SiPM Response

CALICE Meeting Mainz 2018

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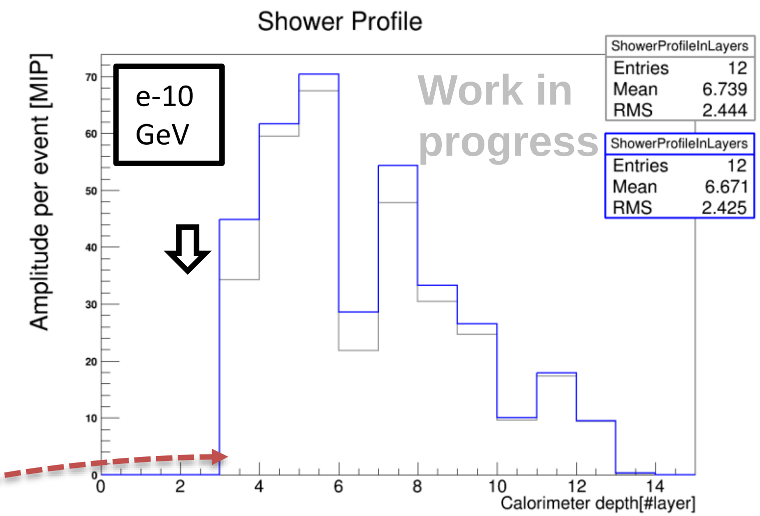
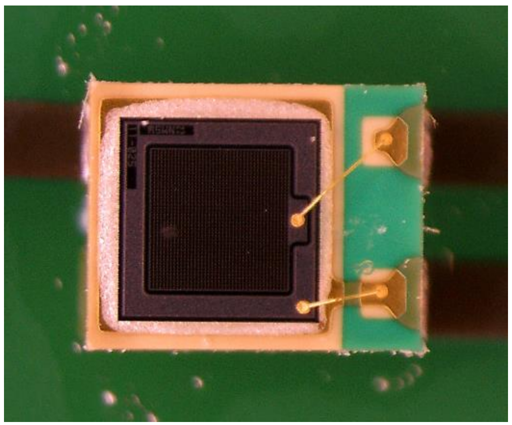
SiPM Response – Outline & Motivation

- Introduction & Definitions
- SiPM Crosstalk measurement
- SiPM Response measurement

Motivation:
Simulated impact of SiPM saturation in CALICE test beam 2015, CERN:





SMD SiPM on PCB
Photo by Yong Liu, JGU Mainz

	SiPM (Hamamatsu)	N_{total}	pixel pitch [μm]	sensitive area [mm^2]	typical gain	trenches
On SMD HBUs since 2016	MPPC S13360 -1325PE	2668	25	1.3×1.3	$7.0 \cdot 10^5$	yes
On first SMD HBU 2015	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:

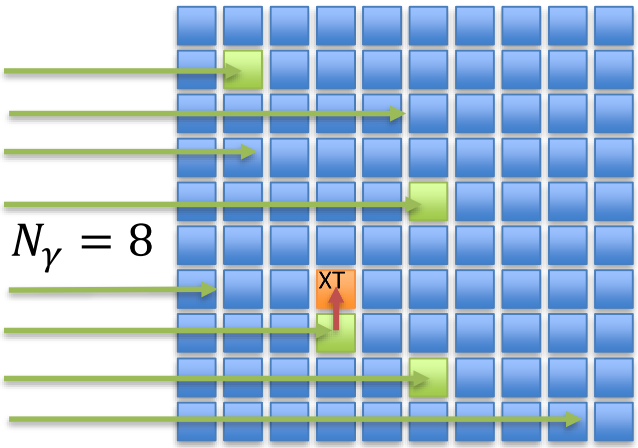
$\epsilon_{PDE} = 0.5$	efficiency
$\mu_C = 1.25$	correlated noise (XT)

← 25% Crosstalk

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

Without saturation
With crosstalk

Calibration region



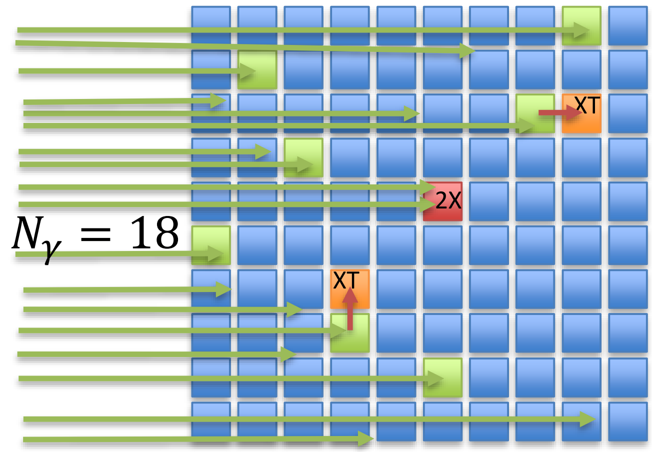
$N_{fired} \stackrel{\text{def}}{=} N_{fired}^{linear} = 5$ (w/o saturation, w/ XT)

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

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

With Saturation
With crosstalk

Saturation region



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

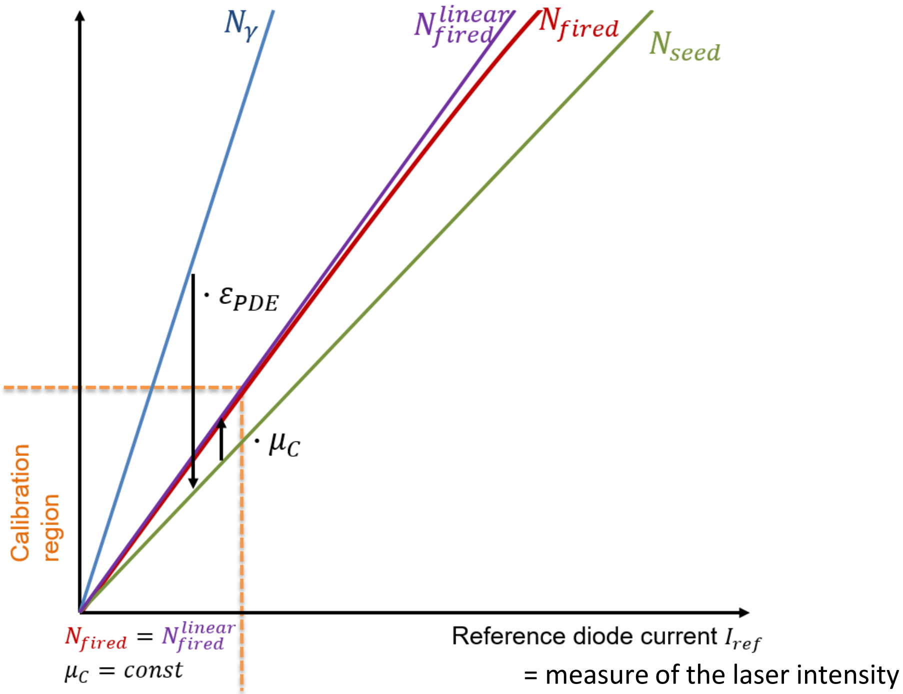
Advanced function which handles saturation & XT

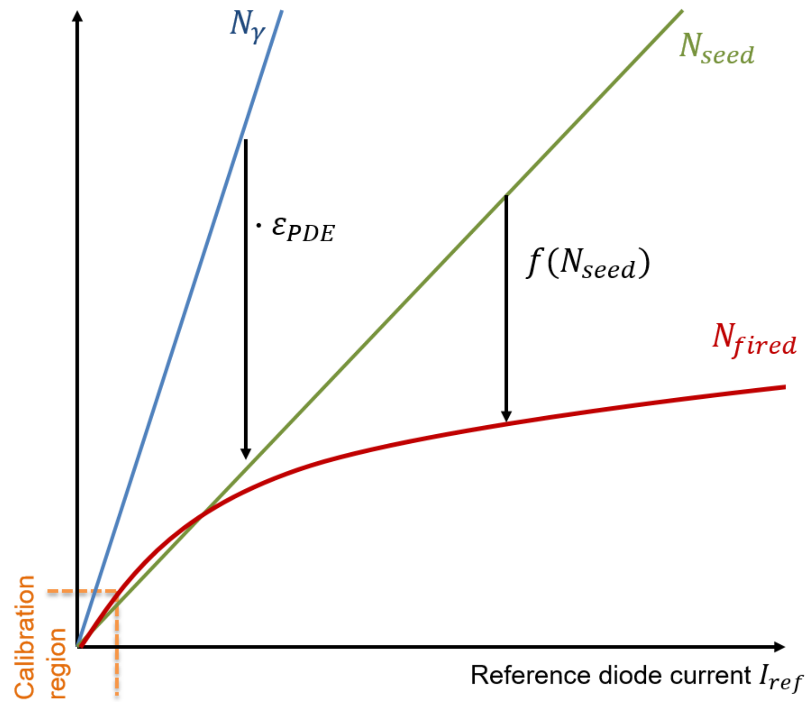
$N_{seed} = 9$ (w/o saturation, w/o XT)

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

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: (arXiv:1206.4154v1) Thanks to Marina!

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

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

invertible!

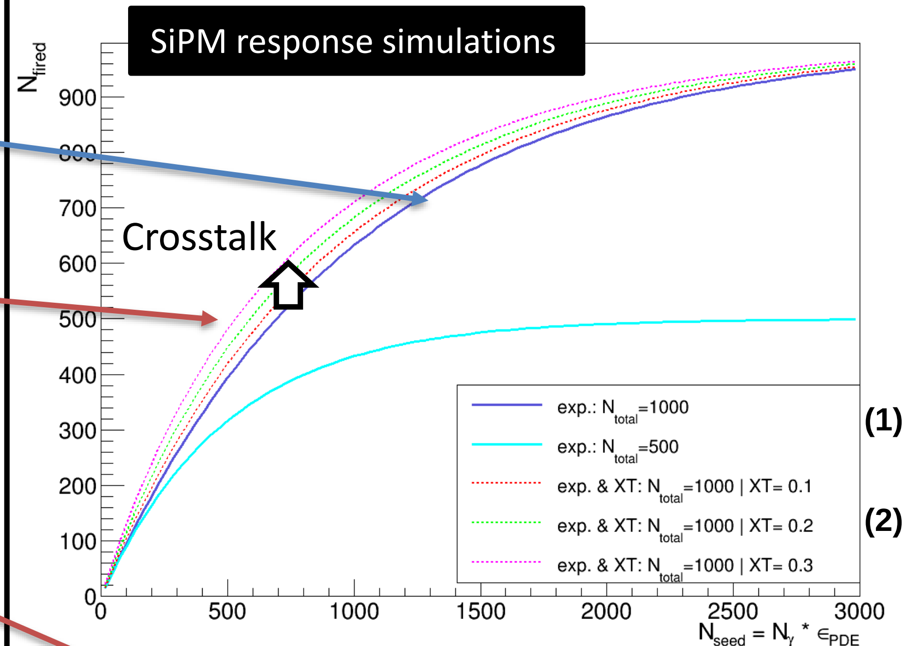
(3) Katsu's **advanced** response function: (arXiv:1510.01102v4)

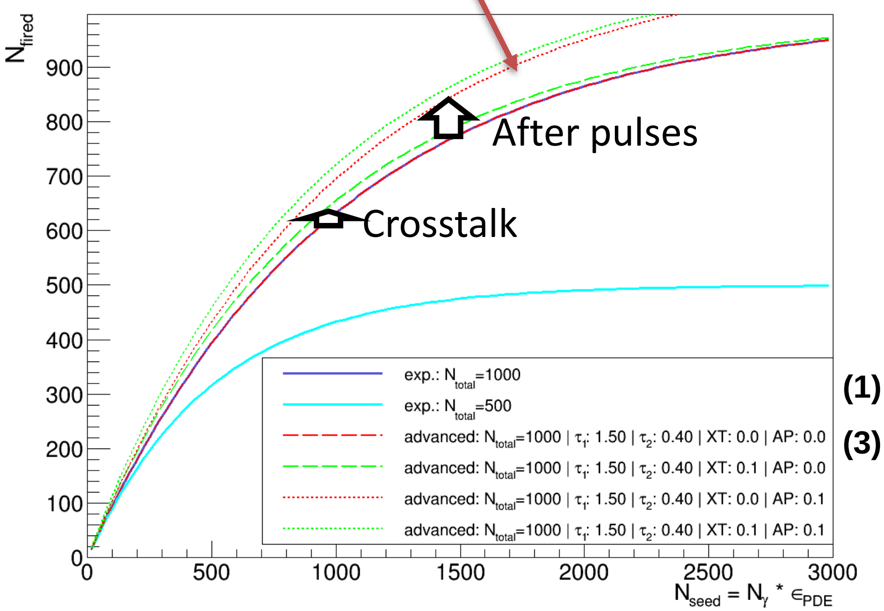
NLO corrections:

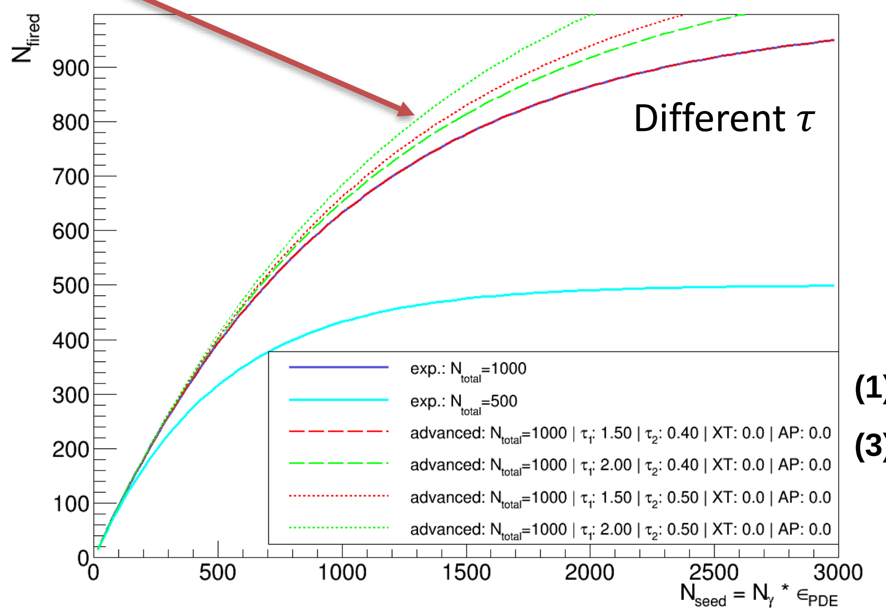
not invertible!

