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

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Content

- Irradiated SiPM modules in Padova
- Experimental setup and software tools for our tests
- Background subtraction and extracting signal
- Preliminary photon spectra studies
- Preliminary time resolution studies
- Conclusion

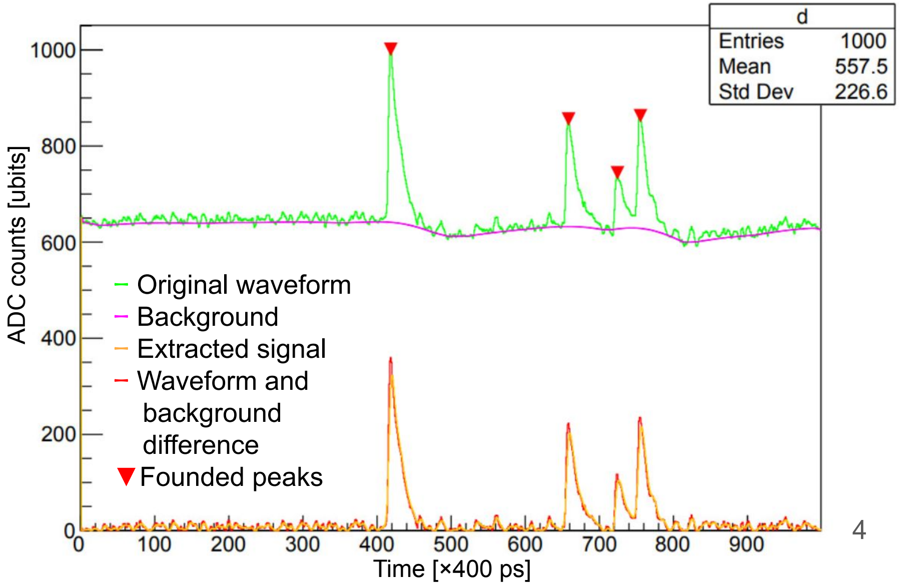
Tests with irradiated modules in Padova

- 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

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



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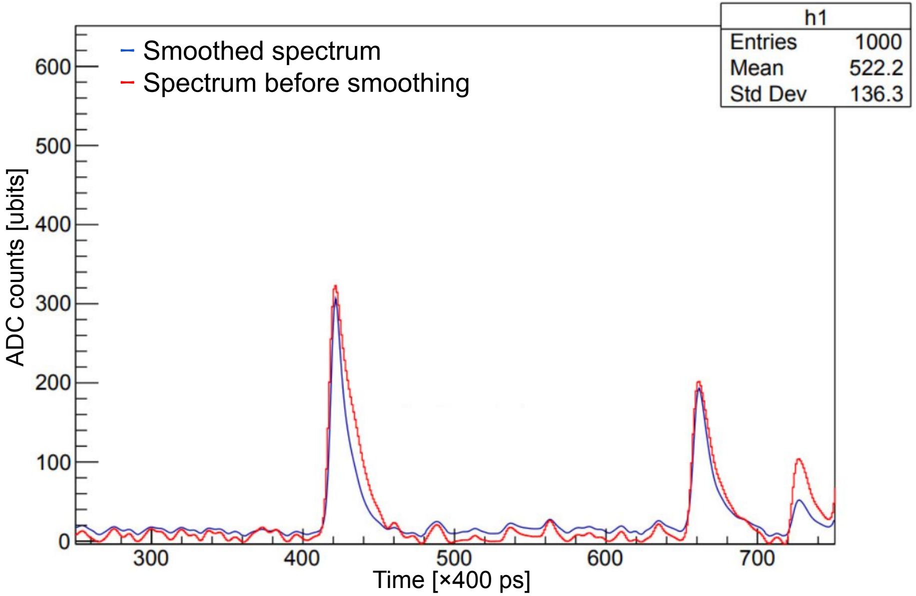
Background subtraction and extracting signal

- 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



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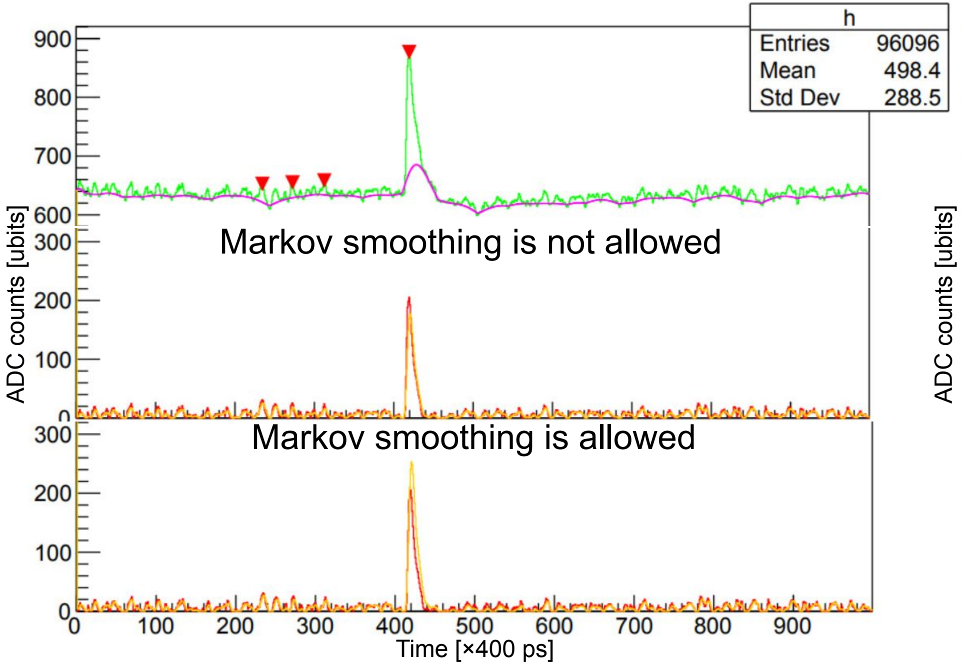
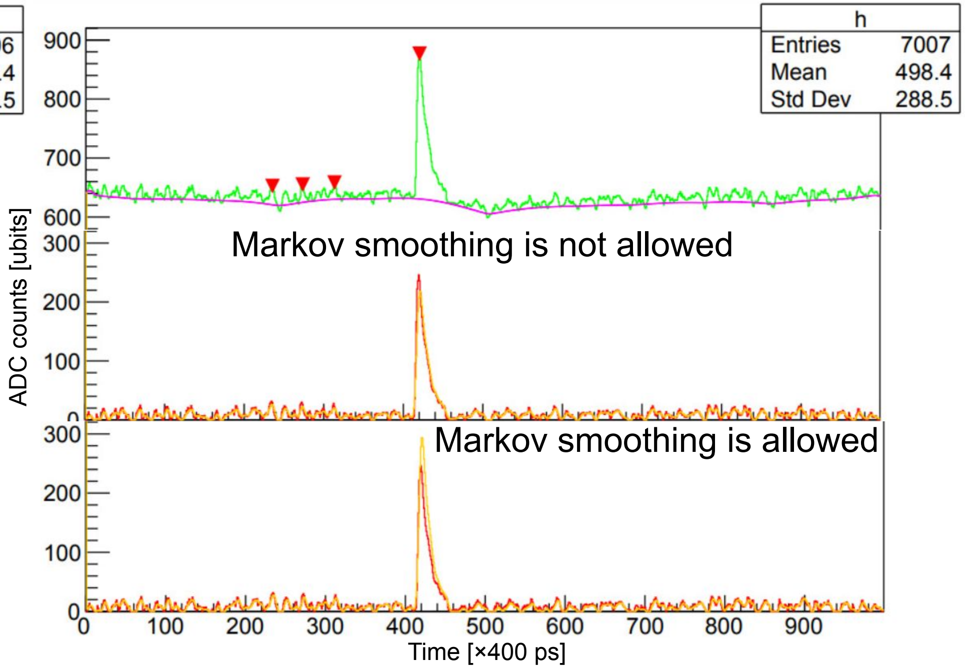
Waveform spectrum for 14th SiPM

