

# MEG II Timing Counter pre-engineering run 2017: Calibration

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Mitsutaka Nakao

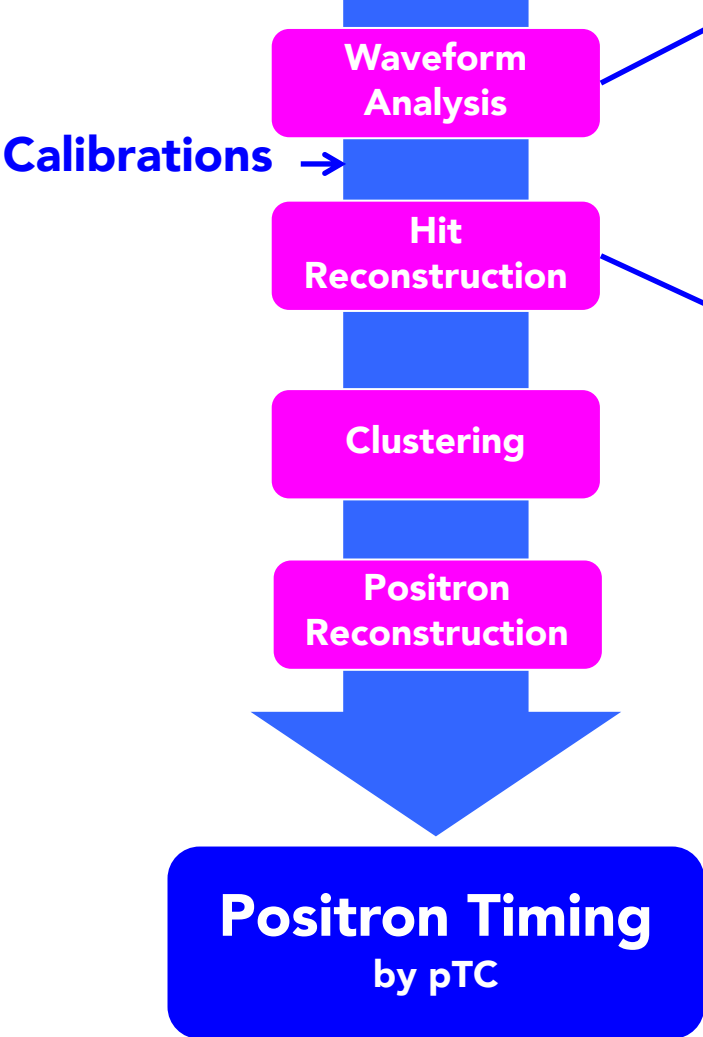
(The University of Tokyo)

On behalf of MEG II Collaboration



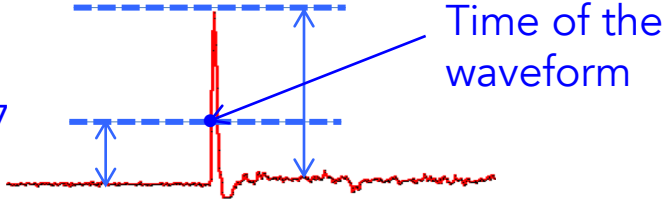
**ICEPP**  
The University of Tokyo

# pTC: reconstruction



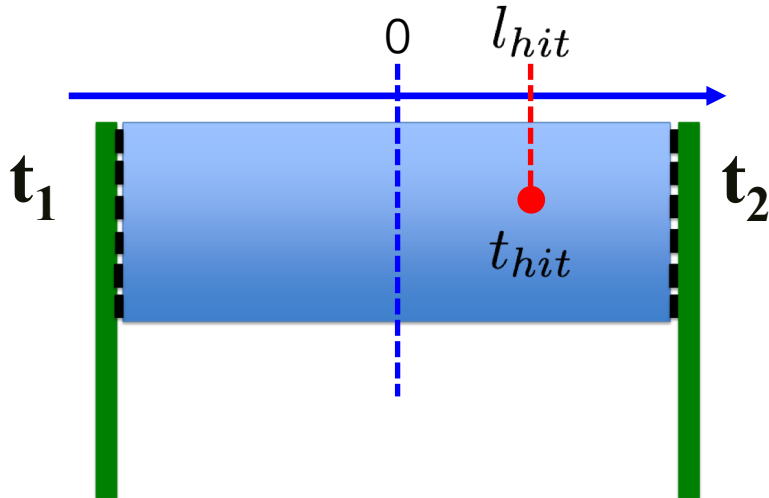
- Waveform time ( $t_1, t_2$ ) is calculated by using constant fraction method.

20% in Pilot Run 2017



- Hit time ( $t_{hit}$ ) is calculated by averaging both ends.

$$t_{hit} = \frac{t_1 + t_2}{2} \quad l_{hit} = v_{eff} \frac{t_1 - t_2}{2}$$



# pTC: calibrations

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Updated

## Time Calibration

- We have to know time offset of all 512 counters with the accuracy of 30 ps.
- We have 2 complementary methods to calibrate time offset b/w counters: [laser-based method](#) and [track-based method](#).
- Radiative Muon Decay ( $\mu \rightarrow e \gamma \nu \bar{\nu}$ ) is used for absolute calibration for relative timing b/w  $e^+$  and gamma.

New

## Position Calibration

- Hit distribution within a counter is aligned to design value.
- For detail in later slides.

## Energy Calibration

- Reconstructed energy (landau distribution) is aligned to MIP peak.

Updated

## Time Calibration

- We have to know time offset of all 512 counters with the accuracy of 30 ps.
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- Radiative Muon Decay( $\mu \rightarrow e \gamma \nu \bar{\nu}$ ) is used for absolute calibration for relative timing b/w  $e^+$  and gamma.

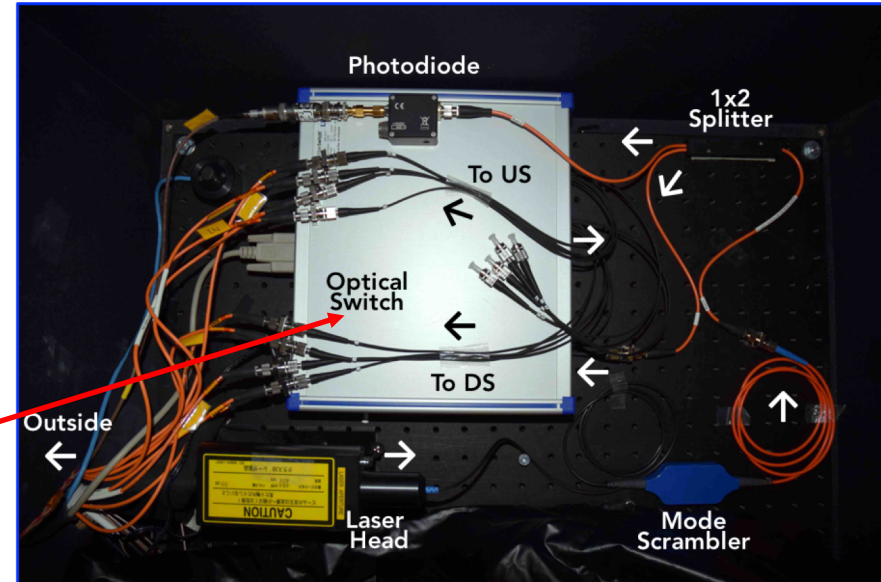
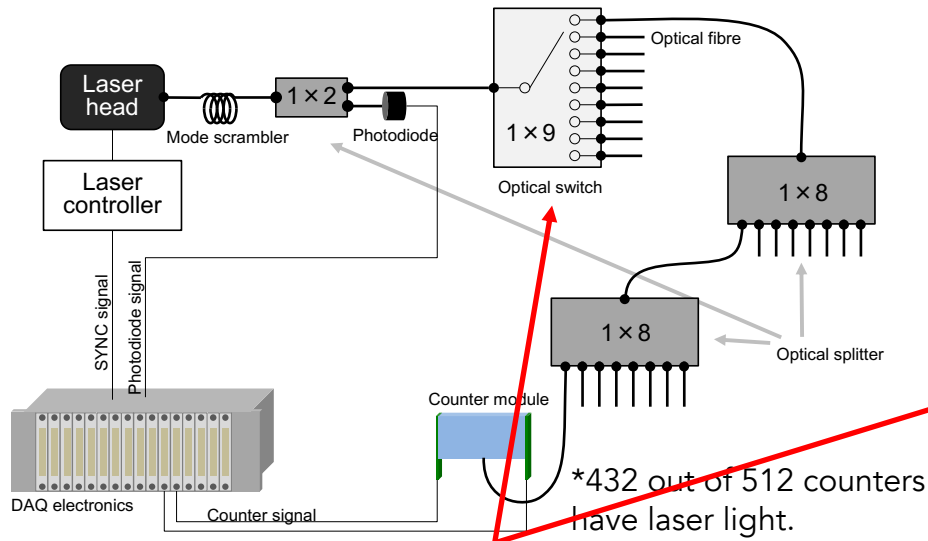
## What we did so far(~2016)

- We performed beam test using  $\frac{1}{4}$  of pTC under the MEG II beam.

## Purpose of This Study(2017)

- Operate full laser calibration system.
- Check stability of time offset.
- Consistency check b/w laser calibration and Michel calibration.

# Laser-based method: concept



**New!! Optical switch will be available from this year!!**

- PLP-10 (Hamamatsu) is used as a light source.



(cited from Hamamatsu HP)

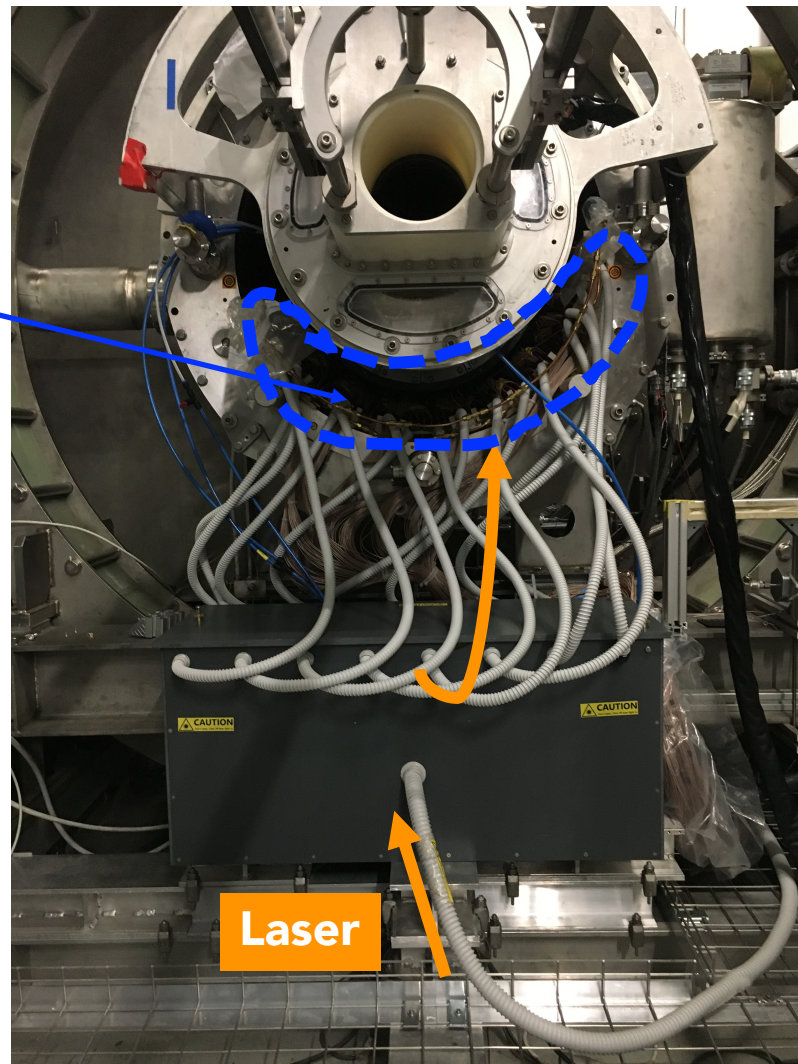
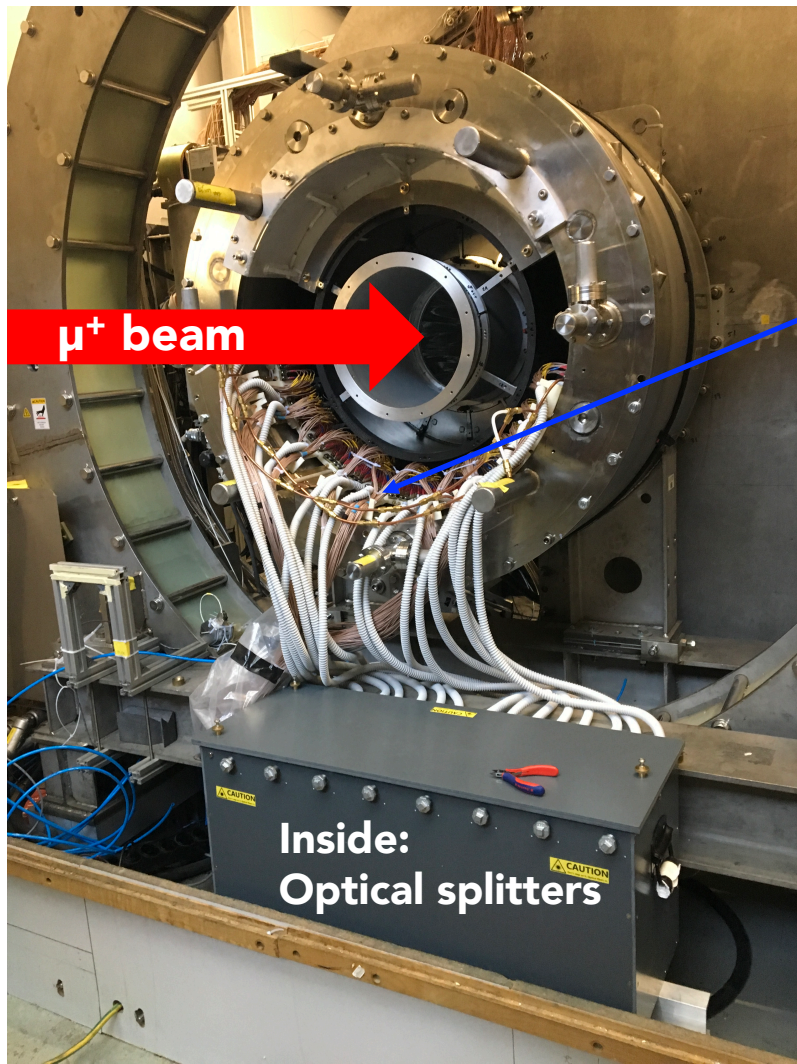
- Wavelength 405 nm
- Wavelength FWHM < 10 nm
- Pulse duration typ. (max) 60 (100) ps

- Pulse laser is divided into each counter simultaneously.
- Time offset of each counter is measured relative to laser-synchronized pulse.
- Calibration uncertainty is estimated as 24 ps by testing all parts of laser calibration system.

