MEG II実験のためのSiPMを用いた
陽電子タイミングカウンターのシミュレーションによる性能評価

Development of the Waveform Simulation for Positron Timing Counter with SiPM for MEG II Experiment

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日本物理学会 2016年春季大会＠東北学院大学泉キャンパス

東京大学
THE UNIVERSITY OF TOKYO

MEG
Mu-E-Gamma Collaboration

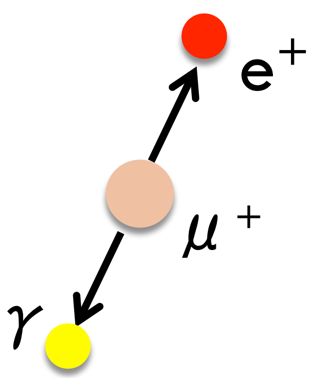
Topics

- MEG II experiment
- Timing Counter Upgrade
- TC Software
- Waveform simulation
  - Resolution for Single counter with noise
  - Simulation at multi counter setup
- Summary

MEG II experiment

- Search for charged Lepton Flavour violation decay $\mu \rightarrow e\gamma$ predicted in Beyond Standard Model (SUSY-GUT, see-saw model etc…)
- Now upgrading to aim for Branching ratio 4×10^{-14}
- Accidental background increase by double rate μ beam → Detector performance is improved
- It is necessary to measure the time, direction, energy for γ and e^+ to identify the signal event

Signal

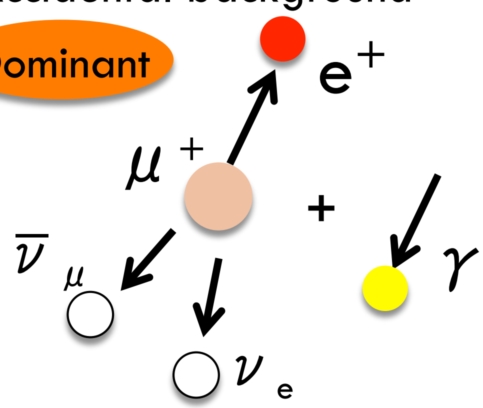


- Same time
- Back to back
- Same energy E=52.8MeV

Background

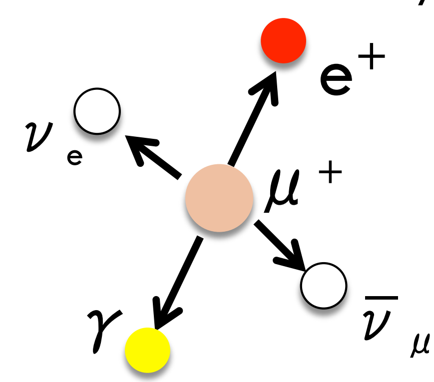
・Accidental background

Dominant



- Accidental hit of e^+ from Michel decay and γ from radiative decay etc.

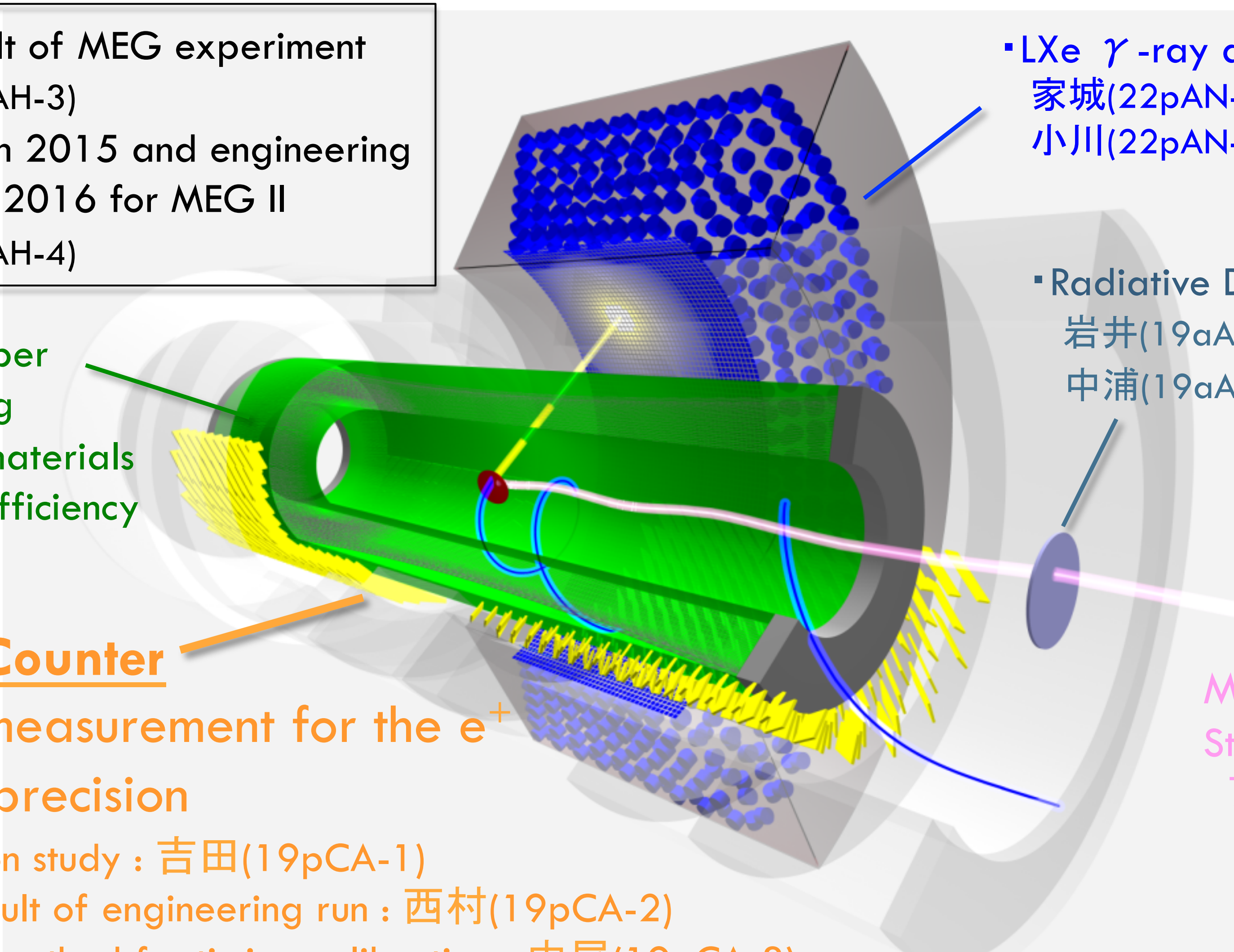
・Radiative muon decay



- Same time
- E<52.8MeV
- No back to back

MEG II Detector

- Final result of MEG experiment
  金子(19aAH-3)
- Pilot run in 2015 and engineering run for in 2016 for MEG II
  内山(19aAH-4)



- LXe γ-ray detector
  家城(22pAN-3)
  小川(22pAN-4)

- Radiative Decay Counter
  岩井(19aAH-10)
  中浦(19aAH-11)

- Drift chamber
  e^+ Tracking
  low mass materials
  and high efficiency

Timing Counter

Timing measurement for the e^+
at high precision

Simulation study : 吉田(19pCA-1)
Initial result of engineering run : 西村(19pCA-2)
Analysis method for timing calibration : 中尾(19pCA-3)

Muon beam
Stopping rate
$7\times10^7\ \mu/s$

Timing Counter Upgrade

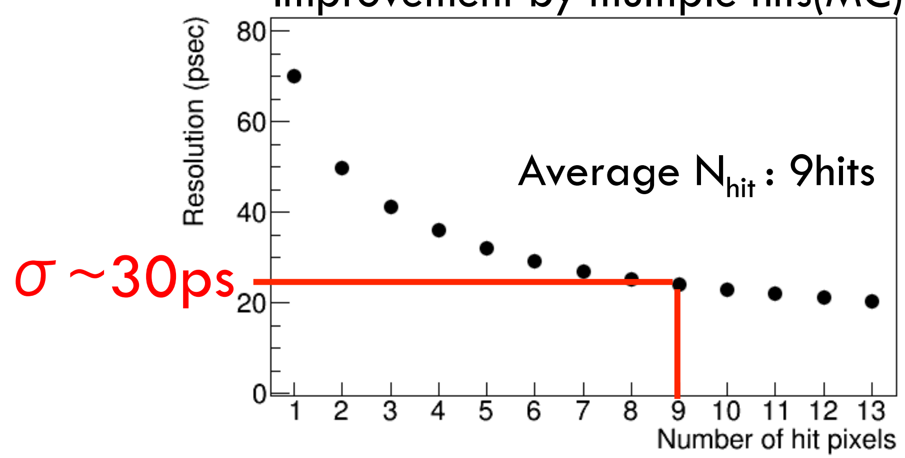
- **Pixelated Timing Counter**
  - To measure the time of positron from $\mu^+ \rightarrow e^+ \gamma$
  - One counter consists of fast plastic scintillator and SiPM
  - Total 512 counters at upstream and downstream
  - It has good timing resolution by multiple hits
  - Low pileup effect under high rate μ
  - **Good time resolution (~30ps)** is demonstrated at the beam test

$$\sigma^2_{\text{overall}}(\mathrm{N_{hit}}) = \frac{\sigma^2_{\text{single}}}{\mathrm{N_{hit}}} + \frac{\sigma^2_{\text{inter-pixel}}}{\mathrm{N_{hit}}} + \sigma^2_{\text{MS}}(\mathrm{N_{hit}})$$

$\sigma_{\text{inter-pixel}} \sim 30\text{ps}$

$\sigma_{\text{MS}} \sim 5\text{ps}$

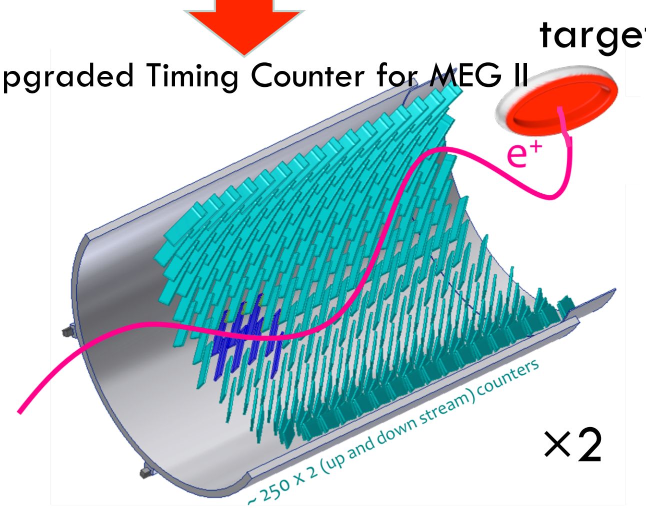
Improvement by multiple hits(MC)



