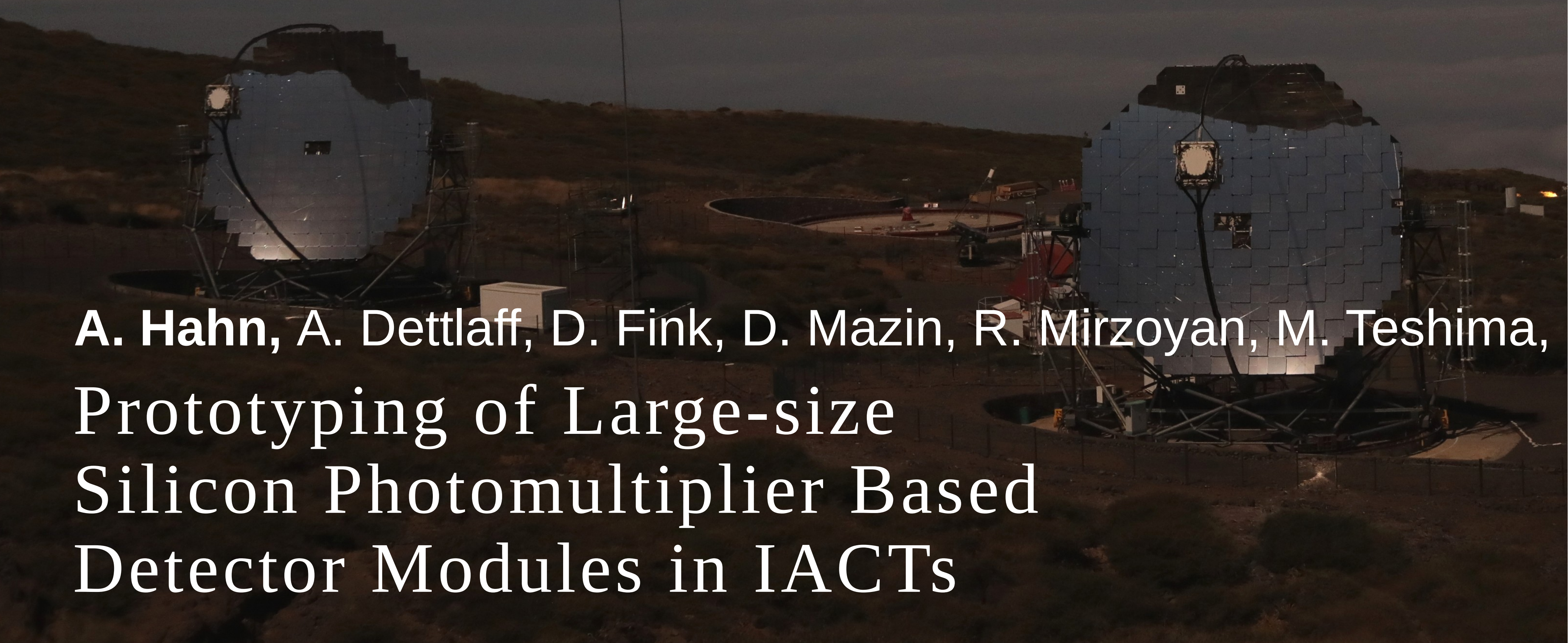
MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

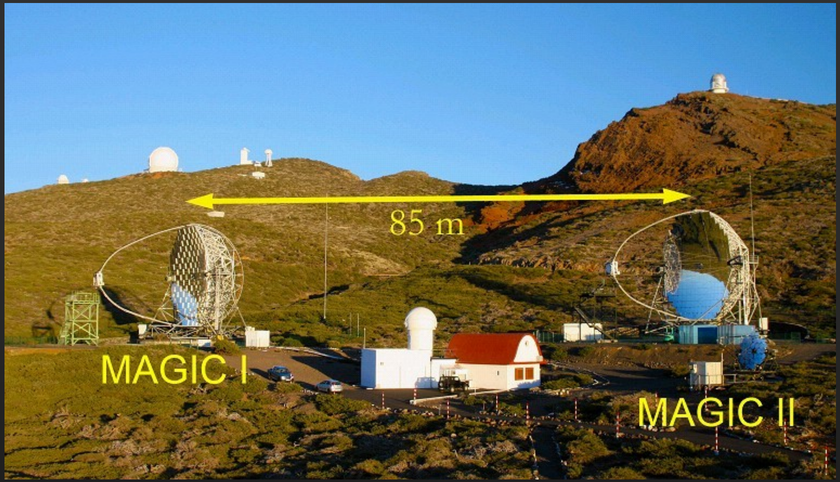


A. Hahn, A. Dettlaff, D. Fink, D. Mazin, R. Mirzoyan, M. Teshima,

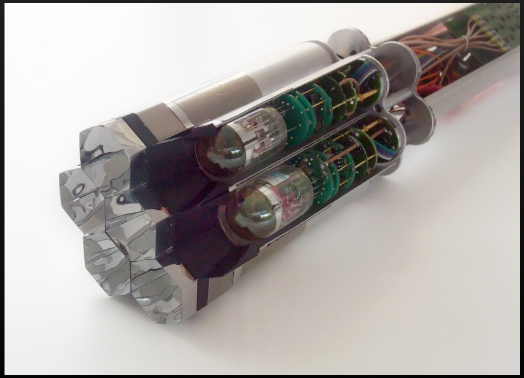
Prototyping of Large-size Silicon Photomultiplier Based Detector Modules in IACTs

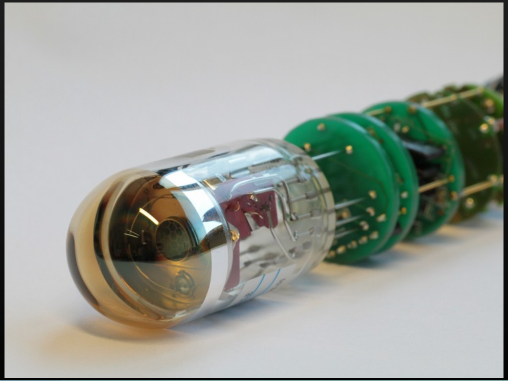
The MAGIC telescopes

[1]



- Canary island of La Palma
- 2200 m above see level
- Two imaging atmospheric Cherenkov telescopes (IACTs)
- Each camera equipped with 1039 PMTs
- 169 clusters, each based on 7-pixels; 6 open slots at vertices of the hexagonal-shape camera





[2]

Motivation

MAX-PLANCK-GESELLSCHAFT

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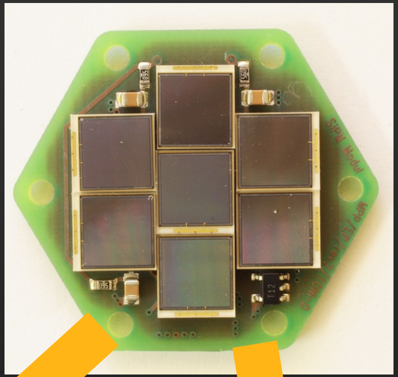
(Werner-Heisenberg-Institut)

- SiPMs challenge PMTs in terms of detection efficiency
- No HV necessary
- No ageing
- Potentially SiPMs can be operated during moon time similar to MAGIC PMT cameras
- Drawbacks: temperature dependence, high background rate due to high sensitivity to LoNS at long-wavelengths
- **Goal:** Compare performance of PMT and SiPM based detectors during real telescope operation

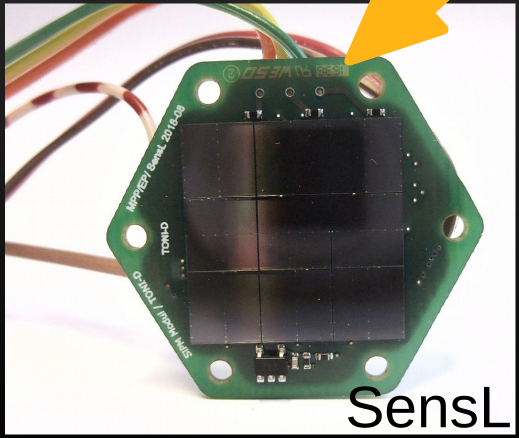
Two Design Generations

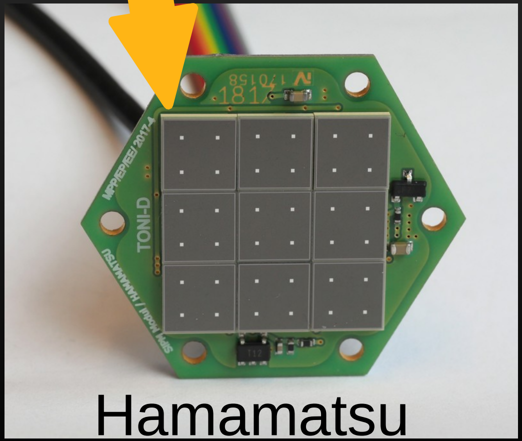
- Using Excelitas, Hamamatsu and SensL SiPMs
- Up to 9 SiPMs/pixel
- Single, summed output of all SiPMs on a pixel
- Common high voltage per cluster (7 pixels)
- Bias voltage adjustment for sub-groups of SiPM
- Optimized heat flow using Aluminium core PCBs

Sensor type	Breakdown voltage
Excelitas C30742-66	~ 95 V
Hamamatsu S13360-6075VS	~ 50 V
SensL MicroFJ-60035-TSV	~ 30 V



