Characterization of irradiated SiPM for the TOP detector at the Belle II experiment

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Content

- Irradiated SiPM modules in Padova
- Studies of current-voltage characteristics for SiPMs depending on:
  - Working temperature
  - Level of irradiation
  - Producers
- Software tools to read waveforms
- Background subtraction and extracting signal
- Preliminary photon spectra studies
- Conclusion

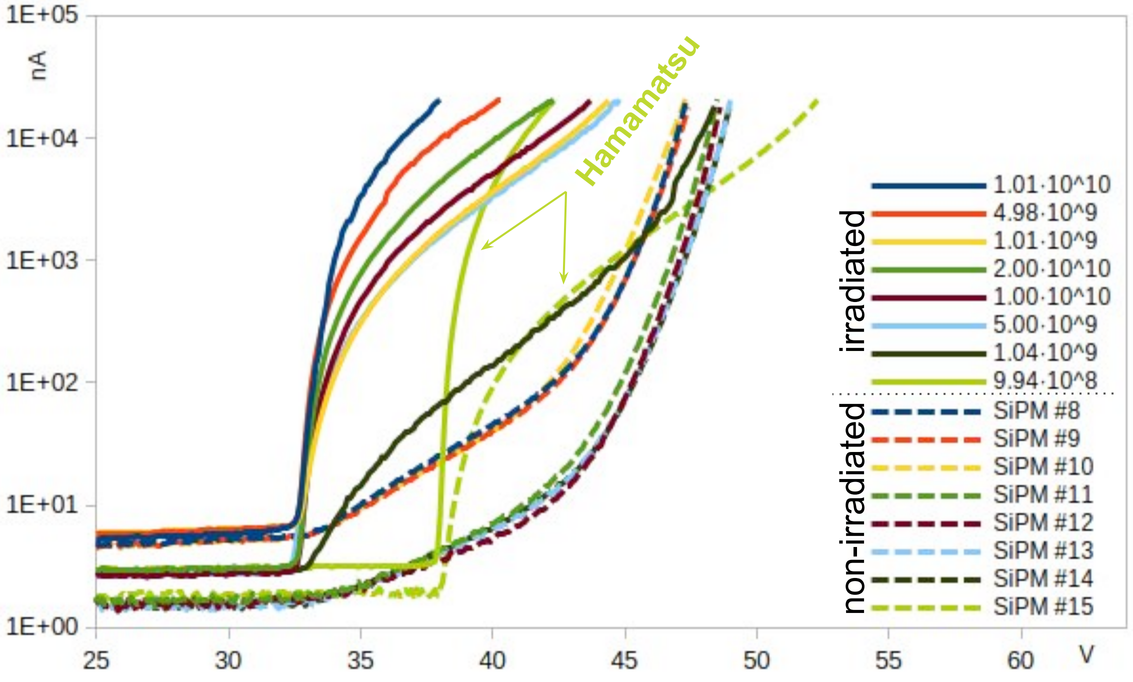
Tests with irradiated modules in Padova

- In Belle II, MCP-PMTs with extended lifetime have been installed and they have limited lifetime depending on accumulated charge.
- We are trying to understand if they eventually can be replaced with SiPMs.
- We irradiated 24 SiPMs modules with different neutron fluxes and tested by laser.
- Eight of them are processed to study their response.
- Collected data are read from modules and analyzed.

Index	Producer	Dimension [mm×mm]	Pitch [μm]	Distance [cm]	Neutron 1 MeV eg/cm^2 fluence	Charge [mC]	Time [h]
8	FBK	3 × 3	15	18.36	$1.0 \cdot 10^{10}$	2.86	5.88
9	FBK	3 × 3	15	18.24	$5.0 \cdot 10^{9}$	1.41	2.90
10	FBK	3 × 3	15	33.24	$1.0 \cdot 10^{9}$	0.94	1.93
11	FBK	1 × 1	15	15.86	$2.0 \cdot 10^{10}$	4.26	8.77
12	FBK	1 × 1	15	30.86	$1.0 \cdot 10^{10}$	8.07	16.61
13	FBK	1 × 1	15	15.74	$5.0 \cdot 10^{9}$	1.05	2.16
14	FBK	1 × 1	15	30.74	$1.0 \cdot 10^{9}$	0.80	1.65
15	Hamamatsu	3 × 3	50	33.46	$1.0 \cdot 10^{9}$	0.95	1.95

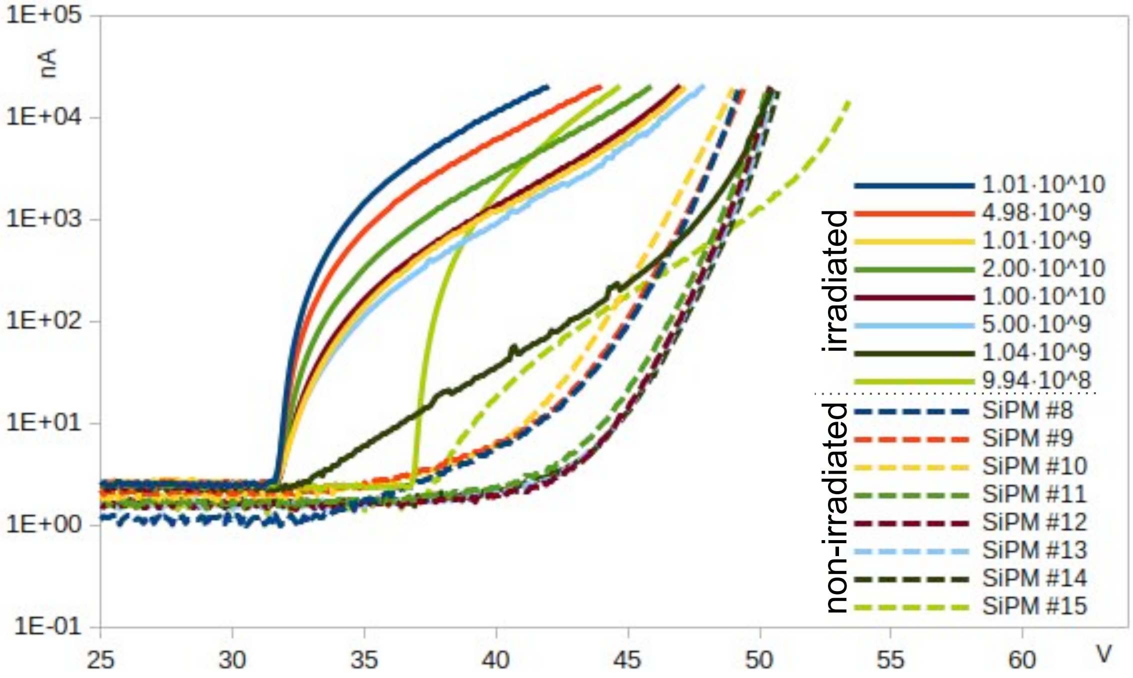
Current-voltage characteristic of some SiPM at +20°C

- Running at room working temperature, it does not change breakdown voltages much.
  - Non-irradiated FBKs ~ 33 V and Hamamatsu ~ 38 V
  - Irradiated FBKs ~ 33 V (mostly same for all) and Hamamatsu ~ 38 V
- Current-voltage characteristic rapidly change if FBKs are irradiated or not.
- Non-irradiated FBKs have shape of characteristic similar, but Hamamatsu has different to FBKs
- High irradiated shapes of FBKs and Hamamatsu are very similar, their tails depends on level of irradiation.
- Less irradiated 14th SiPM is closer to non-irradiated shape



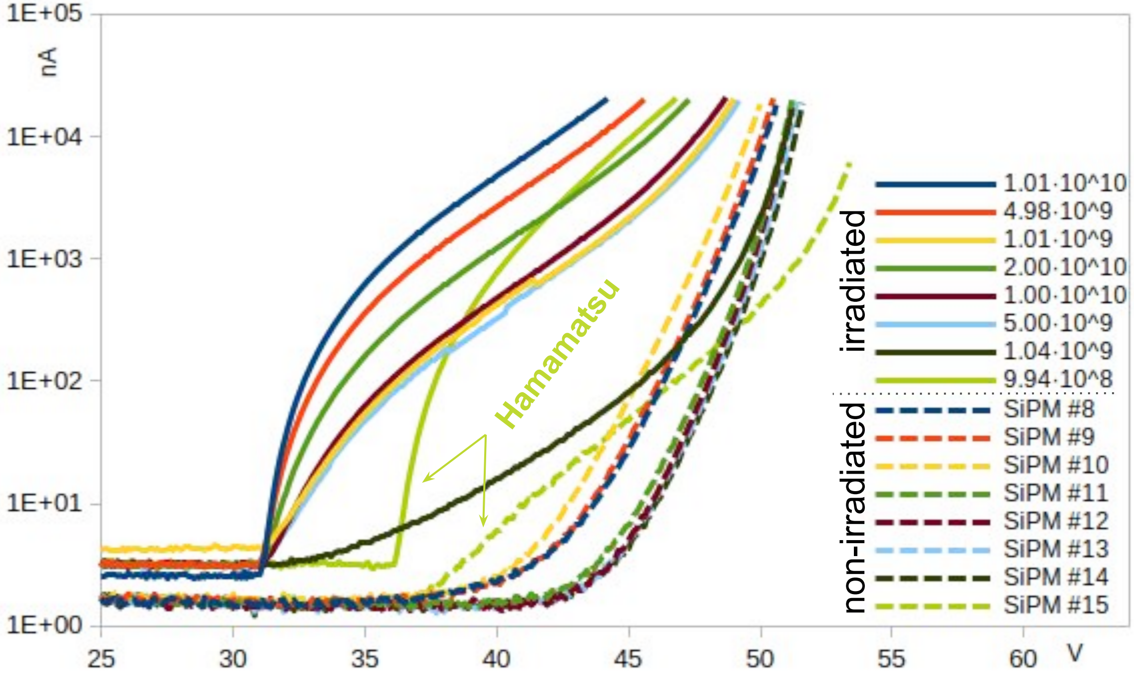
Current-voltage characteristic of some SiPM at -10°C

- Decreasing temperature, breakdown voltages are still similar before and after irradiation
  - Non-irradiated FBKs ~ 33 V and Hamamatsu ~ 38 V
  - Irradiated FBKs ~ 33 V (mostly same for all) and Hamamatsu ~ 38 V
- Current-voltage characteristic rapidly change if FBKs are irradiated or not, but they are closer
- Non-irradiated FBKs have shape of characteristic similar, but Hamamatsu has different to FBKs
- High irradiated shapes of FBKs and Hamamatsu are very similar, their tails depends on level of irradiation.
- Less irradiated 14th SiPM is closer to non-irradiated shape



Current-voltage characteristic of some SiPM at -30°C

- At low temperature, FBK and Hamamatsu SiPMs have different breakdown voltages:
  - Non-irradiated FBKs ~ from 38 to 42 V and Hamamatsu ~ 38 V
  - Irradiated FBKs ~ 30 V (all very close to each other) and Hamamatsu ~ 35 V
- Current-voltage characteristic rapidly change if SiPMs are irradiated highly or not.
- Non-irradiated FBKs have shape of characteristic similar, but Hamamatsu has different to FBKs
- Irradiated shapes of FBKs are fully dependent level of irradiation and dimension, but Hamamatsu is closer to non-irradiated curve in comparison with 12^{th} SiPM (same level of irradiation)



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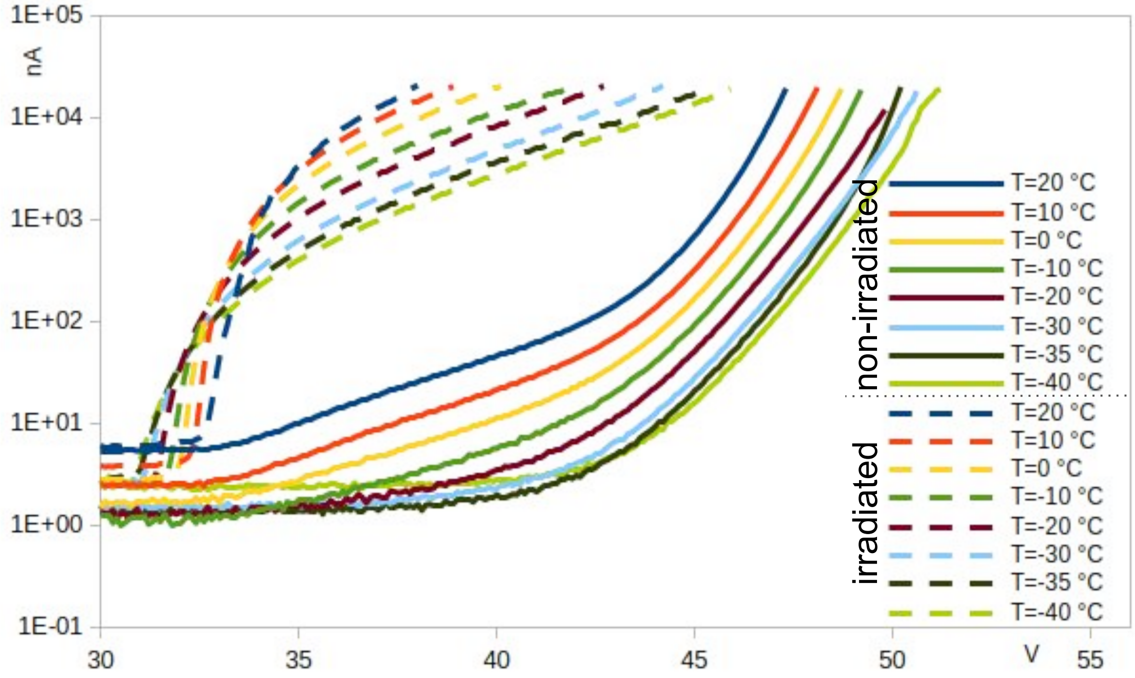
Current-voltage characteristic for FBK 8th SiPM

- Decreasing working temperature, breakdown points are changing a lot:
  - Non-irradiated breakdown points are between 32 to 42 V (it depends on definition)
  - Irradiated breakdown points are between 31 to 33 V
- Huge difference between irradiated and non-irradiated characteristics for high irradiated SiPM
- Non-irradiated characteristics shapes are changing as function of temperature
- Irradiated characteristics are not changing too much in comparison to non-irradiated working temperatures.



