Update on SiPM measurements

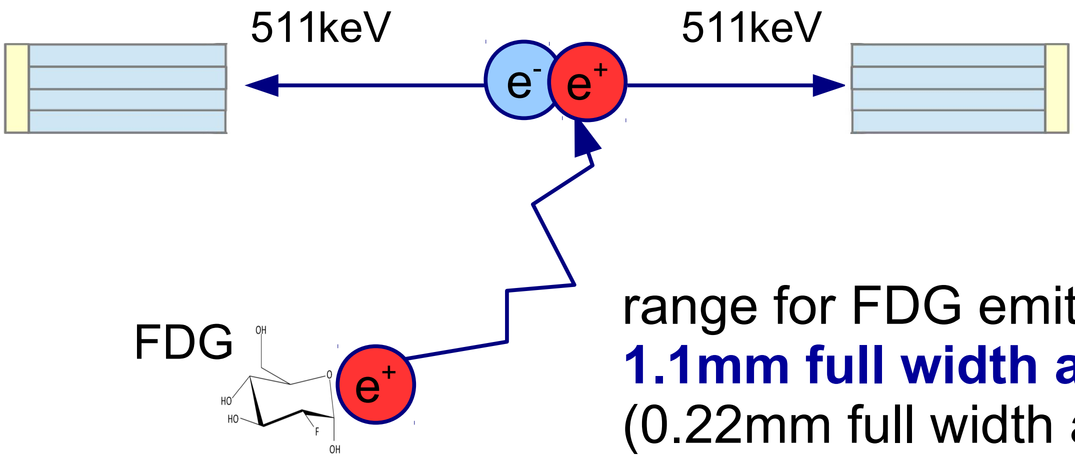
S. Gundacker[1,2], J.W. Cates[3],
E. Auffray[1], S. Levin[3] and P. Lecoq[1]

[1]*European Organization for Nuclear Research (CERN) 1211 Geneva 23, Switzerland*
[2]*Università degli Studi di Milano-Bicocca, Piazza della Scienza 3, 20126 Milano, Italy*
[3]*Molecular Imaging Program, Department of Radiology, Stanford University, Stanford, CA, United States*

This work was carried out in the frame of the Cost Action TD1401 (FAST),
the TICAL ERC Grant 338953 and the Crystal Clear Collaboration

The "10ps TOF-PET challenge"

10ps in TOF-PET: the holy grail?



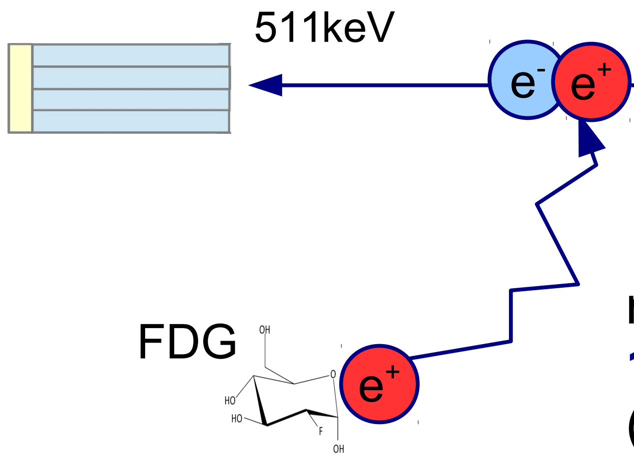
range for FDG emitted positron:
1.1mm full width at ten maximum
(0.22mm full width at half maximum)

→ CTR of **10ps FWHM correspond to 1.5mm resolution** along LOR

→ direct imaging without reconstruction would be possible and very likely could mean a paradigm shift in PET diagnostics

→ other geometries than the standard ring thinkable, like endoscopic probes (EndoTOFPET-US)

10ps in TOF-PET: the holy grail?



range for FDG emitted positron:
1.1mm full width at ten maximum
(0.22mm full width at half maximum)

However,
resolution of actual whole body PET around 3-5mm:

→ Time resolution of 20-35ps FWHM enough for direct imaging
(Still ambitious but important relaxation of constraints)

Where are we on the way to reach 10ps in PET?

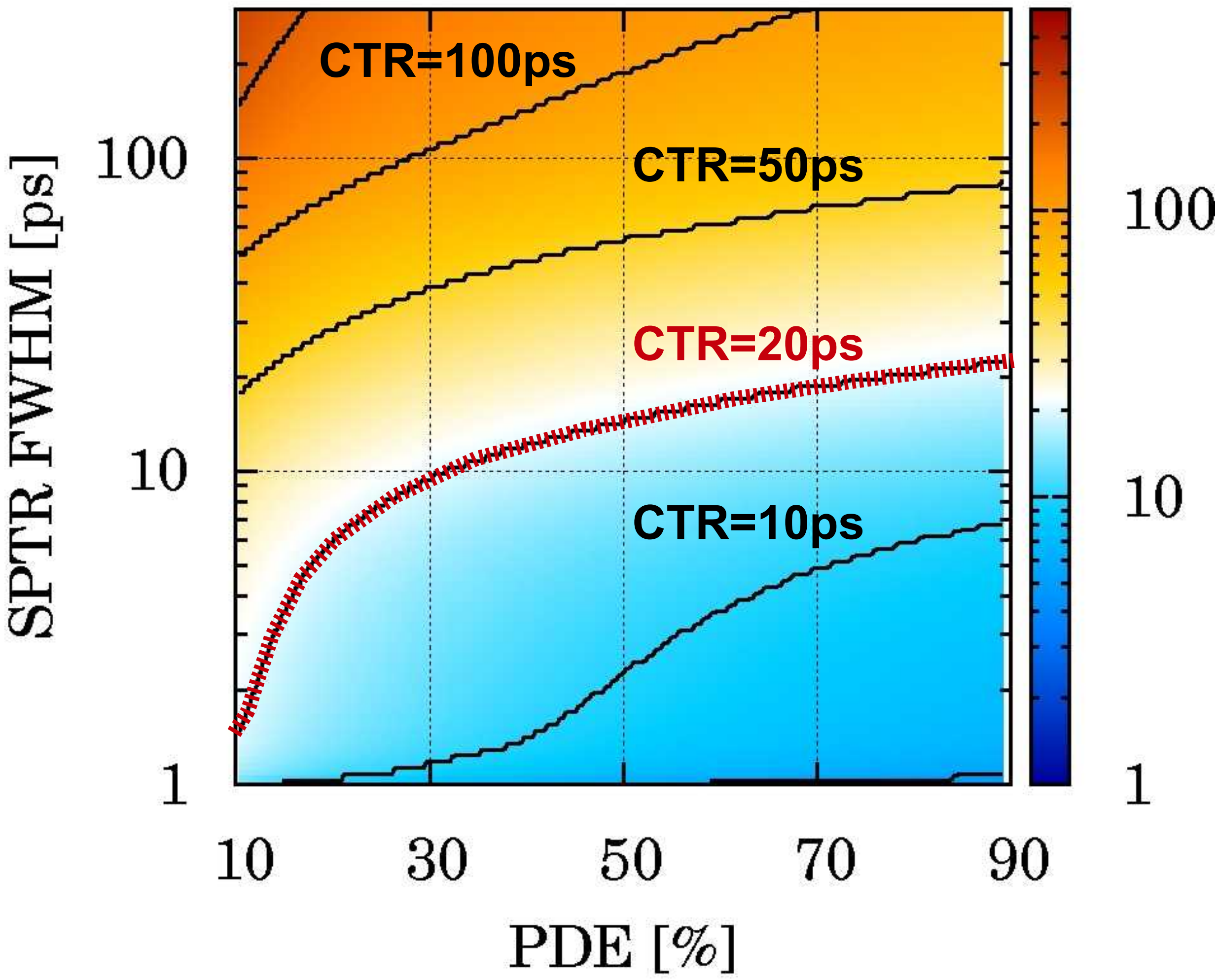
- The light transfer efficiency (LTE) in the crystal:
  - is almost 90% for $2x2x3mm^3$ size
  - and around 50% for $2x2x20mm^3$ size, (when coupled with Meltmount to SiPM without resin)

→ Hence, CTR improvement by more efficient light collection is limited. Additionally the PDE in modern analog SiPMs reaches already 70%.

- Aiming at a CTR of 10ps FWHM needs to put efforts in finding faster scintillators and/or **improving the single photon time resolution (SPTR) of the SiPM**, together with the detection of prompt photons, e.g. Cherenkov and hot intraband luminescence.

Highest SPTR can harness prompt photons

Crámer Rao calculations including photon transfer time spread (PTS) and light transfer efficiency (LTE) of a **2x2x3mm³ LYSO:Ce crystal** with **30 prompt photons produced** (Cherenkov + hot intraband).



scintillator parameters:

rise time:
τ_r=80 ps

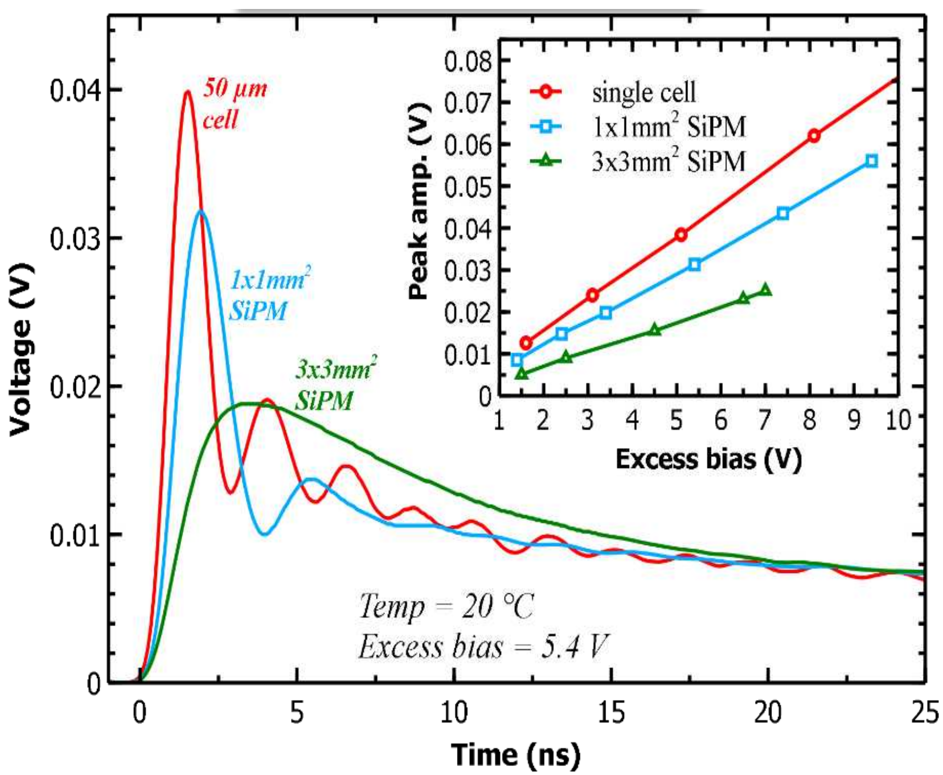
decay time:
τ_d=40 ns

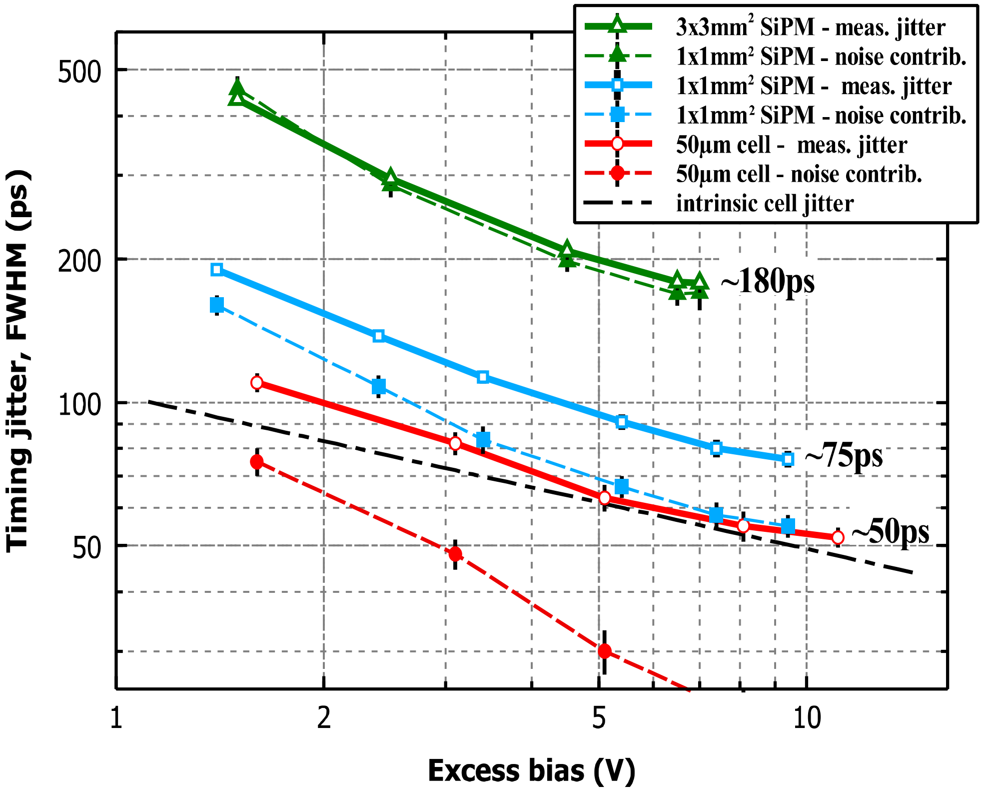
light yield:
LY=40 000 ph/MeV

wrapped in Teflon,
coupled with glue n=1.42

Electr. noise dominates SPTR for large area SiPMs

Improved signal to noise (SNR) via faster and larger signals: $\sigma_{electronic\_jitter} = \dfrac{\sigma_{noise}}{dV/dt}$





Acerbi et al. NIM A 787 pp. 34-37 (2015)

It is important to know the "real" SPTR without the electr. noise contribution in order to estimate and understand the CTR values properly.