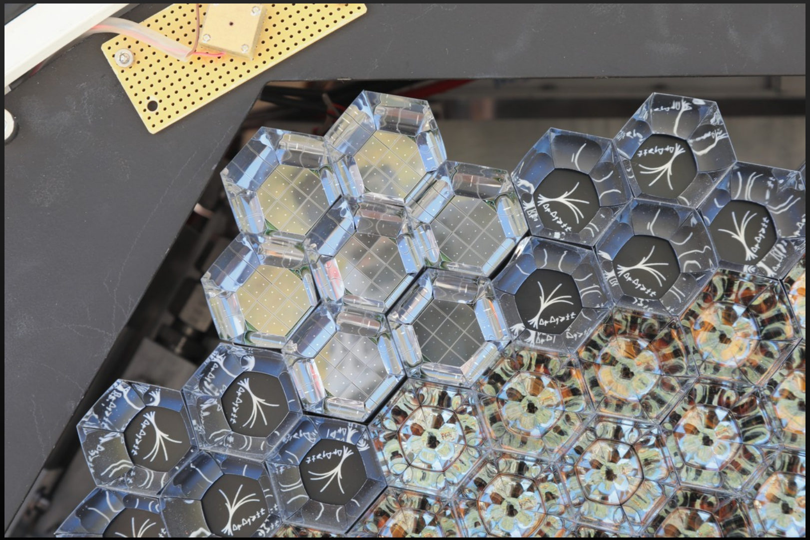
Excelitas

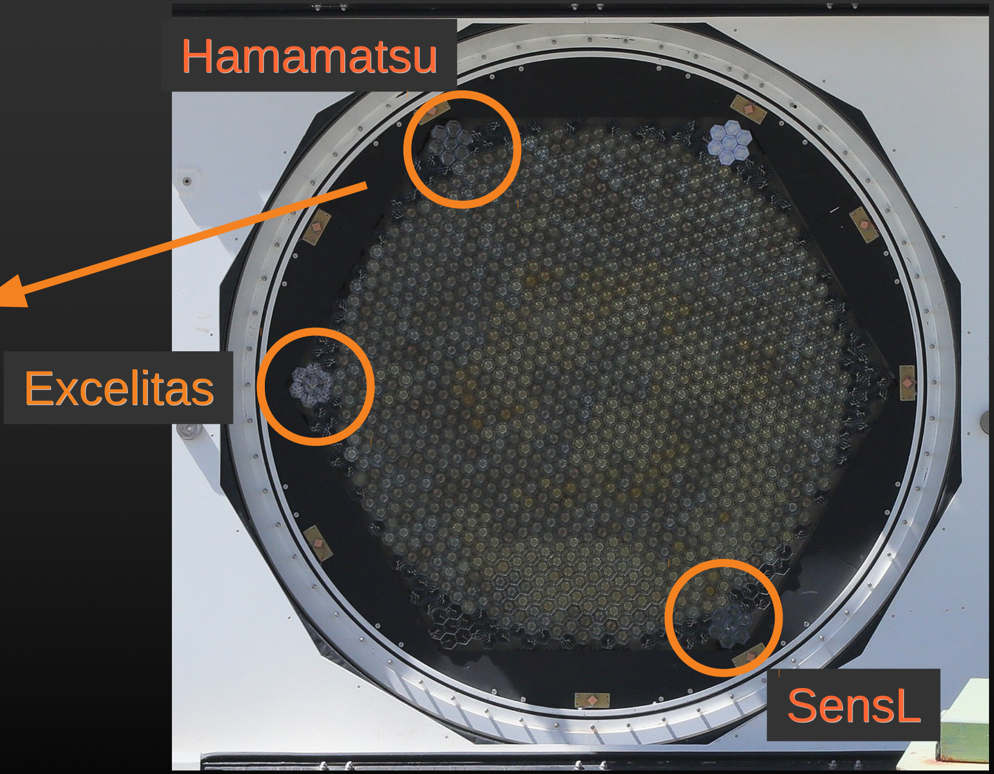




SiPM clusters in the MAGIC Imaging Camera

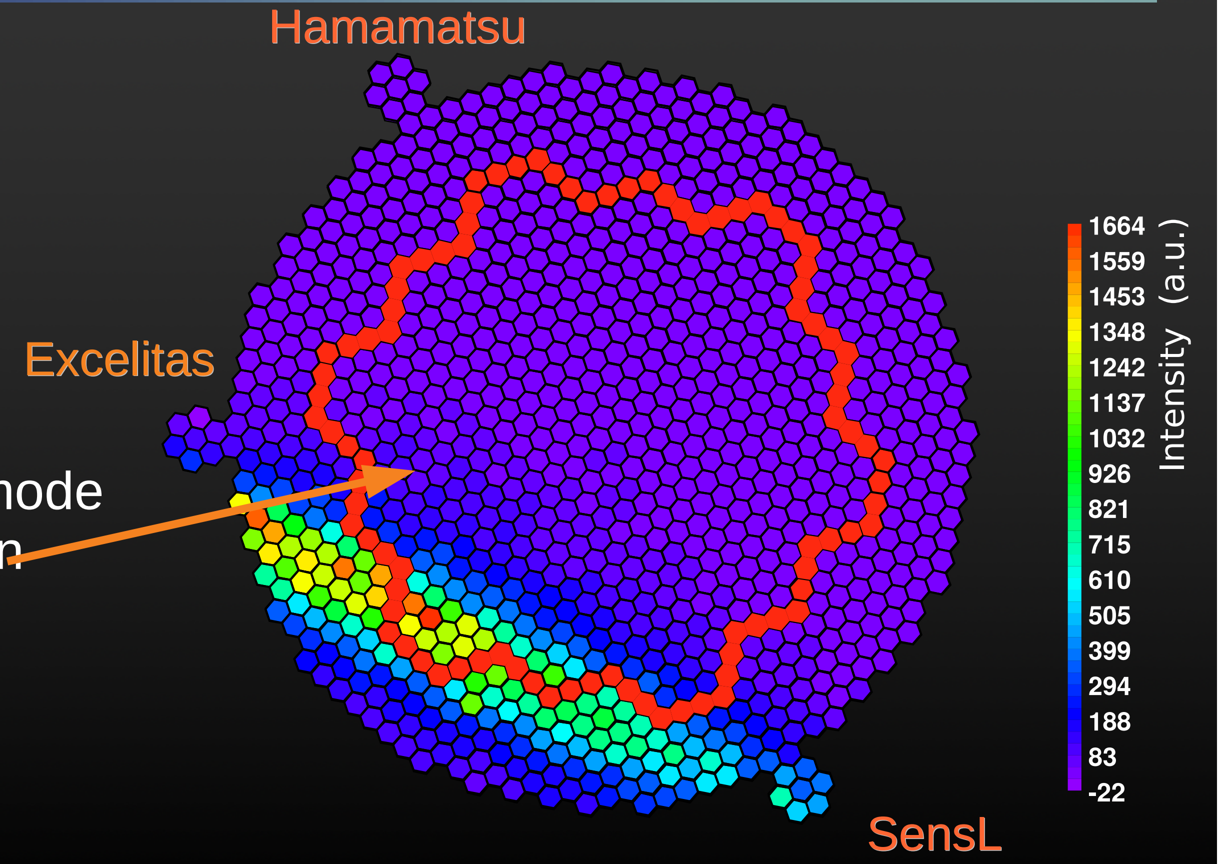
- Installed in 2015 and 2017
- 1 cluster Excelitas
- 1 cluster Hamamatsu
- 1 cluster SensL





SiPM clusters in the MAGIC Imaging Camera

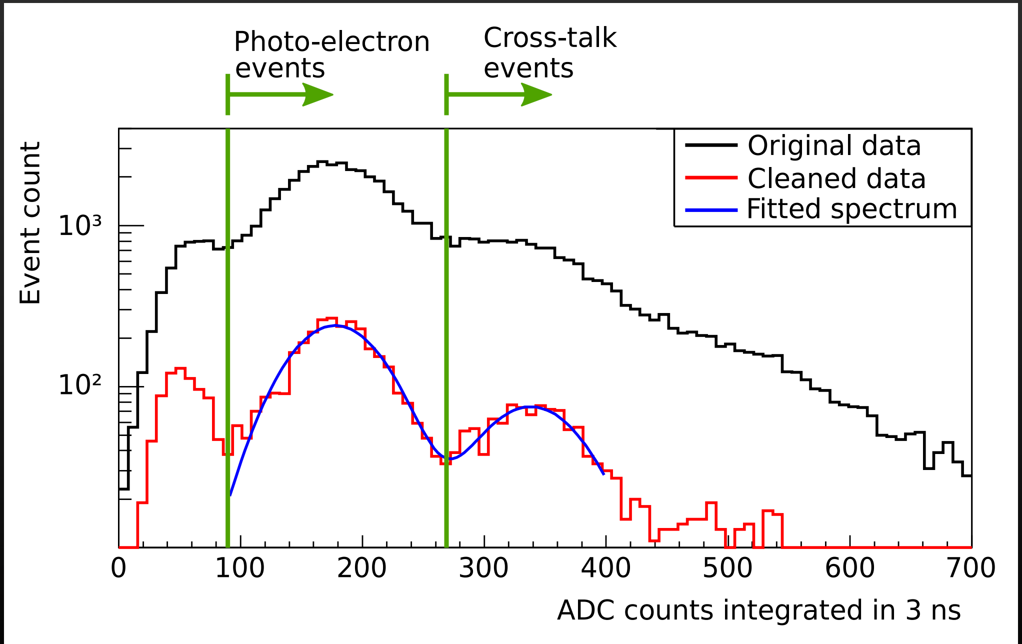
- Installed in 2015 and 2017
- 1 cluster Excelitas
- 1 cluster Hamamatsu
- 1 cluster SensL
- Using the standard readout and data taking
- Operated in parasitic trigger mode on events triggering the shown inner camera region



Calibration

Two methods used

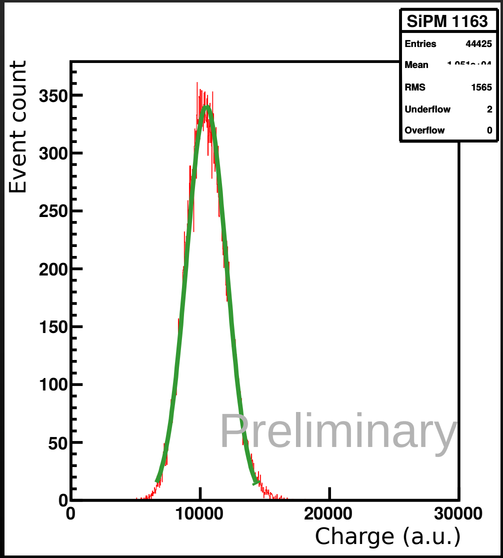
- Single-photoelectron spectrum



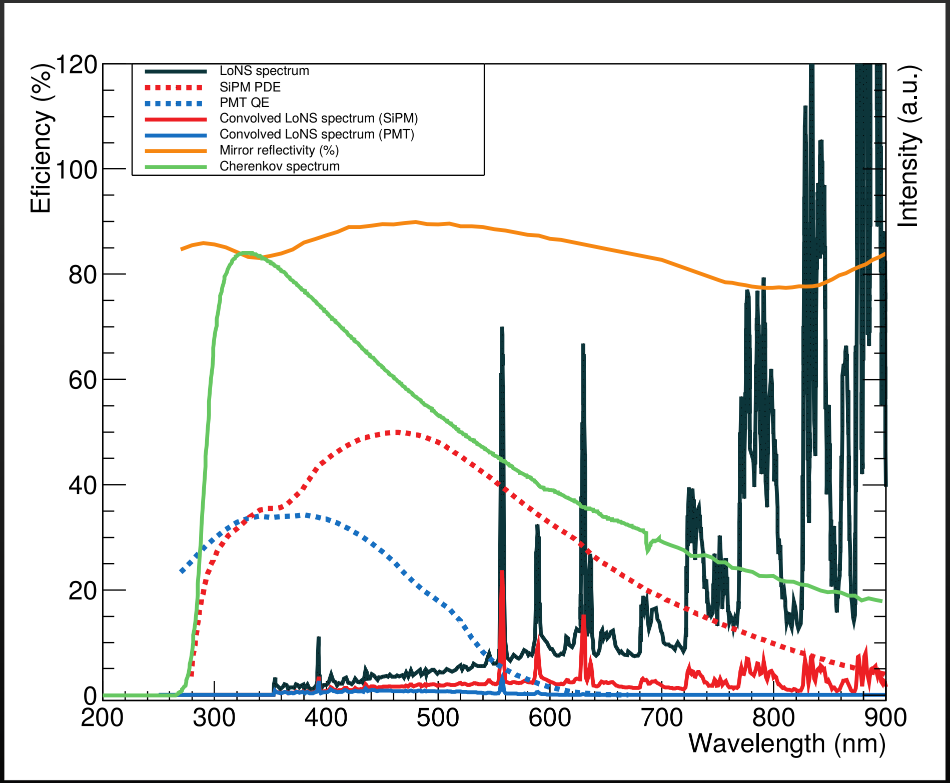
- F-Factor (≡ excess noise)

$$\overline{m_{\mathrm{phe}}} = 8 \cdot \ln(2) \cdot F^2 \cdot \left(\frac{\overline{Q}}{\mathrm{FWHM}} \right)^2$$

