State of the art of silicon detectors for 4D tracking

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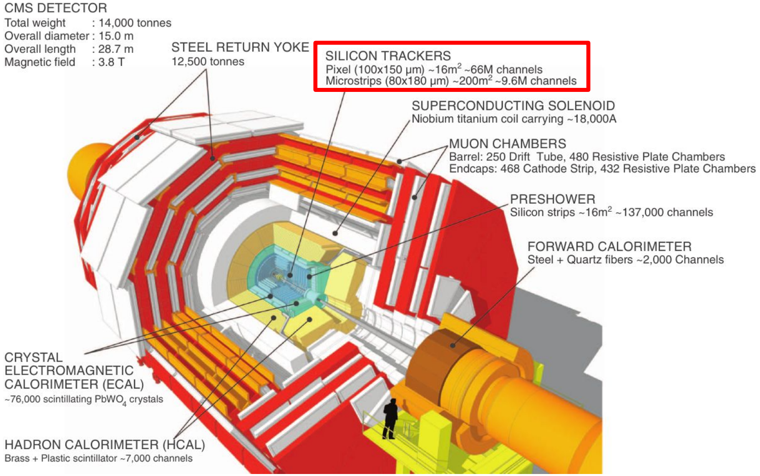
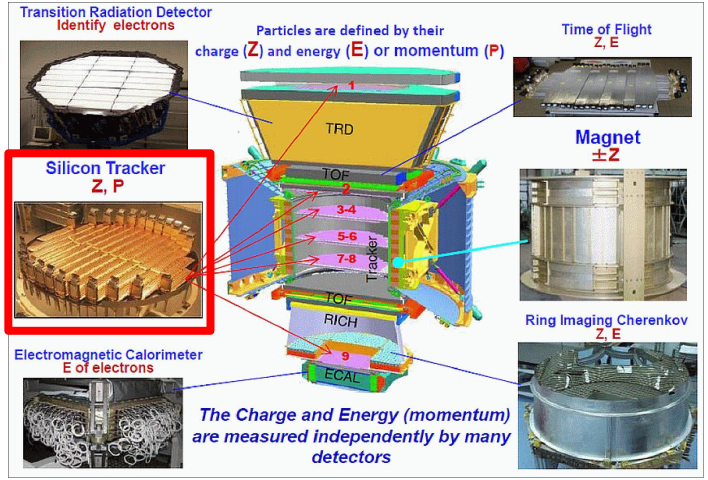
PhD exams - 2021 December session

Charged particles tracking

- The measurement of trajectories of charged particles is ubiquitous in physics areas and applications:
    - Nuclear and particle physics.
    - Cosmic rays detection.
    - Mass spectrometers.
    - Medical treatment with charged particles.

- Many physics experiments use silicon detectors in their tracking sub-detectors.





Silicon detectors

- Silicon detectors can respond to many needs of high energy physic experiments:
  - High spatial granularity: O(10 µm).
  - Large areas coverage: O(100 m^2).
  - Very high data tacking rates: O(10 MHz).
  - High radiation tolerance: O(10^{16} n_{eq} cm^{-2}) with n @ 1 MeV.

- Silicon detectors can measure the arrival time of a particle with a resolution > 200 ps.
  - At the speed of light, flight path uncertainty greater than 6 cm.

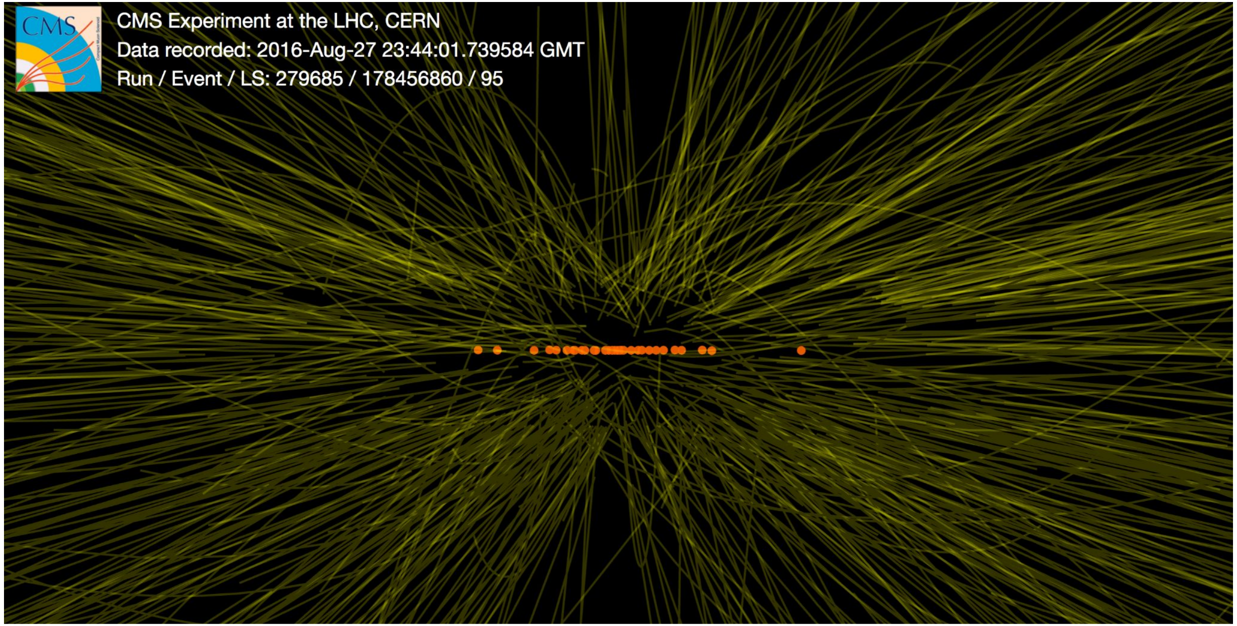
- New types of silicon detectors promise to reach a time resolution of 10 ps.

- It can be interesting for a time-of-flight detector.
- It is a crucial capability for tracking in experiments at high-luminosity colliders.

Pileup at collider experiments

- At each bunch crossing multiple collisions may happen (events).
- A primary vertex is associated to each event.

https://cds.cern.ch/record/2241144



Event at CMS with 30 reconstructed vertices.