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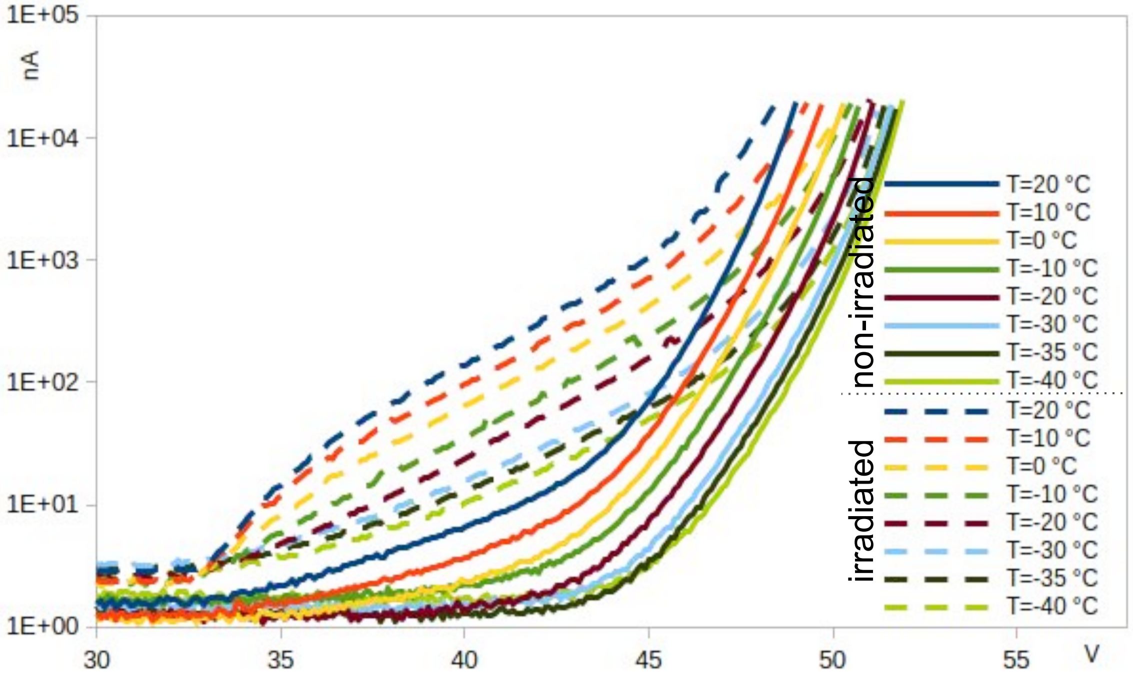
Current-voltage characteristic for FBK 14th SiPM

- Decreasing working temperature, breakdown points are changing a lot:
  - Non-irradiated breakdown points are between 32 to 44 V (it depends on definition)
  - Irradiated breakdown points are between 32 to 34 V
- Small difference between irradiated and non-irradiated characteristics for low irradiated SiPM
- Non-irradiated characteristics shapes are changing as function of temperature
- Irradiated characteristics are changing more in comparison to high irradiated SiPM (similar to non-irradiated working temperatures).



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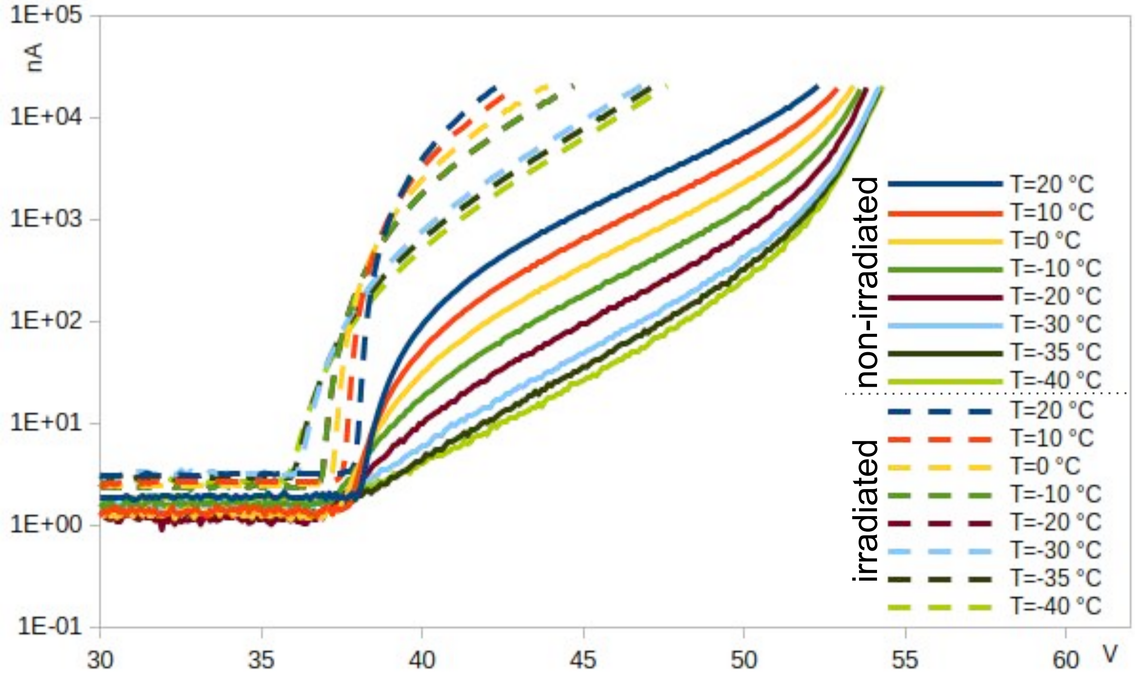
Current-voltage characteristic for Hamamatsu SiPM (15th)

- Decreasing working temperature, breakdown points does not change much
  - Non-irradiated breakdown points are between 36 to 38 V
  - Irradiated breakdown points are between 35 to 37 V
- At high temperatures characteristics are more similar, at low temperatures there is difference
- Non-irradiated characteristics shapes are changing as function of temperature
- Irradiated characteristics are not changing too much in comparison to non-irradiated working temperatures.

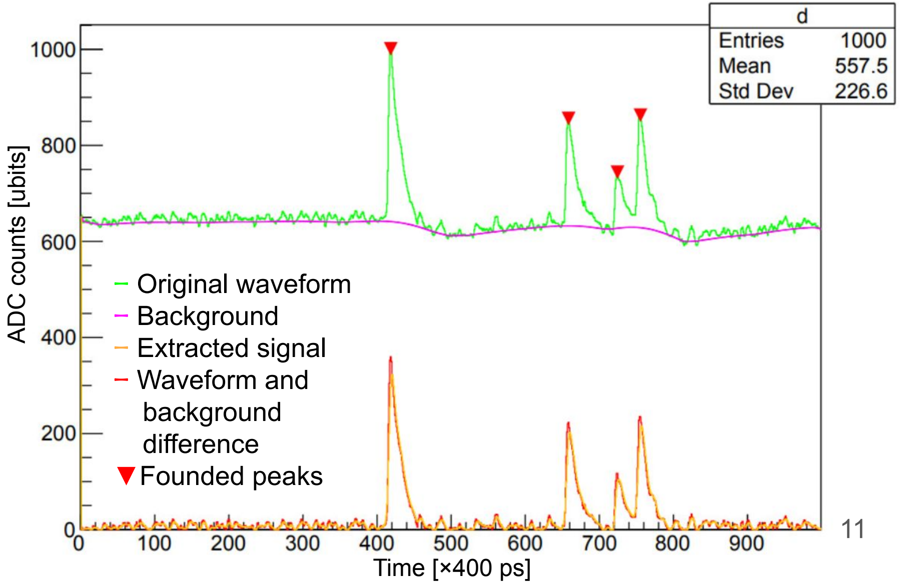


Content

- Irradiated SiPM modules in Padova
- Studies of current-voltage characteristics for SiPMs depending on:
  - Working temperature
  - Level of irradiation
  - Producers
- Experimental setup and software tools for our tests
- Background subtraction and extracting signal
- Preliminary photon spectra studies
- Conclusion

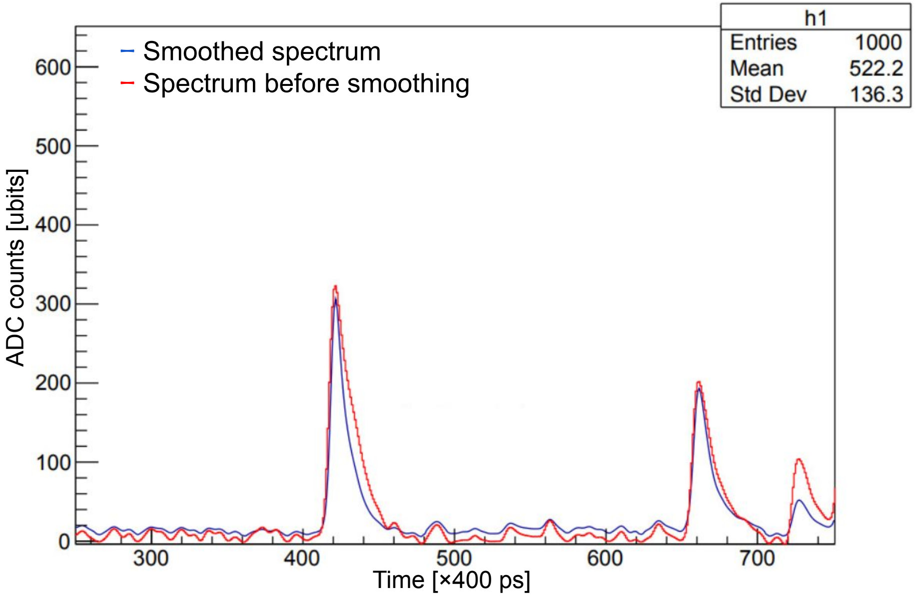
Experimental setup and software tools

- SiPM devices were illuminated with a laser beam with 20 ps time resolution attenuating the beam in order to work with a small number of photons, because in the detector we will have to detect only single photons.
- For data processing, we are using [TSpectrum Class] in ROOT environment
- Peaks are found using [SearchHighRes] function based on
  - Subtraction background using deconvolution
  - Allowing smoothing extracted spectrum using Markov algorithm
  - Returns
    - Number of founded peaks
    - Extracted spectrum



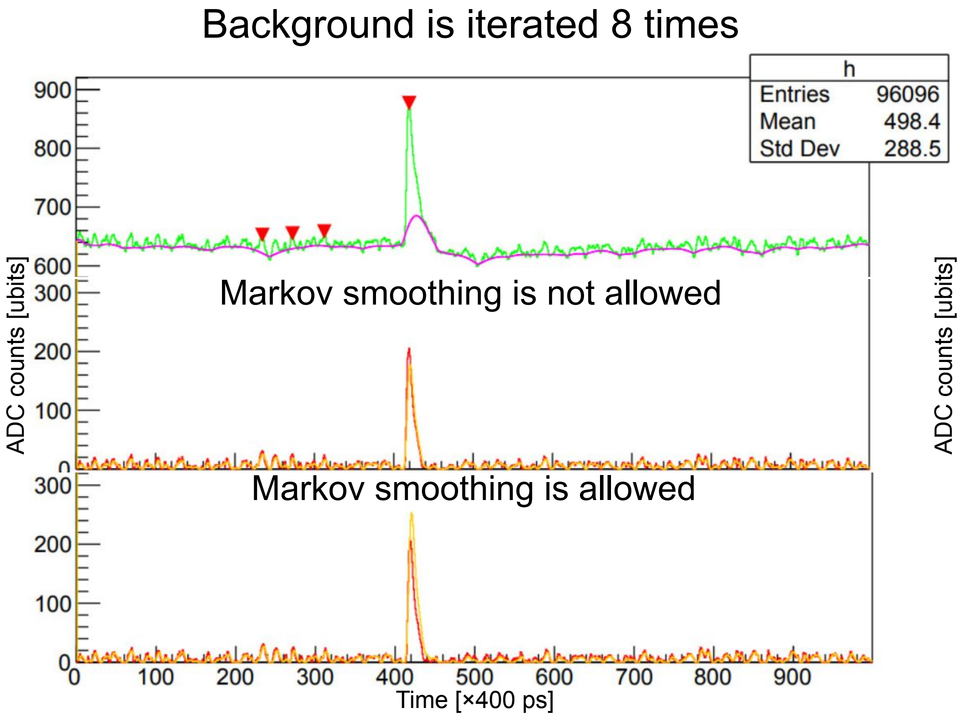
Background subtraction and extracting signal

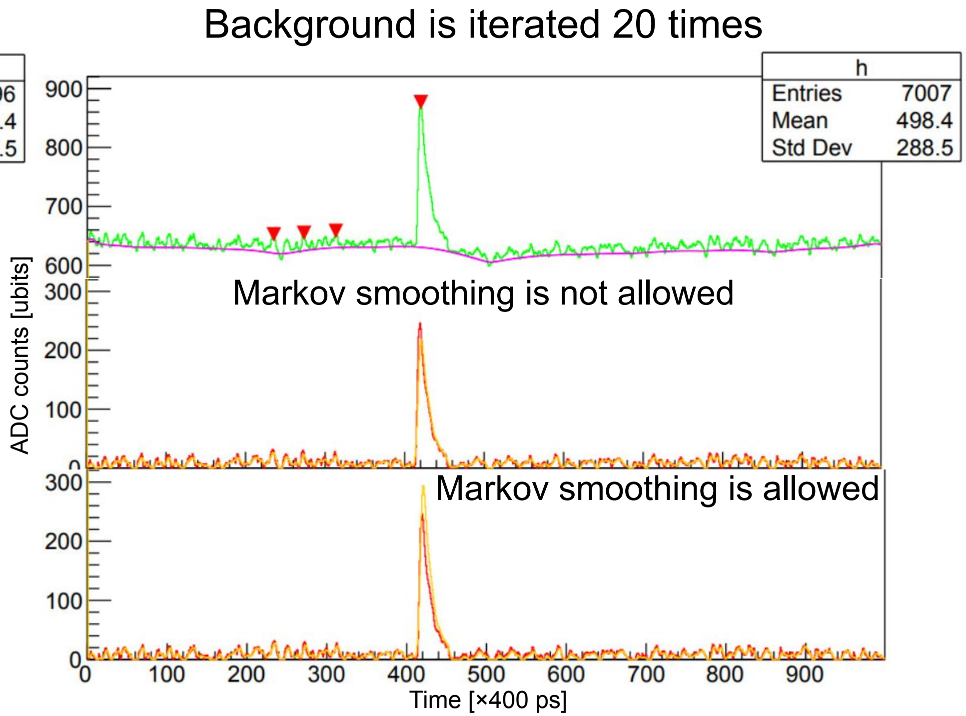
- In TSpectrum Class in ROOT environment, there is another Background function to simply estimate background
- It allows to extract signal spectra by two different methods:
  - As output of SearchHighRes function
  - As difference between original waveform and output of Background function
- Difference between original waveform and output of Background function can be smoothed by Markov algorithm using SmoothMarkov function
- Both methods are compared



Waveform spectrum for 14th SiPM

- Background is determined averaging original waveform in several iterations





- Original waveform
- Background
- Extracted signal
- Waveform and background difference
- ▼ Founded peaks