- Using position and FWHM of charge distribution



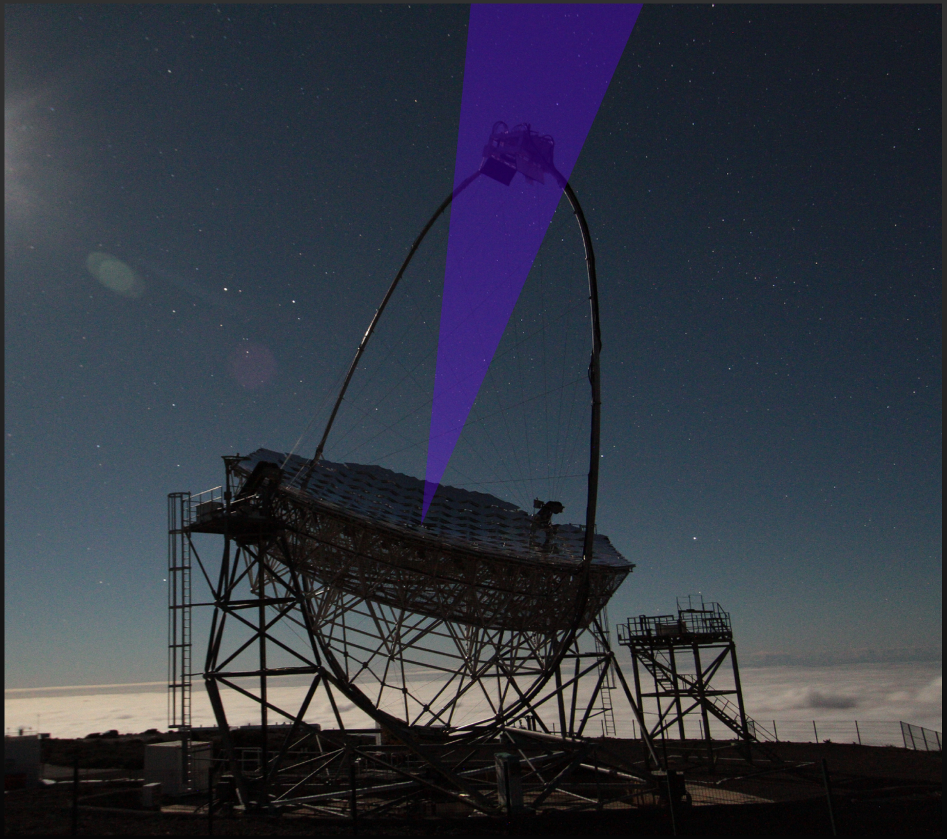
Expectation



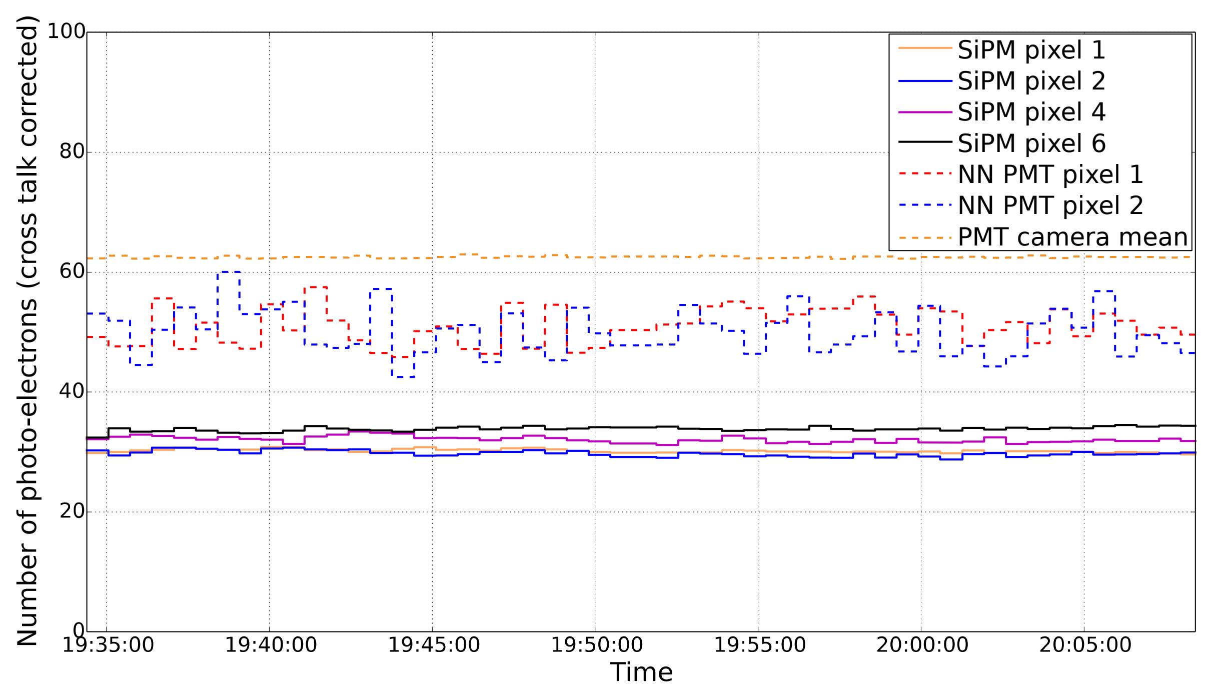
- Calculate expected performance with reference to MAGIC PMTs (type R10408)
  - Light of Night Sky (LoNS)
  - Cherenkov light
- With Hamamatsu SiPM
  - 9.6 times more LoNS
  - 1.9 times more Cherenkov light
- $\sqrt{LoNS}$ Contributes as noise
- CTA uses newer PMTs (type R12992-100, QE 42.6 %)

Performance

- Calibration laserlight pulses
- Illuminating camera
- Fixed frequency (25 Hz)
- Fixed wavelength (355 nm)
- Average light intensity constant
- Used for PMT calibration
- Used for comparing detection efficiencies of SiPMs and PMTs



Performance Gen. 1
Excelitas SiPM

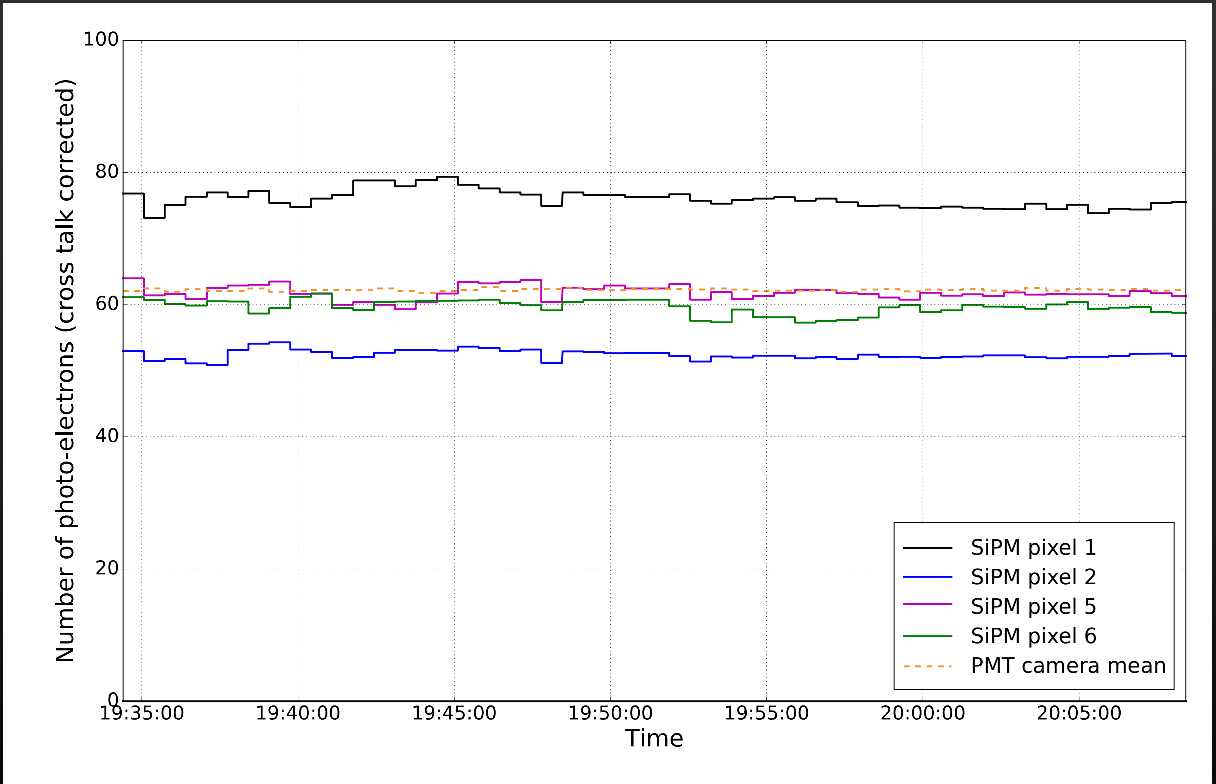


- Calibrated using phe-spectrum
- Dead area of pixel, PDE(λ) $\Rightarrow$ expect ~ 32 phe
- Number of phe is in **expected range**

$\Downarrow$

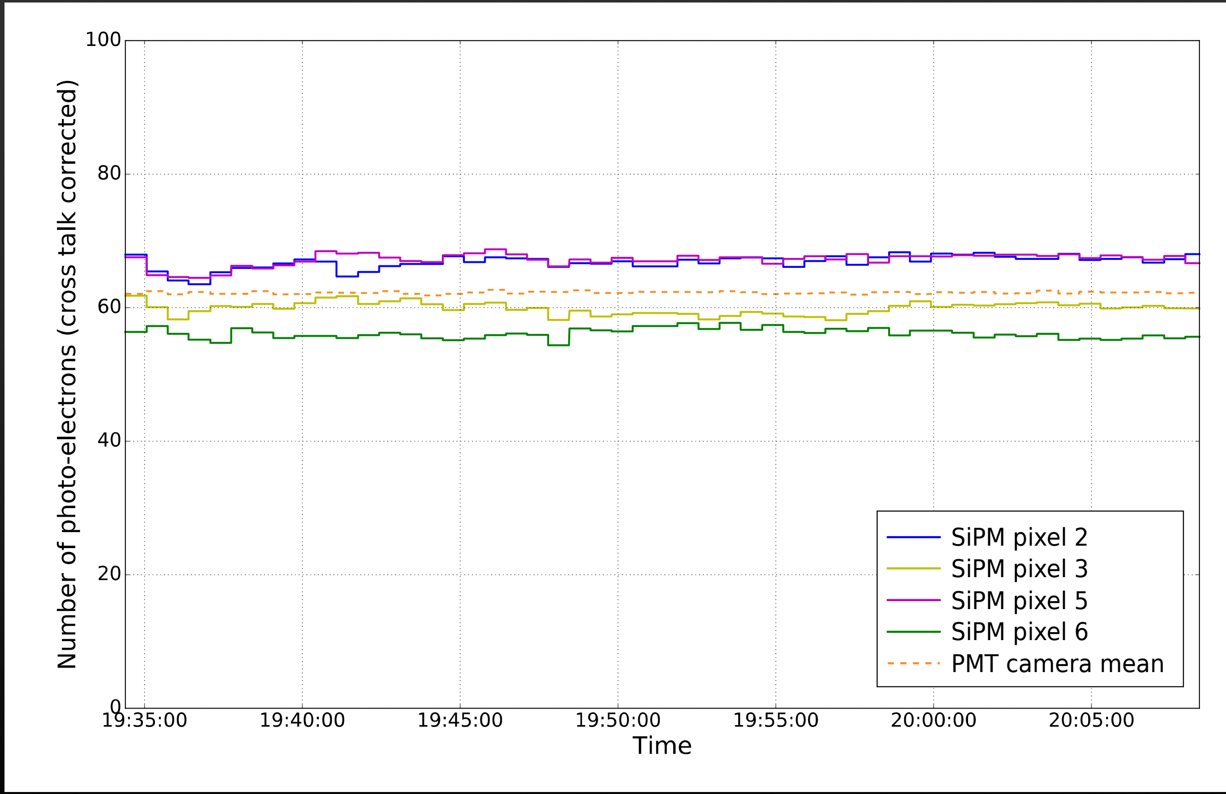
- Hamamatsu and SensL clusters expected to perform as good as current MAGIC PMTs in terms of pixel PDE

Performance Gen. 2
Hamamatsu SiPM



- Calibrated using phe-spectrum
- Number of phe in expected range (dead area of pixel, PDE(λ))
- Number of phe is comparable with installed MAGIC PMTs
- One pixel higher than PMT (same gain as other pixels but lower cross-talk)
- Big spread is caused by differences in cross-talk
→Under investigation

Performance Gen. 2
SensL SiPM

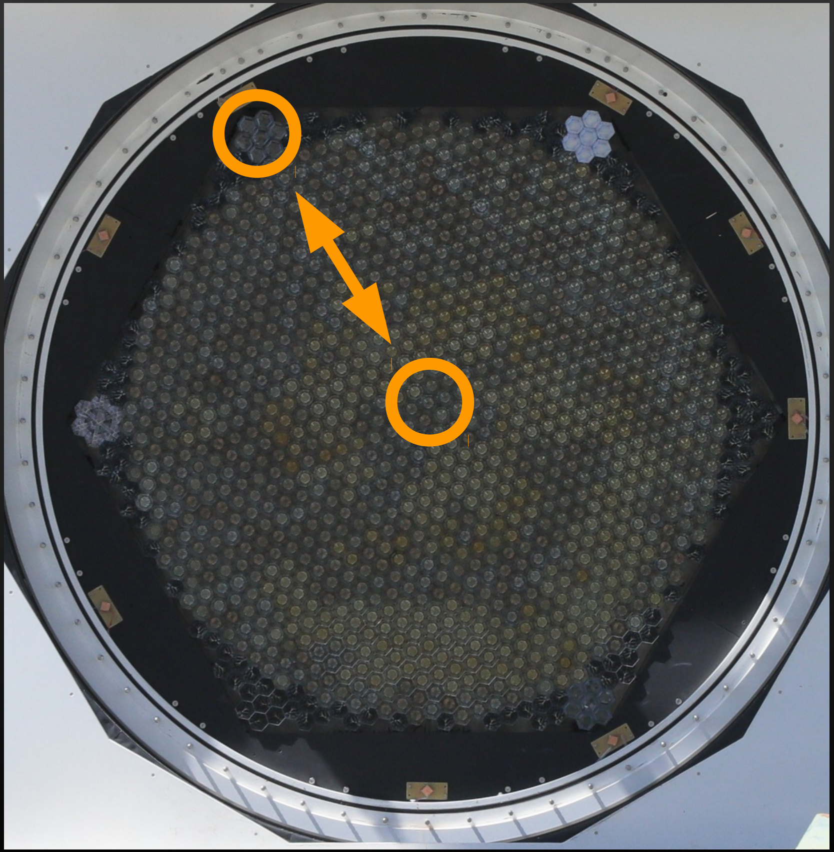


- Calibrated using F-Factor
- Number of phe in expected range (dead area of pixel, PDE(λ))
- F-Factor calibration method gives plausible results
- Number of phe is comparable with installed MAGIC PMTs