# US/DS installation

Upstream (5<sup>th</sup> Sep., 2017)

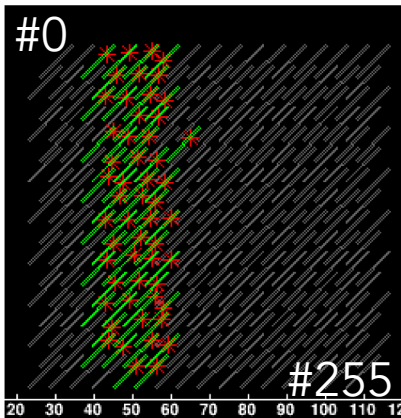
Downstream (25<sup>th</sup> Oct., 2017)



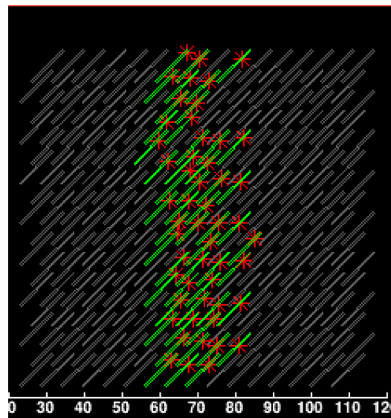
# First full operation (Oct. 2017)

\*different configuration of US/DS because of easier assembly work.

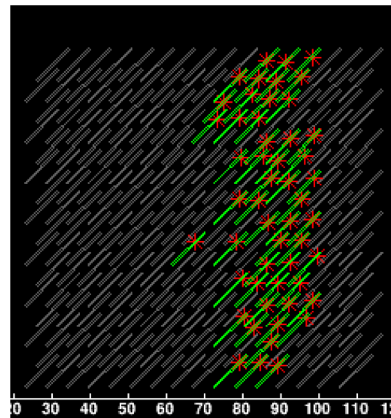
## DS Fiber 1



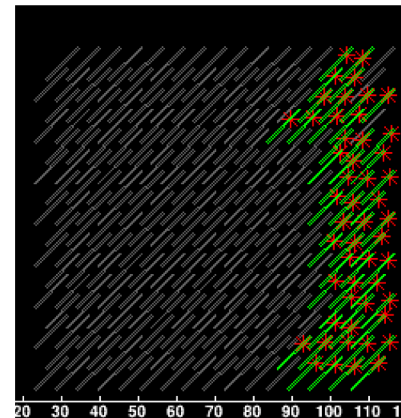
## Fiber 2



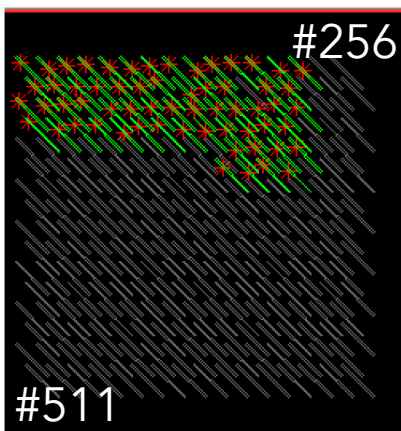
## Fiber 3



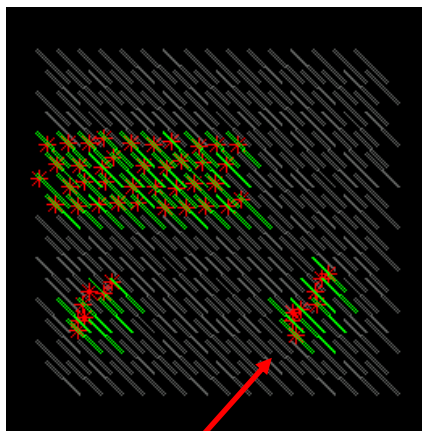
## Fiber 5



## US Fiber 9

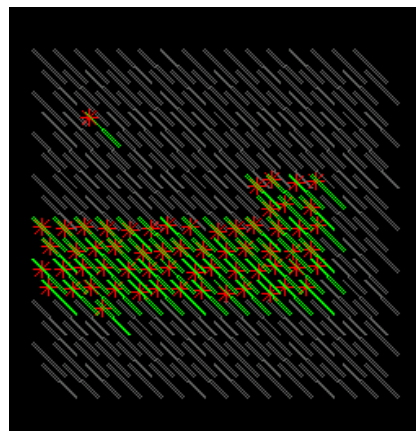


## Fiber 6

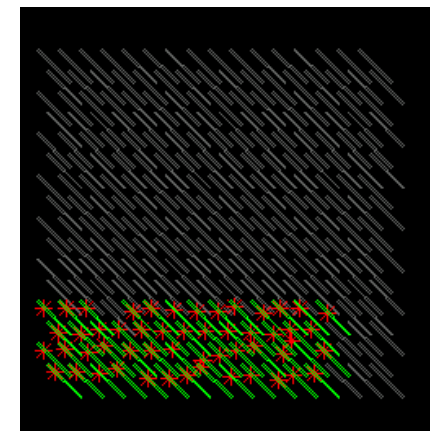


positron track

## Fiber 8



## Fiber 7

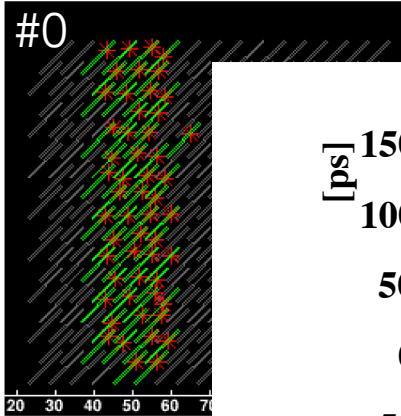


# First full operation (Oct. 2017)

\*different configuration of US/DS because of easier assembly work.

DS

Fiber 1



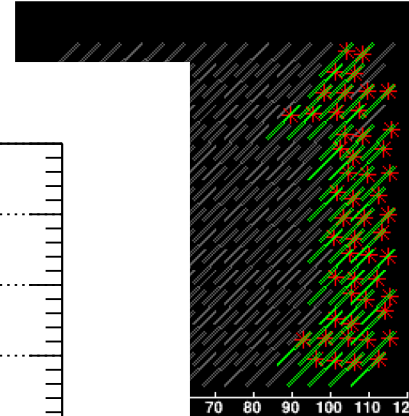
Fiber 2



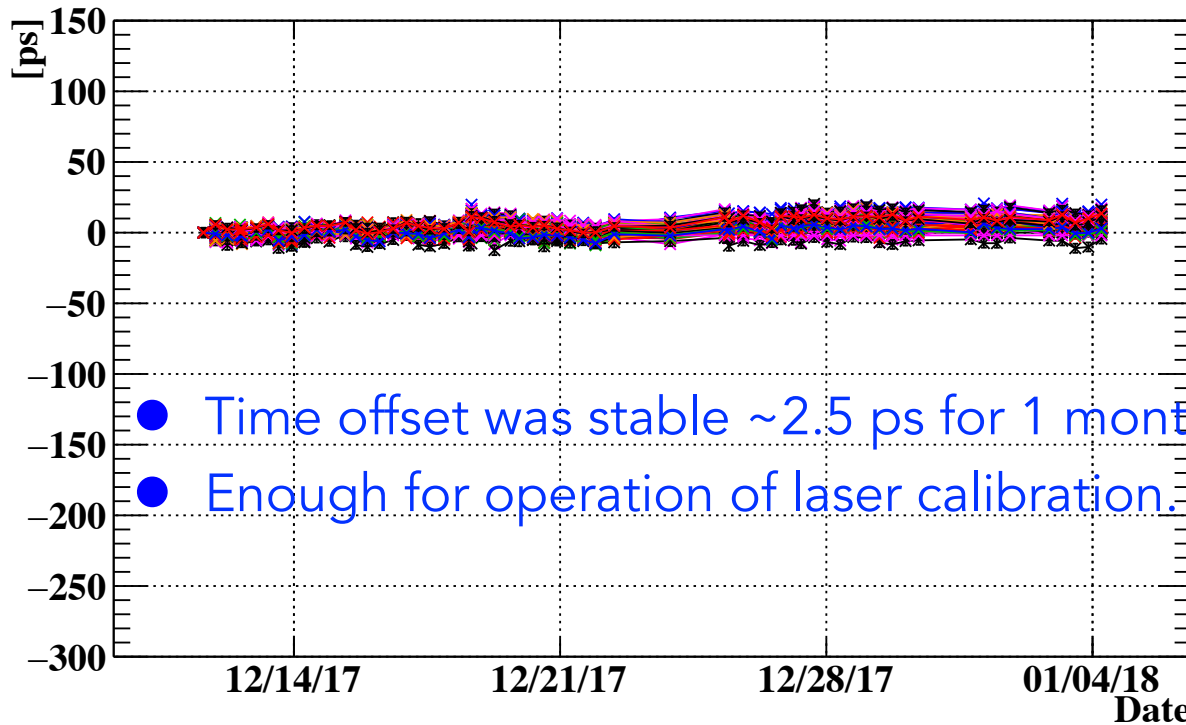
Fiber 3



Fiber 5



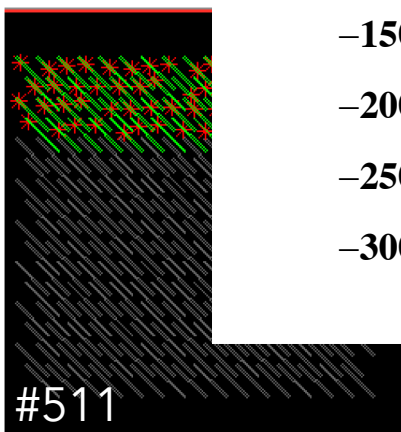
Relative Time offset history (US#8)



- Time offset was stable  $\sim 2.5$  ps for 1 month.
- Enough for operation of laser calibration.

US

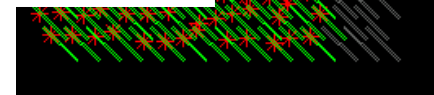
Fiber



#511



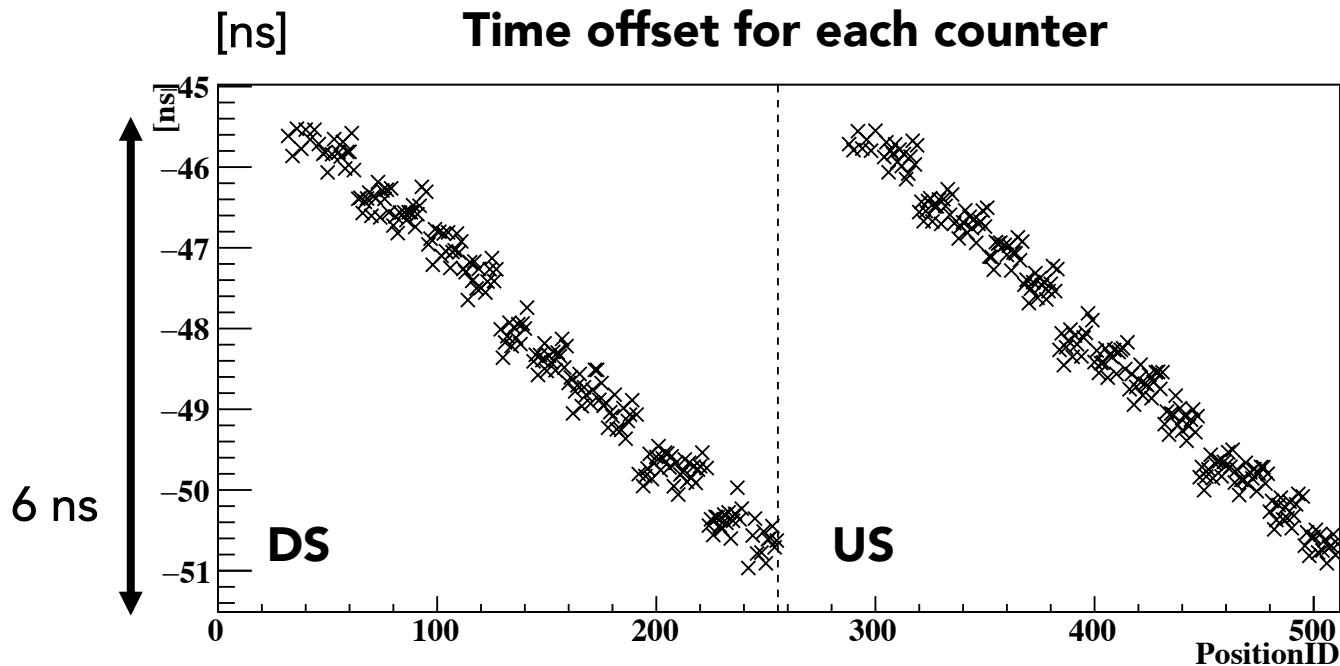
positron track



Fiber 7



- In order to know time offset to calibrate, we need to subtract “laser components” from time offset measured in laser run.



