Timing properties introduction & summary

S. Gundacker on behalf of the ICASiPM timing group
(F. Acerbi, S. Brunner, S. Dolinsky, T. Ganka, A. Gola, M.V. Nemallapudi, J.F. Pratte, E. Popova, E. Venialgo, S. Vinogradov)

International Conference on the Advancement of Silicon Photomultipliers
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This session is as well in the frame of

Working group 3: Photo detectors

of the COST Action TD1401: FAST

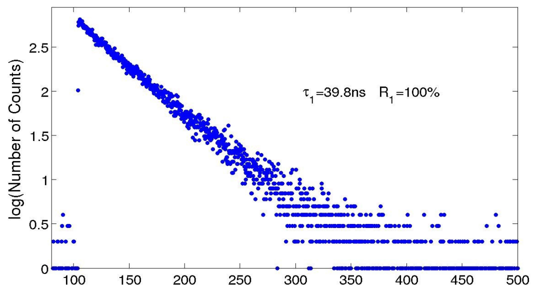
http://fast-cost.web.cern.ch/fast-cost/

Introduction:

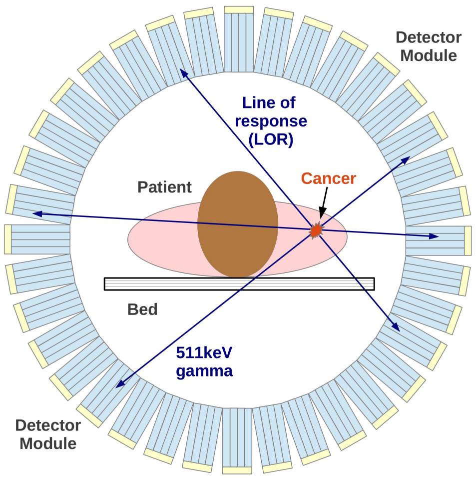
What kind of timing with SiPMs?

Timing application driven motivation

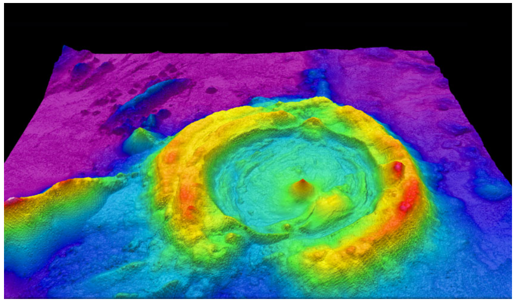
- Single photon detection:
  Time correlated single photon counting (TCSPC) for scintillator research and biomedical applications (fluorescence lifetime imaging) or single shot light detection and ranging (Lidar).



- High photon rate:
  Time resolution of SiPMs when coupled to scintillators for precise time tagging of high energetic particles (1 detected photon every 10ps for LYSO:Ce scintillation light detection).
  → e.g. coincidence time resolution (CTR) in time of flight positron emission tomography (TOF-PET)
  → time resolution in scintillator based high energy physics detectors (e.g. CMS timing layer)



- Few (multi) photon detection: (>1 to 100 detected photons)
  → Cherenkov emission (TOF-PET, RICH),
  → Dark matter search
  → Lidar



LIDAR image

The intrinsic timing property of SiPMs is the response to single photons, i.e. the single photon time resolution (SPTR)

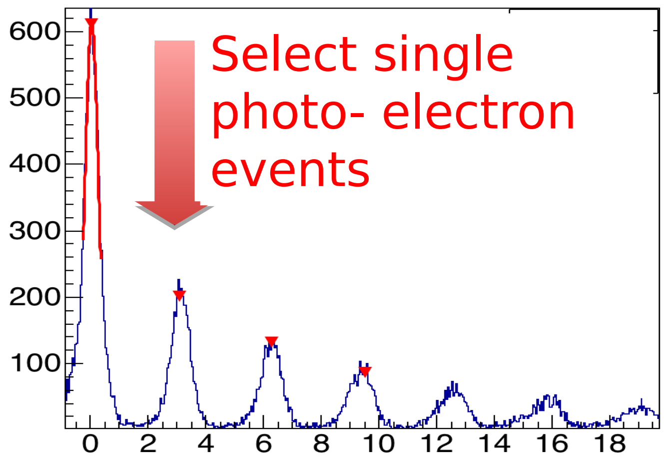
In all timing applications the single photon time resolution (SPTR) of the SiPM plays a crucial role. A proper definition of the SPTR is necessary that values obtained in different research groups and industry can be compared.

SPTR - single photon selection

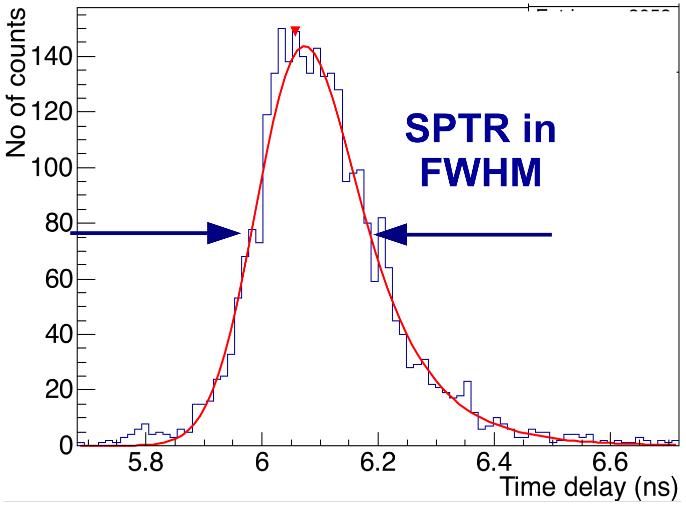
Define the SPTR as an intrinsic photodetector property (analog or digital SiPM) of the whole device (uniform laser illumination – if not stated otherwise), which is inherent to the photodetector and not affected by other SiPM properties, e.g. dark count rate, optical cross-talk, the readout electronics nor laser used. It is a property which by no external means can be improved.

→ SPTR defined for single photoelectron events (make selection):