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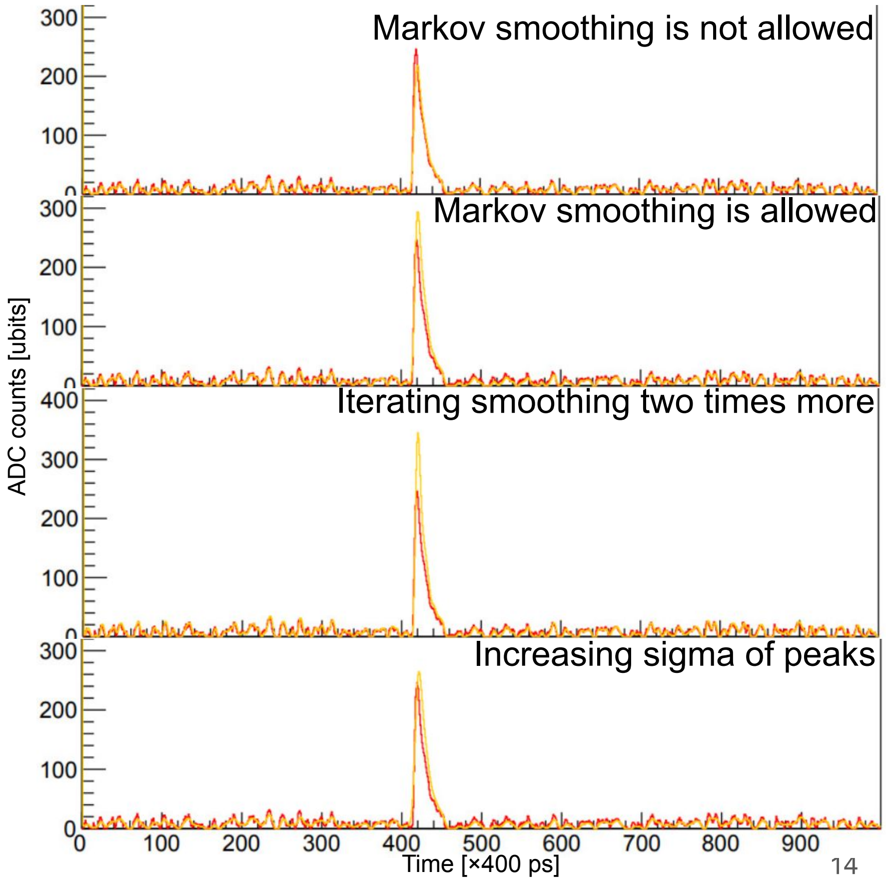
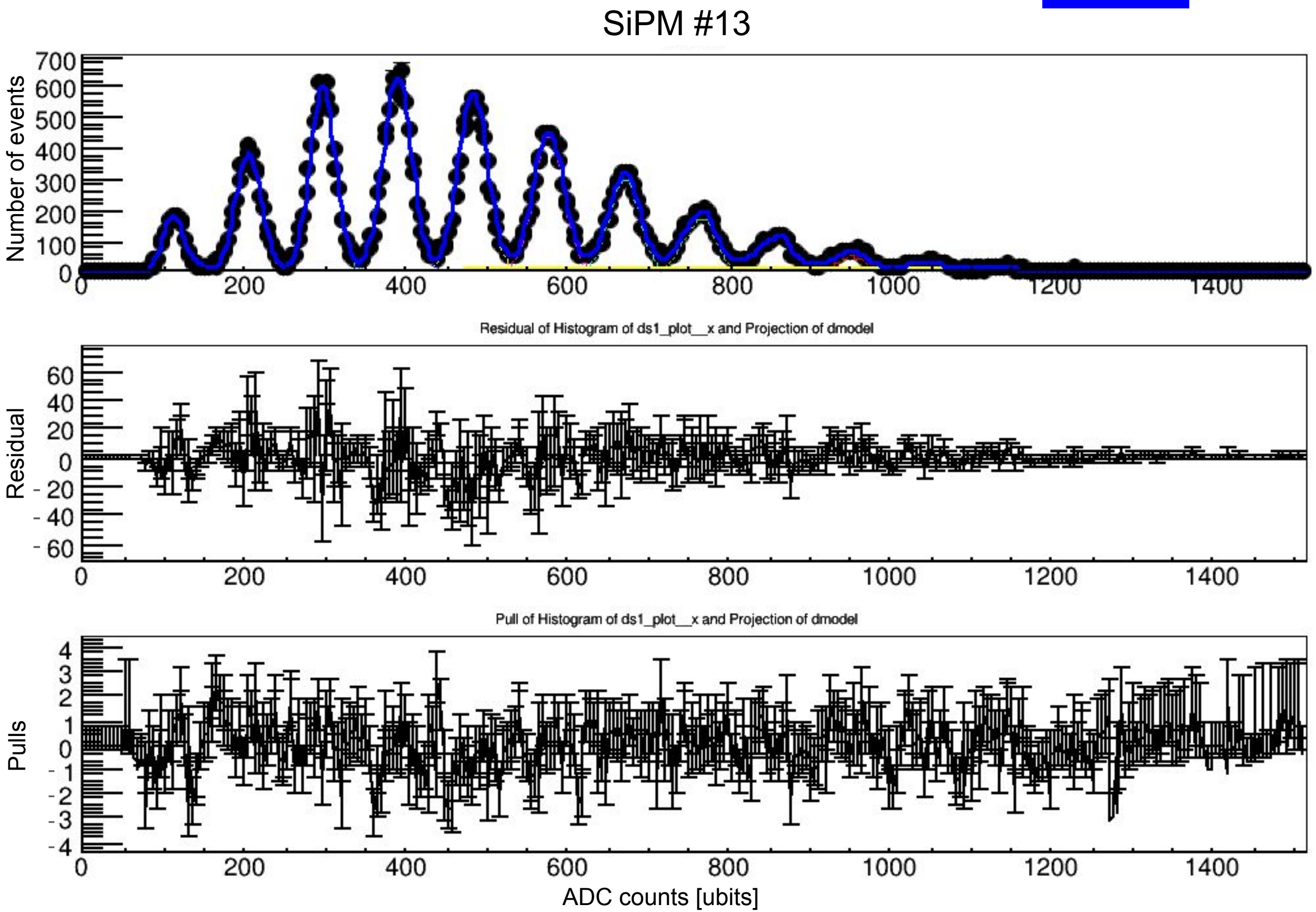
Other options for waveform spectrum for 14th SiPM

- As was shown at slide 6:
  - Higher number background iterations increase peak amplitudes
  - Allowing smoothing using Markov algorithm, peak amplitude rises
- There is another possibilities how to model peak shapes:
  - Increasing smoothing iterations amplitude of peaks grows
  - Wider signal peaks can be found using increasing sigma of founded peaks



Fit of photon spectra

- Photon spectra are extracted
- Photon spectra are fitted sum of convolution poissonian and gaussian distribution to extract gain and average of photons
- From gain we can extract breakdown voltage



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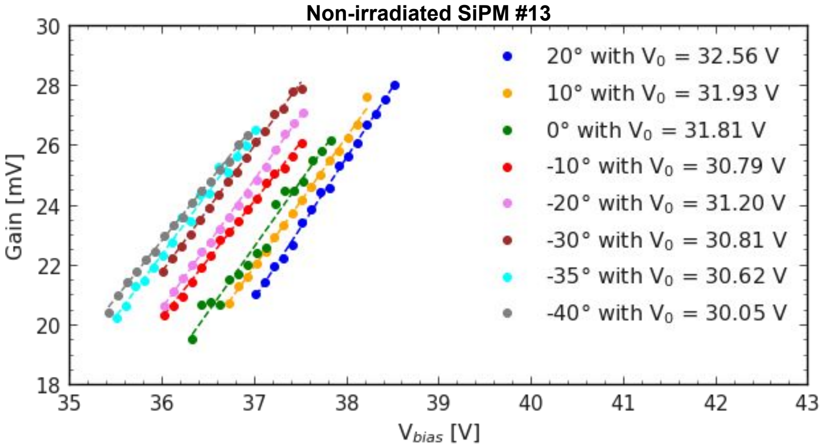
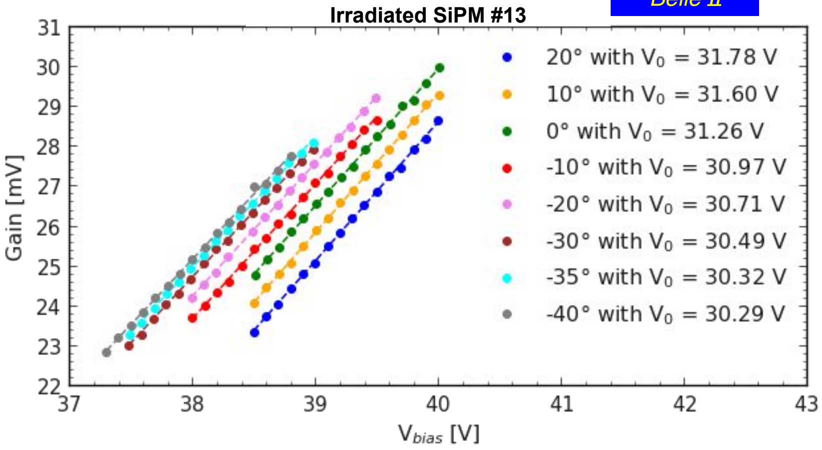
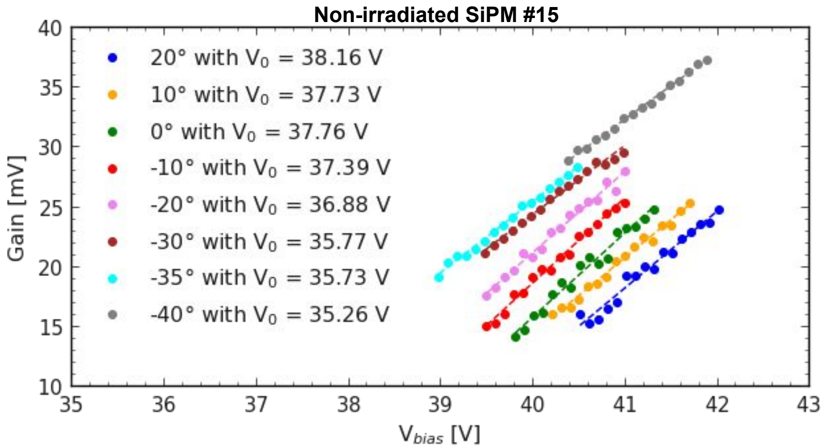
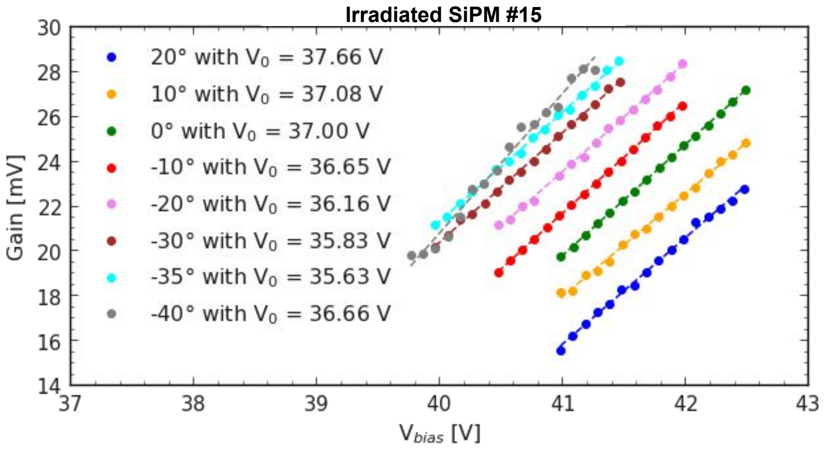
Extraction of breakdown voltage from spectra



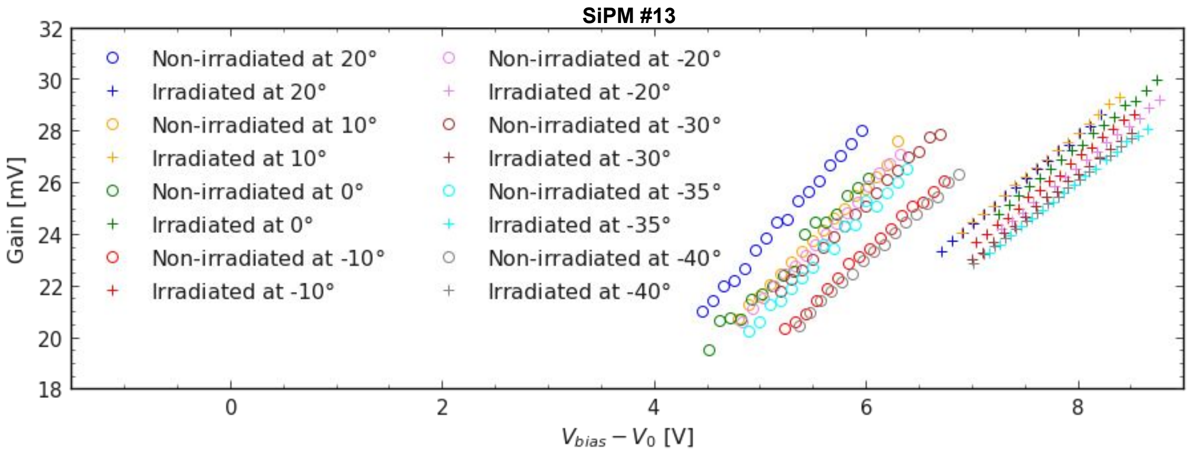


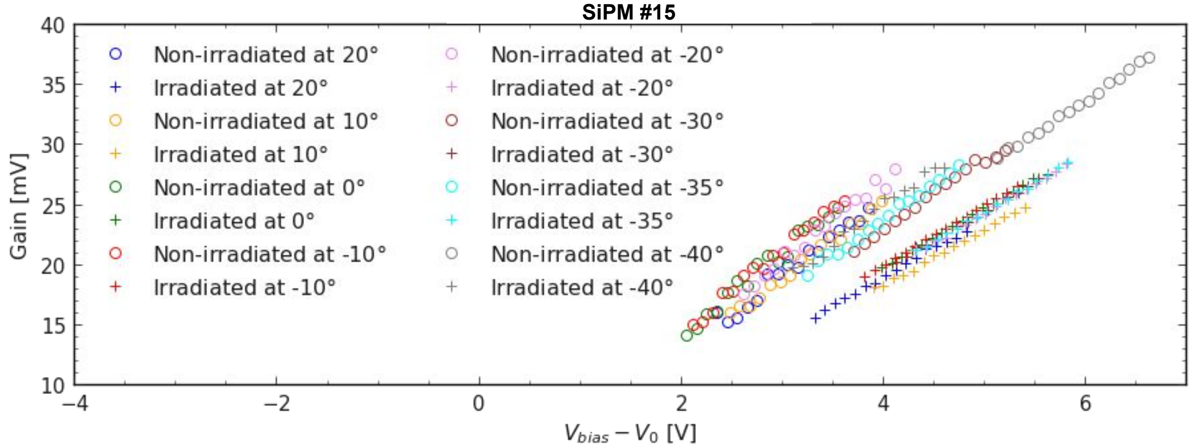




Gain as function of overvoltage

- Extracted breakdown voltage can be subtracted from bias voltage
- Irradiated and non-irradiated results are consistent, but we see some inconsistencies at 0 $^\circ$C, we plan to investigate a source.





