A story in four dimensions

The future of 4D detectors in High Energy Physics

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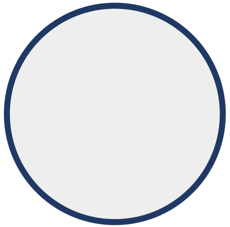
Physics Department Seminar
Sep 28, 2023, **Brookhaven National Laboratory**

Brookhaven National Laboratory

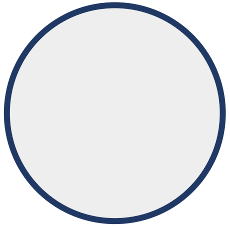
A particle

This is a **particle**



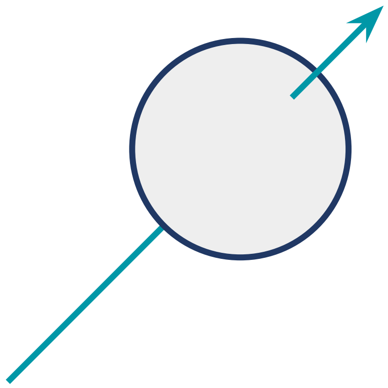
A particle

Our understanding of the universe is based on our **understanding of its proprieties** with **extreme degree of precision**



The hero's journey

We need a way to go from **this**…



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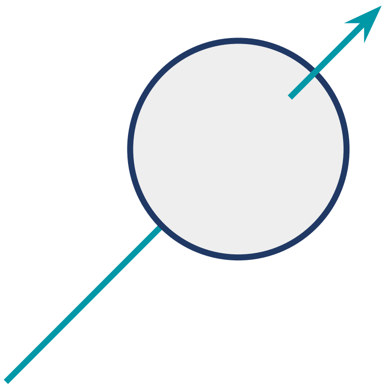
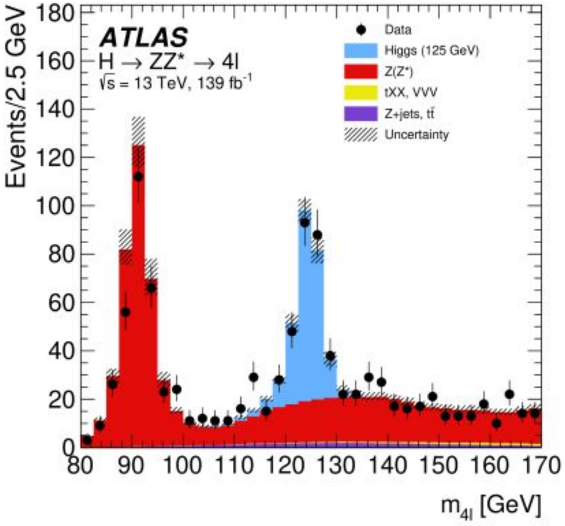


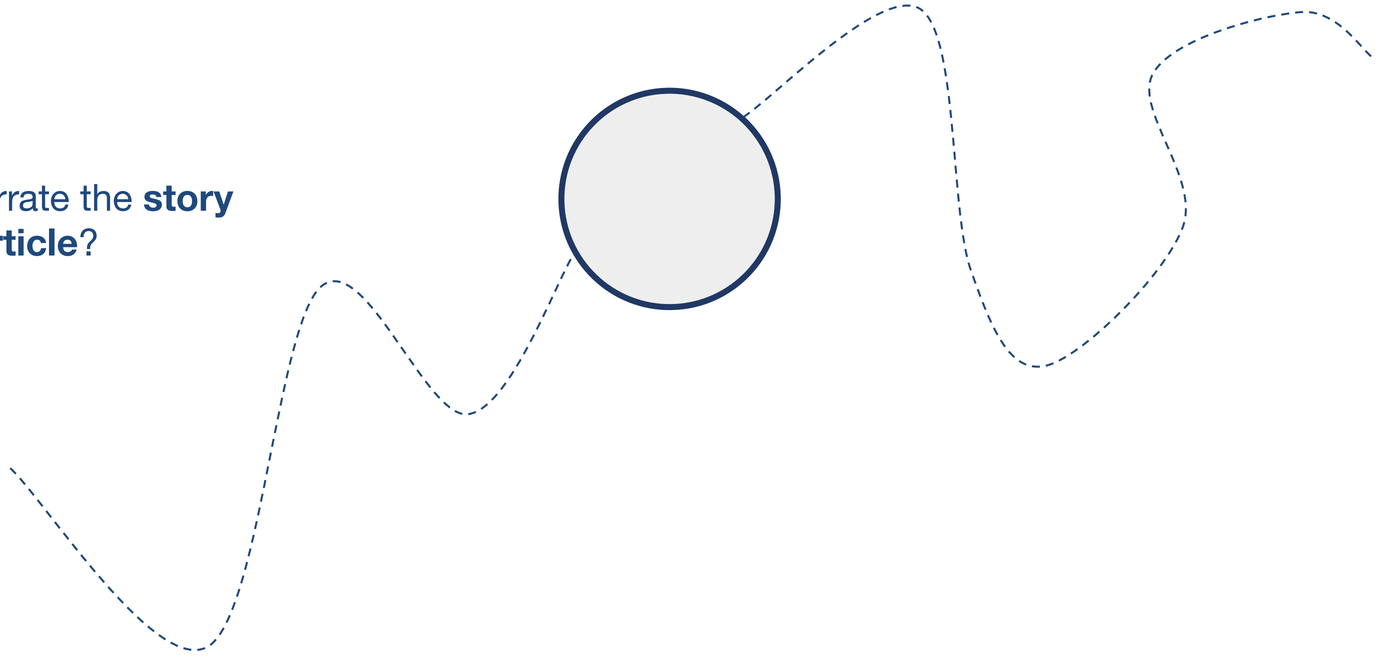
…to **this.**



ATLAS Collaboration, Measurement of the Higgs boson mass from the $H \to ZZ^* \to 4\ell$ channel with the ATLAS detector using 139 fb^{-1} of pp collision data

A particle

How to narrate the **story of this particle**?



Act I

A particle mess

We need more Time
A tree in the forest
A real 4D detector

Open questions in **Particle Physics**

Observation of **Higgs Boson** (2012) confirmed our expectations on fundamental interactions

Coronation of **>50 years of work** by international community…

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c. + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

...but now we need to answer everything else…

- Nature of **Dark Matter** and **Dark Energy**?
- Matter/Anti-matter unbalance
- Mass and nature of Neutrino particles
- Hierarchy Problem
- Gravity (and its quantization)
- and many more…

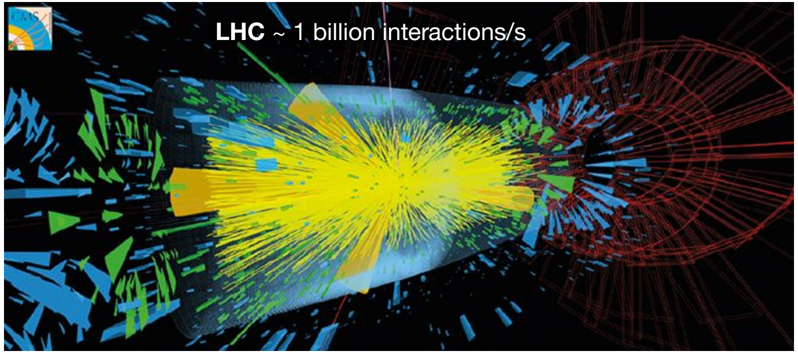
Open questions in Particle Physics

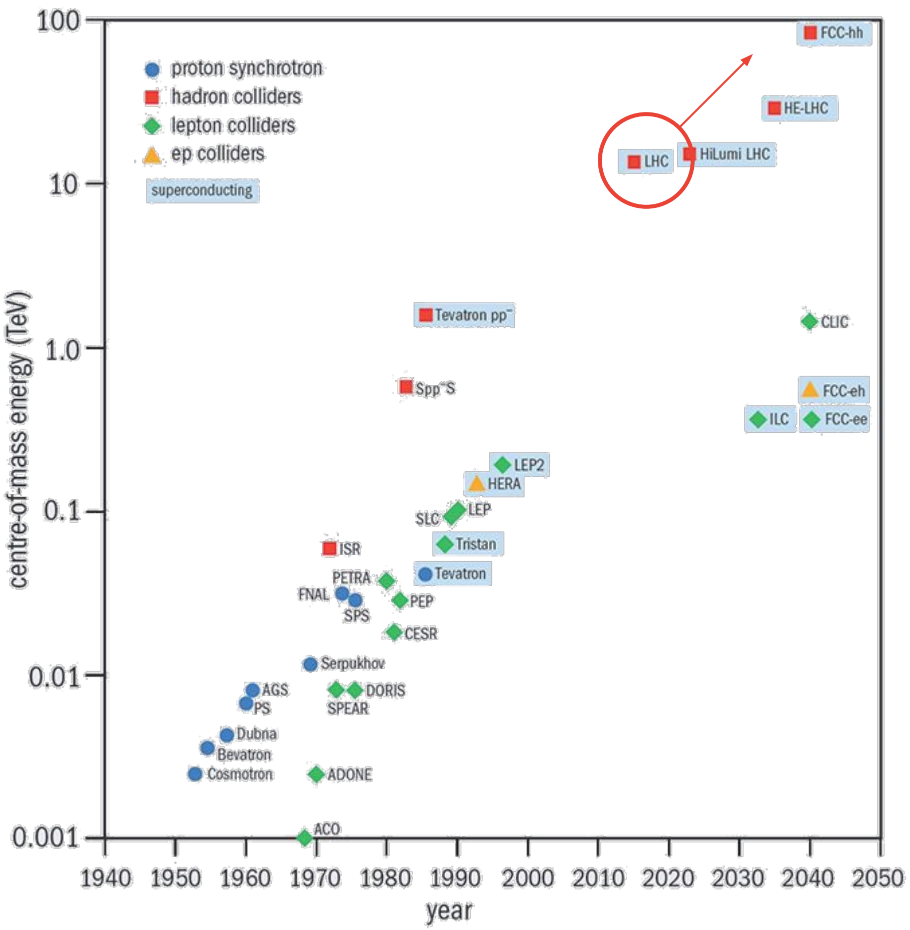
I. Observe them in nature

- Rare events require extreme mitigation of background effects
- Statistics is very low, huge detectors needed

