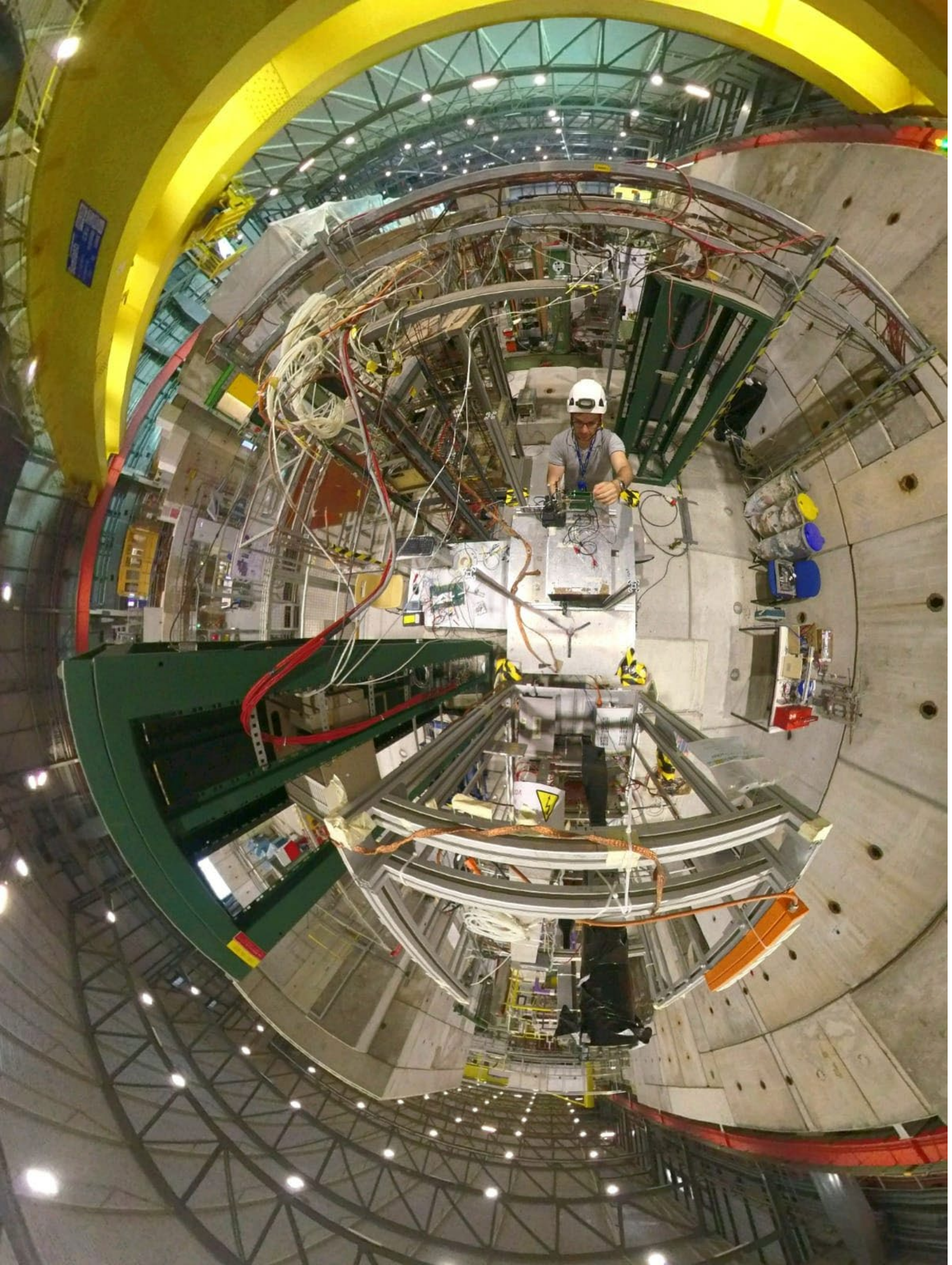


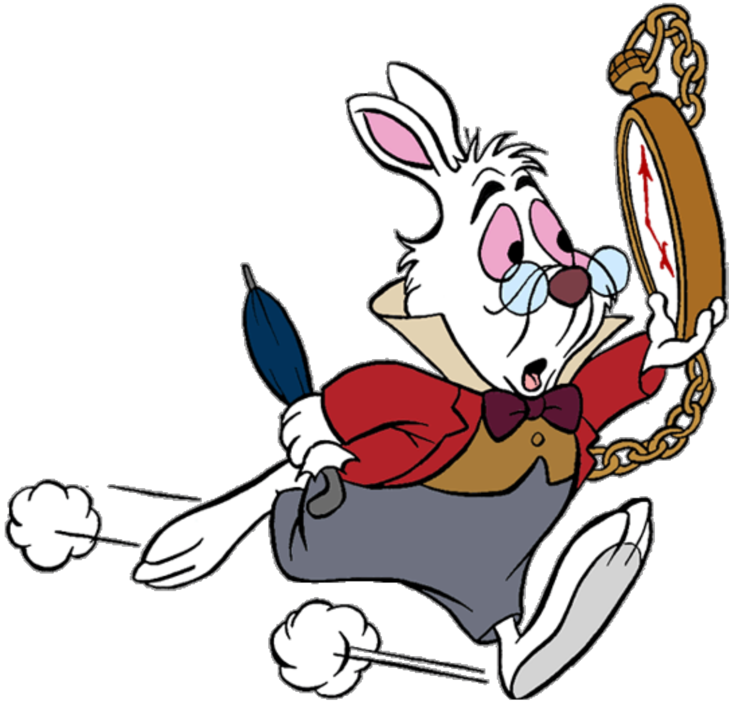
Fast timing detectors for HEP and medical applications

Nicola Minafra
University of Kansas

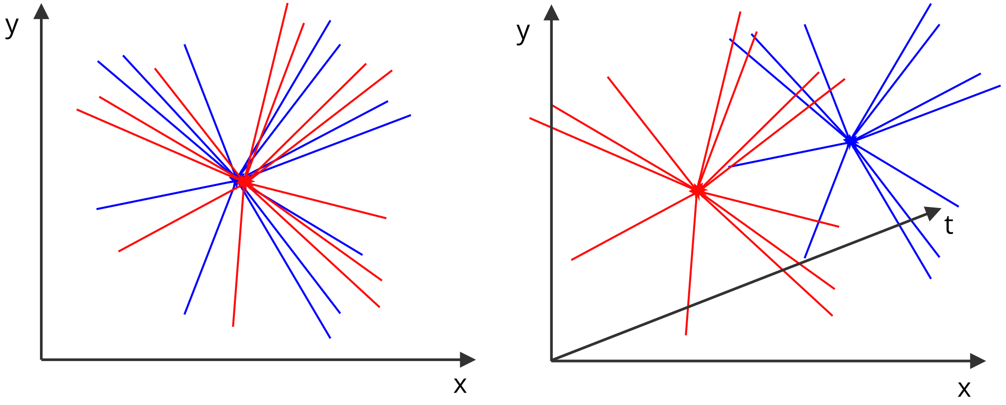
May 3rd 2024

Outline

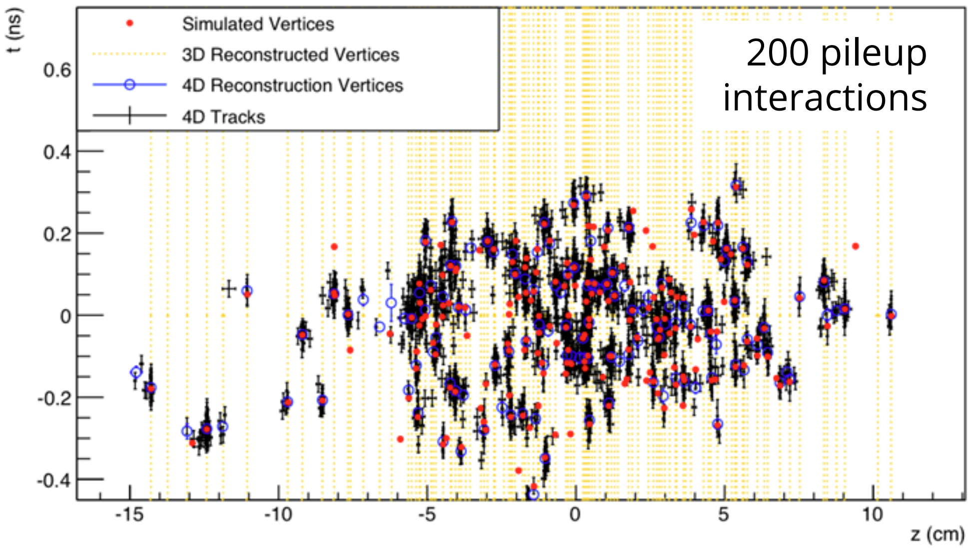
- **Why timing?**
- How timing?
  - Solid State Sensors
  - Front-end electronics
  - Measurement of the arrival time
- Example of Timing Detectors at LHC:
  - CMS MIP Timing Detector
  - TOTEM Timing Detector
- Medical applications of Timing Detectors



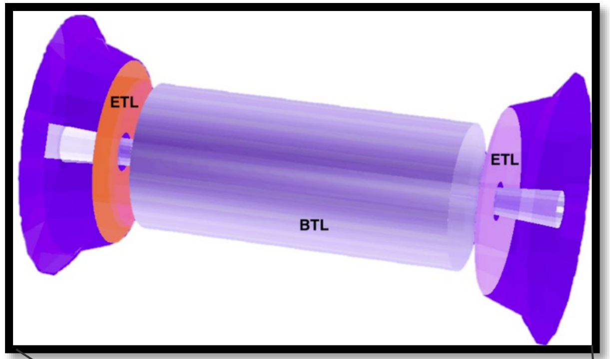
Why timing? Pileup suppression

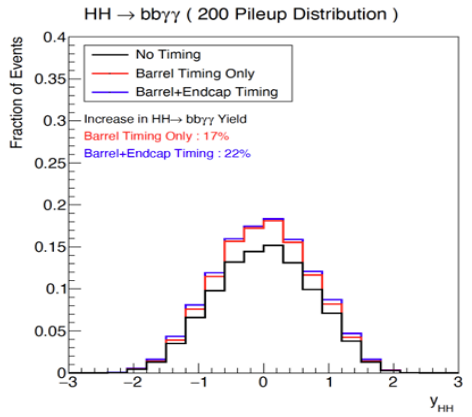


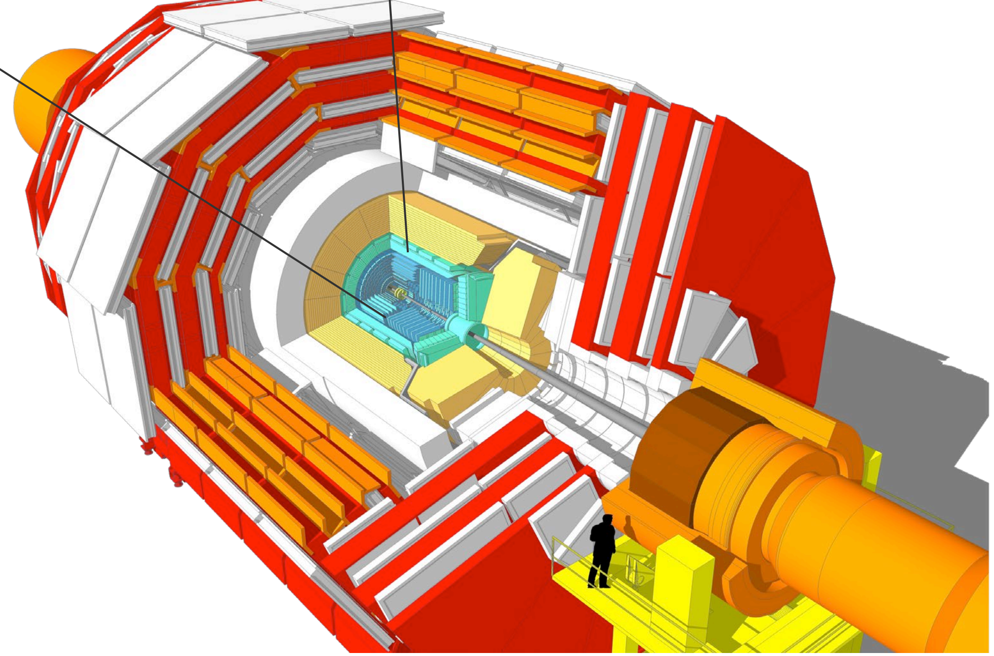
To associate the detected protons to the correct vertex, when there are multiple interaction per bunch crossing (pile-up) it is possible to measure the time difference between the arrival instants.



CMS MIP Timing Detector (MTD)

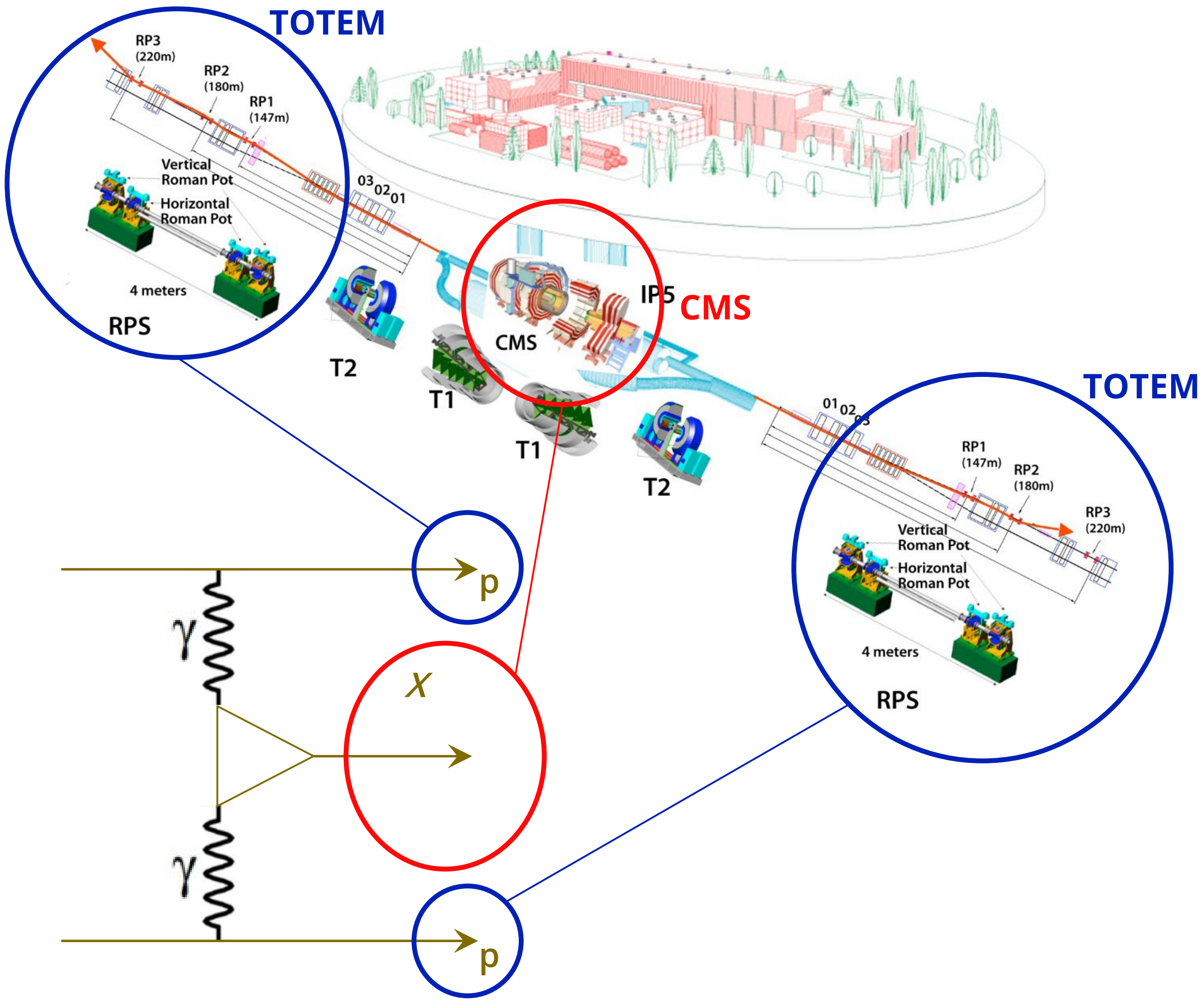






A MIP Timing Detector for the CMS Phase-2 Upgrade

Timing for vertex association in Central Exclusive Production

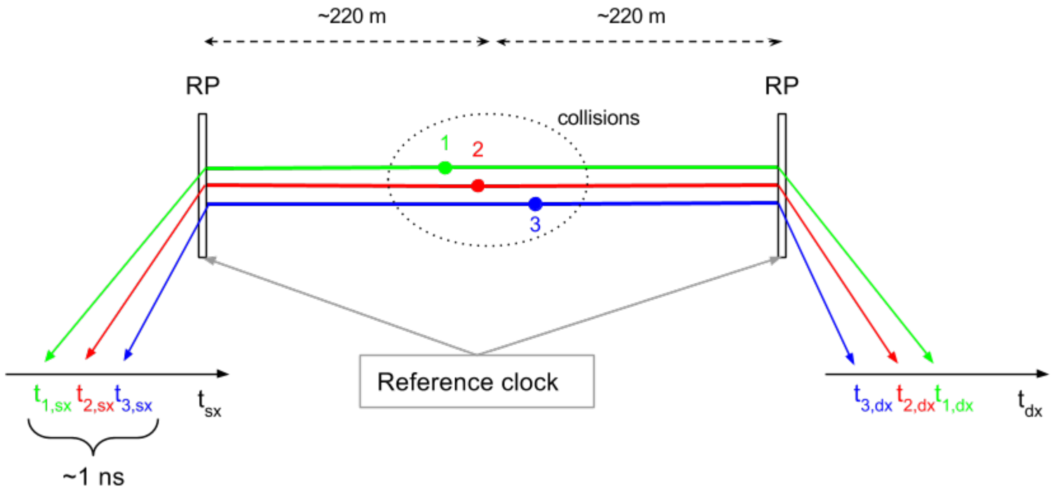


$$p + p \to p \oplus X \oplus p$$

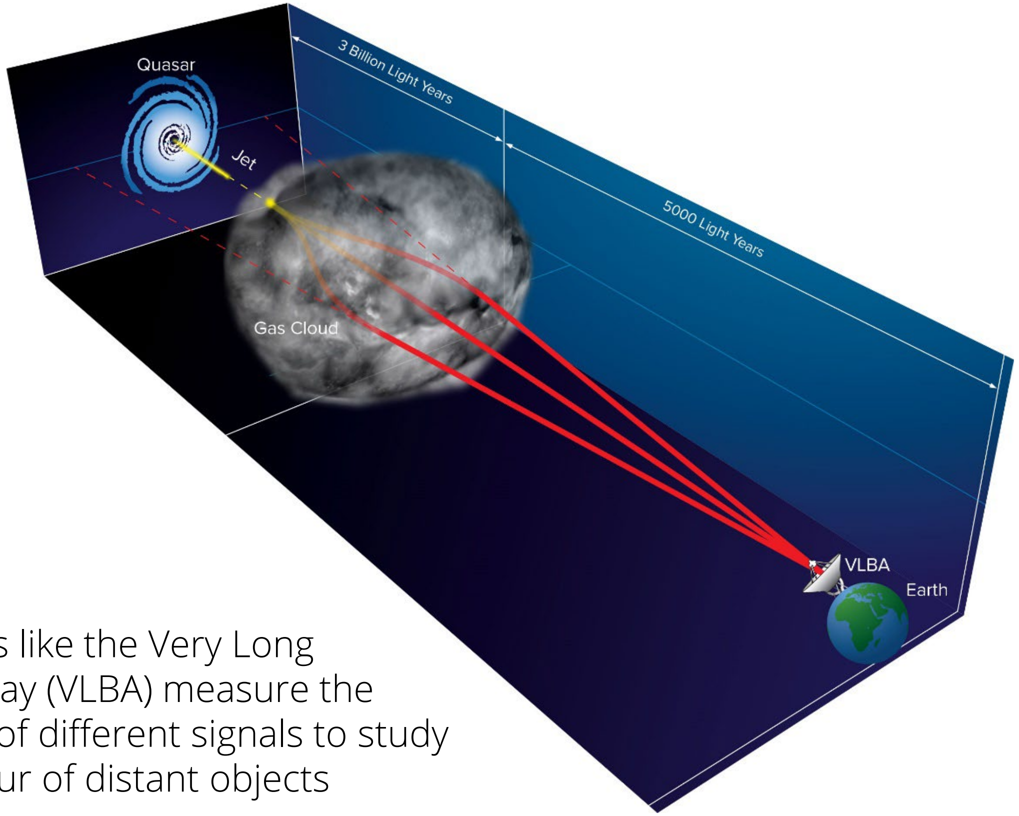
When X is a particle ($J_z^{CP} = 0^{++}$) its mass can be measured using the momentum lost by the leading protons, **even if X cannot be detected!**

$$M_X \sim \sqrt{s\xi_1\xi_2} \quad \text{with} \quad \xi = \frac{\Delta p}{p}$$

Timing detectors for vertex association

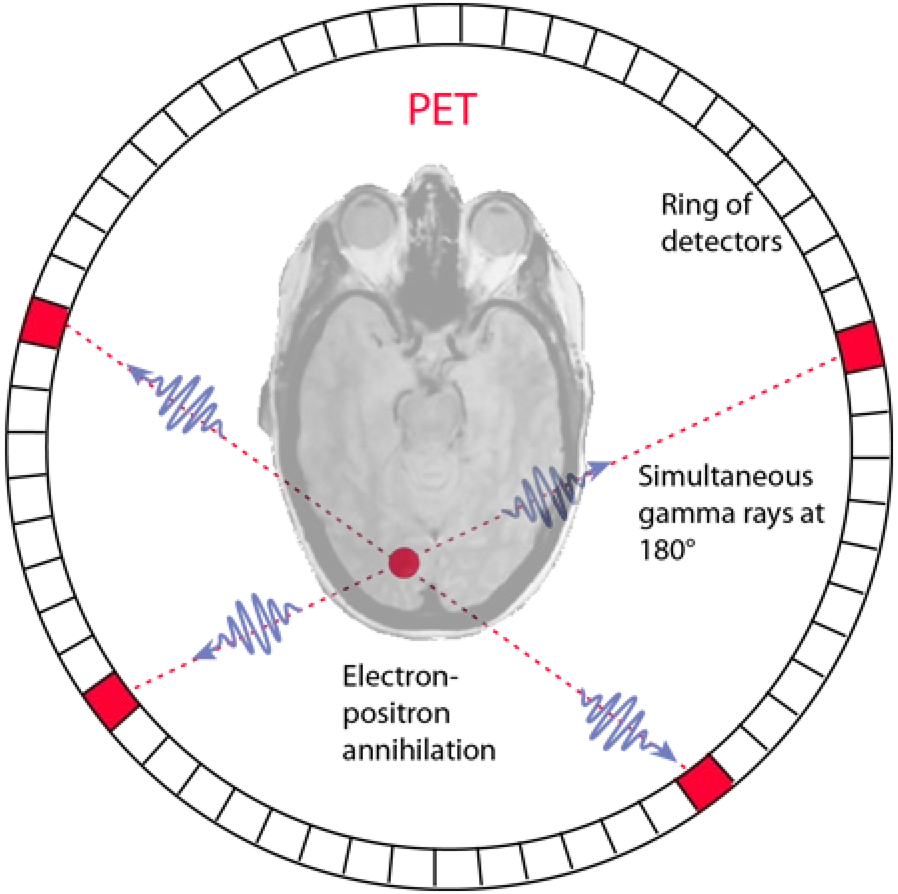


Timing Applications outside HEP



Experiments like the Very Long Baseline Array (VLBA) measure the arrival time of different signals to study the behaviour of distant objects