Breakdown voltages at temperatures for SiPMs

Index of SiPM	11		12		13		14		15	
Producer	FBK		FBK		FBK		FBK		Hamamatsu	
Dimension [mm×mm]	1 × 1		1 × 1		1 × 1		1 × 1		3 × 3	
Pitch [μm]	15		15		15		15		50	
	Breakdown voltage [V_0]		Breakdown voltage [V_0]		Breakdown voltage [V_0]		Breakdown voltage [V_0]		Breakdown voltage [V_0]	
Temperature [°]	non-irr	irr	non-irr	irr	non-irr	irr	non-irr	irr	non-irr	irr
20	33.13	32.63	33.15	32.03	32.56	31.78	32.43	32.17	38.16	37.66
10	33.78	32.20	32.06	31.77	31.93	31.60	32.22	31.89	37.73	37.08
0	31.16	28.45	31.53	31.37	31.81	31.26	31.31	31.50	37.76	37.00
-10	31.36	31.64	31.55	30.25	30.79	30.97	31.20	31.16	37.39	36.65
-20	31.19	31.06	30.95	30.94	31.20	30.71	31.43	31.05	36.88	36.16
-30	31.53	30.79	31.25	30.69	30.81	30.49	30.65	30.54	35.77	35.83
-35	30.45	30.50	30.76	30.44	30.62	30.32	30.41	29.85	35.73	35.63
-40	29.97	30.16	30.59	30.40	30.05	30.29	30.48	30.35	35.26	36.66

- For Hamamatsu device the breakdown voltages agree with previous measurements
- For some FBK devices, the breakdown voltages do not agree with previous measurements.
- After finishing studies related to breakdown voltage, we will continue with extraction time resolution

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Conclusion

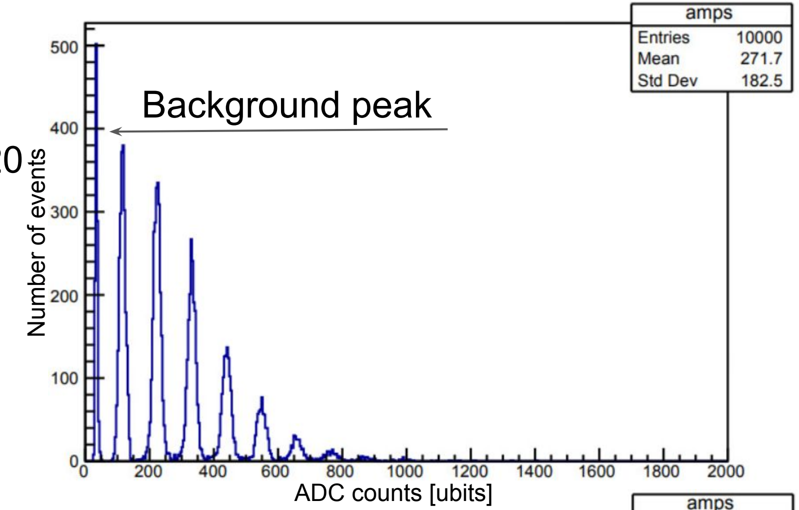
- In Padova it has been irradiated and tested several SiPM modules
- Current-voltage characteristics have been analyzed
  - As function of level of irradiation
  - Working temperature
  - Different producers
- Characteristics are changing in function of irradiation and working temperatures, but it highly depends on the producers
- For some of them data has been processed and analyzed in TSpectrum Class in ROOT environment, where we can
  - Suppress background
  - Smooth and deconvolute spectrum
  - Search for peaks
- Data has been processed to provide photon spectra and it was fitted to extract gain and average of photons.
- From gain we extract breakdown voltage and compare between irradiated and non-irradiated cases.
- We plan study average of photons and time resolution in next weeks.
- These devices will be irradiated again to reach higher doses and currently they are in annealing process at 150 $^{\circ}$C

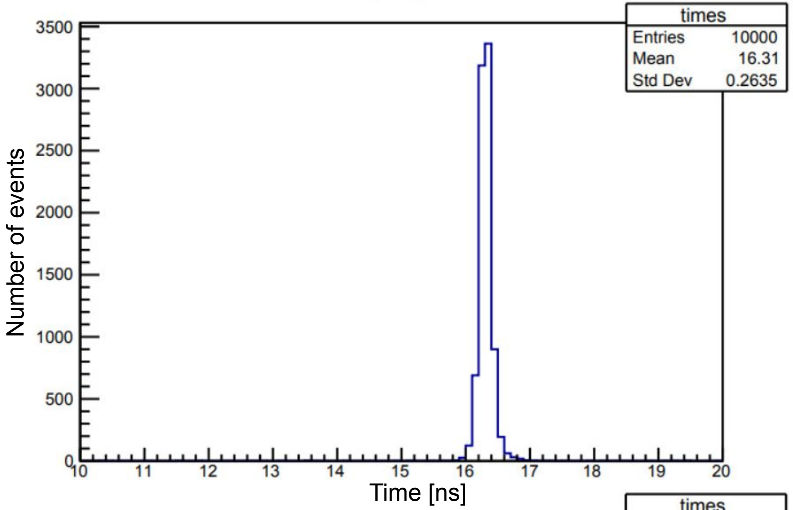
Backup

SiMP #14

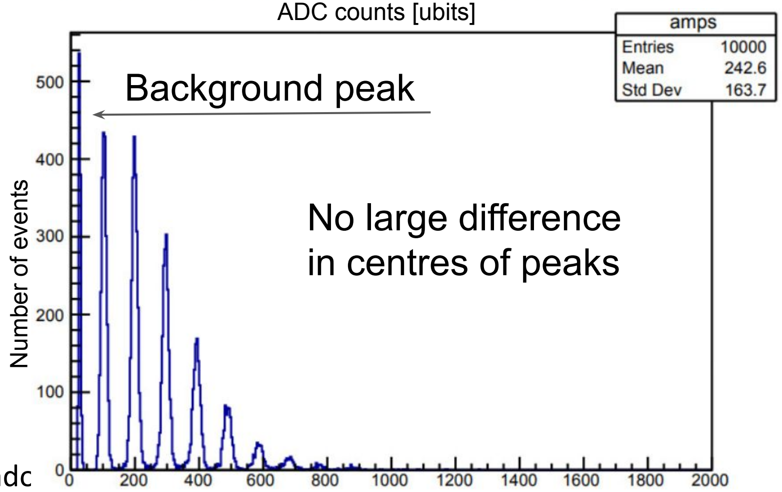
Time resolution and photon spectrum for 14th SiPM

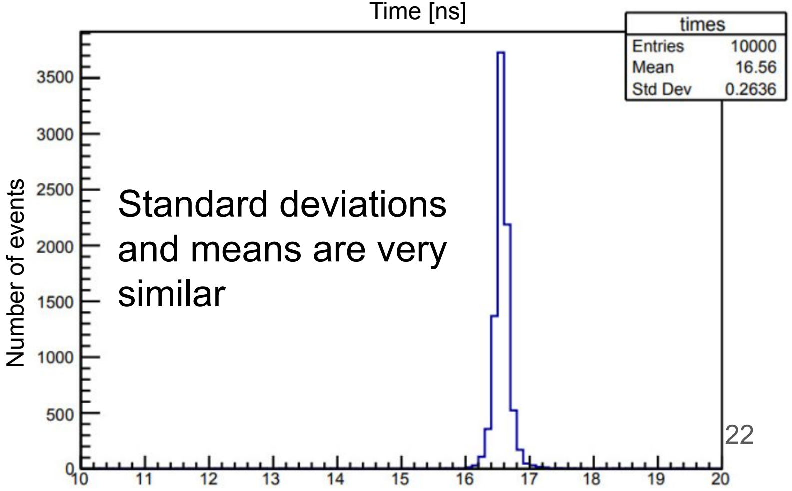
Extracted signal using 20 background iterations without smoothing





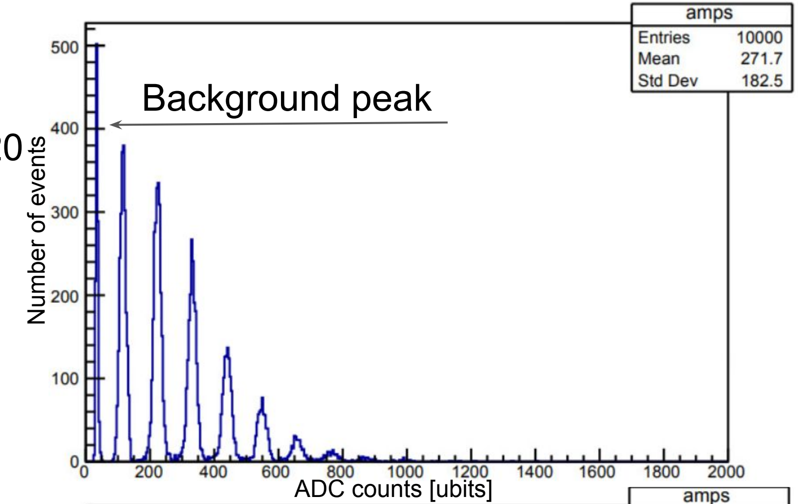
Difference between waveform and background iterated 20 times without smoothing

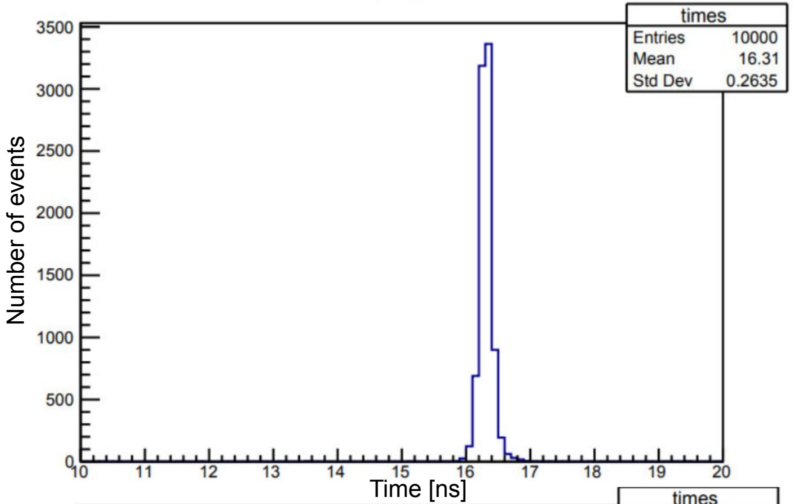




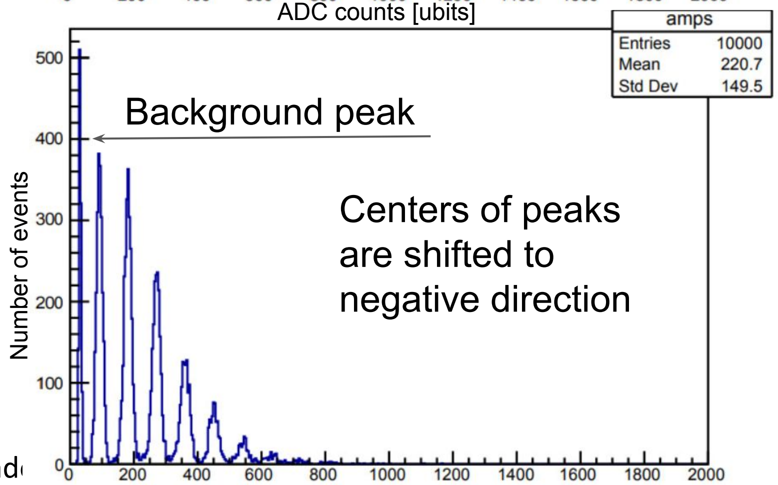
Time resolution and photon spectrum for 14th SiPM

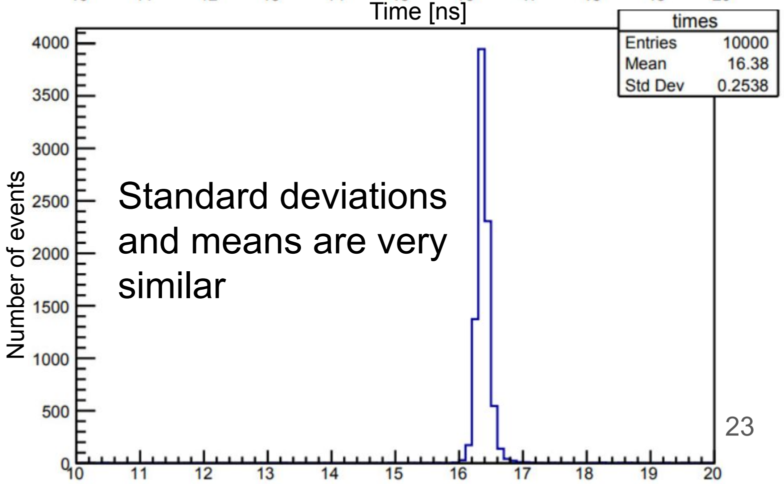
Extracted signal using 20 background iterations without smoothing





