Algorithms for timing measurements using a fast sampling device

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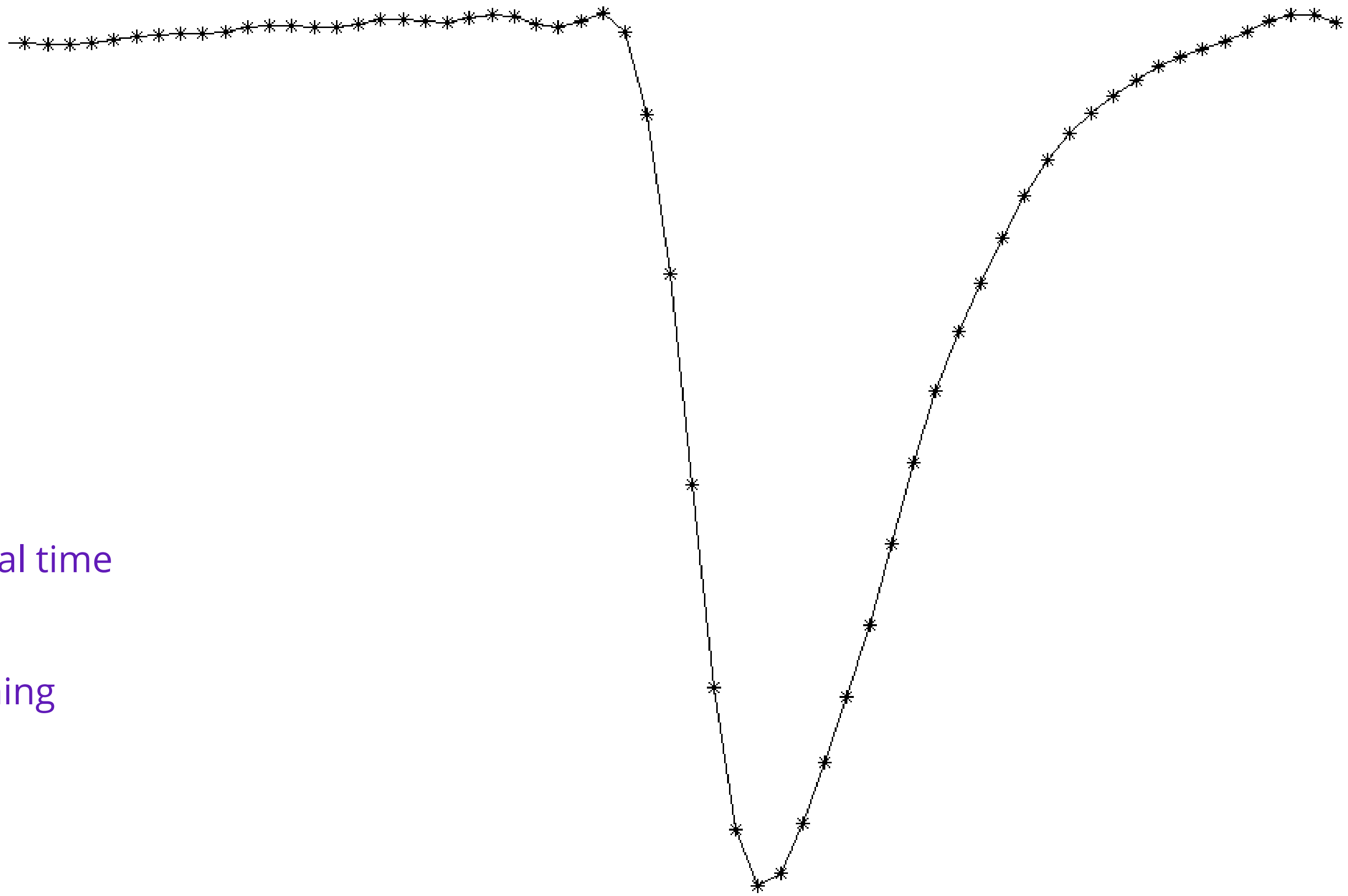
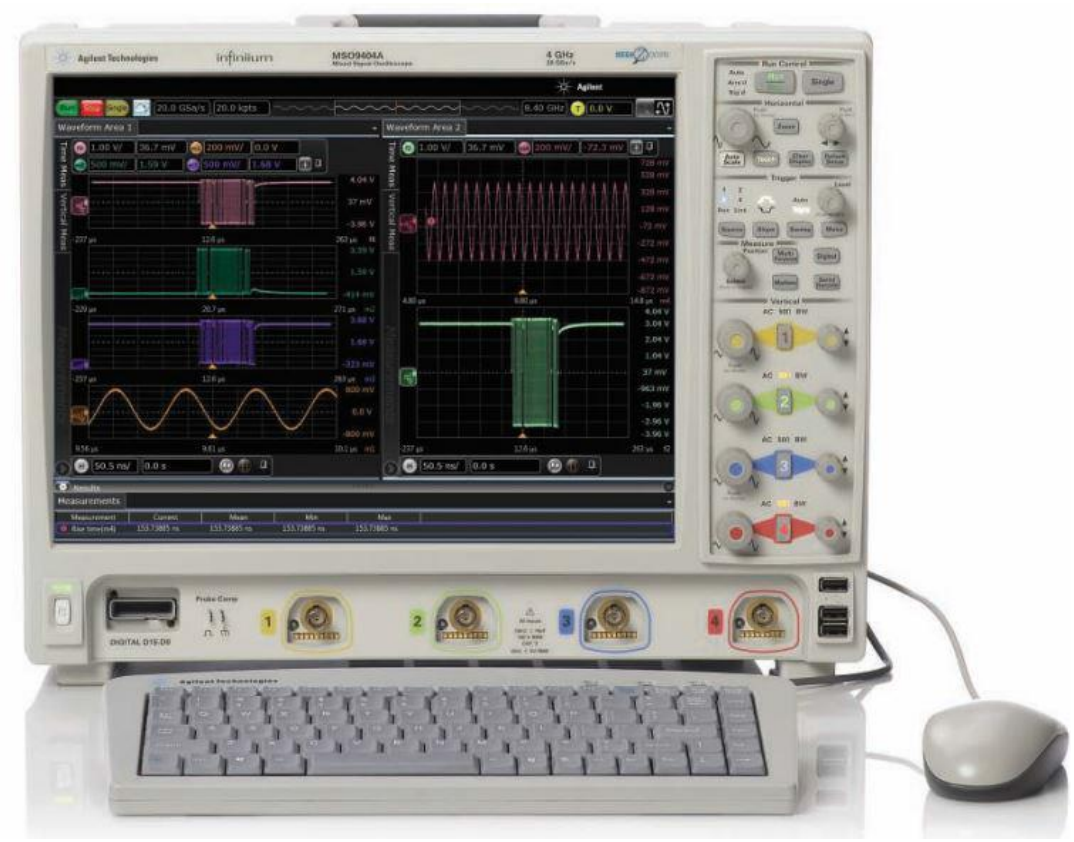
Outline



- Why sampling?
- How sampling?
- Measurement of the arrival time
- Off-line algorithms for timing

Why sampling?

A sampled signal contains all the information needed for a precise measurement and to debug the system.



A Digital Storage Oscilloscope (DSO) is the most common example of a sampling device.

The signal is sampled and digitized and then it is available for any digital analysis.

According to the performance of the device, the information lost (the noise added) can be negligible.

