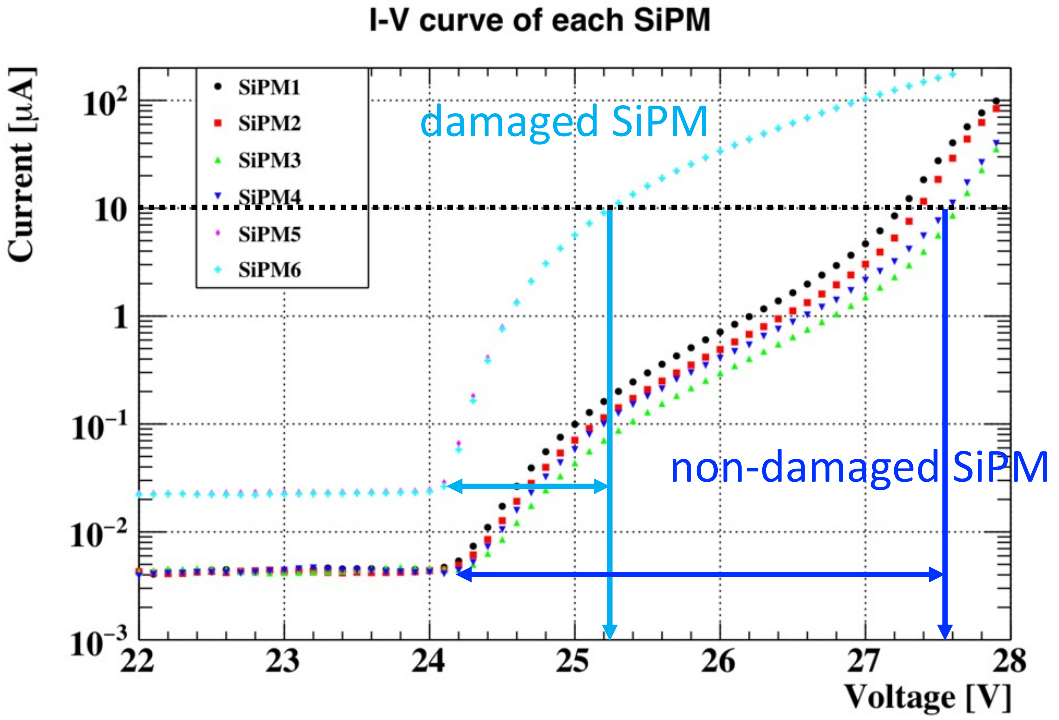


Pattern C

Pulse height behavior (2/2)

➢Interpretation

- Current flowing through each SiPM is common in series-connection
- Difference in I-V characteristics causes overvoltage difference between non-damaged & damaged SiPM
- Non-damaged SiPMs yield higher gain than damaged SiPMs

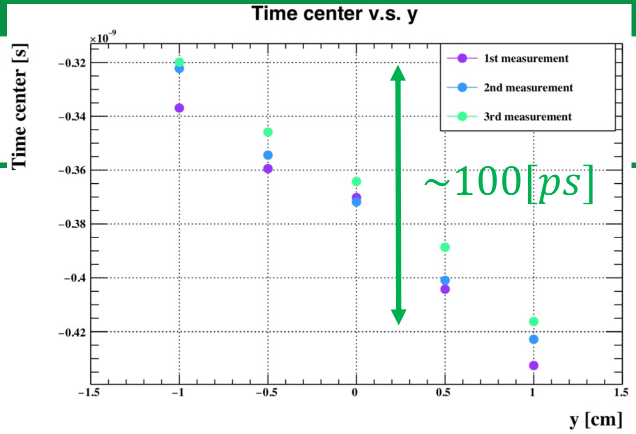


Pattern A

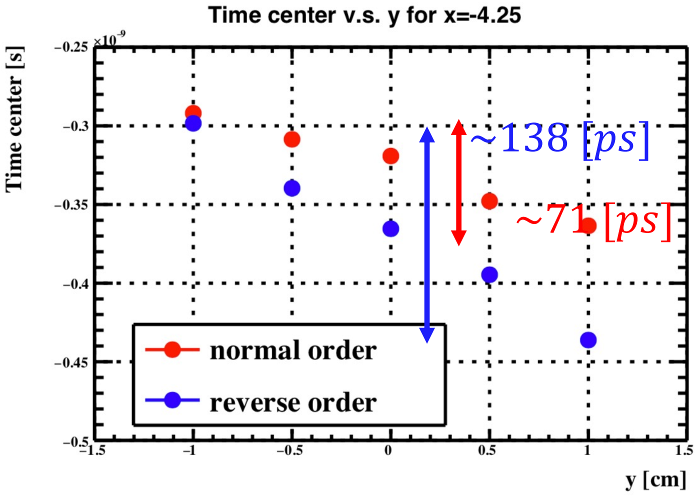
Time center behavior (1/2)

➢Result

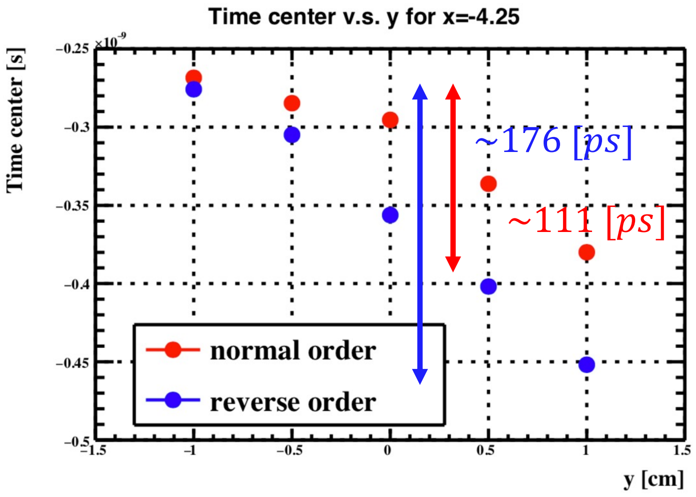
- Intrinsic time offset from counter $\sim 100\ [ps]$
- Similar behavior is seen in all patterns → clear effect of radiation damage
- Deviations from $\sim 100\ [ps]$ is additional effect from radiation damage



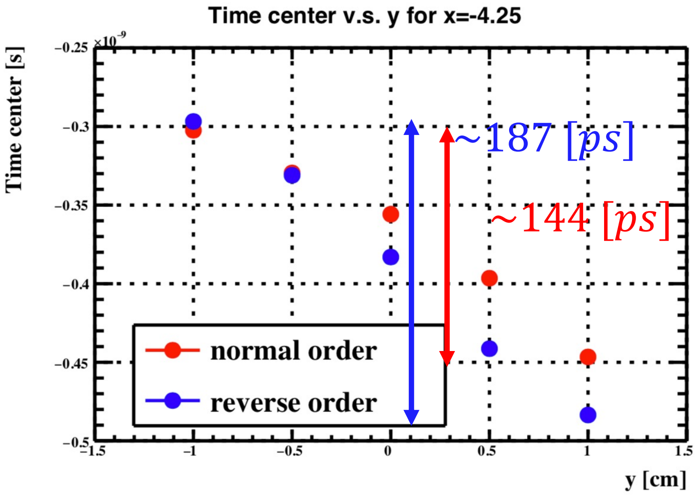
Non-damaged



Pattern A



Pattern B

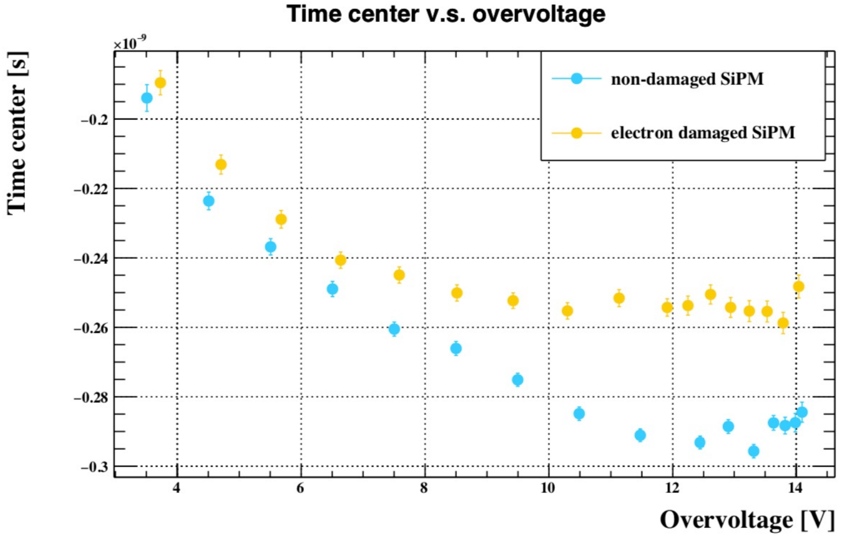


Pattern C

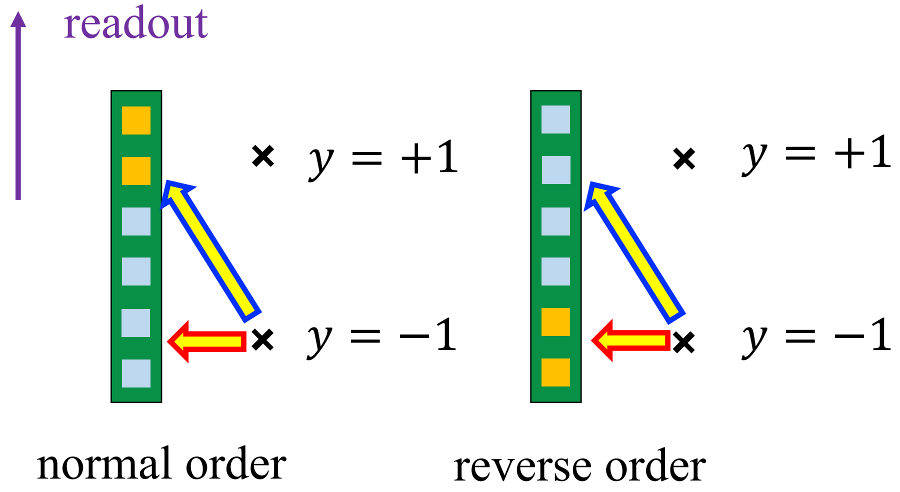
Time center behavior (2/2)