6 parameters:

- 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**

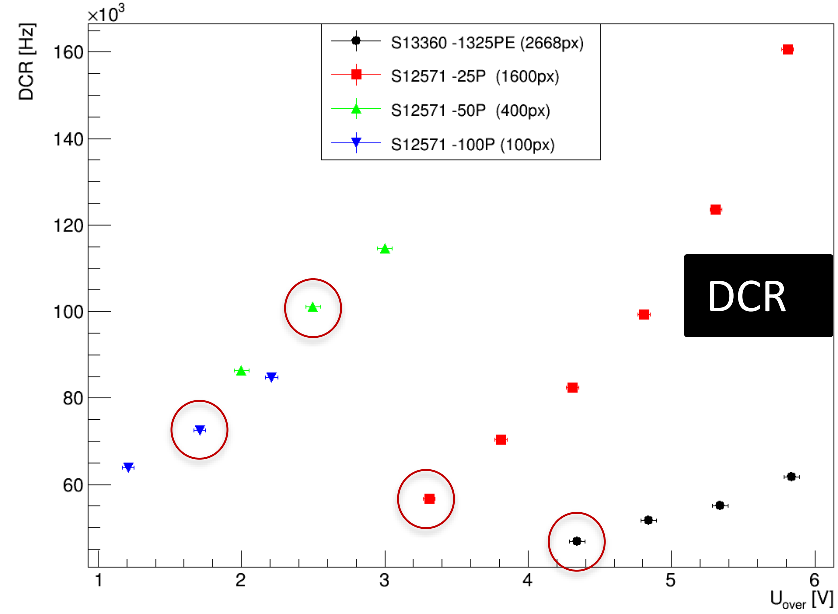






Crosstalk measurement: Average number of correlated pixels fired μ_C

To estimate the average number of correlated pixels fired, the **Borel Model of correlated noise** is used as described in detail in: https://arxiv.org/pdf/1710.11410.pdf by Enrico Junior Schioppa



<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

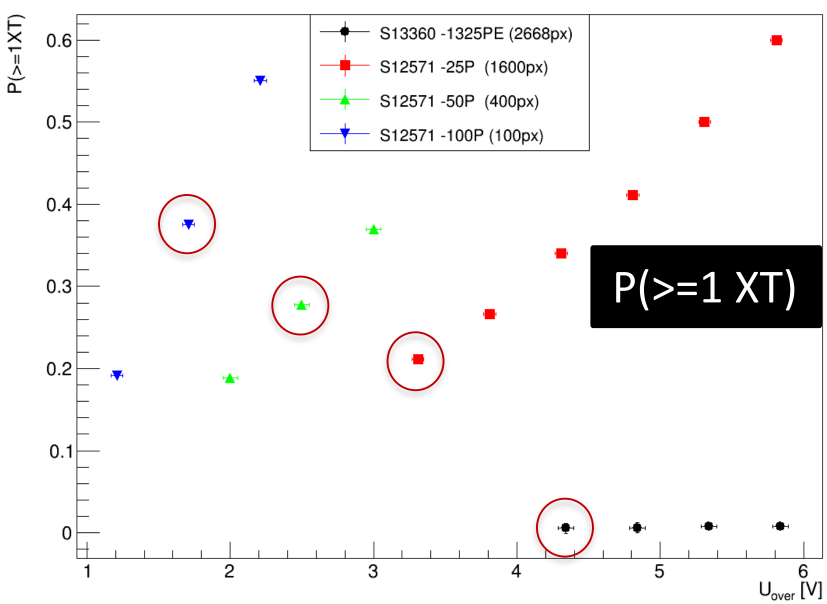
<u>With:</u>

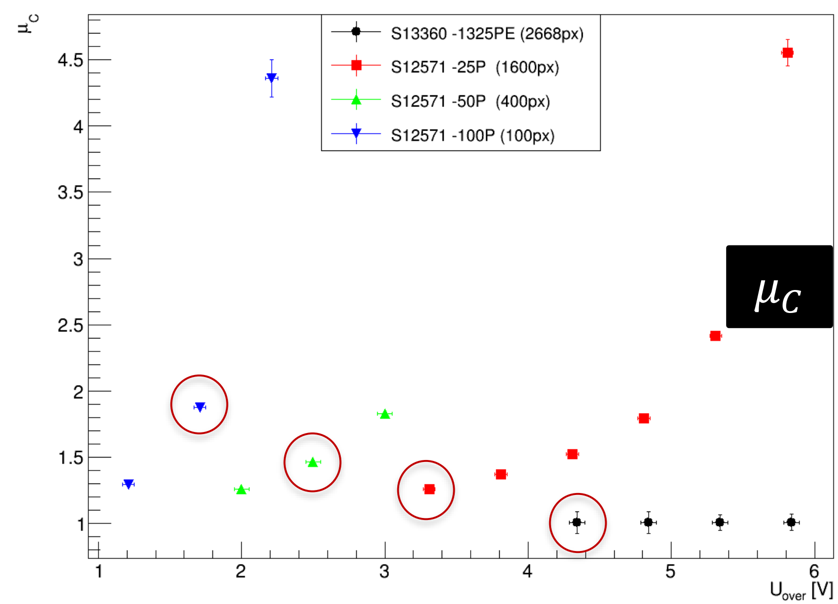
N_0 = total number of events

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

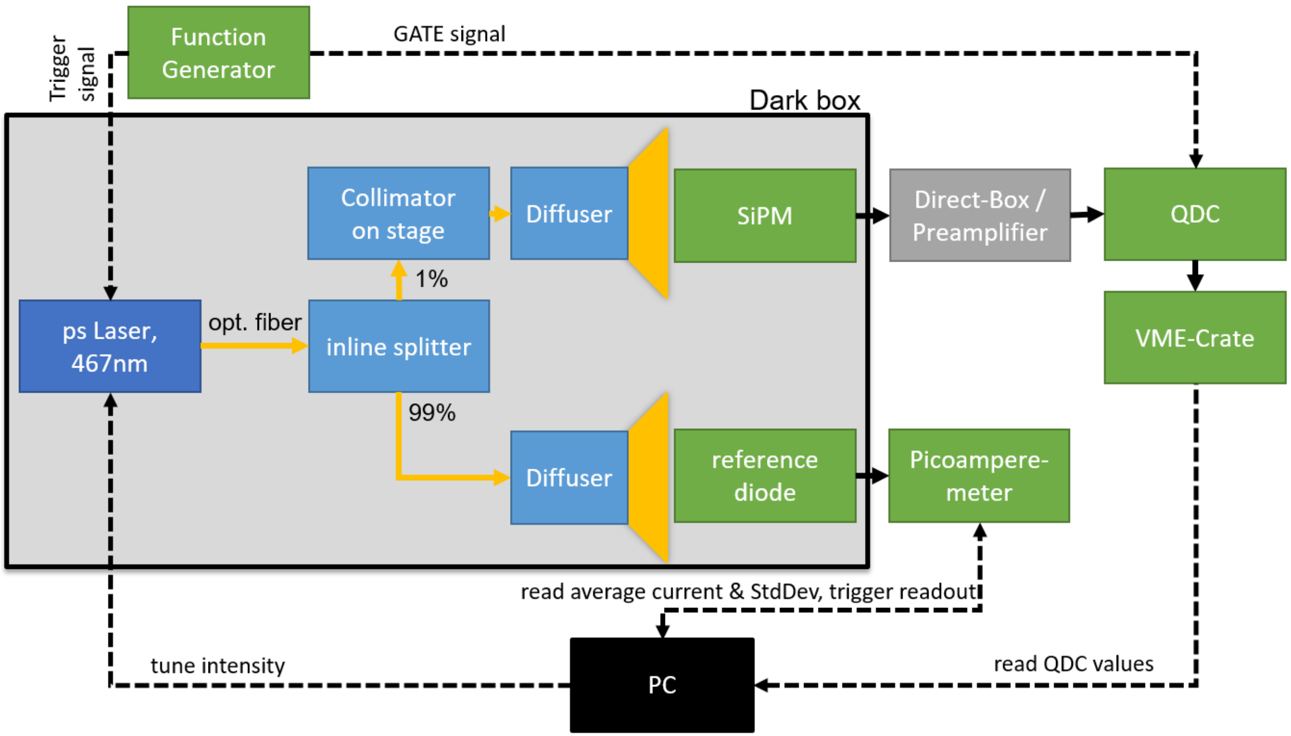
N_2 = events with exactly 1 XT (2 pixels fired in total)

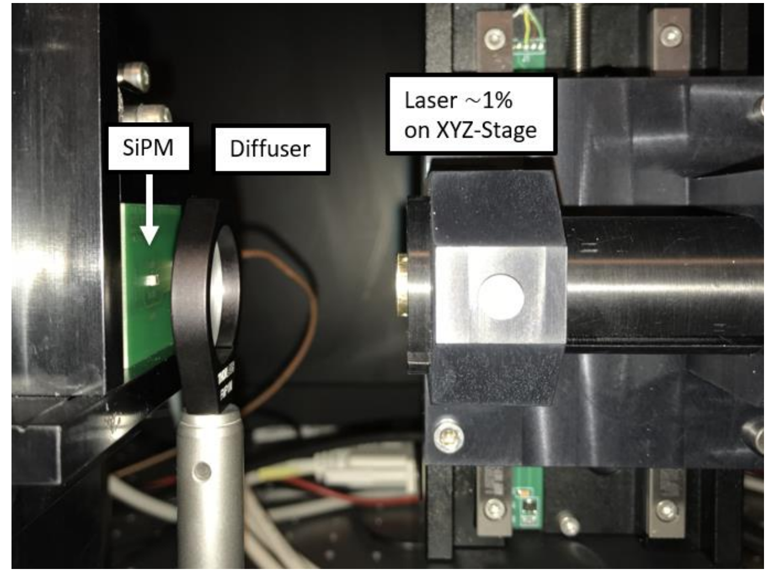
= Response measurement at these over voltages (as used in TB).

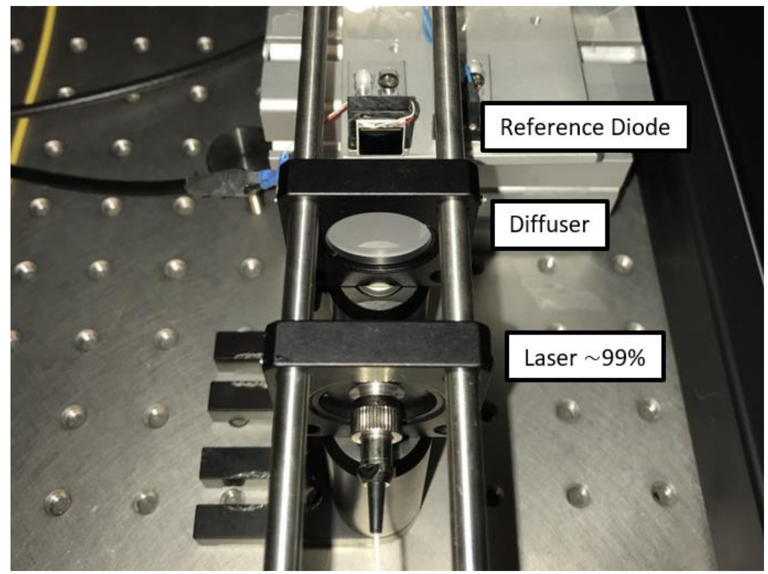




SiPM Response: Setup as part of the PRISMA DetectorLab Mainz







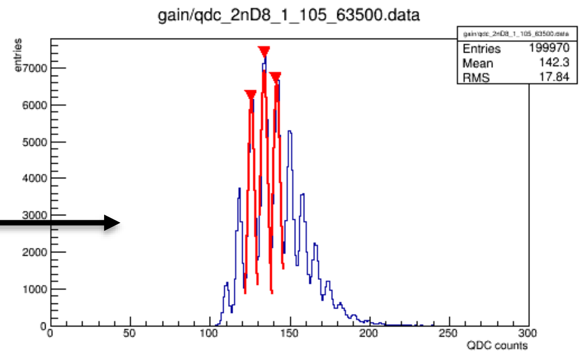
Systematic Uncertainties:
- Direct-Readout-Circuit linear within 1% over full measurement range.
- PreAmp starts to saturate from ~1V output, linear within 2% for lower signals.
- Reference diode linear within 1% over full measurement range.

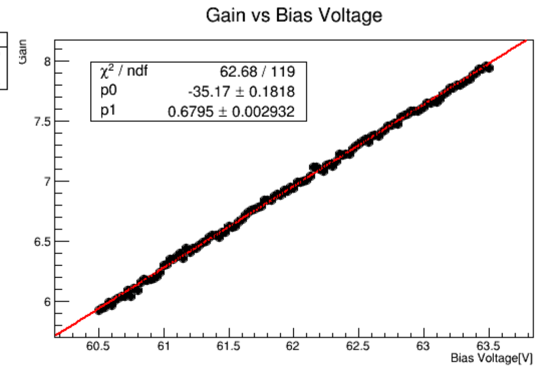
Uniform light distribution:
- Diffusor intensity profile uniform within 1.5%

SiPM Response: Procedure for latest SiPM (2668 pixels)

1. Pedestal correction:
QDC Spectrum with applied bias voltage without laser beam. Used for pedestal determination.

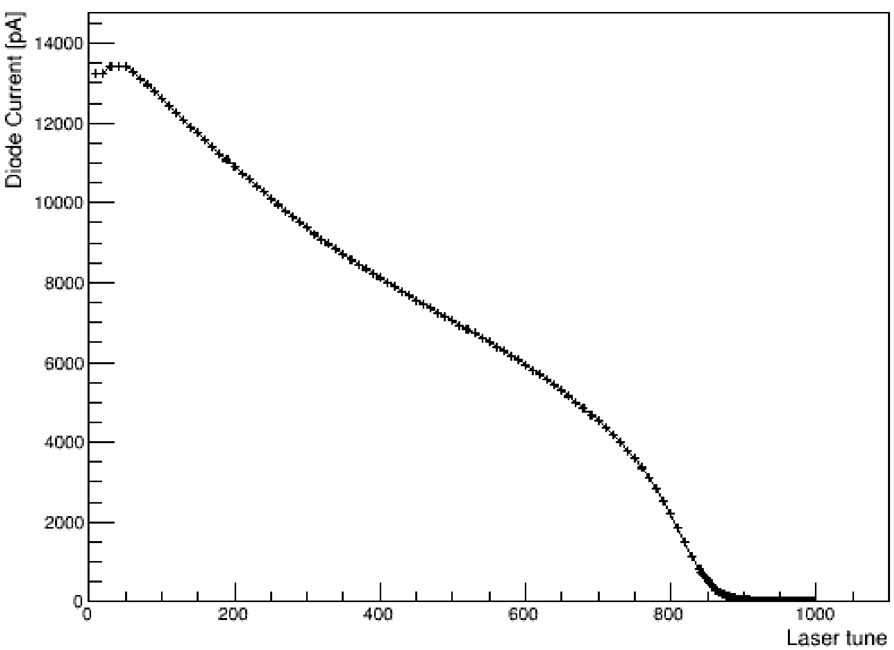
2. Gain measurement:
Difference between adjacent peaks.
In case of 1600 pixel SiPM: use Preamp and Direct Box.



