A Method and Experimental Setup to Measure SiPM Saturation

Sascha Krause, JGU Mainz & PRISMA Detector Lab

&

Saturation Correction in CALICE ScECAL

Katsushige Kotera

ICASiPM

14.06.2018

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

PRISMA DETECTOR LAB

AIDA 2020

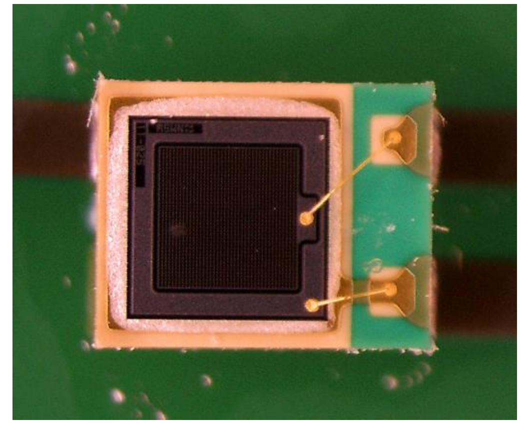
Bundesministerium für Bildung und Forschung

Outline

SiPM saturation measurement setup (S. Krause)

Proceedings paper in preparation:
PM2018 – 14th Pisa Meeting on Advanced Detectors (Q. Weitzel)

- Introduction & definitions
- SiPM response measurement procedure
- SiPM response results


SMD SiPM on PCB
Photo by Yong Liu, JGU Mainz

Saturation correction in CALICE ScECAL (K. Kotera)

arXiv:1510.01102v4

- ScECAL & calibration procedure
- Saturation correction in CALICE
- Advanced saturation model

SiPM (Hamamatsu)	N_{total}	pixel pitch [μm]	sensitive area [mm^2]	typical gain	trenches
MPPC S13360 -1325PE	2668	25	1.3×1.3	$7.0 \cdot 10^5$	yes
MPPC S12571 -25P	1600	25	1×1	$5.15 \cdot 10^5$	no
MPPC S12571 -50P	400	50	1×1	$1.25 \cdot 10^6$	no
MPPC S12571 -100P	100	100	1×1	$2.8 \cdot 10^6$	no

Introduction: SiPM Crosstalk, Saturation & N_{seed}

100 pixel SiPM:

$\epsilon_{PDE} = 0.5$	efficiency
$\mu_C = 1.25$	correlated noise (XT)

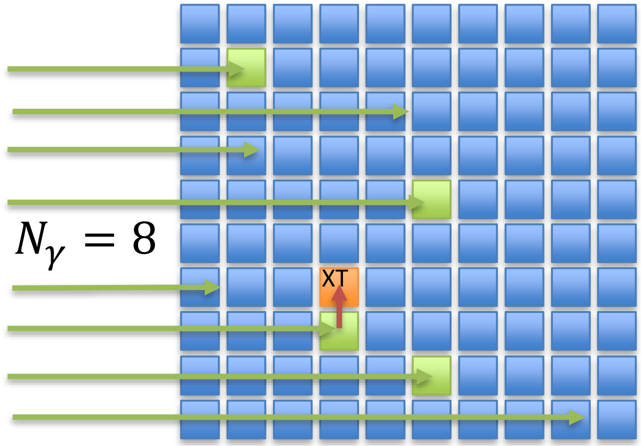
← 25% Crosstalk

Comparable to L. Gruber et al, 2014
https://doi.org/10.1016/j.nima.2013.11.013

$$N_{seed} := N_\gamma \cdot \varepsilon_{PDE}$$

Without saturation
With crosstalk

Calibration region



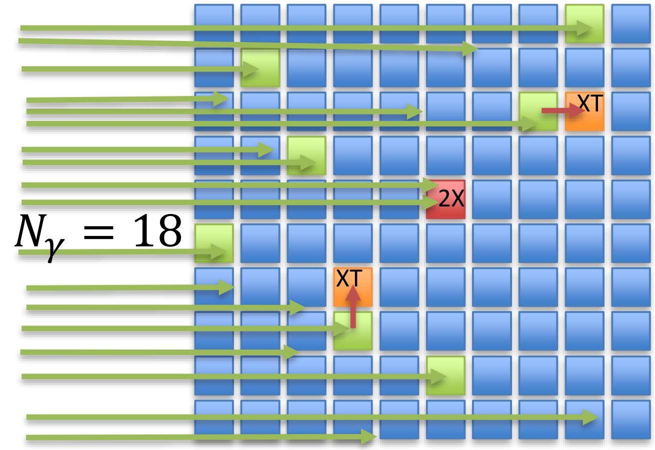
$N_{fired} \stackrel{\text{def}}{=} N_{fired}^{linear} = 5$ (w/o saturation, w/ XT)

XT correction: $N_{fired}^{linear} / \mu_C$

$N_{seed} = 4$ (w/o saturation, w/o XT)

With Saturation
With crosstalk

Saturation region



$N_{fired} = 10$ (w/ saturation & w/ XT)

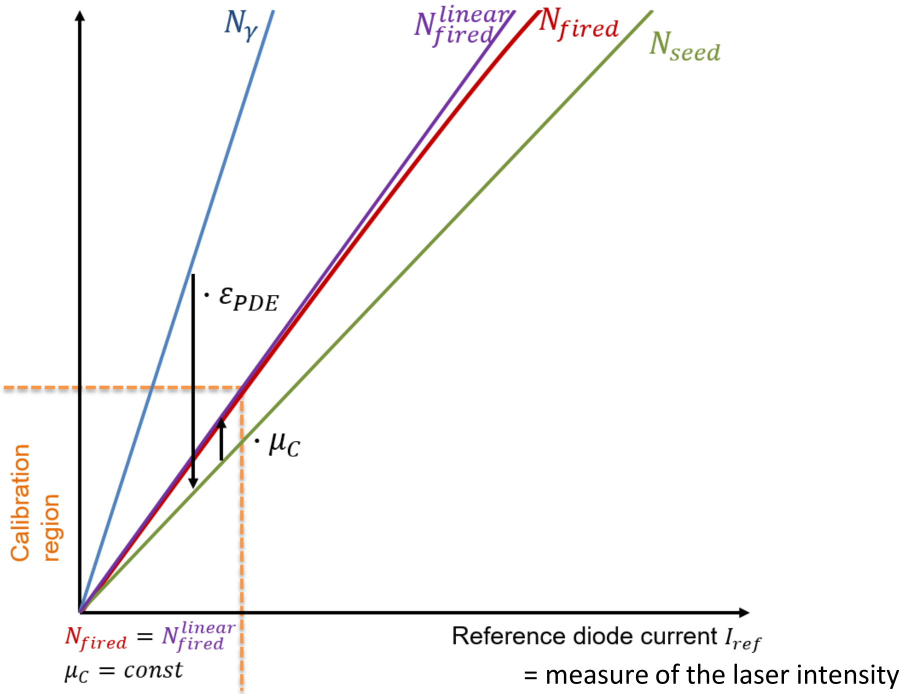
Advanced function which handles saturation & XT

$N_{seed} = 9$ (w/o saturation, w/o XT)

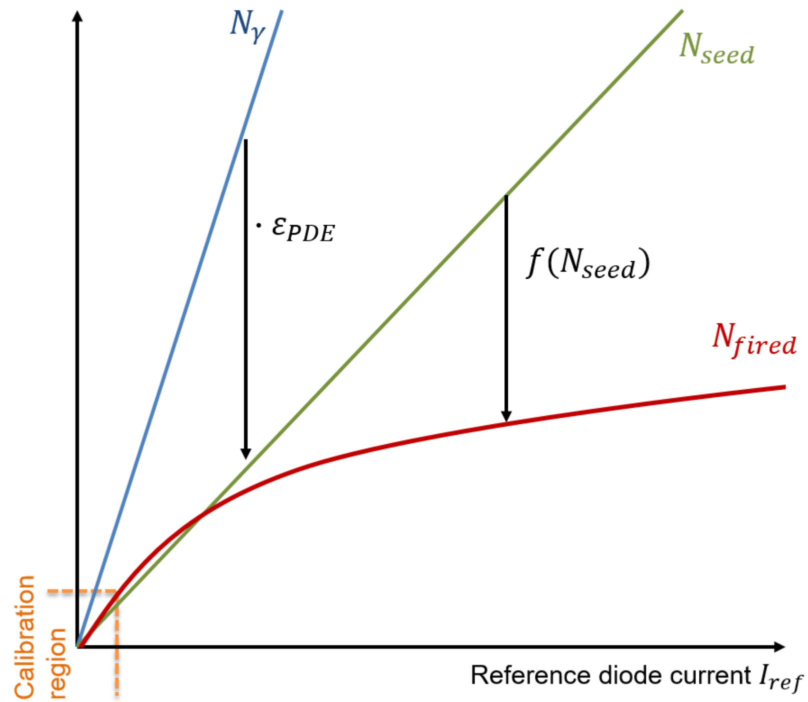
Definitions

Number of seeds N_{seed}:
Number of photons, which hit the sensitive area of the SiPM and could trigger an avalanche (including PDE) in case of linear behavior (no multi-hits on pixels).
$\boldsymbol{N_{seed} \coloneqq N_{\gamma} \cdot \varepsilon_{PDE}}$

N_{γ}: *Number of incident photons*
ε_{PDE}: *Photon Detection Efficiency*
μ_C: *Correlated noise, in first order defined as:* $\mu_C = 1 + E(XT)$
N_{fired}: *Number of pixels fired (main observable)*
f: *Function describing saturation & correlated noise*



In calibration region:
influenced by correlated noise (XT):
$N_{fired} = N_{fired}^{linear} = \boldsymbol{N_{seed} \cdot \mu_C}$
$\Longrightarrow N_{seed} = N_{fired}^{linear} / \mu_C$
In this way, I_{ref} can be calibrated to N_{seed}



In saturation region:
Number of pixels fired influenced by saturation AND correlated noise (XT):
$N_{fired} = f(N_{seed})$

Modeling SiPM Response Saturation

(1) Simple **exp**. response function:

$$N_{fired}(N_{seed}) = N_{total} \cdot \left(1 - exp\left(-\frac{N_{seed}}{N_{total}}\right)\right)$$

(2) **XT - extended** response function: (P. Eckert et al, 2012, https://doi.org/10.1088/1748-0221/7/08/P08011)

$$N_{fired}(N_{seed}) = N_{total} \cdot \frac{1-X}{1-\epsilon_{XT} \cdot X}$$

with $X = exp\left(-\frac{N_{seed}}{N_{total}}\right)$

invertible!

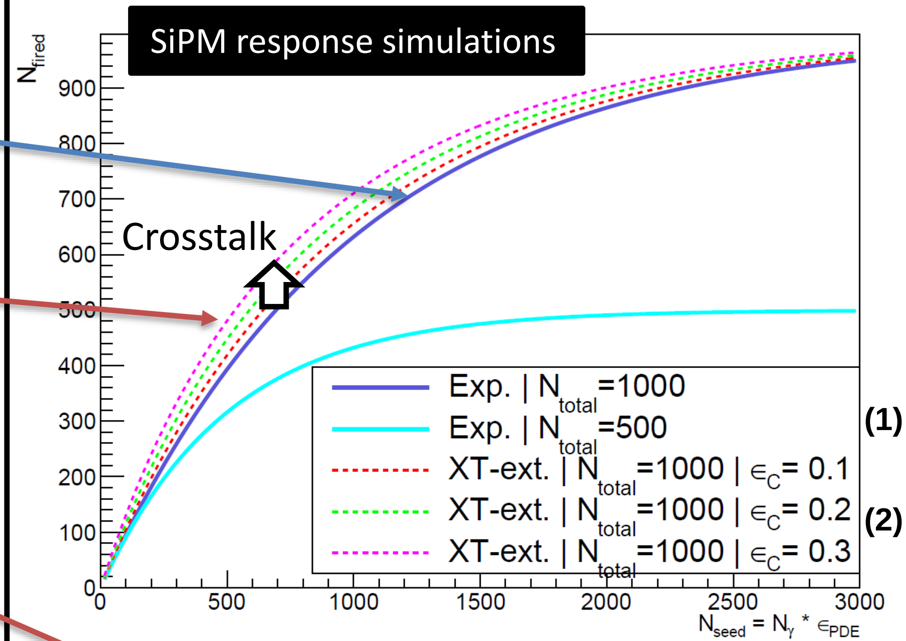
(3) **Advanced** response function: (K. Kotera, arXiv:1510.01102)