Content

- Concept: reduce the effective SiPM capacitance via bootstrap feedback

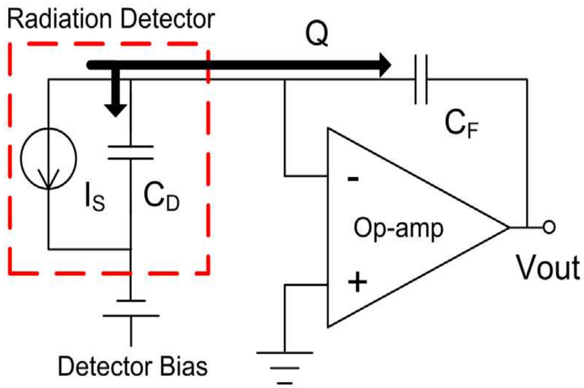
- Two circuits testet:
    1) Active compensation via Op-Amps
    2) Passive compensation via Transformer

- Measured SPTR with NINO versus passive compensation circuit
    - FBK NUV single 40µm SPAD, 1x1mm² and 3x3mm² SiPM
    - FBK NUV-HD 40µm 4x4mm² SiPM
    - HPK 50µm 3x3mm² SiPM
    - SensL SiPM 35µm 3x3mm² SiPM

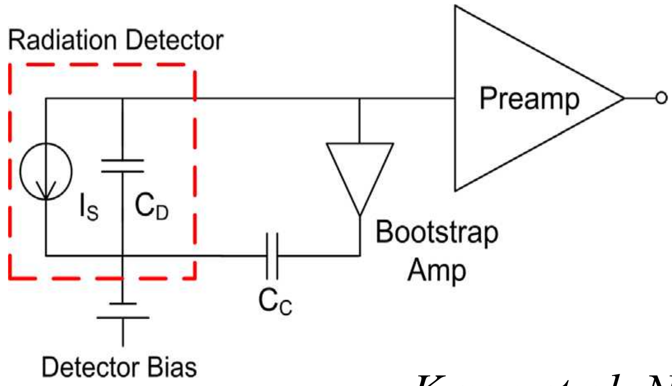
- SPTR limits of a single masked SPAD and the effects on the CTR

Reduced $C_{effective}$ of large area silicon detectors

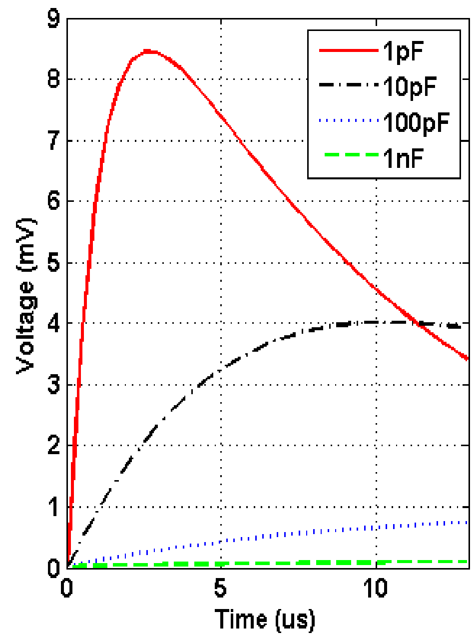
Charge Sensitive Amplifier



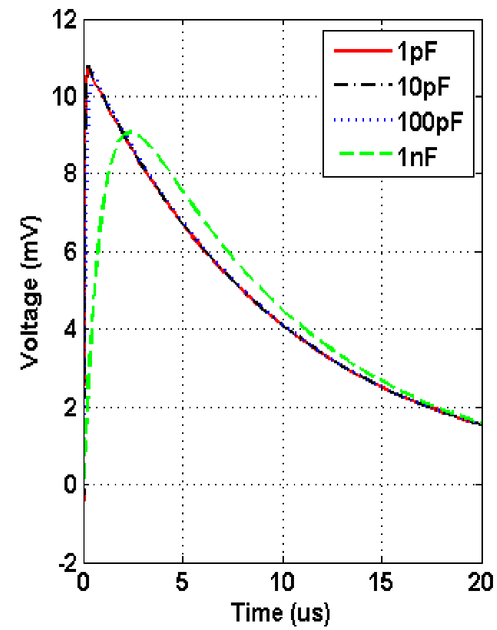
Bootstrap Amplifier Configuration



Detector Pulse Without Compensation



Detector Pulse With Compensation



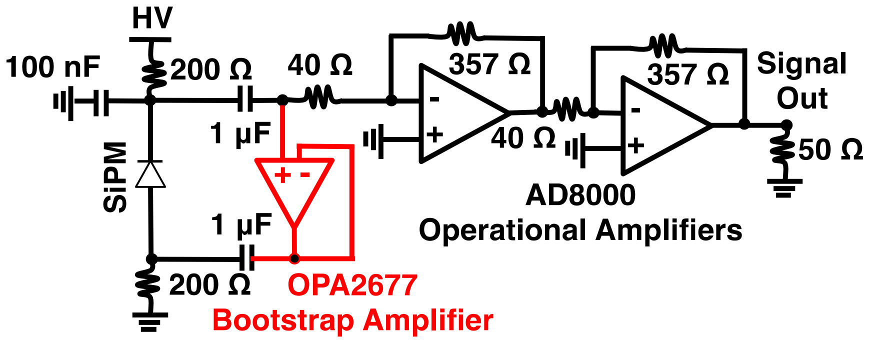
Kwon et al. NIM A 784 pp. 220-225 (2015)

Practical implementation with analog SiPMs

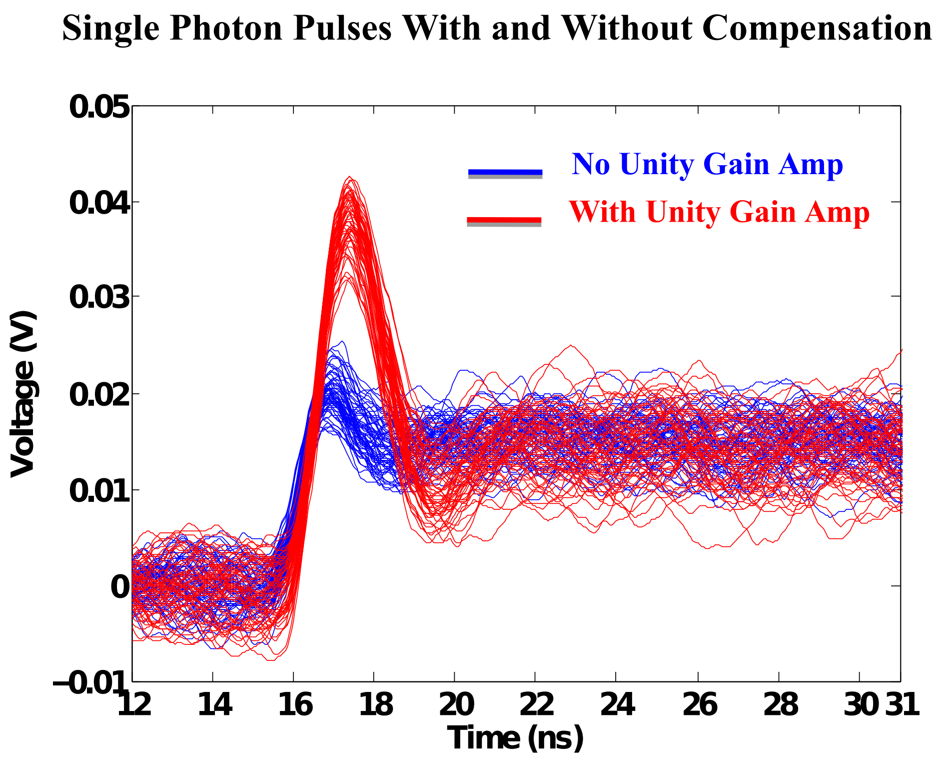
Two concepts tested: active and passive compensation

Bootstrap circuit type 1: based on Op-Amps

Active Compensation Circuit

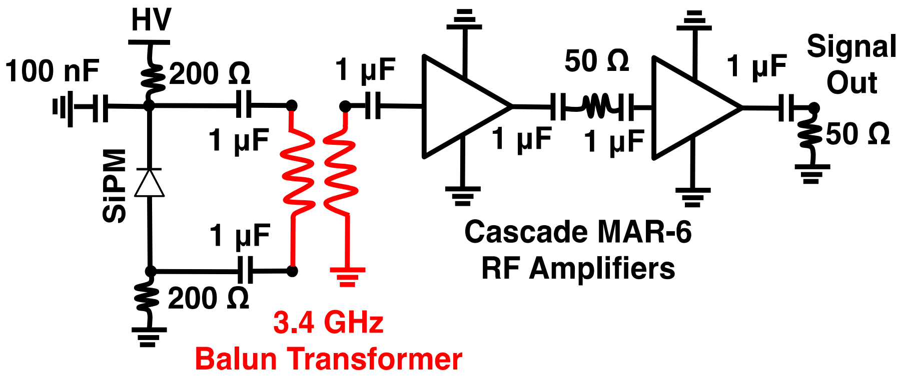


FBK-NUVHD, 4x4mm², 40µm at 38V



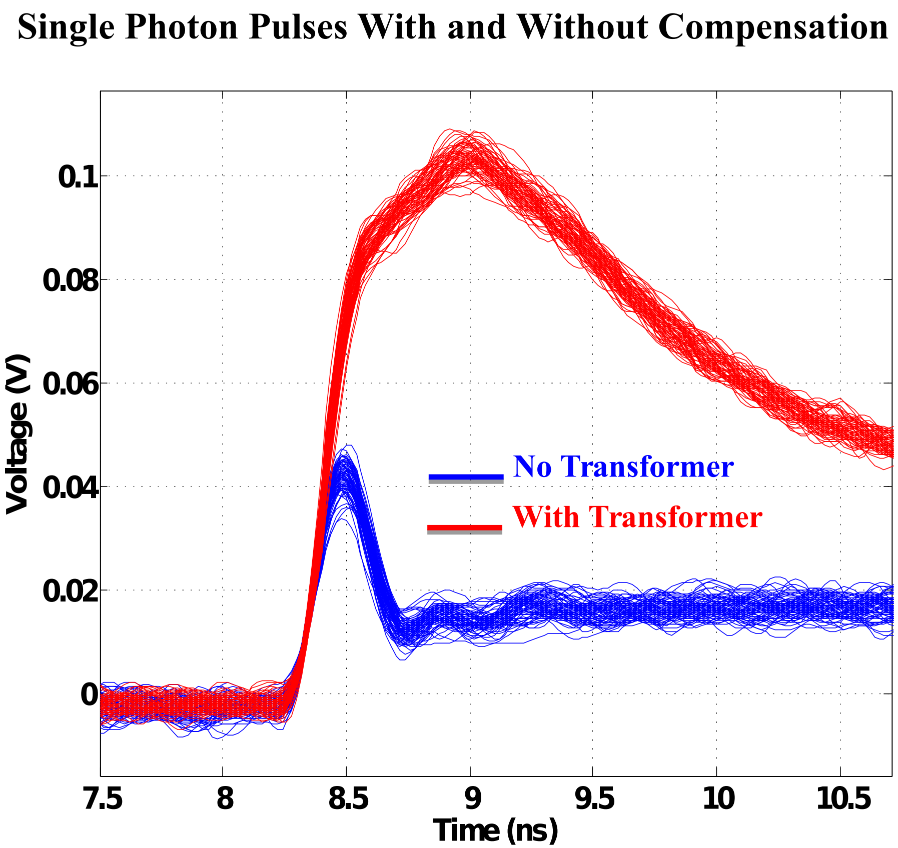
Bootstrap circuit type 2: passive compensation