Pros

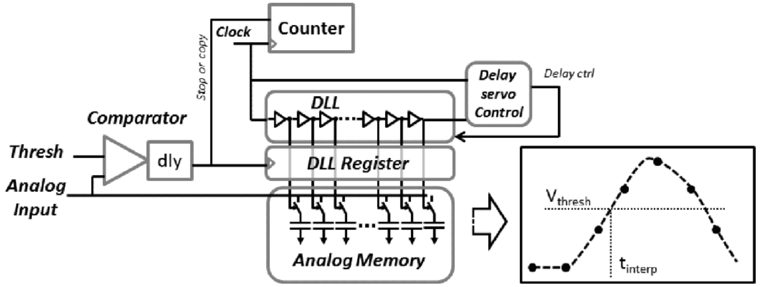
- *Infinite* analysis possibilities
- Digital elaboration (Moore's law)

Cons

- High cost
- Requires computing power
- Usually slow and bulky devices

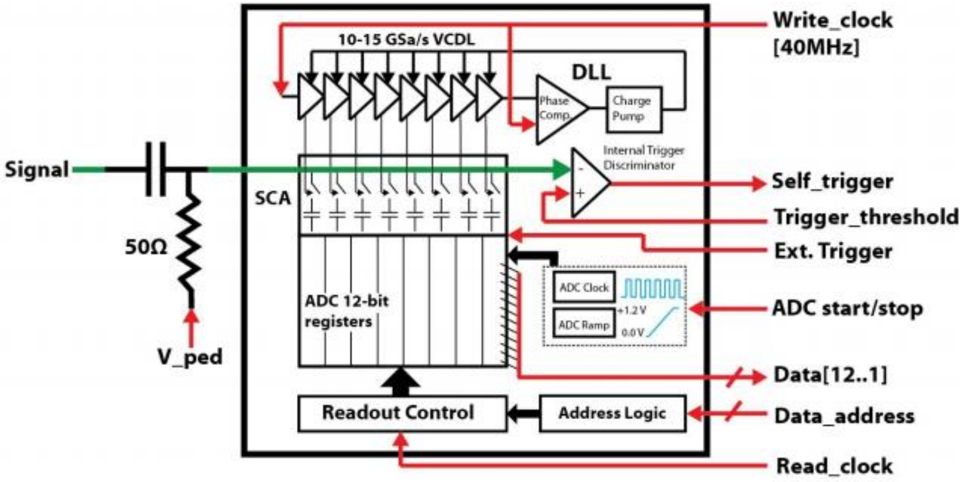
How sampling?

It is useful to analyse the simplest possible case: a diamond detector read using a simple resistor.



A 10 GSa/s, 1.6 GHz Bandwidth, ~10$ per channel

arXiv:1604.02385



A 15 GSa/s, 1.5 GHz Bandwidth Waveform Digitizing ASIC

arXiv:1309.4397

Measuring the arrival time

The main contributions to the error on the time measurements are jitter and time walk.

$$\sigma_t^2 = \sigma_{jitter}^2 + \sigma_{walk}^2 + \sigma_{drift}^2$$

Contribution of the noise:

$$\sigma_{jitter} \sim \frac{\sigma_V}{dV/dt} \sim 1.25\,\frac{\Delta t_{0.1-0.9}}{SNR}$$

OPTIMIZATION OF THE DETECTOR
AND OF THE READ-OUT ELECTRONICS

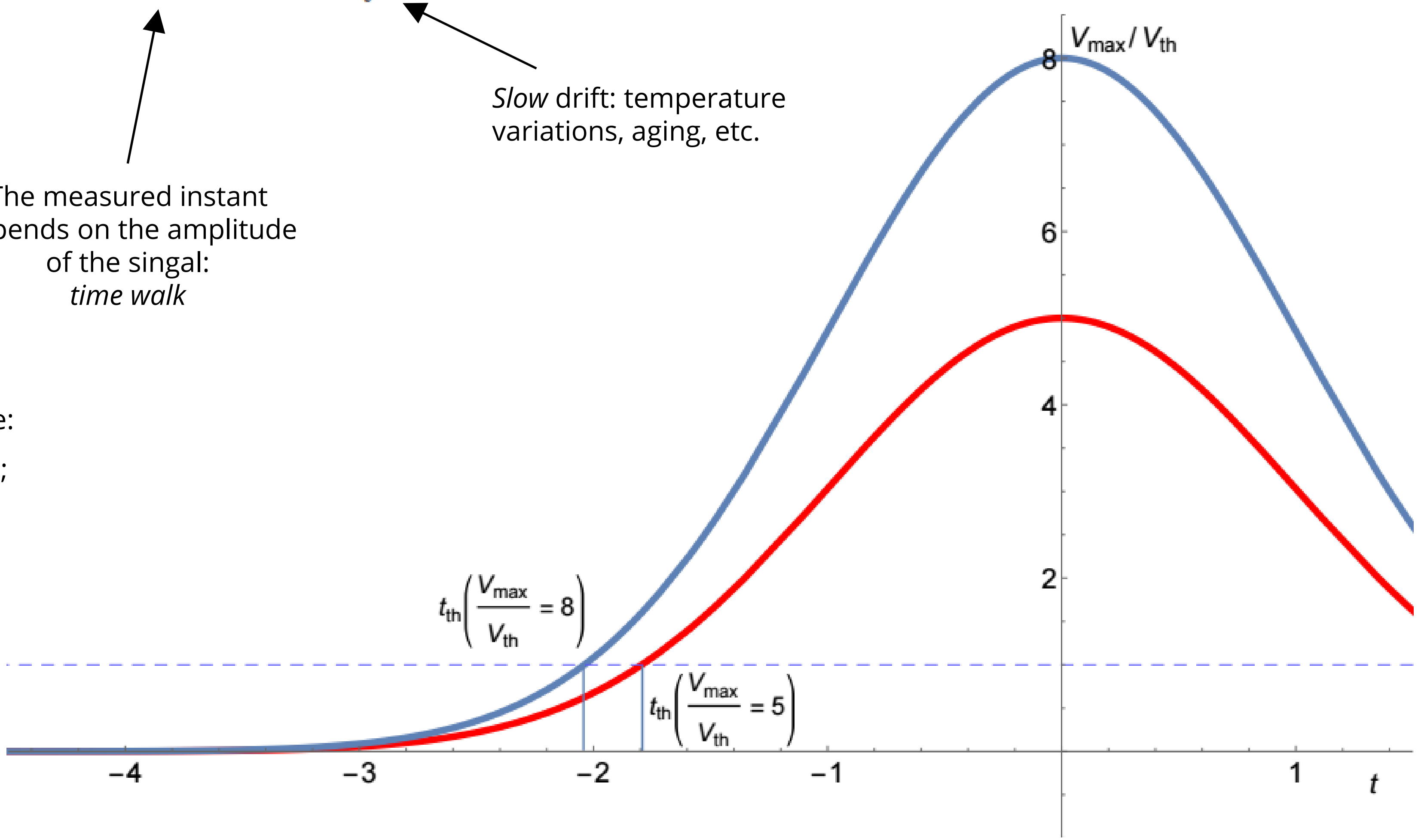
The measured instant depends on the amplitude of the singal: *time walk*

Slow drift: temperature variations, aging, etc.

The main tecniques to correct *time walk* are:

- Costant Fraction Discriminator (CFD);
- Time over Threshold (ToT);
- Cross-Correlation (CC).