Precise triangulation of sources of particle showers



Positron Emission Tomography

Outline

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  - **Solid State Sensors**
  - **Front-end electronics**
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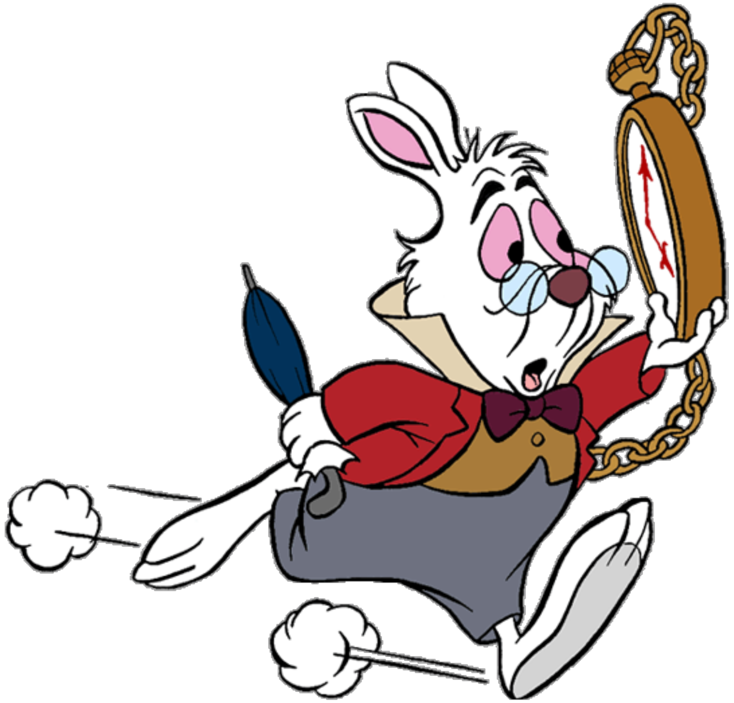


Measuring the arrival time

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

$$\sigma_t{}^2 \sim$$

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 SENSOR

OPTIMIZATION OF THE FRONT-END ELECTRONICS

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

Statistical fluctuations of energy deposit

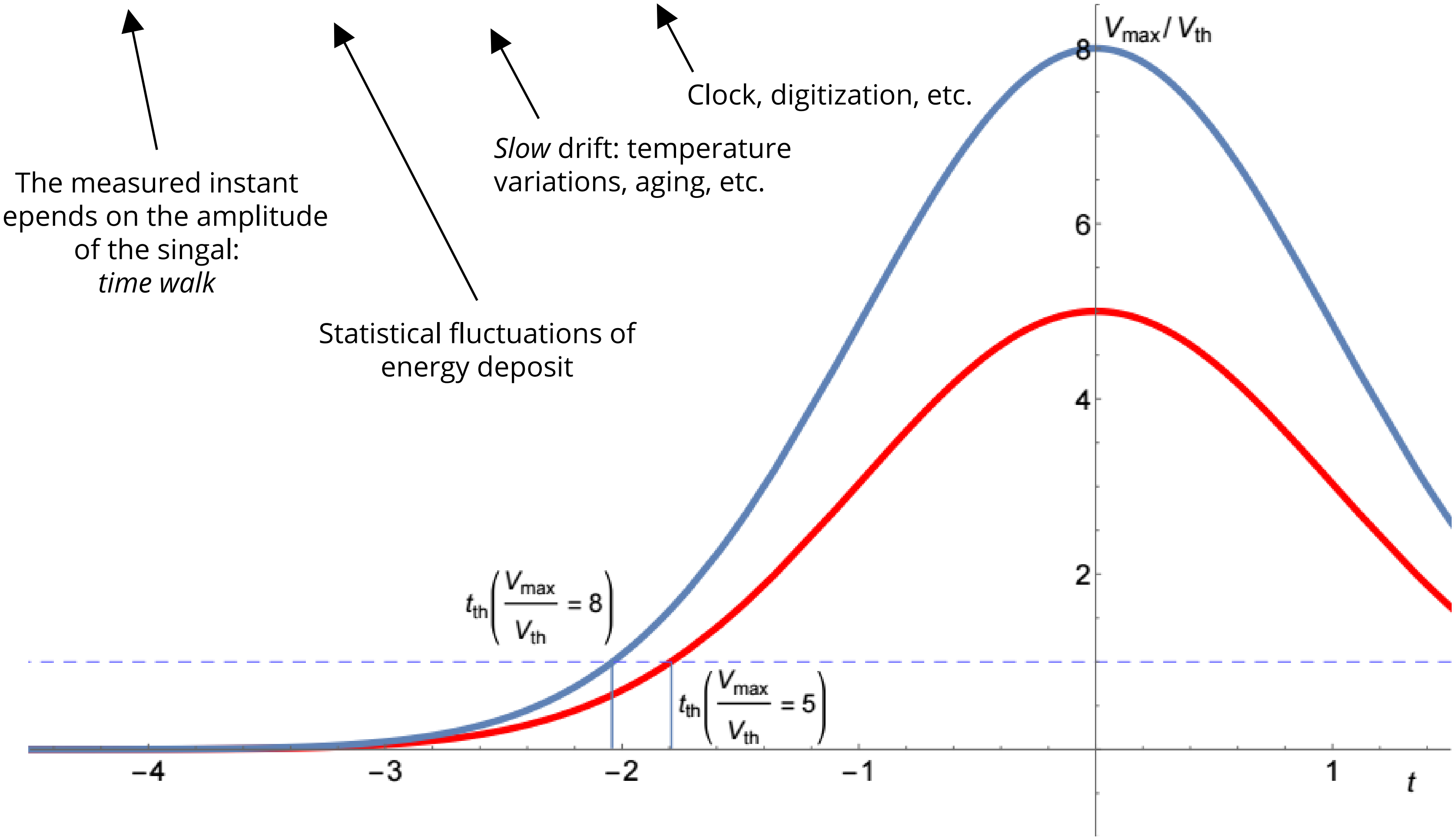
Slow drift: temperature variations, aging, etc.

Clock, digitization, etc.

The main tecniques to correct *time walk* are:

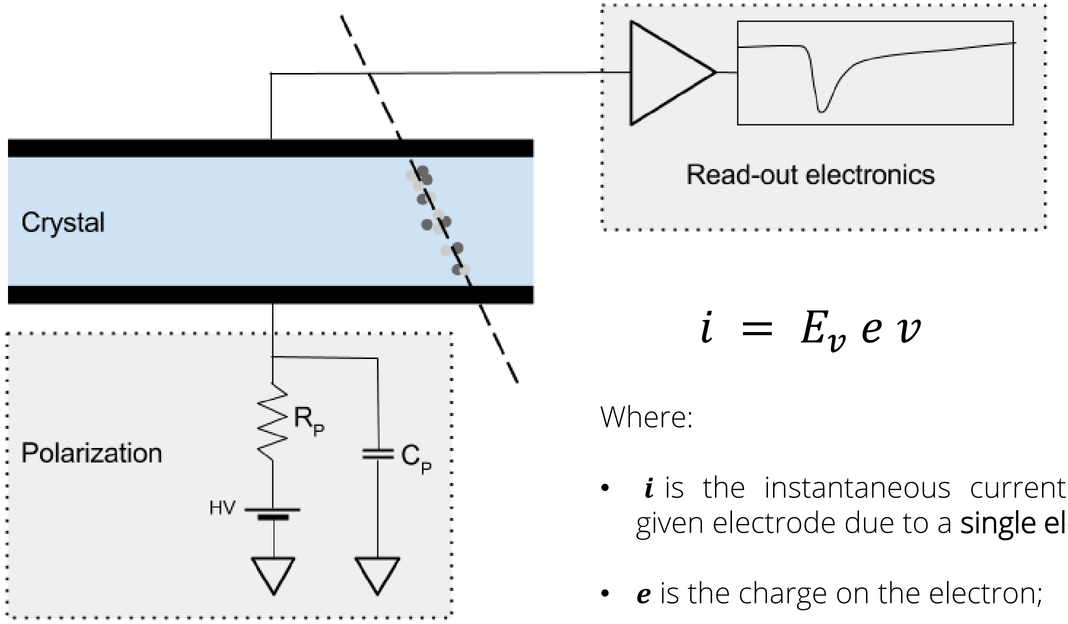
- Costant Fraction Discriminator (CFD);
- Time over Threshold (ToT);
- Cross-Correlation (CC).

OPTIMIZATION OF THE CORRECTION ALGORITHMS (SAMPLING)



Solid State detectors

A particle passing through a crystal will create electron-hole pairs that will drift toward the electrodes because of the bias applied using the polarization circuit; the current induced on the readout electrode can be amplified and acquired.

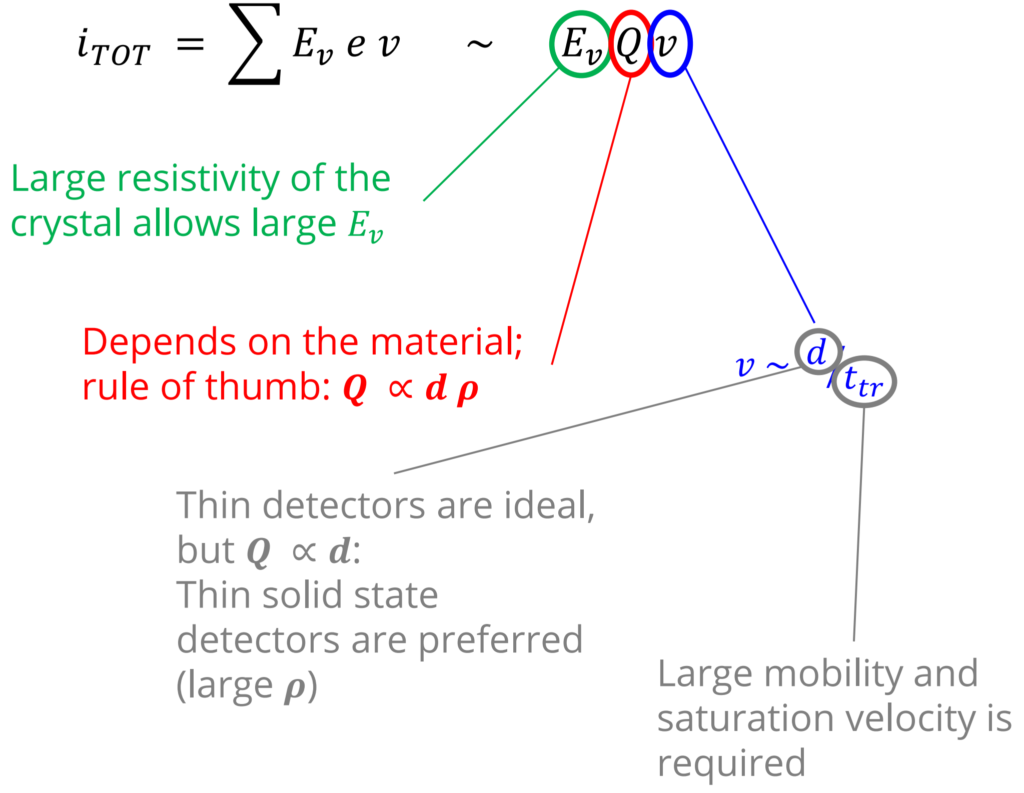


$$i = E_v\, e\, v$$

Where:

- i is the instantaneous current received by the given electrode due to a single electron's motion;
- e is the charge on the electron;
- v is its instantaneous velocity;
- E_v is the component in the direction v of that electric field which would exist at the electron's instantaneous position under the following circumstances: electron removed, given electrode raised to unit potential, all other conductors grounded.

[Currents Induced by Electron Motion, S. Ramo]



$$i_{TOT} = \sum E_v\, e\, v \quad \sim \quad E_v\, Q\, v$$

Large resistivity of the crystal allows large E_v

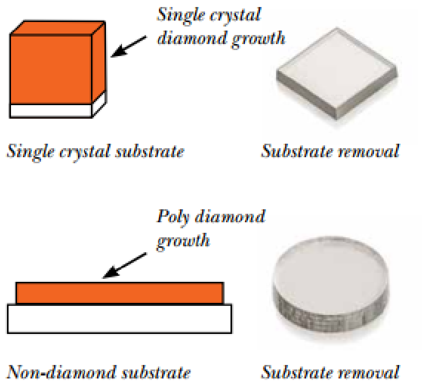
Depends on the material; rule of thumb: $Q \propto d\,\rho$

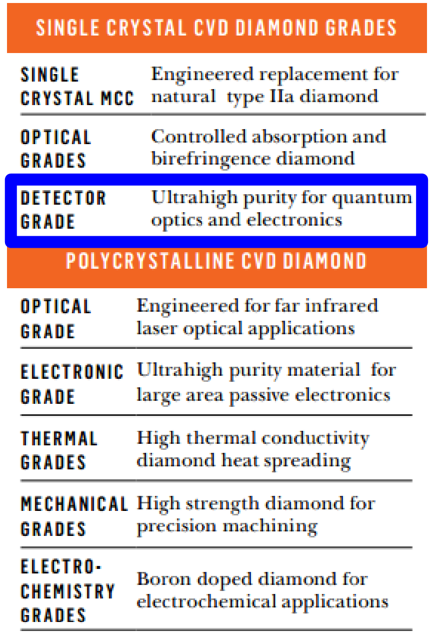
$v \sim d / t_{tr}$

Thin detectors are ideal, but $Q \propto d$: Thin solid state detectors are preferred (large ρ)

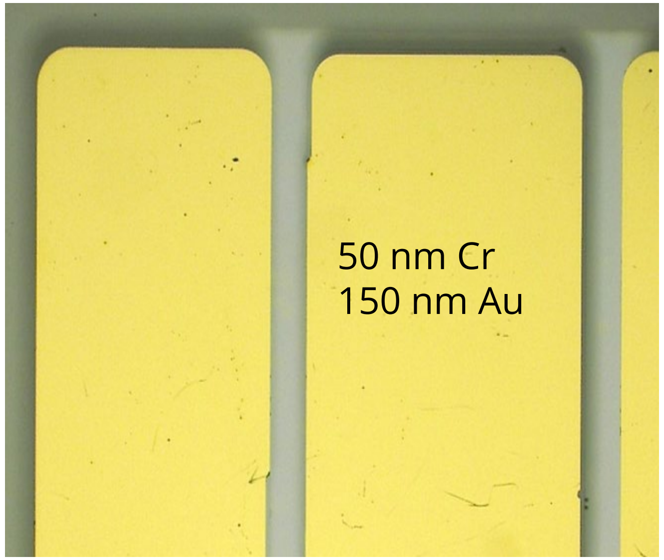
Large mobility and saturation velocity is required

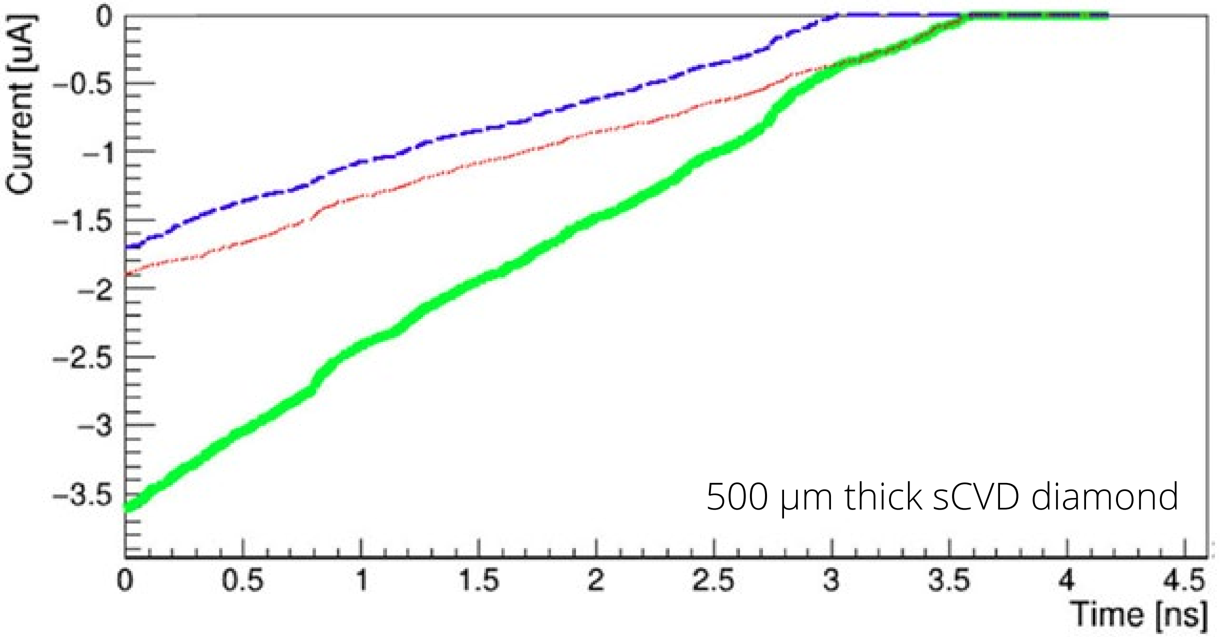
Diamond as a particle detector





SINGLE CRYSTAL CVD DIAMOND GRADES	
SINGLE CRYSTAL MCC	Engineered replacement for natural type IIa diamond
OPTICAL GRADES	Controlled absorption and birefringence diamond
DETECTOR GRADE	Ultrahigh purity for quantum optics and electronics
POLYCRYSTALLINE CVD DIAMOND	
OPTICAL GRADE	Engineered for far infrared laser optical applications
ELECTRONIC GRADE	Ultrahigh purity material for large area passive electronics
THERMAL GRADES	High thermal conductivity diamond heat spreading
MECHANICAL GRADES	High strength diamond for precision machining
ELECTRO-CHEMISTRY GRADES	Boron doped diamond for electrochemical applications

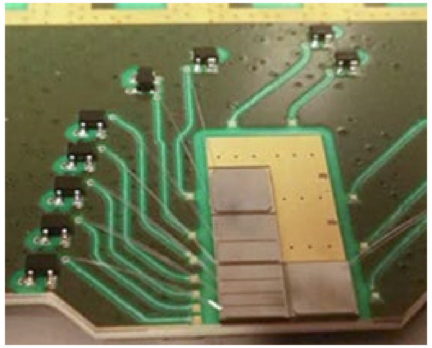




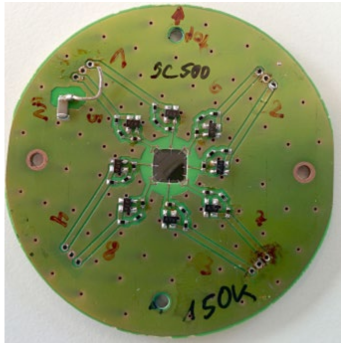
A ultrapure single crystal diamond is needed to have a charge collection efficiency close to 100%

The metallization process has been optimized over the years to avoid poor collection efficiency and rate dependency of the collected charge.