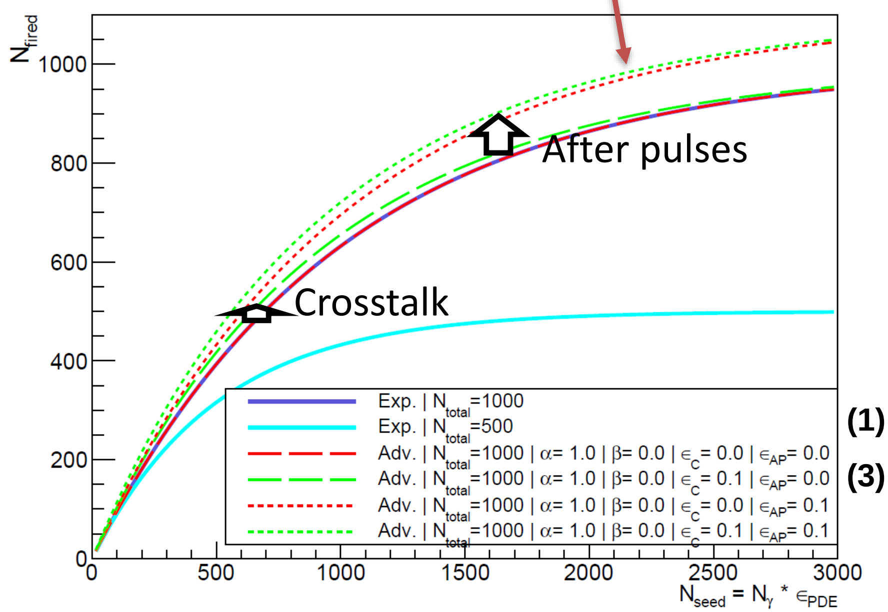
NLO corrections:

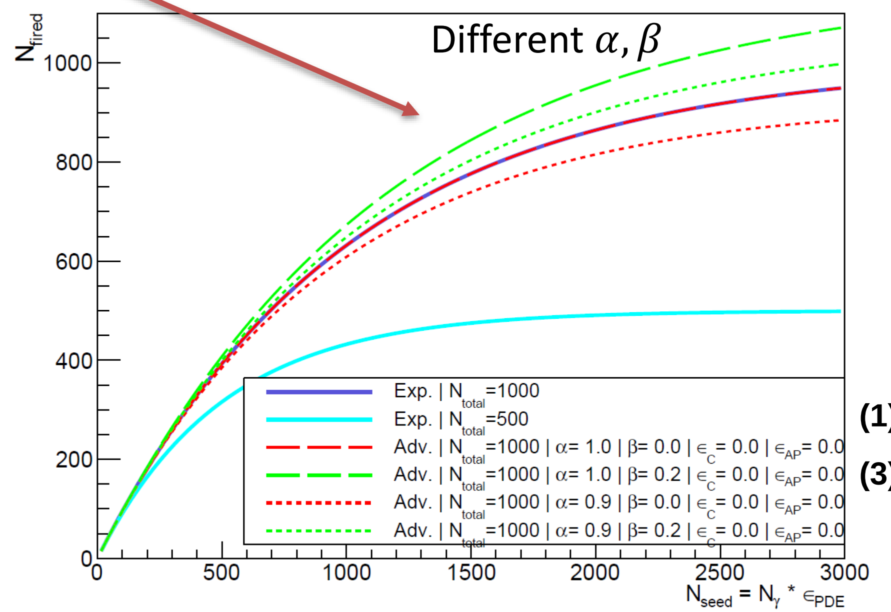
6 parameters:

not invertible!

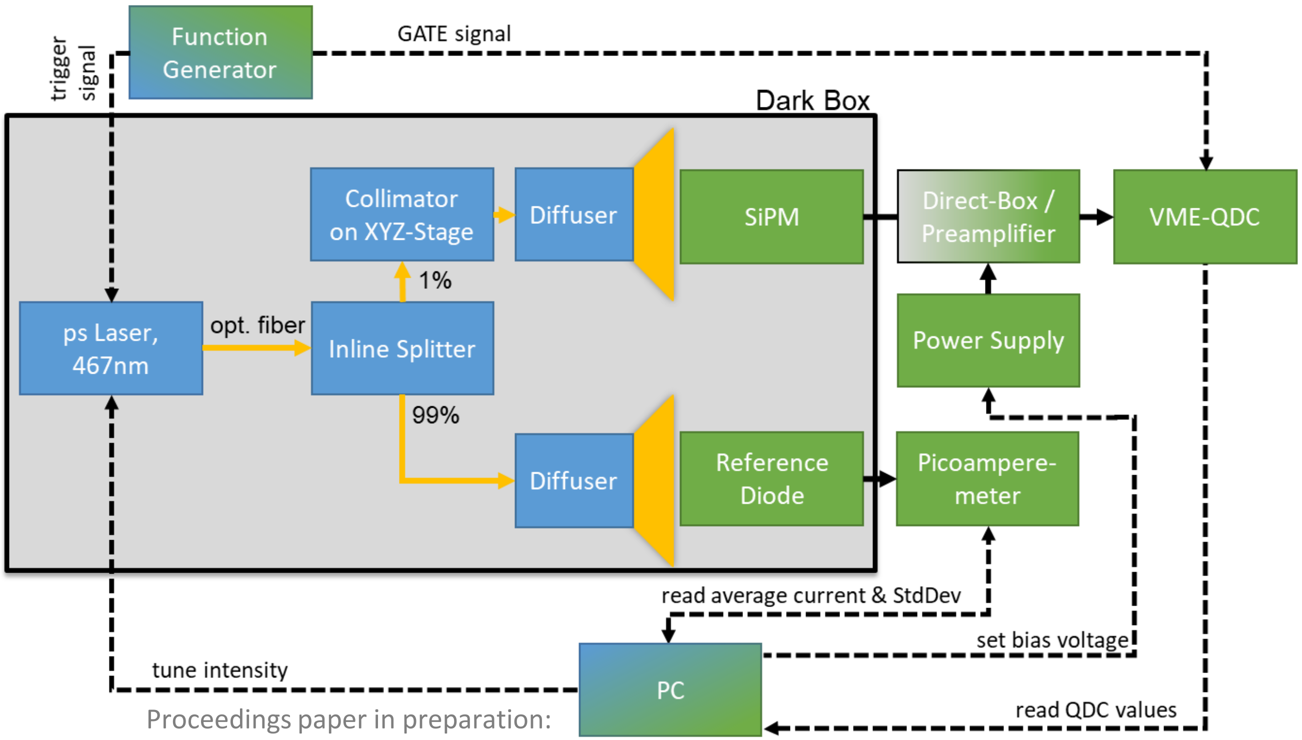
- N_{total}, — fixed to total number of pixels
- scale factor, — fixed to 1
- 2x decay/recovery time variables, — describe **over saturation**
- Crosstalk- & Afterpulse prob. — include **correlated noise**







SiPM Response: Setup as part of the PRISMA DetectorLab Mainz



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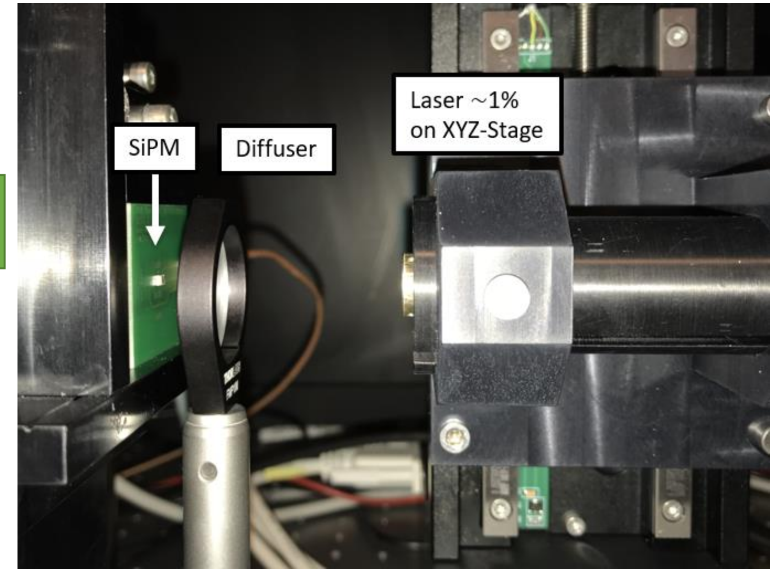
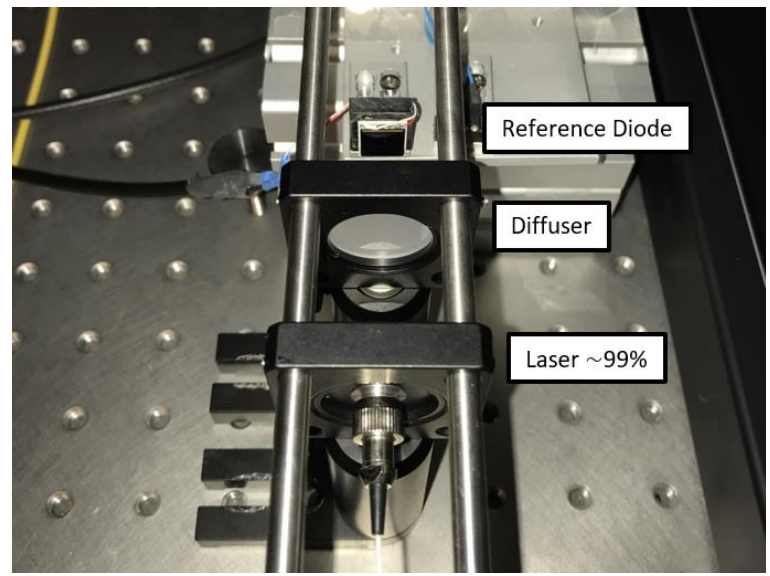




<u>Systematic Uncertainties:</u>

- Direct-Readout-Circuit linear within 1% over full measurement range.
- PreAmp starts to saturate from ~1V output, linear within 2% for lower signals.
- Reference diode linear within 1% over full measurement range.
- Impact of after pulses estimated ~1%.

<u>Uniform light distribution:</u>

- Diffusor intensity profile uniform within 1.5%

SiPM Response: Procedure for latest SiPM (2668 pixels)

0. Dedicated XT measurement:

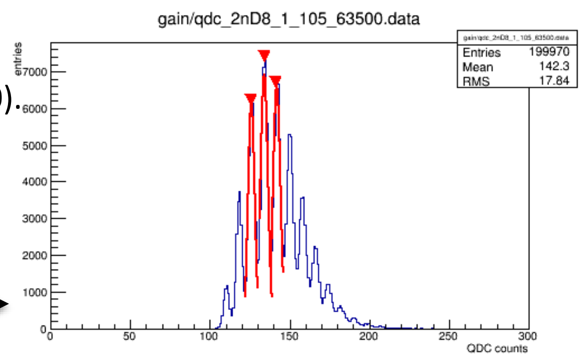
Determine average number of correlated pixels fired, μ_C (Borel Model of correlated noise) (E. Schioppa, 2017, arXiv:1710.11410).

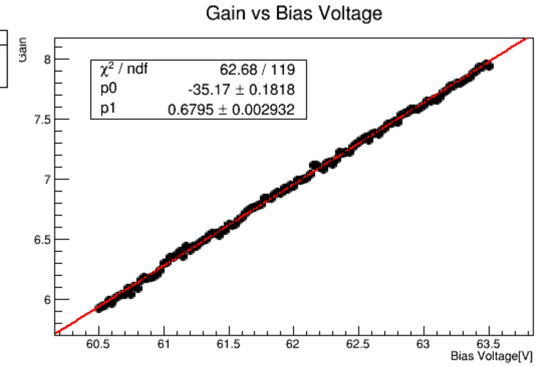
1. Pedestal correction:

QDC Spectrum with applied bias voltage without laser beam.

2. Gain measurement:

Difference between adjacent peaks.
In case of 1600 pixel SiPM: use Preamp and Direct Box.