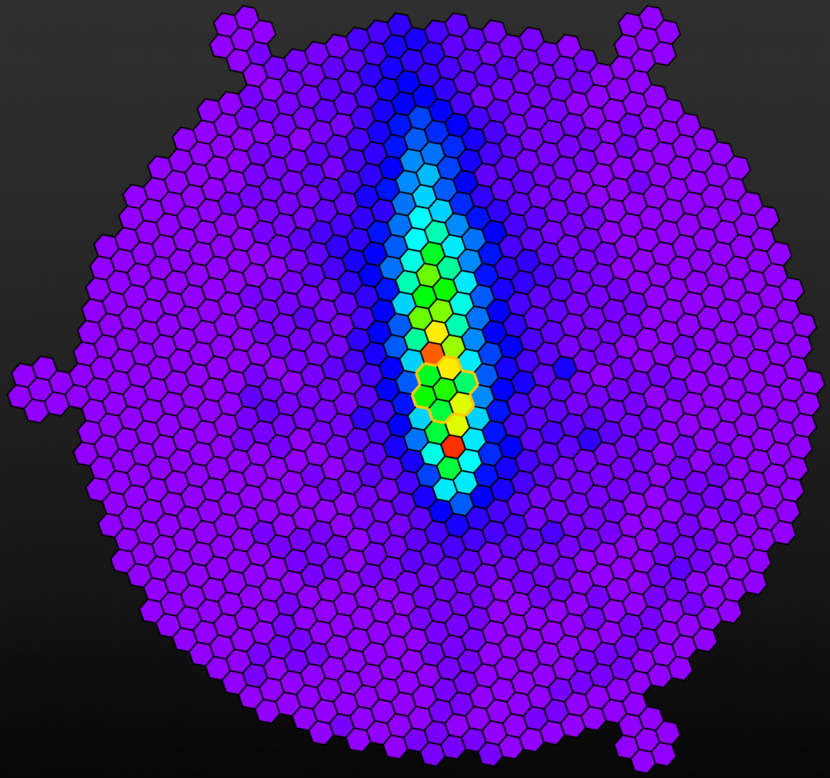
SiPMs in trigger region

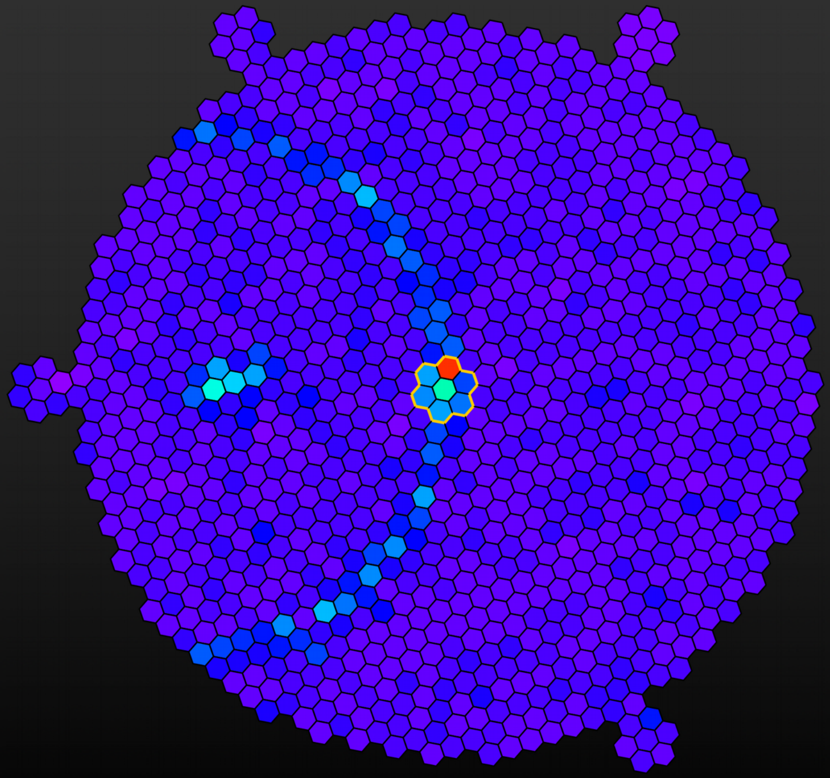
- Comparison of Cherenkov light detection efficiencies
- Systematic uncertainties because of parasitic trigger mode
- Far less problems if SiPMs are installed in trigger region
- Ideally camera centre

⇒ Swapping Hamamatsu SiPM cluster with PMT cluster in centre
1st July 2018



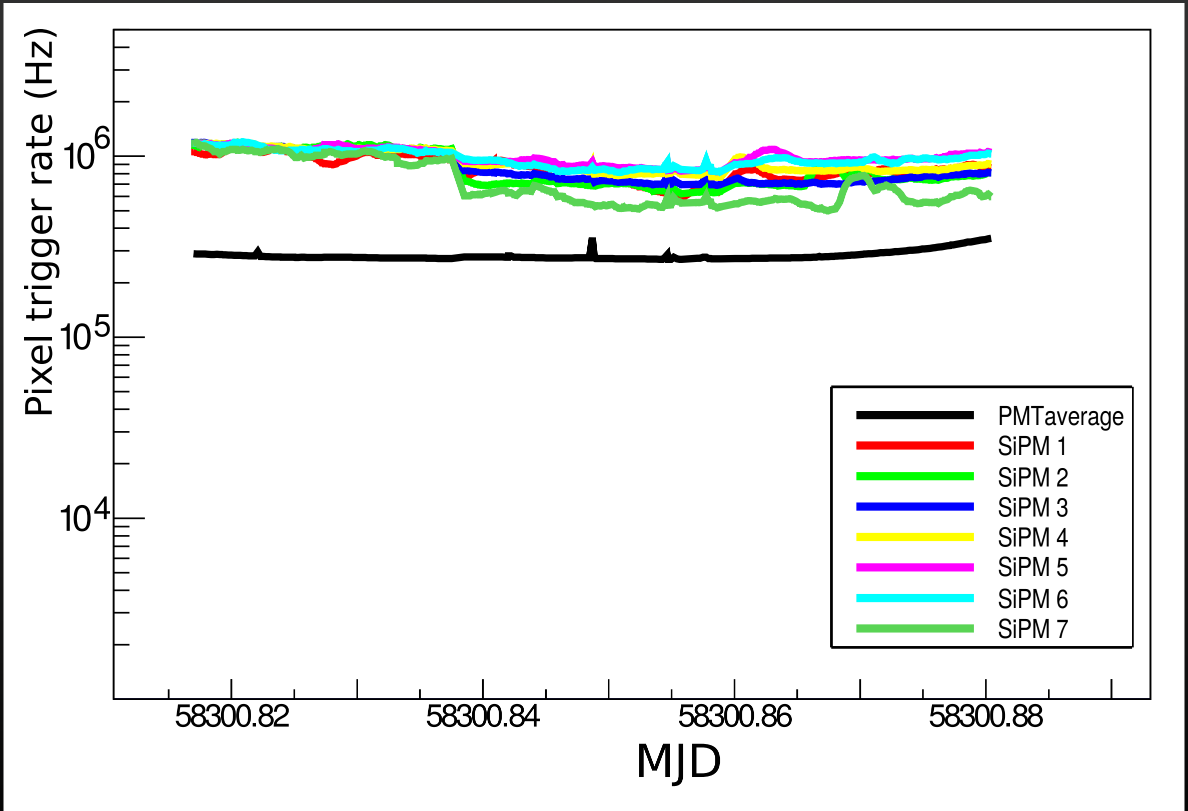
Performance
Cherenkov light





Performance
Cherenkov light

- Compare pixel trigger rates of PMT and SiPM pixels
- Same threshold in phe
- $\sqrt{LoNS}$ leads to ~ 3 times higher trigger rate
- Good agreement with expectation



Summary and Outlook

Goal: Make a fair SiPM-PMT comparative study for exploring the potential of SiPM for IACTs

Achievements

- Three prototypes of different SiPMs installed in MAGIC camera
- Used two calibration procedures
- Measurements of calibration pulses are in accordance with expectations
- Ongoing comparison of detection efficiencies and the signal to noise ratio for measuring Cherenkov light from air showers

Further tasks:

- Perform a rate scan to estimate energy threshold of SiPM based camera
- Cross-calibration using muon events


Thank you for your attention
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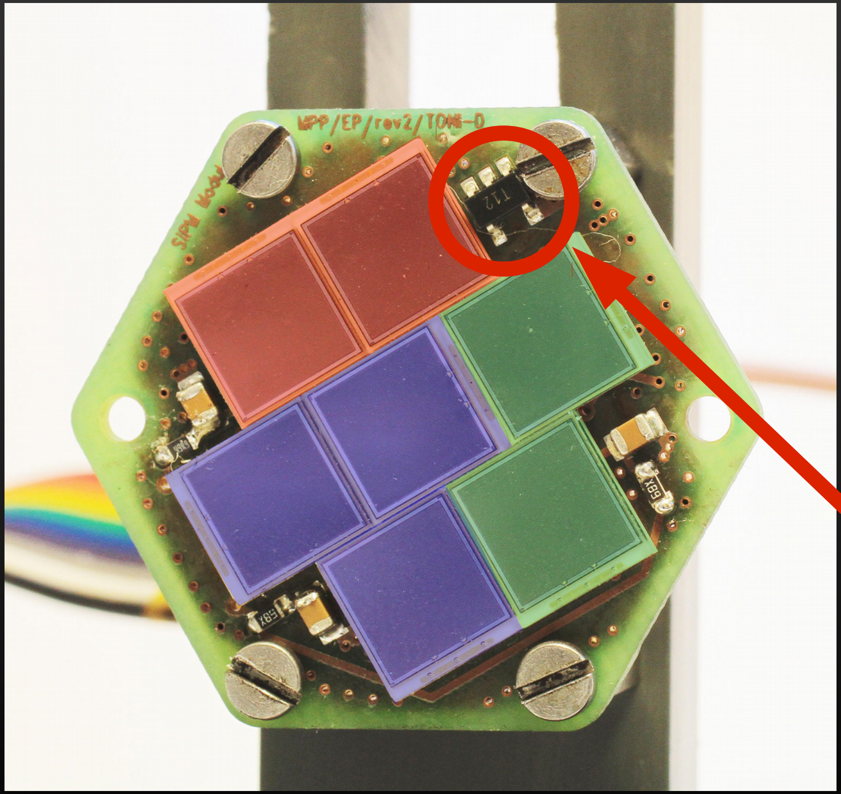
References

- [1] R. Wagner. Picture gallery of the MAGIC telescopes. https://magicold.mpp.mpg.de/gallery/pictures/ . Retrieved 10-2014
- [2] D. Nakajima, et al. New Imaging Camera for the MAGIC-I Telescope, 2013. Proc. of 33rd International cosmic ray conference.
- [3] D. Renker, et. al., Advances in solid state photon detectors, J. Instrum., 4, 2009.
- [4] S. Vinogradov, Analytical models of probability distribution and excess noise factor of solid state photomultiplier signals with crosstalk, NIM-A, 695:247-251, Dec. 2012