The generated signal is clean and fast, but small.



~90 ps
TOTEM, CMS @ CERN

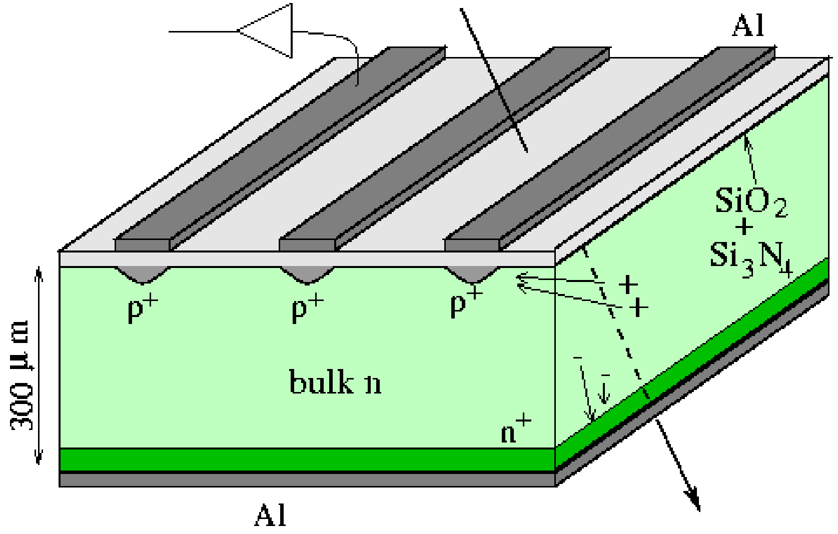


10.1016/j.nima.2010.02.113

~100 ps
HADES @ GSI

Diamond Detectors for Timing Measurements in High Energy Physics

Silicon as particle detector



Needs doping to create depleted region

Lower mobility and/or saturation velocity: slower signals

Lower resistivity: higher noise

Lower displacement energy: worse radiation hardness

Larger dielectric constant: larger capacitance

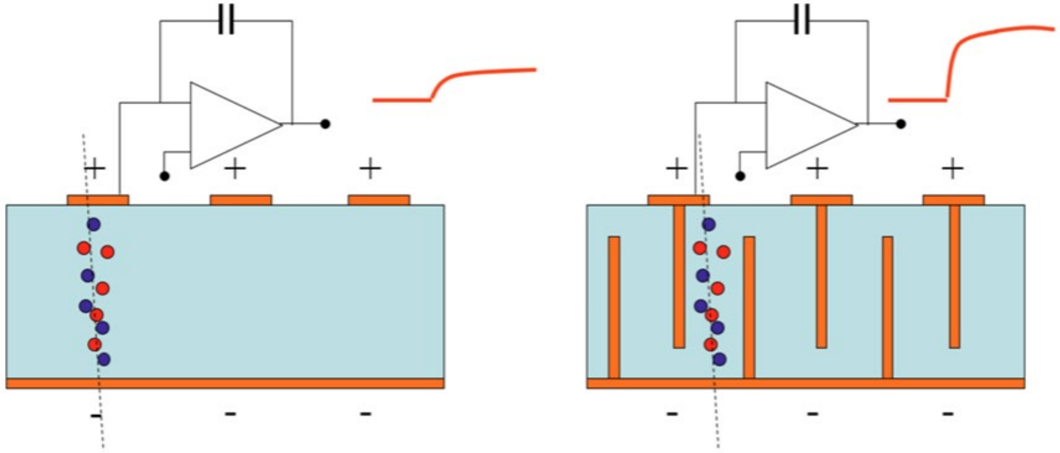
Lower band gap: larger noise, larger signal

Lower density: lower ionization, lower radiation length

	Diamond	Silicon
band gap [eV]	5.48	1.12
intrinsic resistivity [Ω/cm]	> 10^{15}	$2.3\text{x}10^5$
electron mobility [cm^2/V s]	< 4600	1350
hole mobility [cm^2/V s]	< 3400	480
hole lifetime [s]	10^{-10} - 10^{-6}	10^{-3}
saturation velocity [cm/s]	1.6- 2.6 x10^7	10^7
density [g/cm^3]	3.52	2.33
dielectric constant	5.7	11.9
energy to create e-h [eV]	13.1	3.63
energy loss for MIPs [MeV/cm]	4.69	3.21
average pairs created / 1 μm	36	88.9
displacement energy [eV]	37.5 - 47.6	36

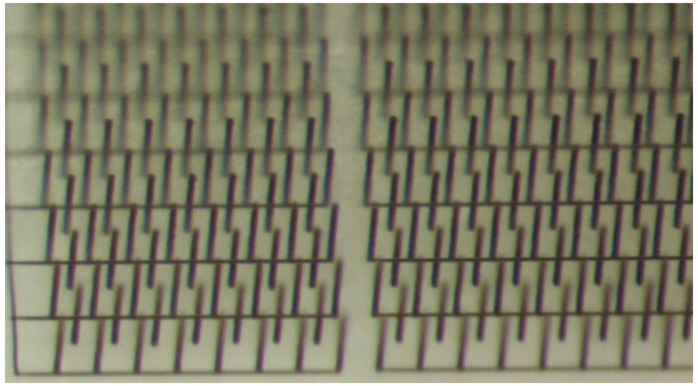
Lower better Larger better Depends…

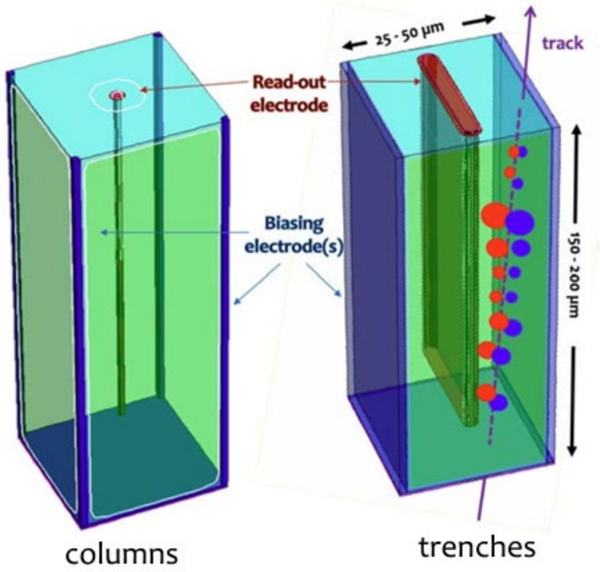
3D sensors

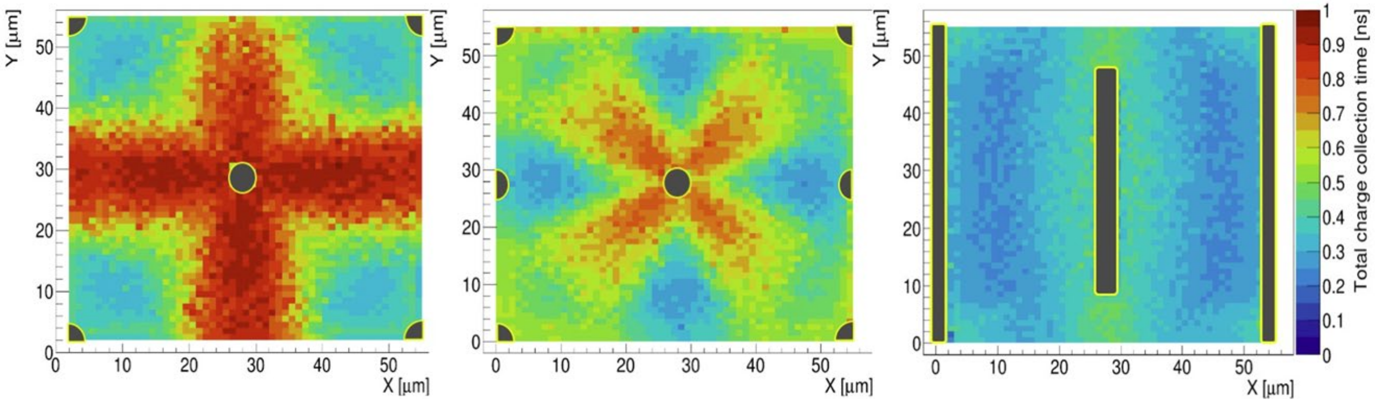


The free charges generated by the passage of the particles can be collected by electrodes parallel to the trajectory:

- Same energy deposited by the particle
- Faster collection time
- Higher capacitance
- More difficult to produce



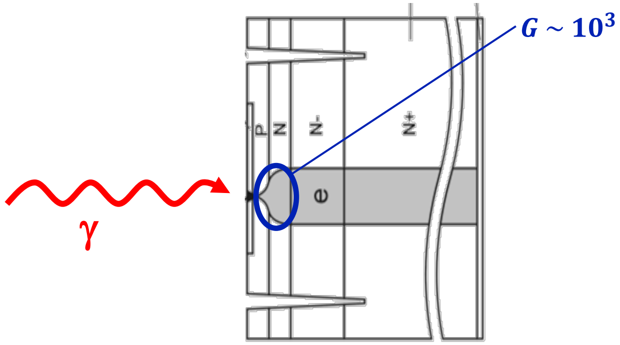




Studies and Tests on 4D pixel sensors, A. Lai

Avalanche PhotoDiodes and Silicon Photomultipliers

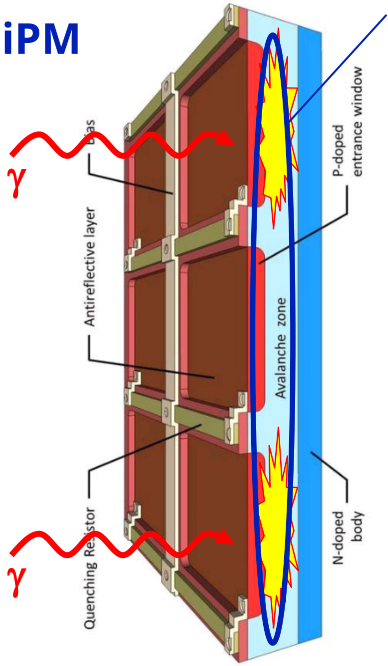
A “gain layer” can be introduced to multiply the charge produced by the primary ionization

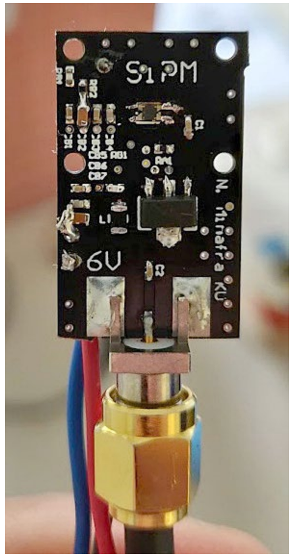


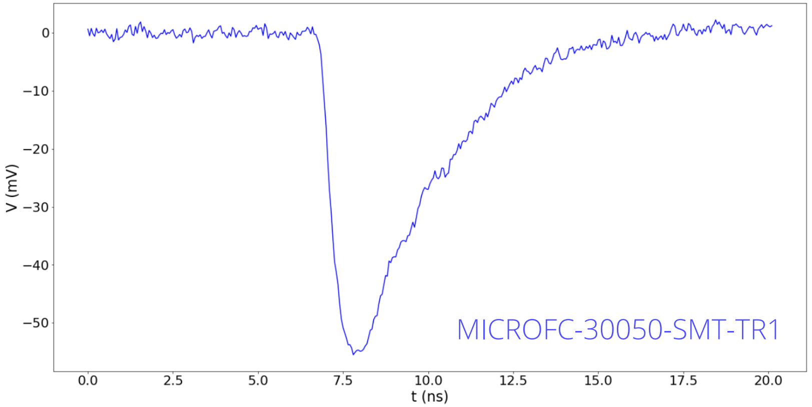
Avalanche Photodiode (APD)

The collected charge is increased without increasing the thickness (hence the collection time)

SiPM







“With great signal comes great noise”

Thermal and shot noise: charge carriers generated because of noise

After pulses: some carriers are trapped and emitted after > 100 ns

Cross-talk: due to photons produced by the avalanche

Cannot be used directly for MIP

Low Gain Avalanche Detectors (LGADs)

LGADs are silicon sensors optimized for timing measurements employing a thin multiplication layer to increase the output signal at the passage of a particle of a factor ~10.

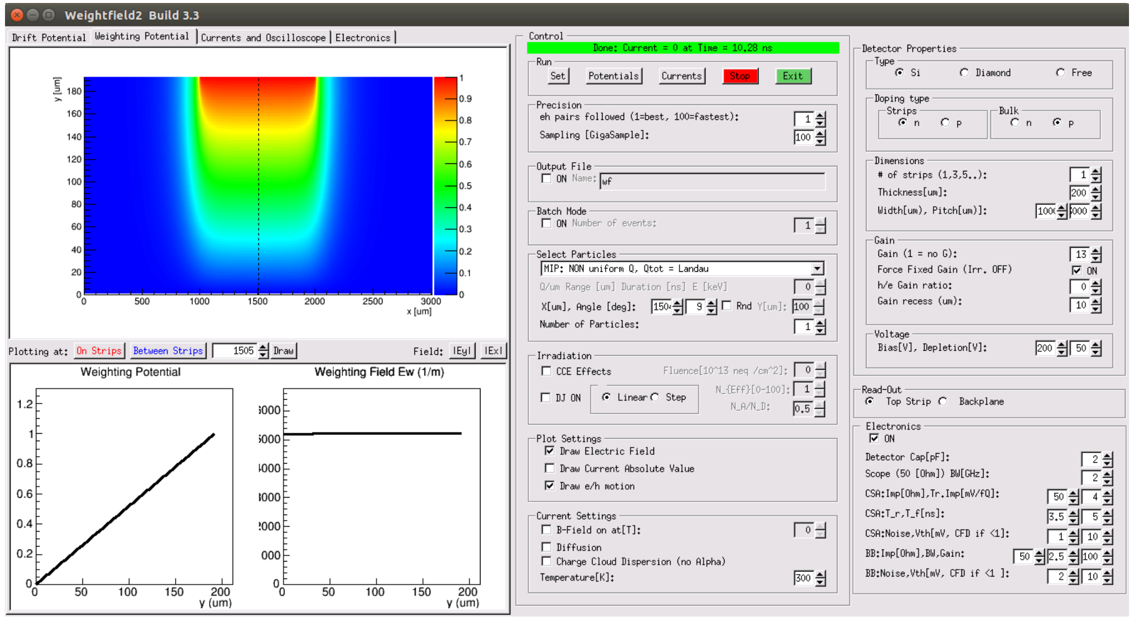
The signal generated at the passage of a MIP by a 50 μm LGAD can be simulated using Weightfield2

arXiv:1608.08681

Timing capabilities of Ultra-Fast Silicon Detector

The signal is "amplified" by a gain layer inside the sensor itself, but the leading edge is slower and depends on the charge that is collected by the gain layer

Time precision: ~30 ps



Control

Done: Current = 0 at Time = 10.28 ns

Precision
eh pairs followed (1=best, 100=fastest): 1
Sampling [GigaSample]: 100

Output File
☐ ON Name: wf

Batch Mode
☐ ON Number of events: 1

Select Particles
MIP: NON uniform Q, Qtot = Landau
Q/um Range [um] Duration [ns] E [keV]: 0
X[um], Angle [deg]: 150 9 ☐ Rnd Y[um]: 100
Number of Particles: 1

Irradiation
☐ CCE Effects Fluence[10^13 neq /cm^2]: 0
☐ DJ ON ● Linear ○ Step N_{Eff}[0-100]: 1
N_A/N_D: 0.5

Plot Settings
☑ Draw Electric Field
☐ Draw Current Absolute Value
☑ Draw e/h motion

Current Settings
☐ B-Field on at[T]: 0
☐ Diffusion
☐ Charge Cloud Dispersion (no Alpha)
Temperature[K]: 300

Detector Properties
Type: ● Si ○ Diamond ○ Free
Doping type: Strips ● n ○ p; Bulk ○ n ● p

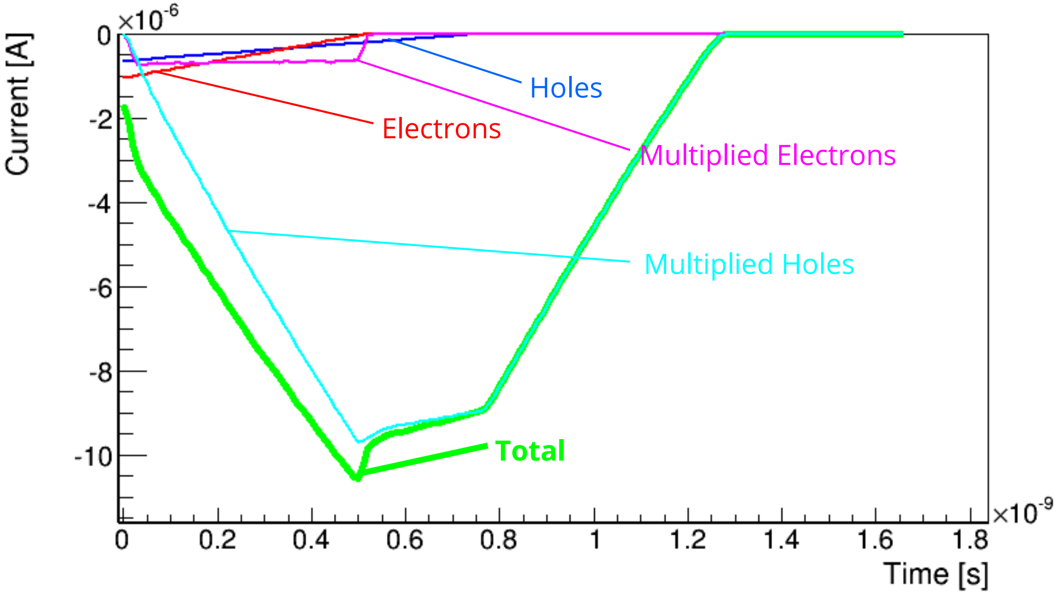
Dimensions
# of strips (1,3,5..): 1
Thickness[um]: 200
Width[um), Pitch[um)]: 100 000

Gain
Gain (1 = no G): 13
Force Fixed Gain (Irr. OFF) ☑ ON
h/e Gain ratio: 0
Gain recess (um): 10

Voltage
Bias[V], Depletion[V]: 200 50

Read-Out
● Top Strip ○ Backplane

Electronics
☑ ON
Detector Cap[pF]: 2
Scope (50 [Ohm]) BW[GHz]: 2
CSA:Imp[Ohm],Tr.Imp[mV/fQ]: 50 4
CSA:T_r,T_f[ns]: 3.5 5
CSA:Noise,Vth[mV, CFD if <1]: 1 10
BB:Imp[Ohm],BW,Gain: 50 2.5 100
BB:Noise,Vth[mV, CFD if <1]: 2 10



50 μm LGAD at 200V with a gain 20

Measuring the arrival time

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

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

Contribution of the noise:

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

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

Statistical fluctuations of energy deposit

Slow drift: temperature variations, aging, etc.

OPTIMIZATION OF THE SENSOR

OPTIMIZATION OF THE FRONT-END ELECTRONICS

The main tecniques to correct *time walk* are:

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- Cross-Correlation (CC).