Timing Counter for MEG

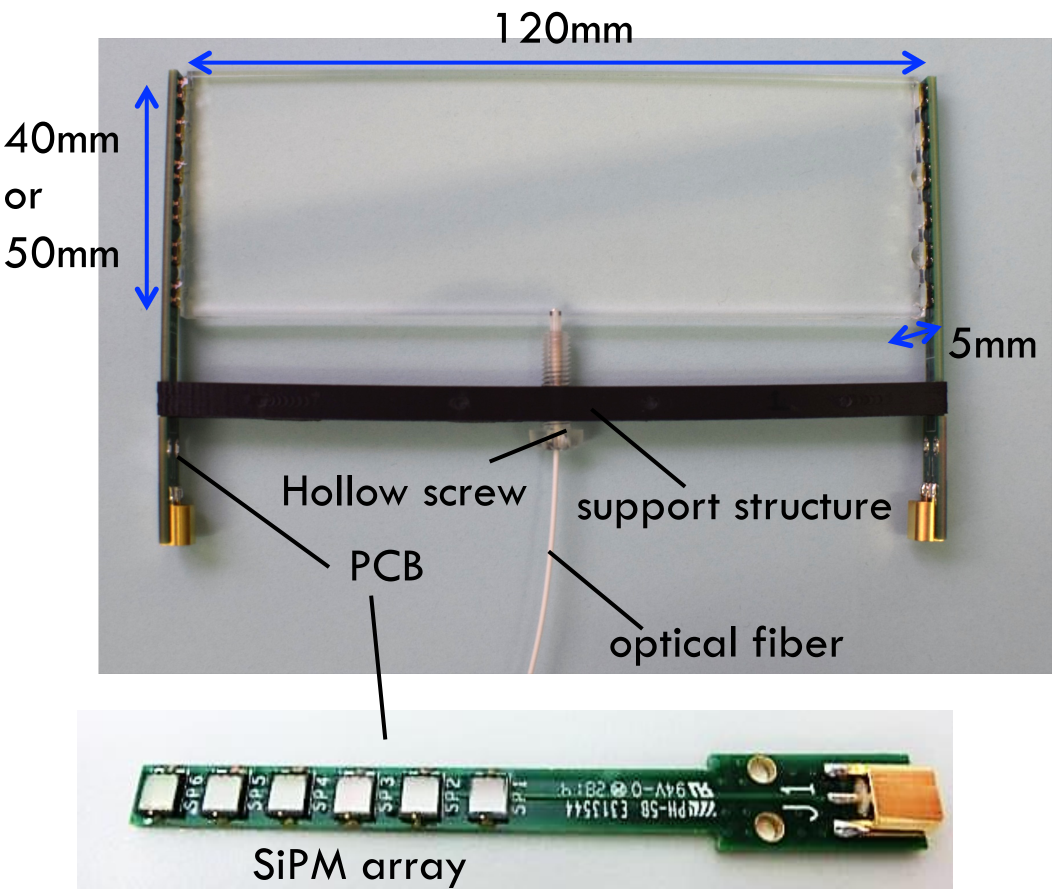
Plastic scintillator bar + PMT

Upgraded Timing Counter for MEG II



Fast plastic scintillator+ SiPM

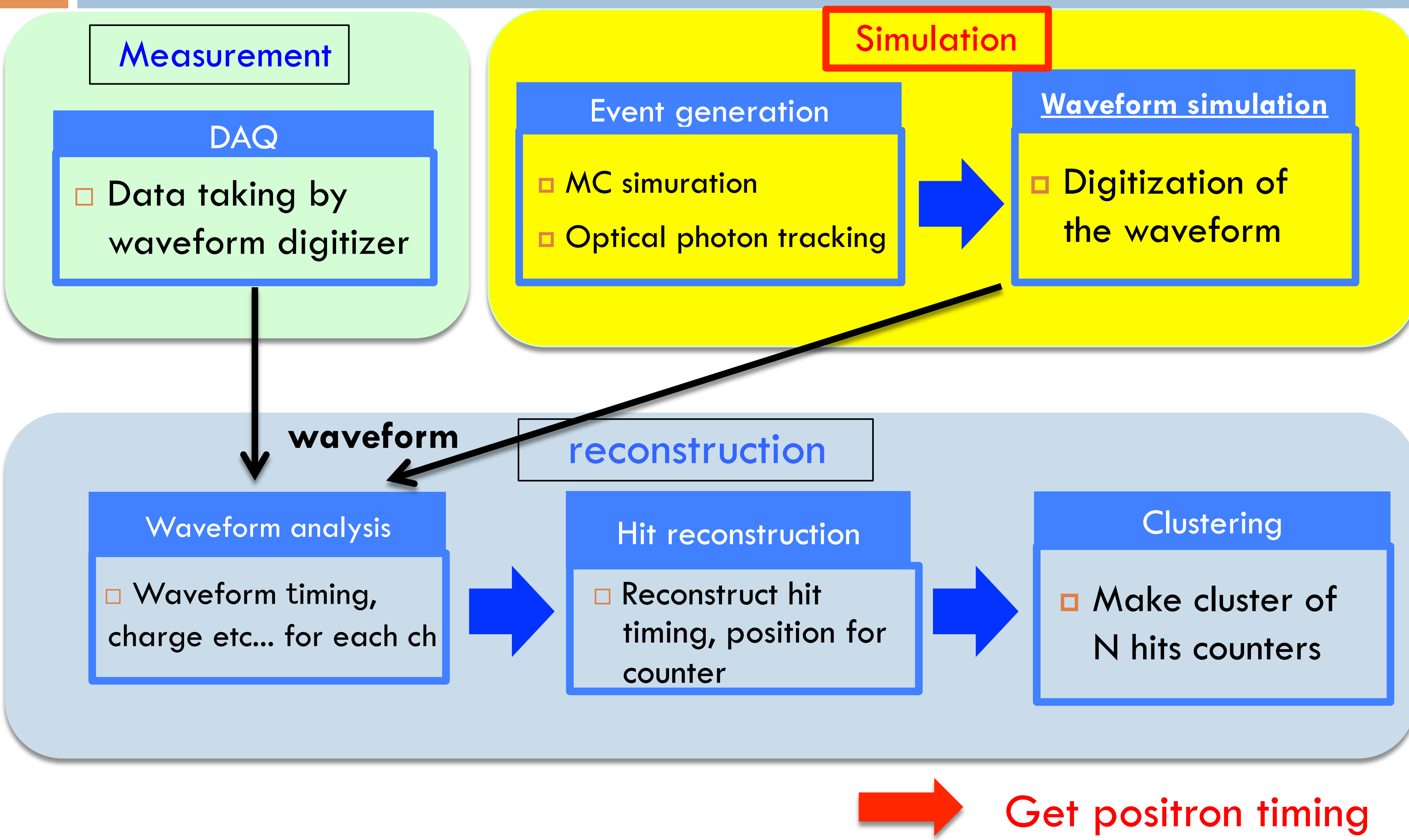
Single Counter



- Fast Plastic scintillator BC422
  - Rise time : < 20ps
  - Light output : 55% of Anthracene
  - Peak wavelength : 370 nm
  - Light attenuation : 8cm
  - $120\times40\times5mm^3$, $120\times50\times5mm^3$
  - Covered by Mirror type reflector (3M ESR film) and black sheet (Tedlar)
- SiPM (ASD-NUV3S-P High-Gain (MEG))
  - $3\times3mm^2$,3600pix made by AdvanSiD
  - SiPM array (6series) on the PCB
  - 2ch readout from both side of the counter
- SiPM and Scintillator connected by optical cement
- Optical fiber and support structure for timing calibration

<u>Timing Resolution ~75ps</u> (for 4cm counter)

Overall of TC software



Waveform simulation

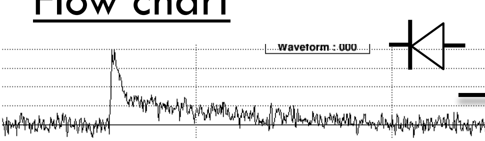
- To evaluate performance and understand the detector
  - Study the effects of pile up, dark noise, crosstalk ,after pulse for timing resolution
- Waveform simulation method
  1. Scintillation photon is generated and tracked by MC
  2. Detected photon timing at SiPM is got
  3. Convolute the photon pulse and 1p.e. response of SiPM array

1p.e. waveform of SiPM array is necessary

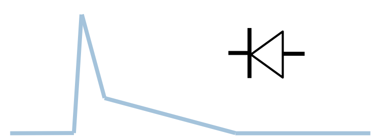
- However, it is difficult to measure 1p.e. signal for 6 series SiPM because of high dark rate
- 1p.e. waveform of SiPM array is simulated from 1p.e. waveform of single SiPM

*About making template waveform
日本物理学会2015年秋季大会
吉田(26aSN03)

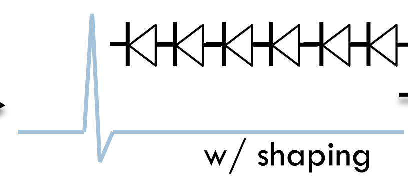
Flow chart



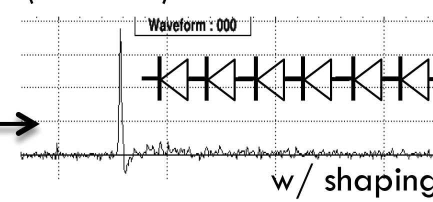
1. Raw 1p.e. waveform from single SiPM by measurement



2. Simulate SiPM circuit and set the parameters by SPICE to get the 1p.e. waveform for single SiPM



3. Simulate the 1p.e. waveform for SiPM array by SPICE



4. Convolute the photon pulse and 1p.e. waveform from SiPM

Waveform Simulation for Single Counter -Previous JPS meeting-

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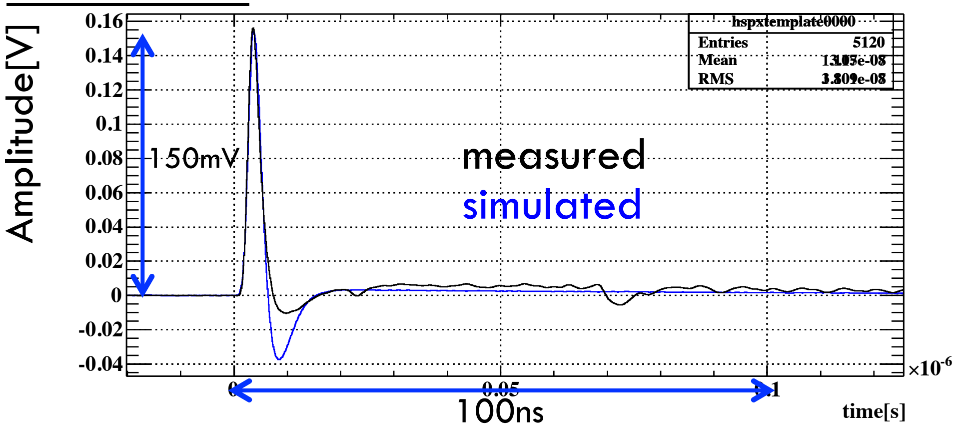
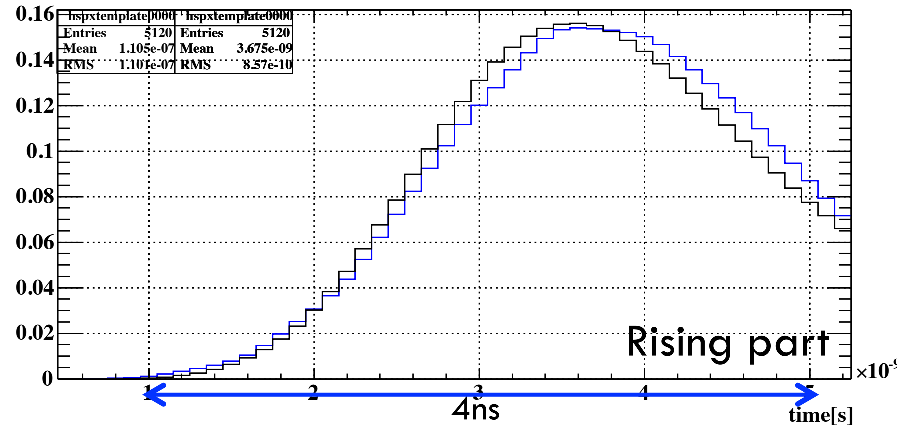
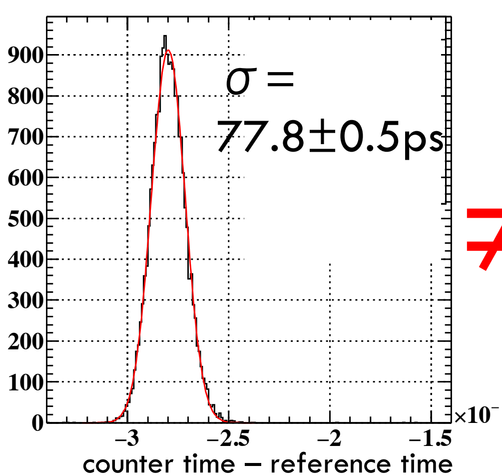
▪ Waveform





▪Timing resolution

measurement



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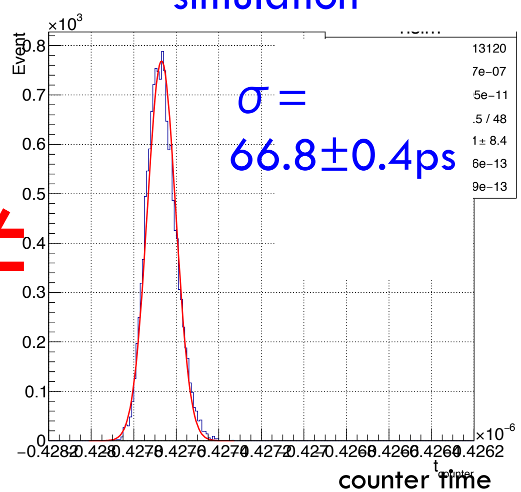
simulation



- Event generation by geant4
  - For single counter
  - e^- from Sr^{90} source (E_{end}=2.3MeV)
  - Tracking scintillation photon
- Convolute 1p.e. template waveform and photon time distribution
- Light yield is set by matching height with actual signal
- Simulated waveform matches the measured waveform

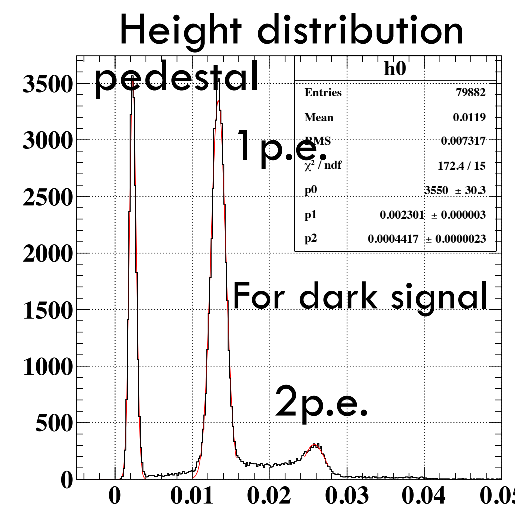
Noise was not included

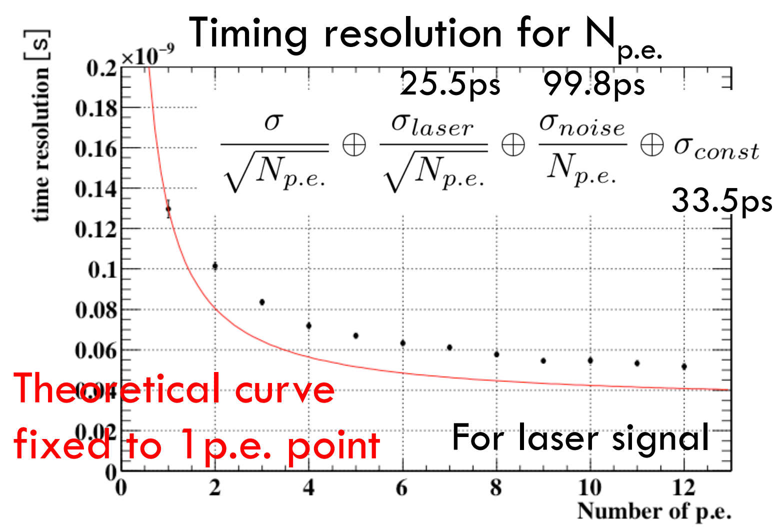
*report better resolution than this value in previous JPS because of bug