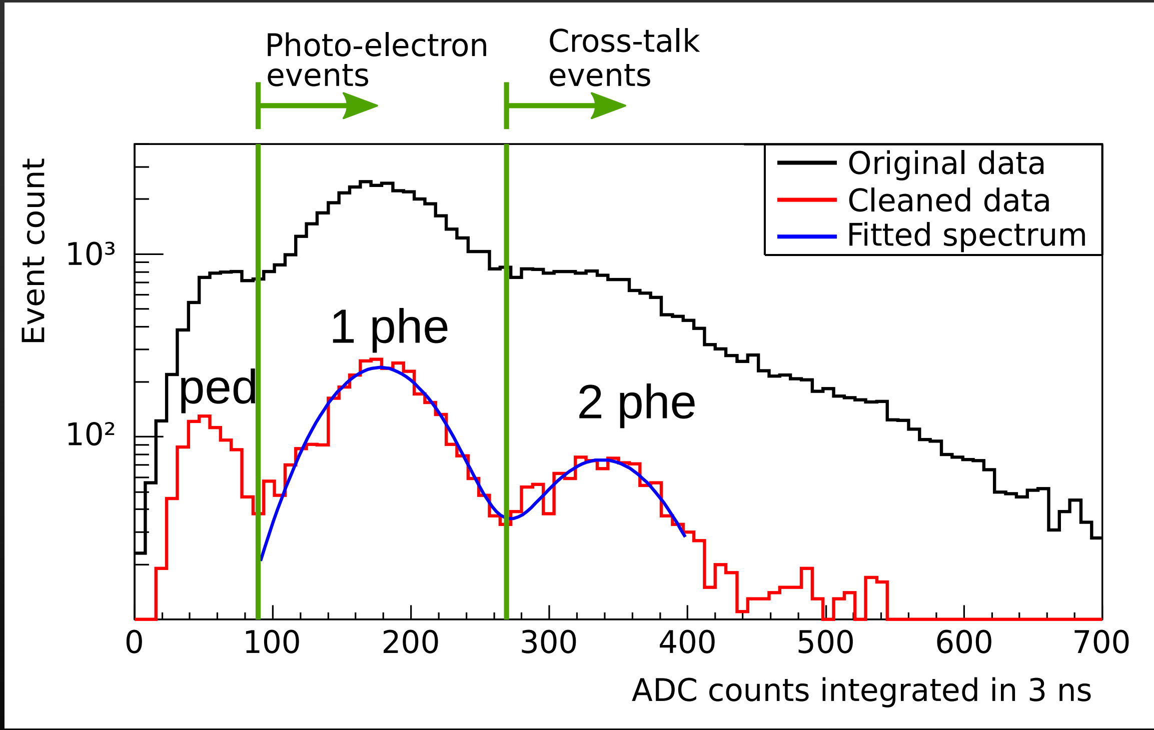
BACKUP

BACKUP



- Excelitas C30742-66 SiPM
- Three groups (2-3-2) of Excelitas 6x6 mm² SiPMs with same breakdown voltage
- Single, summed output of all SiPMs
- Only one high voltage per cluster
- One offset voltage per group used to disable the pixel (star in FOV), adjust gain
- One temperature sensor next to sensors
- Dedicated light guide design
- 31 % dead area

BACKUP



- 100 kEvents @ 300Hz with closed lids
  ⇒ Pedestal / dark count events
- Selection of good events
- Fitting spectrum for gain
- Integrate or fit original data for cross-talk estimation

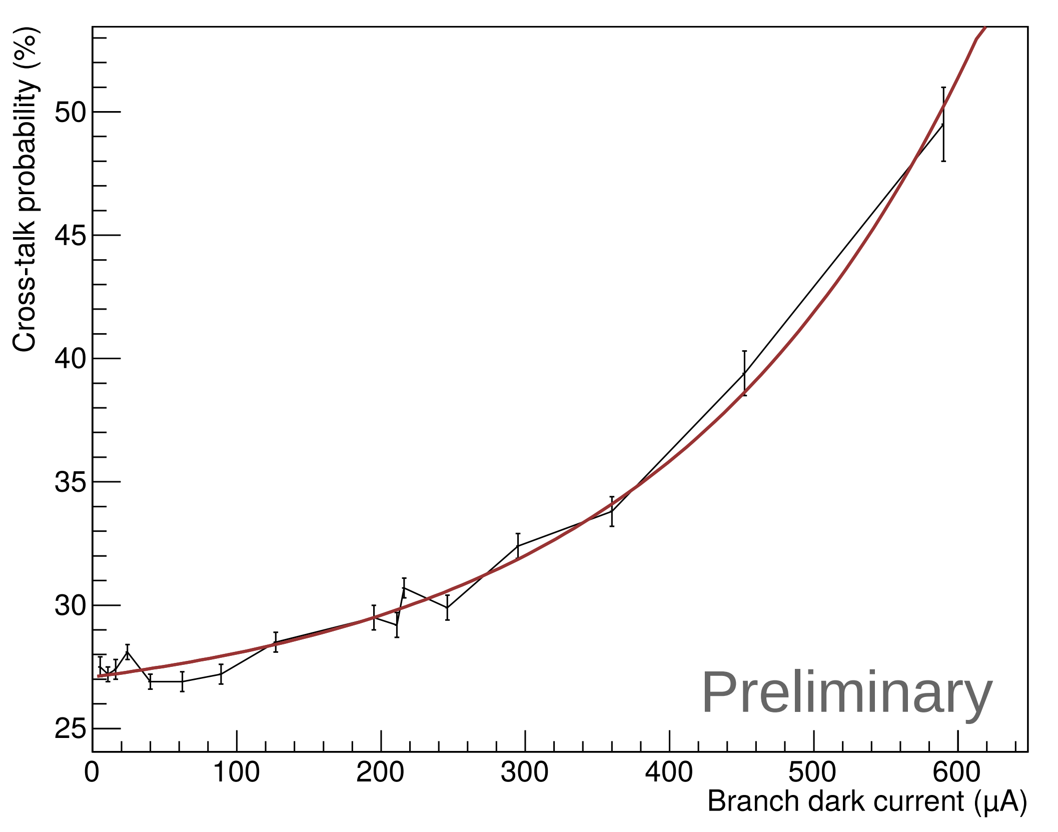
BACKUP

- Calibration via F-Factor method (like PMTs)
- Cross-talk (*p*) defines F-Factor of SiPMs

$$F = 1 + p + \frac{3}{2} p + \mathrm{O}\left(p^3\right)$$

[3, 4]

- Measured cross-talk in lab
- Read dark current during pedestal run ⇒ calculate F-Factor
- Higher order terms in SiPM F-Factor lead to a higher uncertainty in converted phe wrt. PMT conversion

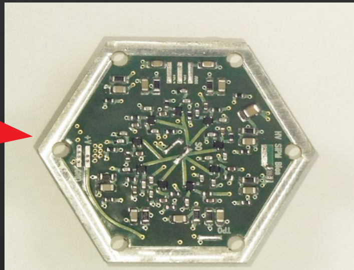


BACKUP

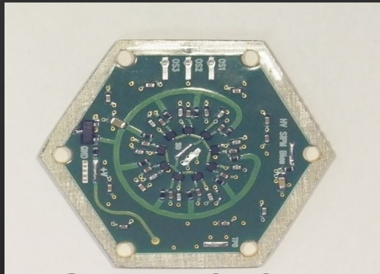
- Aluminium core PCBs
- Improved heat conductivity from pixel to cooling plate

⇒ Reduced operational temperature

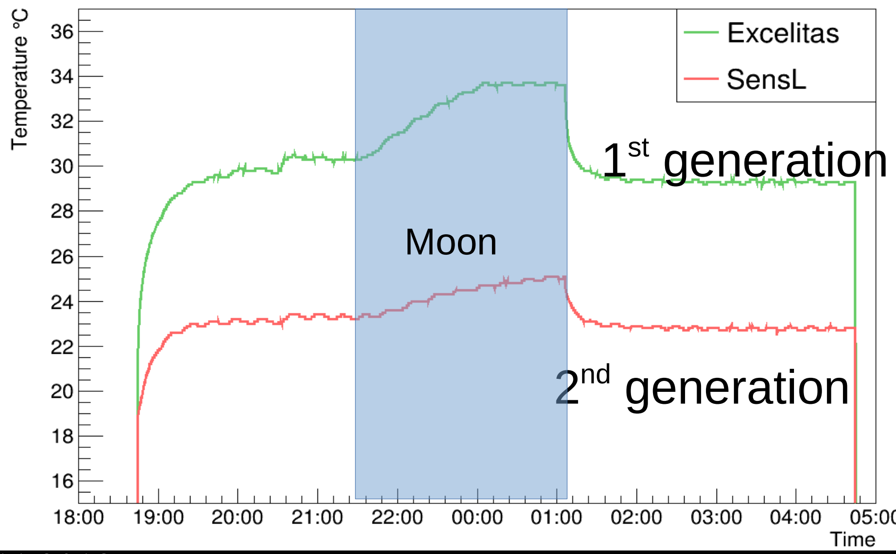
⇒ Reduced temperature variation due to changing background light condition