Pileup at collider experiments

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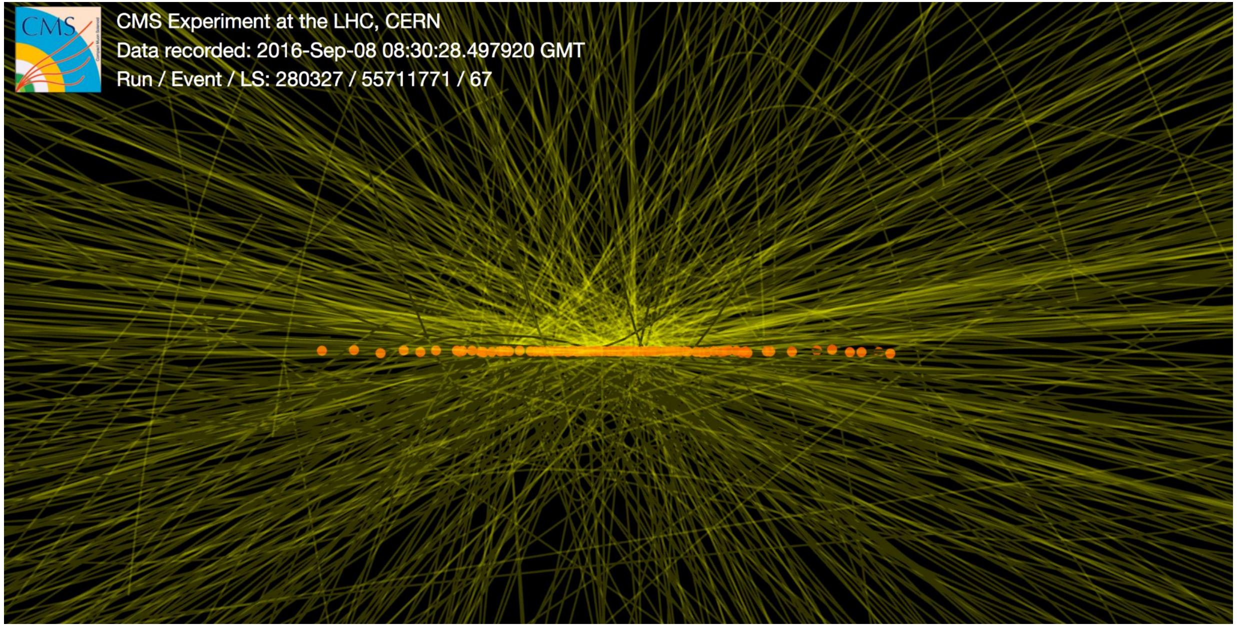
https://cds.cern.ch/record/2241144

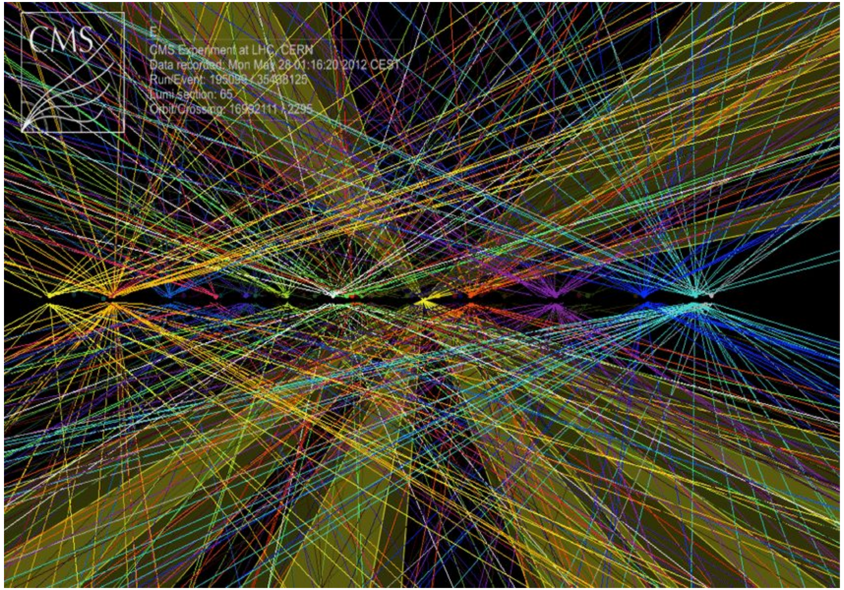


Event at CMS with 86 reconstructed vertices.

Pileup at collider experiments

- Increasing the luminosity also the number of events increases.
- At HL-LHC will be 150-200 events per bunch crossing.
- The spatial density is so high that the vertices will overlap.
- This overlap causes:
  - degradation in the reconstruction precision.
  - Loss of events.
- Events do not happen at the same time:

Event at CMS with ~50 vertices



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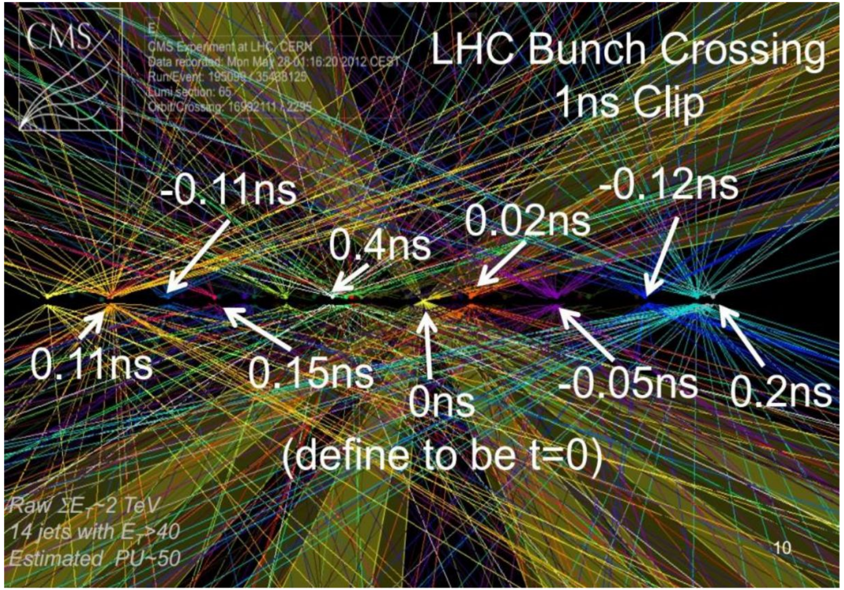
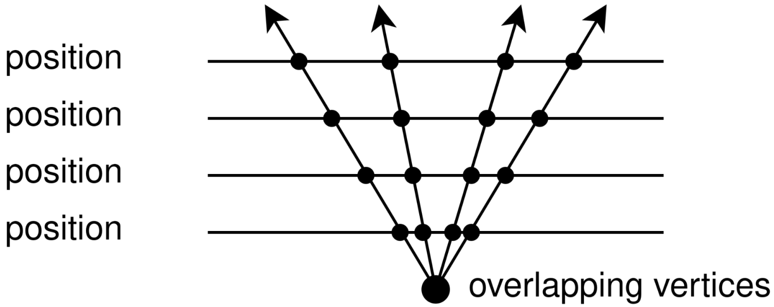
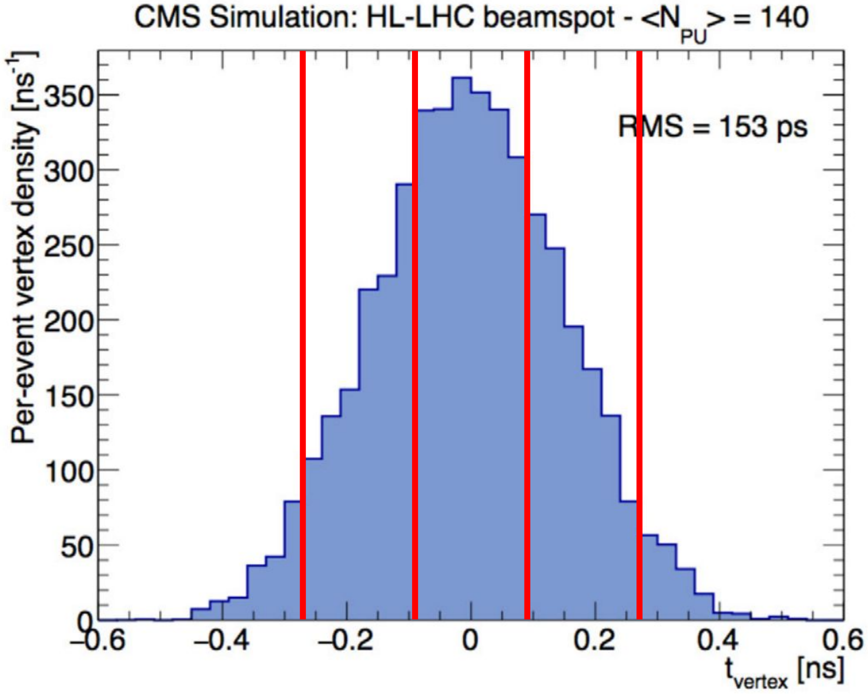


