Study on SiPM saturation using UV light

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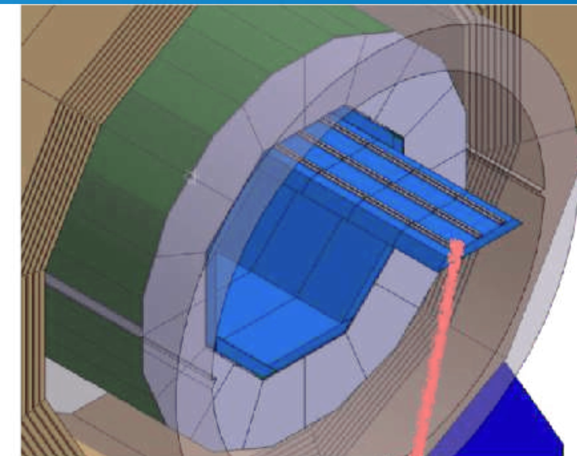
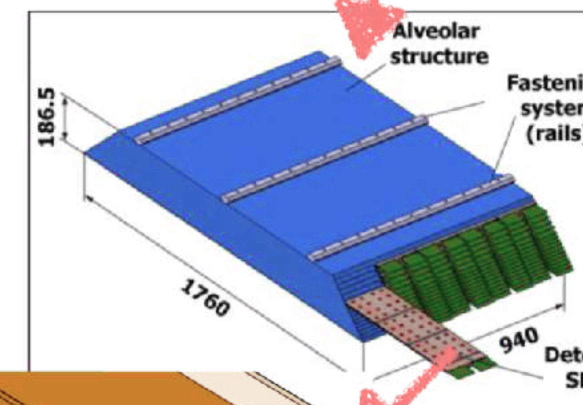
CALICE Collaboration Meeting Everywhere, 24 Mar. 2021

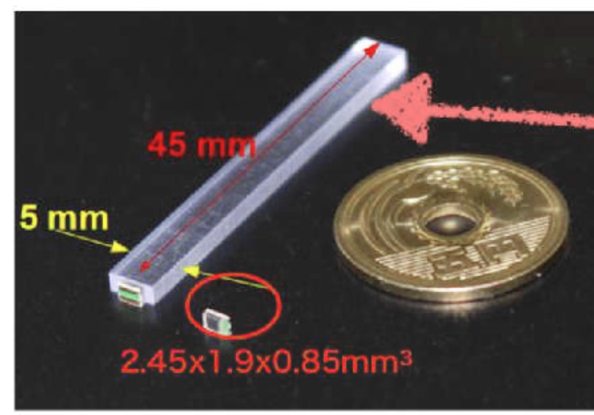
Sc-ECAL

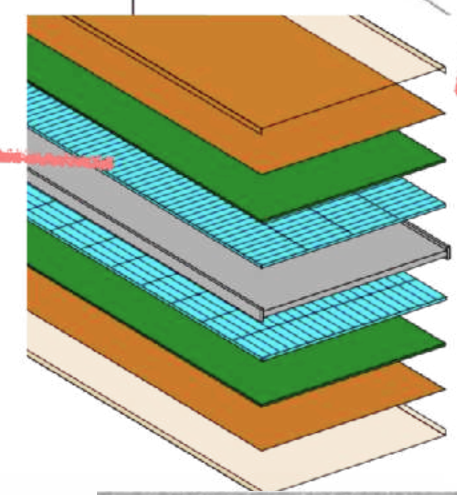


- Scintillator Electromagnetic CALorimeter (Sc-ECAL)
  - Technology option of EM calorimeter for ILD and CEPC

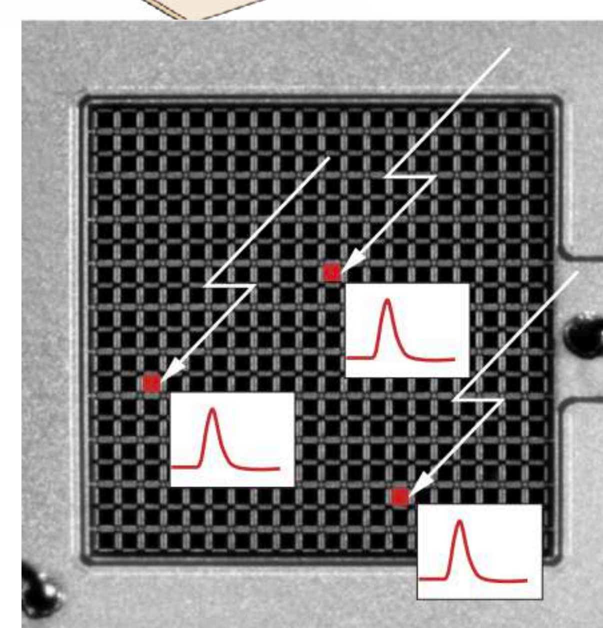


- Based on scintillator strips readout by SiPM
  - 5 × 45 × 2 mm^3 scintillator strip
- Virtual segmentation : 5mm × 5mm with strips in x-y configuration
- Timing resolution < 1 ns
- Low cost





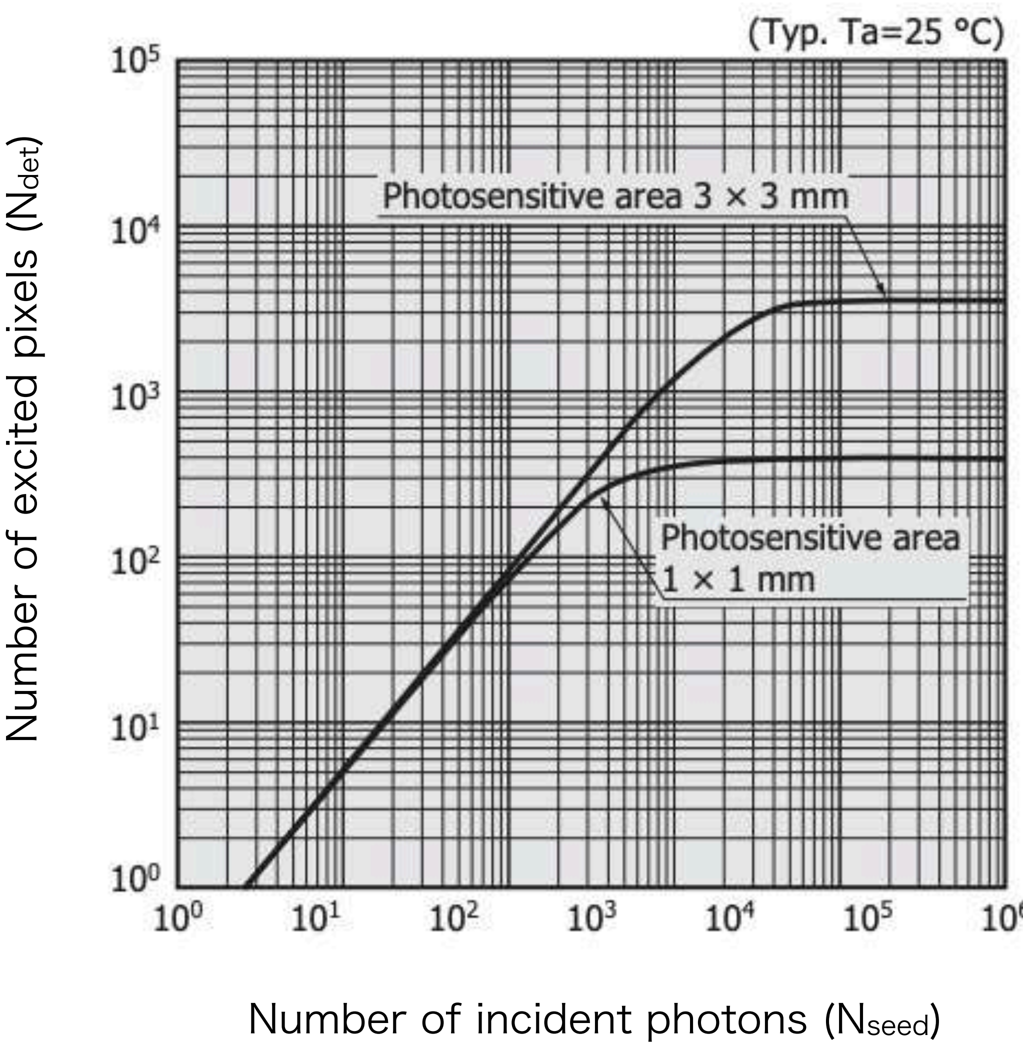
- Silicon PhotoMultiplier (SiPM)
  - Made up of multiple APD pixels operated in Geiger mode
  - Excellent photon-counting capability
  - Small size
  - Low bias operation



Hamamatsu Photonics K.K.,
Opto-semiconductor Handbook

Saturation of SiPMs

- SiPM saturation can be an issue for Sc-ECAL
  - Pile-up hits in small and dense EM shower
  - When a large number of photons are injected to SiPM, output of SiPM can be saturated due to limited number of pixels
- Saturation curve is usually measured by direct injecting fast laser pulse (~400 nm) to SiPM
  - Time constant of emission of scintillation light (few ns) is not negligible compared to recovery time of SiPM cell (dozens ns)
- **Our idea is to measure the SiPM saturation with scintillation light excited by UV pulse laser**
  - **The measured saturation curve can directly be used for saturation correction in Sc-ECAL**



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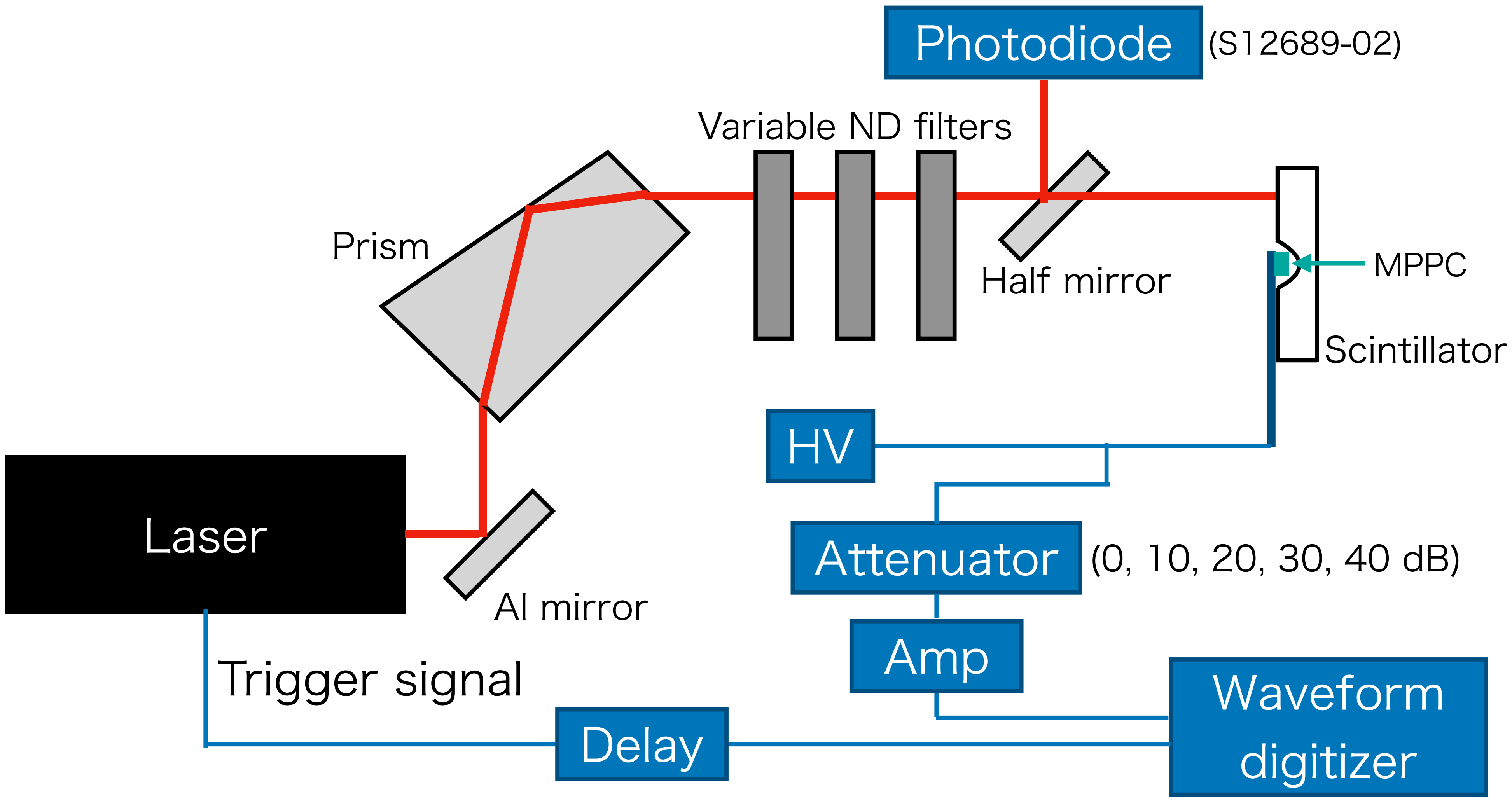
Previous setup

Previous report:
“Study on SiPM saturation using UV laser”
CALICE Collaboration Meeting at CERN, 2019

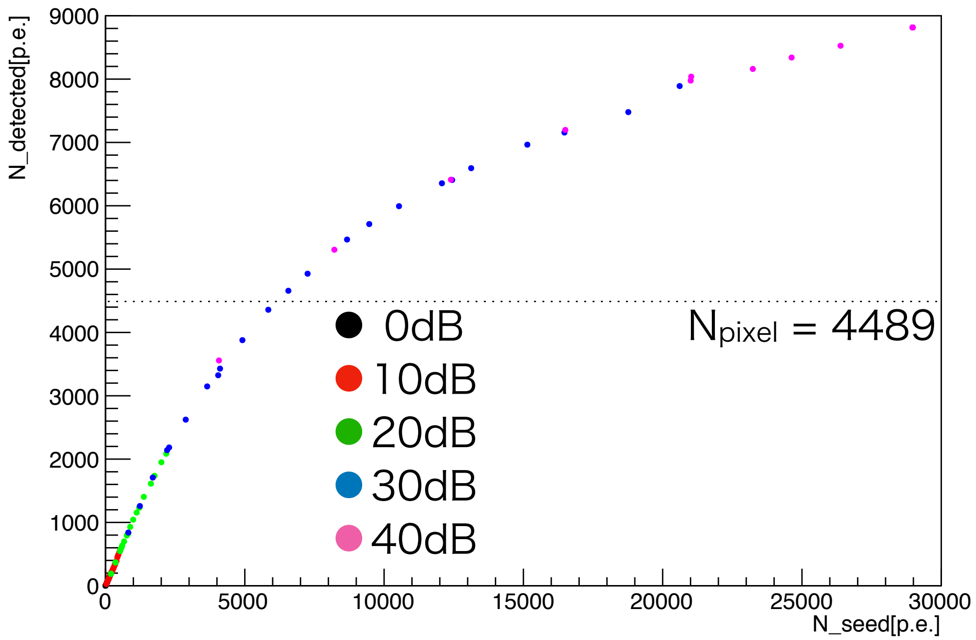
- Excite scintillation light with fast fsec UV pulse laser
  - Laser light is split using half mirror (to scintillator, to photodiode)
  - Incident light intensity is monitored with photodiode
  - MPPC S12571-015P with over voltage of +4 V (Recommended voltage by Hamamatsu)
  - MPPC S14160-1315PS with over voltage of +4 V (〃)
  - Signal attenuations (10 - 40 dB) used to avoid saturation of electronics



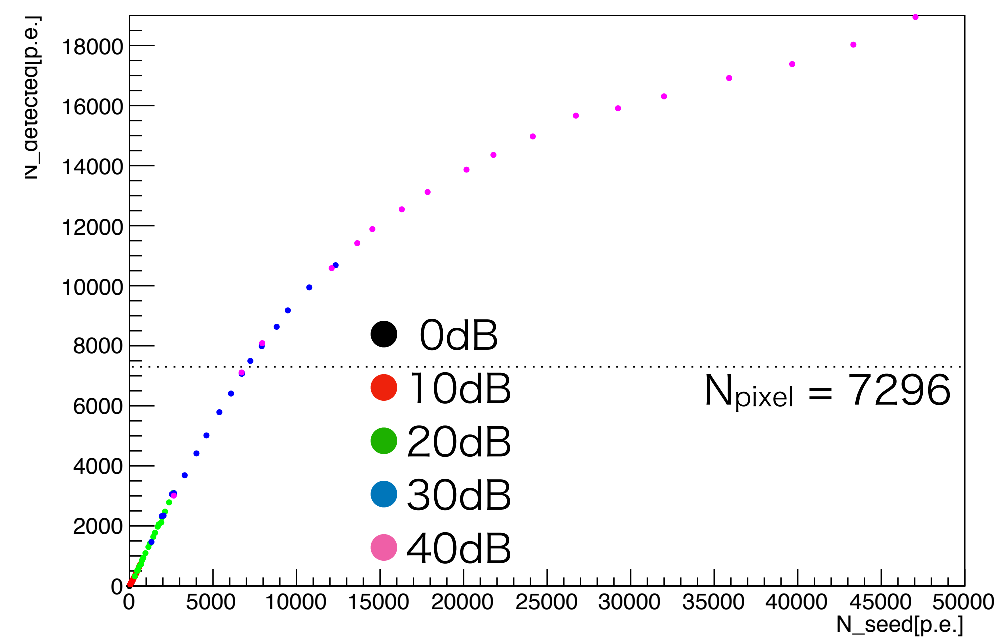
Previous results

- Saturation over the number of pixels is observed for 2 types of SiPMs
- Effect of time constant of scintillation light emission (saturation recovery) observed
  - at the comparison of saturation curves between UV laser and visible laser

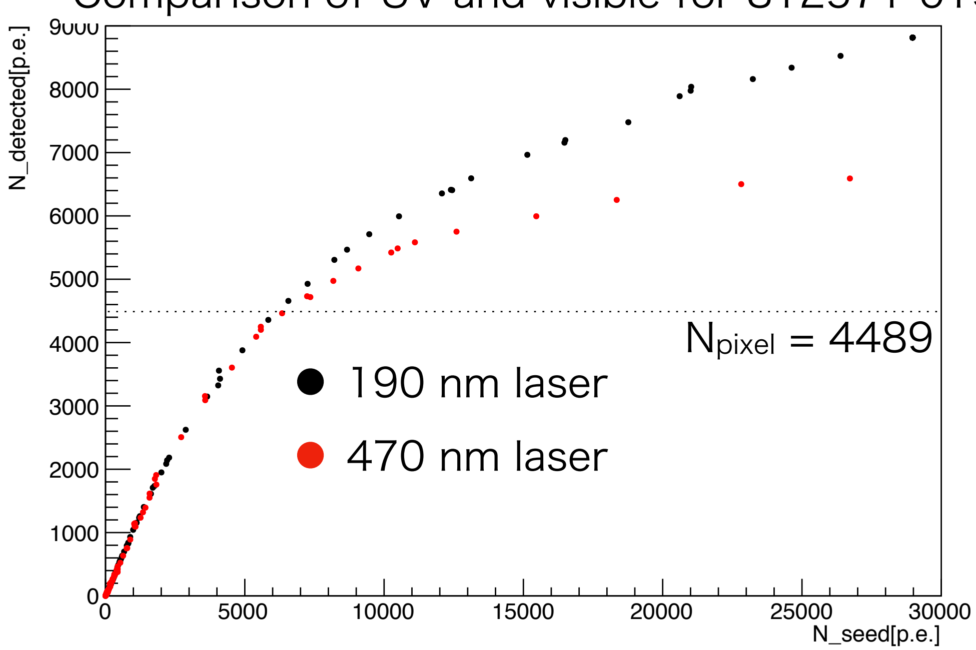
Saturation curve with UV laser for S12571-015P



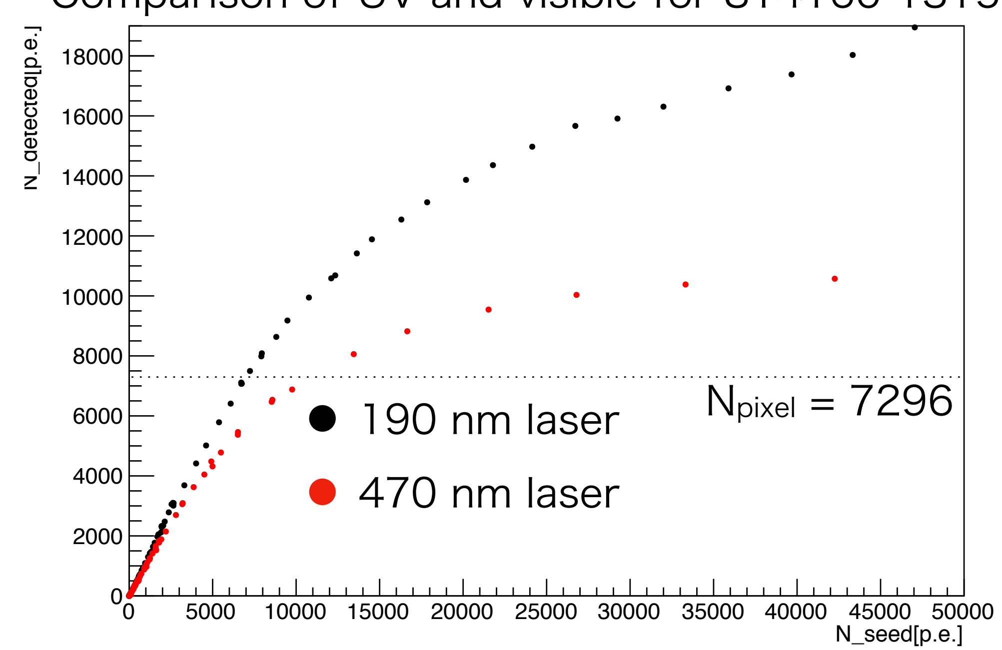
Saturation curve with UV laser for S14160-1315PS