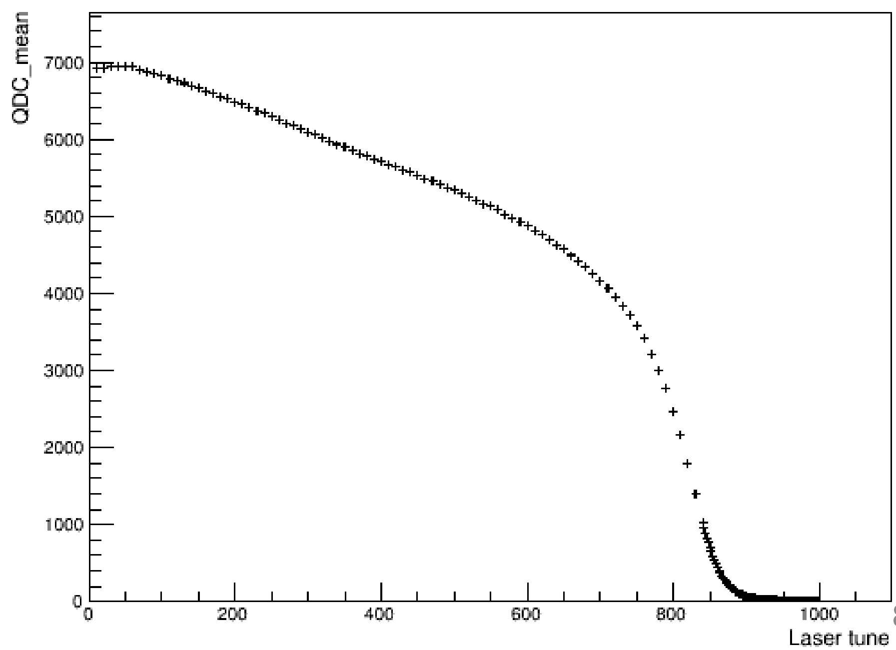


3. QDC High Range to Low Range conversion:
The QDC has a LR and HR amplification. Measure conversion factor.

4. Estimate light intensity with calibrated diode:



5. Plot QDC mean values vs. laser intensity:



SiPM Response: Procedure for latest SiPM (2668 pixels)

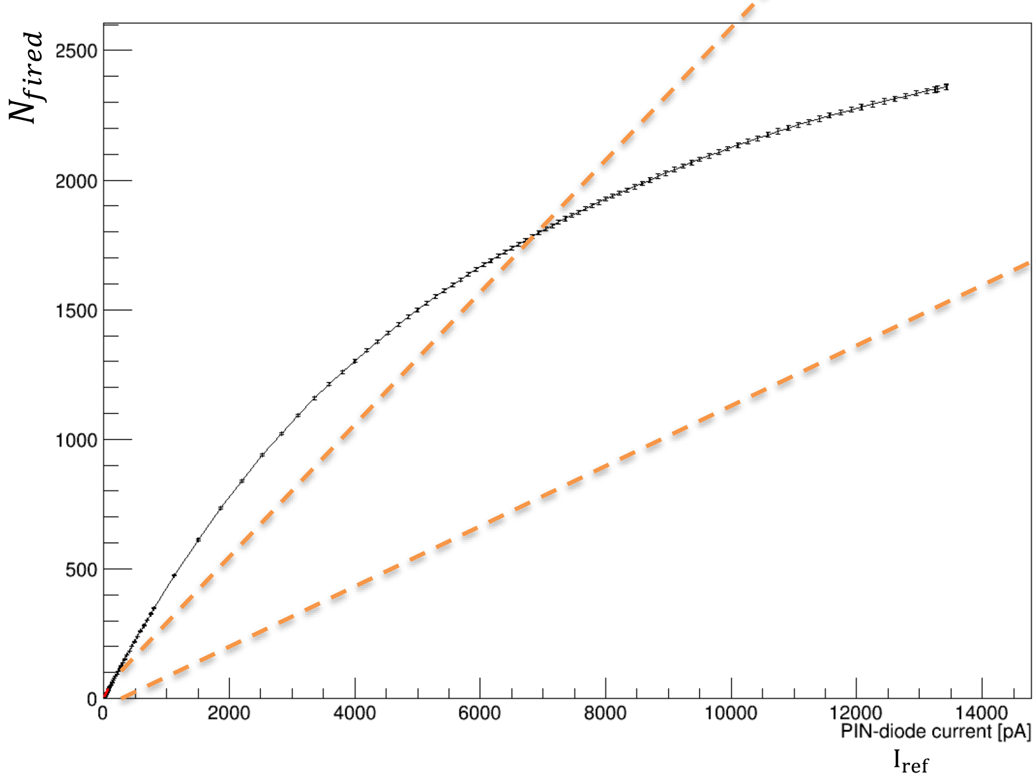
remember introduction:

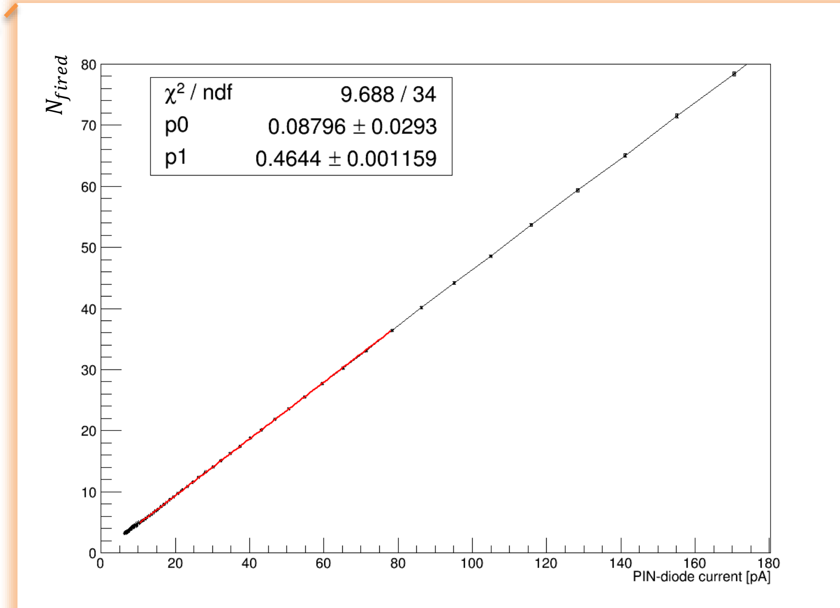
6. Estimate and plot N_{fired} vs laser tune:

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

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}!





In calibration region:

Definition of N_{fired}^{linear}:

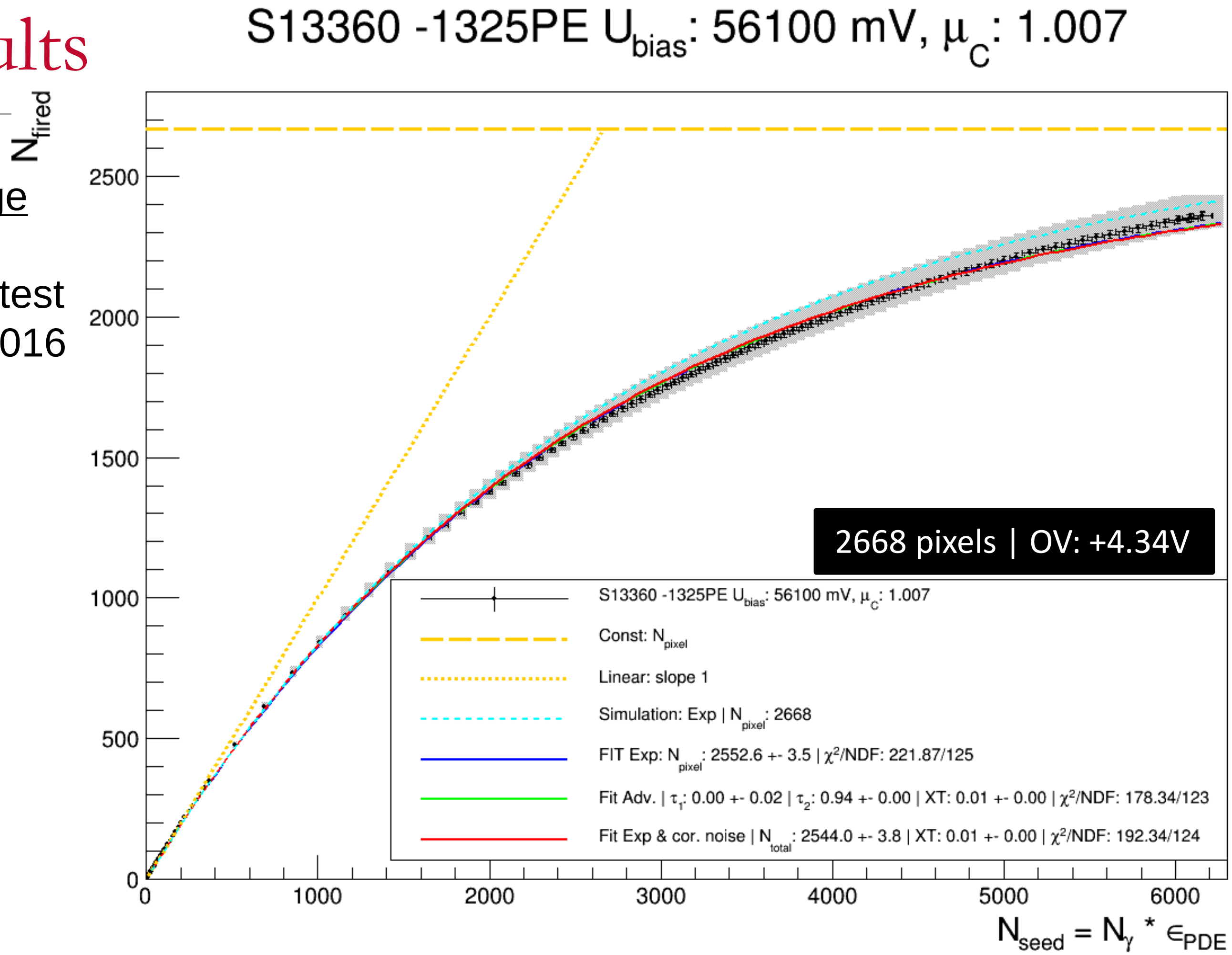
$$N_{fired}^{linear}(i) = p0 + p1 \cdot I_{ref}(i)$$

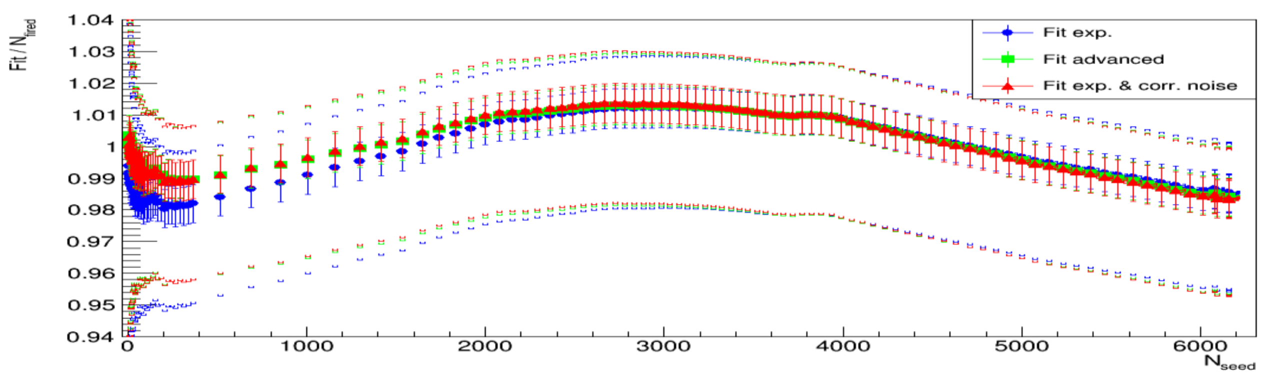
Definition of N_{seed}:

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

$\Longrightarrow$ convert reference current to number of seeds.

Results



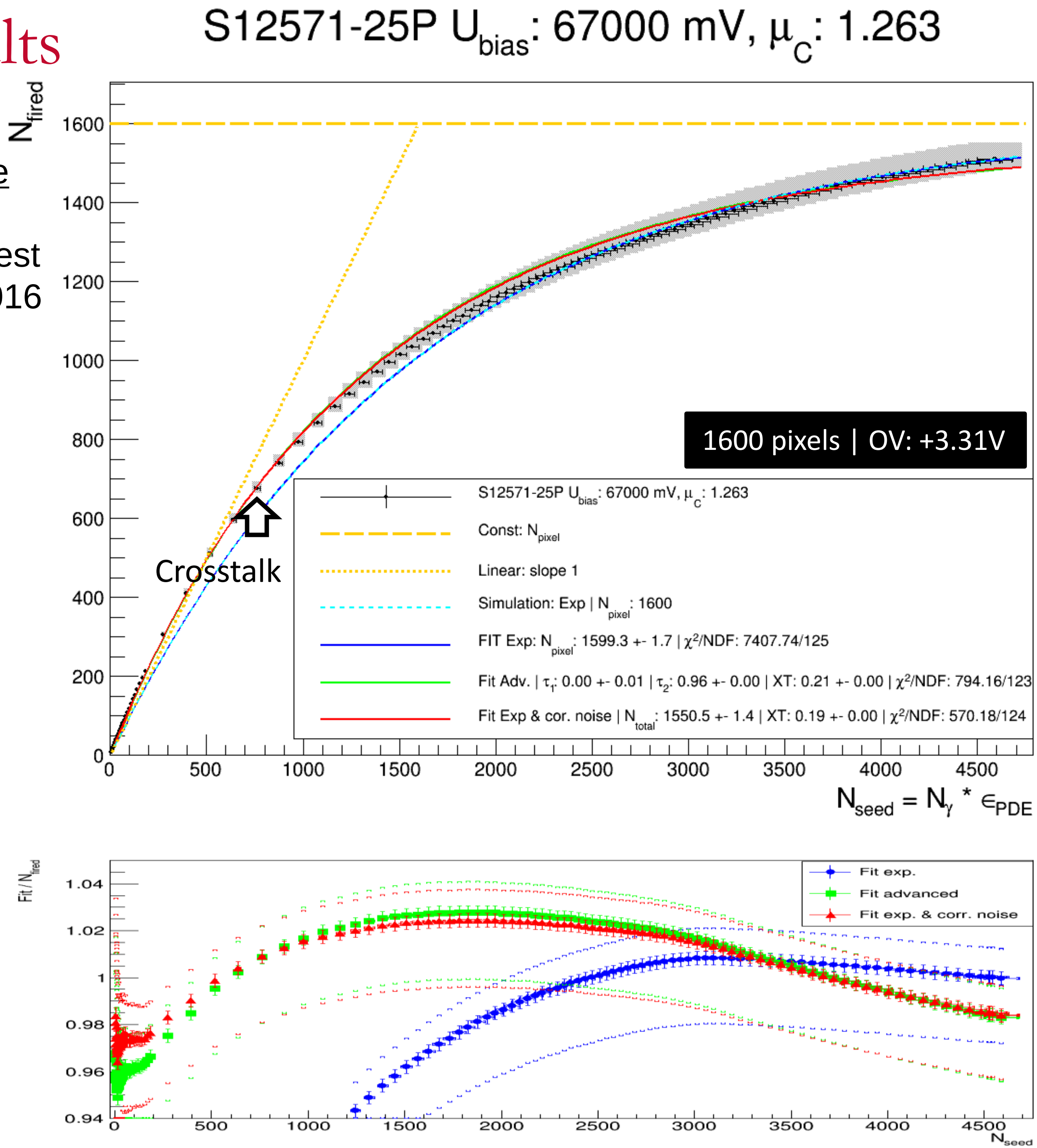


<u>SiPM bias voltage conditions:</u>
Same as during test beams 2015 & 2016

Fit Adv. (Katsu):
N_{total} = fixed
ϵ = 1.0 because of N_{seed}
AP seems correlated with XT and ϵ -> AP ignored.

τ_1 = 0 for all cases without over saturation.