Pileup mitigation with time layer

- The events timing distribution has a RMS of ~150 ps.
- Assigning a time with a resolution of ~30 ps to each track is possible to divide a bunch crossing in 5 groups, each with fewer events.
- A single detection layer with timing capabilities is sufficient.





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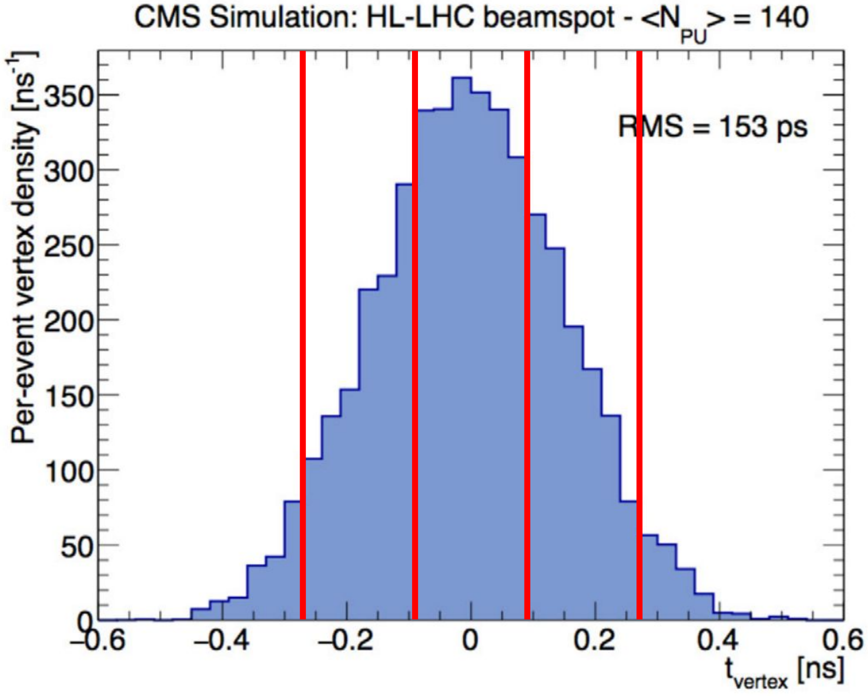
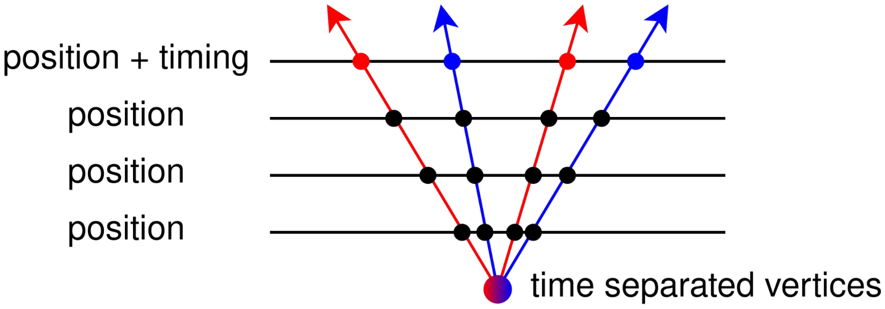
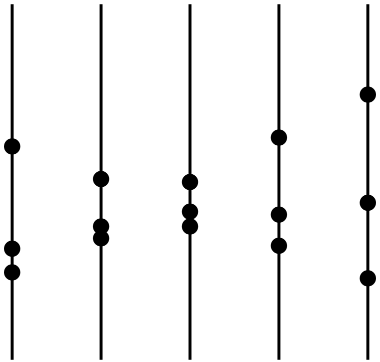




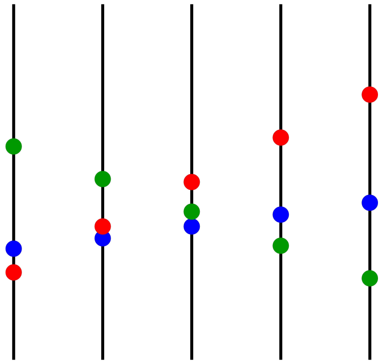
Colors correspond to different time groups

Fully 4D Tracking

- Increasing the luminosity also the number of tracks increases.
  - Computational power for track reconstruction explode exponentially.
- A tracker composed by all layer with timing capabilities associates a time to each hit.
  - Drawback in terms of power and cooling requirements, readout circuits, and costs.
- Considering only time compatible hits during track reconstruction reduces the possible hits combinations.

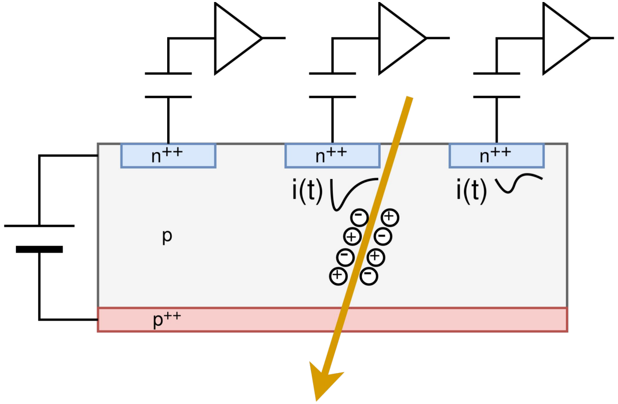


Without timing information it is necessary to search aligned hits trying all the reasonable combination