Comparison of UV and visible for S12571-015P



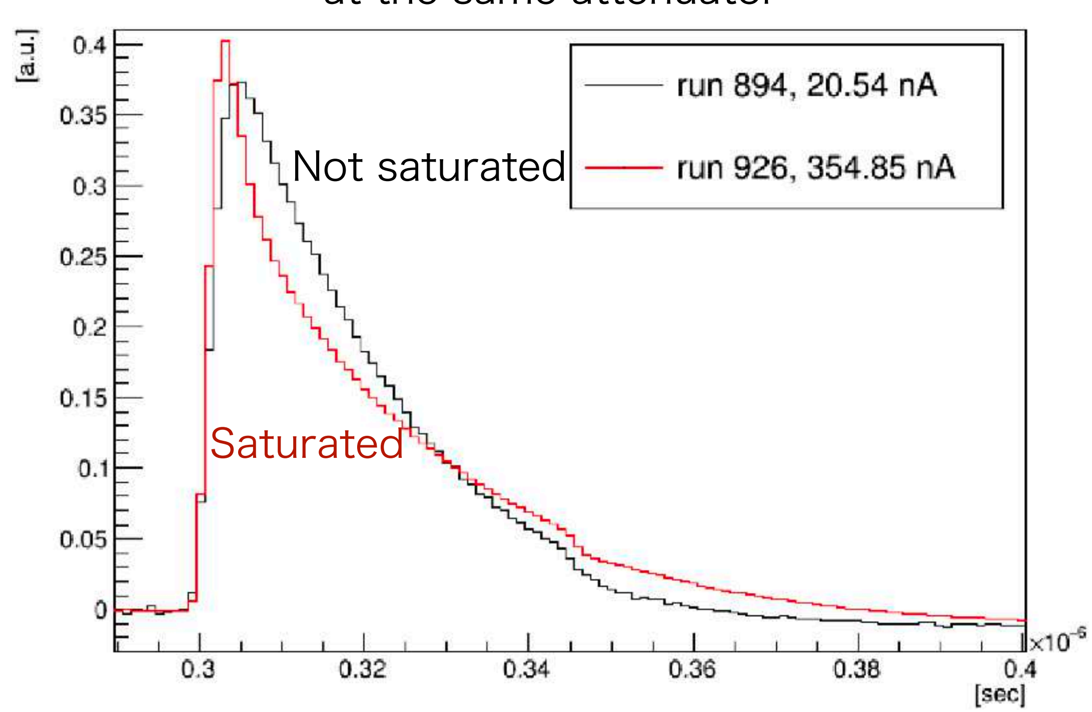
Comparison of UV and visible for S14160-1315PS



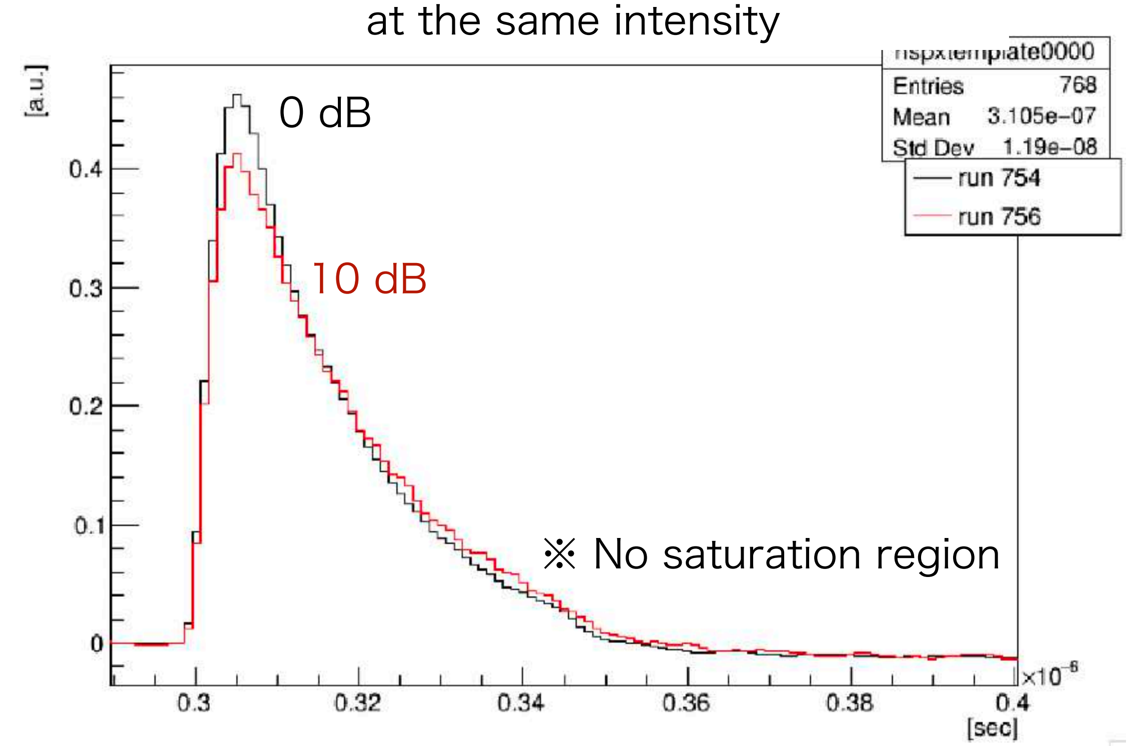
Possible issues

- Different signal attenuators used depending on the signal height
  - to avoid the saturation of the electronics
- Frequency components of the signal varies depending on the level of the saturation
  - The measurement suffers from the nonlinear response of the attenuator due to the limited bandwidth
    - Higher frequency component in the signal is more attenuated
- Necessary to measure SiPM signal without attenuators
  - To avoid the effect of signal attenuators

Waveform comparison with low / high light at the same attenuator

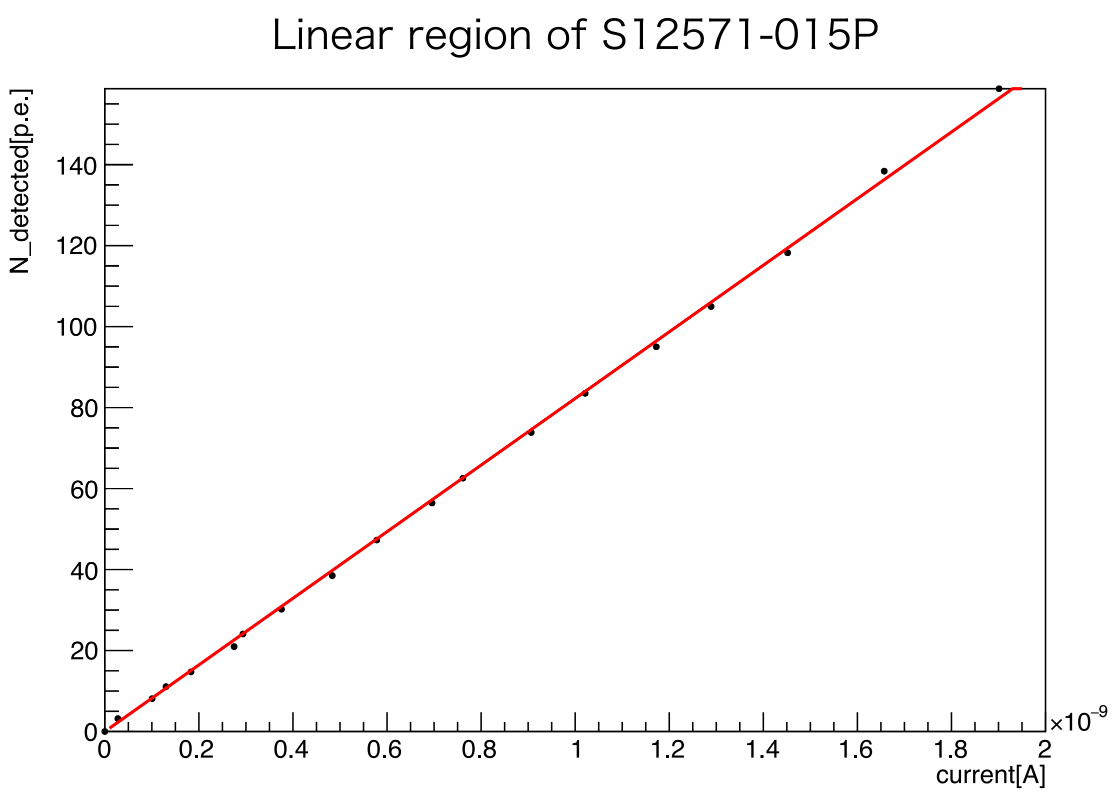


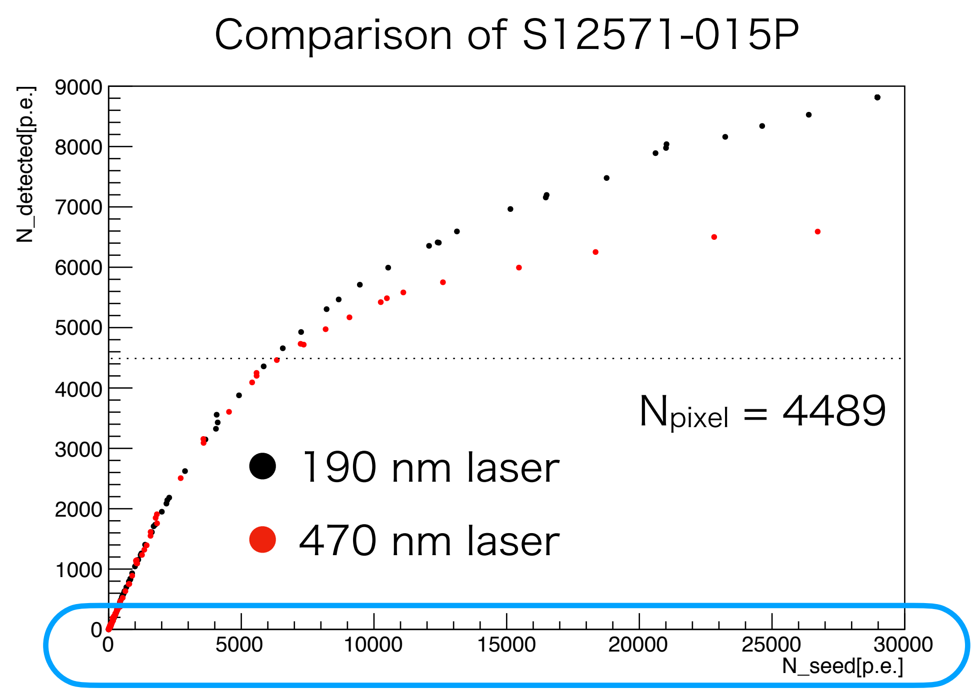
Waveform comparison with 0dB vs 10dB at the same intensity



Possible issues

- Assumption in this measurement:
  - **Scintillation emission is proportional to the intensity of the injected UV laser at whole range**
  - Photodiode current is converted to N_{seed} using calibration constant obtained at the low light intensity where no saturation is anticipated
    - (N_{seed}: nember of photoelectrons when assuming no saturation)
  - Using this proportionality in whole range to estimate scintillation emission
- This relation should be confirmed in the experiment

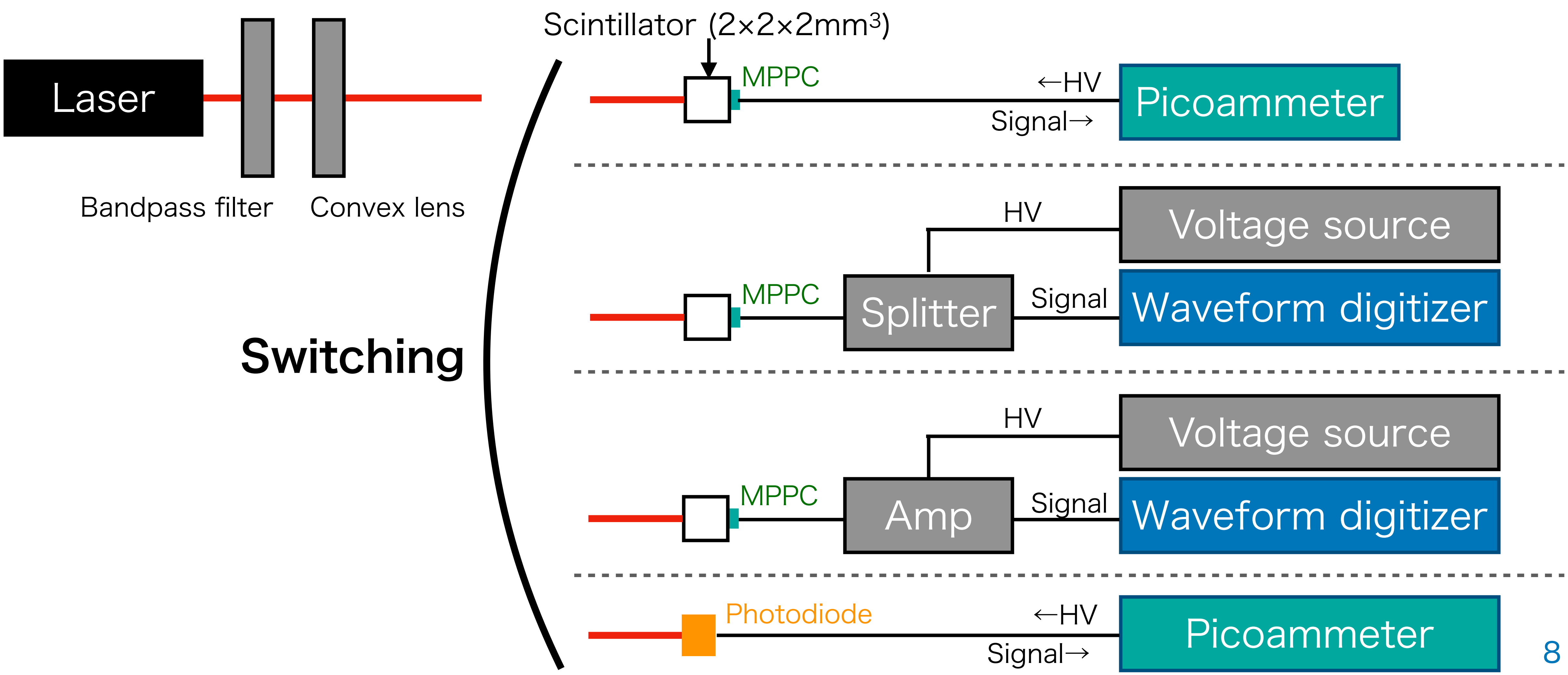




N_{seed} assume no saturation of SiPM and scintillation emission

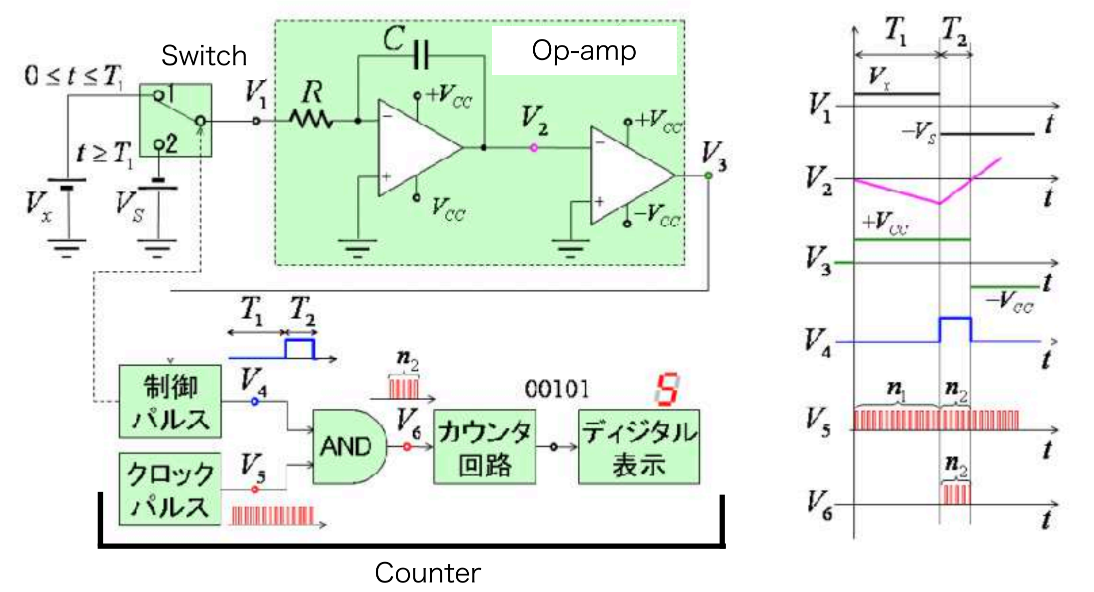
New setup

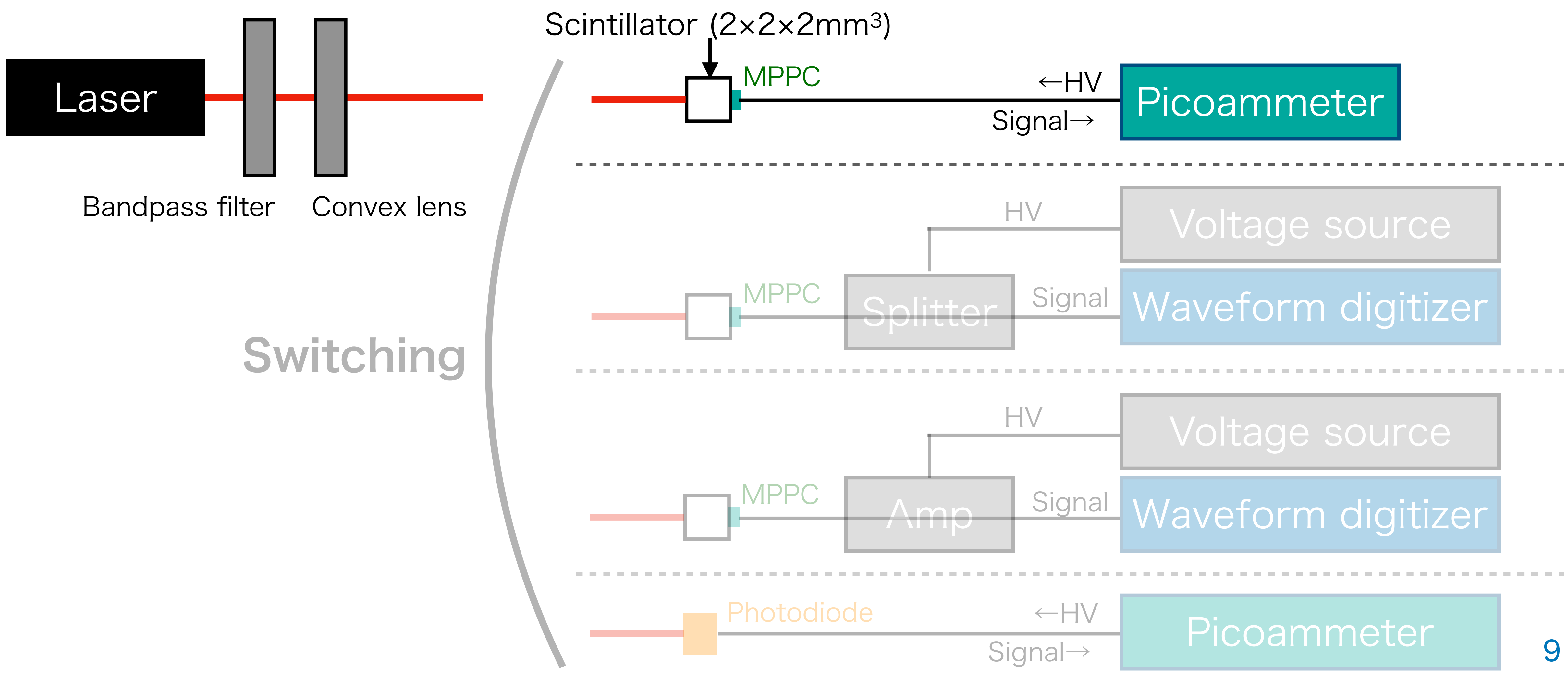
- Switching 4 readout type at the same laser intensity
  - Current readout by picoammeter
  - Raw waveform analyzed by waveform digitizer
  - Measurement of the number of photoelectrons using amp
  - Photodiode to monitor the laser intensity



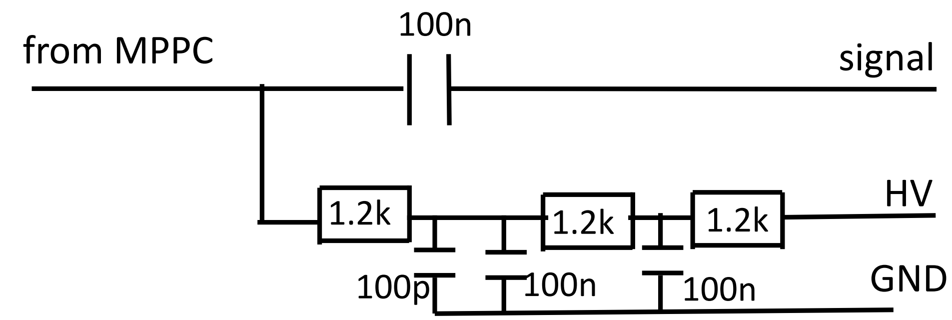
New setup

- Current readout by picoammeter
  - Measure SiPM current in whole range to avoid the effect of signal attenuators
- Keithley 6487 picoammeter
  - Equipped with dual integral A-D converter
  - Calculate the current averaged by integraion time of 20 ms

