High performance timing detectors for high energy physics experiments and new developments for the High Luminosity LHC

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A good timing detector must be fast and thin
Outline

• Why do we need precision timing detectors?
• How is the timing measured?
• What are the available types of detectors?
• What are the new precision timing timing detectors being designed now for the HL-LHC?
APPLICATIONS
Applications of precision timing detectors

Traditionally, fast and precision timing detectors are used in HEP to:

• Trigger events
• **Identify particles**
  – Measure the time of flight between two points to obtain the velocity
  – Combine with momentum information to derive the mass
• Other non-HEP applications:
  – **PET**
  – Mass analysis with ToF mass spectrometry
• Recently new application in HEP:
  – Particle timing measurement to **mitigate pile up effects** at the HL-LHC
Time of flight measurement

We need two measurements to compute the mass of a particle

\[ p = m \gamma \beta \]

\[ \beta = \frac{\nu}{c} \]

\[ \gamma = \frac{1}{\sqrt{1 - \beta^2}} \]

The momentum of a charged particle is measured from the curvature of its track in a magnetic field

\[ p = qBR \]

The velocity \( \beta \) can be measured from the time of flight between two detectors

\[ t = \frac{L}{c \beta} \]

\[ m = \frac{p}{\gamma \beta} \]
Time of flight measurement

\[ m = \frac{p}{(\gamma \beta)} \]

The mass resolution is given by:

\[ \frac{dm}{m} = \frac{1}{m} d \left( \frac{p}{\gamma \beta} \right) = \frac{dp}{p} + \gamma^2 \frac{d\beta}{\beta} \]

The momentum resolution \( \frac{dp}{p} \) is typically 1-2\%,

the mass resolution is dominated by \( \frac{d\beta}{\beta} \sim \frac{dt}{t} \)
Mass separation with time of flight

In High Energy physics experiments the mass separation is more important than the mass resolution. The long lived stable particles that can be observed in collider experiments are:

<table>
<thead>
<tr>
<th></th>
<th>e</th>
<th>µ</th>
<th>π⁺, π⁻</th>
<th>K⁺, K⁻</th>
<th>p, n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (MeV)</td>
<td>0,511</td>
<td>106</td>
<td>140</td>
<td>494</td>
<td>938, 940</td>
</tr>
</tbody>
</table>

→ Flight time difference of two particles $m_1$, $m_2$ with equal momentum $p$:

$$\Delta t = \frac{L}{\beta_1 c} - \frac{L}{\beta_2 c} = \frac{L}{c} \left(\sqrt{1 + \frac{m_1^2 c^2}{p^2}} - \sqrt{1 + \frac{m_2^2 c^2}{p^2}}\right)$$

$$p = mv\gamma = \frac{mv}{\sqrt{1 - \frac{v^2}{c^2}}}$$

→ For relativistic particles $p^2 \gg m^2 c^2$:

$$\Delta t \approx \frac{(m_1^2 - m_2^2) L c}{2 p^2}$$

$$L \sim \Delta t p^2$$

Detectors used are mostly plastic scintillators, typical time resolution of about 0.1 – 0.3 ns (depends on counter size).

At equal $\Delta t$ (time resolution) the length of the flight path $L$ (detector length) increases quadratically with the particles momentum $p$. 
The ALICE TOF

To identify particles in the heavy ion collisions at the LHC
The ALICE TOF:
State-of-the-Art Time-of-Flight

Time-of-flight $\sigma_t \sim 56\text{ps}$ Particle Identification System (semi-relativistic particles) with a time reference ($t_0$) forward detector that uses the high multiplicity of tracks
An application of precision timing: the TOF-PET

A positron emitted by the tracer atom annihilates with an electron in the tissue.

Two 511 keV photons which are detected in coincidence form a line of response (LOR).