Results



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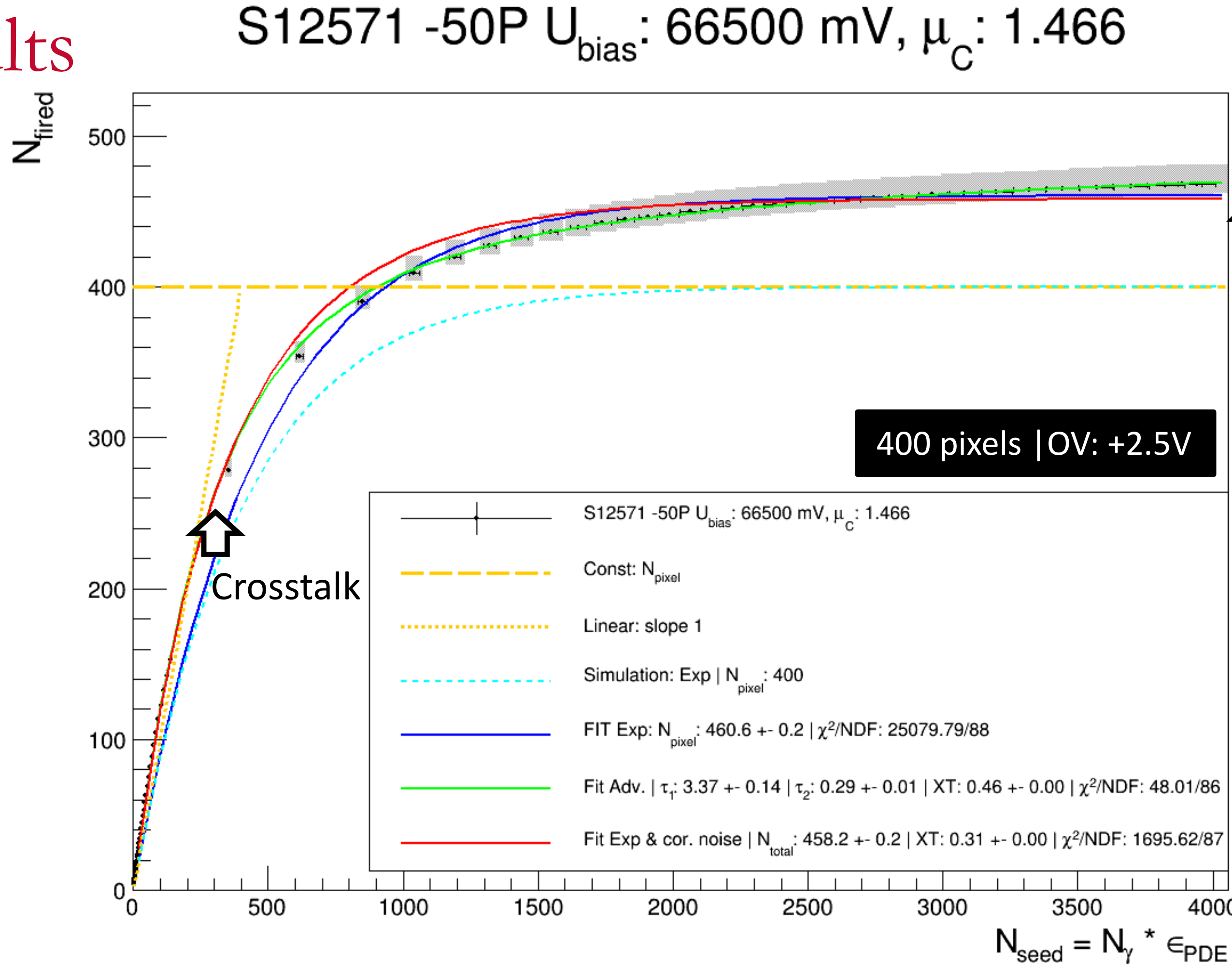
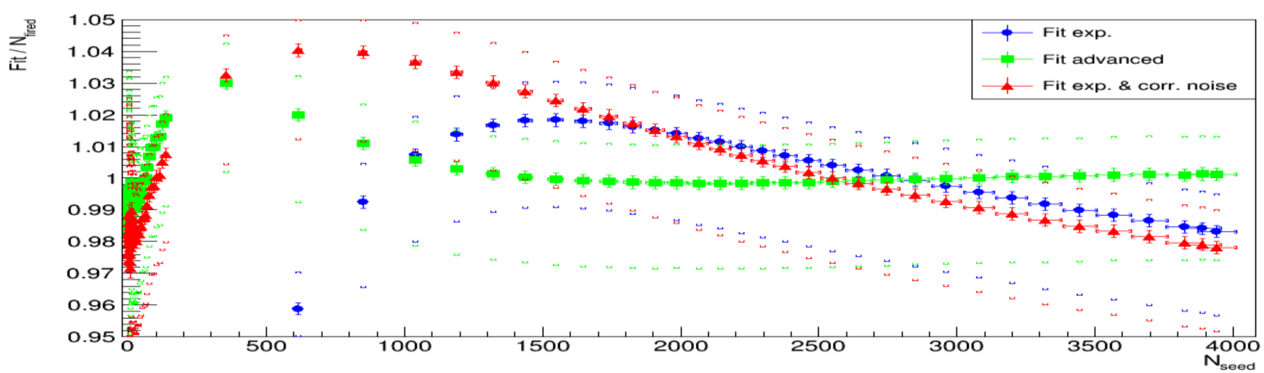


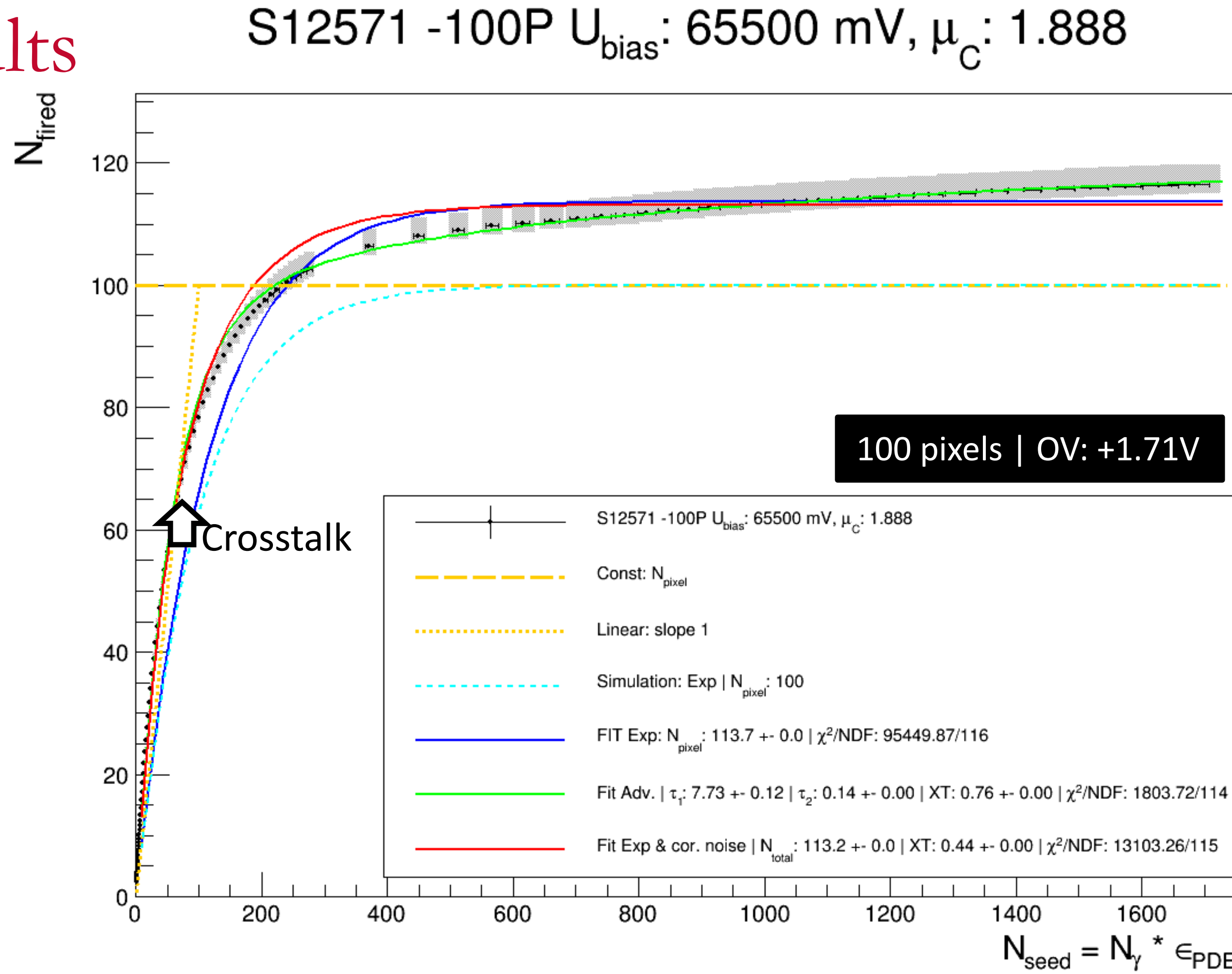
Recovery of pixels

Might be explained by delayed crosstalk and (not-handled) after pulses

$\tau_1 > 0$ for all cases with over saturation.



Results



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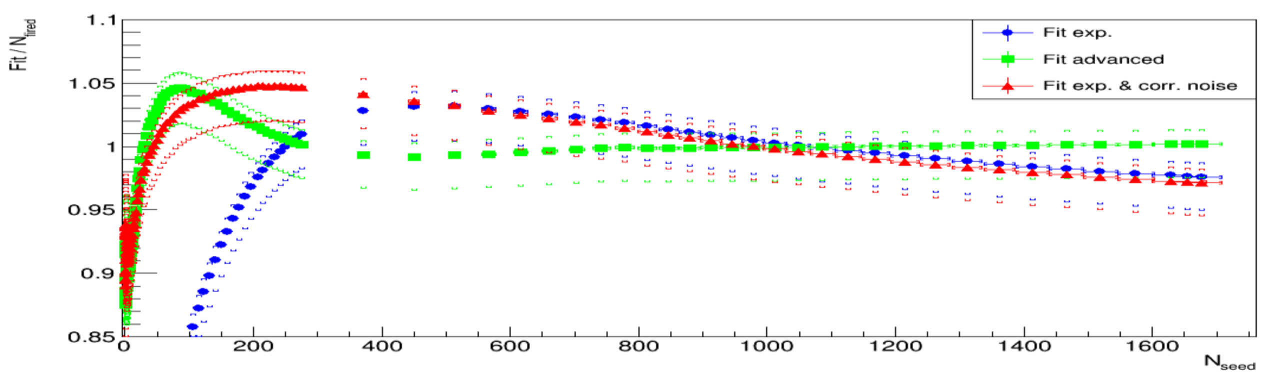
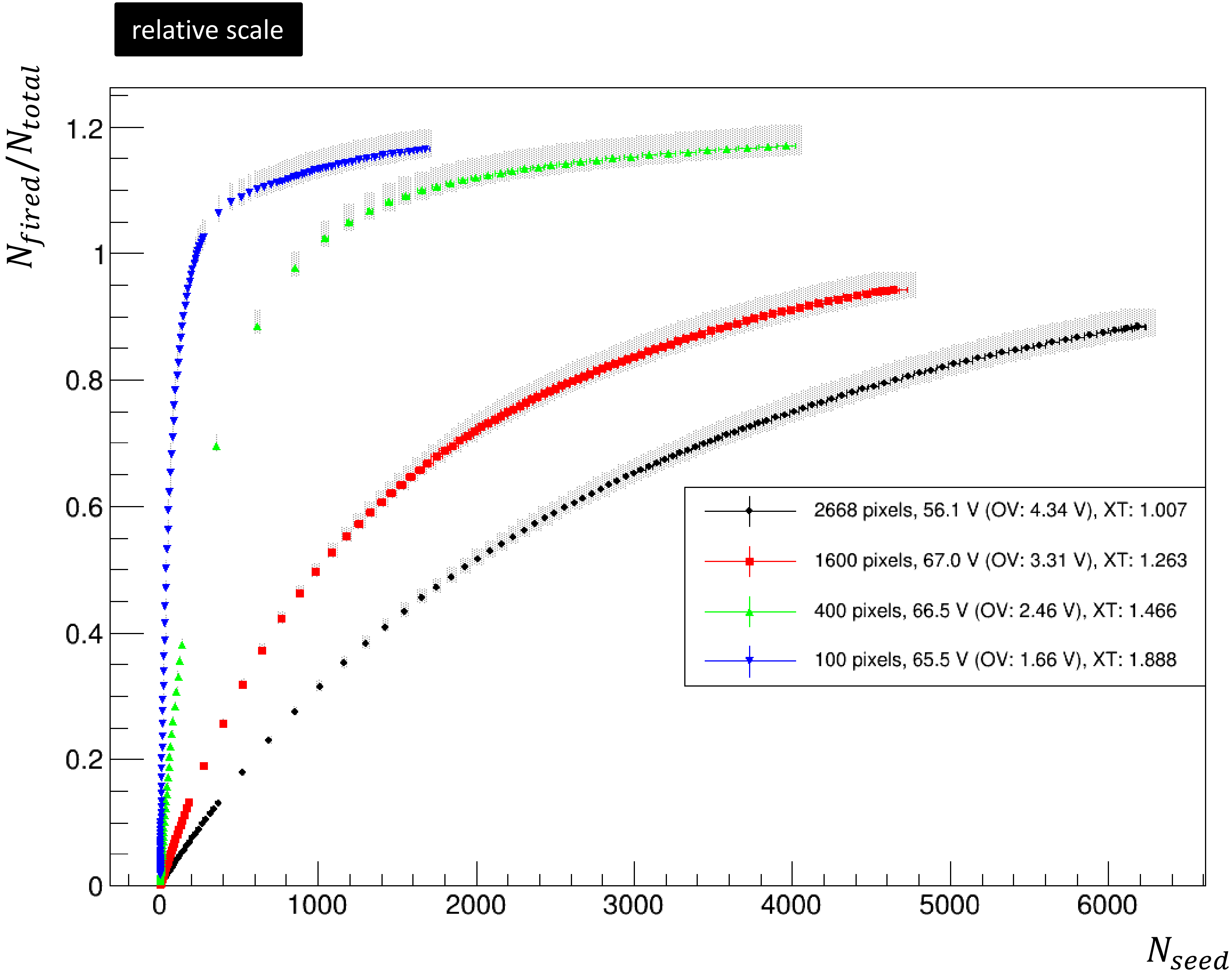


Combined SiPM Response Results



Conclusion

For 4 different SiPM:

Crosstalk measurement performed: μ_C (range between $1.007 \div 1.888$)

Response measurement:

100px and 400px SiPM:

- *Crosstalk* has a large influence.
- For high light intensities, an over-saturation has been observed (best handled by Katsu's function)

1600 and 2668 pixel SiPM:

- Influence of crosstalk:
  - 2668px: negligible
  - 1600px: lower, but still measurable influence.
- The light intensity (& low ε_{PDE}) is too low to reach the region of over-saturation.
- In the case of low crosstalk SiPMs:
  - XT-extended exp. response function shows a good agreement compared to Katsu's advanced function.