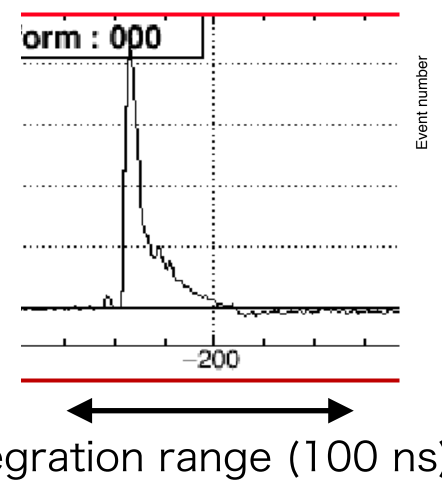


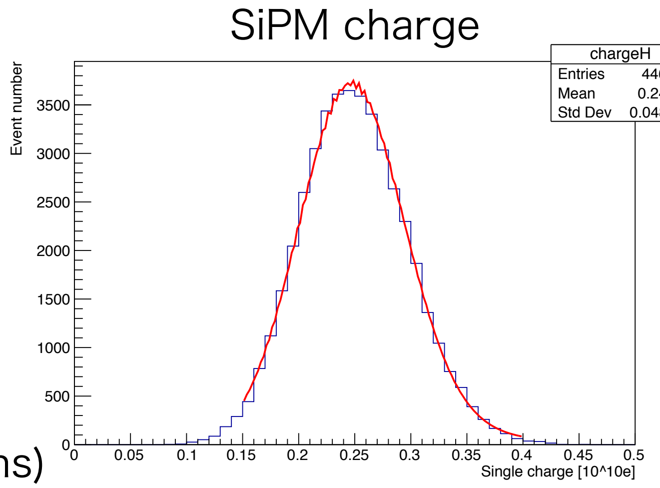


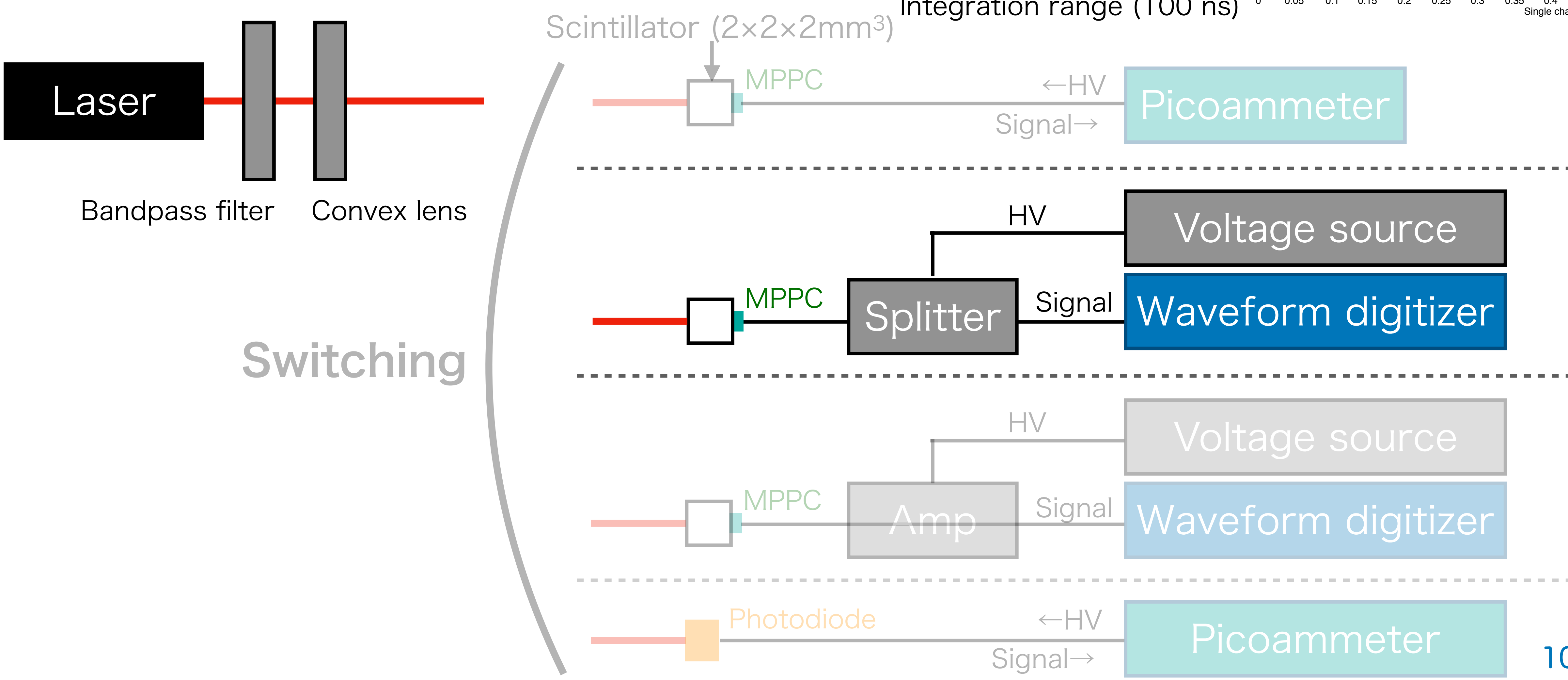
New setup



- Raw waveform analyzed by waveform digitizer
  - HV splitter extract the signal waveform
  - Calibrate current-readout method
- Measure the charge of SiPM using waveform digitizer in whole range without attenuators
  - If number of pixels become large, this method become difficult to cover whole range



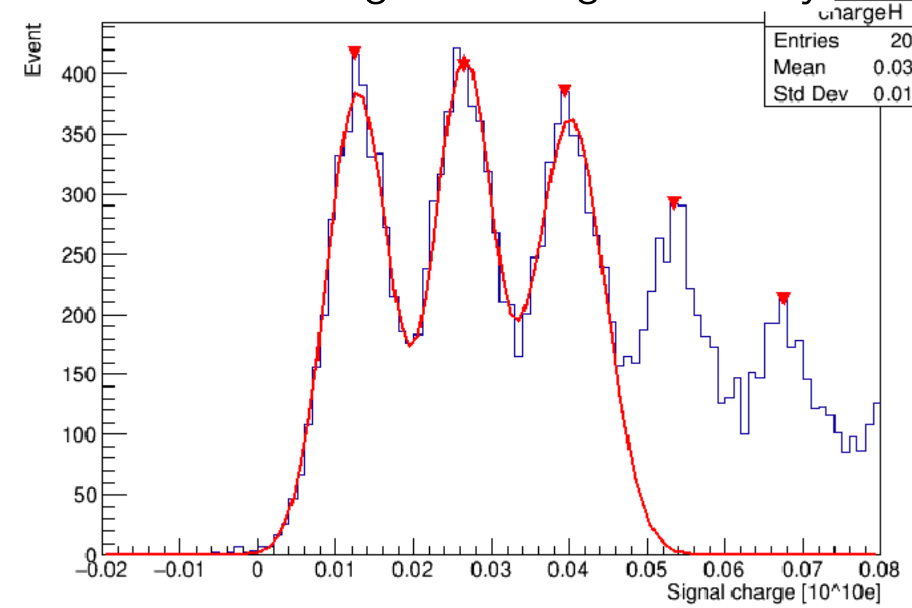


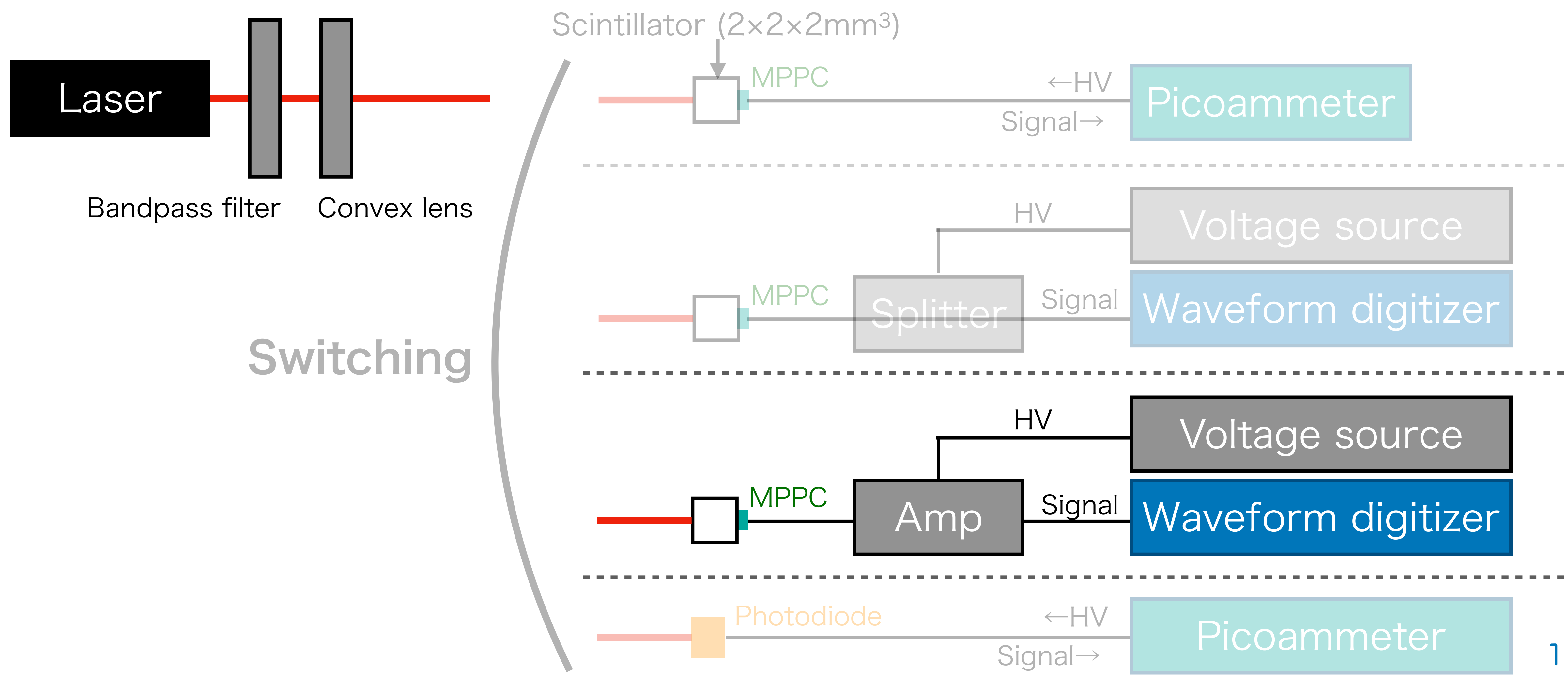


Other modifications

- Measurement of the number of photoelectrons using amp
    - Measure the SiPM charge at the low intensity region
    - until amp occurs the saturation
- The gain (charge of 1 p.e.) can be obtained by waveform digitizer
    - Calculate the number of photoelectrons at each light intensity

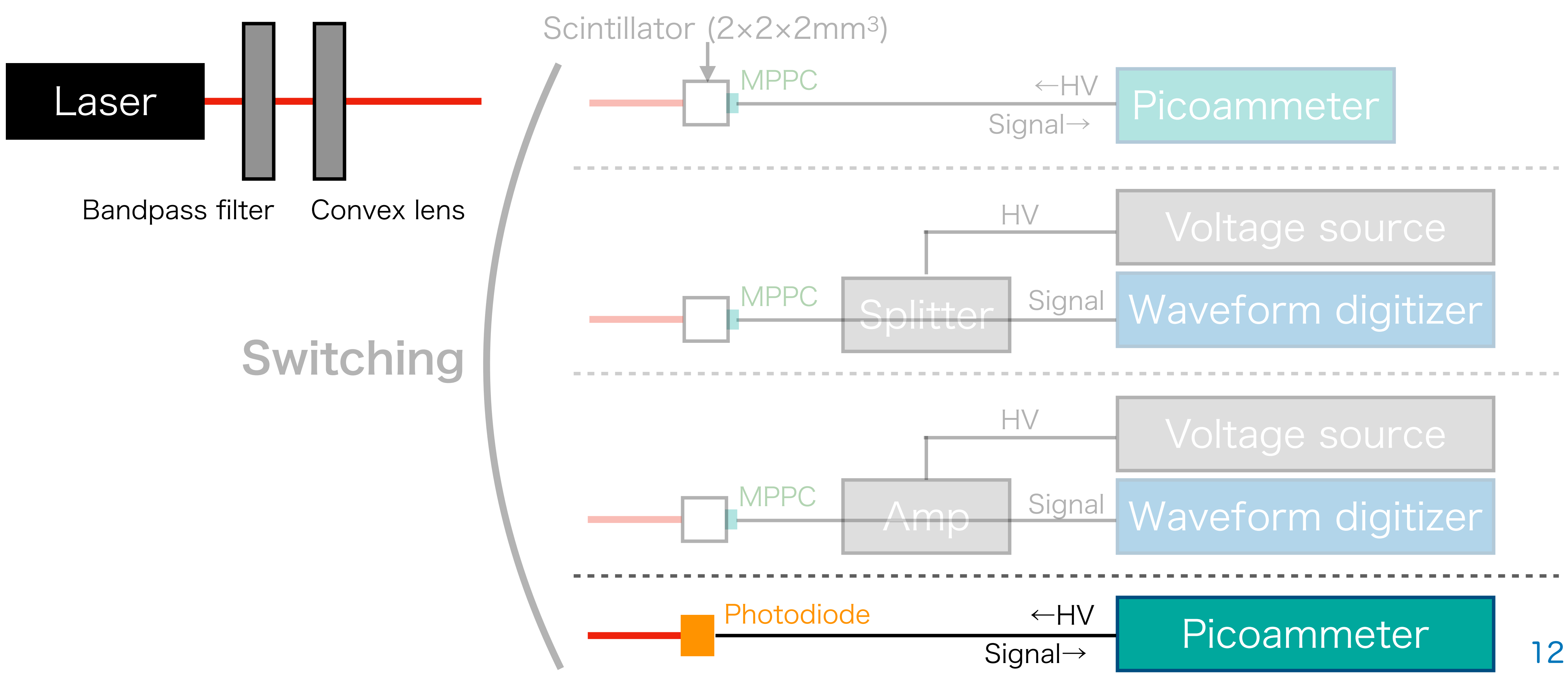
SiPM charge at low light intensity





Other modifications

- Photodiode to monitor the laser intensity
- Hamamatsu S12698-02
  - High UV resistivity
- Measure the current of photodiode by picoammeter



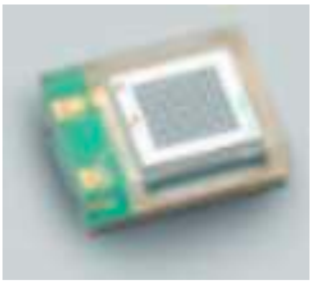
New setup

- Sub-nanosecond Pulsed LED
  - fsec laser is out of order
- PLS-255
  - Wavelength: 255 nm (±10 nm)
  - Pulse width: 800 ps
  - Average power: ~1 μW
  - Scintillation excitation, invisible to MPPC

PicoQuant

- MPPC: S12571 series
  - SiPMs for Sc-ECAL: S12571-015P, -010P
  - Using S12571-025P at this experiment
    - Laser intensity is very low
    - Laser doesn’t have enough light yield for S12571-015P, -010P

Hamamatsu Photonics

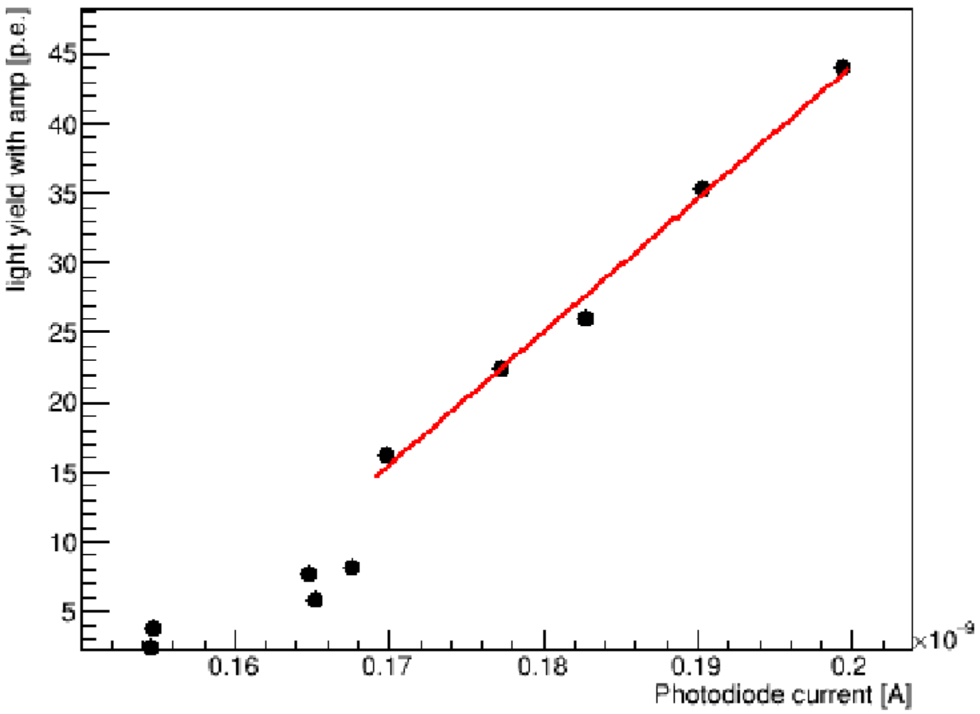


Model number	S12571-025P	S12571-015P	S12571-010P
Photosensitive area	1 mm^2	1 mm^2	1 mm^2
Pixel size	25 μm	15 μm	10 μm
Number of pixels	1600	4489	10000
PDE	35%	25%	10%
Gain	5.15×10^5	2.3×10^5	1.35×10^5
Crosstalk Probability	~20%	~15%	~5%

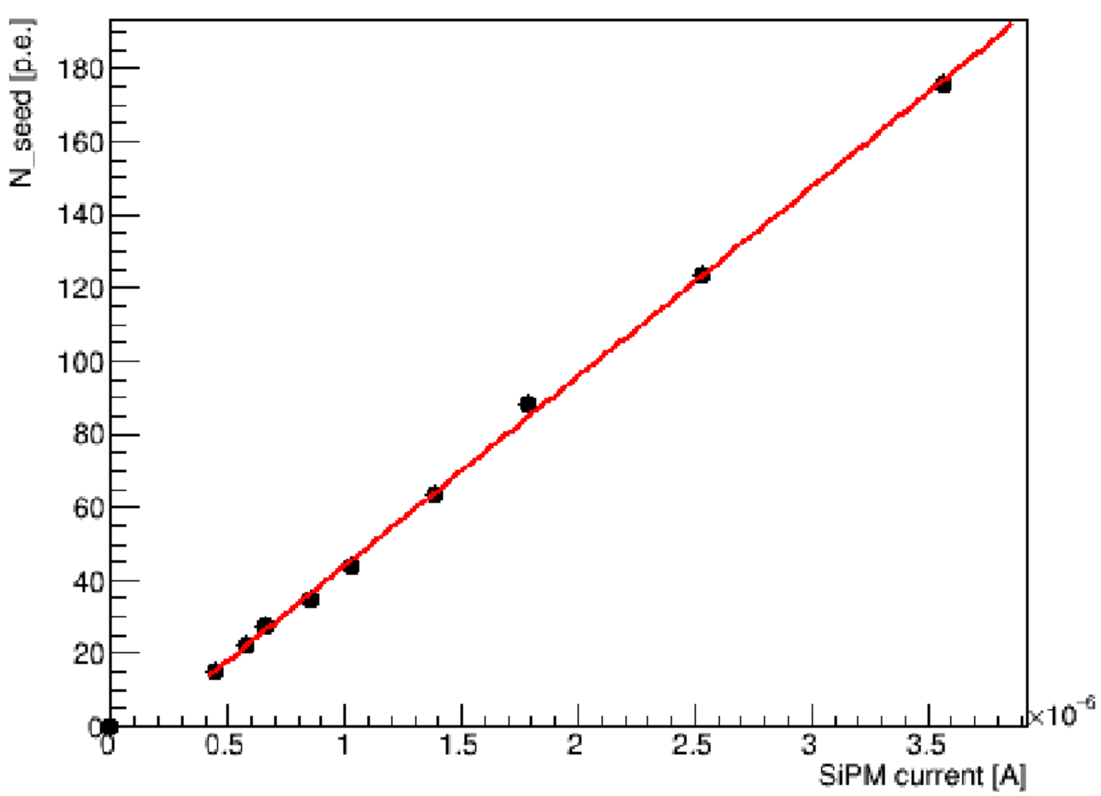
Conversion to Npe

- Photodiode current is converted to N_{seed} using calibration constant obtained at low intensity where no saturation is anticipated
  - (N_{seed}: number of photoelectrons when assuming no saturation)
  - Effect of crosstalk and after-pulse is not corrected yet
- SiPM current and charge of raw waveform is also converted using calibration constant obtained at low intensity

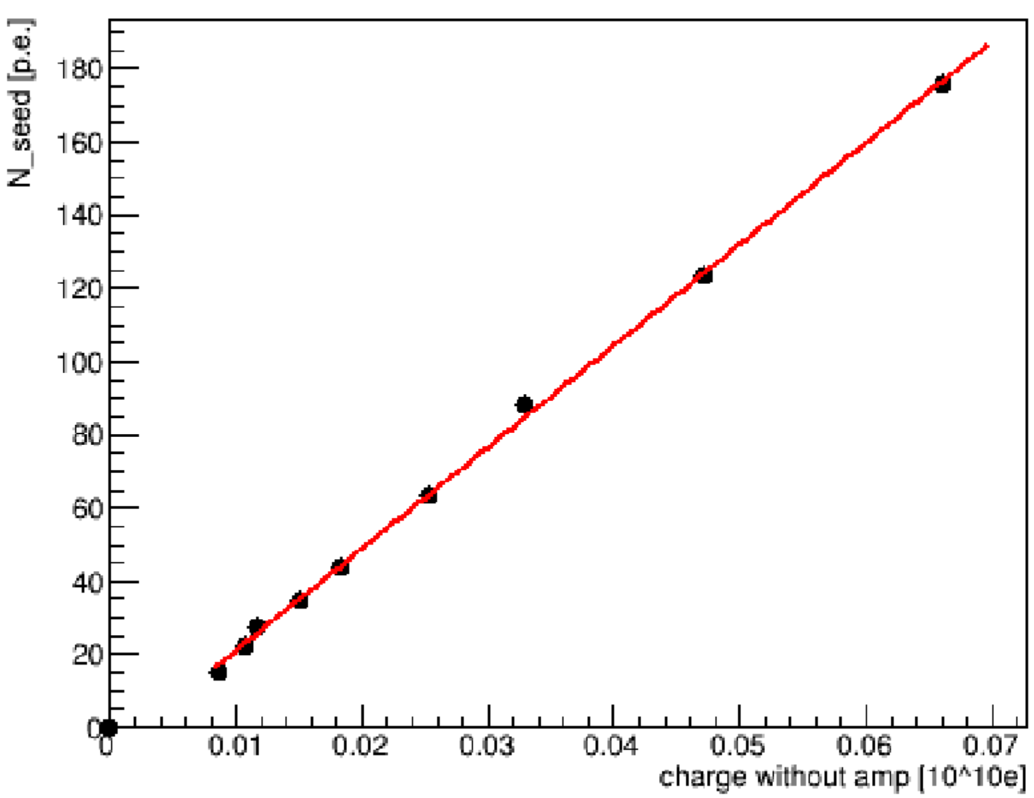
Photodiode current vs. Light yield with amp