OPTIMIZATION OF THE CORRECTION ALGORITHMS



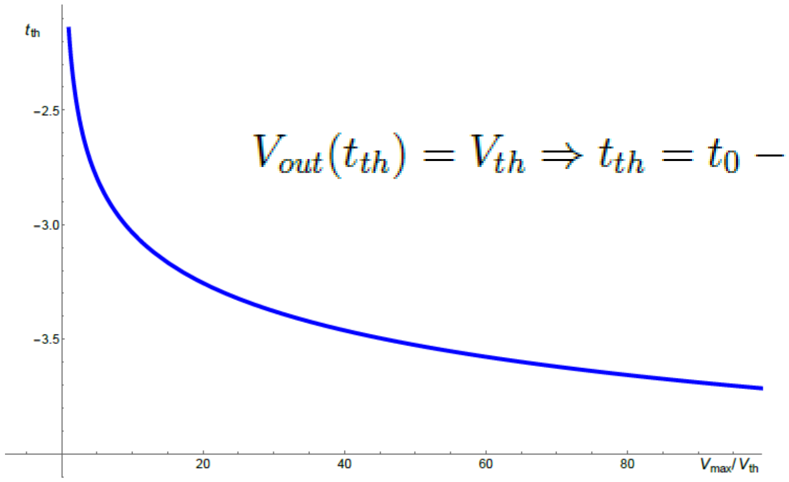
Gaussian pulse

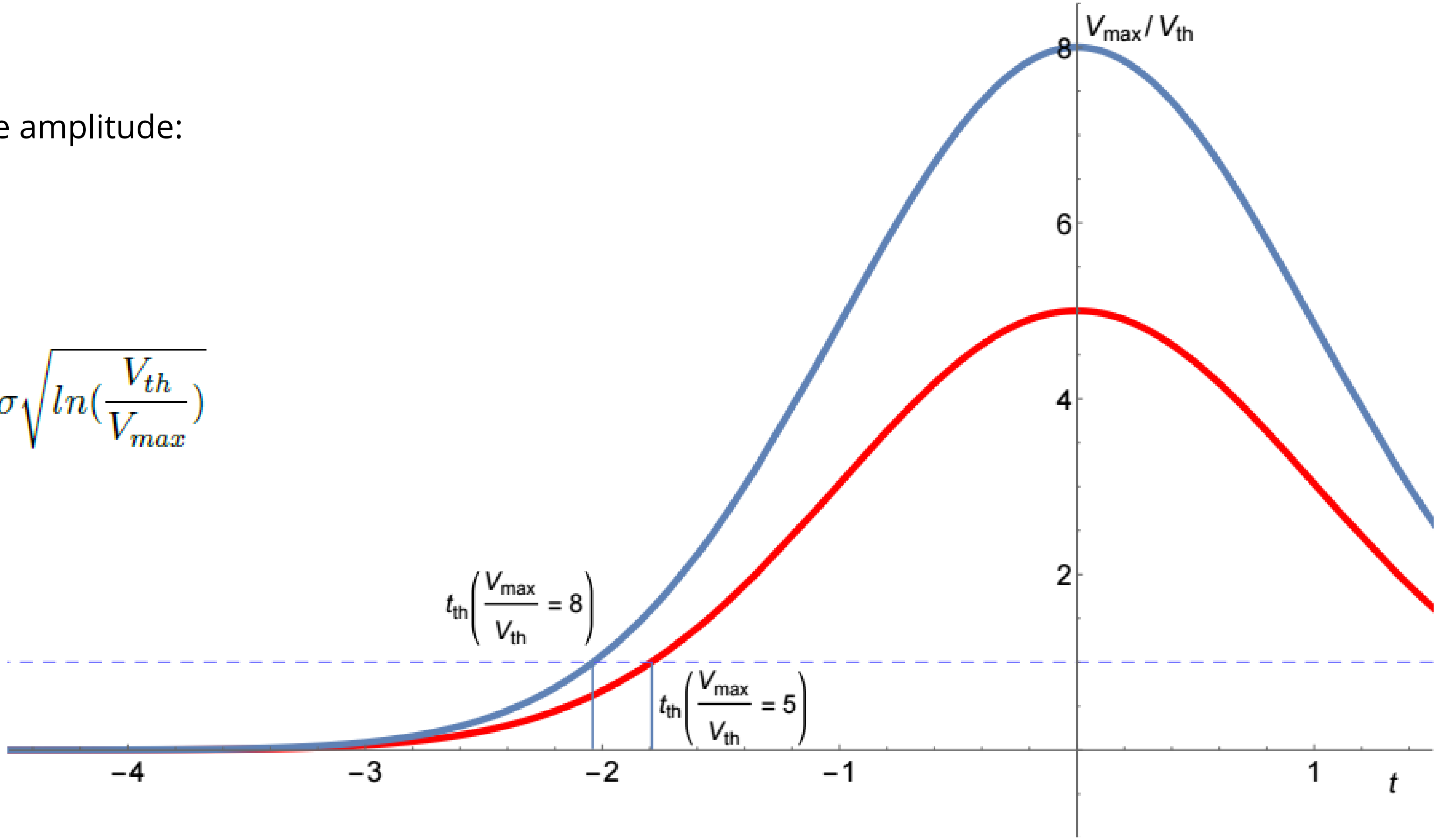
A Gaussian is a good starting point to study different algorithms

$$V_{out}(t) = V_{max}\, e^{-\frac{(t-t_0)^2}{2\sigma^2}}$$

The time of threshold crossing depends on the amplitude:

$$V_{out}(t_{th}) = V_{th} \Rightarrow t_{th} = t_0 - 2\sigma\sqrt{ln(\frac{V_{th}}{V_{max}})}$$





Constant Fraction Discriminator

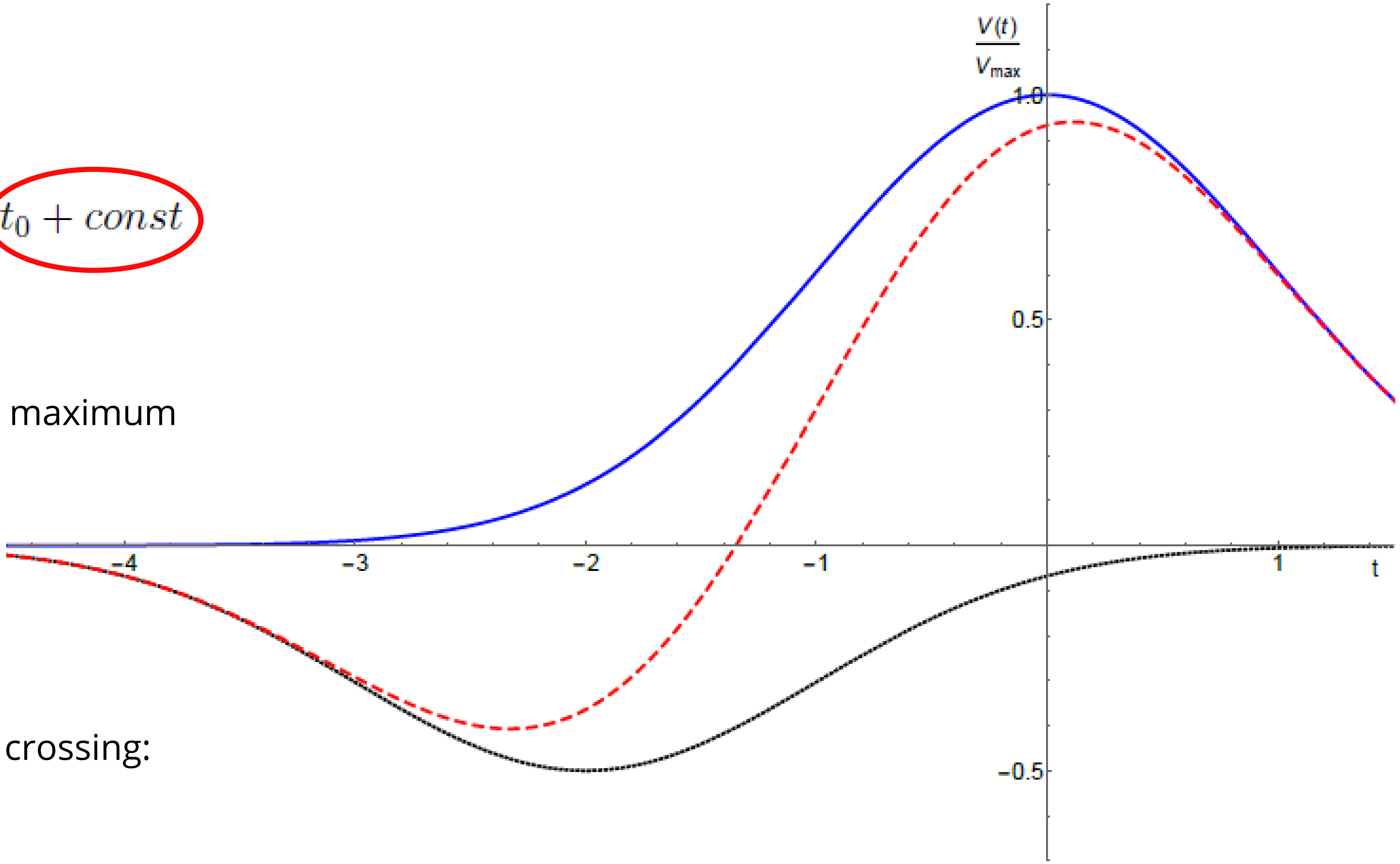
A threshold that is proportional to the amplitude removes the time walk for Gaussian pulses.

$$V_{th} = k_{cfd} V_{max}$$

$$t_{cfd} = t_0 - 2\sigma\sqrt{ln(\frac{V_{th}}{V_{max}})} = t_0 - 2\sigma\sqrt{ln(k_{cfd})} = t_0 + const$$

Problem: the threshold is usually crossed **before** the maximum amplitude is reached!