II. Produce them in controlled environment

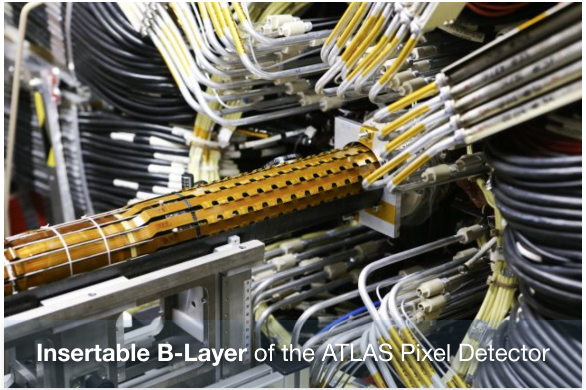
- Massive particles (t, W/Z, H, …) require extremely high energies (**particle accelerators**)
- Very **busy environments**, background can be orders of magnitude higher than event under study



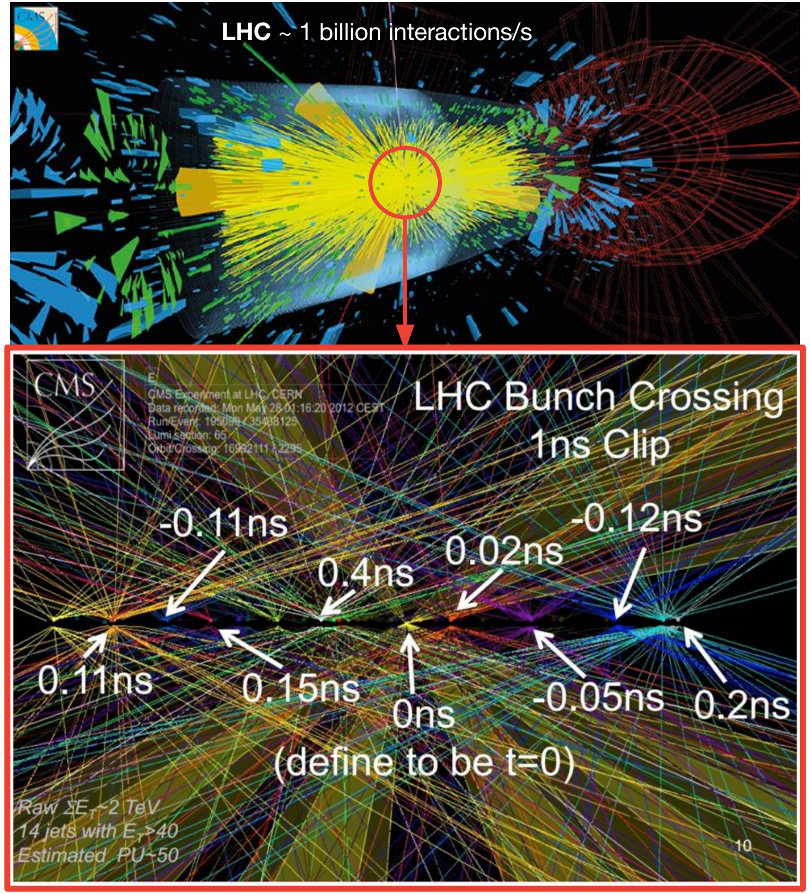


A particle mess

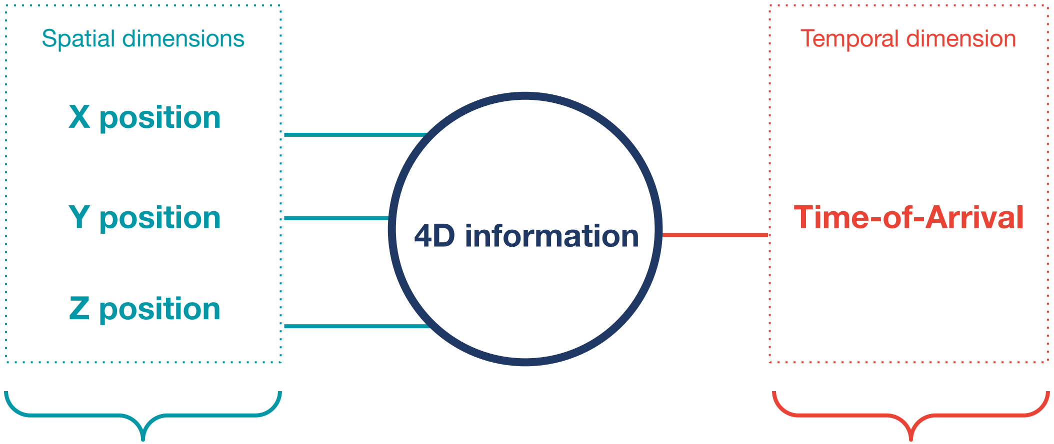
- **Billions of particles** interactions in very short spans of time (s)...
- …but **not at the same moment**
- Knowing **when (Time resolution)** and **where (Space resolution)** the interaction happened is **fundamental to disentangle underlying physics!**
- **Silicon detectors are ideal candidates to achieve both!**



Insertable B-Layer of the ATLAS Pixel Detector



Tackling the future



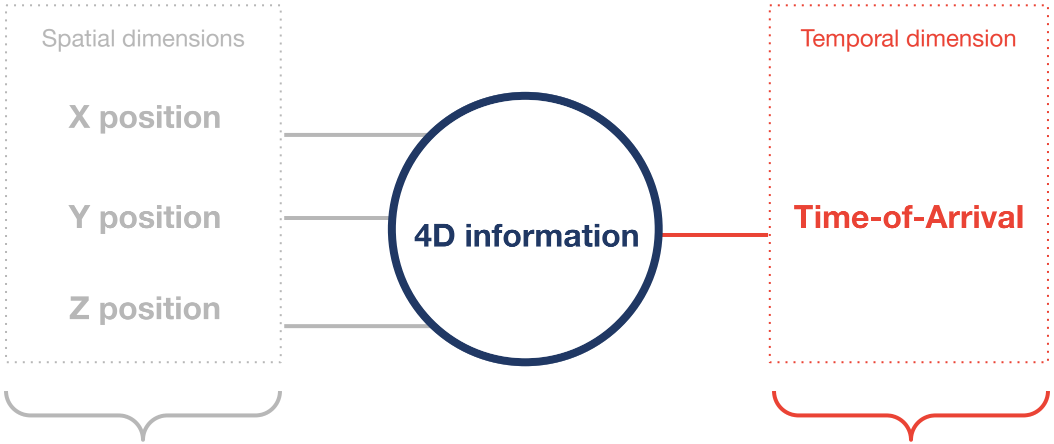
Space resolution σ_{xyz}

The ability to reconstruct with precision the position of a particle in the three dimensions of space [x, y, z]