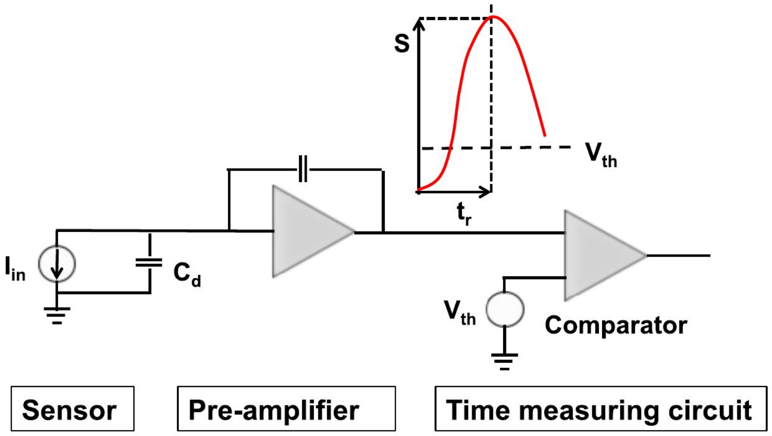
With timing information is possible to group time compatible hits (same color)

Silicon detectors



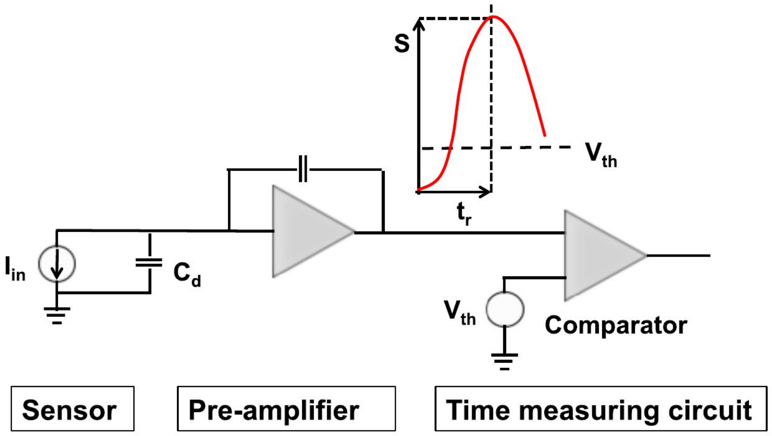
- p doped silicon with n^{++} and p^{++} electrodes.
- n-p junction inversely polarized.
- Incident charged particles create electron-hole pairs along their paths.
- Electron (holes) drift to the n^{++} (p^{++}) electrode, creating an induced current.

Readout



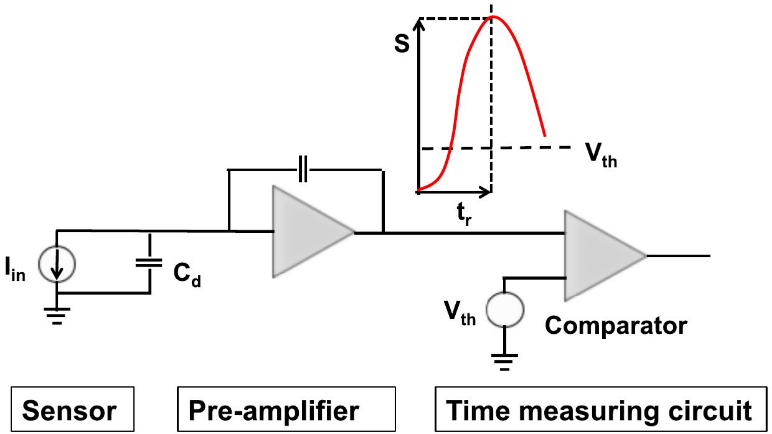
- Sensors is equivalent to a capacitor and a current source in parallel.
- A pre-amplifier shapes the signal (often integrating the current).
- The time measuring circuit compares the signal to a threshold and digitizes the instant t_0 when the signal exceeds it.
- Current reaches its maximum right after the passage of the particle: typical I_{in} = 1.5 µA.
  It ends when the last carrier reaches its electrode: 3(5) ns for electron (hole) (300 µm thick sensor @ 600 V).

Time measurement



- To produce accurate measurements of t_0 the signal (S) must be large and with a short rise time (t_r).
- The rise time depends on the drift time of the carrier, a thinner sensor will have better performances:
  - Thin sensor → short t_r → low σ_t
- Very thin sensors (< 50 µm) have large capacitance:
  - Very thin sensor → high C_d → small S → higher σ_t

Time measurement

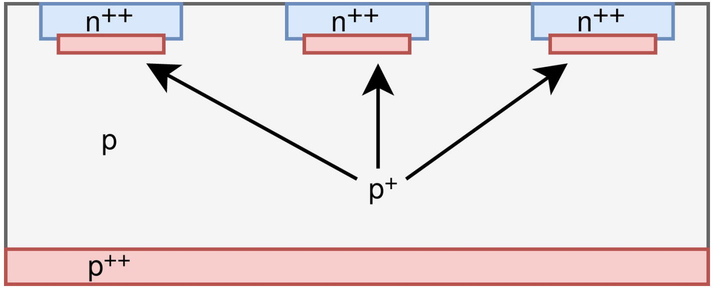


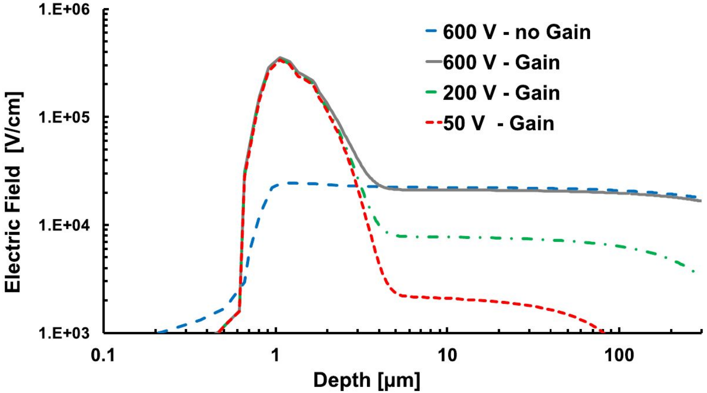
- To produce accurate measurements of t_0 the signal (S) must be large and with a short rise time (t_r).
- The amplitude of the signal depends from the current I_{in}.
- We can increase increase it:
  - Amplifying the current inside the detector.
  - Decorrelating the number of carrier from the distance between electrodes.

Low-gain avalanche detectors

- Devices as SiPM and APD have a high gain to amplify the signal produced by few photons.
    - They have big pixel pitch, and high noise and power consumption when damaged by radiation.

- Charged particles produce a higher number of carrier and the gain can be low.





- In LGADs a p^{+} layer is added close to n-p junction.