SiPM current vs. N_{seed}



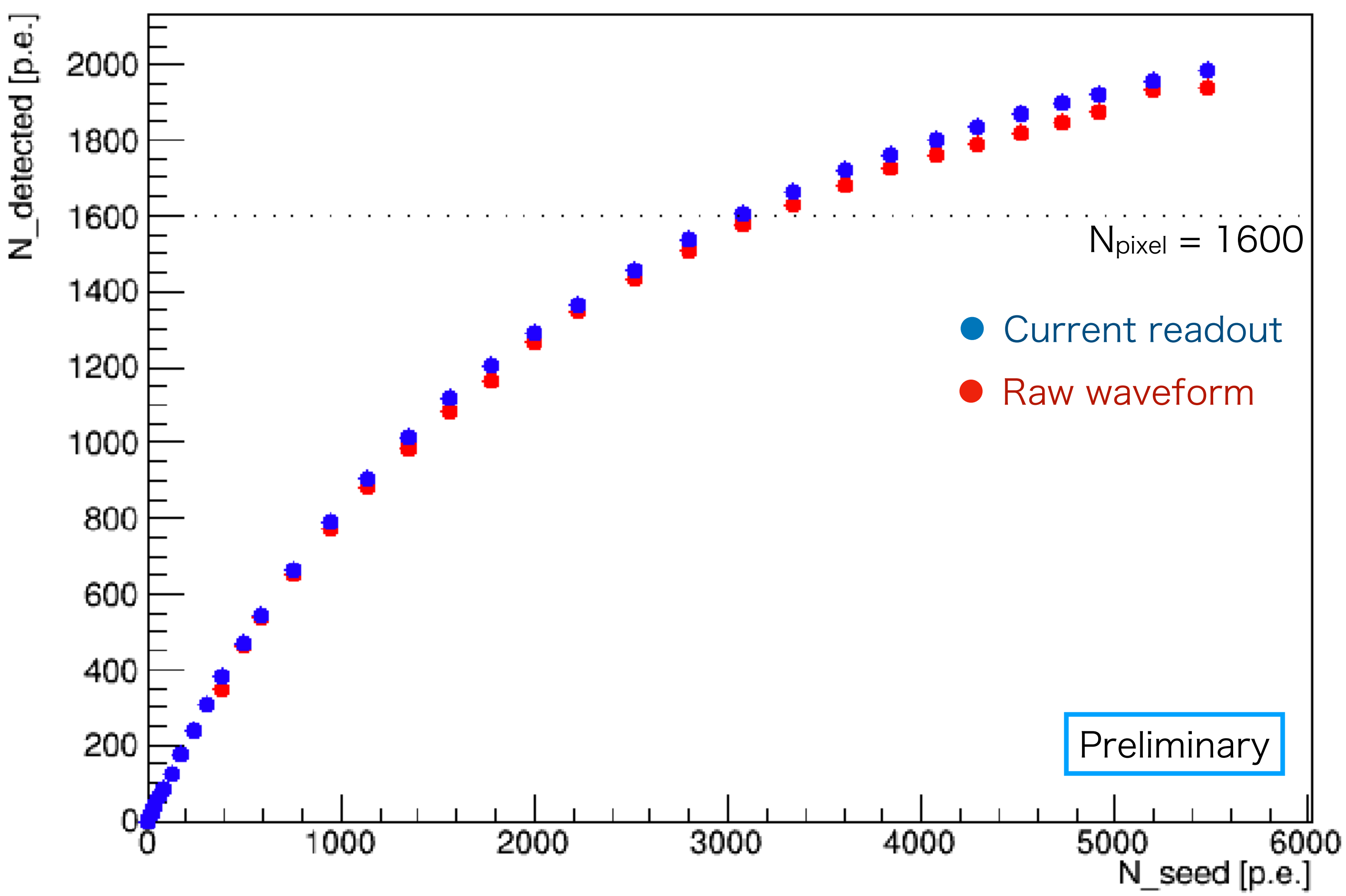
Charge of raw waveform vs. N_{seed}



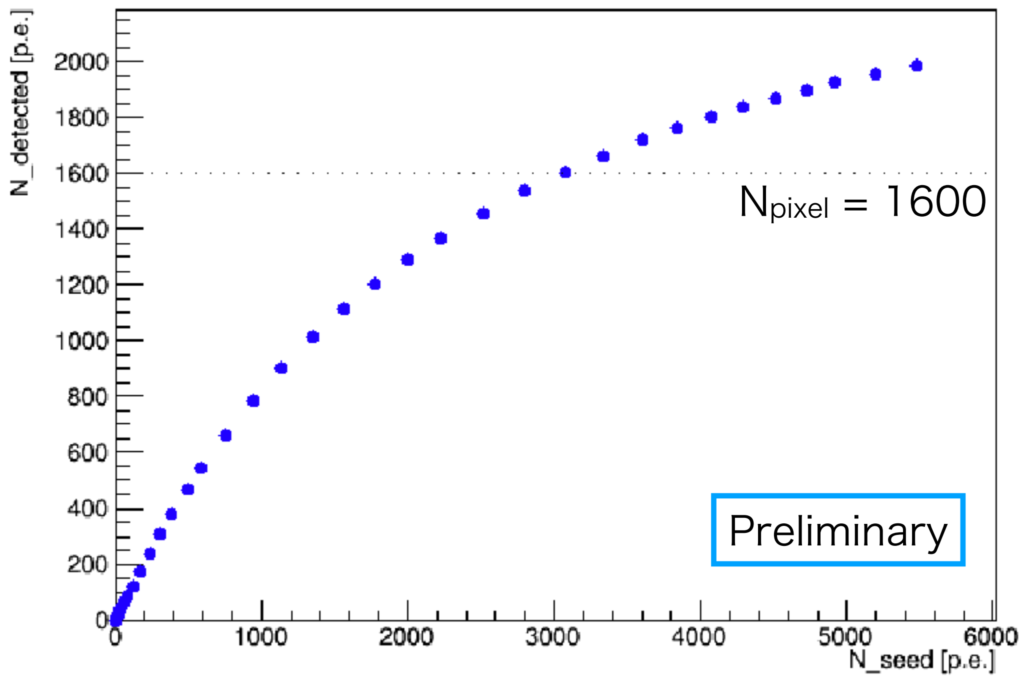
Preliminary result

- Reasonable saturation curve obtained by both readout type
  - Similar to previous measurement
  - Measurement in whole range without attenuator can be done by current-readout

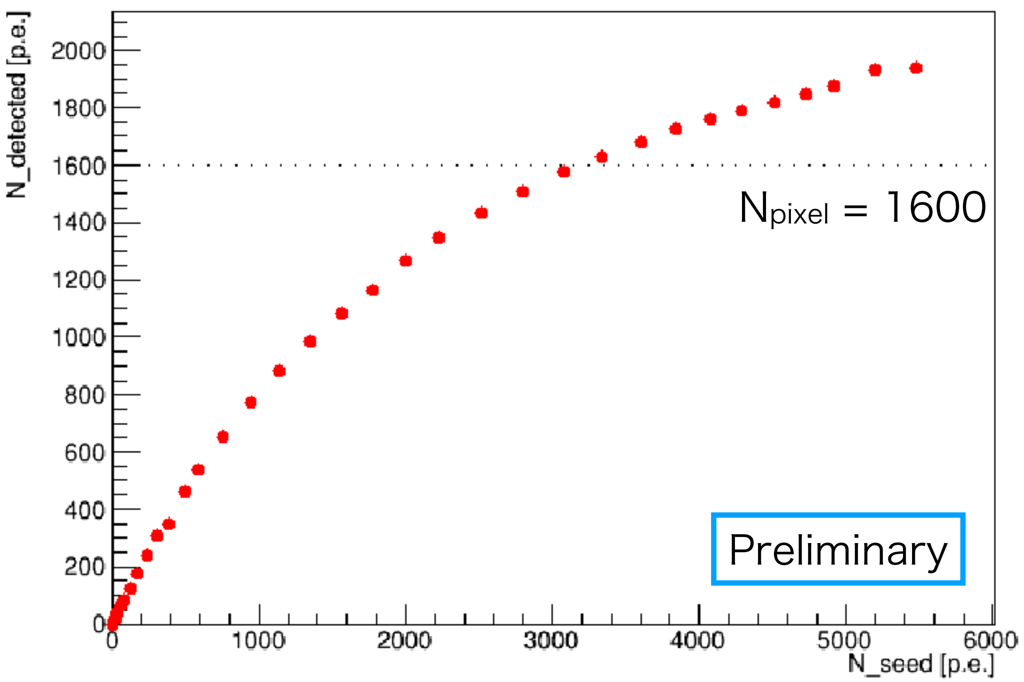
Comparison with SiPM current and raw waveform



Saturation curve using SiPM current



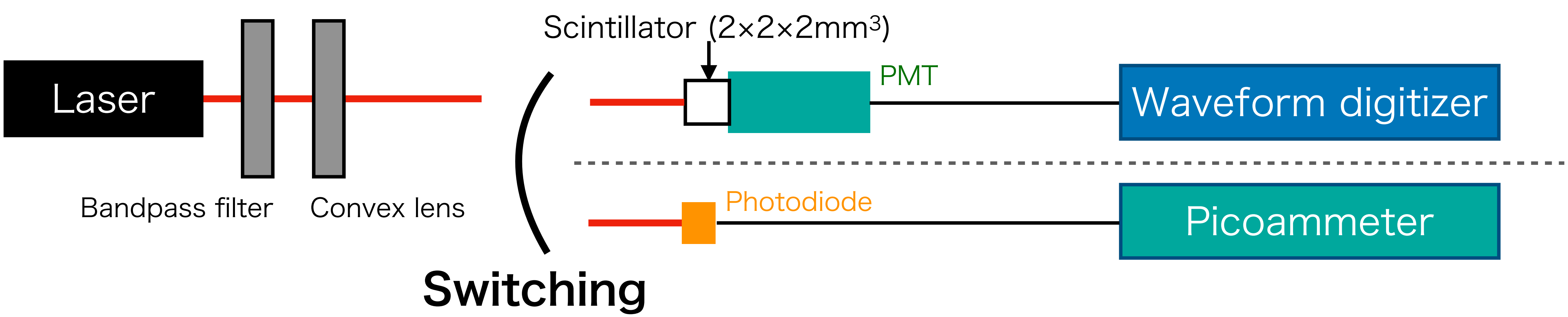
Saturation curve using raw waveform



To do

- Measurement using visible laser in preparation
  - PLS-500
    - Wavelength: 485(±10) nm, Pulse width: 800 ps, average power: ~35 μW
    - No scintillation excitation, directly detected by MPPC

- Measurement of the relation between scintillation emission and UV laser intensity by PMT in preparation
  - PMT has much wider dynamic range than SiPM
  - Non-linearity should be corrected if observed



Summary & to do

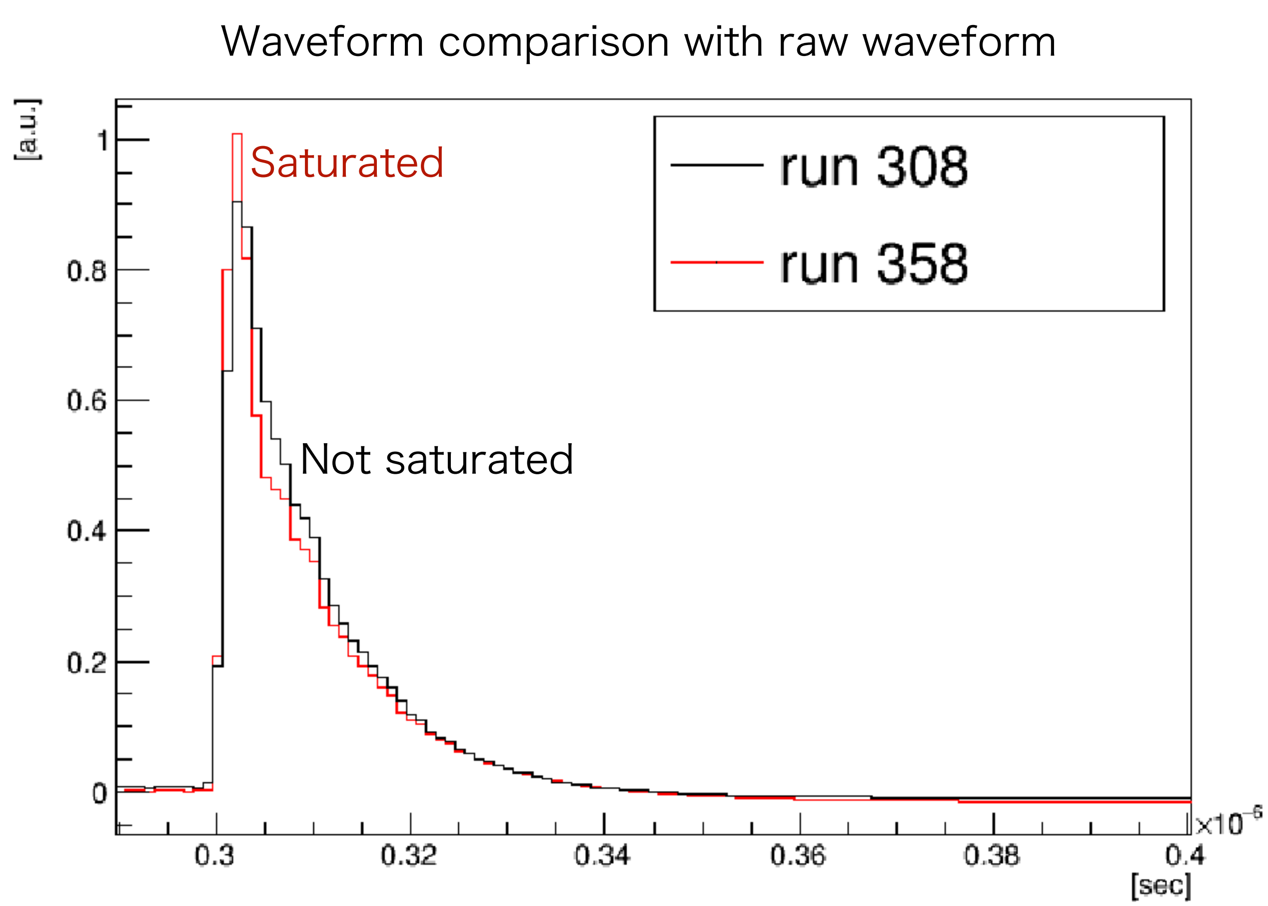
- New idea to measure the saturation curves for SiPMs with scintillation light excited by UV-laser
    - Measured saturation curves can directly be used for correction
    - Previous measurements have some uncertainties about signal attenuators
- New setup
    - Measure the SiPM current by picoammeter
    - Measure the raw waveform without amp and attenuators
- Reasonable saturation curve obtained
    - Measurement in whole range without attenuator can be done

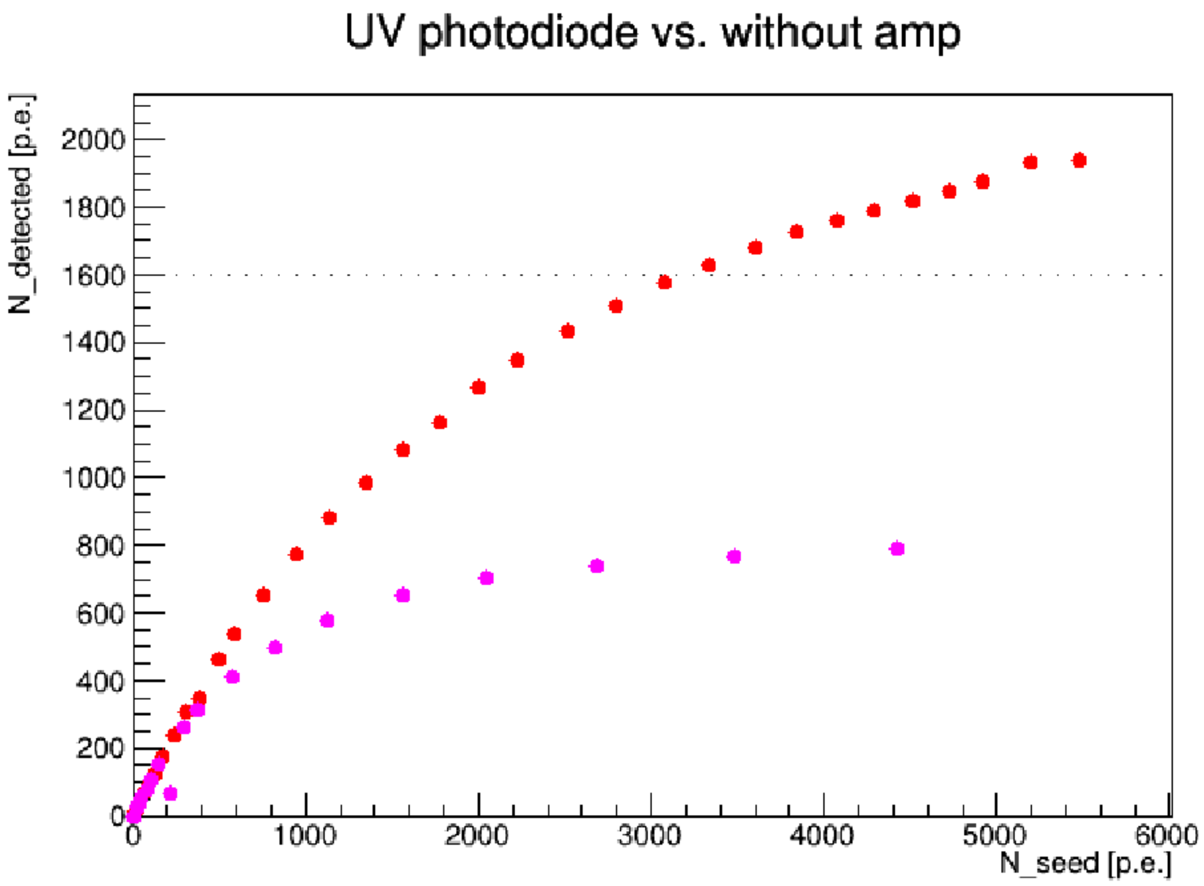
- To do
    - Measurement of saturation curve using visible laser in preparation
    - Measurement using PMT in preparation
    - Measure several types of SiPMs such as S13360-1325PE (for AHCAL)

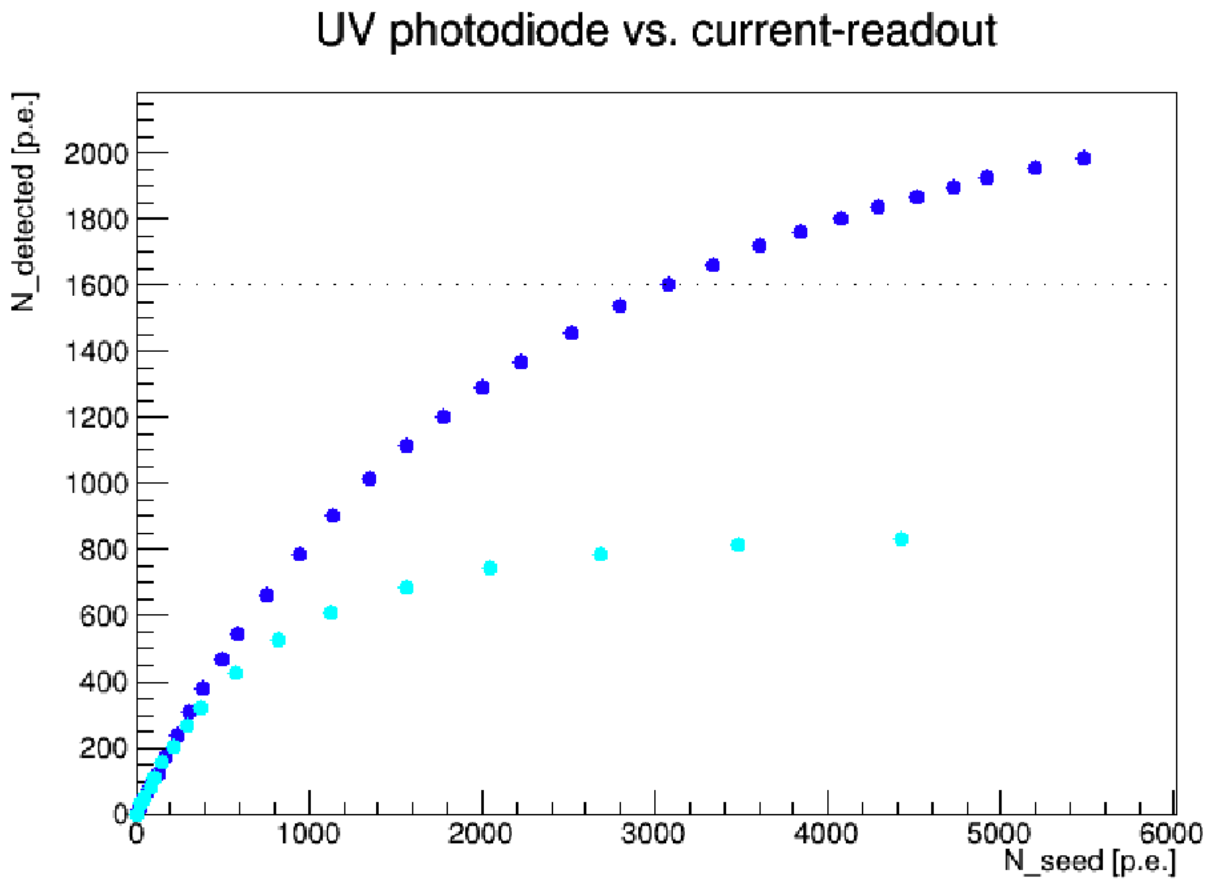
Backup

Waveform comparison

- Raw waveform become sharp at high light intensity
  - Contain more high frequency components
- HV splitter would attenuate the high frequency components
  - Bandwidth of HV splitter: ~200 MHz
- Slight shift of saturation curve using raw waveform is caused by HV splitter




UV photodiode vs. without amp
N_detected [p.e.]
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
1000
2000
3000
4000
5000
6000
N_seed [p.e.]