- This includes
  - cables
  - electronics
- This does not include “laser components”

- Positron tracks from Michel decay ( $\mu^+ \rightarrow e^+ \nu \nu$ ) are used for calibration.

$$\chi^2 = \sum_i^{N_{event}} \sum_j^{N_{hit}} \left( \frac{\overbrace{T_{ij}}^{\text{Measured time}} - \underbrace{\left( T_{0i} + TOF_{ij} + \Delta T_j \right)}^{\text{Expected time}}}{\sigma \text{ Time offset of each counter}} \right)^2$$

:What we want to know

- Calculate TOF values for every counter by Monte Carlo\*.
  - Define  $\chi^2$  as the difference b/w measured time and expected time.
  - Minimize  $\chi^2$  using Millepede II.
  - Find  $\Delta T_j$ .
- Calibration uncertainty is estimated as 6 ps by MC study.

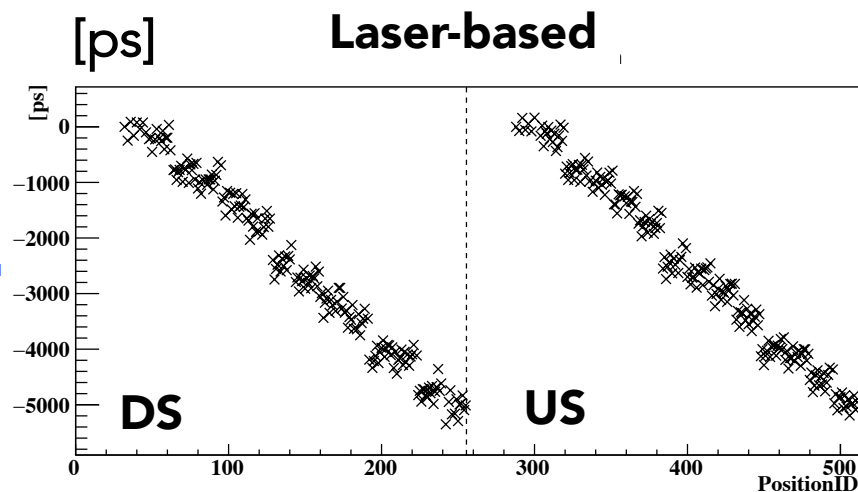
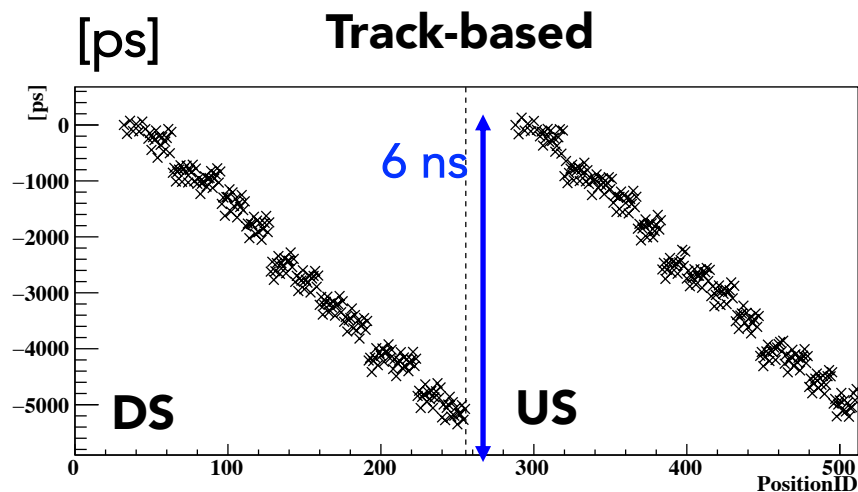
\* This setup is for Pilot Run w/o DCH. TOF will be calculated by DCH in physics run.

Millepede II [www.desy.de/~kleinwrt/MP2](http://www.desy.de/~kleinwrt/MP2)

A software provided by DESY to solve the linear squares problems, such as detector alignment and calibration based on track fits.

# Comparison b/w 2 methods

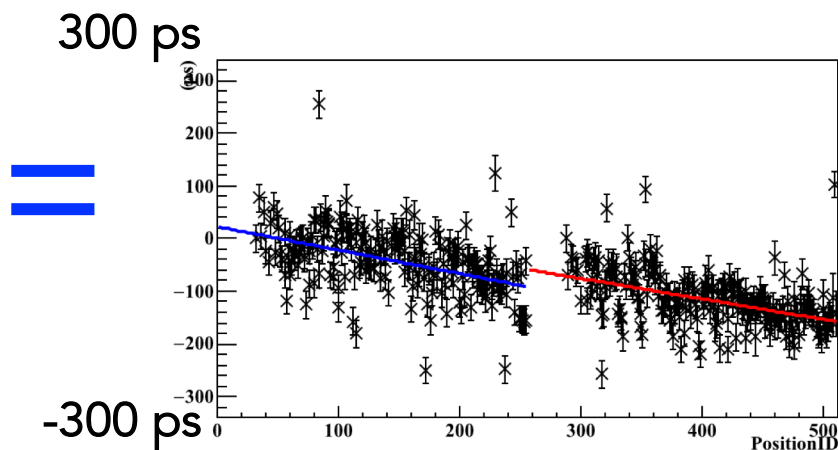
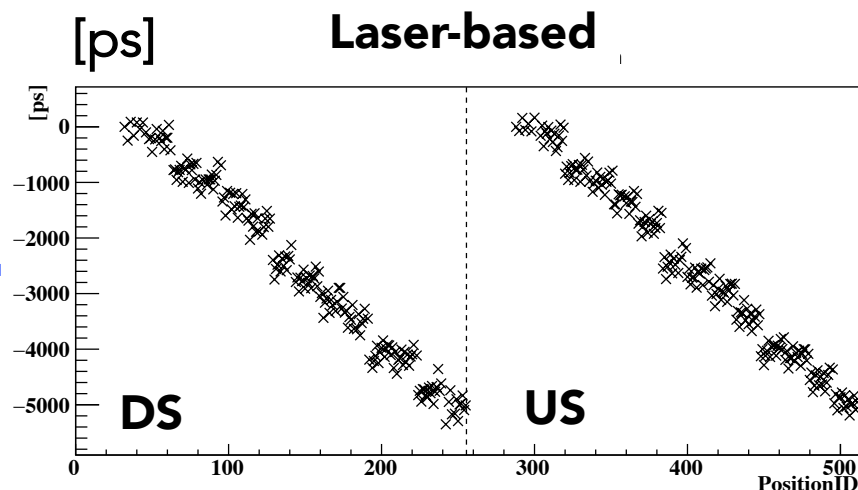
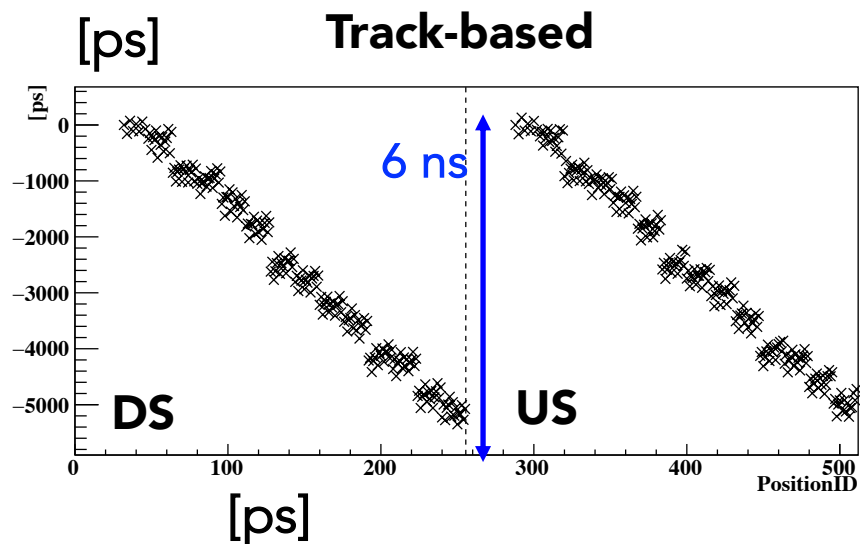
- **Relative** time offset: time offset difference from first counter of each side.
  - position#32 (DS) and position#288 (US) is set to 0 ps.



- Cables
- Electronics

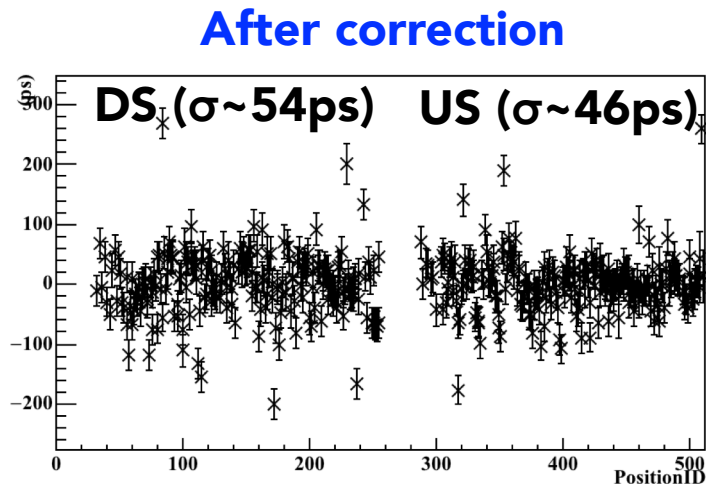
# Comparison b/w 2 methods

- Relative time offset: time offset difference from first counter of each side.
  - position#32 (DS) and position#288 (US) is set to 0 ps.



- TOF difference b/w data and MC accumulates according to counter order and causes this kind of bias (MC studies).
- “Laser” can not cause these bias (no position dependence)
  - can be corrected by using data.

- Systematic difference of TOF used as a reference b/w data and MC causes position dependent bias, but can be corrected (see bottom left).
- 2 methods are consistent within  $\sim 50\text{ps}$  (= "Laser"  $\oplus$  "Track")
- 2 methods are complimentary and they should be integrated.



	Laser	Track
Position dependence	<b>no</b>	yes
DAQ time	<b>short; ~30min</b>	long; ~2 days
Beam	<b>not necessary</b>	necessary
Coverage	84%	<b>100%</b>
Uncertainty	24 ps	<b>6 ps (MC)</b>

- **Our strategy:** time offset calculated from "Track" is mainly used, and its time-dependence is monitored by "Laser" (**established**).
  - effectively, accuracy of  $\frac{50}{\sqrt{2}} \sim 35\text{ps}^*$  is expected.
  - good, but still have room for improvements.

\*this value is not directly used in physics analysis.

- We already know that bias in track-based calibration is coming from miss estimation of TOF values.
- The difference b/w data and MC effects the TOF estimation.
- To minimize the effect, I am trying to add additional “global parameters” to absorb the miss estimation depending on:
  - Geometry
  - How many counters there are before the counter.
  - Track type (A, B, C, depending on the next counter)

What we want to minimize:

$$\chi^2 = \sum_i^{N_{event}} \sum_j^{N_{hit}} \left( \frac{\overbrace{T_{ij}}^{\text{Measured time}} - \underbrace{\left( \overbrace{T_{0i}}^{\text{Local parameter; event by event.}} + \overbrace{TOF_{ij}}^{\text{Global parameter; common to all events}} + \underbrace{\Delta T_j}_{\text{+ additional global parameters}} \right)}^{\text{Expected time}}}{\sigma \text{ Time offset of each counter :What we want to know}} \right)^2$$

- Currently, the improvements are limited and I will review the setup.

- Hit position:  $l_{hit} = v_{eff} \frac{t_1 - t_2}{2}$ 
  - $v_{eff}$  : effective velocity
  - $T_{offset}$  :  $t_1 - t_2$  includes time offset difference b/w 2 channels.

## Goal

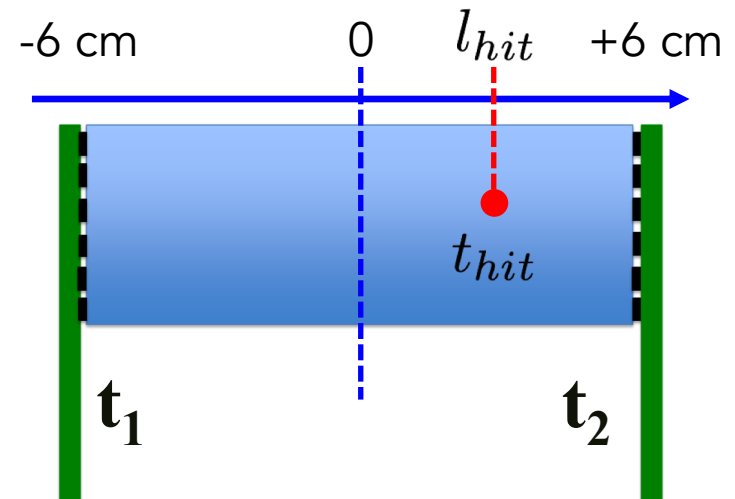
- Calibrate  $v_{eff}$  and  $T_{offset}$ .
- Hit distribution should be aligned less than position resolution  $\sim 1$  cm.