Time resolution σ_t

The ability to reconstruct with precision the Time-of-Arrival of a particle

Tackling the future



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Act **II**

A particle mess

We need more time

A tree in the forest
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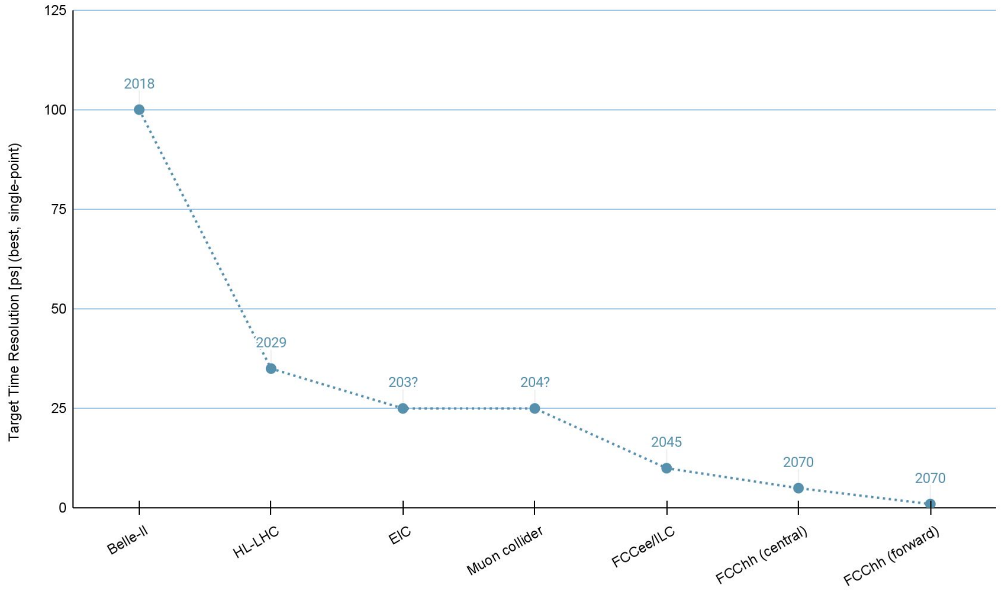
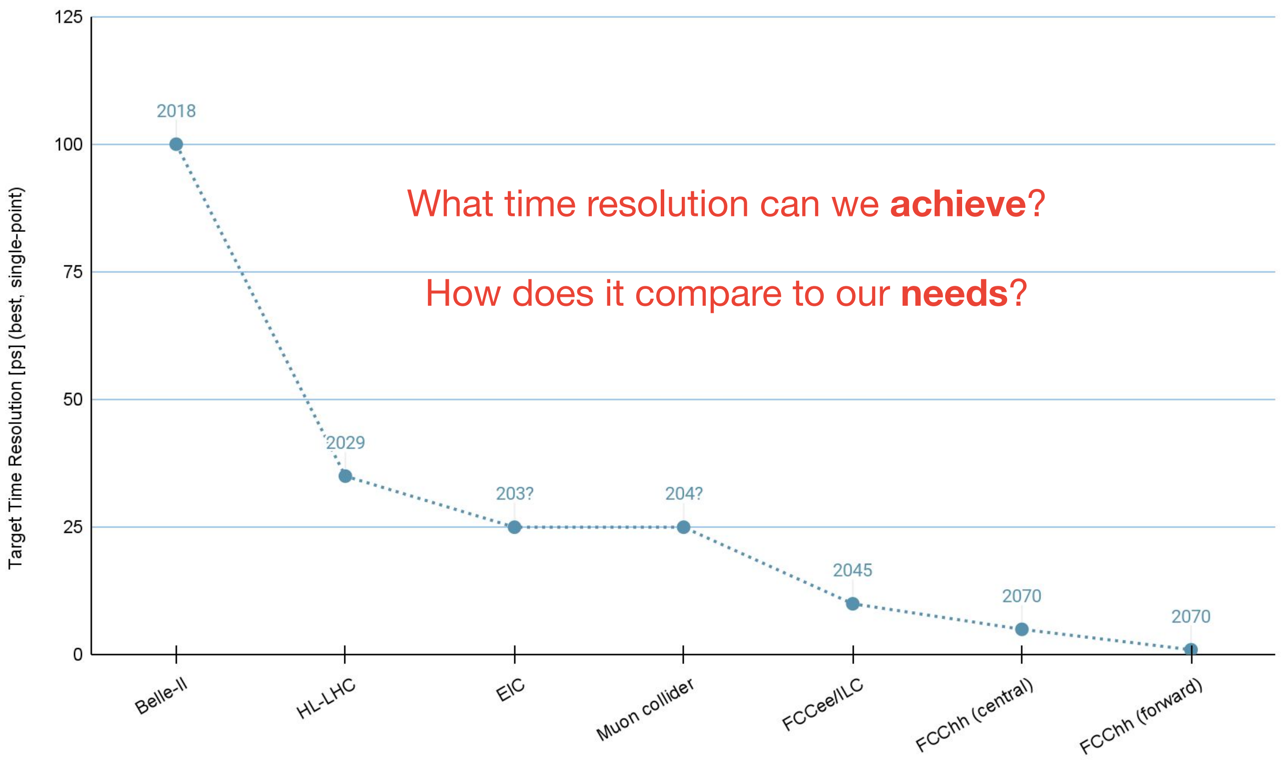
Time resolution for future experiments

Target time resolution

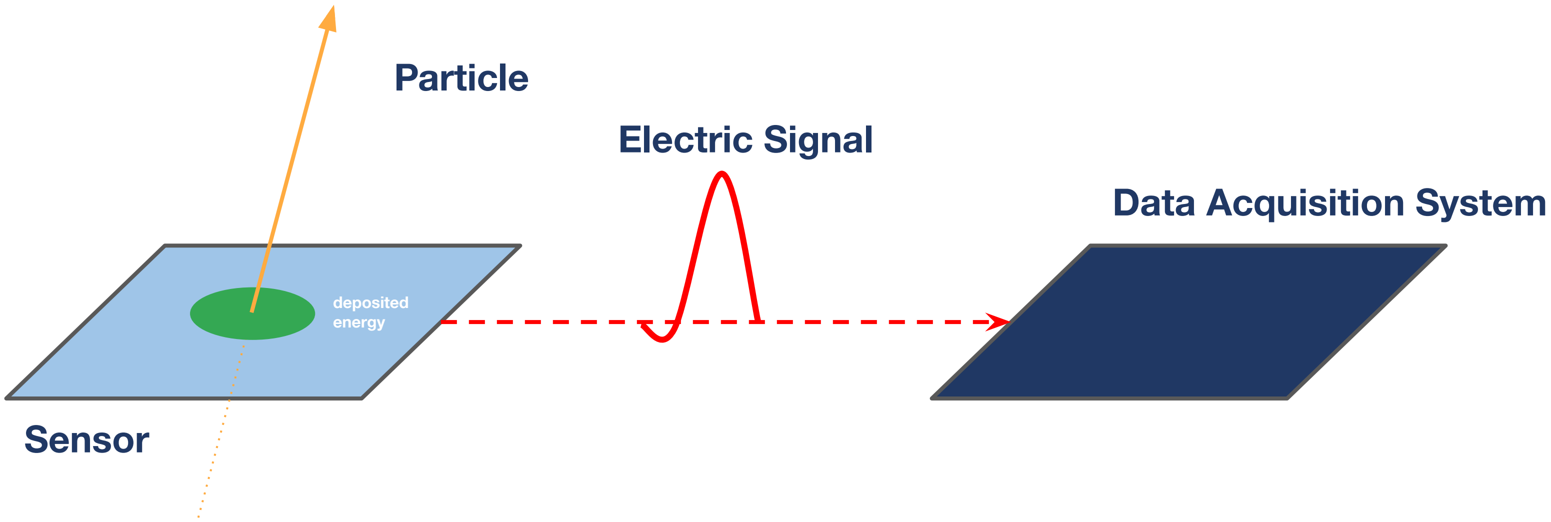
- < O(100 ps) **Belle-II** [B-mesons from $e^+ e^-$ collisions]
  (TOF Particle ID, on single photons)
- ~ 35 ps **HL-LHC** [SM measurements from pp collisions]
  (Timing layer + tracker for pile-up mitigation)
- 20 - 30 ps **Electron Ion Collider** [QCD]
  (ToF for pi/K/p separation)
- 20 - 30 ps **Future Muon Colliders** [Precise Higgs physics]
  (tracker, for Beam Induced Background reduction)
- ~ 10 - 15 ps **Future Lepton Colliders** [Precise SM measurements]
  (Higgs Factories, TOF for Particle ID)
- 1 - 5 ps **Future Hadron Colliders** [Very high energy physics]
  (Pileup-mitigation)



Time resolution for future experiments



How to **improve time resolution**



Sensor

Underlying physics in signal formation

Electronics

Electrical noise

Data Acquisition

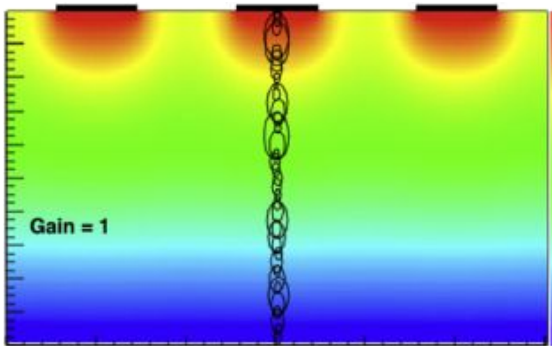
Readout electronics (discretization, noise, etc.)

