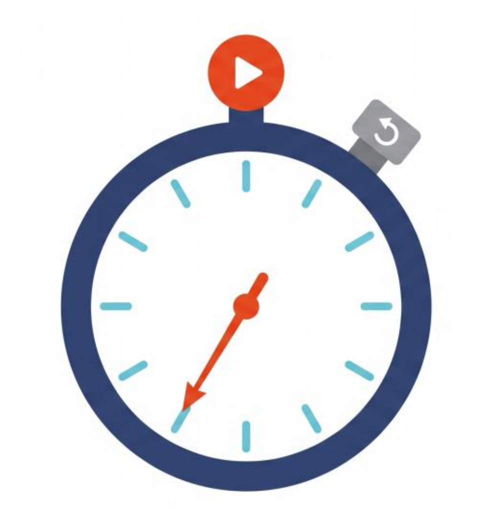
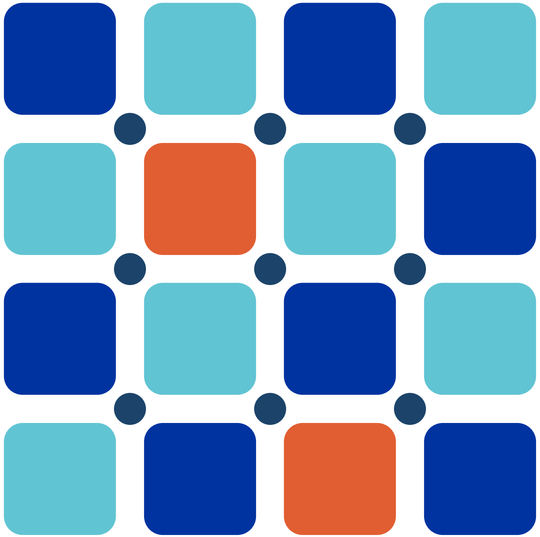




It’s About *Time*:
4D Tracking in Modern Detectors

Luca Menzio – CERN’s Solid State Detectors group

Content

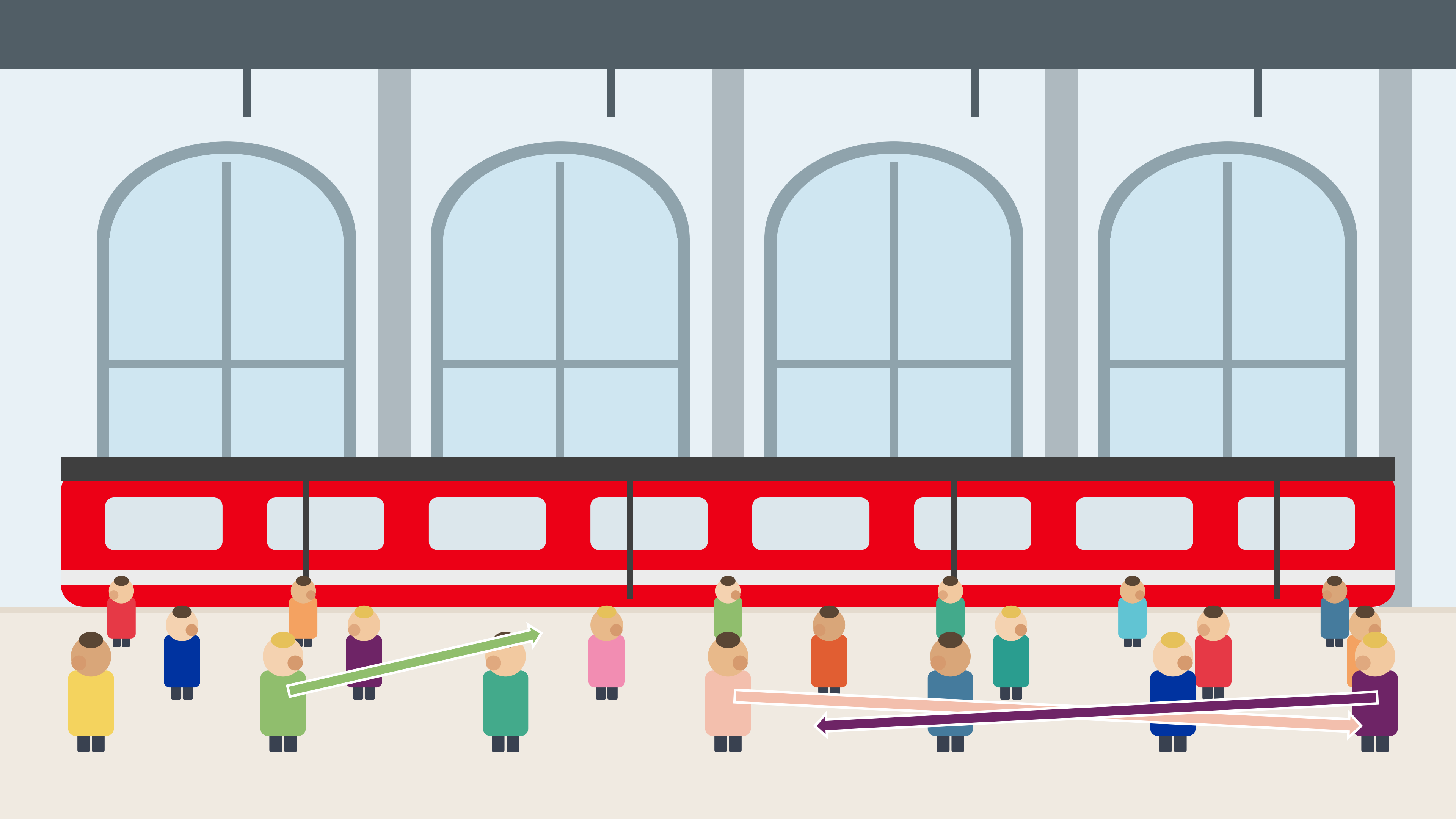
1. **4D tracking**
2. **Timing measurements**
3. **Some valid candidates**
4. **Resistive Silicon Detector(s)**

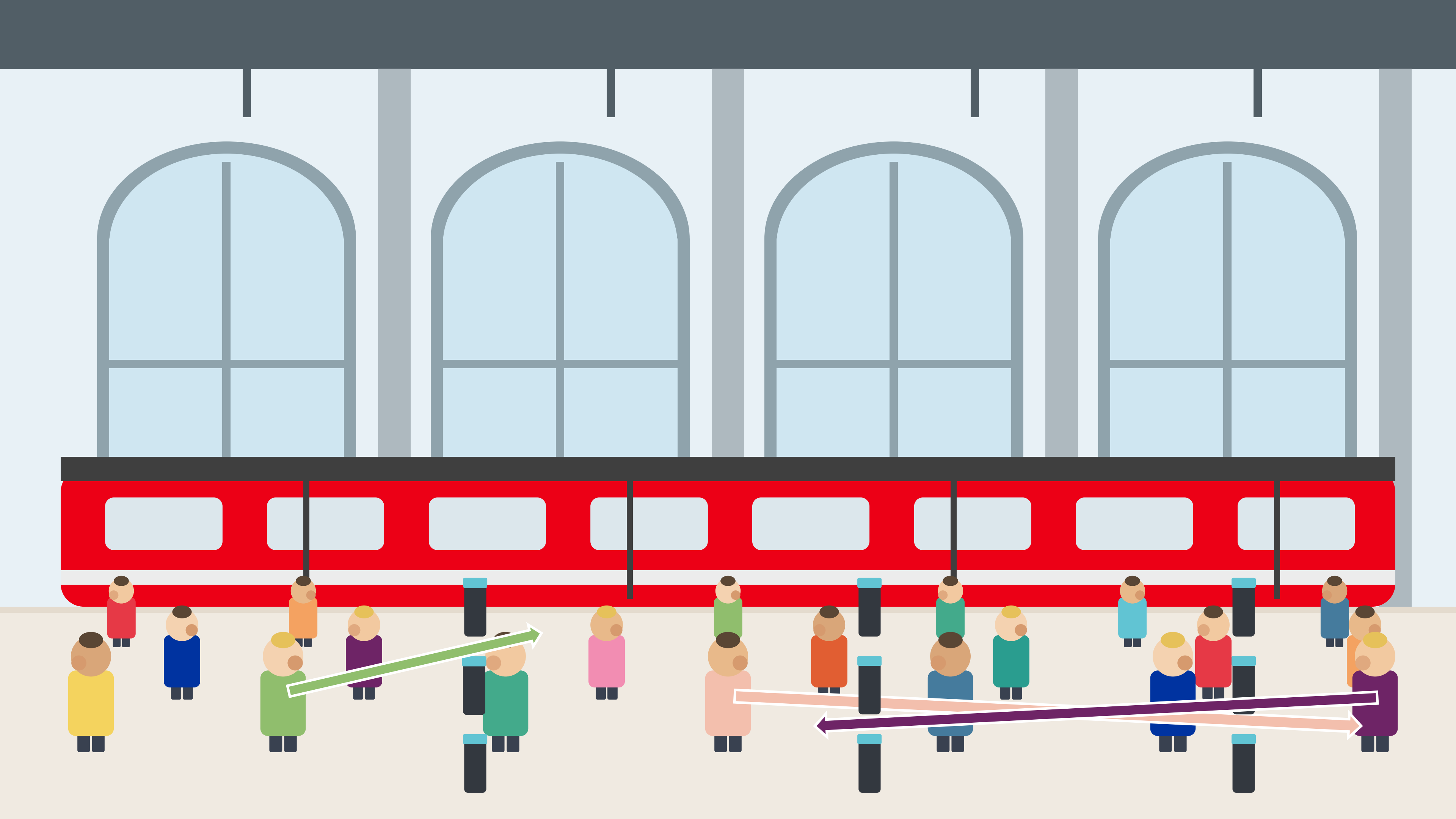
Disclaimer:

I took inspiration from Nicolò Cartiglia and Frank Hartmann's lectures at the 2026 EDIT school for parts of this seminar

Content


Did not pay the ticket

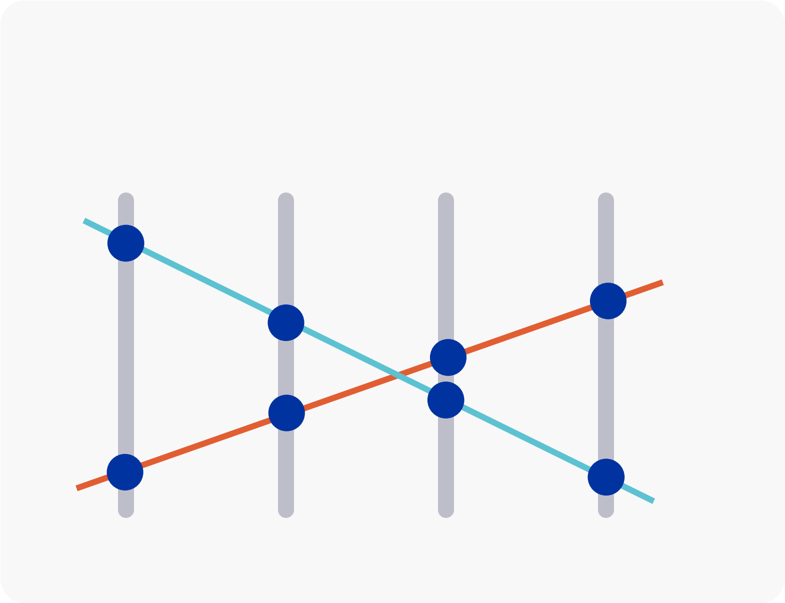




What is 4D Tracking

The classic picture: 3D

- A tracker rebuilds particle trajectories from position “hits” in successive layers → coordinates (x, y, z)
- Excellent spatial precision (~µm), if the number of hits is low reconstructing the track is feasible



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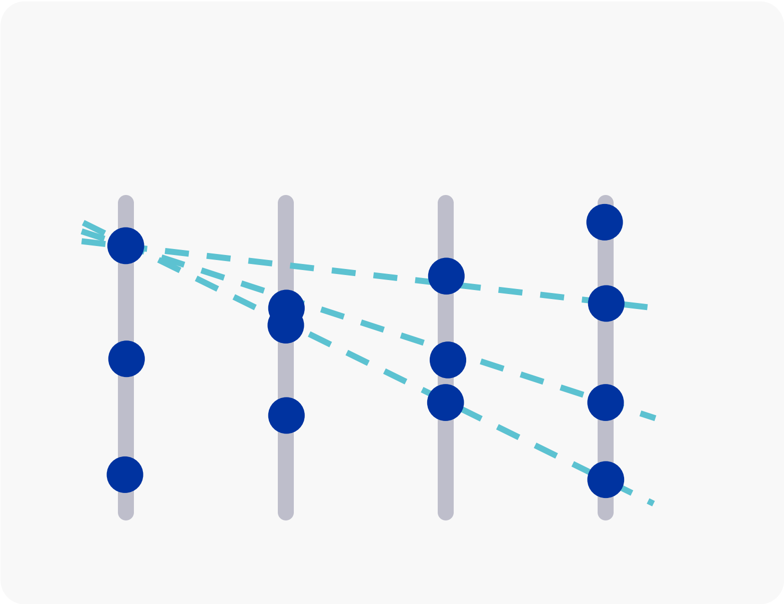

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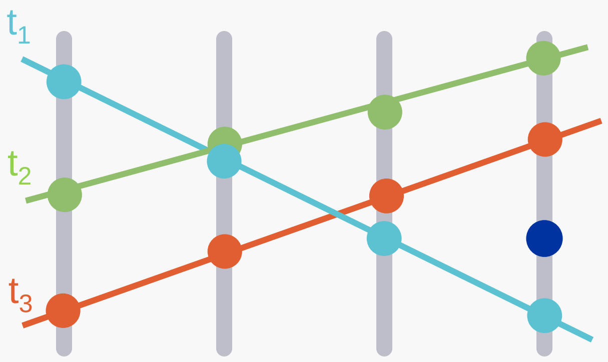


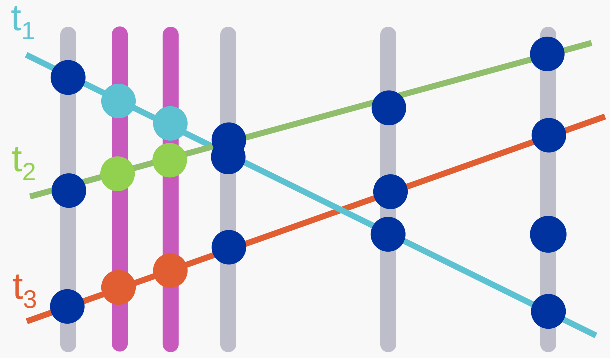
4D tracking

- If we add “stopwatches” each hit has its own timestamp
- 4D tracking **adds a precise timestamp** to the spatial information

What is 4D Tracking

(3+1)D Tracking

- A timing layer added to an existing tracker
- One or two layers time-stamp the whole track
- Far from the interaction point: lower rates, less radiation
- The choice of **CMS** and **ATLAS** at the HL-LHC



Why 4D Tracking

The next generation of colliders pushes **pile-up**, **rates** and **radiation** beyond what position-only tracking can resolve — **time becomes the essential coordinate.**

HL-LHC

The high-luminosity upgrade of the LHC — many more proton collisions, from ~2029.

FCC

A proposed ~90 km circular collider at CERN, with electrons first and protons later.

Muon Collider

A future collider of muons, reaching the energy frontier in a compact machine.

EIC

A new US collider of electrons with protons and ions, probing their inner structure.

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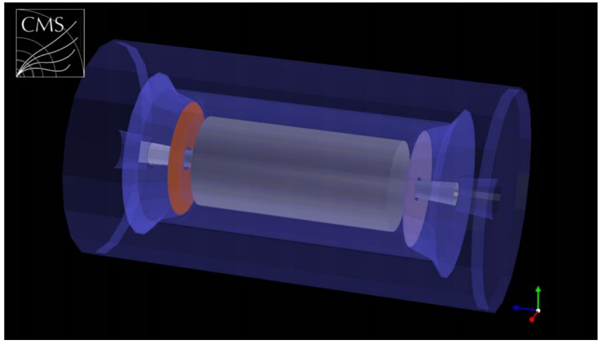
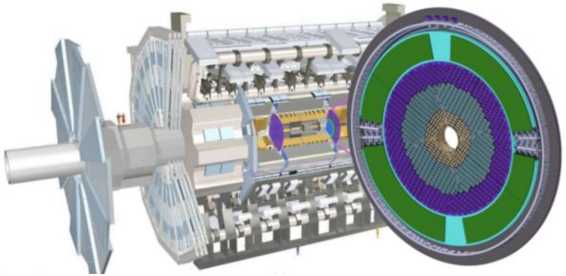
CMS
MIP Timing
Detector



Newest instances of tracking layers **dedicated to timing!**

Will be assembled soon



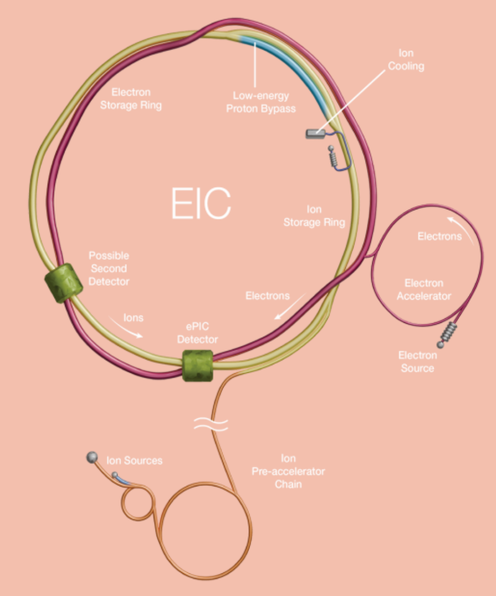
ATLAS
High Granularity
Timing Detector

Why 4D Tracking

The next generation of colliders pushes **pile-up**, **rates** and **radiation** beyond what position-only tracking can resolve — **time becomes the essential coordinate.**