- Background is determined averaging original waveform in several iterations

Background is iterated 8 times



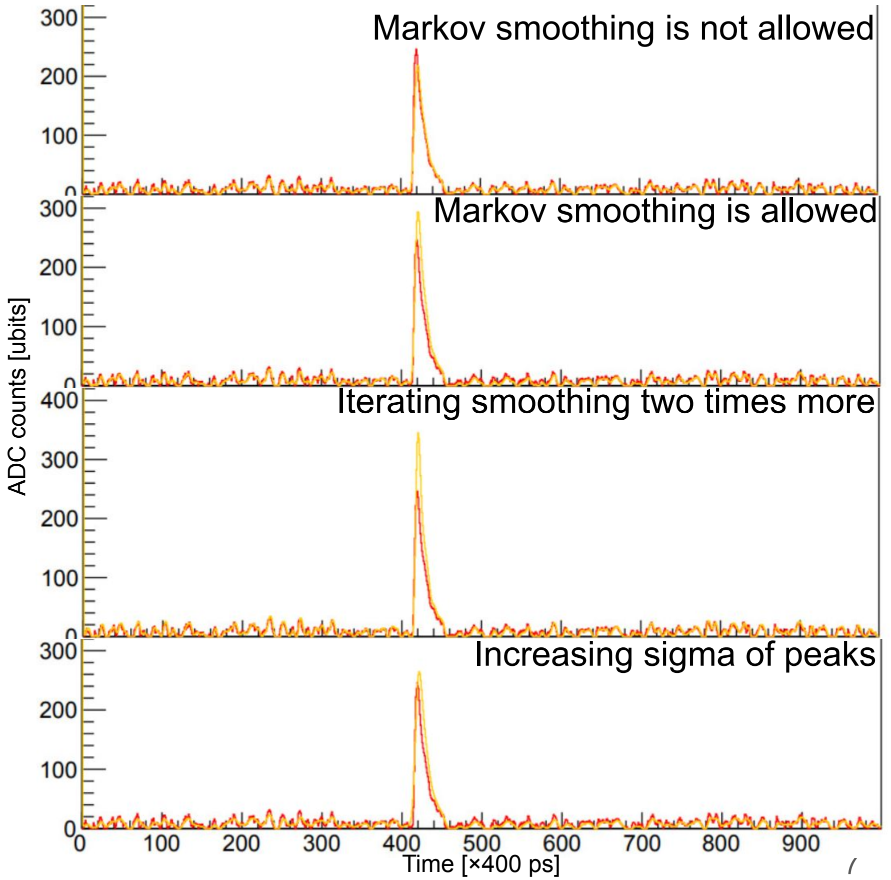
Background is iterated 20 times



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

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



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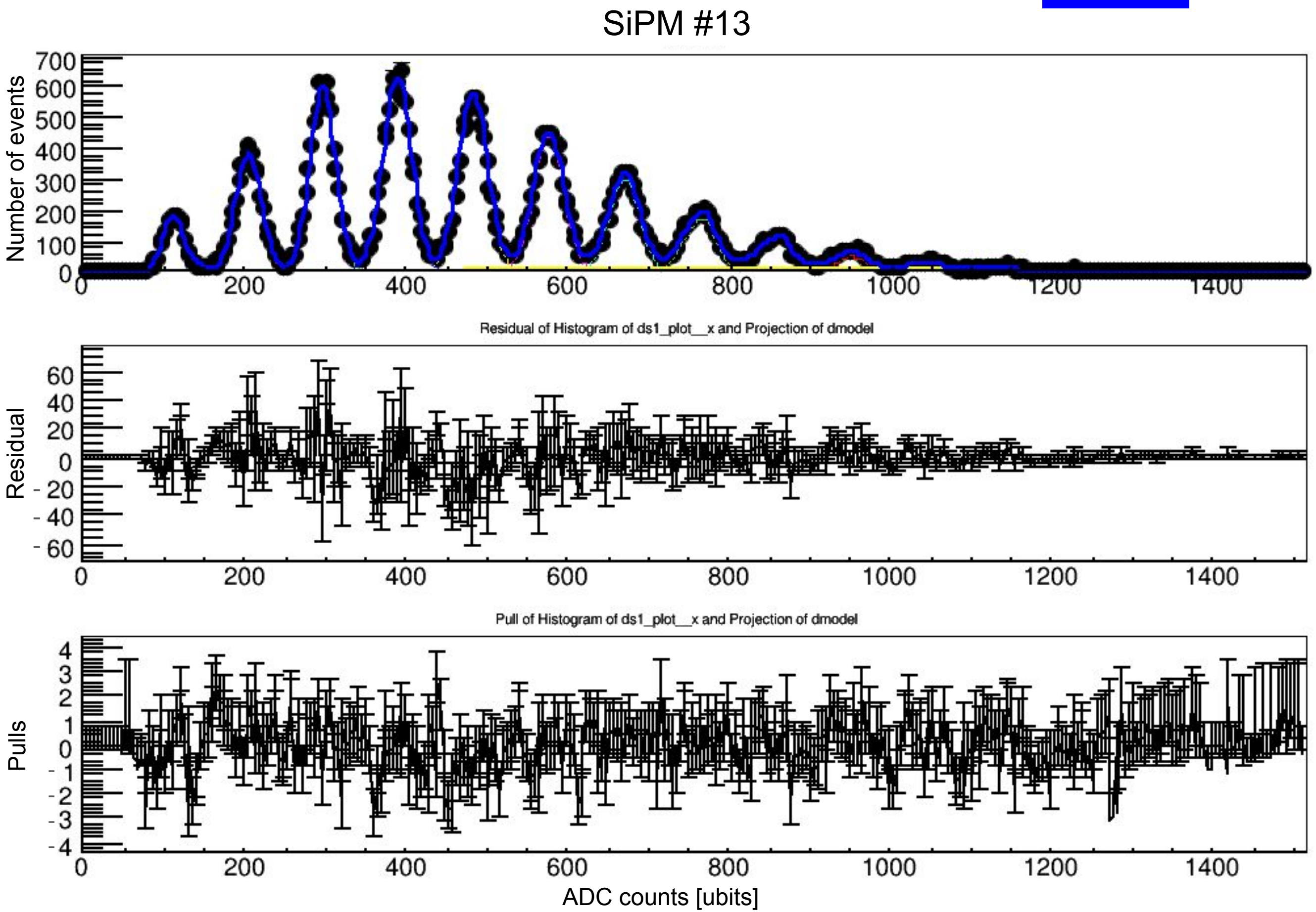
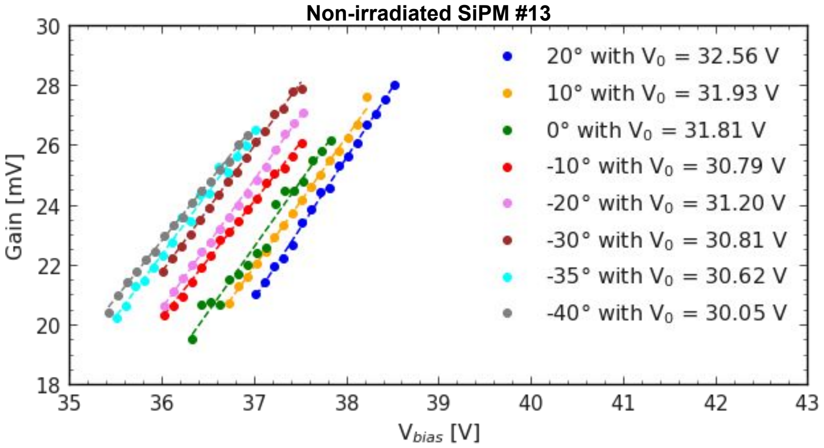
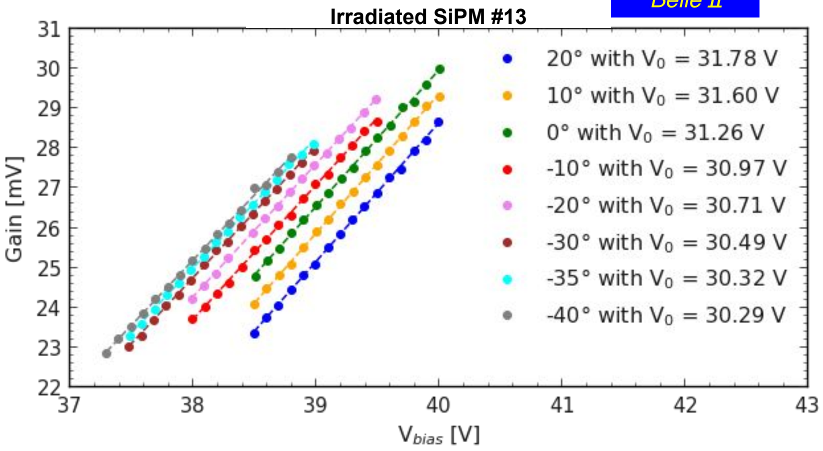
Fit of photon spectra

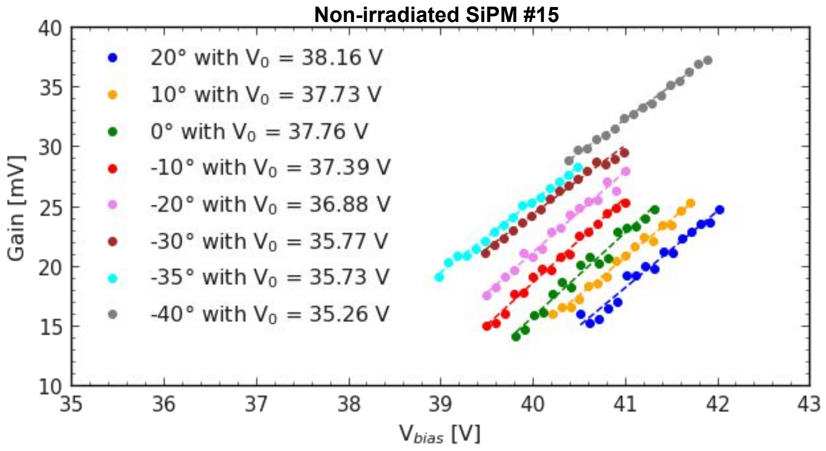
- Photon spectra are extracted
- Photon spectra are fitted sum of convolution poissonian and gaussian distribution to extract gain and average of photons
- From gain we can extract breakdown voltage