Next steps:

- Implementation in CALICE MC digitization and data reconstruction planned.
- Combined SiPM+tile measurement with UV laser

Questions? ☺

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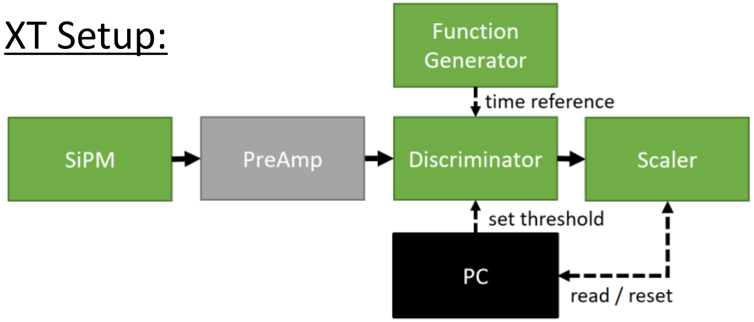
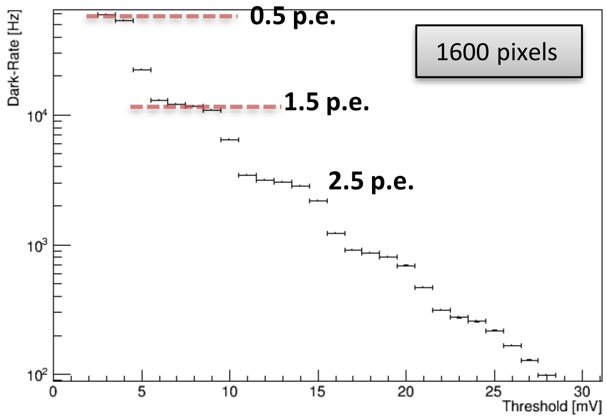
SiPM crosstalk (XT) measurement

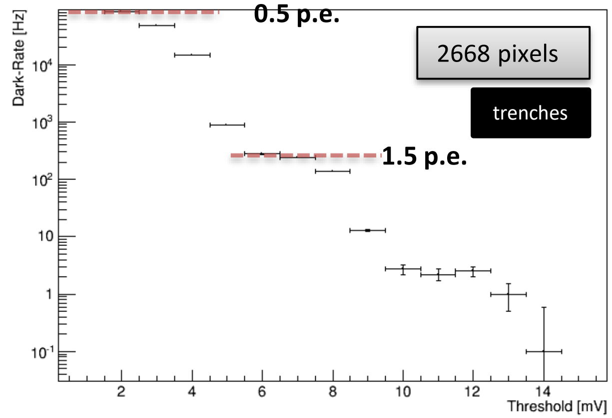
XT Setup:



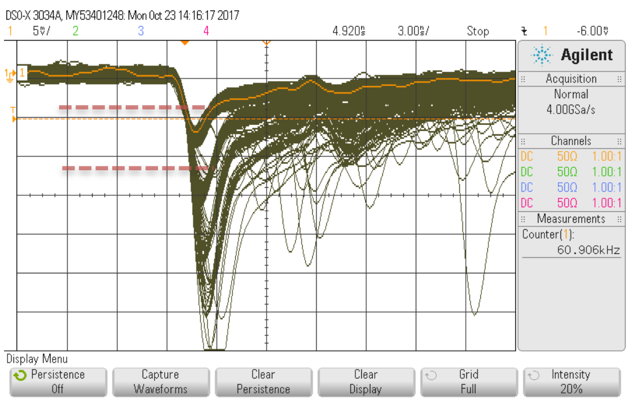
Same SiPM operating conditions as during response measurements.

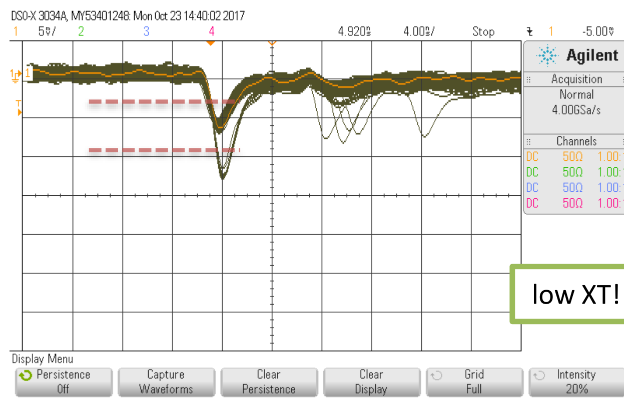
DCR:





Scope:

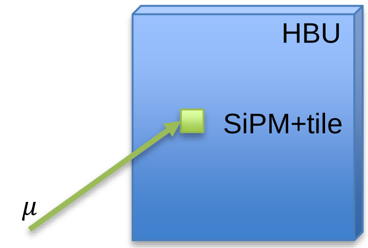




low XT!

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

Implementation in CALICE ?



Default Digitization process:

Crosstalk effect not handled at all:

- LY-calibration is also crosstalk affected!

Ahc2MIP2GeVProcessor: Convert MC energies from GeV to MIP, using a GeV->MIP factor from simulation.

Ahc2ROCThresholdProcessor: Add sub hits, apply 0.5MIP threshold.

Ahc2SiPMStatisticsProcessor:

- MIP -> #pixels: $N_{seed} = E_{MIP}^{MC} \cdot \boldsymbol{LY}$
- Saturate using exp. function: $N_{fired}^{*} = f^{exp}(N_{seed})$
- Binomial smearing $N_{fired} = smear(N_{fired}^{*}, N_{total})$
- #pixels -> ADC: $ADC = N_{fired} \cdot gain$

If we want to use Katsu's advanced SiPM function, we have to use a LY-calibration which is corrected for correlated noise:

$$LY_{seed} = \frac{LY}{\mu_C}$$

In reconstruction:

ADC is converted to Pixels, de-saturated and converted to MIP.

Prediction:

For low number of MIPs, the difference should be small, since the XT is constant and the saturation effect low.

For rising number of MIPs, the crosstalk effect will get smaller, since there are less non-hit pixels on the SiPM. Since the LY is enlarged by a constant XT, the digitized Energy will be higher than it actually is in the default mode. The advanced function with XT corrected LY can handle this effect.

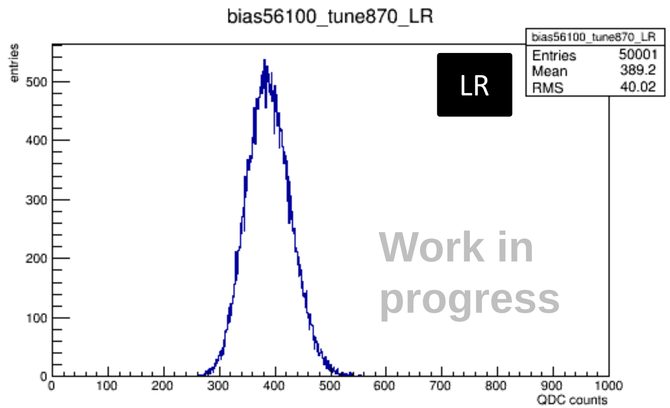
For large number of MIPs, an over-saturation can be described with the advanced function.

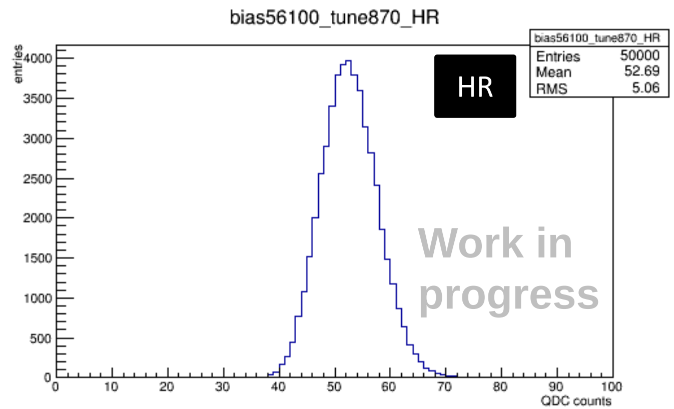
SiPM Saturation: Procedure for latest SiPM (2668 pixels)

3. High Range to Low Range conversion:

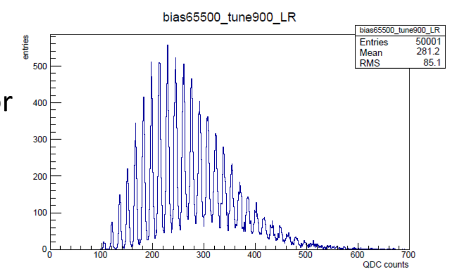
The QDC has a LR and HR amplification.

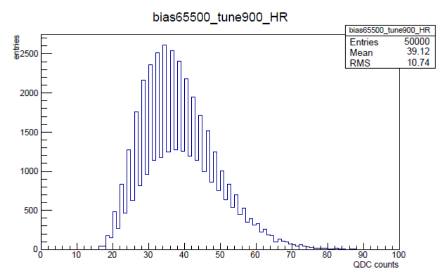
Same events with QDC LR (left) and HR (right) amplification.



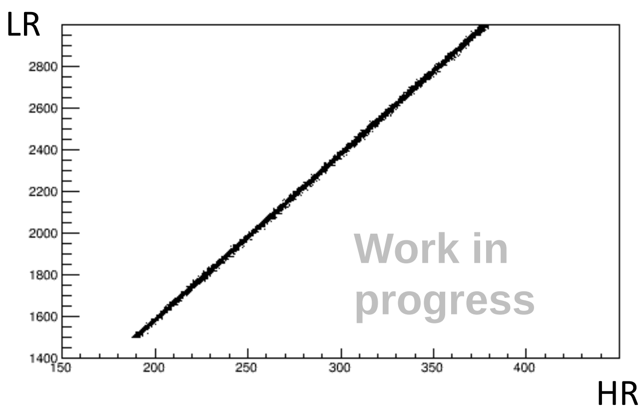


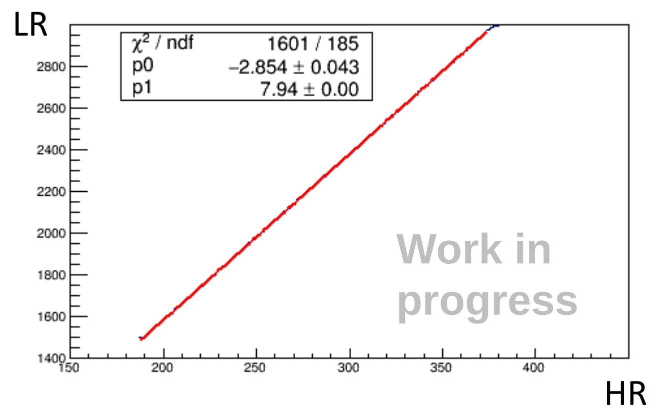
How it looks like for a 100 pixel SiPM with higher gain:





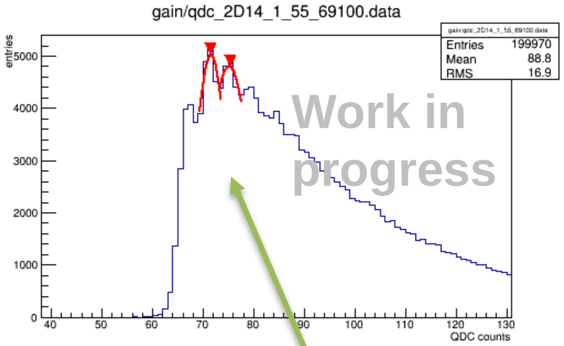
LR vs. HR.
Fit used for conversion.

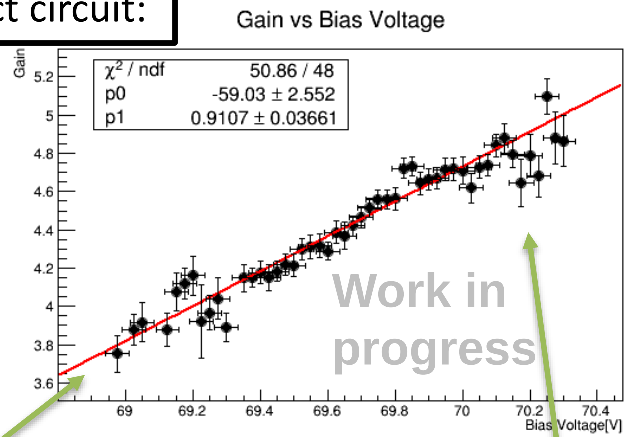


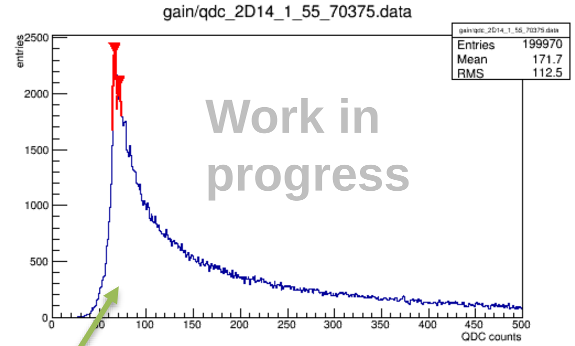


Need for Preamplifier for 1600pix SiPM

No gain measurement possible with direct circuit:







Too low bins to get precise information.

Gain measurement hard to judge. High noise (AP) affects SPS -> Peakfinder suffers:

Use preamplifier:

Issue: PreAmp is only linear in a known range.

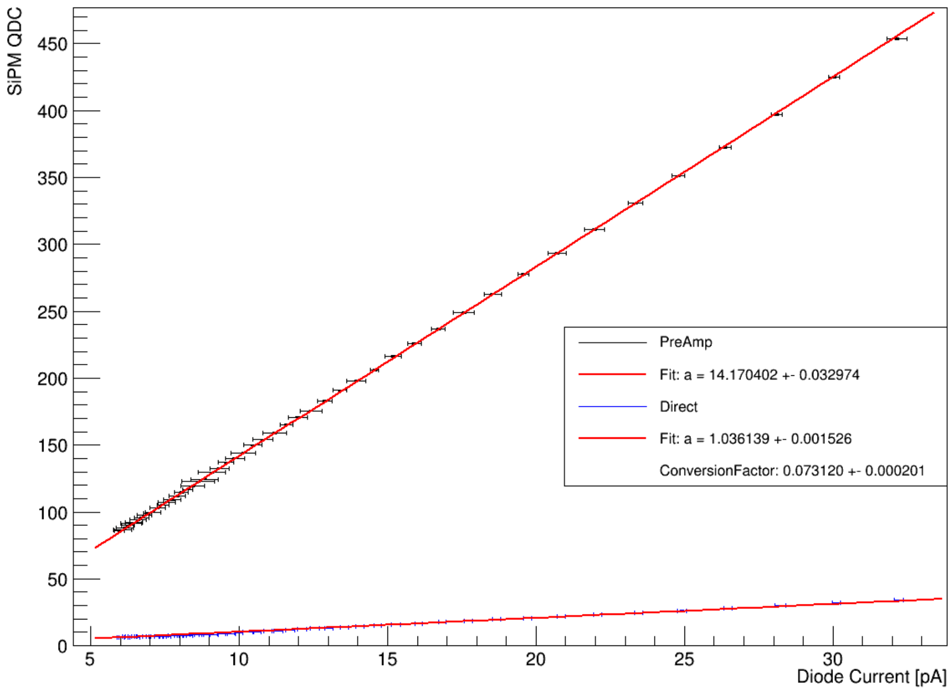
Plan: Measure saturation twice without changing optics:

1. with DirectBox
2. with PreAmp in linear range

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

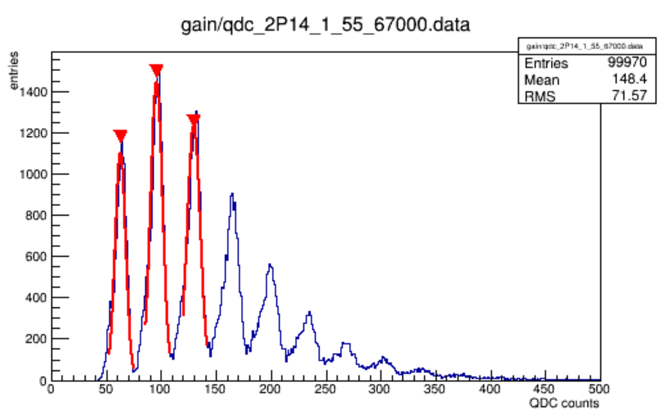
-> gain_Direct = 2,457 +-0,015

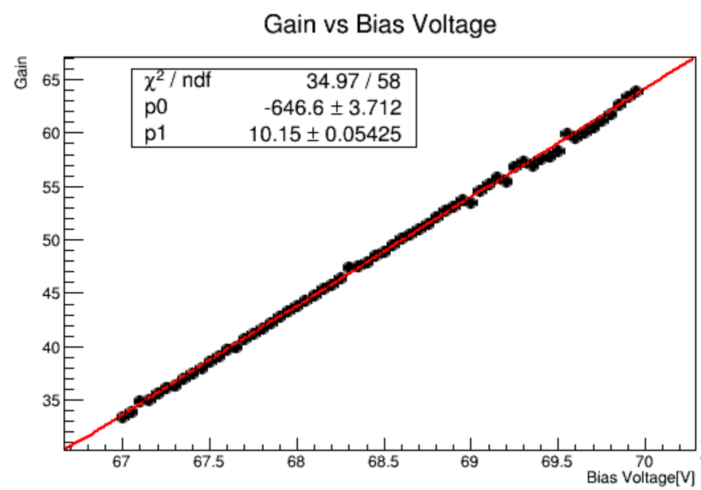
$$\Delta\alpha = \sqrt{\left(\frac{\Delta a_D}{a_P}\right)^2 + \left(-\frac{a_D \cdot \Delta a_P}{a_P^2}\right)^2}$$

$$gain_D = \alpha \cdot gain_P$$

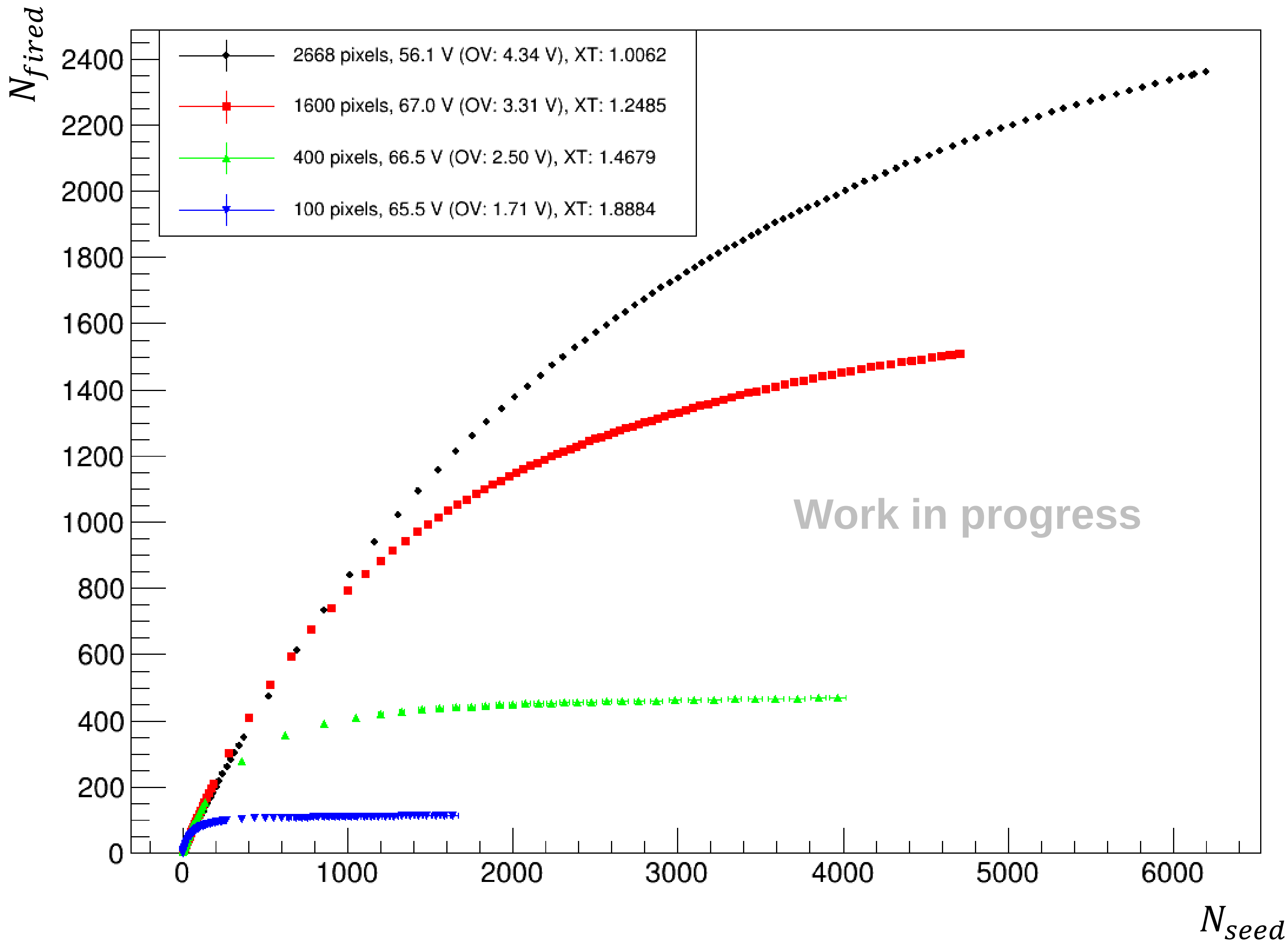
$$\Delta gain_D = \sqrt{(\Delta\alpha \cdot gain_P)^2 + (\alpha \cdot \Delta gain_P)^2}$$

Gain Measurement with PreAmp:

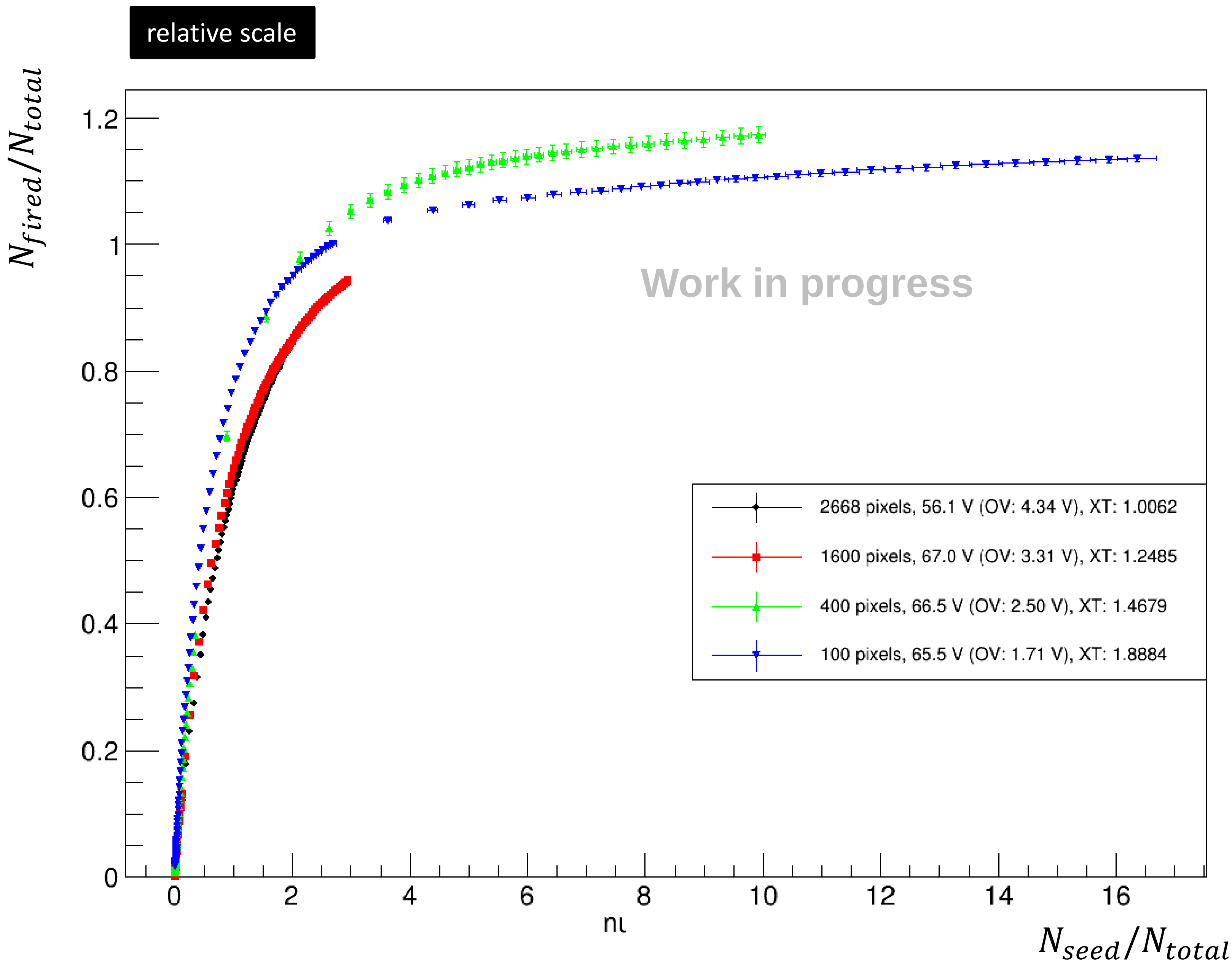




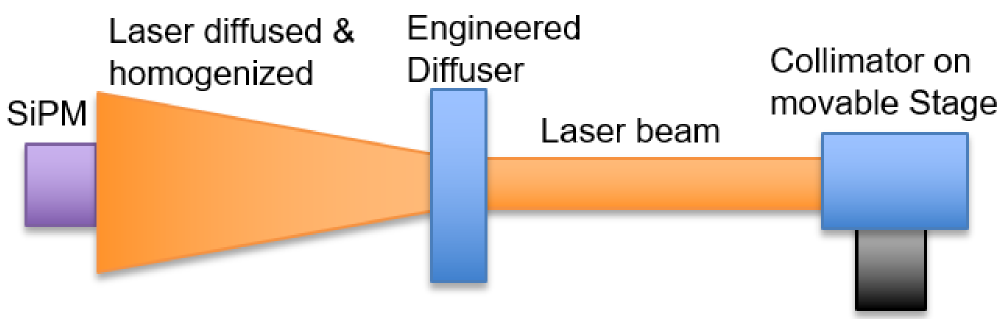
Combined Saturation Measurement Results

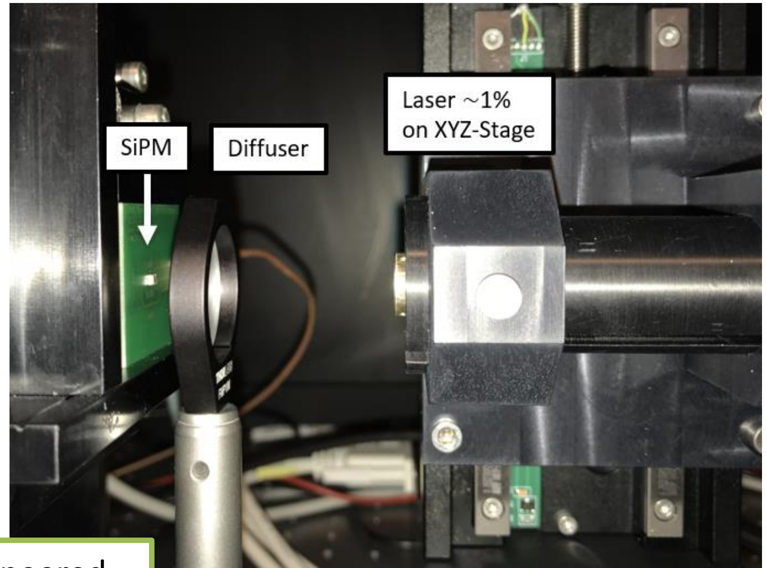


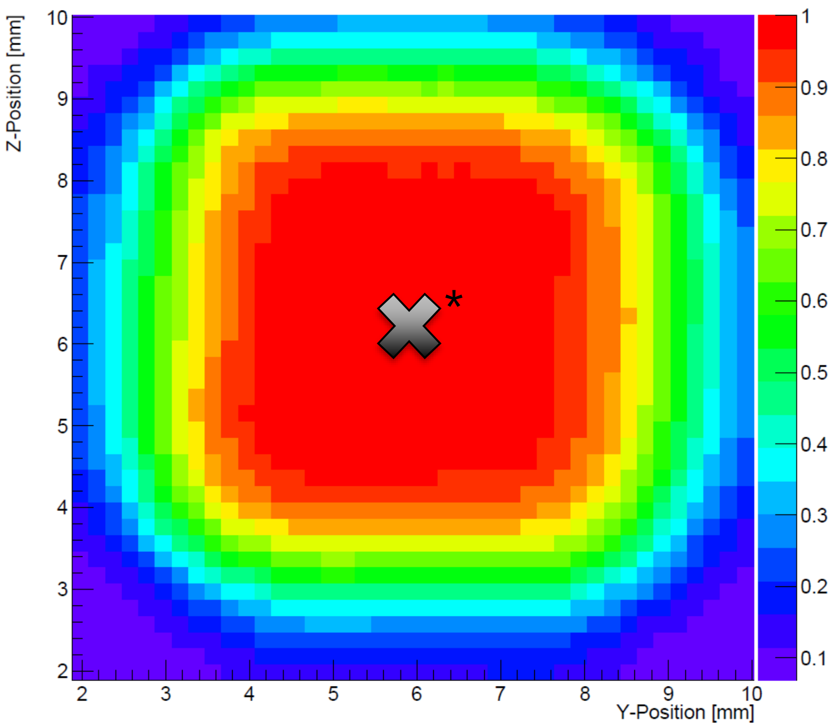
Combined Saturation Measurement Results



Engineered Diffuser Scan







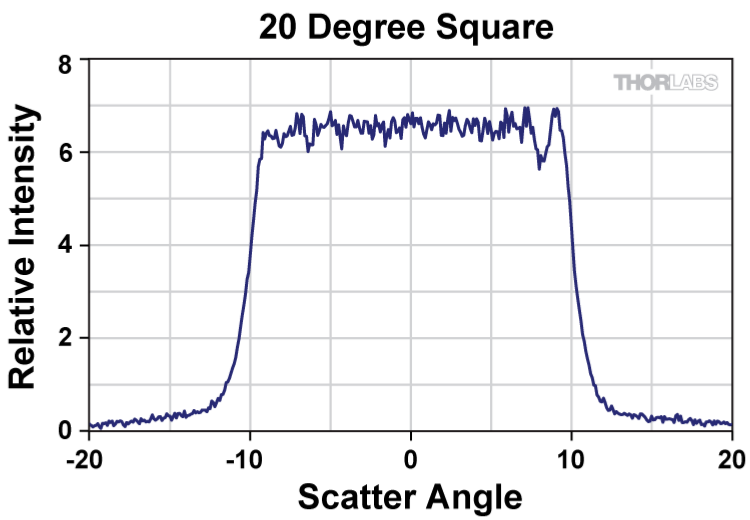
The uniformity of the Engineered Diffuser was tested in a separate measurement. It converts a gaussian beam profile in a so-called top-hat profile with uniform intensity.

Measured with 1600pix SiPM with 1x1mm² 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.

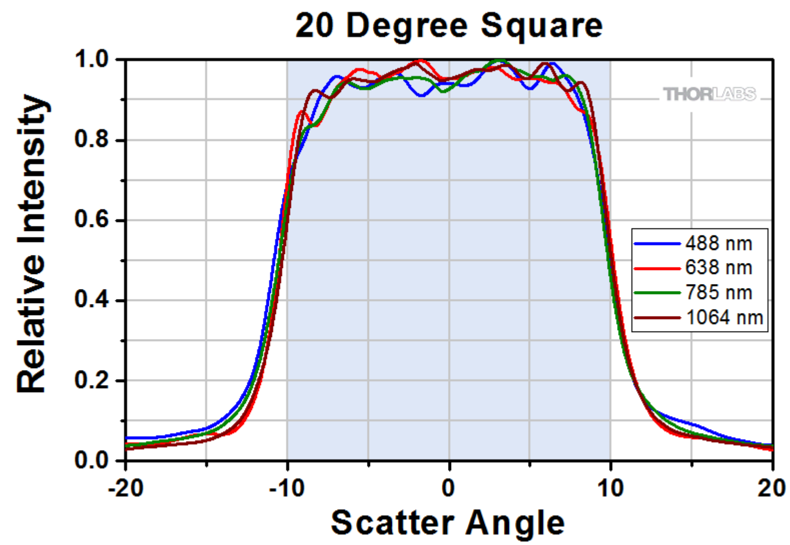
*Position used during saturation measurement.