Passive Compensation Circuit

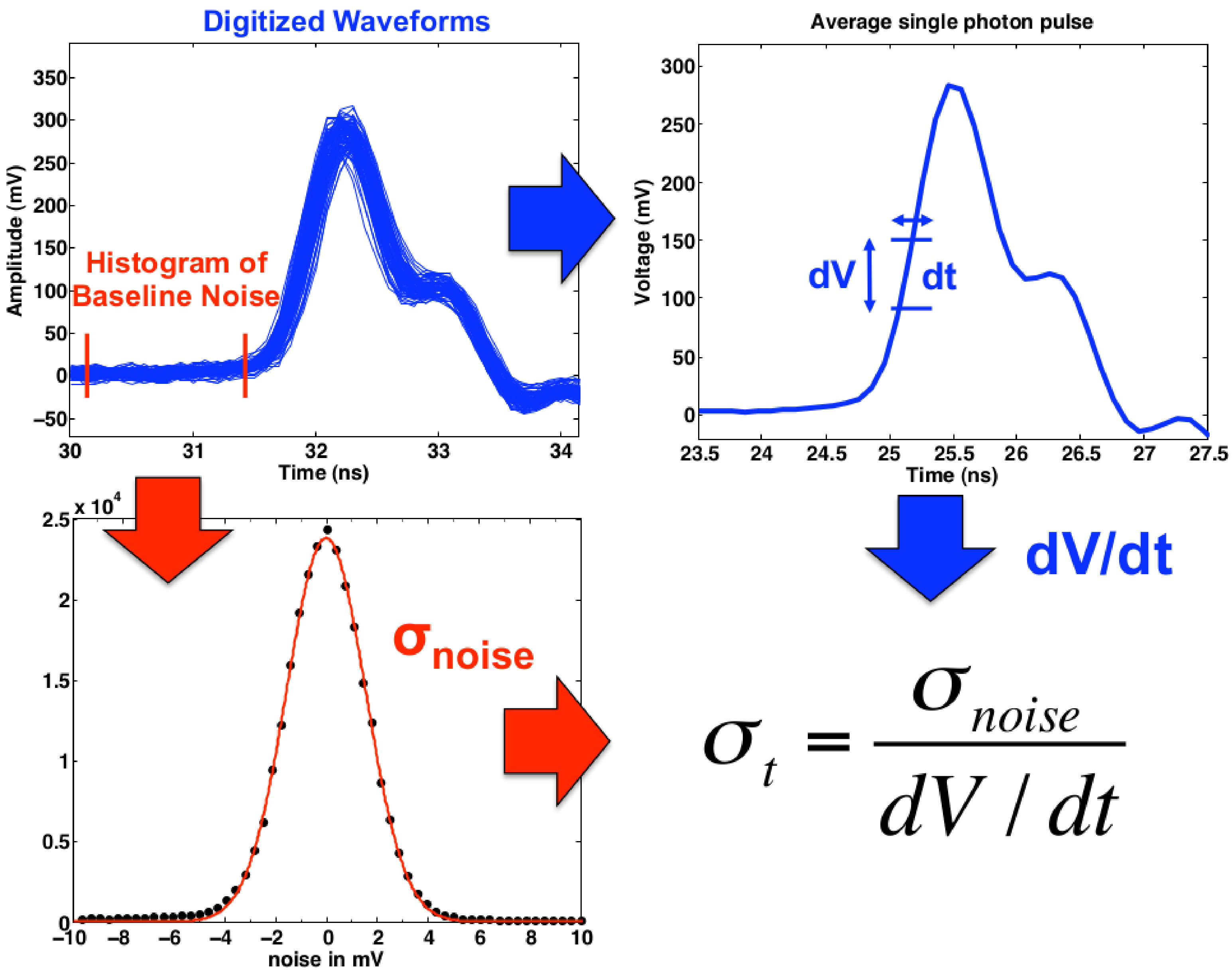


Inspired by method outlined in Zhang and Schmand US Patent: US2016/0327657

FBK-NUVHD, 4x4mm², 40µm at 38V



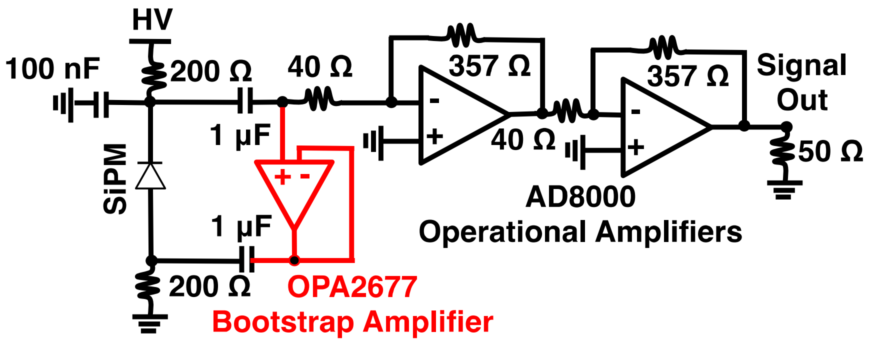
Contribution of electronic noise on SPTR



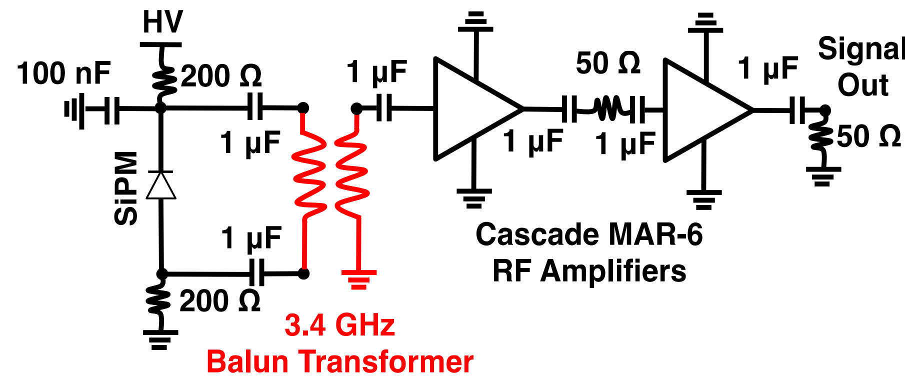
$$\sigma_t = \frac{\sigma_{noise}}{dV / dt}$$