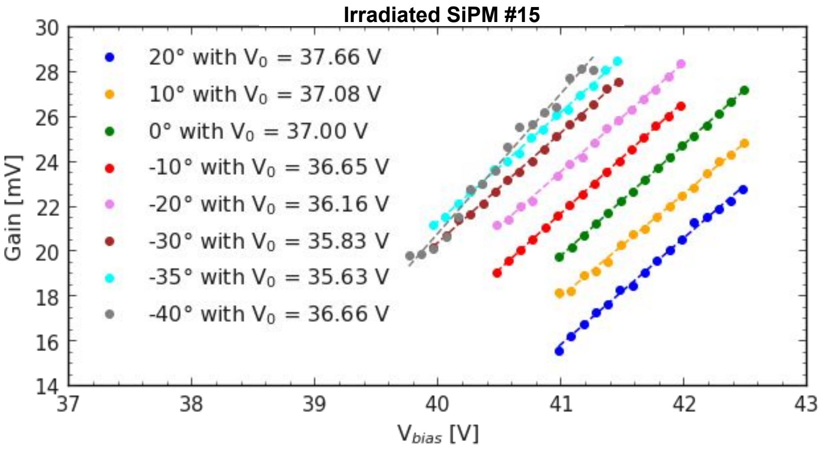


Extraction of breakdown voltage from spectra



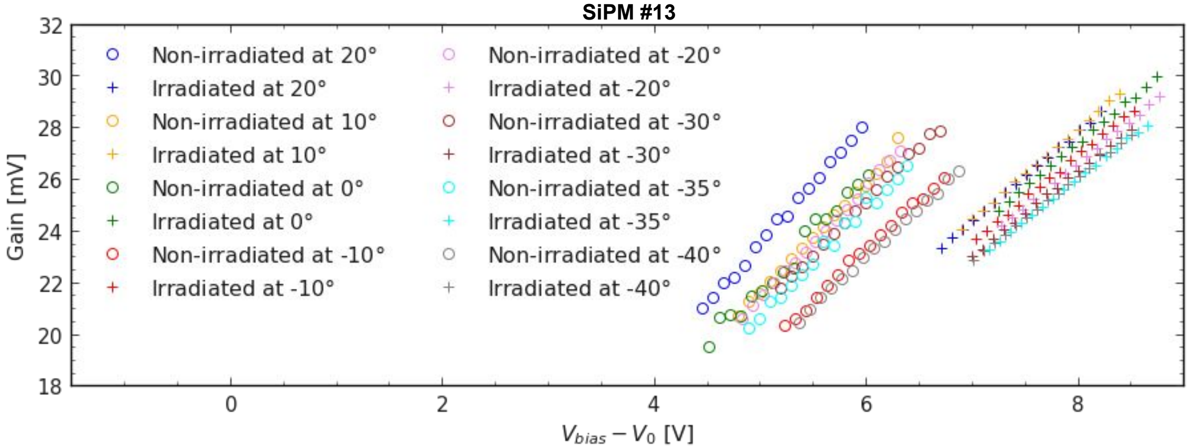


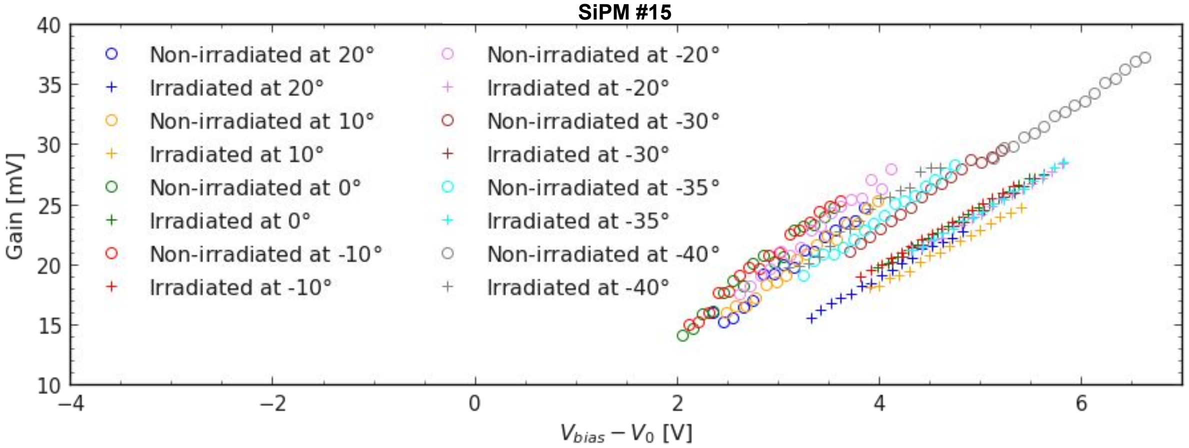




Gain as function of overvoltage

- 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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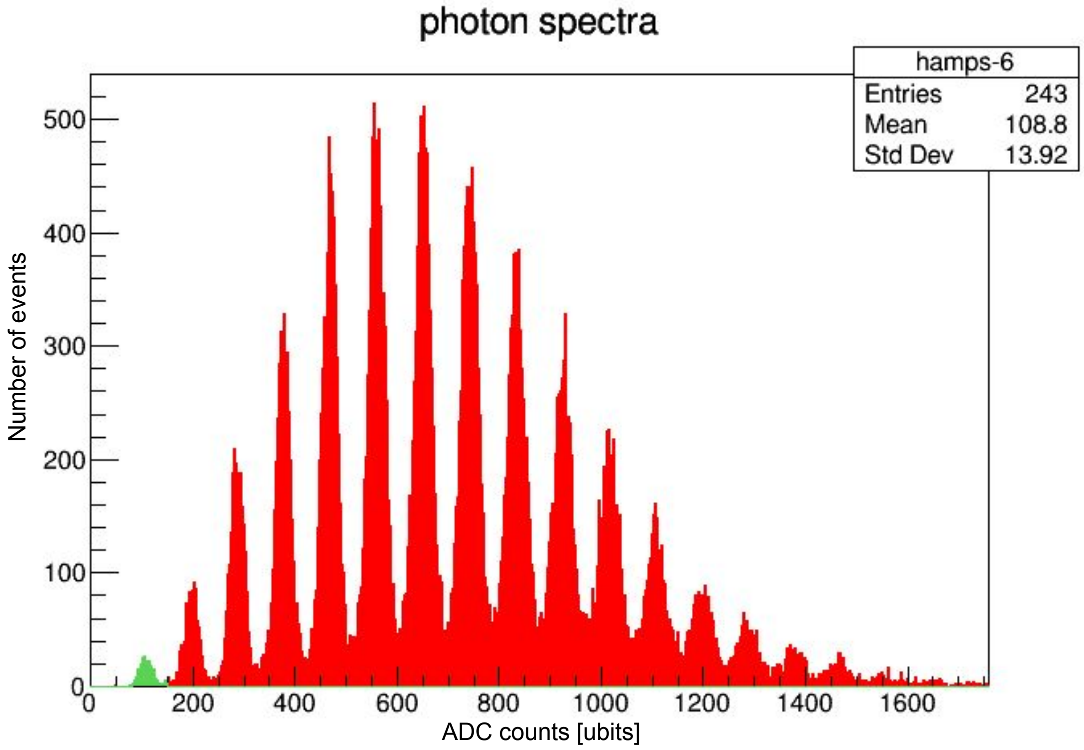
Fit of time resolution

- Split photon spectra into two regions: first photon peak (green) and other photon peaks (red)
- For #13 SiPMs, we fit first photon peak (green) and all photon peaks (green + red)



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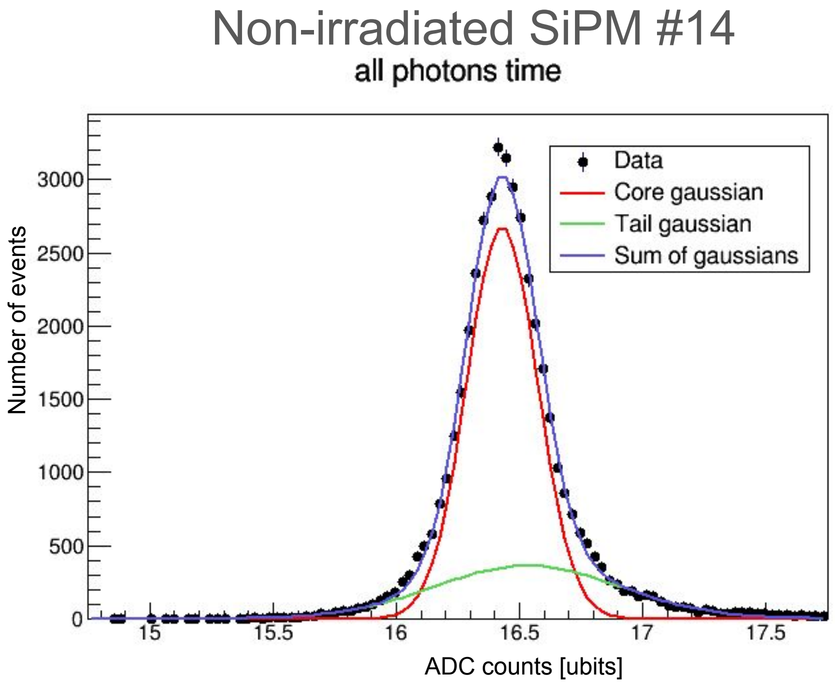
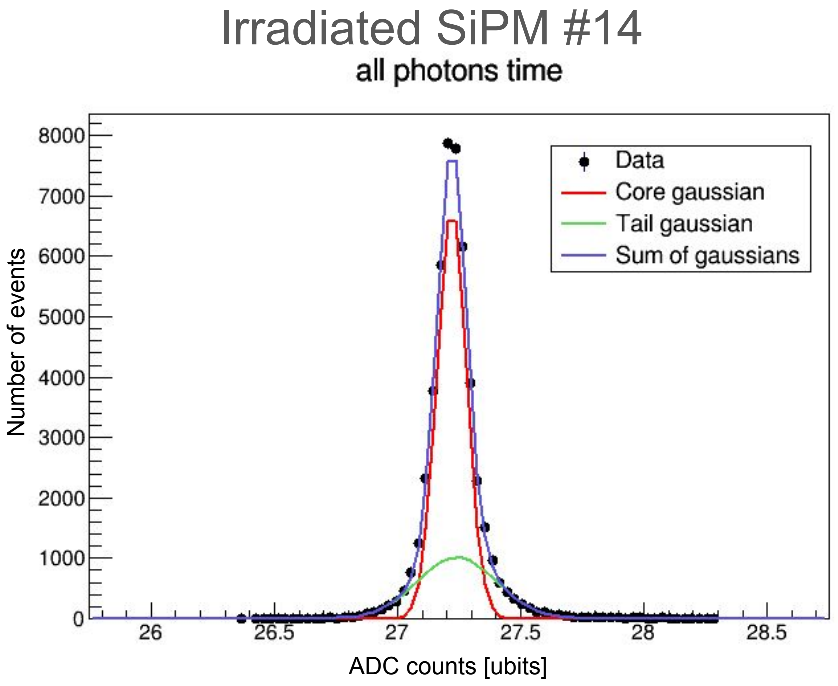
Fit of time resolution for all photon peaks