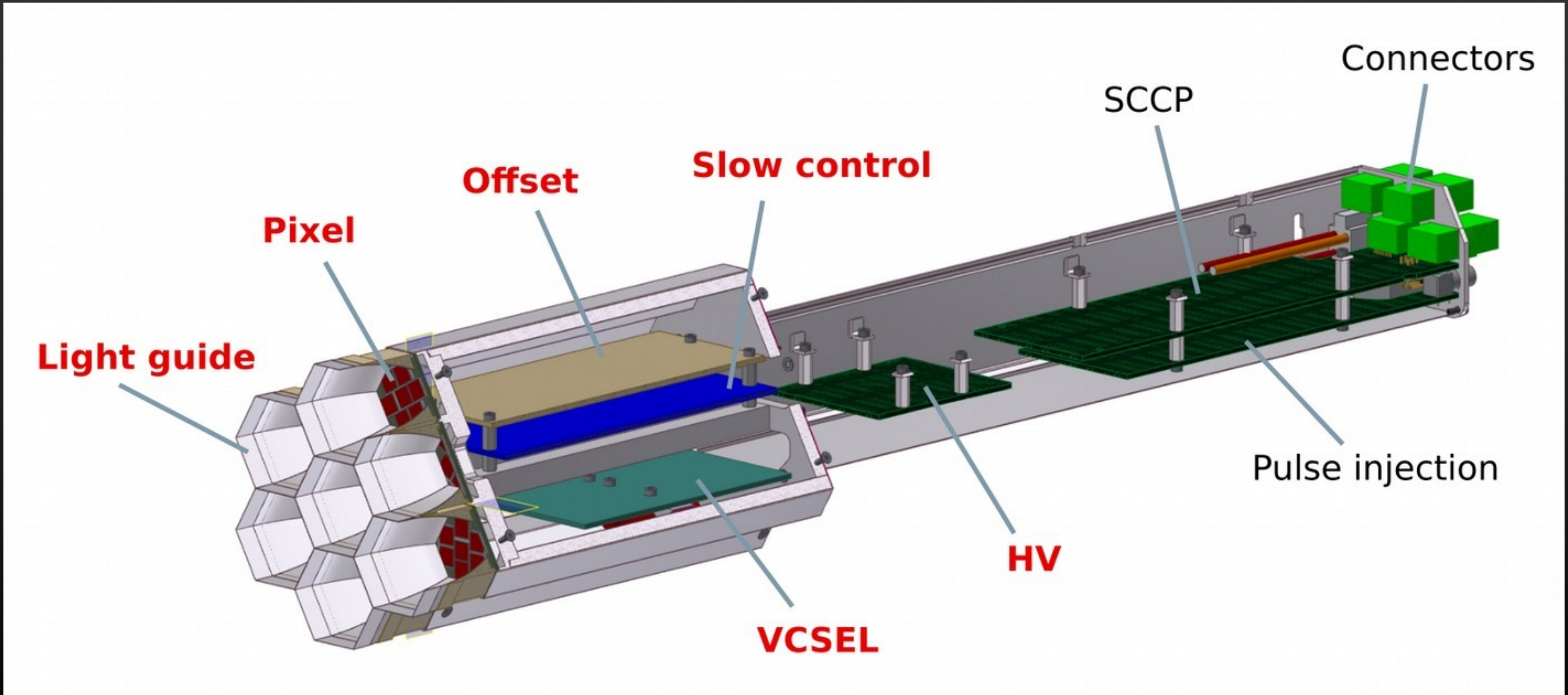
Hamamatsu 3x3



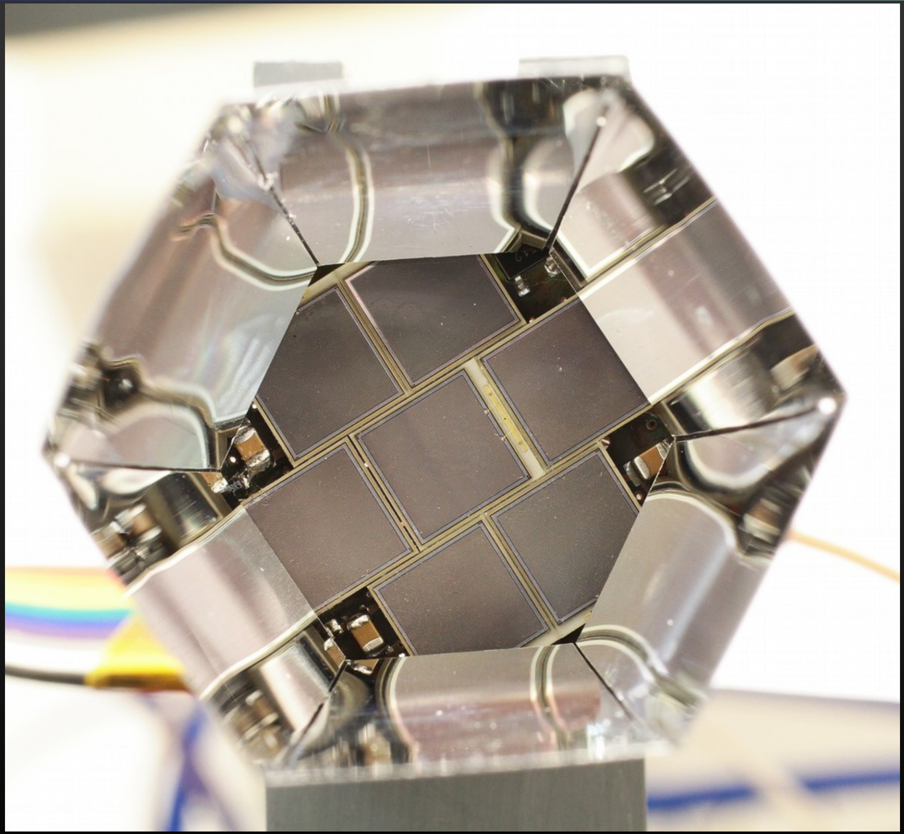
SensL 3x3



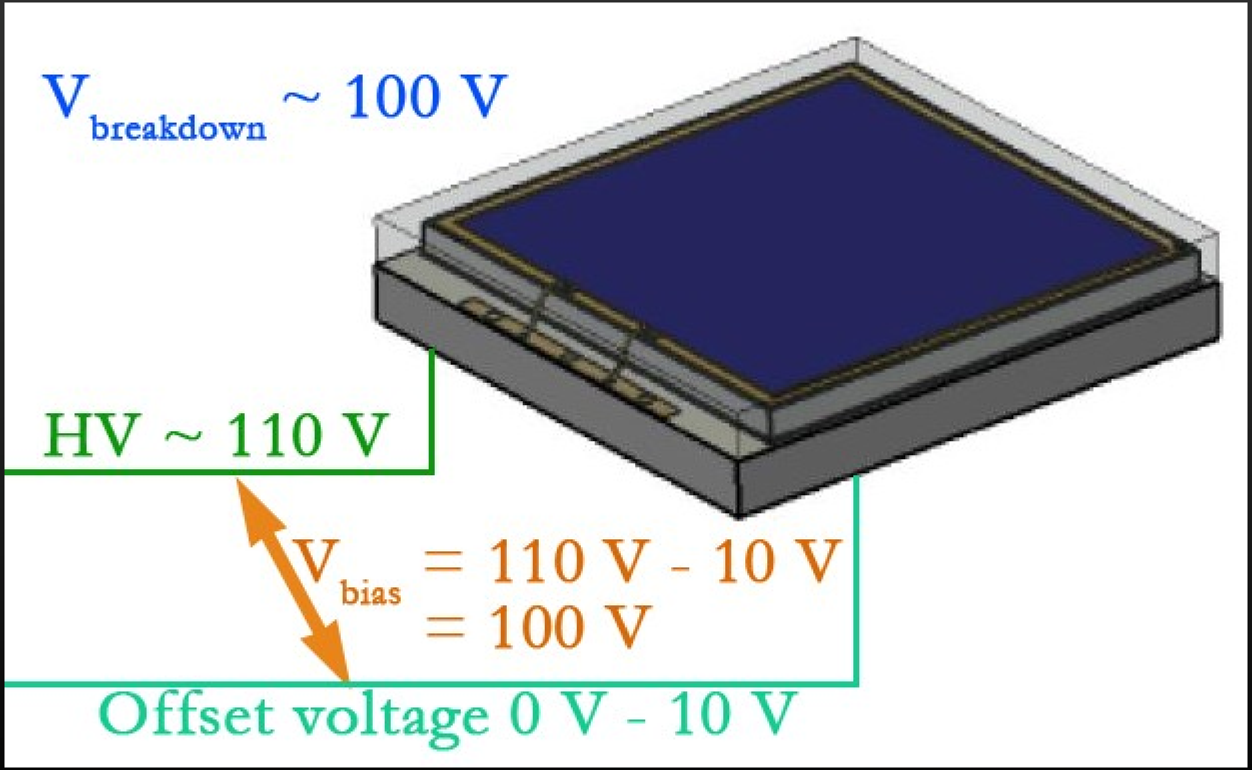
BACKUP


Connectors
SCCP
Slow control
Offset
Pixel
Light guide
Pulse injection
HV
VCSEL

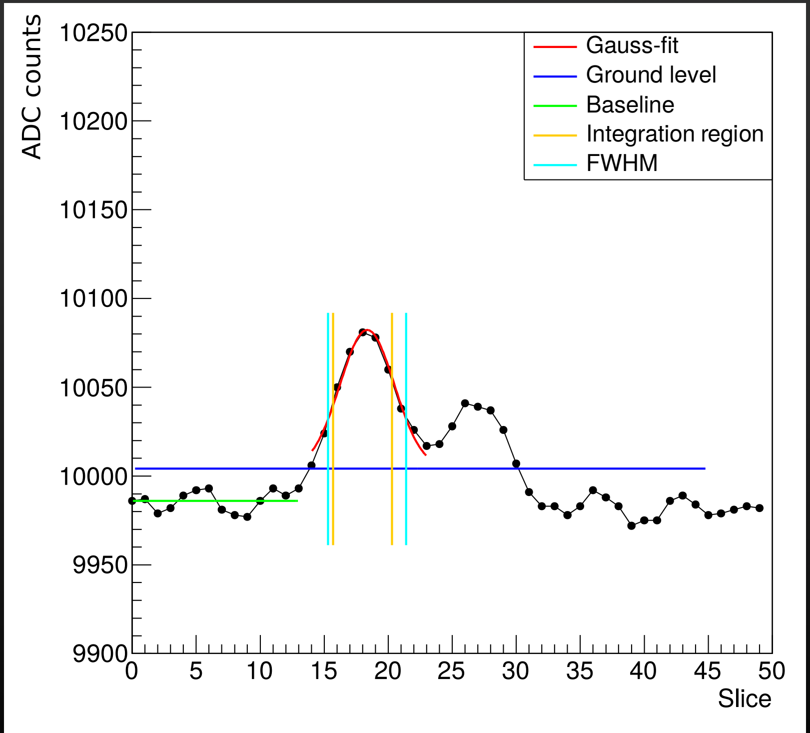
BACKUP



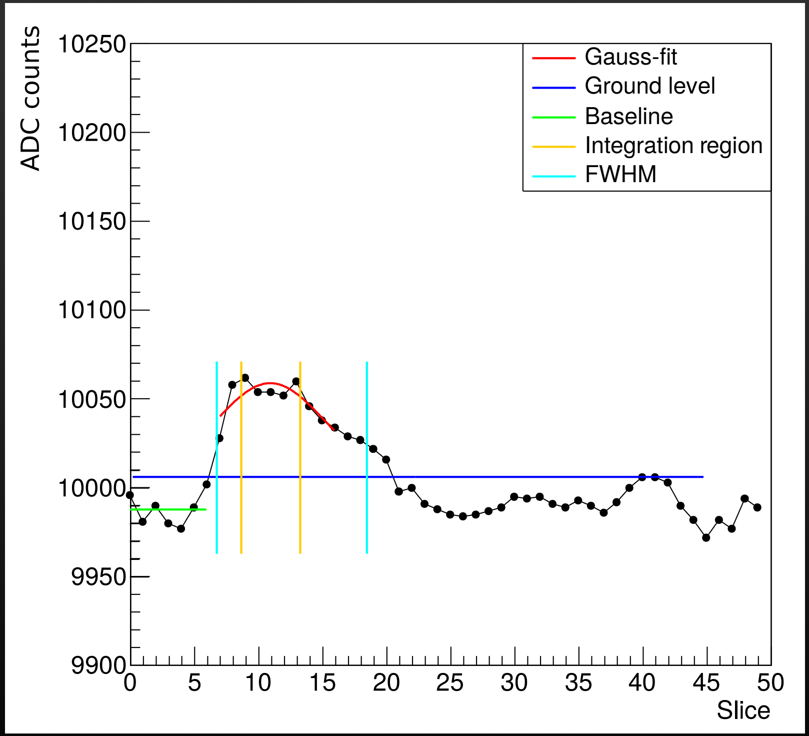
BACKUP


$V_{breakdown} \sim 100$ V
HV ~ 110 V
V_{bias} = 110 V - 10 V
= 100 V
Offset voltage 0 V - 10 V

BACKUP

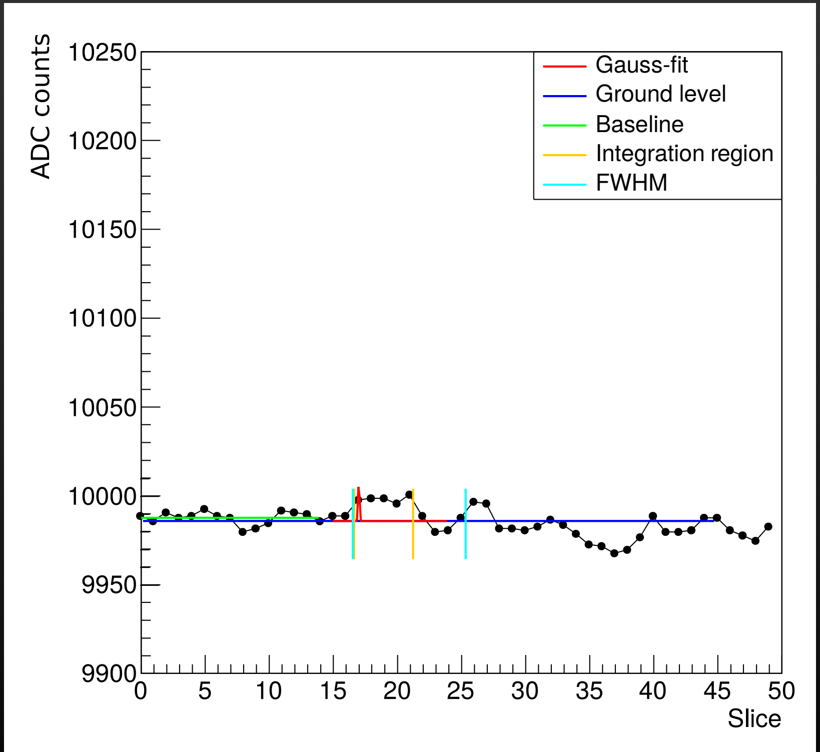


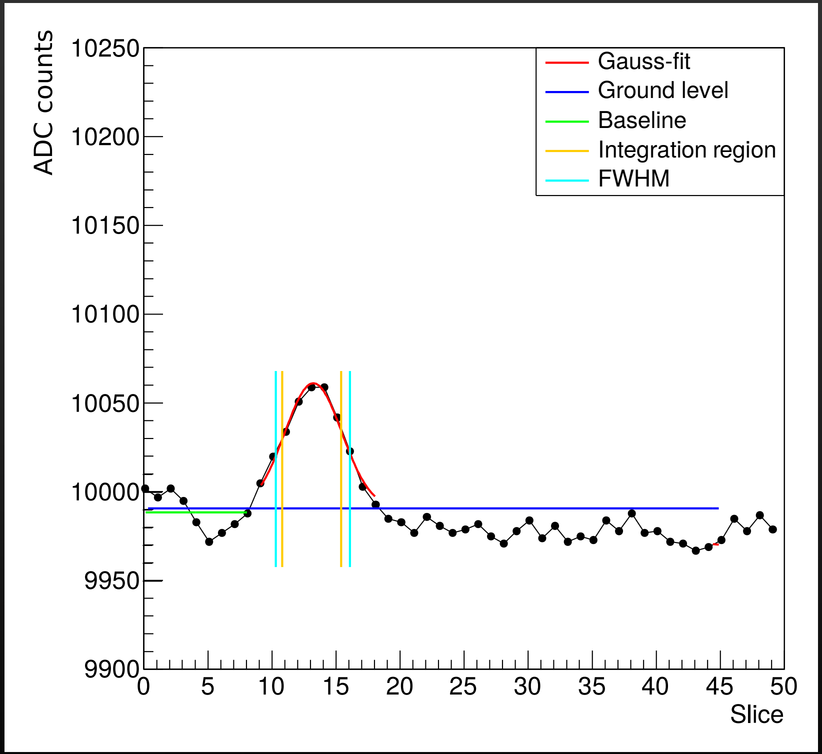
ADC counts
Slice
Gauss-fit
Ground level
Baseline
Integration region
FWHM