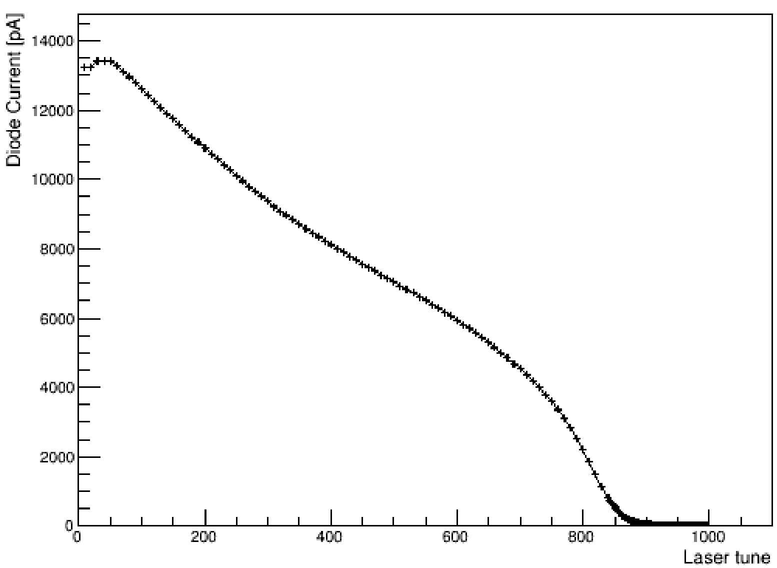




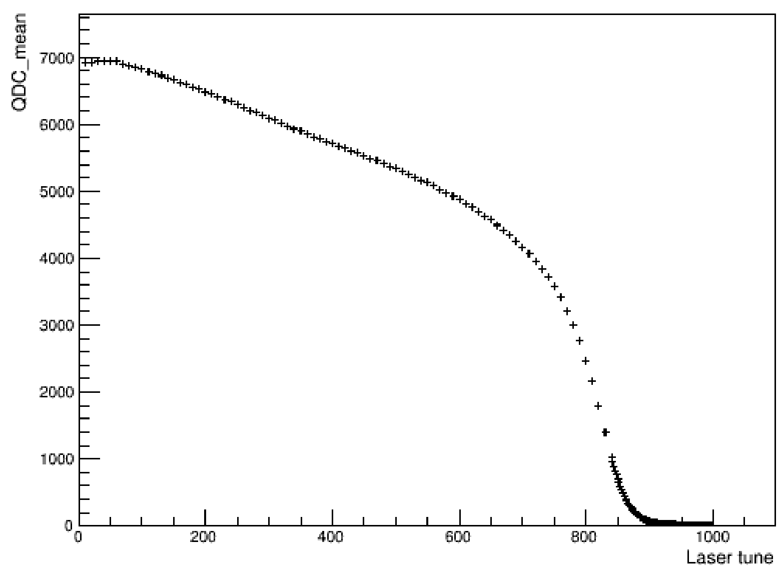
3. QDC High- to Low-Range conversion:

The QDC has two different amplification modes. Measure and apply conversion factor.

4. Estimate light intensity with calibrated diode:



5. Plot QDC mean values vs. laser intensity:



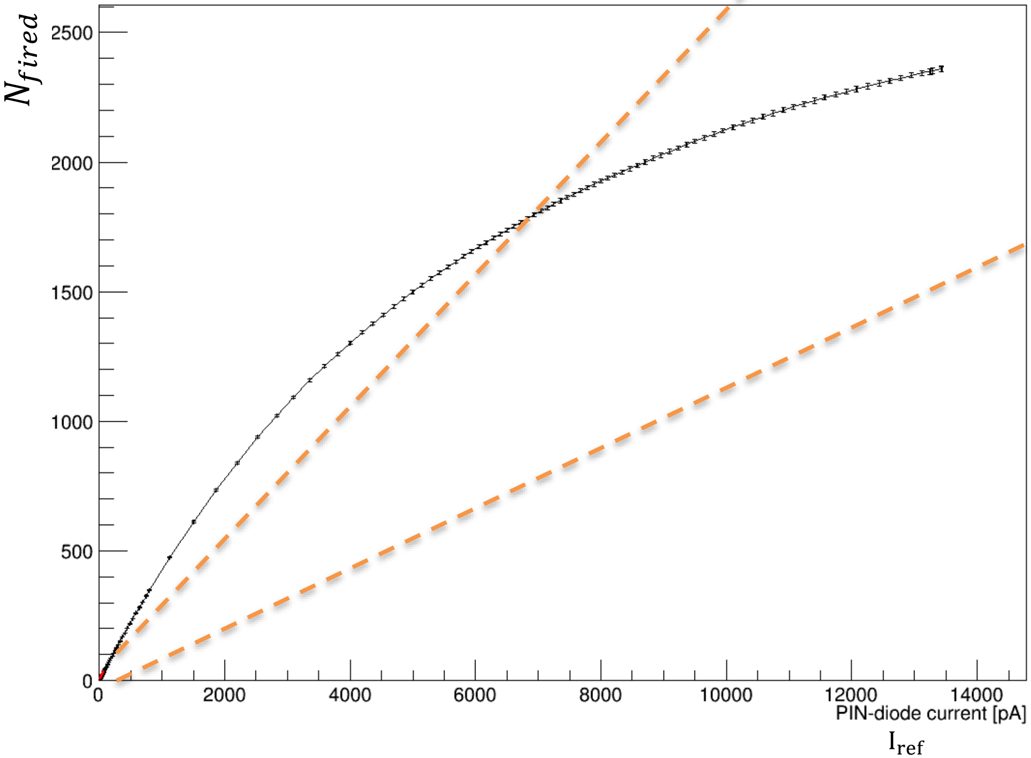
SiPM Response: Procedure for latest SiPM (2668 pixels)

6. Estimate and plot N_{fired} vs laser tune:

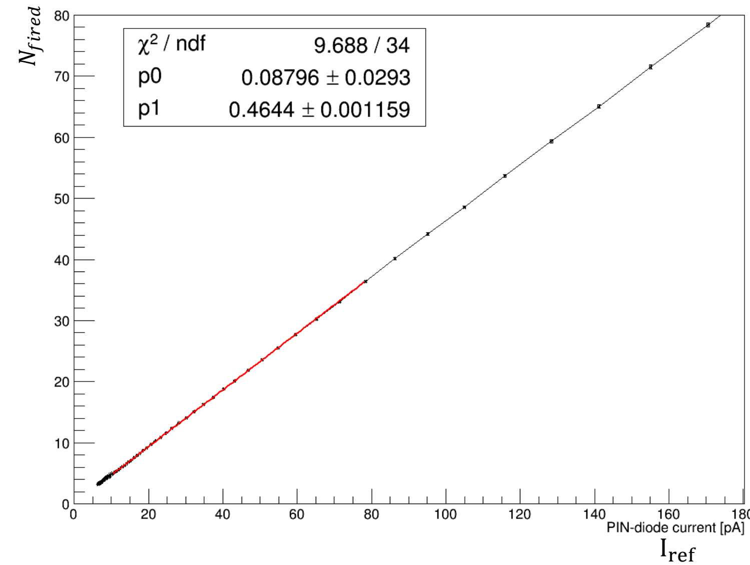
$$N_{fired} = (QDC_{mean} - pedestal)/gain$$

7. Plot #pixels vs reference current.

8. Apply linear fit to first measurement points, where linear behavior is still expected:
Determine number of “**Seeds**”, N_{seed}!



remember introduction:



In calibration region:

Definition of N_{fired}^{linear}:

$$N_{fired}^{linear}(i) = p0 + p1 \cdot I_{ref}(i)$$

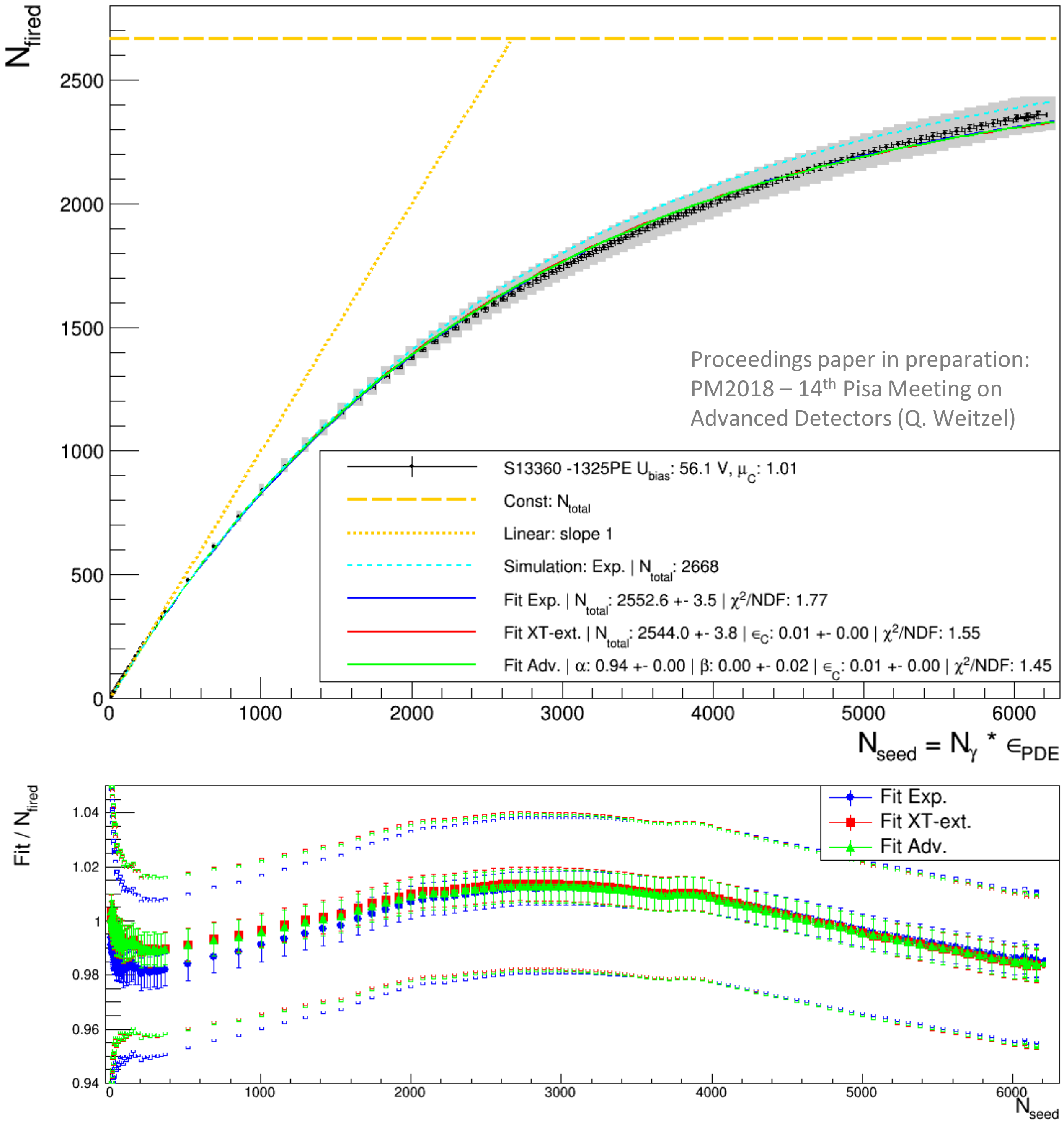
Definition of N_{seed}:

$$N_{seed}(i) = N_{fired}^{linear}(i)/\boldsymbol{\mu_C}$$

$\Longrightarrow$ convert reference current to number of seeds taking into account the correlation factor.

Results

2668 pixels | OV: +4.34V



Fit Advanced:

N_{total} = fixed

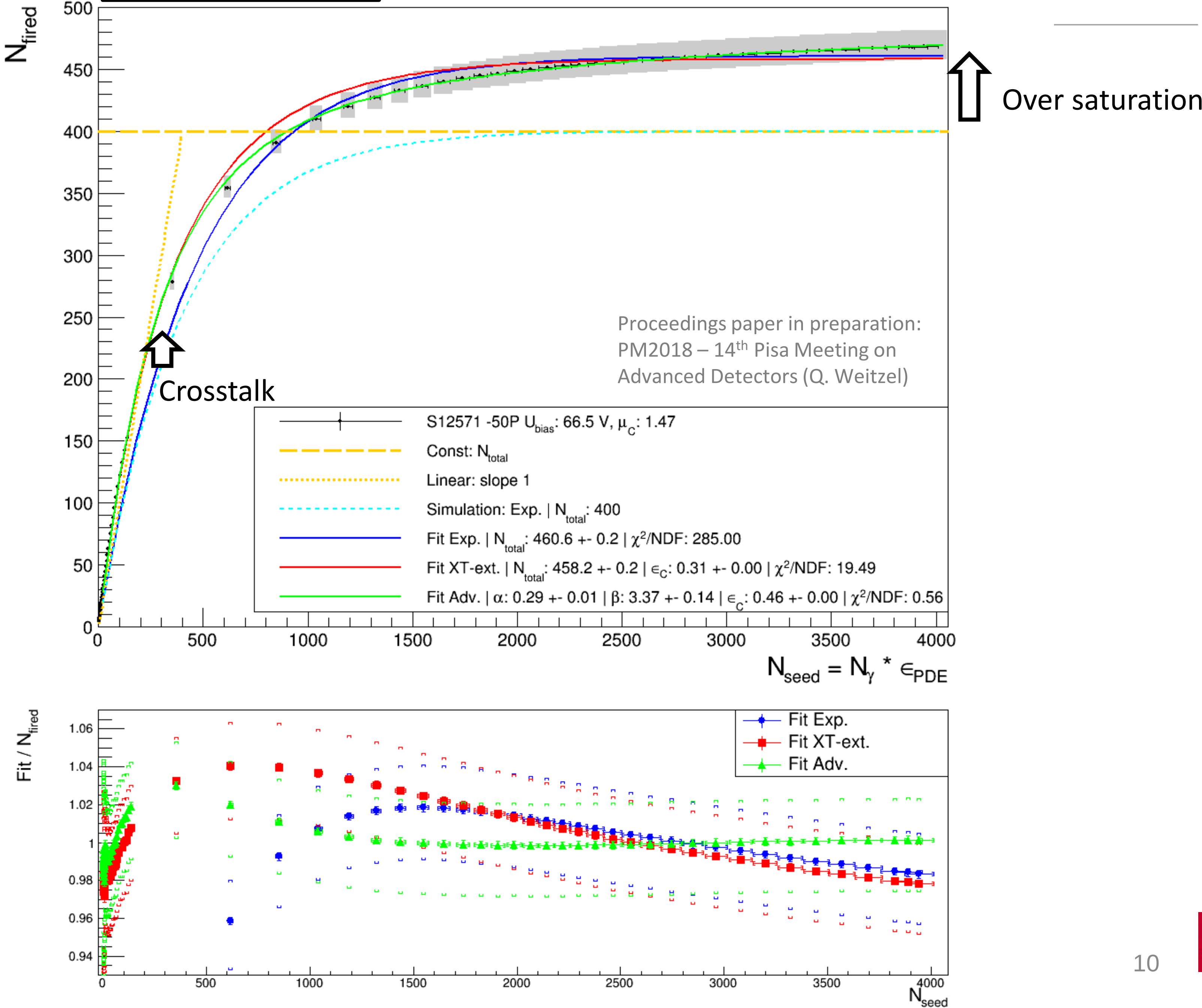
$\epsilon = 1.0$ because of N_{seed}

AP assumed to be 0

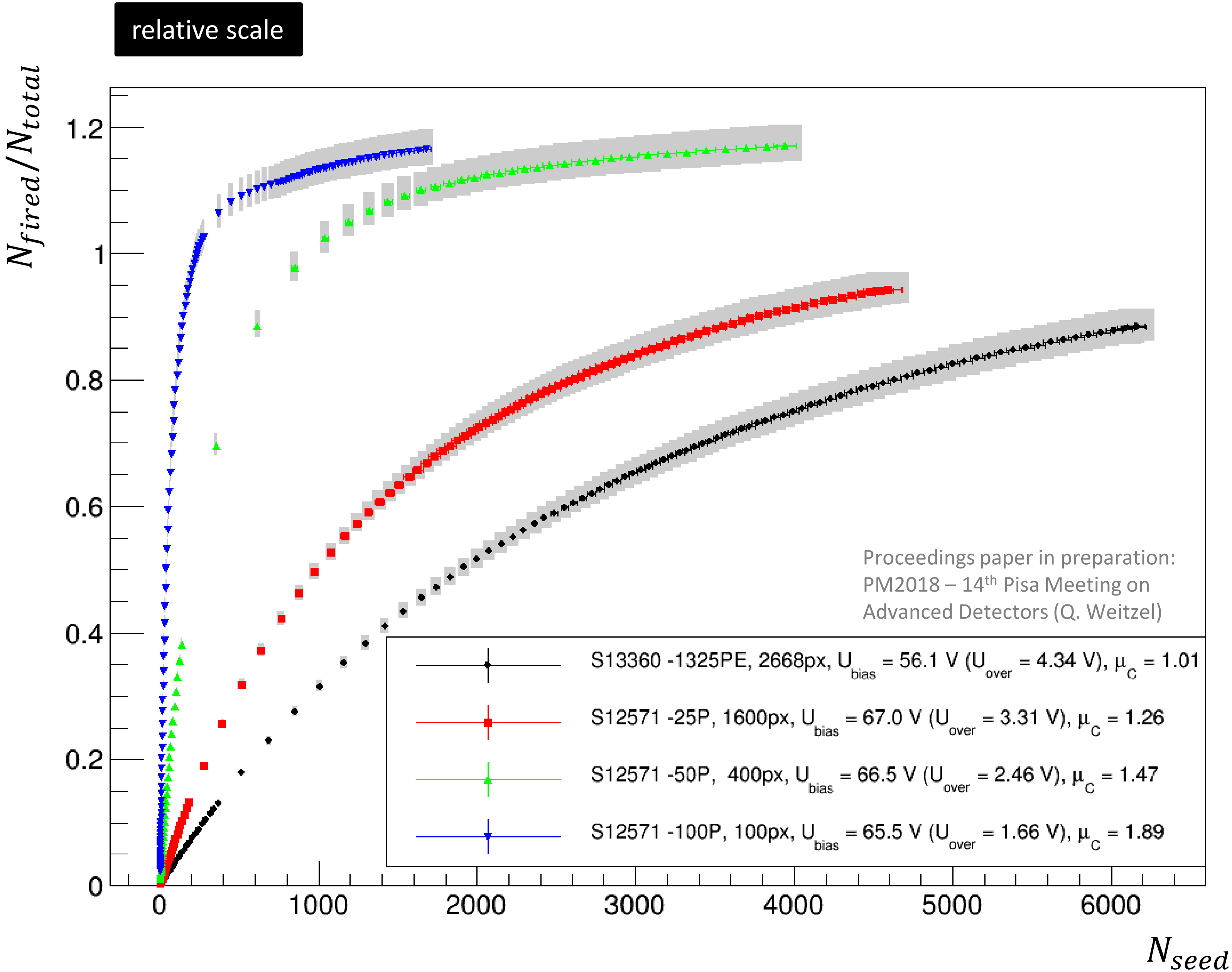
JG|U

Results

400 pixels |OV: +2.5V



Combined SiPM Response Results



Conclusion so far

For 4 different SiPM types:

Crosstalk measurement performed: μ_C (range between $1.01 \div 1.89$)

Response measurement:

Method taking into account the influence of crosstalk in the calibration.

100px and 400px SiPM:

- *Crosstalk* has a large influence on the response behavior.
- For high light intensities, an over saturation has been observed (best handled by Advanced function)

1600 and 2668 pixel SiPM:

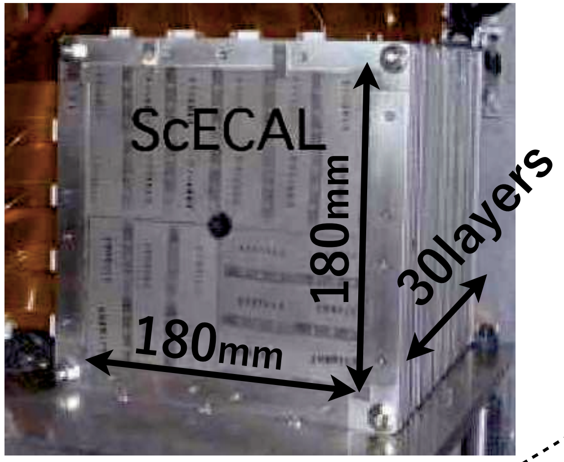
- Influence of crosstalk:
    - 2668px: negligible
    - 1600px: lower, but still measurable influence.
- No hint for over saturation in the measured range.

Next steps in regards to applications in calorimeters:

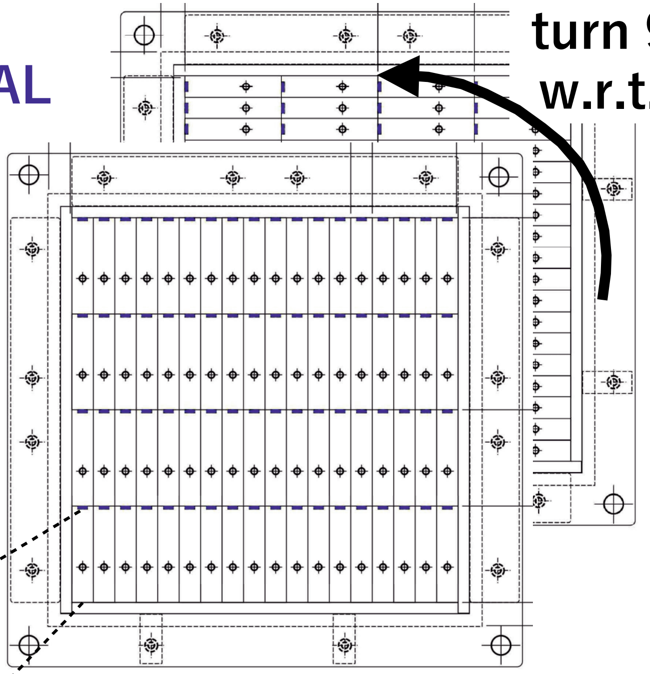
- Setup measuring the combination: scintillator + SiPM