How to **improve time resolution**

$$\sigma^2_t = \sigma^2_{Landau} + \sigma^2_{Time\text{-}walk} + \sigma^2_{jitter} + \sigma^2_{electronics}$$

Landau Noise

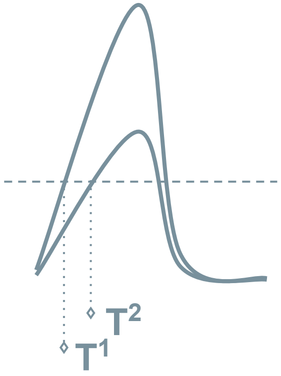
Signal distortion caused by distribution of deposited energy in silicon



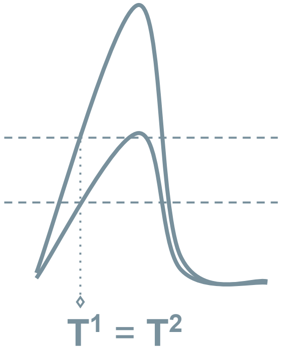
Time-walk

Difference in perceived Time of Arrival

Can be mitigated using **Constant Fraction Threshold**



Fixed Threshold



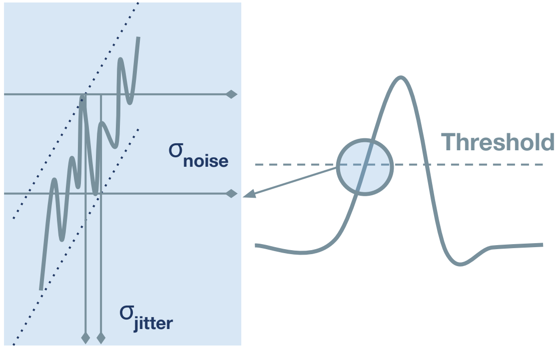
Constant Fraction Discrimination

Jitter

Noise leads to uncertainty in time of arrival

Jitter can be mitigated by ‘**boosting**’ the signal

$$\sigma_{jitter} = \frac{noise}{\left|\frac{dV}{dt}\right|} = \frac{noise}{\left|\frac{S}{t_{rise}}\right|}$$



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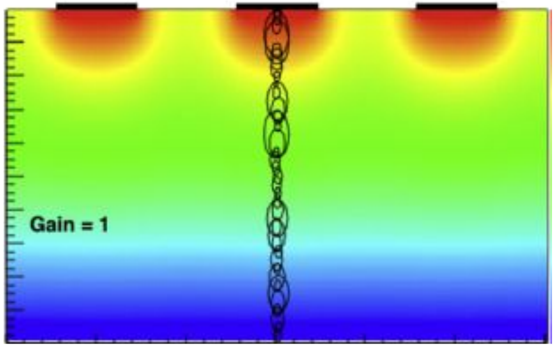

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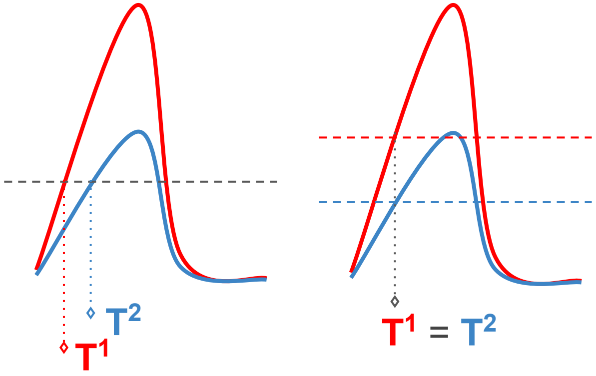

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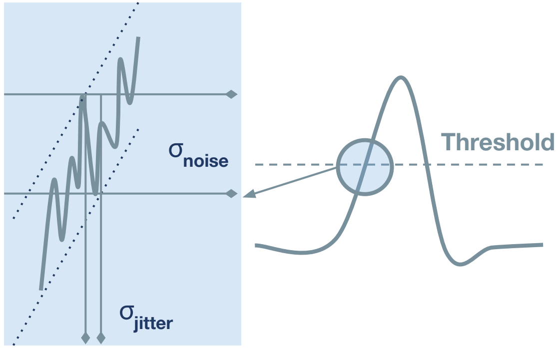

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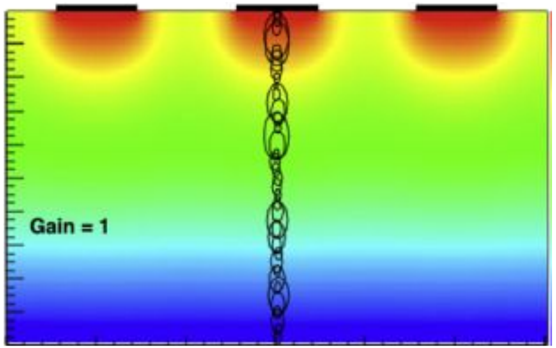

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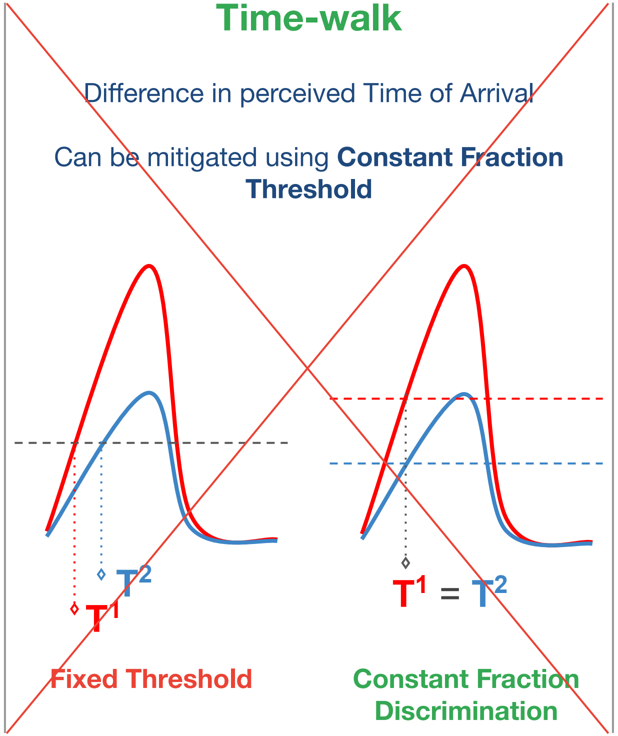

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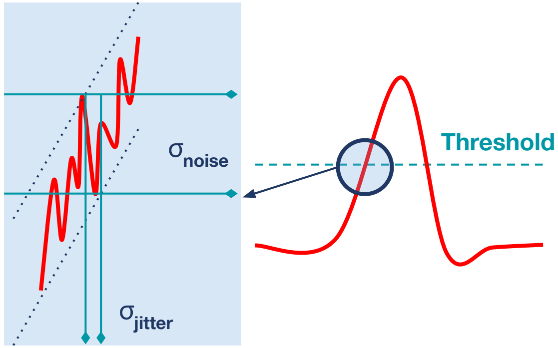
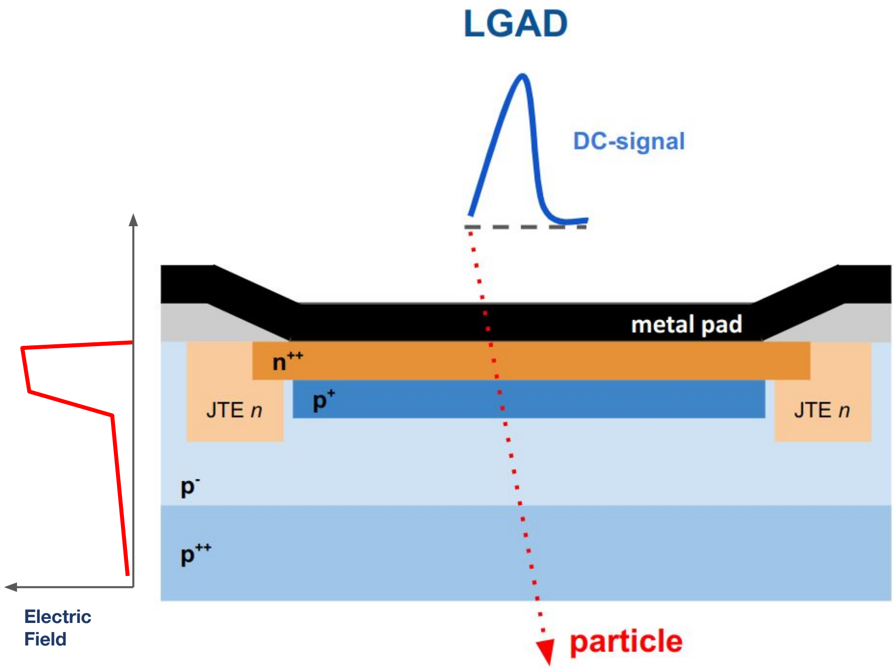


The **Low Gain Avalanche Diode**



Low Gain Avalanche Diode (LGAD)

- Achieve **Signal "boost"** by carefully fine-tuning doping
- **Gain Layer:** p^+ under n^{++} creates high (300 kV/cm) and uniform electric field (**Avalanche Effect**)
- High S/N ratio thanks to gain O(10 - 100)