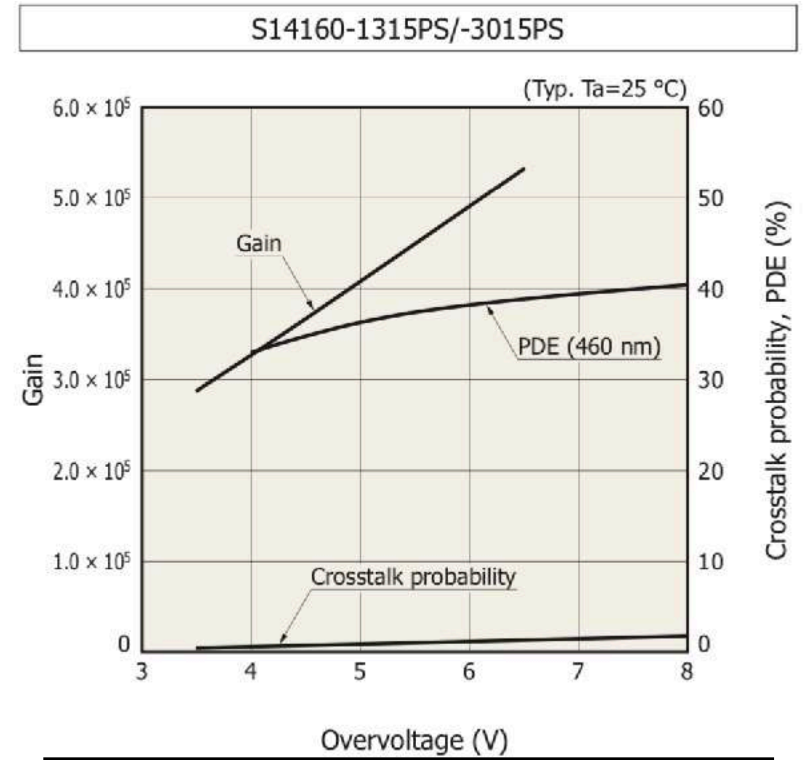

UV photodiode vs. current-readout
N_detected [p.e.]
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
1000
2000
3000
4000
5000
6000
N_seed [p.e.]

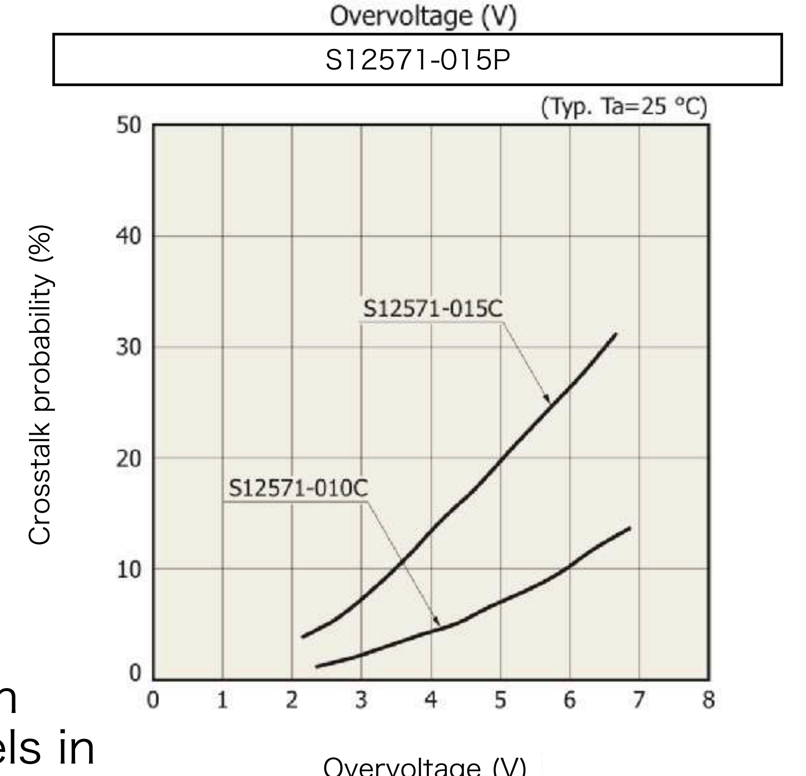
SiPMs for Sc-ECAL

- Hamamatsu MPPC S12571 series
  - Small pixel size : 10 / 15 μm
  - Active area : 1 × 1 mm²
  - Breakdown voltage : 65 V
  - No Trench isolation
- Hamamatsu MPPC S14160 series
  - Small pixel size : 10 / 15 μm
  - Active area : 1.3 × 1.3 / 3 × 3 mm²
  - Breakdown voltage : 38 V
  - 0.5 μm trench isolation → low crosstalk

MPPC : Product name of Hamamatsu SiPM

Crosstalk : IR photons from avalanche in fired pixel can trigger adjacent pixels





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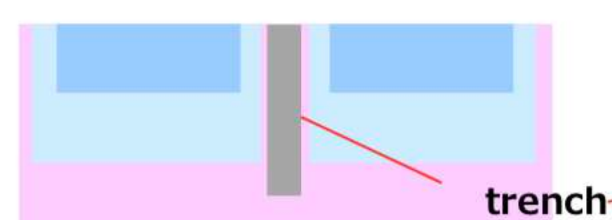
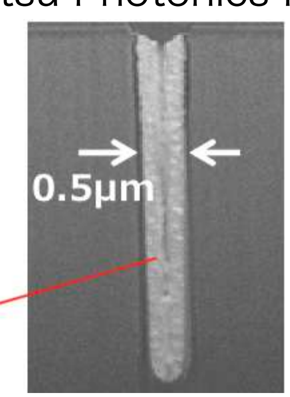
	S12571	S14160 (Latest)
Breakdown voltage	65 V	38 V
Trench isolation	none	Yes
Trench width	-	~ 0.5 µm
Fill factor	10µm: 33% 15µm: 53%	10µm: 31% 15µm: 49%

Trench : Separation between adjacent pixels in order to reduce crosstalk

Cross-section of micro-cells





Trench technique of new MPPC

- MPPC S14160 series employ trench technique
  - Low crosstalk
  - Low operation voltage
  - No reduction of fill factor
- Longer tail due to larger cell capacitance
  - Longer recovery time
- Saturation is improved for new MPPC?
  - Low crosstalk → saturation ↓
  - Longer recovery → saturation ↑

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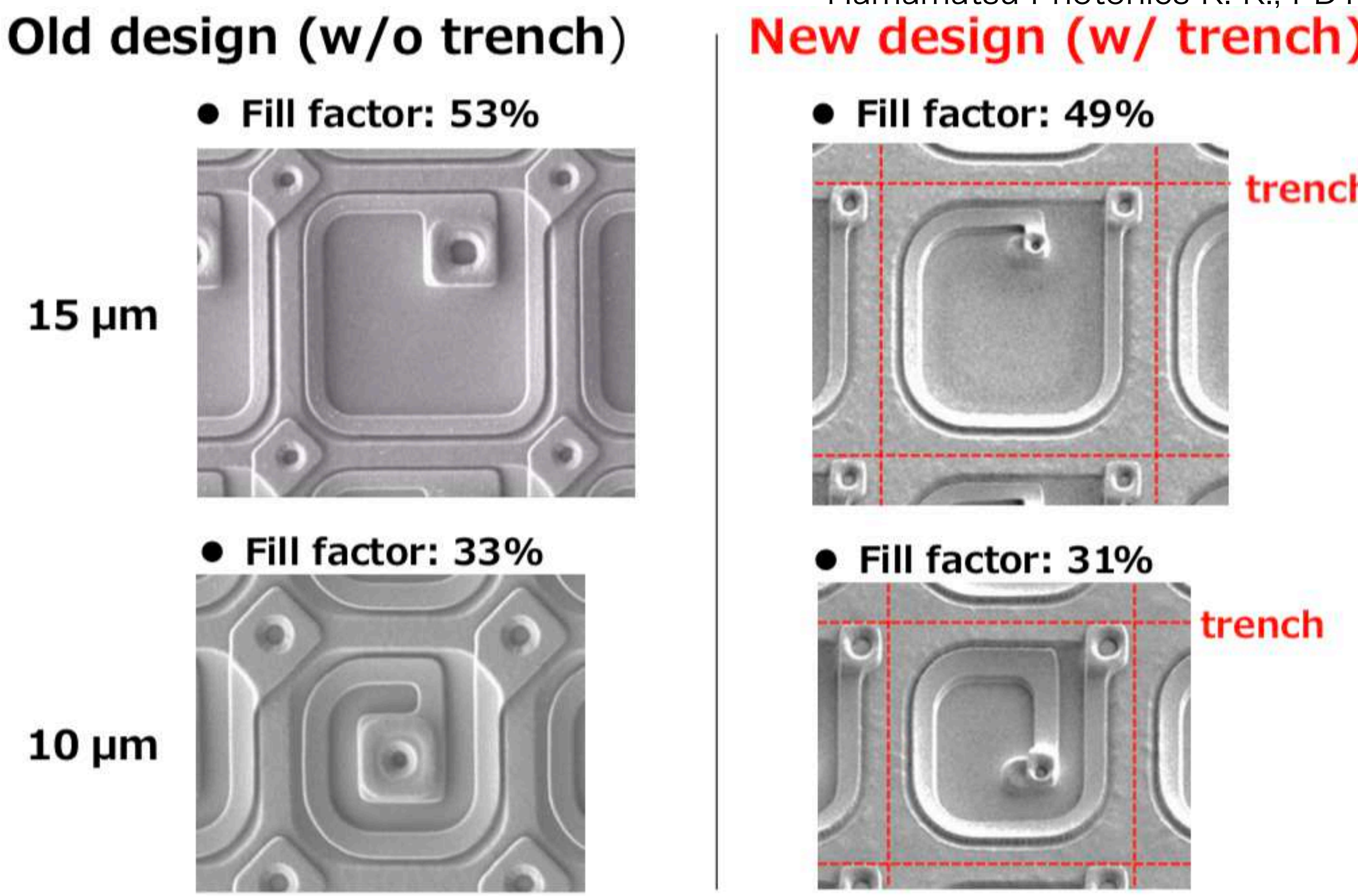
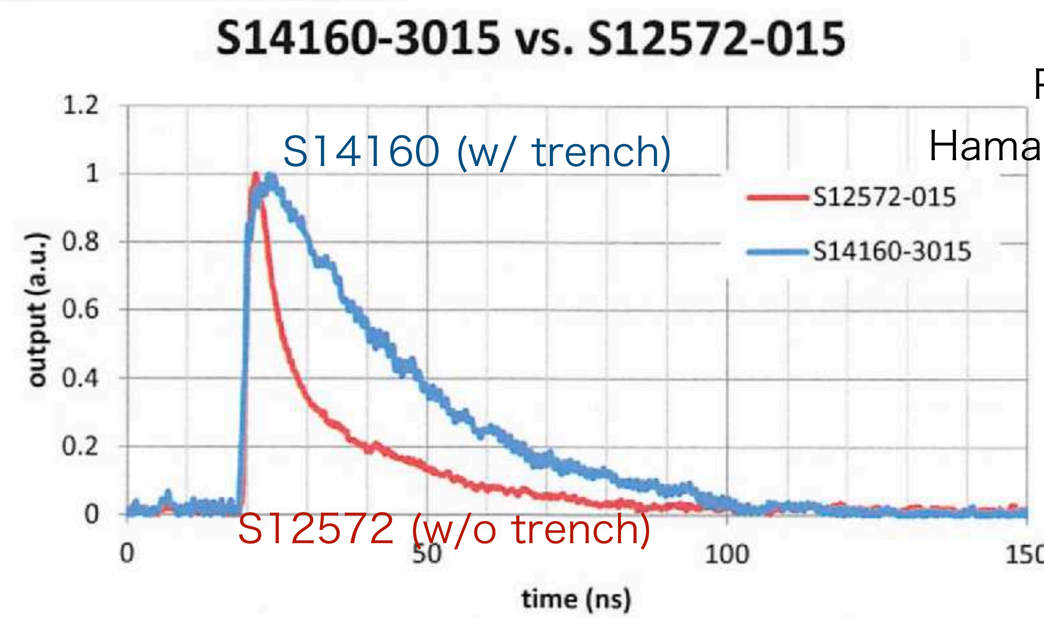


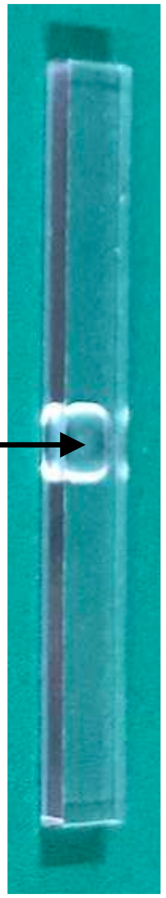


Provided by Hamamatsu Photonics

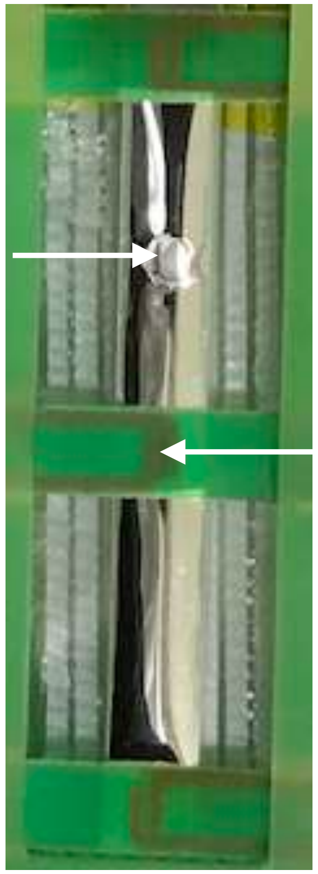
Experimental setup

- Laser
  - **190 nm laser : Scintillation excitation, invisible to MPPC**
  - 470 nm laser : No scintillation excitation, directly detected by MPPC
- Setup for Sc-ECAL
  - 5 × 45 × 2 mm^3 scintillator strip (EJ-212) with center dimple
  - MPPC w/o trench : S12571-015P
    - Active area : 1.0 × 1.0 mm^2
    - Pixel pitch : 15 μm
    - 4489 pixels
  - MPPC w/ trench : S14160-1315PS
    - Active area : 1.3 × 1.3 mm^2
    - Pixel pitch : 15 μm
    - 7296 pixels

Scintillator strip



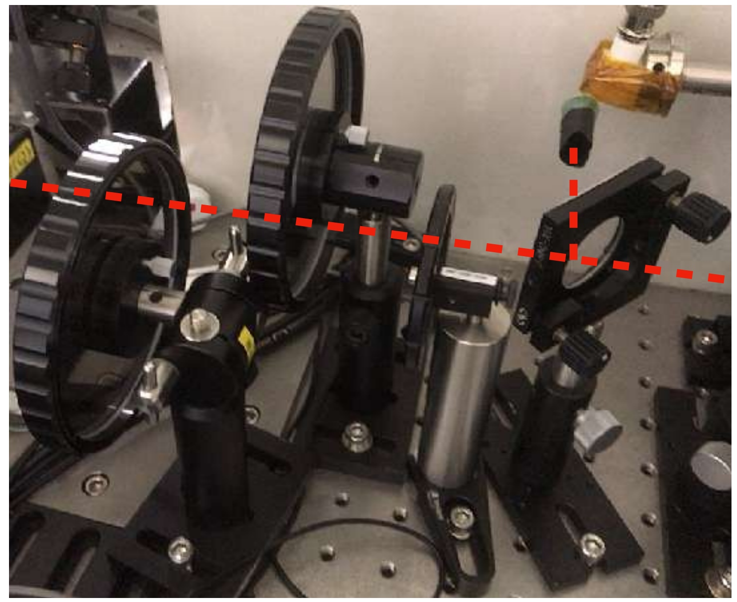
Setup
(wrapped strip + PCB)



Experiment setup

Cut off contamination of other wavelength light

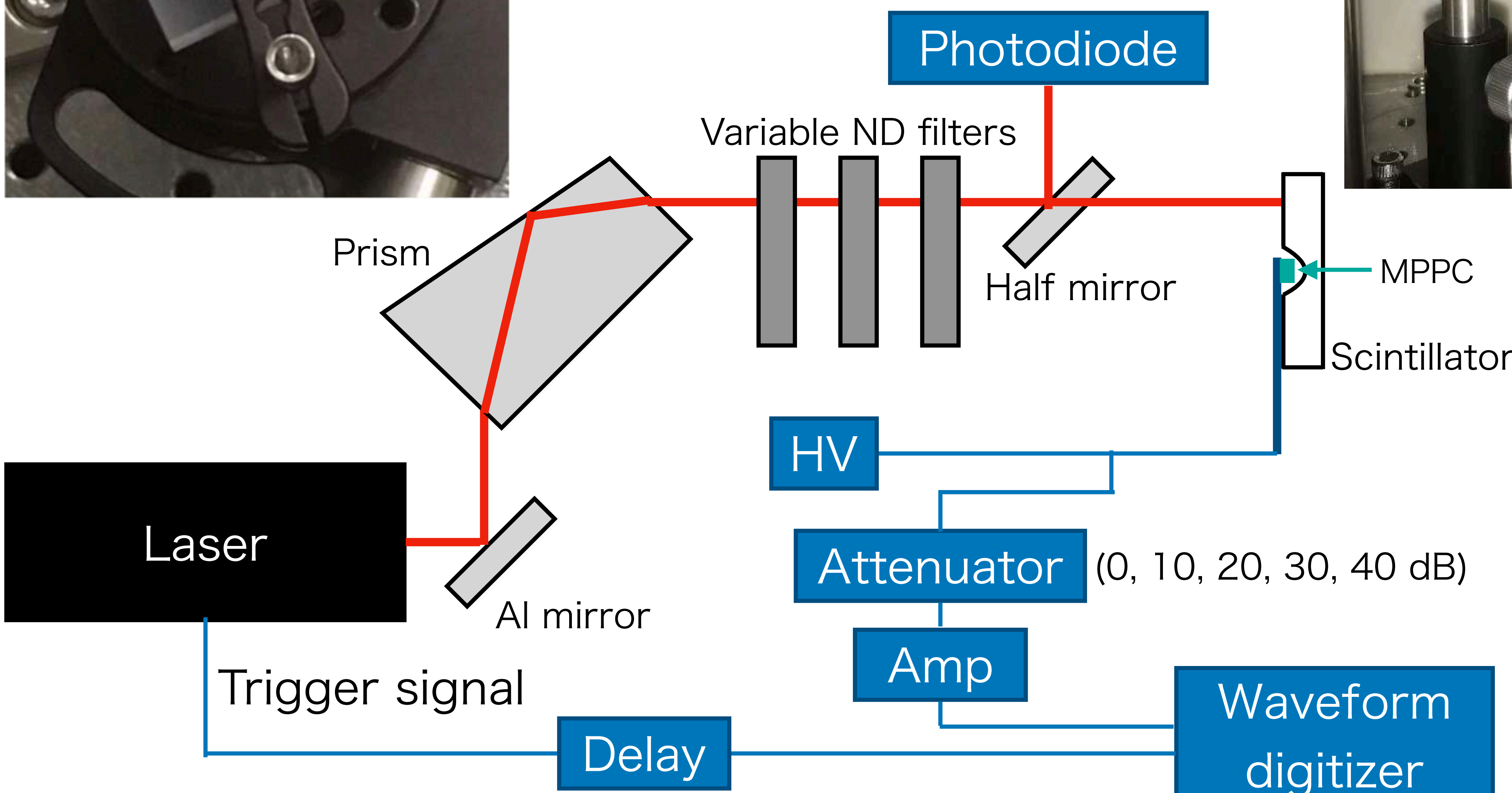
Incident light intensity controlled with three ND filters



Laser Light is split using half mirror

Photodiode

Scintillator & PCB

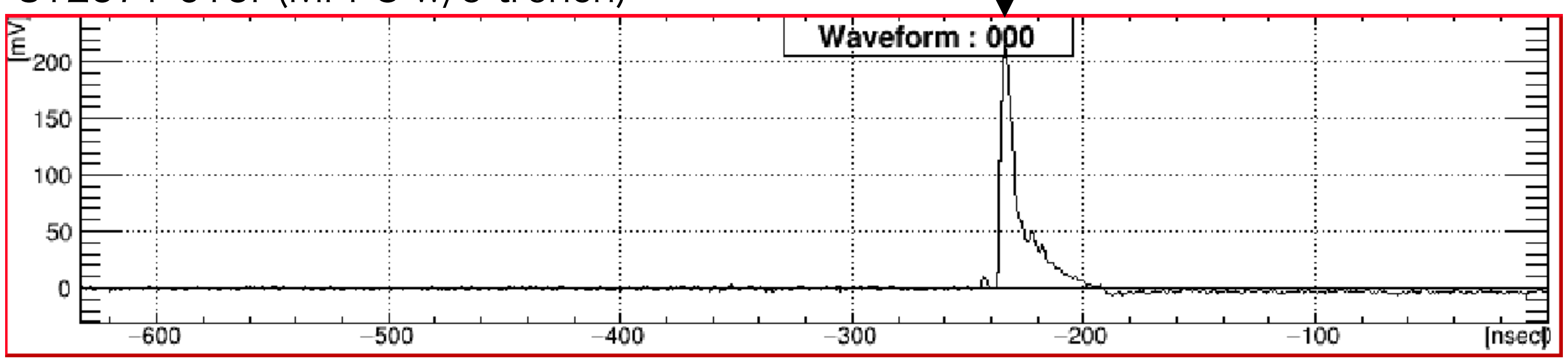


Analysis

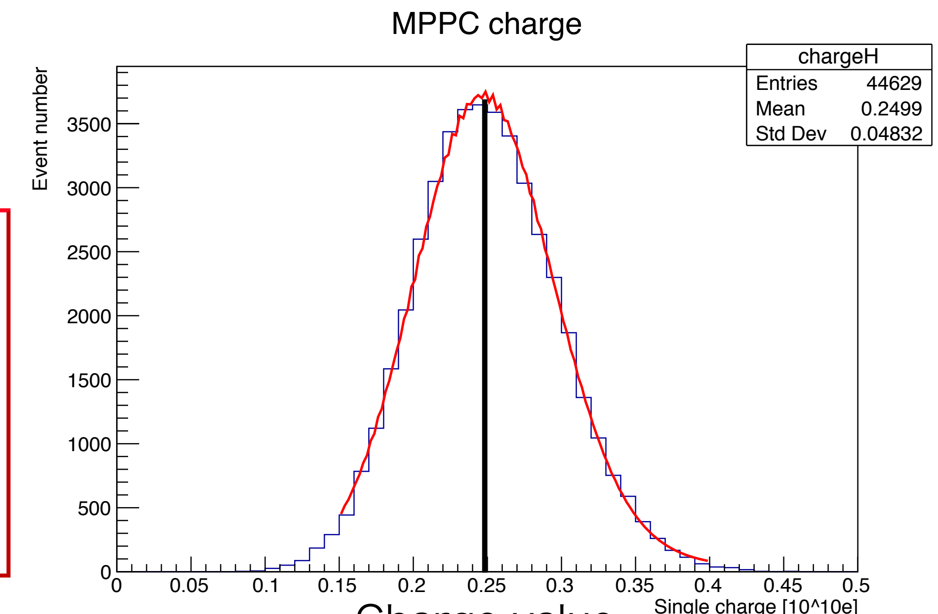
- Digitized waveform is integrated to estimate charge.
- The charge is then converted into number of photoelectrons being divided by single photoelectron charge.
    - Single photoelectron charge is obtained from dark noise signal found in off-time region