The time information can be used to reduce background and directly improve the image quality.
LHC and HL-LHC

LHC:
30-50 protons collide at every bunch crossing

HL-LHC:
From 2026
140-200 protons will collide at every bunch crossing
A typical HL-LHC event

$z_{RMS} \sim 4-5\text{cm}$
Spread of vertices along the beam axis

LHC $\rightarrow$ about 0.3 vertices /mm

HL-LHC $\rightarrow$ up to 1.9 vertices /mm
A typical HEP detector at a collider
High precision (pico second) timing may help in pile-up mitigation. The subdetector providing the precision timing may best be associated to precise and granular detector ⇒ Tracker and electromagnetic calorimeter

- Object reconstruction/PU cleaning
- Object-to-vertex attribution
- $H \rightarrow \gamma \gamma$ vertex
3D vs. 4D Vertex Reconstruction

- Simulated Vertices
- 3D Reconstructed Vertices
- 4D Reconstruction Vertices
- 4D Tracks

**EXAMPLES OF MERGED VERTICES IN 3D**

- **Pile-up = 50**
- **180 ps RMS**
- **5 cm RMS**

- 4D reconstruction with track time information at ~25 ps
Pile-up = 200

CMS Simulation

<table>
<thead>
<tr>
<th>$\langle \mu \rangle$</th>
<th>4D Merged Vertex Fraction</th>
<th>3D Merged Vertex Fraction</th>
<th>Ratio of 3D/4D</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.5%</td>
<td>3.3%</td>
<td>6.6</td>
</tr>
<tr>
<td>200</td>
<td>1.5%</td>
<td>13.4%</td>
<td>8.9</td>
</tr>
</tbody>
</table>

Fast Timing for Collider Detectors - CERN
Academic Training Program
Particle-flow Event Reconstruction

MIP Timing Layer
TIMING RESOLUTION
Timing resolution

The timing resolution is made of different terms, which depend on the detector type and on the electronics.

![Diagram showing timing resolution terms](image)

- **Baseline or pedestal**
- **90%** and **10%**:
- **Leading edge**
- **Max amplitude**
- **FWHM (Full Width at Half Maximum)**
- **Falling edge**
- **slew rate = \( \frac{dV}{dt} \)**
- **\( t_{\text{rise}} \)**
Time Jitter or “Noise term”

Electronic noise $N$

$$\sigma_V = \frac{dV}{dt} \sigma_t \Rightarrow$$

$$\sigma_t = \frac{\sigma_V}{S} = \frac{N}{S} = \frac{t_r}{S/N}$$

Low jitter $\Rightarrow$ high S/N and short rise time
Time walk effect

- Signals of different amplitude cross the thresholds at different times.
- Signal shape may also change depending on the amplitude.

→ This effect can be reduced by correcting the timing using signal shape information or using very low threshold.
Time walk effect corrections

Three possibilities to correct for the time walk effect:

(a) Constant Fraction Discriminator, (b) Time Over Threshold, (c) Multiple Samplings

(a) Constant Fraction Discriminator measures the time at which the signal crosses a fraction of its amplitude.

(b) The measurement of the arrival time of the signal and the Time Over Threshold allows to correct for the shape change due to the different amplitude.

(c) A full digitization of the curve allows to process offline the data to measure the time of arrival of the signal in an optimized way.
Landau fluctuation

- Non-uniform charge deposition in the detectors can cause pulse shape distortion and amplitude change from event to event thus affecting the resolution.
- The energy deposition in a thin slab of material follows the Landau distribution.