How to **improve time resolution**

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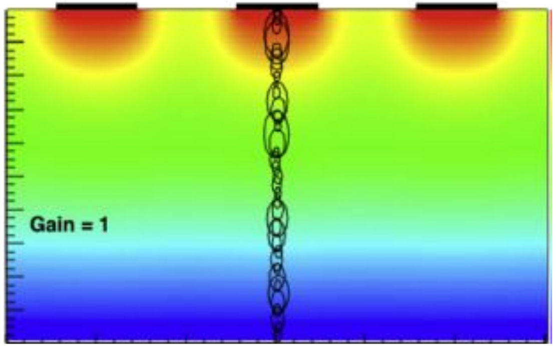
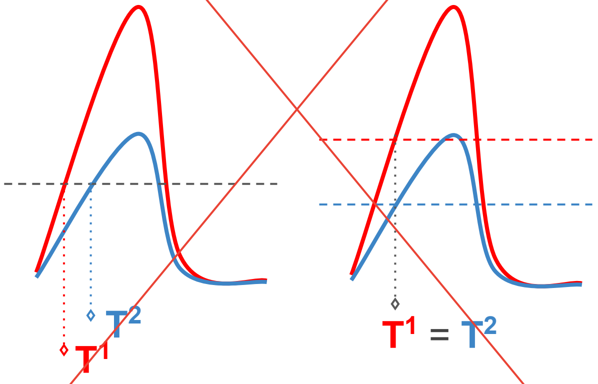


Time-walk

Caused by Landau Distribution

Can be mitigated using **Constant Fraction Threshold**



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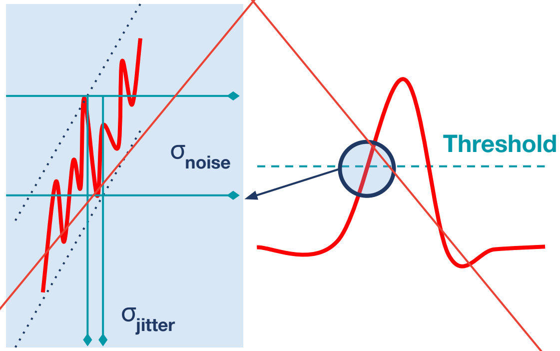
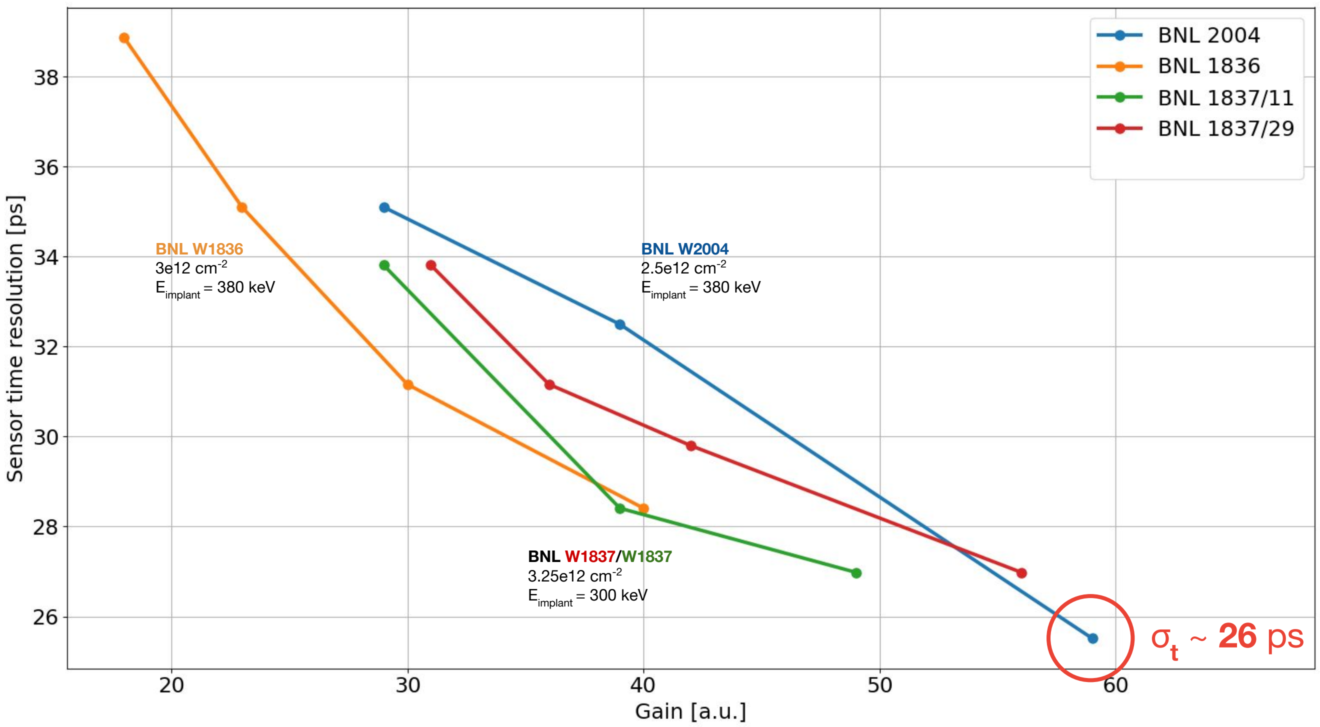
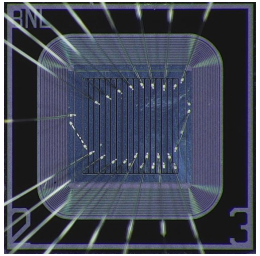


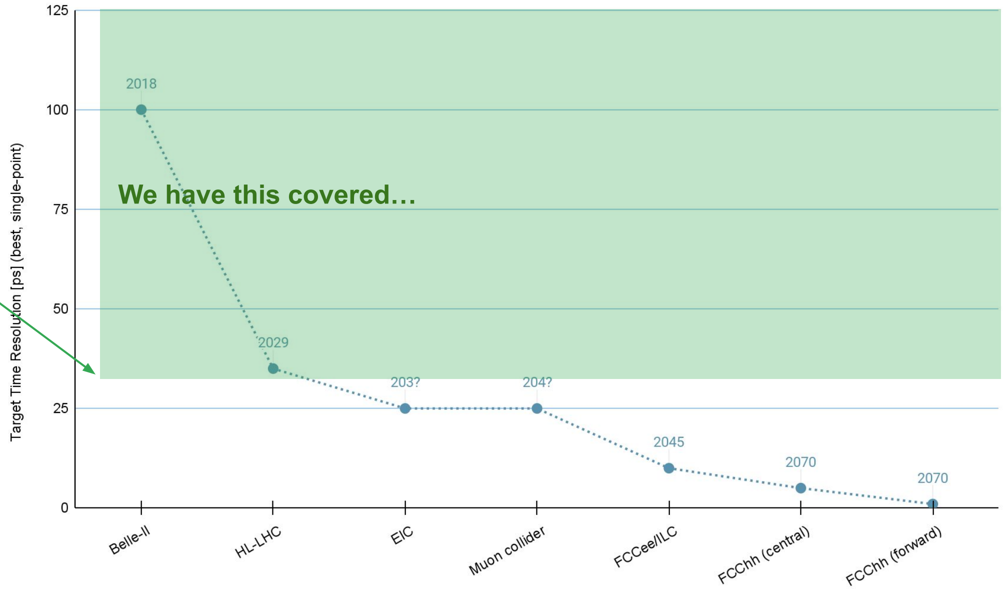
Measuring Time resolution



Time resolution for future experiments



Time resolution levels off at 25 - 30 ps are due to **Landau fluctuations** in particle/sensor interaction (**intrinsic**)...



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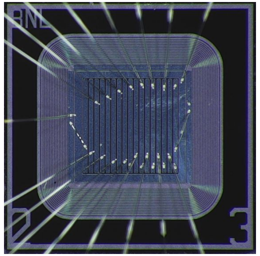