## Motivation

- Calibrate length of signal line
- Better performance in the later analysis
  - Better clustering/tracking in pTC
  - Matching b/w pTC and Cylindrical Drift Chamber ( $e^+$  tracker).
- Pileup rejection

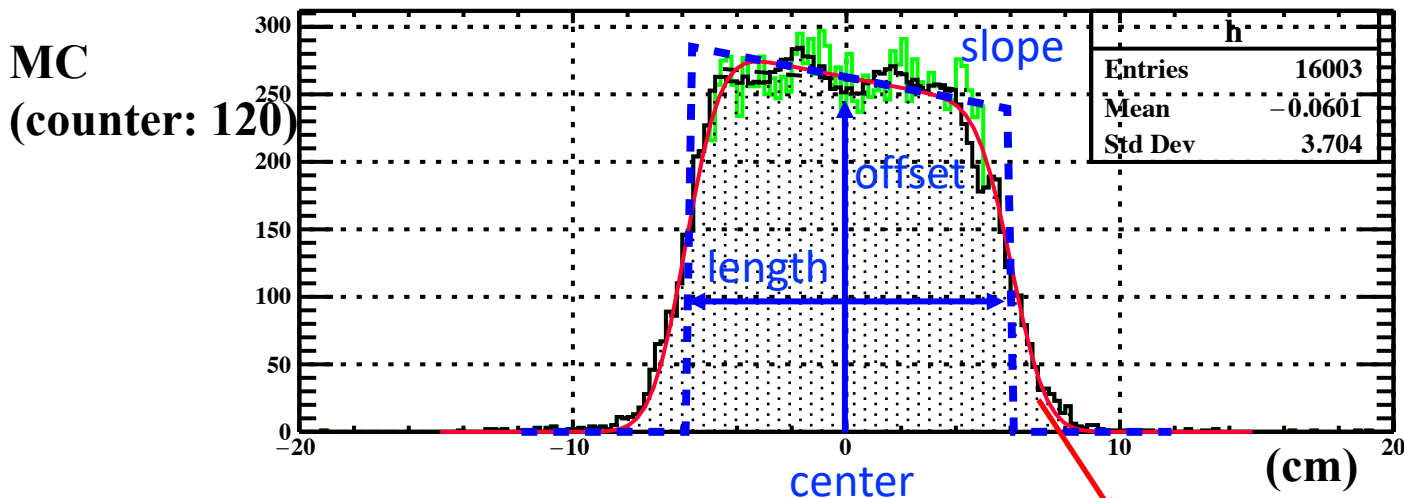
## How to calibrate

- Hit distribution within a counter is aligned to design value.



- Fitting function (red): trapezoid (blue) convoluted with Gaussian<sup>\*,\*\*</sup>.
  - "center": calibration of **Toffset b/w 2 channels/effective velocity**.
  - "length": calibration of **effective velocity**.
  - "sigma": interpreted as **position resolution**.
- Uncertainties of the fitting are estimated using MC to be the followings;
  - **center: 0.11 cm**, length: 0.27 cm, sigma: 0.14 cm

Reconstructed hit distribution in a 12cm-long counter



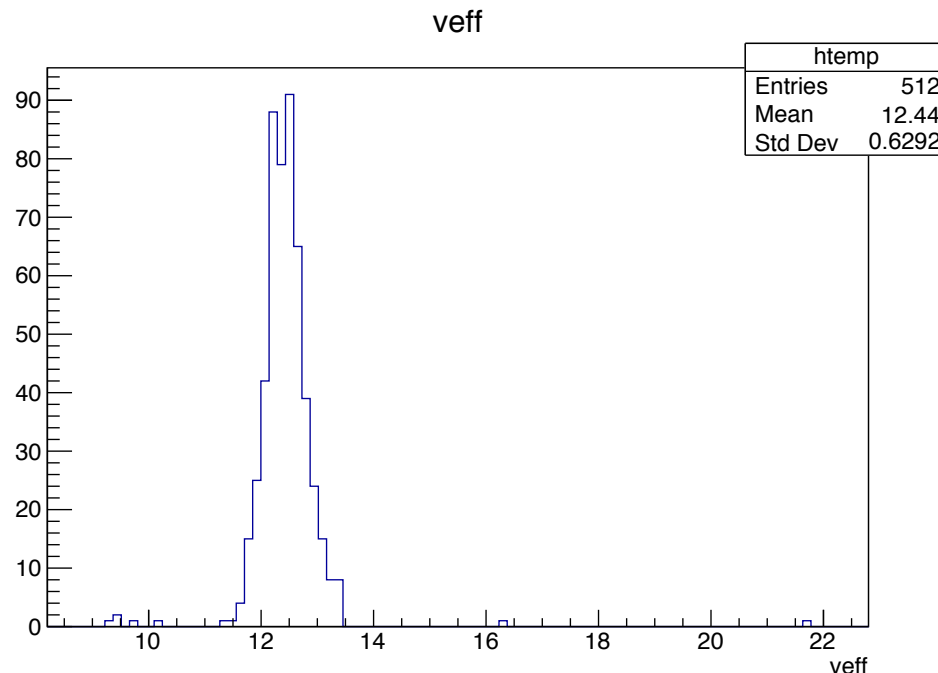
Green: original distribution  
 Black: moving averaged  
 Blue: original trapezoid  
 Red: convoluted with Gaussian

Position  
 resolution

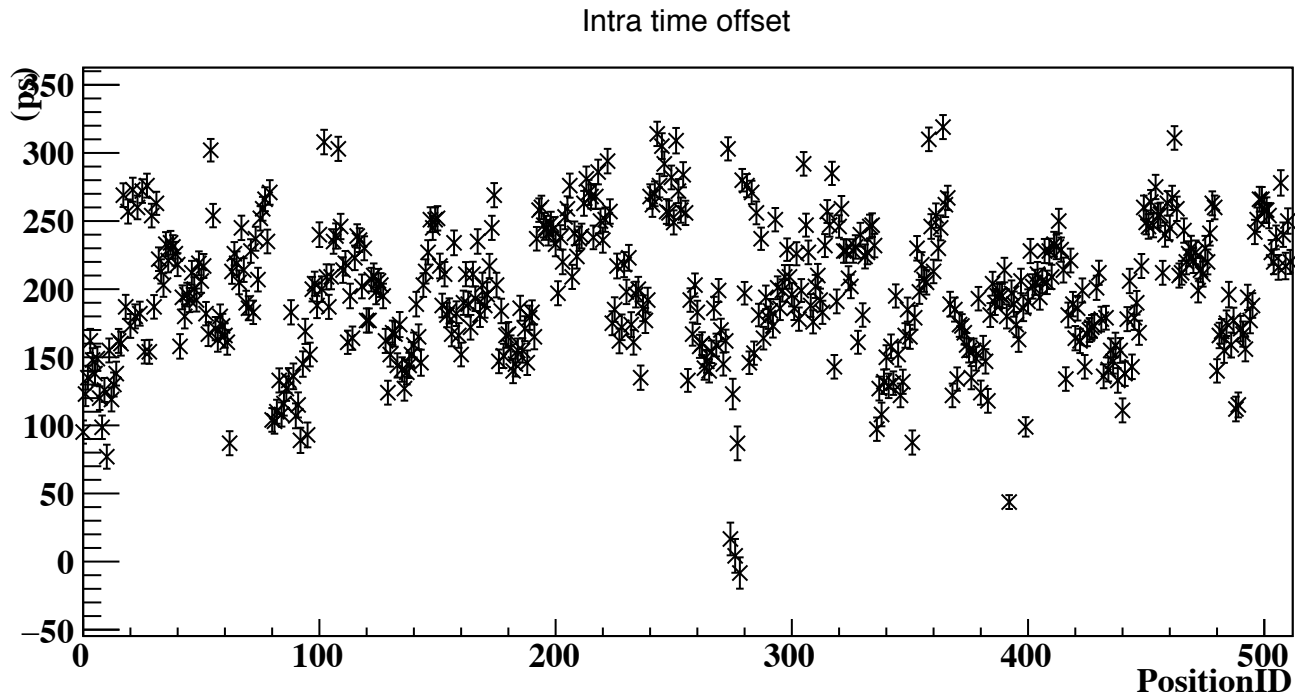
\* for simplicity, I set  
 -convolution step: 100  
 -convolution range:  $\pm 5\sigma$   
 \*\* minimization using  $\chi^2$



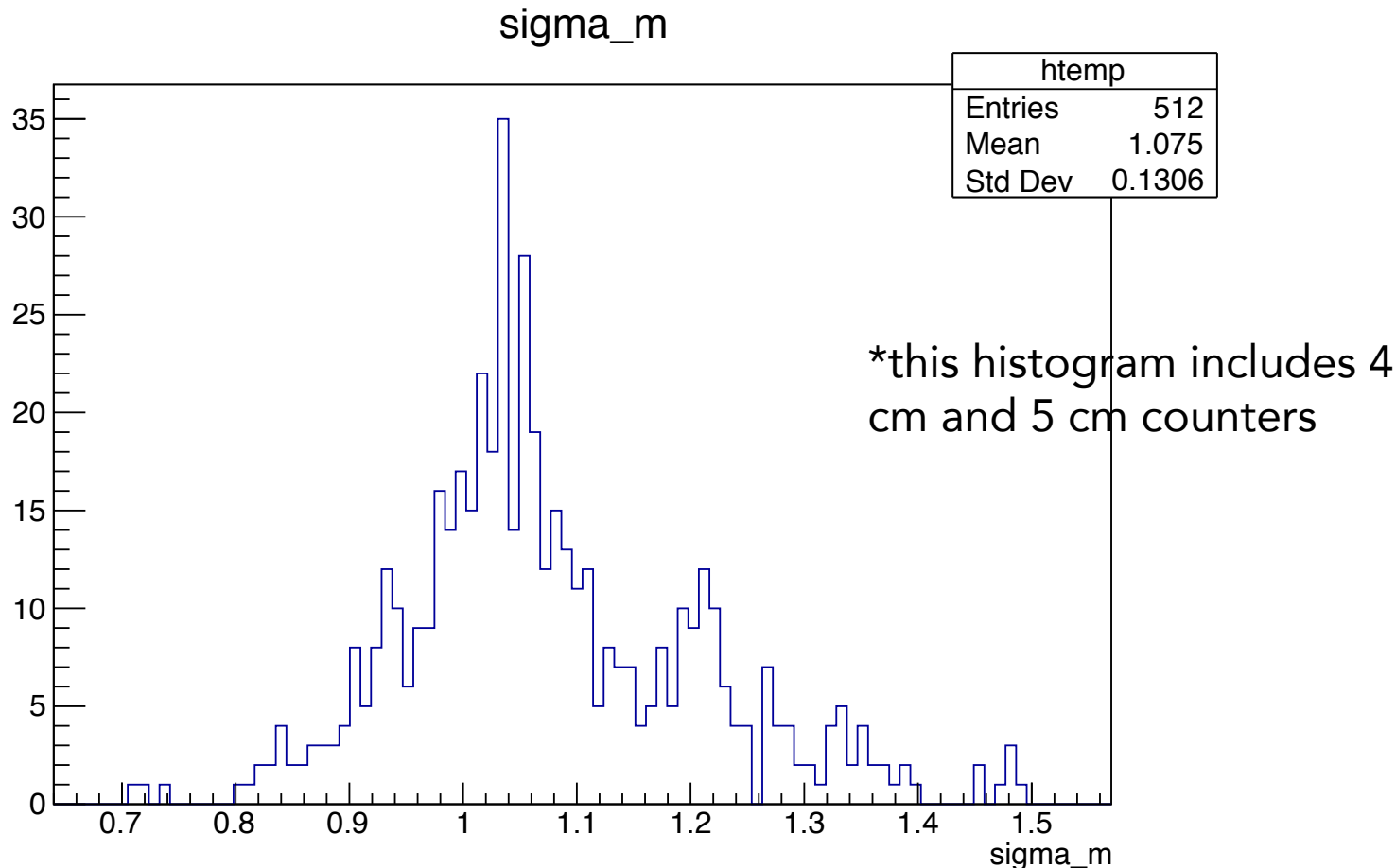
- $v_{\text{eff}} \sim 12.44 \pm 0.40$  cm/ns
- Consistent with results from mass test ( $\sim 12.7$  cm/ns).
- Outliers and counter dependence will be checked.
- The reason of a problem(see bottom right) in method2 is not clear (to be checked).



- The order ( $\sim 200\text{ps}$ ) is consistent with BP+cable measurements.
- But this should not be the same because data includes electronics contributions.