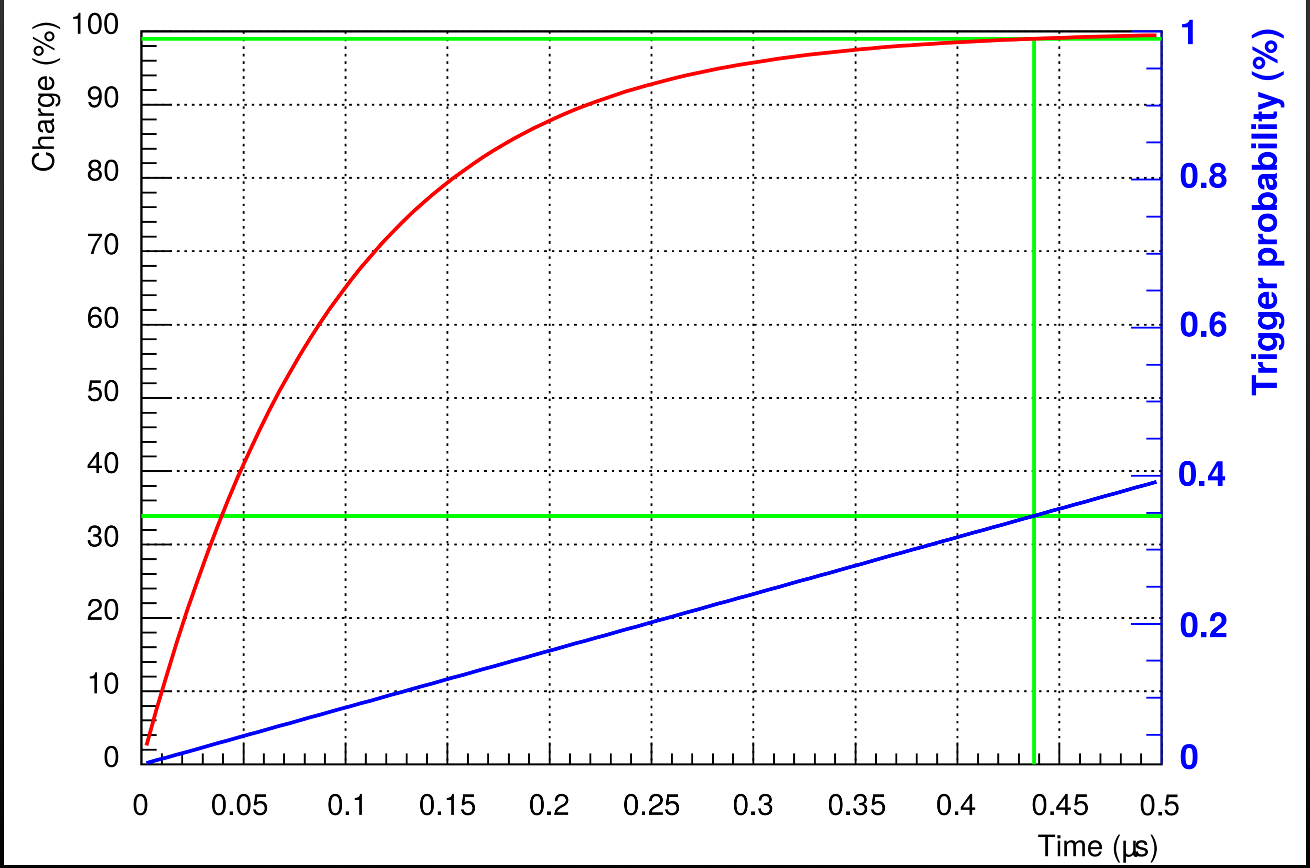
ADC counts
Slice
Gauss-fit
Ground level
Baseline
Integration region
FWHM

BACKUP

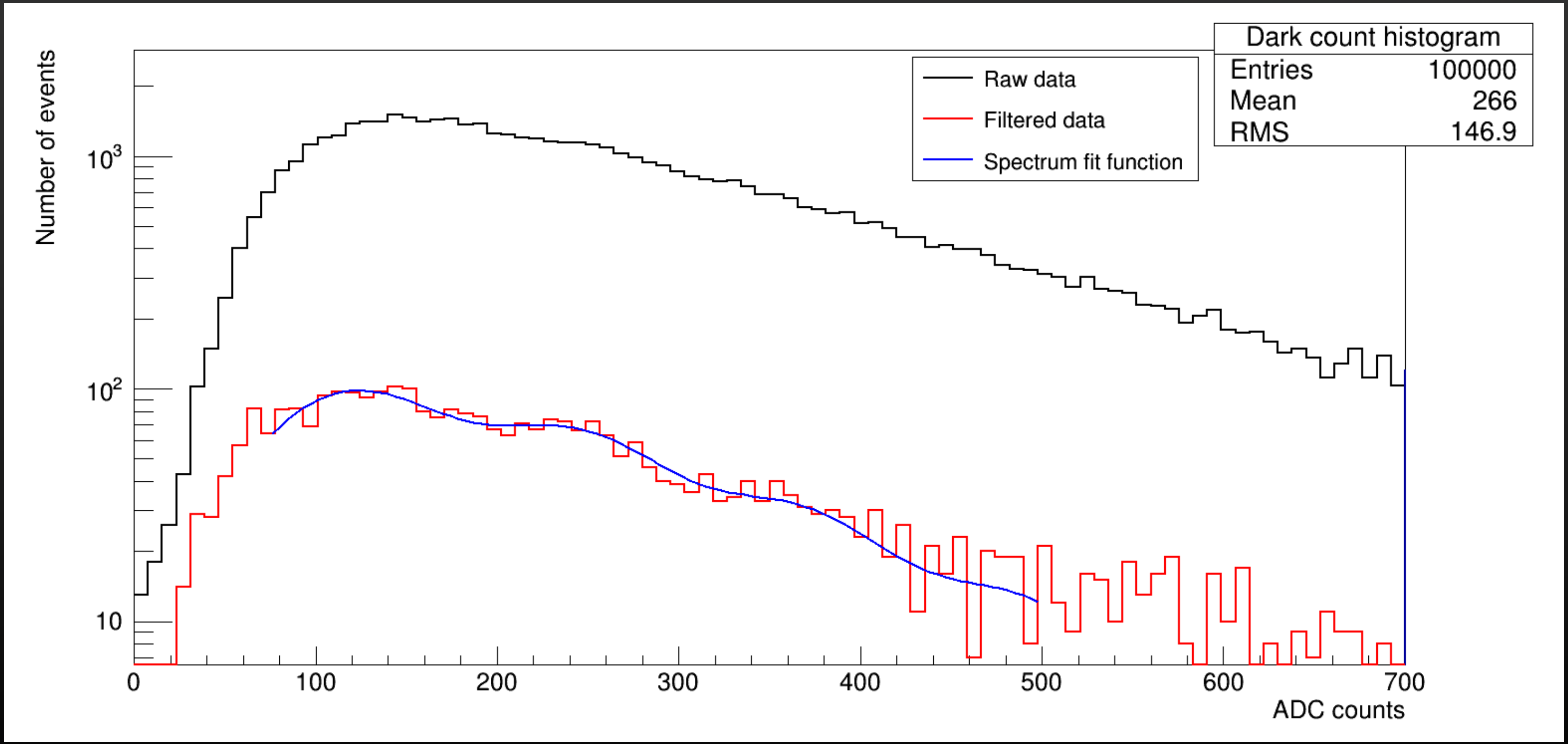

ADC counts
10250
10200
10150
10100
10050
10000
9950
9900
0
5
10
15
20
25
30
35
40
45
50
Slice
Gauss-fit
Ground level
Baseline
Integration region
FWHM


ADC counts
10250
10200
10150
10100
10050
10000
9950
9900
0
5
10
15
20
25
30
35
40
45
50
Slice
Gauss-fit
Ground level
Baseline
Integration region
FWHM

BACKUP

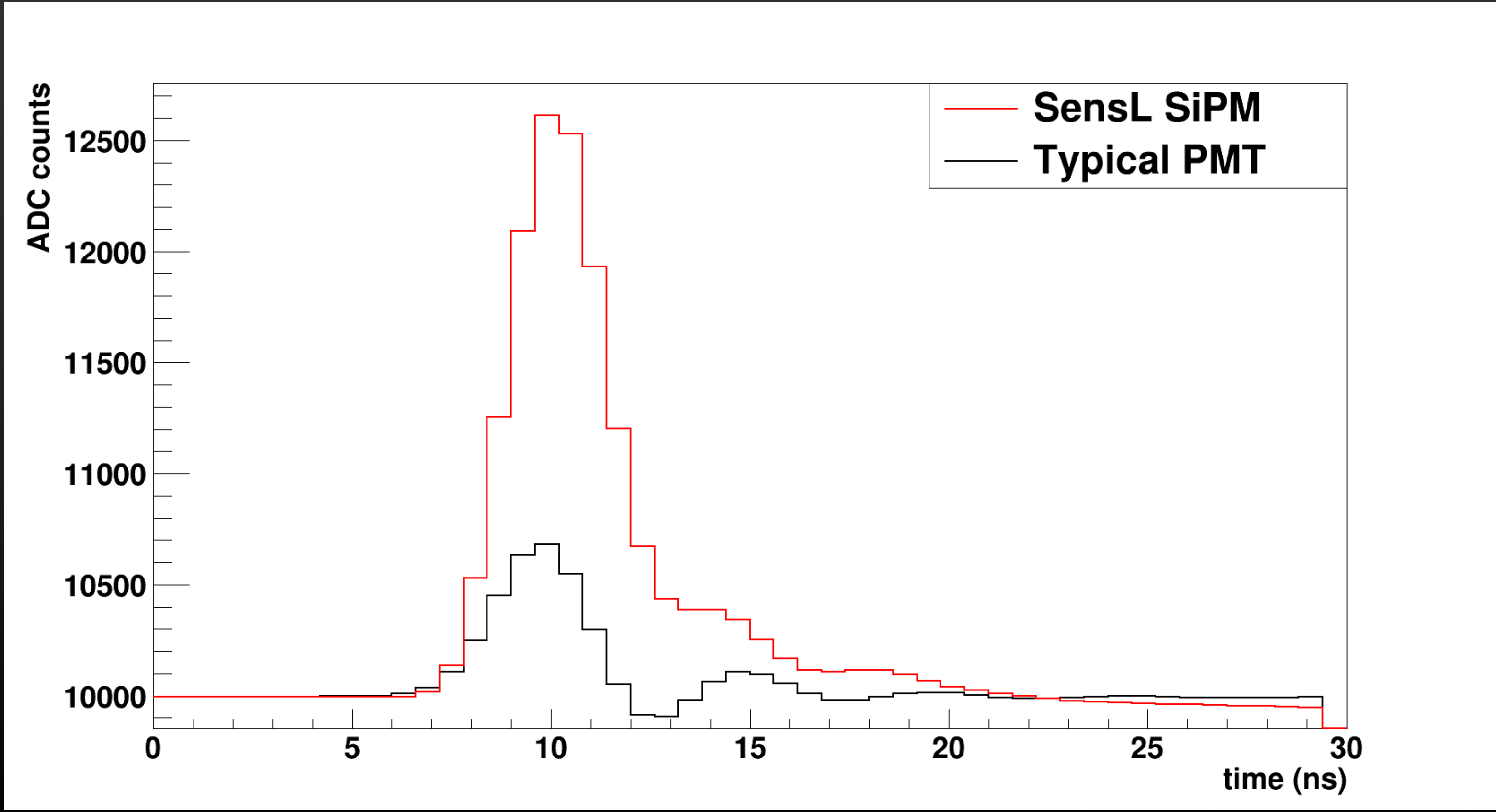

Charge (%)
100
90
80
70
60
50
40
30
20
10
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Time (µs)
1
0.8
0.6
0.4
0.2
0
Trigger probability (%)