Extracted signal using 8 background iterations without smoothing

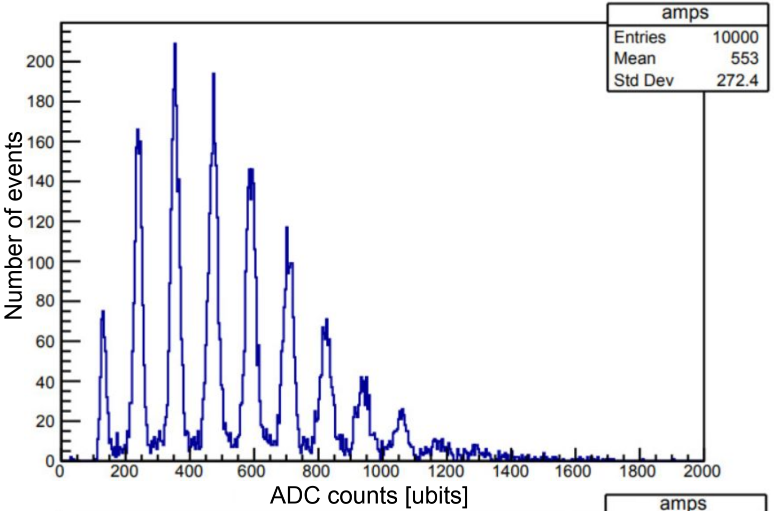


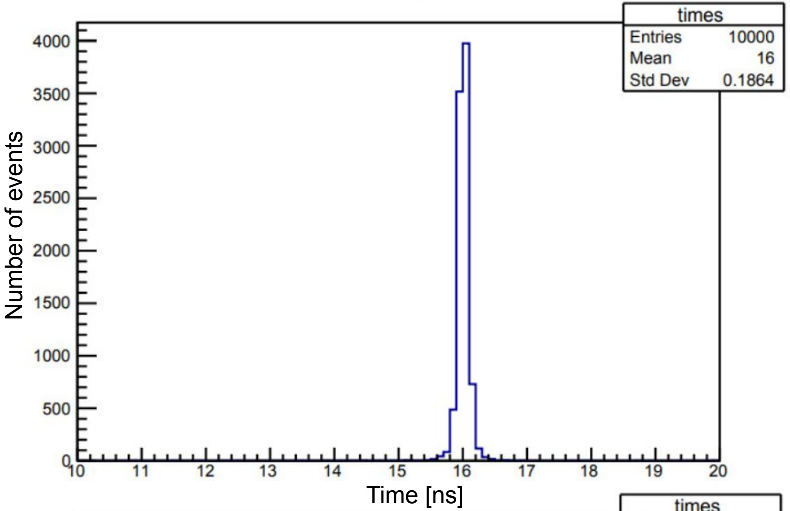


SiMP #13

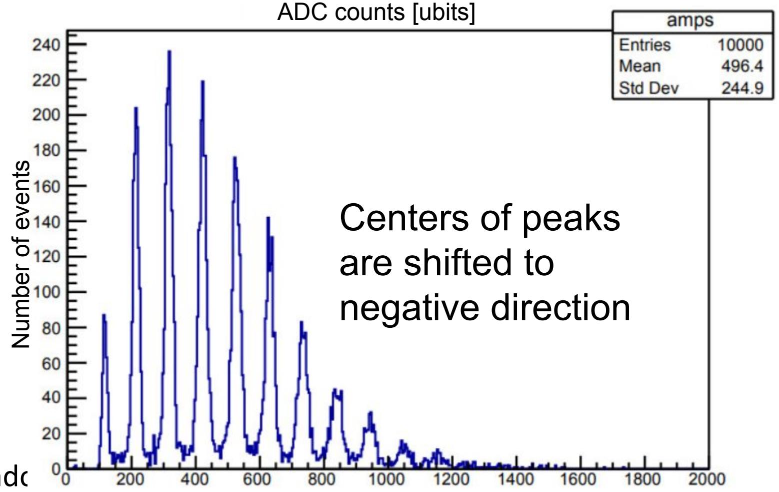
Time resolution and photon spectrum for 13th SiPM

Extracted signal using 20 background iterations without smoothing

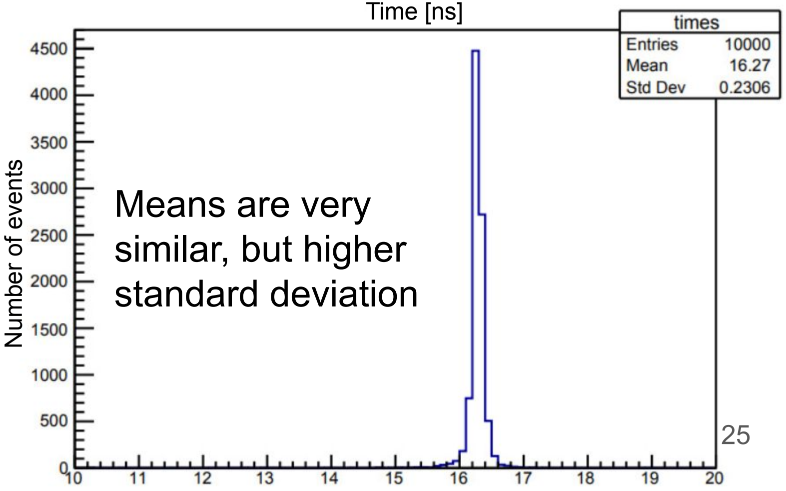




Difference between waveform and background iterated 20 times without smoothing



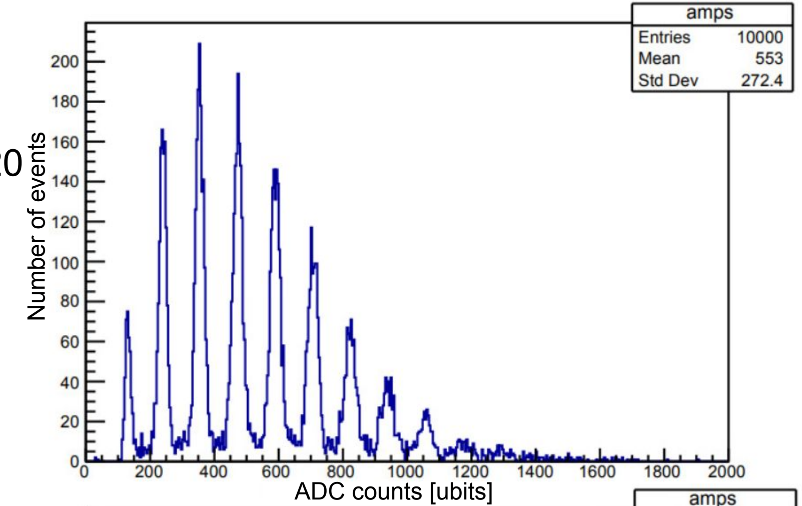
Centers of peaks are shifted to negative direction

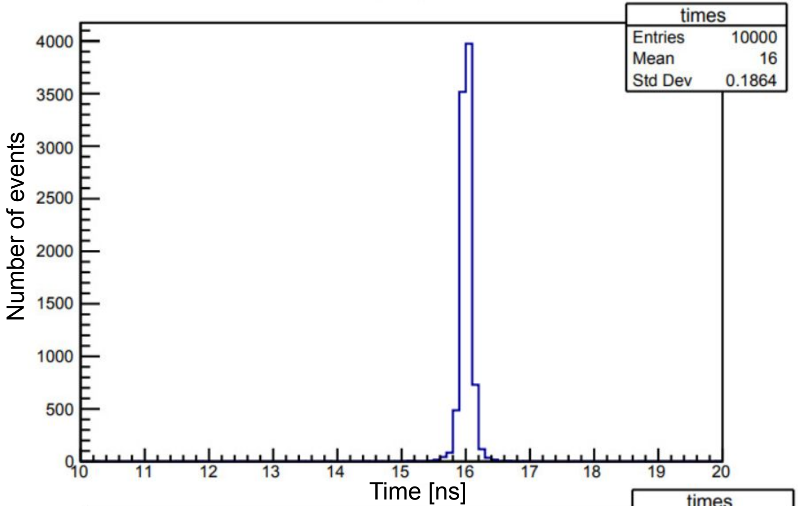


Means are very similar, but higher standard deviation

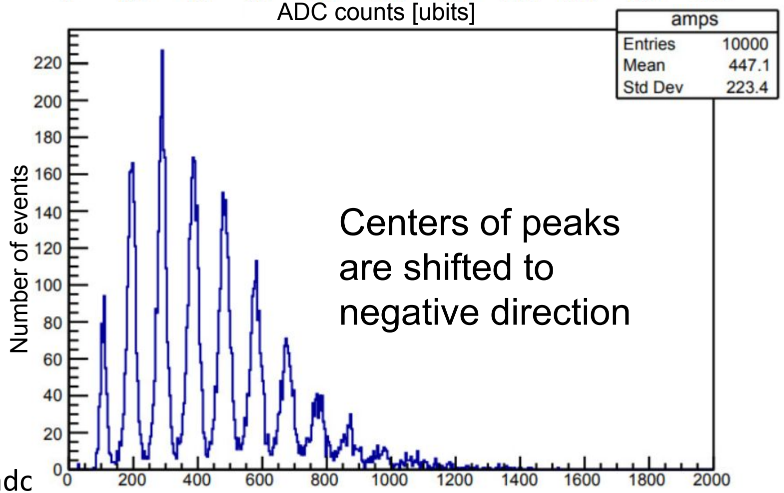
Time resolution and photon spectrum for 13th SiPM

Extracted signal using 20 background iterations without smoothing

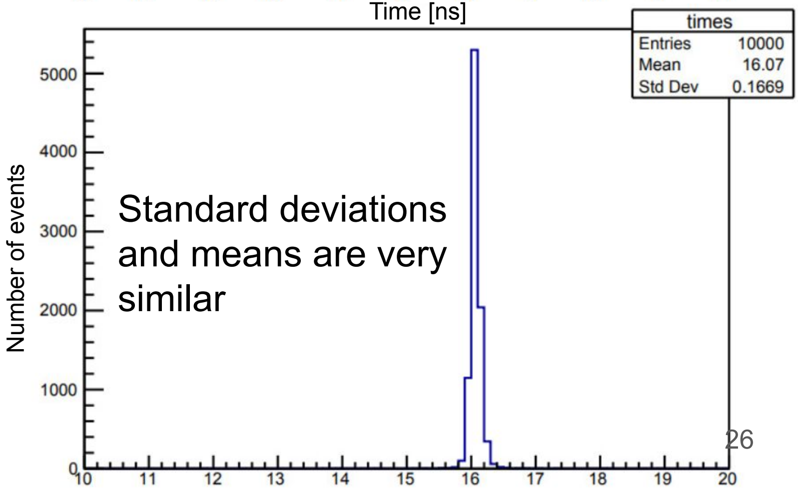




Extracted signal using 8 background iterations without smoothing



Centers of peaks are shifted to negative direction

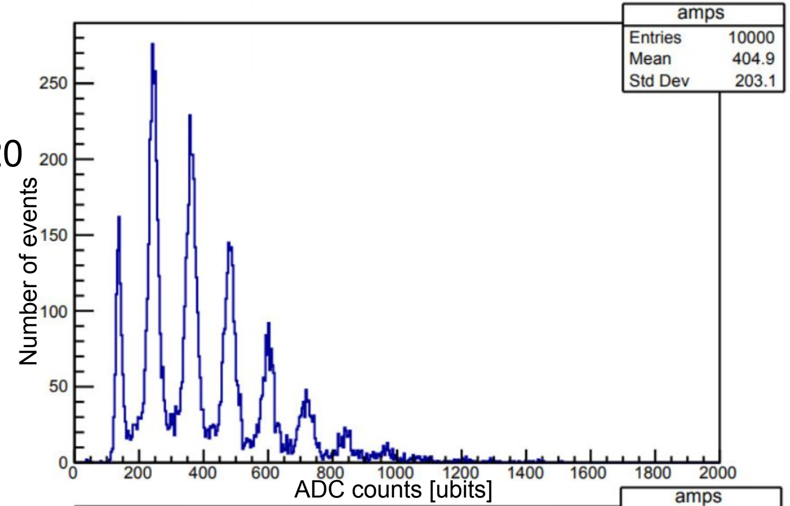


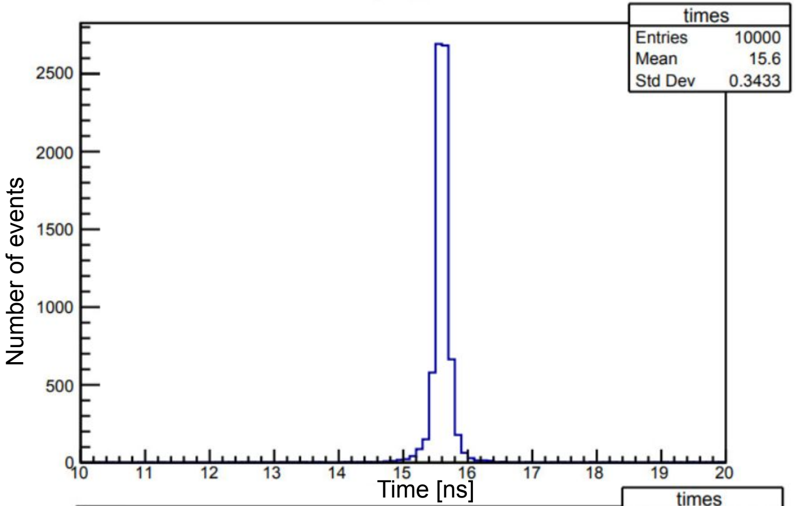
Standard deviations and means are very similar

SiMP #12

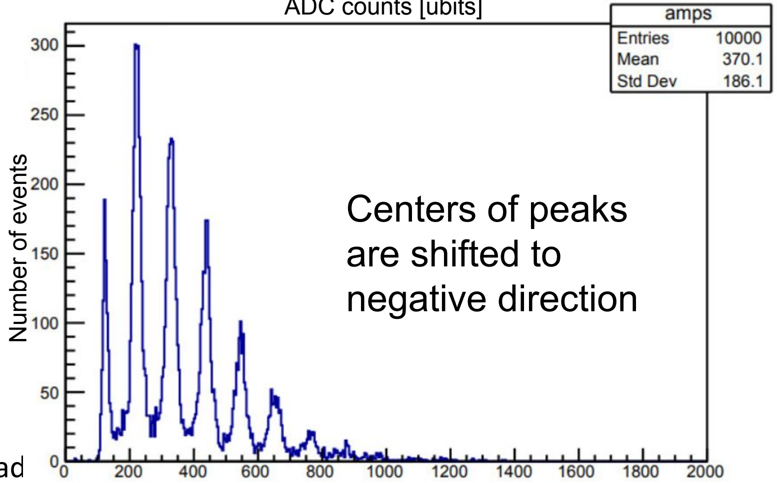
Time resolution and photon spectrum for 12th SiPM