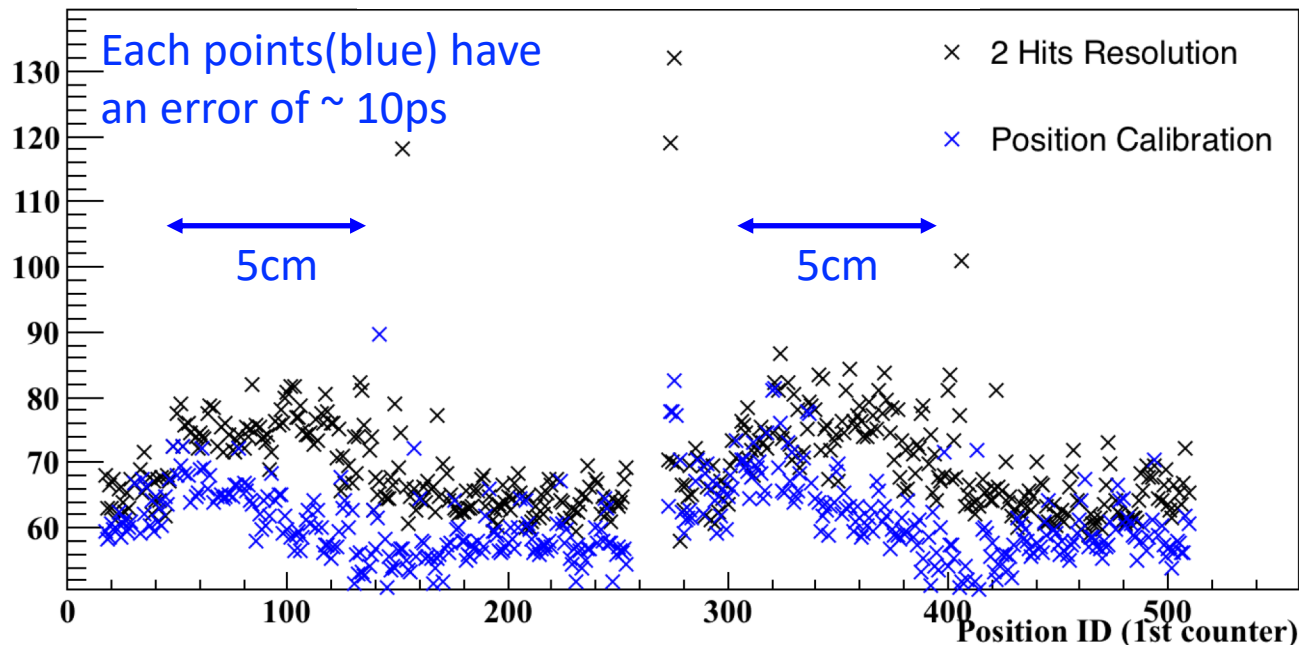


- Position resolution is  $\sim 1.08 \text{ (cm)} \pm 0.14$
- This means single counter resolution is  $\sim 86\text{ps}$  (see next in detail)
- Outliers and counter dependence will be checked.

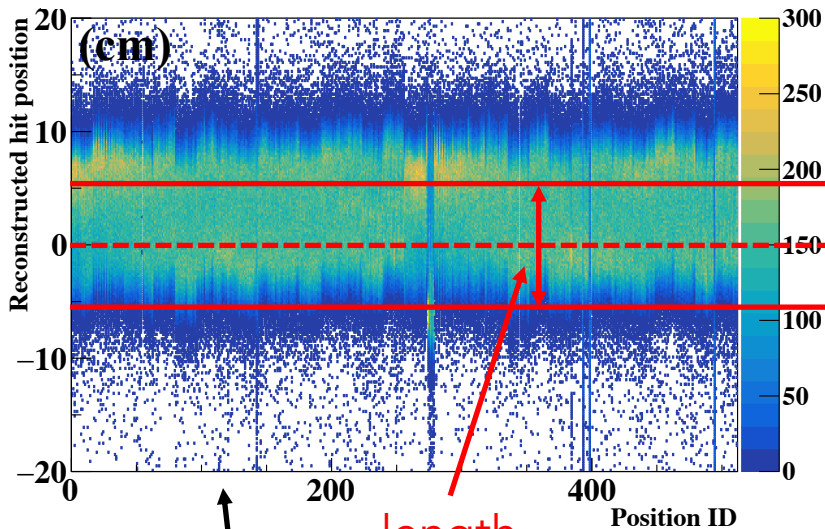


- Time resolution can be calculated from fitted position resolution.
  - $\sigma_{\text{time}} = \sigma_{\text{position}} / v_{\text{eff}}$
- "2 Hits Resolution" is defined as sigma of  $\frac{T_i - T_j}{2}$  where  $T_i$  and  $T_j$  are hit time if adjacent 2 counters (w/o clustering).
- Resolution from position calibration is better than that from "2 Hits" and also have position dependence.
- "2 Hits" can be larger due to the variation of path length.
  - needs checking w/ MC.

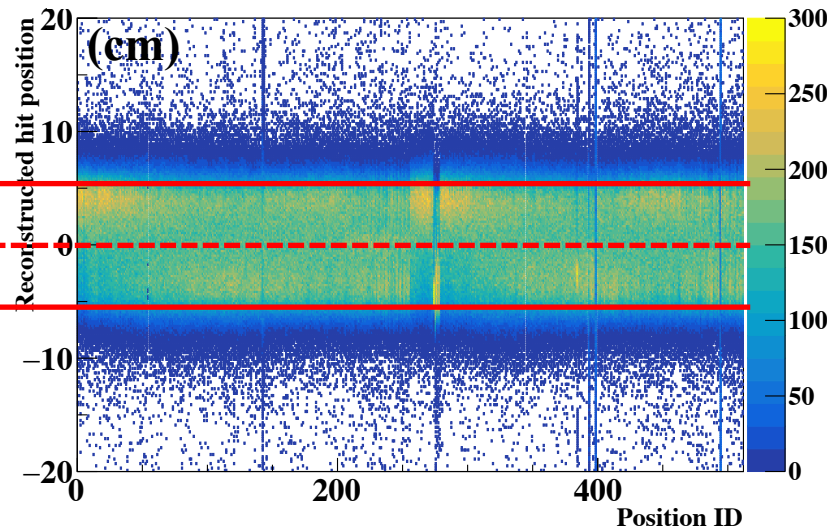
## Time resolution (2 counters)



- Effective velocity ( $12.44 \pm 0.40$ ) under the beam is **consistent** with lab test using  $^{90}\text{Sr}$  source (measured at 3 fixed points).
- Toffset b/w 2 channels are **reasonable** taking into account signal line and electronics contributions.
- **Hit distribution is aligned** (see below).
- Fitting uncertainties: **center(0.11 cm)**, length(0.27 cm) is **better than requirement** ( $\sim 1$  cm).

Reconstructed hit distribution  
(Before)

1 bin = 1 counter

Reconstructed hit distribution  
(After)

center and length is aligned!!

# Summary

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Updated

## Time Calibration

- Full laser system was successfully installed.
- Time offset is enough stable  $\sim 2.5$  ps over 1 month.
- We have established 2 complementary methods to calibrate time offset b/w counters: laser-based method and track-based method.

New

## Position Calibration

- Effective velocity and time offset b/w 2 channels are calibrated.
- Hit distribution is aligned better than position resolution.

## Conclusion

- **pTC calibration is established** and ready for physics run.
- Performance evaluation of pTC/BG study → **see Miki's talk!**

# Backup Slides

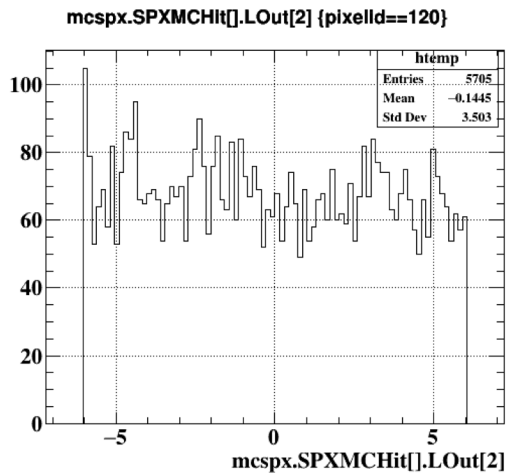
# Position Calibration



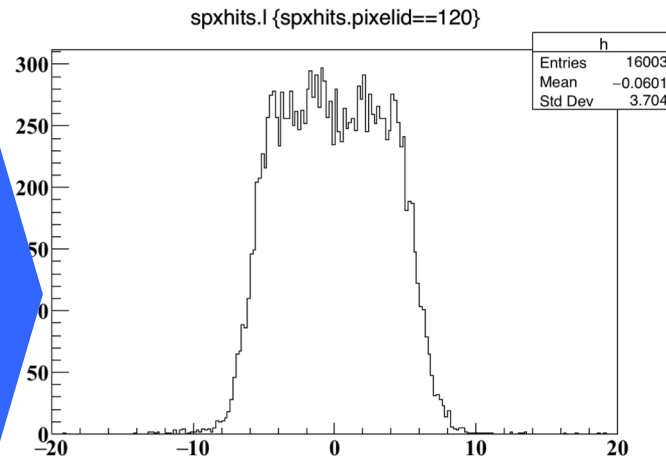
# A first look on the distribution

- All position possibly fitted with same function: trapezoid convoluted with Gaussian.

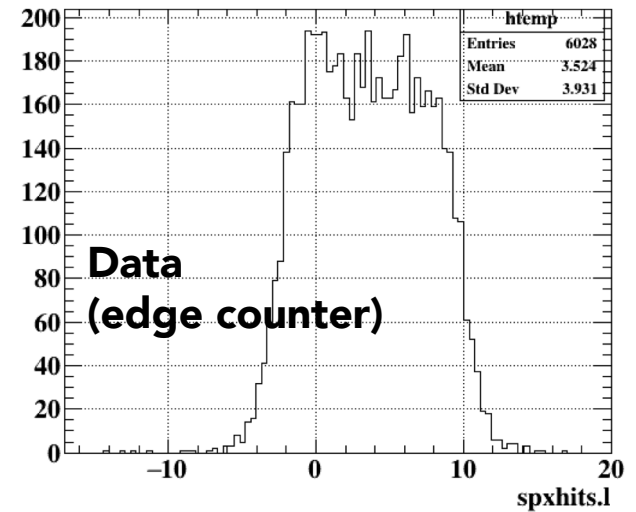
MC truth



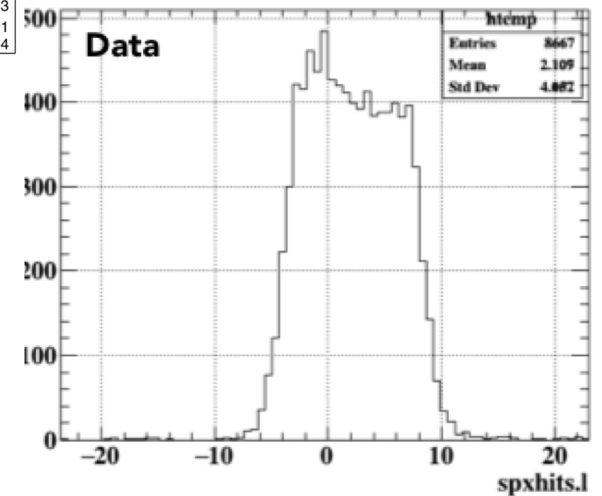
MC after waveform analysis



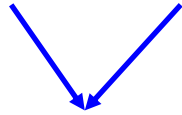
spxhits.l {spxhits.pixelid==252}



spxhits.l {spxhits.pixelid==120}



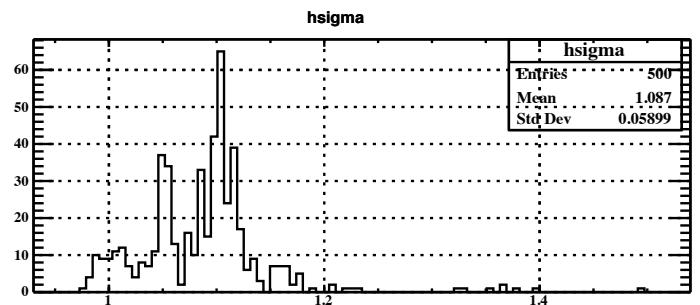
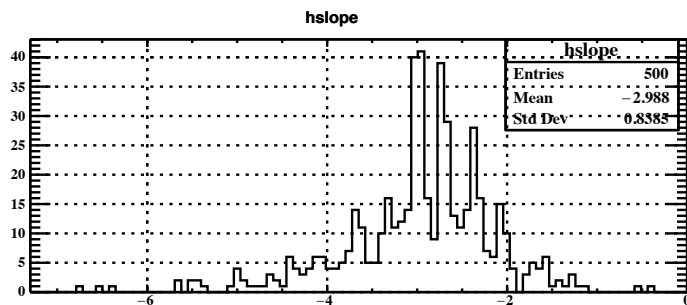
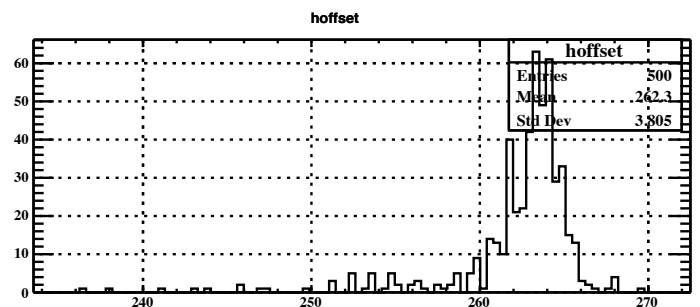
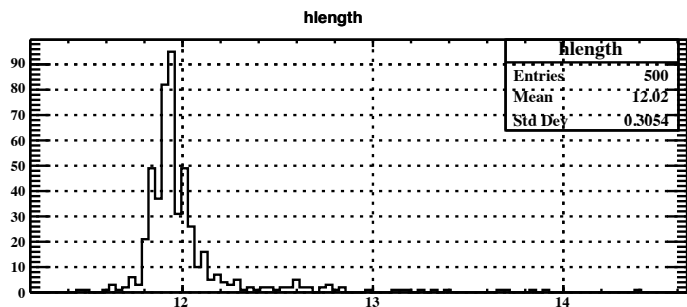
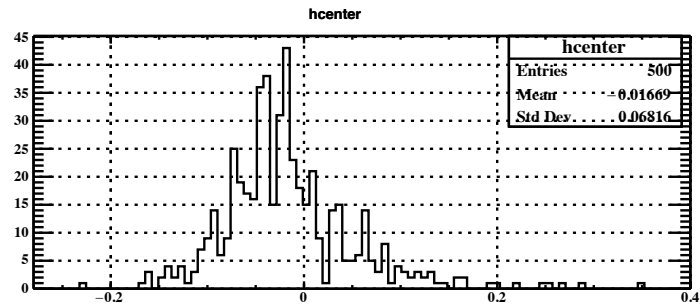
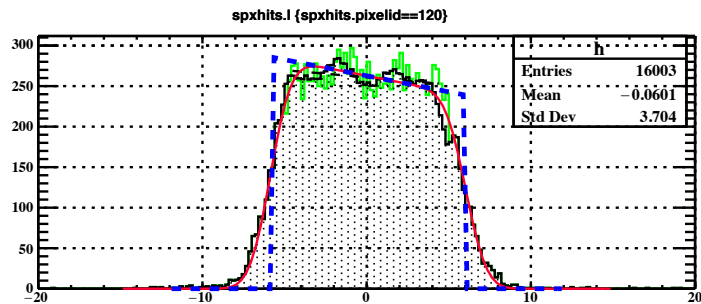
Data MC\*



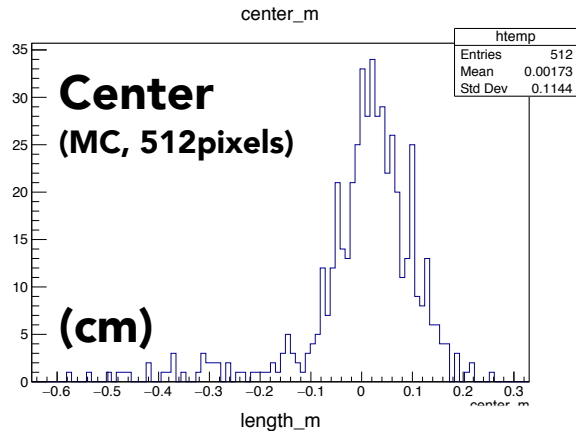
The same analysis both for data and MC.