SAMPLING!



It is possible to do an analog CFD measuring the zero crossing:

$$V_{cfd}(t_{cfd}) = 0 \Rightarrow$$

$$\Rightarrow V_{max}\,(e^{-\frac{(t-t_0)^2}{2\sigma^2}} - k_{cfd}\,e^{-\frac{(t+\Delta-t_0)^2}{2\sigma^2}}) = 0 \Rightarrow$$

$$\Rightarrow e^{-\frac{(t-t_0)^2}{2\sigma^2}} - k_{cfd}\,e^{-\frac{(t+\Delta-t_0)^2}{2\sigma^2}} = 0$$

← No V_{max}

Needs a complex electronics and slow drift of the baseline can introduce an error.

Constant Fraction Discriminator

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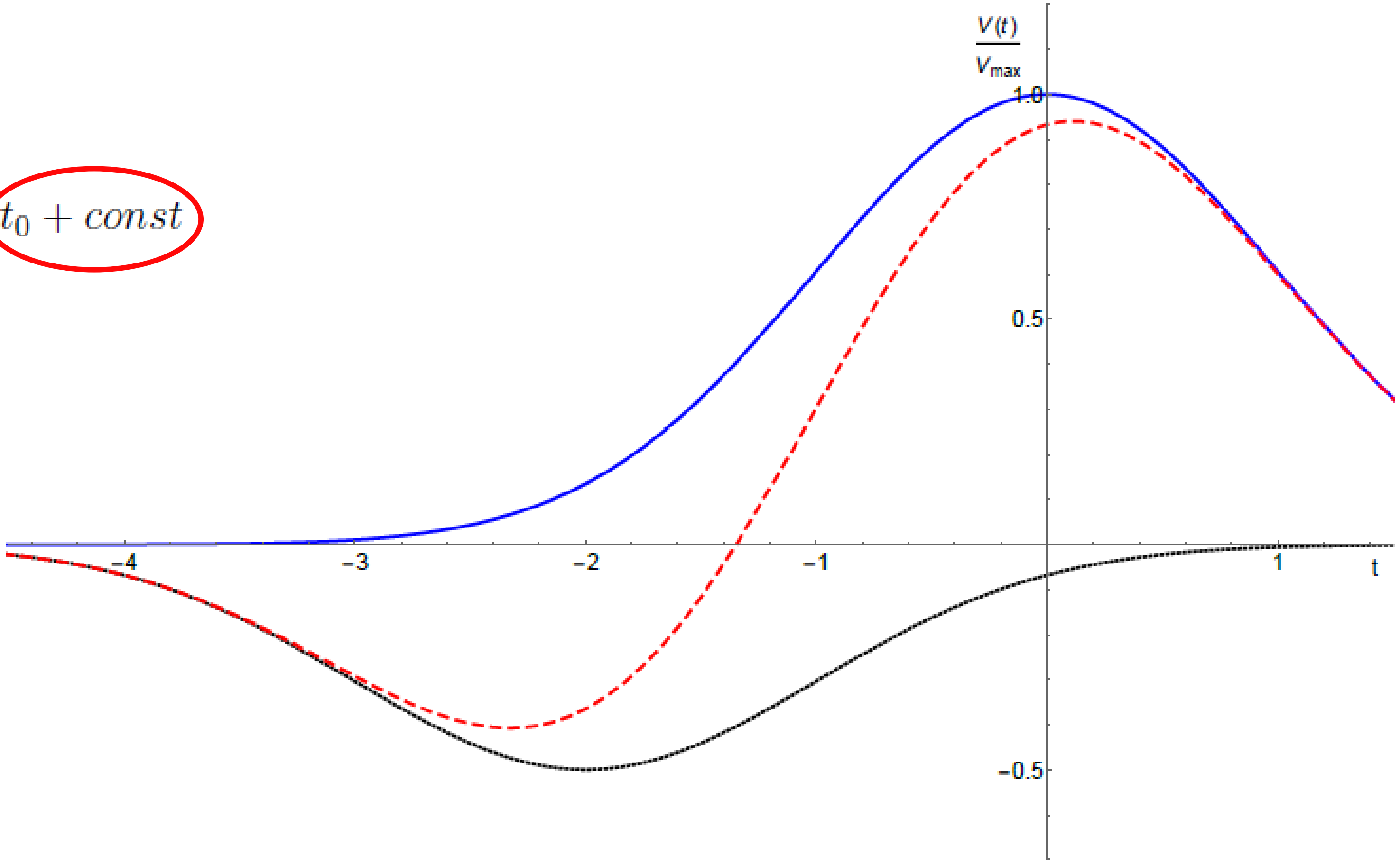


The value of k_{cfd} has to be chosen according to the signal, to maximize the slope at the instant of the threshold crossing.
For a Gaussian pulse the slope is maximum for t = σ

$$V_{best} = \frac{V_{out}}{\sqrt{e}} \Rightarrow k_{cfd} \sim 60\%$$

It is possible to average the results obtained using several k_{cfd}

Time over Threshold

A correction to the threshold crossing can be computed using the Time over Threshold.