Electronic noise in active & passive compensation

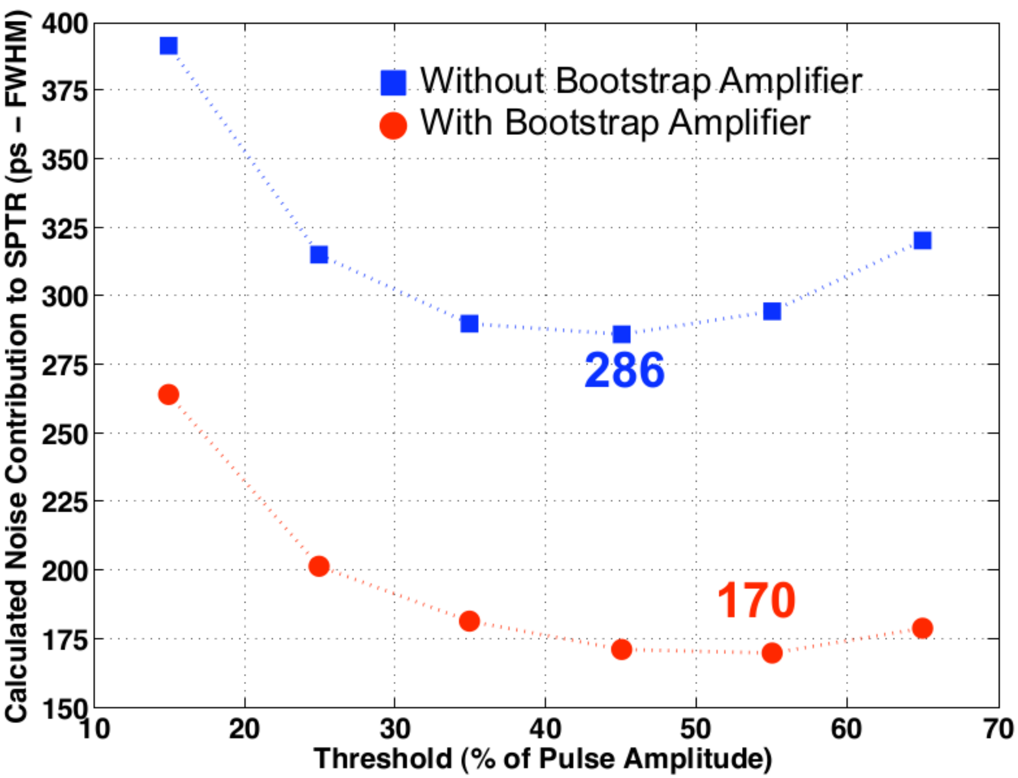
Active Compensation Circuit

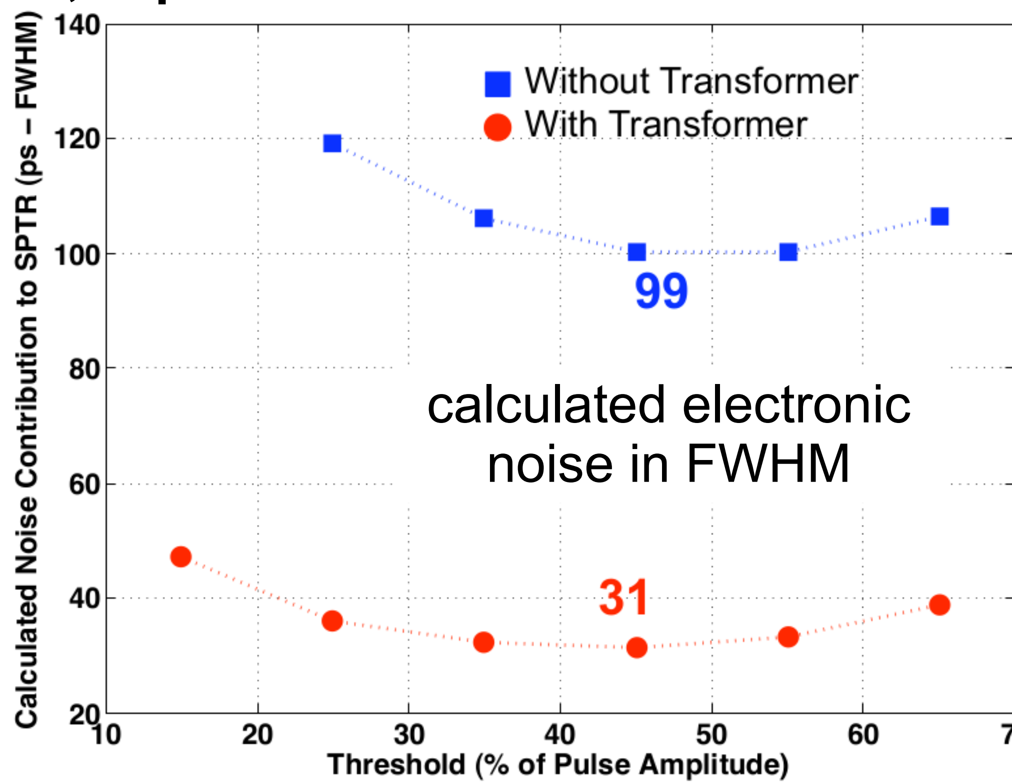


Passive Compensation Circuit

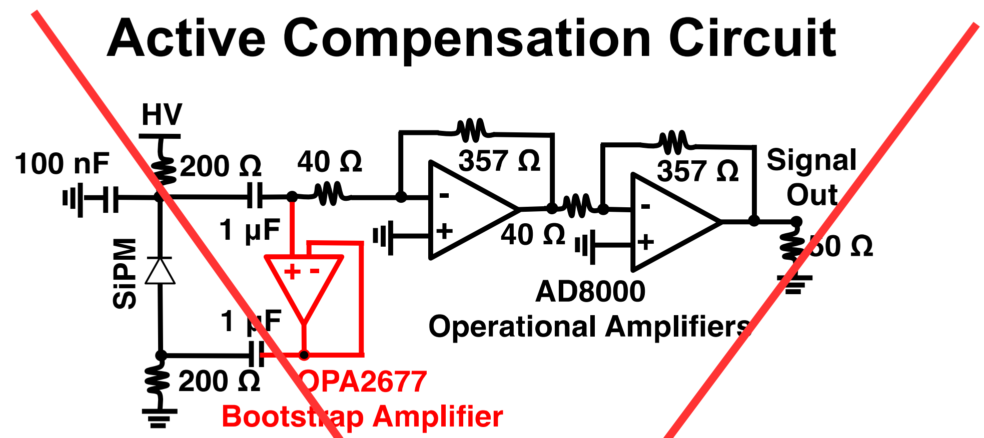


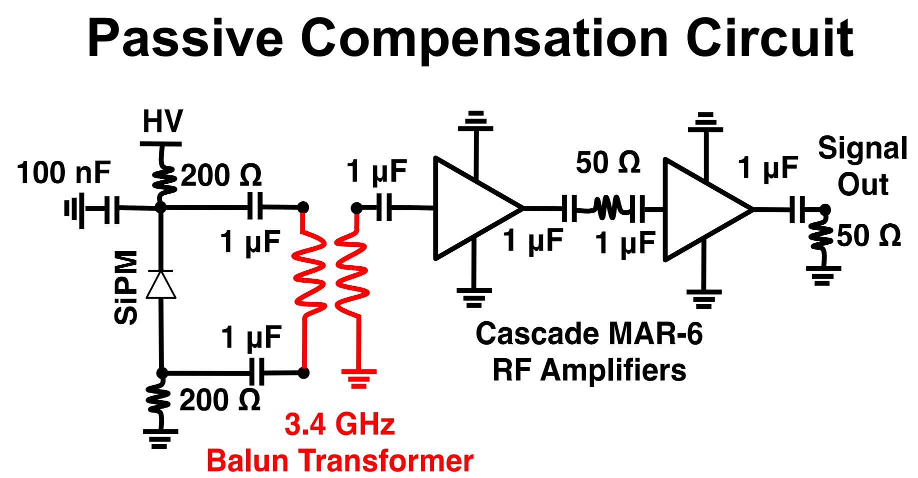
FBK-NUVHD, 4x4mm², 40µm at 38V



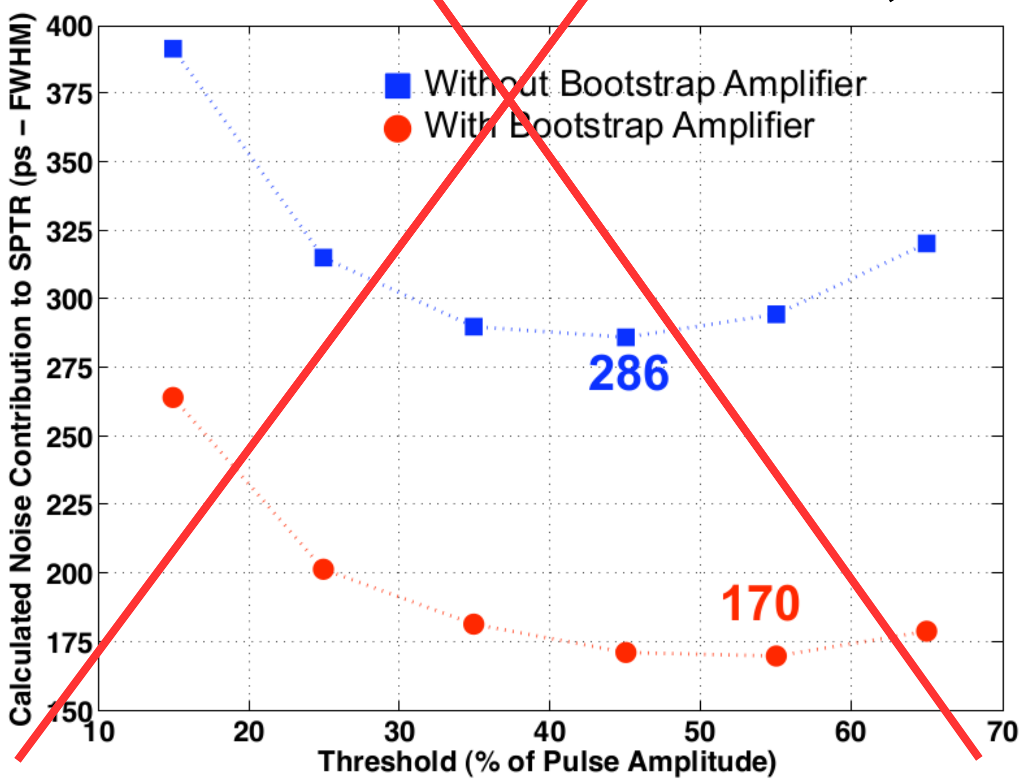


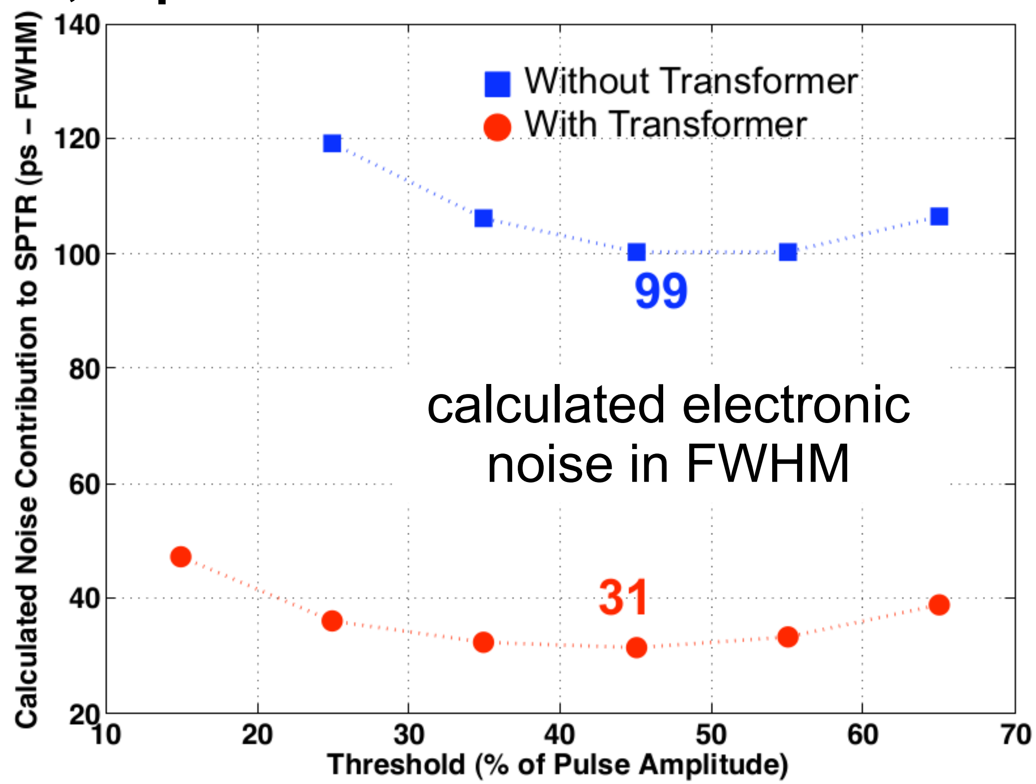
Electronic noise in active & passive compensation





FBK-NUVHD, 4x4mm², 40µm at 38V

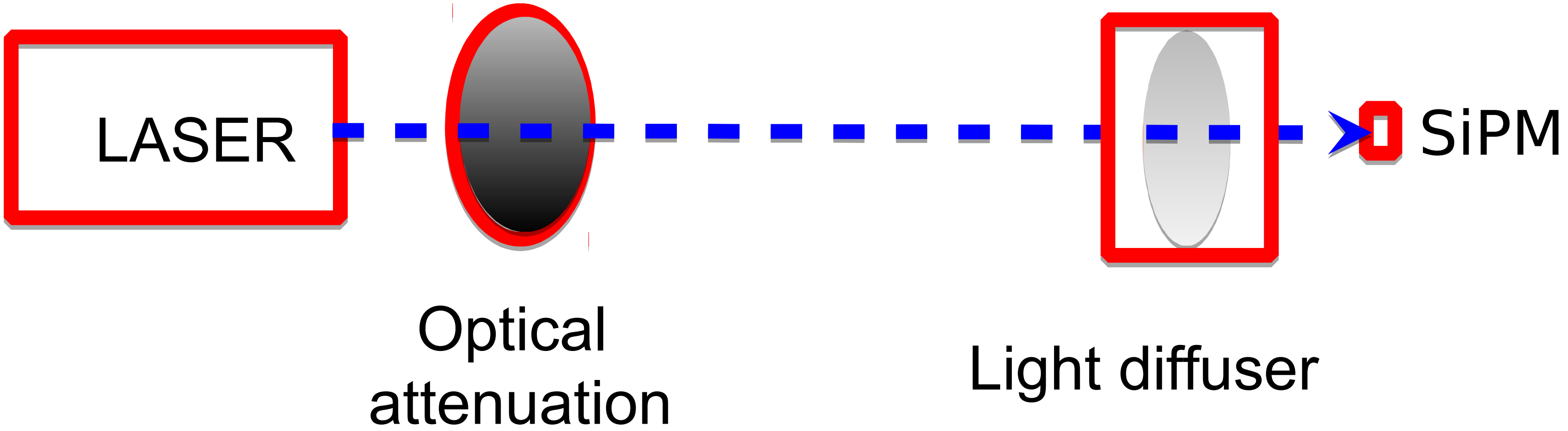




Measured SPTR of various SiPMs

NINO vs passive compensation circuit

Method: measurement setup

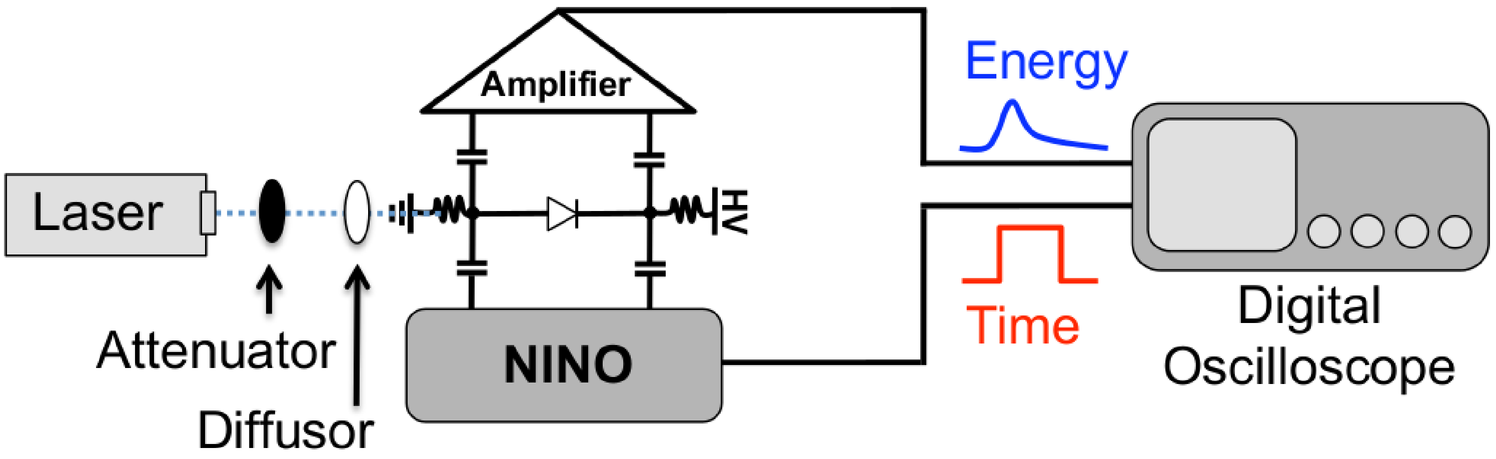


LASER operating parameters

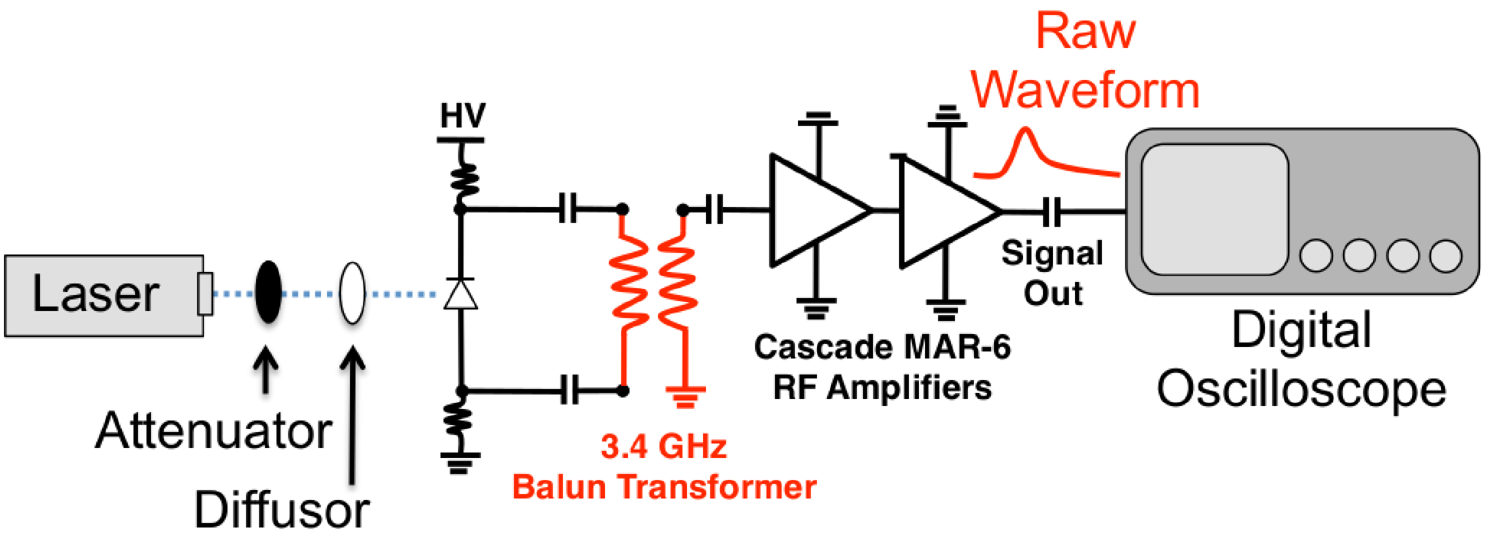
- Wavelength: 420nm
- Repetition : 10kHz
- Attenuation: ND filters for single photon level
- Pulse Width: **42ps (FWHM)**

Method: measurement setups

NINO:

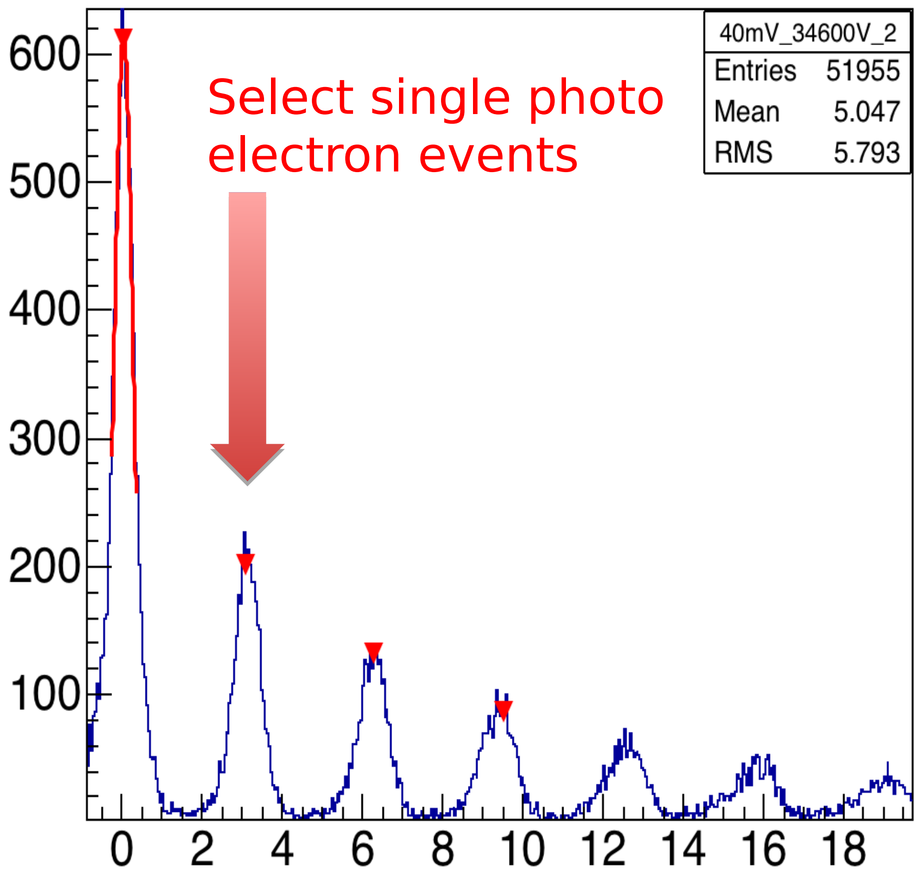


Passive Compensation Circuit:

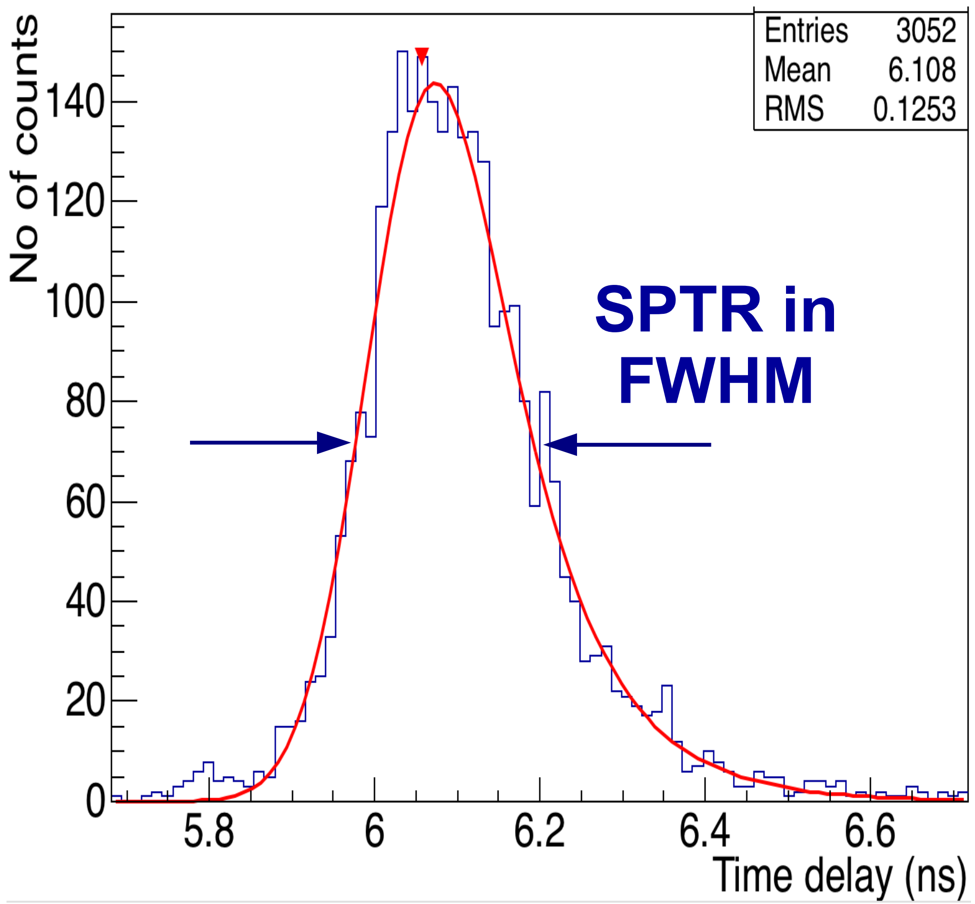


Method: data analysis

Single photon spectrum



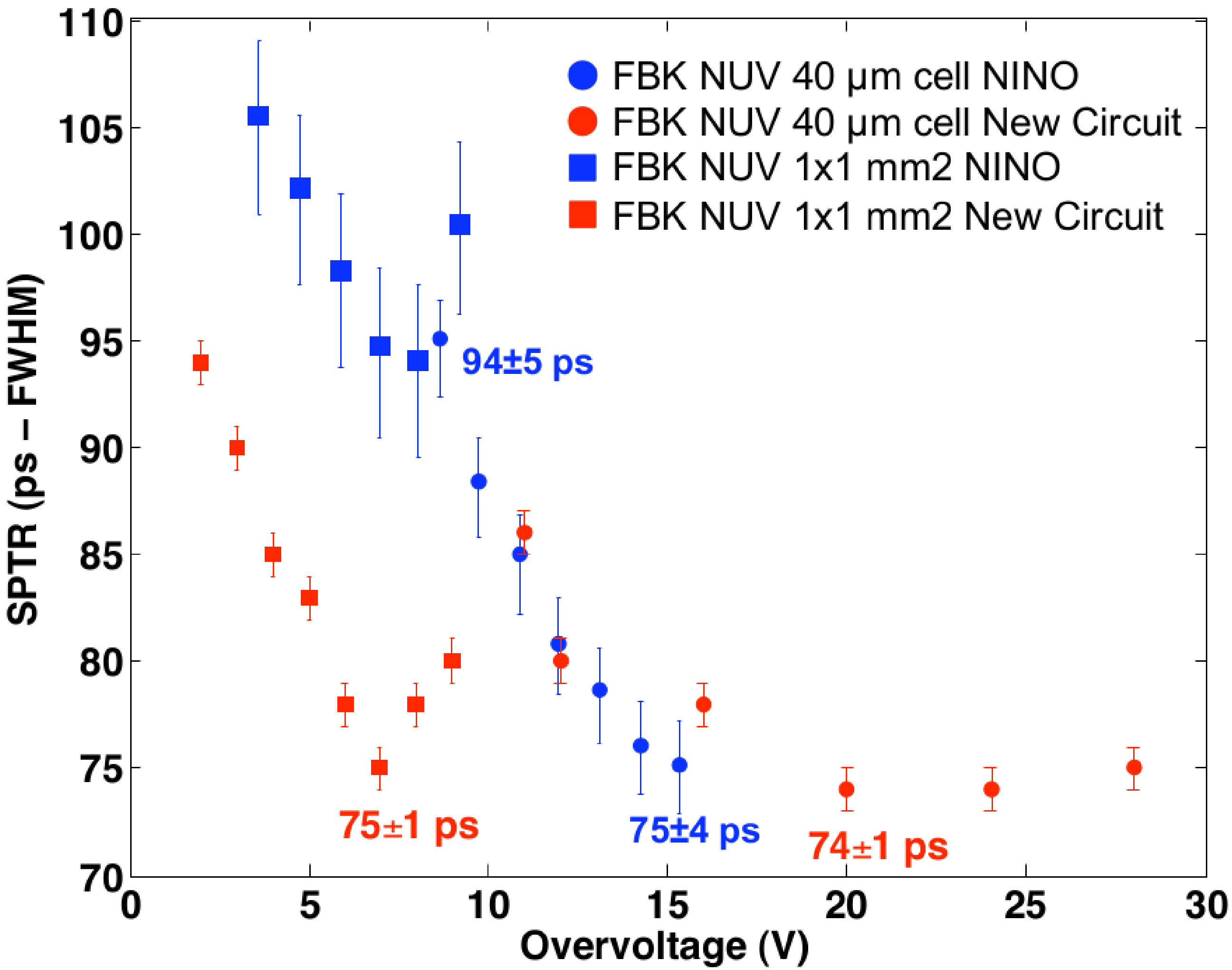
Pulse delay histogram



SPTR measured with FBK SiPMs

SPTR with NUV single 40µm SPAD & 1x1mm² SiPM

Electronic noise is an issue for SPTR measurements even for 1x1mm² SiPMs



<u>FBK NUV single SPAD 40µm:</u>

NINO:	75ps FWHM
new Circuit:	74ps FWHM

<u>FBK NUV 1x1mm² 40µm:</u>

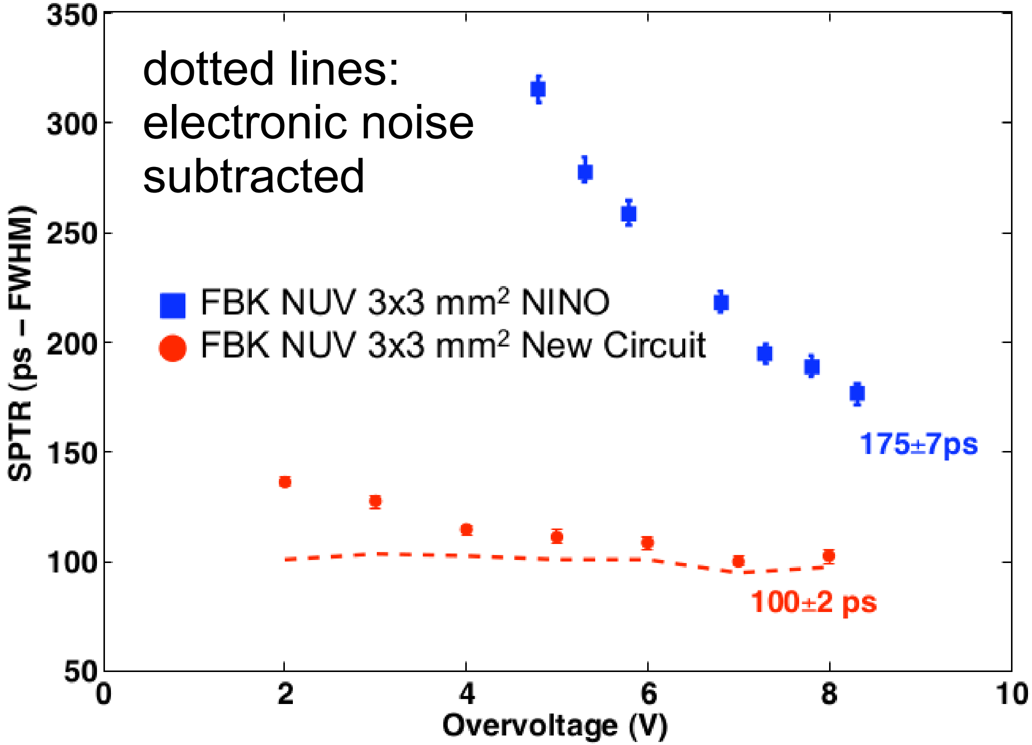
NINO:	94ps FWHM
new Circuit:	75ps FWHM

Laser pulse width: 42ps FWHM

SPTR with NUV 3x3mm² & NUV-HD 4x4mm²

Both SiPMs (3x3mm² NUV and 4x4mm² NUV-HD) have a SPAD size of 40µm.

Laser pulse width: 42ps FWHM



FBK NUV 3x3mm² (40µm):

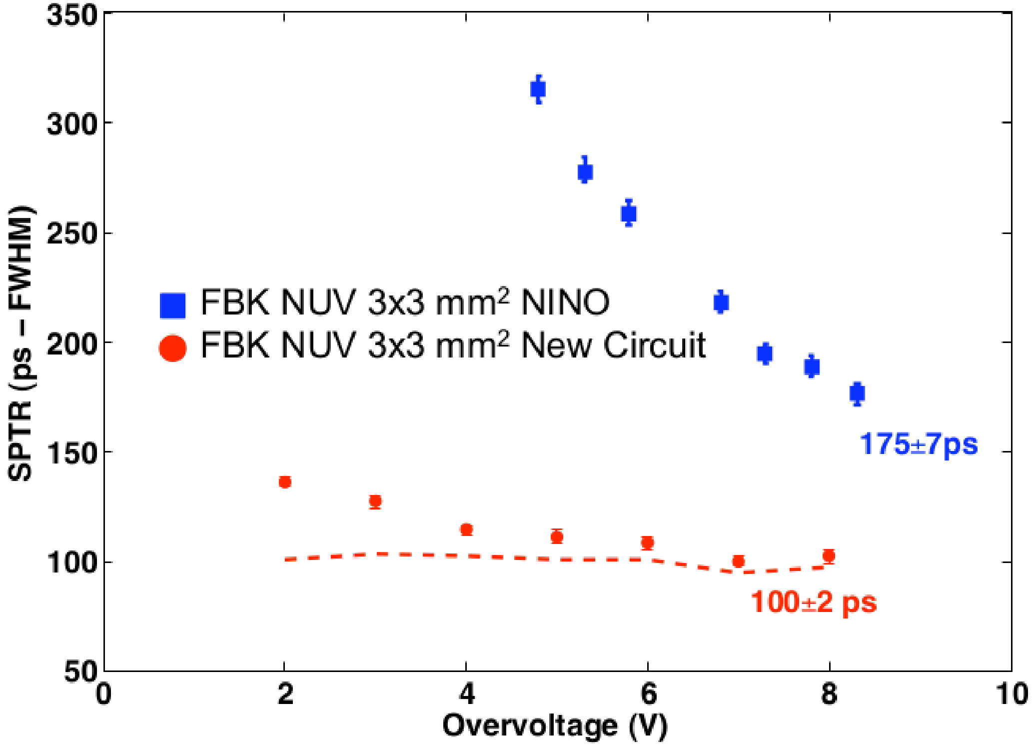
NINO: SPTR=175ps FWHM

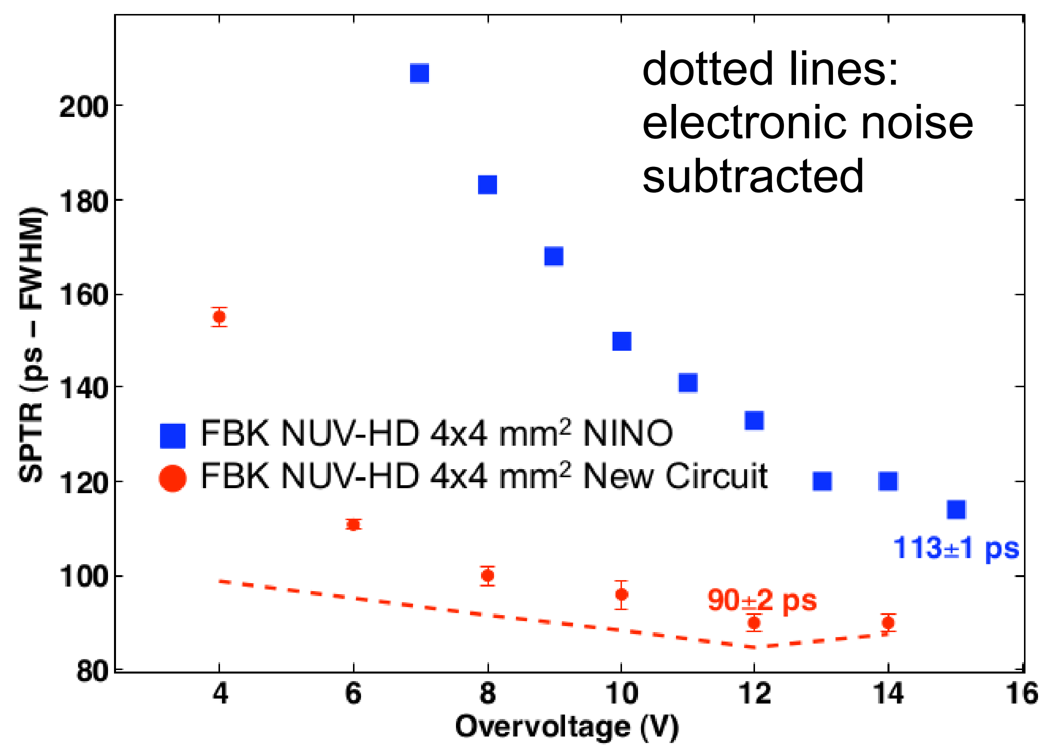
new Circuit: SPTR=100ps FWHM

SPTR with NUV 3x3mm² & NUV-HD 4x4mm²

Both SiPMs (3x3mm² NUV and 4x4mm² NUV-HD) have a SPAD size of 40µm.

