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

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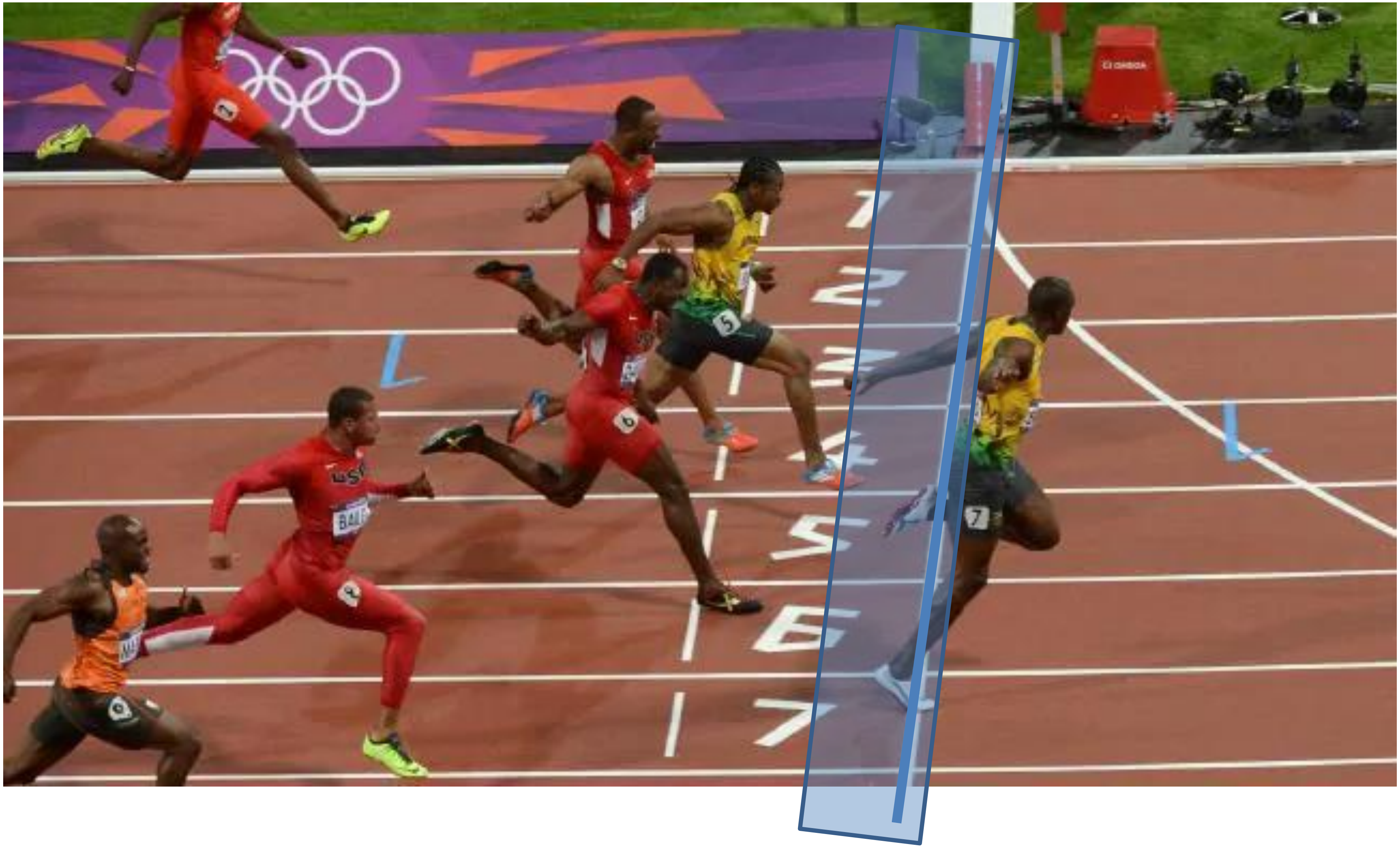


finish line

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 detectors being designed now for the HL-LHC ?

APPLICATIONS

Applications of precision timing detectors

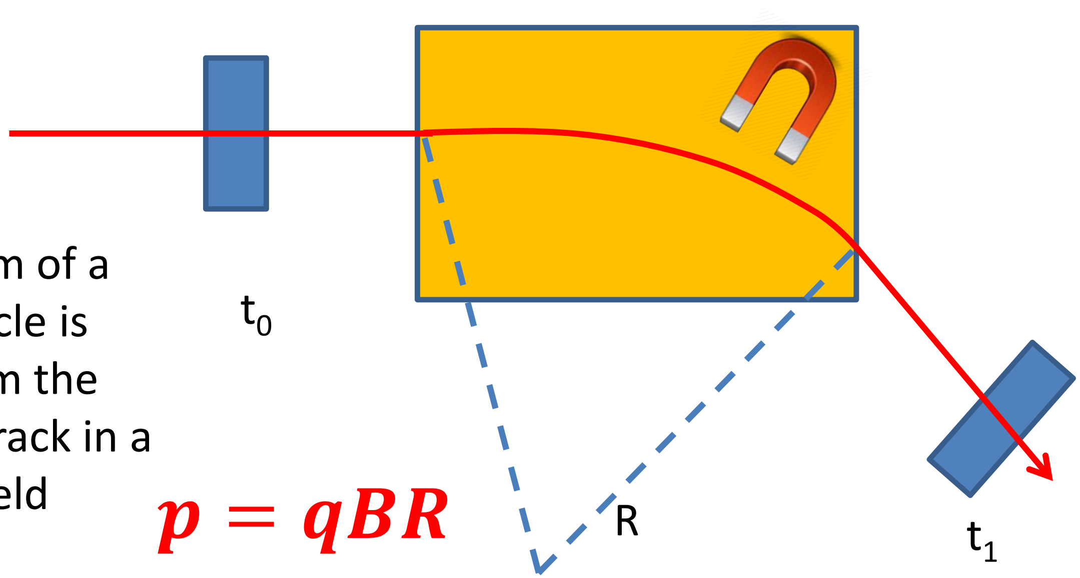
Traditionally, fast and precision timing detectors are used in HEP to:

- 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

momentum $p = m\gamma\beta$ $\beta = \frac{v}{c}$ $\gamma = \frac{1}{\sqrt{1-\beta^2}}$



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

$$\boldsymbol{p = qBR}$$

The velocity β can be measured from the time of flight between two detectors

$$\boldsymbol{t = L/c\beta}$$

$$\boldsymbol{m} = \boldsymbol{p}/(\gamma\boldsymbol{\beta})$$

Time of flight measurement

$$\boldsymbol{m} = \boldsymbol{p}/(\gamma\boldsymbol{\beta})$$

The mass resolution is given by:

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

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

the mass resolution is dominated by $\frac{\boldsymbol{d\beta}}{\boldsymbol{\beta}} \sim \frac{dt}{t}$

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:

	e	μ	π^+, π^-	K^+, K^-	p, n
Mass (MeV)	0,511	106	140	494	938, 940

→ 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 $p^2 \gg m^2c^2$:

$$\Delta t \approx \frac{\left(m_1^2 - m_2^2\right)Lc}{2p^2}$$

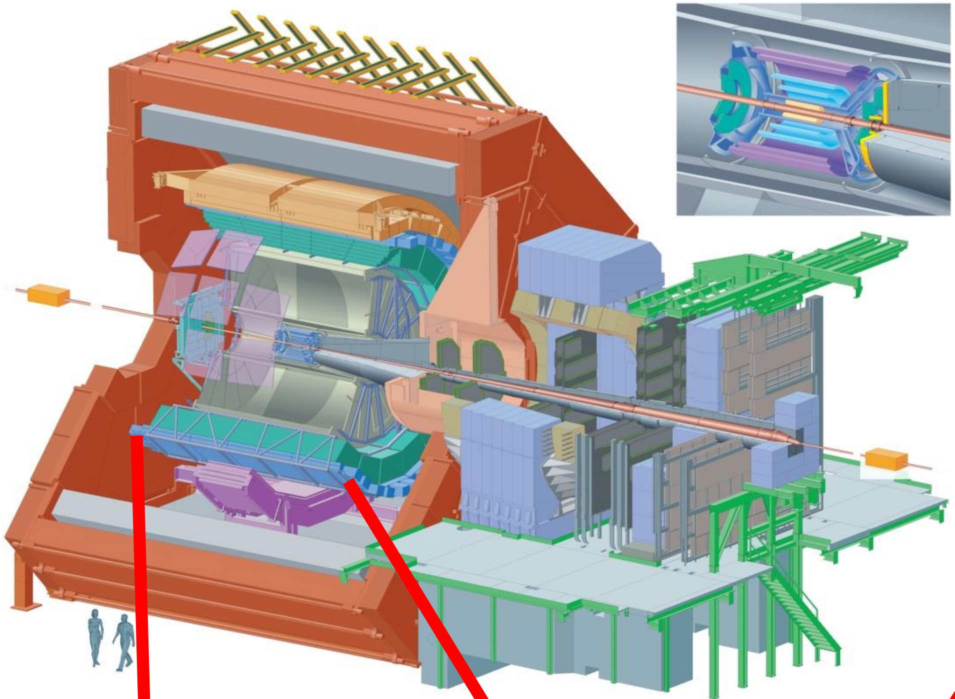
$L \sim \Delta t\, p^2$

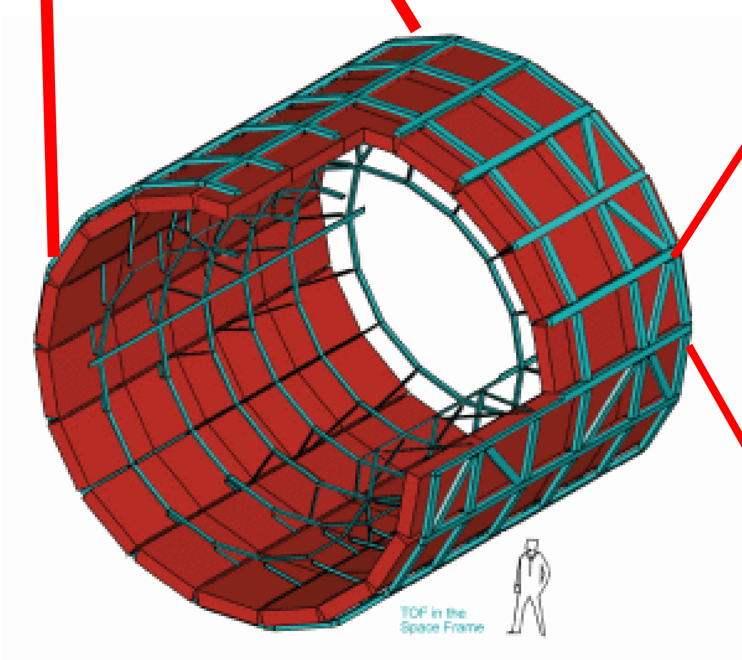
Detectors used are mostly plastic scintillators, typical time resolution of about 0,1 – 0,3 ns (depends on counter size).

At equal Δt (time resolution) the length of the flight path L (detector length) increases quadratically with the particles momentum p.

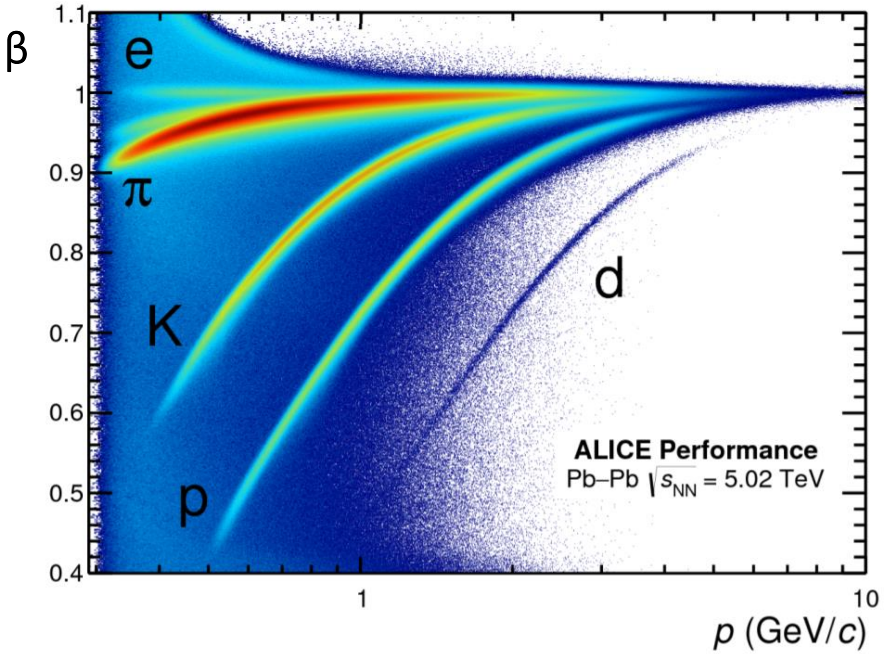
The ALICE TOF

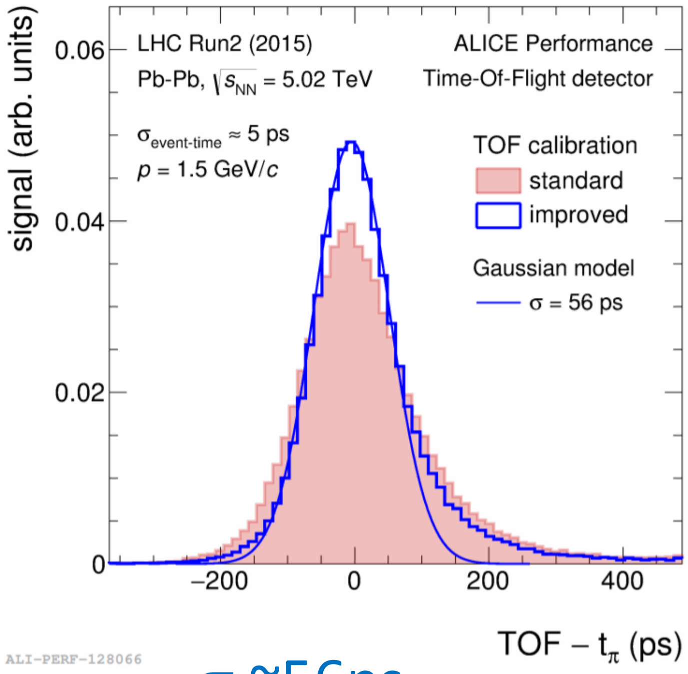
To identify particles in the heavy ion collisions at the LHC





The ALICE TOF: State-of-the-Art Time-of-Flight

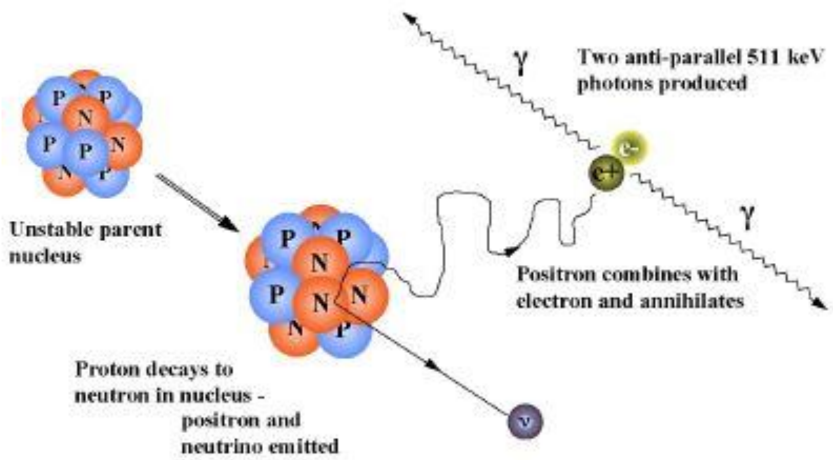




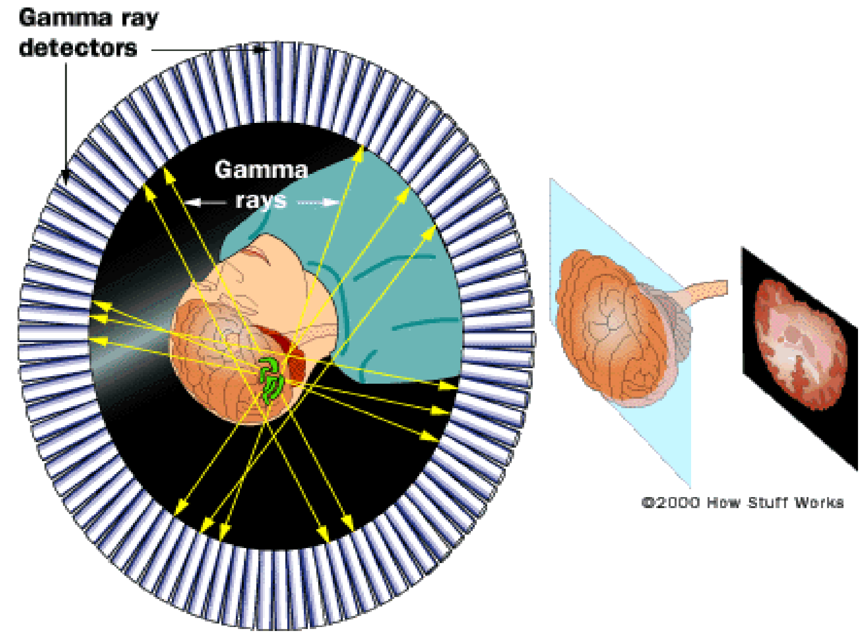
σ_t~56ps

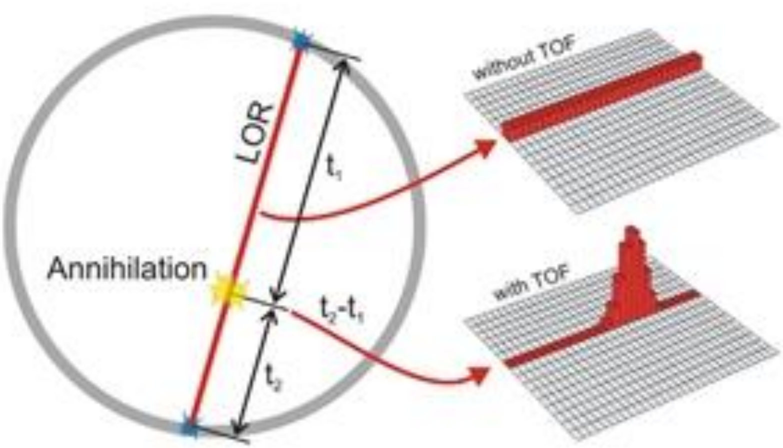
Time-of-flight **σ_t~56ps** Particle Identification System (semi-relativitistic particles) with a time reference (t0) forward detector that uses the high multiplicity of tracks

An application of precision timing: the TOF-PET



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

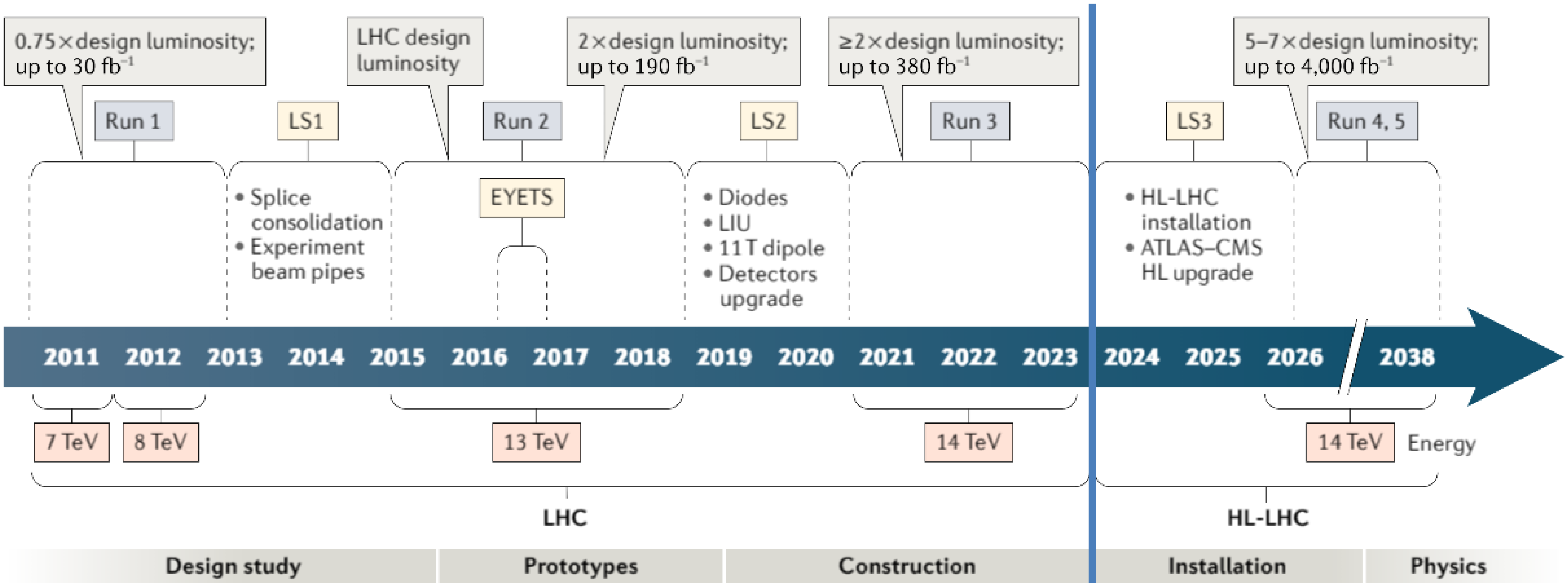




Two 511 keV photons which are detected in coincidence form a line of response (LOR).