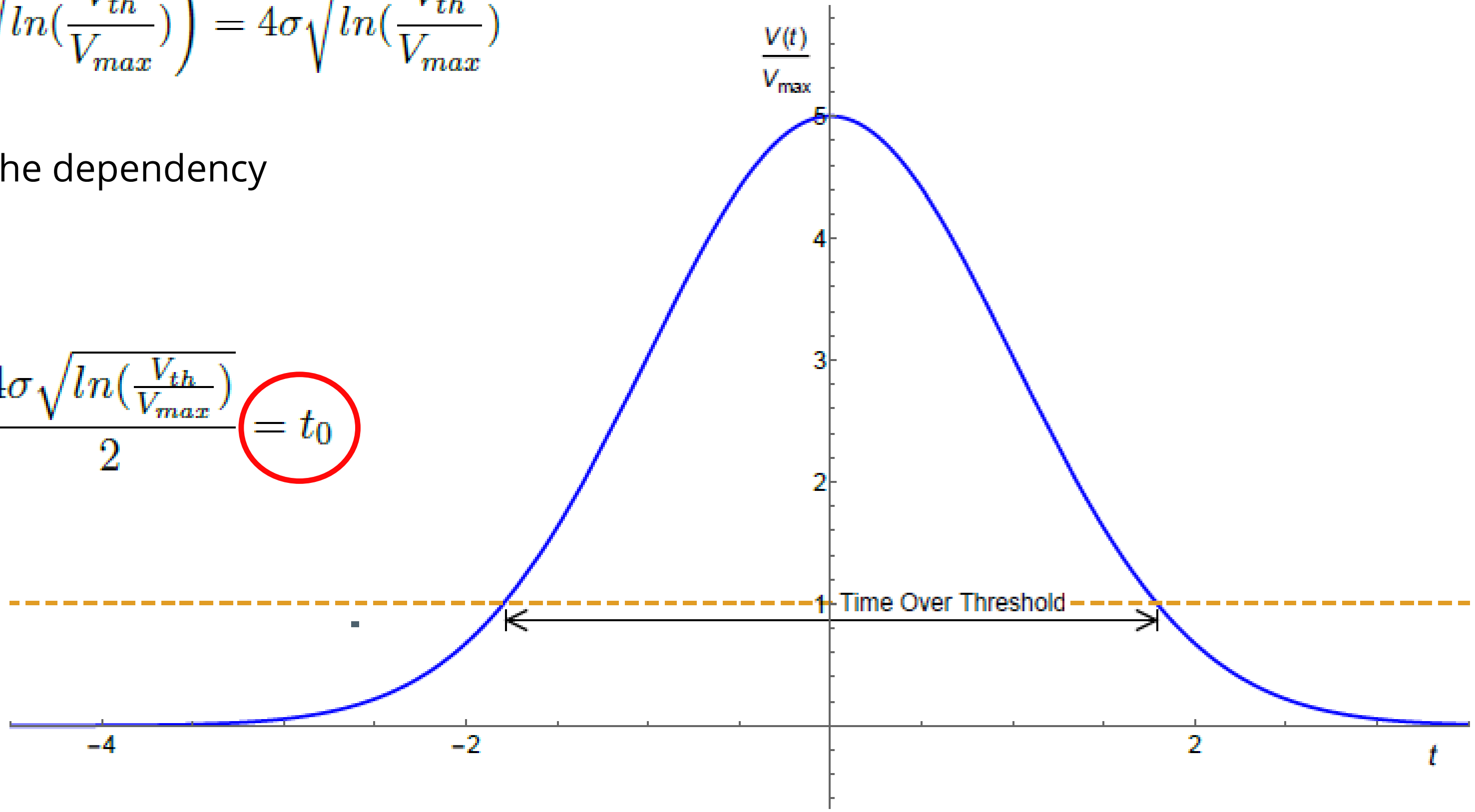
The ToT depends on the amplitude:

$$t_{tot} = t_{th2} - t_{th1} = t_0 + 2\sigma\sqrt{ln(\frac{V_{th}}{V_{max}})} - \left(t_0 - 2\sigma\sqrt{ln(\frac{V_{th}}{V_{max}})}\right) = 4\sigma\sqrt{ln(\frac{V_{th}}{V_{max}})}$$

It is possible to find a function *f* of the ToT to remove the dependency on amplitude:

$$f(t_{tot}) = \frac{T_{tot}}{2}$$

$$t_{corr} = t_{th} + f(t_{tot}) = t_0 - 2\sigma\sqrt{ln(\frac{V_{th}}{V_{max}})} + \frac{4\sigma\sqrt{ln(\frac{V_{th}}{V_{max}})}}{2} = t_0$$



Time over Threshold

A correction to the threshold crossing can be computed using the Time over Threshold.

For more complicated signal $f(t_{tot})$ may not be obtained analytically.

The two ToT measurements t_{tot1} and t_{tot2} are uncorrelated as they depend on the charge released in two completely independent detectors.

$$\Delta t = t_{corr2} - t_{corr1} = t_{th2} + f_2(t_{tot2}) - (t_{th1} + f_1(t_{tot1}))$$

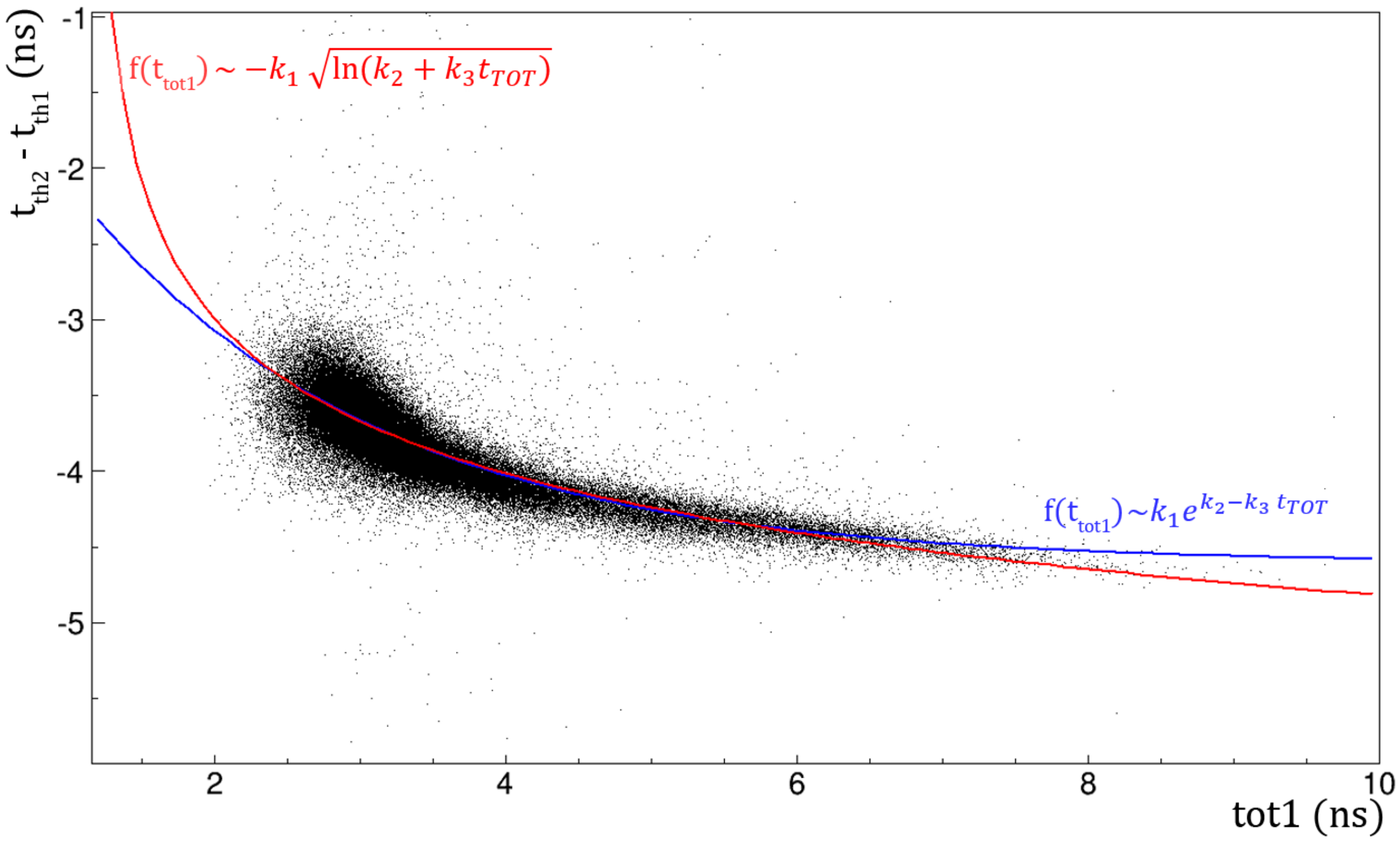
$$f_1(t_{tot1}) = t_{th1} - t_{th2} - f_1(t_{tot2})$$

Averaging over *tot2*:

$$\langle f_1(t_{tot1})\rangle_{tot2} = f_1(t_{tot1}) = t_{th1} - t_{th2} - \langle f_2(t_{tot2})\rangle_{tot2} =$$

$$= -(t_{th2} - t_{th1}) + const$$

Not dependent on the second detector



Time over Threshold

A correction to the threshold crossing can be computed using the Time over Threshold.