4D tracking detector in ePIC

- Time-of-Flight layers
- Barrel + endcaps
- ~30 ps per hit
- Separates π, K and p



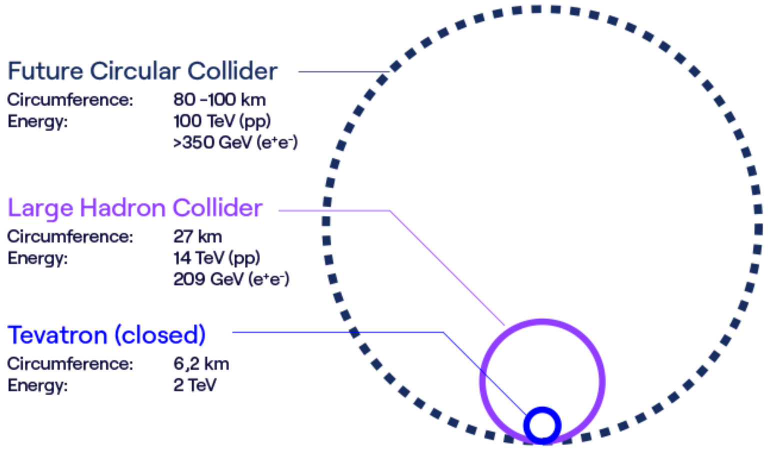
- At Brookhaven Lab (US), from ~2032
- First high-energy electron–ion collider
- Collision energy $\sqrt{s}$ up to ~140 GeV
- Dedicated to nuclear structure studies

EIC

A new US collider of electrons with protons and ions, probing their inner structure.

Why 4D Tracking

The next generation of colliders pushes **pile-up**, **rates** and **radiation** beyond what position-only tracking can resolve — **time becomes the essential coordinate.**



FCC

A proposed ~90 km circular collider at CERN, with electrons first and protons later.

- Two possible stages: FCC-ee, then FCC-hh
- FCC-ee: $\sqrt{s}$ ~90–365 GeV — Higgs & EW factory
- FCC-hh: pp collisions up to ~100 TeV
- Final CERN decision ~2028
- First beams targeted for the ~2045–2048

In summary: why 4D tracking

1 **A new generation of experiments**
HL-LHC, FCC, a muon collider and the EIC are being built.

2 **The conditions get much harsher**
Higher rates and pile-up: current position-only trackers can't cope.

3 **Add the time coordinate**
A timestamp on every hit — 4D tracking — separates overlapping events

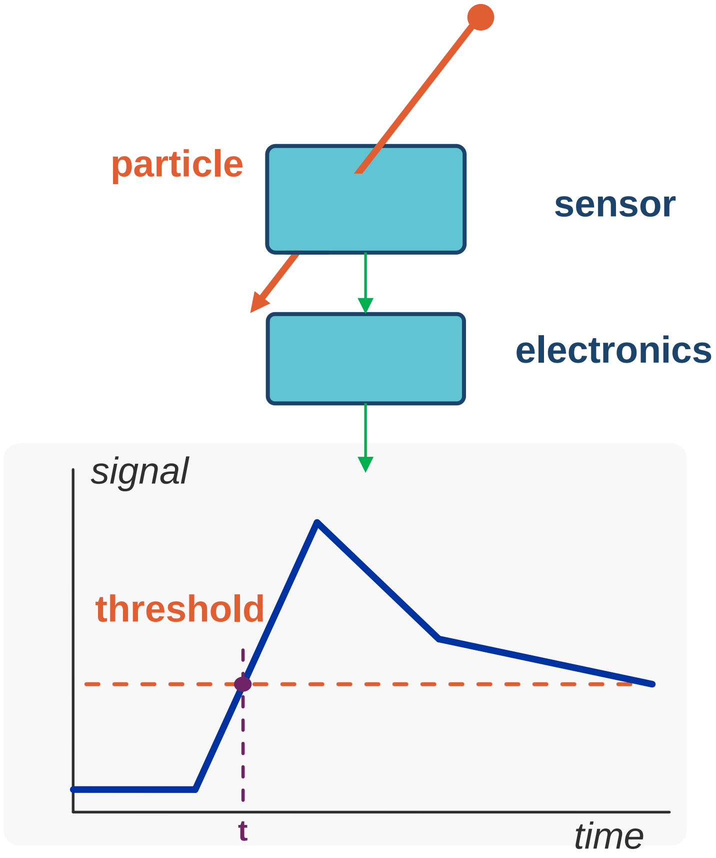
4 **We need timing detectors that can also do tracking**
This seminar (and my job)

Content

1. 4D tracking
2. **Timing measurements**
3. Some valid candidates
4. Resistive Silicon Detector(s)

Measuring Time

- A crossing particle releases charge in the sensor → fast electrical pulse
- The electronics record when the pulse crosses a set threshold — that instant is the arrival time t
- t is always measured against a reference (the collision, or a ‘start’ detector)
- Its **spread** is the time resolution σ_t — 4D tracking aims for at least $\sigma_t \approx 30$ ps



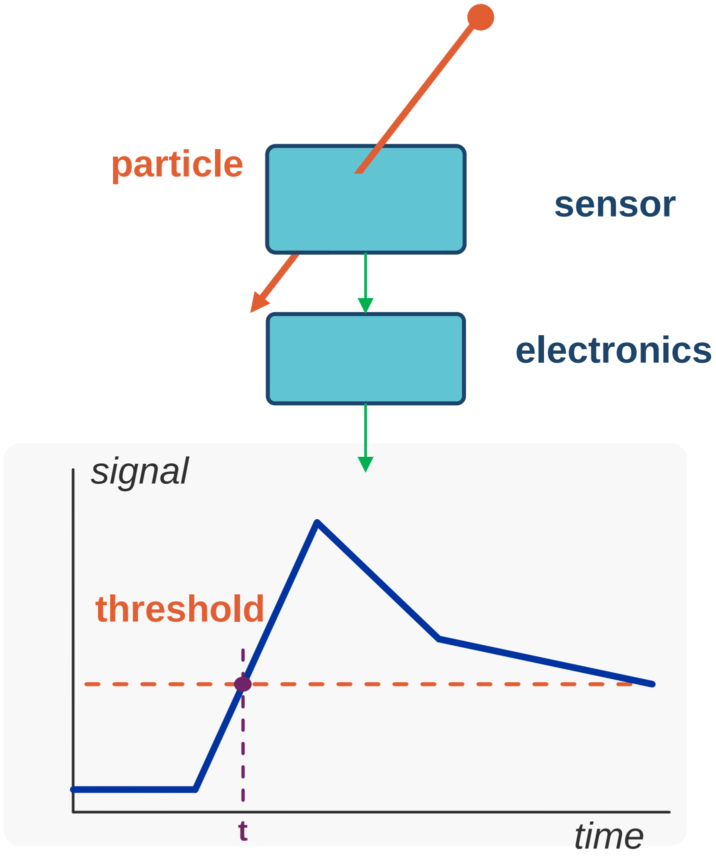
Measuring Time

In all time measurement systems, there are always at least **two equally important components**

- **Detector** ← Today
- **Electronics**

Practically, the time coordinate is extracted by the electronics from the signal provided by the detector.

1. Faster (shorter) signals are better
2. Large signals help the electronics
3. They must be able to fulfill the experiment requirements **together**

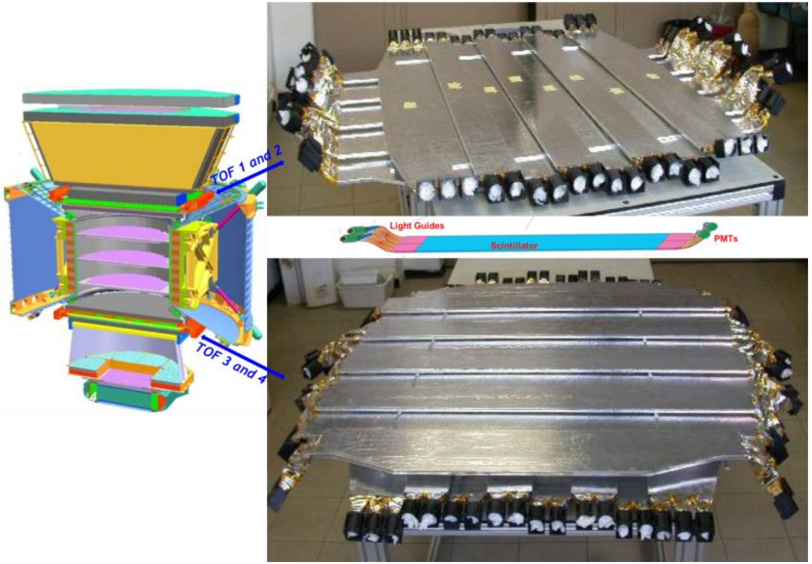


Measuring Time – Detectors: a bit of history

Timing is not new: for decades time-of-flight systems were built with scintillators read out by photodetectors.