Property Measurement for Single SiPM and implementation in waveform simulation

- Measure the single SiPM property to input to simulation
- Dark signal and Laser signal

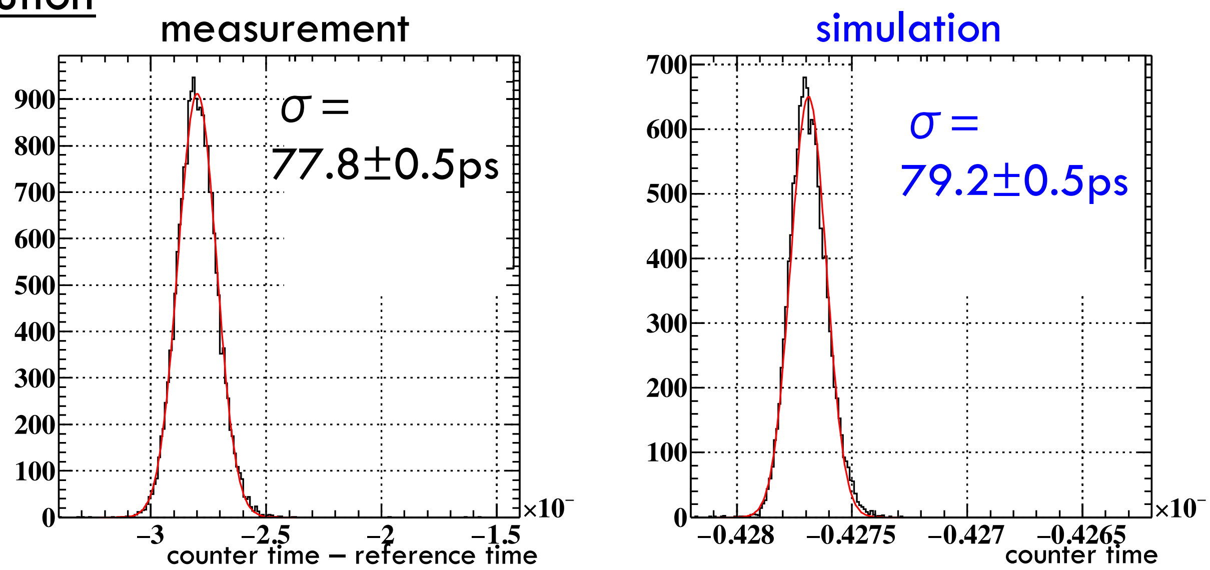
- Dark rate ~ 2.3 MHz (258kHz/mm^2)
  - From poisson distribution : $P(0)=N_{pede}/ N_{tot}$ (k=0)
  - Including the after pulse within 3.5ns from the peak
  - → Implementation by adding random at this rate
- Crosstalk ~ 0.17 (preliminary)
  - $N_{2p.e.\ and\ over}/N_{1p.e.\ and\ over}$
  - → Add 1p.e. signal at neighbor cell in this possibility
- Transit Time Spread(TTS) σ=71.3ps
  - Measurement by using laser
  - → Fluctuate the photon time at this sigma
- Baseline noise σ=2.4mV
  - RMS of baseline noise
  - → White noise following gaussian





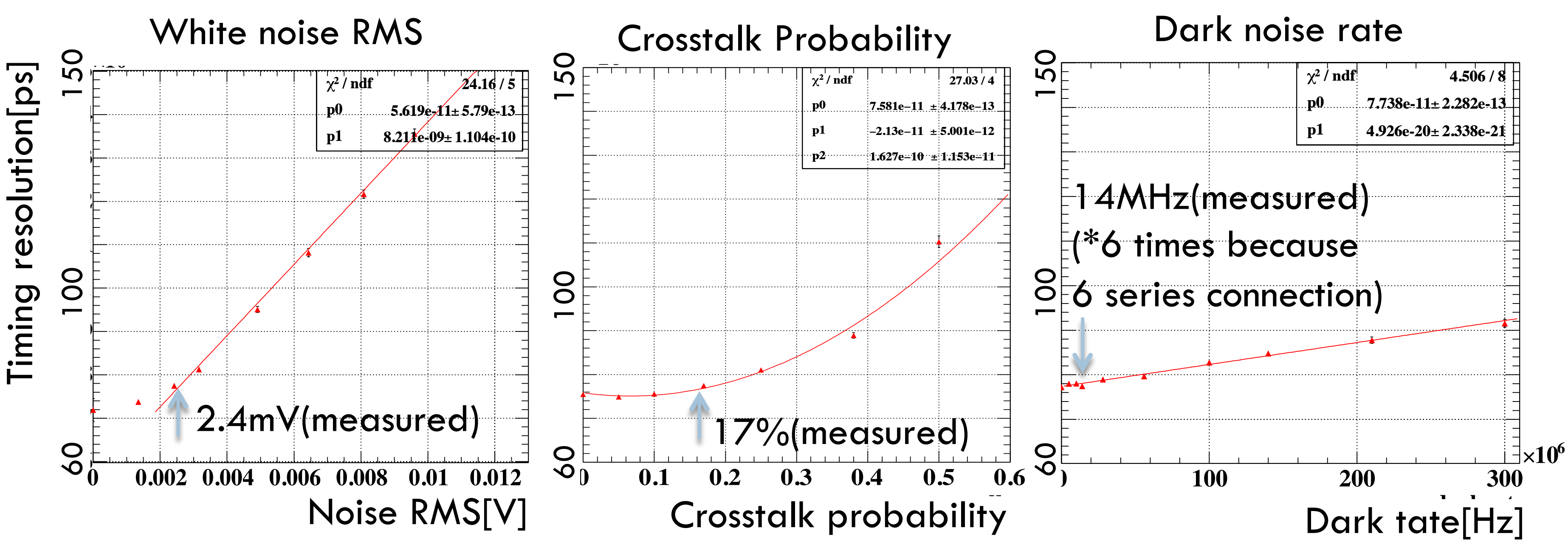
Result of Waveform Simulation with Noise

・ Timing resolution



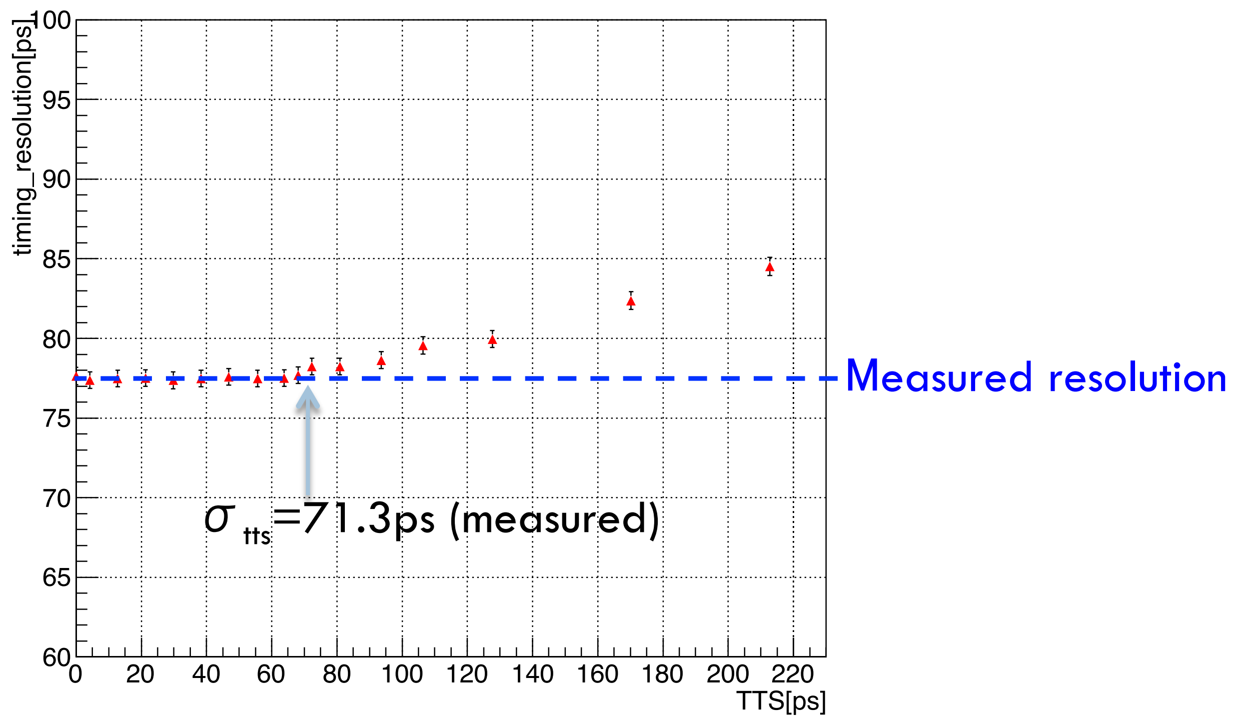
- Not only waveform but timing resolution for single counter is also reproduced by included noise
- Included noise
  - White noise (set as reproducing real noise RMS)
  - Dark noise (measured value ~14MHz)
  - Crosstalk (measured value ~17%)
- After pulse of SiPM is not included

Noise scan in waveform simulation



- Dependence of the timing resolution for each noise
- Dependence for crosstalk and dark noise is small around measured value
- Noise RMS effect is most strong

TTS scan in waveform simulation

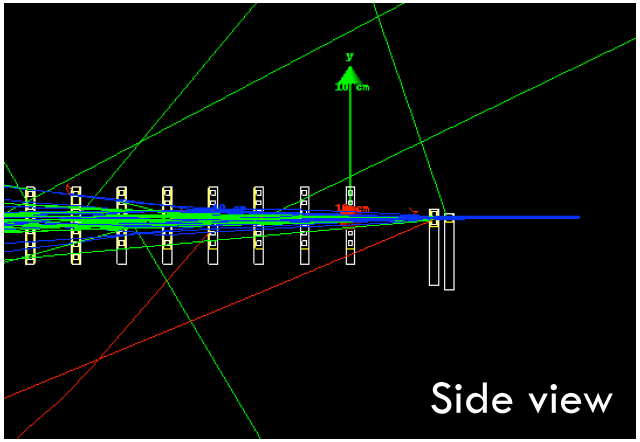


- Dependence of the timing resolution for TTS
- Estimated tts is in Plateau region
- Resolution is not depend on TTS around measured value

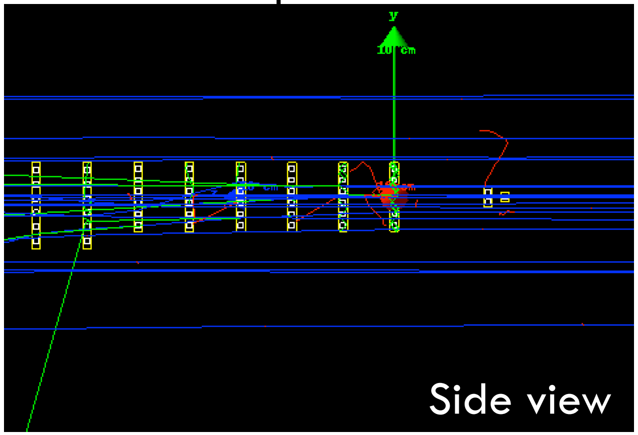
Simulation at multi counter setup

- Waveform simulation at multi counter setup
  - To estimate multiple hits resolution
  - To study pileup effect
- Setup
  - 9 counters (4cm counter:6, 5cm counter:3)
  - 48MeV e^+ beam
  - Trigger event : Selecting the event of hitting reference counter(5×5×5 mm)
  - Pileup event : Hit to whole of counter
  - Mix the waveform of trigger event and pileup event to reproduce pileup