➢Interpretation

- Time response of SiPM (charge collection speed) changes with overvoltage from bias scan result
- Assumptions (in **constant fraction method**) to interpret this result:
  - Main pulse is determined dominantly by SiPMs closest to hit point
  - Rising part of pulse is determined dominantly by SiPMs closest to readout
  - When SiPMs closest to readout have low gain & slow time response (i.e. radiation damage), effect of following SiPMs also become dominant



Bias scan result



Pattern A

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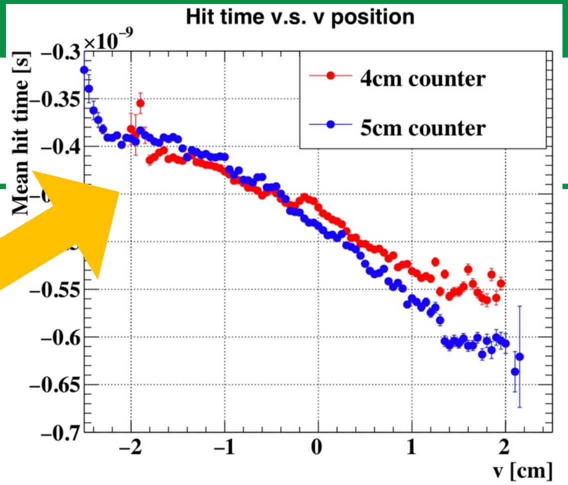
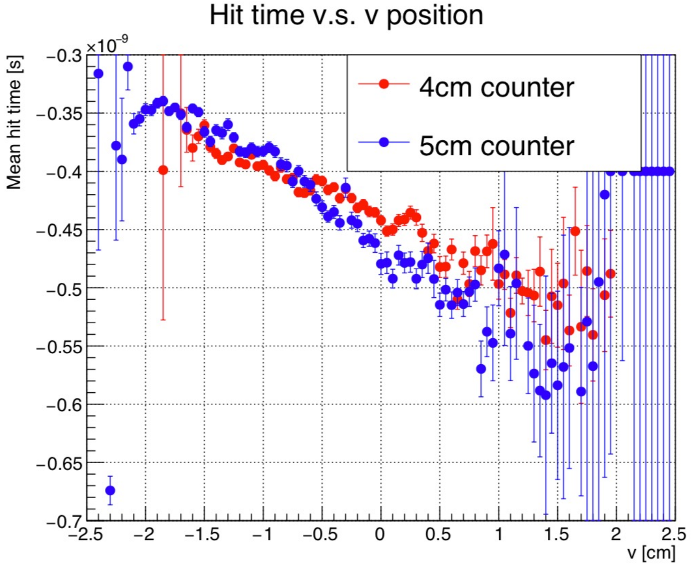
MC study (1/3)

➢Reproducing data

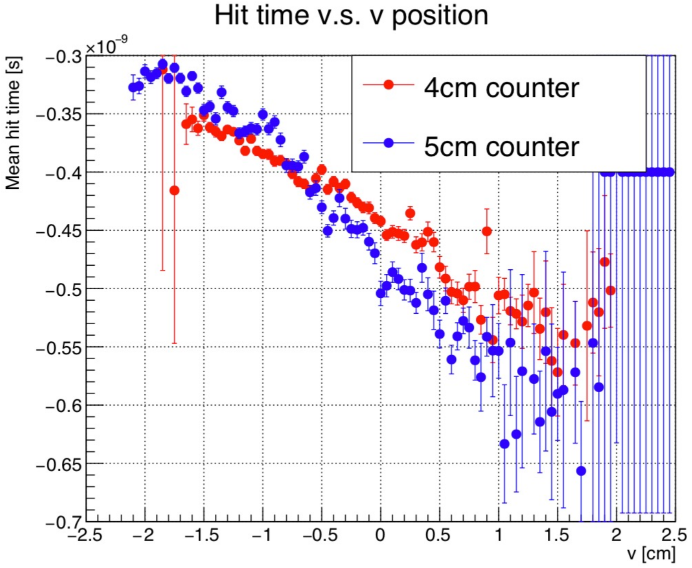
- Vertical position dependence can be reproduced by setting time offset between series-connected SiPMs
- Setting $80\ [ps]$ time offset between each SiPM for 4cm counter best reproduces data



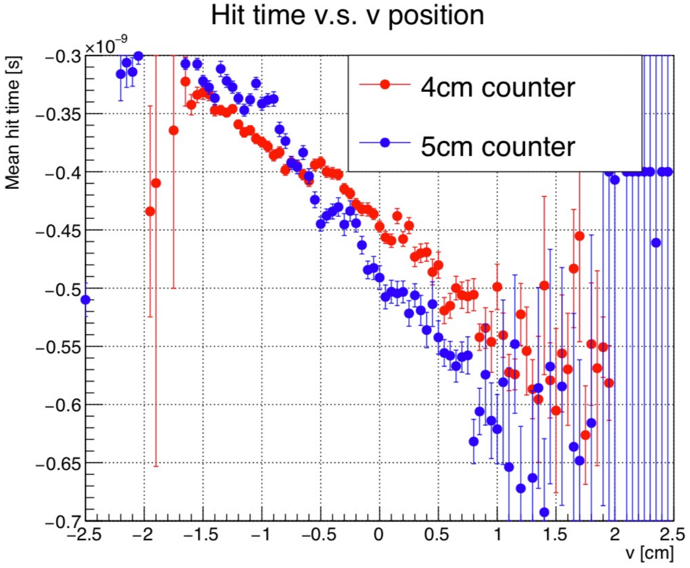
2017 pTC data



$60\ [ps]$



$80\ [ps]$

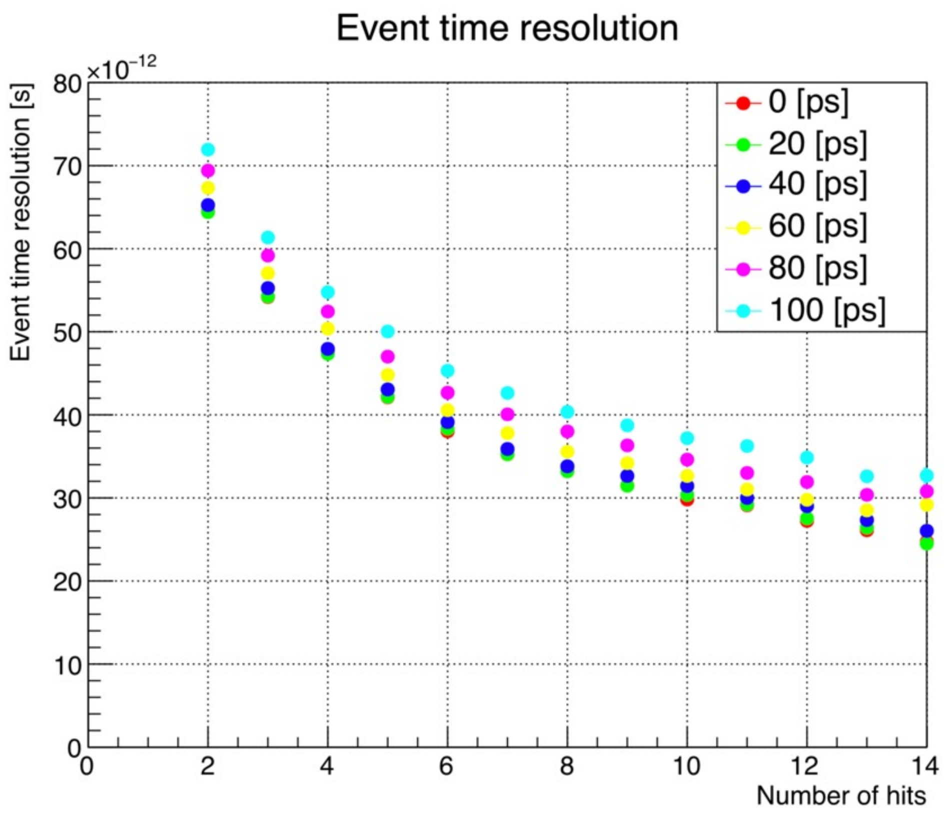


$100\ [ps]$

MC study (2/3)

➢Effect of vertical time offset

- Condition: set various ($0\ [ps]$ - $100\ [ps]$) time offsets between series-connected SiPMs



pTC resolution from MC

- Result:

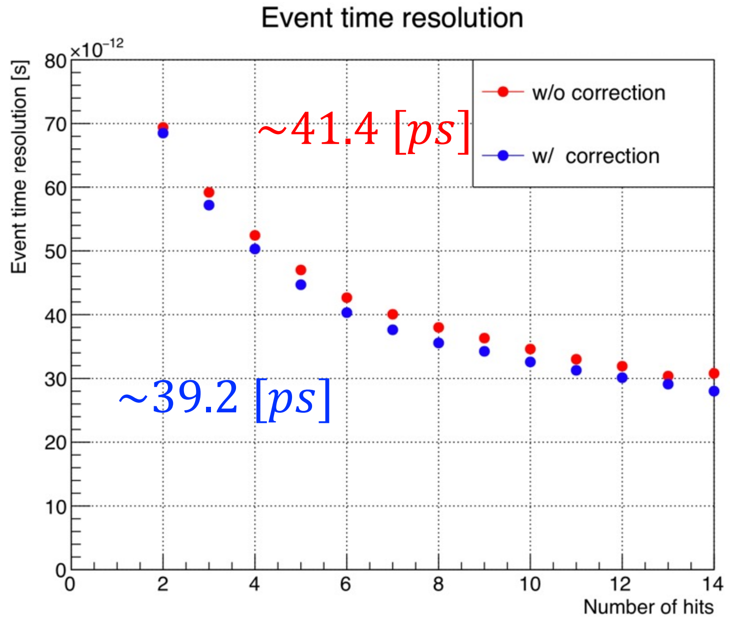
Input time offset	pTC resolution
$0\ [ps]$	$36.5\ [ps]$
$20\ [ps]$	$36.6\ [ps]$
$40\ [ps]$	$37.5\ [ps]$
$60\ [ps]$	$39.1\ [ps]$
$80\ [ps]$	$41.4\ [ps]$
$100\ [ps]$	$44.0\ [ps]$

- Vertical time offset can cause non-negligible pTC performance degradation

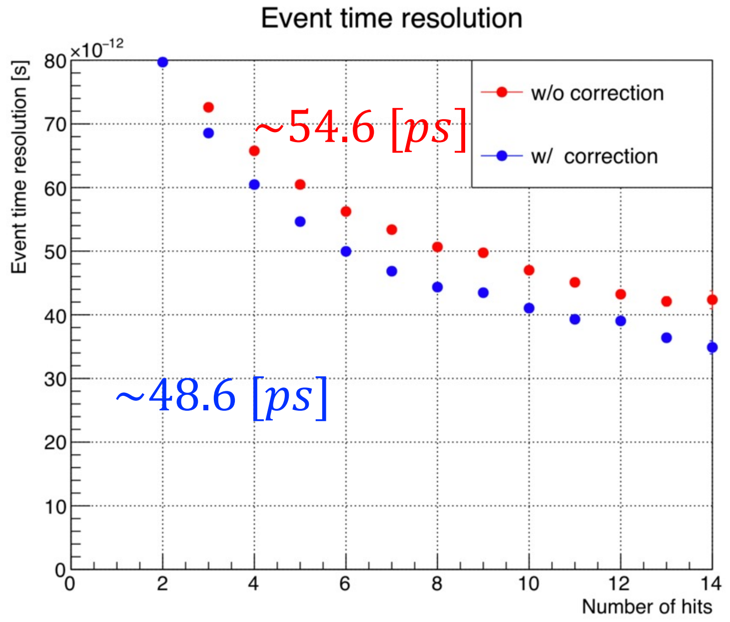
MC study (3/3)

➢Correction

- Vertical position dependence can be corrected from observed position dependence
- Offline time correction can suppress deterioration of pTC performance due to vertical time offset
- Correction becomes more effective when radiation damage to SiPMs accumulate



80 $[ps]$ (MC)



160 $[ps]$ (MC)

pTC performance evaluation

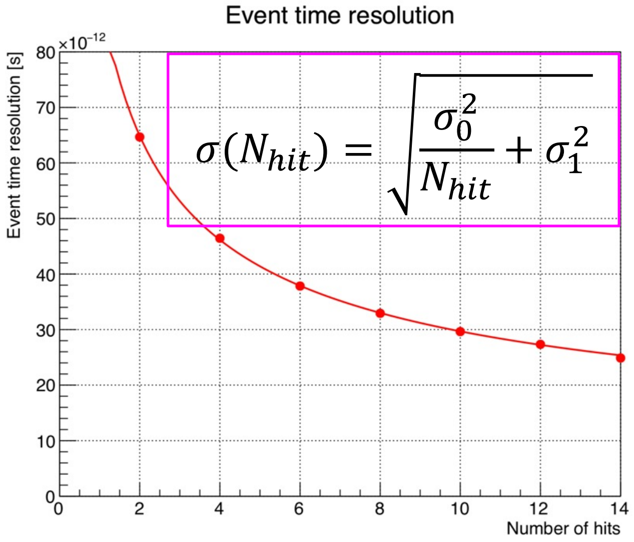
➢Even-odd analysis

- Difficulty of pTC performance evaluation: no reference timing

→ Use odd-hits as timing reference of even-hits

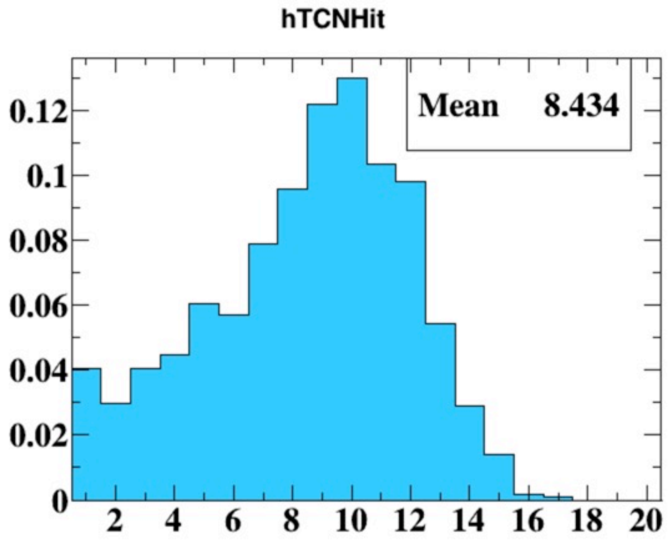
- Effect of vertical time offset cancels out in even-odd analysis

$$t_{even-odd}(N_{hit}) = \frac{1}{N_{hit}} \sum_{i=1}^{N_{pair}} (t_{hit(2i)} - t_{hit(2i-1)} - ToF_{2i-1\rightarrow 2i})$$

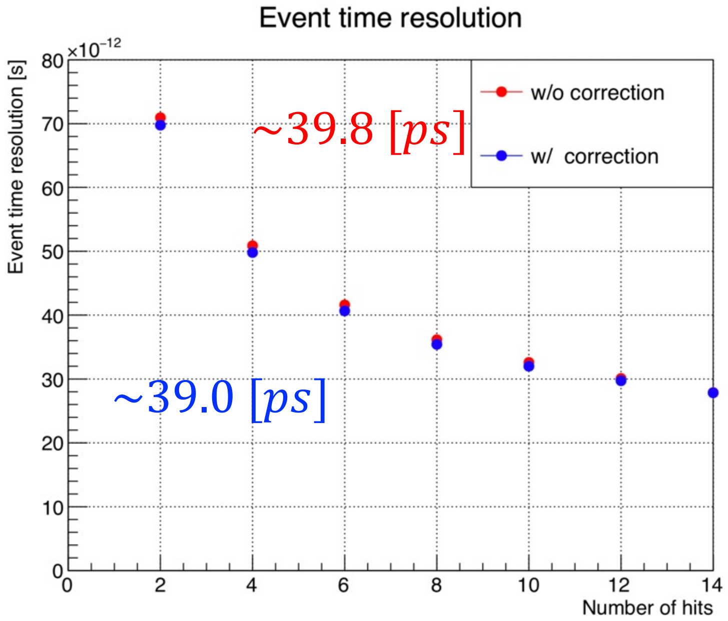


pTC resolution using even-odd analysis

×



Number of hits distribution



80 [ps] (Even-odd)

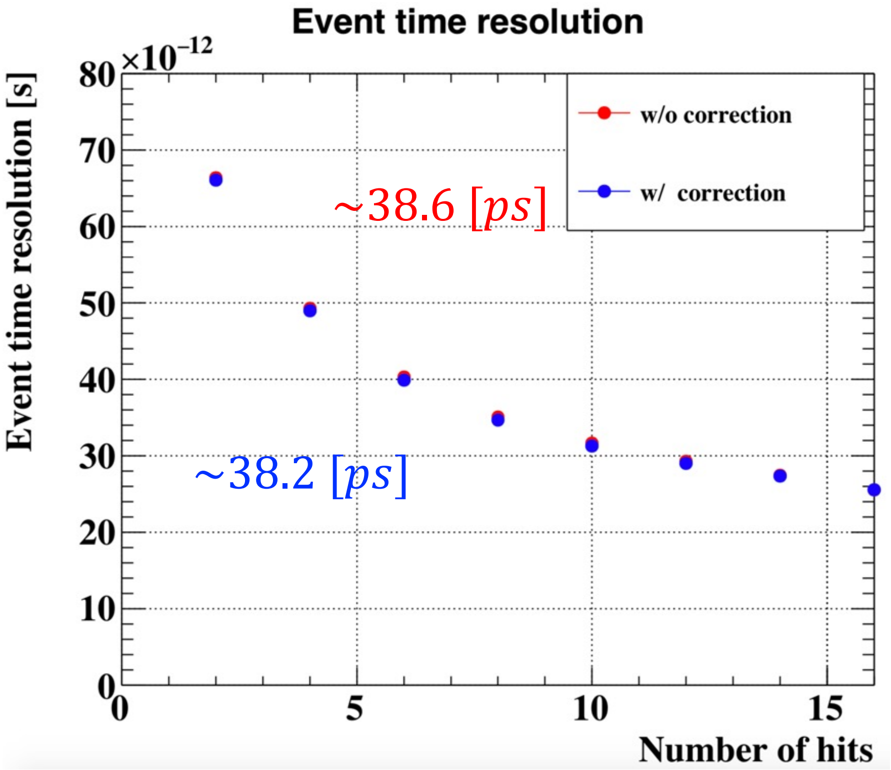
Application on data

➢Correction

- Not as effective as MC
  - Even-odd analysis is used

  → Effect of vertical time offset is canceled out
  - pTC tracking is used

  → Worse position resolution than CDCH tracking
- Correction should improve when we have full CDCH readout



pTC resolution using even-odd analysis on 2017 data

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Summary & prospect

➢Summary

- Position dependence of reconstructed hit time for MEG II pTC was found
- Radiation damage to SiPMs can cause additional effect on position-dependent time offset
- MC simulation study suggests this offset could cause non-negligible pTC performance deterioration
- Offline correction seems effective to some extent