Signal of scintillation light

S12571-015P(MPPC w/o trench)



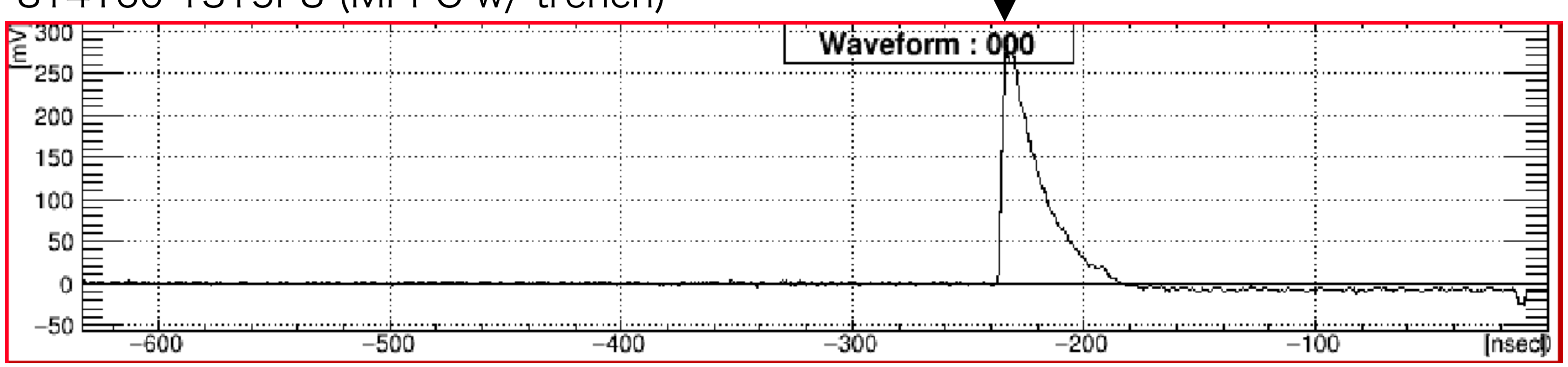
Integration range (100 ns)



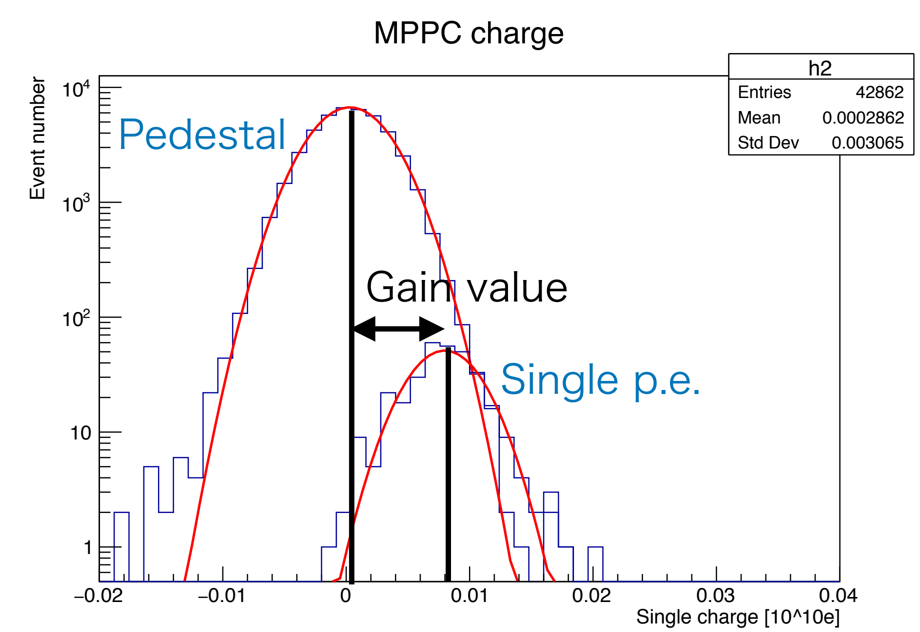
Charge value

Signal of scintillation light

S14160-1315PS (MPPC w/ trench)



Integration range (100 ns)

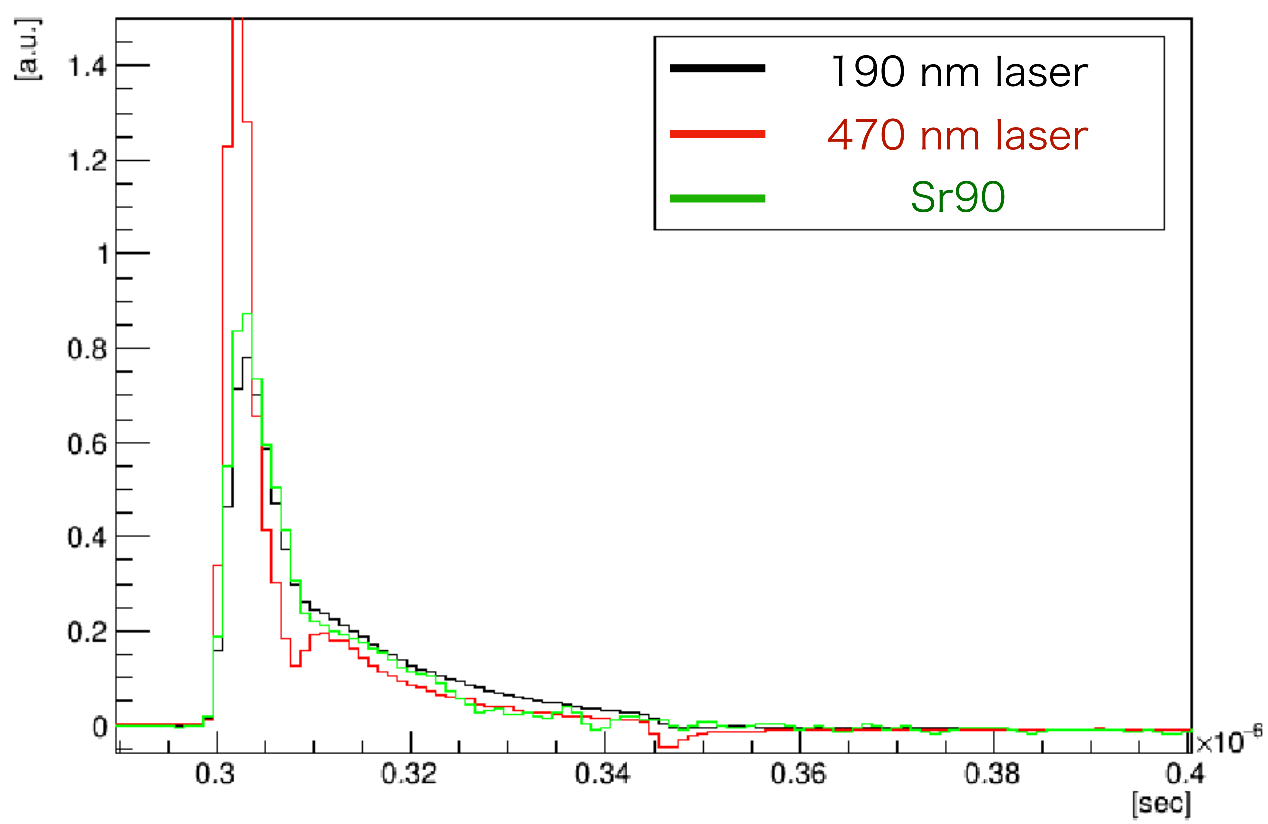


Signal waveform

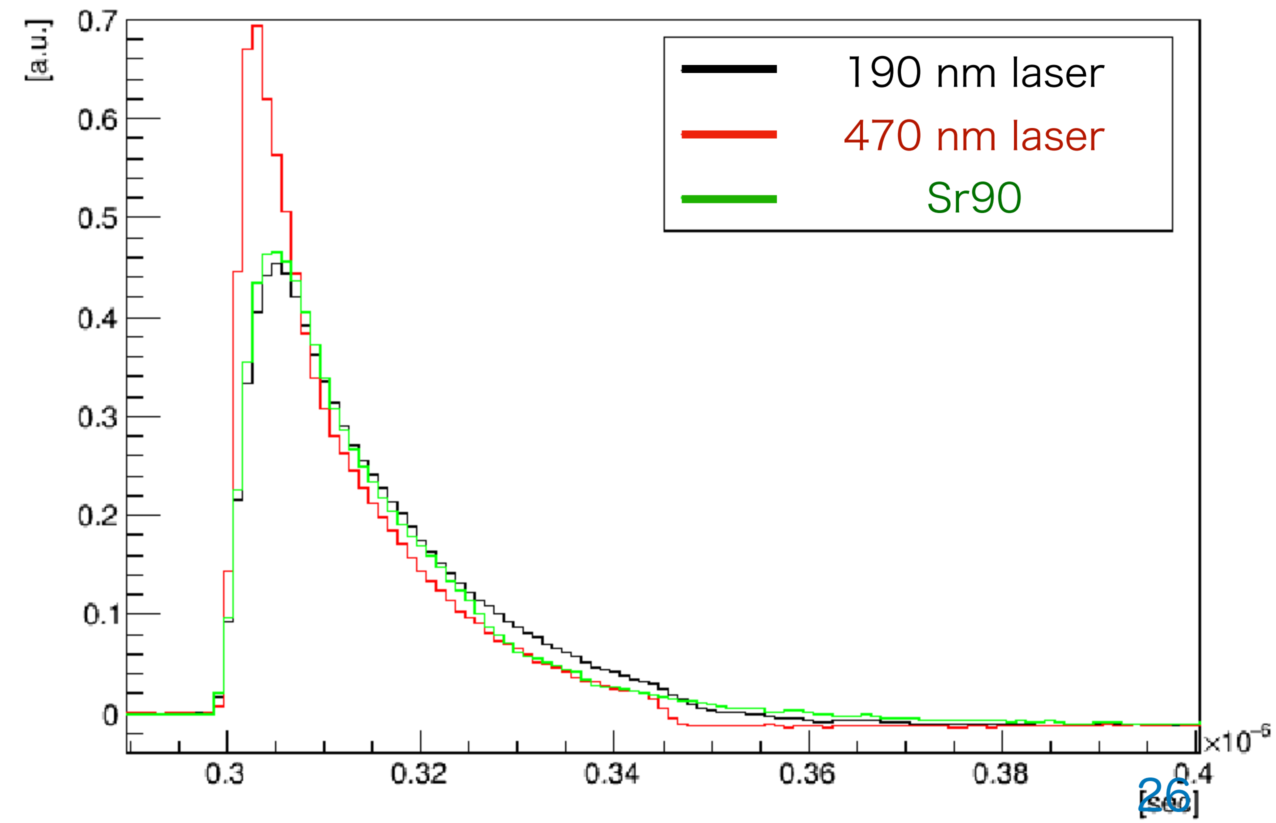
- Waveform is compared among 190 nm laser, 470 nm laser, and Sr90
  - 190 nm laser, Sr90 → MPPC detects scintillation light
  - 470 nm laser → MPPC detects laser light directly
- Almost the same waveform b/w 190 nm and Sr90
- Faster signal for direct injection of 470 nm laser

➡Suggesting that injected UV laser really excites scintillation light !

S12571-015P (MPPC w/o trench)



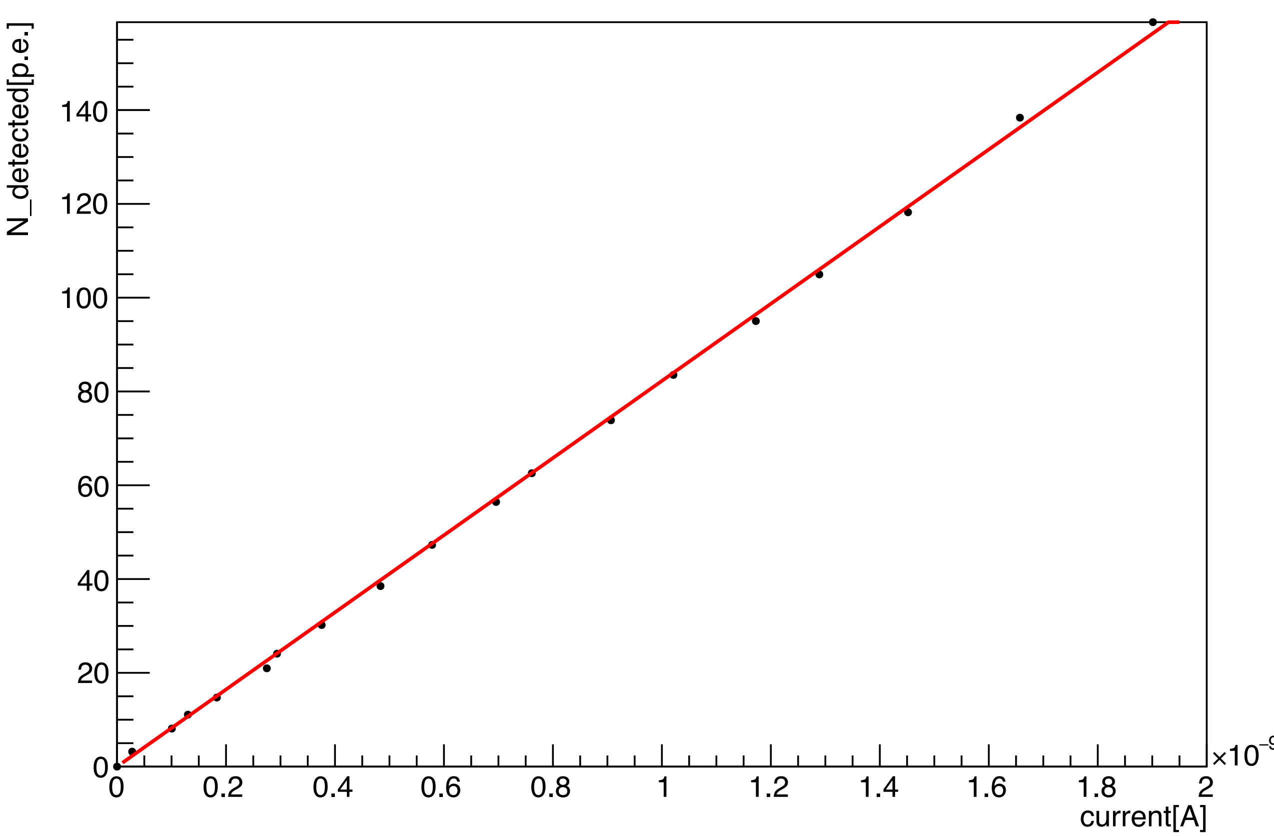
S14160-1315PS (MPPC w/ trench)



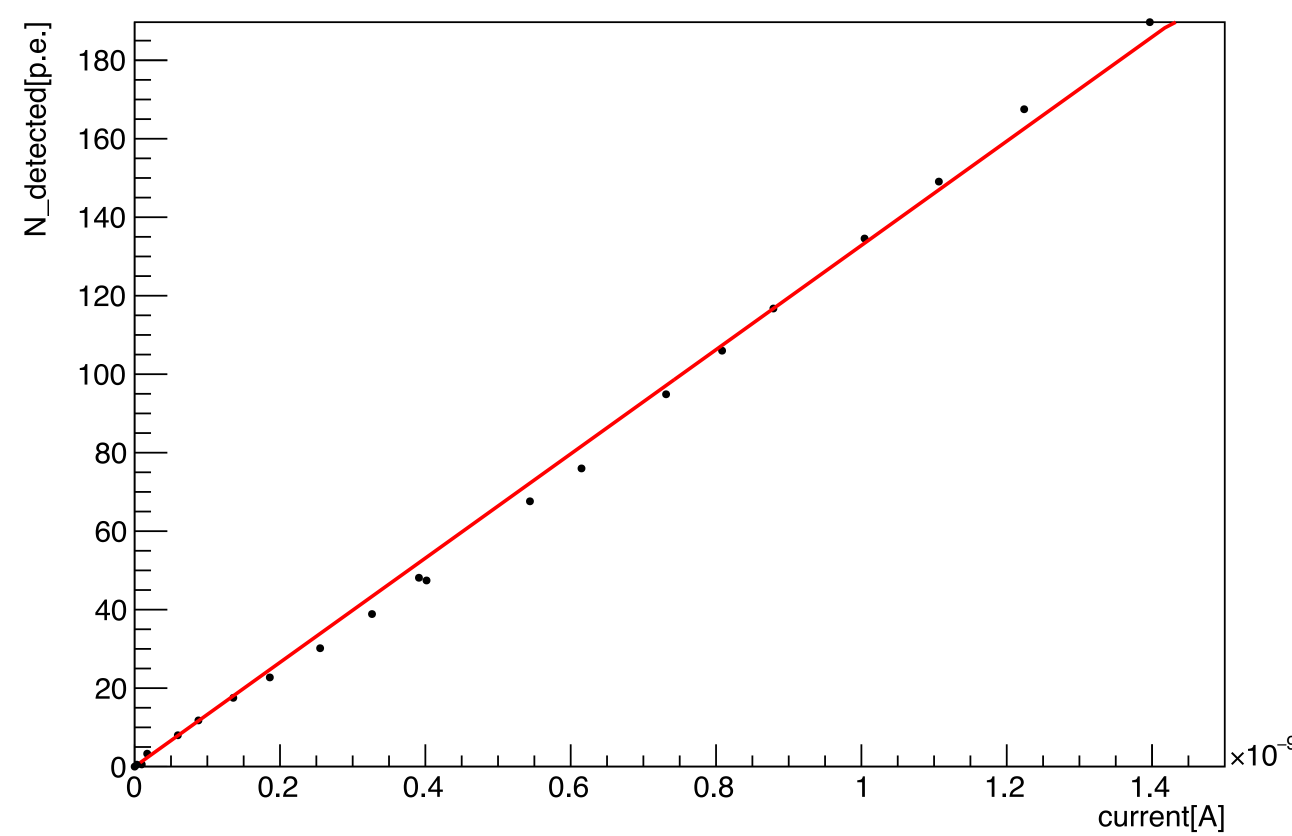
Laser intensity

- Incident light intensity is monitored with photodiode
  - Laser light is split using half mirror
- Photodiode current is converted to N_{seed} using calibration constant obtained at low light intensity where no saturation is anticipated
  - (N_{seed} : number of photoelectrons when assuming no saturation)
- Effect of crosstalk and after-pulse is not corrected yet

Linear region of S12571-015P (MPPC w/o trench)

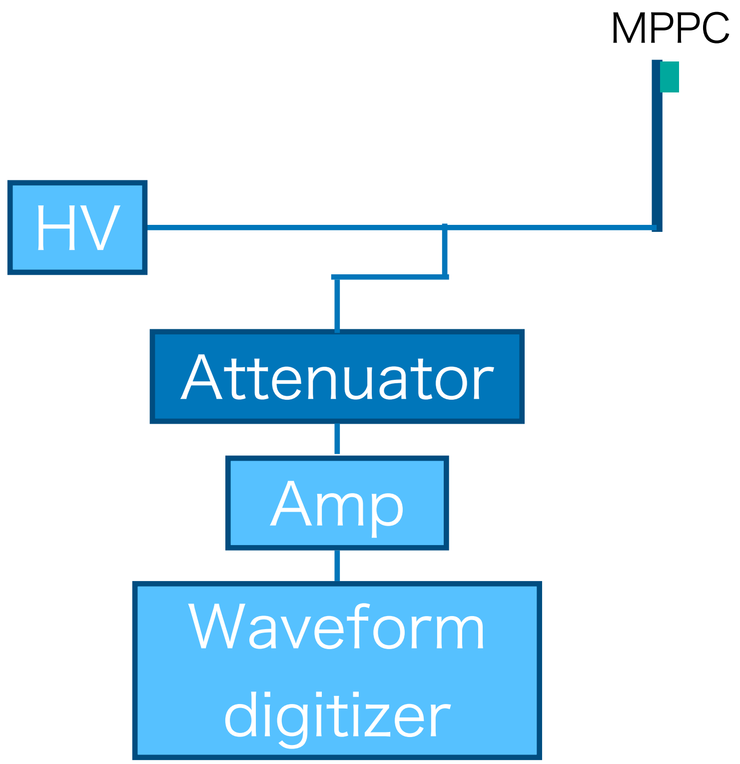


Linear region of S14160-1315PS (MPPC w/ trench)