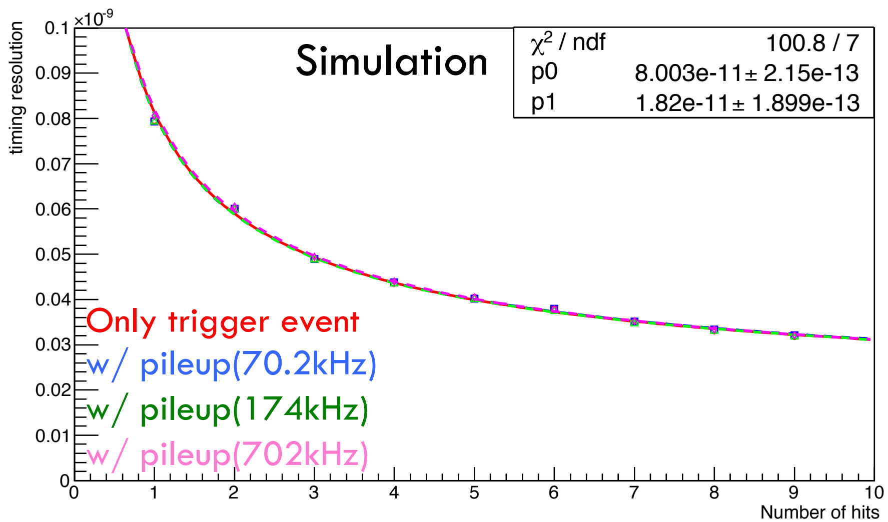
▪Trigger event



▪Pileup event

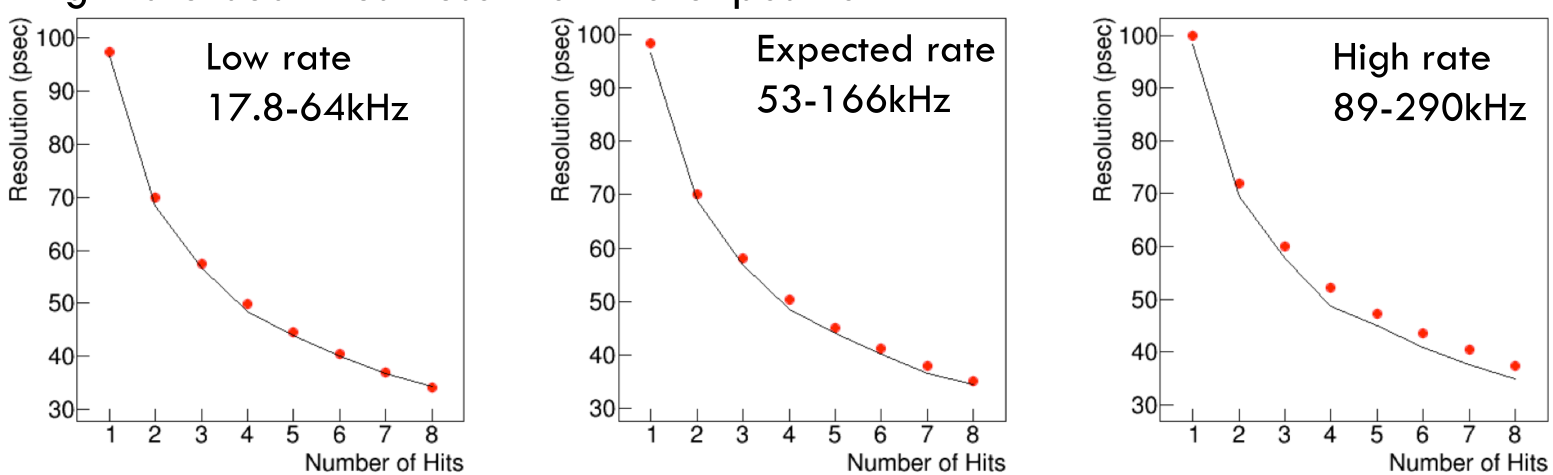


Result for multi counter setup



- Result
  - Timing resolution : ~30ps (9hits)
  - We observed deterioration of resolution by pileup effect in high rate beam test
  - Pileup effect is not reproduced in waveform simulation in actual pileup rate (70.2kHz from MC)
    - w/o after pulse

・High rate beam test result for michel positron



*第70回年次大会
西村(24aDL09)より

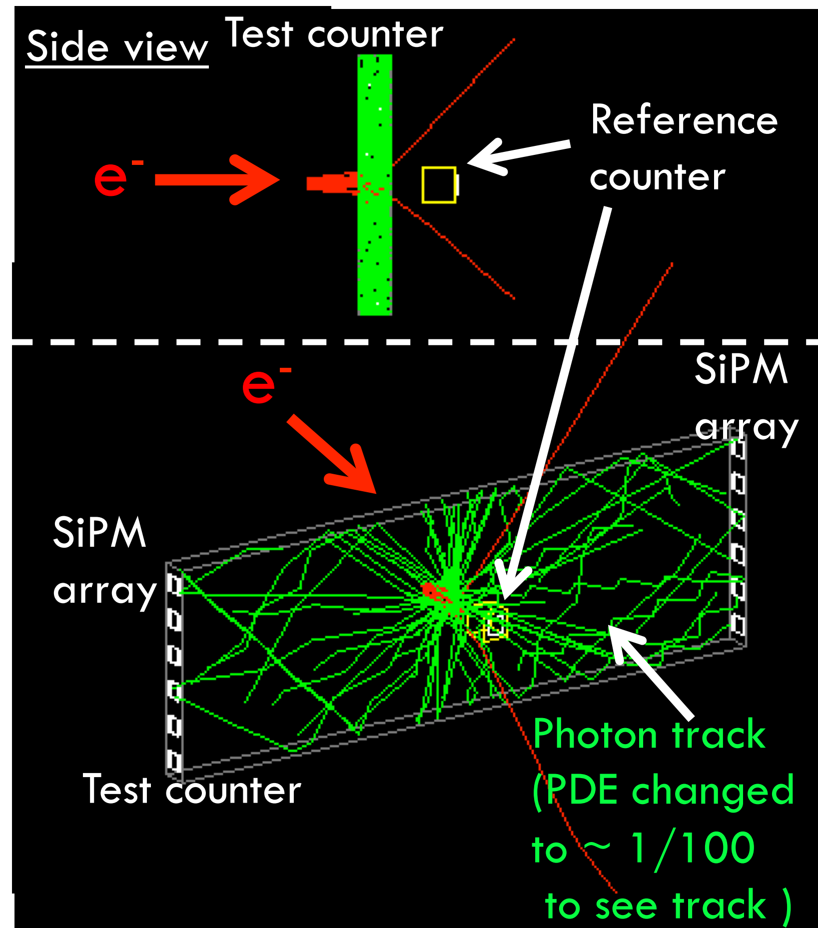
Summary and Prospect

- Summary
  - Single counter resolution is reproduced in waveform simulation by including some noise (Dark noise, Cross talk, White noise)
  - Estimate noise and TTS effect for resolution
  - Expected resolution(~30ps) is reproduced in multiple counter setup at 9hits
  - Pileup effect is not reproduced in waveform simulation
- Prospect
  - Including after pulse effect
  - Simulation at multi counter setup with after pulse
  - Including reflector effect
  - Time difference between SiPMs on the PCB
  - Waveform simulation at actual TC setup

END

MC simulation -Single counter setup-

- A test counter (BC422,120×40×5 mm^3, no wrap, SiPM array on each side)
- A reference counter (BC422, 5×5×5 mm^3, wrapped by teflon, 1SiPM) is set behind test counter
- Irradiating e$^-$ from ^{90}Sr
- Selecting the event of hitting reference counter

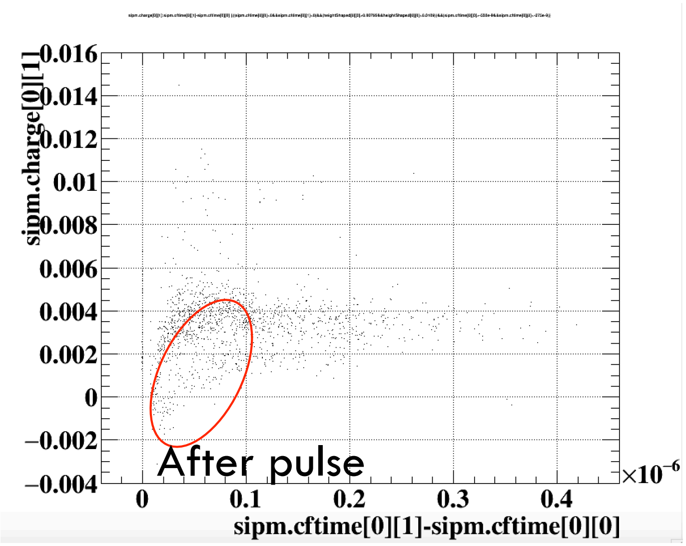


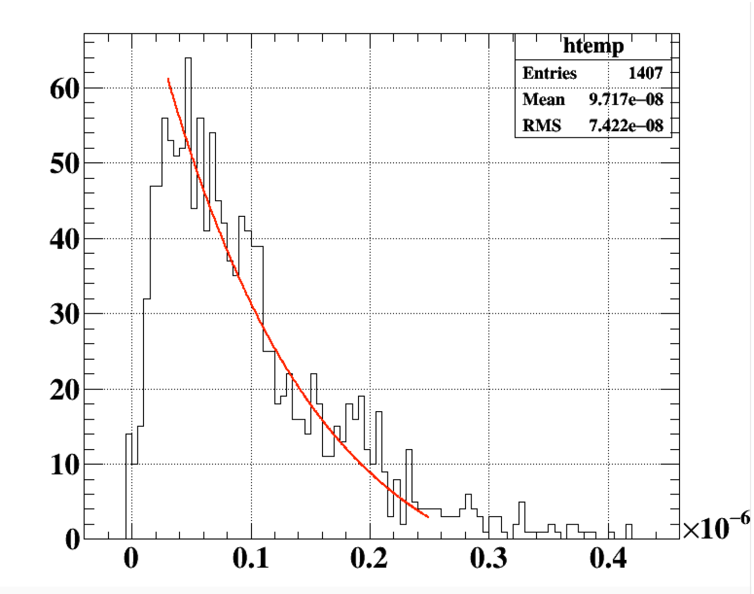
Scintillator setup	
Scintillation yield	8400photons/MeV
Attenuation length (adjusted)	20.6 cm
Refractive index	1.58
Rise time	0 s *
Decay time	1.6 ns

* Reference : R. A. Lerche et al. "Rise Time of BC-422 Plastic Scintillator<20ps", DOI:10.1109/NSSMIC.1991.258899

Single SiPM After pulse

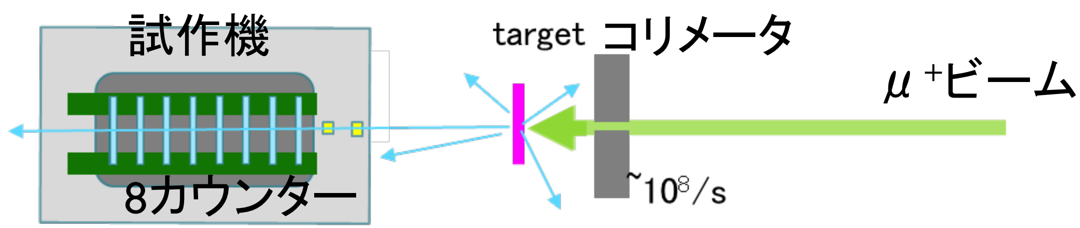
アフター見積もりと実装法

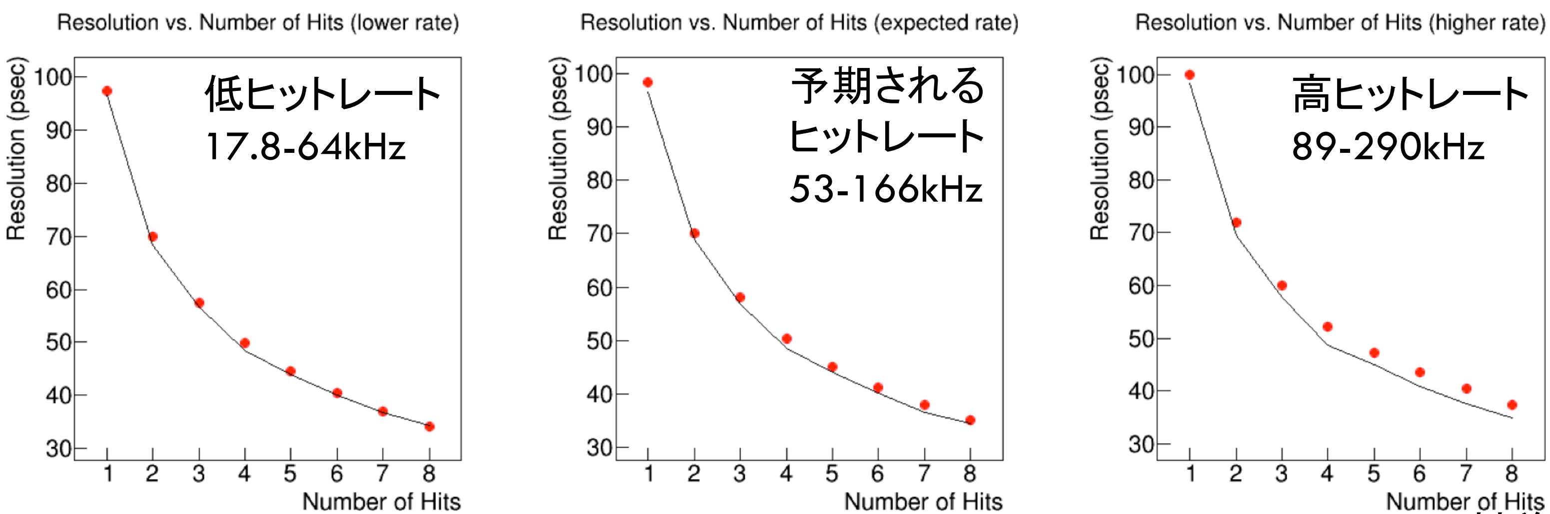




ハイレートビームテスト@PSI

- PSIのπE5ビームラインのミューオンビームをターゲットに照射し、ミッシェル陽電子を用いたハイレート試験でパイルアップの影響を検証
- MCにより予期されるヒットレートにおいても36.5psの優れた時間分解能