Extracted signal using 20 background iterations without smoothing

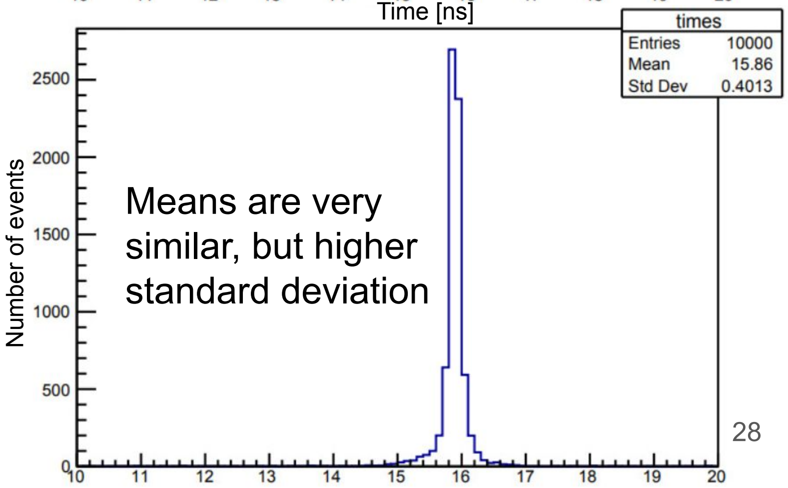




Difference between waveform and background iterated 20 times without smoothing



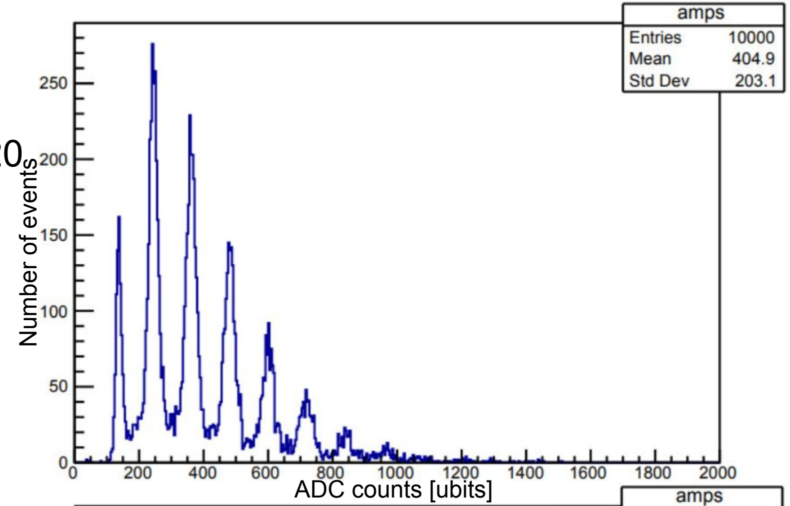
Centers of peaks are shifted to negative direction

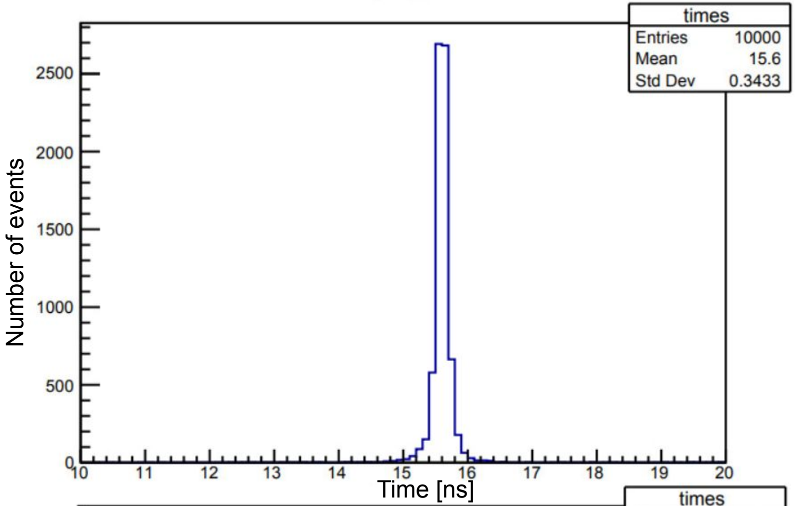


Means are very similar, but higher standard deviation

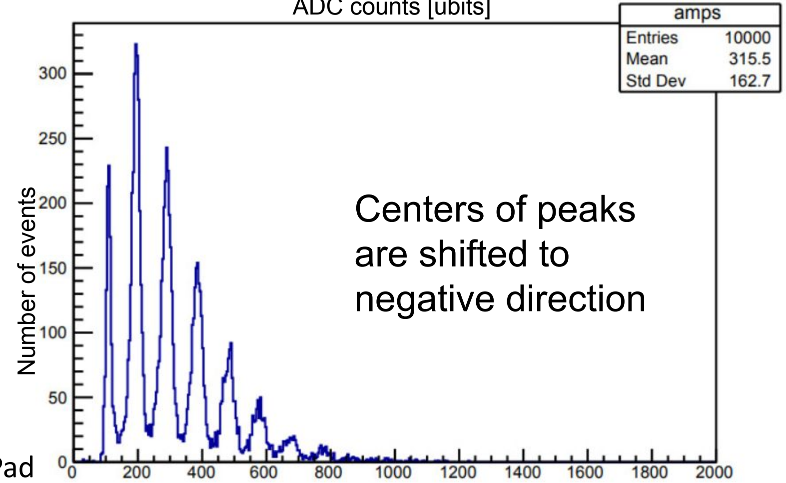
Time resolution and photon spectrum for 12th SiPM

Extracted signal using 20 background iterations without smoothing

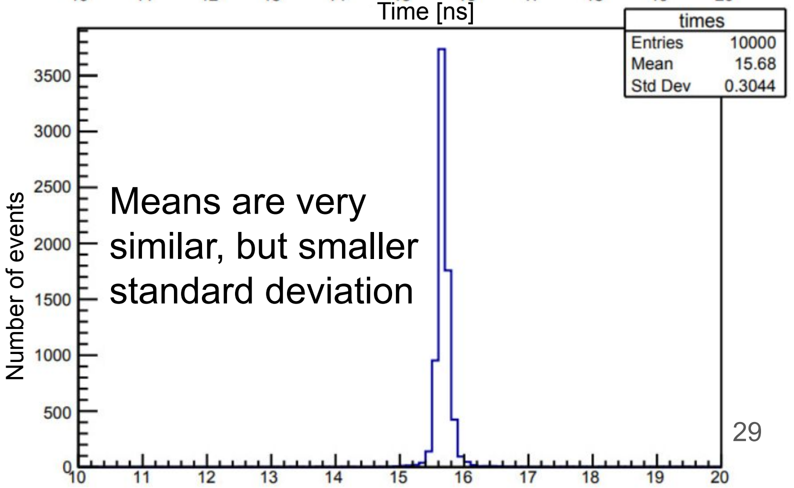




Extracted signal using 8 background iterations without smoothing



Centers of peaks are shifted to negative direction

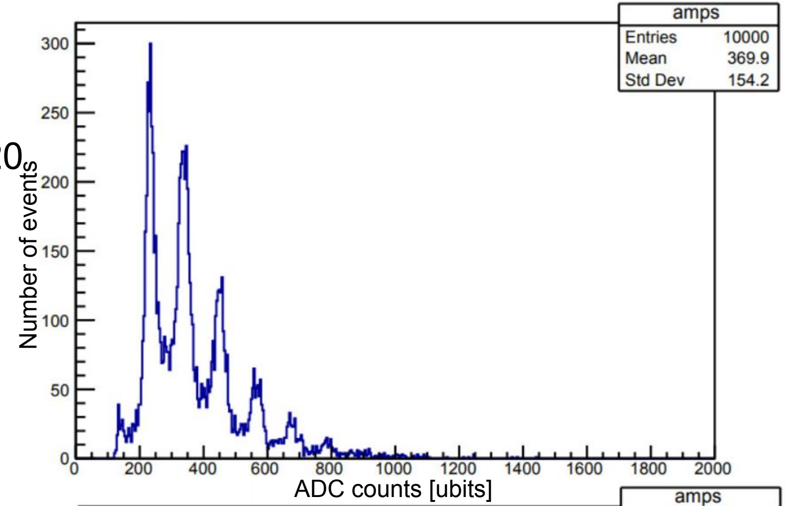


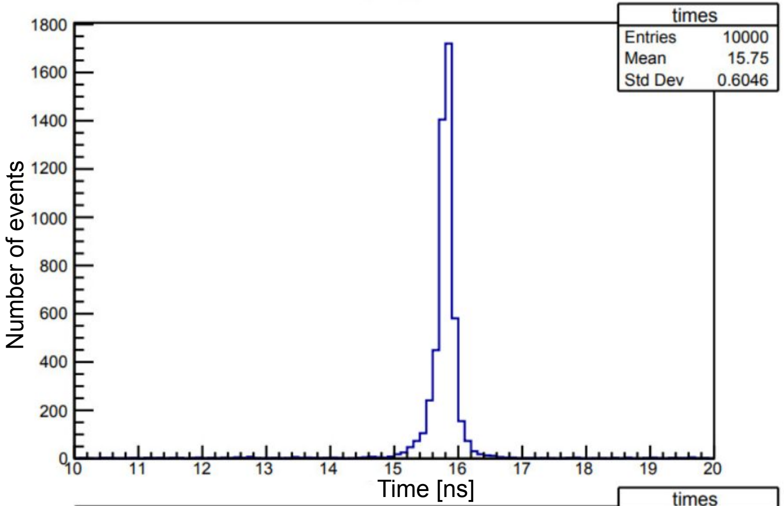
Means are very similar, but smaller standard deviation

SiMP #11

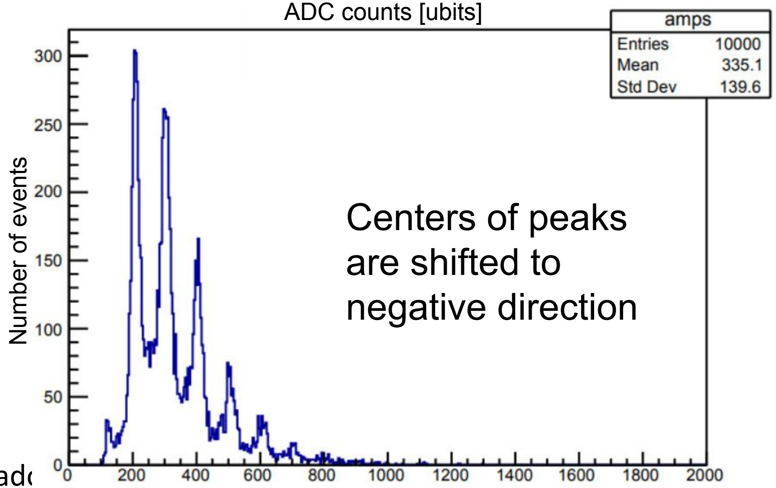
Time resolution and photon spectrum for 11th SiPM

Extracted signal using 20 background iterations without smoothing

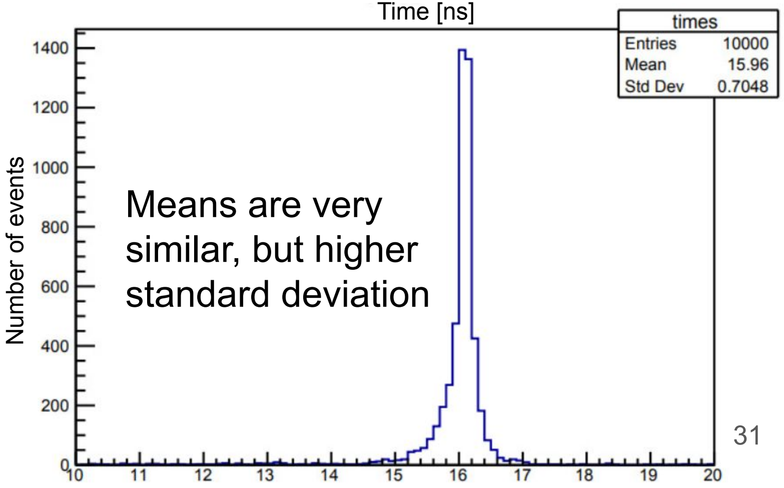




Difference between waveform and background iterated 20 times without smoothing



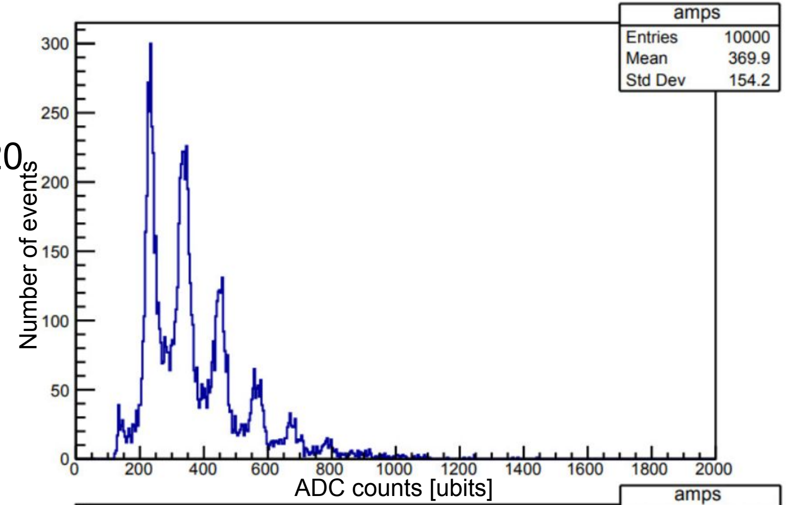
Centers of peaks are shifted to negative direction

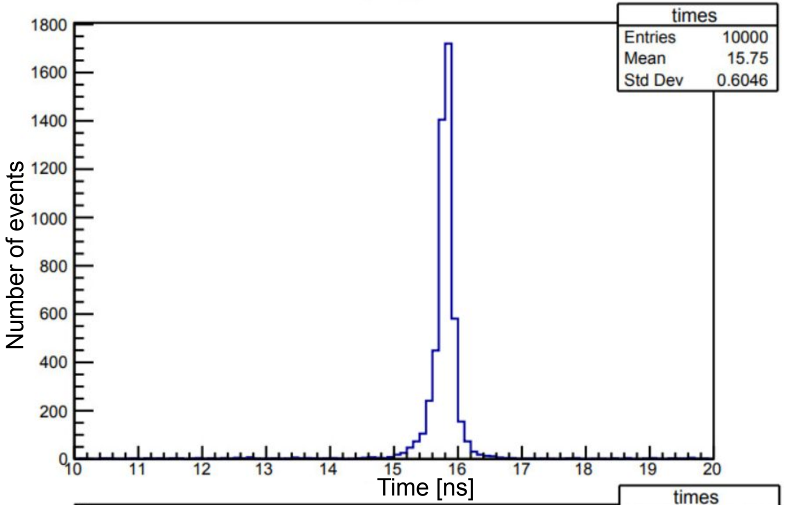


Means are very similar, but higher standard deviation

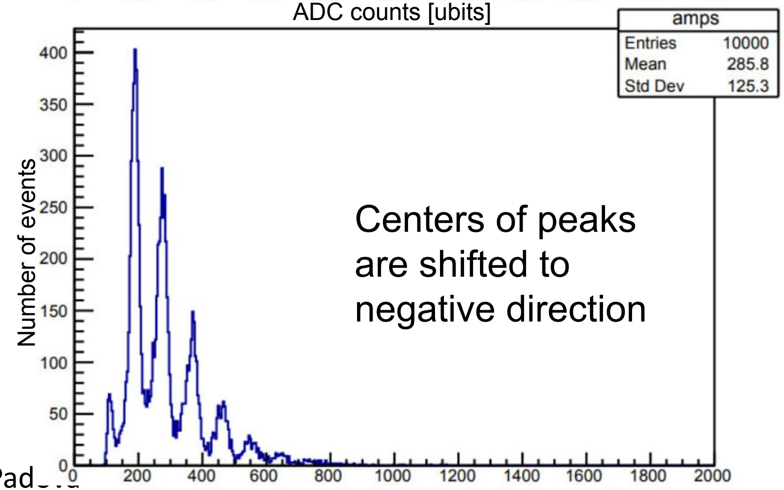
Time resolution and photon spectrum for 11th SiPM