Laser pulse width: 42ps FWHM





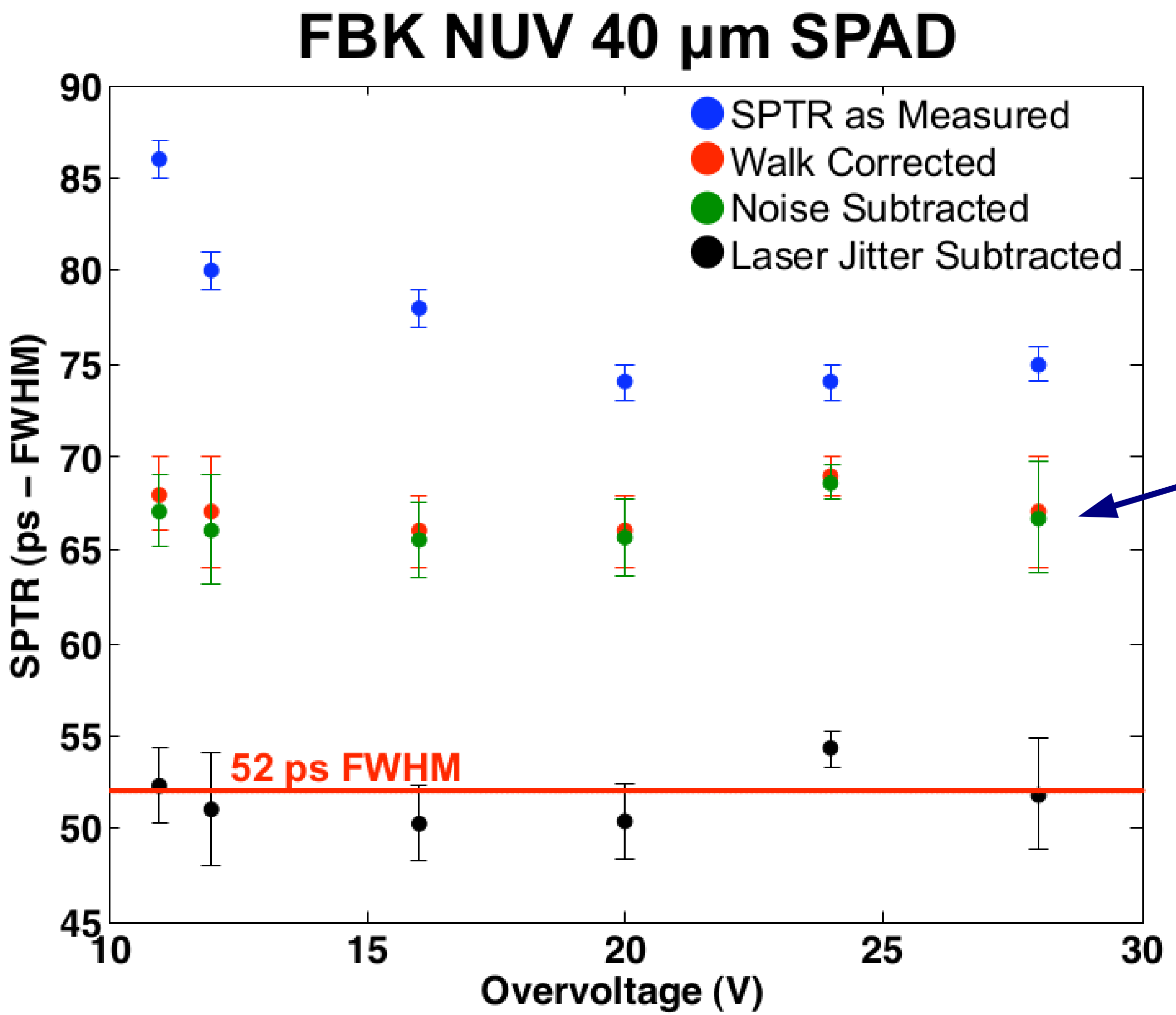
<u>FBK NUV 3x3mm² (40µm):</u>

NINO:	SPTR=175ps FWHM
new Circuit:	SPTR=100ps FWHM

<u>FBK NUV-HD 4x4mm² (40µm):</u>

NINO:	SPTR=113ps FWHM
new Circuit:	SPTR=90ps FWHM

Time walk in single SPADs

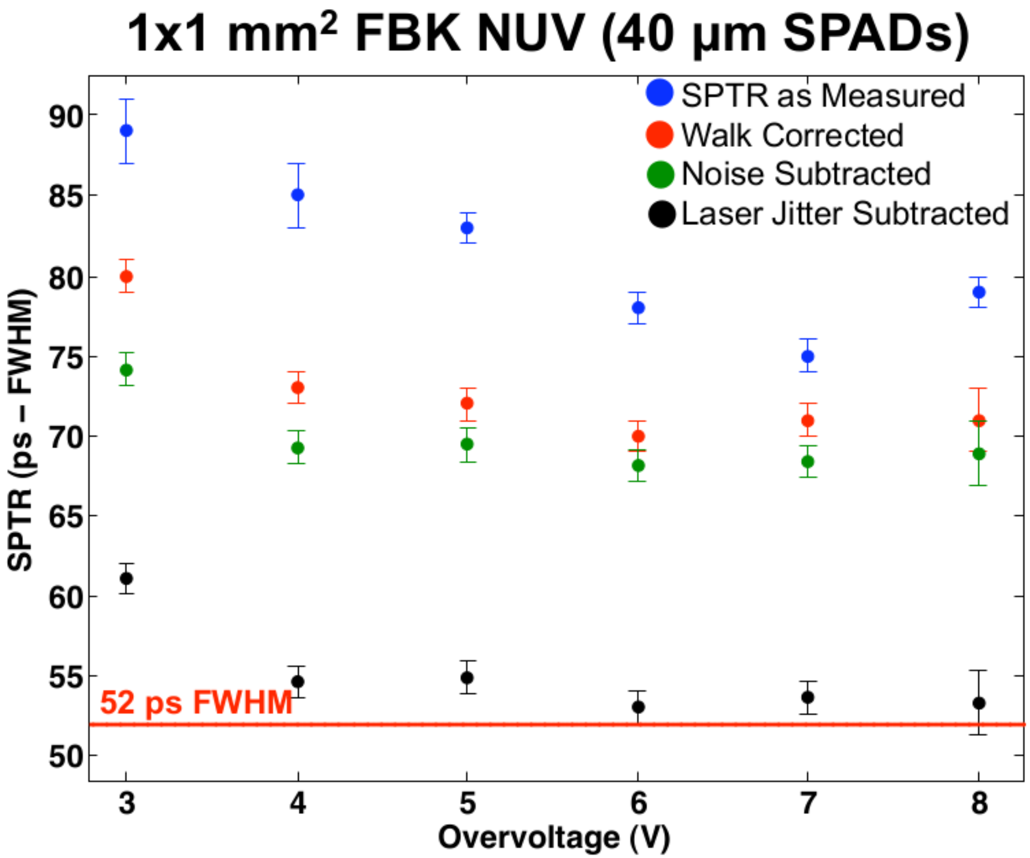


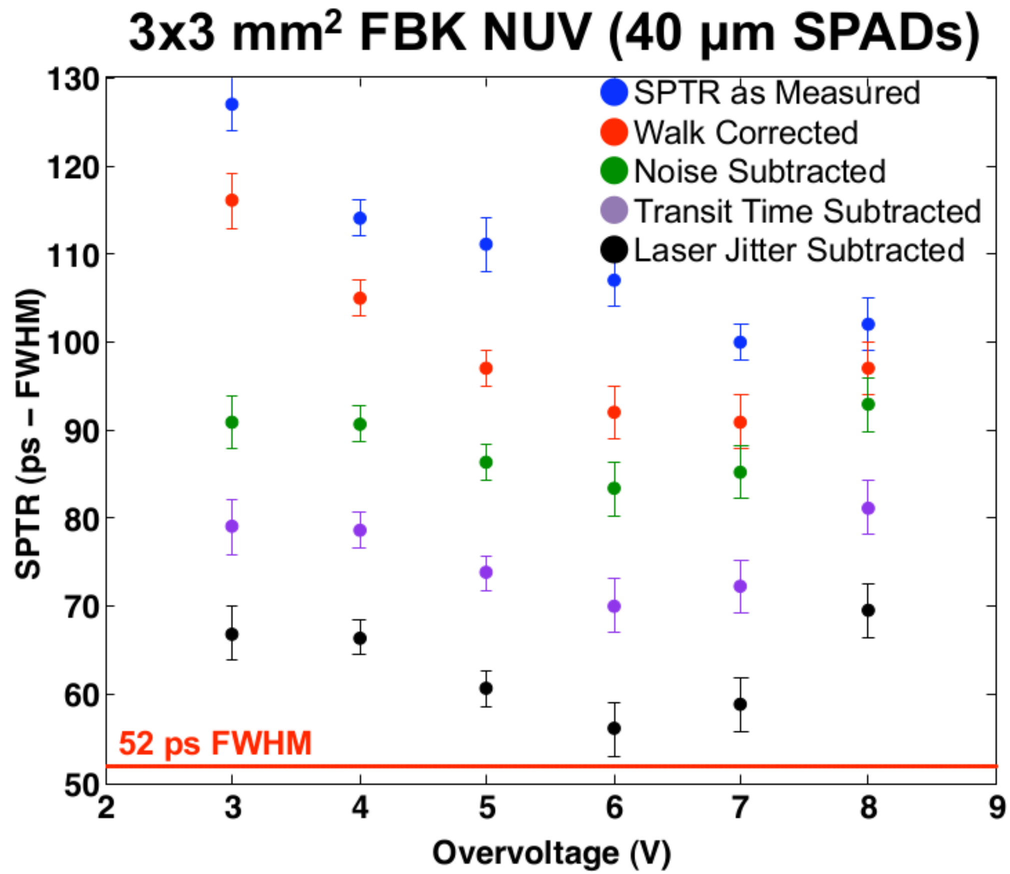
Edge effects cause amplitude fluctuation which causes a time walk effect in the SPTR, which can be corrected via calibration measurements.

Laser pulse width: 42ps FWHM

Time walk and transit time spread

Subtracting the time walk, electr. noise influence, laser jitter and transit time gives a SPTR of 52ps FWHM for the FBK NUV 1x1mm² and 3x3mm² SiPM,