Single photon spectrum

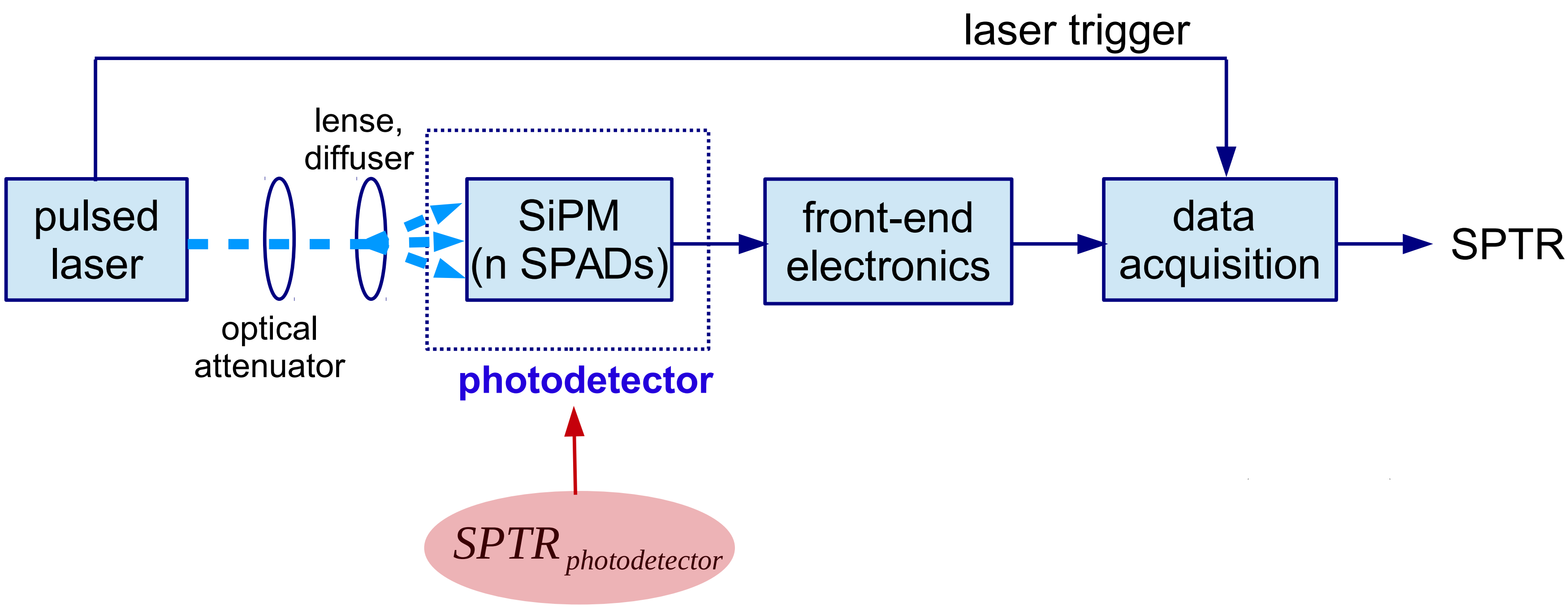


Laser trigger - SiPM delay histogram



SPTR in the analog SiPM

SPTR measurement with analog SiPMs

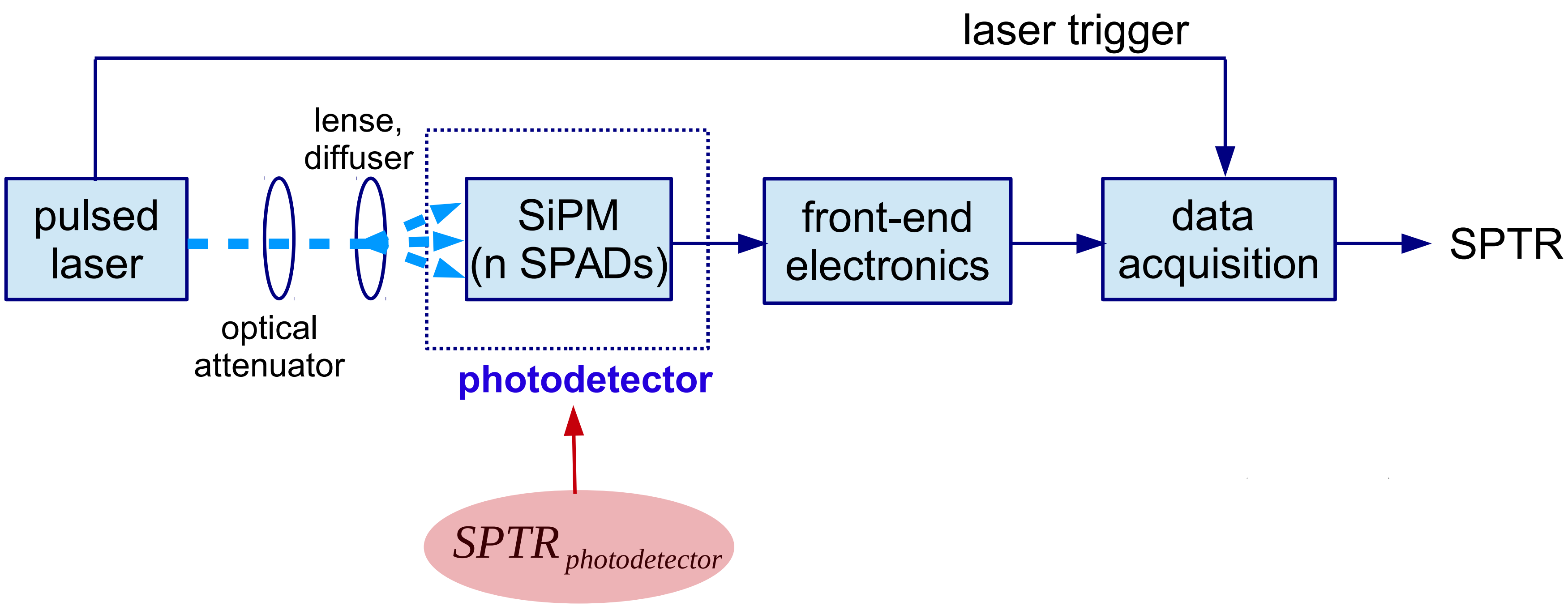


$$SPTR_{photodetector} = SPTR_{aSiPM} = SPTR =$$
$$= single\ SPAD\ time\ resolution \otimes signal\ transfer\ time\ skew \otimes SPAD - SPAD\ variation$$

For analog SiPMs the time resolution of the device is actually what we want to measure.

→ single SPAD time resolution: dependent on bias voltage
→ signal transfer time skew (TTS): dependend on device structure (routing)
→ SPAD-SPAD variation: production process

SPTR measurement with analog SiPMs

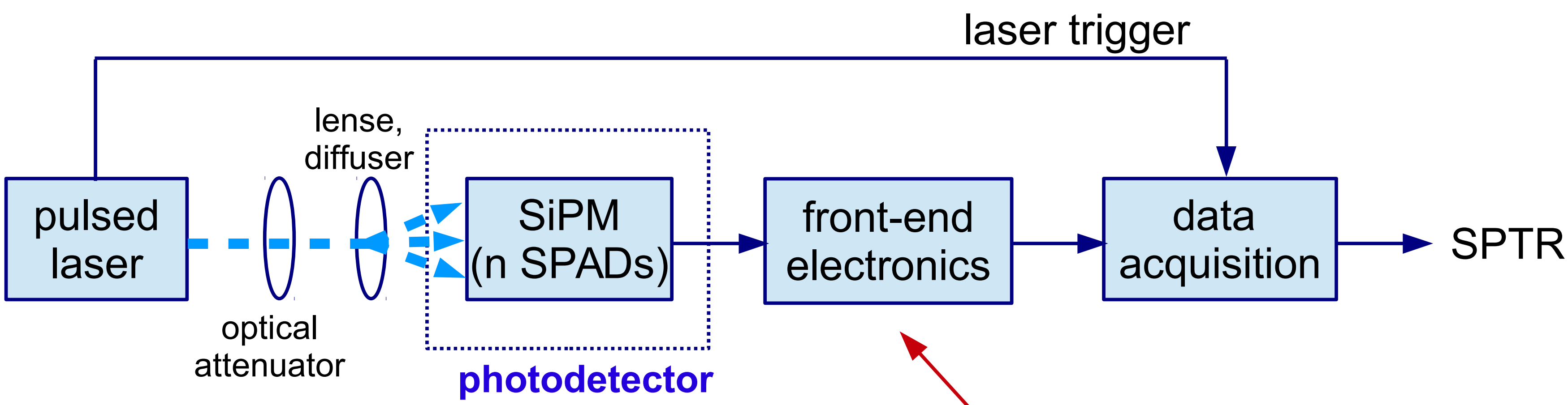


$$SPTR_{photodetector} = SPTR_{aSiPM} = SPTR =$$
$$= single\ SPAD\ time\ resolution \otimes signal\ transfer\ time\ skew \otimes SPAD-SPAD\ variation$$

$$SPTR_{SPAD} = avalanche\, buildup\ jitter \otimes diffusion\, tail \otimes electric\ field\, non-uniformity$$

Depends on SPAD layout, bias voltage, ...
Constitutes the intrinsic limit of the SPTR

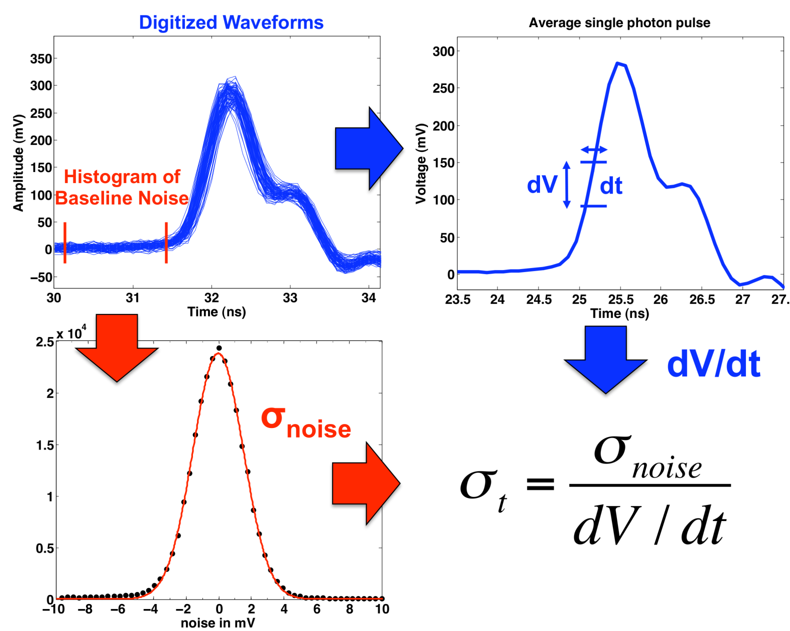
SPTR measurement with analog SiPMs



$$SPTR_{measured} = SPTR_{photodetector} \otimes electronic\ noise\ jitter\left(\frac{\sigma_{noise}}{dV/dt}\right)$$