➢Prospect for MEG II pTC

- Correction to compensate time offset effect will be performed in MEG II pTC
- Divide pTC in several sectors according to radiation damage level & monitor time offset
- Update correction values periodically

Backup slides

cLFV (charged Lepton Flavor Violation)

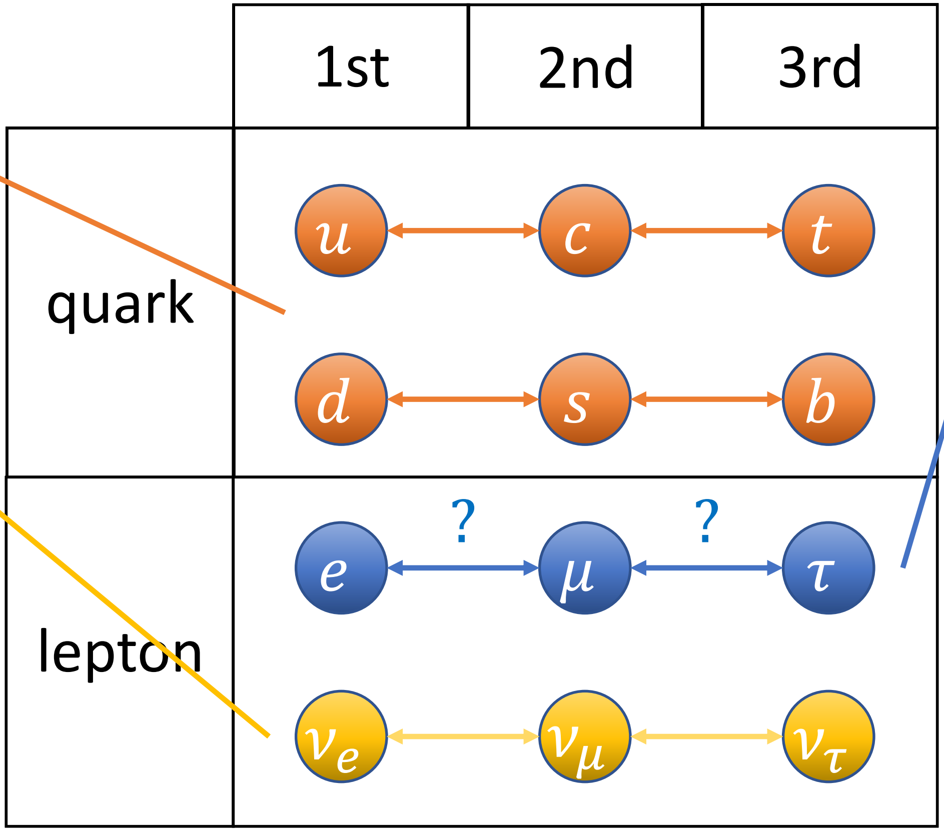
➢ Quark mixing

- Included in SM
- Explained by CKM theory

➢ Neutrino oscillation

- Discovered in Super-Kamiokande
- Forbidden in SM
- Firm proof of bSM physics

→ Suggests possibility of flavor violation in charged lepton sector



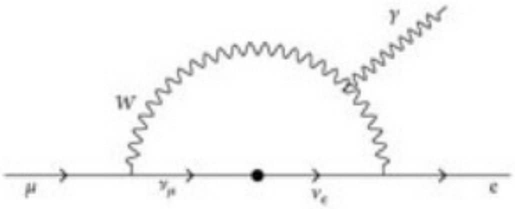
➢ Charged lepton flavor violation (cLFV)

- Forbidden in SM
- Included in many new physics models
- If discovered, certain proof of new physics
- Has been searched in many experiments

$\mu \to e\gamma$ reaction

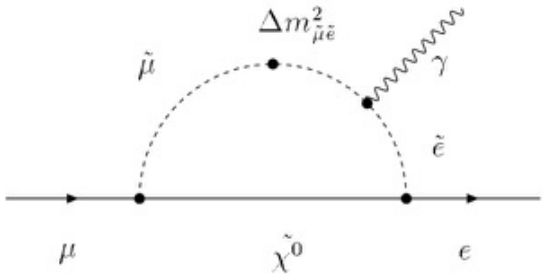
➢Motivation

- Considering neutrino oscillation, possible but very rare
- Included in many new physics models at observable rate
- Can search for new physics w/o directly creating new heavy particles



SM + neutrino oscillation

$Br(\mu \to e\gamma)\sim 10^{-54}$
(little background)

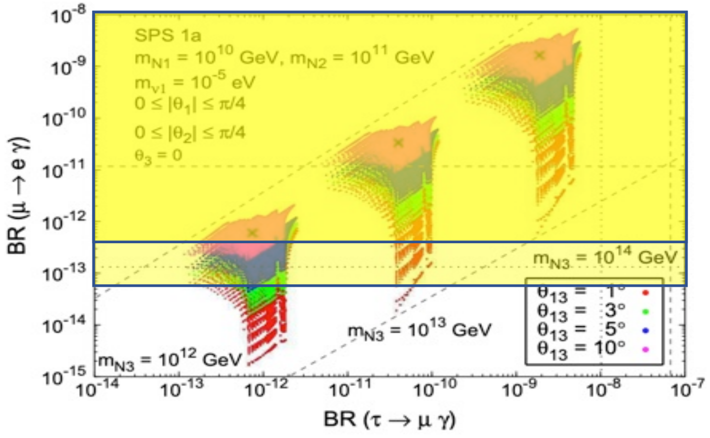


SUSY model

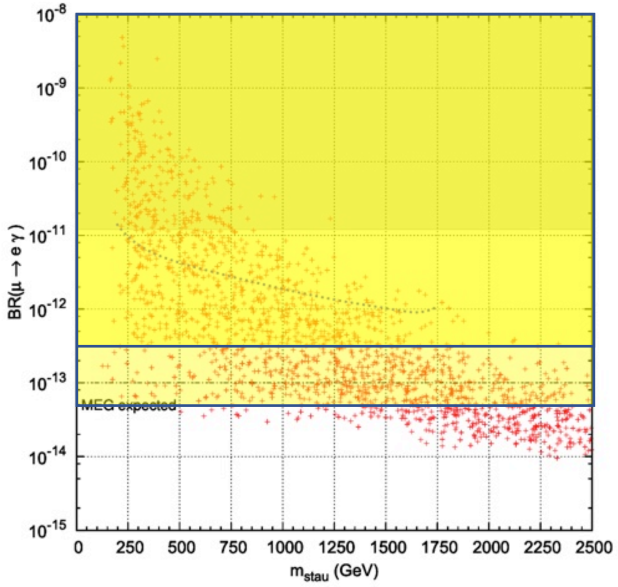
$Br(\mu \to e\gamma)\sim 10^{-15} - 10^{-11}$

➢Status of cLFV search

- Current upper limit is obtained by MEG
  - $Br(\mu \to e\gamma) < 4.2\times10^{-13}$ (90% C.L.)
- MEG II aims for one order higher sensitivity
  - $\sim 6.0\times10^{-14}$