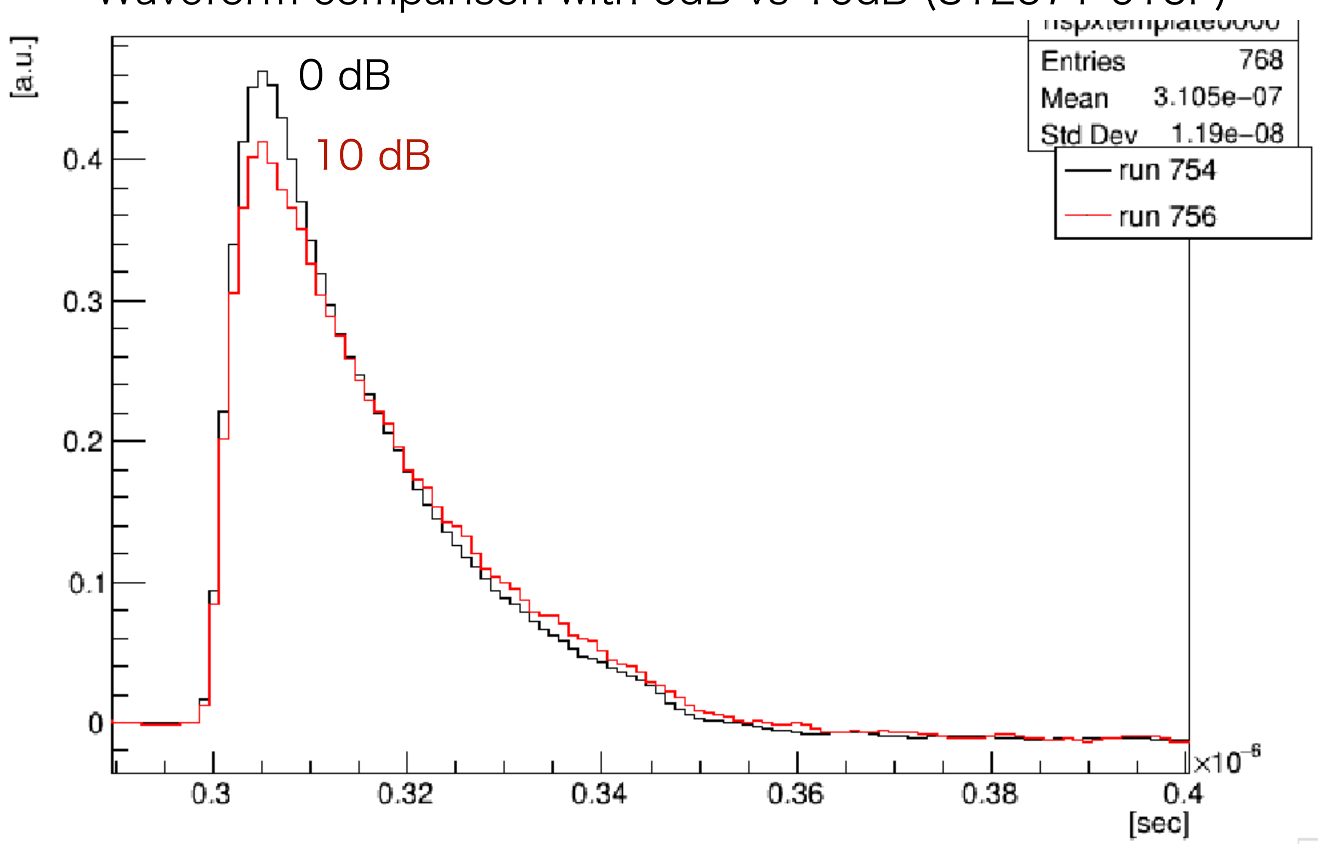


Attenuation factor

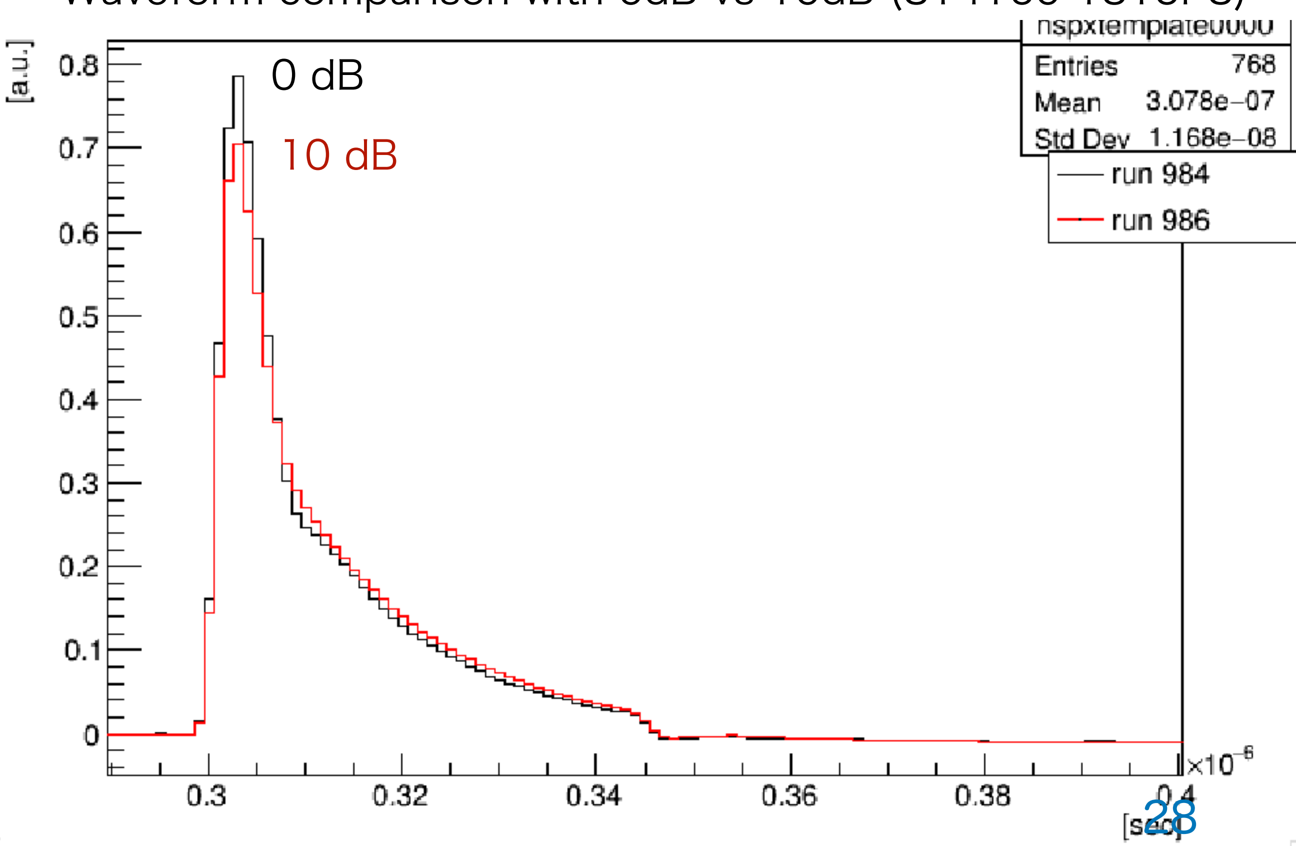
- Dynamic range of DAQ is not sufficient to cover whole light intensity range
  - Need signal attenuation to avoid saturation in electronics
  - 10-40 dB attenuator used
- There is a frequency dependence of attenuator
  - Attenuation rate depends on input pulse shape



Waveform comparison with 0dB vs 10dB (S12571-015P)



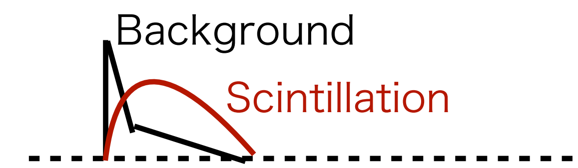
Waveform comparison with 0dB vs 10dB (S14160-1315PS)



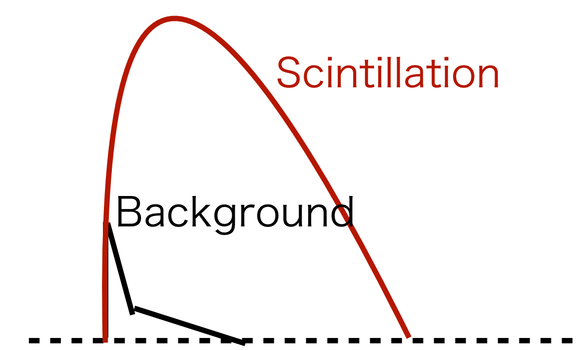
Variation of waveform

- Variation of waveform depending on light intensity was observed
- Effect of constant background light at low light intensity
  - Background light comes from optical setup and laser reflection
    - Faster than scintillation light because directly injected to MPPC
  - Significant contribution from fast component of background at low light intensity

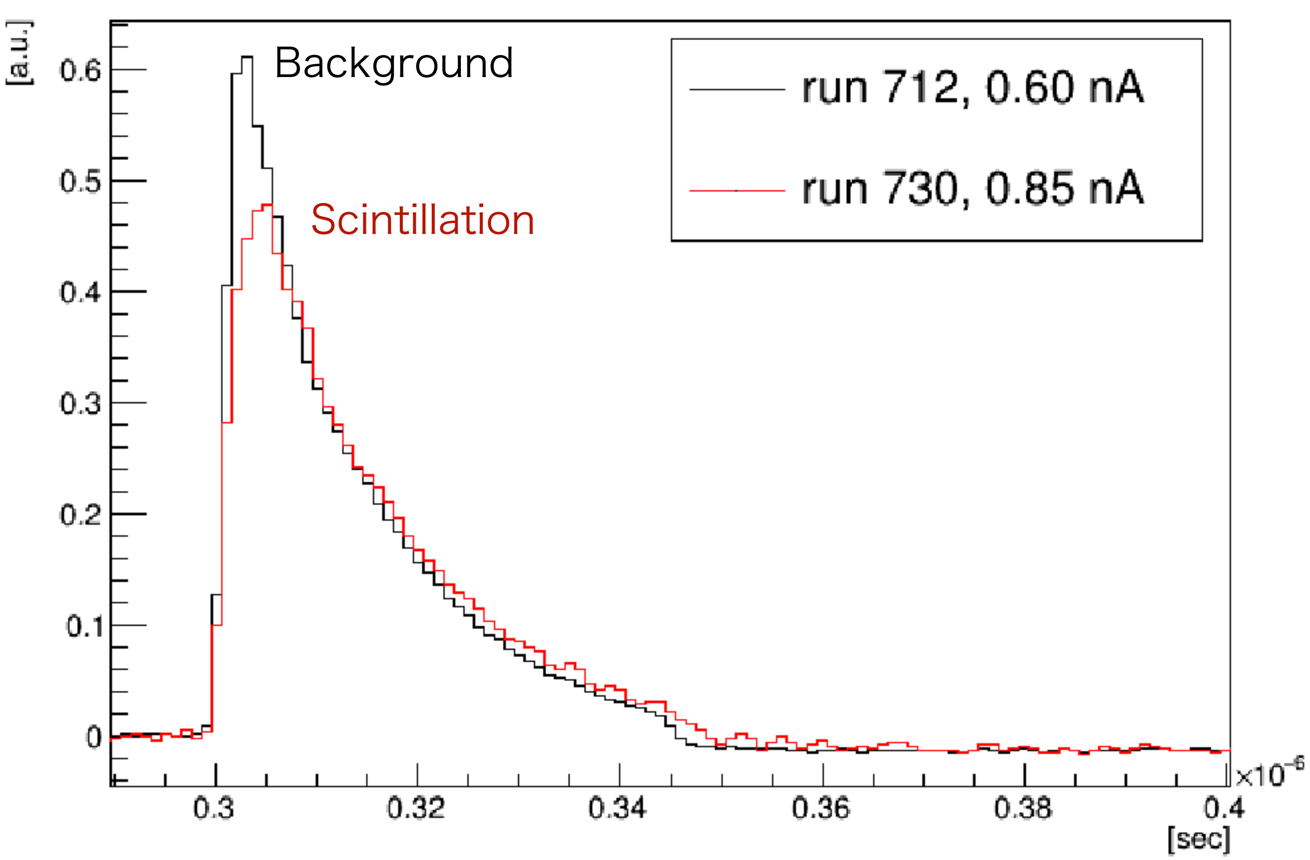
At low light intensity, background is dominant



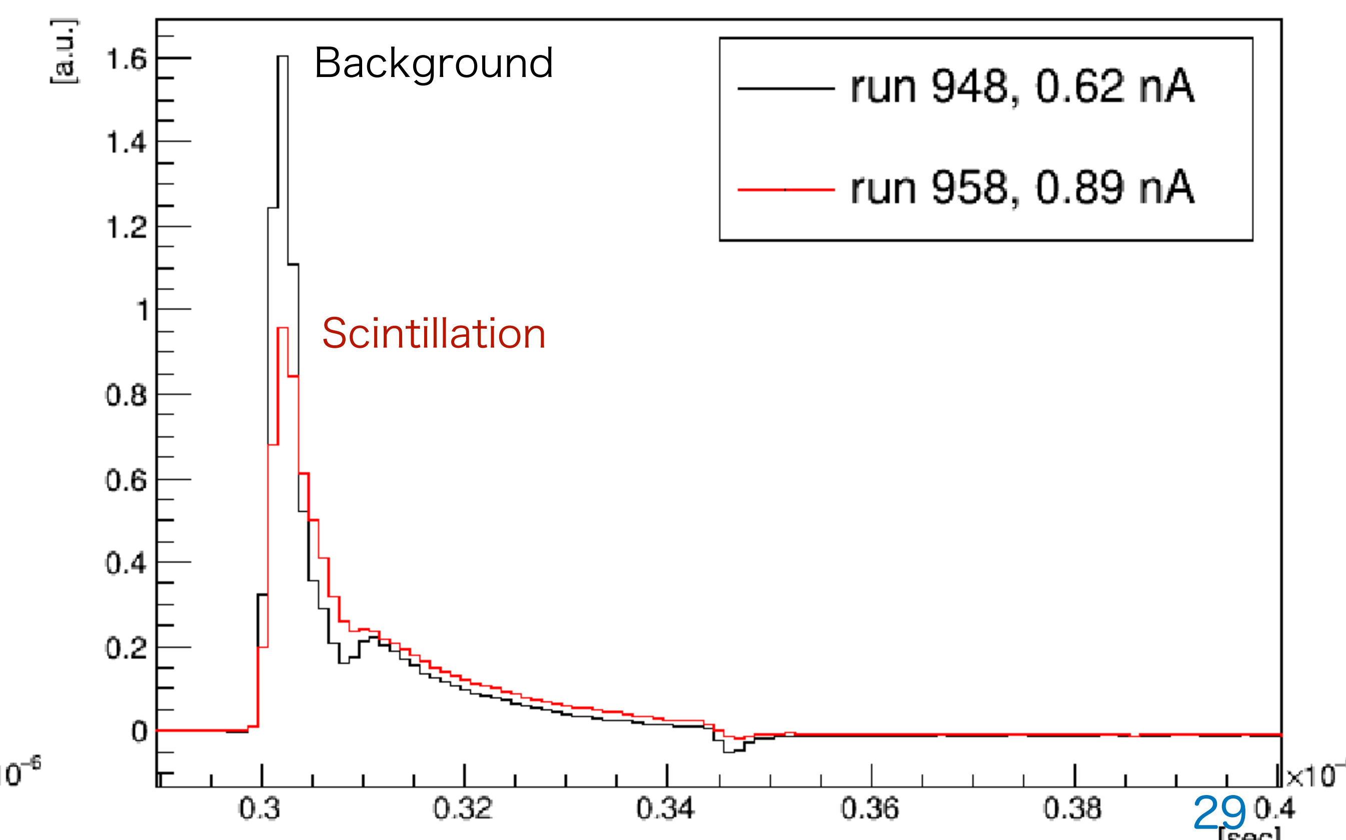
At higher light intensity, background is negligible



Waveform comparison with 0dB attenuator (S12571-015P)



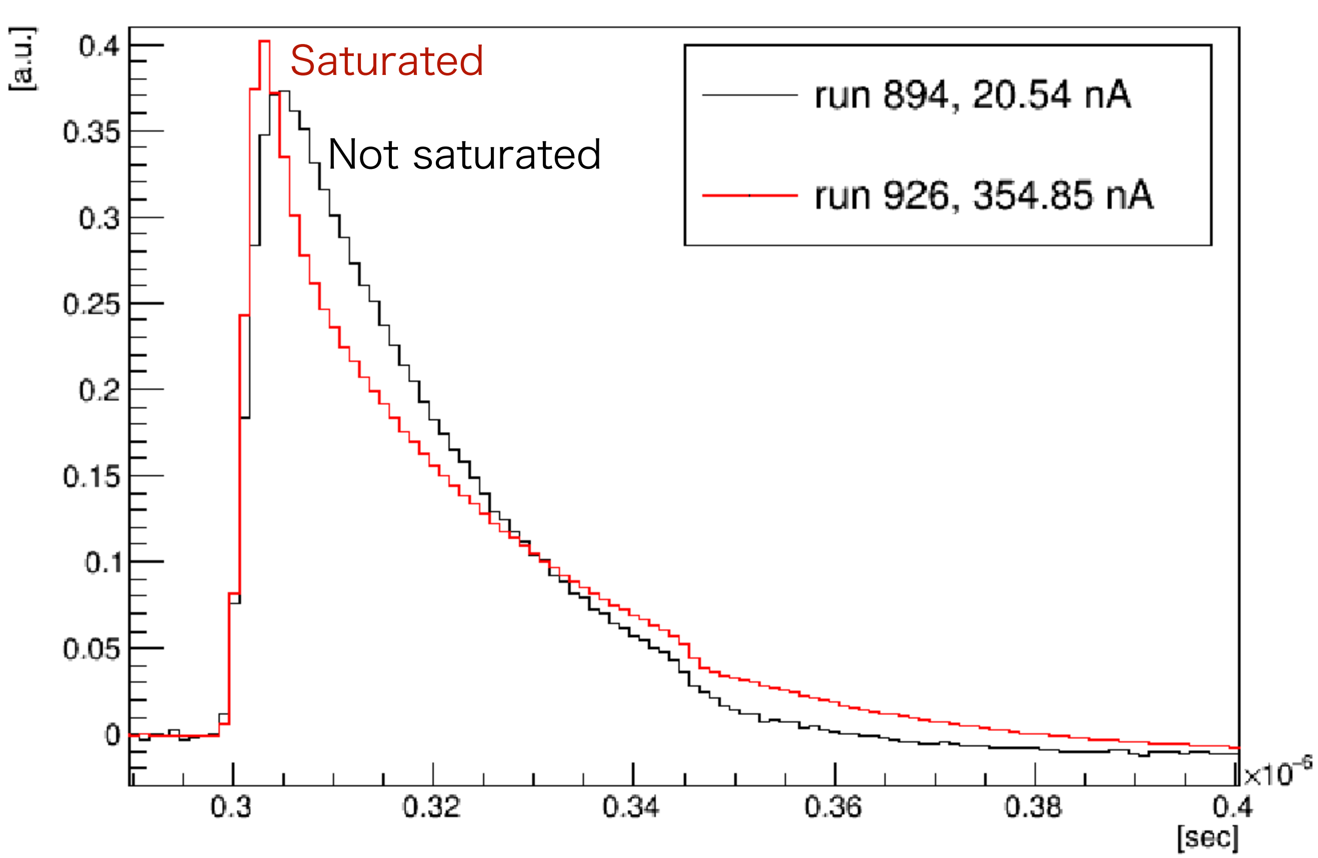
Waveform comparison with 0dB attenuator (S14160-1315PS)



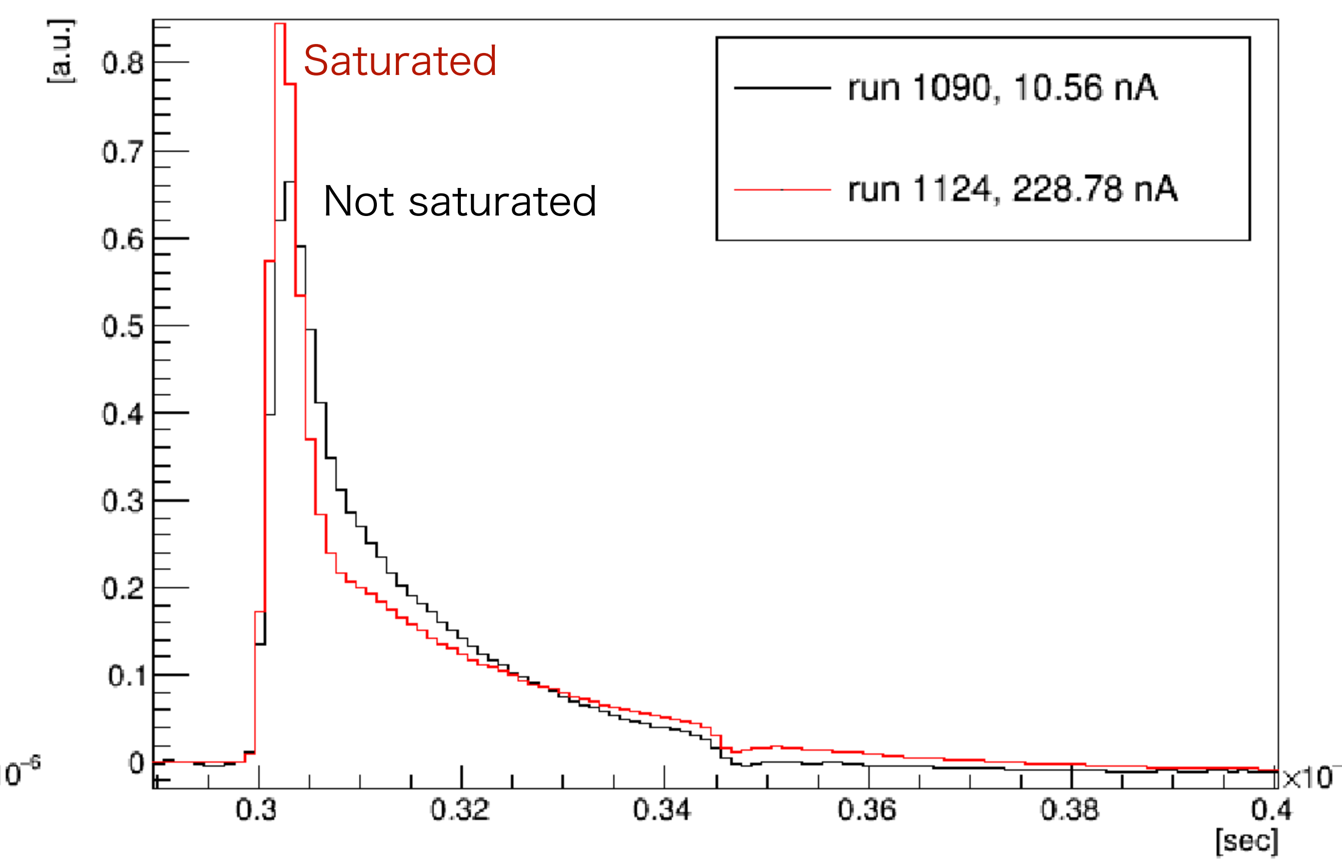
Variation of waveform

- Effect of SiPM saturation at high light intensity
  - Saturation deforms waveform at very high light intensity
- These effects change the attenuation rate depending on light intensity
  - Not yet calibrated

Waveform comparison with 40dB attenuator (S12571-015P)