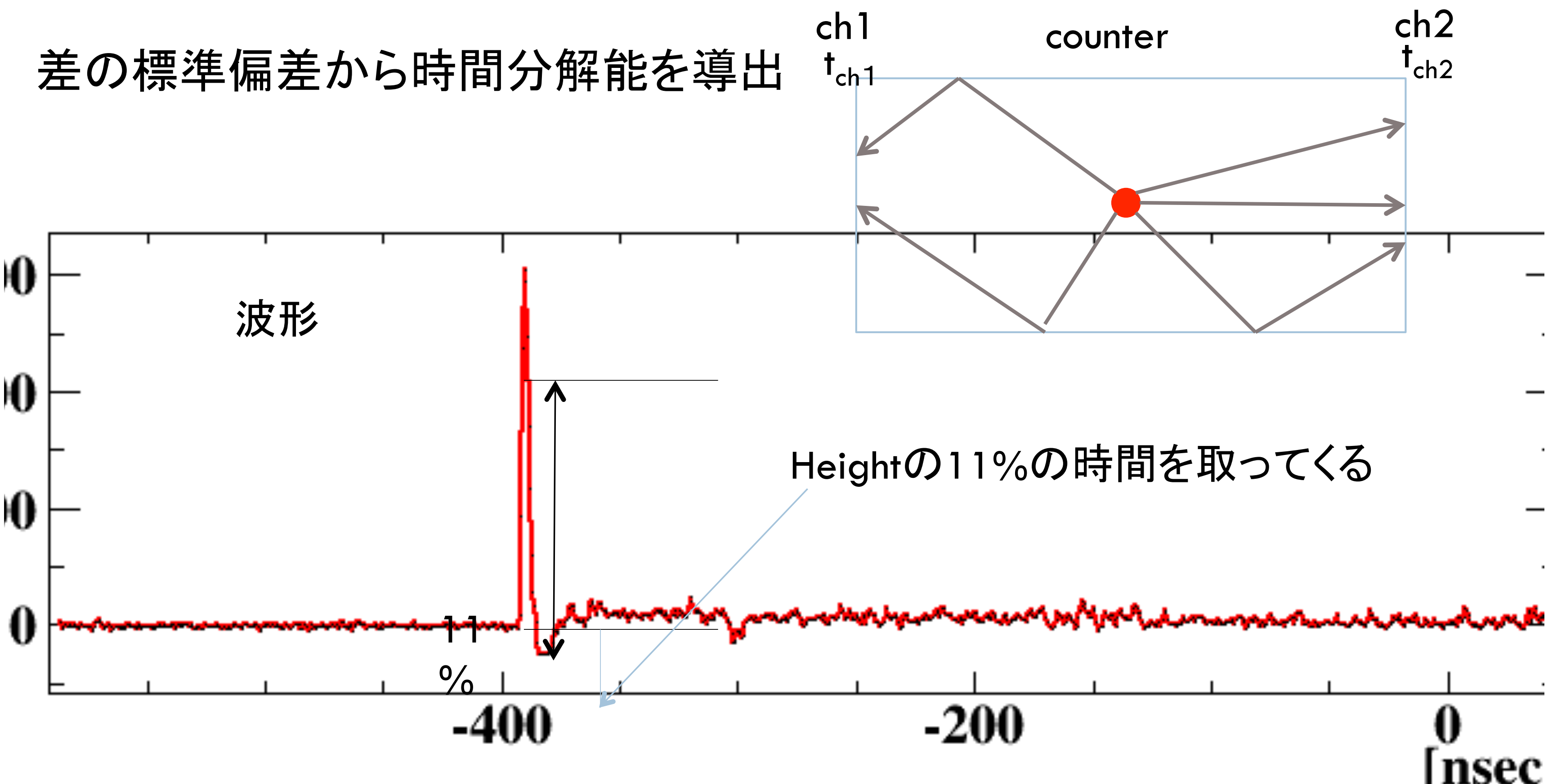


※西村美紀氏より

波形解析

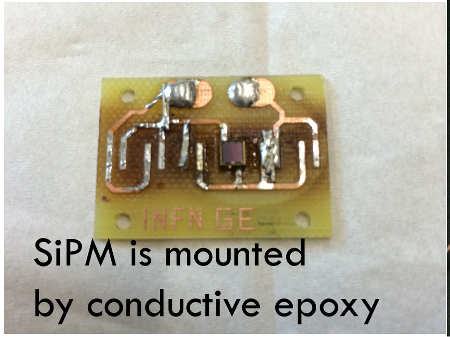
1. ch毎のconstant fraction time(11%)をシグナルの時間とする
2. 2chのシグナル時間の平均 $(t_{ch1}+t_{ch2})/2$ を各カウンターのヒット時間とする
3. カウンターのヒット時間とレファレンス時間(RC1,RC2のヒット時間の平均)の

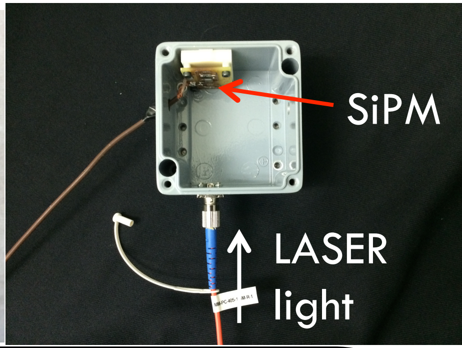
差の標準偏差から時間分解能を導出



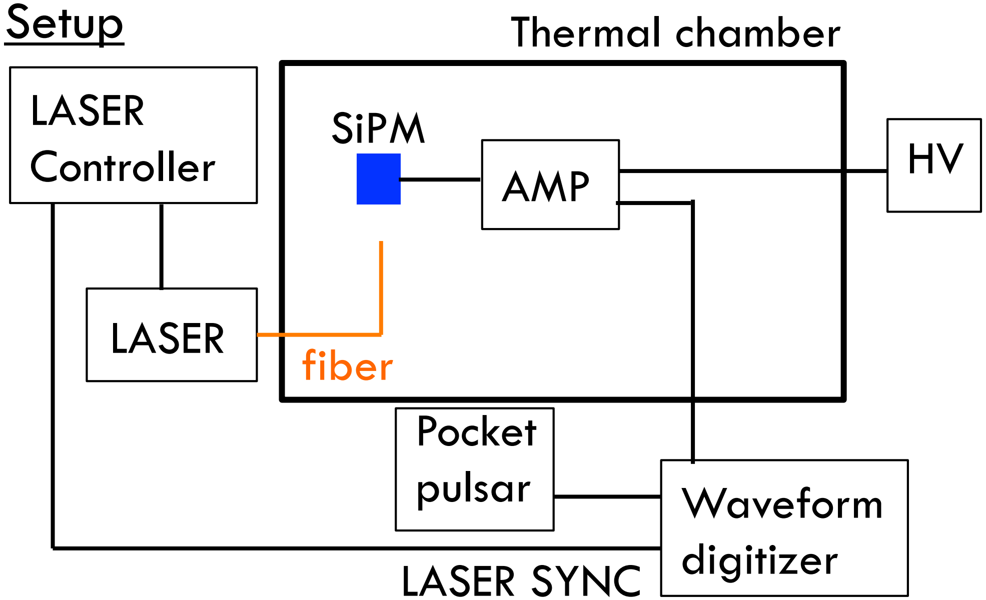
Measurement for Single SiPM

- It is necessary to measure these topics for single SiPM to get 1p.e. response from SiPM array and input property to simulation
  - 1p.e. waveform of single SiPM
  - Gain
  - Dark rate
  - Crosstalk probability
  - Single p.e. timing resolution (SPTR)

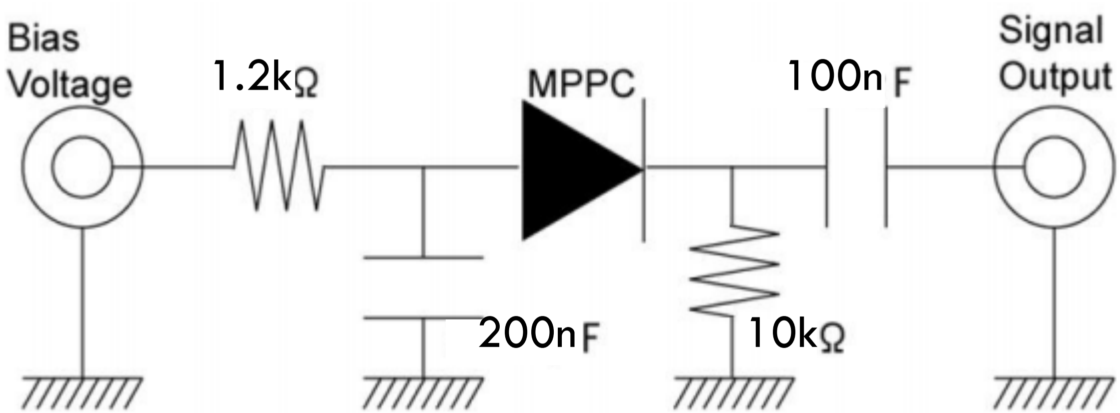




Setup



- SiPM : same to actual TC
  (ASD-NUV3S-P High-Gain (MEG))
- OV : 3.0V
- 30 degree
- LASER : Picosecond Light Pulsar (Hamamatsu PLP-10)
  wavelength 401nm
  For measurement of timing resolution
- Trigger : Random by pocket pulsar for Dark signal
  : LASER SYNC for measurement
  of timing resolution
- Signal Timing : constant fraction time

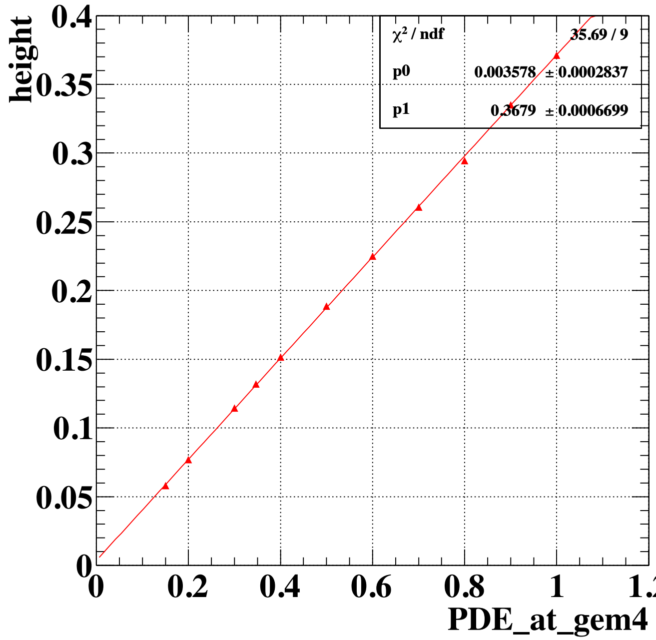


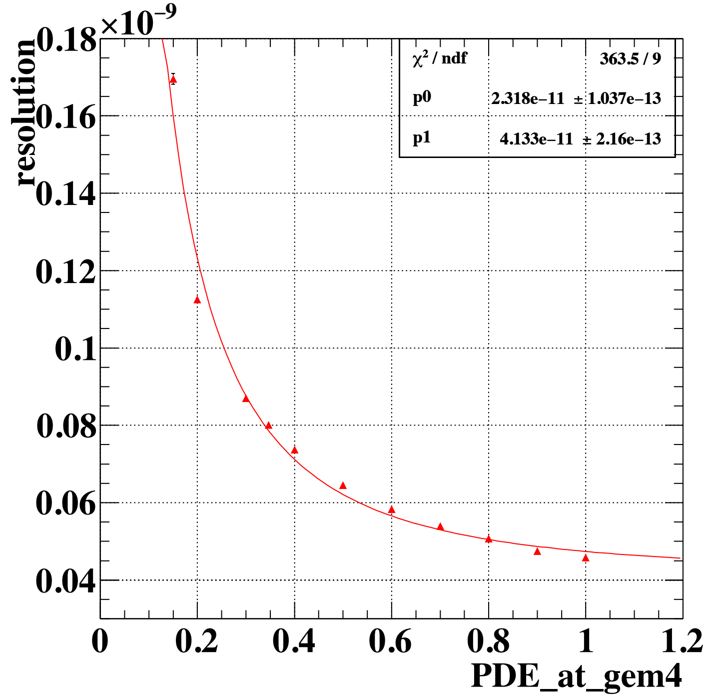
ローパス

ハイパス

PDE setting

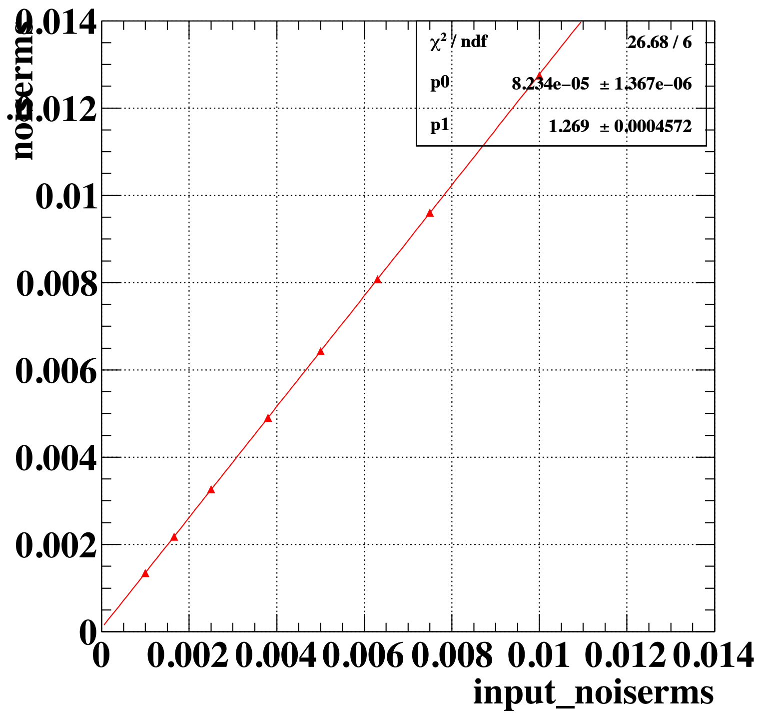
- New TTS is decided and PDE spectrum is changed for AdvanSiD SiPM →reset pde , noiserms
- PDE scan to decide input PDE in gem4 by matching height with real counter