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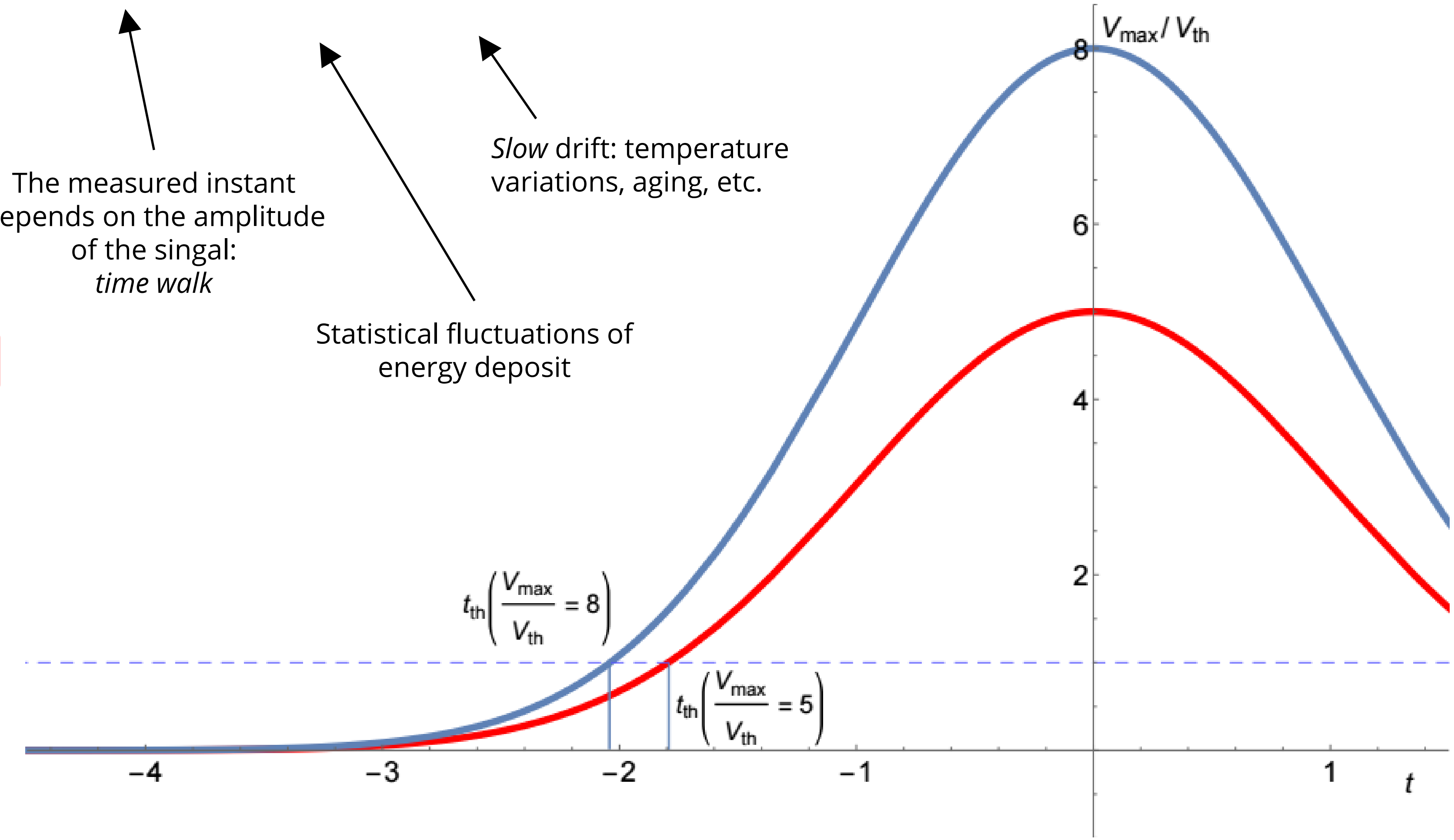
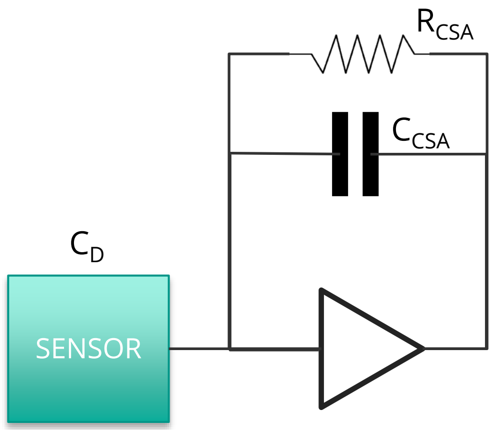


Charge Sensitive Amplifier

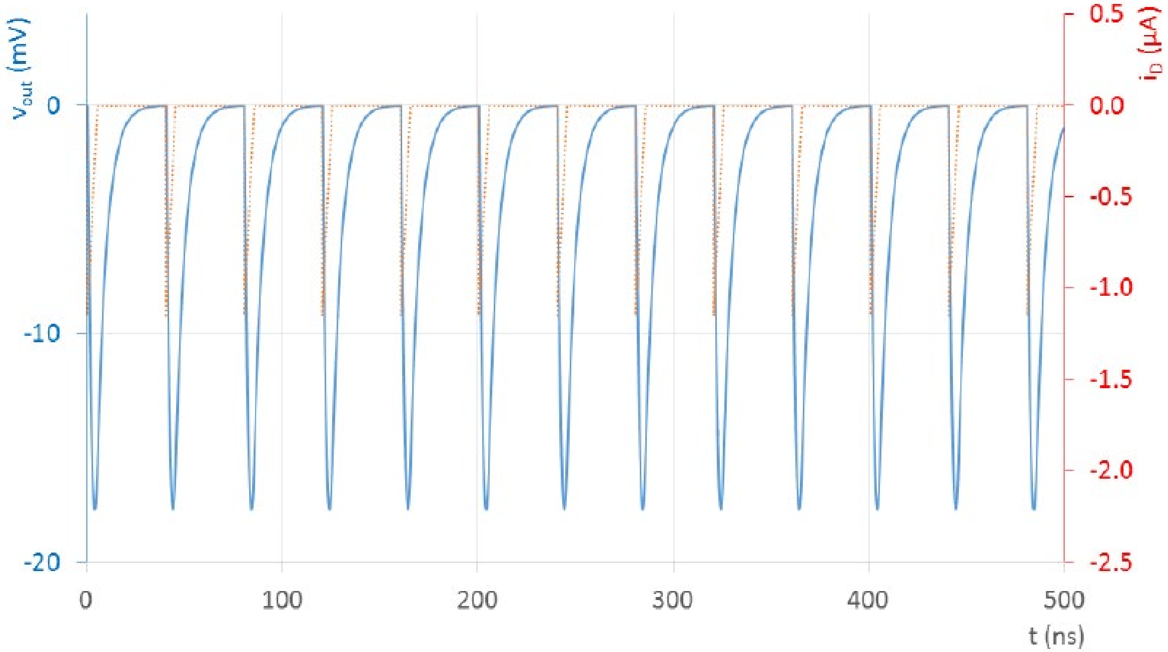
The output of a Charge Sensitive Amplifier (CSA) is proportional to the charge injected by the sensor.



$$v_{out} = -\frac{C_D}{C_{CSA}}\frac{1}{1+\frac{C_D}{C_{CSA}}}Q_{gen}$$

$Q_{gen} = \int i_{gen}\, dt$ → Good solution for:

- *Large* SNR
- *Slow* signal

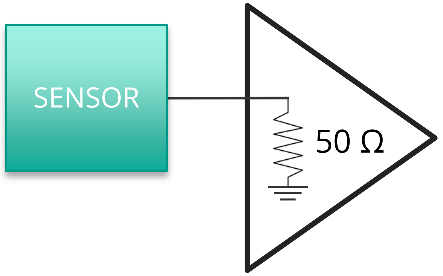


Simulation of a diamond detector read-out using a ideal Charge Sensitive Amplifier

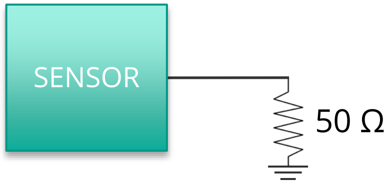
More details: Sec. 4.5 of Development of a timing detector for the TOTEM experiment at the LHC

Broadband amplifier

A Broadband Amplifier (BDA) can take advantage of a fast signal.



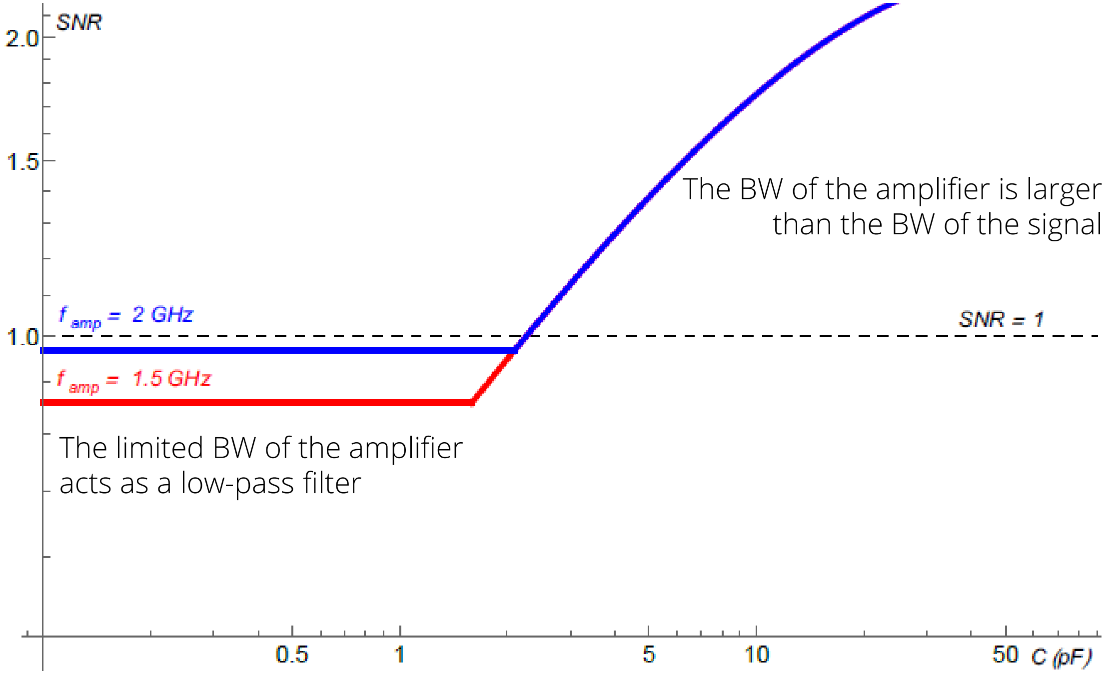
SNR for the ideal case of a read-out resistor:



$$SNR = \frac{SNR_R}{\sqrt{F}} = \frac{k_0}{\sqrt{F}} \frac{R_i C}{\sqrt{k_B T C}} \left(t_{tr} + R_i C \ln \left(\frac{R_i C}{R_i C + t_{tr}} \right) \right)$$

F: Noise Factor
only contribution from the amplifier

Good solution for *large* and *fast* signals.



The BW of the amplifier is larger than the BW of the signal

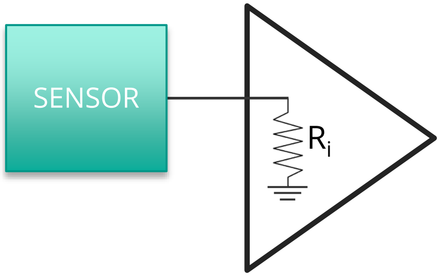
The limited BW of the amplifier acts as a low-pass filter

Simulated diamond detector read for F ~ 1.5 at T = 300K.

More details: Sec. 4.4 of [Development of a timing detector for the TOTEM experiment at the LHC]

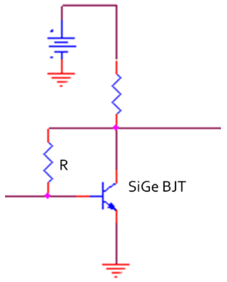
Amplifier with high input impedance

A different approach that has some advantage of a BDA and some of the CSA is an amplifier with High Input impedance (Himp).



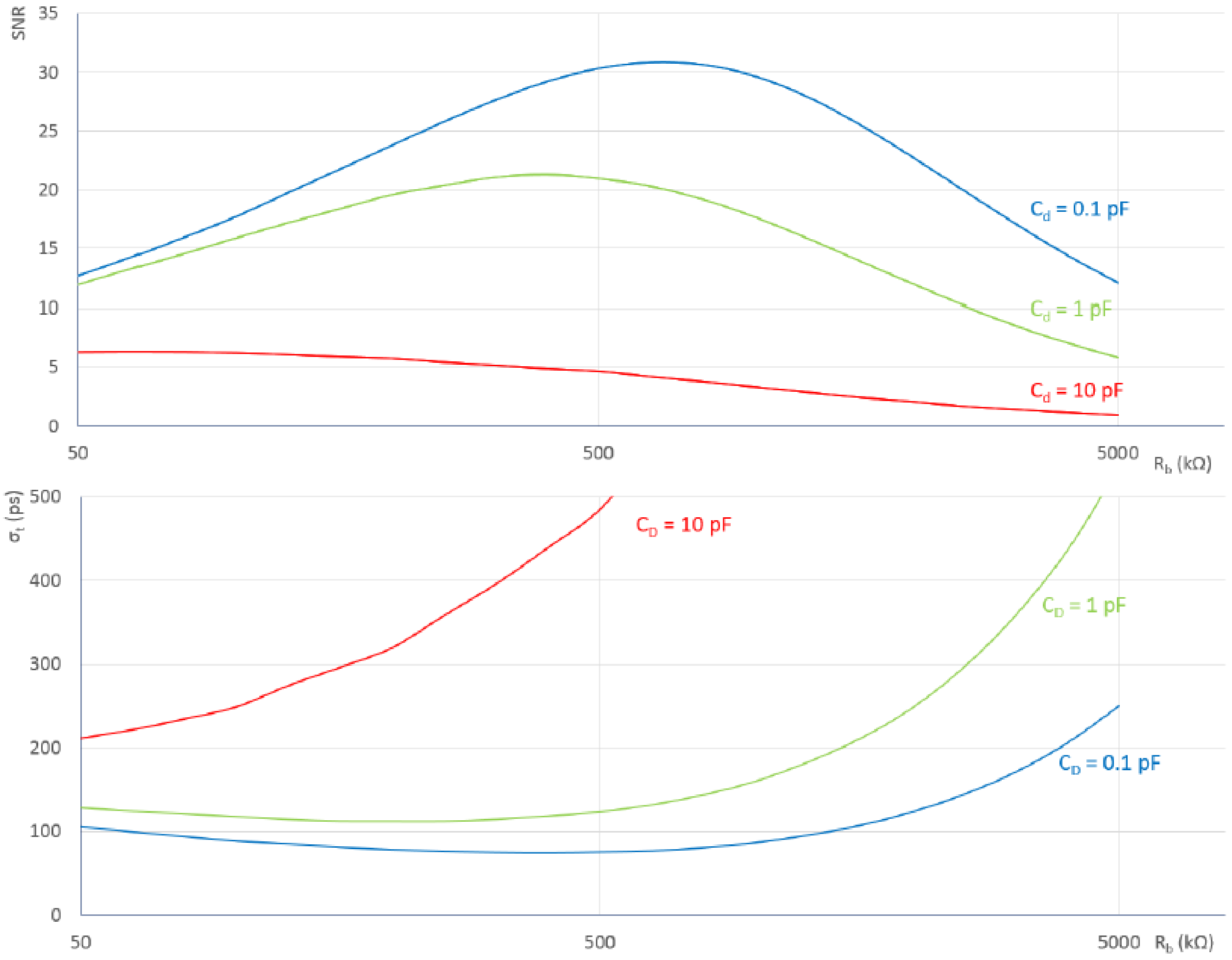
The input impedance has to be selected according to the characteristics of the sensor.

The main advantage/disadvantage is that there are no COTS solutions!



The best value of R for timing has to be optimized according to the sensor:

- High for diamonds (R ~ 100 kΩ)
- Lower for thick UfSD (R ~ 10 kΩ)
- Low for 50 µm UfSD



Simulated SNR and time precision for a diamond detector.

More details: Sec. 4.6 of Development of a timing detector for the TOTEM experiment at the LHC

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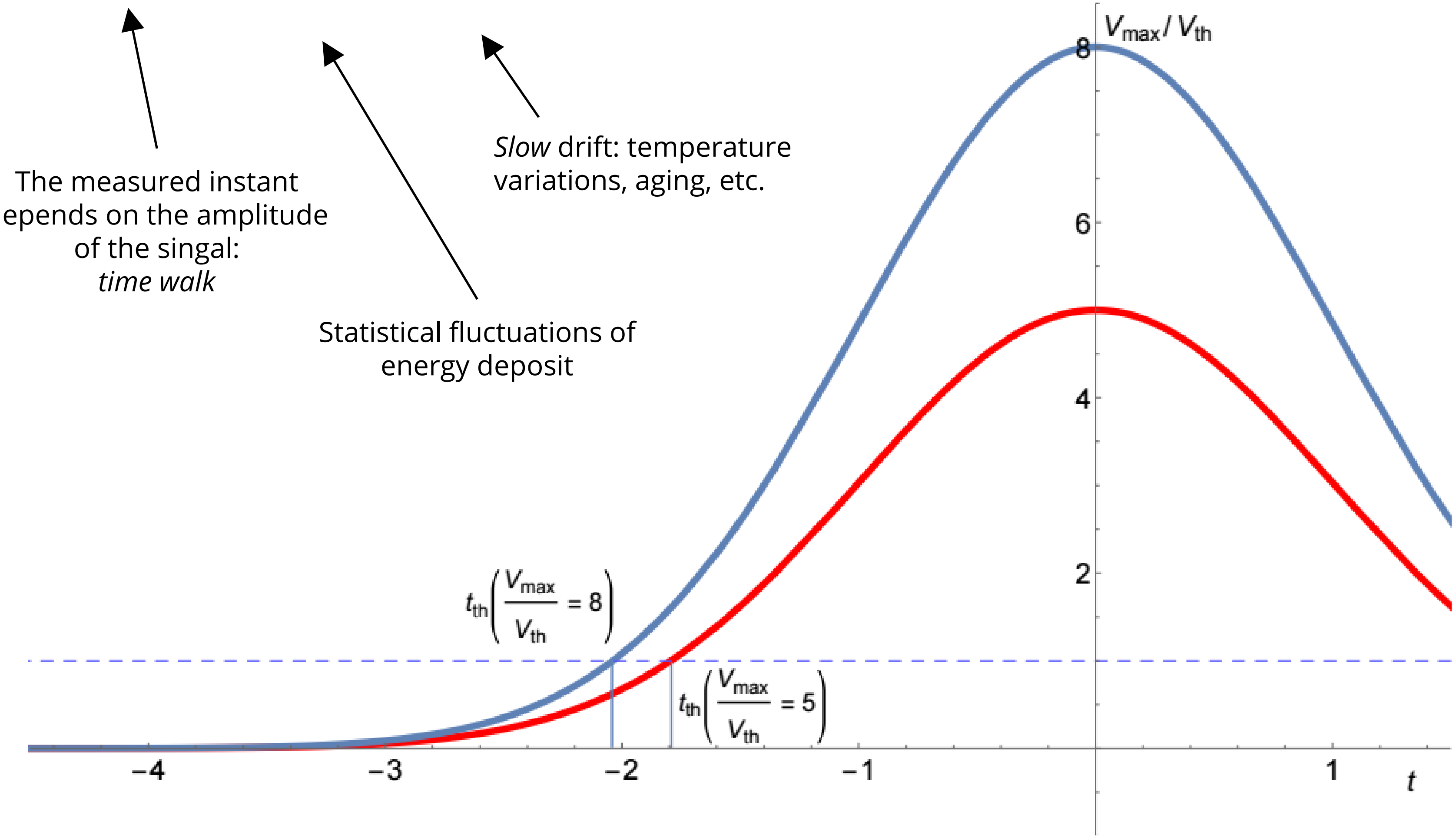