W.R. Leo,
Pulse shape distortion

Any detector inhomogeneity, or difference in response with respect to the impact point, or non linearity may affect the pulse shape and create a jitter in the response.
TDC error

This is the error connected with the TDC bin

\[ \sigma_{TDC} = \frac{\Delta t_{TDC}}{\sqrt{12}} \]

It can be reduced by optimizing the readout electronics
Timing resolution

\[ \sigma_t^2 = \sigma_{\text{Jitter or Noise}}^2 + \sigma_{\text{Time Walk}}^2 + \sigma_{\text{Landau}}^2 + \sigma_{\text{Distortion}}^2 + \sigma_{\text{TDC}}^2 \]

The effects are independent and can be added in quadrature.
Achieving below 50ps is non trivial!
VARIOUS TYPES OF DETECTORS
The ideal timing detector

- Very fast signal
- Large amplitude
- Shape stability
- High counting rate
- Radiation hard
- Cheap
Families of detectors

Light based devices
- Scintillating crystals coupled to photo-detectors with amplification
- Cherenkov medium coupled to photo-detectors with amplification
- Vacuum devices

Gas based devices
- Ionization

Silicon detectors
Micro Channel Plates

Vacuum devices
Based on secondary emission
Channels typical diameter: 10 \( \mu \text{m} \), length: 400\( \mu \text{m} \).

More stacks of micro-channel plates in a < configuration or Z configuration can be done. Gain \( \sim 10^6 \) for 2 stacks.
Micro Channel Plates

- MCP can be used as PMT for light detection, or for X ray detection, or coupled to a quartz radiator for Cherenkov light detection
- Excellent time resolution
- Large signal
- Magnetic field tolerant

- Very expensive 😞
- There is an effort to produce large area MCP at lower cost LAPPD (20x20 cm² and Gain~$10^7$)

Micro Channel plates

Beam test setup

- 3GeV/c π⁻ beam
  - at KEK-PS π2 line
- PMT: R3809U-50-11X
- Quartz radiator
  - 10⁰x40²mm with Al evaporation

https://indico.cern.ch/event/13750/contributions/146262/attachments/113680/161492/MCP.pdf
Micro Channel plates

MCP resolution: 40-50 ps with single photons

**Beam test result**

- **With 10mm quartz radiator**
  - +3mm quartz window
  - Number of photons ~ 180
  - Time resolution = 6.2ps
  - Intrinsic resolution ~ 4.7ps

- **Without quartz radiator**
  - 3mm quartz window
  - Number of photons ~ 80
  - Expectation ~ 20 photo-electrons
  - Time resolution = 7.7ps

https://indico.cern.ch/event/13750/contributions/146262/attachments/113680/161492/MCP.pdf
Multi-gap RPC

Multigap resistive plate chambers of the ALICE Time Of Flight detector

https://www.youtube.com/watch?time_continue=9&v=kLa36SmiC4Q
Multi-gap RPC

The ALICE TOF detector
Multi-gap RPC

F. Wang et al. arXiv:1812.02912v2

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<th></th>
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<tbody>
<tr>
<td>ALICE</td>
<td>2</td>
<td>5</td>
<td>250</td>
<td>104</td>
</tr>
<tr>
<td>CBM</td>
<td>2</td>
<td>4</td>
<td>250</td>
<td>110</td>
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<tr>
<td>STAR</td>
<td>1</td>
<td>6</td>
<td>220</td>
<td>114</td>
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<tr>
<td>BESIII</td>
<td>2</td>
<td>6</td>
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<td>103</td>
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<tr>
<td>RefMRPC</td>
<td>4</td>
<td>6</td>
<td>160</td>
<td>135</td>
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<tr>
<td>THU1</td>
<td>4</td>
<td>8</td>
<td>104</td>
<td>159</td>
</tr>
<tr>
<td>THU2</td>
<td>1</td>
<td>6</td>
<td>250</td>
<td>109</td>
</tr>
</tbody>
</table>

**Time resolution for these detectors depends on:**
- The number of gaps (better many gaps)
- The thickness of the gaps (better thin gaps)

Rather cheap devices, and can be made in large areas (ALICE 160 m²), suitable for a TOF detector.
Silicon sensors

Conventional Silicon sensors:
a Minimum Ionizing Particle in Silicon creates ~ 100 e/h pairs per micron that drift towards the electrodes under the influence of an external voltage.