The time information can be used to reduce background and directly improve the image quality

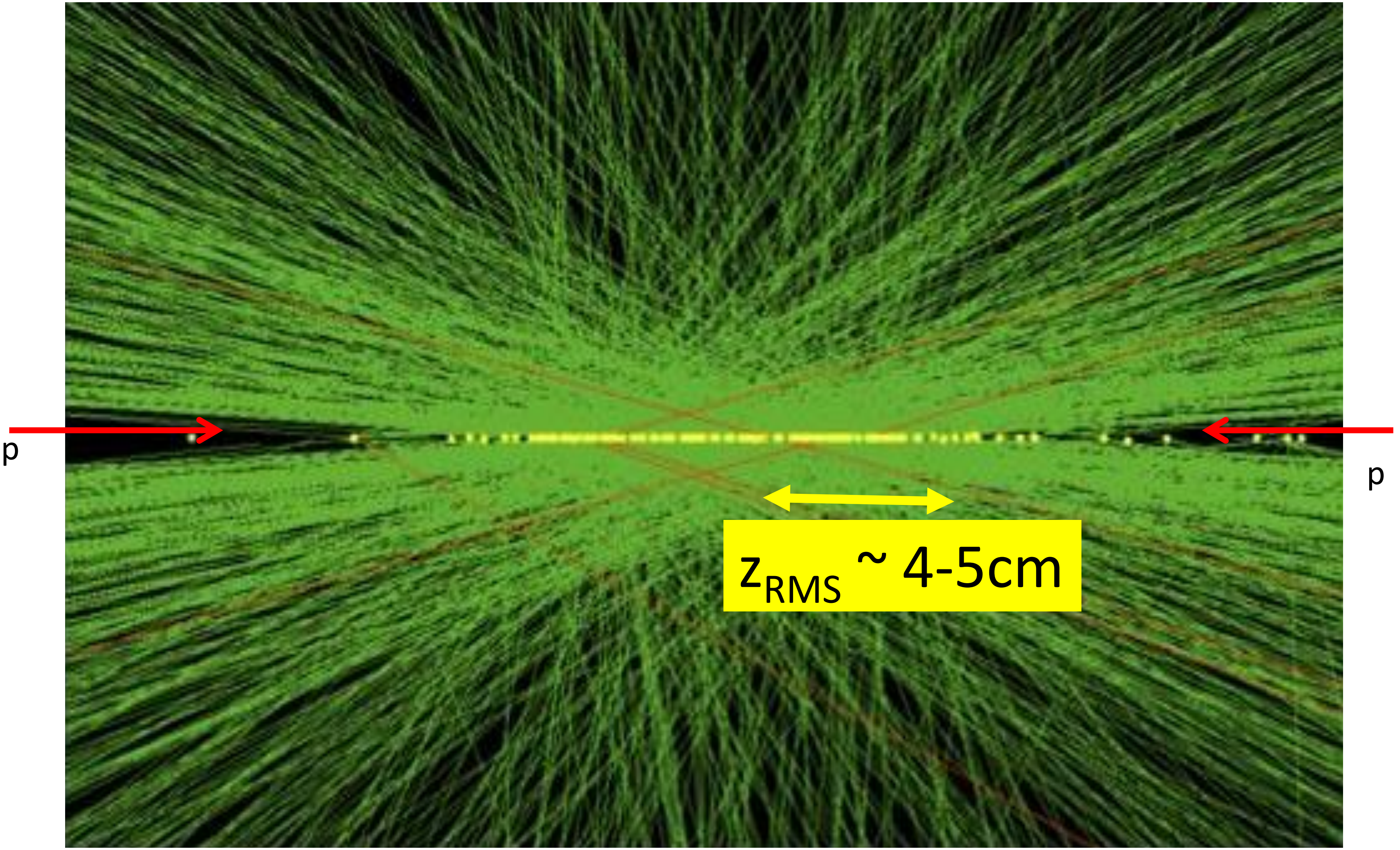
LHC and HL-LHC



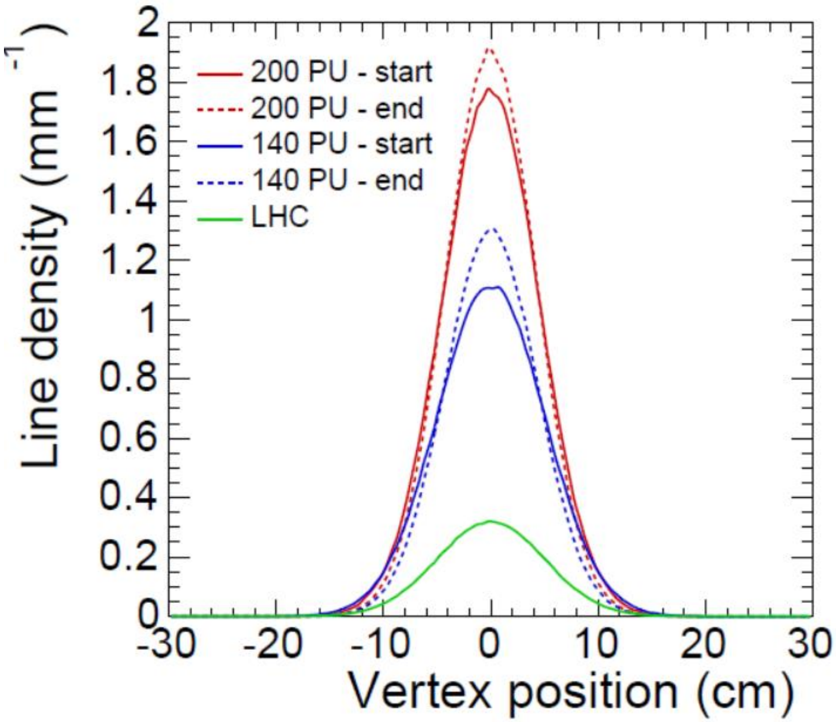
LHC:
30-50 protons collide at every bunch crossing

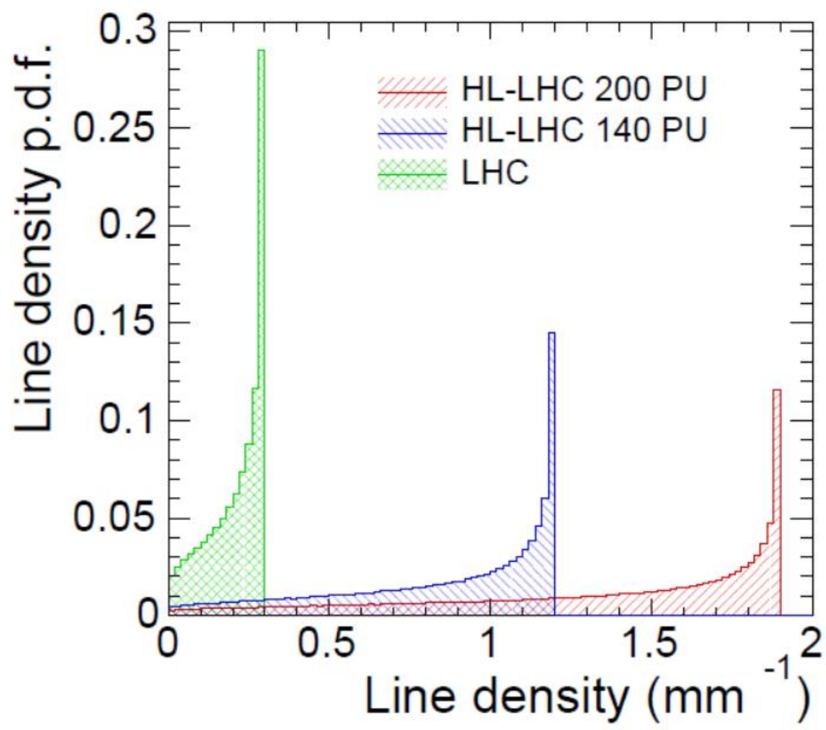
HL-LHC:
From 2026
140-200 protons will collide at every bunch crossing

A typical HL-LHC event



Spread of vertices along the beam axis

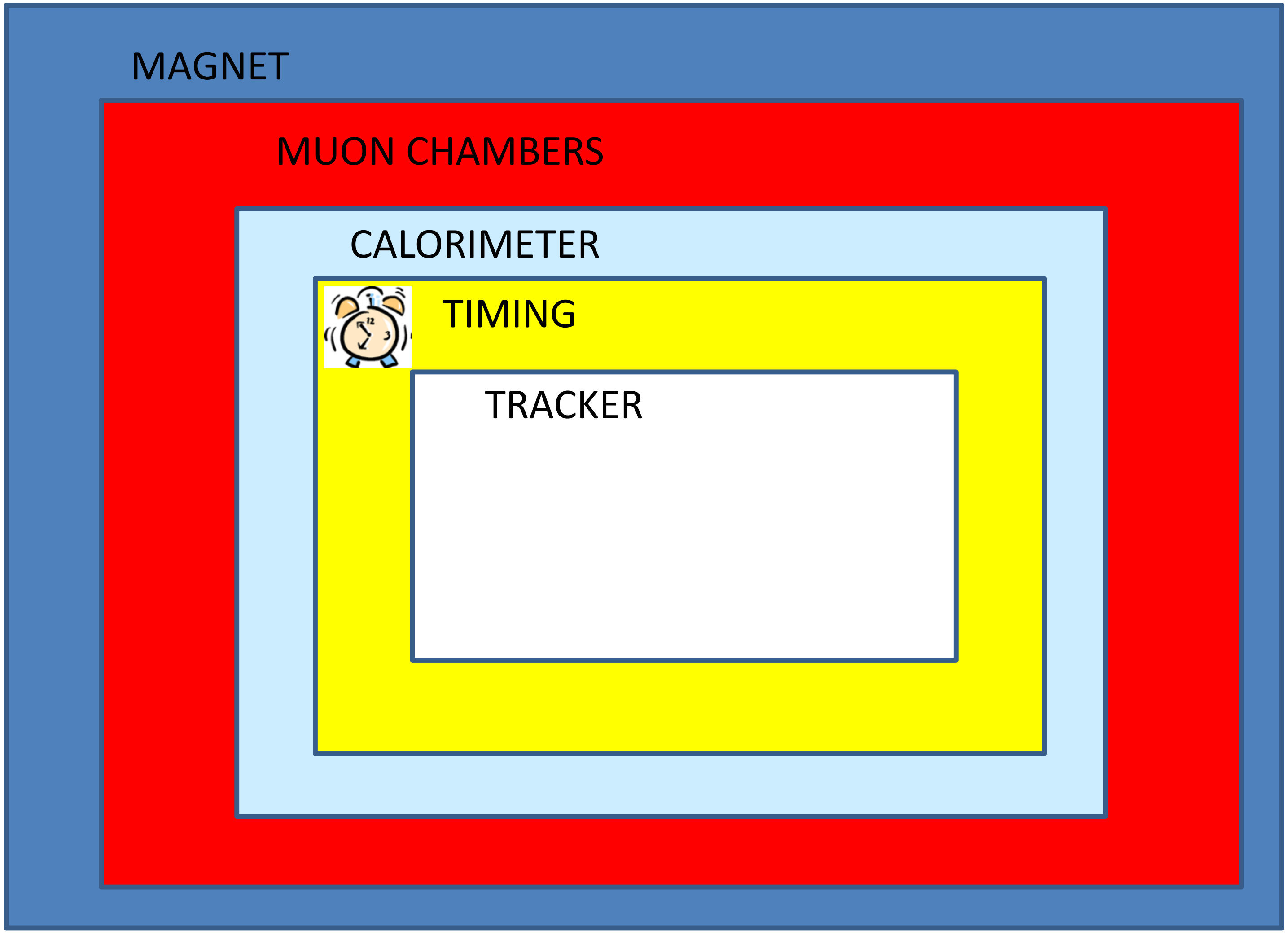




LHC → about 0.3 vertices /mm

HL-LHC → up to 1.9 vertices /mm

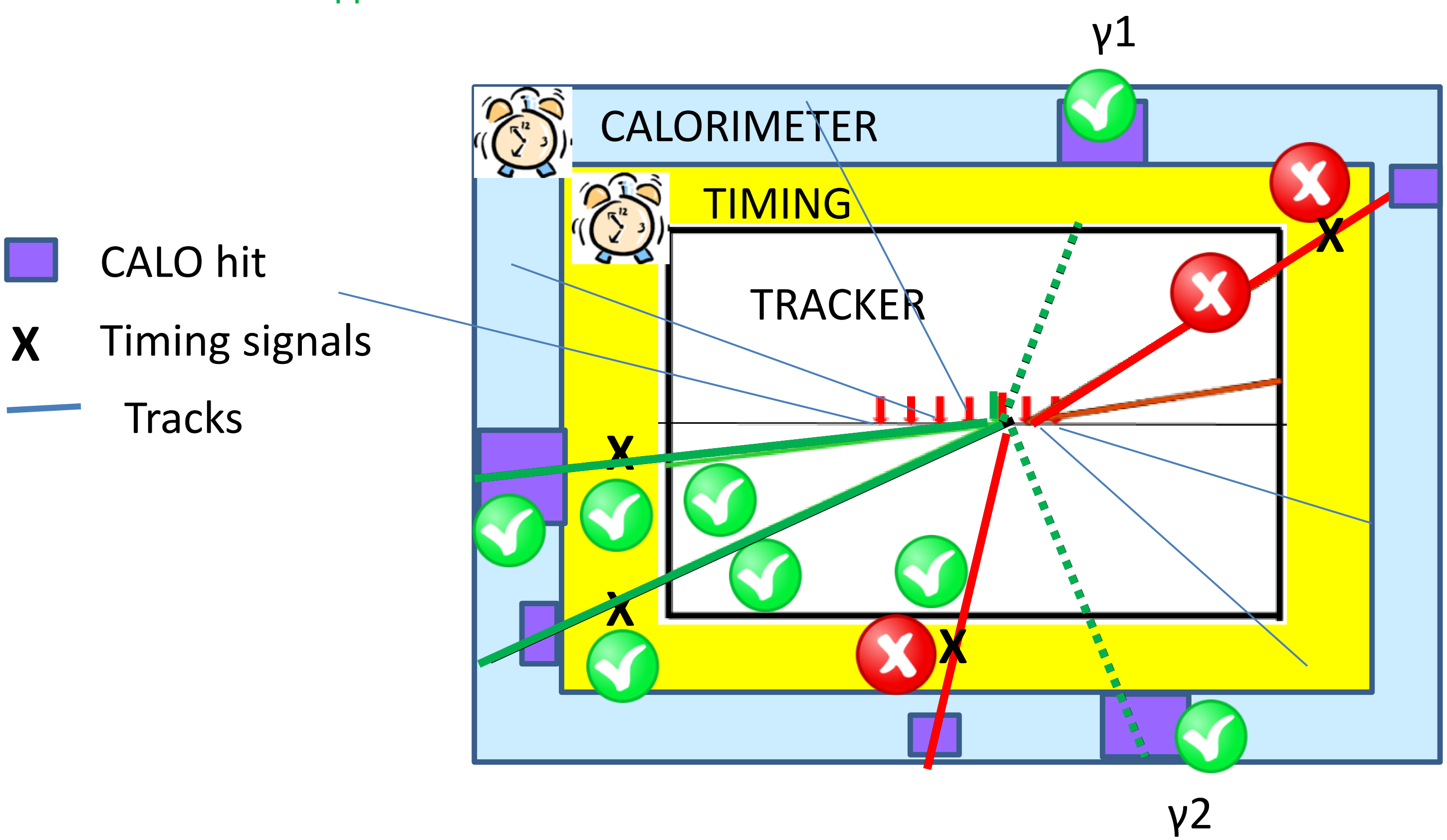
A typical HEP detector at a collider



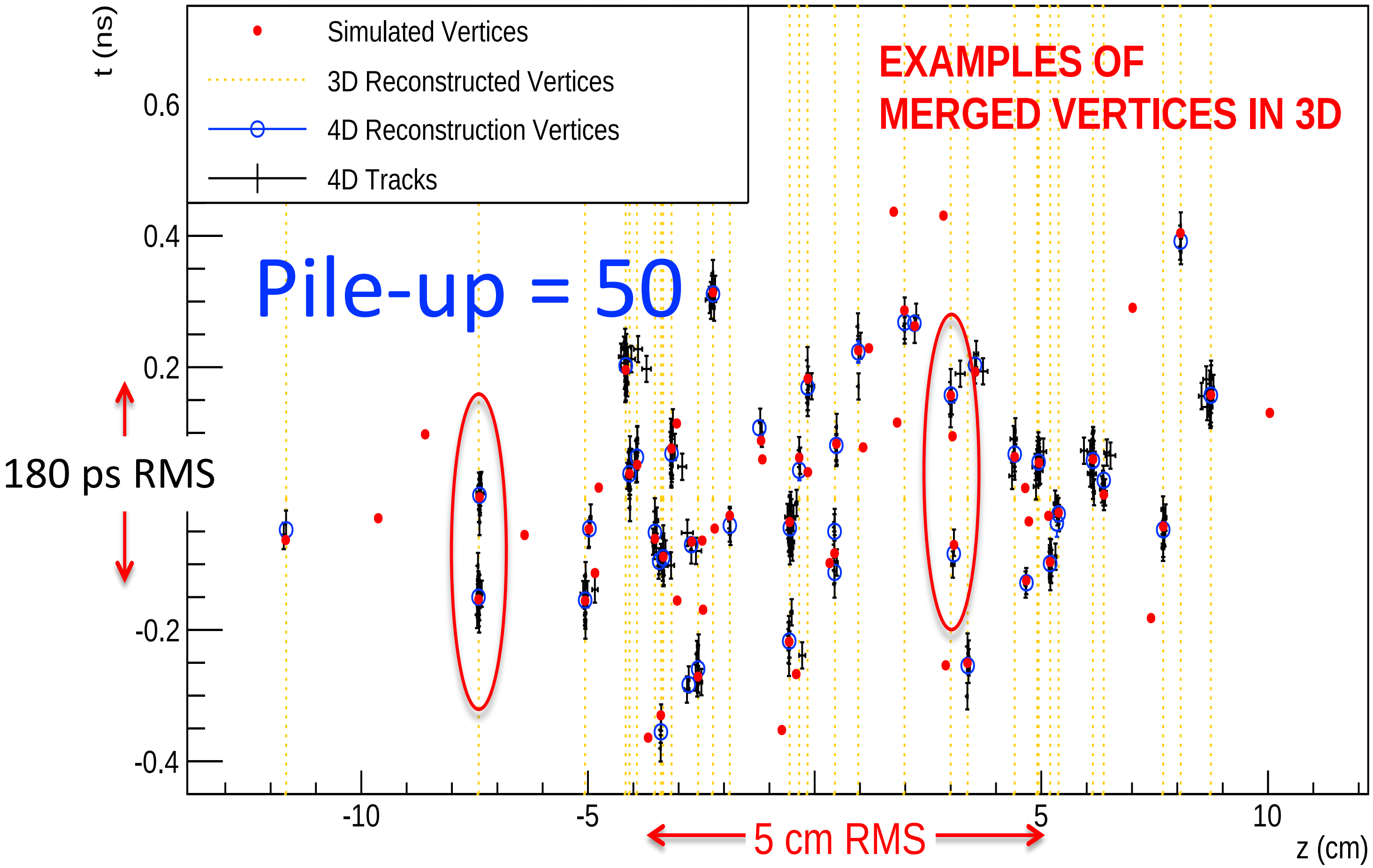
Pile-up Mitigation with timing

- **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→γγ vertex

a H→ γ γ event

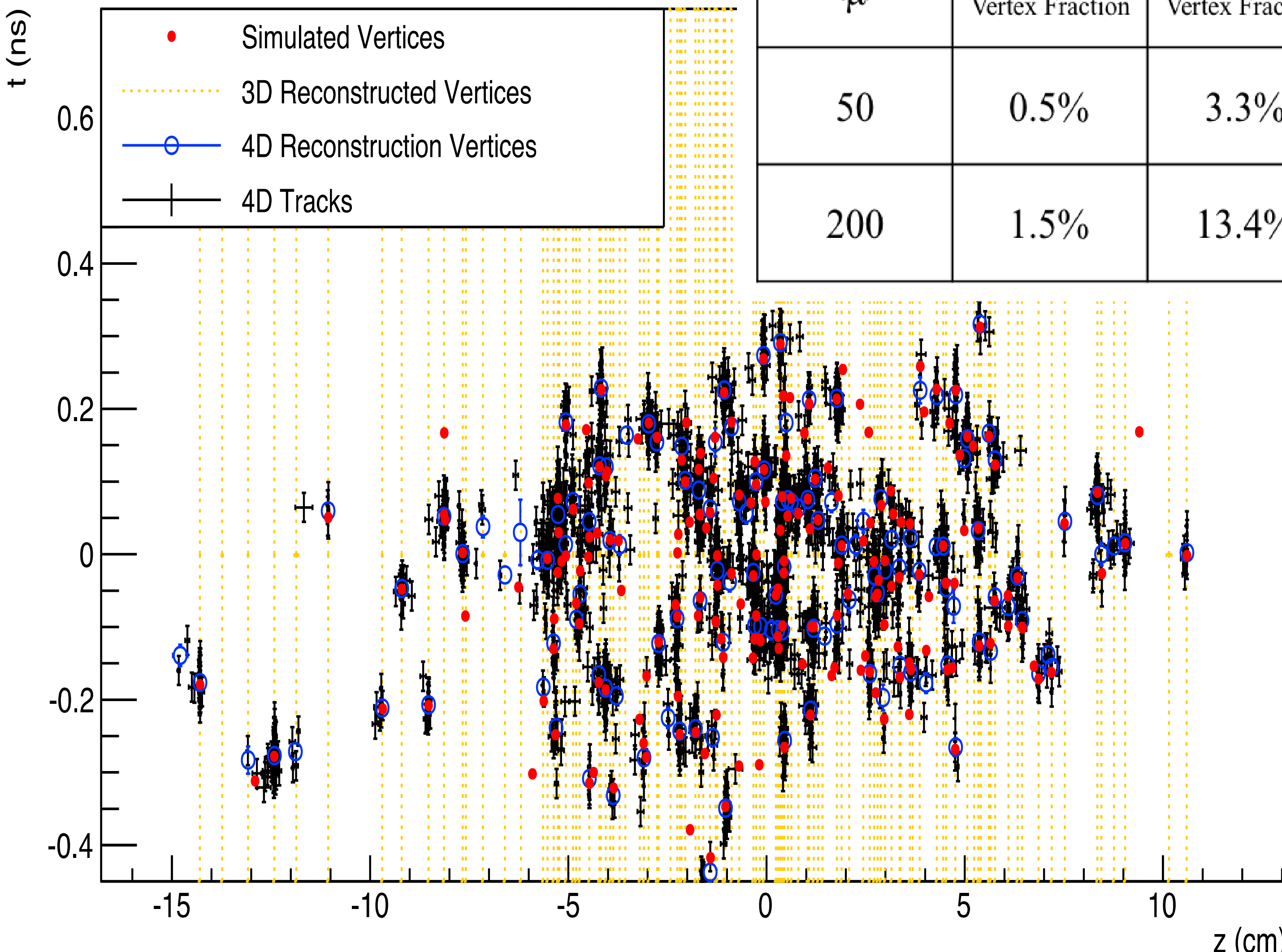


3D vs. 4D Vertex Reconstruction



- 4D reconstruction with track time information at ~25 ps

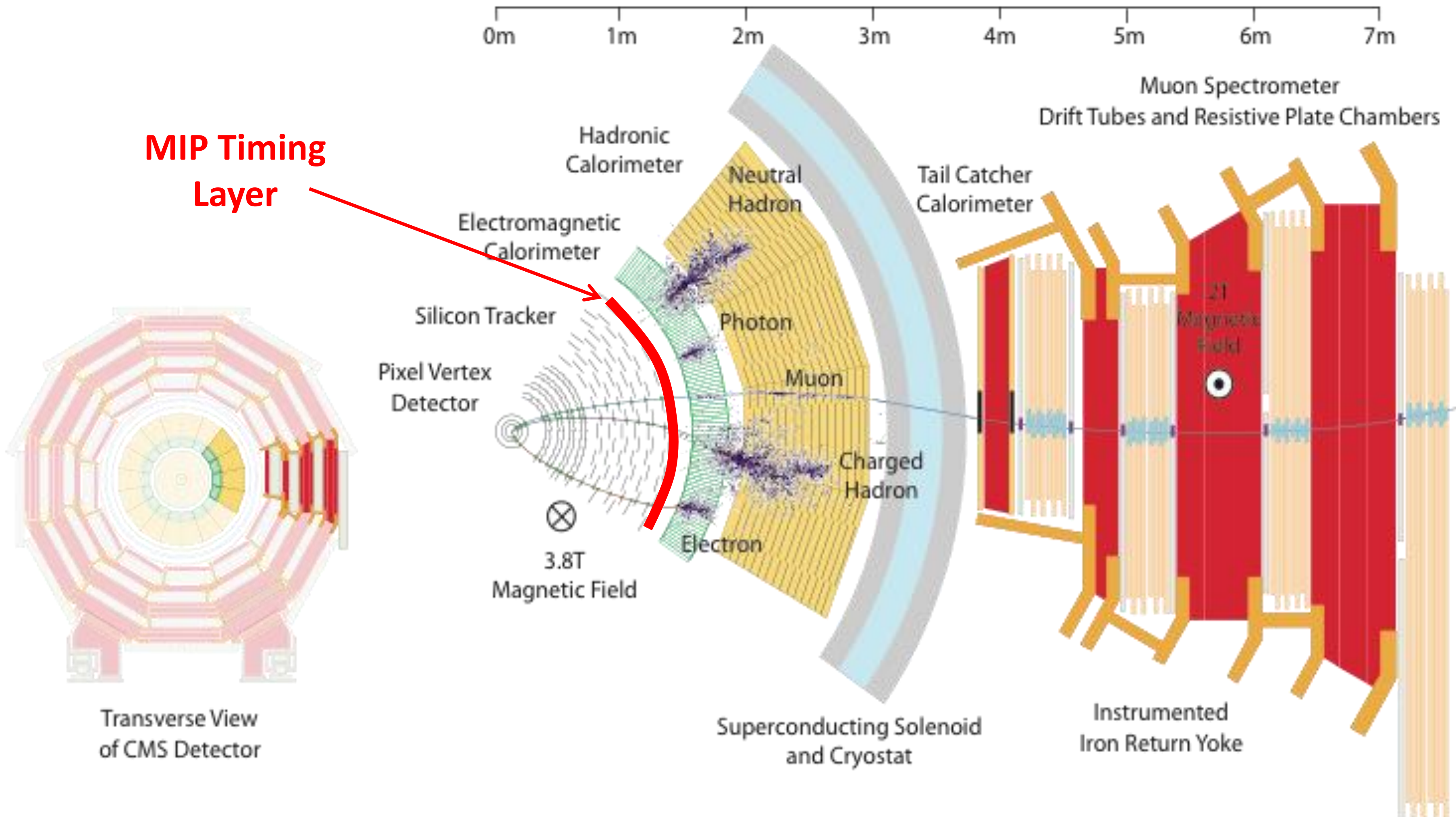
Pile-up = 200



CMS Simulation

<μ>	4D Merged Vertex Fraction	3D Merged Vertex Fraction	Ratio of 3D/4D
50	0.5%	3.3%	6.6
200	1.5%	13.4%	8.9