Constant Fraction Discriminator

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

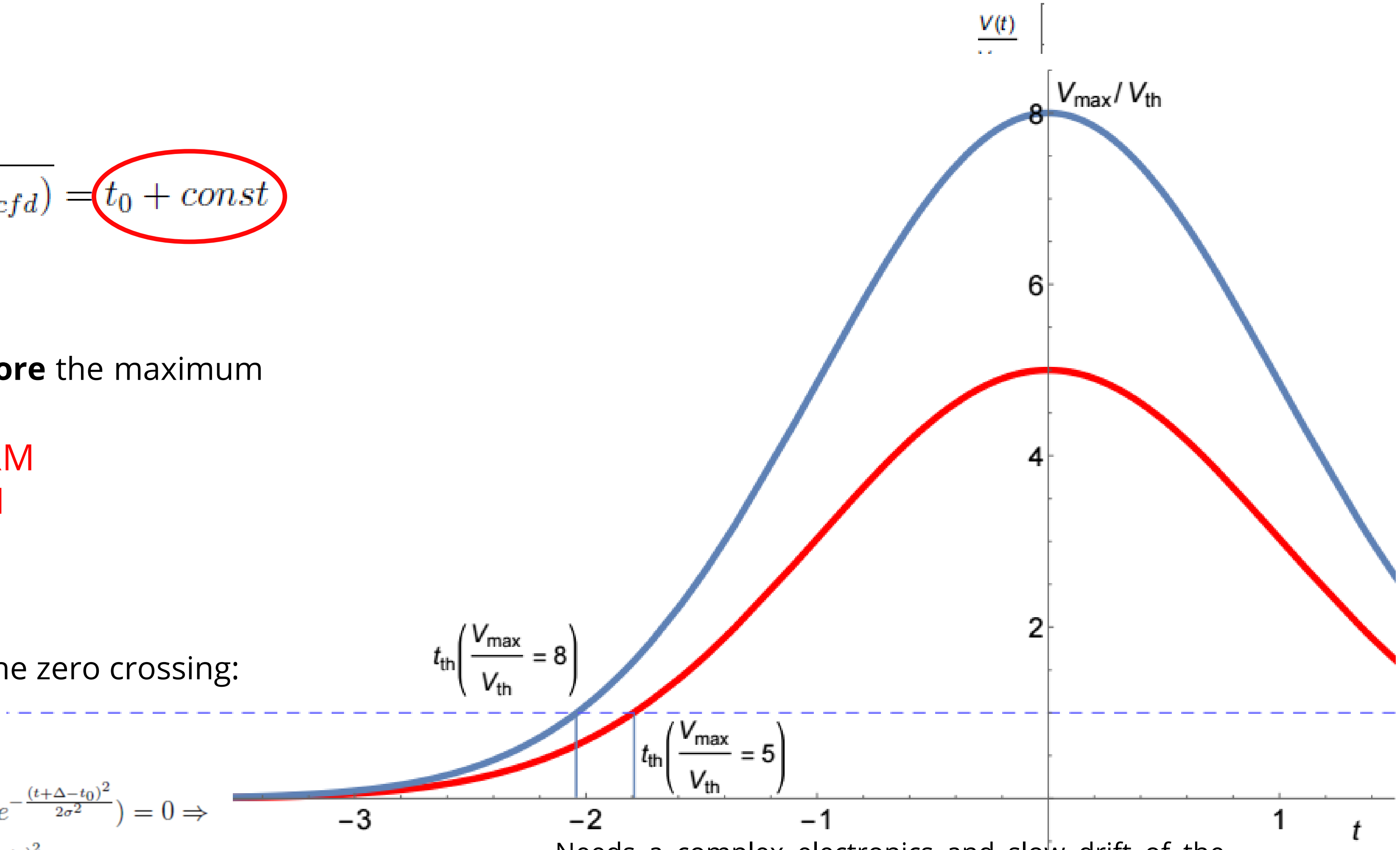
$$V_{th} = k_{cfd} V_{max}$$

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

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

FULL WAVEFORM DIGITIZATION

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



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

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

$$\Rightarrow e^{-\frac{(t-t_0)^2}{2\sigma^2}} - k_{cfd}\, e^{-\frac{(t+\Delta-t_0)^2}{2\sigma^2}} = 0 \longleftarrow \text{No } V_{max}$$

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

Time over Threshold

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

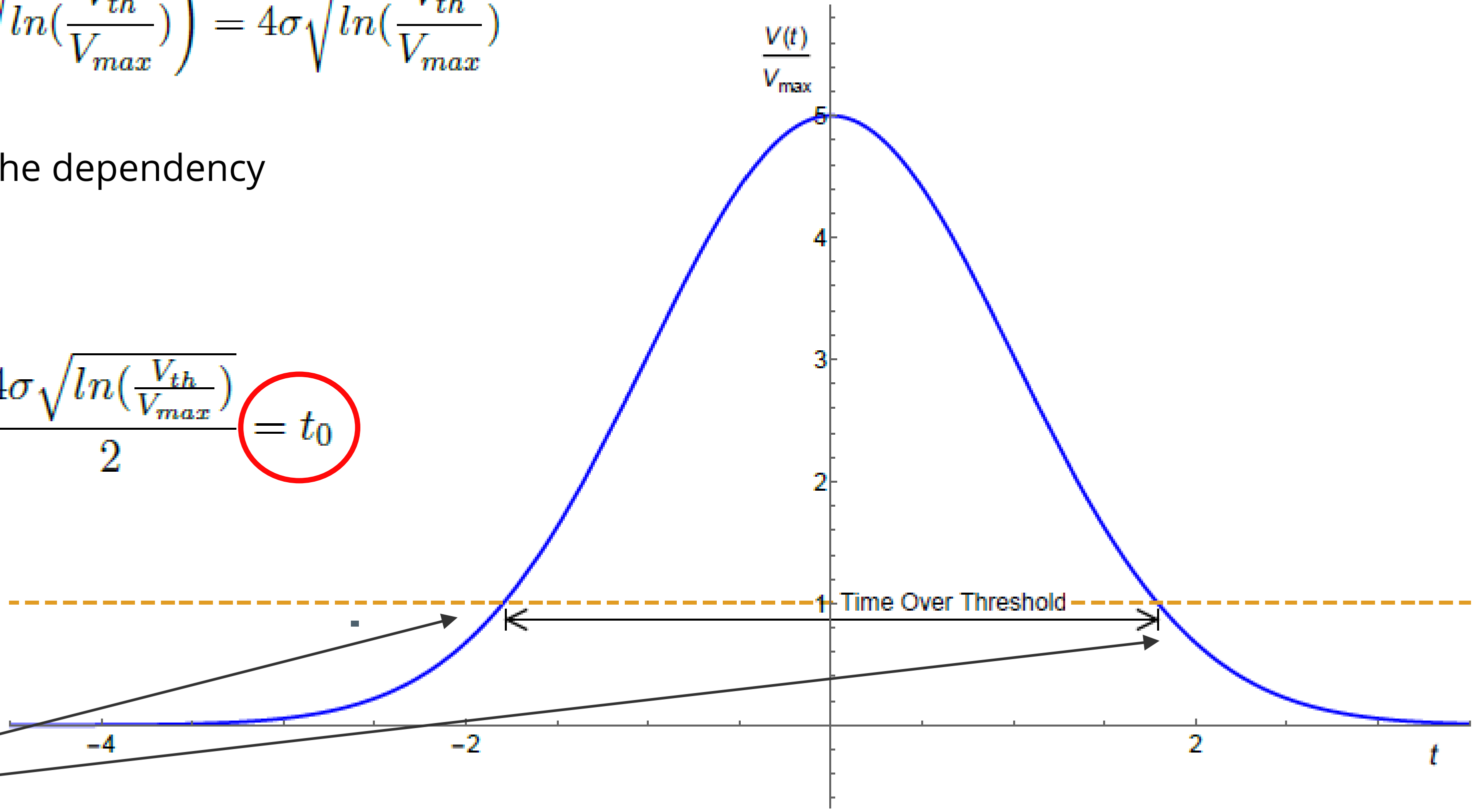
The ToT depends on the amplitude:

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

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

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

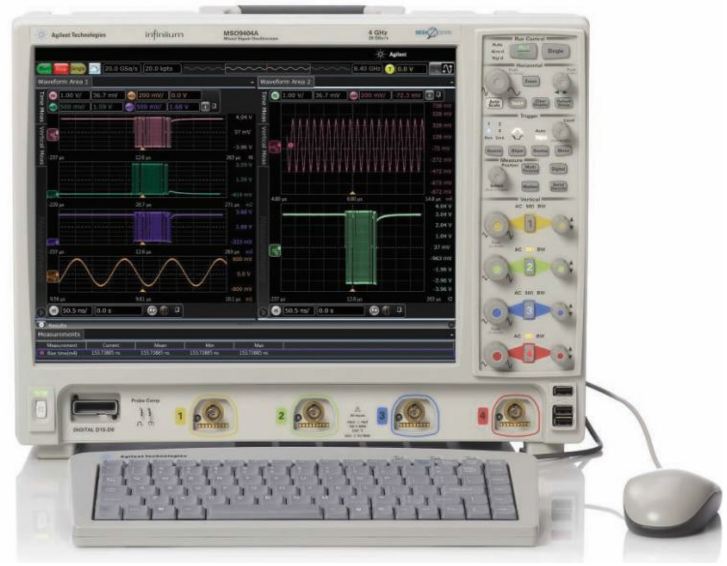
$$t_{corr} = t_{th} + \boxed{f(t_{tot})} = t_0 - 2\sigma\sqrt{ln(\frac{V_{th}}{V_{max}})} + \frac{4\sigma\sqrt{ln(\frac{V_{th}}{V_{max}})}}{2} \boxed{= t_0}$$



$$\sigma_{jitter} \sim \frac{\sigma_V}{dV/dt}$$

Digitization of the signal…. Why?

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



Advantages of sampling:

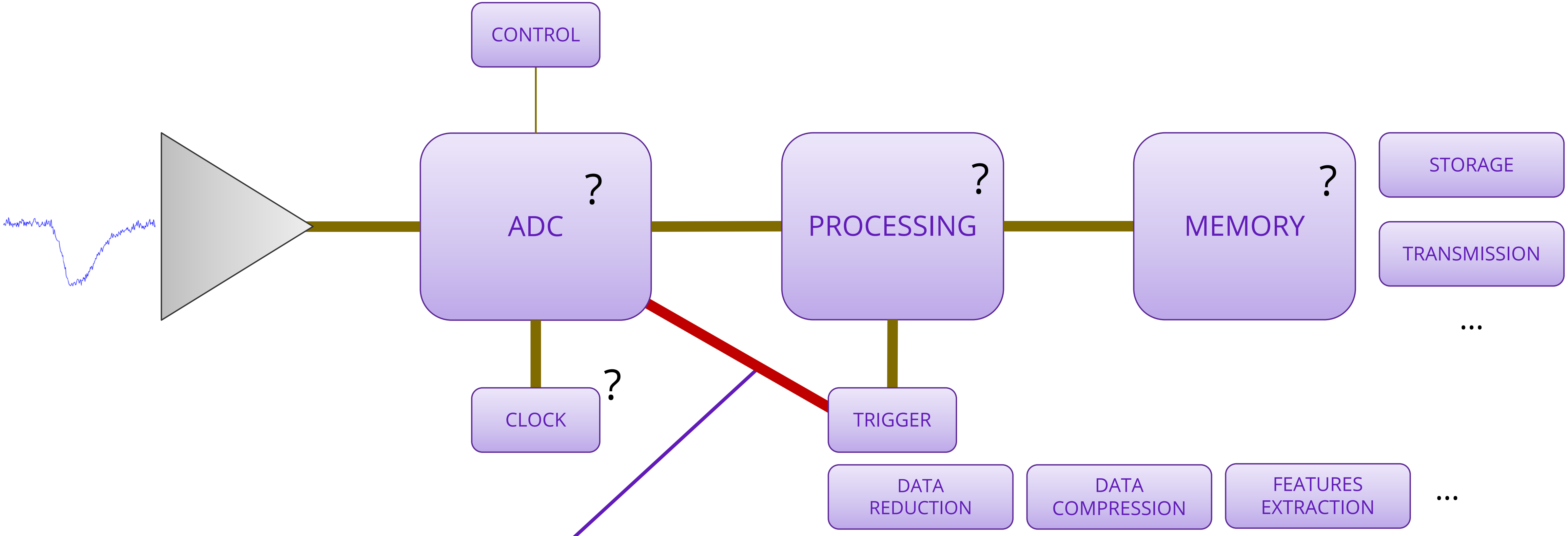
- *Infinite* analysis possibilities (AI…)
- Possible to improve performance off-line
- Digital elaboration (Moore's law)

Cons

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

Digitization of the signal…. How?

After the analog signal is amplified, it is digitized using an Analog to Digital Converter (ADC)



Only possible if trigger arrives **before** the signal

Digitization “without” loss of information

The system can be designed in a way the measurement is limited by the detector and not by the digitizer

1- Nyquist–Shannon sampling theorem $f_{SAMPLING} \geq 2\, f_{SIGNAL}$ (assuming sinc antialiasing)

Rule of thumb (conservative): $f_{SAMPLING} \sim 3 f_{SIGNAL}$

2- Quantization noise

$SNR\ [\mathrm{dB}] = (6.02\ ENOB) + 1.76$

quantization error is uniformly distributed between −1/2 LSB and +1/2 LSB for a sine wave

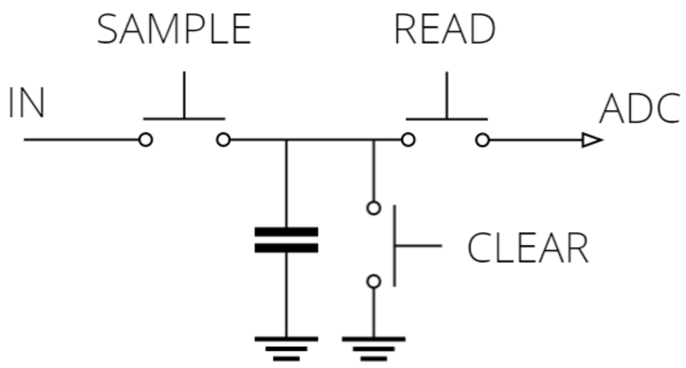
ENOB: effective number of bits

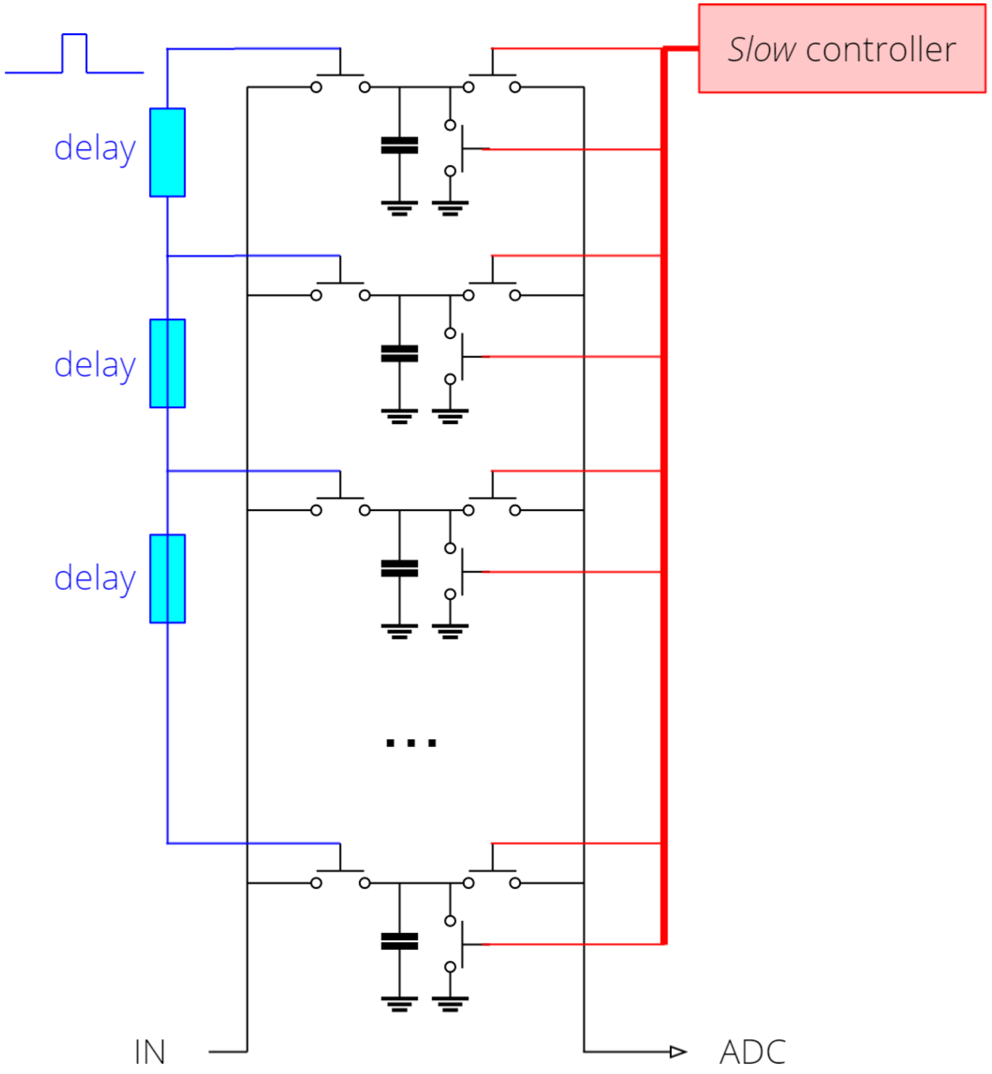
ENOB 8 bits: SNR ~48 dB (256)

Diamond SNR ~ 28 dB (25) -> quantization is degrading the SNR by ~0.5%
LGAD SNR ~ 40 dB (100) -> quantization is degrading the SNR by ~7%

Can we decouple sampling and digitization?

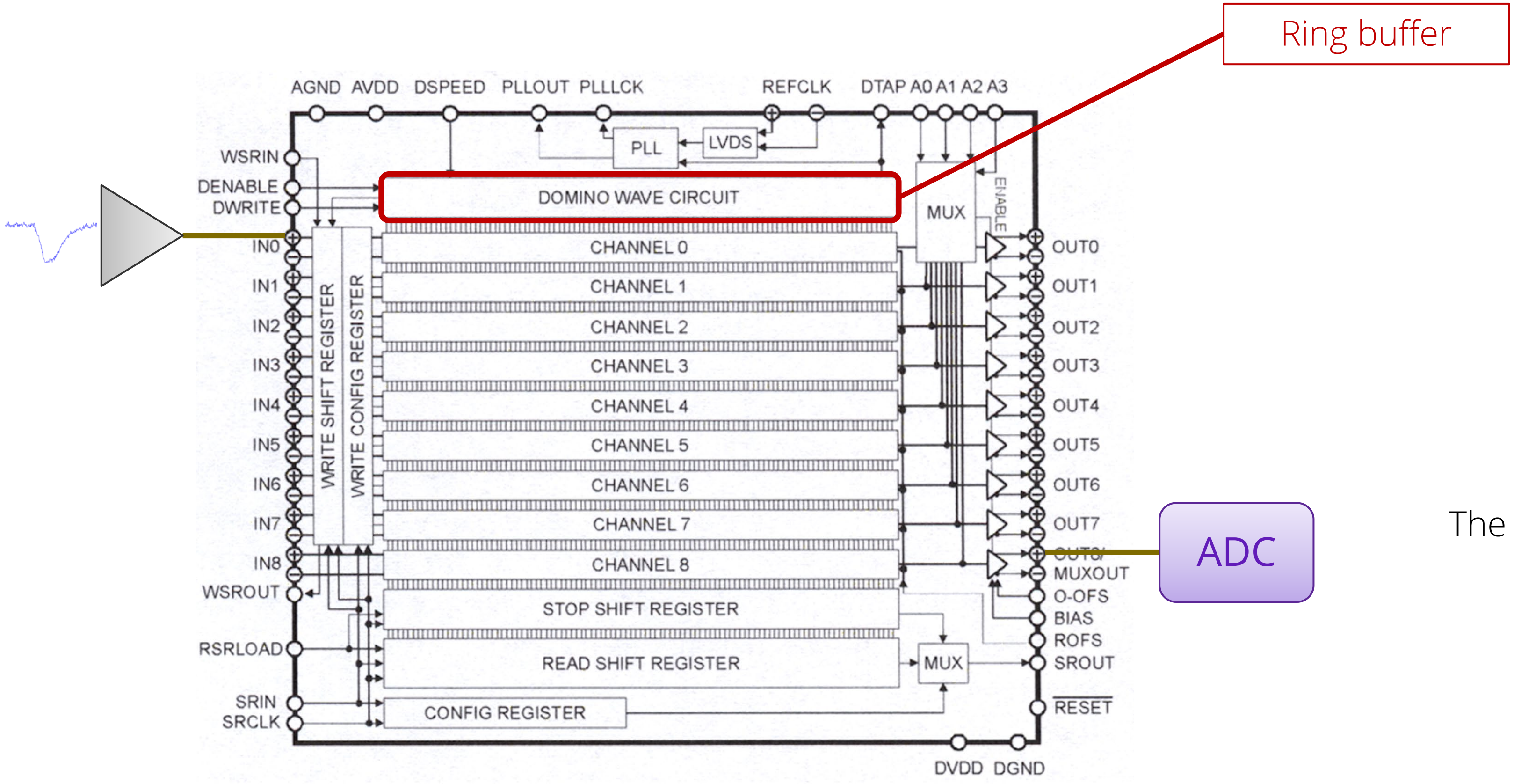
We can use a fast electronics to sample the signal and then a slower electronics to digitized the sampled signal