- Both distributions are fitted by double gaussians

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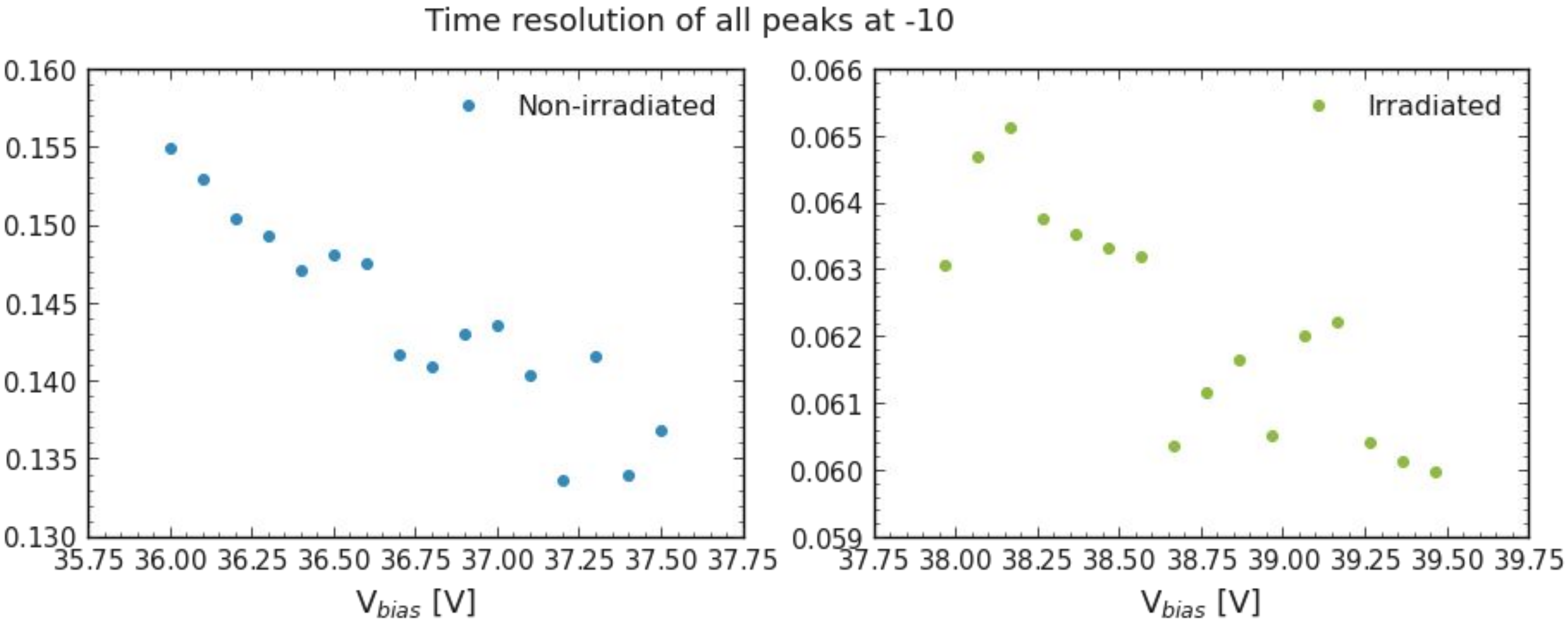
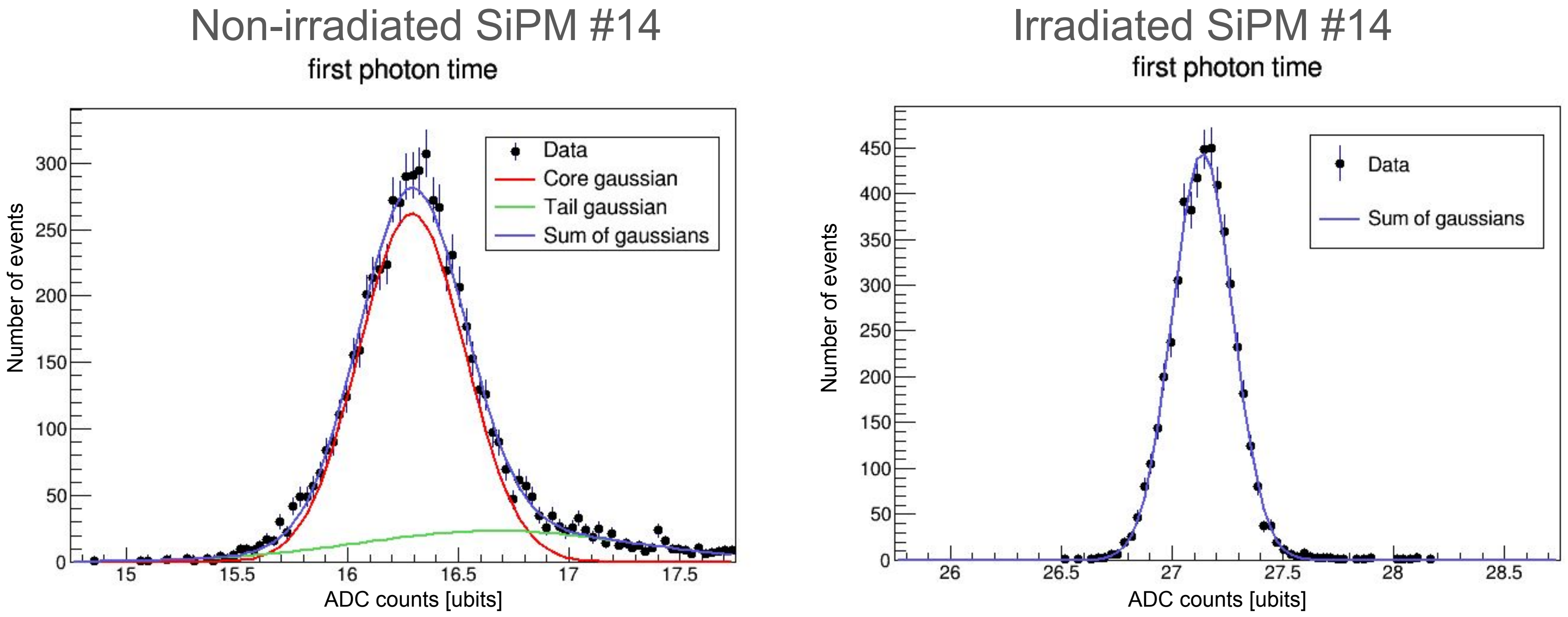
Time resolution for all photon peaks of SiPM #14



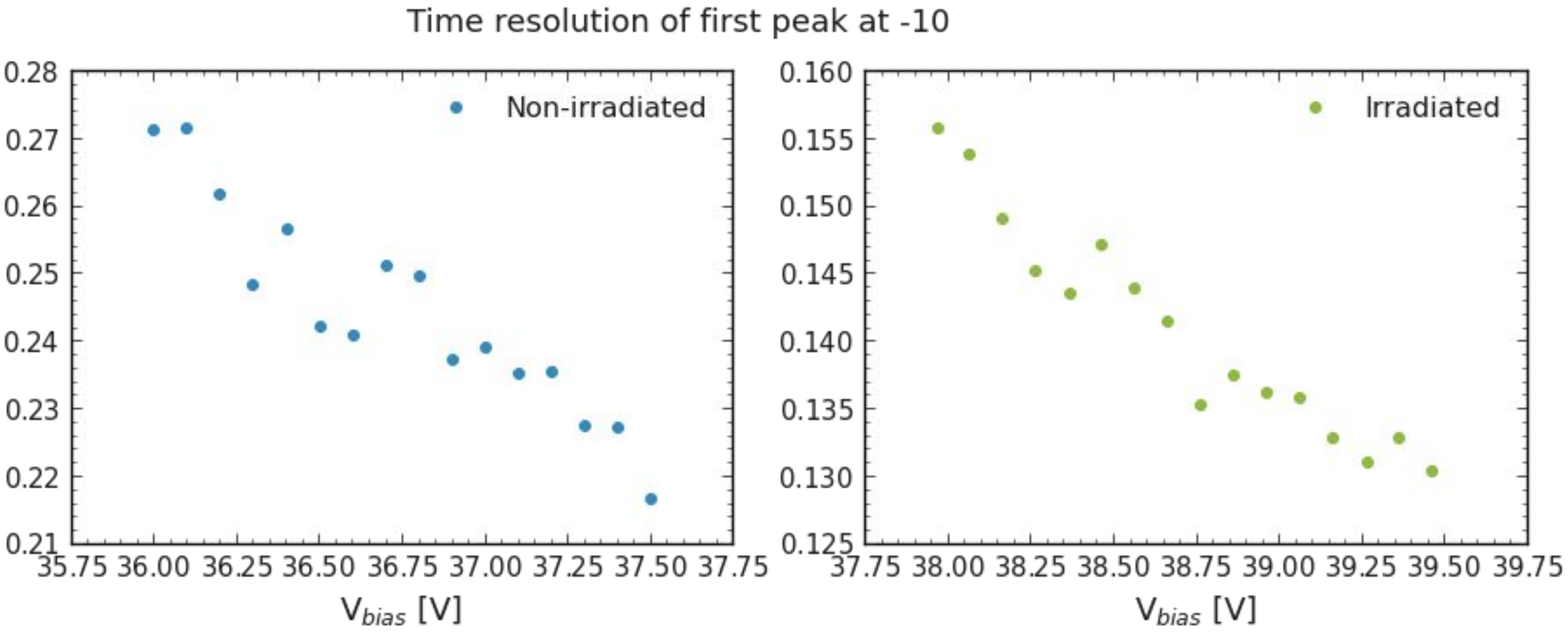
- Time resolution for non-irradiated SiPM #14 is worse than irradiated