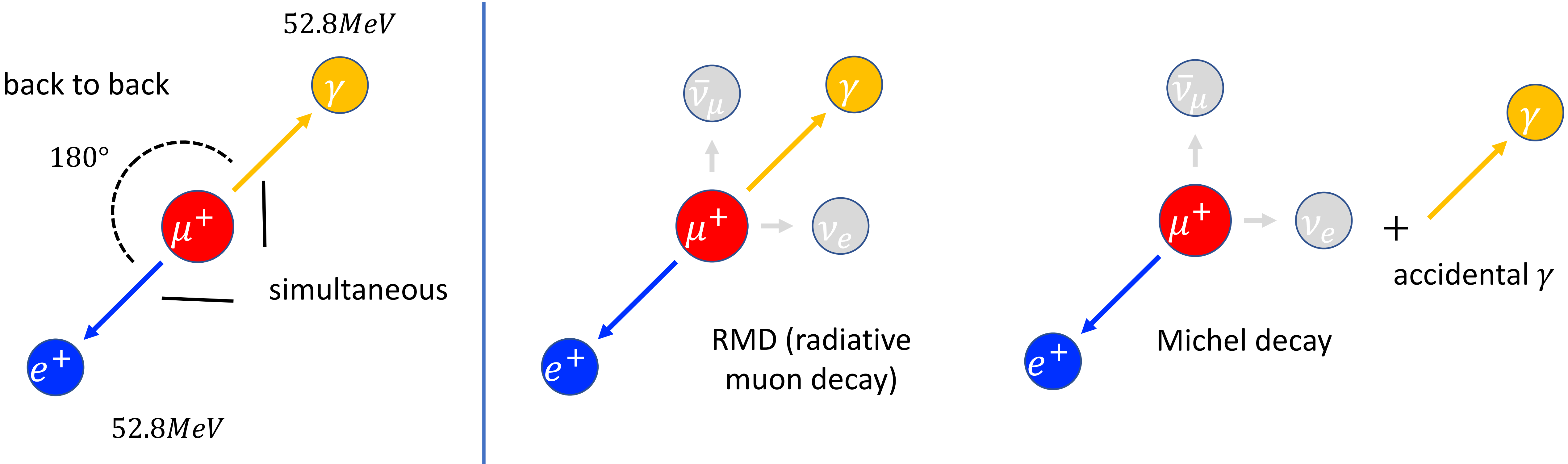
SUSY see-saw



SUSY GUT

SUSY-Seesaw Lorenzo Calibbi et al. "Flavour violation in supersymmetric SO(10) unication with a type II seesaw mechanism." JHEP, 0912:057, 2009.
SO(10) SUSY-GUT: S. Antusch et al. "Impact of θ23 on Lepton Flavour Violating processes within SUSY Seesaw" Journal of High Energy Physics 2006 (11), 090

Signal & background events

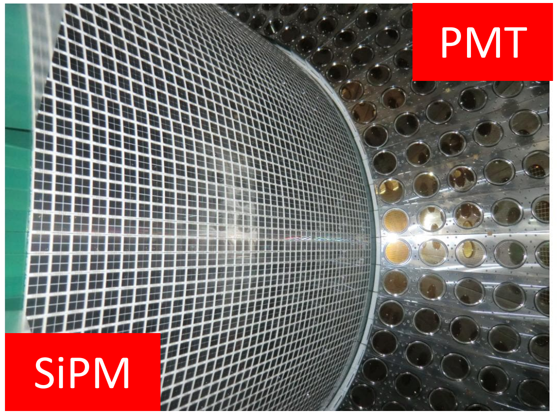


Signal

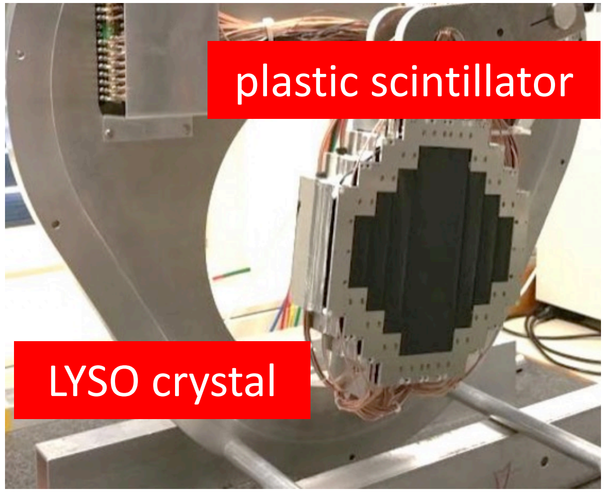
Physics background

Accidental background

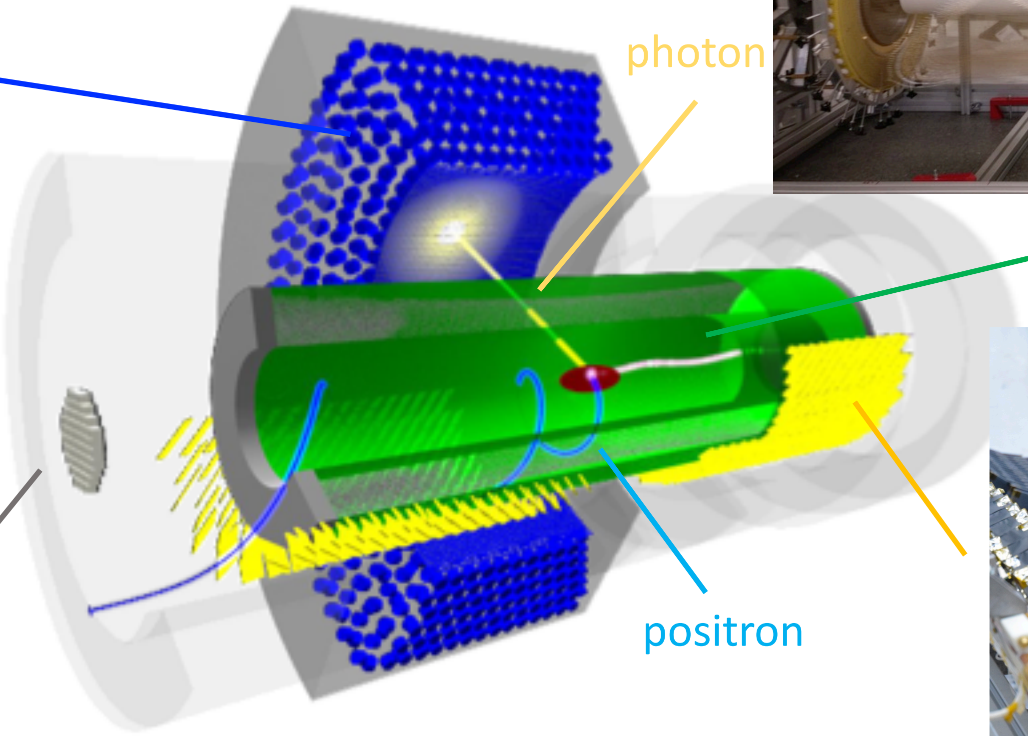
Detectors

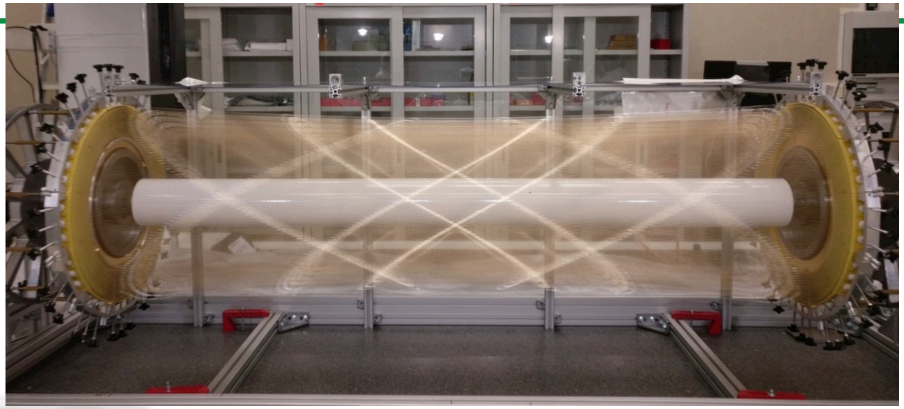


LXe calorimeter

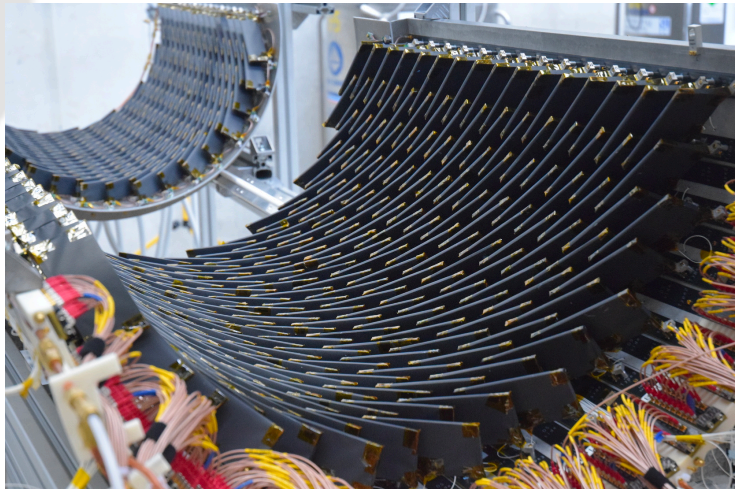


RDC





CDCH



pTC

Positron spectrometer

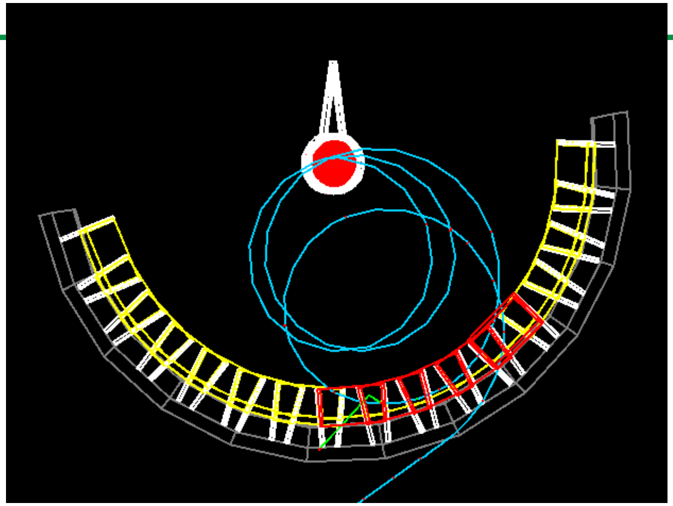
➢COBRA (COnstant Bendint RAdius)