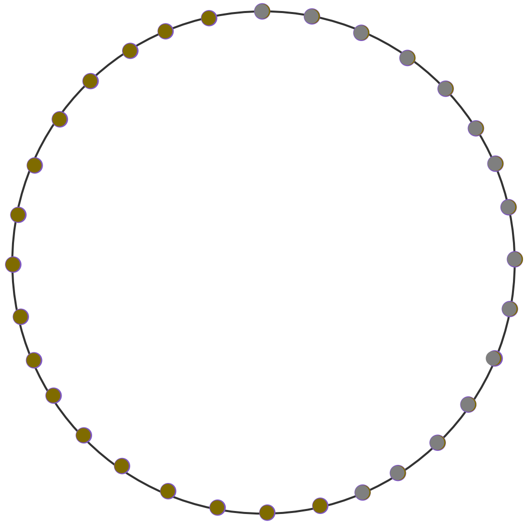




DRS4: Domino Ring Sampler

9 ch, up to 5 GS/s, 950 MHz BW, 1024 sampling cells, 140 mW





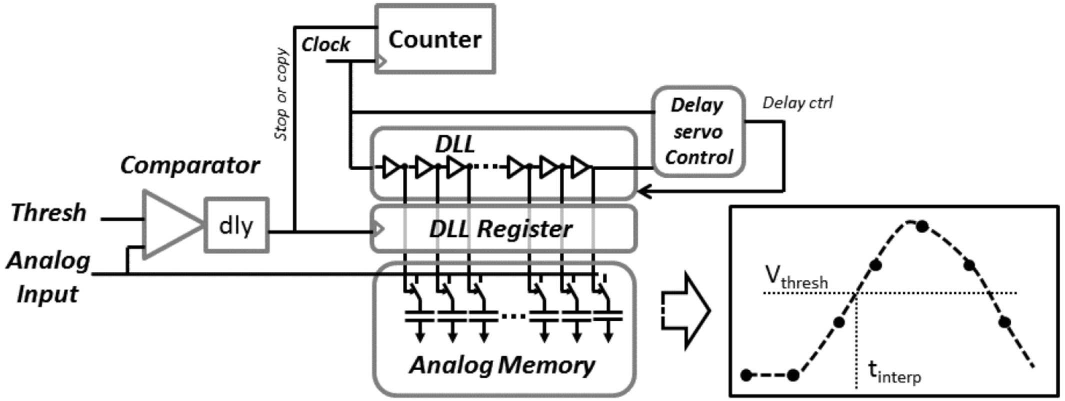
The trigger **stops** the sampling

Digitization starts (sampler is stopped)

Sampling starts again

Wavecatcher & friends…

All samples of one channel can be digitized at once: lower dead time



SAMPIC: a readout chip for fast timing detectors in particle physics and medical imaging

Measurements of timing resolution of ultra-fast silicon detectors with the SAMPIC waveform digitizer

Wavecatcher (SAMLONG chip)

2 ch, up to 3.2 GS/s, 500 MHz BW, 12 bits, 1024 sampling cells, conversion time <66 us, 400 mW

SAMPIC

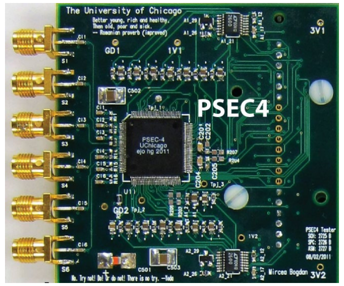
16 ch, up to 10 GS/s, >1 GHz BW, 11 bits, 64 sampling cells, conversion time 0.1 – 1.6 μs, 180 mW

PSEC4

6 ch, up to 15 GS/s, 1.5 GHz BW, 11 bits, 256 sampling cells, conversion time 4 μs, 100 mW

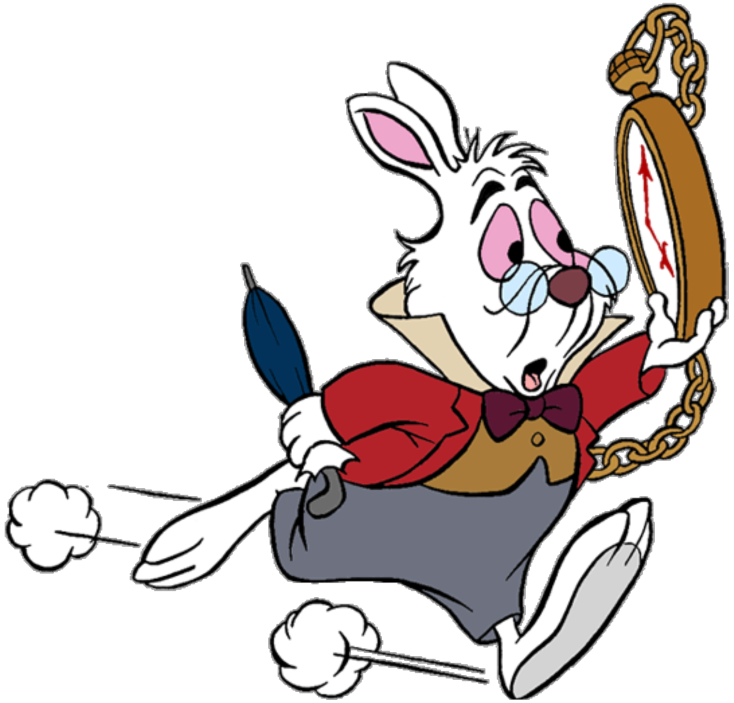
SCA ASIC

8 ch, >5 GS/s, 1 GHz BW, 12 bits, 128 sampling cells, conversion time 4 μs

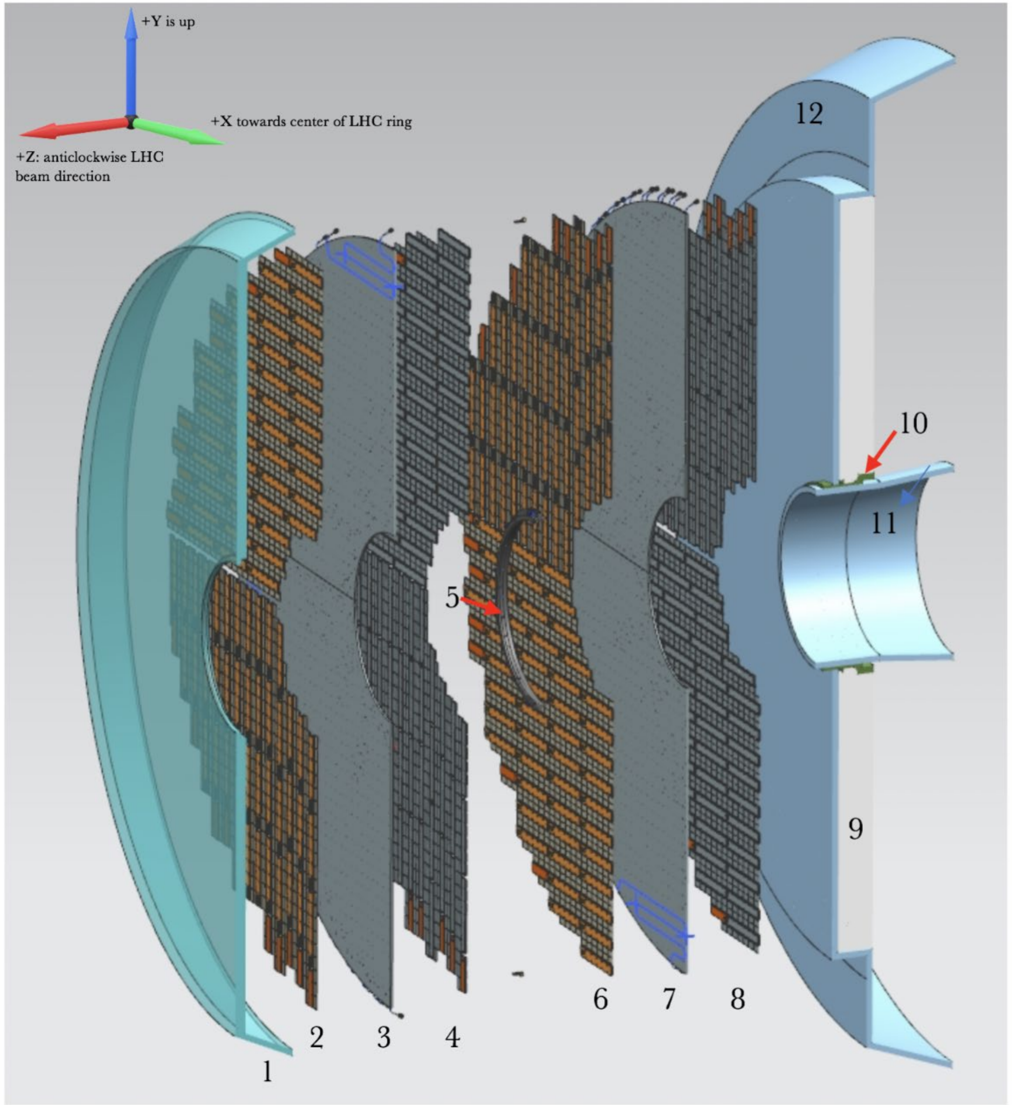


Outline

- Why timing?
- How timing?
    - Solid State Sensors
    - Front-end electronics
    - Measurement of the arrival time
- **Example of Timing Detectors at LHC:**
    - **CMS MIP Timing Detector**
    - **TOTEM Timing Detector**
- Medical applications of Timing Detectors



LGADs for the MTD End Caps



1: ETL Thermal Screen
2: Disk 1, Face 1
3: Disk 1 Support Plate
4: Disk 1, Face 2
5: ETL Mounting Bracket
6: Disk 2, Face 1
7: Disk 2 Support Plate
8: Disk 2, Face 2
9: HGCal Neutron Moderator
10: ETL Support Cone
11: Support cone insulation
12: HGCal Thermal Screen

Two disks of LGADs (per side) $1.6 < |\eta| < 3.0$:

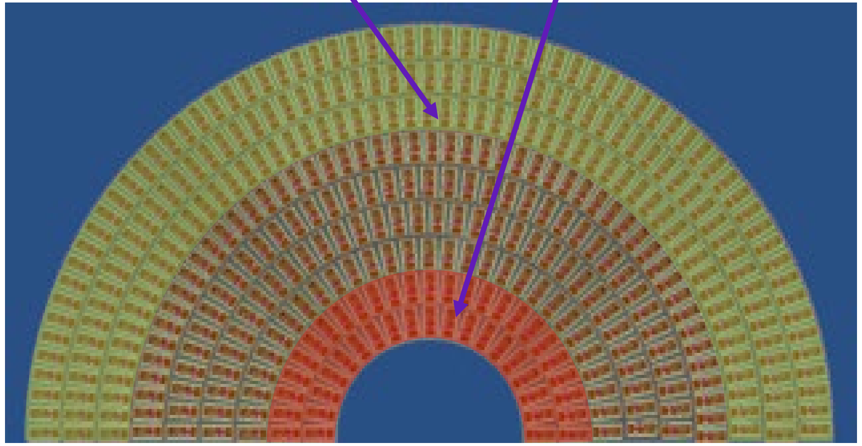
Average 1.8 hits per track

Designed for **σ < 50 ps** per hit

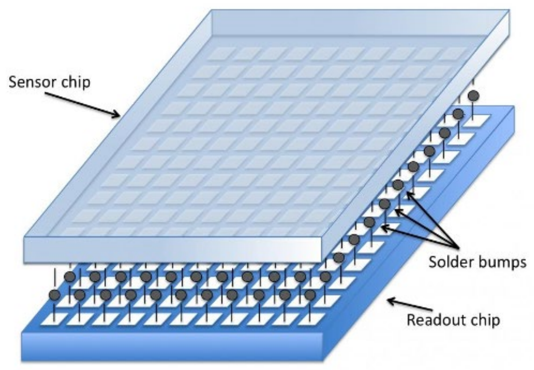
- Pad size: 1.3 x 1.3 mm^2
- High fill factor (>85% per layer)
- ~30k sensors of 2x2 cm^2

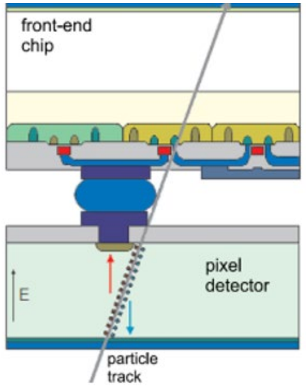
Less than 4×10^{14} n_{eq}/cm^2 for 50% of sensors

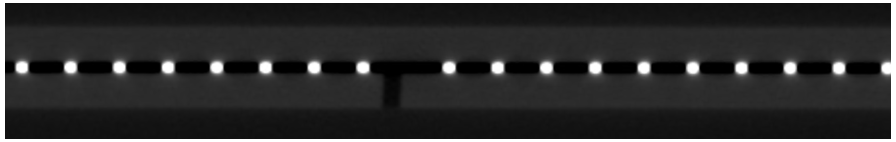
Up to 2×10^{15} n_{eq}/cm^2 for 15% of sensors



ETROC: CMS ETL ReadOut Chip

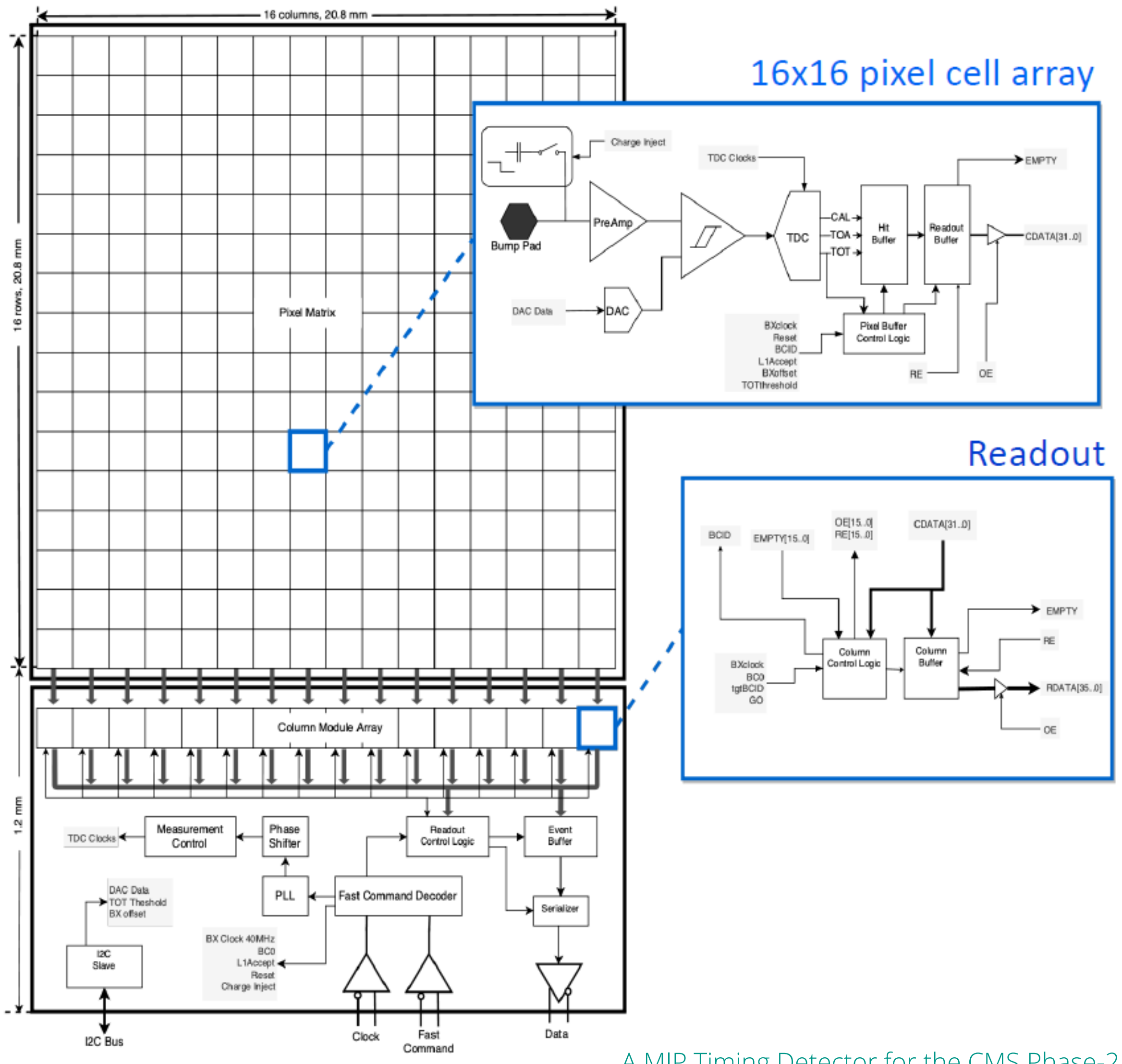






The readout chip is bump bonded to the sensor and wedge bonded to the readout board

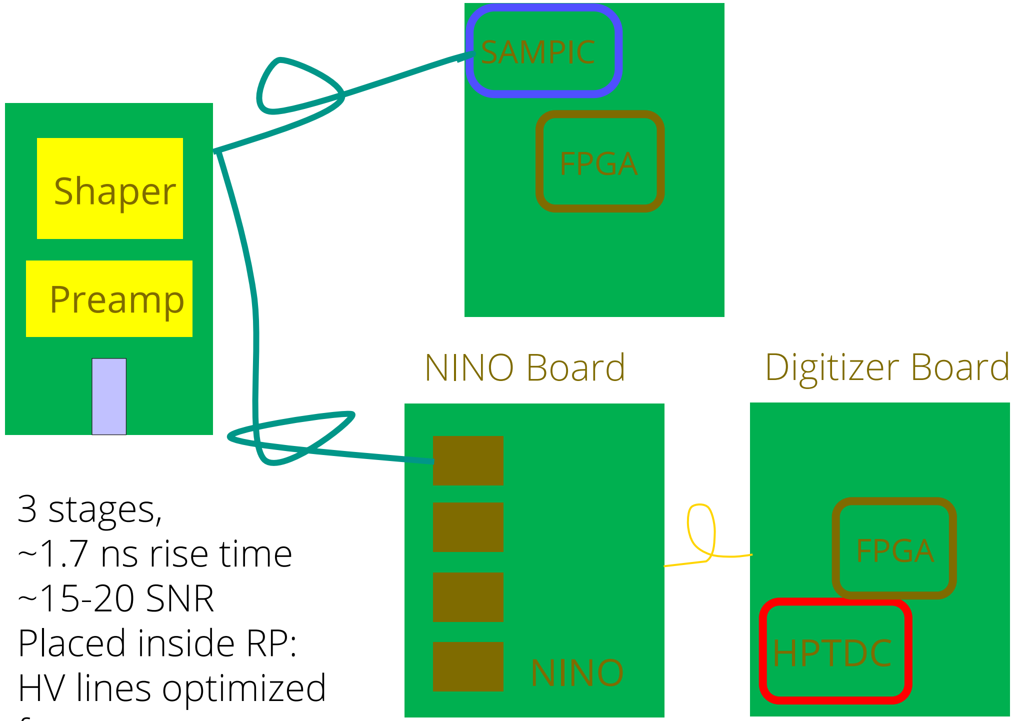
- ASIC contribution to time precision <40 ps
- Power consumption: <4 mW/ch (80 kW total)
- Trigger rate: Up to 1 MHz



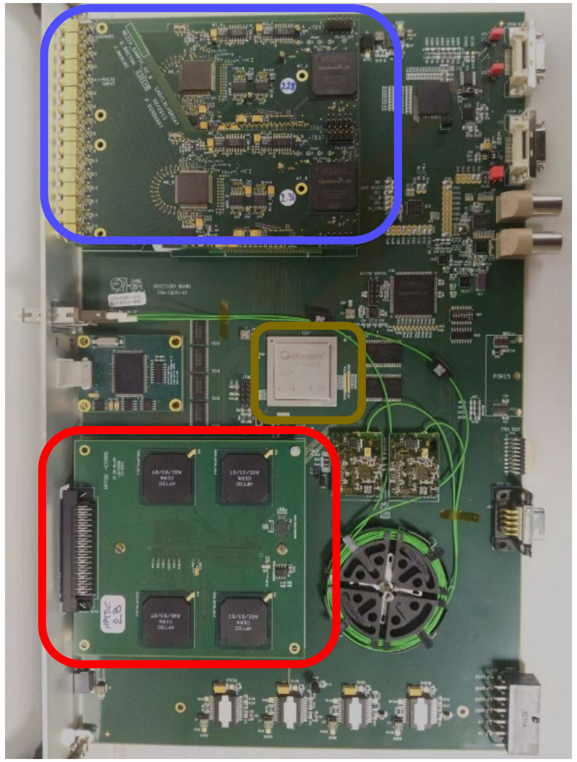
A MIP Timing Detector for the CMS Phase-2 Upgrade