Fit of time resolution for first photon peak



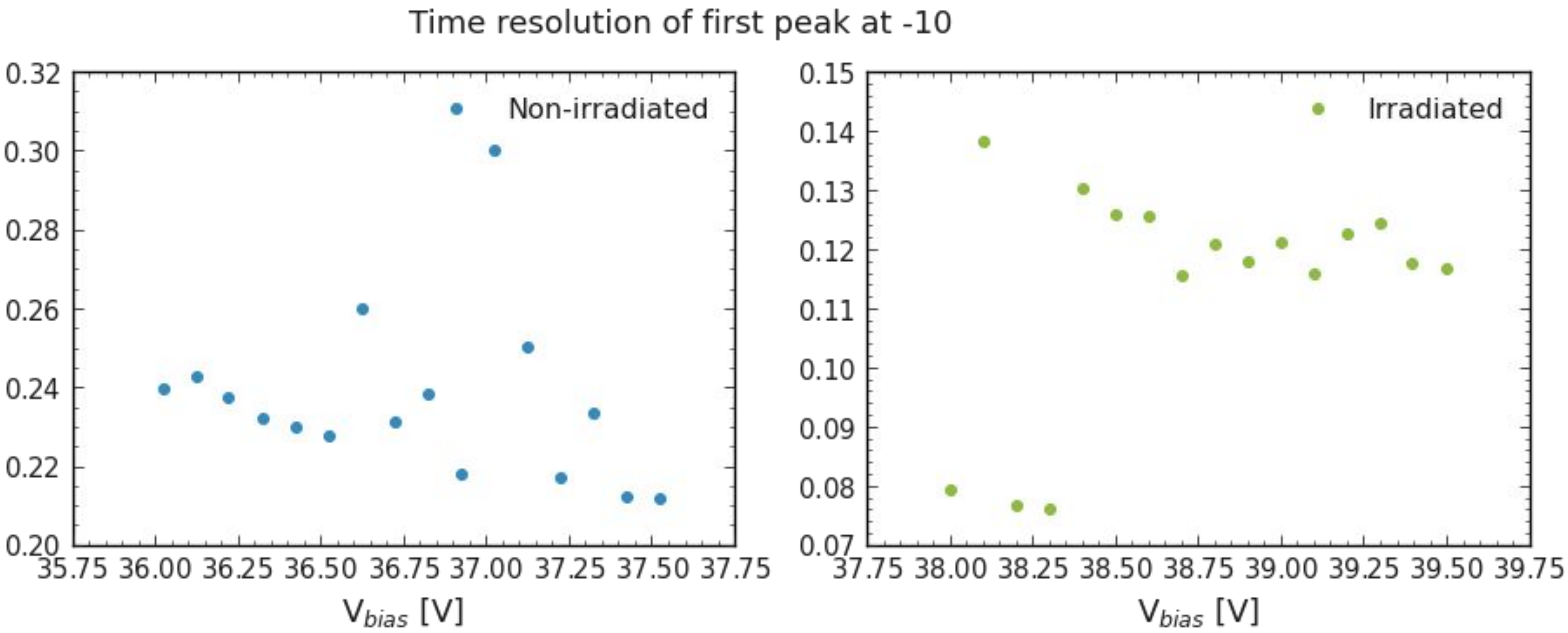
- Non-irradiated distribution fitted by double gaussian
- Irradiated distribution fitted by a single gaussian

Time resolution for first photon peak of SiPM #14



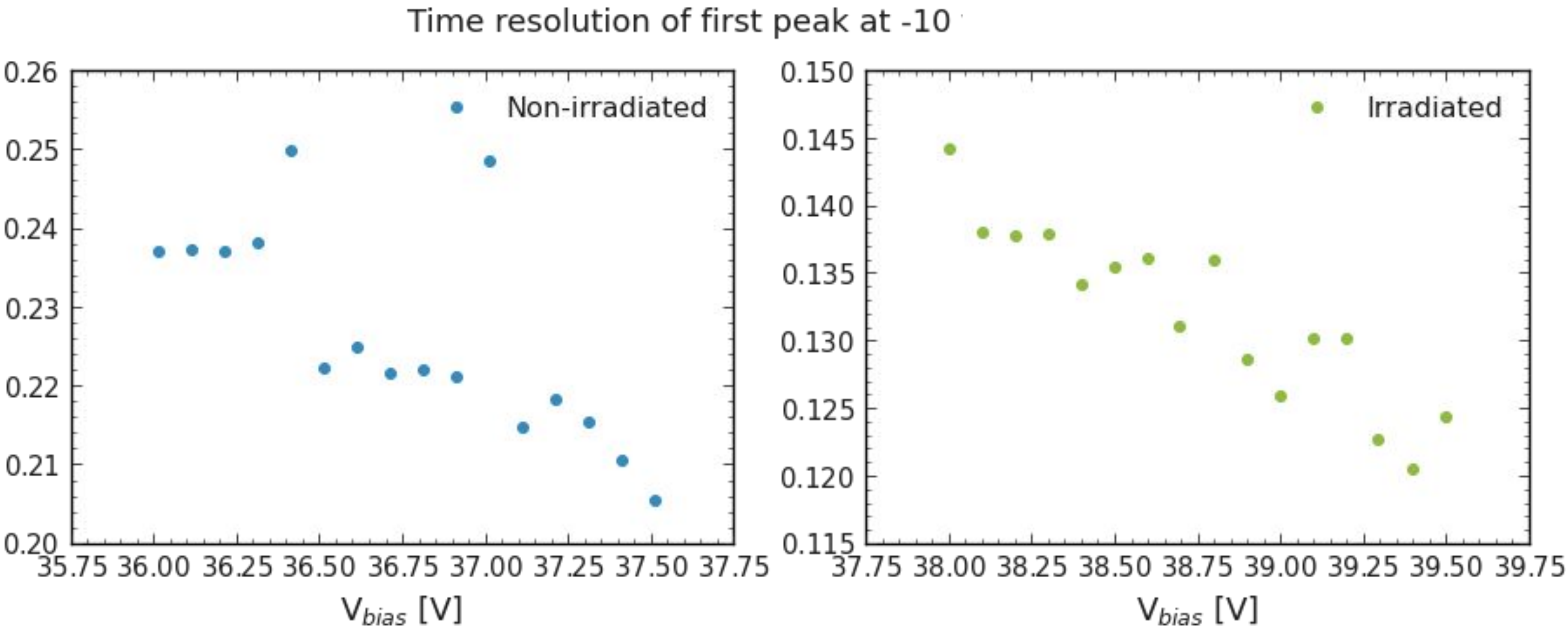
- Time resolution for non-irradiated SiPM #14 is worse than irradiated