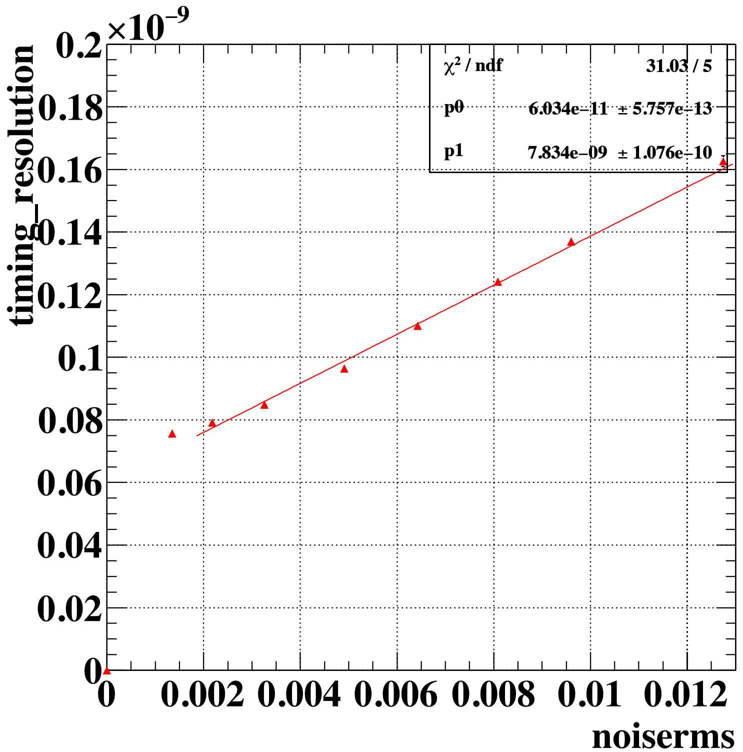




NoiseRMS setting

- Noise RMS scan to match with noise RMS of real measurement

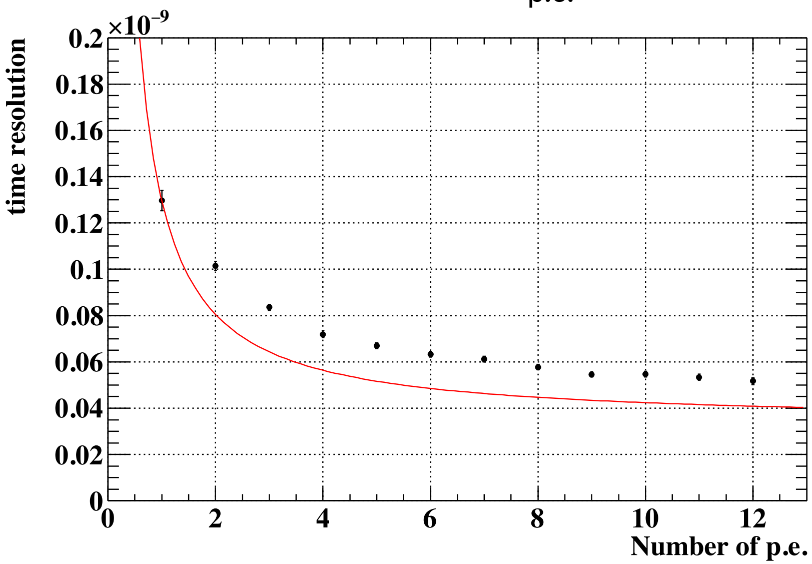




TTS estimation

- SiPM timing resolution resolution for $N_{p.e.}$ $$\frac{\sigma}{\sqrt{N_{p.e.}}} \oplus \frac{\sigma_{laser}}{\sqrt{N_{p.e.}}} \oplus \frac{\sigma_{noise}}{N_{p.e.}} \oplus \sigma_{const}$$
  - True resolution $\sigma_{tts}/\sqrt{N}$
  - Laser duration $\sigma_{laser}/\sqrt{N}$ → σ_{laser}=25.5ps (from catalog)
  - Noise effect σ_{noise}/N → by fake pulse
  - Constant term(from electronics jitter and analysis fluctuation) σ_{const} → by resolution at high p.e.

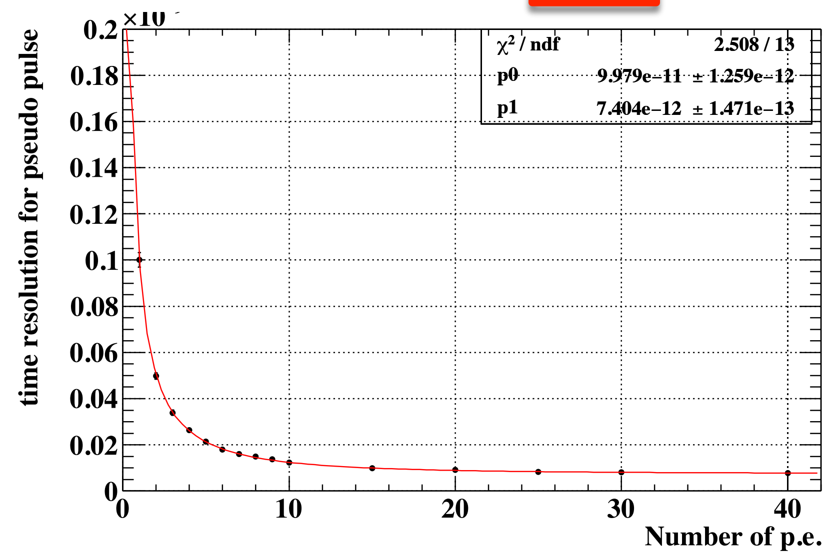
Timing resolution for $N_{p.e.}$ by Laser light



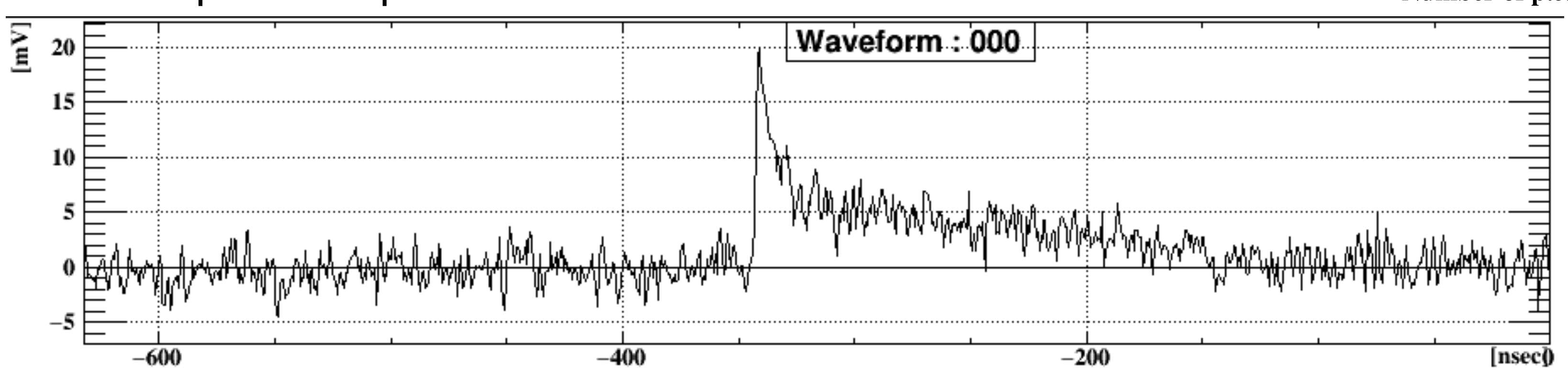
TTS estimation

- Fake pulse convoluted 0p.e. event and $N_{p.e.}$ template wavaform
- The template waveform don't have fluctuation
- Estimate the resolution of fake pulse for $N_{p.e.}$ to estimate the noise effect for $\sigma_{noise}/N_{p.e.}$
- $\sigma_{noise} = 99.8\text{ps}$

$$\frac{\sigma}{\sqrt{N_{p.e.}}} \oplus \frac{\sigma_{laser}}{\sqrt{N_{p.e.}}} \oplus \frac{\sigma_{noise}}{N_{p.e.}} \oplus \sigma_{const}$$



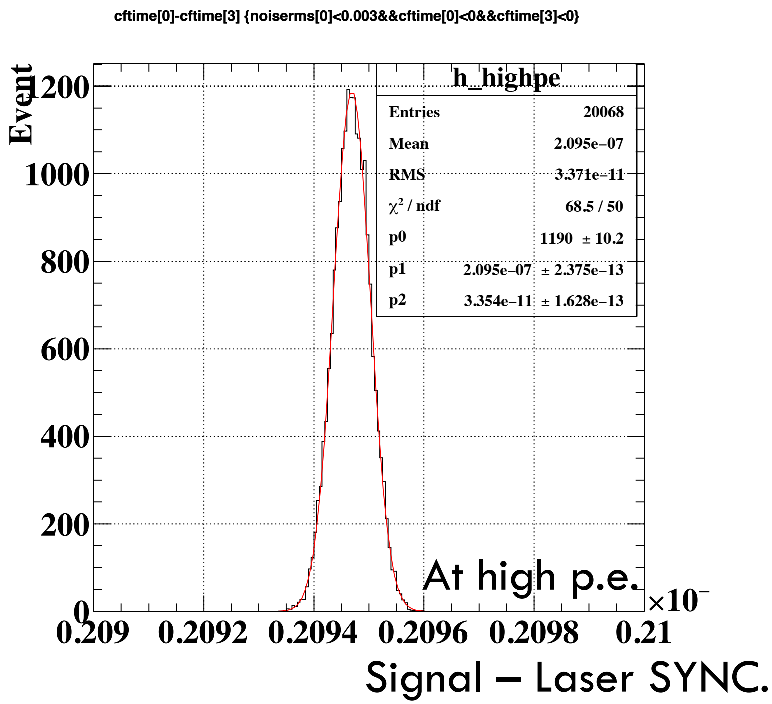
Fake pulse of 1p.e.