Scintillator + PMT

- Since the 1950s: the workhorse of time-of-flight
- A charged particle makes light in the scintillator; a photomultiplier turns it into a fast pulse
- $\sigma_t \approx$ 50–100 ps for a whole counter
- Big, no position information and sensitive to magnetic fields



The ams-02 time of flight. Image taken from here

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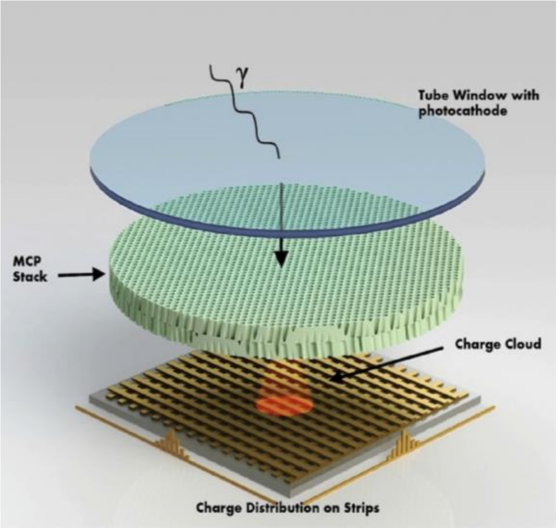


Image taken from here

Micro-Channel Plate PMT

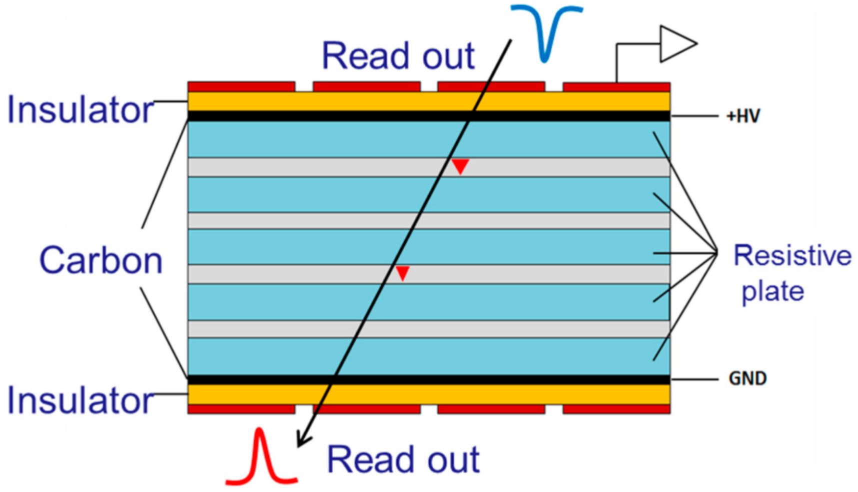
- A thin plate of micro-tubes multiplies the photoelectrons over a very short path
- σ_t of a few ps to ~10 ps — some of the best timing available
- Used in Cherenkov timing (e.g. Belle II TOP)
- Fragile, expensive, needs light — hard to build a large tracker with it

Measuring Time – Detectors: gas and the limits

Gaseous detectors brought precise timing over very large areas — but not the tracking performance we now need.

Multigap Resistive Plate Chambers

- A stack of thin gas gaps between resistive plates: the avalanche starts immediately, everywhere
- $\sigma_t \approx$ 60–80 ps over ~150 m² — the ALICE TOF wall at the LHC
- Cheap per unit area, ideal for particle identification
- Coarse granularity (cm-size pads) and slow rate capability



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What these detectors cannot do

- No µm-level position measurement: **they time, they do not track well**
- Large volumes and high voltages — heavy material budget, little space in a modern tracker
- Rate and radiation tolerance far below HL-LHC or FCC conditions
- Since ~10 years → **silicon devices**

Measuring Time – Requirements

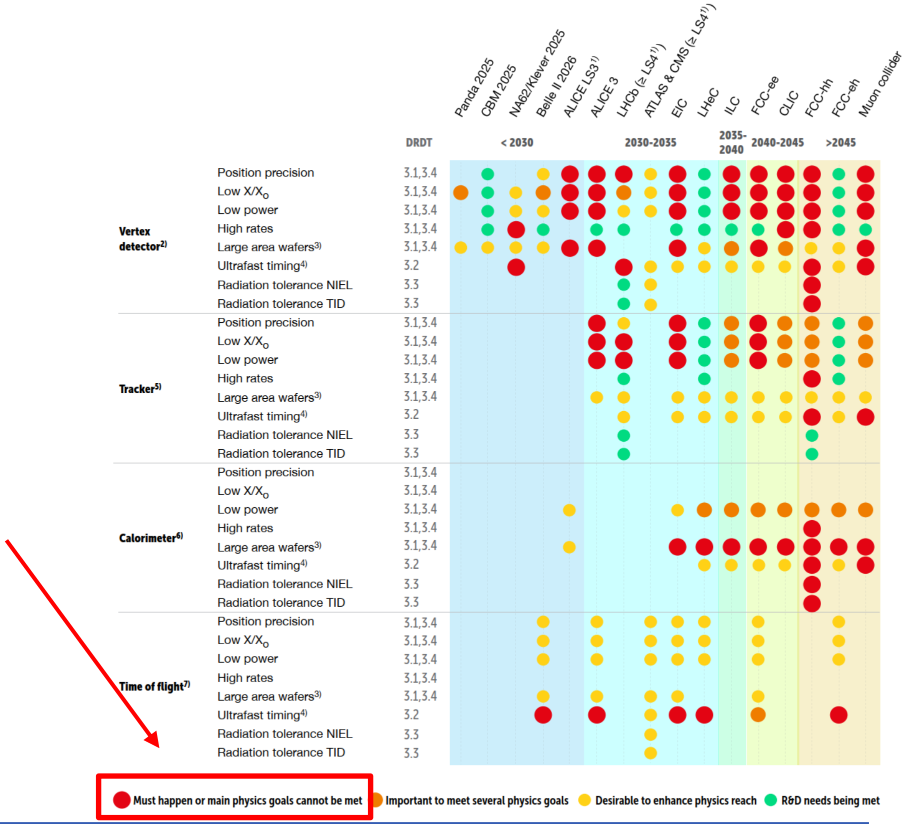
The experiment requirements are what we follow for detectors R&D. Some of the most important are:

Space resolution	*Power consumption*
Time resolution	*Material budget*
Radiation tolerance	*Particle rate*

Luckily, **experts draw documents** that summarize all that we need in a simple(r) way

There are also **international collaborations** such as **CERN's DRD** program that *found, collect* and *steer R&D* in this field.

There's **a lot to do** and plenty of **room for improvement** → **great field?**



Why silicon?

A reverse-biased diode: the depleted volume is the detector itself.

- **Great precision** in manufacturing
- High density of electron-hole pairs per unit length
- High charge carrier mobility
- Compatible with industrial fabrication processes
- Good radiation resistance can be achieved

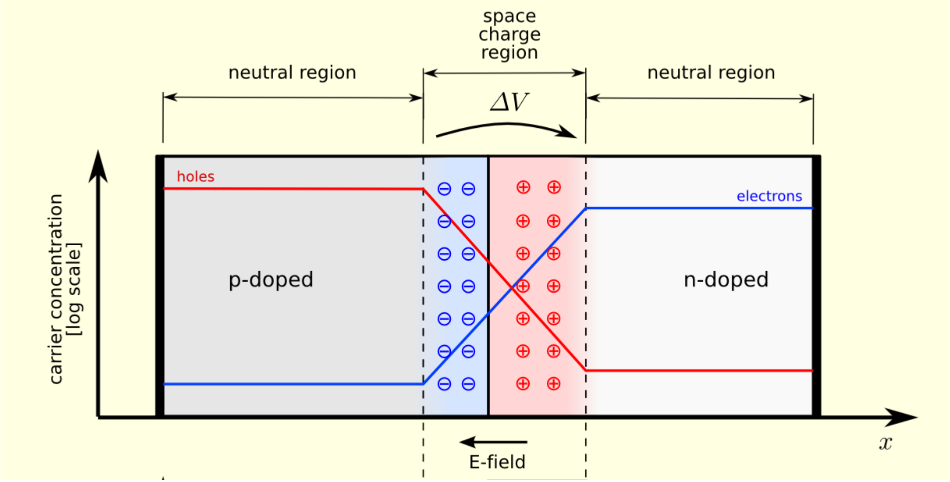
→

- Very small pixels are feasible
- Large signals
- Fast signals
- Relatively cheap
- It “ages” well in the experiments

How silicon (diode)?