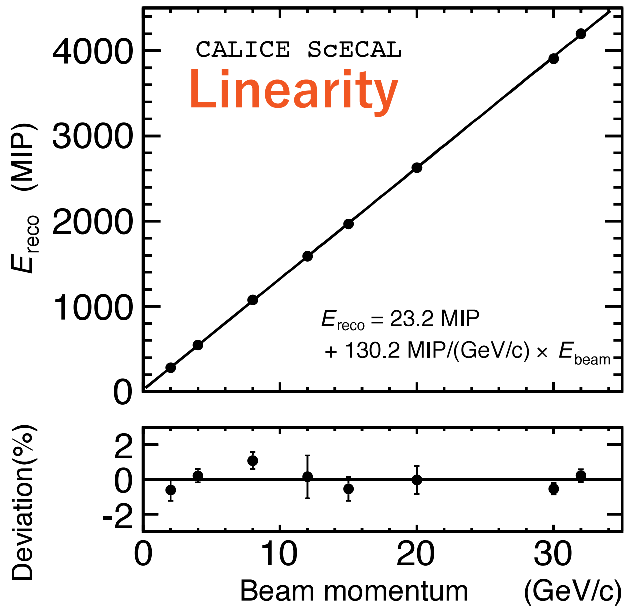
CALICE ScECAL

ScECAL in front of AHCAL

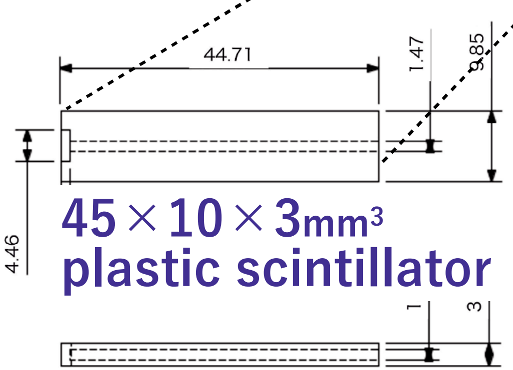


turn 90° every layer w.r.t. previous layer

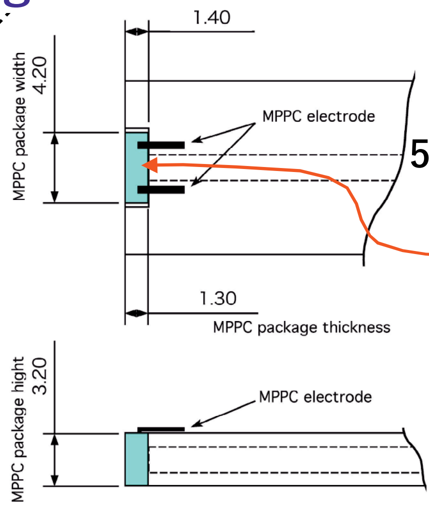




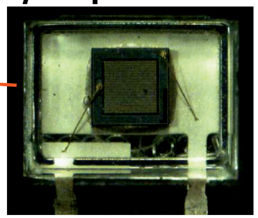
wrapped by a reflecting foil



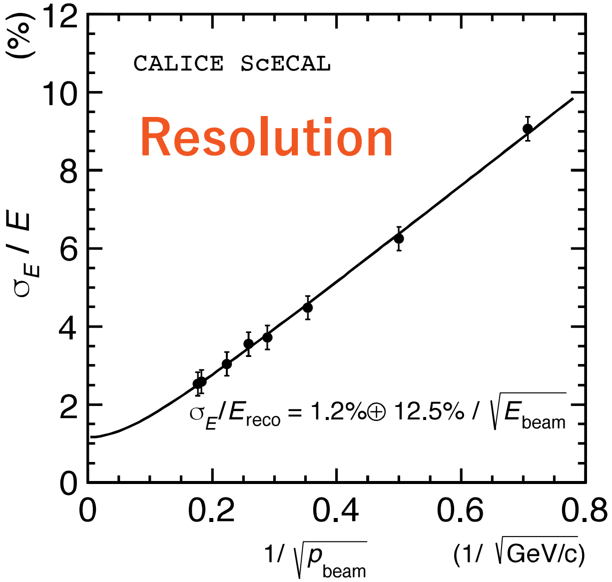
45×10×3mm³ plastic scintillator



50 μm pitch in 1mm²



1600 pixels

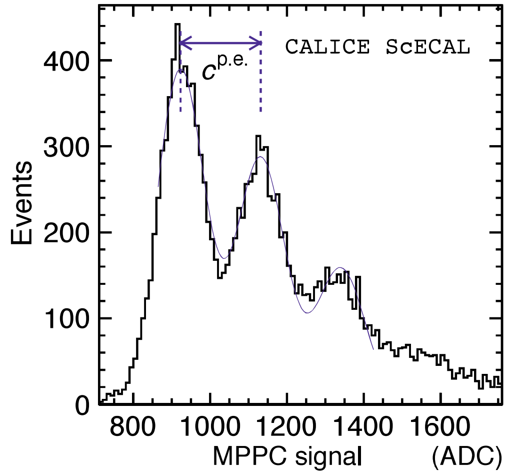


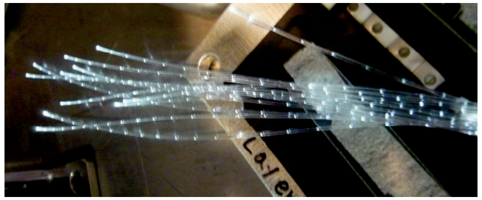
installed 2160 Hamamatsu MPPCs

Calibration procedure of ScECAL

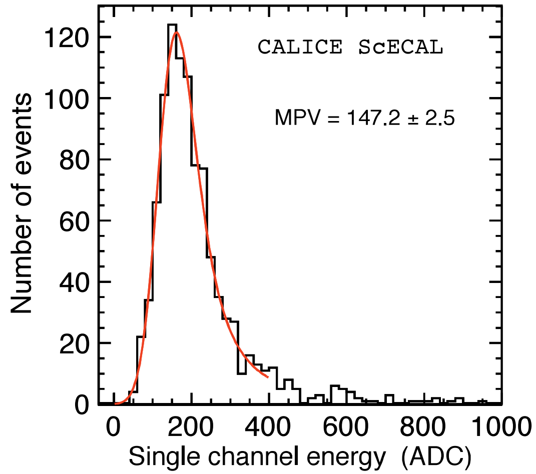
(Note: omit Inter-calibration const. between high/low gain modes of DAQ for simplicity.)

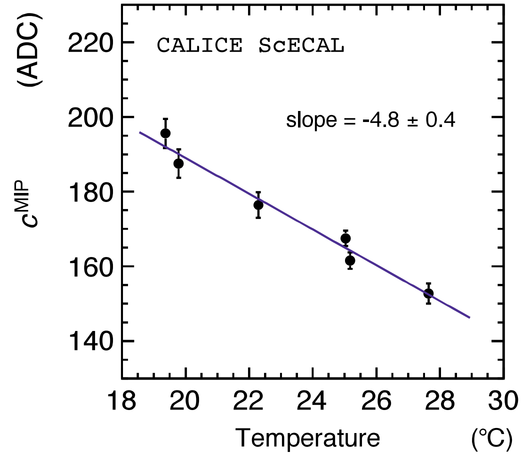
Physics signal in ADC (Start)





LED lights were distributed via clear fibers on each scintillator strips on site.





ADC/p.e.

$(ADC/p.e.)^{-1}$

fired pixels by signal

F^{-1}(# fired pix)

saturation corrected # of photons in signal

saturation corrected ADC in signal

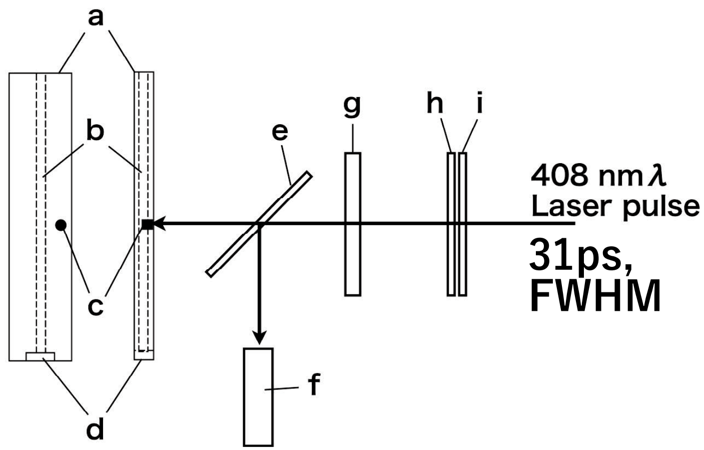
ADC/MIP

MIP(Temp.)

Deposited Energy measured in MIP (goal)

Saturation correction of ScECAL

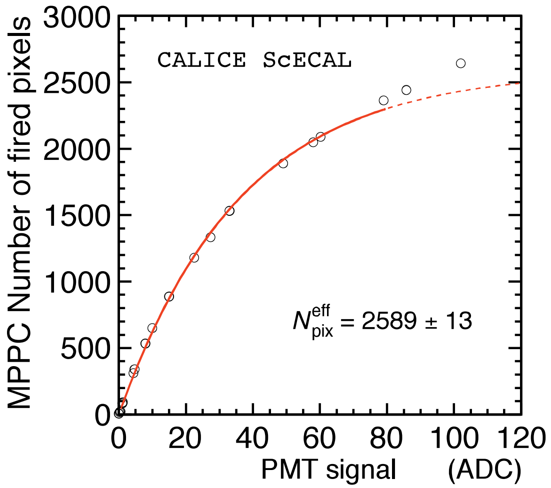
to get F-1(# fired pix), $F^{-1}(N_{\text{fire}})$



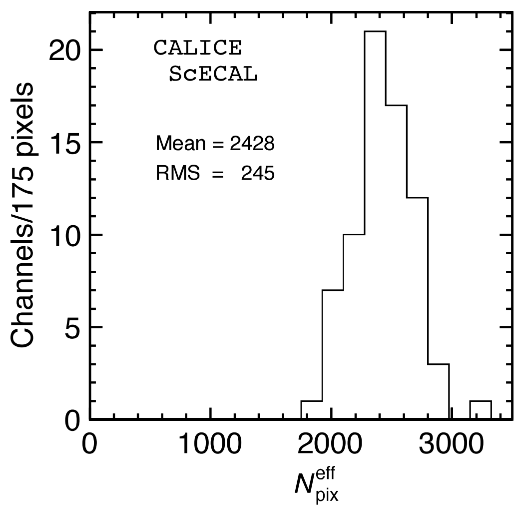
a. Scintillator, 3x10x45mm³,
b. WLS fiber,
c. a hole on reflector,
d. MPPC 25 μm pitch, in 1x1mm²
e. half mirror
f. PMT,
g. lens,
h, i. polaroid.

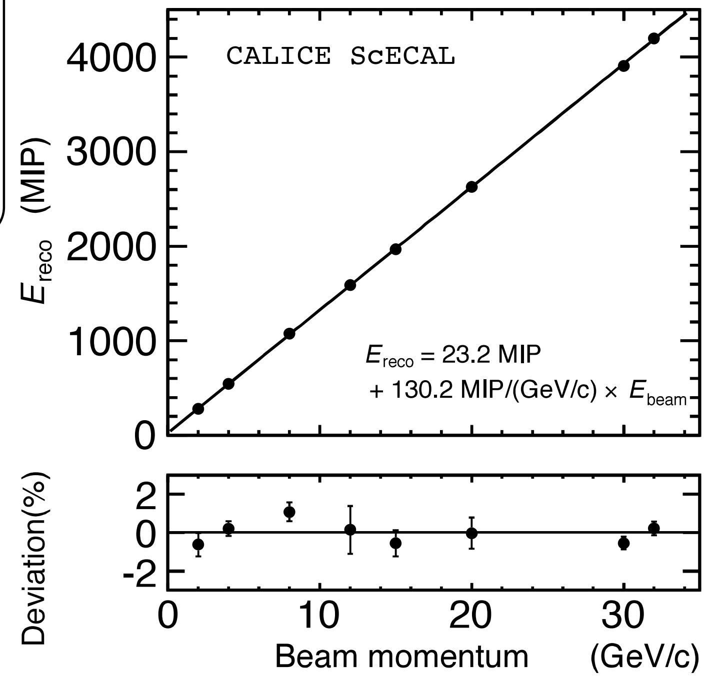
$$N_{\text{fire}} = N_{\text{pix}}^{\text{eff}}\left(1 - e^{\frac{-\epsilon N_{\text{in}}}{N_{\text{pix}}^{\text{eff}}}}\right) = F(N_{\text{in}})$$

1/72samples



mean



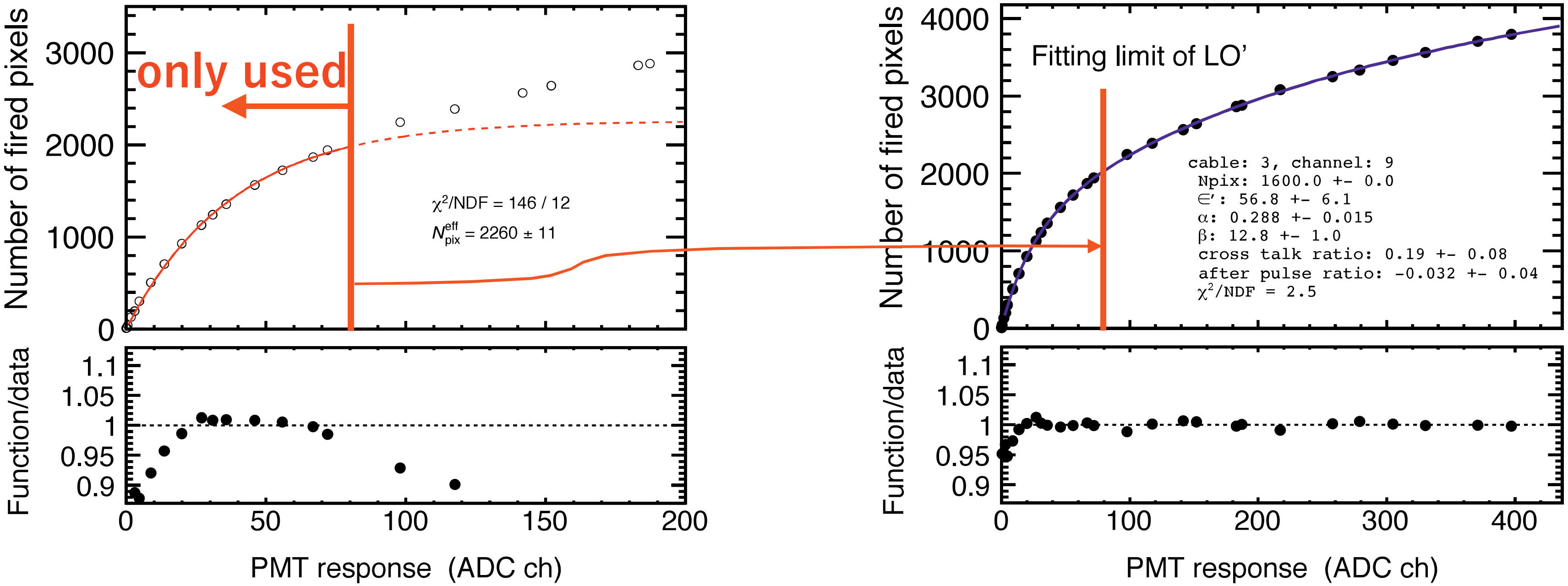


deviation < 1%

Note: AHCAL group measured all 7608 SiPMs ➡ Individually used

Saturation correction
: Farther improvement : an approximation

Calibrate 10^7 SiPMs in ILC cal. ➡ need fast and wide range

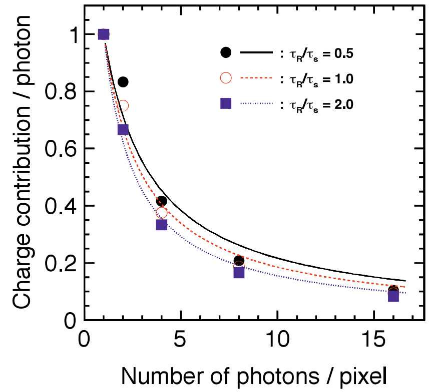


Increase only one parameter { 2(α , β) - 1($N_{\mathrm{pix}}^{\mathrm{eff}} \rightarrow N_{\mathrm{pix}}$)}

$$N_{\mathrm{fire}}^{LO} = N_{\mathrm{pix}}\left(1 - \mathrm{e}^{\frac{-\epsilon N_{\mathrm{in}}}{N_{\mathrm{pix}}}}\right) =: LO$$

$$N_{\mathrm{fire}}^{LNO} = (1-\alpha)LO + \alpha\epsilon N_{\mathrm{in}} =: NLO$$ ➡**simple recovery**

$$N_{\mathrm{fire}}^{NLO'} = N_{\mathrm{fire}}^{NLO}\frac{\beta+1}{\beta+\epsilon N_{\mathrm{in}}/LO} =: NLO'$$ ➡**approx. charge contribution**