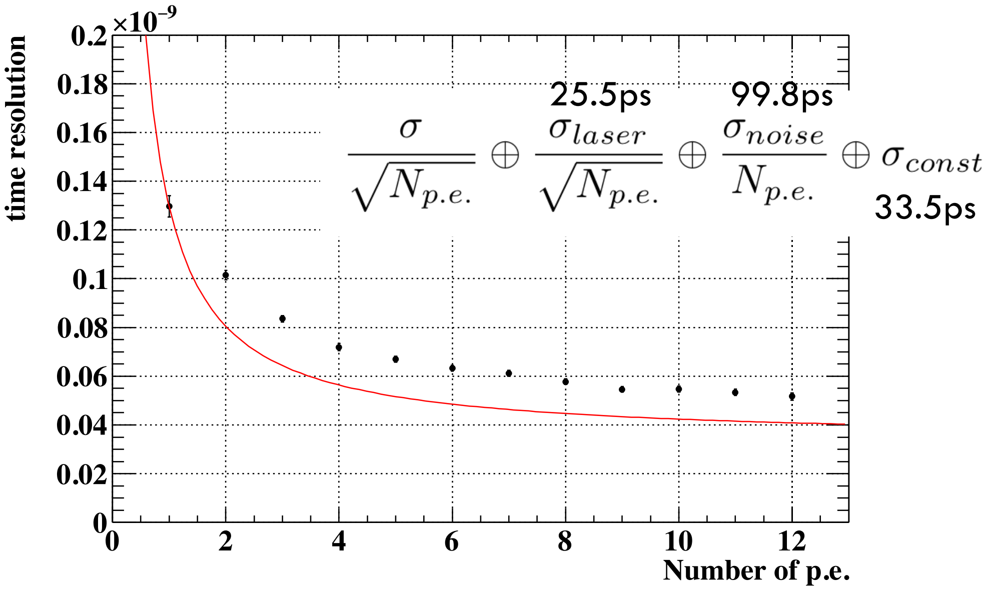
TTS estimation

- Timing resolution of SiPM at high p.e. (~1000p.e.) by laser light
- σ_{const} =33.5ps

$$\frac{\sigma}{\sqrt{N_{p.e.}}} \oplus \frac{\sigma_{laser}}{\sqrt{N_{p.e.}}} \oplus \frac{\sigma_{noise}}{N_{p.e.}} \oplus \sigma_{const}$$



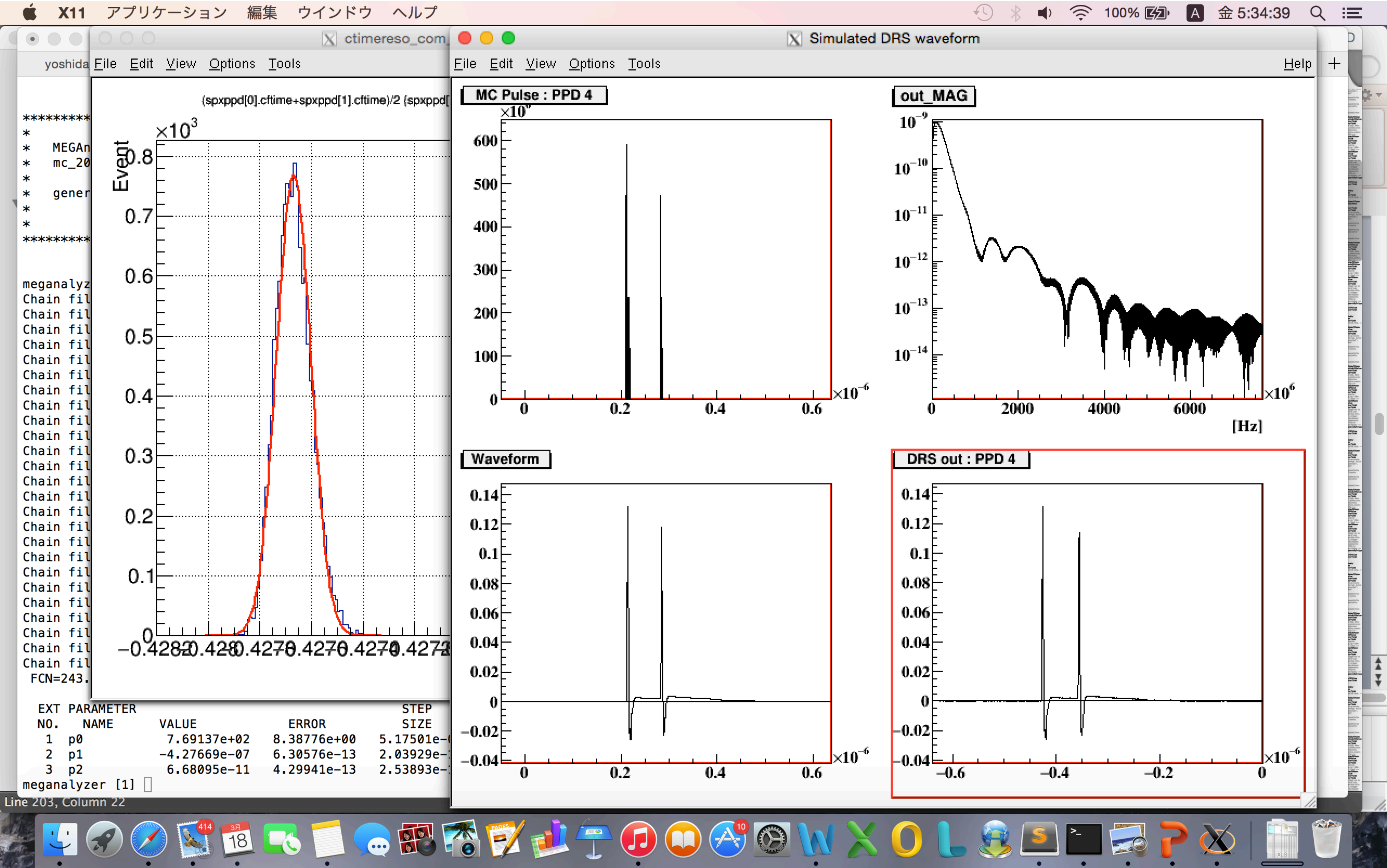
TTS estimation



- Laser duration $\sigma_{laser} = 25.5$ps
- Noise effect $\sigma_{noise} = 99.8$ps
- Constant term $\sigma_{const} = 33.5$ps

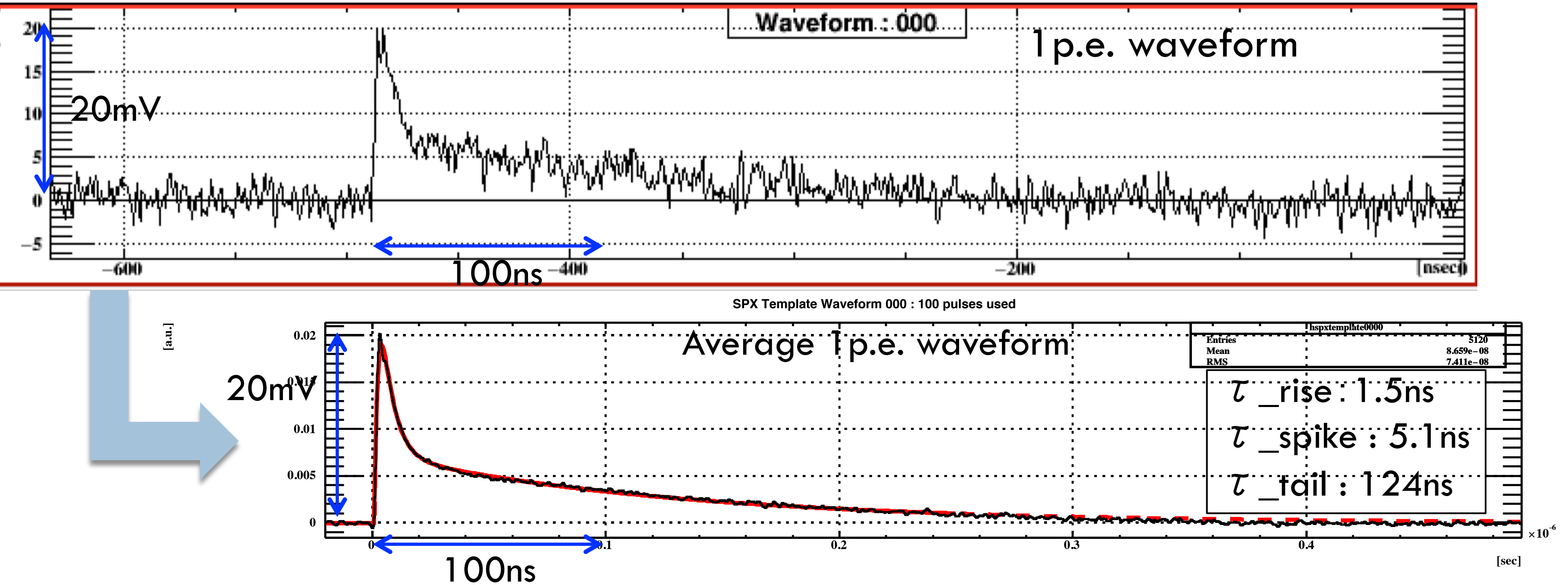
  → Transit time spread $\sigma_{tts} = 71.3$ ps
- Red line is fixed at 1p.e. point but it is not match because of CTAP?

Waveform of pileup event



Waveform for single SiPM

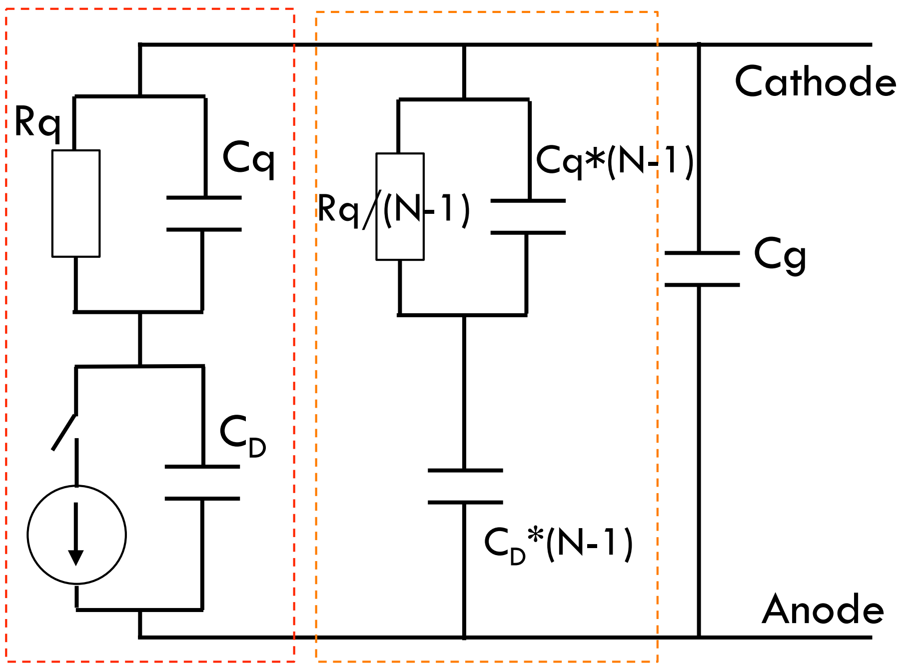
remainder



- 1p.e. average waveform for single SiPM from 100 waveforms
- Selecting the waveforms which have no after pulse, flat baseline
- Fitting function : [0]*(exp(-t/[τ _rise])-[1]*exp(-t/[τ _spike])-(1-[1])*exp(-t/[τ _tail]))

SiPM circuit model

Circuit model of N pixel SiPM

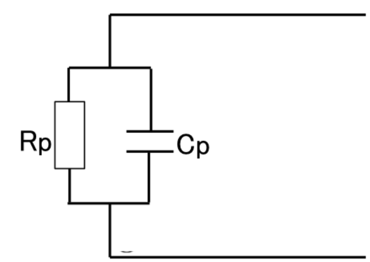


- Rq : Quenching resistance
- Cq : Stray quenching capacitance
- C_D : p-n junction capacitance
- Cg : Stray grid capacitance
- N : Number of pixels

- Measurement to decide parameter
  - Rq is measured by I-V curve at forward bias
  - Cq, C_D, Cg is estimated by SiPM Gain and LCR measurement

$$Q = V_{OB}(C_D + C_q)$$

- Equivalent circuit for LCR measurement



$$C_D = \sqrt{\frac{1+\omega^2 (C_D + C_q)^2 R_q^2}{\omega^2 N_{tot} R_q R_p}}$$

$$C_g = C_p - N_{tot} C_D + \frac{\omega^2 {C_D}^2 R_q^2 N_{tot} (C_D + C_q)}{1 + \omega^2 R_q^2 (C_D + C_q)^2}$$

Reference : S. Seifert et al. " Simulation of Silicon Photomultiplier Signals", IEEE TRANSACTIONS ON NUCLEAR SCIENCE, Vol. 56, No. 6:3726-3733, 2009