\* previously I used MCHitRec (hit is smeared w/ 2 Gaussian) w/o waveform simulation.

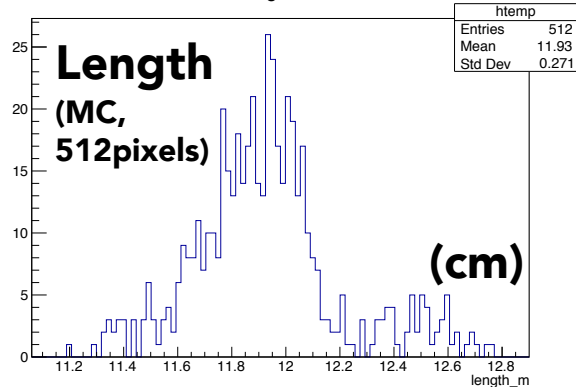
1. Waveform analysis.
2. Hit reconstruction.
3. Hit distribution *w/o any cuts*.
4. *Moving average* around top part.
  - We already know hit distribution has some structure depending on hit pattern.
  - This method should be insensitive to these structure and find rough estimation of  $v_{eff}/T_{intra}$  information.
5. Fitting using *trapezoid convoluted with Gaussian*.
6. Repeat the fitting *500 times* w/ randomly set initial values.
  - Fitting using MINUIT, chi2 minimization using SIMPLEX.
  - MIGRAD/MINOS is not used because there are a lot of local minimums in this fitting, needs fast fitting, and no needs precise error estimation.
7. Get results from mean of 500 fittings.
  - Estimation of the uncertainties using MC.



- Uncertainties are estimated using MC for all 512 pixels.

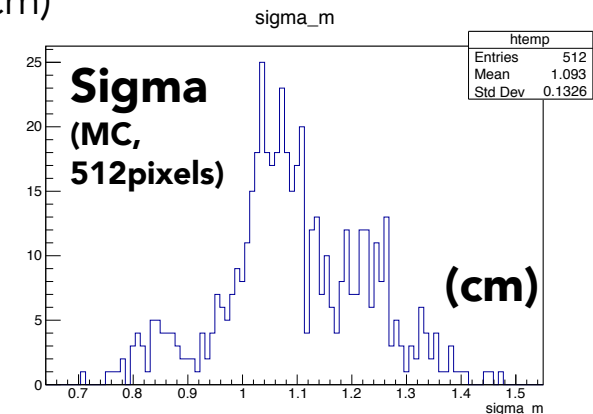


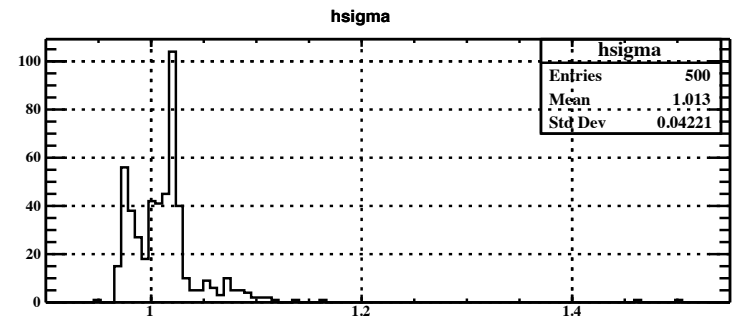
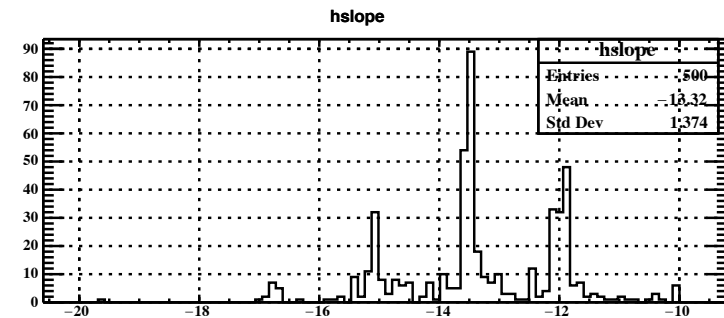
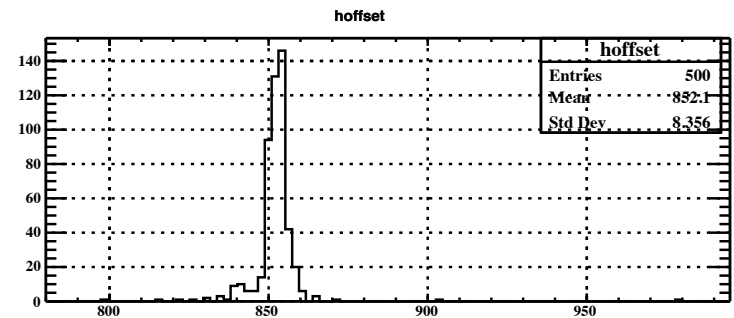
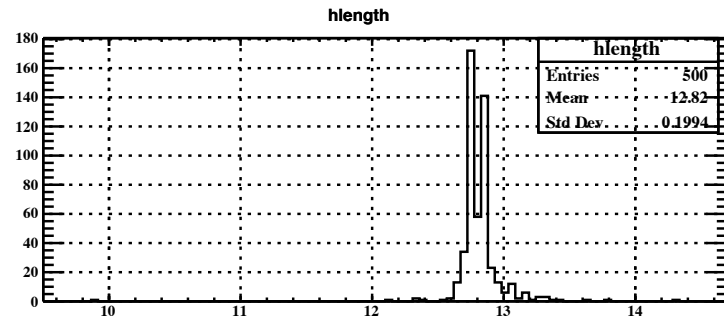
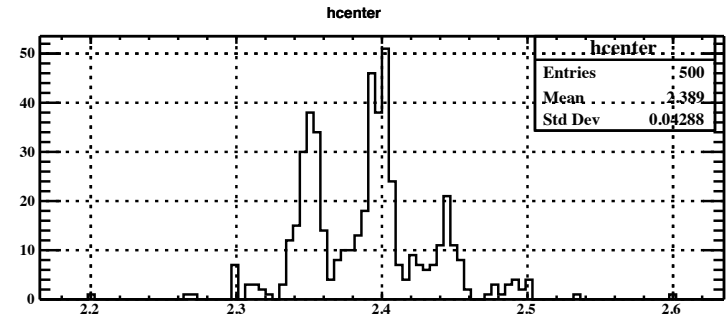
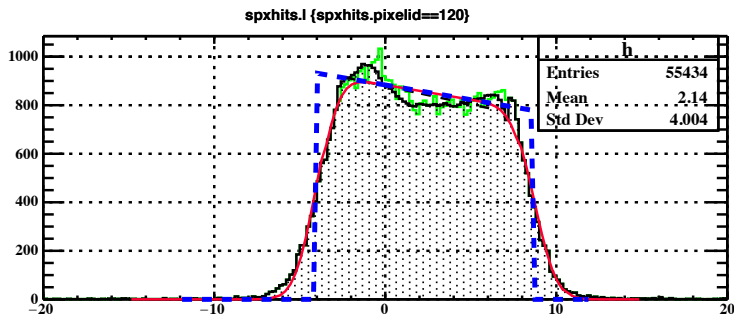
- **Center** position should be 0 in MC.
- RMS from 0 is defined as the uncertainty of center estimation.
- 0.11 (cm)



- **Length** should be 12 or slightly below in MC taking into account effective area of scintillator.
- StdDev is defined as the uncertainty of length estimation.
- 0.27 (cm)
- Effective length: 11.93 (cm)

- **Sigma**(position resolution should be 1.06.  
←  $\sigma_t = 79\text{ps}$  in waveform simulation,  $v_{\text{eff}} = 13.4$  in MC.
- RMS from 1.06 is defined as the uncertainty of sigma estimation.
- 0.14 (cm)





## Effective velocity: $v_{\text{eff}}$

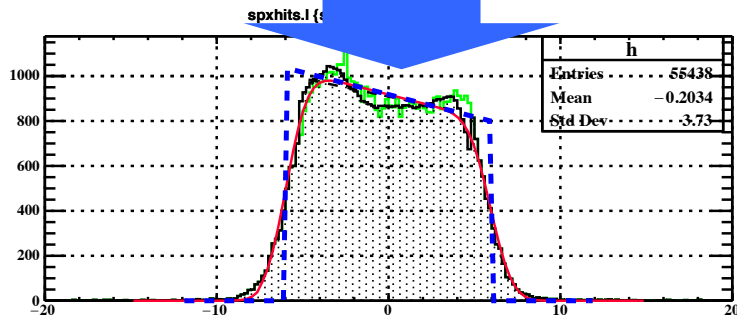
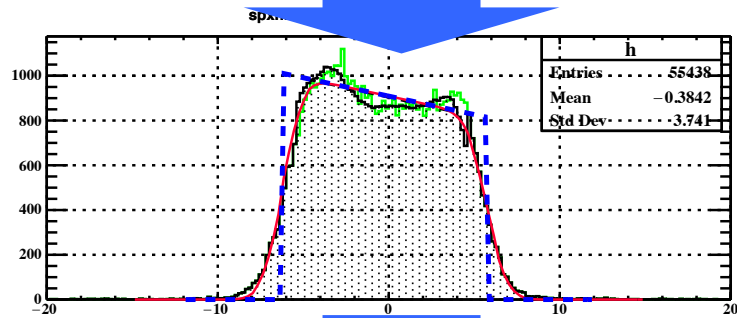
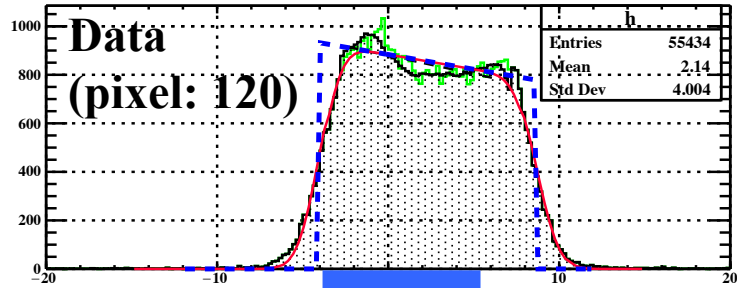
- Length is used.
- If  $v_{\text{eff}}$  is true,  $v_{\text{eff}} * t = L \sim 12(\text{cm})$ 
  - $L$ : (effective) scintillator length.
  - $v_{\text{eff}}$ : effective velocity.
  - $t$ : effective measured time which it takes for scintillator light to go from one side to the other side.
- Now  $v_{\text{eff}}$  is originally set to  $v_{\text{eff}}_{\text{before}} = 13.4$ .
- So,  $L_{\text{data}} = v_{\text{eff}}_{\text{before}} * t$  and it is larger than  $L \sim 12(\text{cm})$ .
- To get  $v_{\text{eff}}$ ,  
$$v_{\text{eff}} = (L/L_{\text{data}}) * v_{\text{eff}}_{\text{before}}$$

## Intra time offset: $T_{\text{intra}}$

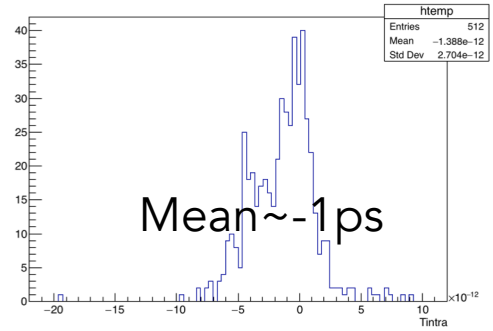
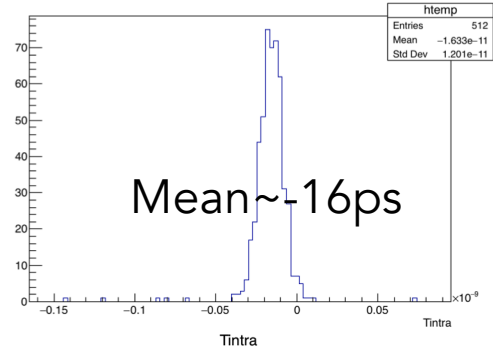
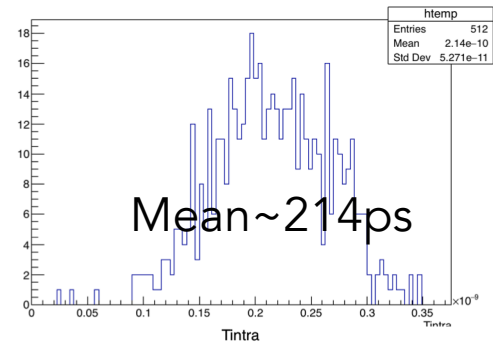
- Center position is used.
- $\text{Center} = T_{\text{intra}} * v_{\text{eff}}$
- If  $T_{\text{intra}}$  is 0, center should be 0.
- Then,  $T_{\text{intra}} = \text{Center}/v_{\text{eff}}$

- Iterate the whole procedure until the results is not changed.