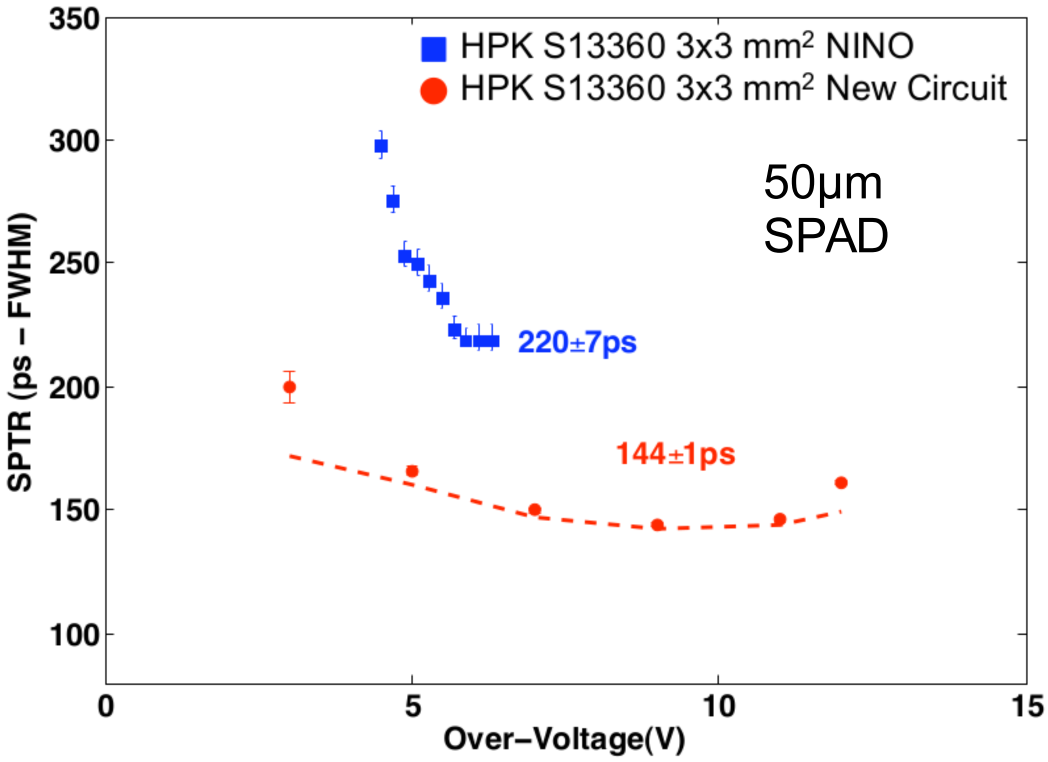


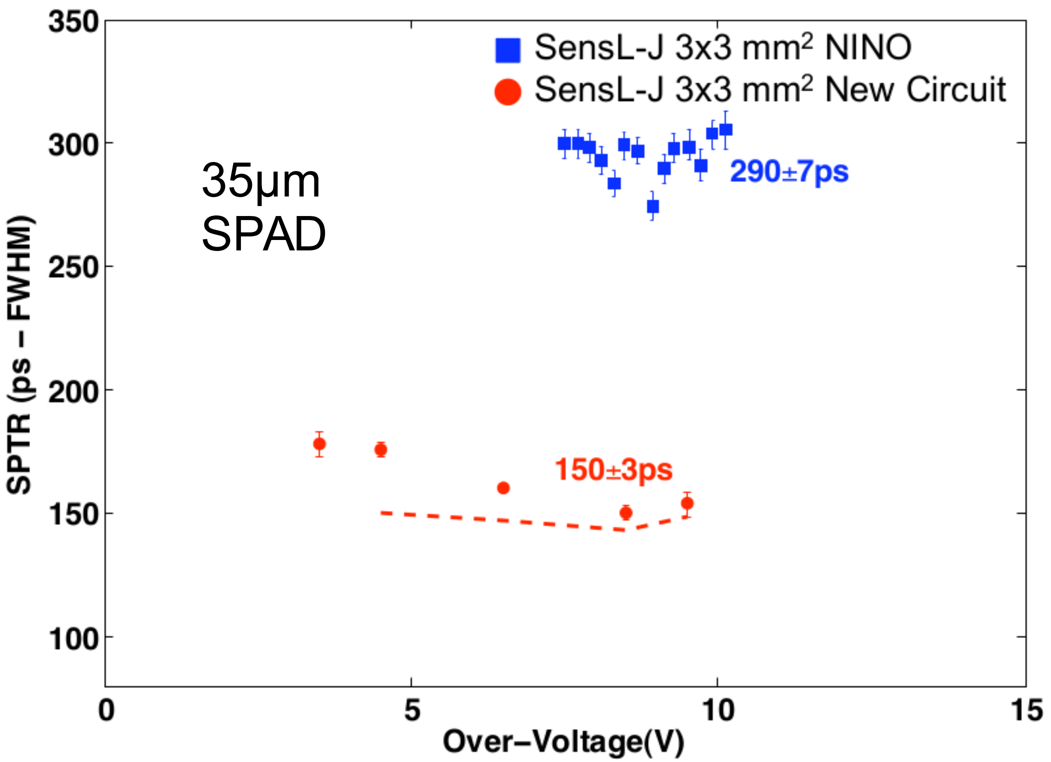
Laser pulse width is 42ps FWHM and the transit time of 45ps for the 3x3mm² SiPM taken from F. Acerbi et. al, "Analysis of transit time spread on FBK silicon photomultipliers", JINST 10 P07014 2015.

SPTR measured with HPK and SensL SiPMs

SPTR for 3x3mm² HPK and SensL

Other manufacturers like HPK and Sensl show similar but slightly worse SPTR values as compared to FBK when reducing electronic noise.

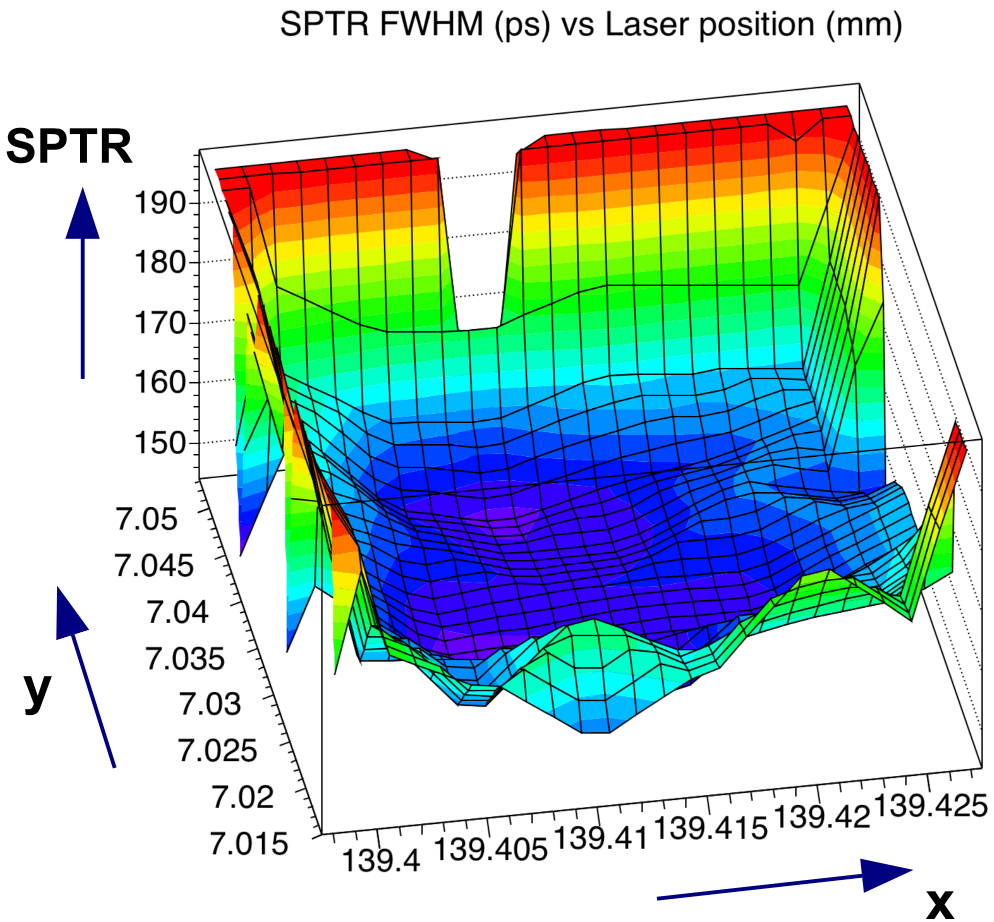




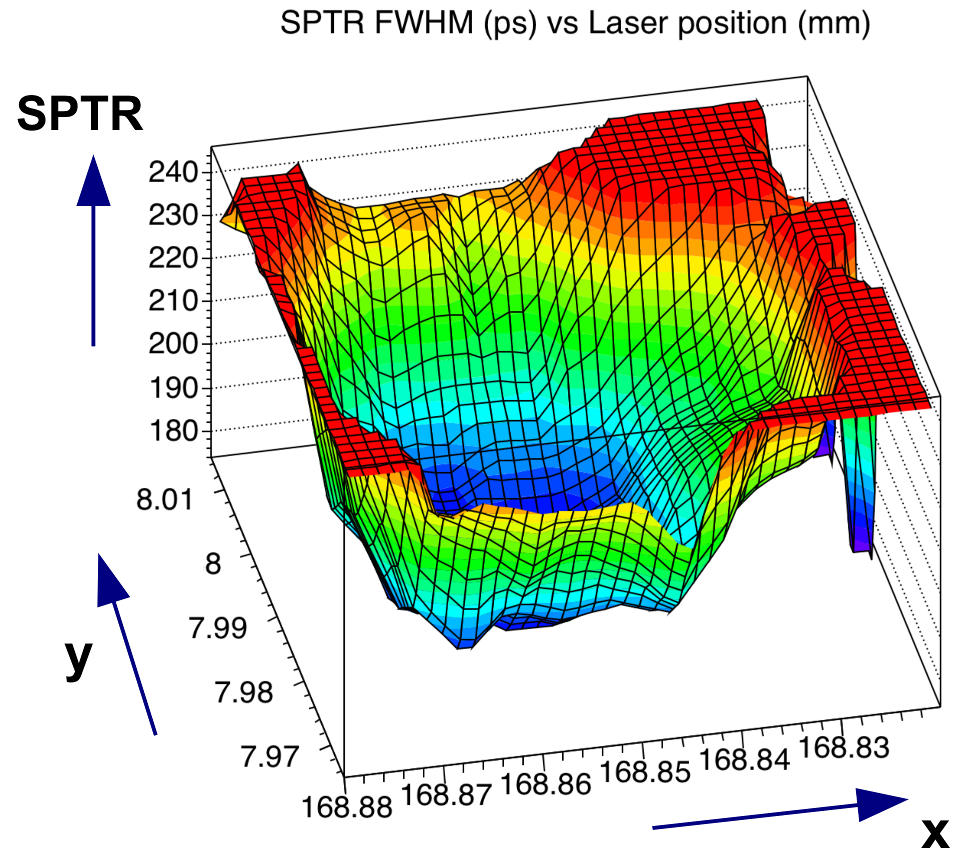
dotted lines: electronic noise subtracted

Focused laser scans within a SPAD

Scan of single SPADs within a full SiPM shows that the SPAD can be improved



FBK NUV



HPK TSV

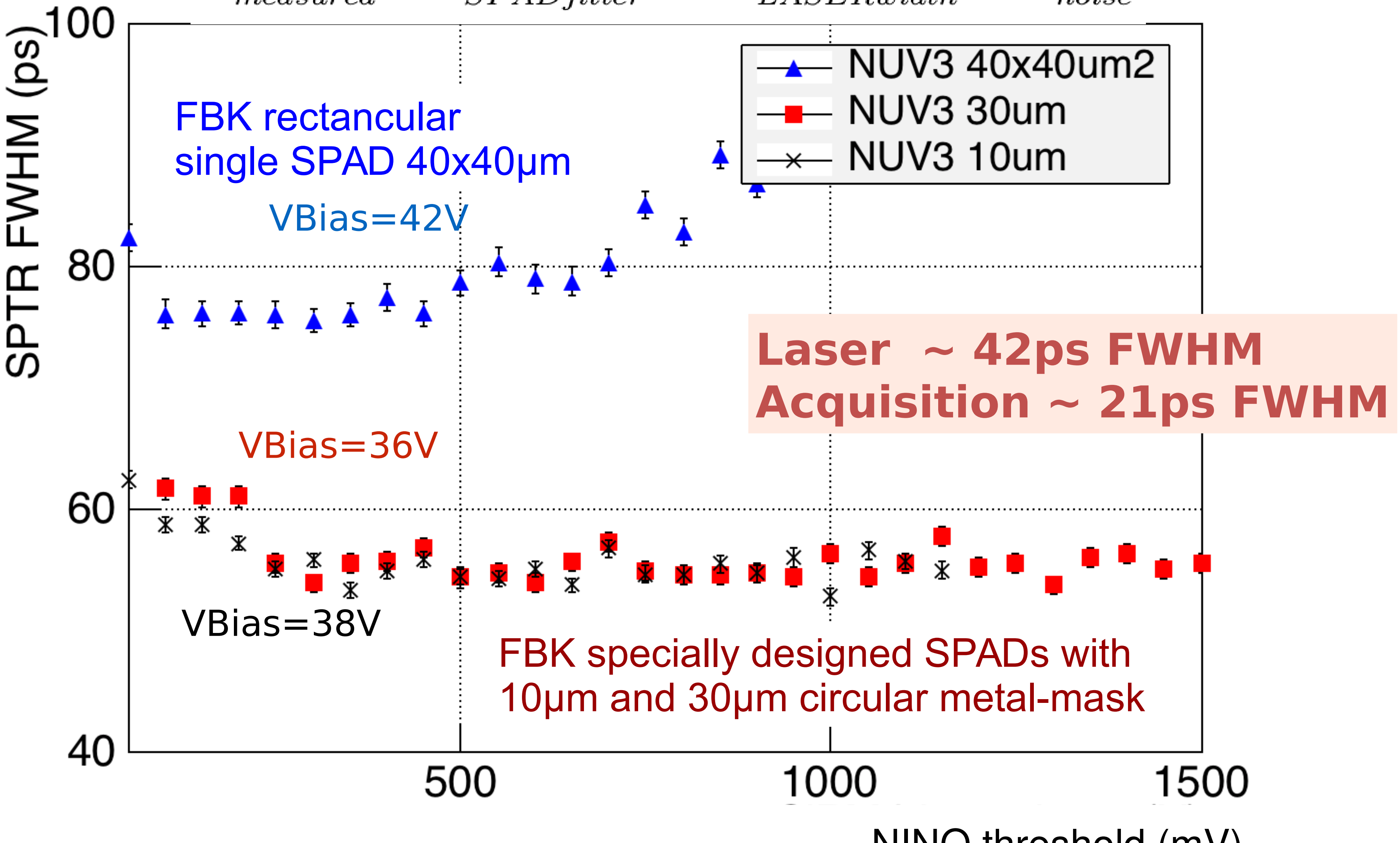
M.V. Nemallapudi et.al, October 2016. JINST 11 P10016

Where are the limits of a single SPAD?