Quenching resistance

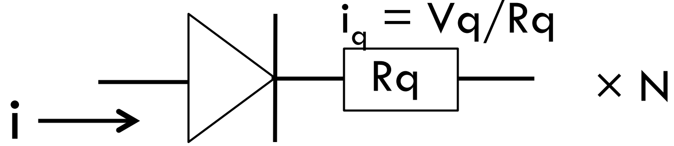
remainder

SiPM

p-n junction

Quenching resistance

$i_q = Vq/Rq$



$i_d = i_0(\exp(eV_d/kT) - 1)$

$I = iN$

i : current of 1pixel

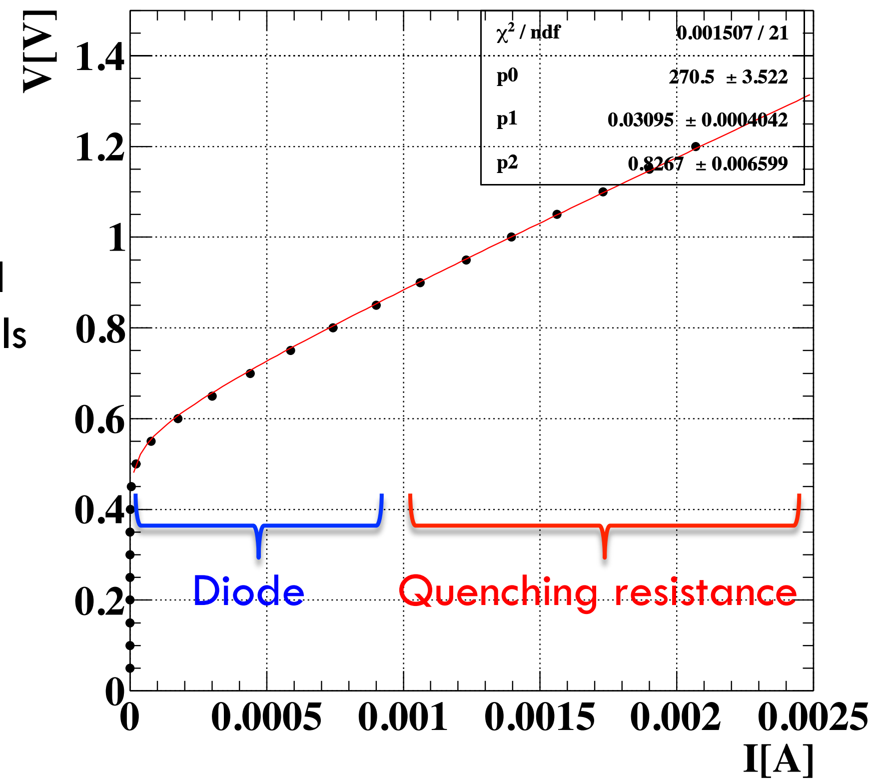
N : number of pixels

Quenching resistance

$$V = C_0 I + C_1 \log I + C_2$$

Diode characteristic

$$C_0 = R_q/N$$



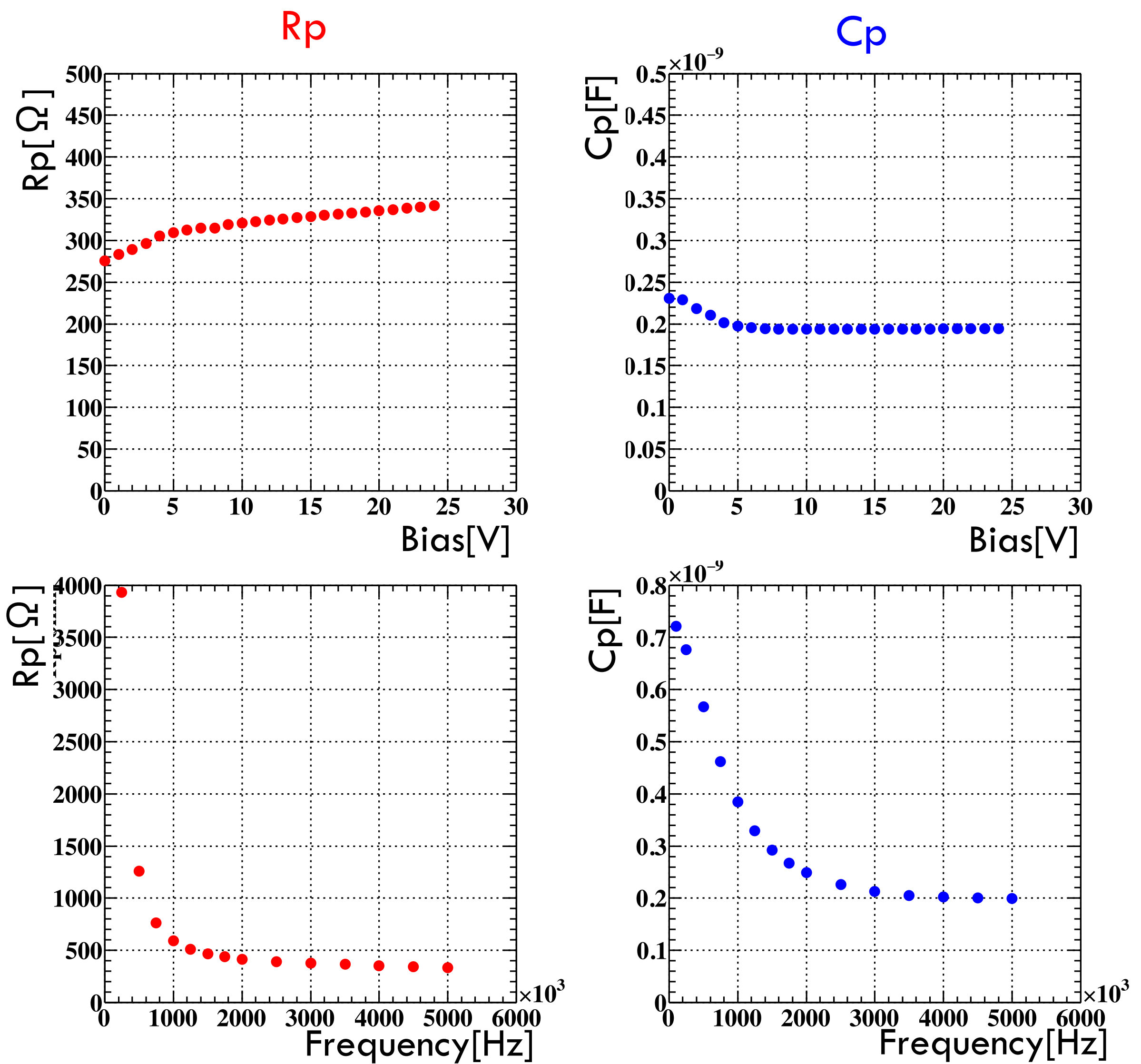
- SiPM pixels consist of diode and quenching resistance
- quenching resistance is measured from I-V curve at forward bias
- $Rq = 974 \pm 13\ k\Omega$

remainder

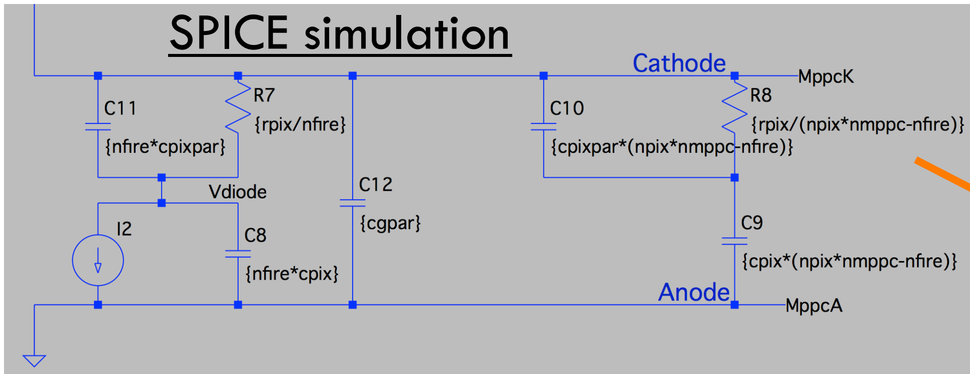
LCR measurement

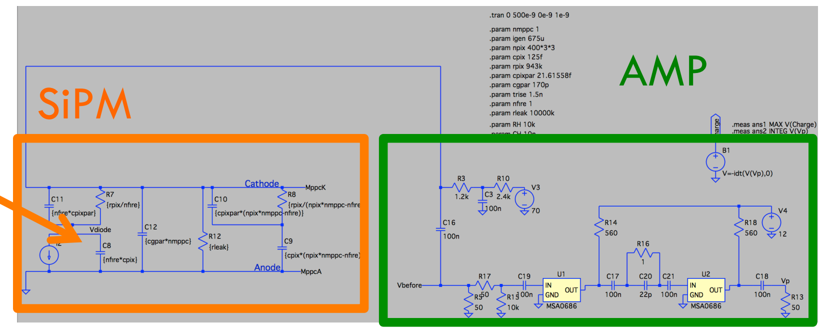
- Rp and Cp is measured by LCR meter (HIOKI LCR HiTESTER 3532-50)
- LCR meter input sine wave and measure impedance and phase difference by Four-terminal Method
- Rp and Cp are saturated at high frequency and high bias
  - So, we used the value at high frequency and high bias

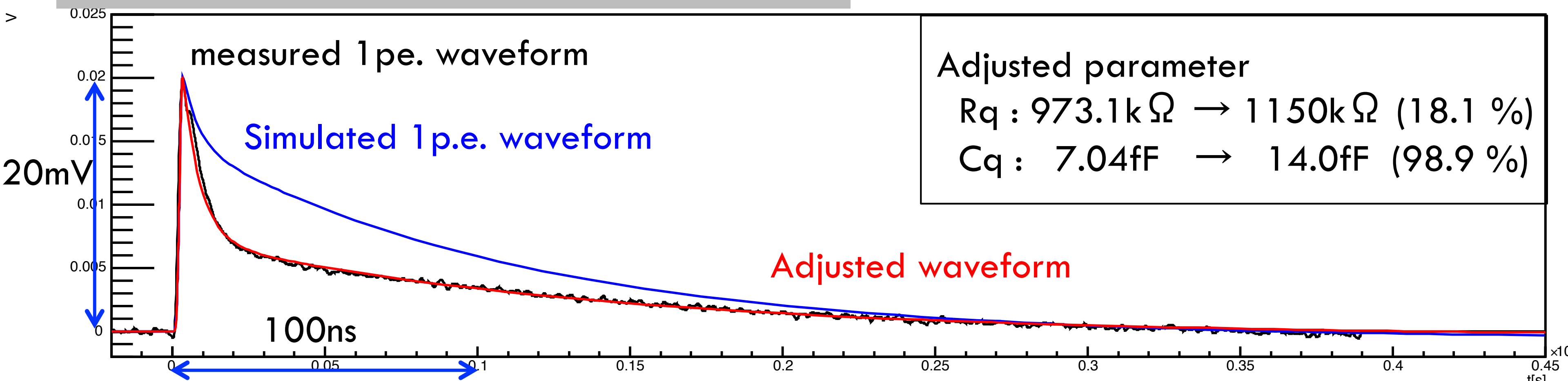
> ・From I-V curve
> Rq ~ 973.8 kΩ
>
> ・From SiPM Gain and LCR measurement
> C_D ~ 97.0 fF
> Cq ~ 7.04 fF
> Cg ~ 141.4 pF



SPICE simulation for single SiPM

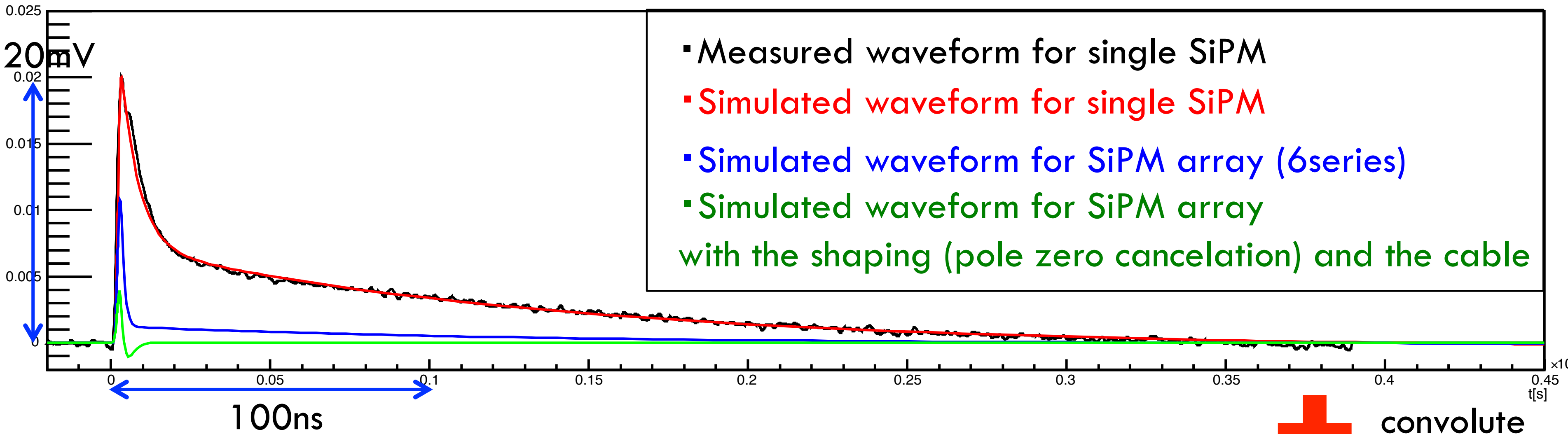




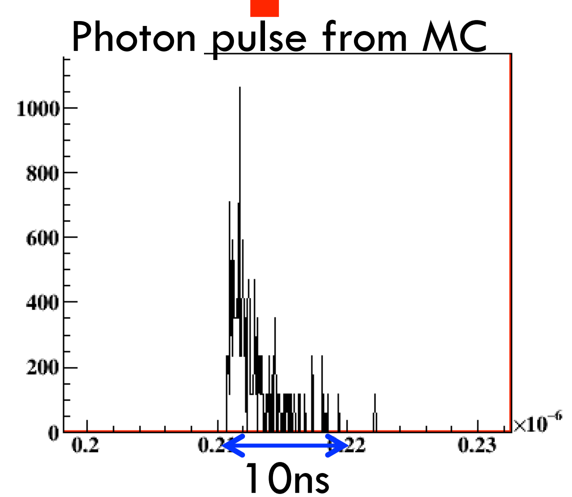


- Input the measured circuit parameter and simulate the 1p.e. waveform of single SiPM
- The simulated waveform don't match measured waveform
- The parameters is adjusted as reproducing measured waveform
- Probably, the uncertainty for Cq is large

SPICE simulation for SiPM array



convolute



- Simulating 1p.e. waveform for SiPM array by using the adjusted parameter
- Shaping by pole zero cancelation
- Including the actual long cable effect by measurement
- Convoluting with photon timing pulse from MC