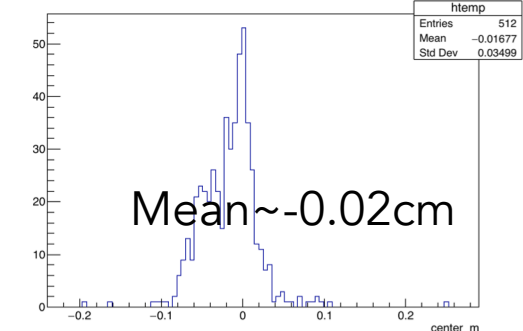
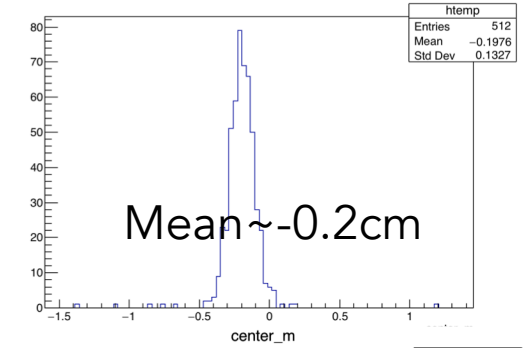
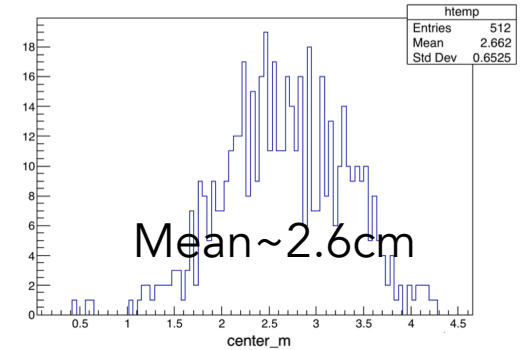
## An example of the fitting



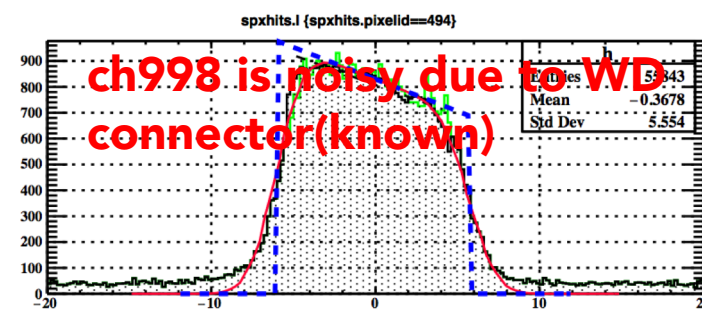
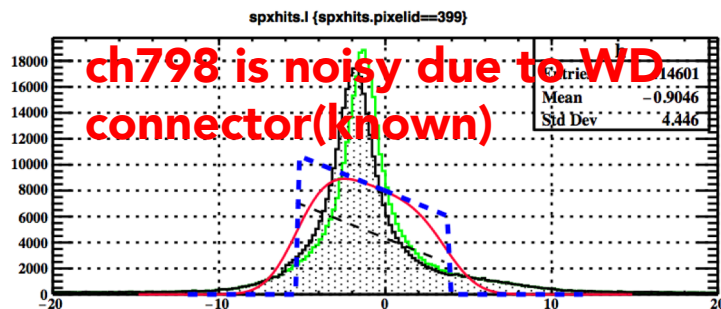
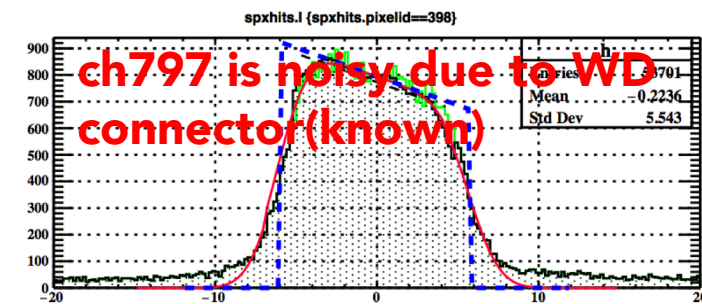
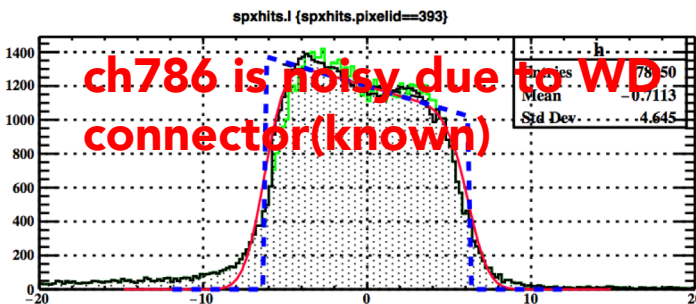
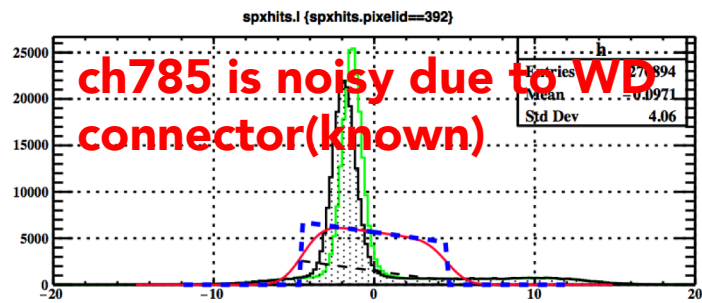
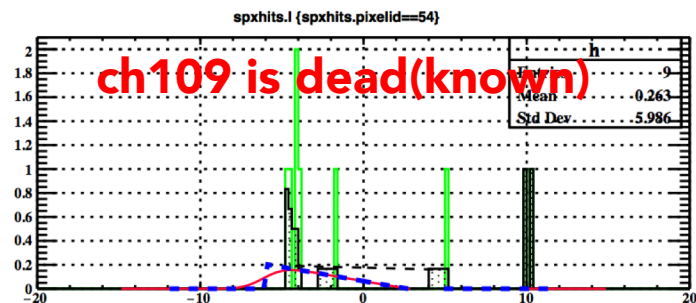
## Tintra



## Center



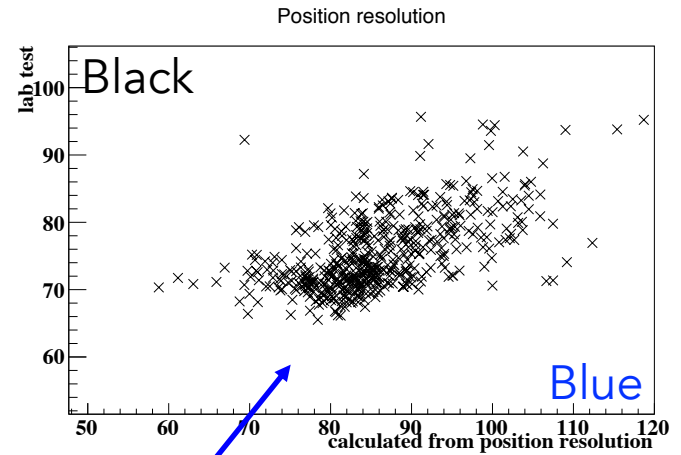
- There are several bad pixels: position#54, 392, 393, 398, 399, 494
- All of them are known and noisy channels can be recovered by event selection(not yet).



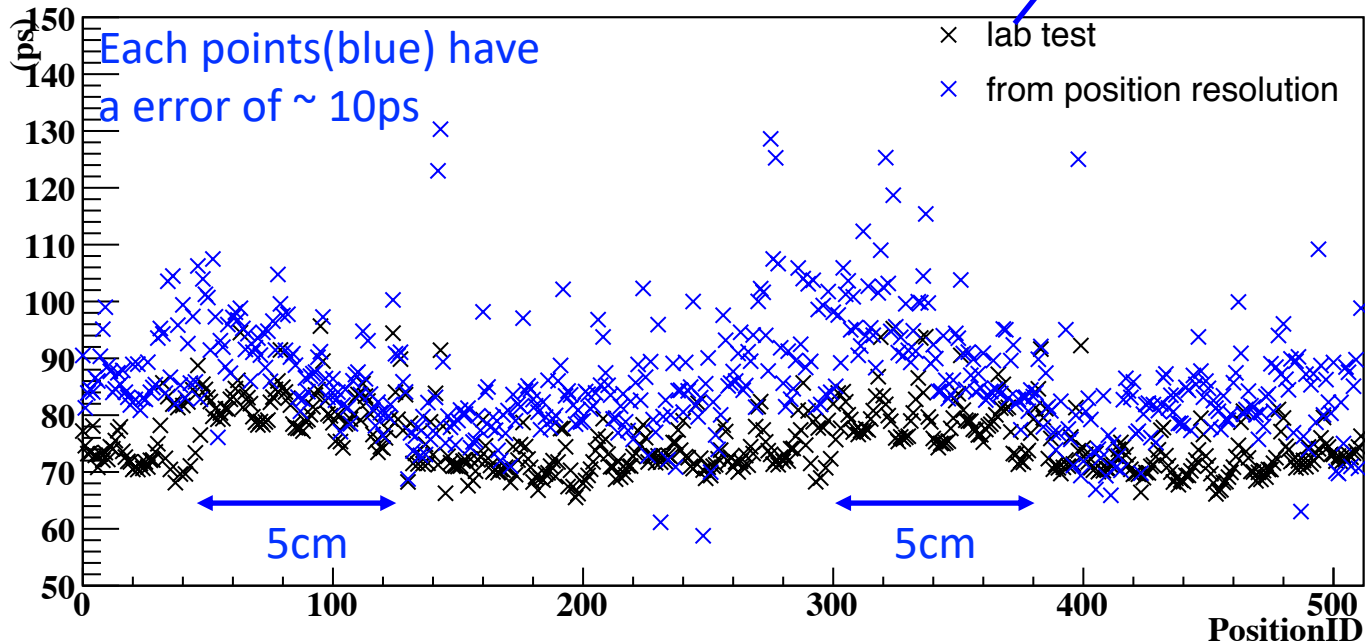


# Results(4): time resolution

- Time resolution can be calculated from fitted position resolution.
  - $\sigma_{\text{time}} = \sigma_{\text{position}} / v_{\text{eff}}$
- 2 results have correlation.
- Larger value than lab test possibly coming from noise condition, edep difference (not yet included)



Time resolution (single counter) scatter plot of these 2 points

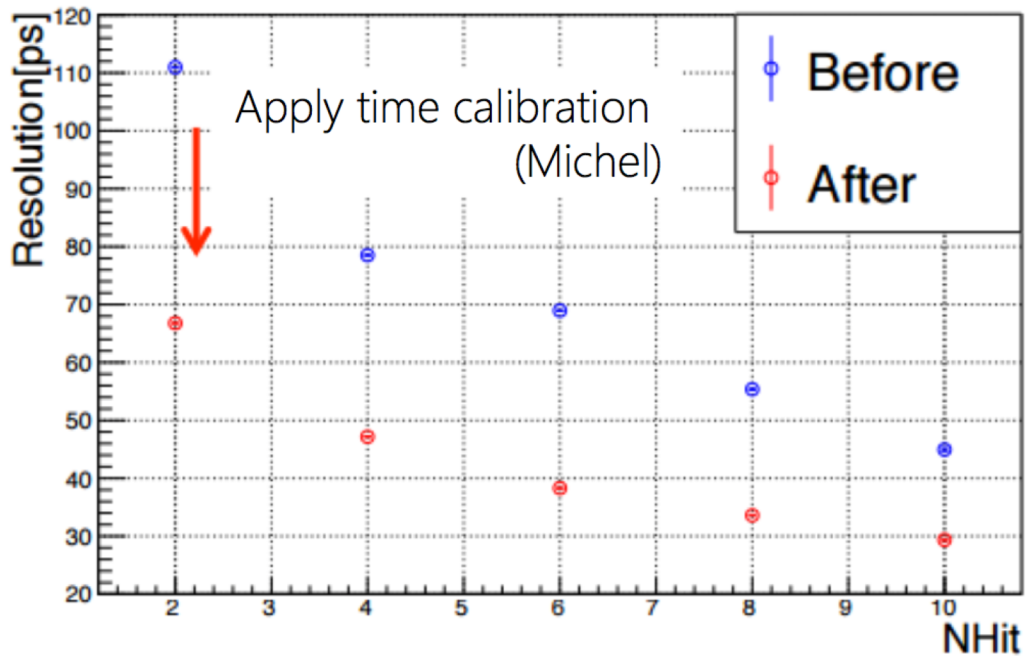
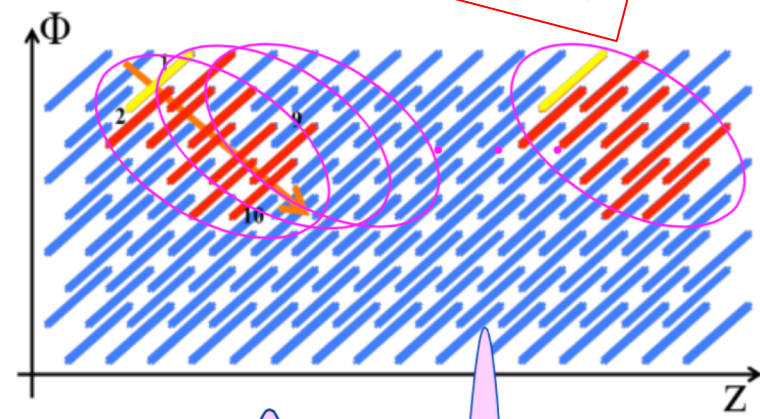