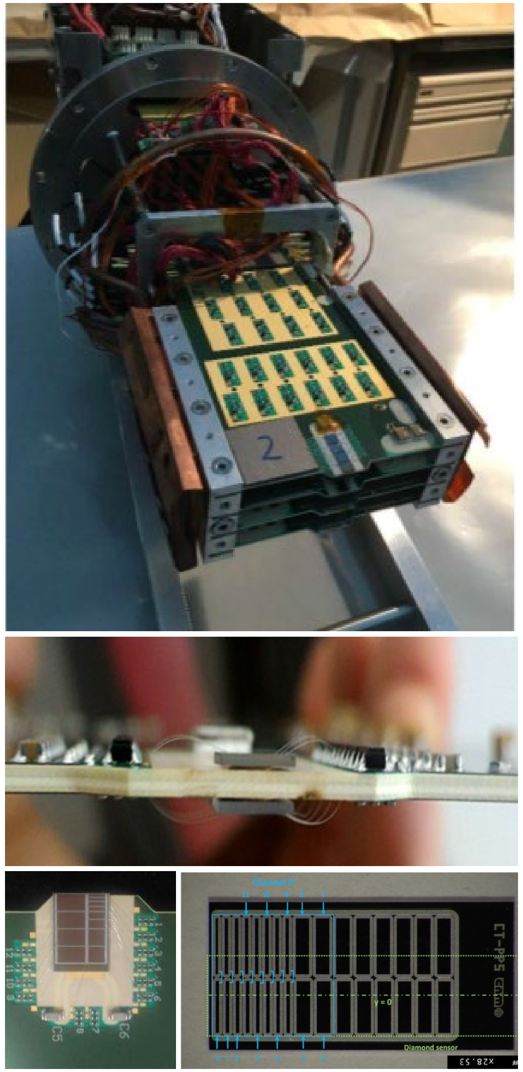
Timing detectors of CMS-TOTEM

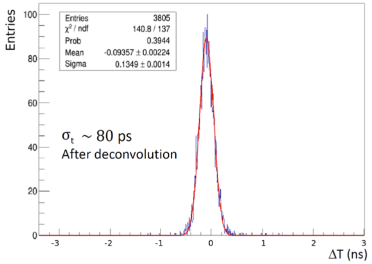
Different sensors are read-out by a trans-impedance preamplifier, then the signal can be digitized using SAMPIC or discriminated and digitized using HPTDC



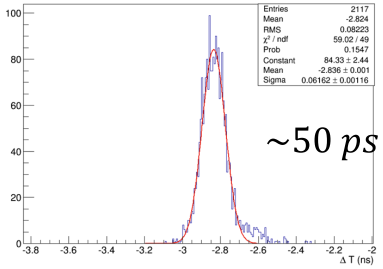
3 stages,
~1.7 ns rise time
~15-20 SNR
Placed inside RP:
HV lines optimized
for vacuum







Single diamond



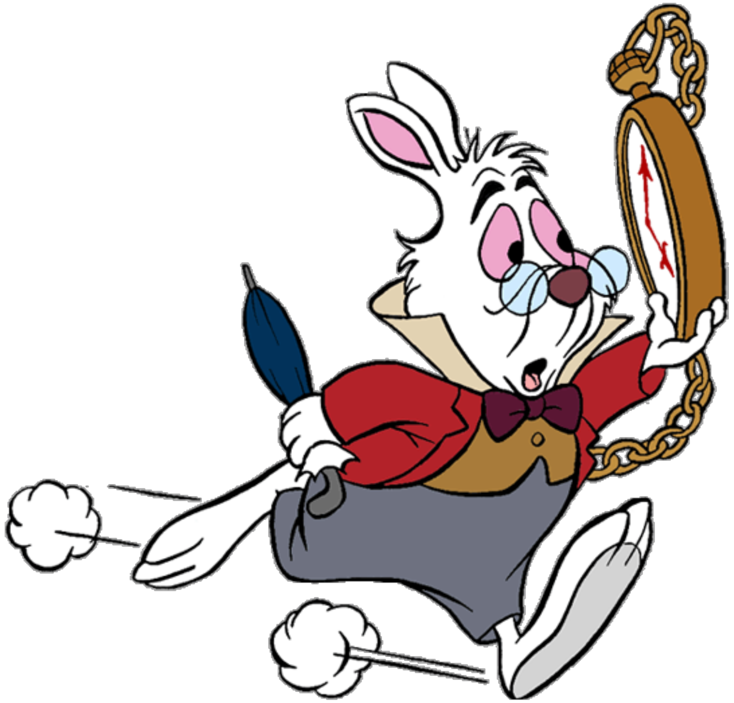
Double diamond

Diamond detectors for the TOTEM timing upgrade

Timing performance of a double layer diamond detector

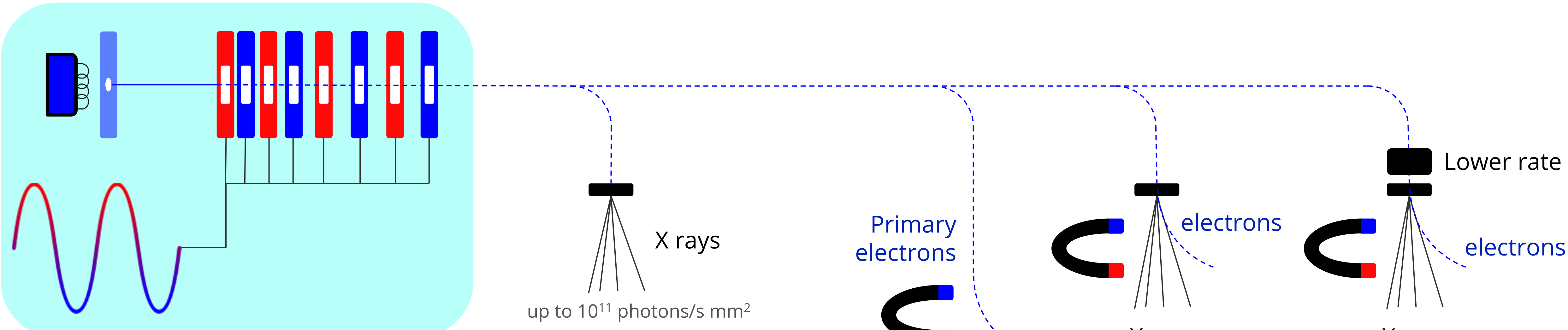
Outline

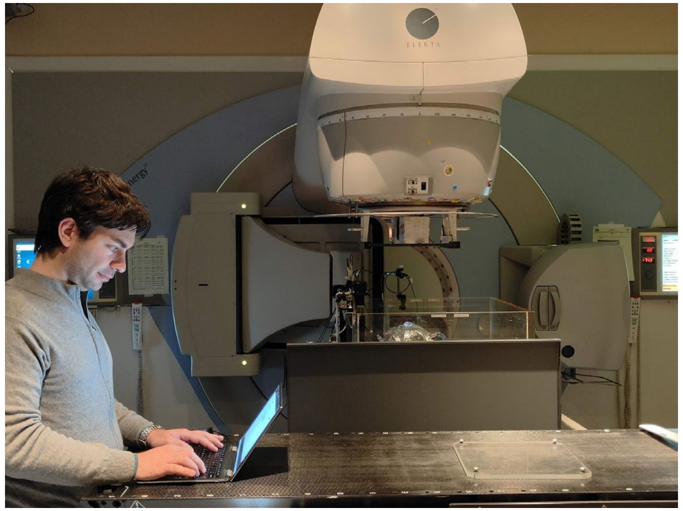
- Why timing?
- How timing?
    - Solid State Sensors
    - Front-end electronics
    - Measurement of the arrival time
- Example of Timing Detectors at LHC:
    - CMS MIP Timing Detector
    - TOTEM Timing Detector
- **Medical applications of Timing Detectors**



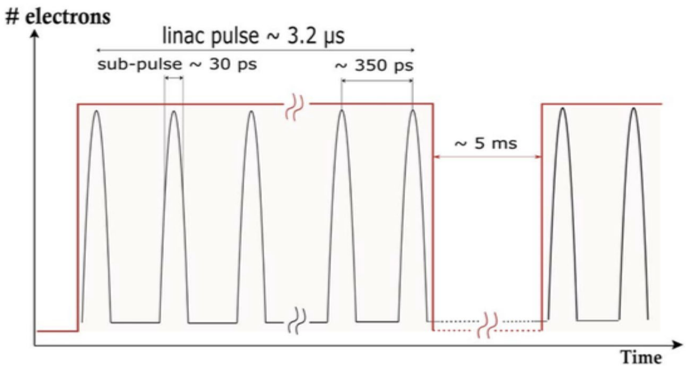
Particle accelerators for medical applications

A LINAC designed for radiotherapy can be used in different configurations





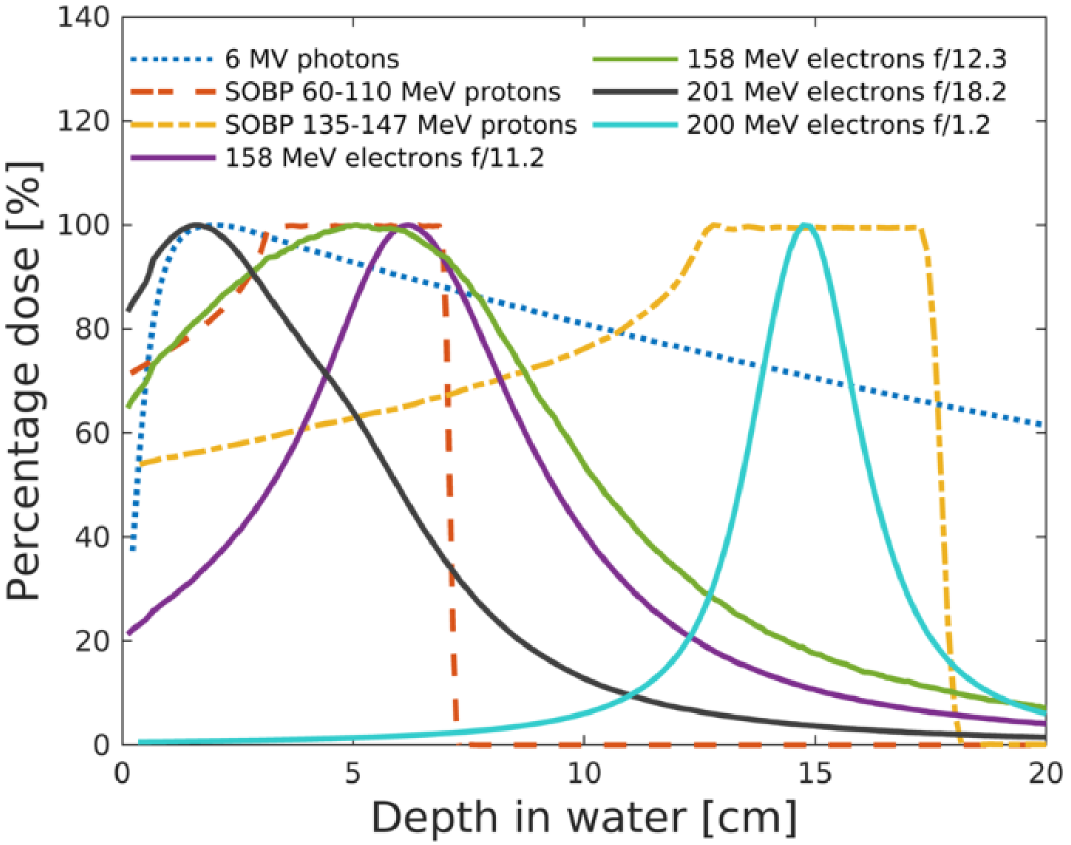
St. Luke Hospital
Dublin



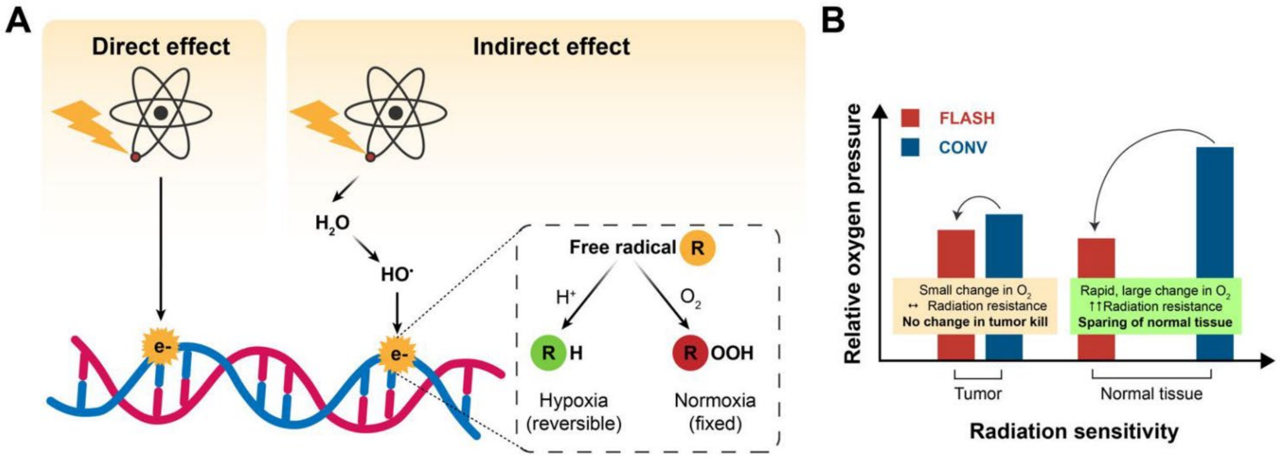
Performance of a low gain avalanche detector in a medical linac and characterisation of the beam profile

“Very” High Energy electrons and proton beams and FLASH therapy

Simulations of **axial dose** distributions in a water phantom for different beam geometries and energies.



*Spread Out Bragg Peak



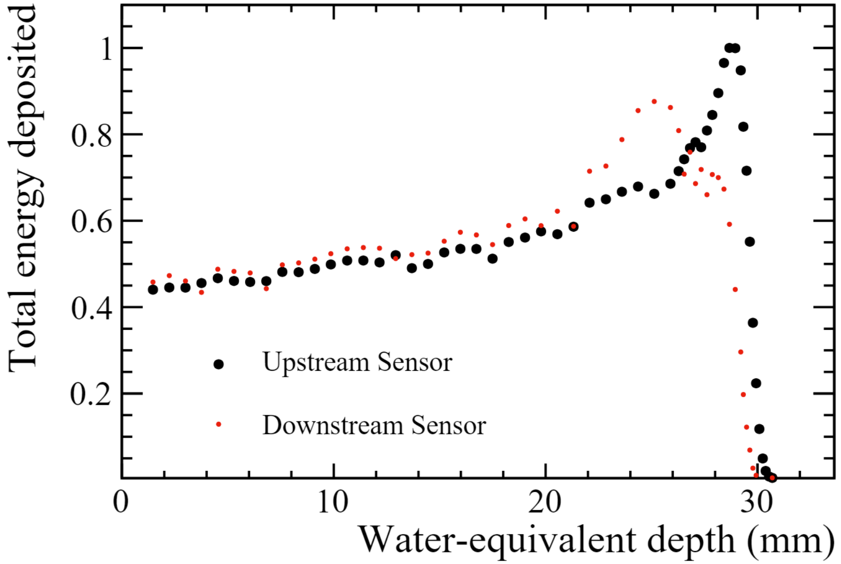
[Treatment of a first patient with FLASH-radiotherapy]

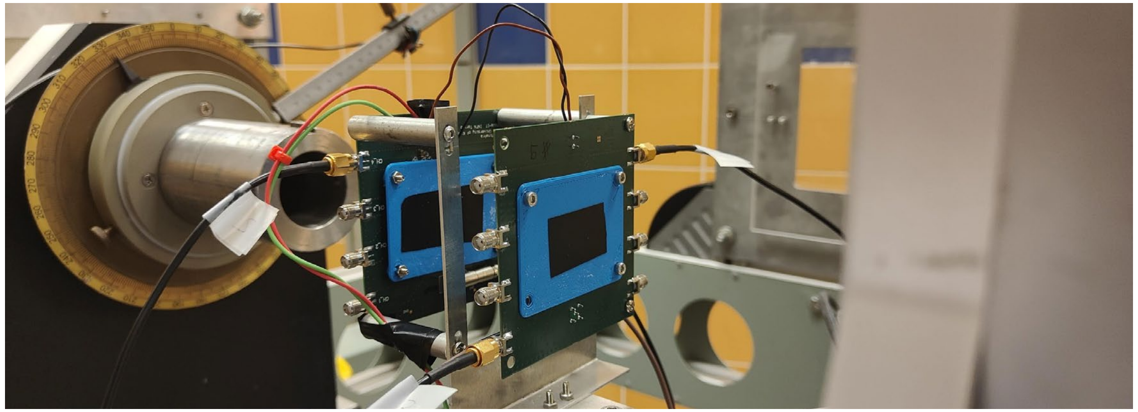
[Radiobiological Aspects of FLASH Radiotherapy]

[An experimental study of focused very high energy electron beams for radiotherapy]

Particle accelerators for medical applications

AIC-144: 58 MeV proton cyclotron at the Institute for Nuclear Physics in Krakow

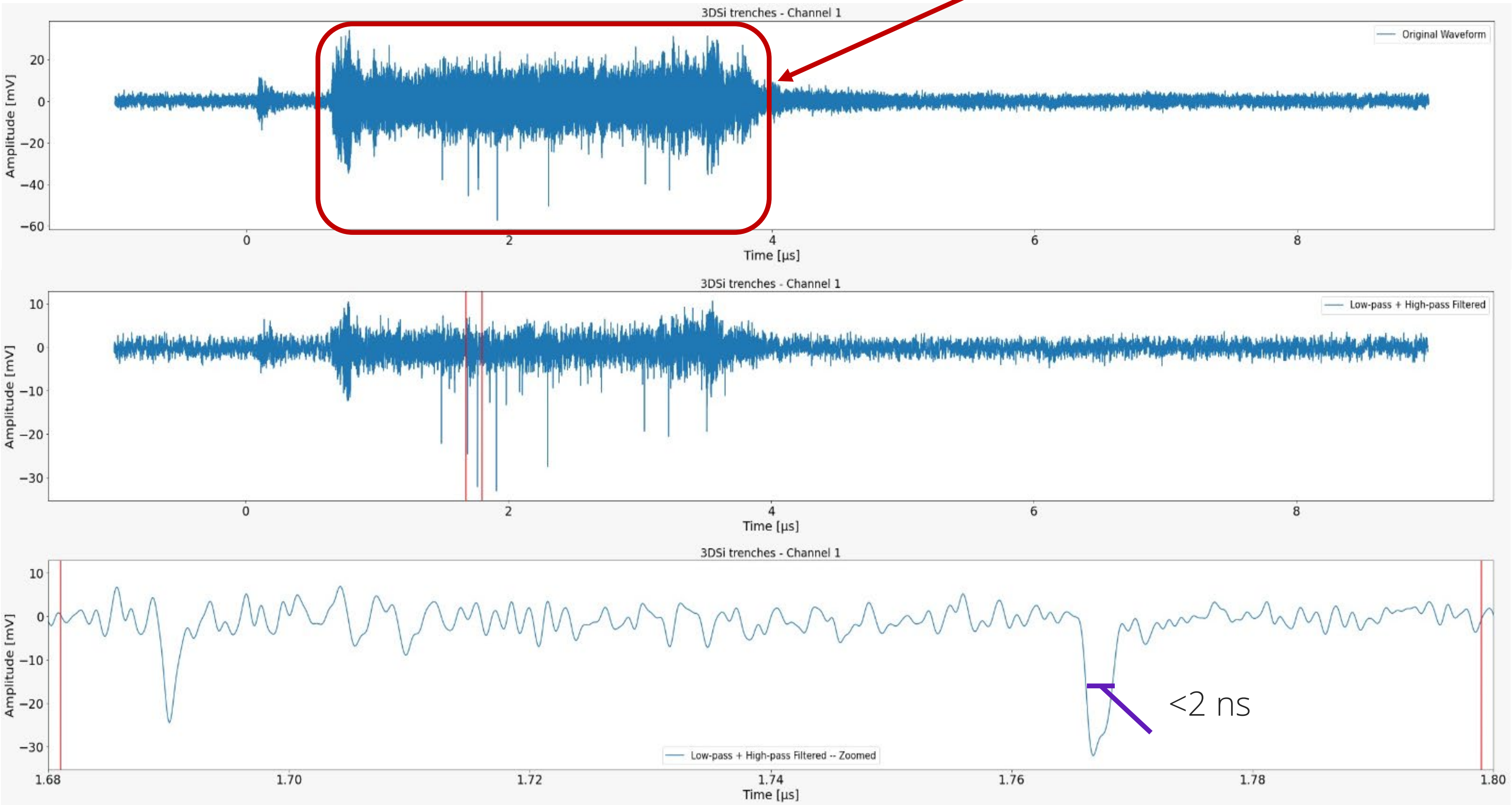




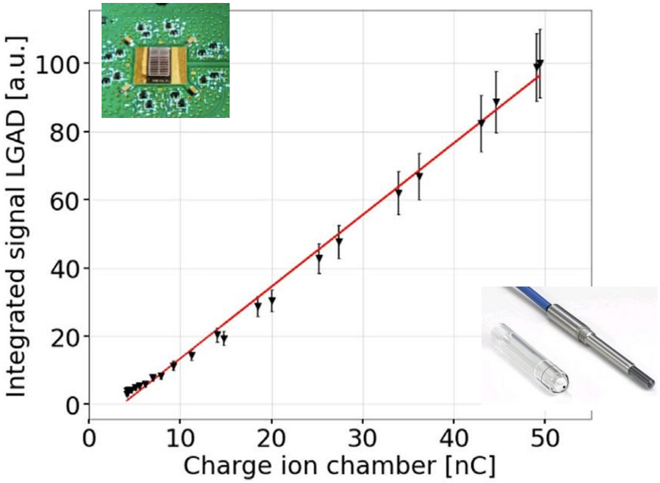
Application of fast silicon detectors to proton therapy ....soon!