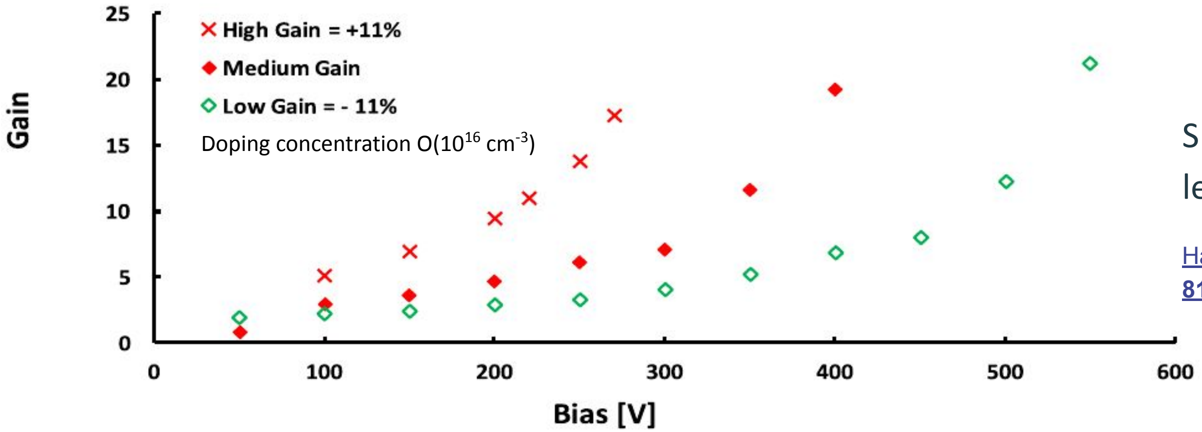
- The electric field results ennanched near the junction.

- Electrons drifting toward the n^{++} electrode are multiplied by avalanche effect (gain ~20).

Low-gain avalanche detectors

- First measurements of LGAD sensors were publicated in 2014.
- First thin (50 µm) LGAD production was presented in 2016.
- Produce LGAD sensors is challenging, since the gain depends strongly on the doping concentration of the gain layer → it is crucial to control this concentration at per cent level.

Gain as a function of bias for 50-micron thick Hamamatsu sensors with 3 different gain layer doping

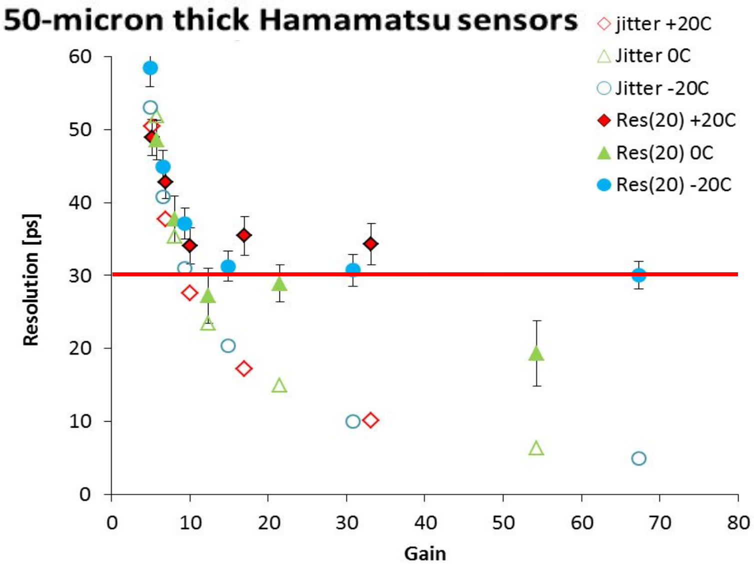


Small changes in doping concentration lead to big changes on gain value.

Hartmut F-W Sadrozinski *et al* 2018 *Rep. Prog. Phys.* **81** 026101

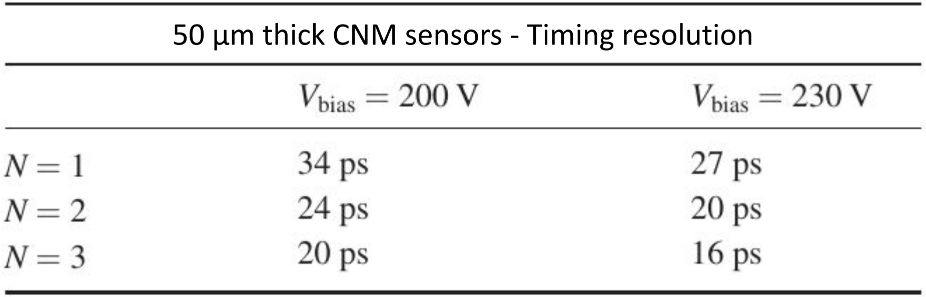
LGAD - time resolution

- Beam tests performed on LGAD show a time resolution ~30 ps (suitable for experiments at HL-LHC).
- Combining the measurements of N devices the resolution scale as σ(N) = σ(1)/√N



The difference in timing resolution and the time jitter is caused by the non-uniform charge deposition

Hartmut F.-W. Sadrozinski, "Time Resolution of LGAD", Trento 2017



50 µm thick CNM sensors - Timing resolution

	$V_{\text{bias}} = 200$ V	$V_{\text{bias}} = 230$ V
$N = 1$	34 ps	27 ps
$N = 2$	24 ps	20 ps
$N = 3$	20 ps	16 ps

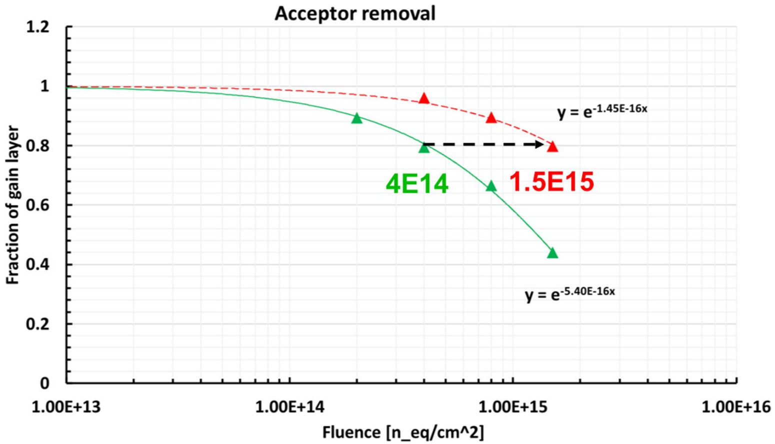
N. Cartiglia et al., Beam test results of a 16ps timing system based on ultra-fast silicon detectors, Nuclear Instruments and Methods in Physics Research Section A, Volume 850, 1 April 2017, Pages 83-88

LGAD - radiation hardness

- Studies pointed out that LGAD gain is compromised when the sensor is irradiated.
- Neutron irradiation lowers the doping in the gain layer through acceptor removal.

- After 6 10^{14} n_{eq} cm^{-2} the gain of a sensor is equivalent to the pre-radiated gain of a sensor with a 30% lower doping (expected fluence at HL-LHC is 10^{16} n_{eq} cm^{-2} y^{-1}).