Time resolution for first photon peak of SiPM #13



- Time resolution for non-irradiated SiPM #13 is worse than irradiated

Time resolution for first photon peak of SiPM #12



- Time resolution for non-irradiated SiPM #12 is worse than irradiated

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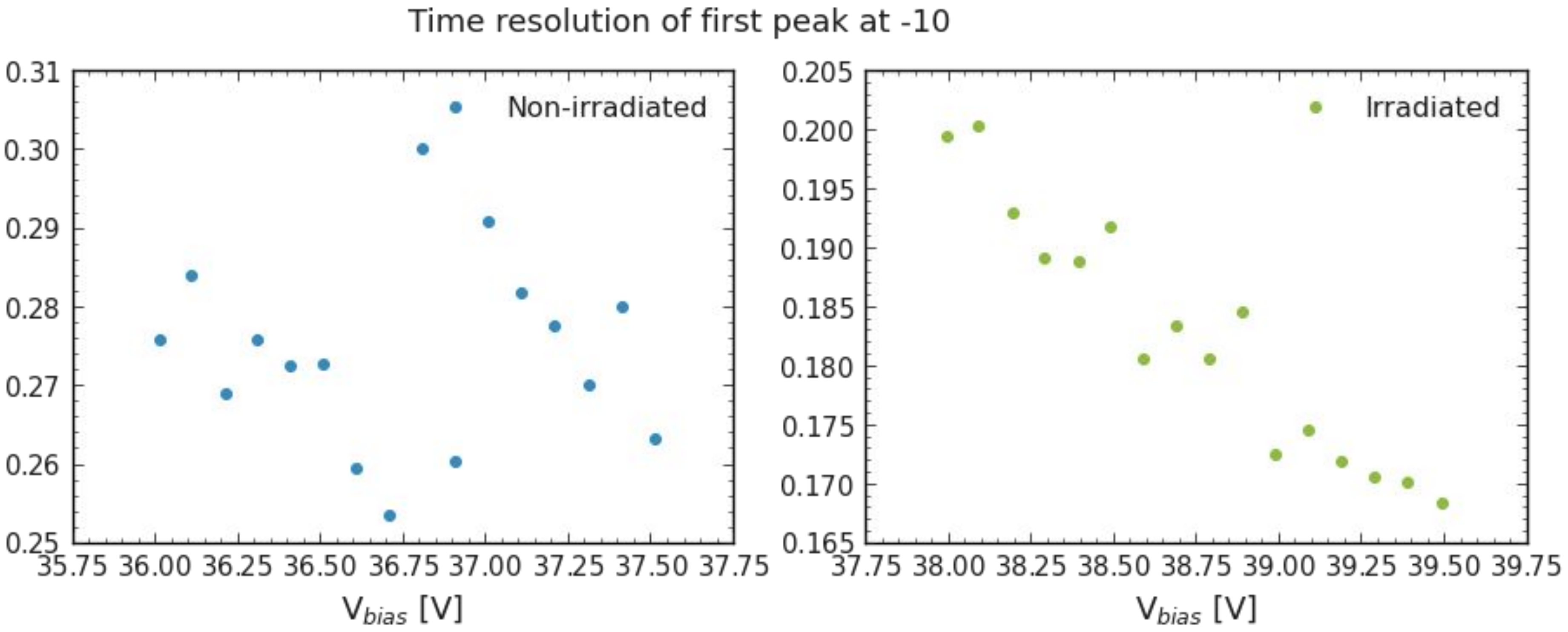
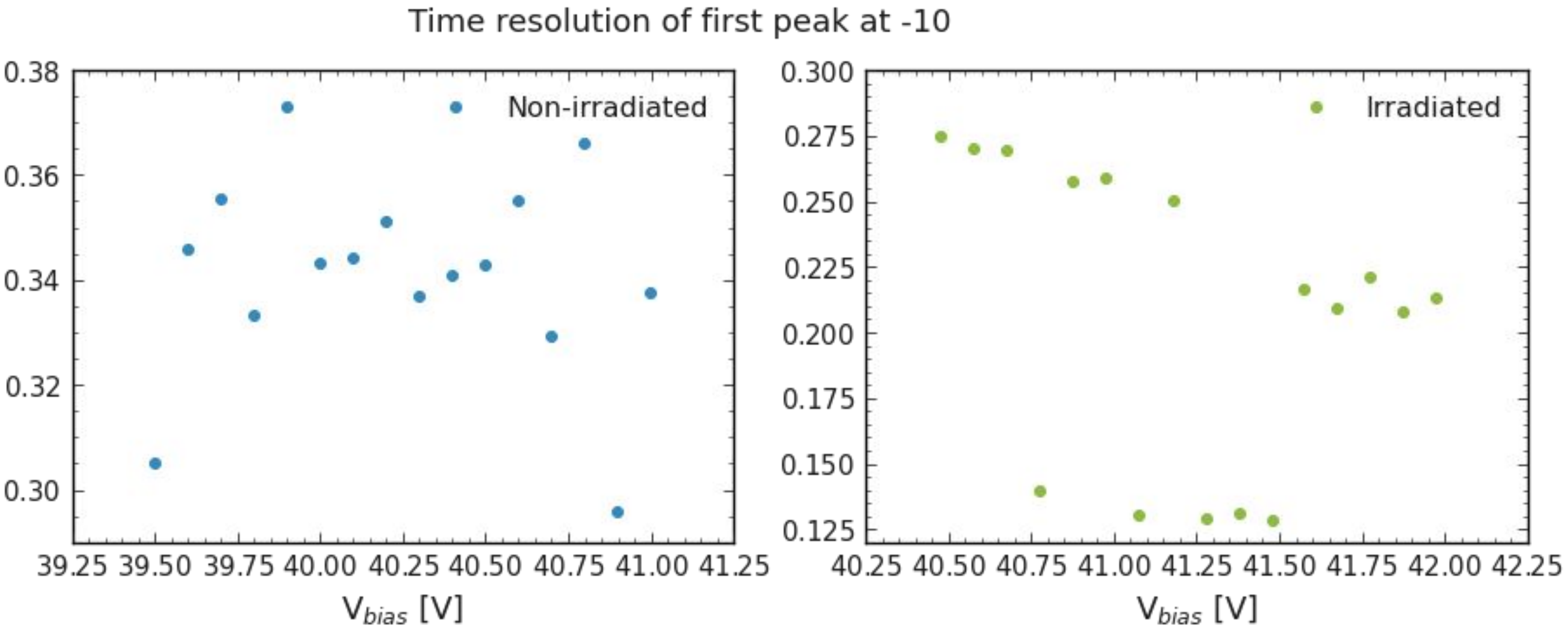
Time resolution for first photon peak of SiPM #11



- Time resolution for non-irradiated SiPM #11 is worse than irradiated

Time resolution for first photon peak of SiPM #15



- Time resolution for non-irradiated SiPM #15 is worse than irradiated

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Conclusion

- In Padova it has been irradiated and tested several SiPM modules
- 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.
- Time resolution studies showing worse resolution for non-irradiated samples as for irradiated, why?
- These devices will be irradiated again to reach higher doses and currently they are in annealing process at 150 $^{\circ}$C

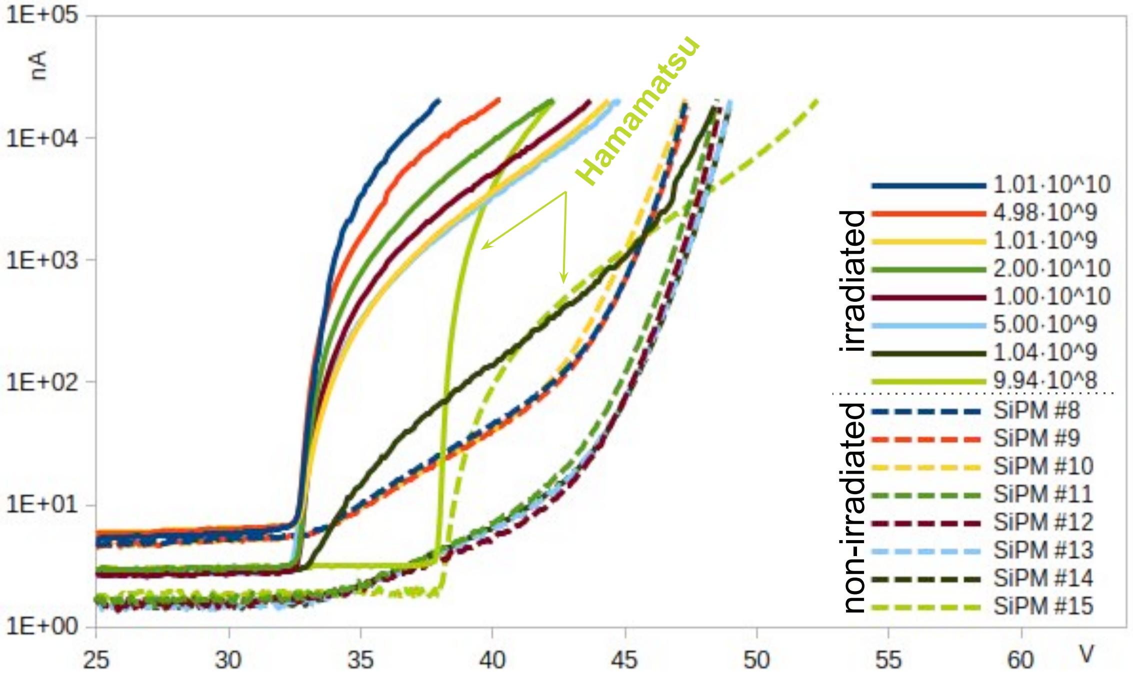
Backup

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

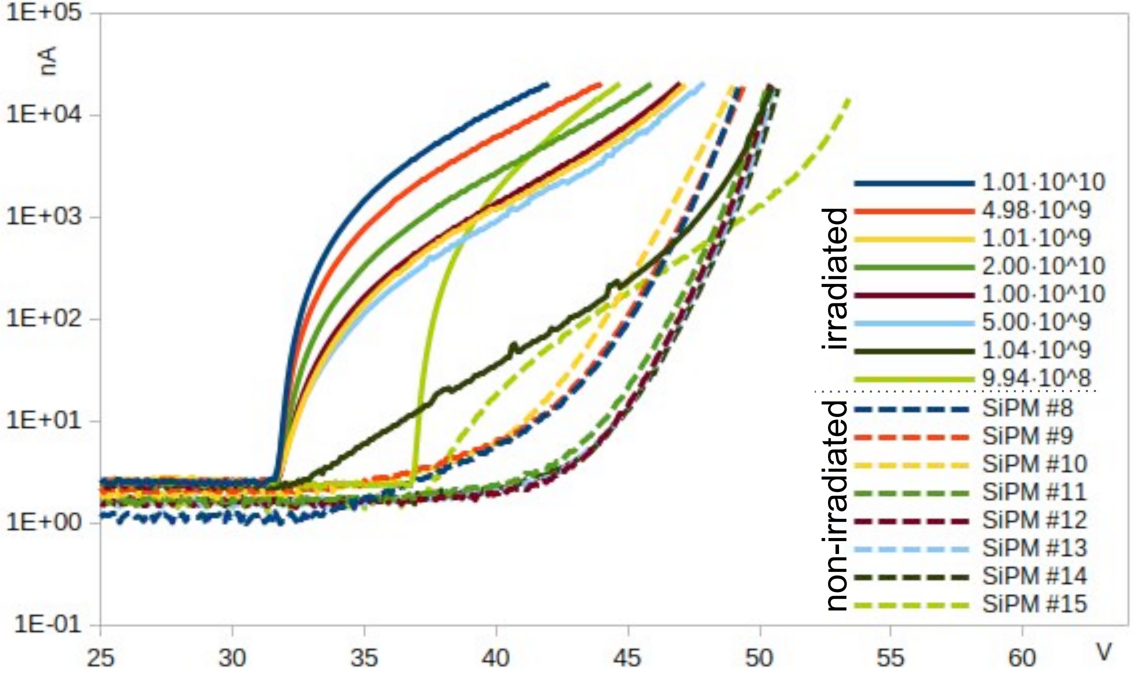
Current-voltage characteristic of some SiPM at +20°C