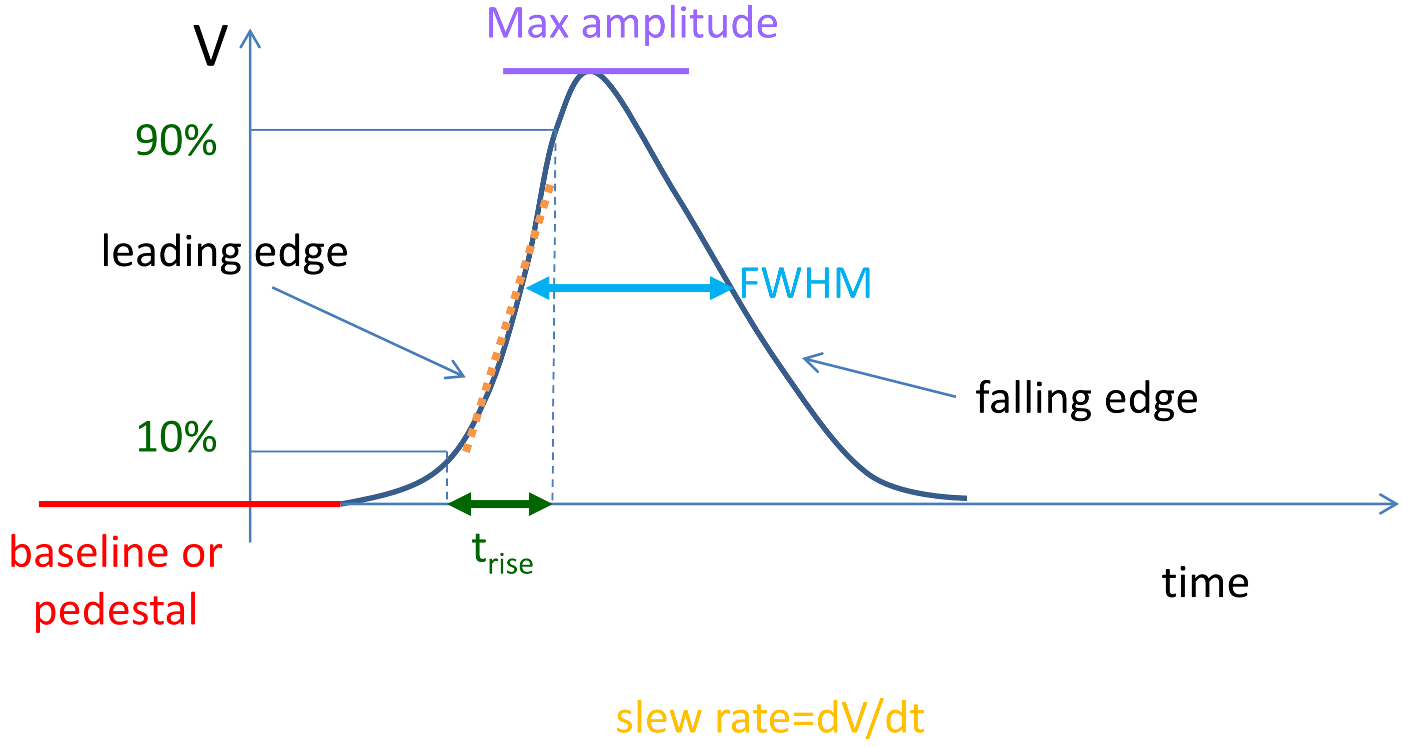
Particle-flow Event Reconstruction

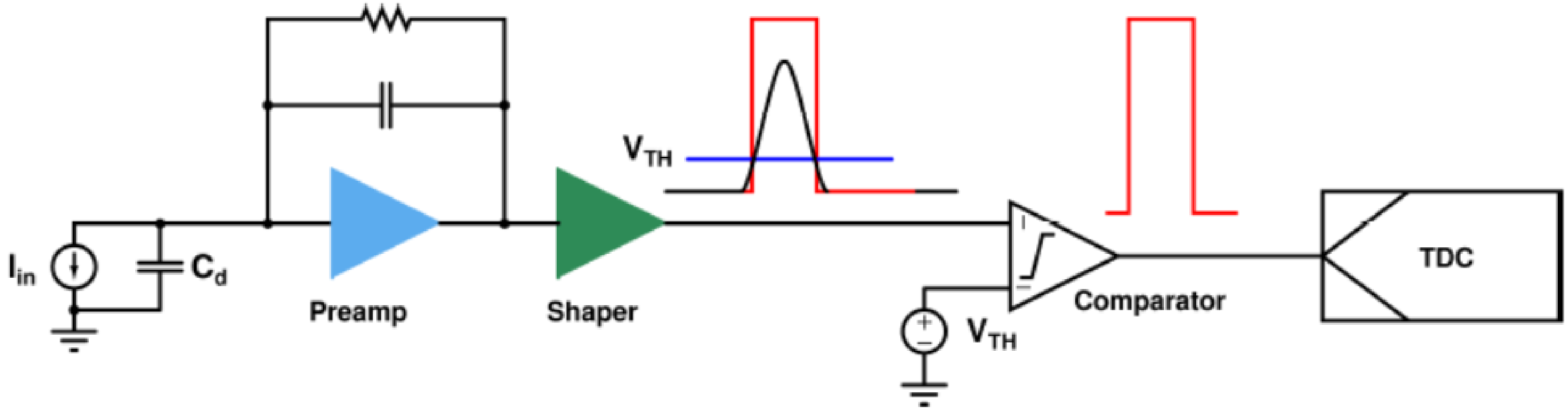


TIMING RESOLUTION

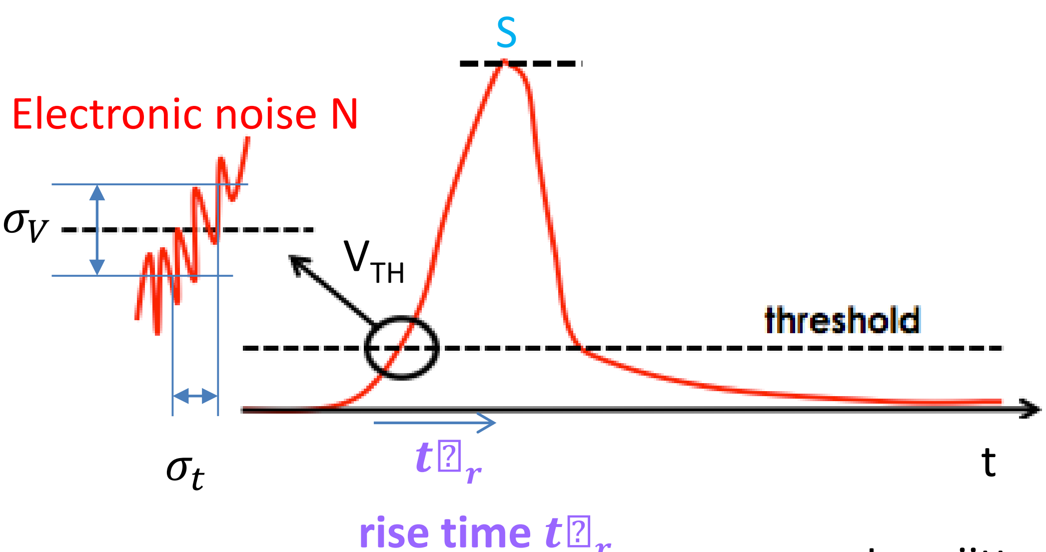
Timing resolution

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





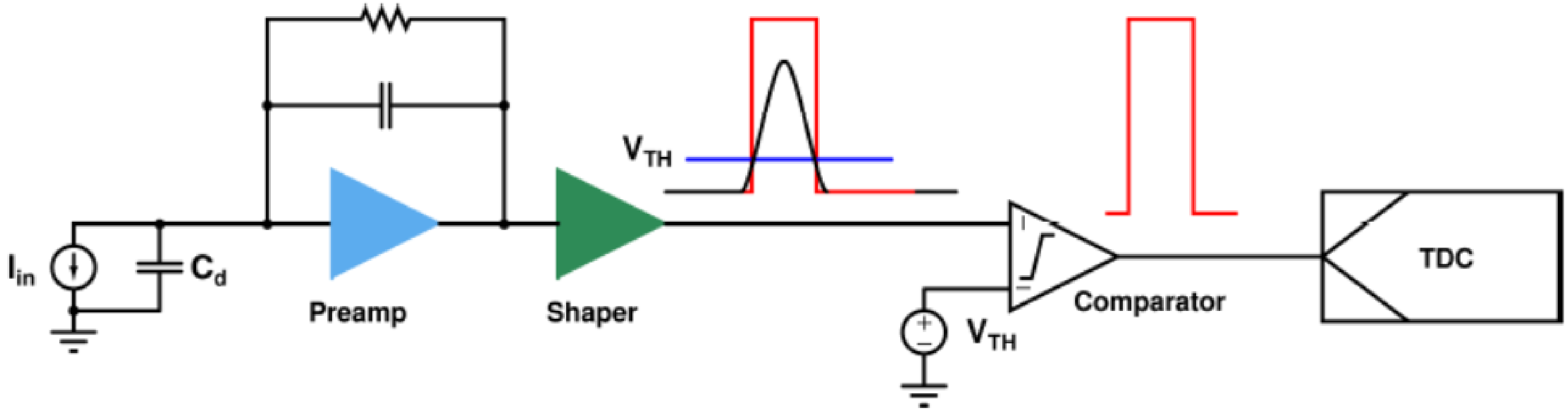
Time Jitter or “Noise term”



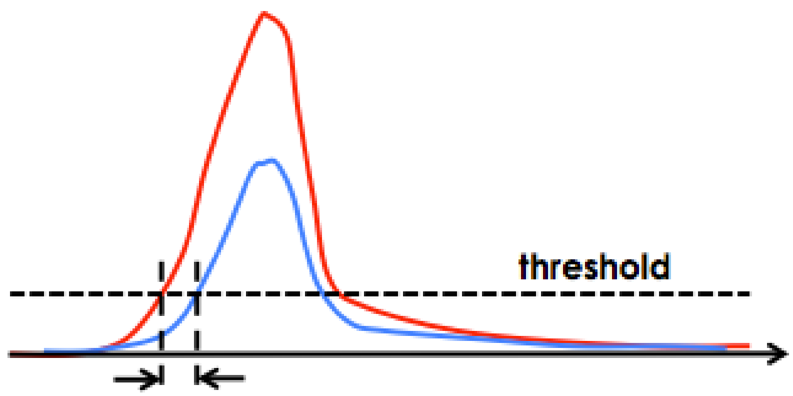
$$\sigma_V = \frac{dV}{dt}\sigma_t \Rightarrow$$

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

Low jitter → high S/N and short rise time



Time walk effect

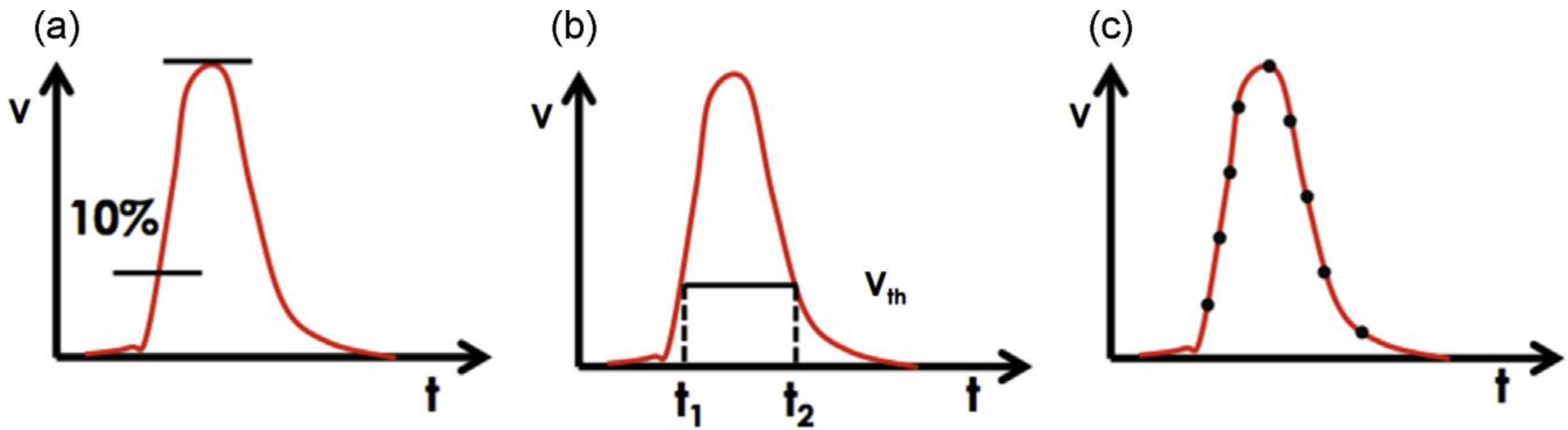


- Signals of different amplitude cross the thresholds at different times.
- Signal shape may also change depending on the amplitude.

→ 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:

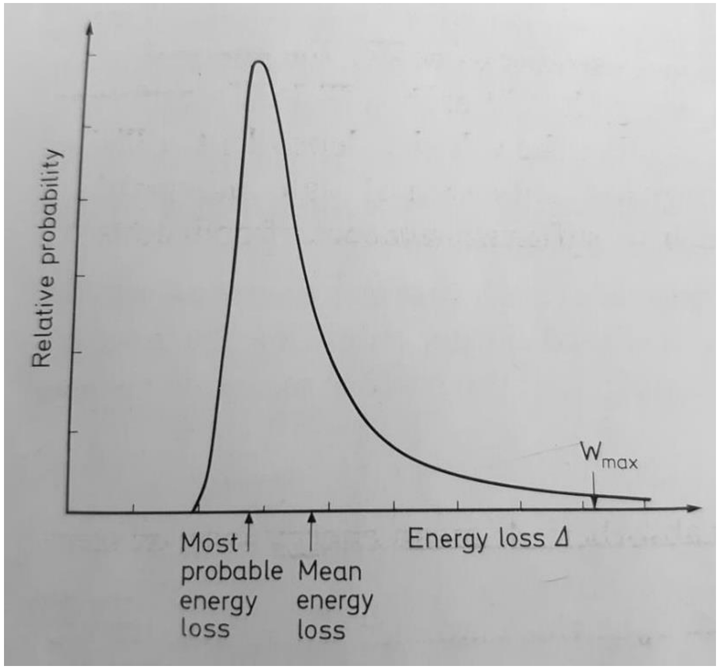


(a) Constant Fraction Discriminator, (b) Time Over Threshold, (c) Multiple Samplings

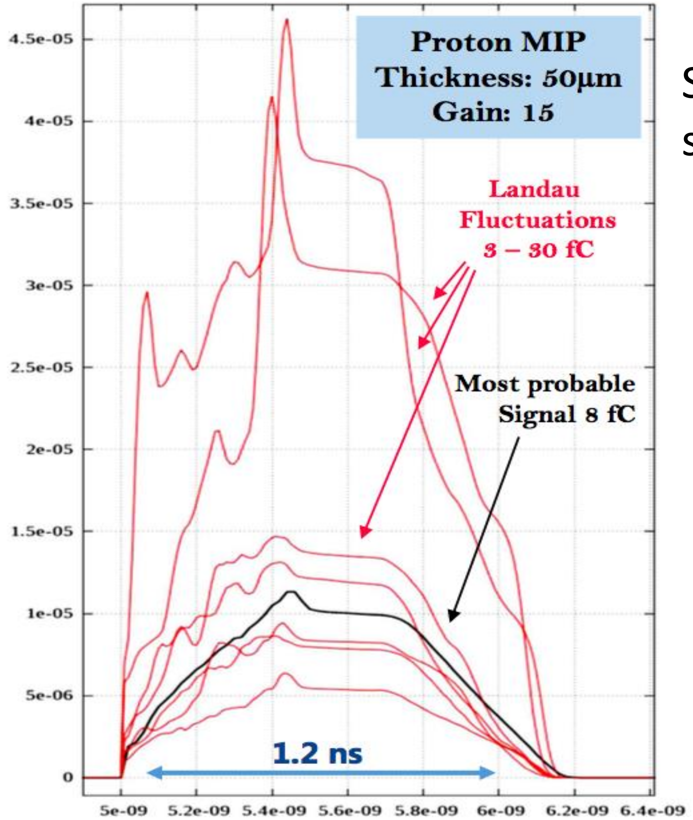
a) Constant Fraction Discriminator measures the time at which the signal crosses a fraction of its amplitude.
b) The measurement of the arrival time of the signal and the Time Over Threshold allows to correct for the shape change due to the different amplitude
c) A full digitization of the curve allows 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.



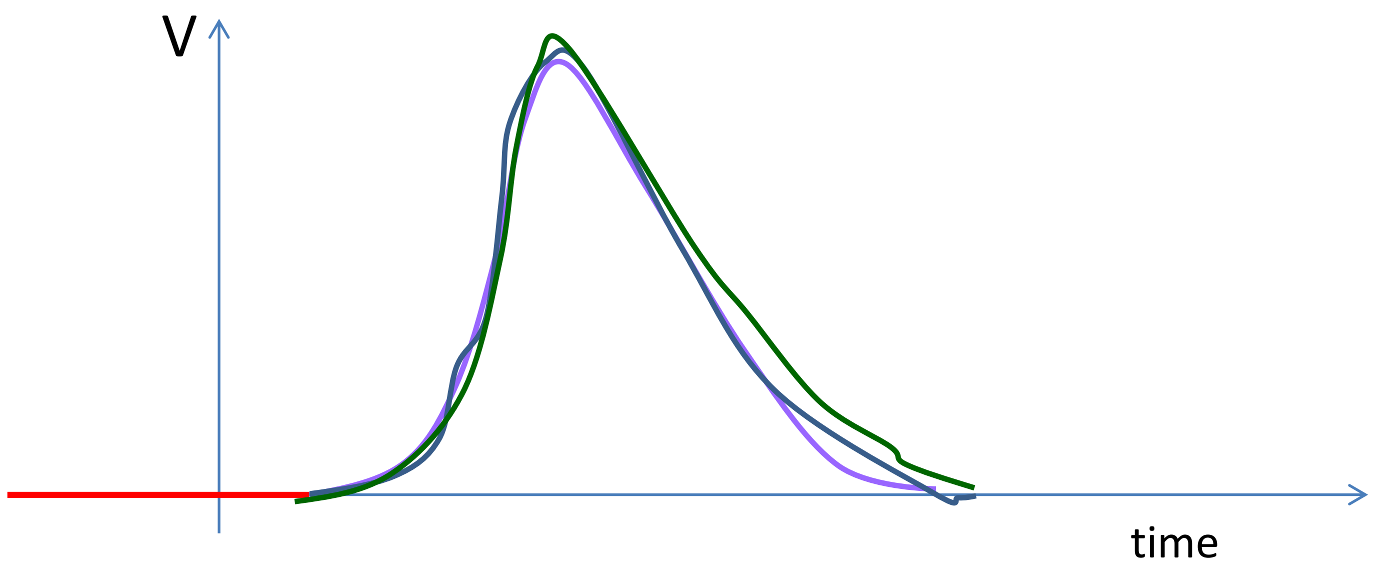
W.R. Leo,
Techniques for Nuclear and Particle Physics Experiments, ISBN: 3-540-17386-2



Si LGAD sensors

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.



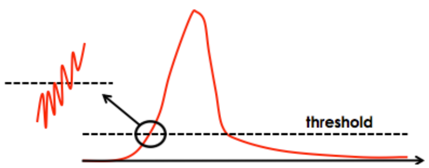
TDC error

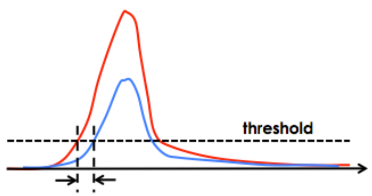
This is the error connected with the TDC bin

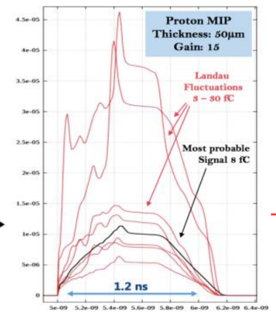
$$\sigma_{TDC} = \frac{\Delta t_{TDC}}{\sqrt{12}}$$

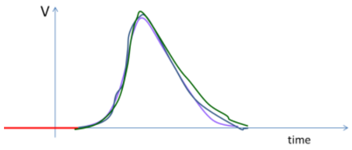
It can be reduced by optimizing the readout electronics

Timing resolution









$$\sigma^2_t = \sigma^2_{\text{Jitter or Noise}} + \sigma^2_{\text{Time Walk}} + \sigma^2_{\text{Landau}} + \sigma^2_{\text{Distortion}} + \sigma^2_{\text{TDC}}$$

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

ionization

Gas based devices

Silicon detectors

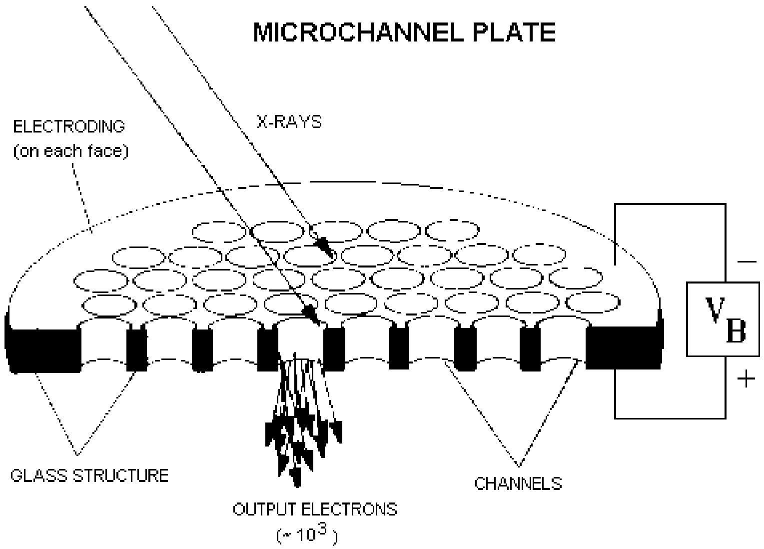
Light based devices

Scintillating crystals coupled to photo-detectors with amplification

Cherenkov medium coupled to photo-detectors with amplification

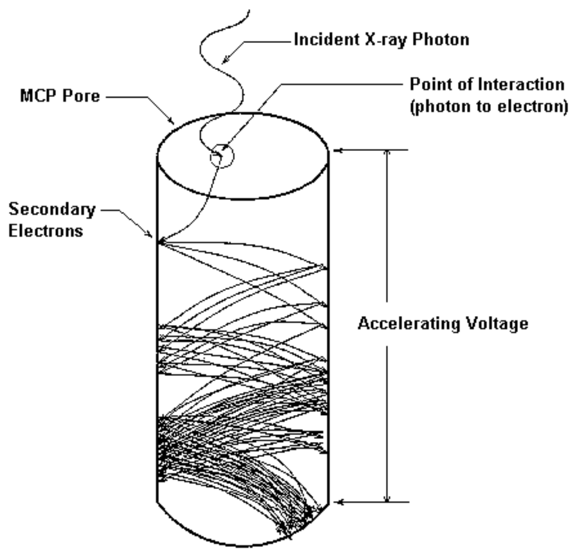
Vacuum devices

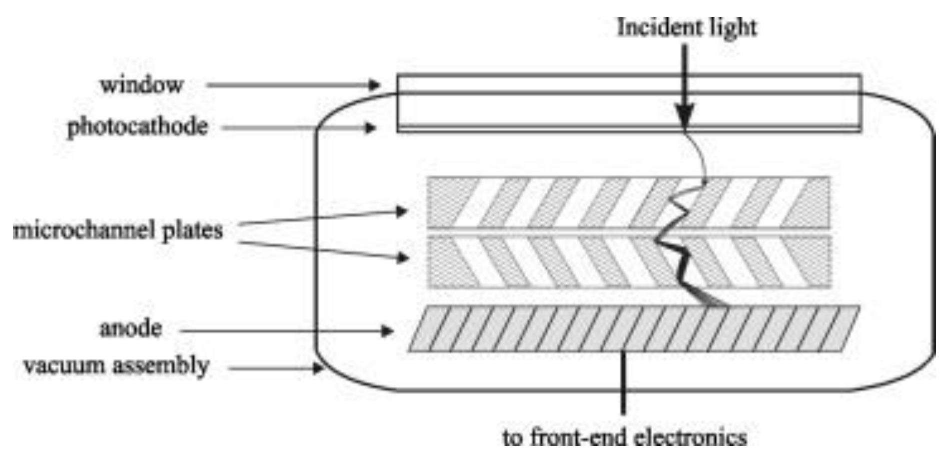
Micro Channel Plates



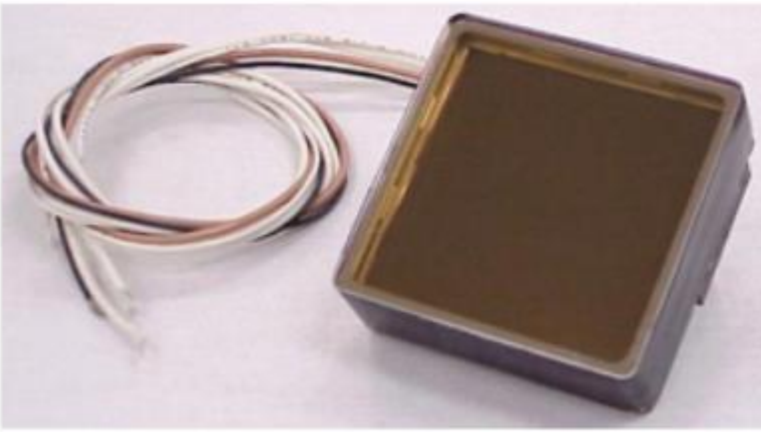
Vacuum devices
Based on **secondary emission**
Channels typical diameter:10 µm, length:400µm.