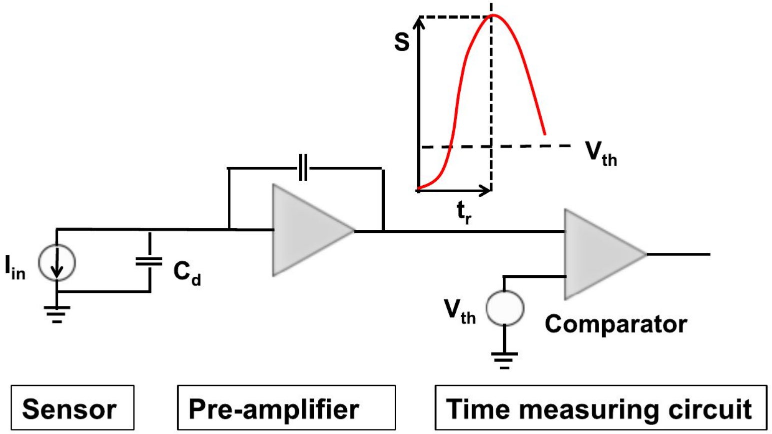
- Several studies are exploring how to improve the LGAD radiation hardness.
- Carbon in the gain layer reduces the acceptor removal mechanism.



Active fraction of gain layer in LGAD as a function of irradiation. The green curve represents the typical behavior for prototypes manufactured in 2016 while the red curve for those manufactured by FBK in 2018 with carbon infusion.

N. Cartiglia et al., LGAD designs for Future Particle Trackers, Nuclear Instruments and Methods in Physics Research Section A, Volume 979, 1 November 2020, 164383

Time measurement



- To produce accurate measurements of t_0 the signal (S) must be large and with a short rise time (t_r).
- The amplitude of the signal depends from the current I_{in}.
- We can increase increase it:
  - Amplifying the current inside the detector.
  - Decorrelating the number of carrier from the distance between electrodes.

Current in a silicon detector

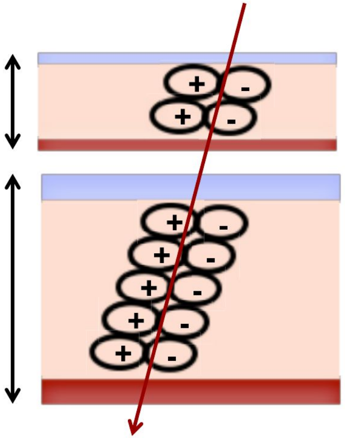
According to Ramo–Shockley's theorem, the current induced by a charge carrier is:

$$i(t) = -q\,\overrightarrow{v}\,\overrightarrow{E_w}$$

Where:

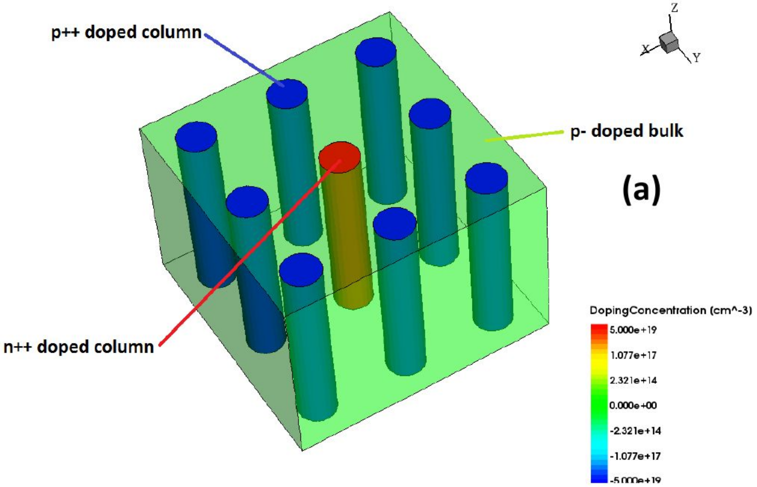
- $\overrightarrow{v}$: drift velocity, constant if the electric field is high enough everywhere.
- $\overrightarrow{E_w}$: weighting field, represents the coupling of a charge to the read-out electrode.

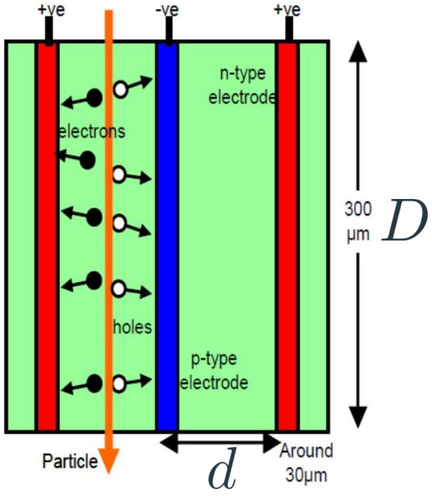
- It must be multiplied by the number of carrier.
- The number of carriers is proportional to sensor thickness (*d*).
- The weighting field is inversely proportional to the distance of the electrodes (also *d*).
- The current in a silicon detector should not depend on sensor thickness.



3D silicon detectors

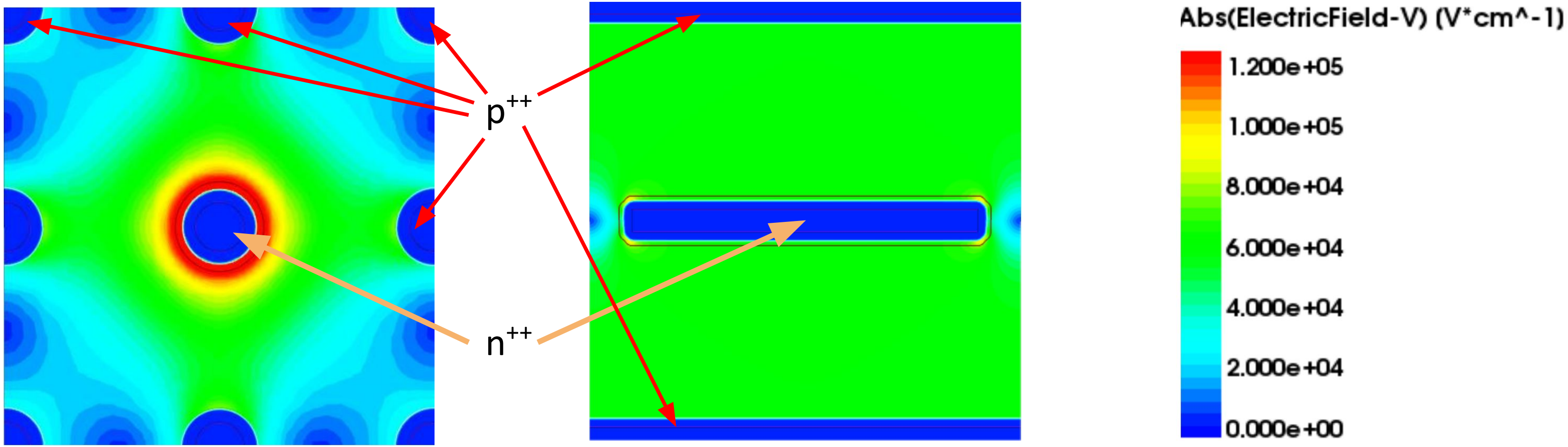
- In 1997 a new architecture was proposed: a 3D array of electrodes that penetrate into the detector bulk.
    - ○ 2011: study about timing performance.
    - ○ 2017: first studies for the realization of a real sensor optimized for timing measurements.
- Sensor thickness (*D*) and electrodes distance (*d*) are now uncorrelated.
- The current is enhanced respect to a plain sensor because is now proportional to *D/d*.