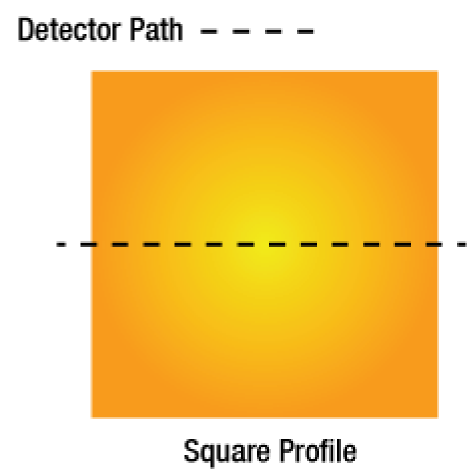
Diffusor: Thorlabs provided data

Thorlabs:
Theoretical Data



Thorlabs:
Measured Data





Katsu’s advanced SiPM function

Katsu‘s advanced SiPM function includes NLO corrections:

6 parameters:

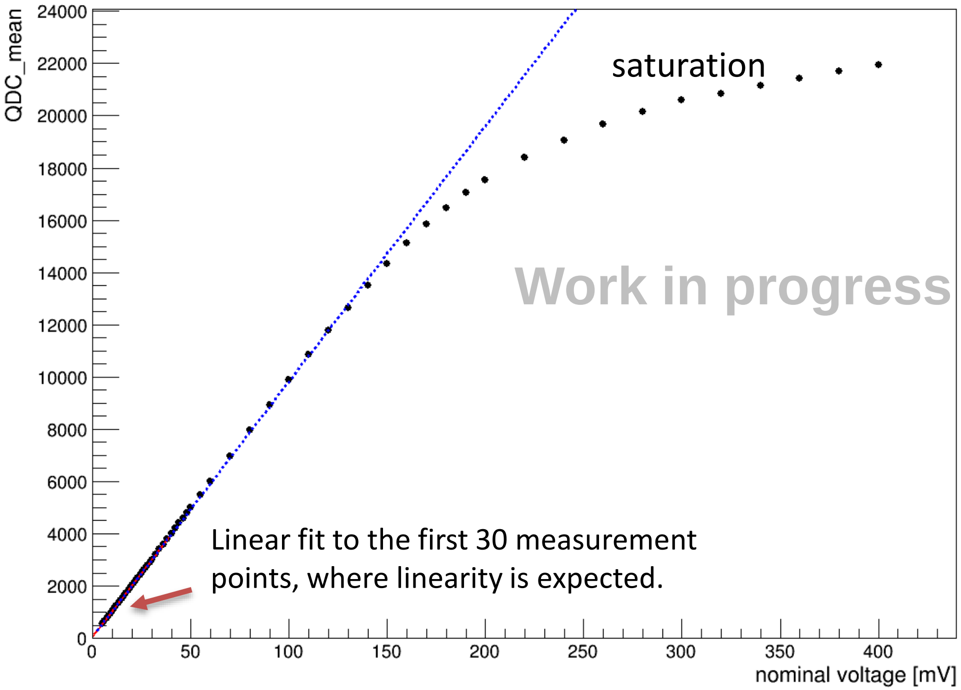
- #pixels, fixed to real number of pixels
- scale factor, fixed to 1
- 2x decay-/recovery time variables, describe over-saturation
- Crosstalk- & Afterpulse prob. includes correlated noise

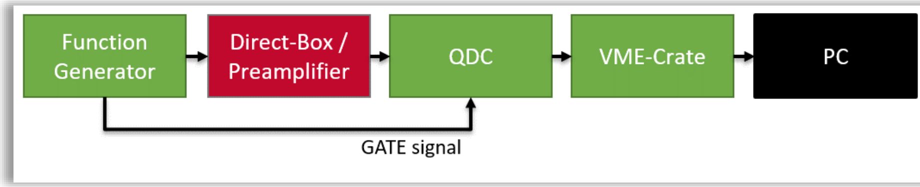
```
Double_t tquenchPfour ( Double_t *x, Double_t *par )
{
        Float_t xx = x[0];
        Double_t f = par[0] * (1 - std::exp( - xx*par[1]/par[0] ) );
        Double_t ff = f  + par[3] * ( xx*par[1] - f ) ;
        f = ff * ( par[2] + 1)/(par[2] + (xx*par[1]/f)) ;
        f = f * ( 1 + par[4]*std::exp( - xx*par[1]/par[0]  )) * ( 1 + par[5] );
        return f;
}
//{#pixels, scalefactor=1, timeConstant1, timeConstant2, Crosstalk, Afterpulse}
```

First order exp. behavior as before

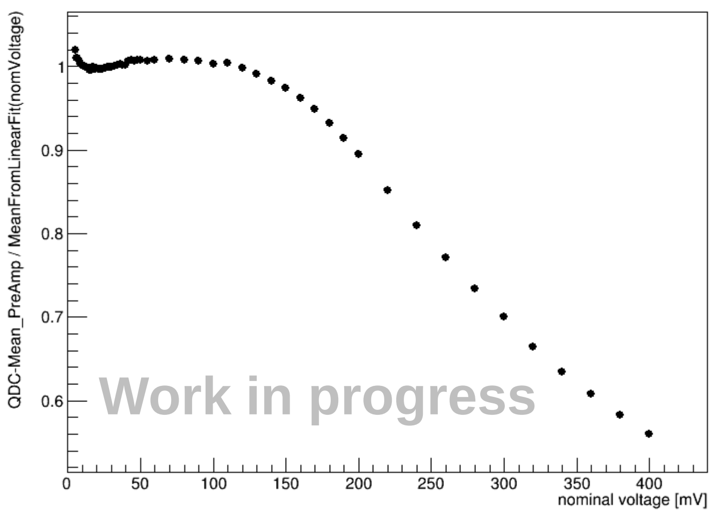
by: K. Kotera

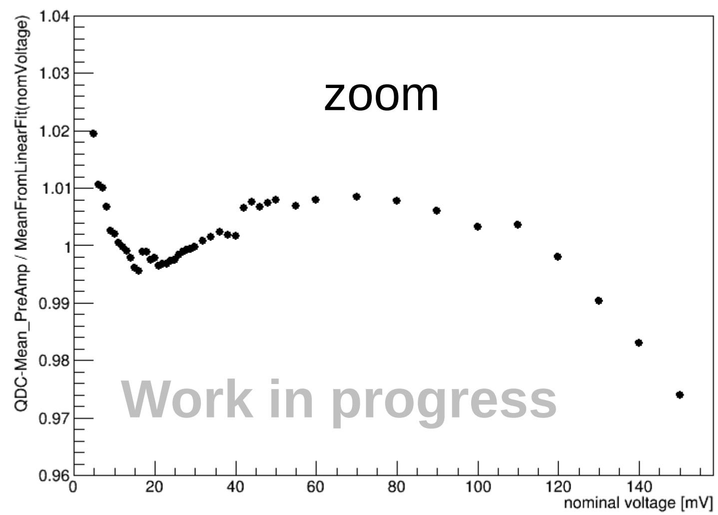
PreAmp Characterization



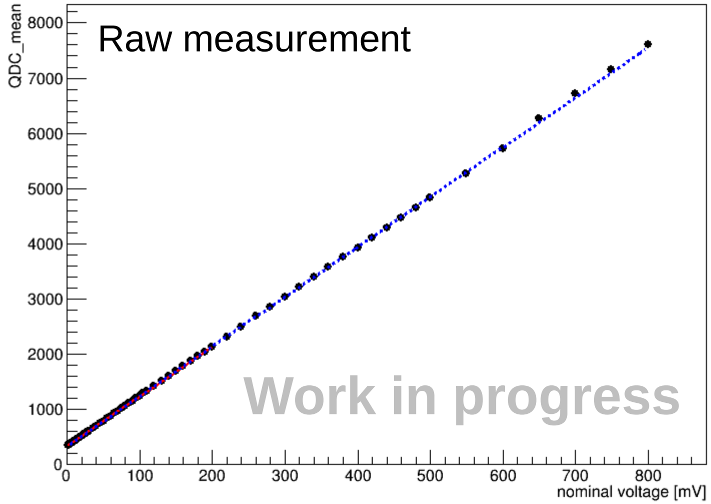


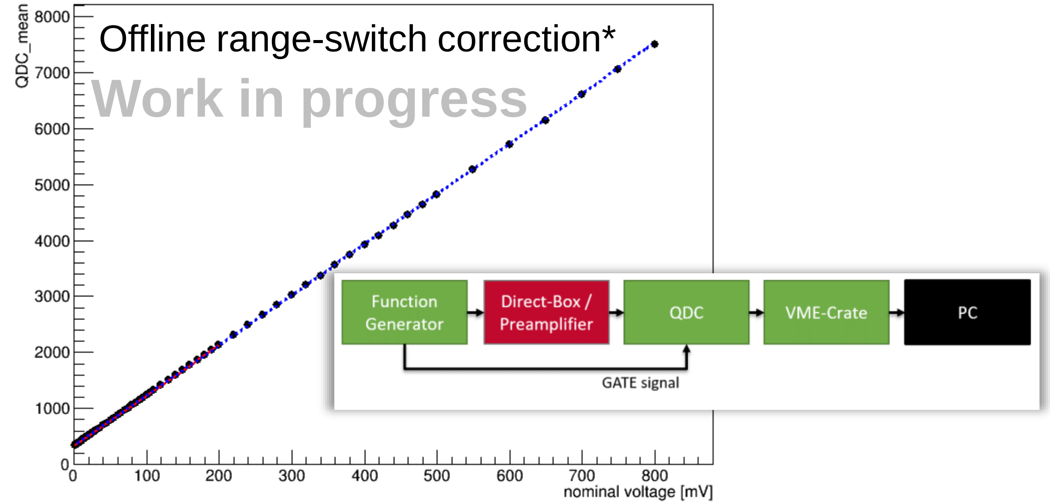
A clear saturation of the preamplifier is visible, starting around > 130 mV input voltage, which corresponds to a resulting output voltage of around 1V , assuming the amplification is 8. For lower values, the linearity is given by approx. 1 to 2 %.

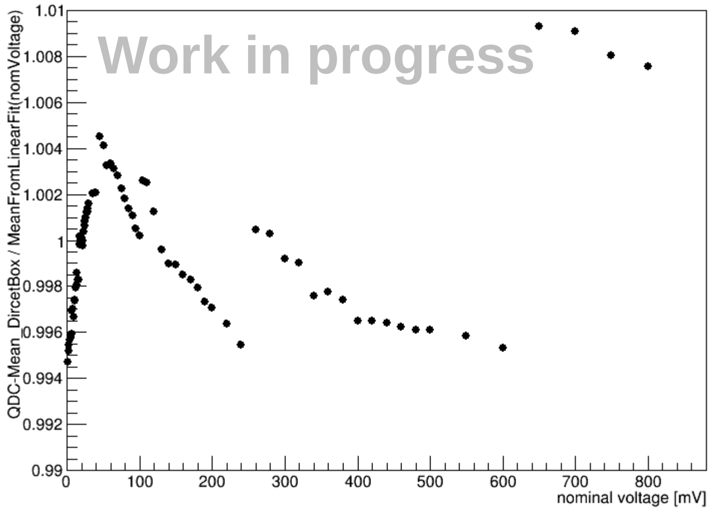


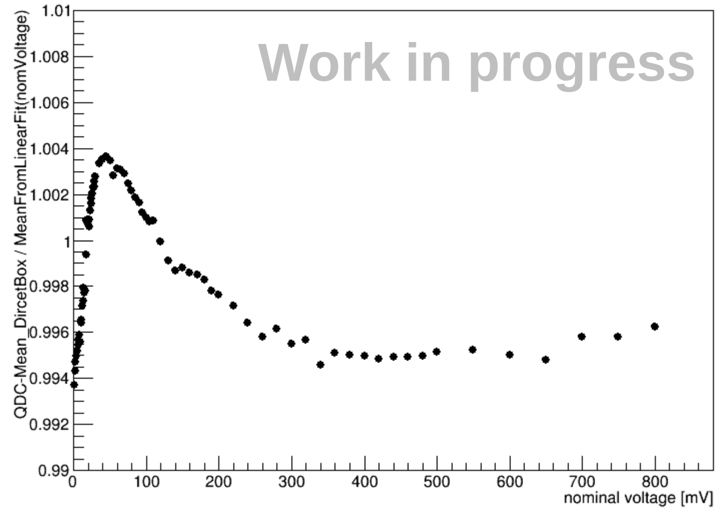


Direct Box Characterization (linear within 1% dev.)









*

at the position of change:

g_QDC_mean_correction[fileNumber] = ((g_QDC_mean[fileNumber-1]-g_QDC_mean[fileNumber-2]) + g_QDC_mean[fileNumber-1])-g_QDC_mean[fileNumber];

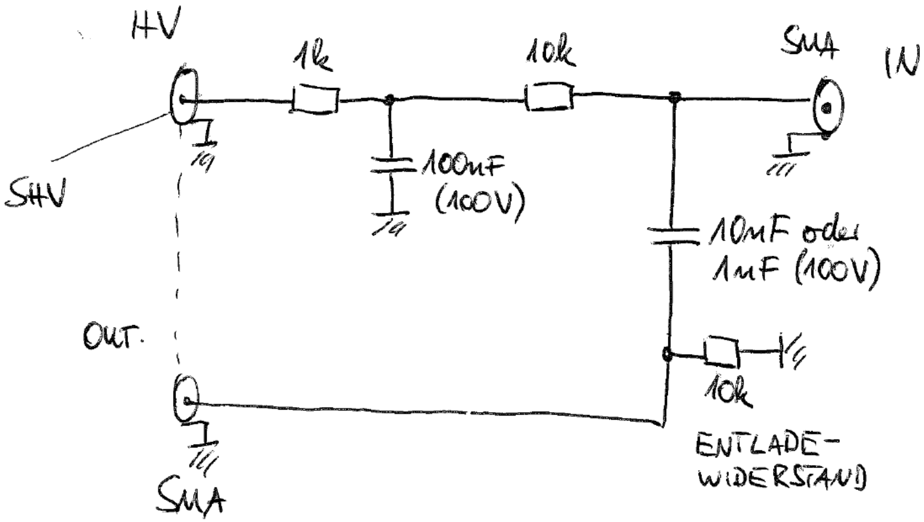
at the following positions without further change:

g_QDC_mean_correction[fileNumber] = g_QDC_mean_correction[fileNumber-1];

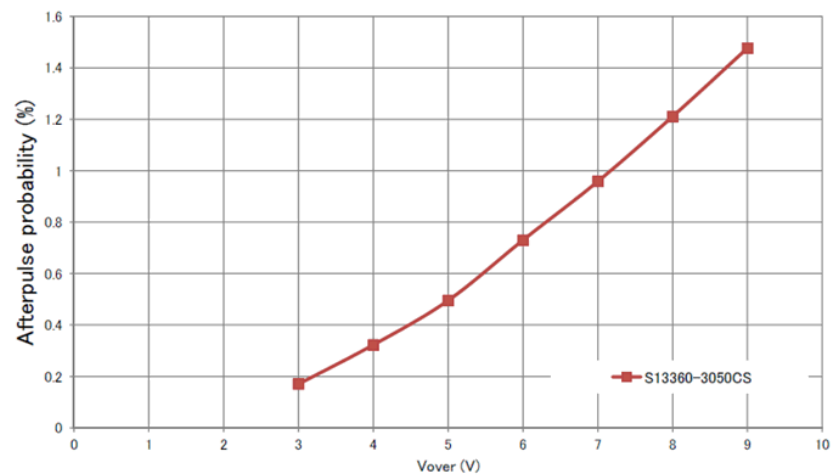
Correction:

g_QDC_mean[fileNumber] = g_QDC_mean[fileNumber] + g_QDC_mean_correction[fileNumber];

Direct Box Circuit & After Pulse Prob.