# Time Calibration

# Resolution incl. time calibration

pER2016

- Even – odd analysis is insensitive to time offset when testing a given combination
- Select 22 10-counter combinations
  - ▣ Different combinations have different center for  $T(\text{even} - \text{odd})$  if time offset is not calibrated.
  - ▣ Accumulate  $T(\text{even} - \text{odd})$  for all the combinations

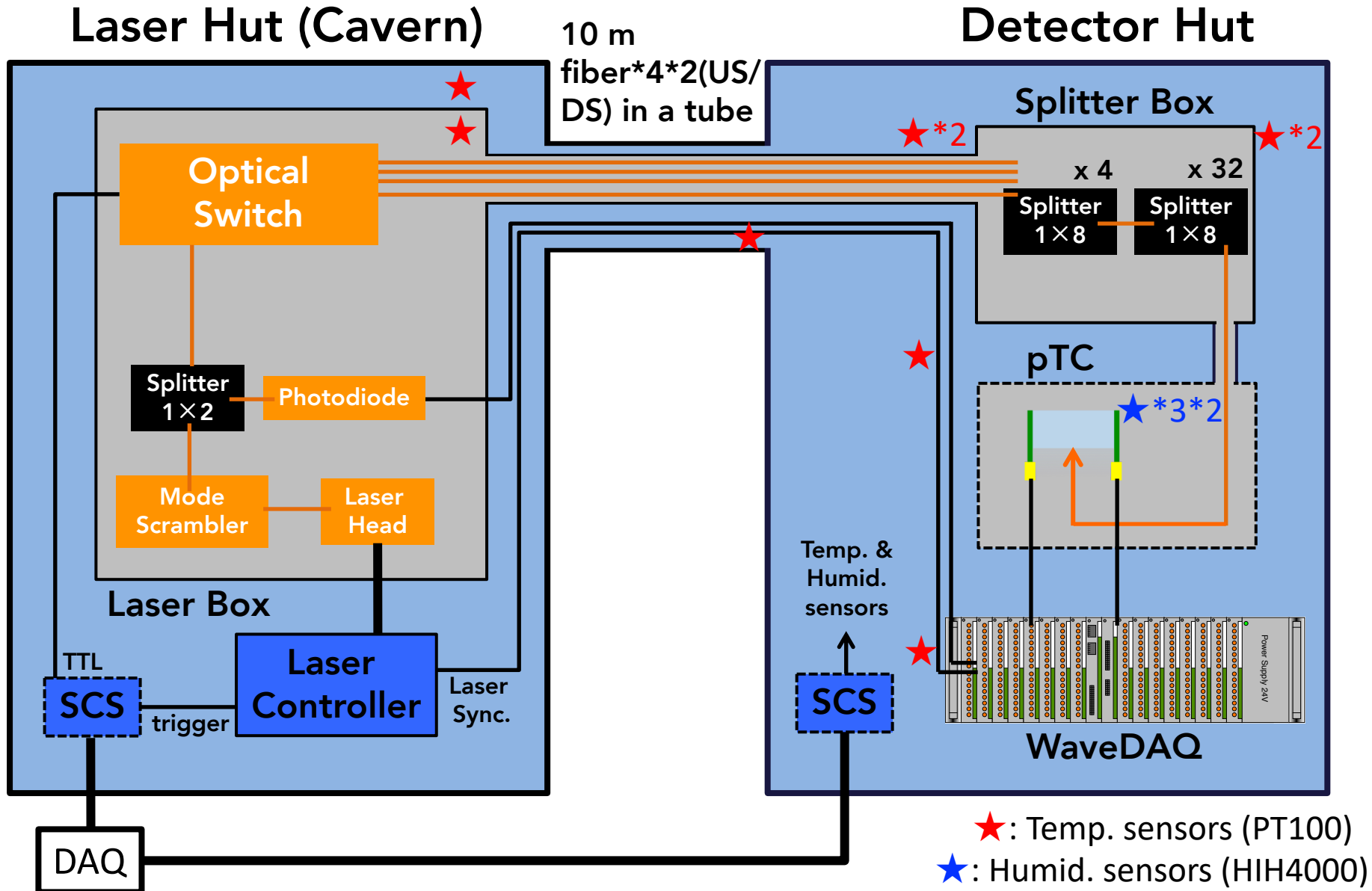


YUSUKE UCHIYAMA

- No degradation
- Validation of a good time calibration
- Achieved  $\sigma(N=8) = 34$  ps including time calibration contribution

# Laser Calibration

# Laser calibration system



# Summary of uncertainties

Items	(ps)
Laser mass test (May.-Aug., 2017)	5.4
Laser run statistics (pER2017)	1.0
Laser run stability (pER2017)	5.2
Reproducibility of laser system (R&D)	11
Other systematic uncertainties related to laser calibration (R&D)	21
Voltage correction (pER2017)	1.5
Time-walk factor (pER2017)	4.2
Height estimation (pER2017)	~0

→ see next

## Comments

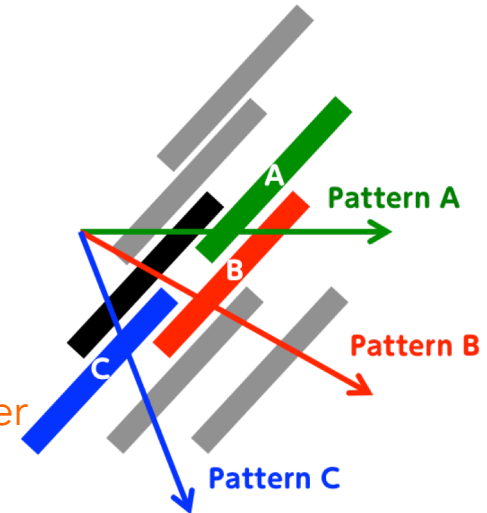
- No systematics related to Michel calibration is included.

# Michel Calibration (Track-based method)

- Positron tracks from Michel decay ( $\mu^+ \rightarrow e^+ \nu \nu$ ) are used for calibration.
  1. Assume every counter has 3 different TOF b/w counters (pattern A, B and C).
  2. Calculate these TOF values for every counter by Monte Carlo\*.
  3. Define  $\chi^2$  as the difference b/w measured time and expected time.
  4. Minimize  $\chi^2$  using Millepede II.
  5. Find  $\Delta T_j$ .
- Calibration uncertainty is estimated as 6 ps by MC study.

$$\chi^2 = \sum_i^{N_{event}} \sum_j^{N_{hit}} \left( \frac{\text{Measured time } T_{ij} - (\text{Expected time } T_{0i} + TOF_{ij} + \Delta T_j)}{\sigma \text{ Time offset of each counter}} \right)^2$$

:What we want to know



\* This setup is for Pilot Run w/o DCH. TOF will be calculated by DCH in physics run.

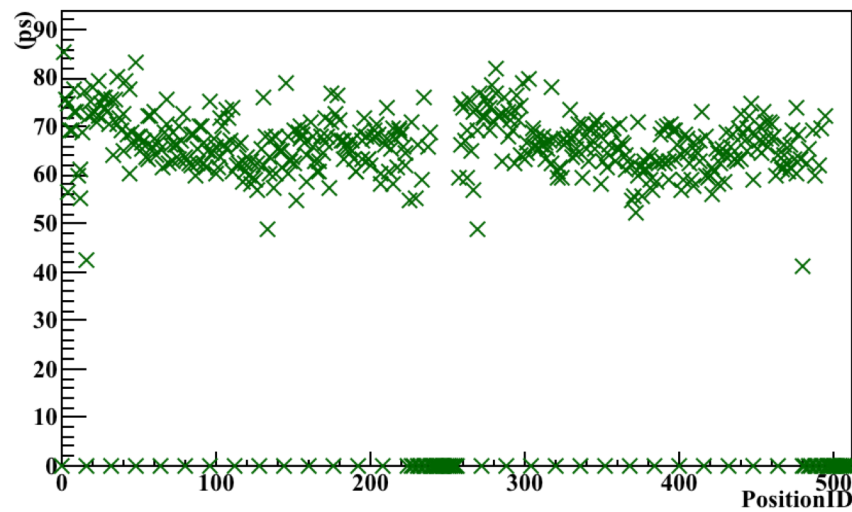
Millepede II [www.desy.de/~kleinwrt/MP2](http://www.desy.de/~kleinwrt/MP2)

A software provided by DESY to solve the linear squares problems, such as detector alignment and calibration based on track fits.

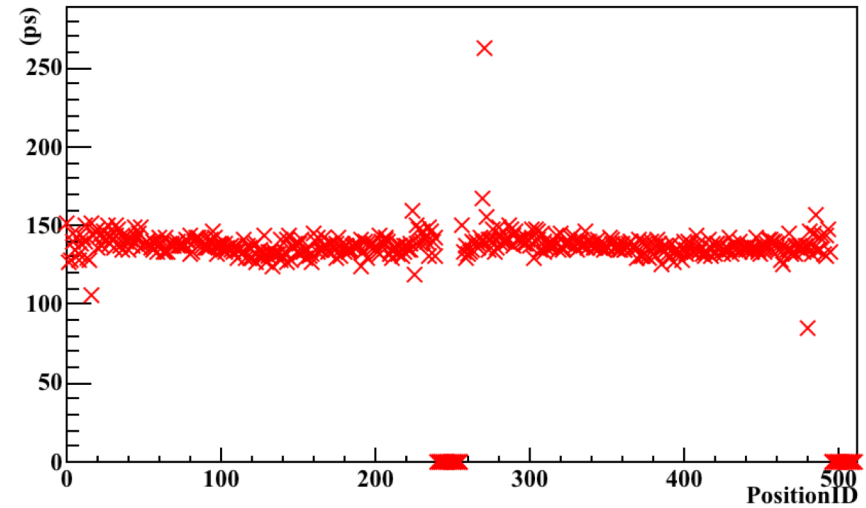


# TOF (MC)

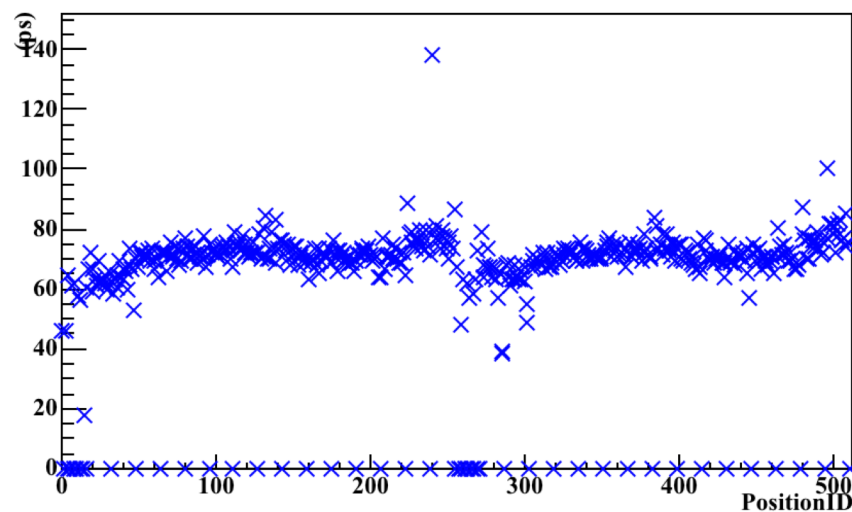
TOF1



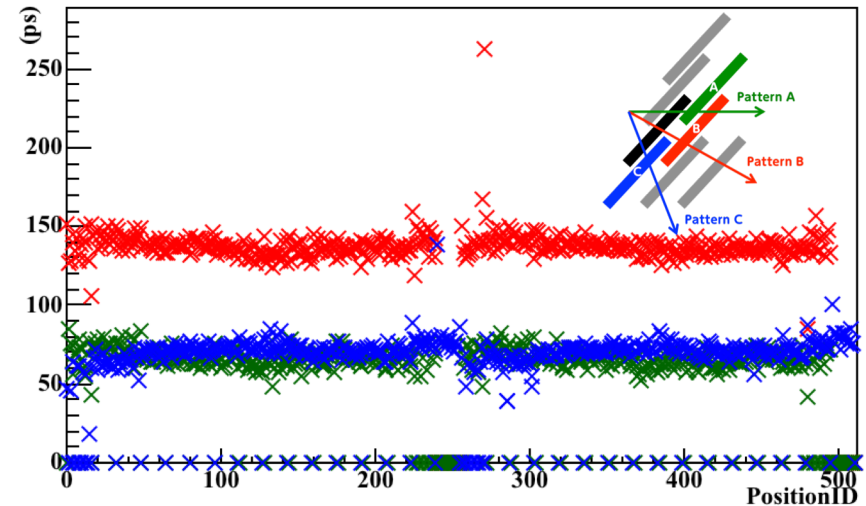
TOF2



TOF3



TOF2



# Results (MC)

Calculated TOF - true TOF(randomly generated)