\[
\frac{dE}{dx} = 1-2 \text{MeV/(g/cm}^2) \quad \rho(\text{Si}) = 2.32 \text{g/cm}^3 \\
\frac{dE}{dx} = 1.5 \text{MeV} \times 2.32 \text{g/cm}^3 \times \text{cm} = 3.5 \text{ MeV/cm} = 350 \text{ eV/\mu m}
\]

\[\mathcal{E}(\text{e/h pair in Si}) = 3.6 \text{ eV}\]

\[\frac{dN(\text{e/h pairs})}{dx} = \frac{dE}{dx}/\mathcal{E} = 350/3.6 /\mu \text{m}
\]

~100 e/h pairs /\mu m

inelastic collision with the atomic electrons of the material
Silicon sensors

The drift velocity increases with the electric field and reaches a saturation value $v_{\text{drift}} = 10^7 \text{ cm/s} = 100 \mu\text{m/ns}$ → in a 300µm detector the signal is collected in 3ns.

For many e/h pairs produced all along the particle path
Silicon sensors

The signal $I_{\text{max}}$ does not depend on the sensor thickness. Thin and thick detectors have the same maximum current, but thick sensors have longer signals and larger overall charge collected. So the time resolution of thin and thick sensors is very similar.

$$I_{\text{max}} \propto 75qv_{\text{drift}} \sim 1 - 2 \mu A$$

$$\sigma_t = \frac{\sigma_v}{dV/dt} = \frac{N}{S} = \frac{t_r}{S/N}$$

N.Cartiglia et al NIMA 796 (2015) 141-148
Silicon sensors with gain:

A high doping region $p^+$ creates a very high local electric field ($E \sim 300\text{KV/cm}$). Under this electric field the electrons acquire sufficient energy to generate additional e/h pairs. The multiplication factor is called the gain. Typically the gain is about 20.

The gain increases the signal amplitude.

$$\sigma_t = \frac{\sigma_V}{dV/dt} = \frac{N}{t_r} = \frac{S}{S/N}$$

N.Cartiglia et al NIMA 796 (2015) 141-148
Silicon sensors with gain

\[ \sigma_t = \frac{\sigma_V}{dV/dt} = \frac{N}{S} \frac{t_\tau}{t_\tau} = \frac{t_\tau}{S/N} \]

The signal slew rate \( \frac{di}{dt} \) is proportional to the ratio of the Gain over the thickness.

\[ \frac{di}{dt} \sim \frac{dV}{dt} \propto \frac{G}{d} \]

\( \sigma_t \) \( \tau \)

Response of sensors with different thickness and same gain.
The amplitude depends on the Gain, the slew rate depends on the thickness.

Thin detectors with high gain have the best time resolution.

N.Cartiglia et al NIMA 796 (2015) 141-148
Design of the CMS Mip Timing Detector (MTD)

- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of 30-50 ps
- Hermetic coverage for |\eta|<2.9

**BARREL**
- Surface: ~ 40 m²
- Number of channels: ~ 332k
- Radiation level: ~ $2 \times 10^{14}$ $n_{eq}/cm^2$
- Sensors: LYSO crystals + SiPMs

**ENDCAPS**
- Surface: ~ 15 m²
- Number of channels: ~ 8000k
- Radiation level: ~ $2 \times 10^{15}$ $n_{eq}/cm^2$
- Sensors: Low gain avalanche diodes
LGAD (Low Gain Avalanche Diodes) technology sensors optimized for timing measurements

The idea: add a thin layer of doping to produce low controlled multiplication (the gain layer)
Moderate gain (10-20)

Sensor optimization for CMS MTD:
- Thin detectors to maximize signal slew rate \( (dV/dt) \): \(~50\ \text{um}\)
- Small sensors filled with pixels for optimal wafer usage
- Maximize efficiency (85→92%) by reducing the no-gain region between pixels (100 um → 50 um)
Wafer UFSD3 production from FBK
Uniform E-Field