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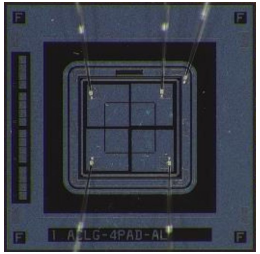
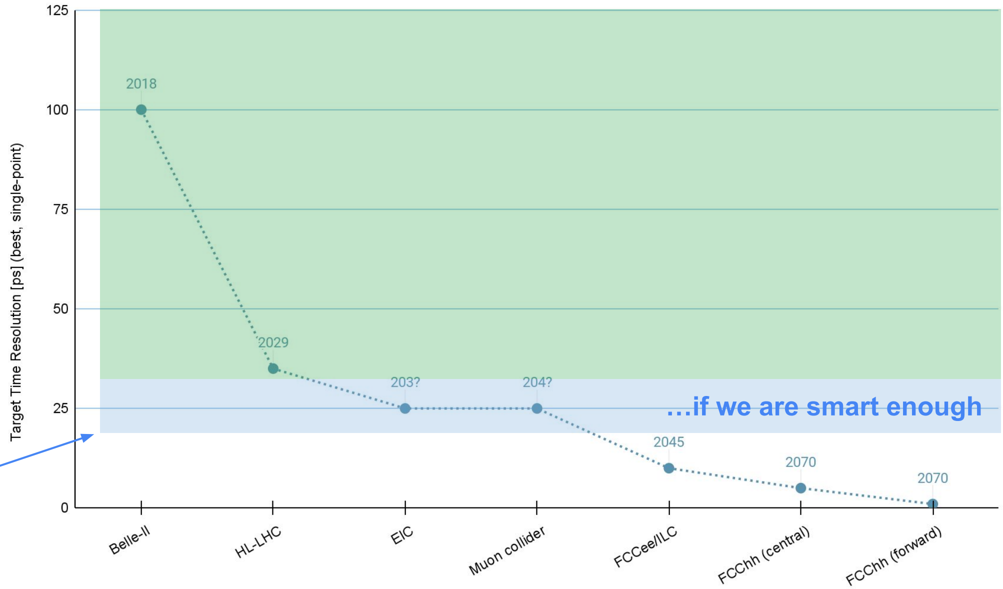
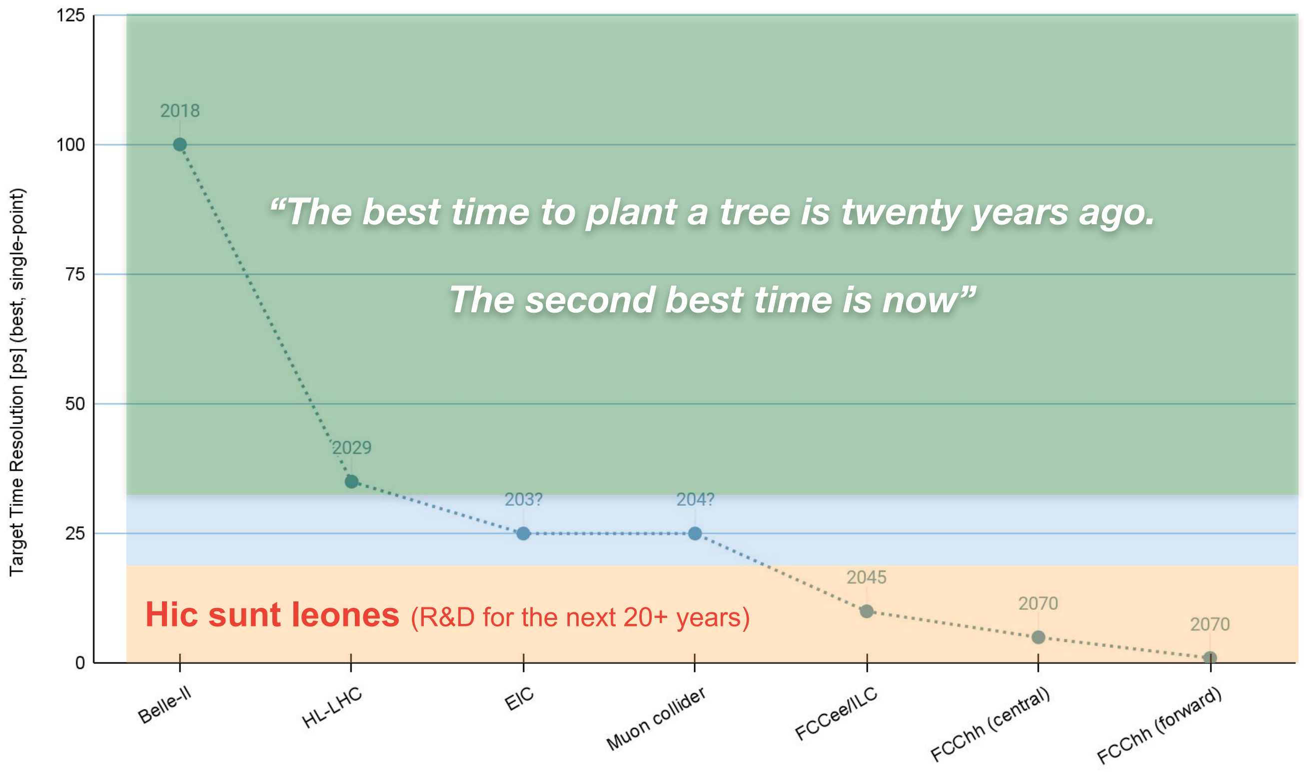


…but with better reconstruction, and **thinner sensors** we can bring it down**!**



Thanks to Prof. K. Nakamura (KEK, JP) and Hamamatsu Photonics

Time resolution for future experiments



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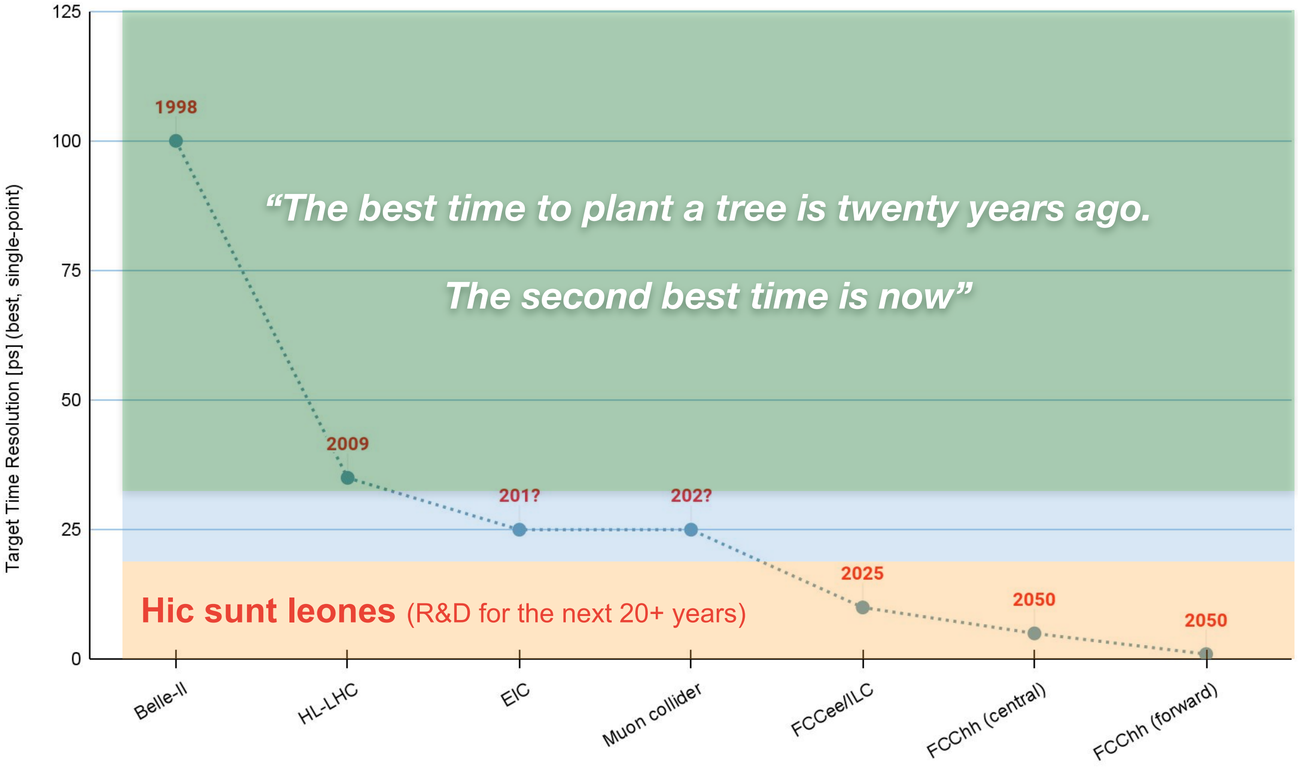


Beyond timing

Spatial dimensions

X position

Y position

Z position

4D information

Temporal dimension

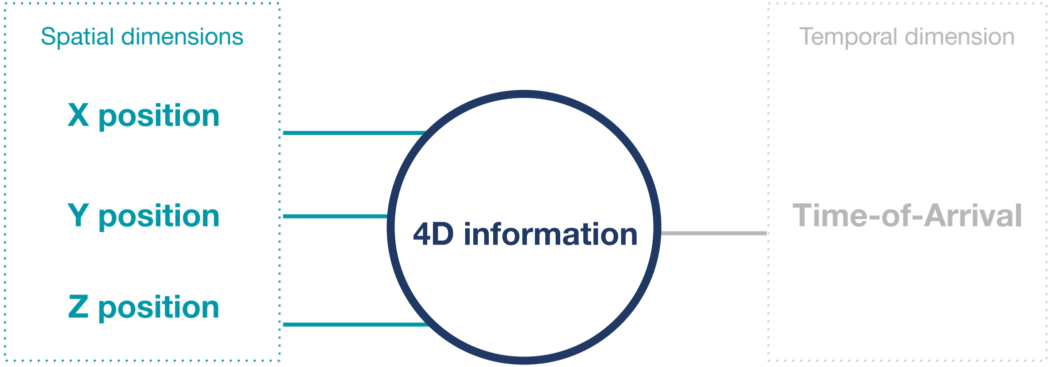
Time-of-Arrival

Space resolution σ_{xyz}

The ability to reconstruct with precision the position of a particle in the three dimensions of space [x, y, z]