Extracted signal using 20 background iterations without smoothing

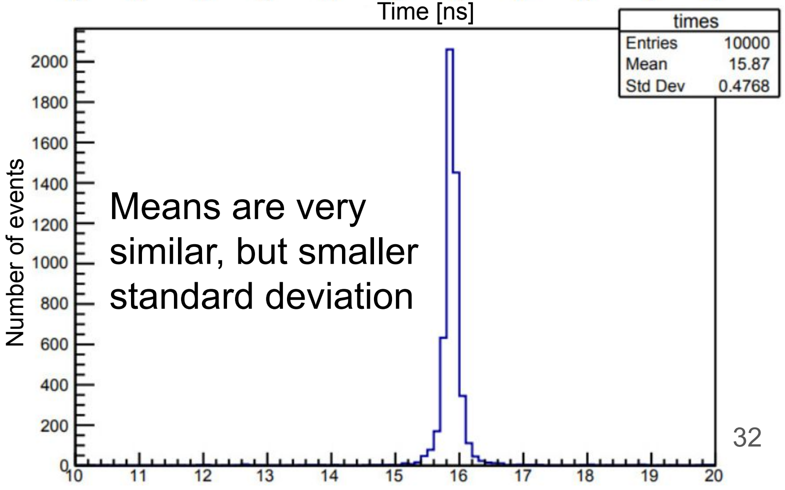




Extracted signal using 8 background iterations without smoothing



Centers of peaks are shifted to negative direction

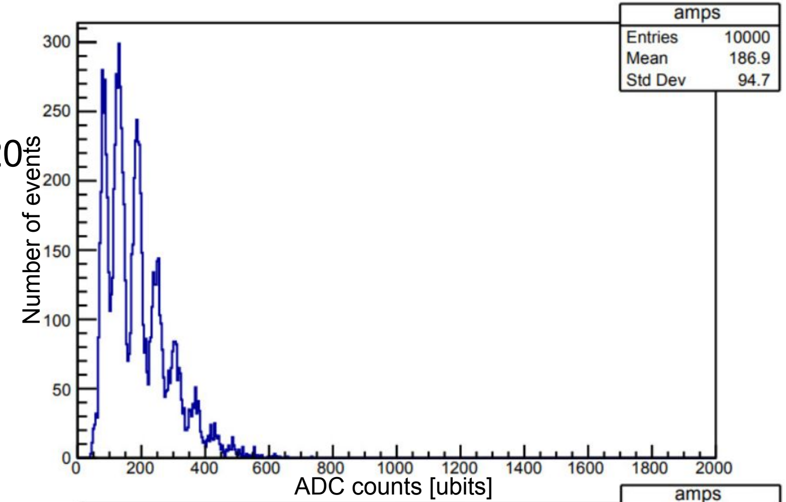


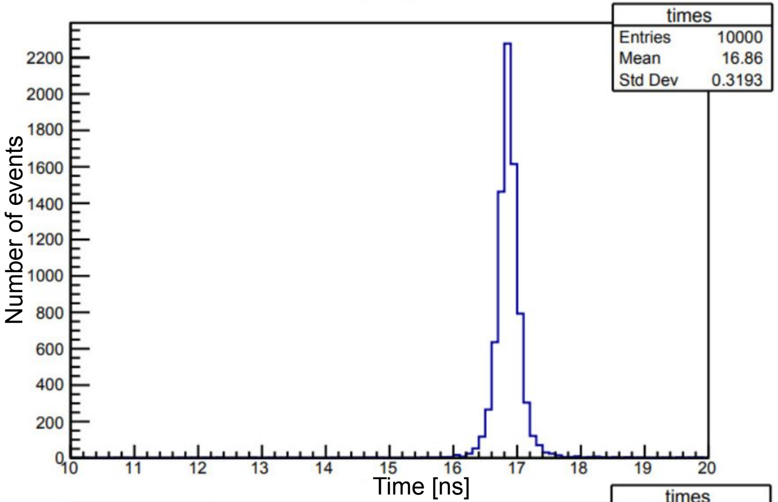
Means are very similar, but smaller standard deviation

SiMP #15

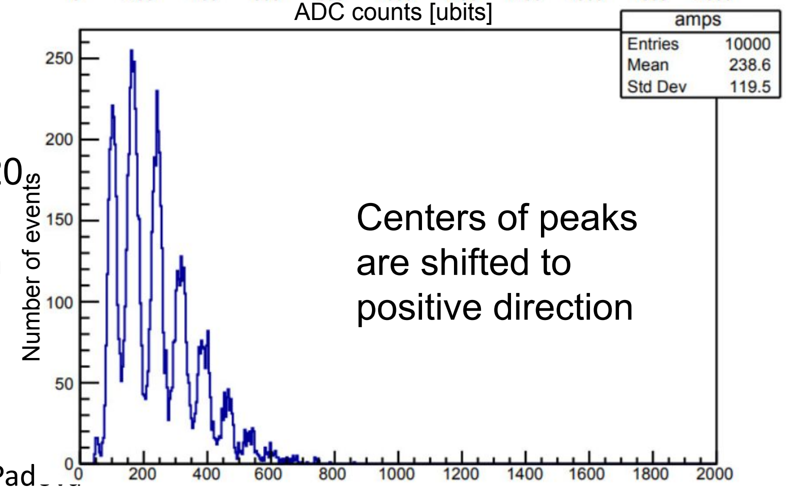
Time resolution and photon spectrum for 15th SiPM

Extracted signal using 20 background iterations without smoothing

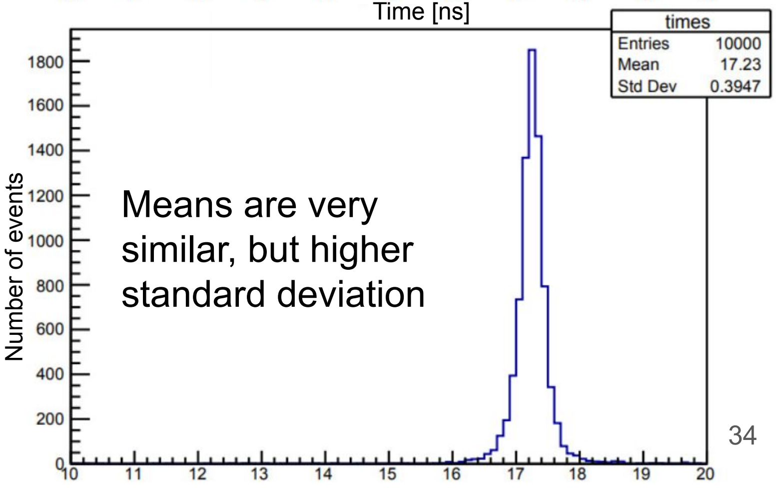




Extracted signal using 20 background iterations with smoothing



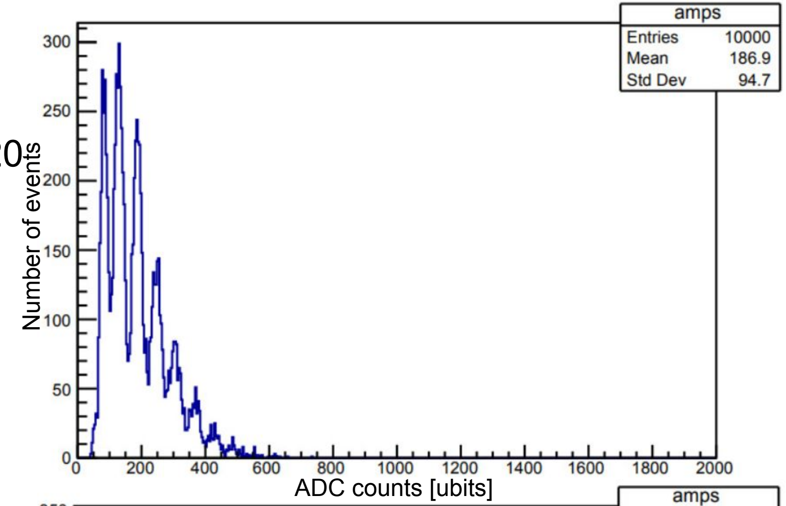
Centers of peaks are shifted to positive direction

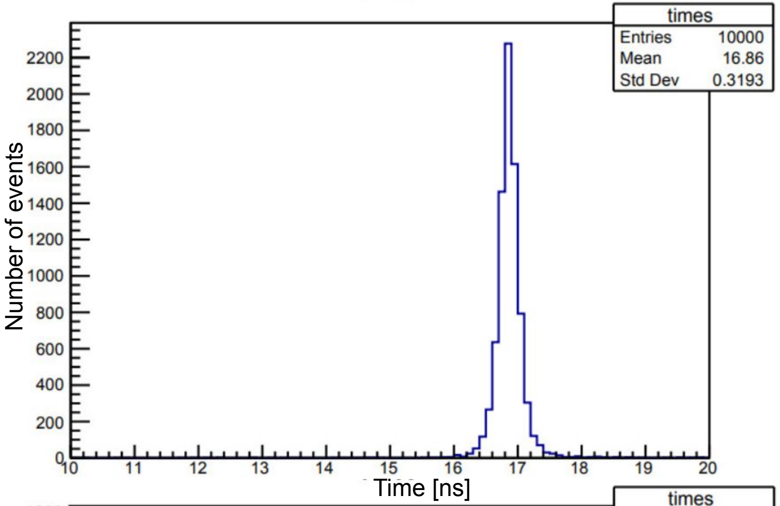


Means are very similar, but higher standard deviation

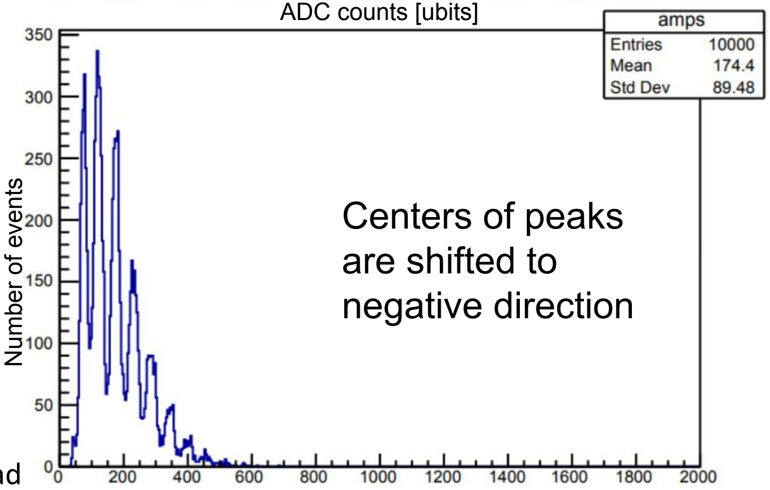
Time resolution and photon spectrum for 15th SiPM

Extracted signal using 20 background iterations without smoothing

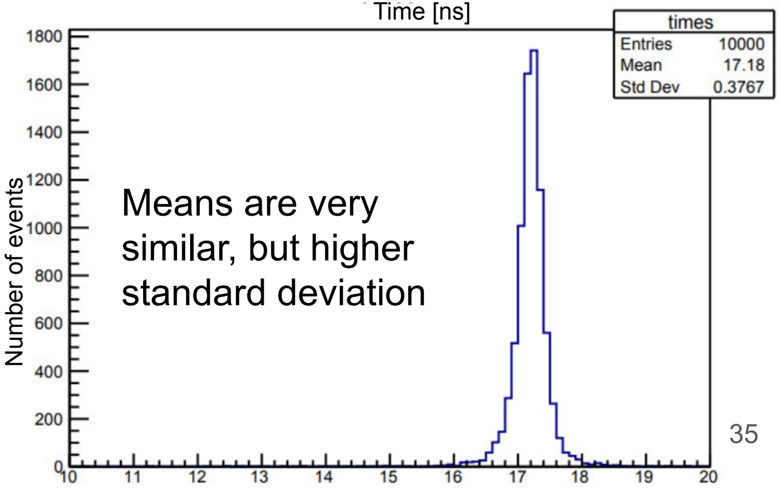




Difference between waveform and background iterated 20 times without smoothing



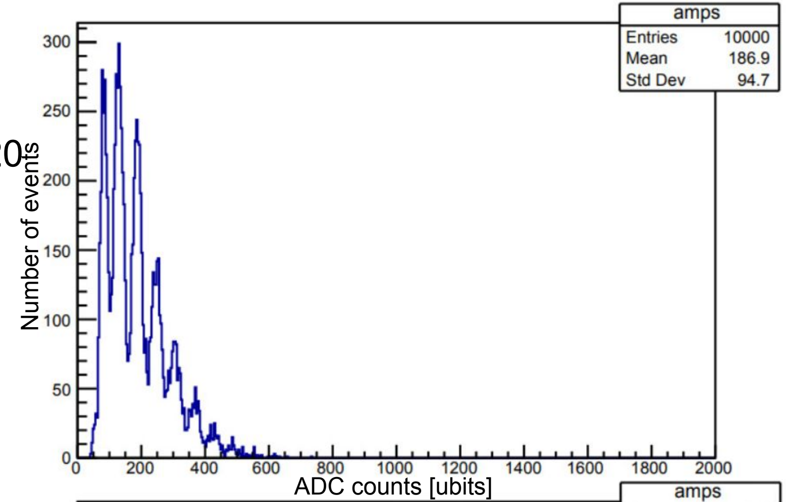
Centers of peaks are shifted to negative direction