The limits of single SPADs are promising

Single photon level at optimum bias voltage

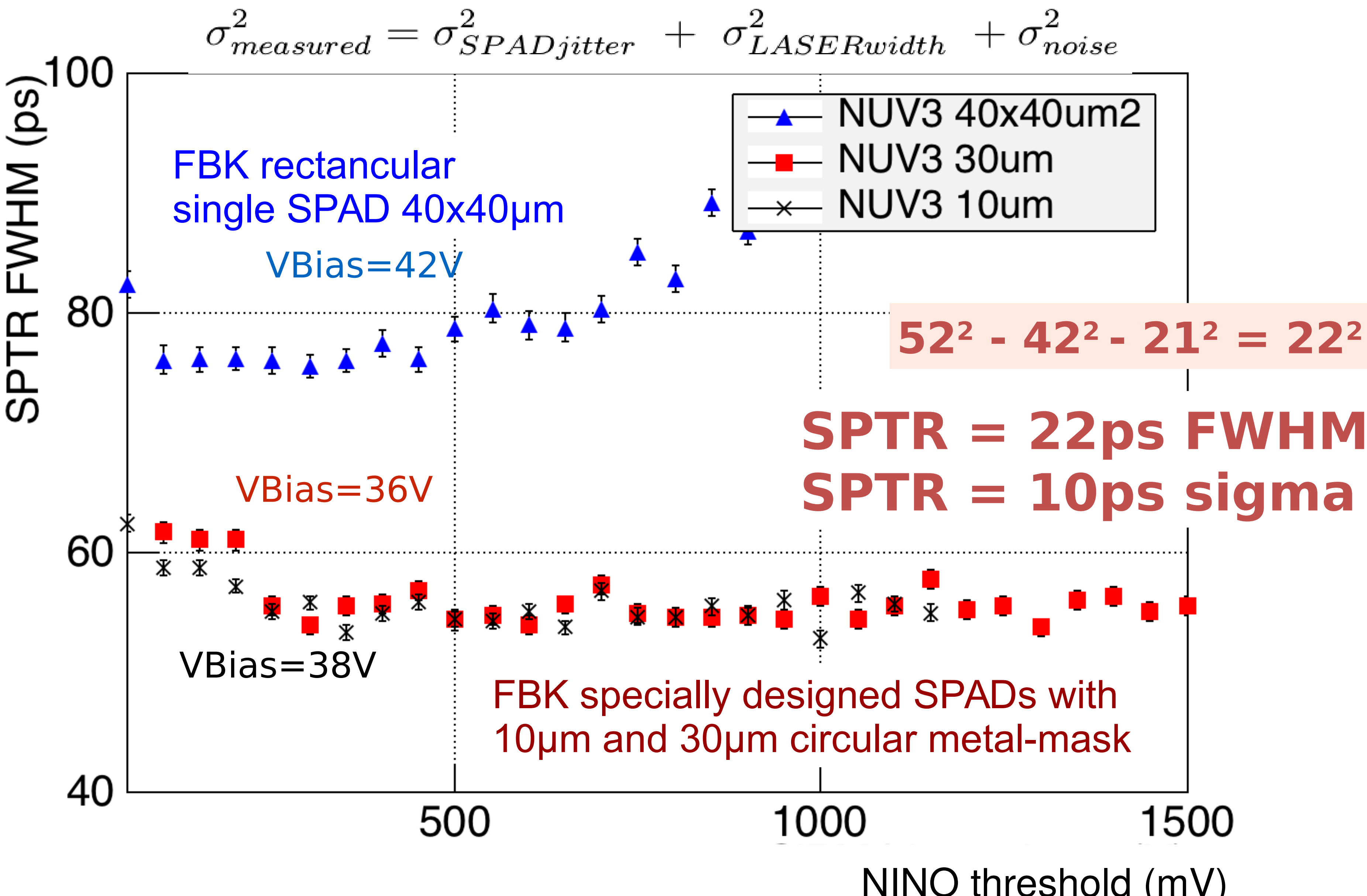
$$\sigma^2_{measured} = \sigma^2_{SPADjitter} + \sigma^2_{LASERwidth} + \sigma^2_{noise}$$



M.V. Nemallapudi et.al, October 2016. JINST 11 P10016

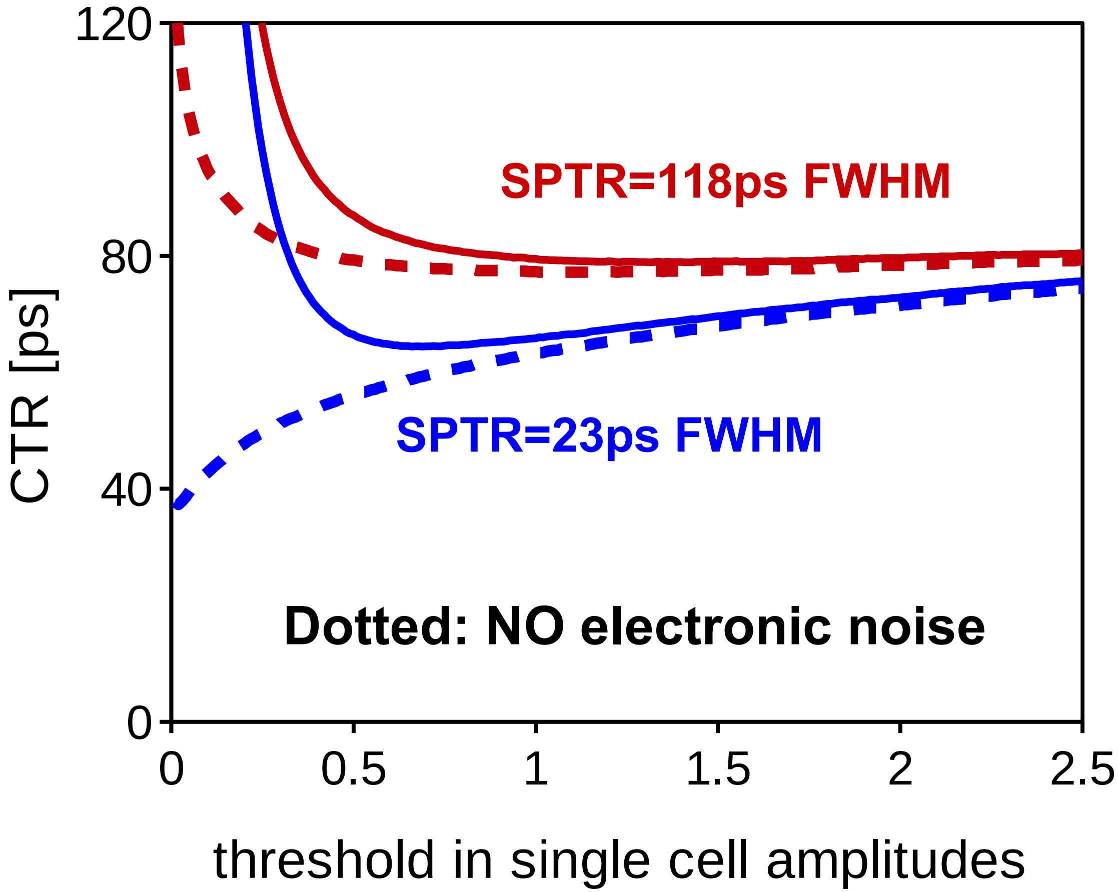
The limits of single SPADs are promising

Single photon level at optimum bias voltage



M.V. Nemallapudi et.al, October 2016. JINST 11 P10016

High SPTR and 30 prompt photons with a-SiPMs



Impact of the electronic noise:

-) **30 prompt photons produced**

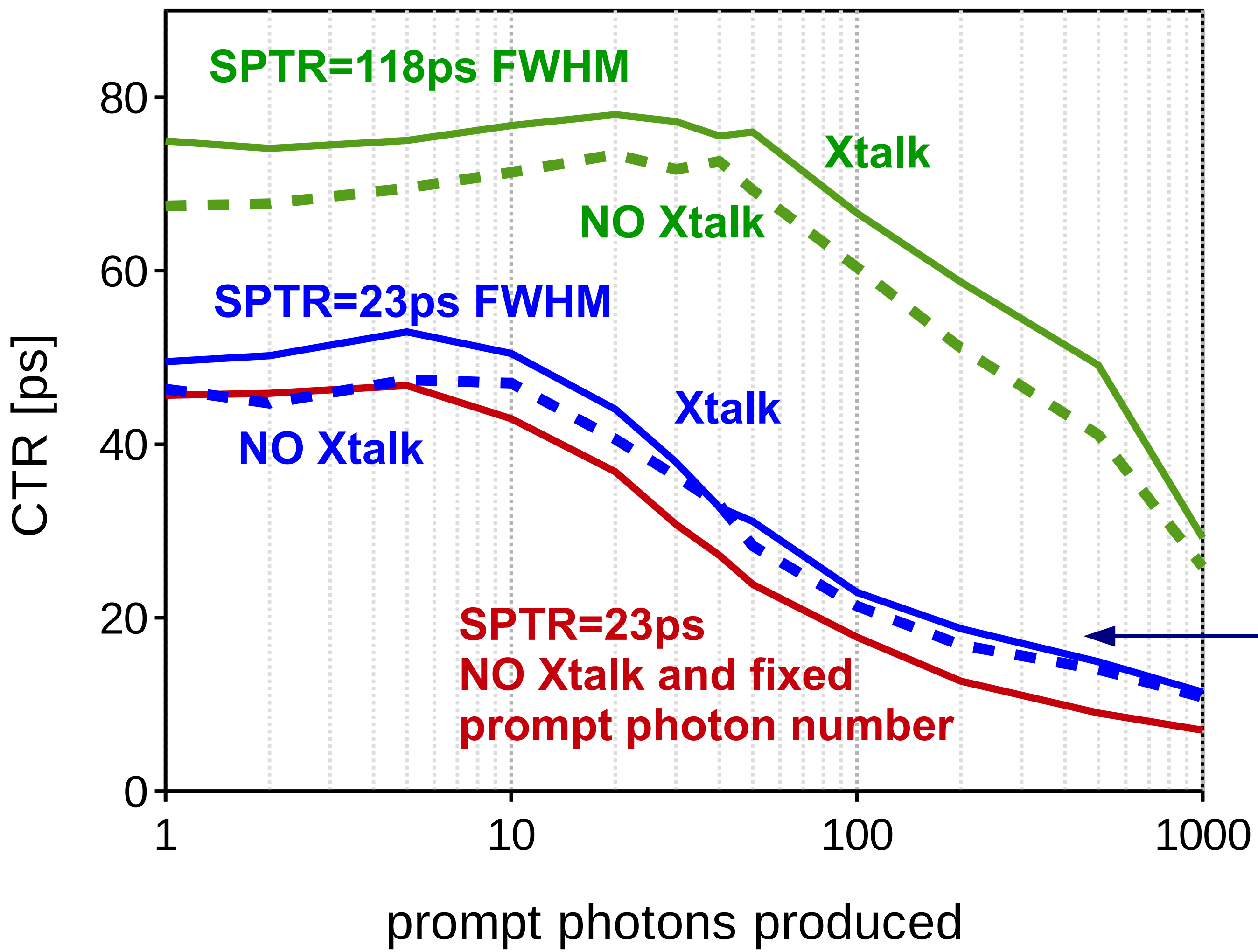
-) full MC simulation of FBK NUV-HD 40µm with scintillator size $2x2x3mm^3$ and, i^{th} crosstalk modeled as Gaussian with:

$$\mu = \mu_0 + SPTR * \sqrt{i}$$

$$\sigma = SPTR * \sqrt{i}$$

Maybe the digital SiPM is the only way to reach these low detection thresholds? Even more because having the time stamp of the first photon seems to be enough.

10ps with a 2x2x3mm³ LSO + prompt photons ?



Promising sources for “prompt” photons are nanocrystal, e.g. CdSe, ZnO. However, the challenges are to build a detector out of it.

Prompt photons are produced with 30% energy resolution on top of Poisson

If the SPTR shows low values (~10ps) and the crosstalk follows this trend, crosstalk seems not to be the limiting factor (for very low detection thresholds)

Conclusions

- Front-end electronics that minimize the influence of electronic noise can make substantial improvements on SPTR for large area, analog SiPMs.

Sensor	NINO (FWHM)	passive comp. (FWHM)	without laser 42ps (FWHM)
single masked SPAD (30μm)	52 ps	-	<30 ps
FBK NUV 40μm SPAD	75 ps	74 ps	61 ps
FBK NUV 1x1mm² (40μm)	94 ps	75 ps	62 ps
FBK NUV 3x3mm² (40μm)	175 ps	100 ps	91 ps
FBK NUV-HD 4x4mm² (40μm)	**113 ps**	**90 ps**	**80 ps**
HPK S13360 3x3mm² (50μm)	220 ps	144 ps	138 ps
SensL J 3x3mm² (35μm)	290 ps	150 ps	144 ps

- For ASIC realization the SiPM could adapt to deliver the proper electronic signal to achieve similar improvements.

Conclusions

- Front-end electronics that minimize the influence of electronic noise can make substantial improvements on SPTR for large area, analog SiPMs.
- Proper field engineering in the SPAD is important, however, when detecting prompt photons with a SiPM as well a bit of PDE can be sacrificed, if it helps to reach highest SPTR (order of 20ps).
- Having a very high SPTR to harness prompt photons shows new challenges:

  => need of very low leading edge thresholds

  => electronic noise and front-end will be (again) the limiting factor

  => digital SiPM?
- 30 prompt photons (already produced now) could be enough to reach a CTR of ~30ps in short 3mm long crystals, if the SPTR is as high as 20ps FWHM.
- If similar values should be reached in longer crystals ~500 prompt photons have to be produced (e.g. in nanocrystals) and the detector design has to be re-invented (e.g. depth-of-interaction correction)

Questions?

S. Gundacker[1,2], J.W. Cates[3],
E. Auffray[1], S. Levin[3] and P. Lecoq[1]

[1]*European Organization for Nuclear Research (CERN) 1211 Geneva 23, Switzerland*
[2]*Università degli Studi di Milano-Bicocca, Piazza della Scienza 3, 20126 Milano, Italy*
[3]*Molecular Imaging Program, Department of Radiology, Stanford University, Stanford, CA, United States*

This work was carried out in the frame of the Cost Action TD1401 (FAST),
the TICAL ERC Grant 338953 and the Crystal Clear Collaboration