To summarize (*very* quickly) how a diode works:

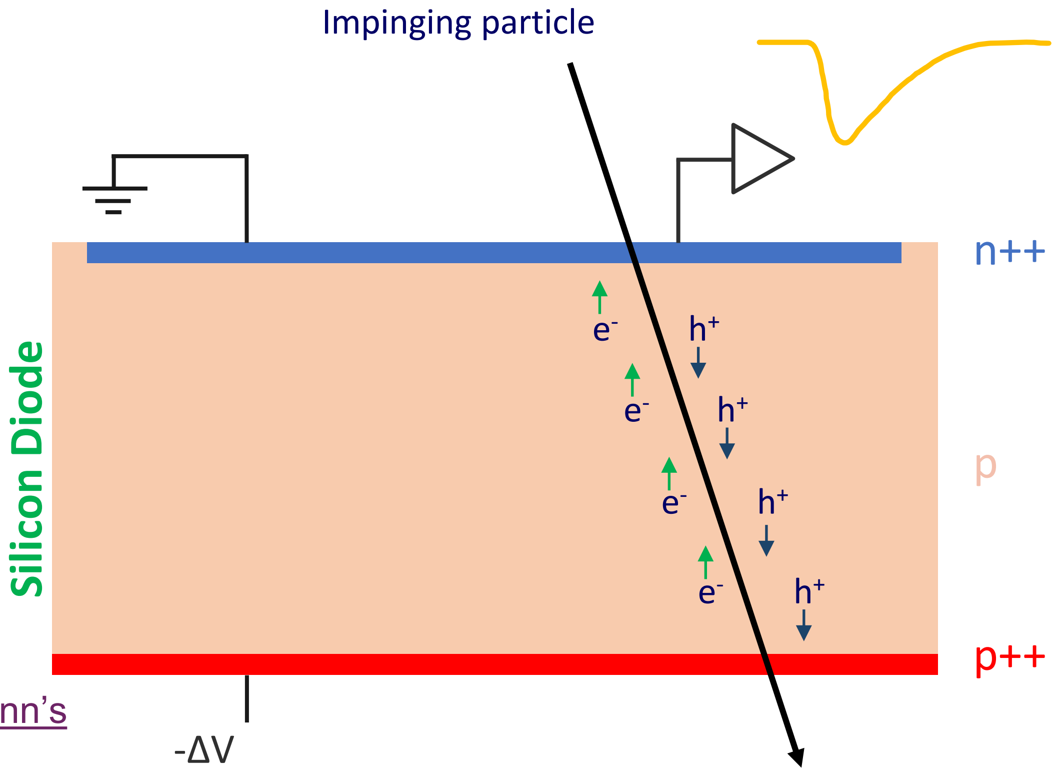
- if a certain voltage is applied to the sensor**,** the charges are free to move



How silicon (diode)?

To summarize (*very* quickly) how a diode works:

- if a certain voltage is applied to the sensor, the charges are free to move
- when a particle hits the diode volume, electron-hole pairs are created
- Electron-hole pairs migrate towards the electrodes
- an electrical signal is induced on the electrodes



For (way) more about this topic see F. Hartmann's lecture at the 2026 EDIT school

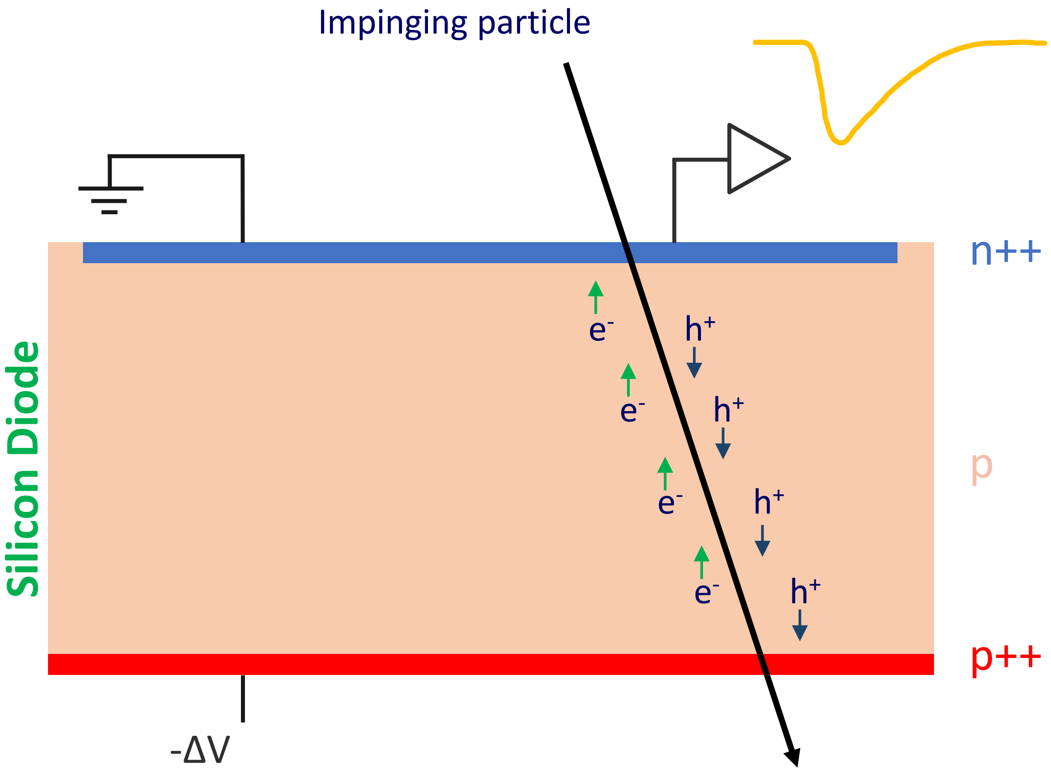
Why silicon?

Such devices have been employed in trackers (3D) for decades now.

Traditionally, though, they **do not provide good timing** performances

Silicon started becoming interesting for **timing** measurements in **recent years**

Device engineering (or re-engineering)



Measuring Time – Some Theory

Sensor | Electronics

$$\sigma_t^2 \approx \underbrace{\sigma^2_{Spatial\ Fluctuation} + \sigma^2_{jitter} + \sigma^2_{Distortion}}_{\text{Sensor}} + \underbrace{\sigma^2_{TDC} + \sigma^2_{Time\ walk}}_{\text{Electronics}}$$

Again, for an in-deep lecture about timing see N. Cartiglia’s talk at the 2026 EDIT school

Measuring Time – Some Theory

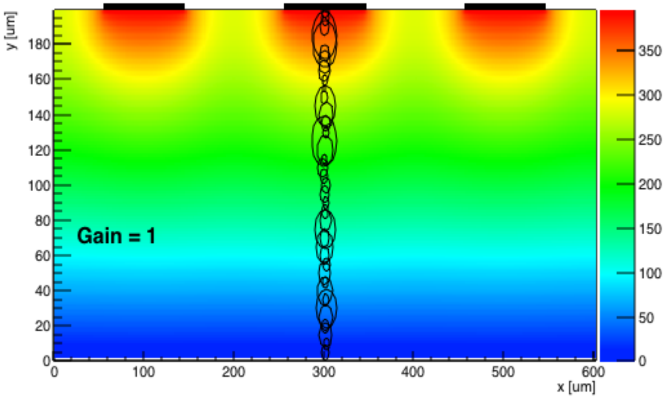
Go thin

$$\sigma_t^2 \approx \sigma^2_{Spatial\ Fluctuation} + \sigma^2_{jitter} + \sigma^2_{Distortion} + \sigma^2_{TDC} + \sigma^2_{Time\ walk}$$

Due to **non-uniform energy deposition**

Someone calls it also “Landau contribution”

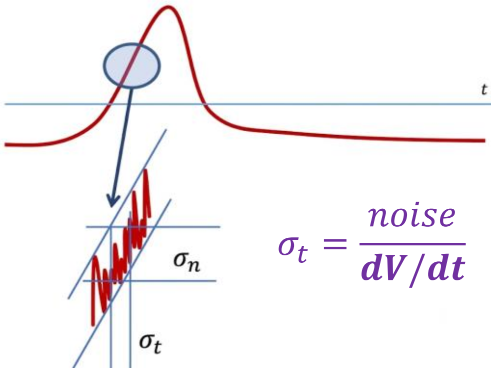
Becomes **more relevant with larger distance in between the electrodes** (i.e. thickness for a standard diode)



Measuring Time – Some Theory

Go thin — **Increase S/N**

$$\sigma_t^2 \approx \sigma^2_{Spatial\ Fluctuation} + \sigma^2_{jitter} + \sigma^2_{Distortion} + \sigma^2_{TDC} + \sigma^2_{Time\ walk}$$



$$\sigma_t = \frac{noise}{dV/dt}$$

Jitter contribution

Due to interplay between noise and signal shape.
In principle, one needs

- fast and large signal
- low noise.