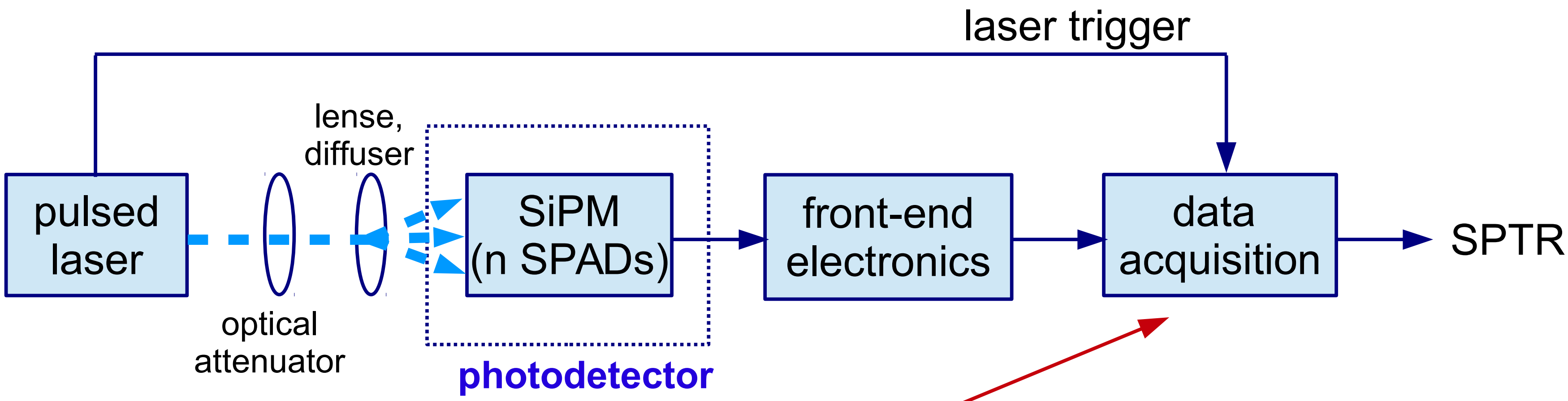
For waveform-sampling this can be estimated directly from the data.

For ASICs, testpulses describing the same shape as the SiPM signal have to be applied (same input capacitance).



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

SPTR measurement with analog SiPMs



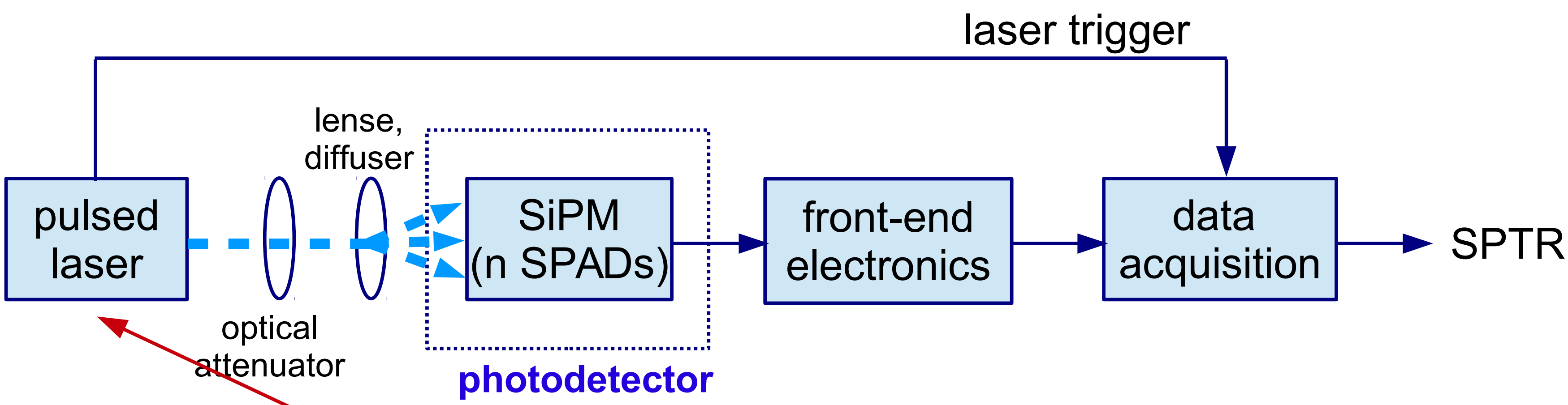
$$SPTR_{measured} = SPTR_{photodetector} \otimes \; electronic\ noise\ jitter\left(\frac{V_{noise}}{dV/dt}\right)$$

$$\otimes \; aquisition\ jitter$$

Data aquisition jitter might be the time resolution of a TDC or ADC. Here as well the TDC and ADC noise on the front-end signal plays a role.

For waveform-sampling this can be estimated from the data.
For ASICs testpulses can be applied (in this case the electronic noise jitter and acquisition jitter might be measured as one quantity).

SPTR measurement with analog SiPMs



$$SPTR_{measured} = SPTR_{photodetector} \otimes electronic\ noise\ jitter\left(\frac{V_{noise}}{dV/dt}\right) \otimes aquisition\ jitter \otimes laser\ pulse\ shape \otimes laser\ trigger\ jitter$$

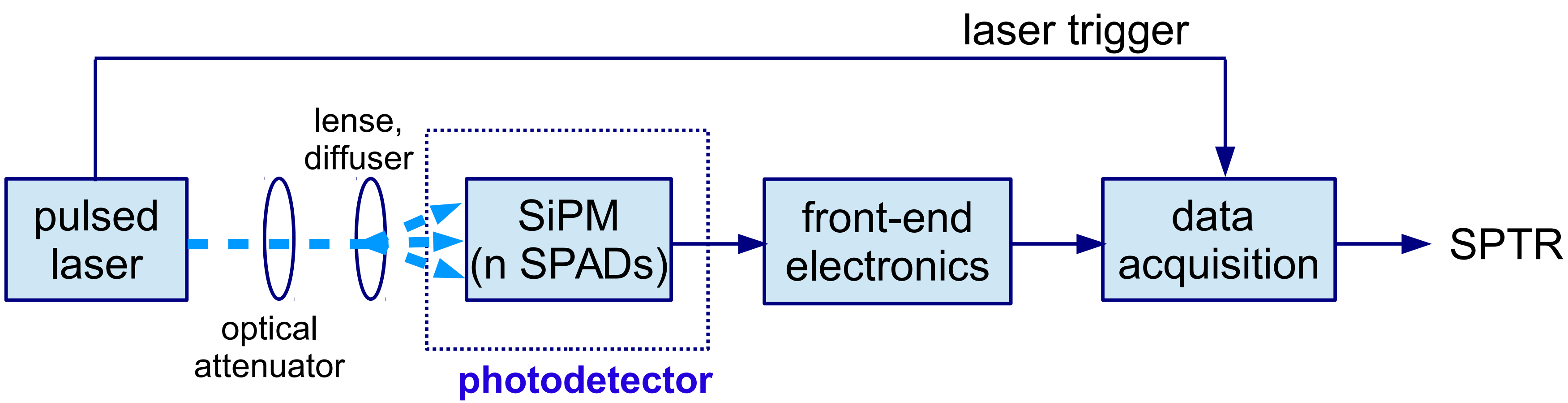
Following quantities have to be stated:

–) Manufacturer (data sheet)

–) Laser single photon pulse width and shape
(measurements with fast single SPADs or Streak Camera)

–) Laser electronic trigger jitter
(splitting the laser light signal can be used as laser trigger with defined jitter)