In principle, ToT correction does not require sampling: discriminator + TDC

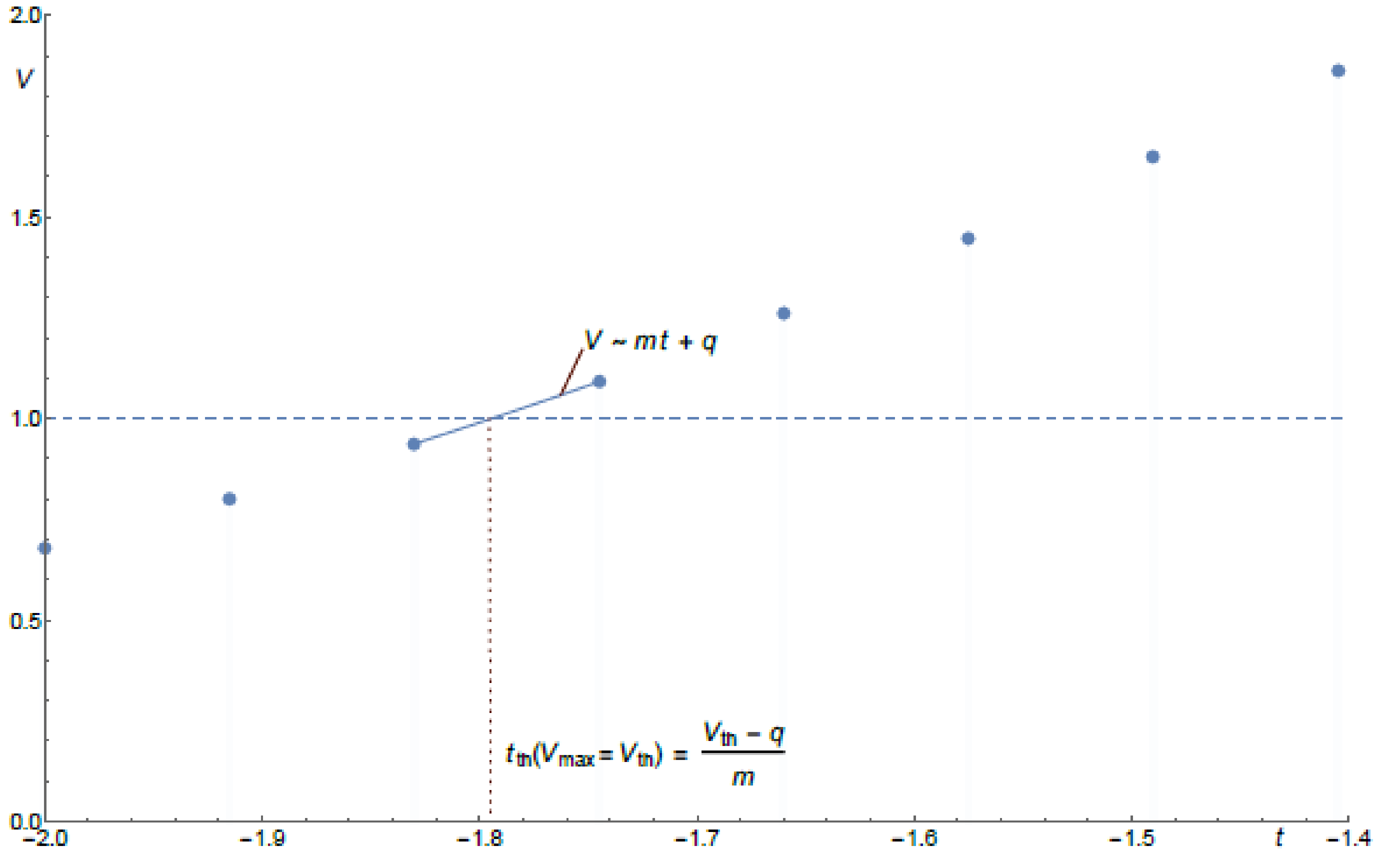
However:

$$\sigma_{TDC} \sim \frac{\text{bin width}}{\sqrt{12}}$$

Other disadvantage of TDC:

- No interpolation possible
- No correction possible
- Same threshold for discrimination and ToT

Possible solution: multiple thresholds



Cross Correlation

The correlation of the signal with a template can be used to compute the arrival time.

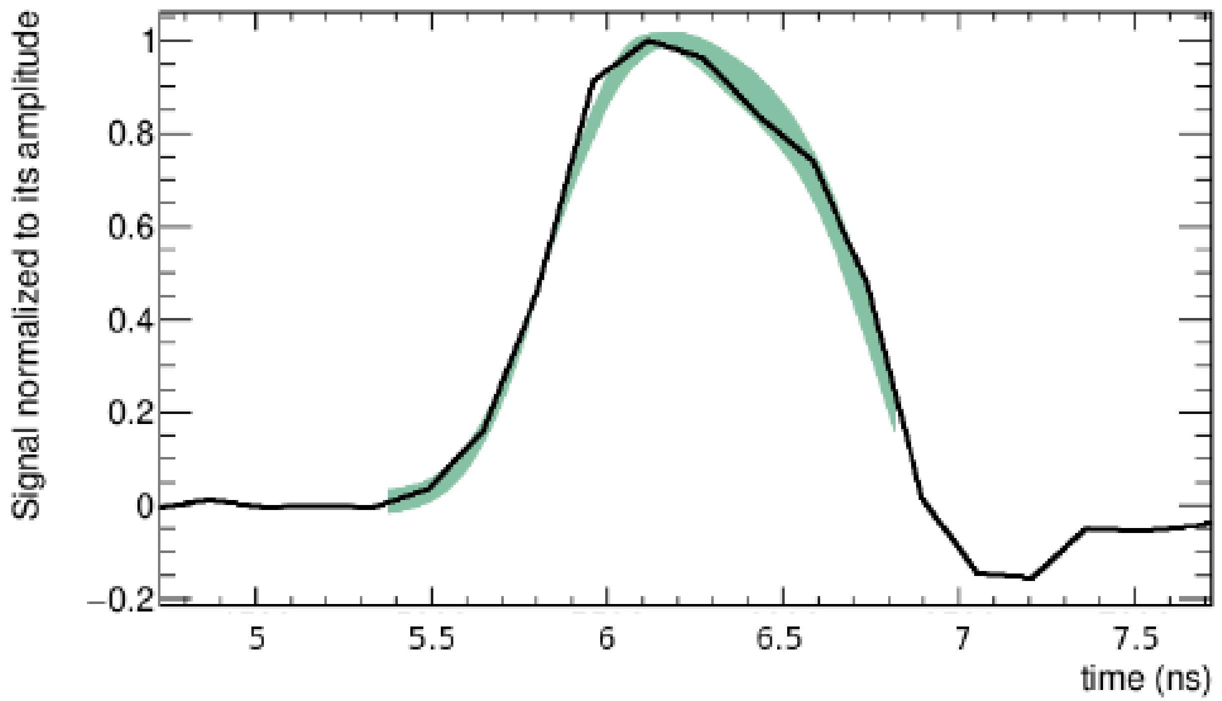
A template can be generated averaging many signal shapes

The template is translated over the signal to find the maximum of the correlation:

$$c\left[j\right] = \sum s\left[t_i\right] \; g\left[t_{i+j}\right]$$

This process is time consuming, so this process is repeated in a small time window defined using CFD.

The advantage of the cross-correlation method is that the information of all the sampled points can be included in the computation whereas other algorithms only uses a few points.



Synchronization performed between a template (band) and a signal (line).

Measurements of timing resolution of ultra-fast silicon detectors with the SAMPIC waveform digitizer
http://dx.doi.org/10.1016/j.nima.2016.08.019

Digital filtering

Off-line elaboration can be also used to filter the digitized signal.