- S1336x Series (25, 50, 75 μm)



- **Afterpulse probability depends on Vover**

Digitization

```
/*---------------------- simulate SiPM behaviour ---------------------------*/
    //        energy mips to pixels
    //        saturate
    //        smear
    //        unsaturate
    //        energy pixels to mip

Ahc2SiPMStatisticProcessor:

float simHitPx = simHitMIP * lightYield;                                          // energy MIP -> pixels
float satHitPx =  satFunc->saturate( simHitPx );                                  // saturate
float prob = satHitPx / satFunc->getNeffPix();                                    // calculate p for binomial smearing
float satSmearedHitPx = _randomGenerator->Binomial(satFunc->getNeffPix(), prob);  // binomial smearing
if(_physicsMode)
        simHitADC = satSmearedHitPx * gainValue / interCalibrationValuePhys;      //energy pixels -> ADC
else
        simHitADC = satSmearedHitPx * gainValue;
```

In reconstruction, ADC is converted to Pixels, de-saturated and converted to MIP.

Statistical Method

3.2 Borel model of correlated noise

As shown in [7, 6], a possible model to describe the generation of correlated noise is by a Borel distribution

$$\Pi_k(\xi) = B_{k+1}(\xi) = \frac{((k+1)\xi)^k e^{-(k+1)\xi}}{(k+1)!}. \tag{11}$$

Such a model depends on a single parameter - ξ - taking values in the interval $[0, 1]$ and representing the average number of correlated counts that are generated at each step of the chain. The expected value

$$\mu = \frac{1}{1-\xi} \tag{12}$$

then gives the average number of correlated noise counts that are generated over the full chain.

3.3 Equations for the Borel model

Since the number of parameters has been reduced to two (λ and ξ), one may try and consider just two equations to be solved simultaneously. By choosing the two equations obtained from 9 for $k = 0$ and $k = 1$, the system may be reduced to

$$\begin{cases} \lambda = n_{21} - \xi e^{-\xi} \\ \xi\left(e^{-\xi} - 1\right) = n_{21} + \log n_1 \end{cases}, \tag{13}$$

where

$$n_{21} = \frac{N_2}{N_1}, \tag{14}$$

is the ratio between the areas of first two peaks in the charge spectrum.

With:

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)

$$n_1 = \frac{N_1}{N_0}$$

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

$$\mu = \frac{1}{1-\xi}$$

Reference: https://arxiv.org/pdf/1710.11410.pdf

JG|U

Factor of correlated pixels fired

To estimate the average number of correlated pixels fired, the **Borel Model of correlated noise** is used as described in detail in:
https://arxiv.org/pdf/1710.11410.pdf by Enrico Junior Schioppa

Borel Model:

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

With:

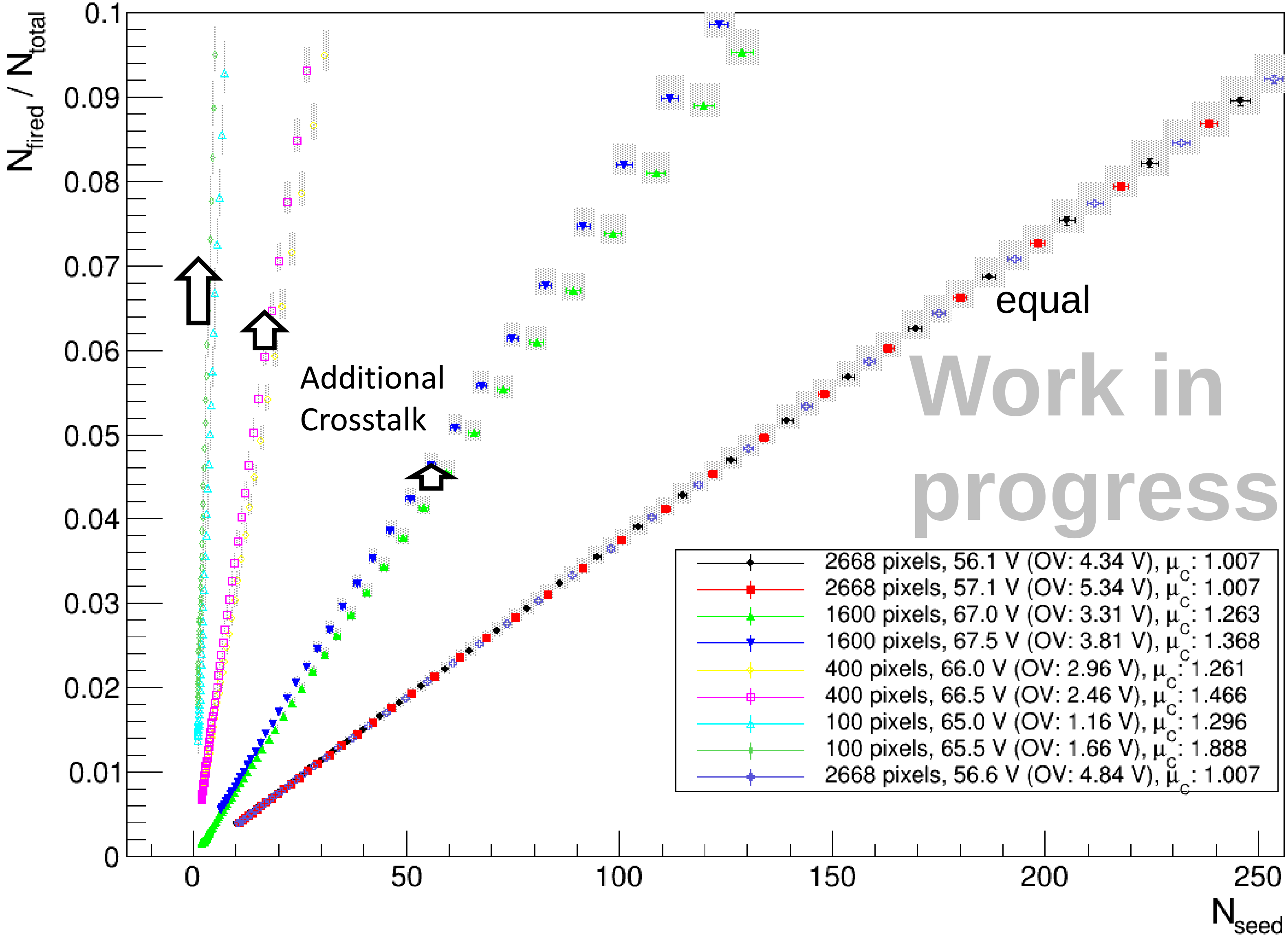
N_0 = total number of events

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

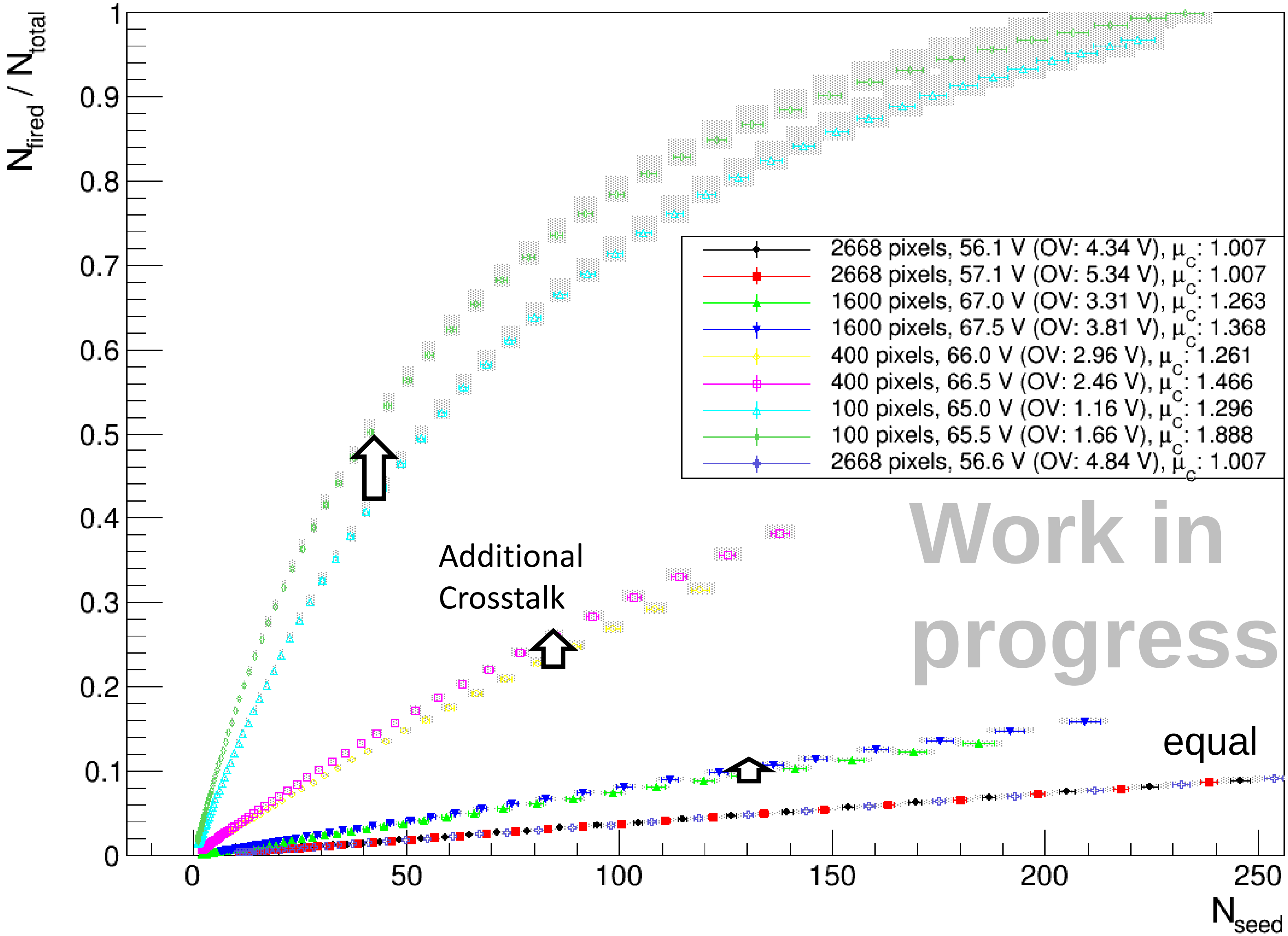
N_2 = events with exactly 1 XT (2 pixels fired in total)

SiPM MPPC	N_{total}	$P(\geq 1XT)$	N_0	N_1	N_2	ξ	μ_C
S13360 -1325PE	2668	0.54%	46789	46535	251	0.006	1.006
@ U_{over} = 4.34 V		±0.65%	(100%)	(99.46%)	(0.54%)	±0.077	±0.078
S12571 -25P	1600	21.22%	56123	44211	8819	0.208	1.263
@ U_{over} = 3.31 V		±0.39%	(100%)	(78.78%)	(15.71%)	±0.015	±0.024
S12571 -50P	400	27.98%	99877	71935	17380	0.318	1.466
@ U_{over} = 2.46 V		±0.29%	(100%)	(72.02%)	(17.40%)	±0.009	±0.019
S12571 -100P	100	38.18%	71307	44082	13420	0.470	1.888
@ U_{over} = 1.66 V		±0.28%	(100%)	(61.82%)	(18.82%)	±0.008	±0.028

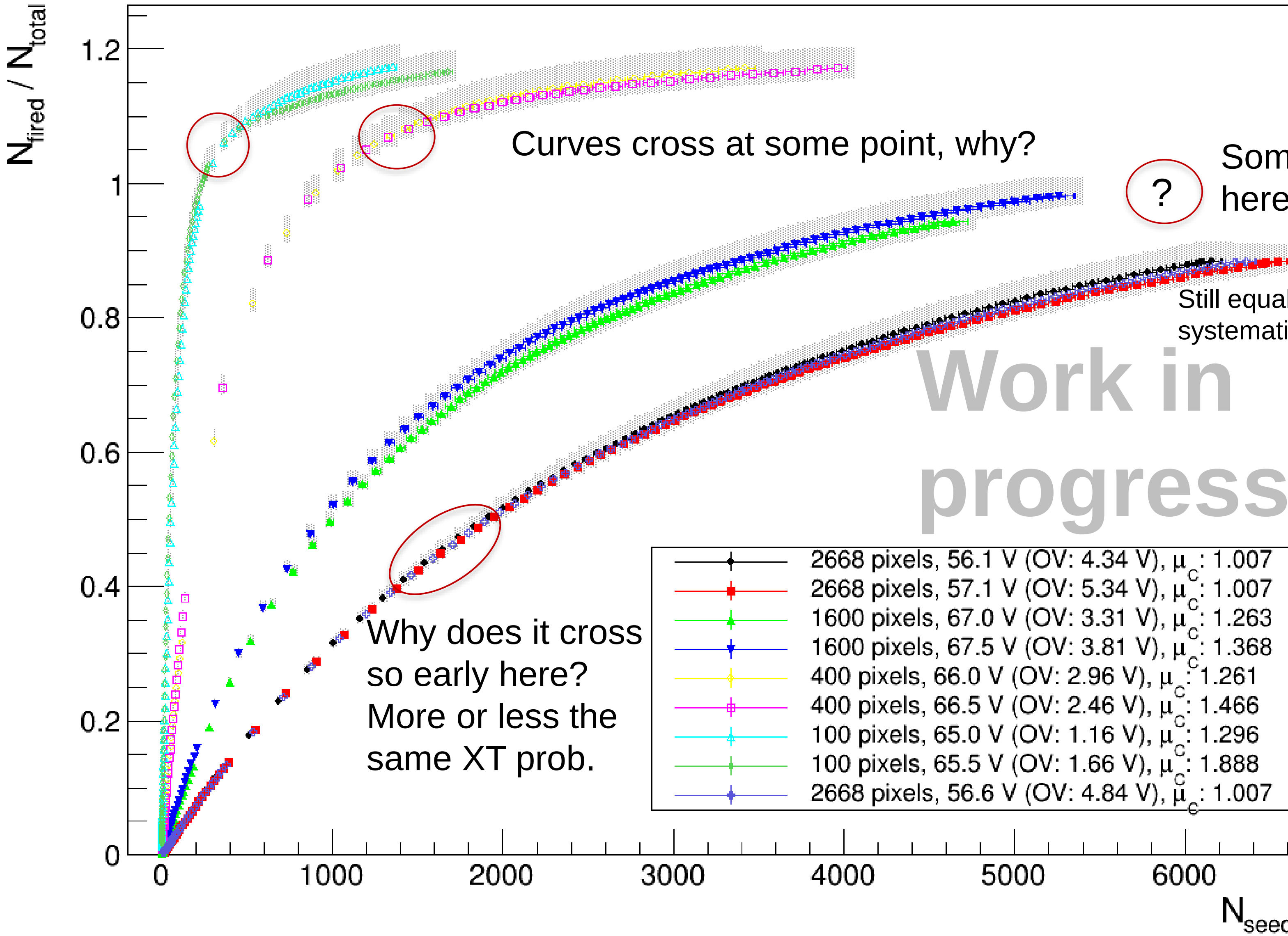
Different Bias Voltages: Low Light Region



Different Bias Voltages: Mid. Light Region



Different Bias Voltages: Full Range



After pulses might play a non-negligible role which influences the definition of N_{seed}... Adds an additional sys. uncert. to X-Axis.

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PRISMA DETECTOR LAB

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