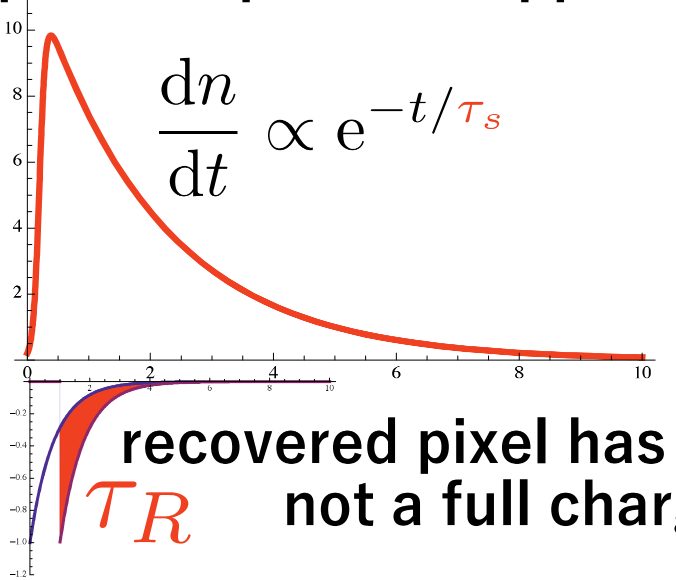


$$N_{\mathrm{fire}}^{NLO'_{\mathrm{C.A.}}} = NLO' \times (1 + P_C \mathrm{e}^{-\epsilon N_{\mathrm{in}}/N_{\mathrm{pix}}})(1 + P_A)$$

Xtalk and after pulse

Charge contribution of each hit

a pulse of photons approaching SiPM



charge contribution by a photon

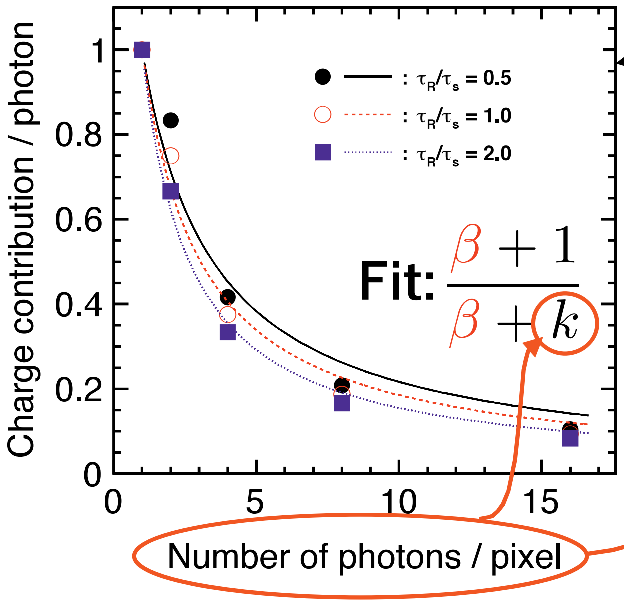
D. Jeans arXiv:1511.06528

$$\boxed{Q^{(k)}/k =} \; Q_0\left[1 + \sum_{j=2}^{k}\left\{1 - \frac{\zeta}{\zeta + (k+1-j)^{-1}}\right\}\right]/k$$

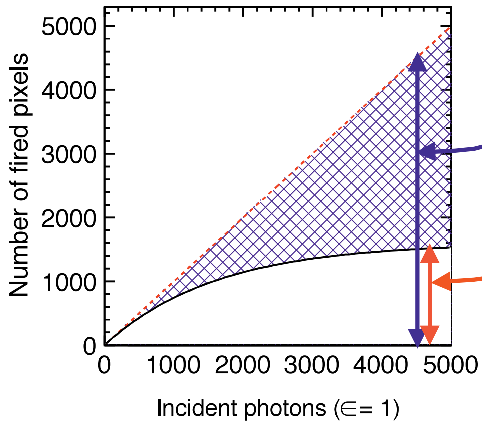
k : # of photons on a pixel in this event,

Q_0 : charge by a single photon,

$$\zeta = \frac{\tau_R}{\tau_s}$$



$$\langle \#\text{photon}/\text{pixel}_{\text{fired}} \rangle = \langle k \rangle = \frac{\epsilon N_{\text{in}}}{LO}$$



$$N_{\text{fire}}^{NLO'} = N_{\text{fire}}^{NLO}\frac{\beta + 1}{\beta + \epsilon N_{\text{in}}/LO}$$

Thank you for your attention!

SiPM saturation measurement setup (S. Krause)

Crosstalk measurement performed: μ_C (range between $1.01 \div 1.89$)

Response measurement:

Method taking into account the influence of crosstalk in the calibration.

100px and 400px SiPM:

- *Crosstalk* has a large influence on the response behavior.
- For high light intensities, an over saturation has been observed (best handled by Advanced function)

1600 and 2668 pixel SiPM:

- Influence of crosstalk:
  - 2668px: negligible
  - 1600px: lower, but still measurable influence.
- No hint for over saturation in the measured range.

Saturation correction in CALICE ScECAL (K. Kotera)

- CALICE ScECAL using scintillator tiles wrapped with reflective foil read out by SiPM.
- Calibration procedure correcting for the saturation of SiPM.
- Saturation Correction:
  - Naive model with effective number of total pixels N_{total}^{eff} (to handle pixel recovery).
  - Advanced model, fixing N_{total}, adding recovery, approx. charge contribution, XT and AP.

Questions? ☺

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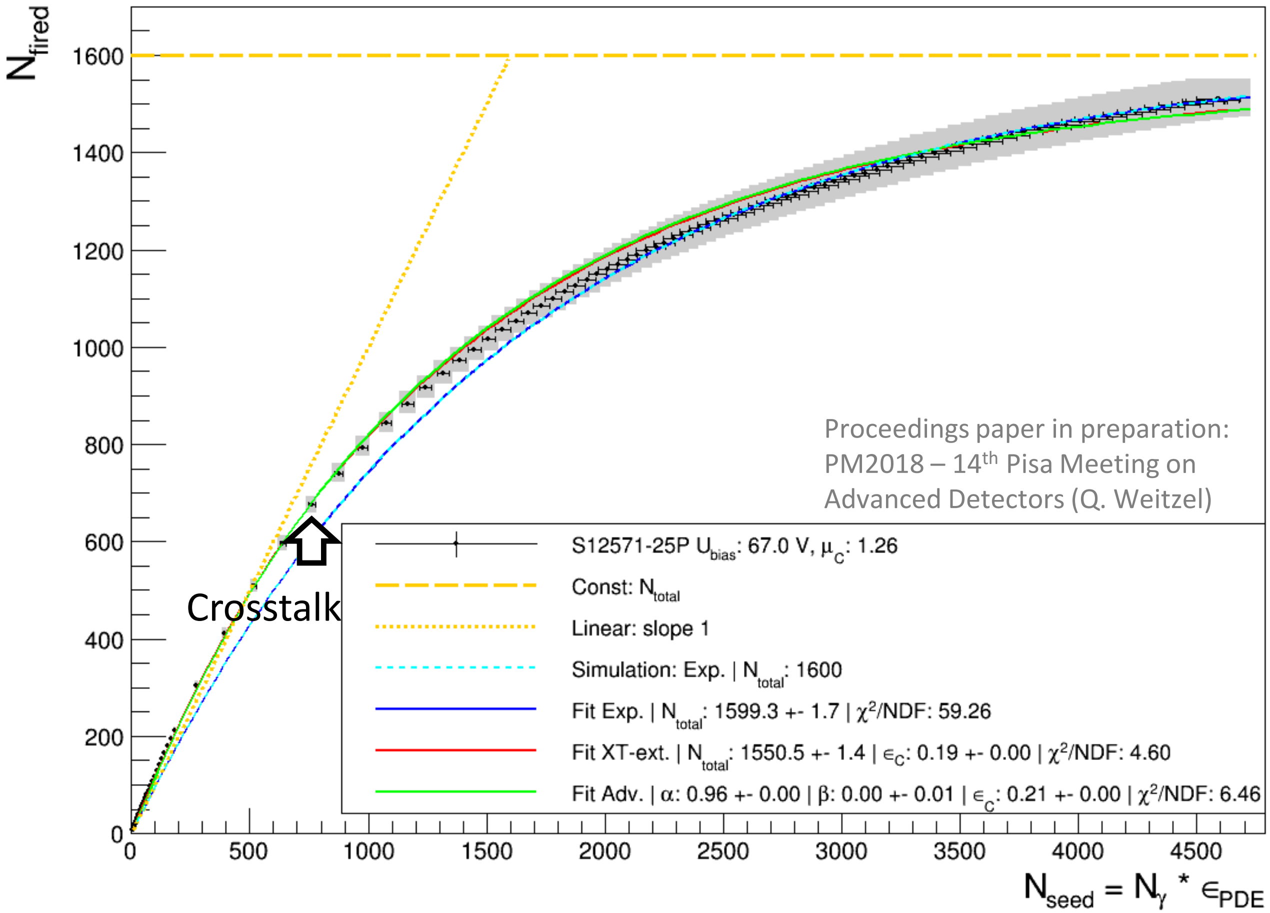
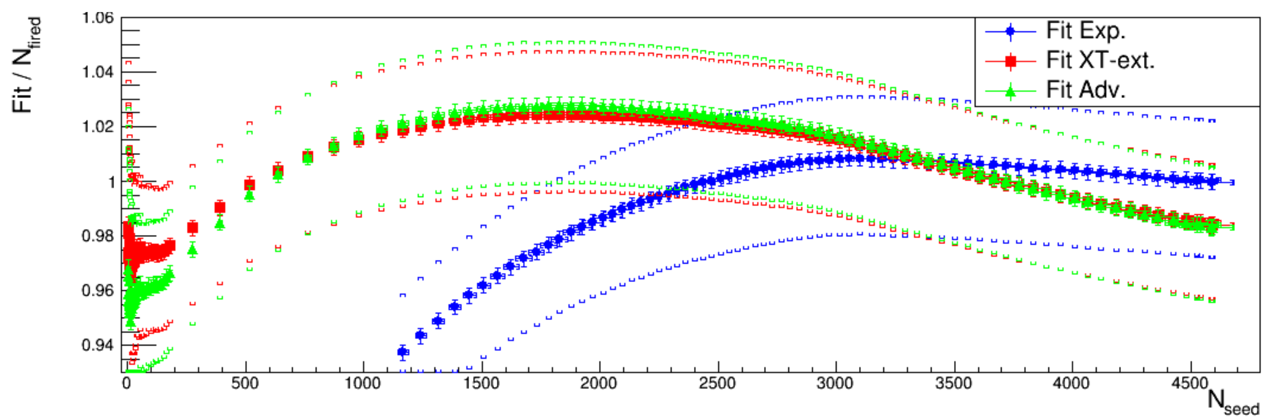
Results

1600 pixels | OV: +3.31V

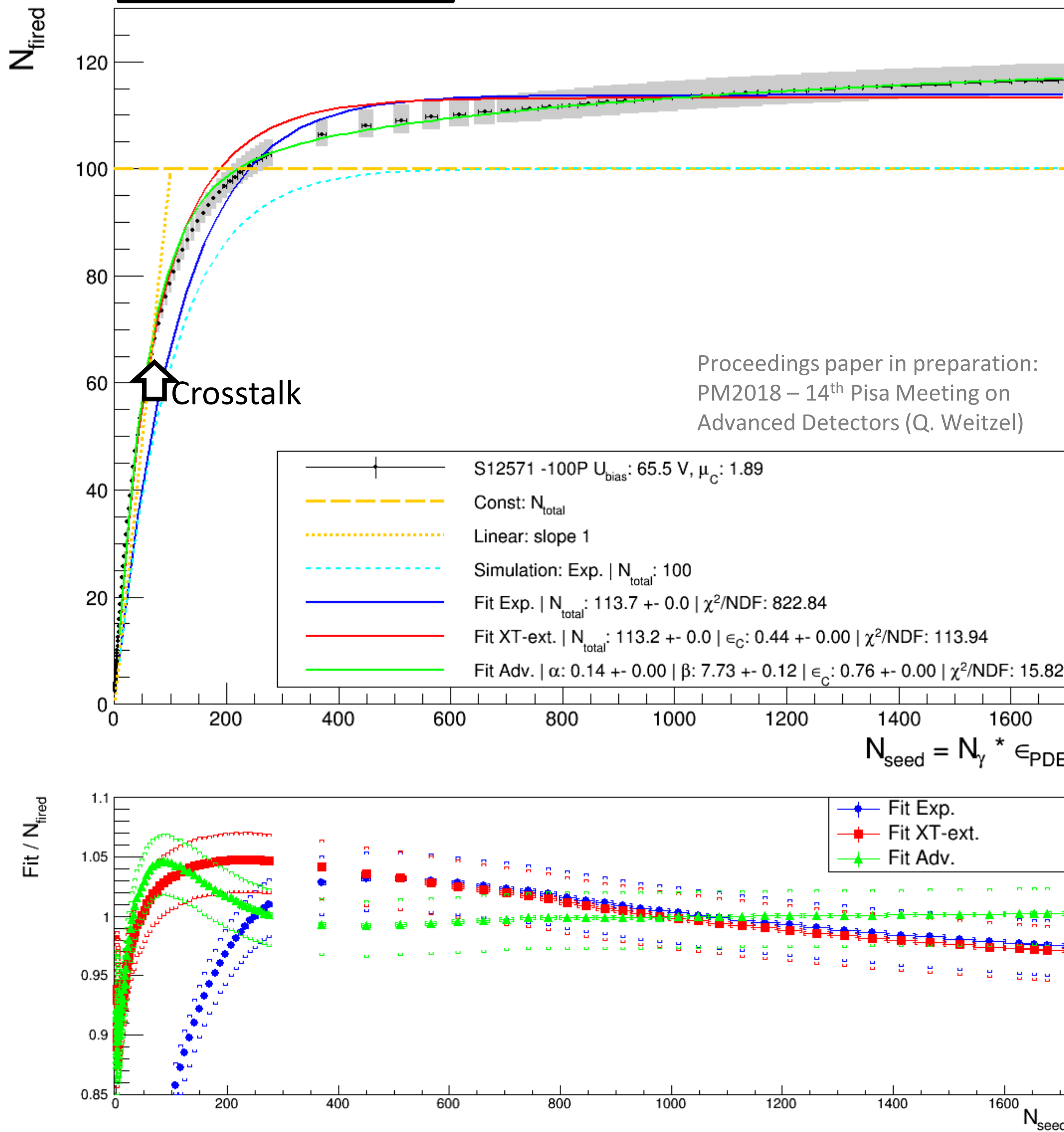




$\beta = 0$ for all cases without oversaturation.