- Bends positrons at a constant radius independent of emission angles

→ Signal positrons enter pTC region

- Gradient field to sweep positrons away from detector region

→ Reduce pile-up



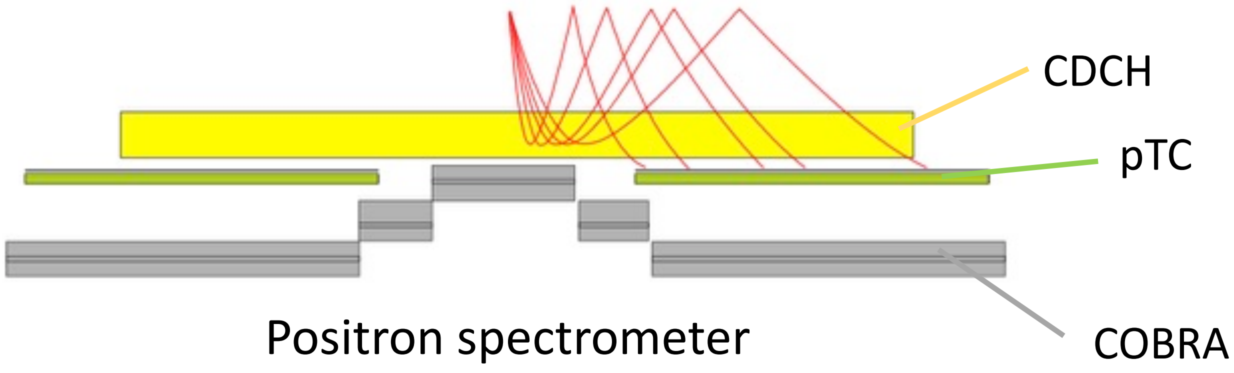
Positron event display

➢CDCH (Cylindrical Drift CHamber)

- Reconstructs positron track

➢pTC (pixelated Timing Counter)

- Reconstructs positron time



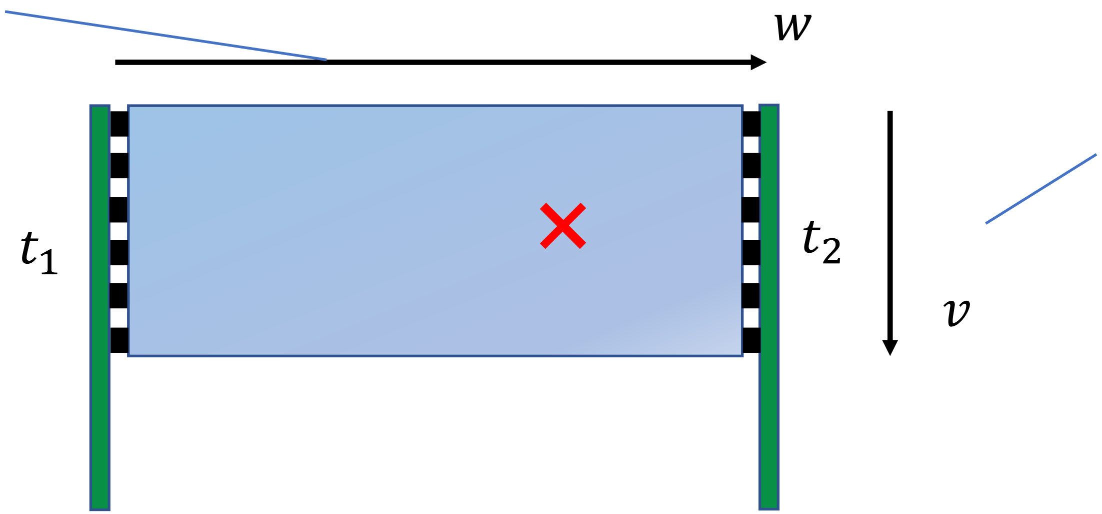
Positron spectrometer

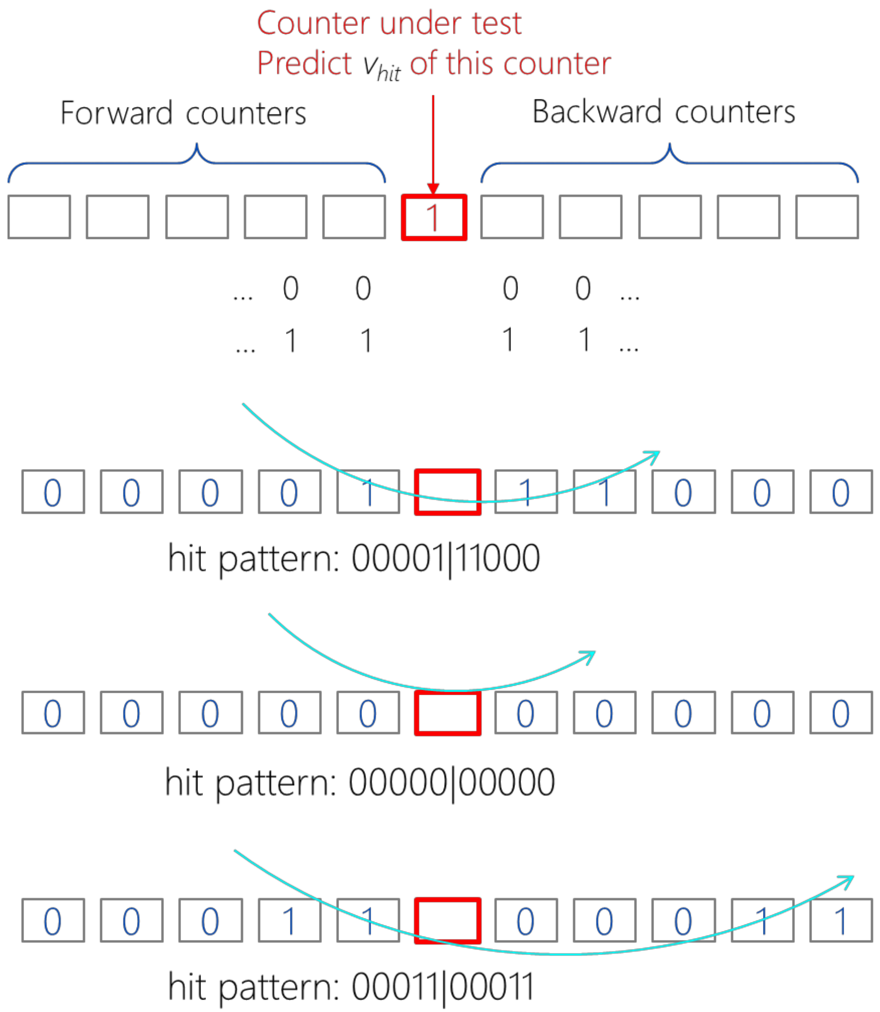
pTC tracking

➤Idea

- Horizontal position can be reconstructed from the time difference of two channels
- Radial coordinate can be reconstructed from hit pattern information

$$w_{hit} = v_{eff} \times \frac{t_2 - t_1}{2}$$

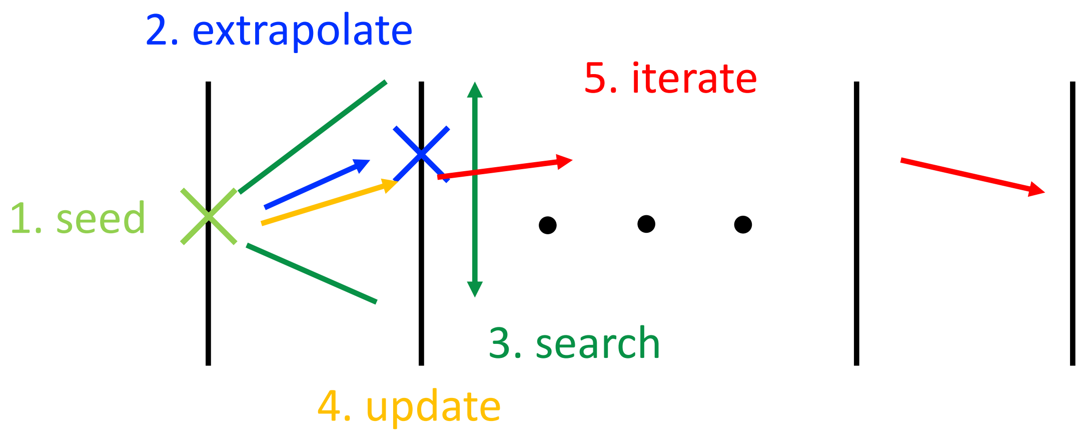




Intra-pixel position correction

➢Positron tracking

- Combine discontinuous hit information into single positron track
- Kalman Filter technique is used to extrapolate track and include following hits
- Segments are fitted with GENFIT
- Two types of tracking (pTC tracking & CDCH tracking) exists
  - CDCH tracking is used for MC study
  - pTC tracking is used for data analysis (due to limited CDCH readout electronics)



Kalman Filter
Efficient recursive algorithm to estimate the state vector & its covariance matrix based on previous steps
GENFIT
Generic toolkit for track reconstruction for experiments in particle & nuclear physics