→ **large signal/noise (S/N)**

Measuring Time – Some Theory

Go thin **Increase S/N** **Be uniform**

$$\sigma_t^2 \approx \boxed{\sigma^2_{Spatial\ Fluctuation} + \sigma^2_{jitter} + \sigma^2_{Distortion}} + \sigma^2_{TDC} + \sigma^2_{Time\ walk}$$

Distortion Contribution

It comes from *Shockley-Ramo*'s theorem

Due to a **position-dependent coupling** of the drifting charges to the electrode (non-uniform weighting field)

- Parallel plate geometry
- Saturated drift velocities

Signal shape is determined by it

$$i \propto q v E_w$$

Weighting field

Drift velocity

Content

1. 4D tracking
2. Timing measurements
3. Some valid candidates
4. Resistive Silicon Detector(s)

From Theory to practice

Go thin — Increase S/N — Be uniform

$$\sigma_t^2 \approx \boxed{\sigma^2_{Spatial\ Fluctuation} + \sigma^2_{jitter} + \sigma^2_{Distortion}} + \sigma^2_{TDC} + \sigma^2_{Time\ walk}$$

There are various strategies to decrease the time resolution. Some *examples* are:

- **3D sensors** – (very) short drift of charges + great S/N thanks to the diode being “vertical”
- **SiPM** – normally coupled with scintillators. Exploit the Gaiger Mode S/N
- Sensors with **internal gain** – they device engineering to achieve signal multiplication

Requirements

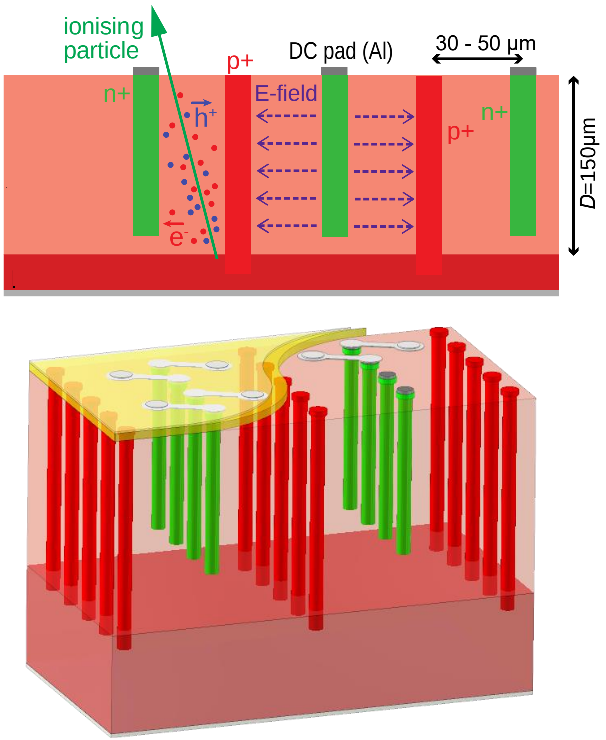
Before jumping into the technologies, it is important to keep in mind the **objectives**:
each machine sets its own targets in **time**, **space**, **radiation hardness** and **material budget**.

No single sensor wins everywhere

Experiment (timing detector)	Time res. / hit	Spatial res.	Fluence [n_eq/cm²]
HL-LHC	30–50 ps	~1 mm pads	up to 2.5×10^{15}
FCC-ee — full-Si vertex/tracker	10–30 ps	5–10 µm	$< 10^{14}$
EIC — ePIC ToF	~25–30 ps	20–30 µm	$\sim10^{13}$
Muon collider — tracker	~30 ps	5–25 µm	$\sim10^{15}$

3D detectors

$$\sigma_t^2 \approx \sigma_{Spatial\ Fluctuation}^2 + \sigma_{jitter}^2 + \sigma_{Distortion}^2$$



Dalla Betta G-F and Povoli M (2022) Progress in 3D Silicon Radiation Detectors. Front. Phys. 10:927690. doi: 10.3389/fphy.2022.927690

3Ds minimize drift path by “rotating” the diode with respect to the particle path → the particle is **parallel to the junction**

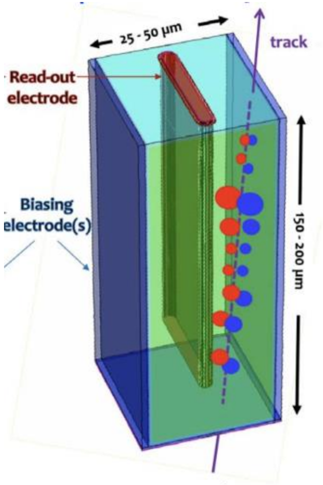
They were adopted at the **High-Luminosity LHC**

- **Longer ionization path** – More charge
- **Shorter drift path**
  - **Radiation resistance** – above $\Phi = 10^{16}\ n_{eq}/cm^2$ (very good)
  - **Less power** – goes with (electrode distance)^2
  - **Time resolution** – the jitter contribution is very low

But the columnar configuration is **not ideal for the distortion term**

3D detectors Trenches

$$\sigma_t^2 \approx \sigma_{Spatial\ Fluctuation}^2 + \sigma_{jitter}^2 + \sigma_{Distortion}^2$$



Trenches instead of **columns!**

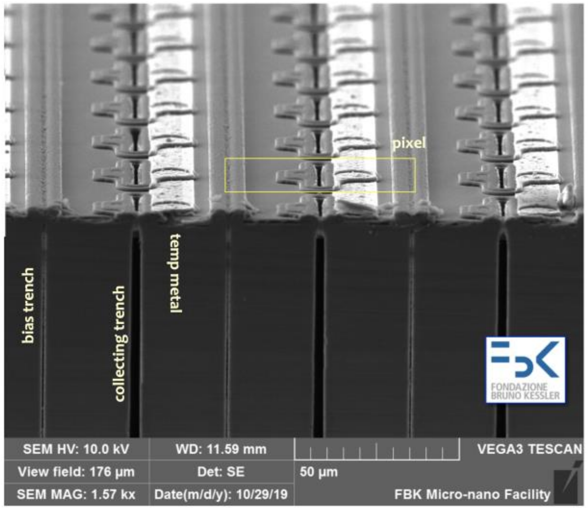
Parallel plate geometry is restored – distortion term becomes small again

Very impressive results achieved:

- **10 ps** time resolution
- **10 µm** space resolution
- Very high efficiency at **>> 10^{16} n_{eq}/cm^2**

Small cells = a lot of channels

Ideal where the **radiation resistance** is fundamental and the **power budget** is not an issue



TimeSPOT results – A. Lai – Vertex 2022

TIME and **SP**ace real-time **O**perating **T**racker

Sensors with Internal Gain

Internal multiplication can be achieved when the electric field is high enough

Charge Multiplication: $G = e^{\alpha l}$

l = distance
α_e ~ 0.7/µm for electrons,
α_h ~ 0.1/um for holes

Two multiplication regimes: electrons-only, or electrons-holes

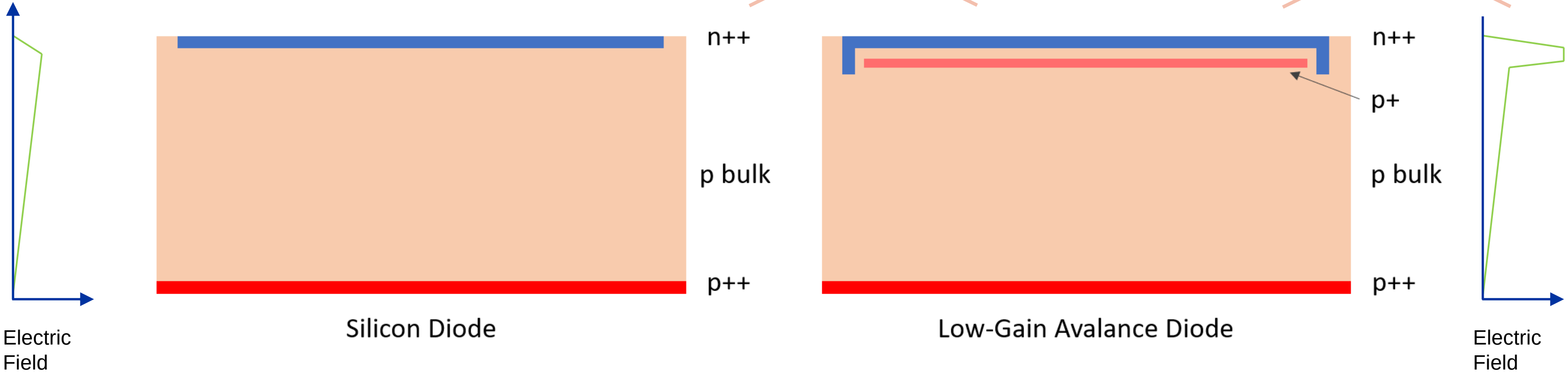
Electrons-holes tends to be more unstable and is closer to an avalanche mode.