It is very important to have a uniform E field \(\rightarrow\) stable shape independent of the impact point \(\rightarrow\) stable response

LGAD achieves uniform E-field with a wide implant

Values of \(E_w\) for two different segmented geometries: on the left side the geometry is 300 \(\mu\)m strip pitch with a 50 \(\mu\)m strip implant width while on the right the strip implant is 290 \(\mu\)m.
Target time resolution of 30 ps achieved
- Noise jitter term <25 ps for gain>15
  - $\sim N/(dV/dt)$
- Intrinsic limit from Landau fluctuations:
  - Spatially non-uniform energy deposits along the track because of event-by-event pulse distortions
  - Constant: $\sim$25 ps

$1\text{mm}^2$ 50 um detector HPK UFSD, lab measurement with beta source
CMS MTD endcaps - test beam results

- Efficiency within pixel area ~100%
- Fill factor of the sensor array ~90%
- Uniformity of sensor response within 2%
Radiation hardness of Si detectors

- Hadrons kick the Si atoms from their lattice sites, and create defects in the Silicon lattice.
- The defects can change the effect of the doping in the gain layer reducing the gain
- The charge collection efficiency is reduced
- A higher voltage is required to achieve the same gain
- The leakage current increases \(\rightarrow\) must operate the detector at lower temperature to decrease the leakage current (-7%/°C)

see G. Casse lectures
Silicon detectors rad hardness

- Sensors irradiated to different fluences
- Time resolution <40 ps achieved with irradiated sensors
  - Increase of bias is required to compensate for gain losses due to radiation damage
  - Cooling to -30°C is required to minimize leakage current

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**HPK 50-micron sensors**

- **Gain vs. Bias, T = -20 °C & T = -30 °C**
- **Time Resolution vs Gain, T = -20°C**
Design of the CMS Mip Timing Detector (MTD)

- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of 30-50 ps
- Hermetic coverage for |\(\eta|<2.9$

### BARREL
- Surface: \(\sim 40 \text{ m}^2\)
- Number of channels: \(\sim 332k\)
- Radiation level: \(\sim 2\times10^{15} \text{n}_{eq}/\text{cm}^2\)
- Sensors: LYSO crystals + SiPMs

### ENDCAPS
- Surface: \(\sim 15 \text{ m}^2\)
- Number of channels: \(\sim 800k\)
- Radiation level: \(\sim 2\times10^{15} \text{n}_{eq}/\text{cm}^2\)
- Sensors: Low gain avalanche diodes
Time-of-Flight Position Emission Tomography (TOF-PET)

The sensor for the CMS-MTD were developed for the TOF-PET

LOR = Line-of-Response

Standard conversion $1\text{ps} \rightarrow 300$ microns

SiPM photodetectors

LYSO crystals (thick)
MTD Barrel crystals

- **L(Y)SO:Ce crystal as scintillator**
  - Excellent radiation tolerance
  - Dense (>7.1 g/cm³), bright (40000 ph/MeV) → high signal
  - Fast rise time O(100)ps and decay time ~40 ns
SiPM is an array of small cells called SPADS connected in parallel on a common substrate and operated in Geiger mode. Each cell has its own quenching resistor, and a common bias is applied to all cells. The cells fire independently, and the output signal is the sum of the signals produced by the individual cells.

The cell size depends on the application. For high light yield devices, linearity may be a concern, so a small cell size is optimal. Also, for coupling to fibers for example, you may need to spread the light over the full surface of the device.