SPTR measurement with analog SiPMs



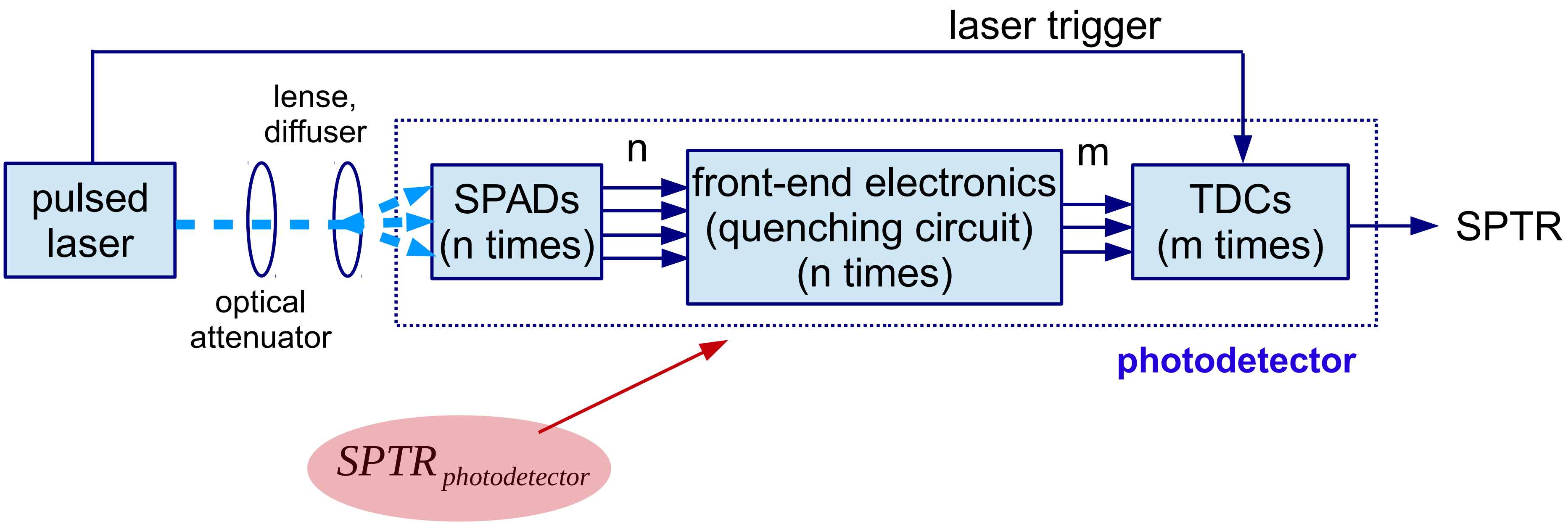
$$SPTR_{measured} = SPTR_{photodetector} \otimes \; electronic \; noise \; jitter\left(\frac{V_{noise}}{dV/dt}\right) \otimes \; aquisition \; jitter \; \otimes \; laser \; pulse \; shape \; \otimes \; laser \; trigger \; jitter$$

Decoupling of electronic noise and acquisition jitter allows the user to employ their own electronics of which they know the performance. The SPTR is the intrinsic time resolution of the SiPM due to physical limitations.

How the setup looks like and how to measure the SPTR more in detail will be discussed by Fabio Acerbi in the talk right after.

SPTR in the digital SiPM

SPTR measurement with <u>digital</u> SiPMs

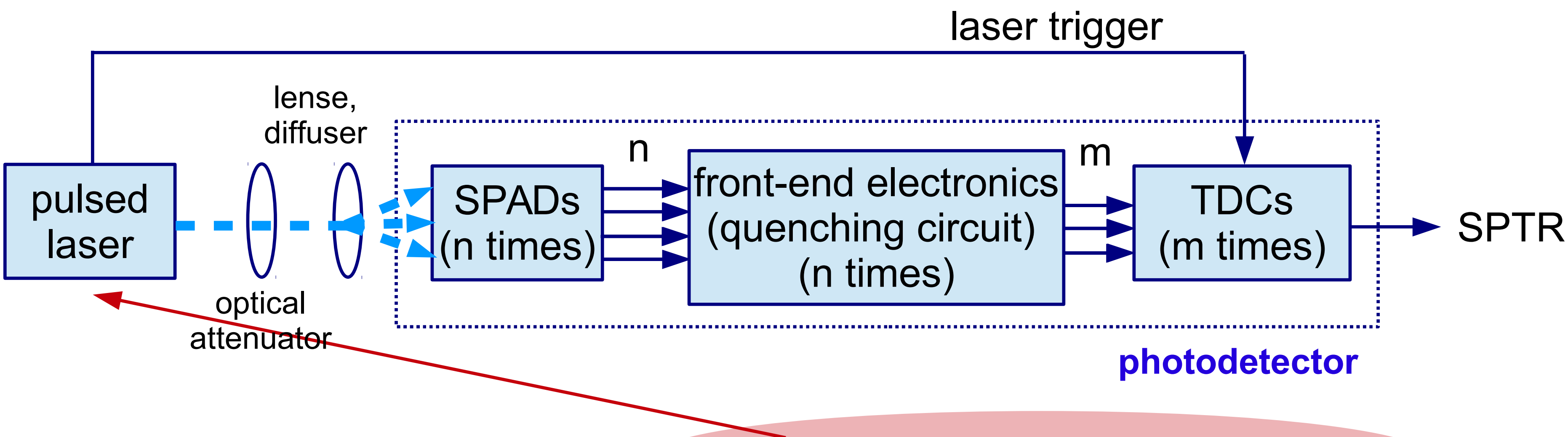


$$SPTR_{photodetector} = SPTR_{dSiPM} = SPTR =$$
$$= SPAD\ time\ resolution \otimes signal\ transfer\ time\ skew \otimes SPAD - SPAD\ variation \otimes front-end\ electronics\ jitter \otimes TDC\ LSB + jitter$$

The front-end electronics (quenching circuit) jitter and TDC LSB+jitter is a property of the detector (inherent). For applications the SPTR is a system value including the readout (although the quenching circuit and TDC LSB+jitter can be measured and stated).

The direct coupling of the front-end (quenching circuit) to the SPAD allows better noise performance. Corrections for signal transfer time skew are principally possible (address has to be known).

SPTR measurement with <u>digital</u> SiPMs



$$SPTR_{measured} = SPTR_{photodetector} \otimes laser\ pulse\ shape \otimes laser\ trigger\ jitter$$

Following quantities have to be stated:

–) Manufacturer (data sheet)

–) Laser single photon pulse width and shape
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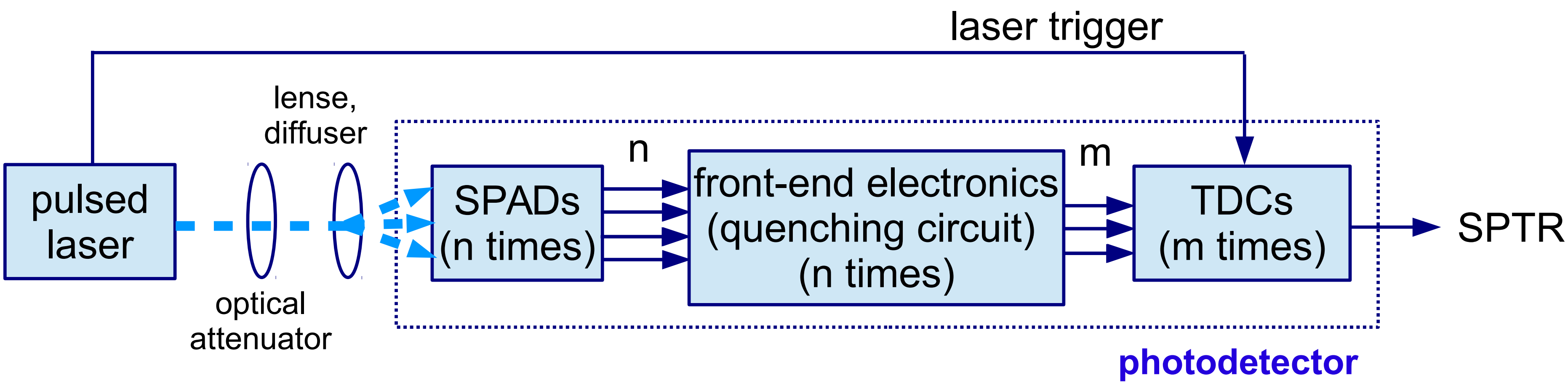
SPTR measurement with digital SiPMs