- 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



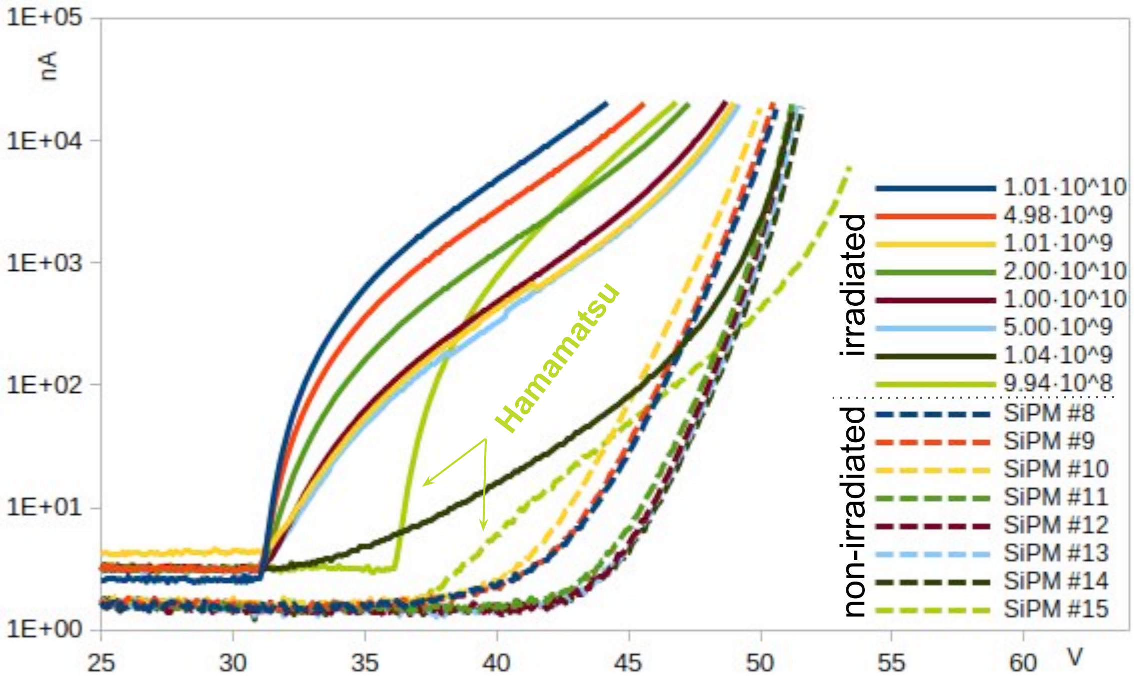
Current-voltage characteristic of some SiPM at -10°C

- 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 12th SiPM (same level of irradiation)



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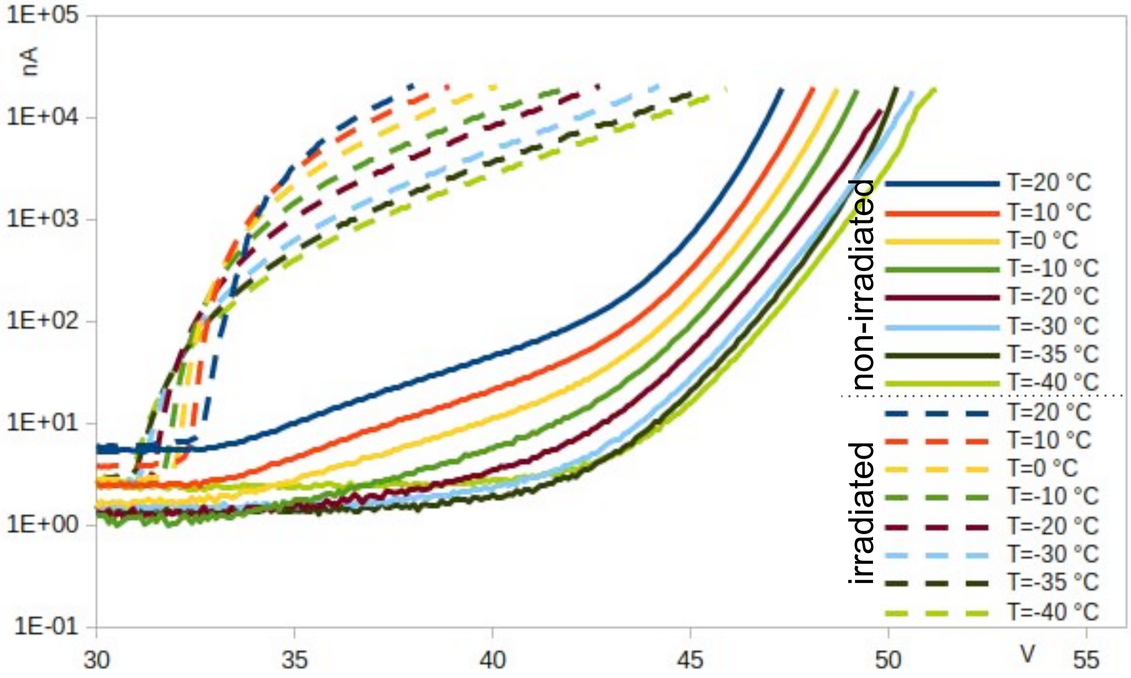
Current-voltage characteristic for FBK 8th SiPM

- 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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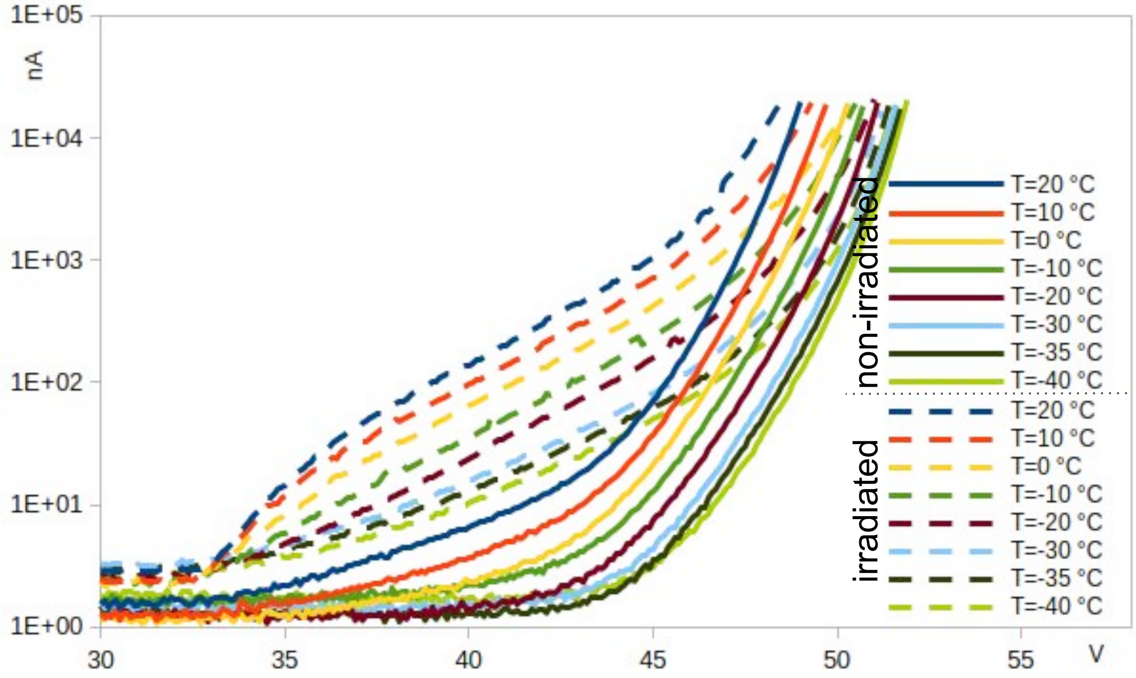
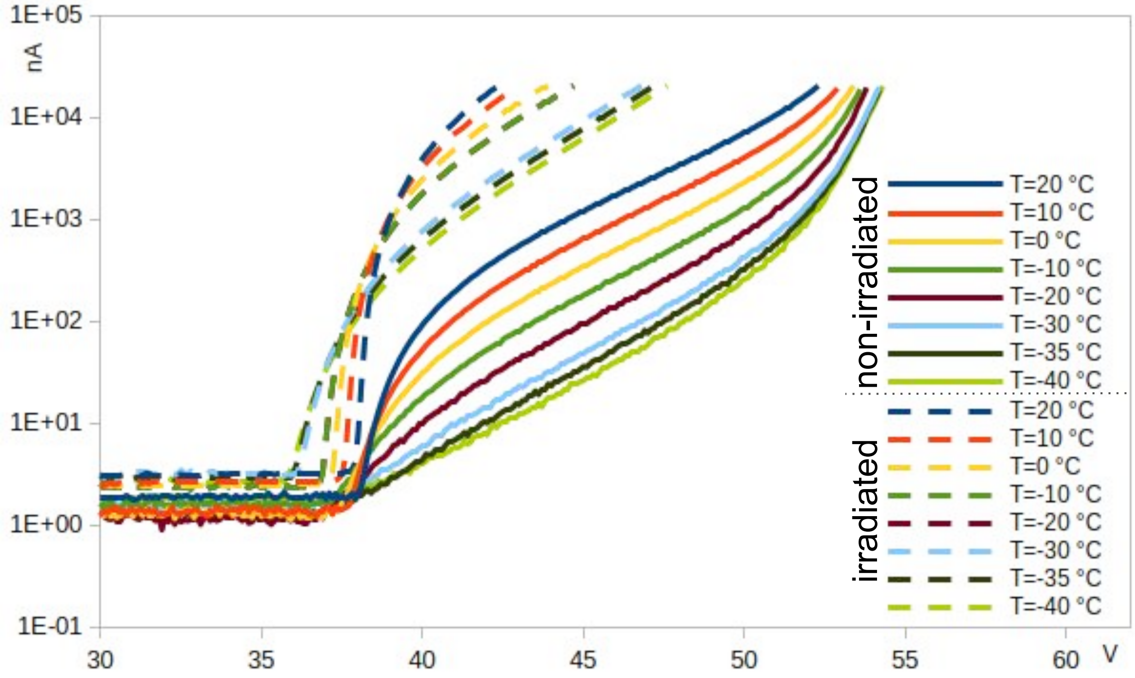
Current-voltage characteristic for FBK 14th SiPM

- 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).



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.