More stacks of micro-channel plates in a **<** configuration or **Z** configuration can be done. Gain ~10^6 for 2 stacks.

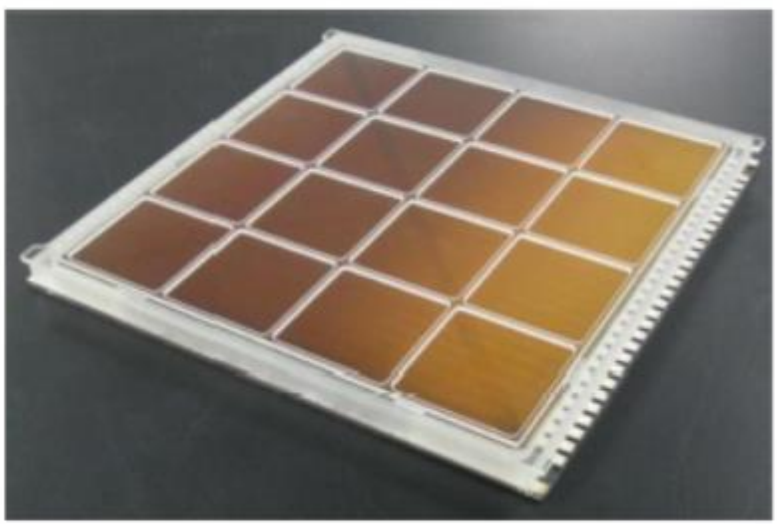




Micro Channel Plates



- 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



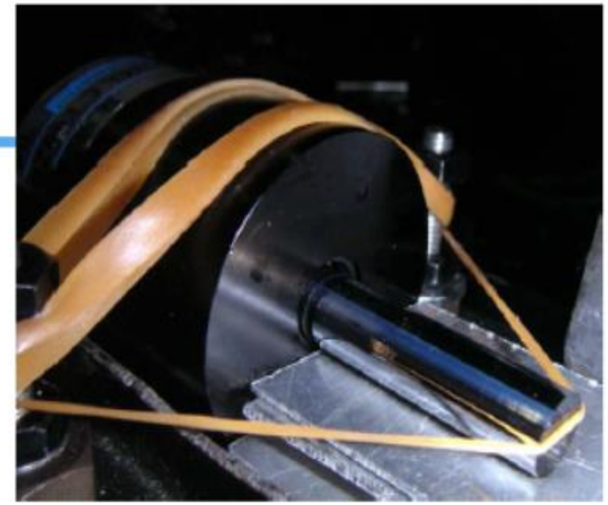
- **Very expensive**
- There is an effort to produce large area MCP at lower cost LAPPD (20x20 cm^2 and Gain~10^7)

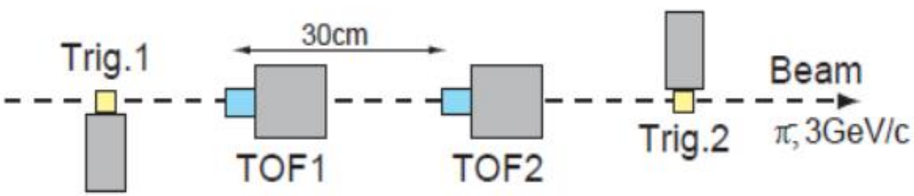
https://arxiv.org/pdf/1603.01843.pdf

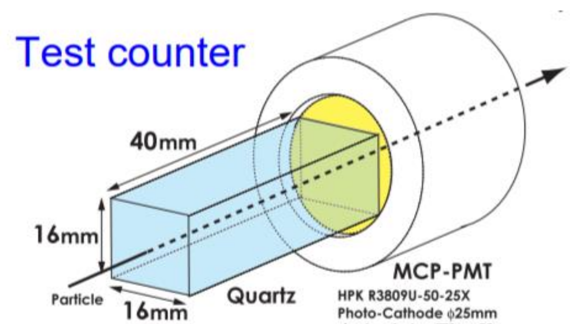
Micro Channel plates

Beam test setup

- 3GeV/c π^- beam
  - at KEK-PS π2 line
- PMT: R3809U-50-11X
- Quartz radiator
  - 10^{ϕ}x40^{z}mm with Al evaporation







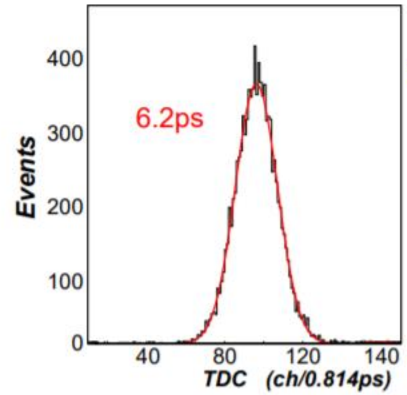
https://indico.cern.ch/event/13750/contributions/146262/attachments/113680/161492/MCP.pdf

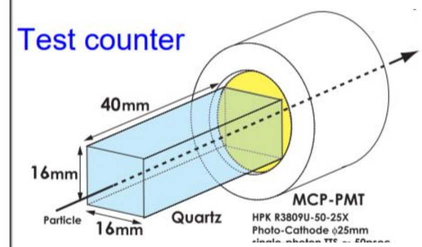
Micro Channel plates

MCP resolution: 40-50 ps with single photons

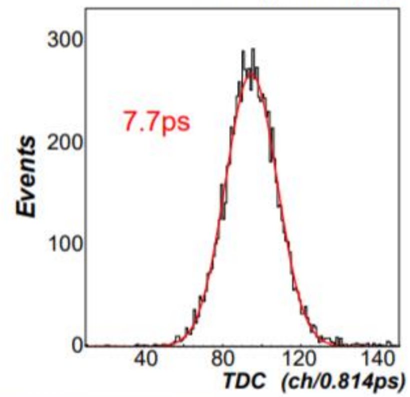
Beam test result

- 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



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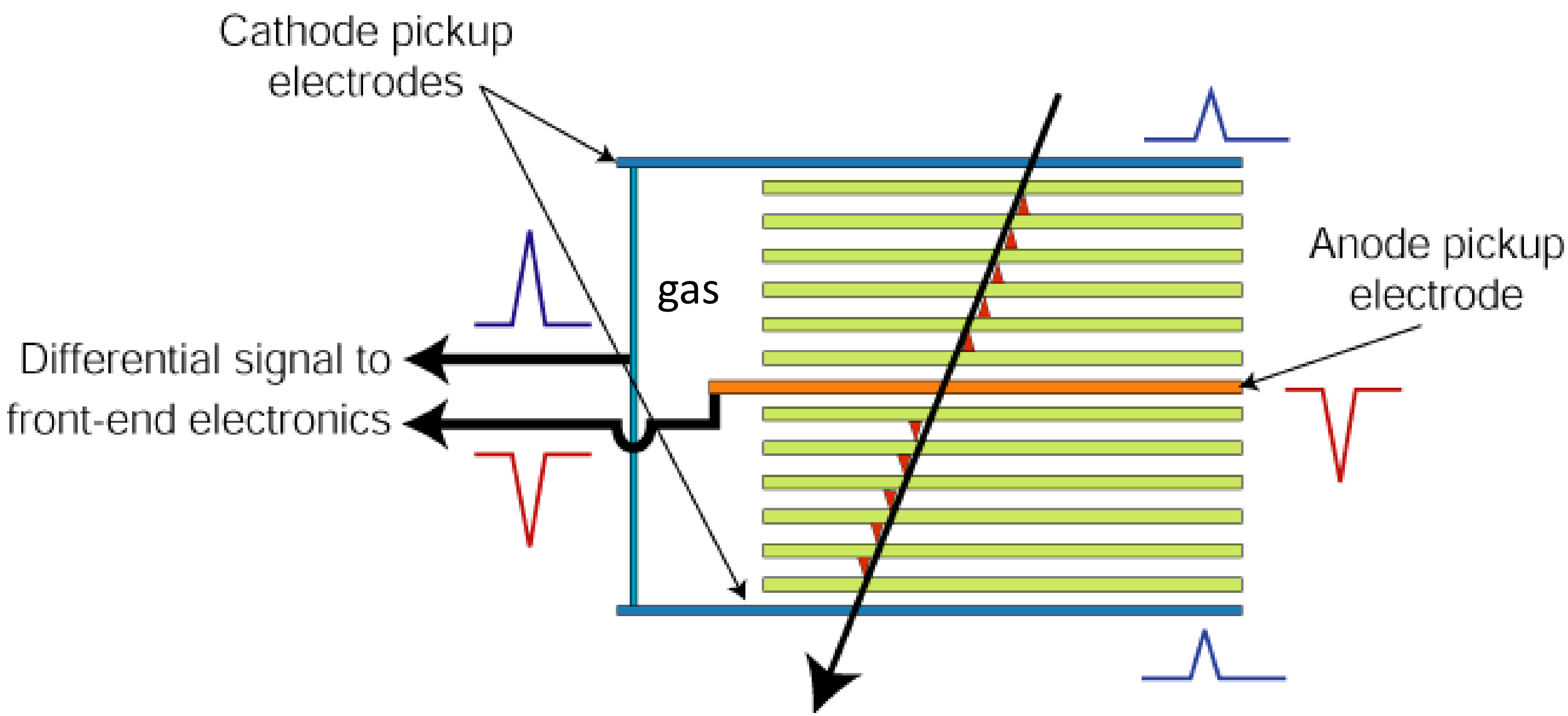
Multi-gap RPC

https://www.youtube.com/watch?time_continue=9&v=kLa36SmiC4Q

Multi-gap RPC

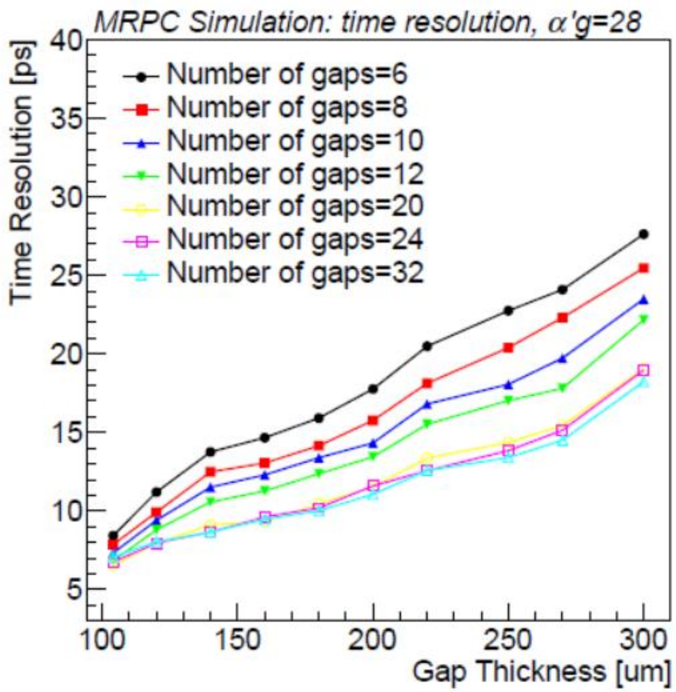
The ALICE TOF detector



Multi-gap RPC

F. Wang et al. arXiv:1812.02912v2

Experiments	StackNo.	GapNo.	Thickness[μm]	Working E [kV/cm]
ALICE	2	5	250	104
CBM	2	4	250	110
STAR	1	6	220	114
BESIII	2	6	220	103
RefMRPC	4	6	160	135
THU1	4	8	104	159
THU2	1	6	250	109

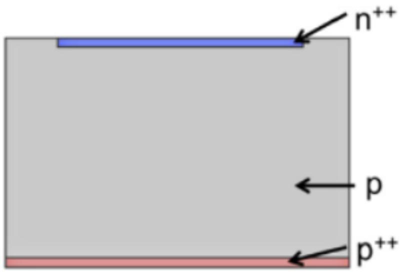


Time resolution for these detectors depends on:

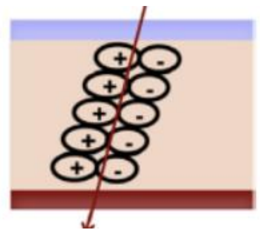
- The number of gaps (better many gaps)
- The thickness of the gaps (better thin gaps)

Rather cheap devices, and can be made in large areas (ALICE 160 m^2), suitable for a TOF detector.

Silicon sensors

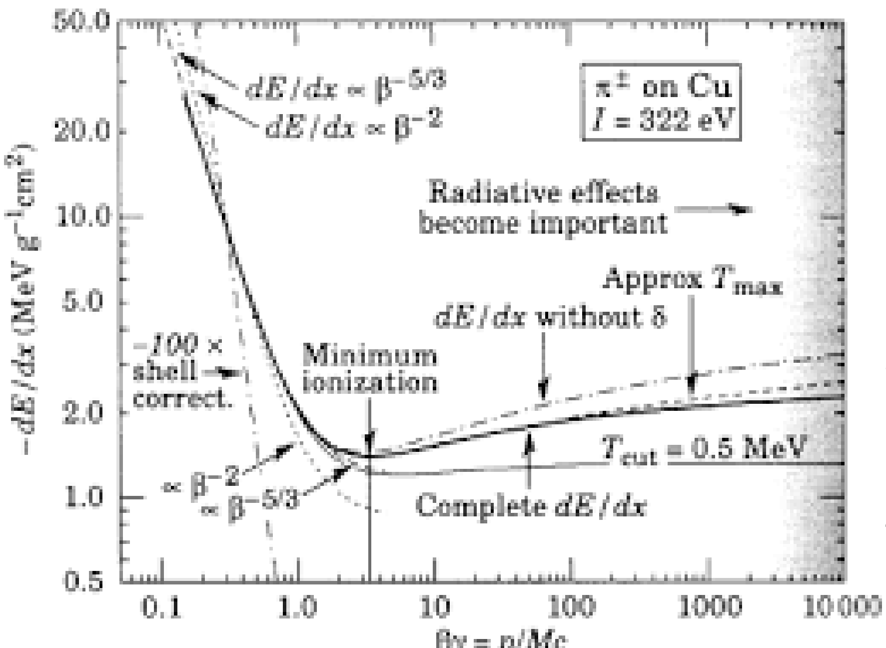


Traditional Silicon Diode



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.



inelastic collision with the atomic electrons of the material

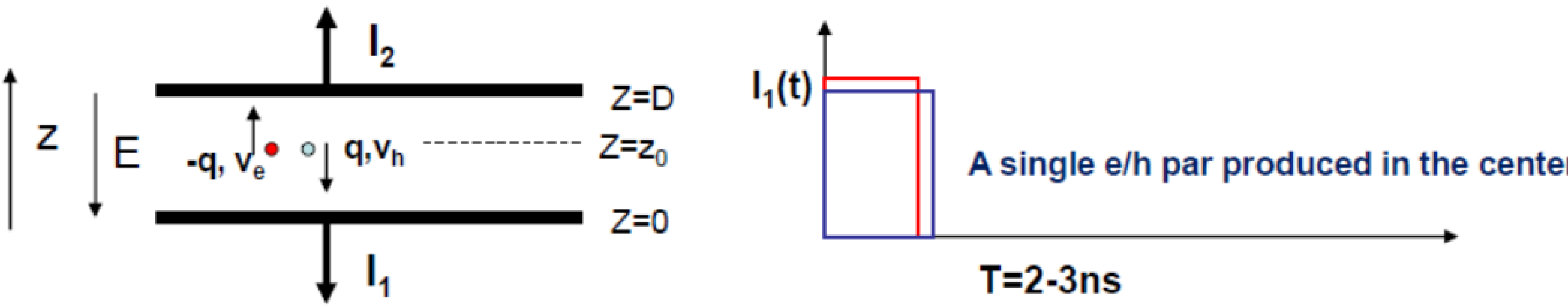
dE/dx=1-2MeV/(g/cm^2) ρ(Si)=2.32g/cm^3
dE/dx=1.5MeV*2.32g/cm^3*cm=3.5 MeV/cm=
= 350 eV/µm

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

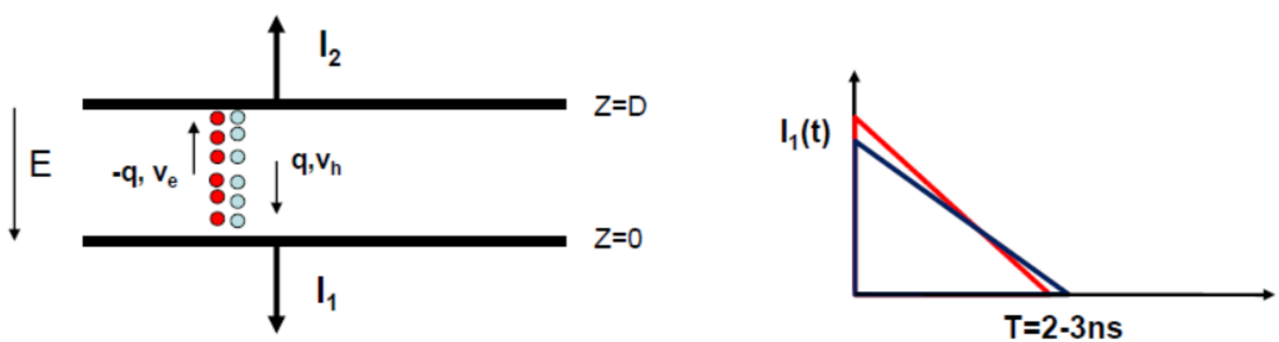
dN(e/h pairs)/dx=dE/dx/$\mathcal{E}$=350/3.6 /µm
~100 e/h pairs /µm

Silicon sensors

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



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

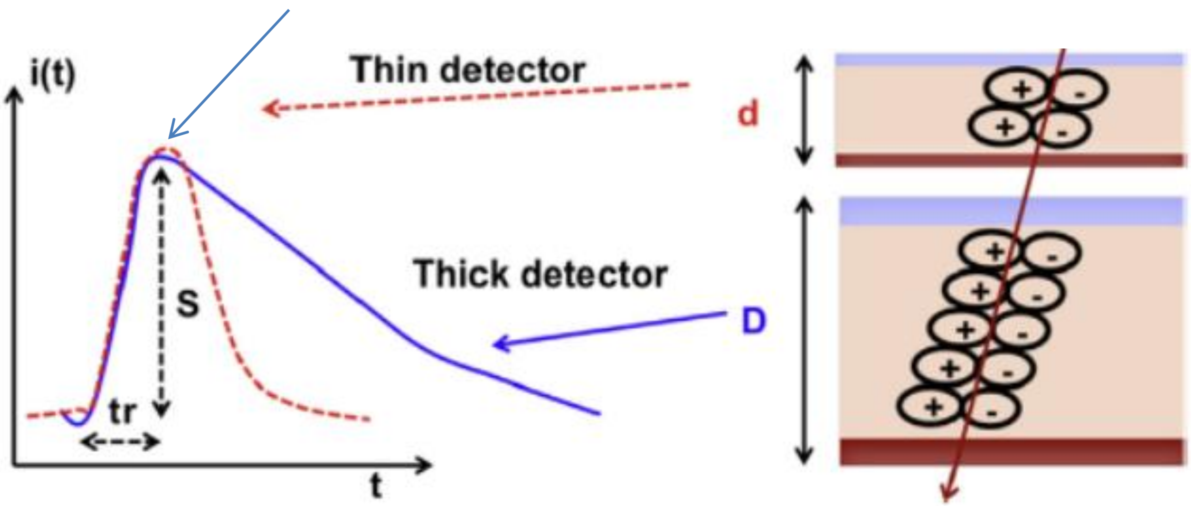


Silicon sensors

The signal I_{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.