CF scan

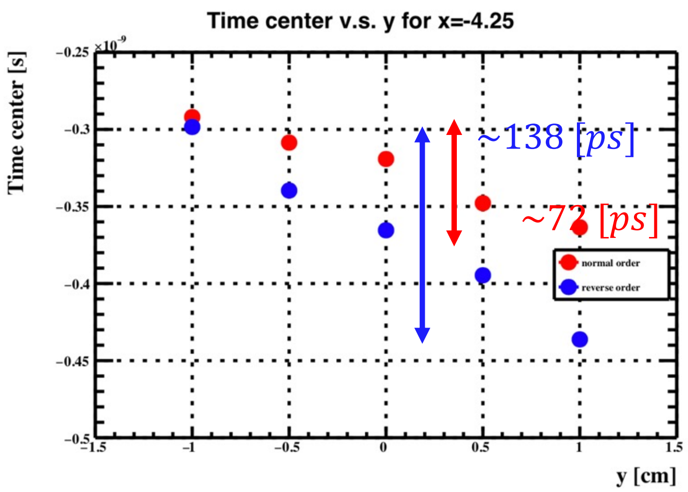
➢Pattern A

- Time center behavior for normal order changes drastically with CF value

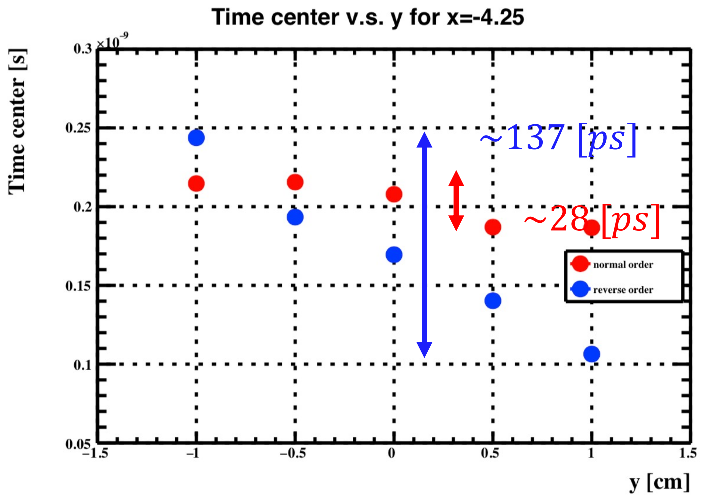
→ Longer path components become dominant at higher CF values

- Time center behavior for reverse order is almost same at all CF values

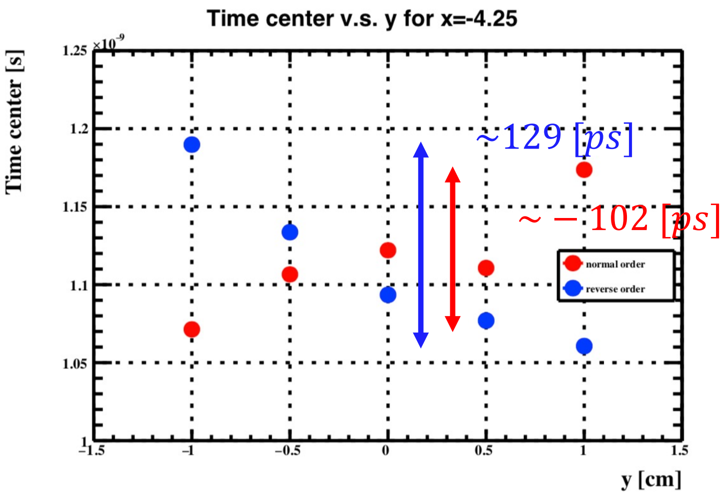
→ Short path component is dominant



CF 20%



CF 50%



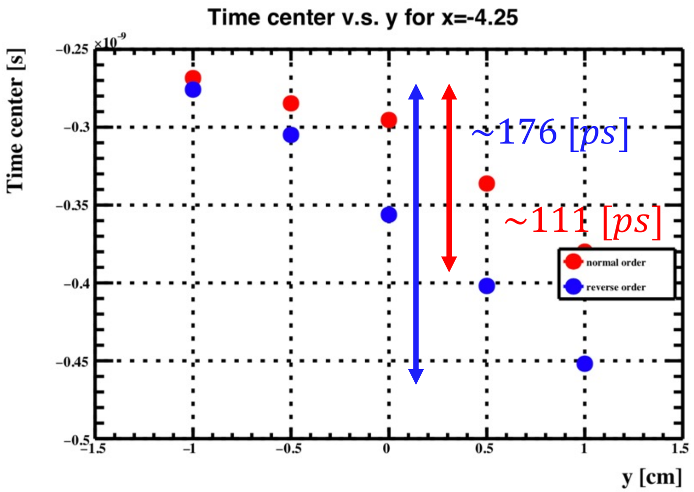
CF 100%

CF scan

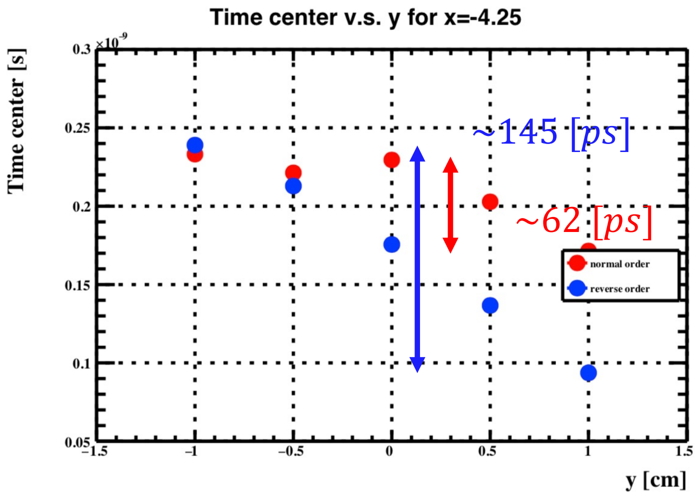
➢Pattern B

- Time center difference for both normal & reverse order changes with CF value

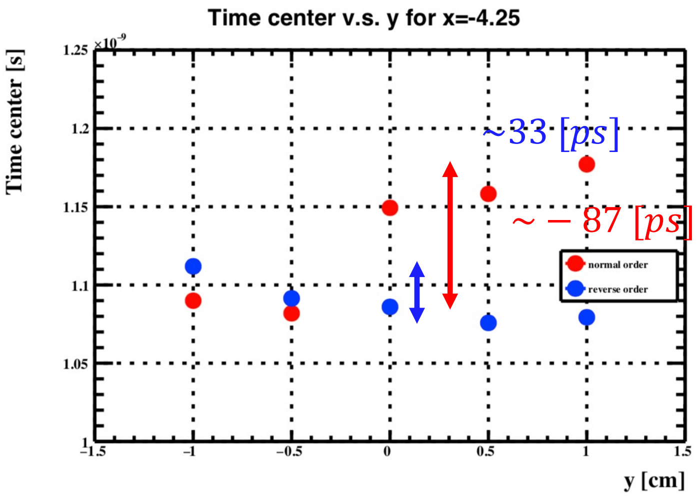
→ Dominant contribution changes from short-path to long-path component with higher CF value (2 non-damaged SiPMs are enough to form pulse rise for CF 20% case but not for CF $> 50\%$)



CF 20%



CF 50%



CF 100%

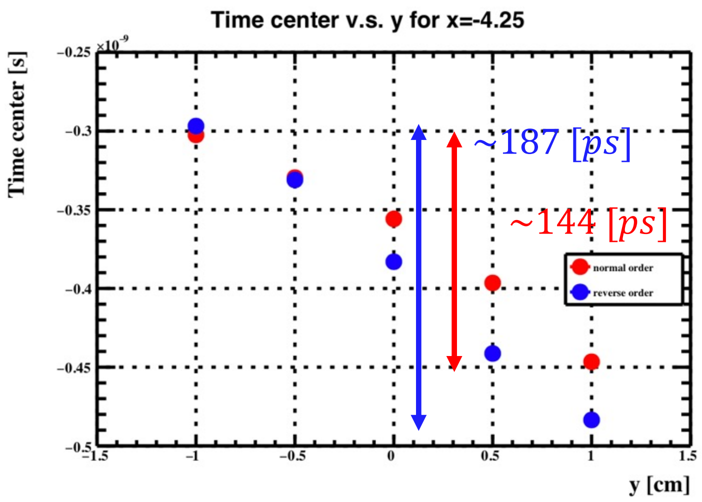
CF scan

➢Pattern C

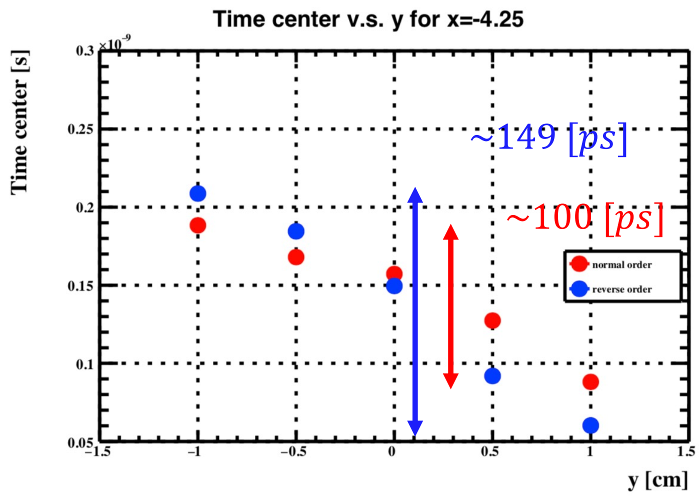
- Time center difference for both normal & reverse order changes moderately with CF value