Most gain-based silicon detectors operate ΔV ~ 300 kV/cm → **electrons-only**

1. **Use external bias** - V_{bias} ~ 1500 V in a 50 µm-thick sensor **almost impossible to achieve**
2. **Use doping** in silicon

LGADs

$$\sigma_t^2 \approx \sigma_{Spatial\ Fluctuation}^2 + \sigma_{jitter}^2 + \sigma_{Distortion}^2$$



Low-Gain Avalanche Diodes (LGADs) exploit a p++ doping layer to create high field

The low gain (10-30) allows for:

- **Thinner devices** – better spatial fluctuation term
- **Larger Signal/Noise** – better jitter term
- **The parallel plate geometry** is maintained – good distortion term

} **U**ltra **F**ast **S**ilicon **D**etectors (UFSDs)

LGADs

$$\sigma_t^2 \approx \sigma_{Spatial\ Fluctuation}^2 + \sigma_{jitter}^2 + \sigma_{Distortion}^2$$

The LGAD is a **mature technology**

- They can provide 20-40 ps time resolution and ~100% efficiency up to
- Baseline technology of **ATLAS HGTD** and **CMS MTD** at the High-Luminosity LHC

The electronics side is also mature: ALTIROC and ETROC provide exceptional results with low power budget

The couple **Detector + Electronics are ready for HL-LHC** (after 10+ years of R&D)

Drawbacks

- **radiation resistance** is limited to ~2.5×10^{15} n_{eq}/cm^2
- **no-gain region between pads** limits segmentation → **Resistive Silicon Detectors** (aka AC-LGAD), **TI-LGAD**

CMS & ATLAS timing layers

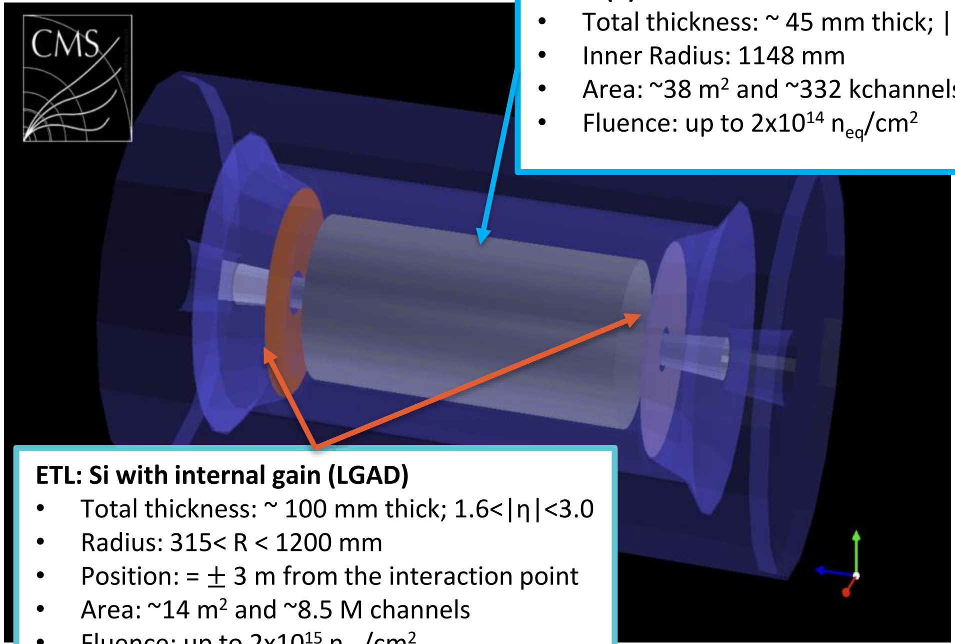
CMS MTD

- **Barrel:** LYSO:Ce + SiPMs, **38 m^2**
- **Endcap:** LGADs, **14 m^2**, 8.5 M ch.
- ETROC ASIC, 65 nm

ATLAS HGTD

- **Endcap:** LGADs, **6.4 m^2**, 3.5 M ch.
- ALTIROC ASIC, 130 nm
- Both: 1.3 × 1.3 mm^2 pads

Both timing layers will **drastically improve the reconstruction efficiency** during HL-LHC operations



BTL: L(Y)SO bars + SiPM readout:

- Total thickness: ~ 45 mm thick; $|\eta|<1.45$
- Inner Radius: 1148 mm
- Area: ~38 m^2 and ~332 kchannels
- Fluence: up to 2×10^{14} n_{eq}/cm^2

ETL: Si with internal gain (LGAD)

- Total thickness: ~ 100 mm thick; $1.6<|\eta|<3.0$
- Radius: 315< R < 1200 mm
- Position: = $\pm$ 3 m from the interaction point
- Area: ~14 m^2 and ~8.5 M channels
- Fluence: up to 2×10^{15} n_{eq}/cm^2

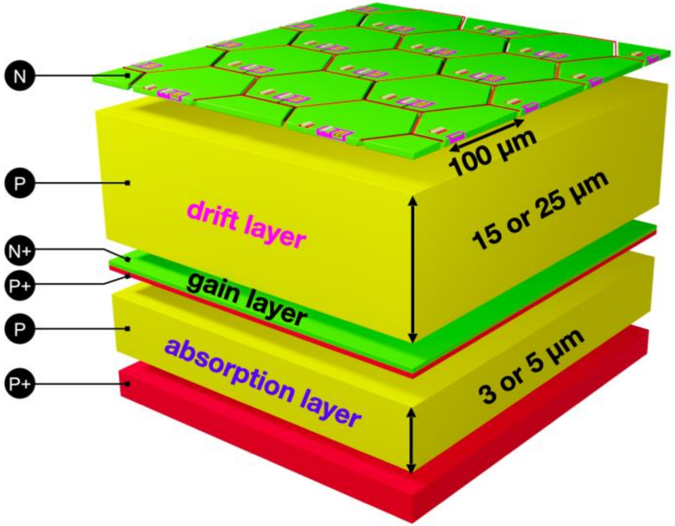
Monolith and PicoAD

MONOLITH: sensor and **fast SiGe BiCMOS front-end on the same chip** → no bump bonding, low capacitance, very fast rise time

- **~20 ps** per hit already without internal gain
- **~13 ps** adding the **PicoAD** gain layer

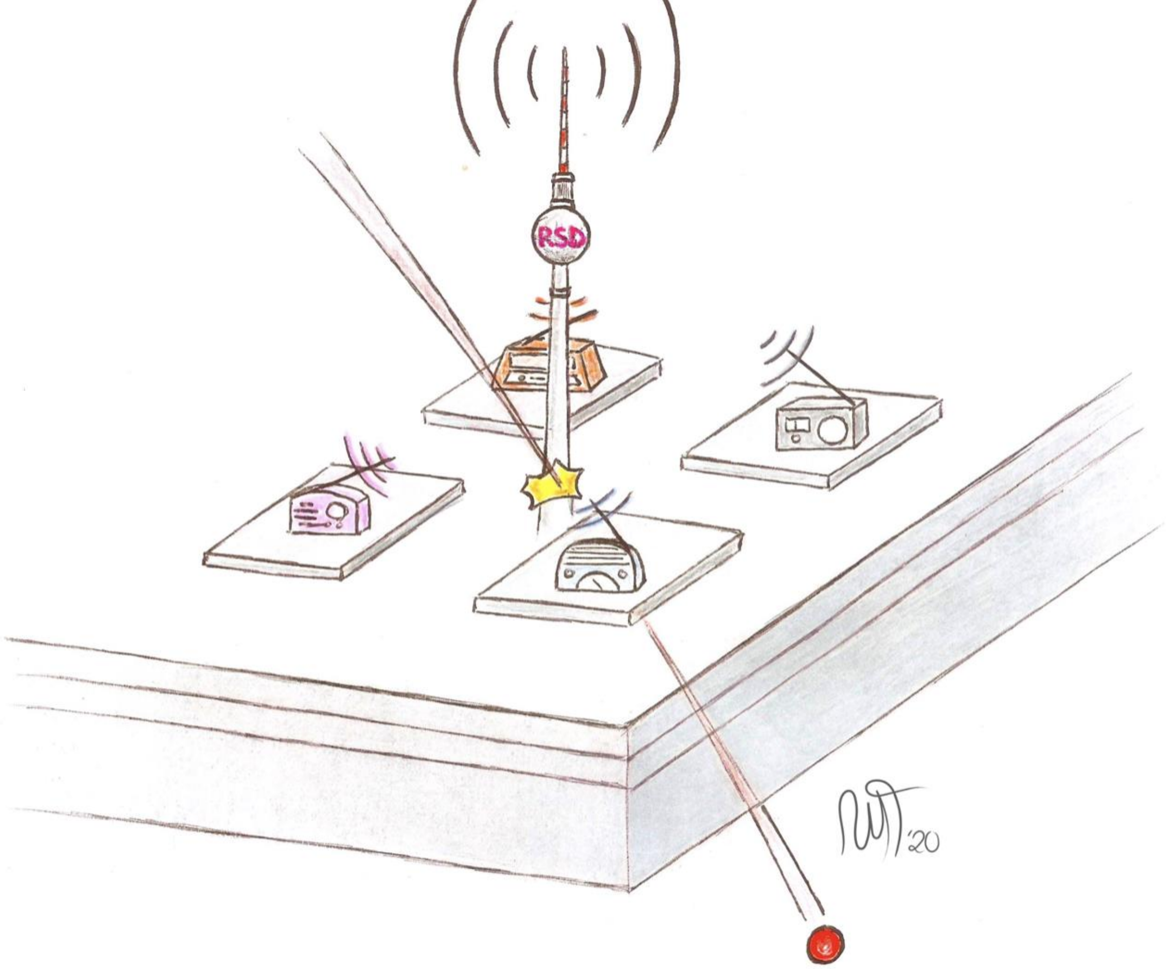
PicoAD = a **continuous, buried gain layer** under the whole pixel matrix → uniform gain and **100% fill factor**, with ~100 µm pixels