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

$$I_{max} \propto 75 q v_{drift} \sim 1 - 2 \mu A$$



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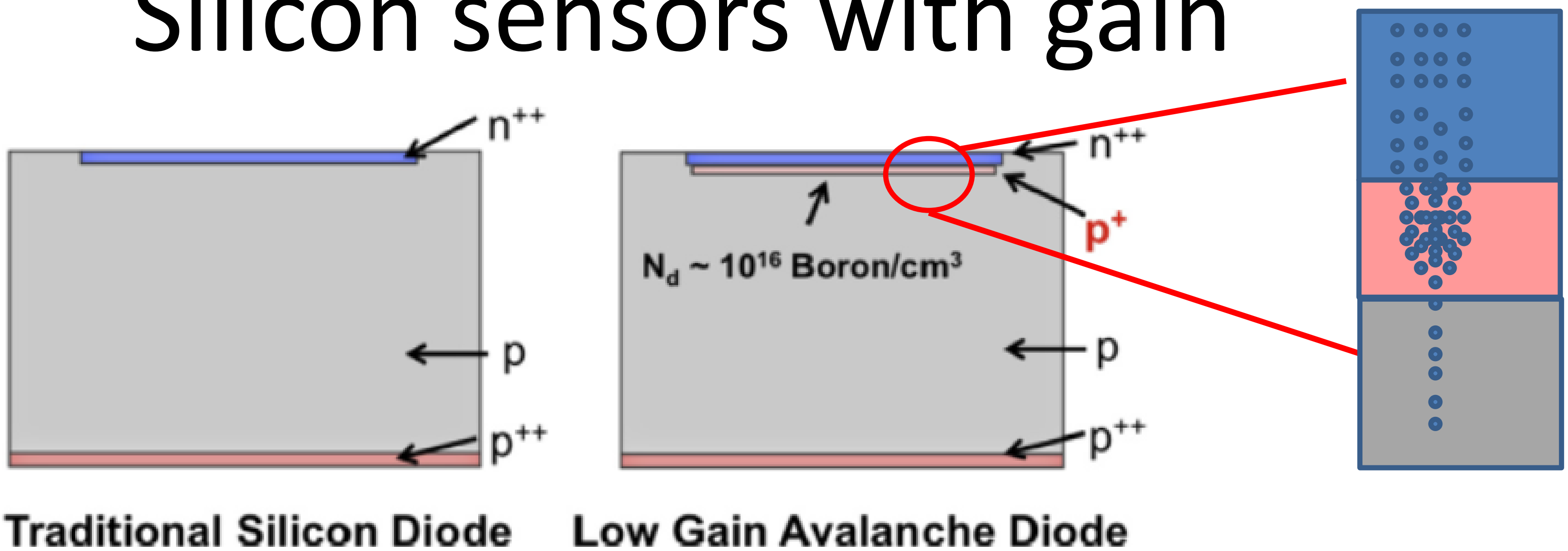
Silicon sensors with gain



Silicon sensors with gain:

A high doping region p+ creates a very high local electric field (E~300kV/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.

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

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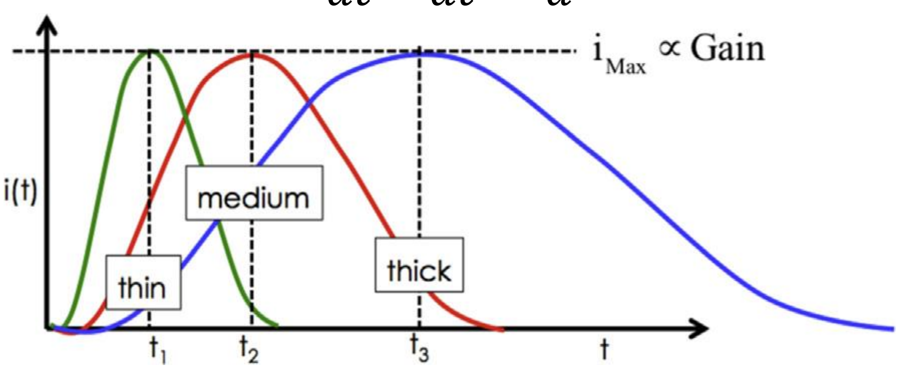
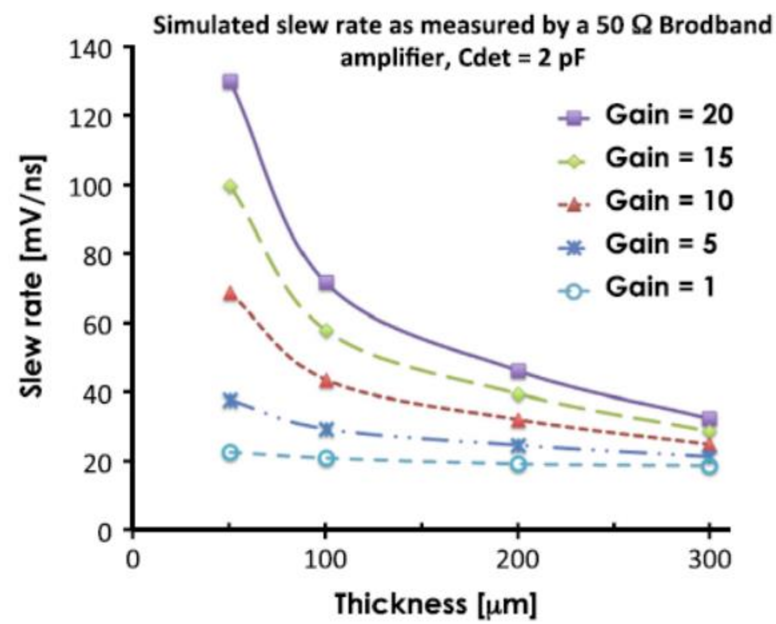
Silicon sensors with gain

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

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

$$\frac{di}{dt} \sim \frac{dV}{dt} \propto \frac{G}{d}$$





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.

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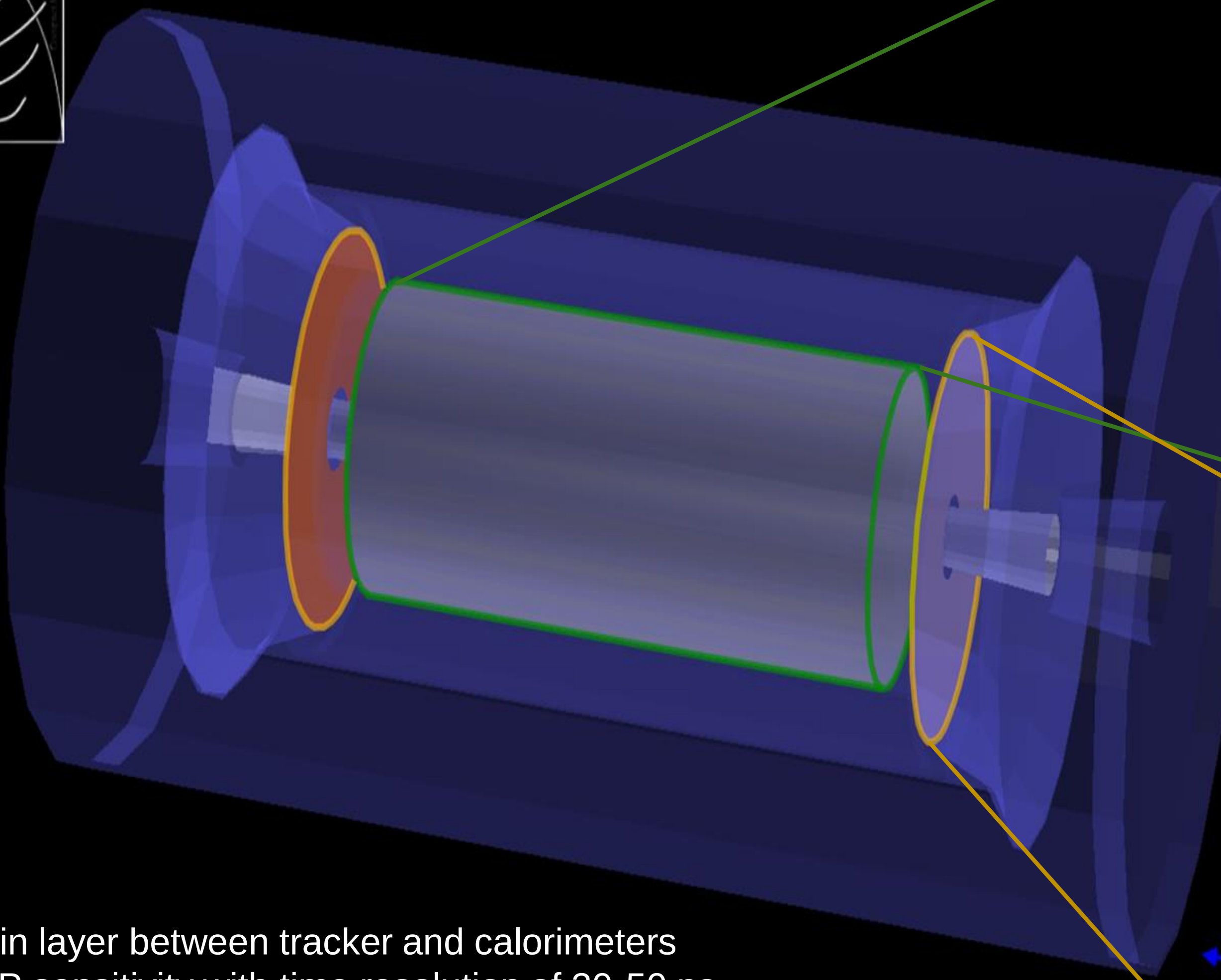
THE CMS MIP TIMING DETECTOR

Design of the CMS Mip Timing Detector (MTD)

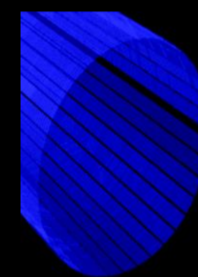


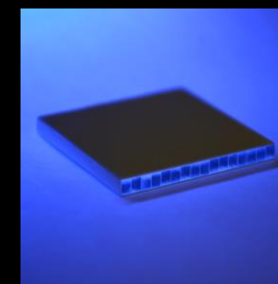
BARREL

Surface	~ 40 m²
Number of channels	~ 332k
Radiation level	~ $2x10^{14}$

n_{eq}/cm^2

Sensors: LYSO crystals + SiPMs



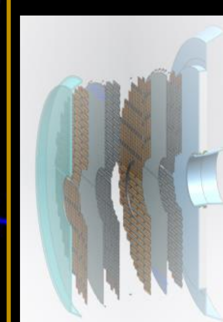


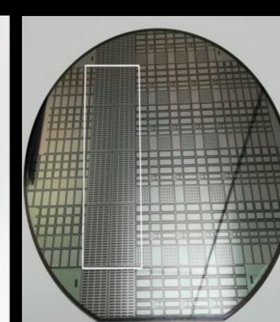
ENDCAPS

Surface	~ 15 m²
Number of channels	~ 8000k
Radiation level	~ $2x10^{15}$

n_{eq}/cm^2

Sensors: Low gain avalanche diodes





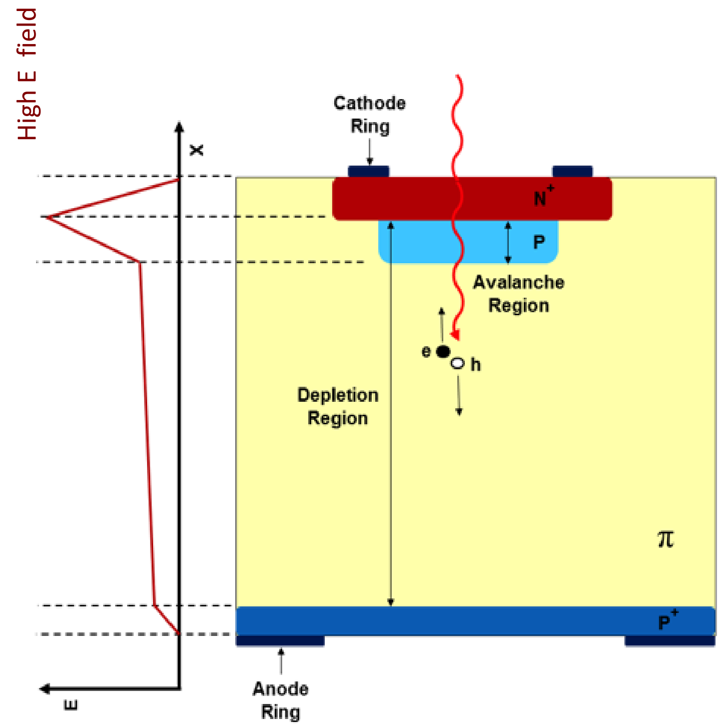
- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of 30-50 ps
- Hermetic coverage for |η|<2.9

CMS MTD endcap

LGAD (Low Gain Avalanche Diodes) technology sensors optimized for timing measurements

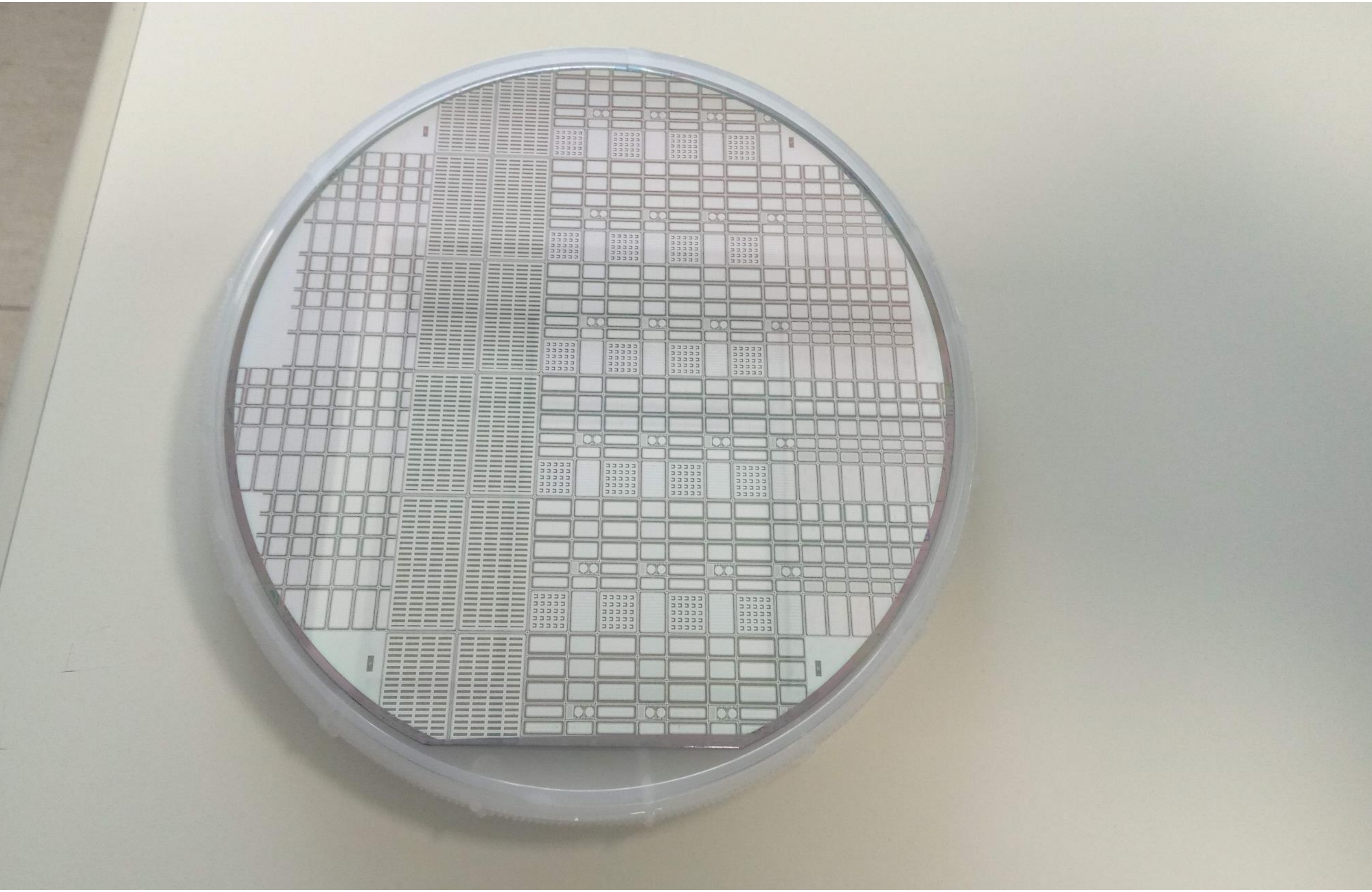
The idea: add a thin layer of doping to produce low controlled multiplication (the gain layer)

Moderate gain (10-20)



Sensor optimization for CMS MTD:

- Thin detectors to **maximize signal slew rate** (dV/dt): ~50 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)

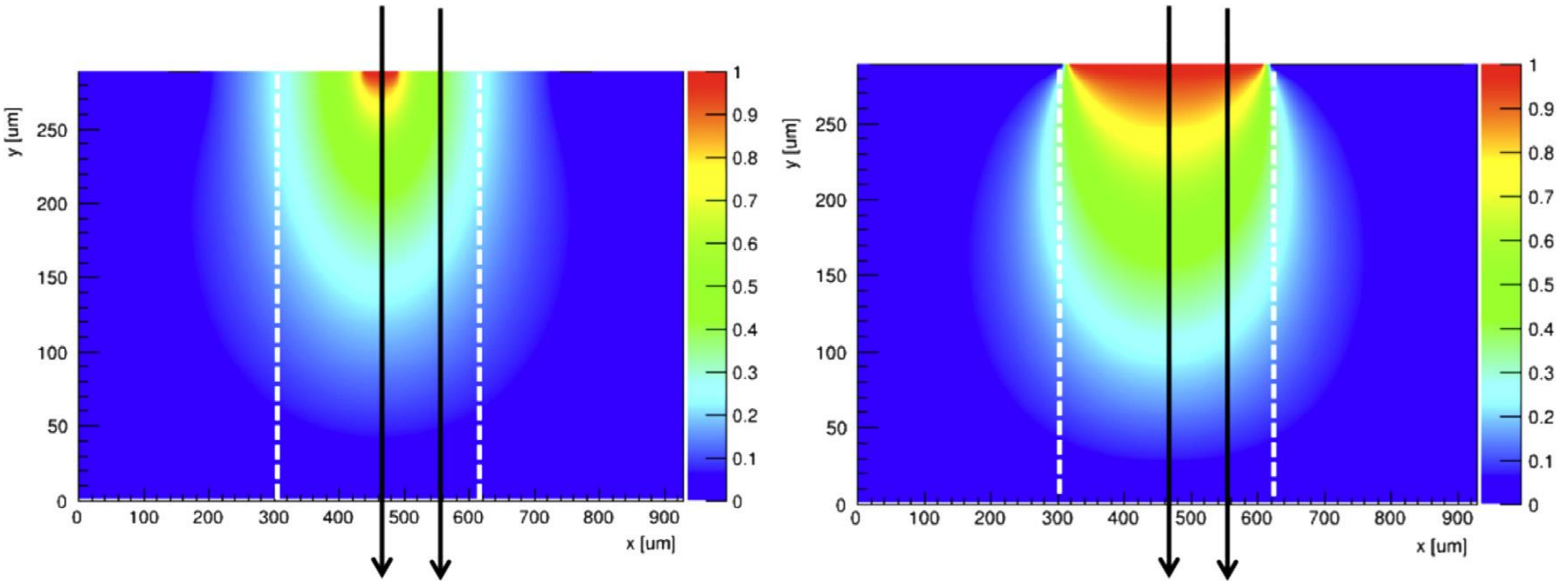


Wafer UFSD3 production from FBK

Uniform E-Field

It is very important to have a uniform E field → stable shape independent of the impact point → stable response

LGAD achieves uniform E-field with a wide implant

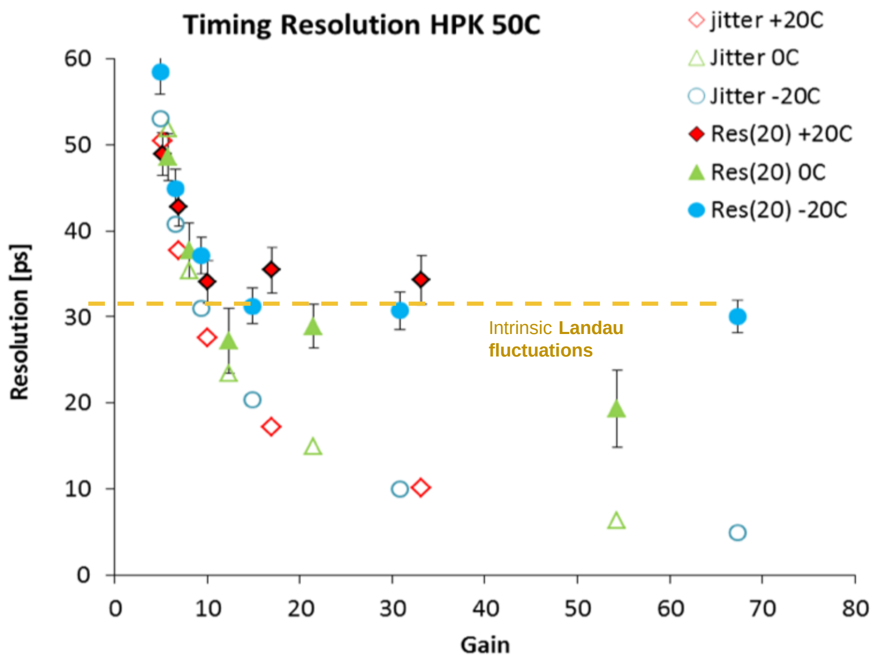


Values of Ew for two different segmented geometries: on the left side the geometry is 300 µm strip pitch with a 50 µm strip implant width while on the right the strip implant is 290 µm.