Silicon Photomultipliers as photo-detectors for the CMS MTD:
- Compact, insensitive to magnetic fields, fast
- Optimal SiPM cell size: **15 μm**
  - High dynamic range,
  - Good Photon Detection Efficiency at 420 nm: **20-40%**

(EDIT-2011, CERN)
MTD Barrel sensors
MTD barrel - test beam results

Test beam results:
- Target time resolution of 30 ps achieved
- Uniform time response vs impact point
- Uniform time resolution vs impact point
Performance of the MTD barrel

- Detector timing performance evolution during operation:
  - Negligible contributions from CMS clock distribution, digitization and electronics
  - Photostatistics and noise term dominating

- Radiation damage will cause an increase of the SiPM dark counts (DCR)

- DCR noise mitigation by:
  - Cooling at -30°C
  - Annealing cycles at 15°C during shutdowns
  - Decreasing SiPM operating voltage
  - Dedicated noise filtering in the electronic circuit
CMS ECAL UPGRADE FOR PRECISION TIMING
The CMS electromagnetic calorimeter (ECAL)

**CMS Characteristics:**
- Tracker coverage up to $\eta<2.5$
- Magnetic Field 3.8 T
- ECAL fully contained inside the coil

**ENDCAPS (EE)**
- $1.48 < |\eta| < 3.0$
- 14,648 crystals

**BARREL (EB)**
- $|\eta| < 1.48$
- 61,200 crystals

**Granularity Barrel**
- $\Delta\eta \Delta\phi = 0.0174 \times 0.0174$

**PbWO₄ crystals**
- $X_0 = 0.89 \text{ cm}$
- $\text{LY} \sim 100 \gamma/\text{MeV}$

**Pb/Si preshower**
- $1.65 < |\eta| < 2.6$

**Energy Resolution (Barrel)**

\[
\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E(\text{GeV})}} \oplus \frac{12\%}{E(\text{GeV})} \oplus 0.3\%
\]

The energy resolution for photons from $H \rightarrow \gamma\gamma$ in EB is 1.1% to 2.6% and in EE 2.2% to 5%.
The ECAL role in CMS

- The excellent ECAL energy resolution led to the discovery of the H boson in the \( \gamma \gamma \) decay mode
- Electrons and photons are used in many other analyses (\( H \rightarrow WW, ZZ^*, Z' \)) and SM physics analyses (W, Z, top, ...)
- Timing is also used in search for long lived SUSY particles

see D. Barney talk
Timing performance of the present ECAL

- No dedicated TDC or other electronics
- PWO+APD pulse is shaped by a pre-amplifier with $\tau \sim 40\text{ns}$.
- Sampling ADC at 40 MHz (10 samples are stored)
- Request to have timing stability of $\sim 1\text{ns}$

Timing is computed from the ratio of the 4th to the 5th sample.  
*A fit would take too long for computation.*
Timing performance of the present ECAL

Actual performance is much better than 1 ns!

Test-beam 2008
Difference of timing for neighboring crystals

Timing resolution measured in CMS from $Z \rightarrow ee$ electrons time difference

Timing resolution measured in CMS from showers deposited in between two crystals
Same electronics

Different electronics

Timing resolution measured in CMS from showers deposited in between two crystals

\[
\sigma(t) = \frac{N}{A_{\text{eff}}/\sigma_n} \oplus \sqrt{2C}
\]

When the crystals share the same electronics card, the resolution is better than when the crystals have different electronic card. In particular the clock distribution is what matters.
Electromagnetic showers in a long scintillating crystal

Scintillation light propagation through the crystal takes time and causes dispersion of the pulse shape.

EM shower propagation snapshot  Scintillation light propagation $c_s < c$

100 GeV photon
Simulation of the light ray tracing inside the crystals shows that the fast component has a large contribution from Cerenkov light.
ECAL Barrel upgrade

Extract the 36 SM from CMS

36 Supermodule

1700 LeadTungstate crystals
Testbeam results

- e beam
- Plastic scintillators
- 2 MCP
- PbWO$_4$ crystals
- APD
- TIA
- CAEN digitizer (5GS/s)

Resolution [ps]

Normalized Amplitude [$A/\sigma$]
CMS ECAL Timing resolution

\[ \sigma_T^2 = \left( \frac{N \cdot \sigma_n}{A} \right)^2 + \left( \frac{S}{\sqrt{A}} \right)^2 + C^2. \]