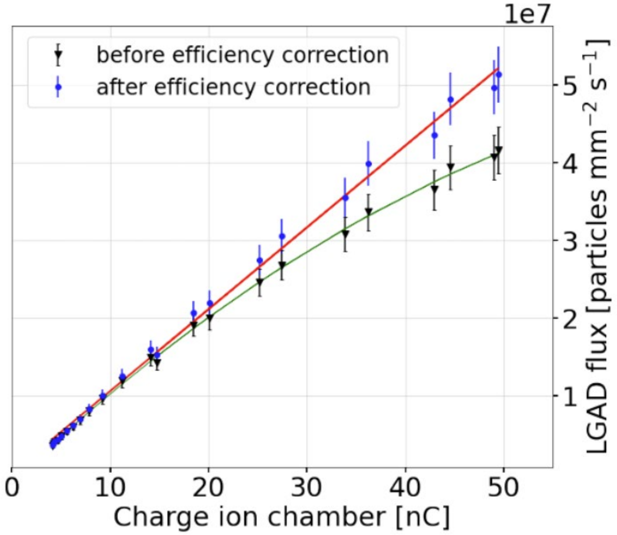
Single Particle counting for accurate dosimetry

macro-pulse of ~2.5 μs



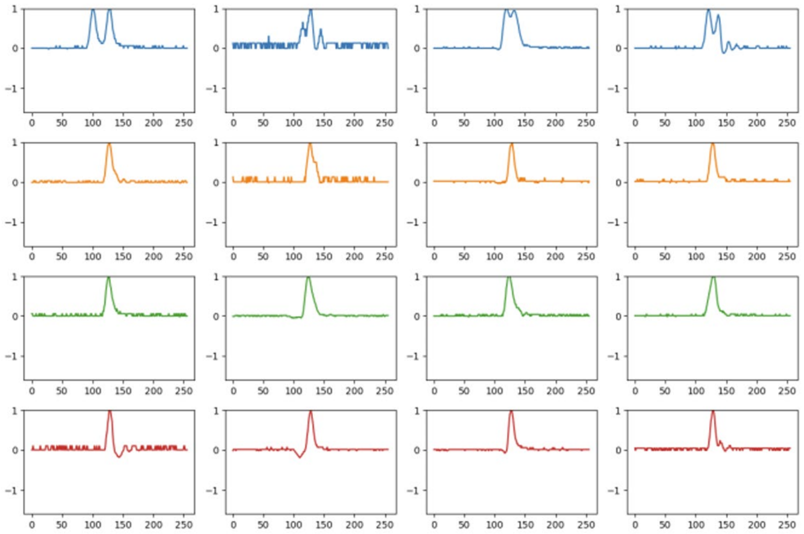
<2 ns





Particle counting: insensitive to environmental changes, fast, precise

Can we improve the performance at high rate?
Deep Neural Networks

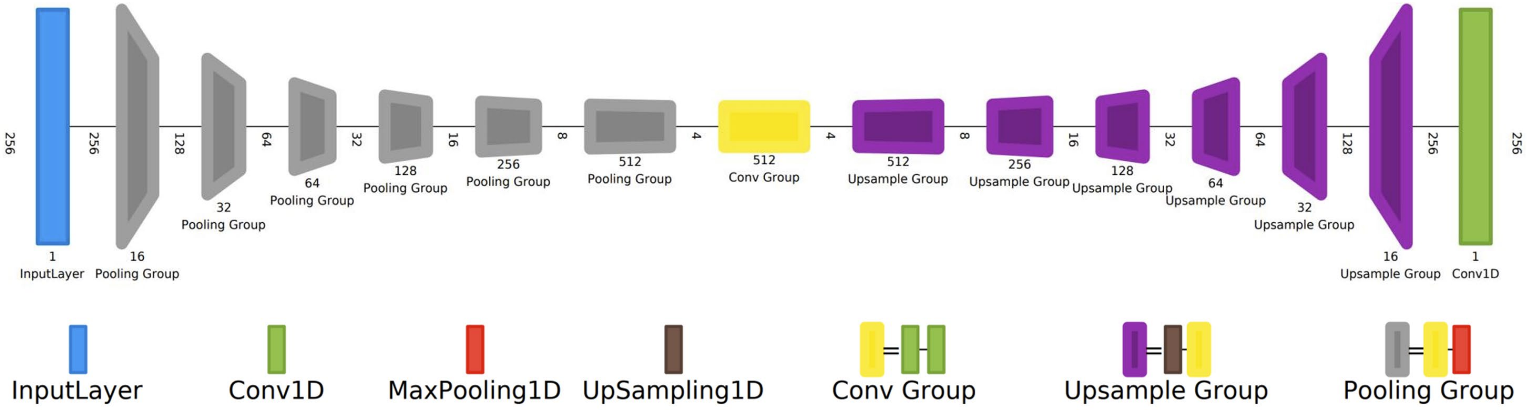


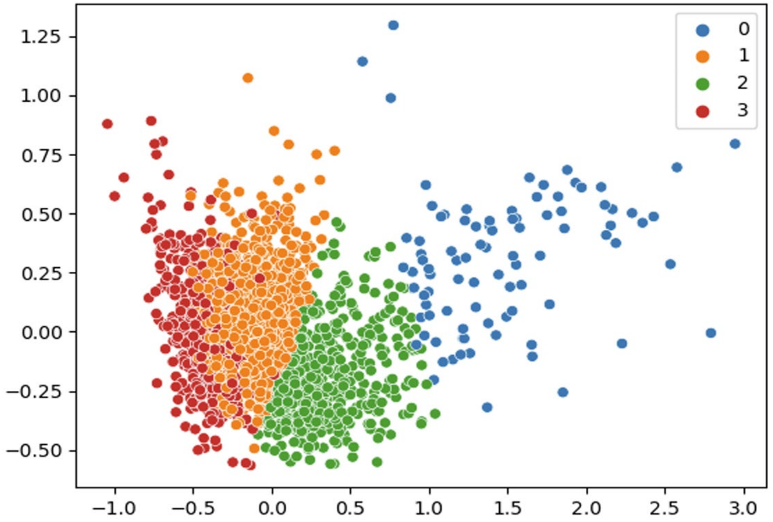
Supervised Learning: relies on labeled values (truth values)

Unsupervised Learning: focuses on uncovering relationships within data

Autoencoder Neural Network:

An autoencoder can extract the most important features and it does not require supervision

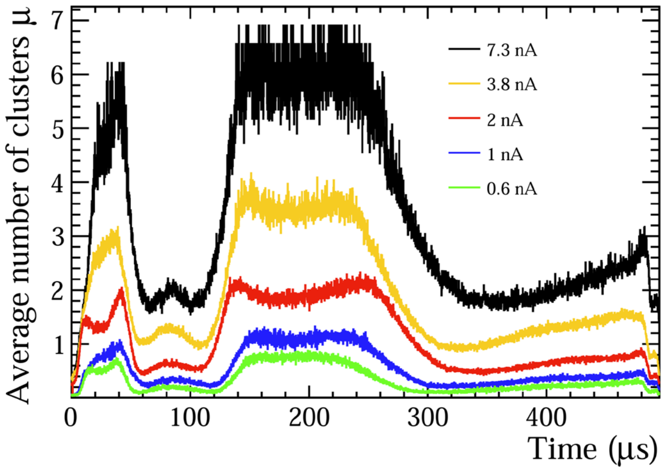




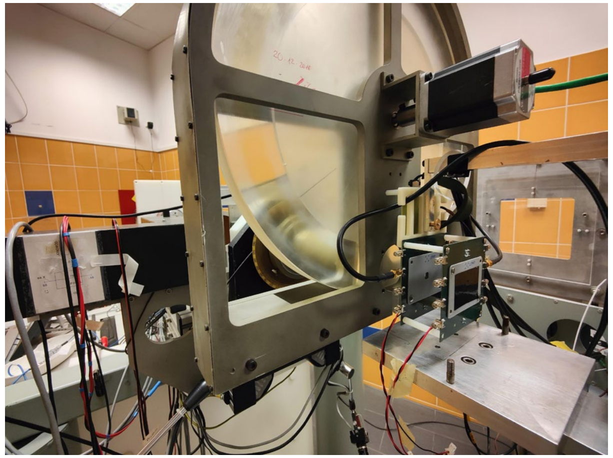
[Machine Learning for Analysis of Fast Particle Detector Data for Proton Therapy Application]

Can we do more?

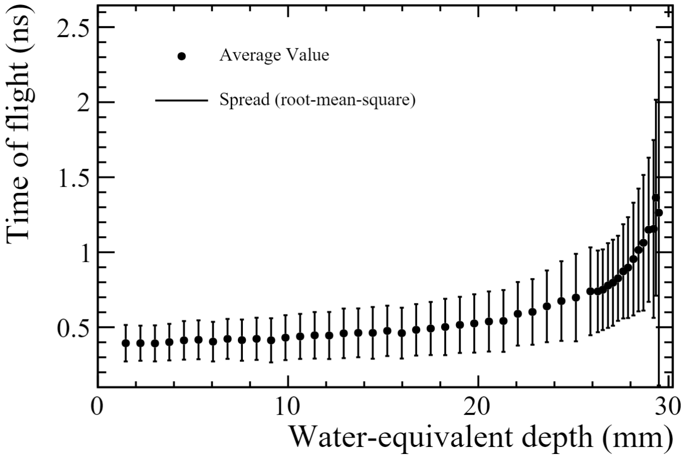
Fluctuation of the beam intensity

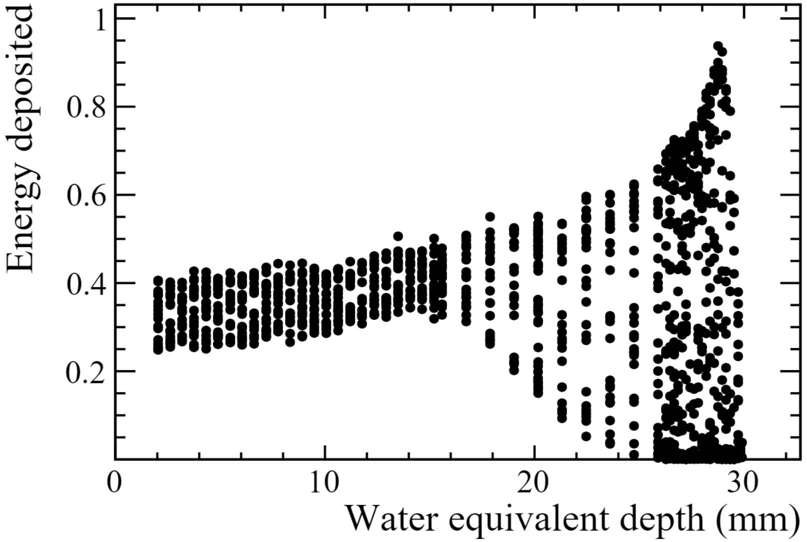


Online monitoring of SpreadOut Bragg Peak



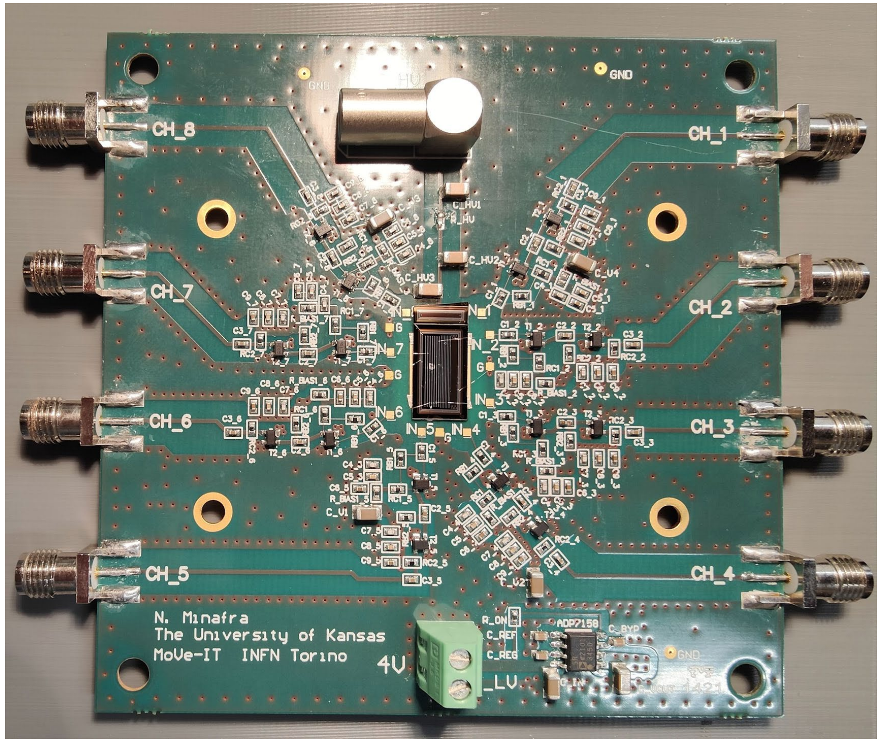
Energy of the beam can be measured using Time of Flight



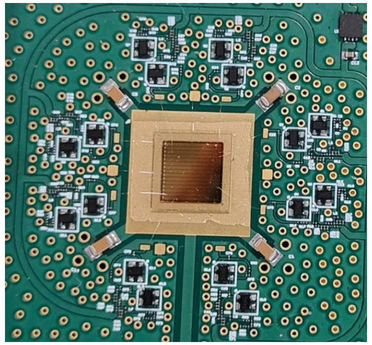


Medical accelerators for sensor characterization

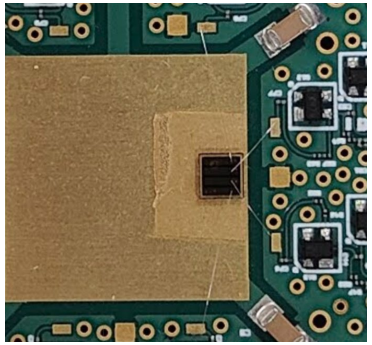
The LINAC at St. Luke Hospital was used to characterize sensors in high-rate environment (for future Electron Ion Collider)



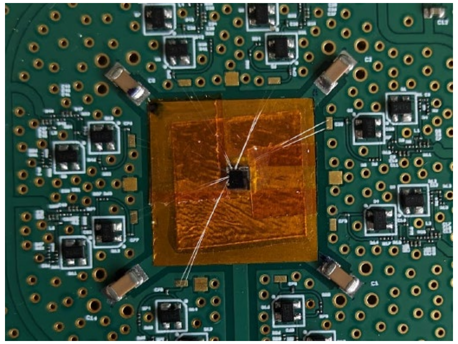
pcCVD diamond

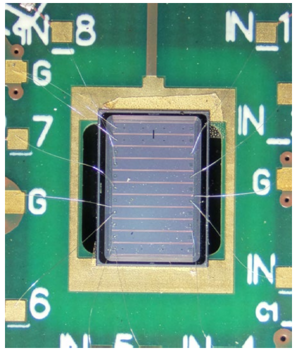


scCVD diamond

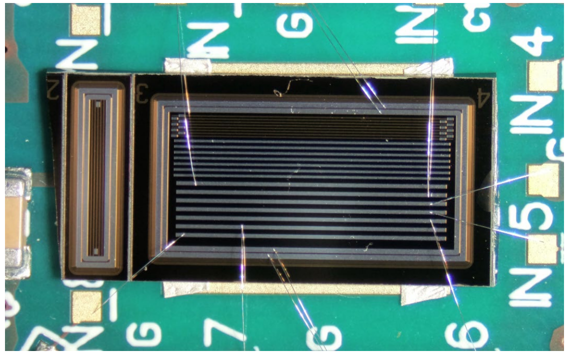


3D scCVD diamond

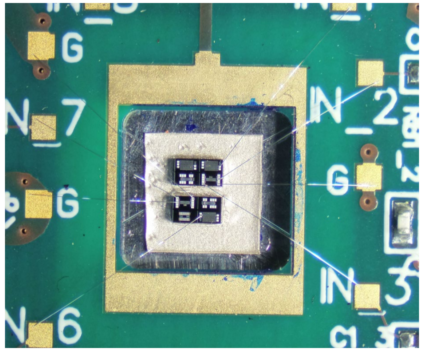




Thin LGAD

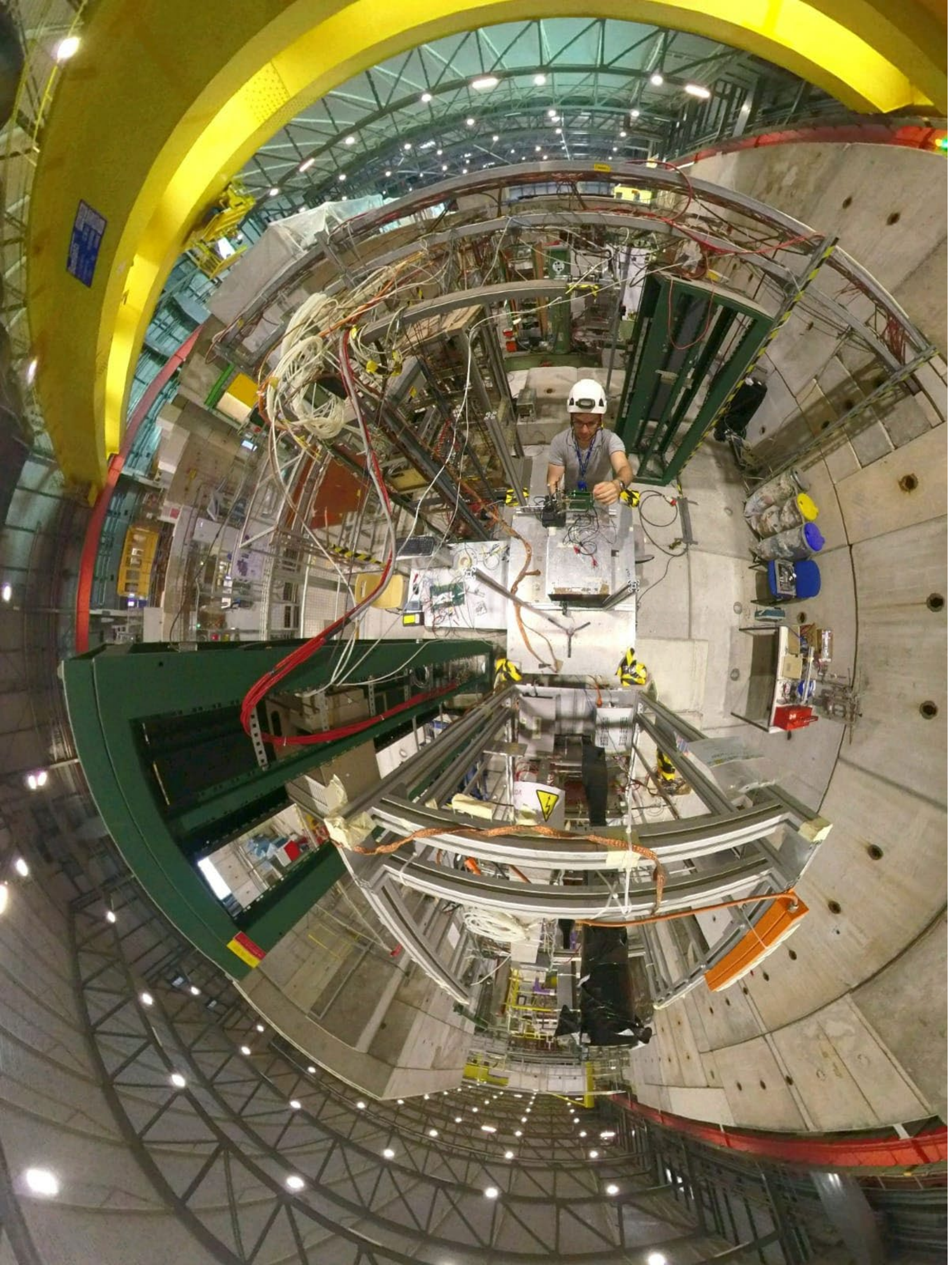


AC-LGAD



3D Silicon (Trench)

Tests performed Apr 15-19th ... Stay tuned!



Fast timing detectors for HEP and medical applications

Nicola Minafra

University of Kansas

May 3rd 2024