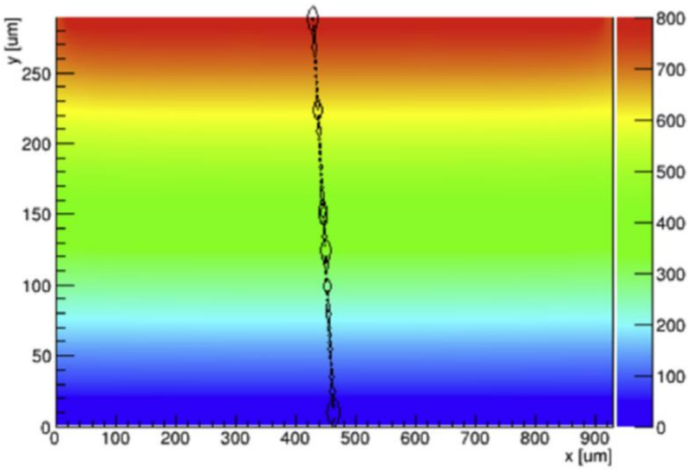
CMS MTD endcap – Ultra-fast silicon detectors

Target time resolution of 30 ps achieved

- Noise jitter term <25 ps for gain>15
  - ~N/(dV/dt)
- Intrinsic limit from Landau fluctuations:
  - Spatially non-uniform energy deposits along the track because of event-by-event pulse distortions
  - Constant: ~25 ps



1mm^2 50 um detector HPK UFSD, lab measurement with beta source



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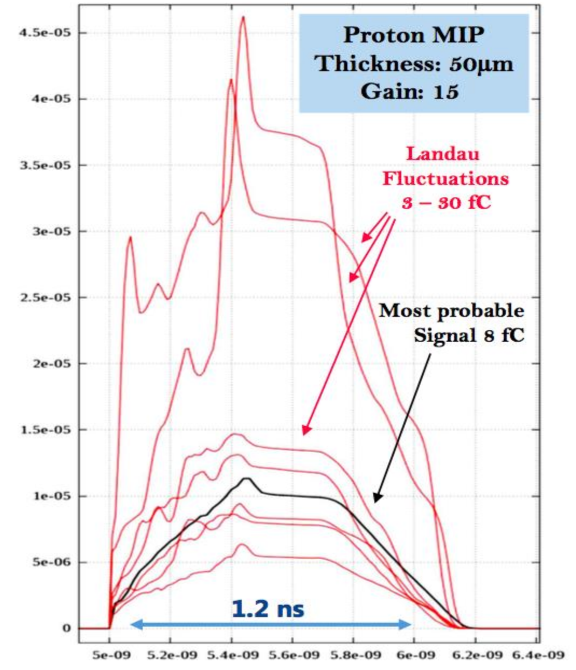
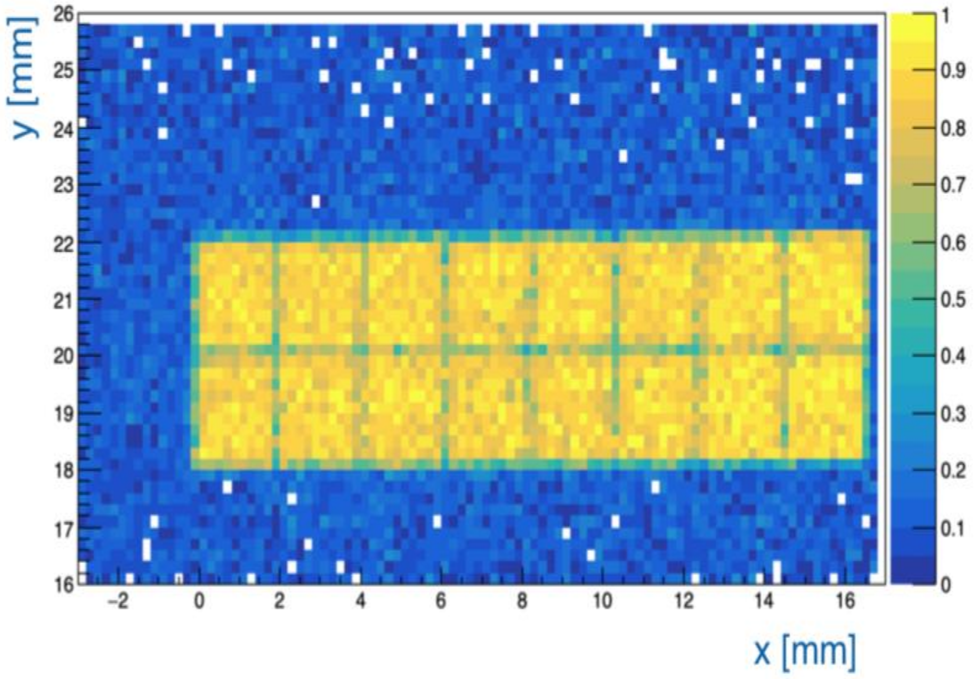


CMS MTD endcaps - test beam results

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

FBK sensor array: efficiency to proton beam



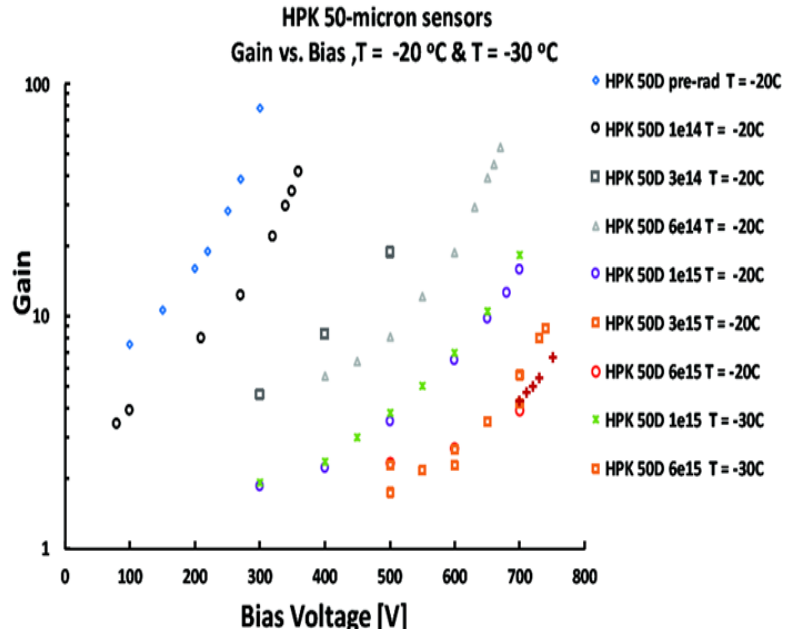
Radiation hardness of Si detectors

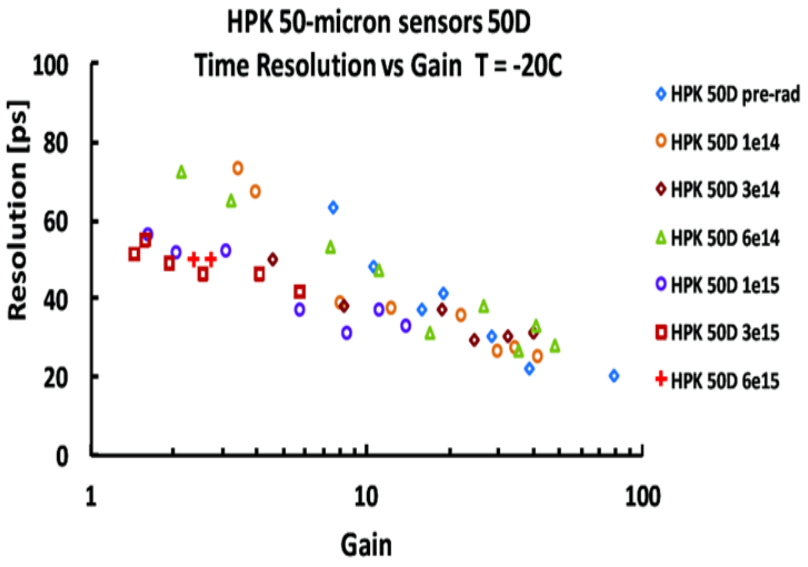
- Hadrons kick the Si atoms from their lattice sites, and create defects in the Silicon lattice.
- The defects can change the effect of the doping in the gain layer reducing the gain
- The charge collection efficiency is reduced
- A higher voltage is required to achieve the same gain
- The leakage current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

see G. Casse lectures

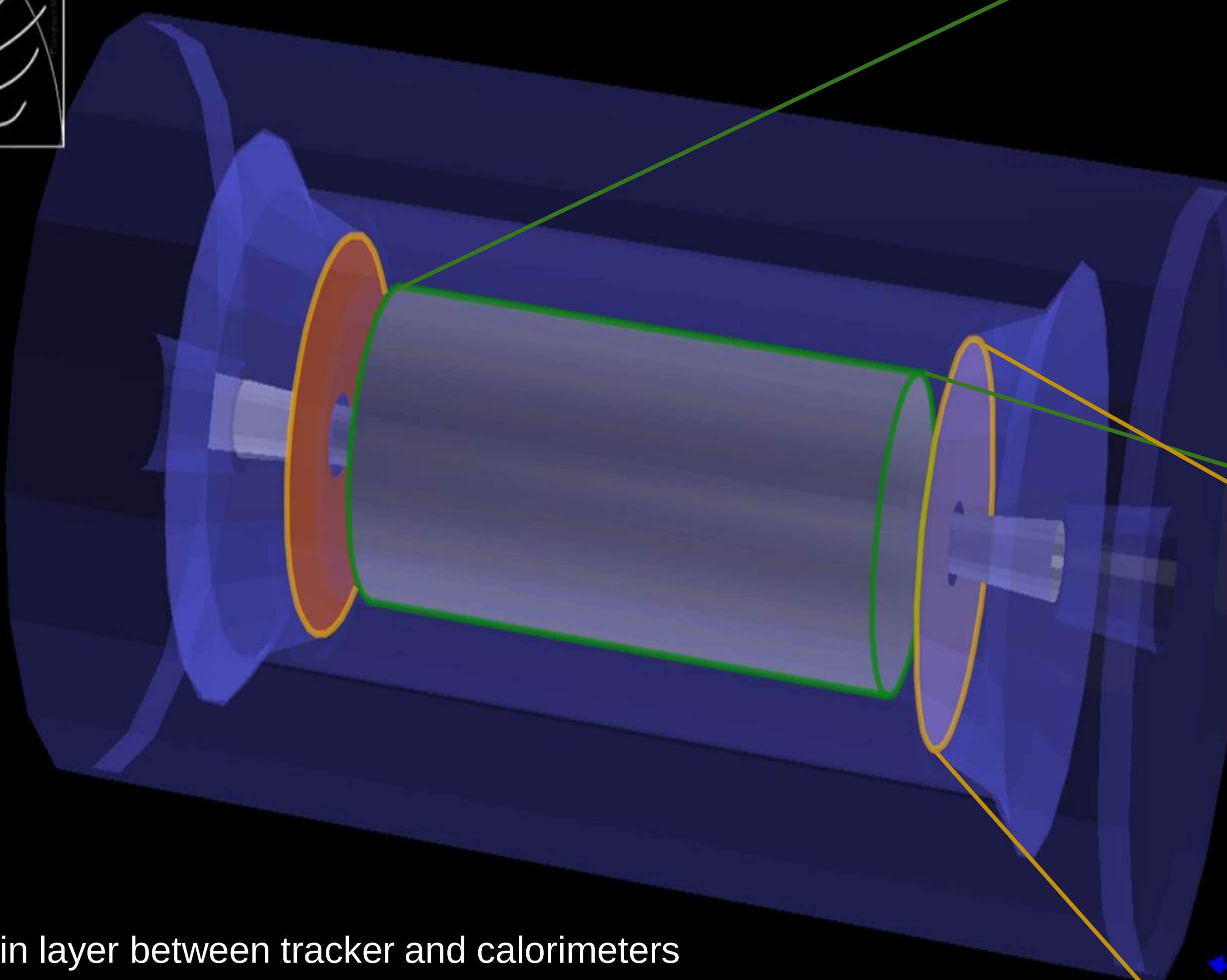
Silicon detectors rad hardness

- 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





Design of the CMS Mip Timing Detector (MTD)



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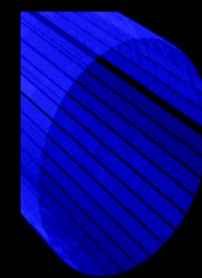
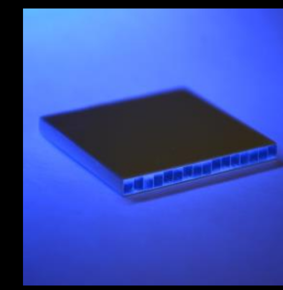
Radiation level	~ 2×10^{14}

n_{eq}/cm^2

Sensors: LYSO crystals + SiPMs





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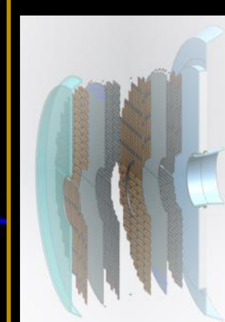
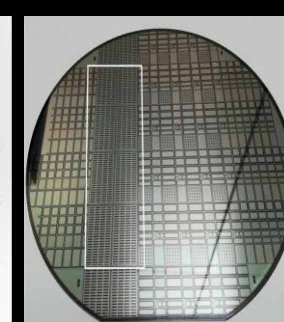
Sensors: Low gain avalanche diodes

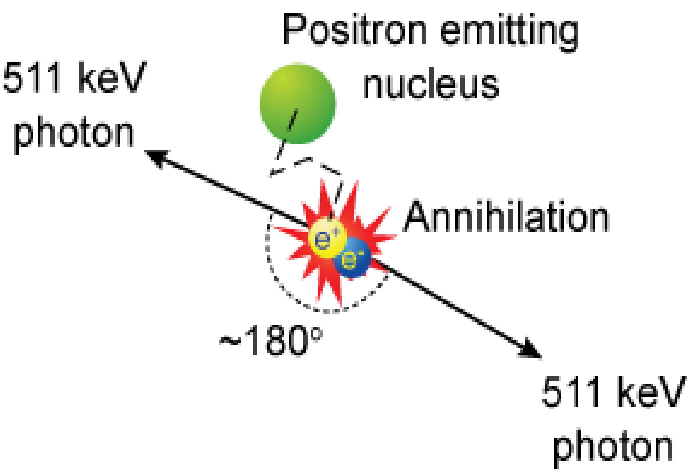


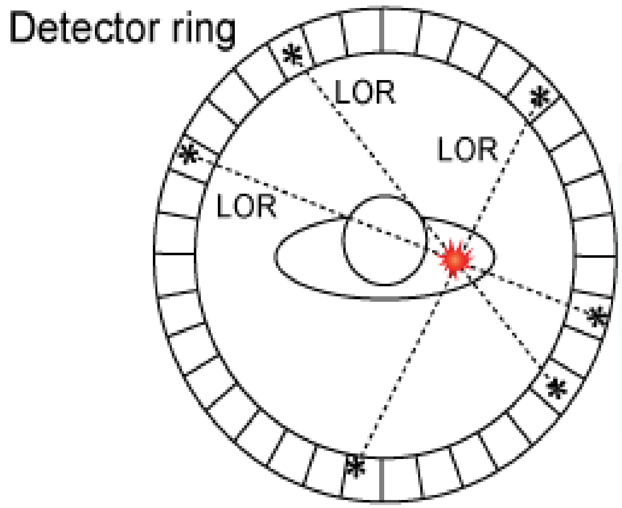


- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of 30-50 ps
- Hermetic coverage for $|\eta|<2.9$

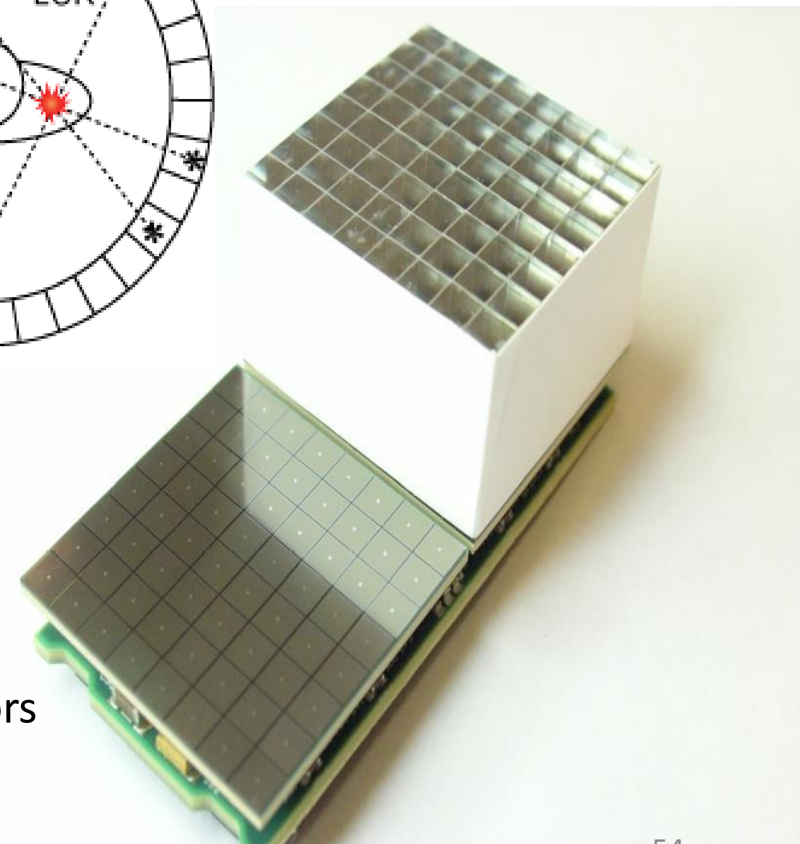
Time-of-Flight Position Emission Tomography (TOF-PET)

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





LYSO crystals (thick)



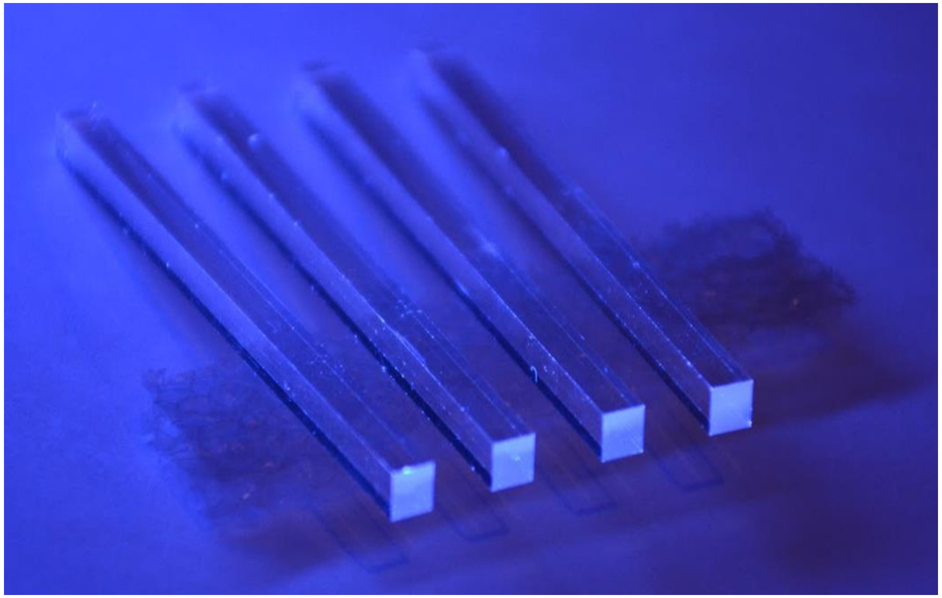
LOR = Line-of-Response

Standard conversion 1ps → 300 microns

SiPM photodetectors

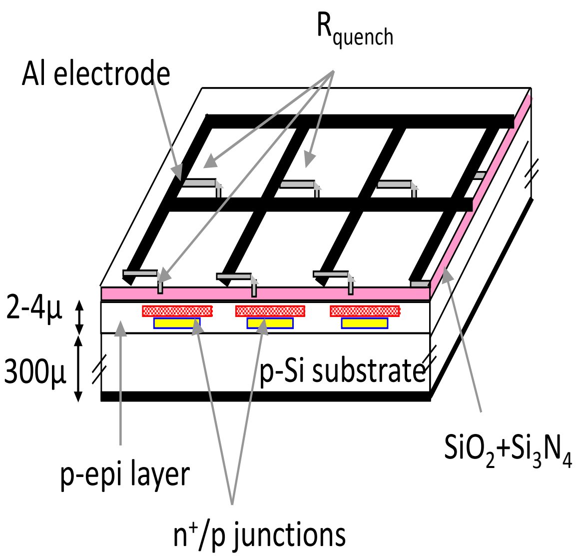
MTD Barrel crystals

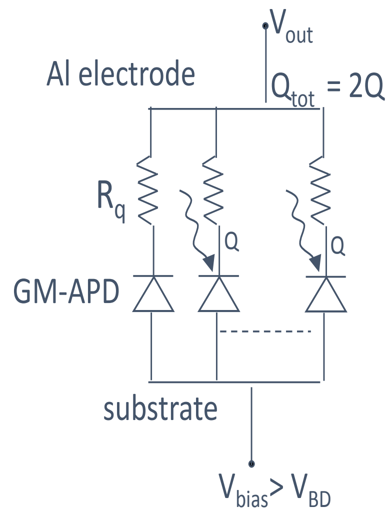
- L(Y)SO:Ce crystal as scintillator
  - **Excellent radiation tolerance**
  - Dense (>7.1 g/cm³), bright (40000 ph/MeV) → high signal
  - Fast rise time O(100)ps and decay time ~40 ns



Silicon Photo-Multiplier (SiPM)

Structure and principles of operation (briefly)





(EDIT-2011, CERN)

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
A common bias is applied to all cells
The cells fire independently
The output signal is the sum of the signals produced by the individual cells

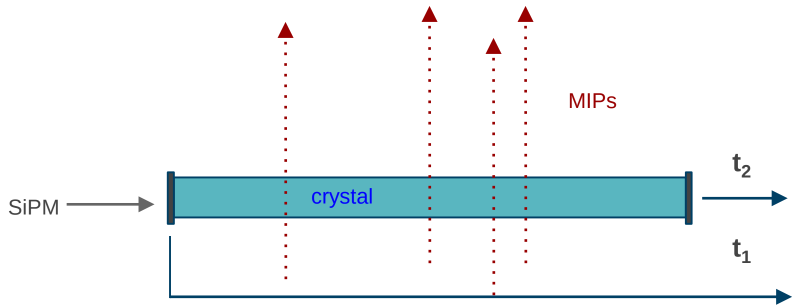
The cell size depends on the application.
For high light yield devices, linearity may be a concern→small cell size.
Also, for coupling to fibers for example you may need to spread the light over the full surface of the device.

Silicon Photomultipliers as photo-detectors for the CMS MTD

- Compact, insensitive to magnetic fields, fast
- Optimal SiPM cell size: **15 um**
  - High dynamic range, good radiation tolerance
  - Good **P**hoton **D**etection **E**fficiency at 420 nm: **20-40%**

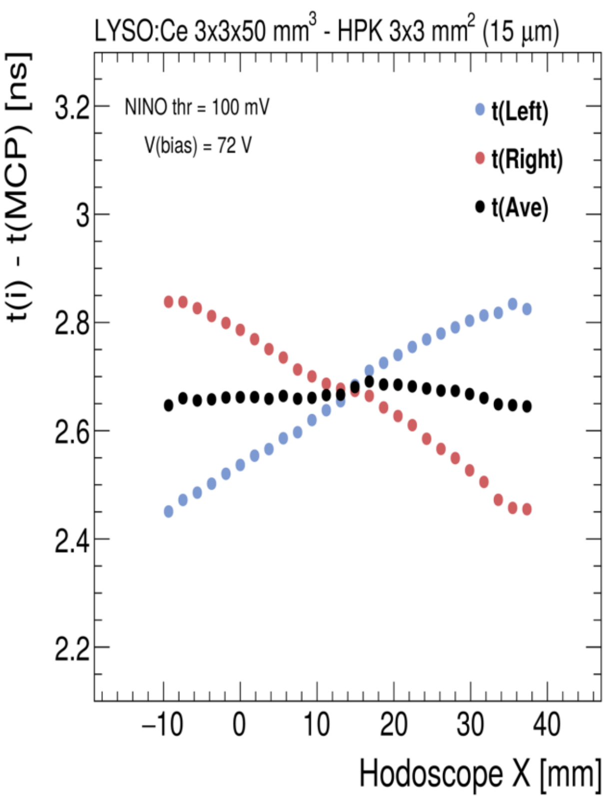
MTD Barrel sensors

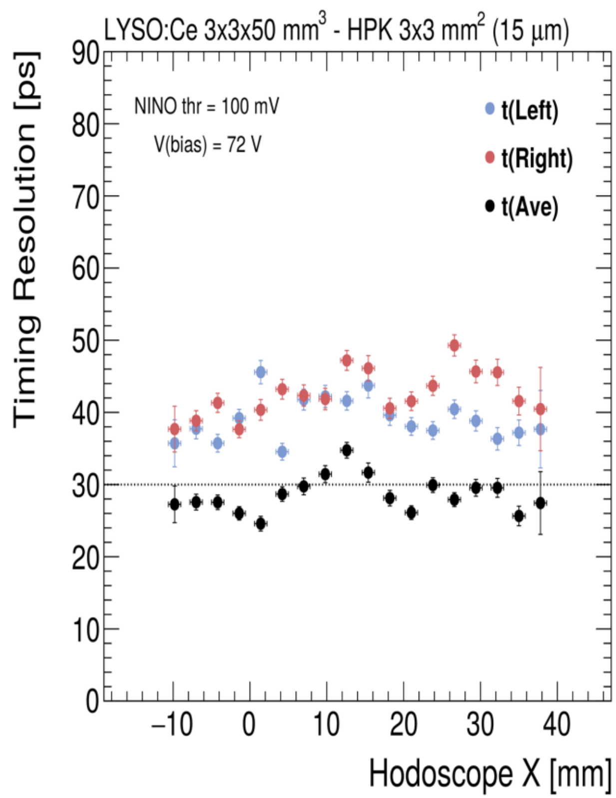
MTD barrel - test beam results



$t = (t_1+t_2)/2$

$\sigma_t = \sigma_{1,2} / \sqrt{2}$





Test beam results:

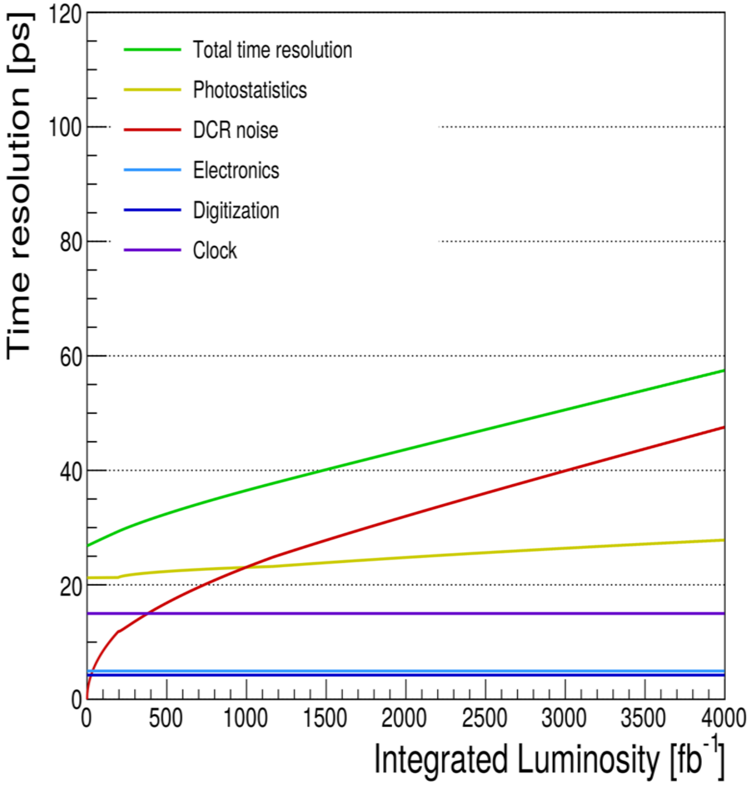
- Target time resolution of **30 ps** achieved
- **Uniform time response** vs impact point
- **Uniform time resolution** vs impact point

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

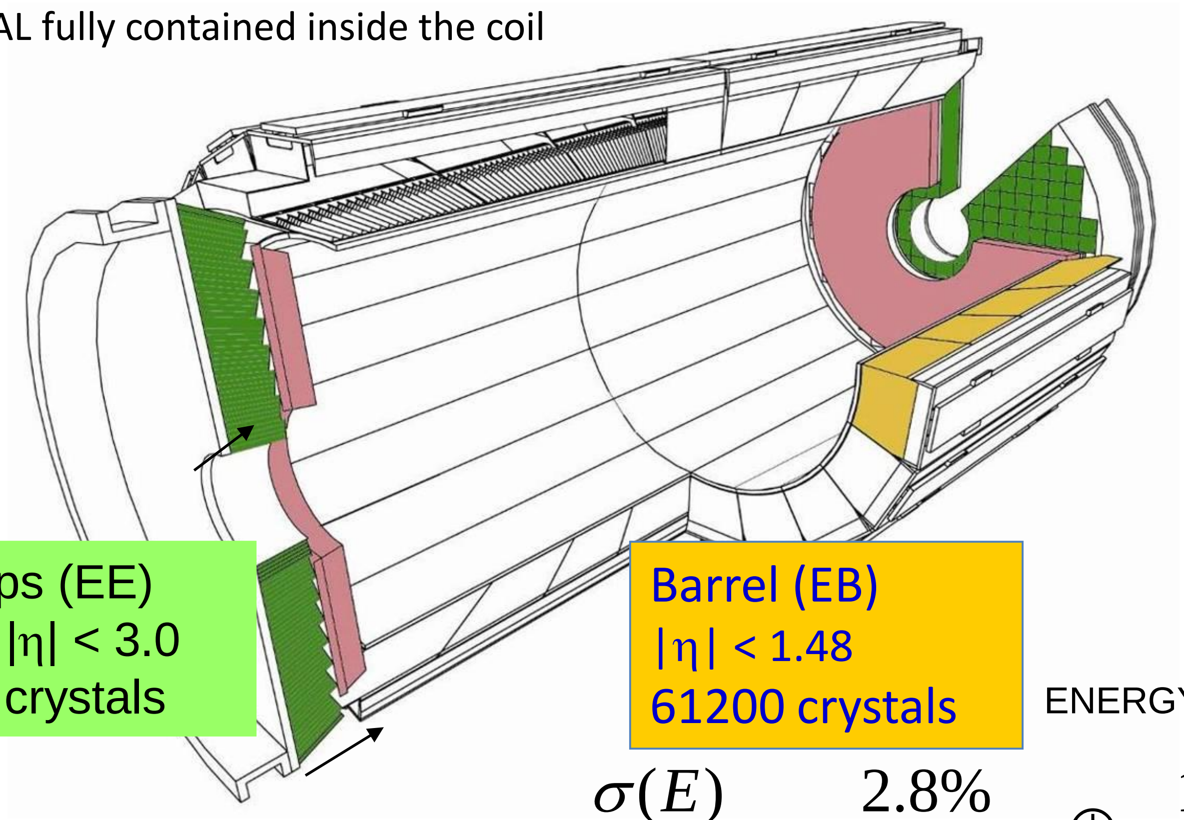


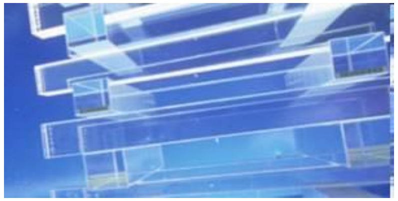
CMS ECAL UPGRADE FOR PRECISION TIMING

The CMS electromagnetic calorimeter (ECAL)

CMS Characteristics:

- Tracker coverage up to η<2.5
- Magnetic Field 3.8 T
- ECAL fully contained inside the coil





$PbWO_4$ crystals
$X_0 = 0.89$ cm
LY~100 γ/MeV

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

Endcaps (EE)
$1.48 < |\eta| < 3.0$
14648 crystals

Barrel (EB)
$|\eta| < 1.48$
61200 crystals

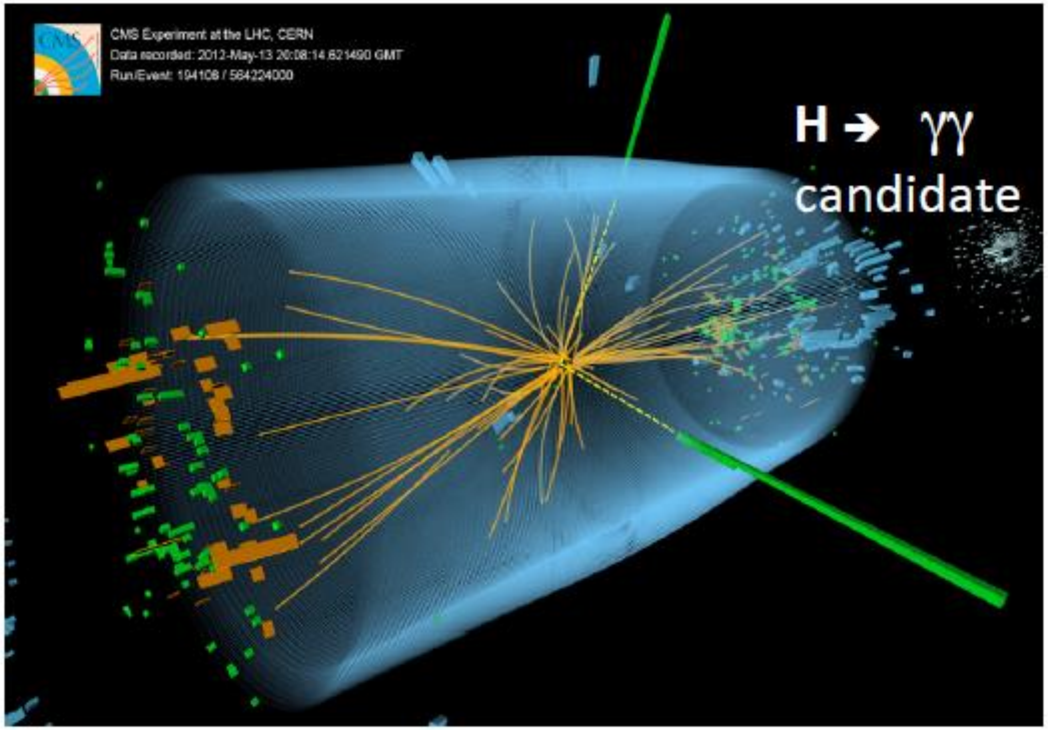
Pb/Si preshower
$1.65 < |\eta| < 2.6$

ENERGY RESOLUTION (BARREL)

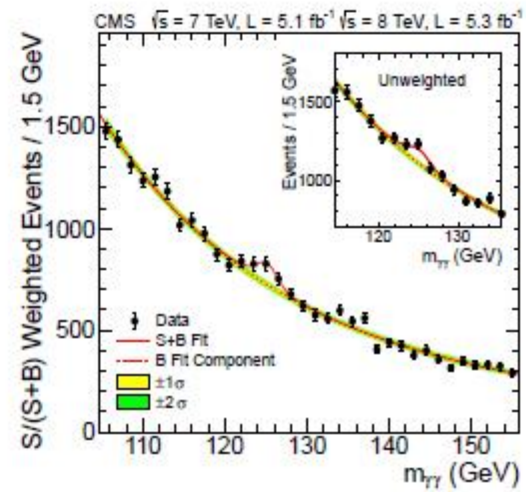
$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E(GeV)}} \oplus \frac{12\%}{E(GeV)} \oplus 0.3\%$$

The energy resolution for photons from H→γγ in EB is 1.1% to 2.6% and in EE 2.2% to 5% .

The ECAL role in CMS



CMS Collaboration,
Phys. Lett. B716 (2012) 30-61

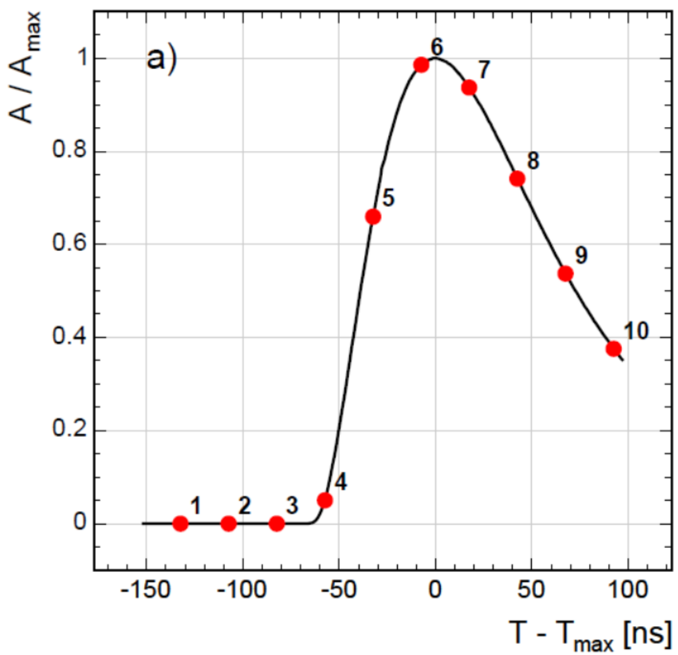


- The excellent ECAL energy resolution led to the discovery of the H boson in the γγ decay mode
- Electrons and photons are used in many other analyses (H→WW, ZZ*, Z') and SM physics analyses (W, Z, top ,...)
- Timing is also used in search for long lived SUSY particles

see D. Barney talk

Timing performance of the present ECAL

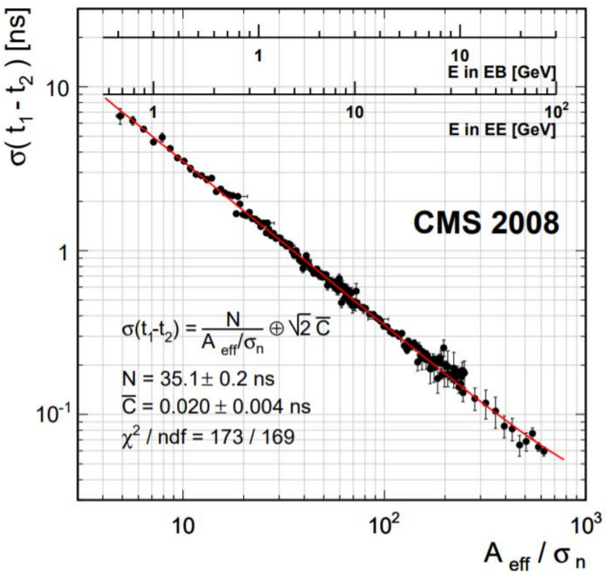
- No dedicated TDC or other electronics
- PWO+APD pulse is shaped by a pre-amplifier with τ ~40ns.
- Sampling ADC at 40 MHz (10 samples are stored)
- Request to have timing stability of ~1ns

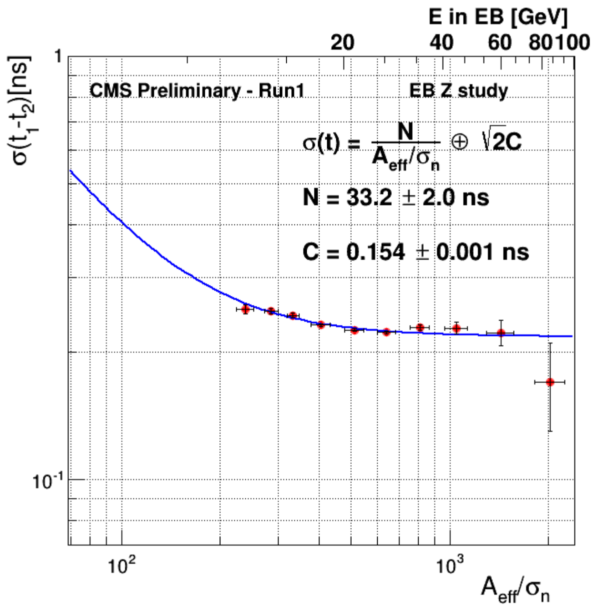


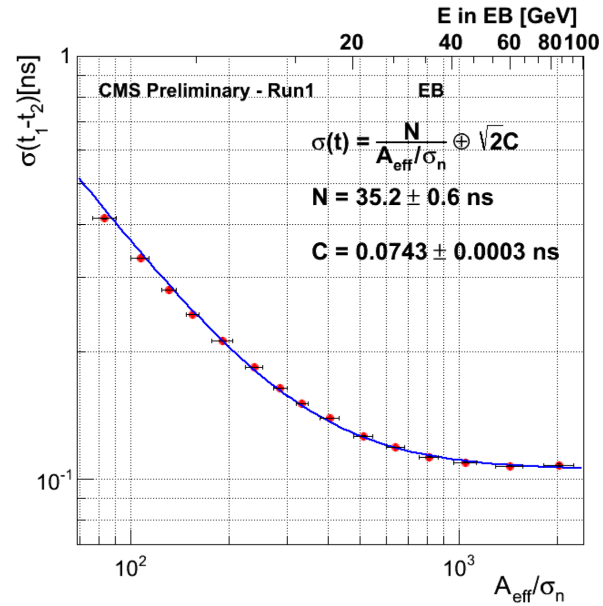
Timing is computed from the ratio of the 4th to the 5th sample.
A fit would take too long for computation.

Timing performance of the present ECAL

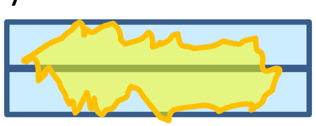
Actual performance is much better than 1 ns !





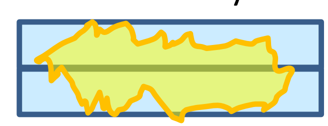


Test-beam 2008
Difference of timing
for neighboring
crystals

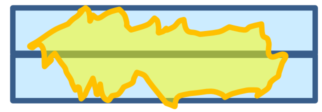


Timing resolution measured in CMS from
Z→ee electrons time difference

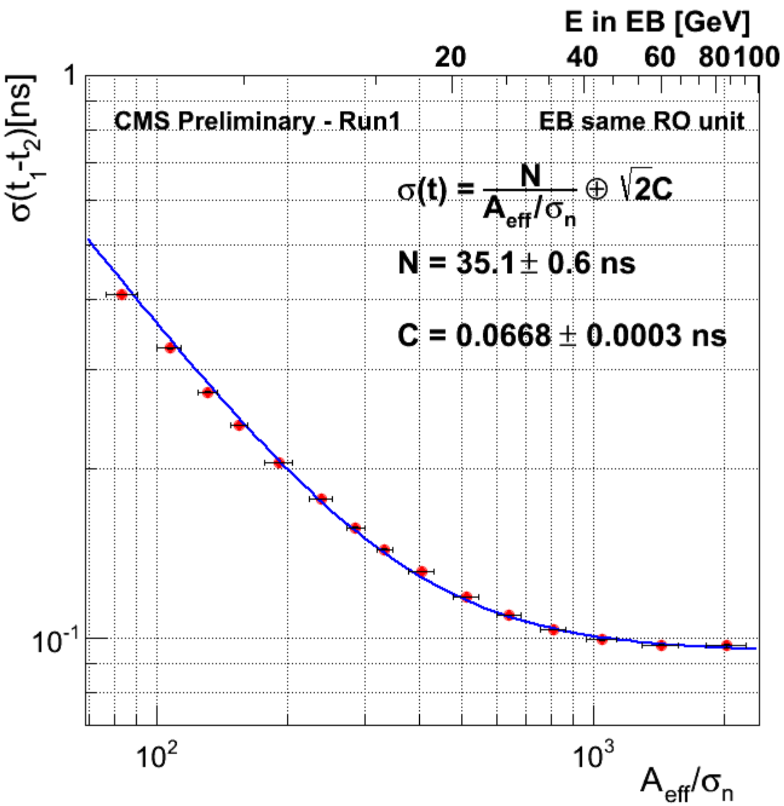
Timing resolution
measured in CMS from
showers deposited in
between two crystals



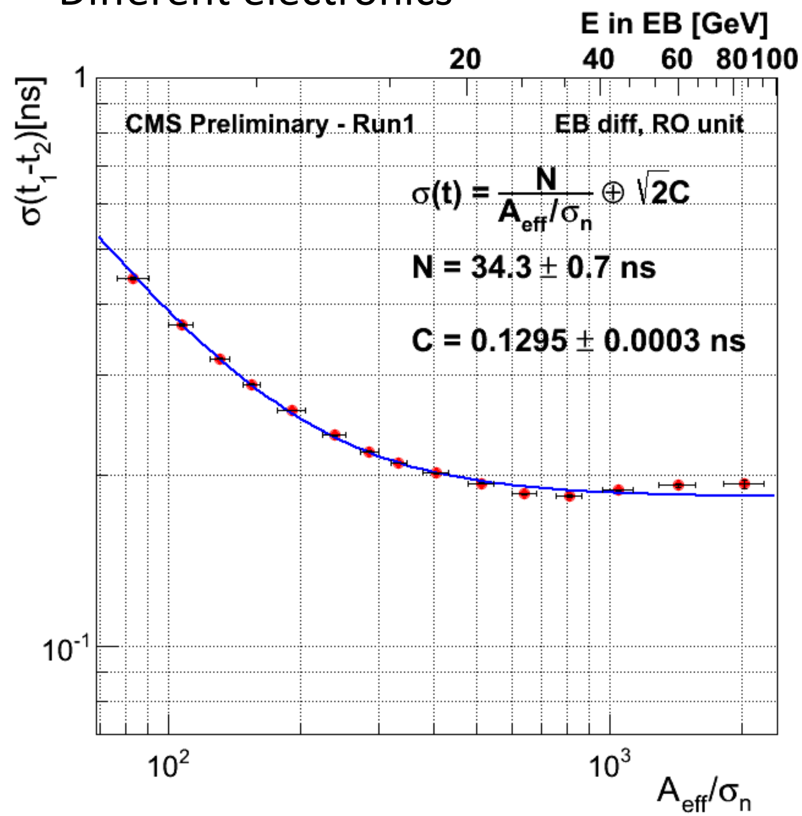
Timing resolution measured in CMS from showers deposited in between two crystals



Same electronics



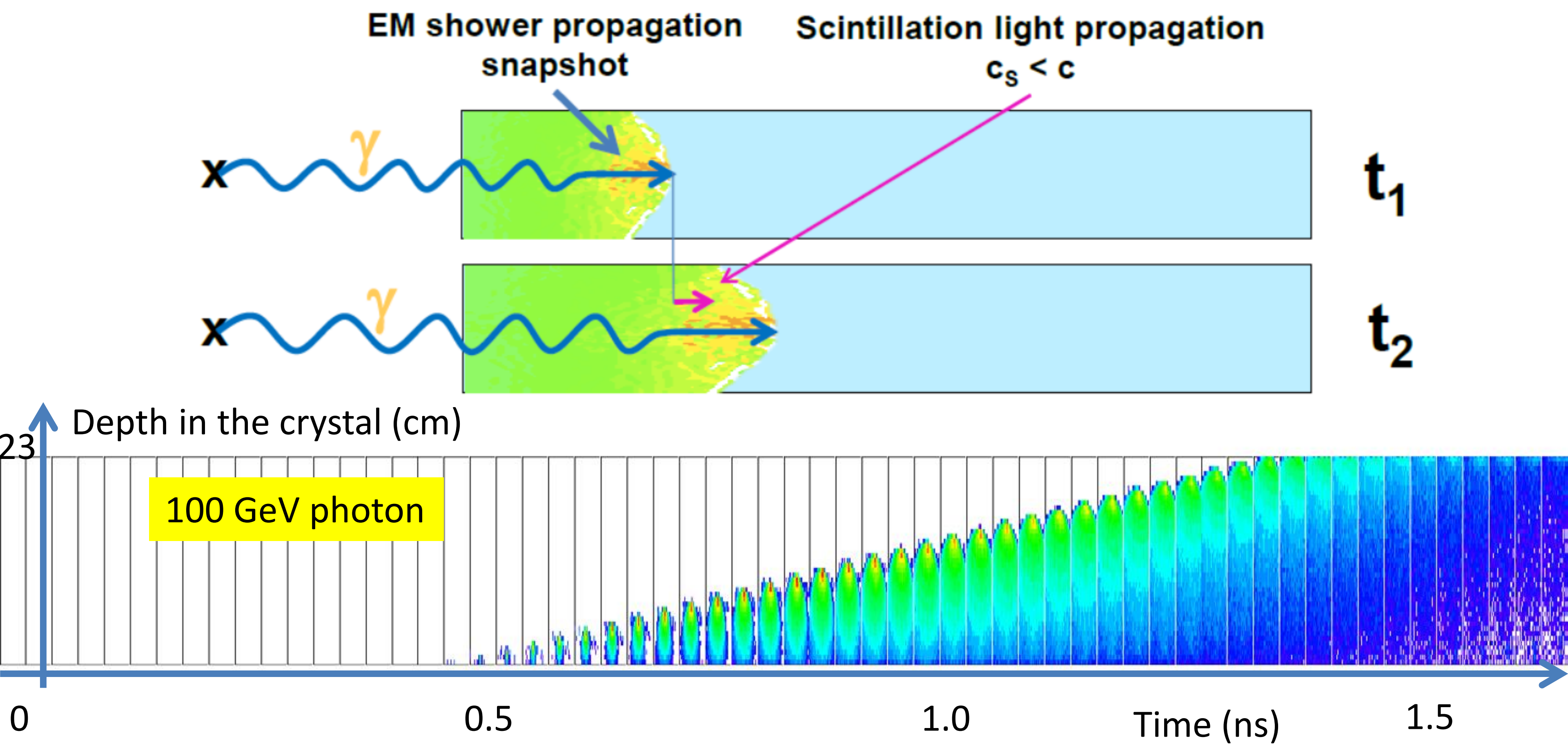
Different electronics



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.