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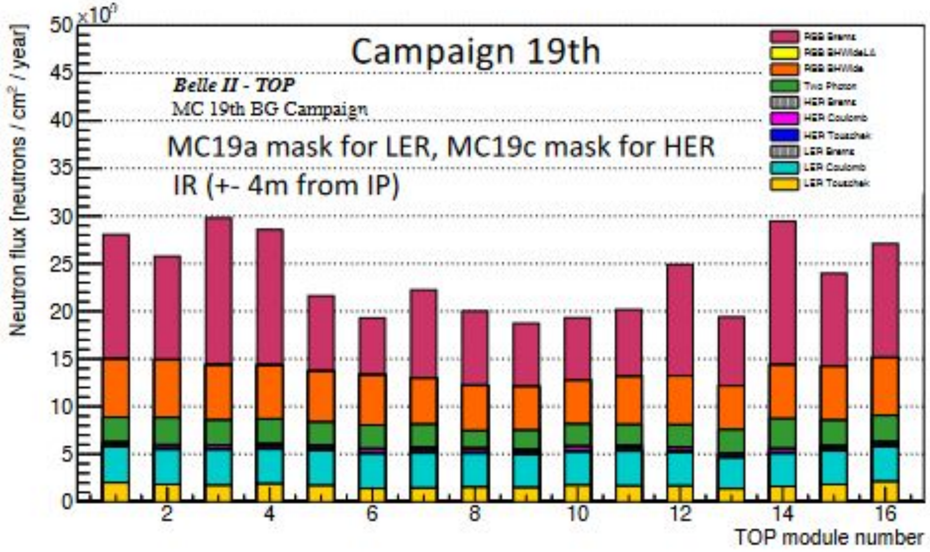
Conclusion

- 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 °C

Background level and expected neutron flux

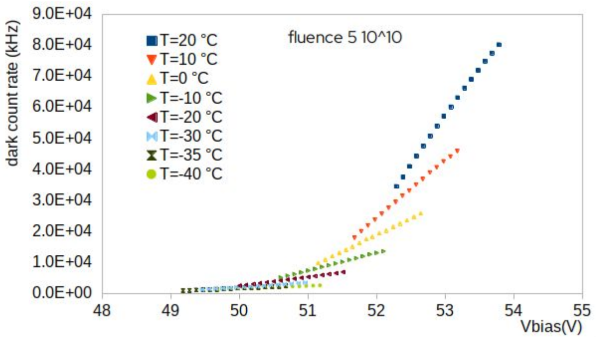
- For MCP-PMT the most crucial background is degradation of quantum efficiency
- Instead for SiPM the most critical is neutron flux, because increase count rate
- Study of neutron flux is part of background studies at LS2, which is ongoing
- Current study (based on 19th Monte Carlo Campaign) report about 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}

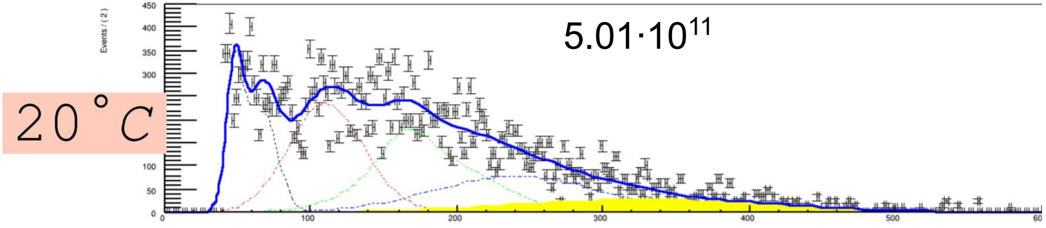


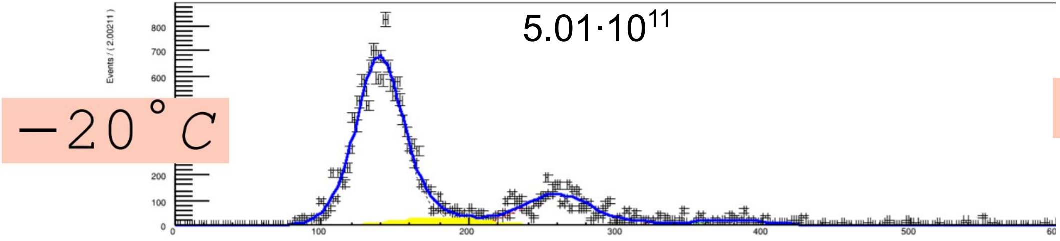
First result on irradiated SiPM Hamamatsu

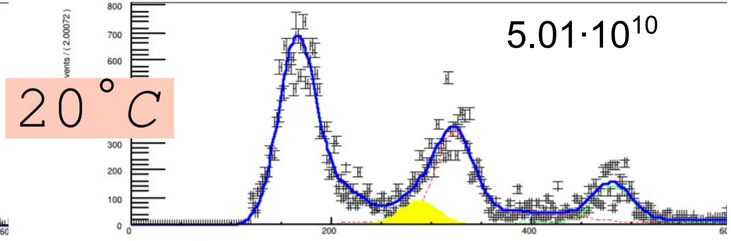
- In winter 2022, 8 Hamamatsu 1.3x1.3 mm^2 x 50 μm cells (S13360-1350PE) SiPMs were measured in Padova
- SiPMs were irradiated at different distances from target and different integration times
- SiPMs was irradiated with fluences in range from $1 \cdot 10^9$ to $5 \cdot 10^{11}$ neutrons cm^2
- Increase 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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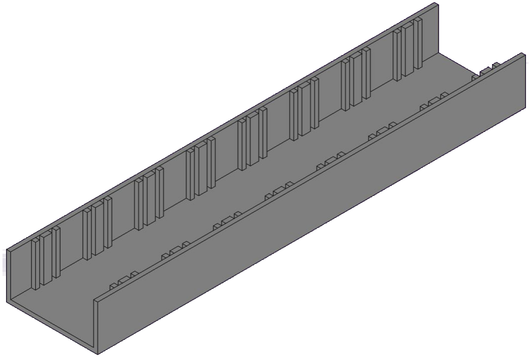
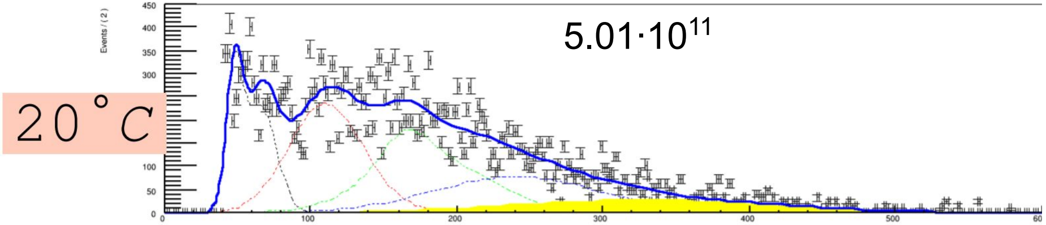
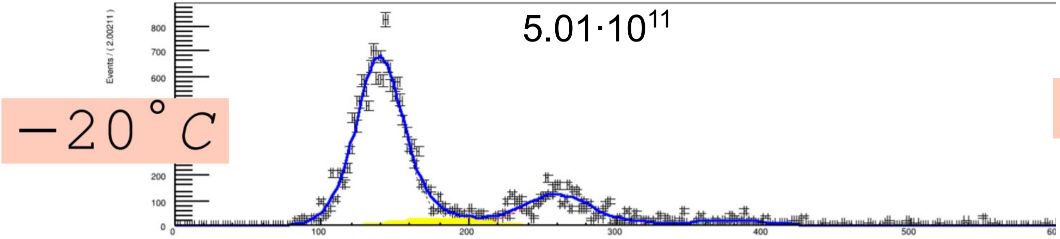
First result on irradiated SiPM Hamamatsu

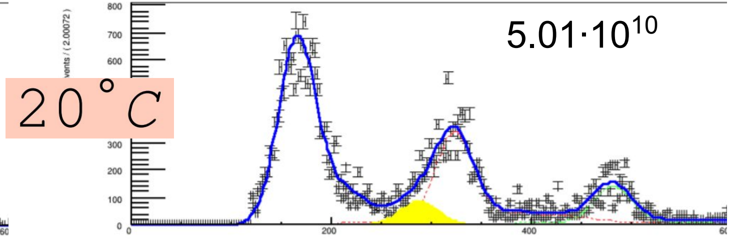
- In winter 2022, 8 Hamamatsu 1.3x1.3 mm^2 x 50 µm cells (S13360-1350PE) SiPMs was measured in Padova
- SiPMs was irradiated at different distances from target and different integration times
- SiPMs was irradiated with fluences in range from $1{\cdot}10^9$ to $5{\cdot}10^{11}$
- Damage could be partially recovered by operating SiPMs at low temperature

# 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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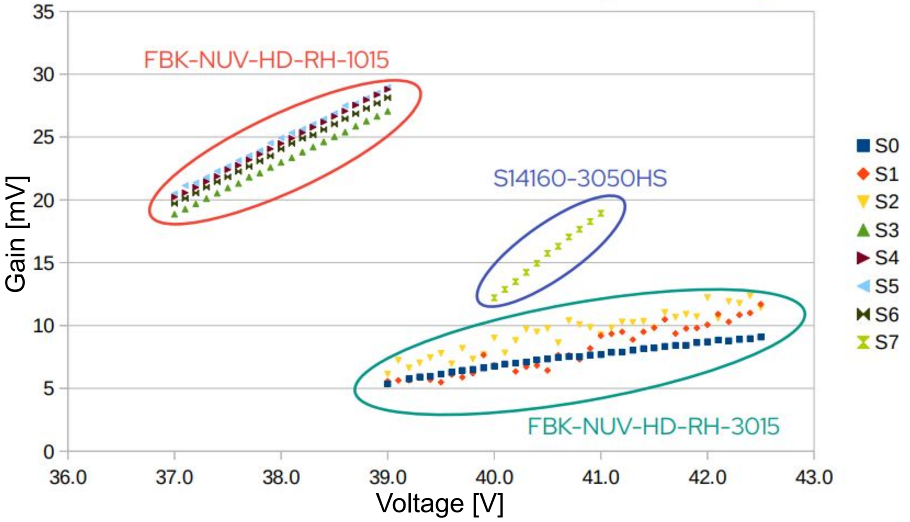
Further plans with SiPM

- 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



- 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)

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