→ Dominant contribution changes from short-path to long-path component with higher CF value

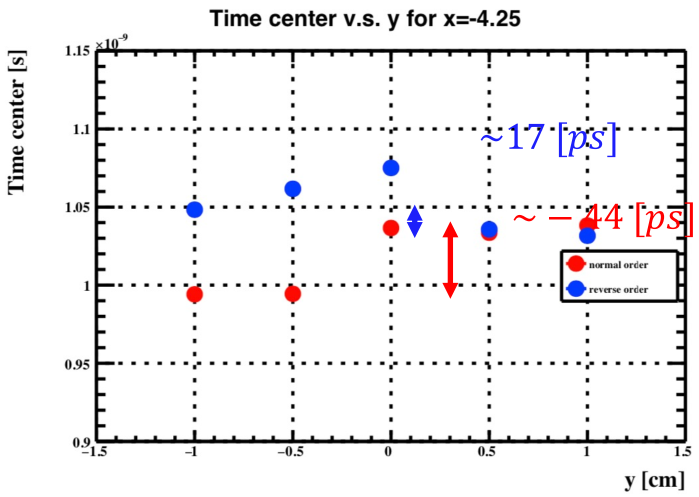
- CF dependence is relatively small because overvoltage shift is small for pattern C (clear from pulse height behavior)



CF 20%



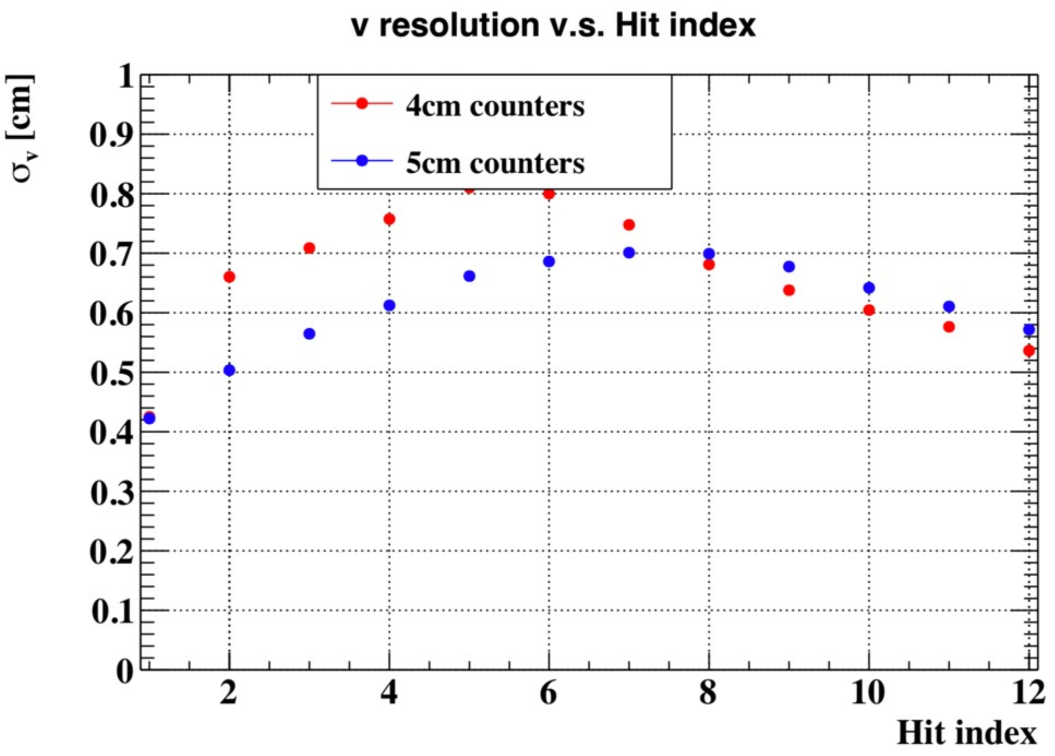
CF 50%



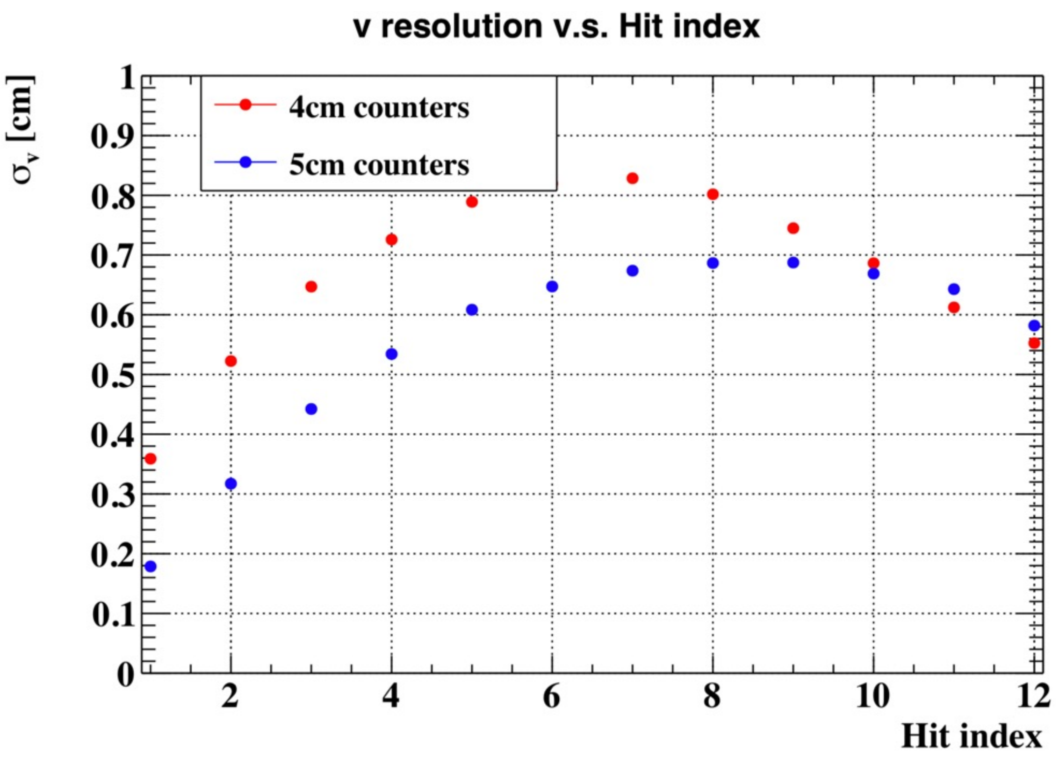
CF 100%

v resolution

➢pTC tracking

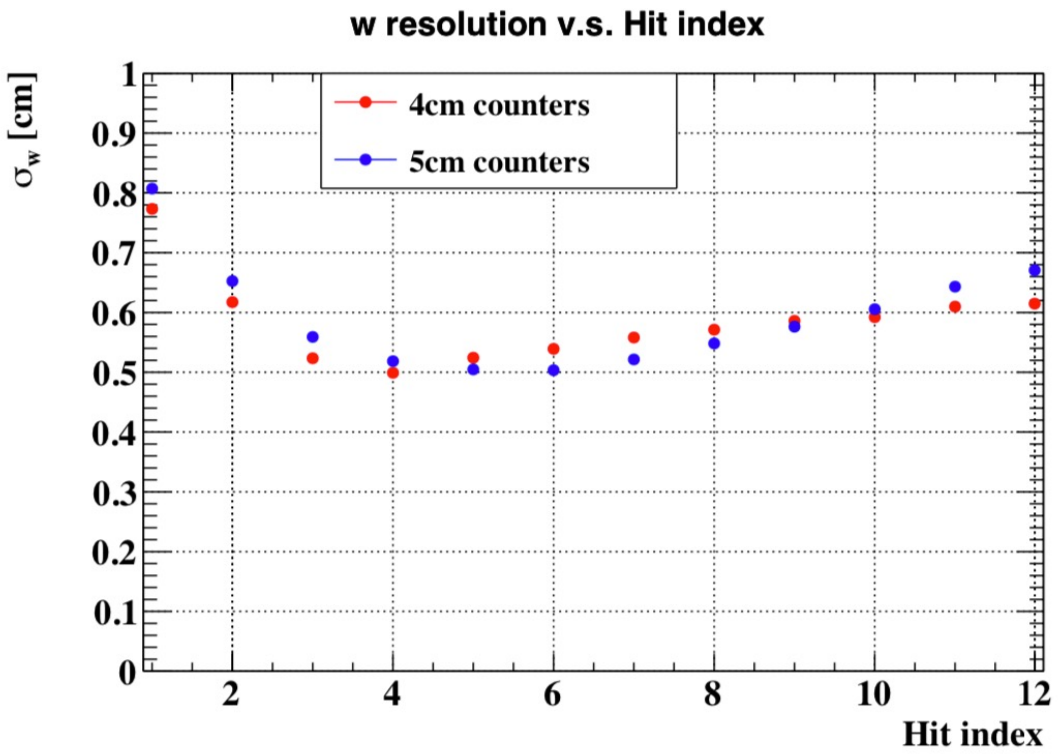


➢CDCH tracking



w resolution

➢pTC tracking



➢CDCH tracking