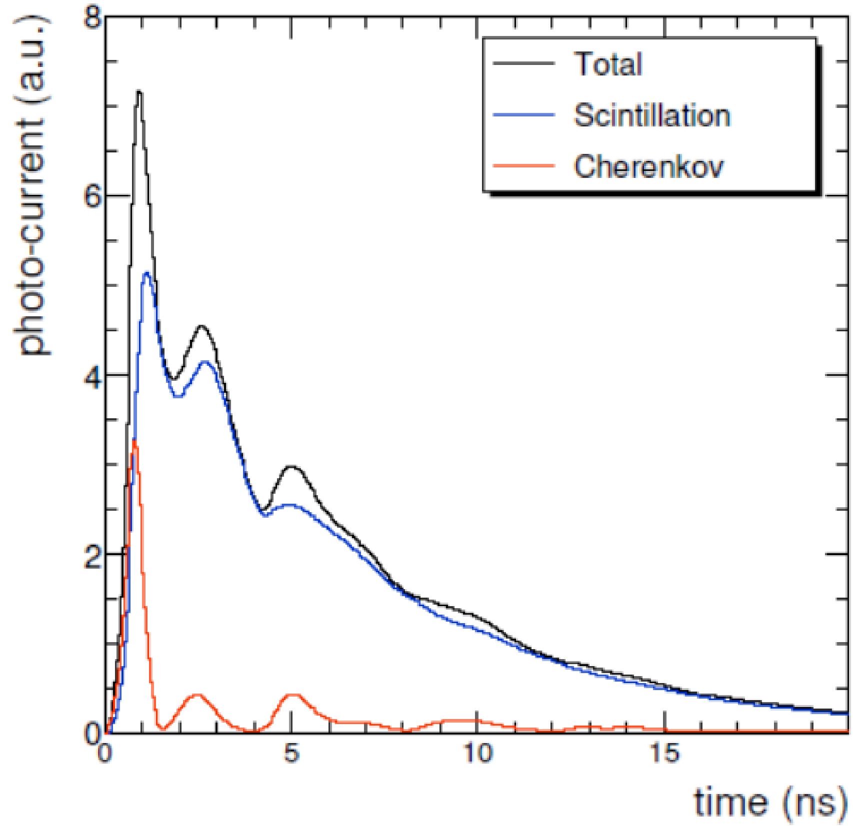
Electromagnetic showers in a long scintillating crystal

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



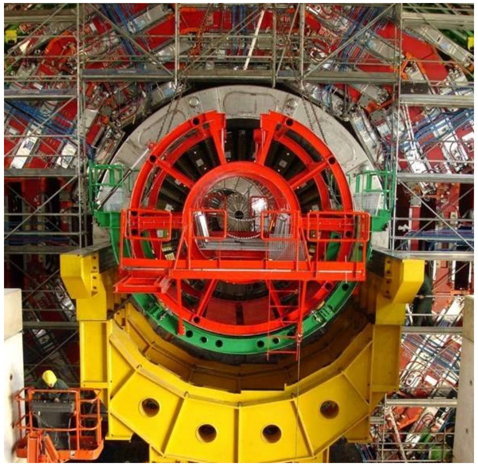
Simulation of the shower

Simulation of the light ray tracing inside the crystals shows that the fast component has a large contribution from Cerenkov light



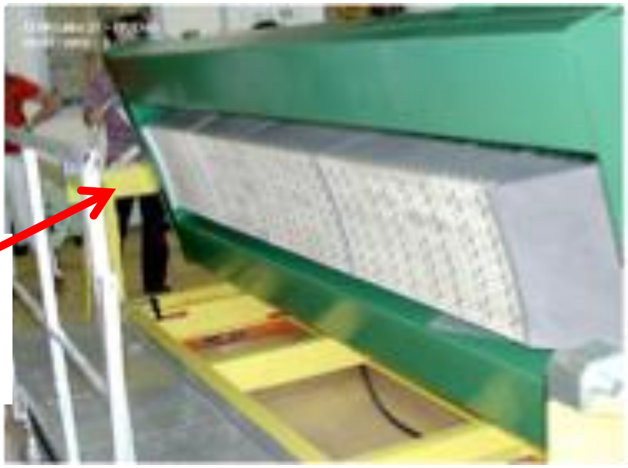
CMS-TDR-17-002

ECAL Barrel upgrade



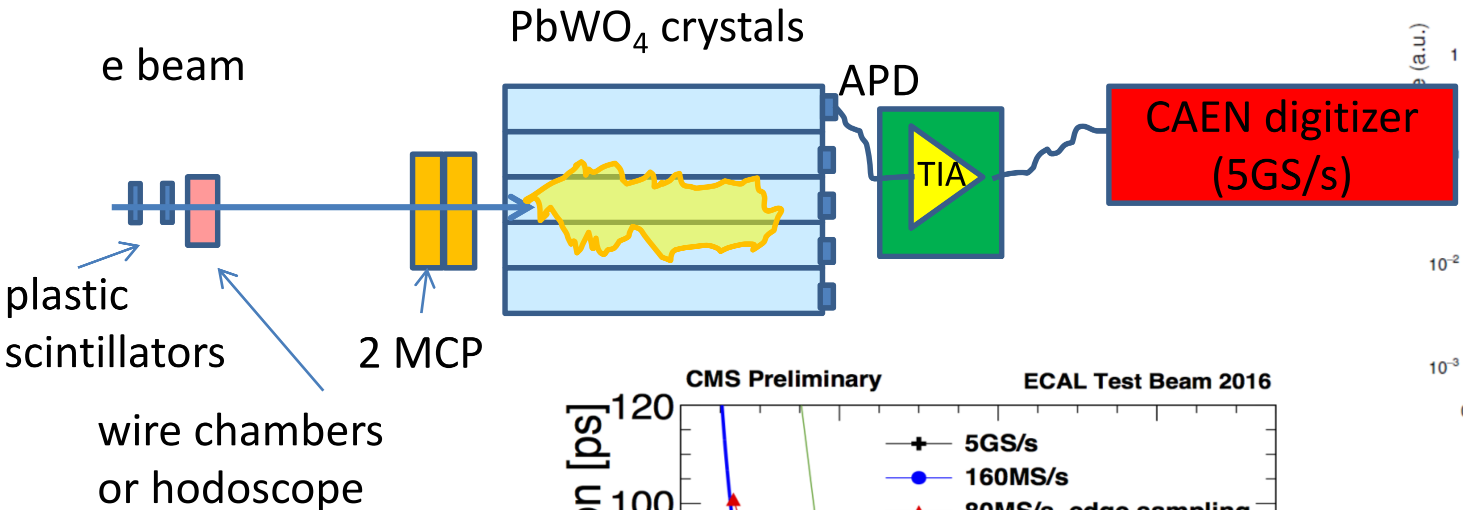
Extract the 36 SM from CMS

36 Supermodule

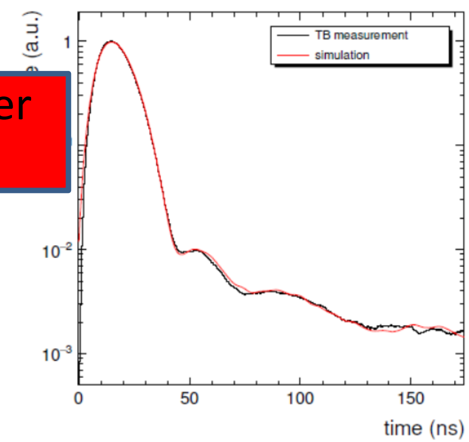


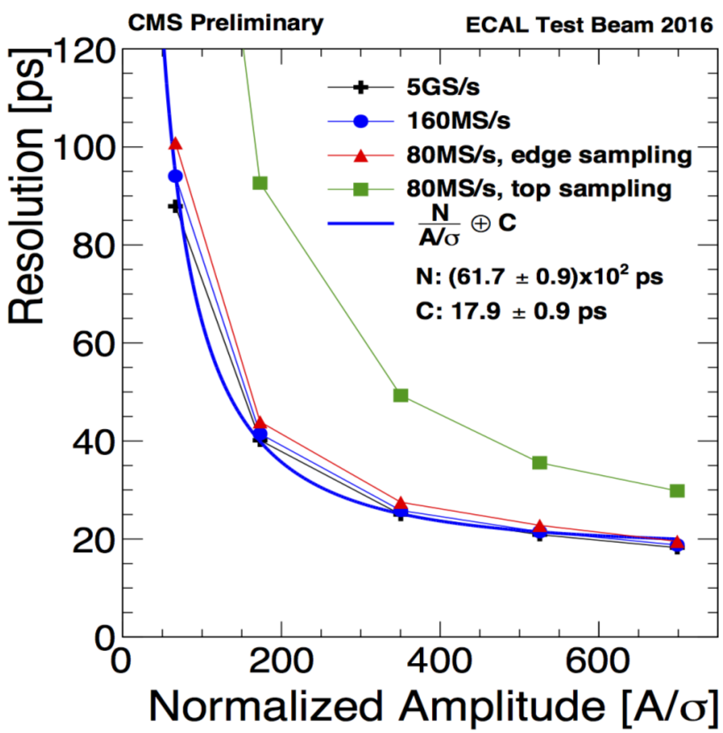
1700 LeadTungstate crystals

Testbeam results



pulse shape

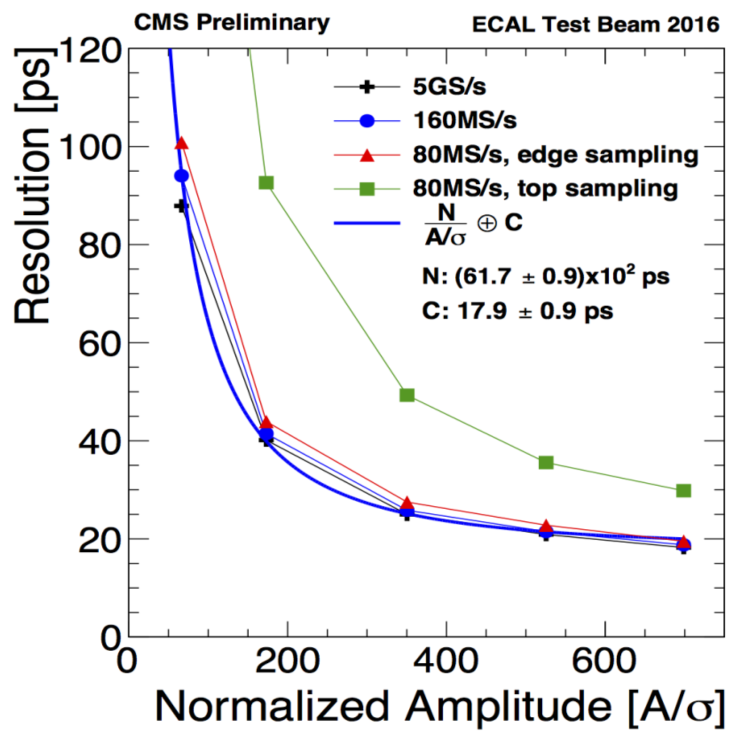




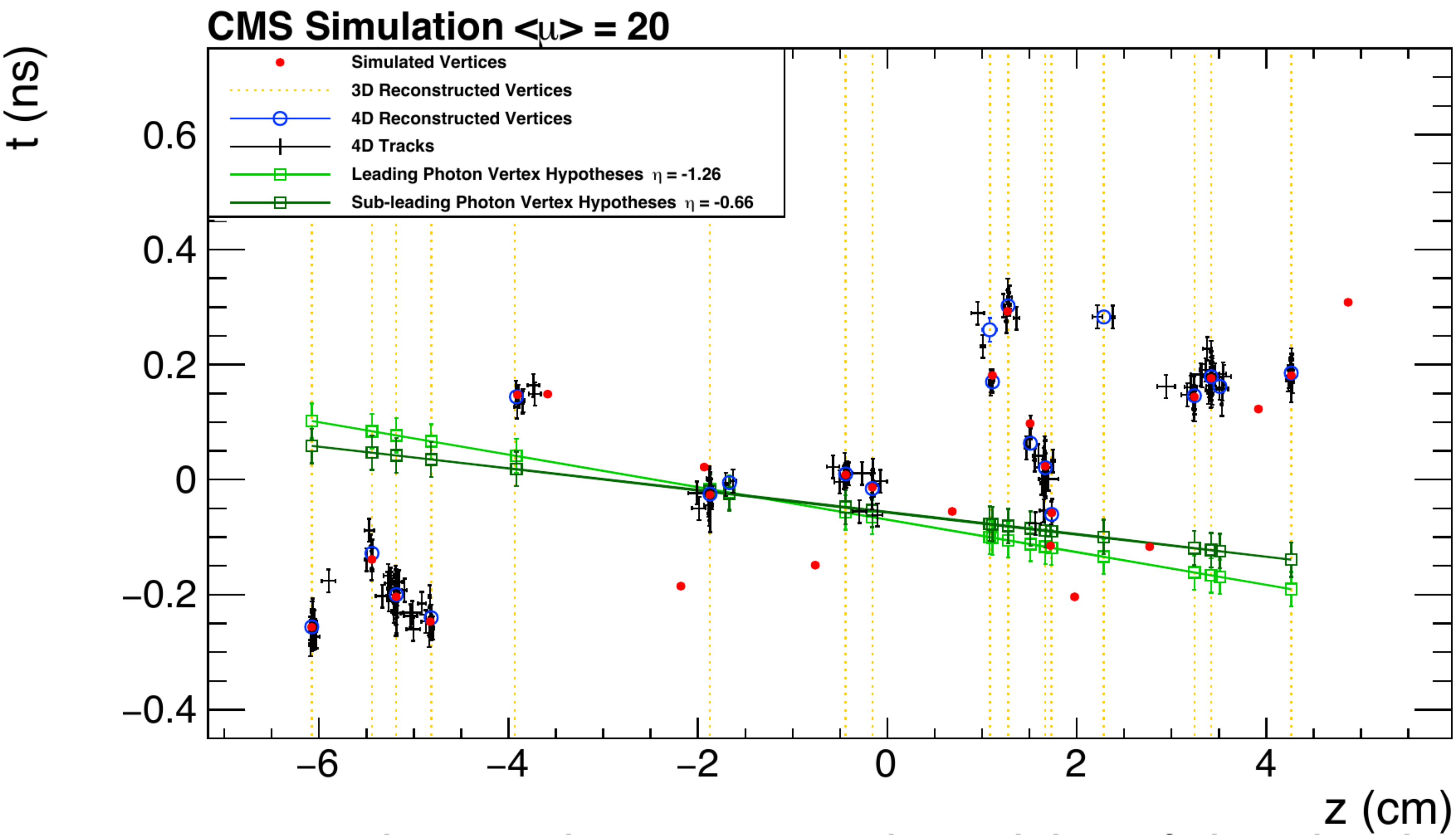
CMS ECAL Timing resolution

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

- Noise term due to noise fluctuations N (jitter term)
- S/√A → stochastic term, due to fluctuations in the shower and in the emission of scintillation photons (small)
- C → 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



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

$$\sigma_t = \frac{\sigma_V}{\frac{dV}{dt}} \qquad \frac{dV}{dt} \approx \frac{V}{t_r} \rightarrow \sigma_t = \frac{t_r}{SNR}$$

Checks:

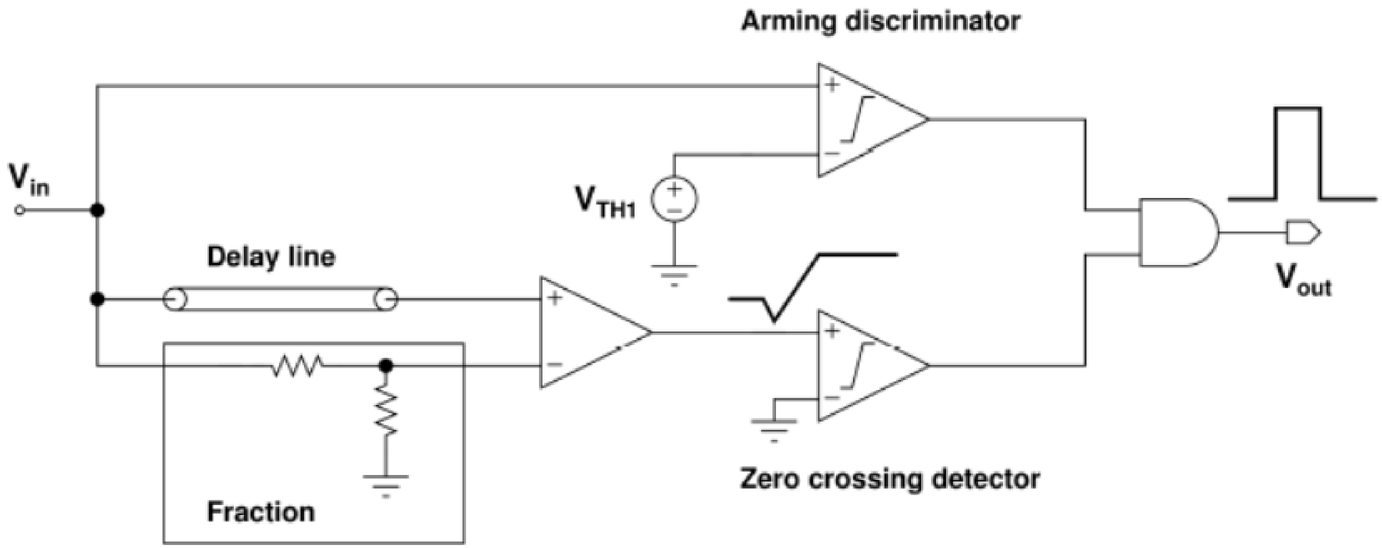
$t_r = 1$ ns, $SNR = 10 \rightarrow \sigma_t = 100$ ps

$t_r = 40$ ns, $SNR = 500 \rightarrow \sigma_t = 80$ ps

$$t_r \propto \frac{1}{BW} \qquad SNR \propto \frac{1}{\sqrt{BW}} \rightarrow \boxed{\sigma_t \propto \frac{1}{\sqrt{BW}}}$$

- 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

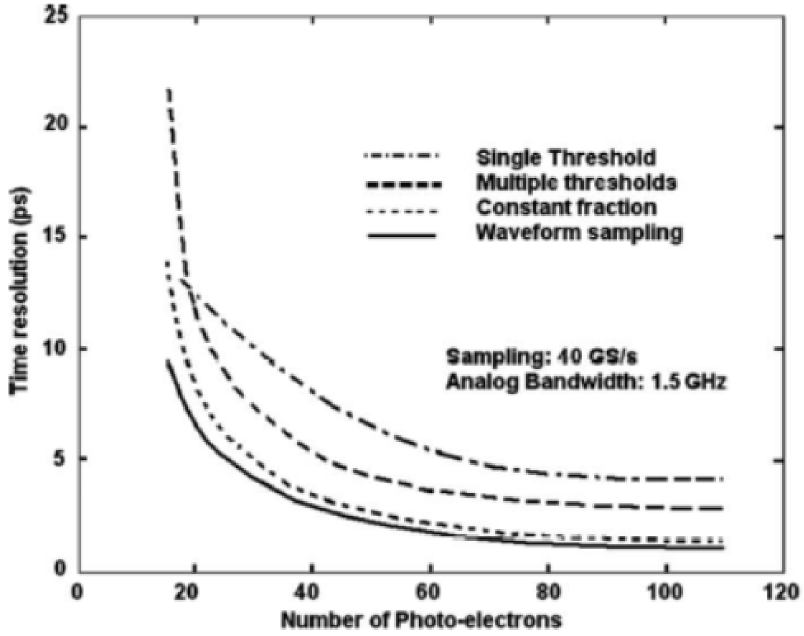
- Different algorithms are used to compute the timing from the digitized samples
- There is nothing such an optimal method
- Some techiques can be more suited that others for real time execution on FPGA

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

To learn more: E. Delagnes, Precise Pulse Timing based on Ultra-Fast Waveform Digitizers, Lecture given at the IEEE NSS Symposium, Valencia, 2011

Some comparison

J. F. Genat et al. Signal processing for picosecond resolution timing measurements, NIM A 607 (2009) 387-393



- 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: **TDR-17-002**

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

New ECAL electronics

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)

ADC at 160 MHz

- Improve timing measurement
- Improve signal vs spike discrimination

Data Transmission Unit

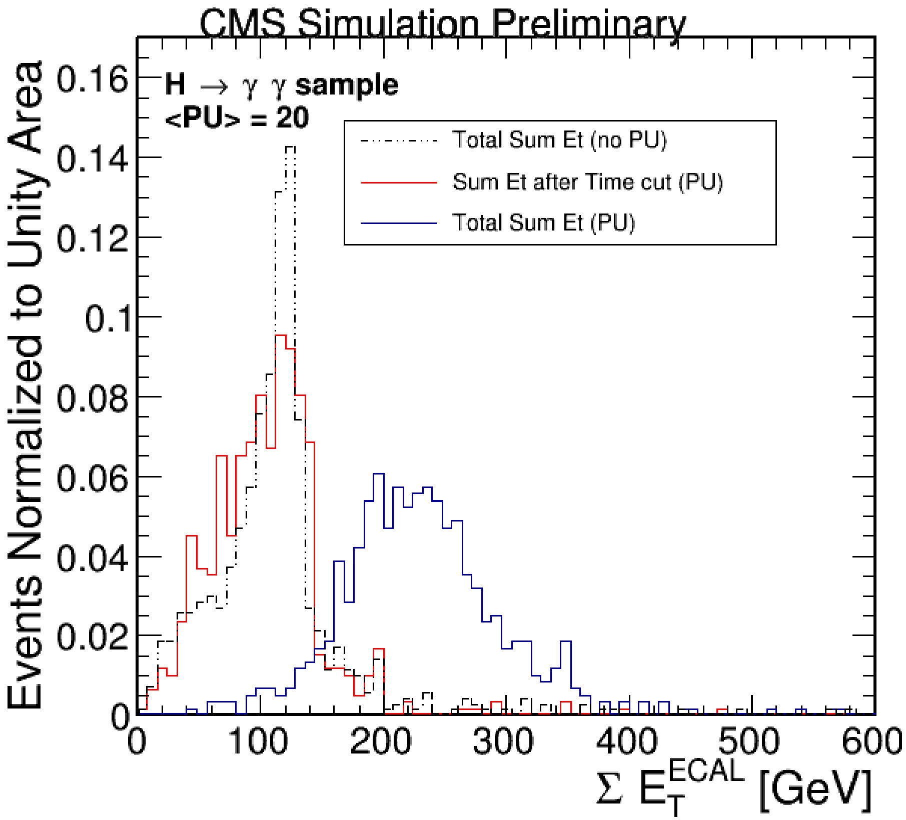
Loss-less data compression

lpGBT

- Data readout in streaming towards off-detector elec.
- Trigger formation in powerful off-detector electronic boards

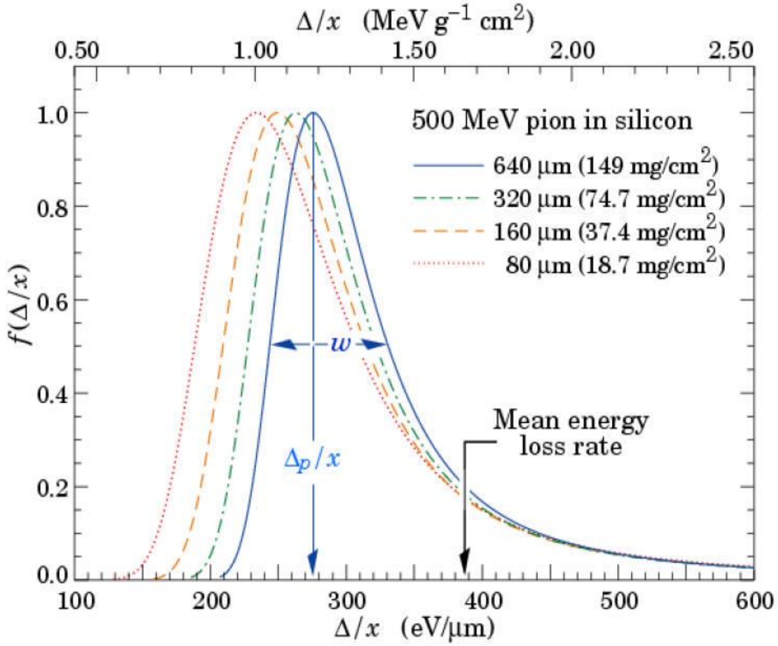
ECAL Clean-up using Timing

- **Effect of timing cut** on ΣE_T^{ECAL} variable
  - sum of all ECAL hits with E > 1GeV.
- O(30 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**



D. Del Re talk at CALOR2014

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