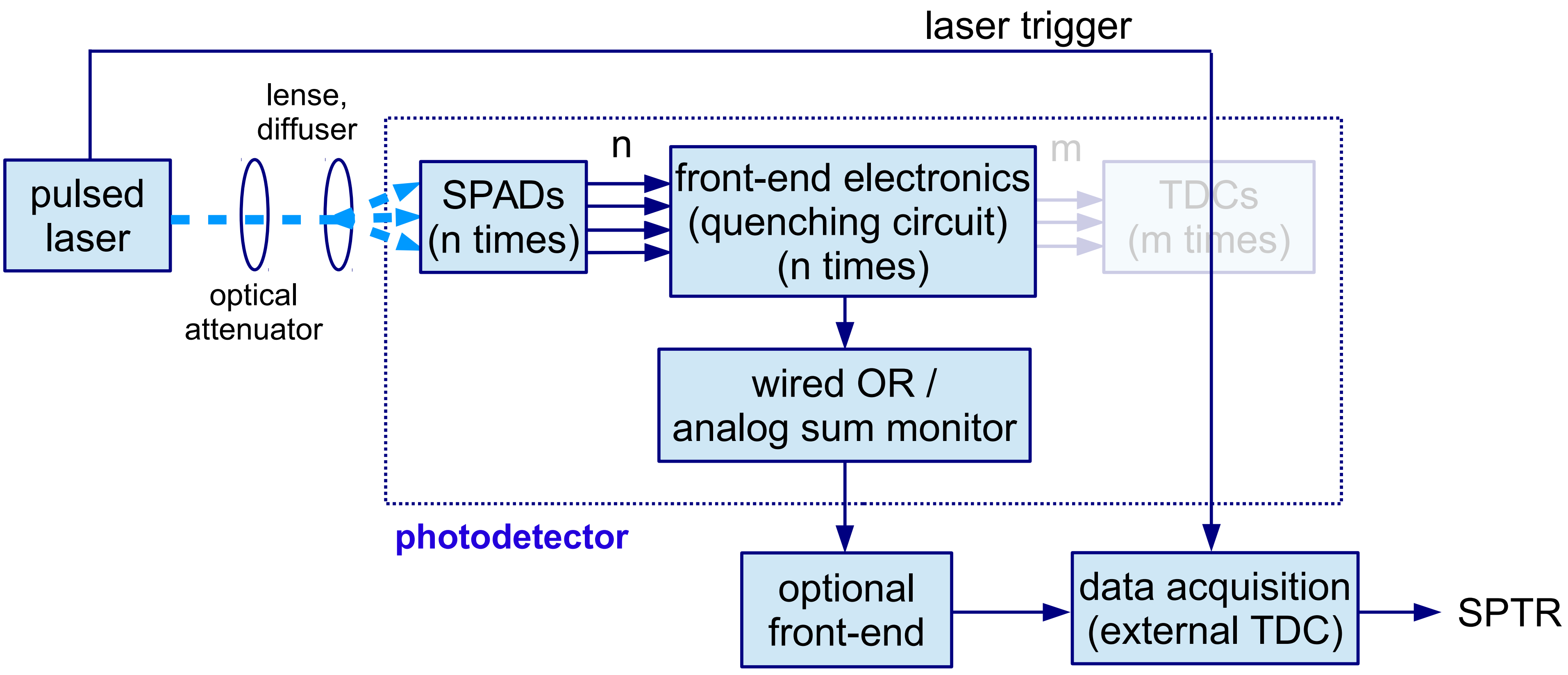


$$SPTR_{measured} = SPTR_{photodetector} \otimes \; laser \;\; pulse \; shape \; \otimes \; laser \; trigger \;\; jitter$$

$$SPTR_{photodetector} = SPTR_{dSiPM} = SPTR =$$
$$= SPAD \;\; time\, resolution \;\; \otimes \;\; signal \; transfer \;\; time \; skew \;\; \otimes \;\; SPAD - SPAD \;\; variation$$
$$\otimes \;\; front - end\, electronics \; jitter \;\; \otimes \;\; TDC \; LSB + jitter$$

- The laser spot uniformity can be checked via imaging in digital SiPMs (if address of SPAD is recorded or by switching on and off SPADs).
- Single SPAD time resolution can be measured by switching off all other SPADs.
- In this way the signal transfer time skew can be measured as well

SPTR measurement with digital SiPMs (options)



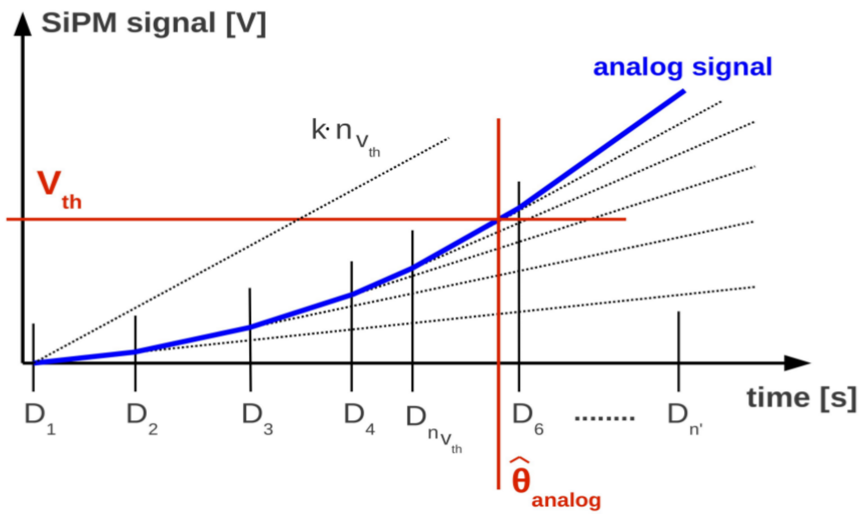
If the TDC in the d-SiPM limits the performance an "analog monitor" summing the quenching circuit outputs or a "wired OR" after the first stage electronics can be implemented or used if available in the layout.

More information about SPTR measurements with digital SiPMs will be given by Esteban Venialgo very soon.

Applications and multi-photon time resolution (MPTR)

SPTR influence on the CTR with analog SiPMs

One example why we have to take care of a proper definition of the SPTR: electronic noise and intrinsic SPTR in analog SiPMs.



Average of the stochastic "true" SPTR with n photons:
(multi photon time resolution)
MPTR ~ SPTR/sqrt(n)

Average of the noise term:
$\sigma_{noise}/(dV/dt) \sim 1/n$
(will diminish rapidly and has small effect for 10 photons averaged as usual in PET with LYSO:Ce)

$$V = \sum_{i=1}^{n'} k\,(t - D_i)\,\Theta(t - D_i) \quad \Rightarrow \quad \widehat{\theta}_{analog} = \frac{V_{th}}{n_{V_{th}} k} + \frac{1}{n_{V_{th}}} \sum_{i=1}^{n_{V_{th}}} D_i$$

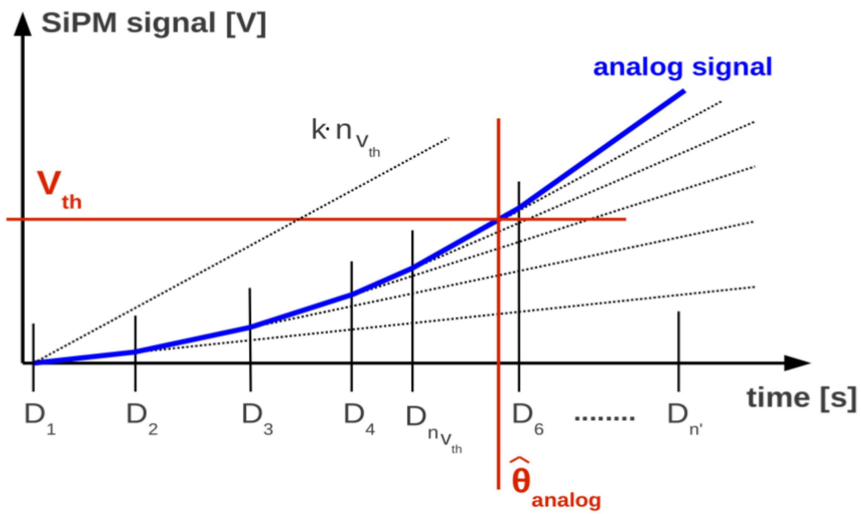
Leading edge discrimination acts like average of first photon times.

If the timing estimator is not averaging, this model can deviate. But electronic noise behaves differently as the stochastic SPTR term for multiple photons in analog SiPMs.

Hence, it is the most useful to quote only the stochastic part of the SPTR as we propose.

SPTR influence on the CTR with analog SiPMs

One example why we have to take care of a proper definition of the SPTR: electronic noise and intrinsic SPTR in analog SiPMs.



Average of the stochastic "true" SPTR with n photons: (multi photon time resolution) MPTR ~ SPTR/sqrt(n)

Average of the noise term: $\sigma_{noise}/(dV/dt) \sim 1/n$ (will diminish rapidly and has small effect for 10 photons detected as usual in PET with LYSO:Ce)

That electronic noise becomes negligible compared to the stochastic SPTR term if averaging many photons can allow to use the multi photon time resolution (MPTR) to estimate the SPTR (as we defined, without electronic noise).

More information on how to do that with a look on multi photon applicatons will be given by Elena Popova later.