Results

100 pixels | OV: +1.71V

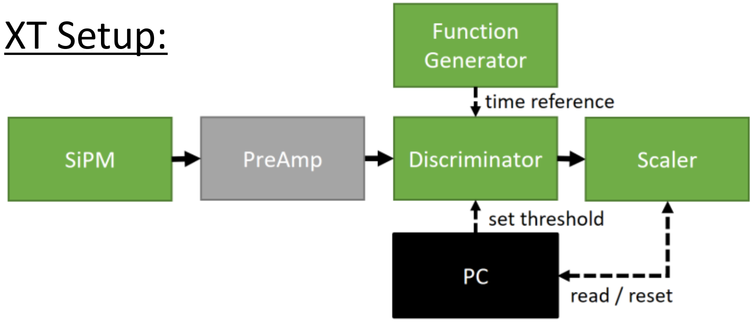


Over saturation

$\beta > 0$ for all cases with oversaturation.

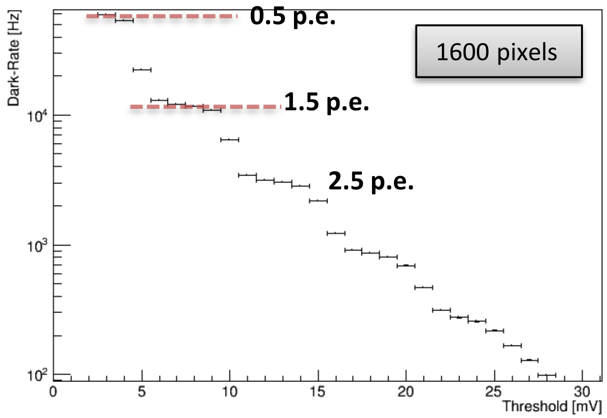
SiPM crosstalk (XT) measurement

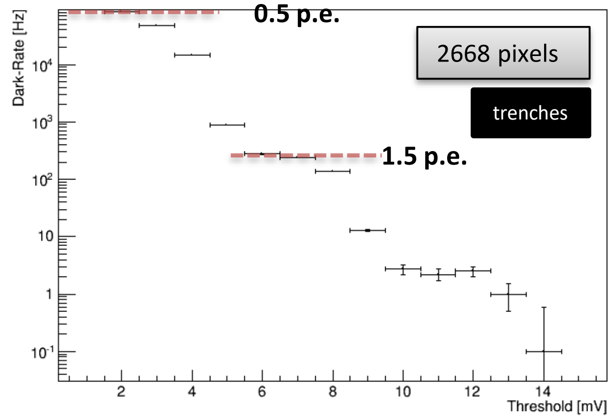
XT Setup:



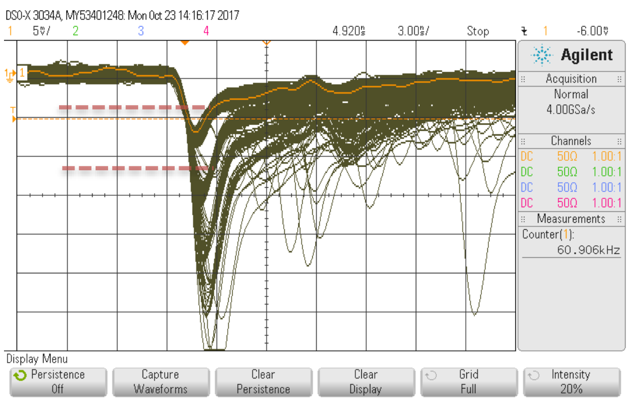
Same SiPM operating conditions as during response measurements.

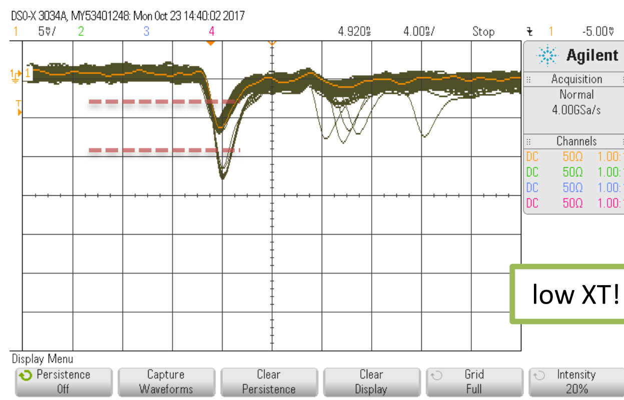
DCR:





Scope:





low XT!

Low amount of after pulses for each SiPM! -> neglected.

Crosstalk measurement: Average number of correlated pixels fired μ_C

To estimate the average number of correlated pixels fired, the **Borel Model of correlated noise** is used as described in detail in arXiv:1710.11410v1

<u>Borel Model:</u>

Equation to be solved: $\xi\left(e^{-\xi}-1\right)=\frac{N_2}{N_1}+\log\left(\frac{N_1}{N_0}\right)$

Expected value: $\mu=\frac{1}{1-\xi}$

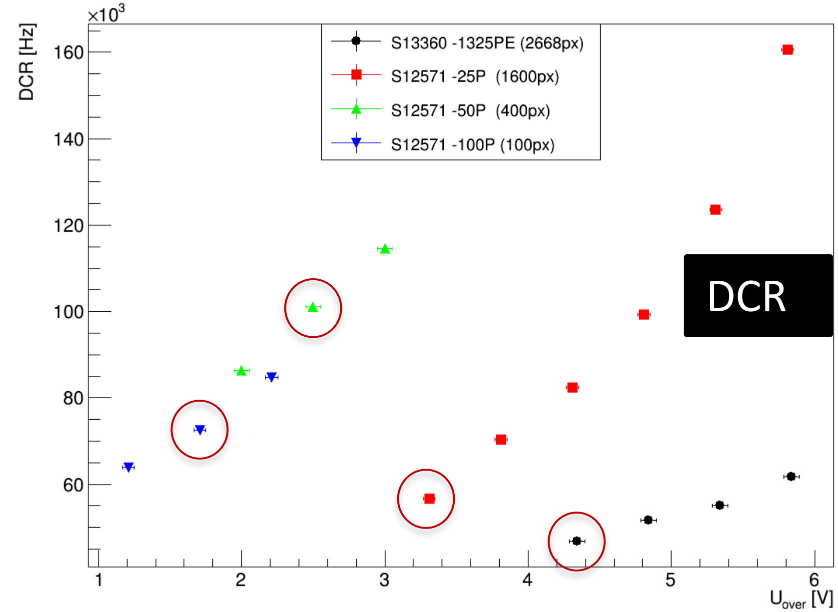
arXiv:1710.11410v1

<u>With:</u>

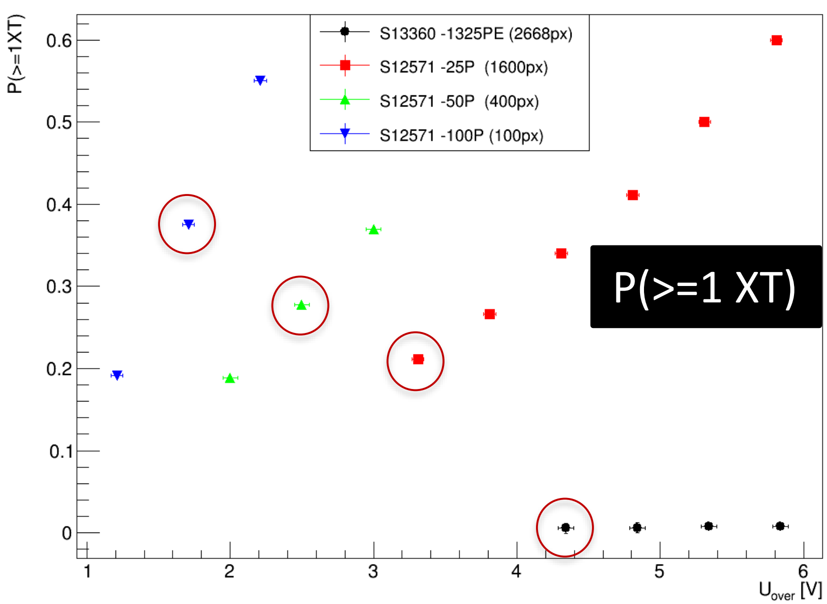
N_0 = total number of events

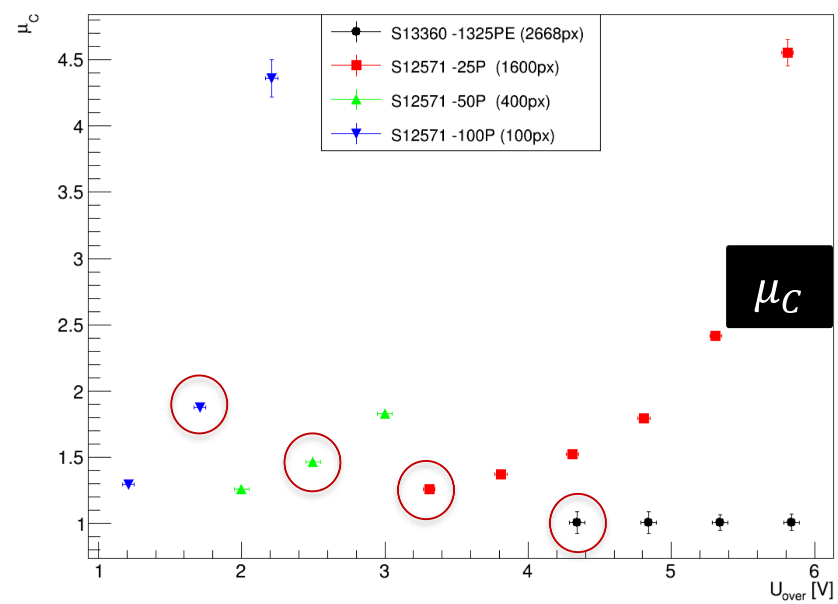
N_1 = all events with exactly one pixel fired (no XT)

N_2 = events with exactly 1 XT (2 pixels fired in total)