- Noise term due to noise fluctuations \( N \) (jitter term)
- \( S/VA \) \( \rightarrow \) stochastic term, due to fluctuations in the shower and in the emission of scintillation photons (small)
- \( C \) \( \rightarrow \) constant term: clock jitter, shower starting point, time intercalibration among crystals, difference in pulse shapes among crystals (dominates at high energy, important to have stable clock distribution!)
H→γγ vertex with timing from calorimeter

CMS Simulation $<\mu> = 20$

- Simulated Vertices
- 3D Reconstructed Vertices
- 4D Reconstructed Vertices
- 4D Tracks
- Leading Photon Vertex Hypotheses $\eta = -1.26$
- Sub-leading Photon Vertex Hypotheses $\eta = -0.66$
Conclusions

• New applications have raised the interest in detectors with precision timing capabilities
• New projects have challenging requirements on the detector timing resolution
• Are you ready for the challenge?
Timing jitter: single sample

\[ \sigma_t = \frac{\sigma_y}{\frac{dV}{dt}} \quad \frac{dV}{dt} \approx \frac{V}{t_r} \rightarrow \sigma_t = \frac{t_r}{SNR} \]

Checks:

- \( t_r = 1 \text{ ns}, \ SNR = 10 \rightarrow \sigma_t = 100 \text{ ps} \)
- \( t_r = 40 \text{ ns}, \ SNR = 500 \rightarrow \sigma_t = 80 \text{ ps} \)

\[ t_r \propto \frac{1}{BW} \quad SNR \propto \frac{1}{\sqrt{BW}} \rightarrow \sigma_t \propto \frac{1}{\sqrt{BW}} \]

Match the front-end rise time with the sensor rise/collection time
CFD: the principle

- The input signal is both **delayed** and **attenuated**
- The delayed and attenuated signals are **combined** to yield a bipolar waveform
- The **zero crossing** of the bipolar waveform is used for **timing**
Digital timing extraction

- Different **algorithms** are used to compute the timing from the digitized samples
- There is nothing such an **optimal method**
- Some techniques can be **more suited** that others for real time execution on FPGA

Some examples of digital algorithm:
- Digital leading edge
- Digital constant fraction
- Interpolation
- Initial slope approximation
- Reference pulse
- ...

Some comparison


- Simulations based on MCP signal
- No sampling jitter added
- The barrier of 10 ps broken around 20 pe
- Practical equivalency between WS and CFD
Calorimeter Upgrade TDR

**TDR highlights:**
- Operating ECAL at lower temperature to reduce APD noise
- New ECAL electronics
- HCAL barrel decision on partial scintillator replacement in Spring 2018

**Pulse amplification with a TIA**
- To reduce sensitivity to increased APD dark current,
- To reduce effect of out of time PU,
- To improve signal vs spike discrimination,
- To improve timing measurement (first TIA chip available)

**New ECAL electronics**

**ADC at 160 MHz**
- Improve timing measurement
- Improve signal vs spike discrimination

**Data Transmission Unit**
- Loss-less data compression

**IpGBT**
- Data readout in streaming towards off-detector elec.
- Trigger formation in powerful off-detector electronic boards
ECAL Clean-up using Timing

- **Effect of timing cut** on $\sum E_T^{ECAL}$ variable
  - sum of all ECAL hits with $E > 1\text{GeV}$.
- $O(30 \text{ ps})$ resolution detector simulated
- Require ECAL timing (time-of-flight subtracted) within a **90 ps window**
- Most of the **PU extra energy gone**
  - able to almost recover no PU conditions
- Timing-based selection looks promising for high PU environment

![Graph showing CMS Simulation Preliminary results](image)
Landau fluctuations in Silicon

Energy loss per µm of thickness. The width changes little for the various curves.
→ so the smallest Silicon detector thickness gives the smallest fluctuations.

http://meroli.web.cern.ch/lecture_stragglingfunction.html