Summary:

List of materials and methods of SPTR measurements with some recommendations to be discussed

Materials and methods of SPTR measurements

- Optical (laser) part
- SiPM part
- Front-end electronics + data acquisition

  (analog and digital SiPMs have to be considerated separate)
- Data analysis

Optical part of the SPTR setup (analog and digital SiPM)

- **These parameters should be stated:**
  1) Laser emission wavelength (PET ~400nm, Lidar ~800nm)
  2) Laser pulse width + shape (may be dependent on laser intensity)

- **These parameters have to be checked:**
  1) Secondary emission pulses of the laser (dependent on intensity)
  2) Electronic laser trigger jitter should be negligible or at least measured and stated and/or removed quadratically.
  3) Attenuators, diffusers, lenses should not introduce reflections. If a second peak in the delay histogram does not change with varying SiPM overvoltage, reflections in the setup can be assumed.
  4) Optical fibers should be multi-mode with graded index or single-mode.

Practical advice if laser pulse shape is dependent on intensity regulation: High laser intenstiy leading to narrow laser pulse but secondary peak can be used to measure the SPTR FWHM. Low laser intensity without secondary peak can be used to measure long tails of the SPTR.

Photodetector part of the SPTR setup (analog and digital SiPM)

- **These parameters should be stated:**
  1) Generally the SPTR should state the intrinsic time resolution of the full photodetector and, hence, the SiPM should be illuminated uniformly. If focused light SPTR measurements are performed to determine the transit time skew the spot size and shape used should be stated.
  2) The bias overvoltage has to be stated (for analog and digital SiPM)
  3) For the analog SiPM the used leading edge threshold should be given.
  4) Temperature and breakdown voltage should be given.

- **These parameters have to be checked:**
  1) Select only to one photon detected in the analysis (no crosstalk)
  2) For single SPADs double photon detection should be negligible (1 photon detection out of 20 triggers - gives 2.5% detection of double photons)

Front-end and data acquisition (analog SiPM)

- **These parameters should be stated:**

  1) The electronic noise of the front-end electronics plus the data acquisition jitter of the digitization (ADC, TDC):

     --) In the case of waveform sampling that contribution can be calculated from the data ($\sigma_{noise}/(dV/dt)$).

     --) For ASICs a test-pulse measurement should be provided. This can be done by applying a test pulse which leads to the same single photon pulse height as in the real measurement when the same capacitance is seen by the electronics as for the SiPM case.

- **These parameters have to be checked:**

  1) High speed (large slew rate, dV/dt) amplifiers, proper (as high as the rising slope of the SiPM output signal implies) bandwidth amplifiers, using short trace lengths and low input impedance is recommended.

  2) Baseline shifts should be taken care off (e.g. high-pass filtering, pole-zero compensation, offline baseline substraction, ...)

Electronics and data acquisition (digital SiPM)

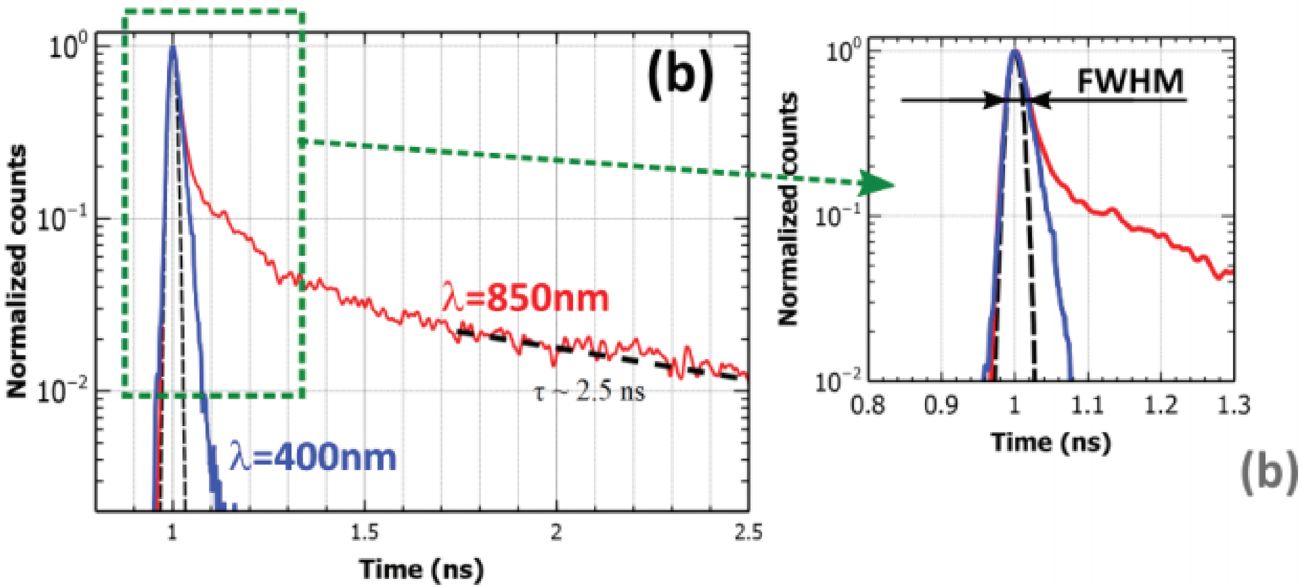
- **These parameters should be stated:**

1) TDC DNL and INL (state if the DNL and INL were corrected for)
2) TDC LSB and jitter
3) Block diagram of the front-end and digital signal processing if implemented
4) State if the signal time transfer skew is corrected
5) Optional: Front-end to digitization jitter (measureable with an input voltage step function of $V_{overvoltage}$ height)
6) All bias voltages (SiPM, electronic supply) if they have influence on the SPTR

- **These parameters have to be checked:**

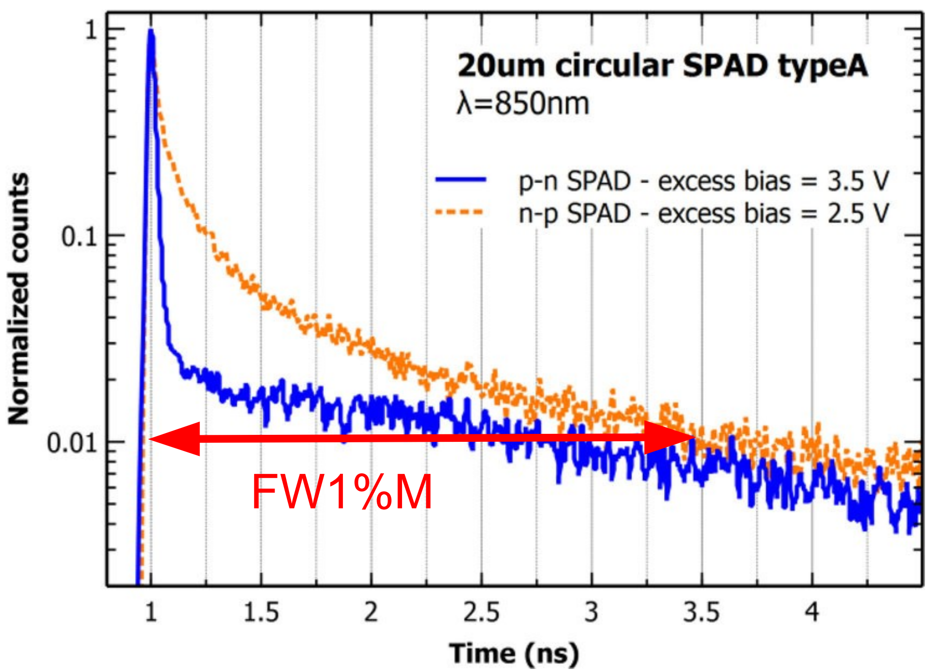
1) TDC calibration correction (LSB has to be correct)

Data analysis (analog and digital SiPM)



Especially for applications where infrared light is detected tails are important (Lidar)

Normally less problematic for wavelengths around 400nm.



p on n FBK SPADs show as well higher tails for infrared light compared to n on p SPADs.

In this case long tails, which might be important for some applications, can be given via the full width tenth maximum (FWTM or FW10%M) and full width hundreds maximum (FW1%M) in addition to the SPTR in FWHM.

Data analysis (analog and digital SiPM)

The SPTR can be stated as the full width at half maximum (FWHM) of the distribution (preferably extracted numerically from a fit in order to minimize binning errors).