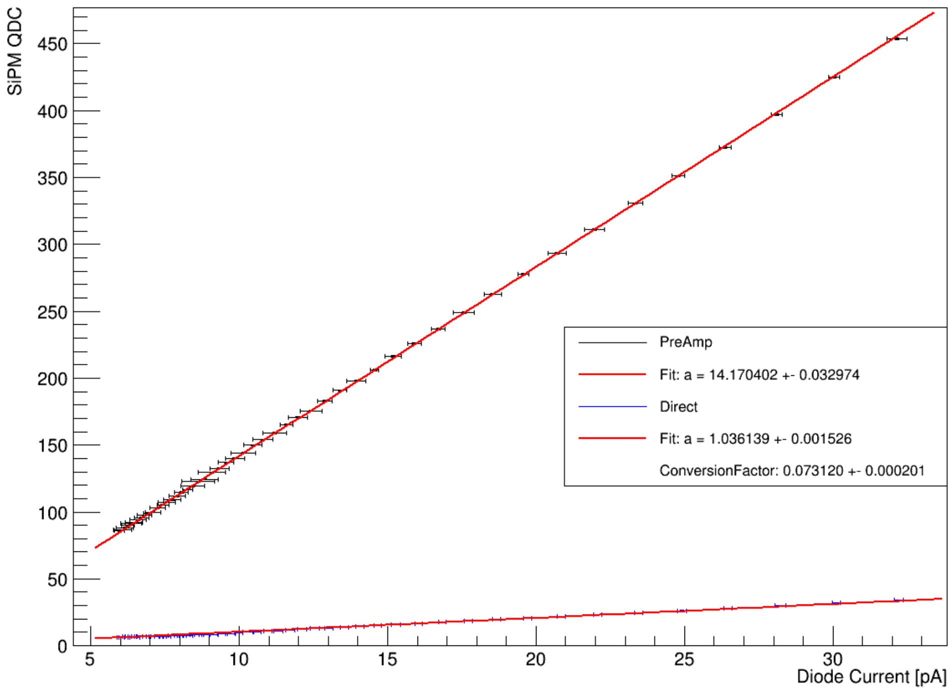
○ = Response measurement at these voltages





Gain Estimation with PreAmp | Conversion factor: PreAmp -> DirectBox

Plot QDC values vs. diode current
Apply linear fits:



Conversion Factor:

$$\alpha = \frac{f_D}{f_P} = \frac{a_D}{a_P} = 0.073120 \pm 0,000201$$

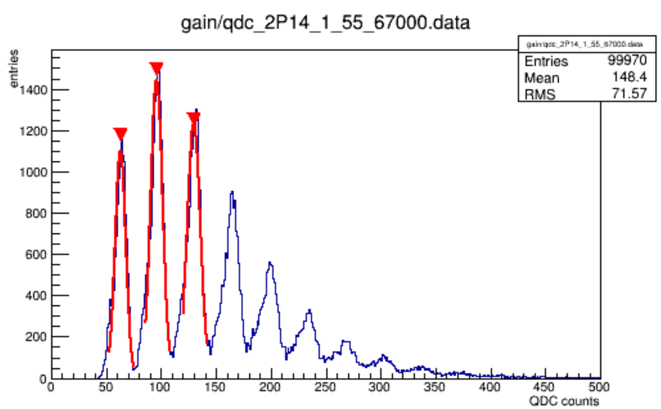
With this factor, the gain value can be estimated:

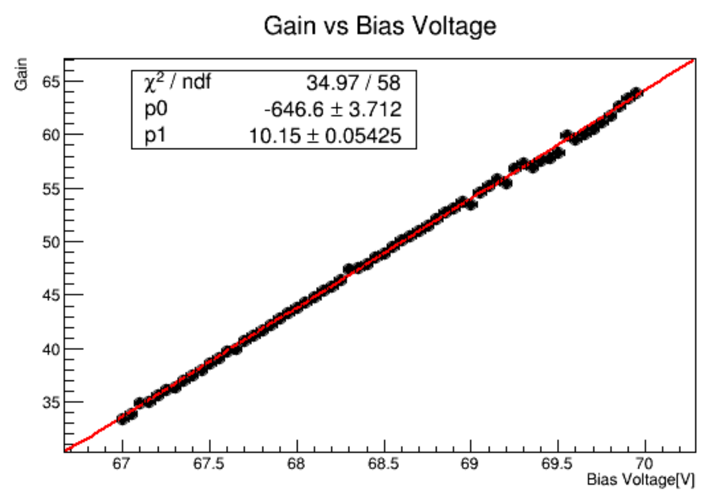
gain_PreAmp = 33.61

-> gain_Direct = 2,457 +-0,015

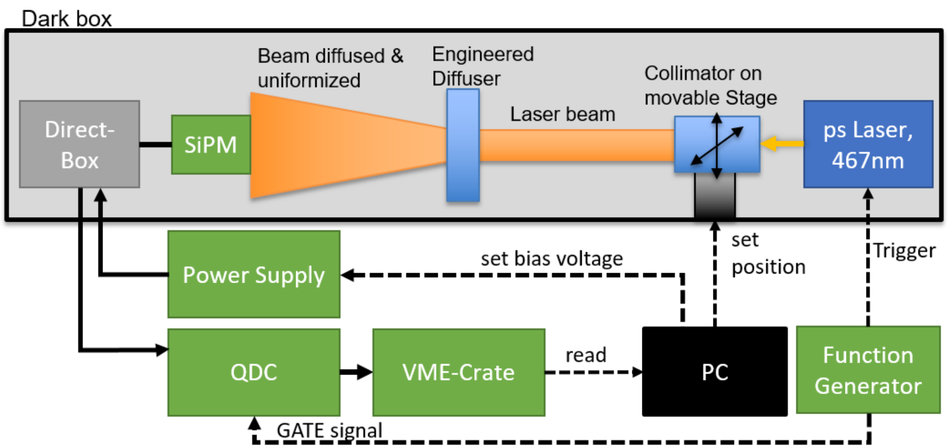
$$gain_D = \alpha \cdot gain_P$$

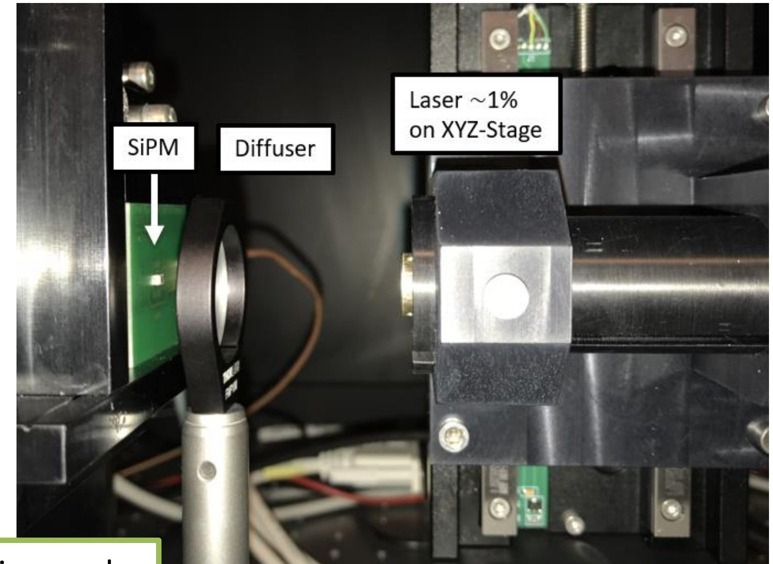
Gain Measurement with PreAmp:

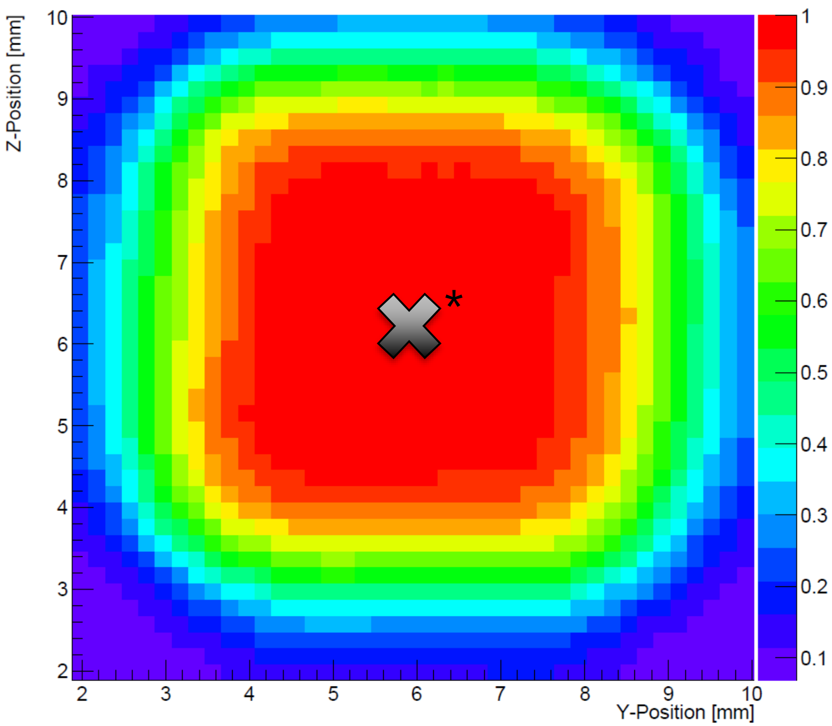




Engineered Diffuser Scan





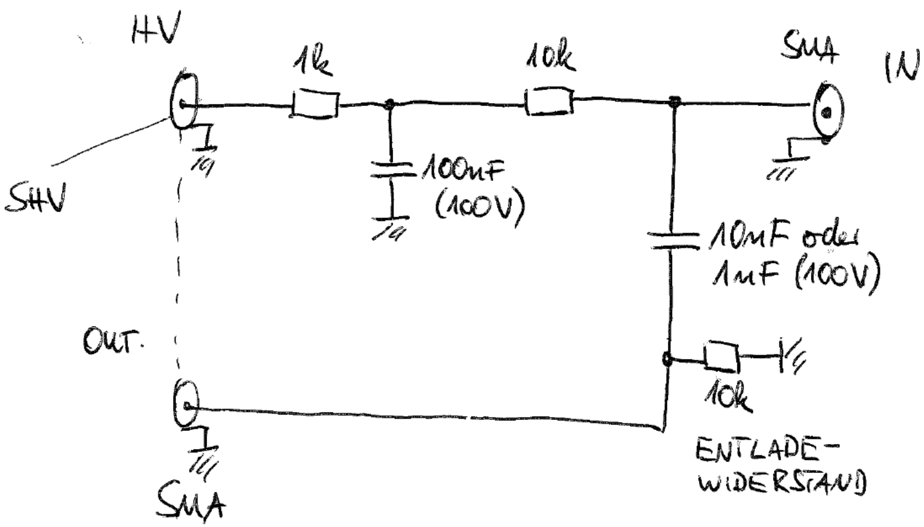


The uniformity of the Engineered Diffuser was tested in a separate measurement. It converts a gaussian beam profile in a so-called top-hat profile with uniform intensity.

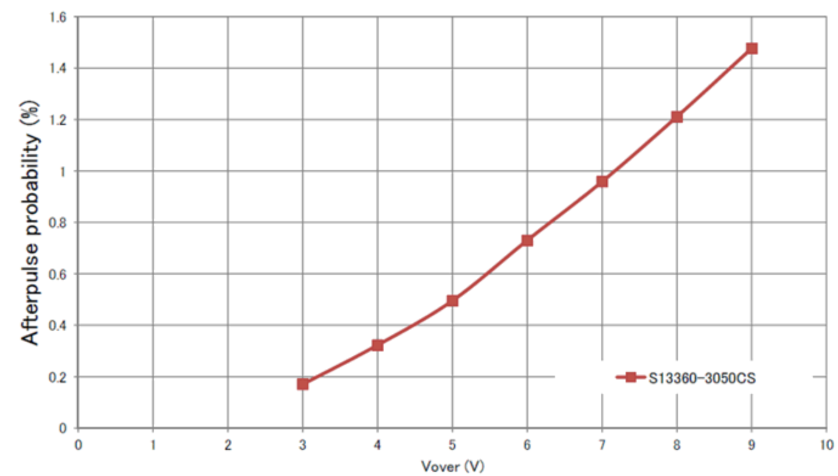
Measured with 1600pix SiPM with $1x1mm^2$ active surface.
The red area indicates a very uniform illumination of the SiPM.
The green halo corresponds to the cases, where only parts of the SiPM are hit.

*Position used during saturation measurement.

Direct Box Circuit & After Pulse Prob.



◆ S1336x Series (25, 50, 75 μm)



- **Afterpulse probability depends on Vover**

After pulse probability of HAMAMATSU MPPC S1336x series, kindly provided by HAMAMATSU

JG|U

Components

- PiLas Picosecond Laser (A.L.S. GmbH), 60ps FWHM, $\lambda = 467$nm
- 2x2 Fiber Optic Coupler (Thorlabs), splitting ratio 99:1, center wavelength 488 ± 15nm
- Engineered diffuser ED1-S20-MD (Thorlabs), 20°
- Ground glass diuser DG10-220 (Thorlabs)
- Movable stage (M-403.2DG) 50 mm travel range, 0.2μm minimum incremental motion, resolution 0.018μm
- Fast wideband amplifier (A1423B), 1.5 GHz bandwidth, tunable gain [+18,+54]dB
- 8 channel dual range multievent QDC, CAEN V965A, 12 bit
- Reference Diode FDS1010-CAL, (Thorlabs)
- Picoamperemeter (Model 6485, Keithley)
- Power supply EA-PSI 6150
- Function generator (33500B former Agilent, now Keysight Technologies)