It can be useful to remove certain frequencies from the signal, i.e. mobile phones, radio…

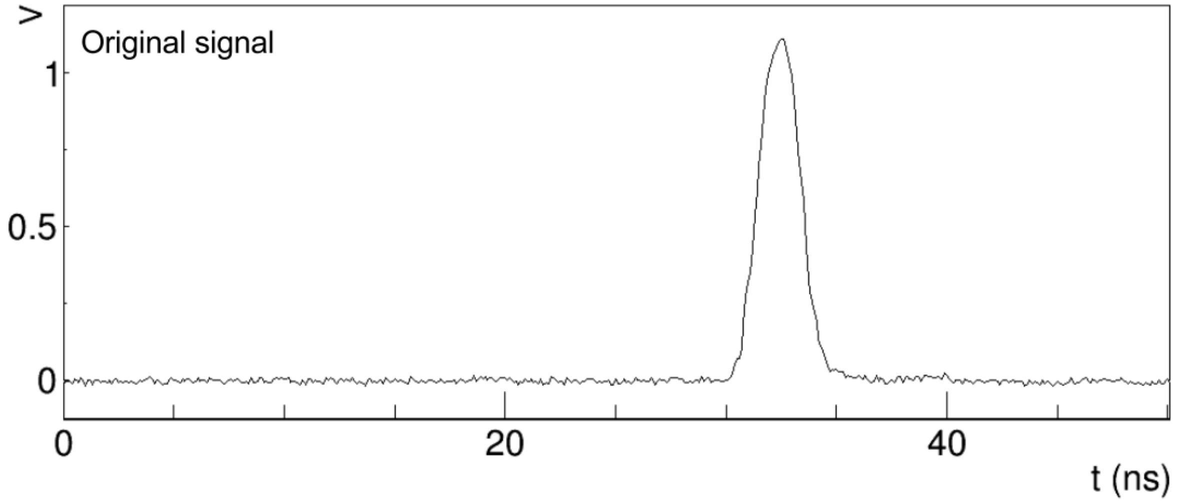
Using a sampled signal those frequencies can be removed *a posteriori*:

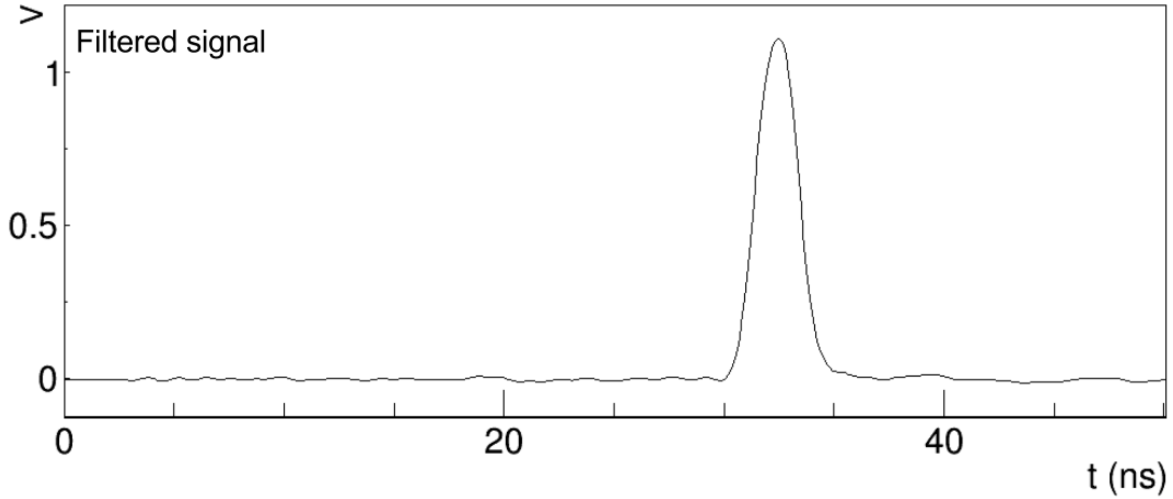
- No need to modify the electronics according to the environment!
- Possibility of time dependent corrections:

  Reduce bandwidth when noisy

  Full bandwidth when not noisy

Test beam in NA at CERN: crane moving!





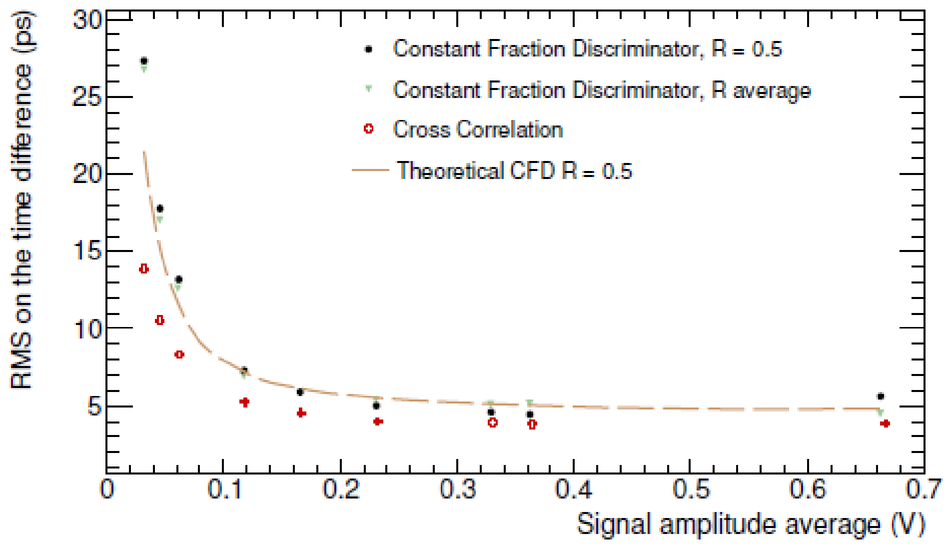
Application to real signals

RMS on the time difference between two signals with respect to the signal amplitude.

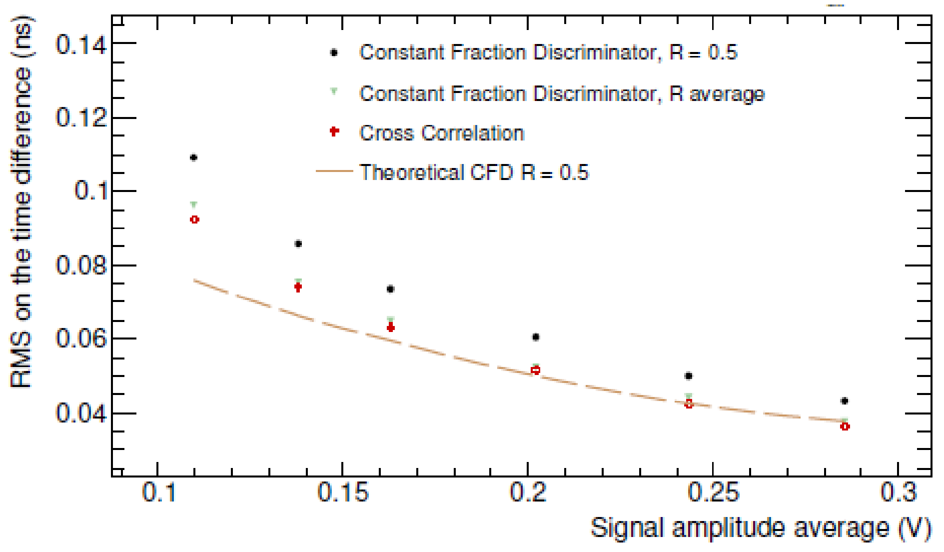
	Offline method	ΔT_{12} fitted-value, (ΔT_{12} RMS), [resolution]
1	Simple Threshold	1450 (1490) [1025] ps
2	Position of the Maximum	719 (754) [508] ps
3	Normalized Threshold (70%)	467 (491) [330] ps
4	Normalized Threshold (50%)	353 (359) [250] ps
5	Normalized Threshold (30%)	336 (341) [238] ps
6	Fitted Normalized Threshold (35%)	308 (315) [217] ps
7	Offline CFD	306 (298) [210] ps
8	Extrapolation of normalized Threshold	277 (281) [196] ps

Many other algorithms are possible, but usually with *similar* performance.
Example with two diamond detector read using Cividec C6 Amplifiers.