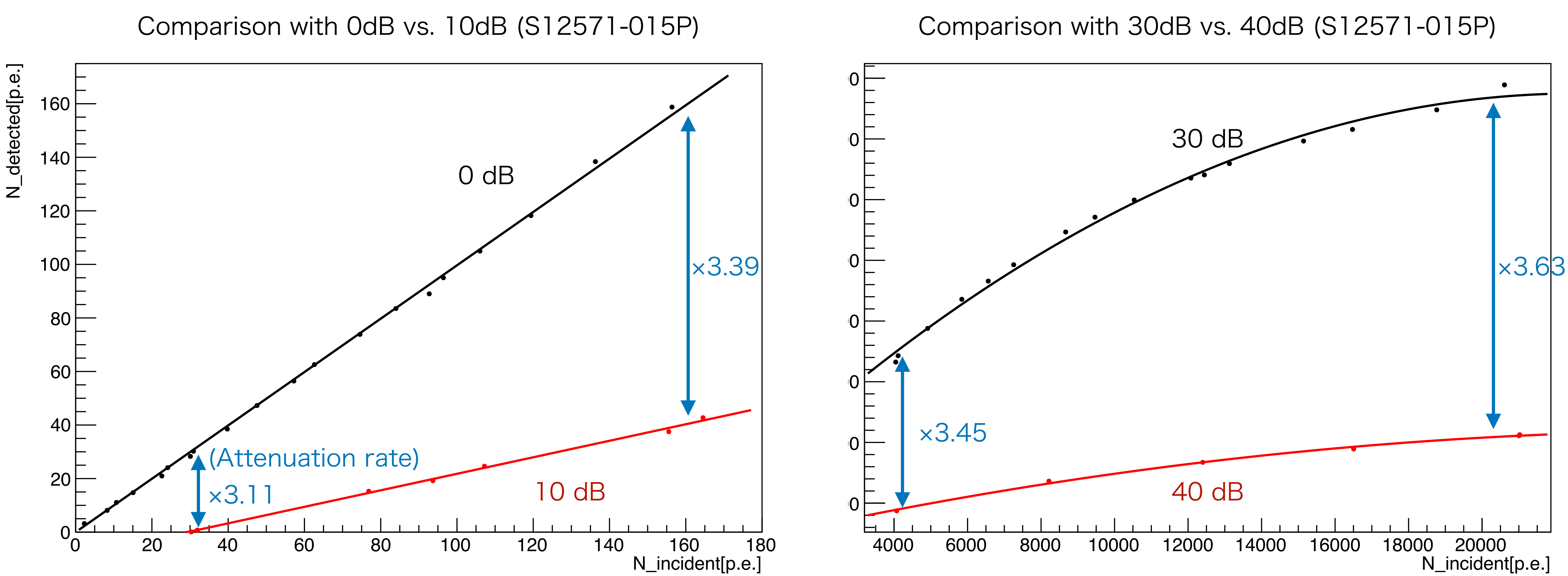


Waveform comparison with 40dB attenuator (S14160-1315PS)



Attenuation Calibration

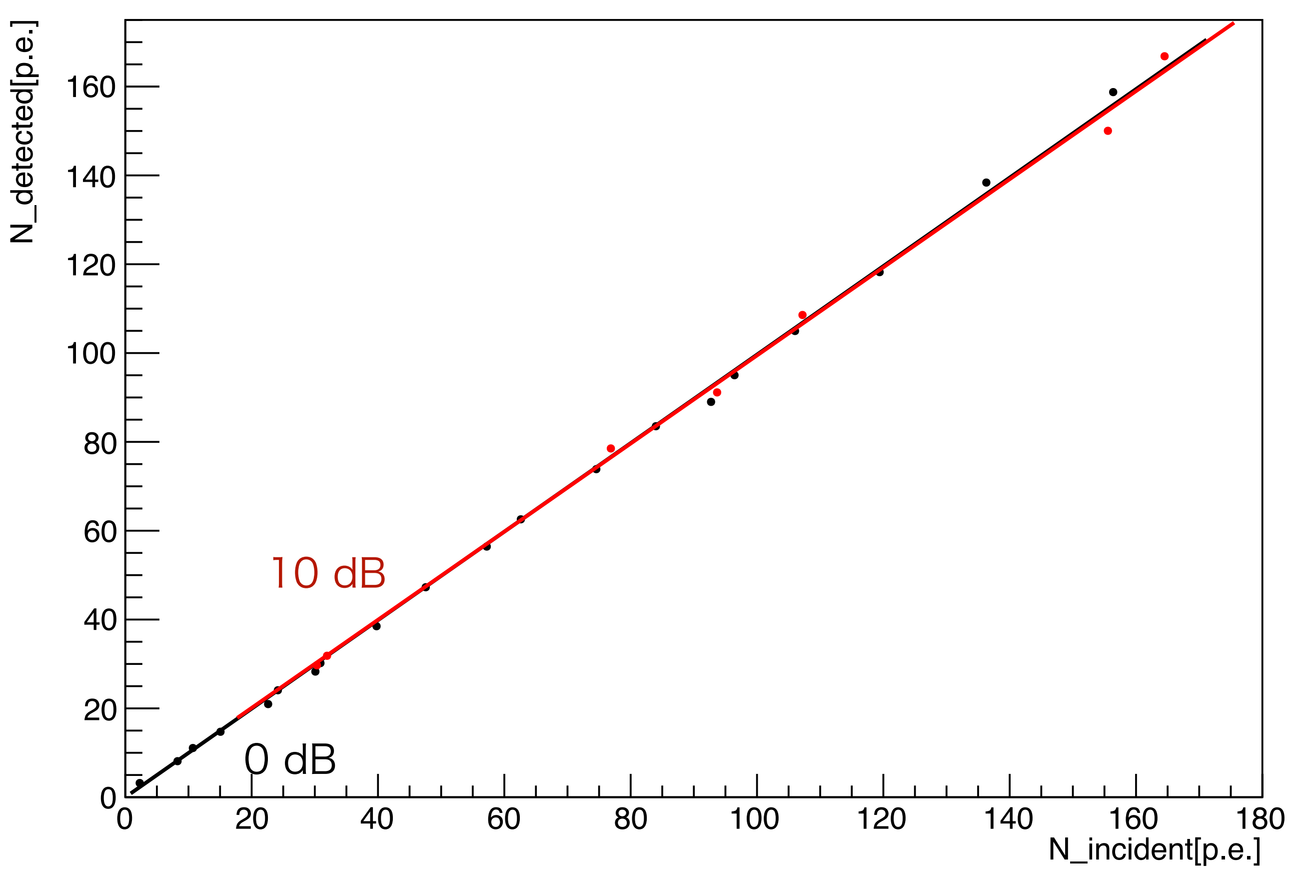
- Attenuation rate is optimized with factor and offset : $N_{opt} = A * N_{pe} + B$
  - Fit with linear function and calculate coefficients to match the lines
- Specious factor and offset are used at high light intensity
  - Saturation and waveform variation change the attenuation rate depending on light intensity
  - Fit with polynomial function



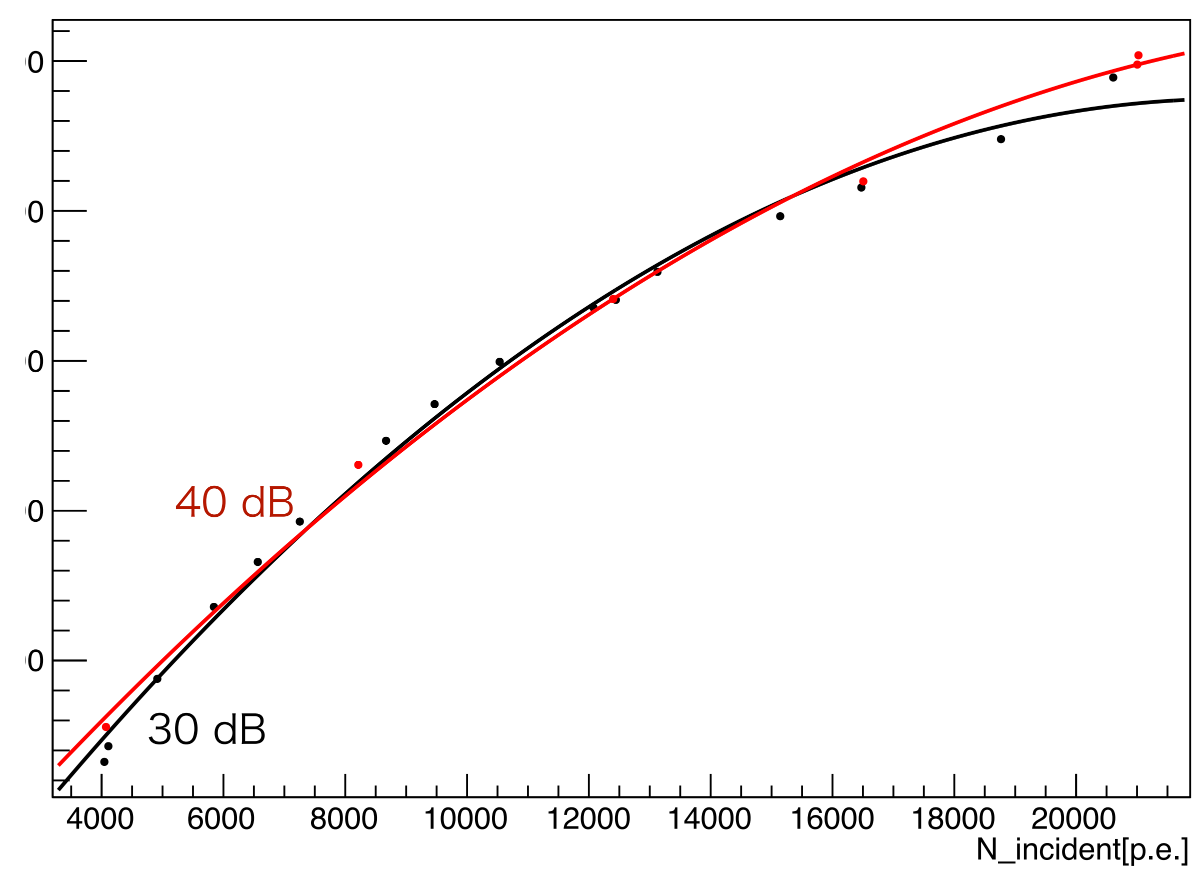
Attenuation Calibration

- Attenuation rate is optimized with factor and offset : $N_{opt} = A * N_{pe} + B$
  - Fit with linear function and calculate coefficients to match the lines
- Specious factor and offset are used at high light intensity
  - Saturation and waveform variation change the attenuation rate depending on light intensity
  - Fit with polynomial function

Calibrated results with 0dB vs. 10dB (S12571-015P)

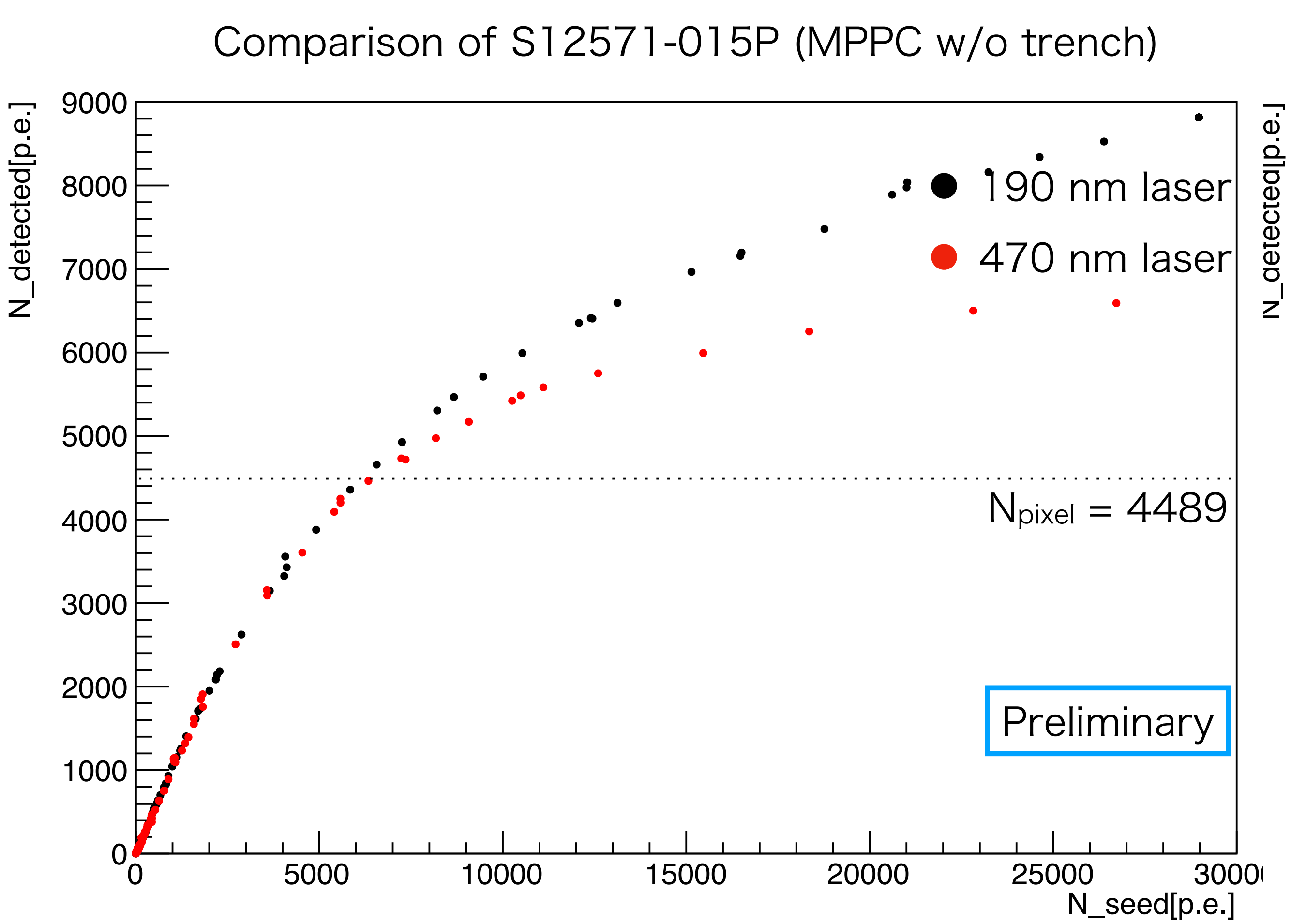


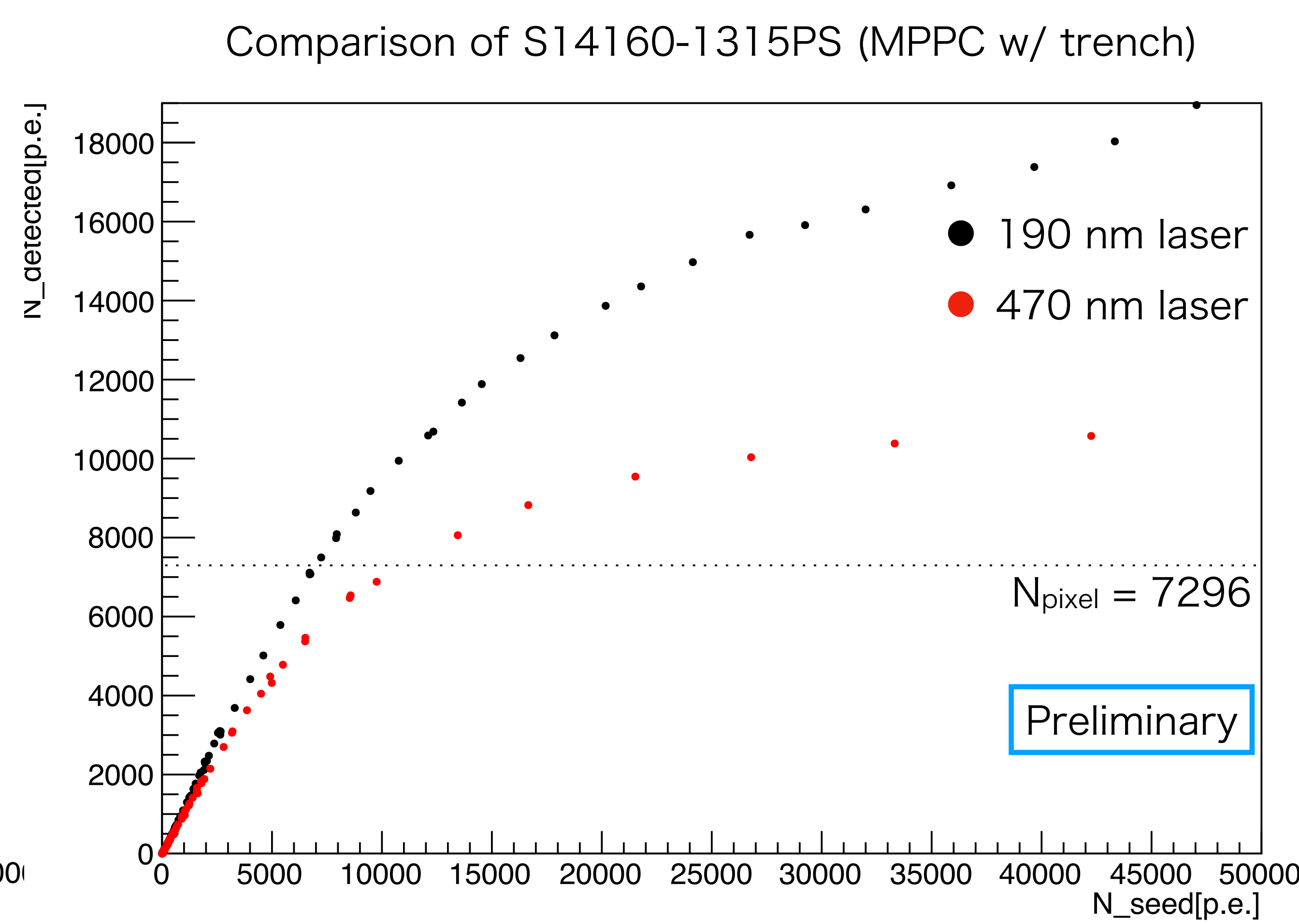
Calibrated results with 30dB vs. 40dB (S12571-015P)



Comparison of 190 nm and 470 nm laser

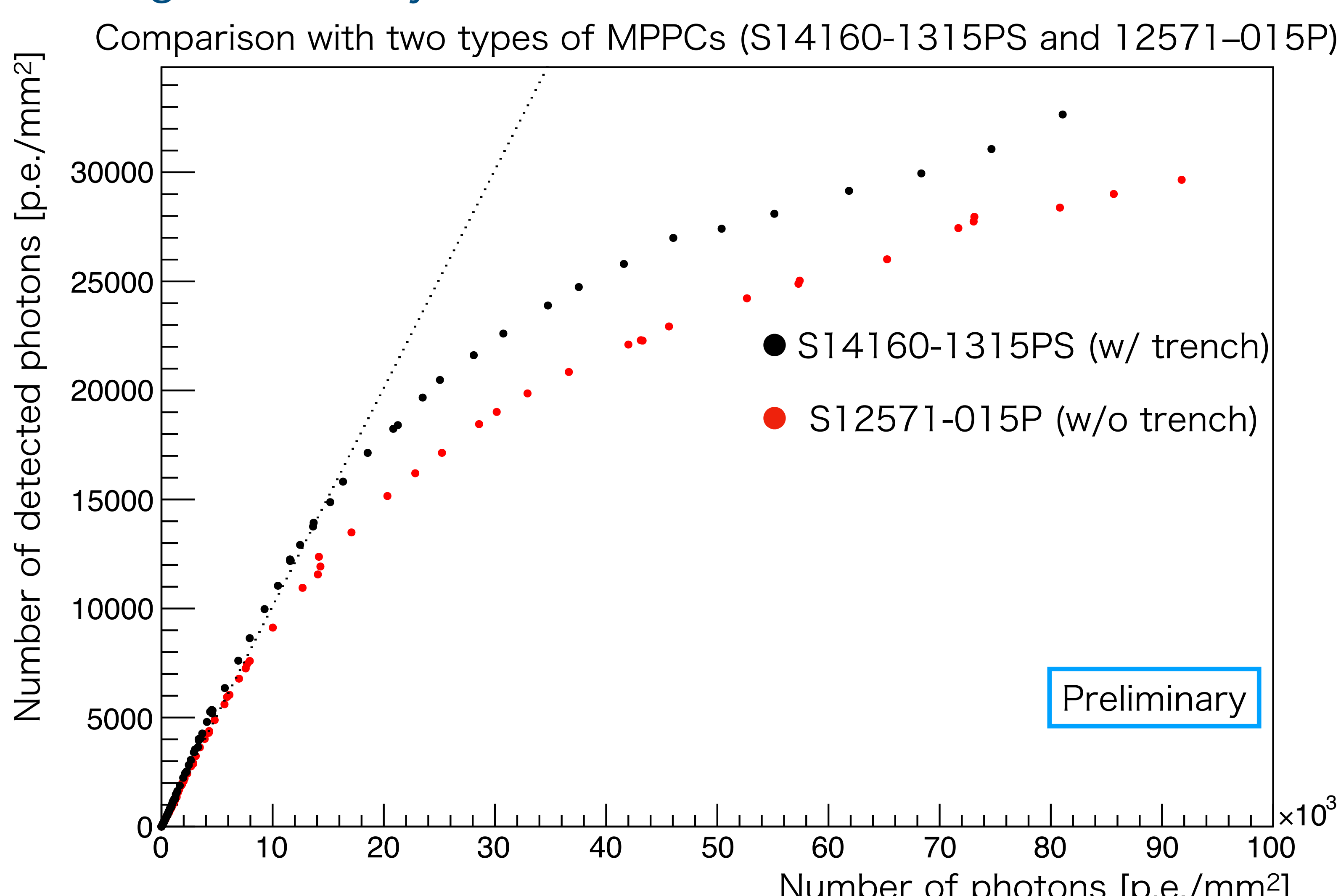
- Significant difference between saturation curves with 190 nm and 470 nm laser
- **The effect of time constant of scintillation light emission is observed**
  - Can be a big impact on saturation correction





Comparison of two MPPCs with 190 nm laser

- Normalized by sensor area, PDE and crosstalk probability to compare saturation curves between two MPPCs
- MPPC w/ trench is less saturated compared to MPPC w/o trench
  - Few plots above the linear function (because of wrong attenuation factor?)
- **[For S14160-1315PS (w/ trench)]**
  (Lower crosstalk → saturation ↓) > (Longer recovery time → saturation ↑)
  - Effect of longer recovery time is small because of scintillation emission time



Comparison of two MPPCs with 470 nm laser

- S12571-015P (w/o trench) is less saturated compared to S14160-1315PS (w/ trench)
- **[For S14160-1315PS (w/ trench)]**
  (Lower crosstalk → saturation ↓) < (Longer recovery time → saturation ↑)
  - Effect of longer recovery time is large because of short duration of laser pulse