Time resolution < 30 ps
currently achievable with LGAD technology

Beyond timing



Space resolution σ_{xyz}

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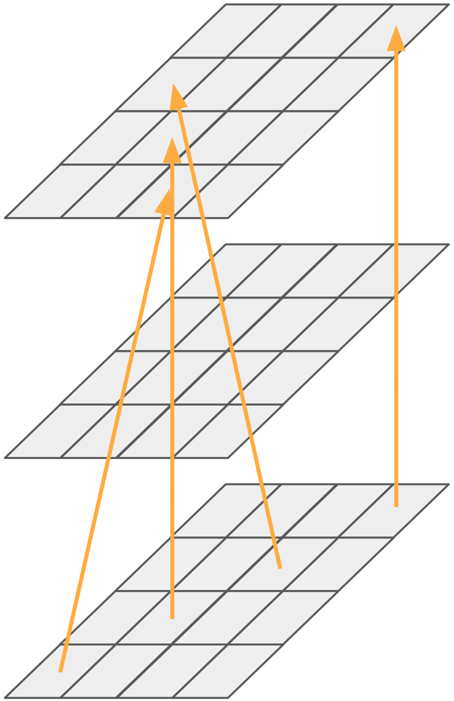
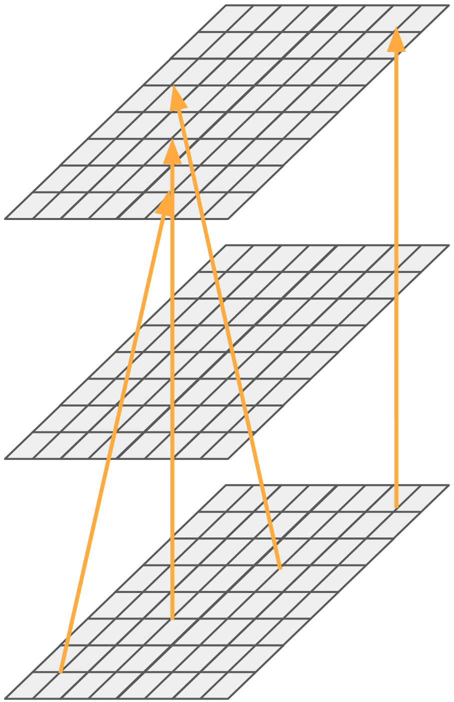
Time resolution σ_t

Time resolution < 30 ps currently achievable with LGAD technology

How to **improve space resolution**



Higher **granularity** =
better space resolution?



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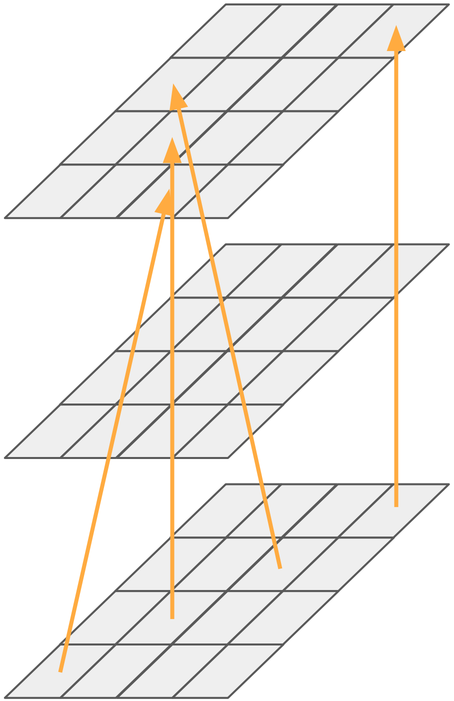

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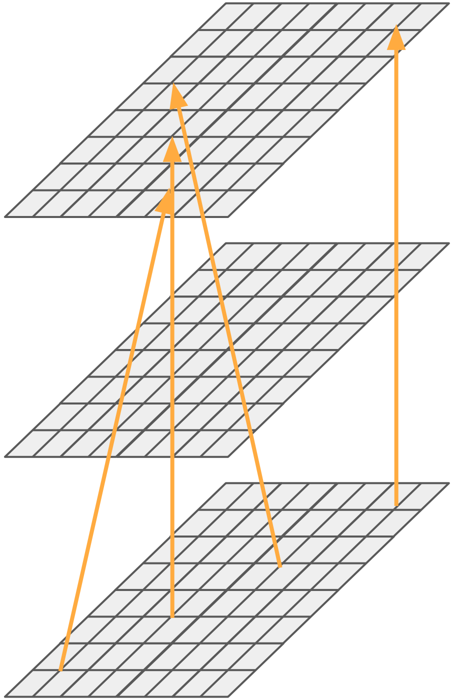


Yes…but:

- **Technologically** very challenging
- Increases **readout bandwidth**
- Increases **power consumption**
- **What's the alternative?**

Act **III**

A particle mess
We need more time

A tree in the forest

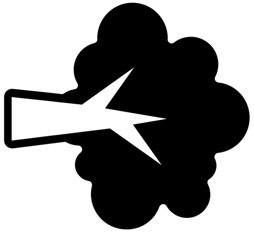
A real 4D detector

A tree in the forest

There is a **tree** in the forest

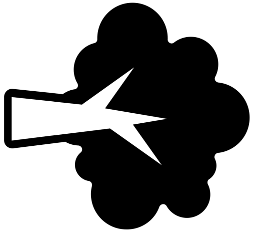
A tree in the forest

It **falls**



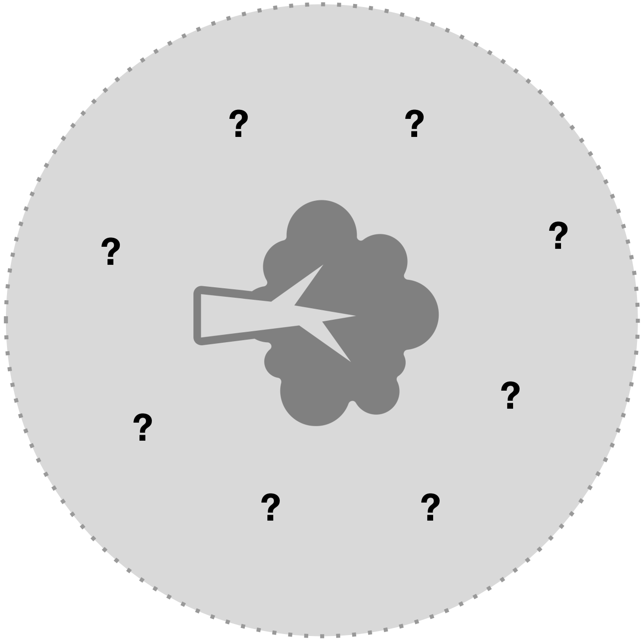
A tree in the forest

It **falls** :(



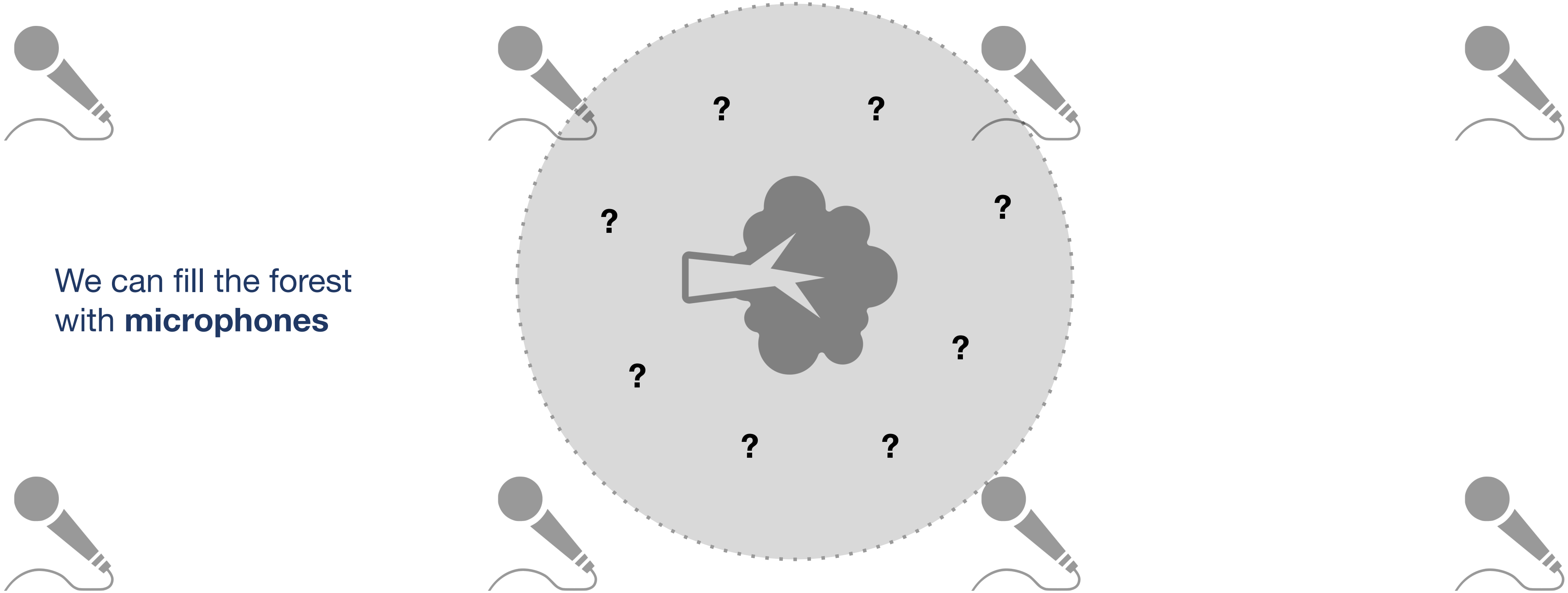
A tree in the forest

Where did it fall?