Timing performance of diamond detectors with Charge Sensitive Amplifier readout



Signal generator, acquired using the SAMPIC chip at 6.4 GS/s.



Laser tests with 300 μm USFDs read-out with Cividec C2 BDA, acquired using the SAMPIC chip at 6.4 GS/s.

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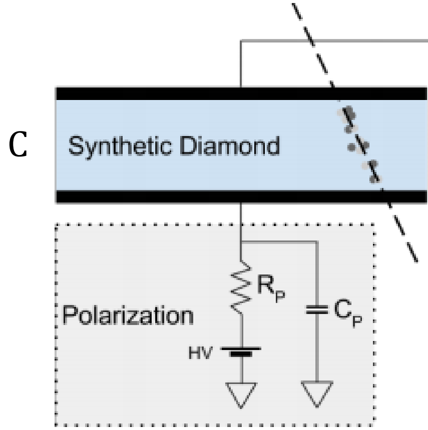
More details: Sec. 6.3 of Development of a timing detector for the TOTEM experiment at the LHC

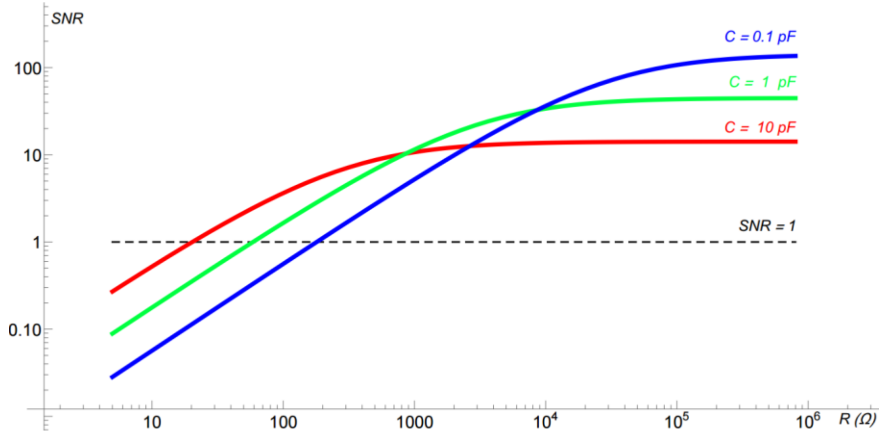
Front-end electronics: amplifier

It is useful to analyse the simplest possible case: a diamond detector read using a simple resistor.

For $R < \sim 100\ \Omega$ the signal is not separated from the noise ($SNR \sim 1$) also for $C \sim 0.1$ pF.

The only way to have a SNR > 1 is to increase the value of the read-out resistor.

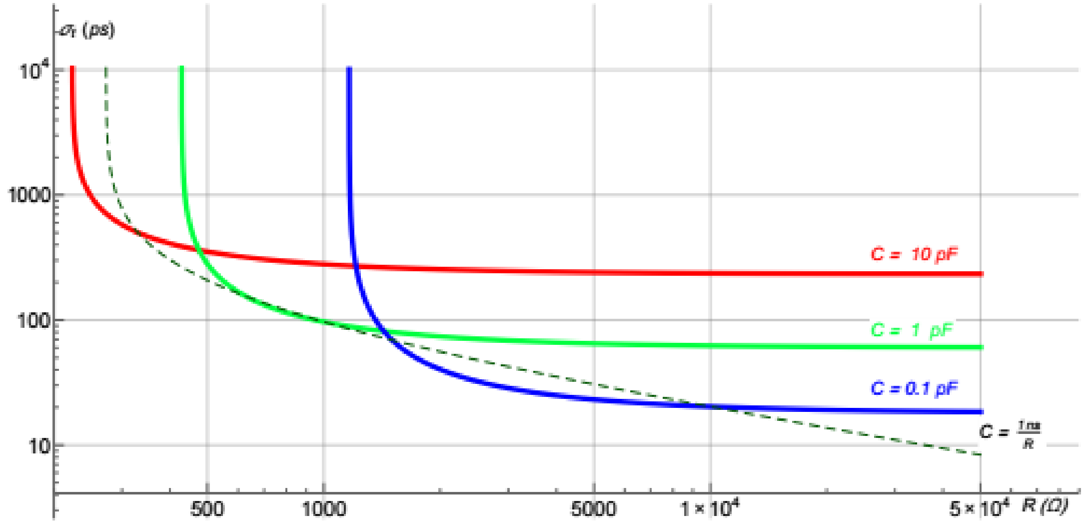




However, the time resolution is given by:

$$\sigma_t \sim \frac{\sigma_V}{MAX[\frac{dV}{dt}]}$$

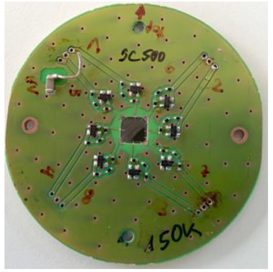
And higher R means slower signal:

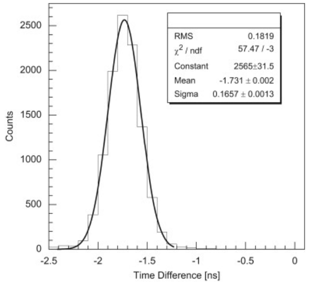


A useful rule of thumb: **minimize C and use R ~ 1 ns/C**

Amplifier as close as possible to the sensor (minimize C)
First stage with input resistor ~ kΩ

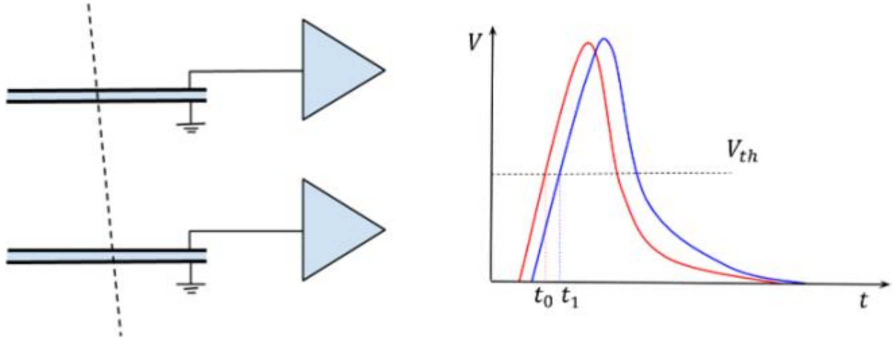
Strategy suggested by HADES @ GSI
10.1016/j.nima.2010.02.113





The TOTEM timing detector: timing performance

To measure the time resolution of two identical detectors it is possible to measure the arrival time of a particle crossing both sensors.

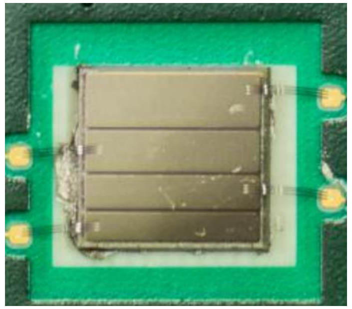


The measured time difference will be distributed around the true value because of the limited resolution of the detectors:

$$\sigma^2_{TOT} \sim \sigma^2_{det1} + \sigma^2_{det2} \sim 2\sigma^2_{det1} \longrightarrow \sigma_{meas} \sim \sqrt{2}\sigma_{det}$$

However, the time resolution depends on the capacitance of the detector!

A series of tests were done using a sensor with pads of different surface, i.e. capacitance.



Time difference between a sensor of 17.6 mm^2 (~1.7 pF) and sensors of different size