But still R&D: small prototypes, **power density** can be an issue

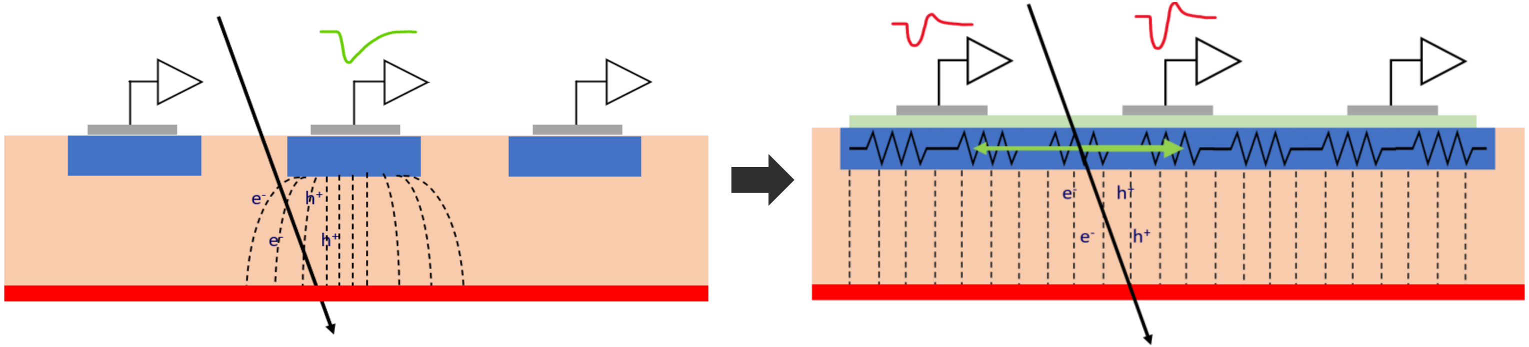


Content

Disclosure: what ***I do***, I am biased
Open collaboration **with a group here in KIT**


RSD
'20

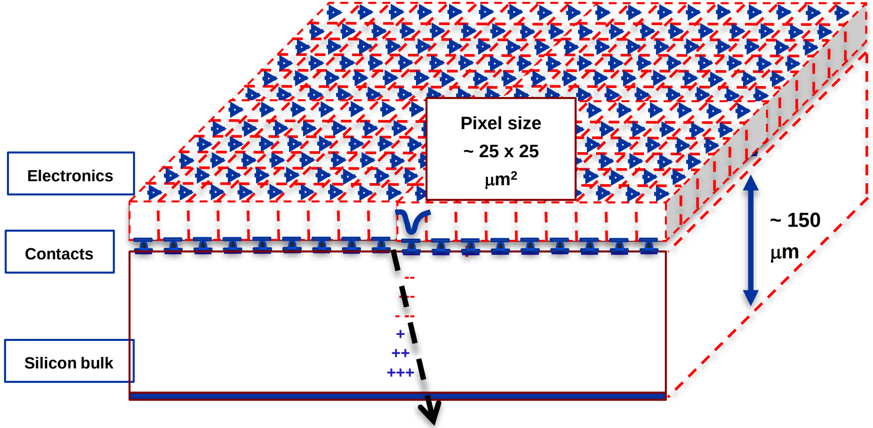
Resistive Read-out



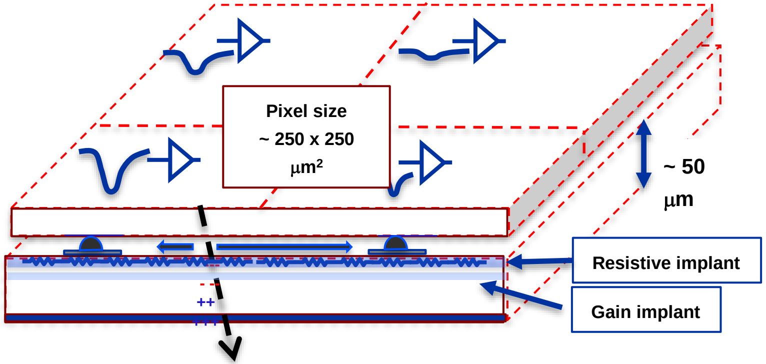
- In resistive read-out, instead of many p-n diodes, there is a **single diode**
- The n-doped implant is resistive and acts as a **signal divider**
- The LGAD gain layer provides **large signals**
- **Very uniform weighting field**: perfect geometry for timing

Standard pixels vs Resistive Readout

Standard Silicon Detector



Resistive Read-out Detector



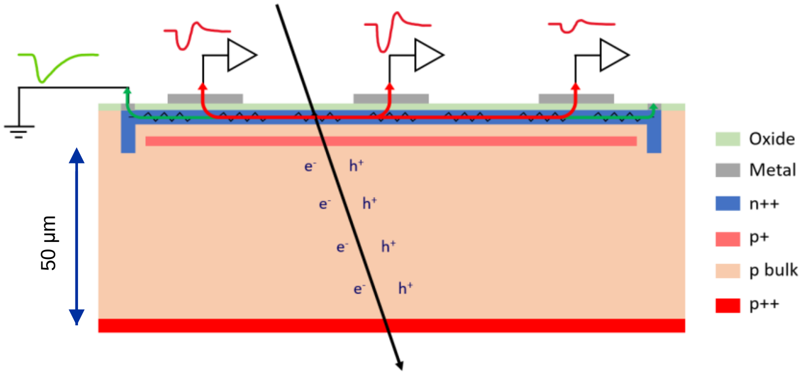
Pros

- Low channel density
- Thin sensors

⇨

- Low power consumption
- Low material budget

RSDs Principles of Operation



- **Electrons are multiplied (LGAD)**
- Charge is induced in the n+ layer (resistive layer)
- Nearby electrodes see a fast signal
- Charges in the n+ flow to ground ↳ **Signal sharing**

In normal pixel detectors $\sigma_x = k\frac{pitch}{\sqrt{12}}$ with $k \sim 0.5 - 1$

Resistive read-out sensors have

- $\boldsymbol{\sigma_x \ll \mathbf{pitch}}$ (distance from two neighboring electrodes)
- **Time resolution typical of thin LGADs**

RSDs – Some Results

The RSDs have been studied for 4 years now.

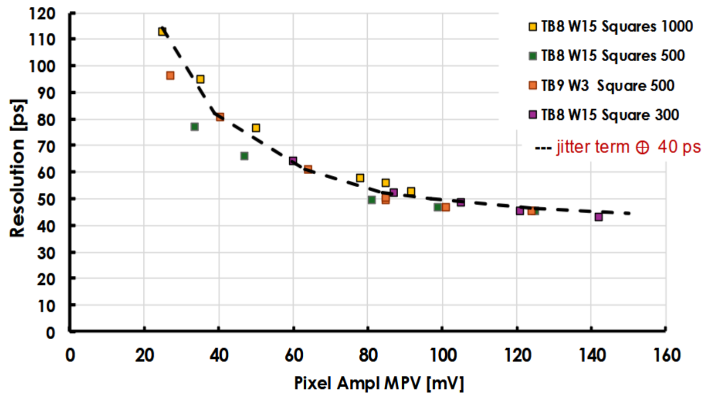
2 different types, AC- and DC- coupled

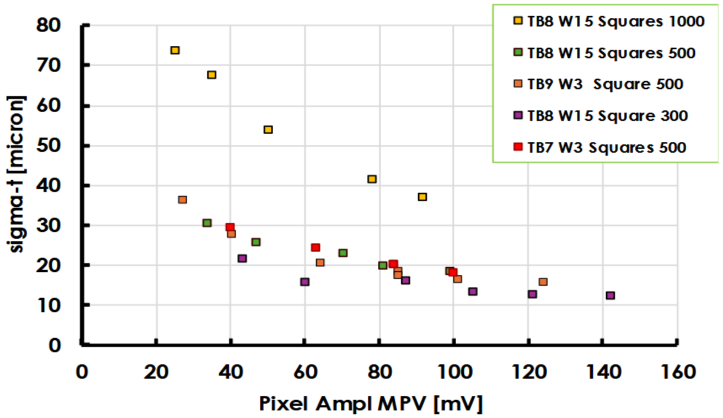
They have proven to provide:

- **Exceptional spatial resolution**
  - about **x10 better** than traditional pixelated sensors
  - **Fewer pixels** – less power consumption

- **Time resolution comparable to the one of LGADs** (very good)

A lot of different groups started fabricating these detectors, probably the idea is a good one!





Content

Time is the new coordinate

We need new detectors to **enable future high physics experiments**

Many technologies, **no winner(s) yet** — a lot to do in this field

10–30 ps and **tens of µm** are already on the table

RSDs and 4D Tracking at KIT: there is room for you in this story

Questions?

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