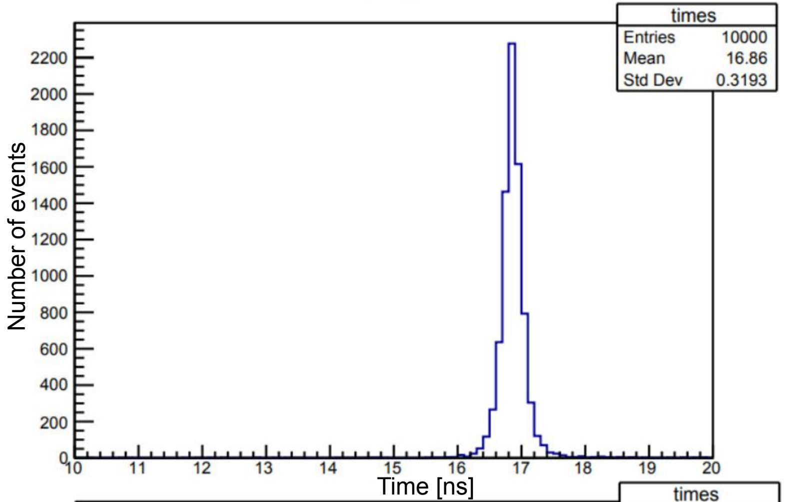


Means are very similar, but higher standard deviation

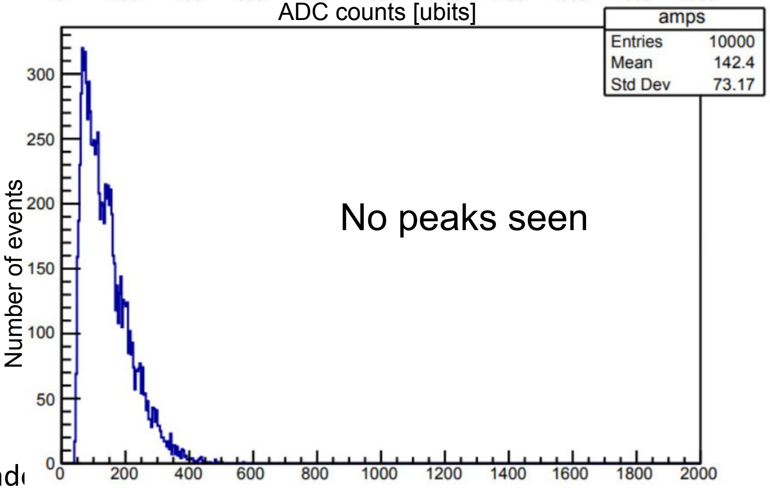
Time resolution and photon spectrum for 15th SiPM

Extracted signal using 20 background iterations without smoothing

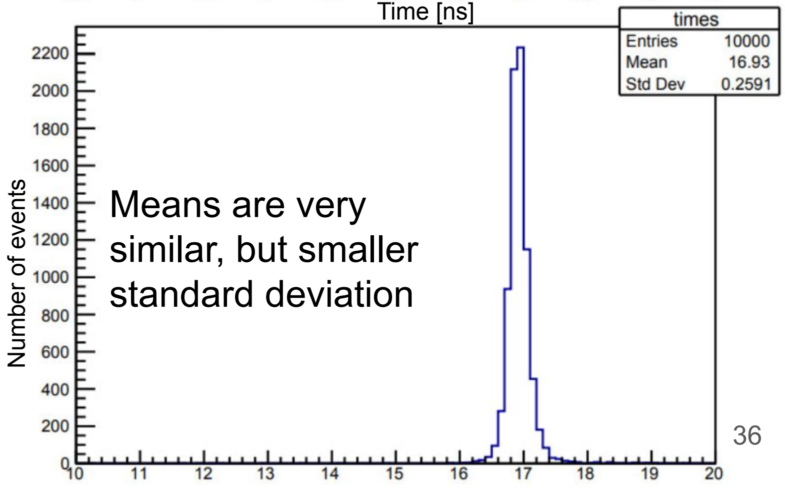




Extracted signal using 8 background iterations without smoothing



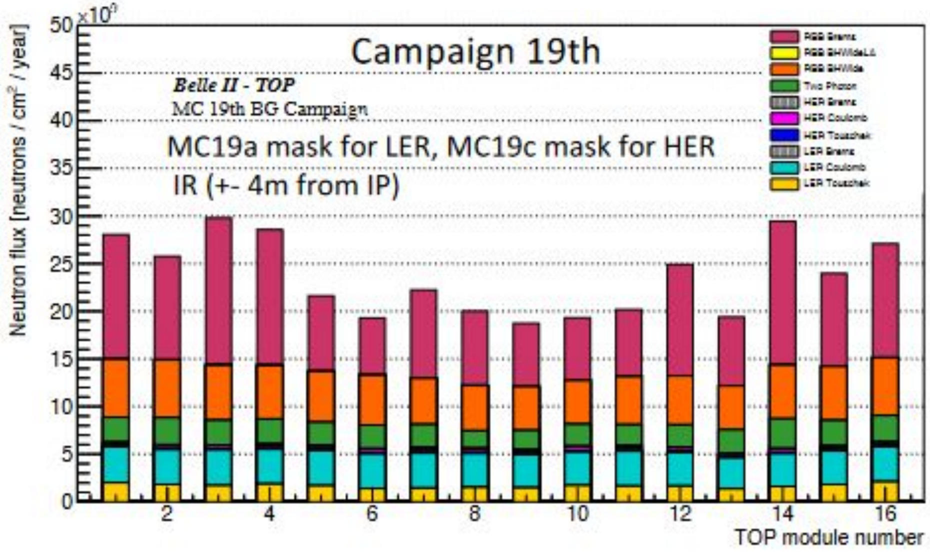
No peaks seen



Means are very similar, but smaller standard deviation

Background level and expected neutron flux

- For MCP-PMT the most crucial background is degradation of quantum efficiency
- Instead for SiPM the most critical is neutron flux, because increase count rate
- Study of neutron flux is part of background studies at LS2, which is ongoing
- Current study (based on 19th Monte Carlo Campaign) report about neutron flux at TOP at level of 2.5 $\cdot 10^{10}$ neutrons/cm^2/year (with luminosity $8 \cdot 10^{35}$ cm^{-2} s^{-1})
- Now expected luminosity at LS2 is $6.0 \cdot 10^{35}$ cm^{-2} s^{-1}



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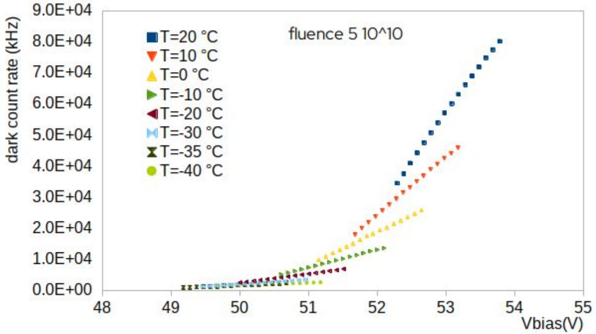
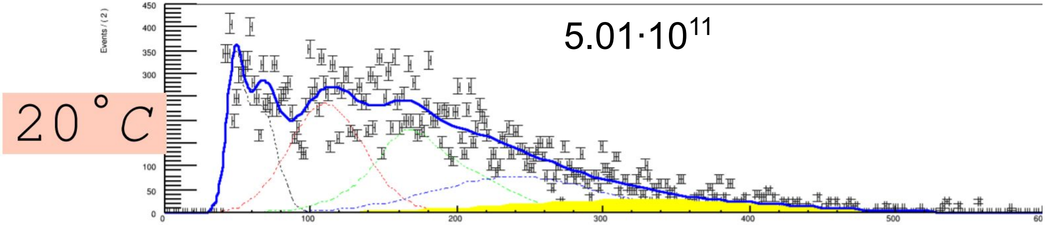
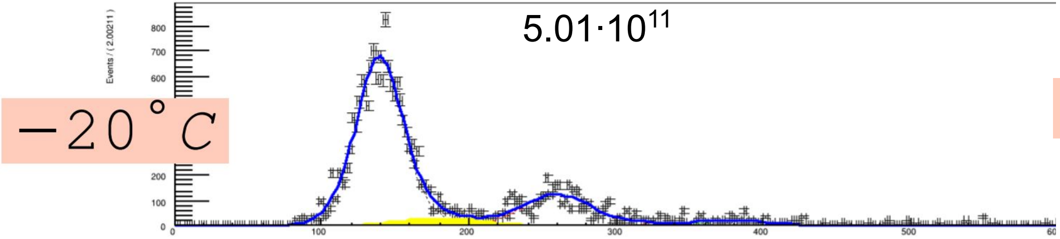
First result on irradiated SiPM Hamamatsu

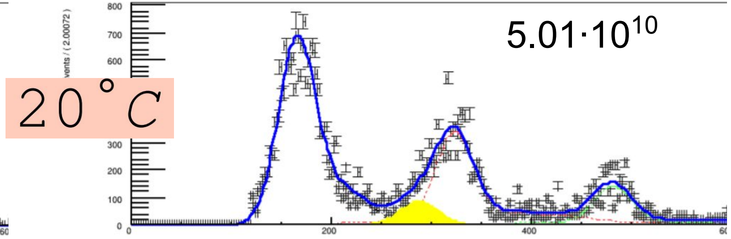
- In winter 2022, 8 Hamamatsu 1.3x1.3 mm^2 x 50 µm cells (S13360-1350PE) SiPMs were measured in Padova
- SiPMs were irradiated at different distances from target and different integration times
- SiPMs was irradiated with fluences in range from $1 \cdot 10^9$ to $5 \cdot 10^{11}$ neutrons cm^2
- Increase of dark counting due to neutron irradiation can be partially compensated by operating SiPMs at low temperature, damages produced by neutron irradiation can be partially recovered with annealing process

# SiPM	Distance [cm]	Neutron 1 MeV eq/cm^2 fluence	Charge [mC]	Time [h]
0	4.3	$5.01 \cdot 10^{11}$	7.94	16.34
1	6.8	$2.00 \cdot 10^{11}$	7.94	16.34
2	9.3	$1.00 \cdot 10^{11}$	7.94	15.30
3	11.8	$5.01 \cdot 10^{10}$	5.98	12.31
4	14.3	$2.42 \cdot 10^{10}$	4.25	8.74
5	16.8	$1.01 \cdot 10^{10}$	2.44	5.03
6	19.3	$5.00 \cdot 10^{9}$	1.60	3.29
7	21.8	$1.01 \cdot 10^{9}$	0.41	0.85









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- SiPMs was irradiated with fluences in range from $1 \cdot 10^9$ to $5 \cdot 10^{11}$
- Damage could be partially recovered by operating SiPMs at low temperature

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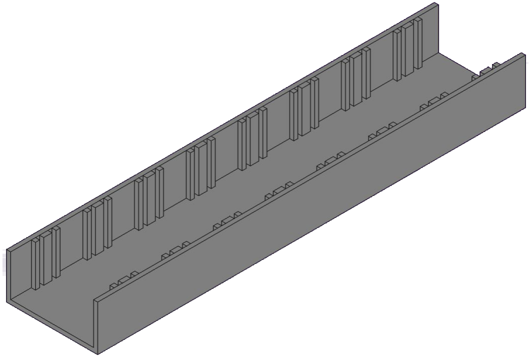

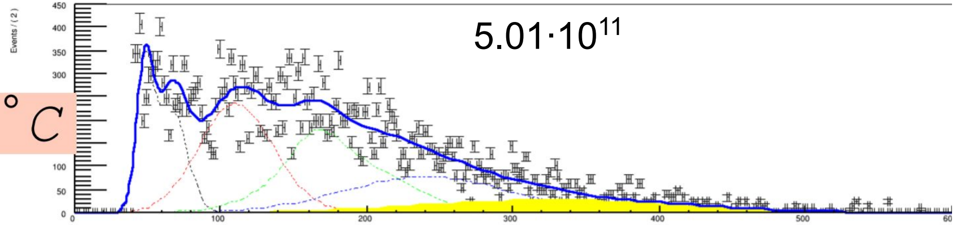

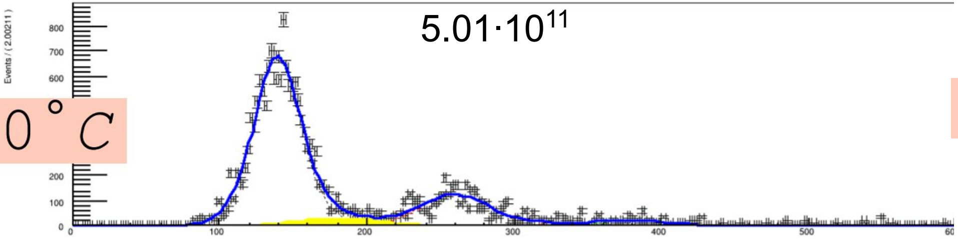

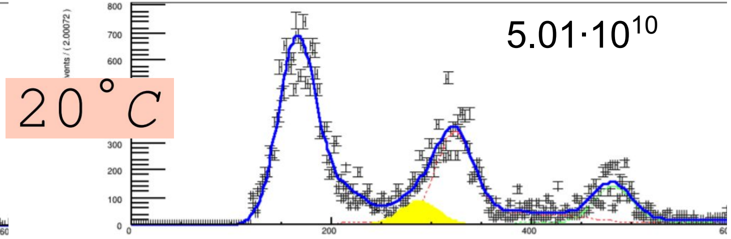

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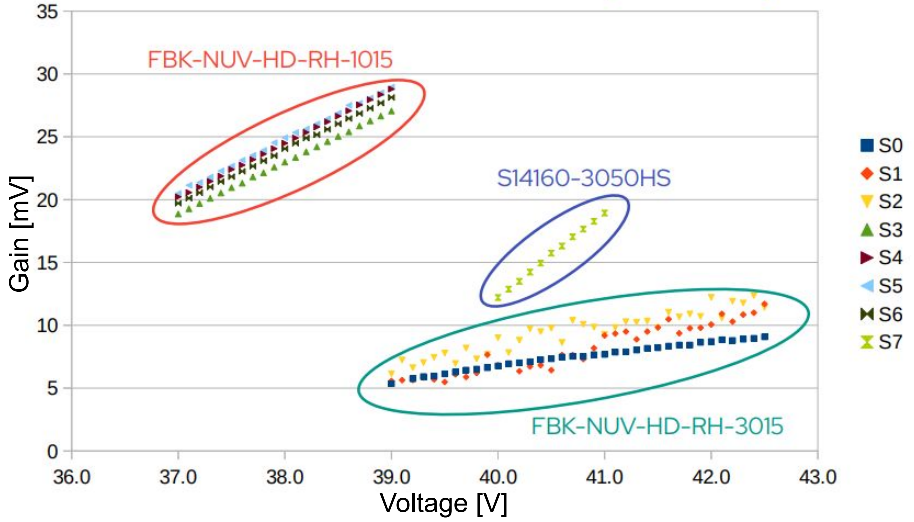
Further plans with SiPM

- In Summer 2023 next irradiated test will be done:
  - 3 FBK 3x3 mm^2 x 15 µm cells (FBK-NUV-HD-RH-3015)
  - 4 FBK 1x1 mm^2 x 15 µm cells (FBK-NUV-HD-RH-1015)
  - 1 Hamamatsu 3x3 mm^2 x 50 µm cells (S14160-3050HS)
- Irradiation measurement based on 16 SiPMs.
- The maximum fluence is planned $1 \cdot 10^{11}$
- The goal is identify the cell size giving better radiation hardness performance (lower cell size is expected to be better).
- Try to recover from irradiation to heat SiPMs around 150 °C for 3 weeks

preliminary results



- After Summer 2023 irradiation tests, a new SiPM prototype will be developed with FBK, the production of masks will take 6 months and cost 50 keurs financed with AIDAinnova (EU project).
- The goal is the further improvements the low field technology (regions with high field increase the count rate)