We propose a function obtained by the convolution of a Gaussian and two exponential decays (light conversion/absorption and diffusion tail) with the respective relative intensities (a) and (1-a) for the fit:

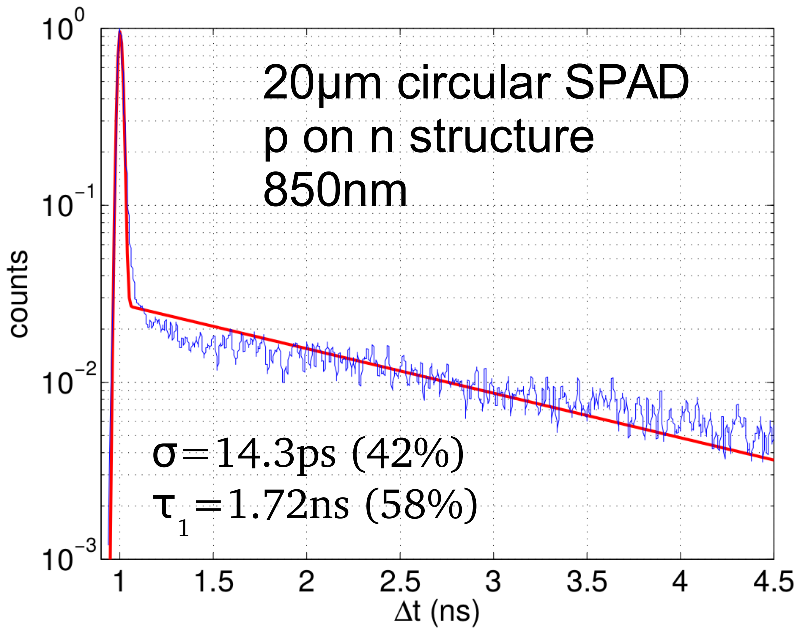
$$f_{SPTR}(t;\mu,\sigma,\tau_1,a,\tau_2) = \frac{1}{\sqrt{2\pi\sigma^2}}\, e^{-\frac{(t-\mu)^2}{2\sigma^2}} \circledast \left(\frac{a}{\tau_1}\, e^{-t/\tau_1} + \frac{1-a}{\tau_2}\, e^{-t/\tau_2}\right) \Theta(t)$$

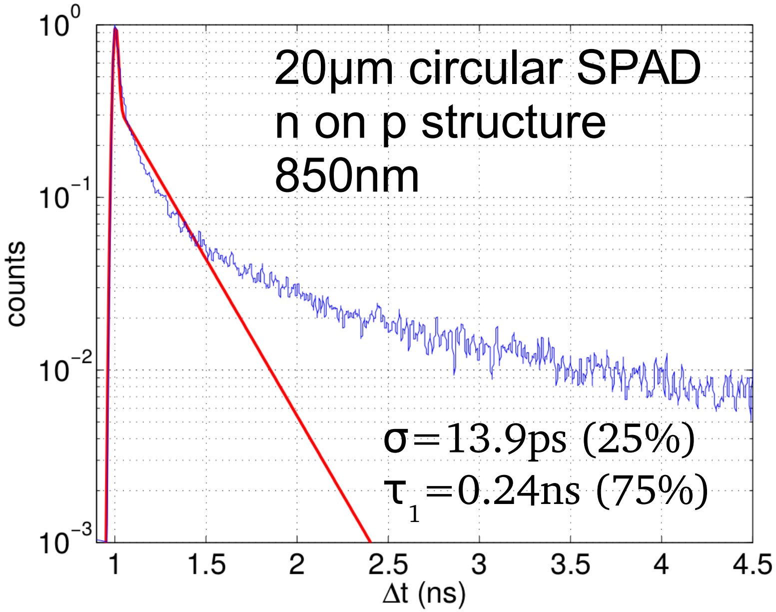
In the limit $\tau_1 \rightarrow 0$ this equation becomes: (assumes only one tail component)

$$f_{SPTR}(t;\mu,\sigma,a,\tau_2) \simeq \frac{a}{\sqrt{2\pi\sigma^2}}\, e^{-\frac{(t-\mu)^2}{2\sigma^2}} + \frac{1-a}{2\tau_2}\, e^{\frac{2\mu+\sigma^2/\tau_2-2t}{2\tau_2}} \left(1 - erf\left[\frac{\mu+\sigma^2/\tau_2 - t}{\sigma\sqrt{2}}\right]\right)$$

For the various applications different functions may apply and can be used. The goodness of the used fit function should be demonstrated and the extracted quantities have to be well defined.

Data analysis

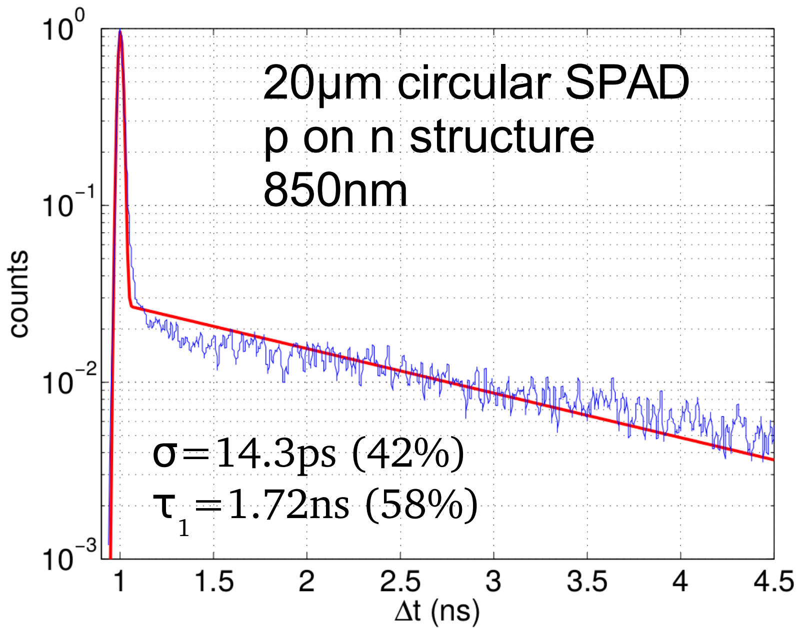


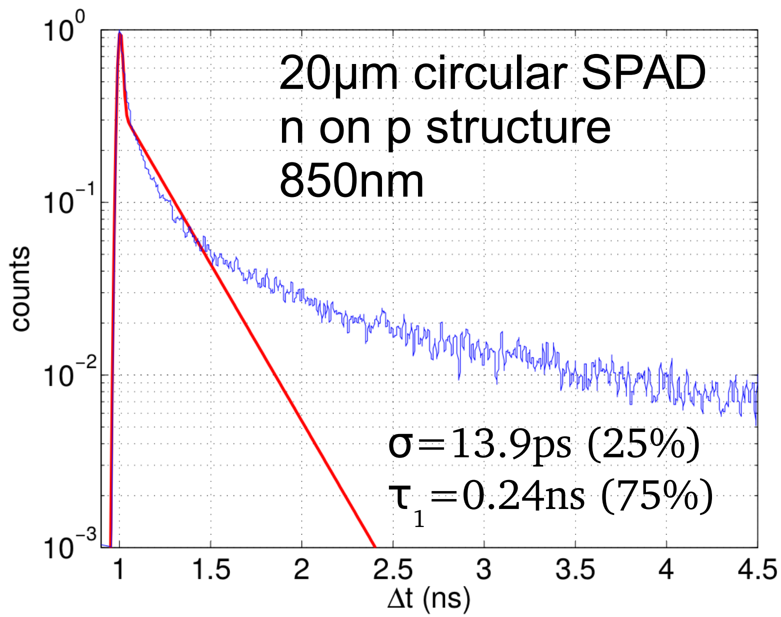


$$f_{SPTR}(t;\mu,\sigma,a,\tau_2) \simeq \frac{a}{\sqrt{2\pi\sigma^2}}\, e^{-\frac{(t-\mu)^2}{2\sigma^2}} + \frac{1-a}{2\tau_2}\, e^{\frac{2\mu+\sigma^2/\tau_2-2t}{2\tau_2}} \left(1 - erf\left[\frac{\mu+\sigma^2/\tau_2-t}{\sigma\sqrt{2}}\right]\right)$$

For example the fit function shown above (accounting only for a possible diffusion tail) can sufficiently well describe the long tail for p on n SPADs illuminated with 850nm, but is less effective for n on p SPADs.

Data analysis (special cases)





Furthermore, the interpretation of these fit parameters is not easy nor straigth forward.

Therefore, in addition to stating the SPTR in FWHM the FWTM and/or FW1%M in order to characterize long tails can be given. The fit should be used to extract these values.