3D silicon detectors - geometry

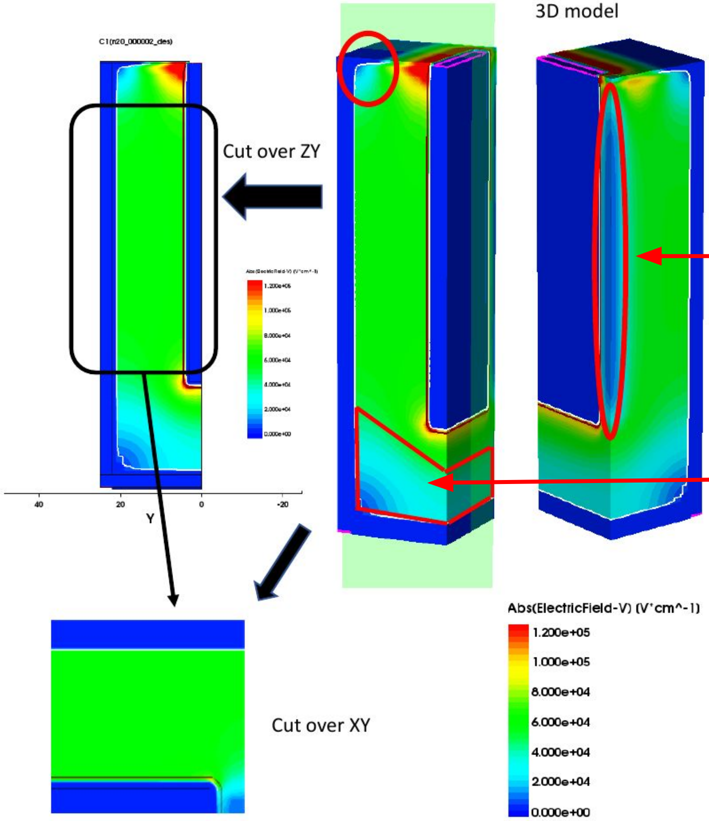
- The columnar geometry do not produce uniform electric field and it drop to zero between border electrodes → not uniform drift velocity, impact on weighting field → worst time resolution.
- Studies explored different geometries choosing a square pixel with parallel trench configuration (geometry as close as possible to a parallel plate capacitor).



A. Loi, Design of 3D silicon sensors for high resolution time measurements, 13th “Trento” Workshop on Advance Silicon Radiation Detectors, Munich, 19-21 February 2018

3D silicon detectors - geometry

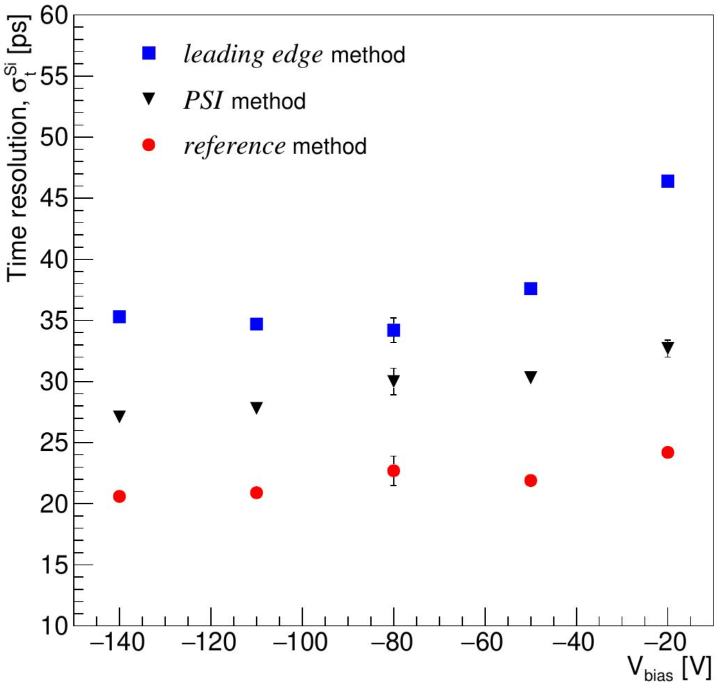
- A 3D geometry is not trivial and needs to be studied in the entire volume.
- Also the production of the sensor is challenging.



A. Loi, Design of 3D silicon sensors for high resolution time measurements, 13th “Trento” Workshop on Advance Silicon Radiation Detectors, Munich, 19-21 February 2018

3D silicon detectors - time resolution

- Beam tests show a time resolution between 20 and 35 ps depending on how the time of arrival are computed (suitable for experiments at HL-LHC).



Time resolution of the 3D-trench silicon sensor as a function of the sensor bias for different analysis methods.

The *PSI* method is based on a constant fraction discrimination where the treshold is proportional to the signal amplitude, and it is one of the most common method.

L. Anderlini et Al., Intrinsic time resolution of 3D-trench silicon pixels for charged particle detection, 2020 JINST 15 P09029

Summary

- At high-luminosity collider, the spatial density of collision will not permit to separate the vertices.
- Event reconstruction will require a huge computation power due to the high-number of possible hits combinations.

- Add time information to hits is a possible solution to these challenges.

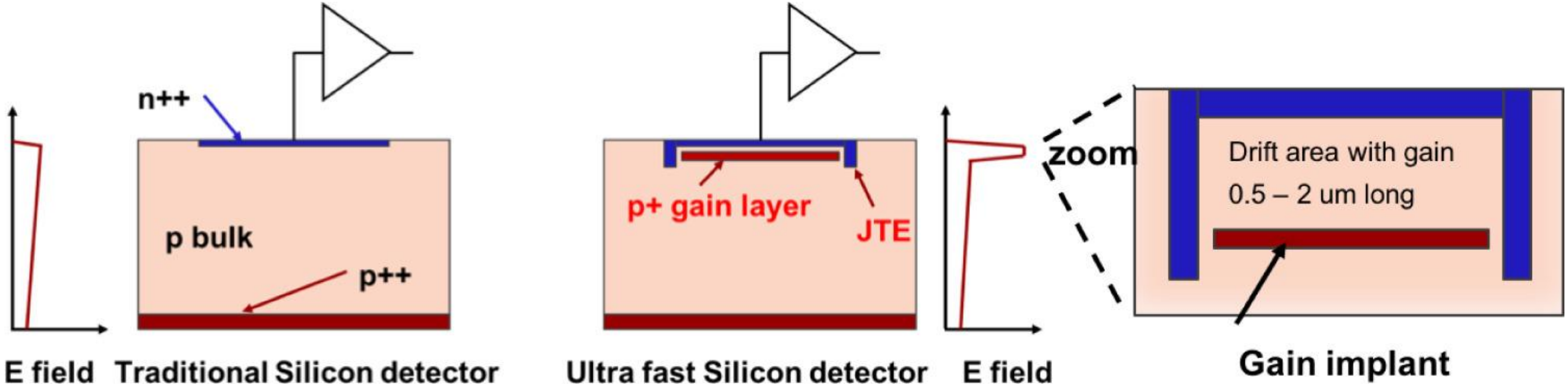
- Silicon detectors of new generation can measure the time of arrival of a particle with resolution suitable for experiments at HL-LHC (~30 ps):

- Low-gain avalanche detectors are already produced by sensors manufacturer, and several studies are exploring how to improve their radiation hardness.