BACKUP



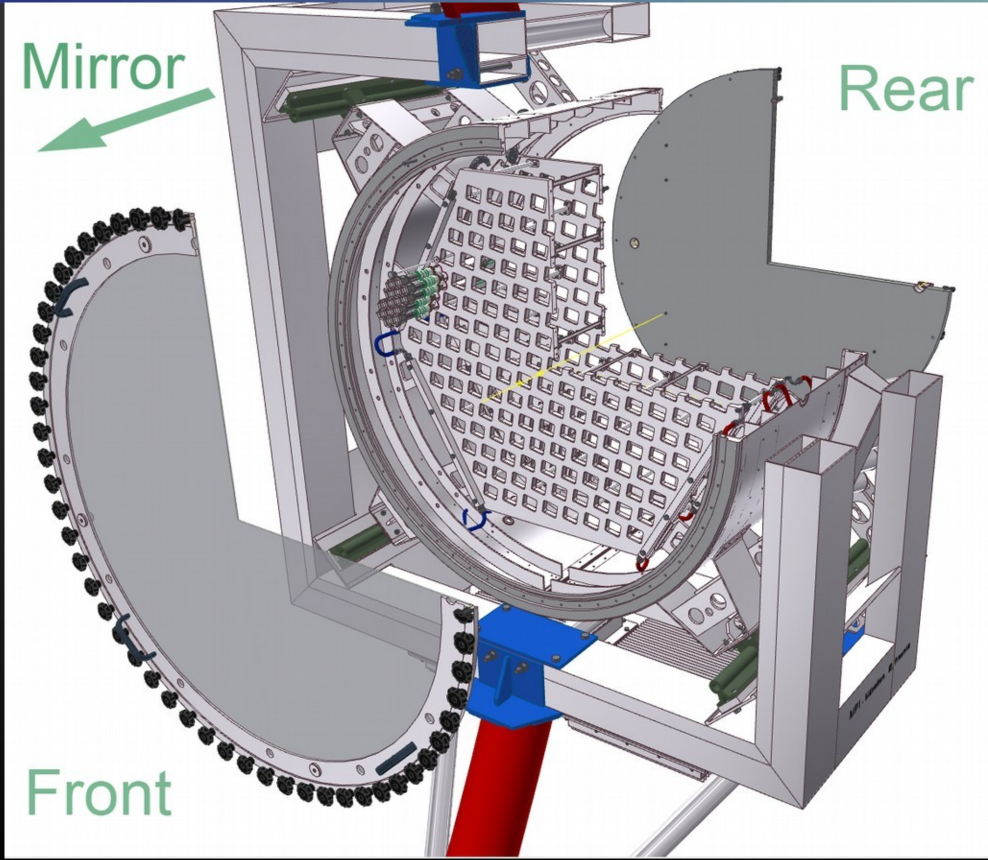
Dark count histogram
Entries 100000
Mean 266
RMS 146.9
Raw data
Filtered data
Spectrum fit function
Number of events
10^3
10^2
10
0
100
200
300
400
500
600
700
ADC counts

BACKUP

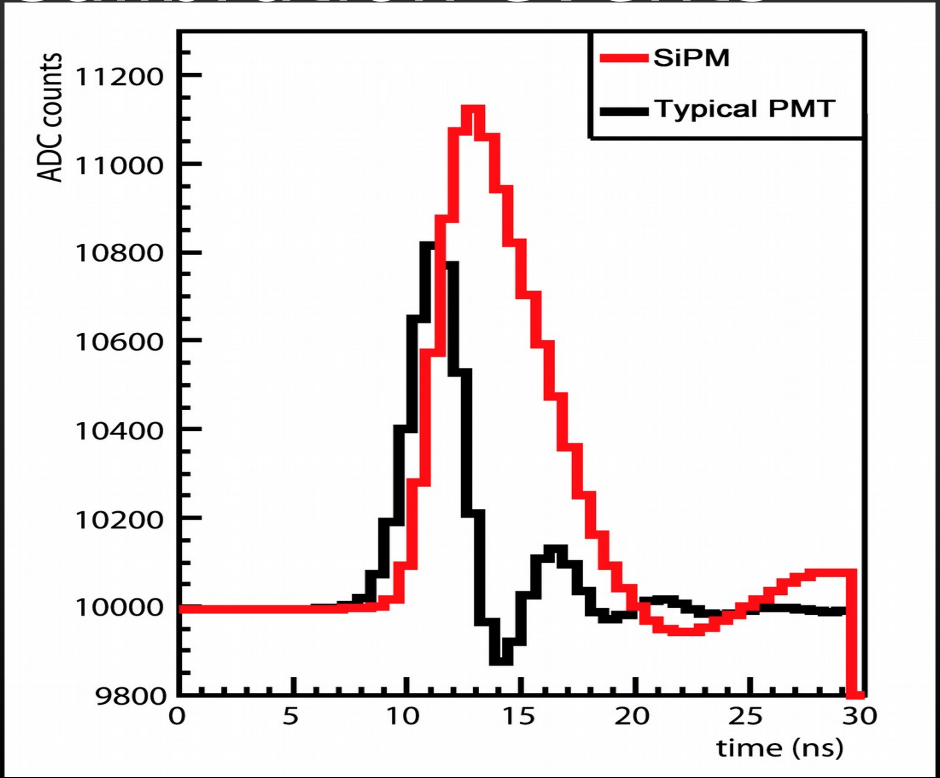


ADC counts
12500
12000
11500
11000
10500
10000
0
5
10
15
20
25
30
time (ns)
SensL SiPM
Typical PMT

BACKUP



Calibration events

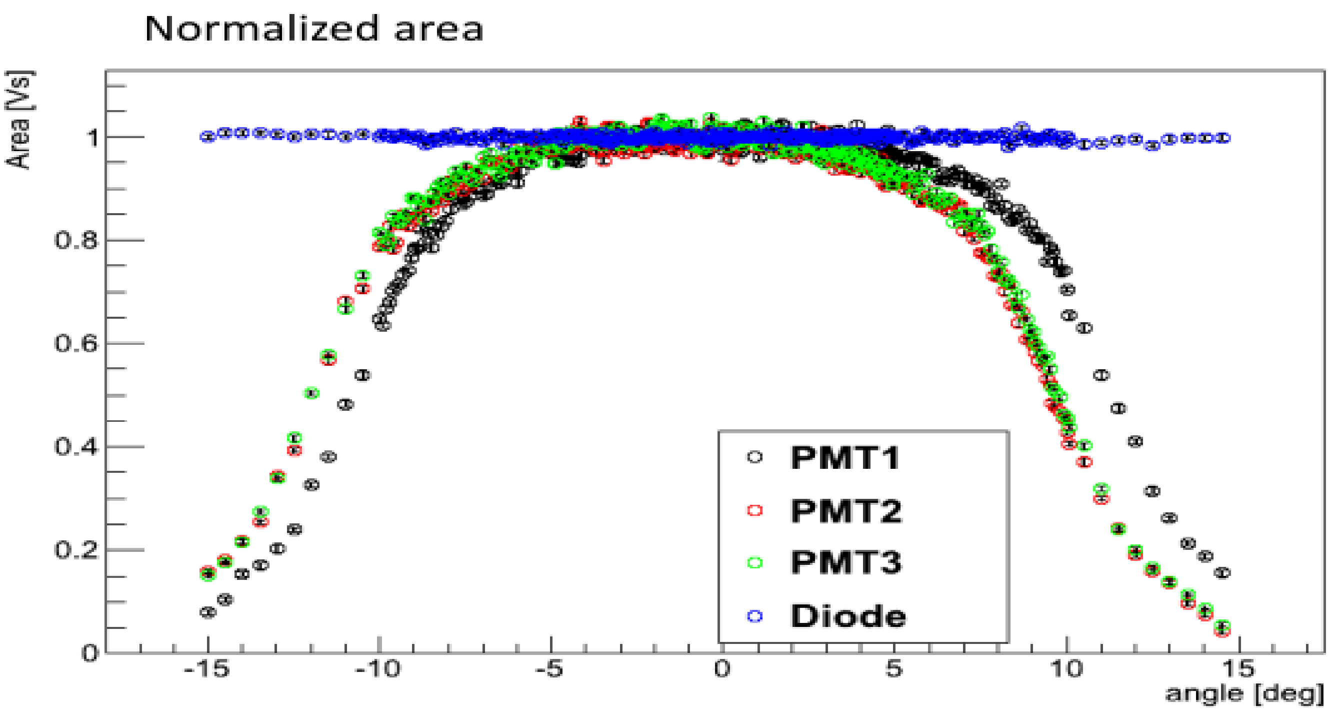


Laser pulses with constant intensity from the calibration box in the centre of the mirror dish

- Superimposed averaged calibration events of a SiPM and a PMT pixel
- Undershoots due to DRS4 readout
- FWHM(PMT) ≈ 2 ns
  FWHM(SiPM) ≈ 5 ns

BACKUP

Uniformity in illumination



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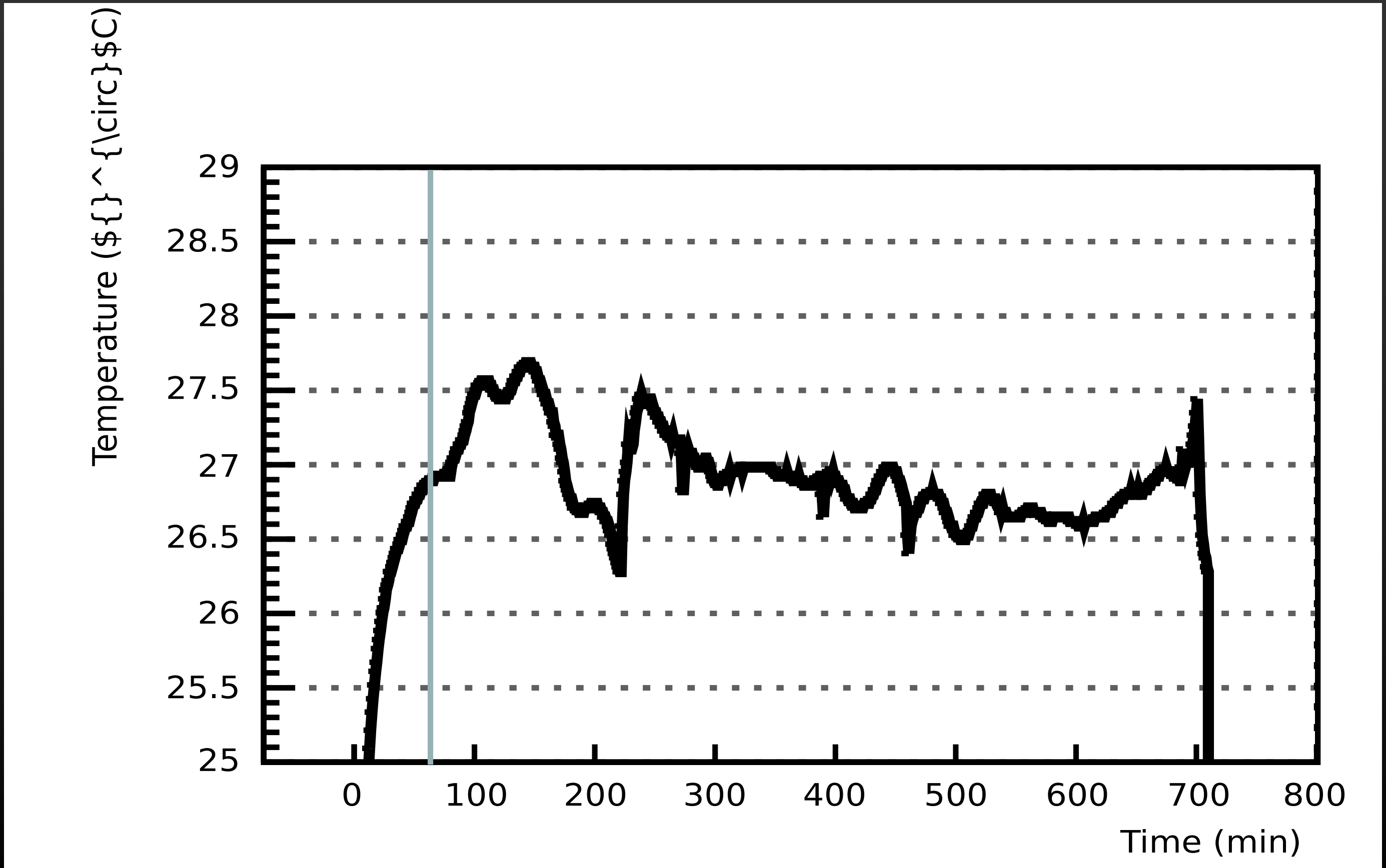

Temperature (${}^{\circ}$C)
29
28.5
28
27.5
27
26.5
26
25.5
25
0
100
200
300
400
500
600
700
800
Time (min)