Alternatively tails could be described in terms of quantiles, e.g. time of detecting 95% of photons minus time of detecting 5% of photons. In any case the quantile and method has to be stated. Attention: for this method the normalization and measurement of the full tail is important! --> a full fit to the data can provide that information.

Discussion

S. Gundacker on behalf of the ICASiPM timing group
(F. Acerbi, S. Brunner, S. Dolinsky, T. Ganka, A. Gola, M.V. Nemallapudi, J.F. Pratte, E. Popova, E. Venialgo, S. Vinogradov)

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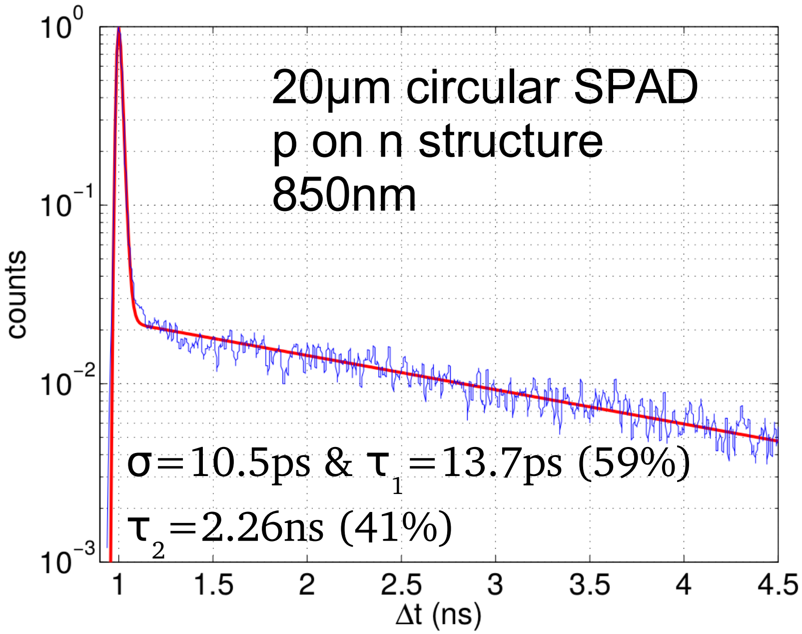
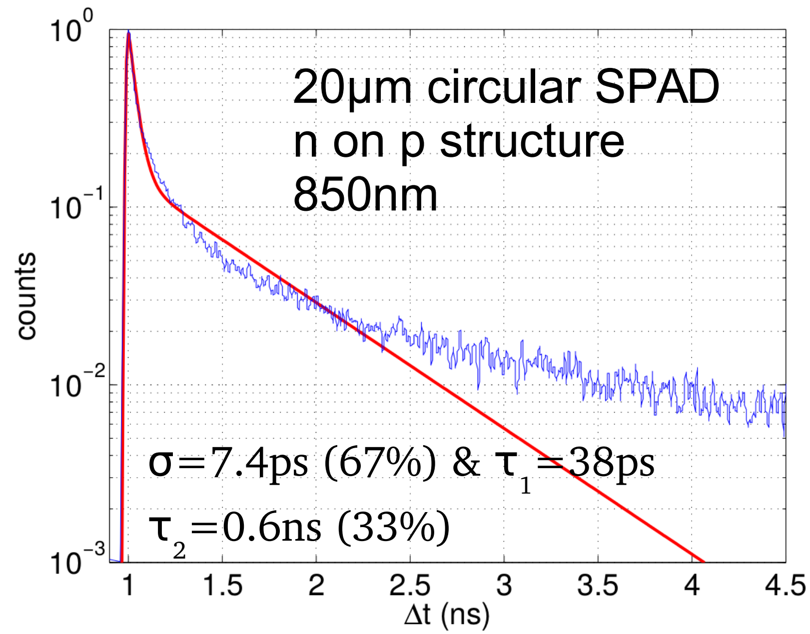
Backup slides

Data analysis (special cases)

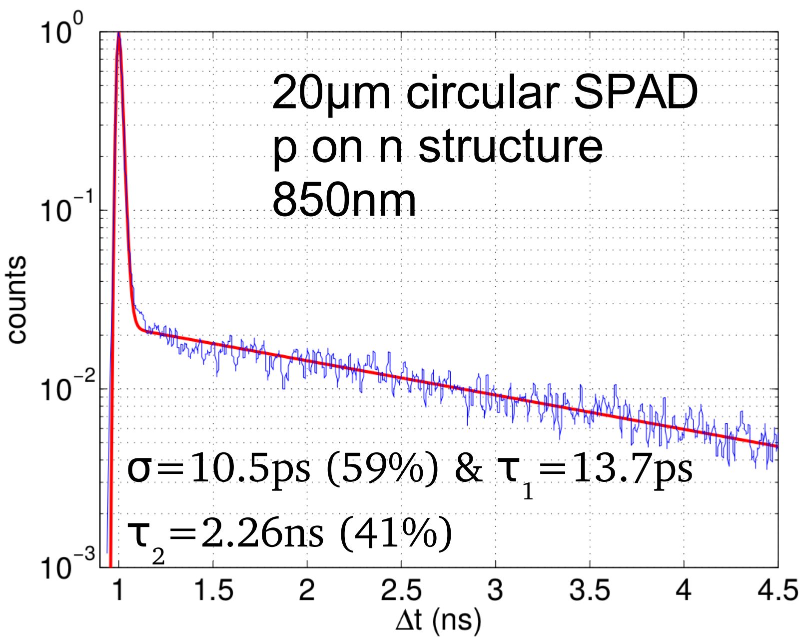


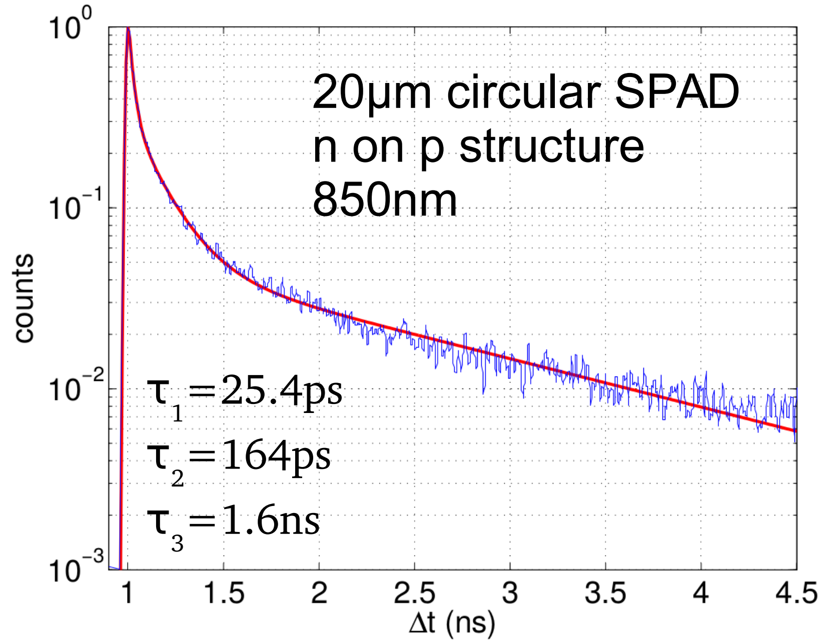


$$f_{SPTR}(t;\mu,\sigma,a,\tau_2) = \frac{a}{2\tau_1}\, e^{\frac{2\mu+\sigma^2/\tau_1-2t}{2\tau_1}} \left(1 - erf\left[\frac{\mu+\sigma^2/\tau_1 - t}{\sigma\sqrt{2}}\right]\right) + \frac{1-a}{2\tau_2}\, e^{\frac{2\mu+\sigma^2/\tau_2-2t}{2\tau_2}} \left(1 - erf\left[\frac{\mu+\sigma^2/\tau_2 - t}{\sigma\sqrt{2}}\right]\right)$$

Extending the fit function to contain two decays (one describing the light conversion and one diffusion) the measured time delay histogram for p on n SPADs illuminated with 850nm is perfectly described, but still not for n on p SPADs.

Data analysis (special cases)





Finally three decays describe as well the measured SPTR for n on p SPADs illuminated with 850nm. However, the interpretation of these fit parameters is not easy nor straigth forward.

Therefore, in addition to stating the SPTR in FWHM, we propose to use FWTM and/or FW1%M in order to characterize long tails. The fit should be used to extract these values.

Alternatively tails could be described in terms of quantiles, e.g. time of detecting 95% of photons minus time of detecting 5% of photons. In any case the quantile and method has to be stated. Attention: for this method the normalization and measurement of the full tail is important!