- The application of 3D silicon detectors for timing measurements is relatively new, however radiation hardness and time resolution are promising.

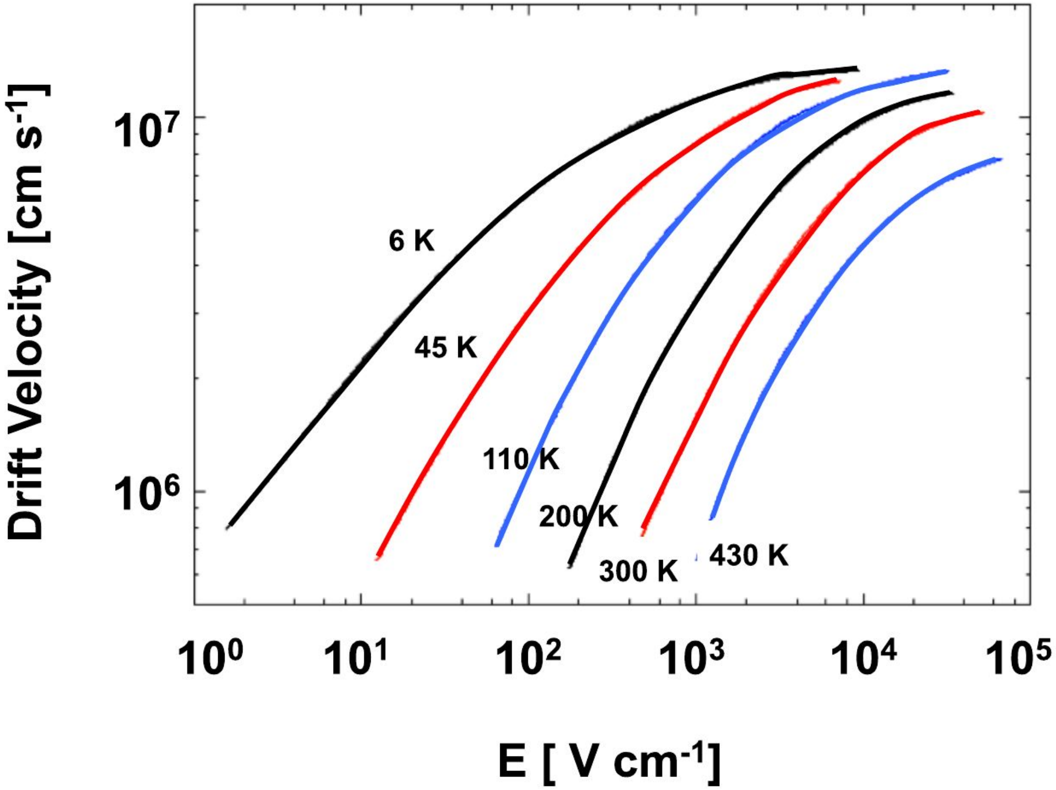
Backup

LGAD structure



N. Cartiglia et al., LGAD designs for Future Particle Trackers, Nuclear Instruments and Methods in Physics Research Section A, Volume 979, 1 November 2020, 164383

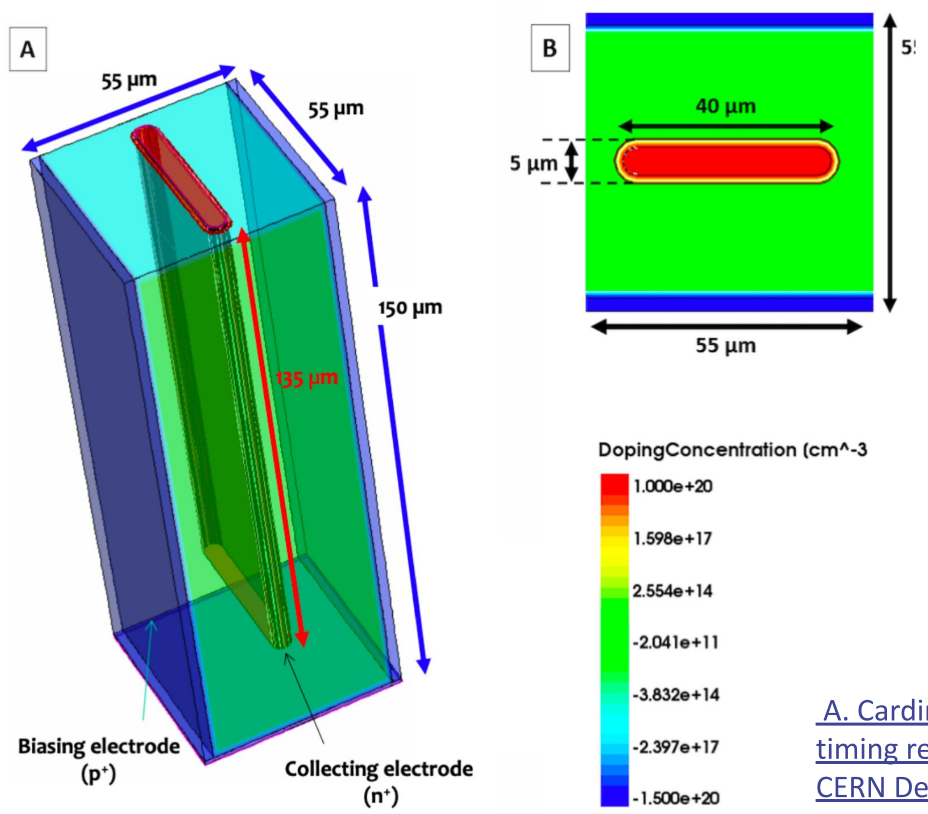
Drift velocity



Electron drift velocity as a function of the electric field E for different temperatures.

C. Jacoboni et al., A review of some charge transport properties of silicon, Solid-State Electronics, Volume 20, Issue 2, February 1977, Pages 77-89

3D-trench silicon sensor sizes



A. Cardini, Tracking charged particles with 20ps timing resolution using 3D-trench Silicon Pixels, CERN Detector Seminar 2020