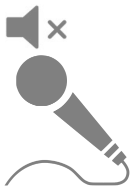


A tree in the forest

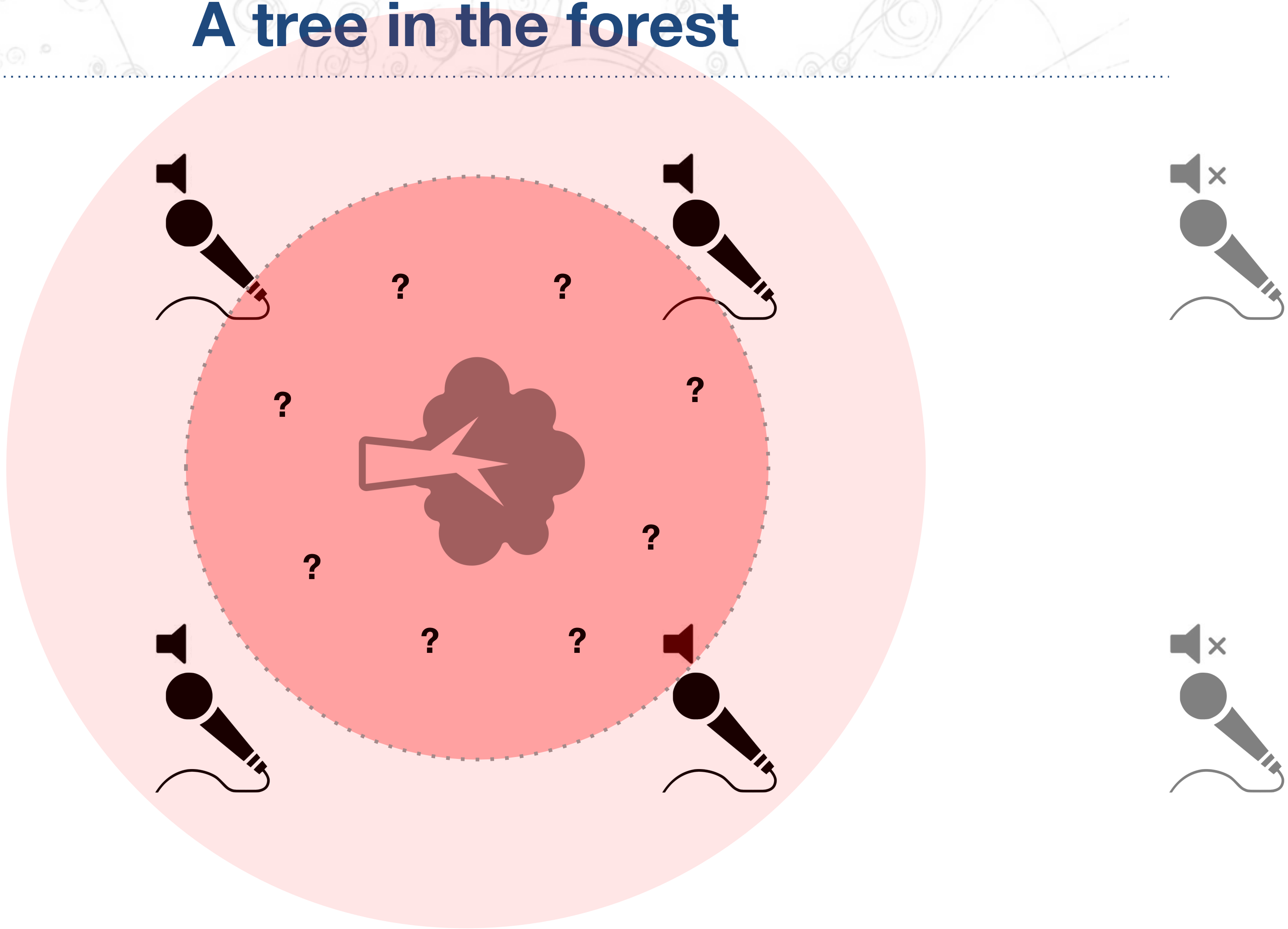
We can fill the forest with **microphones**



A tree in the forest



All the microphones close to the tree will raise a flag *"I have heard it"* (**binary information**)



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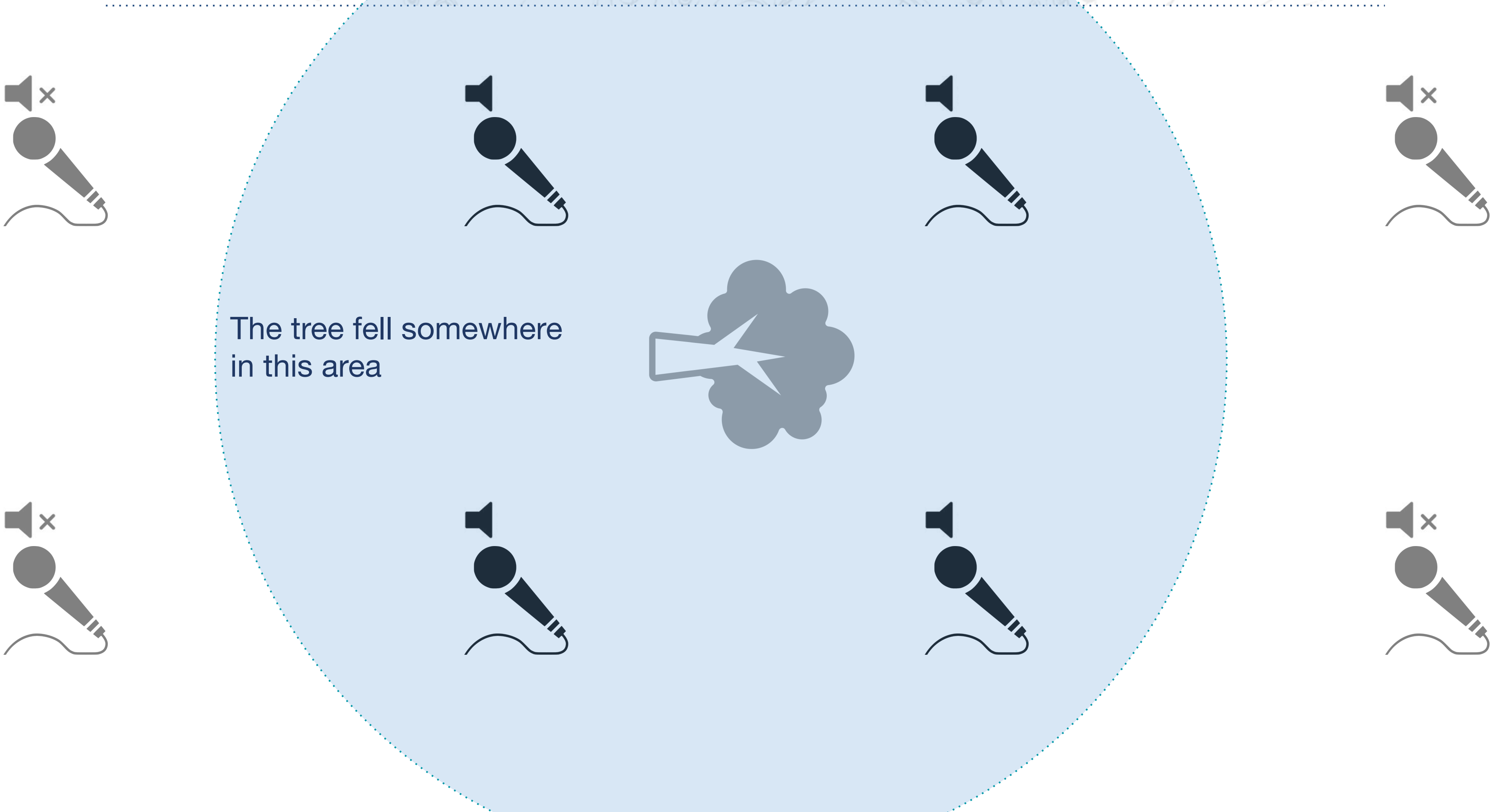

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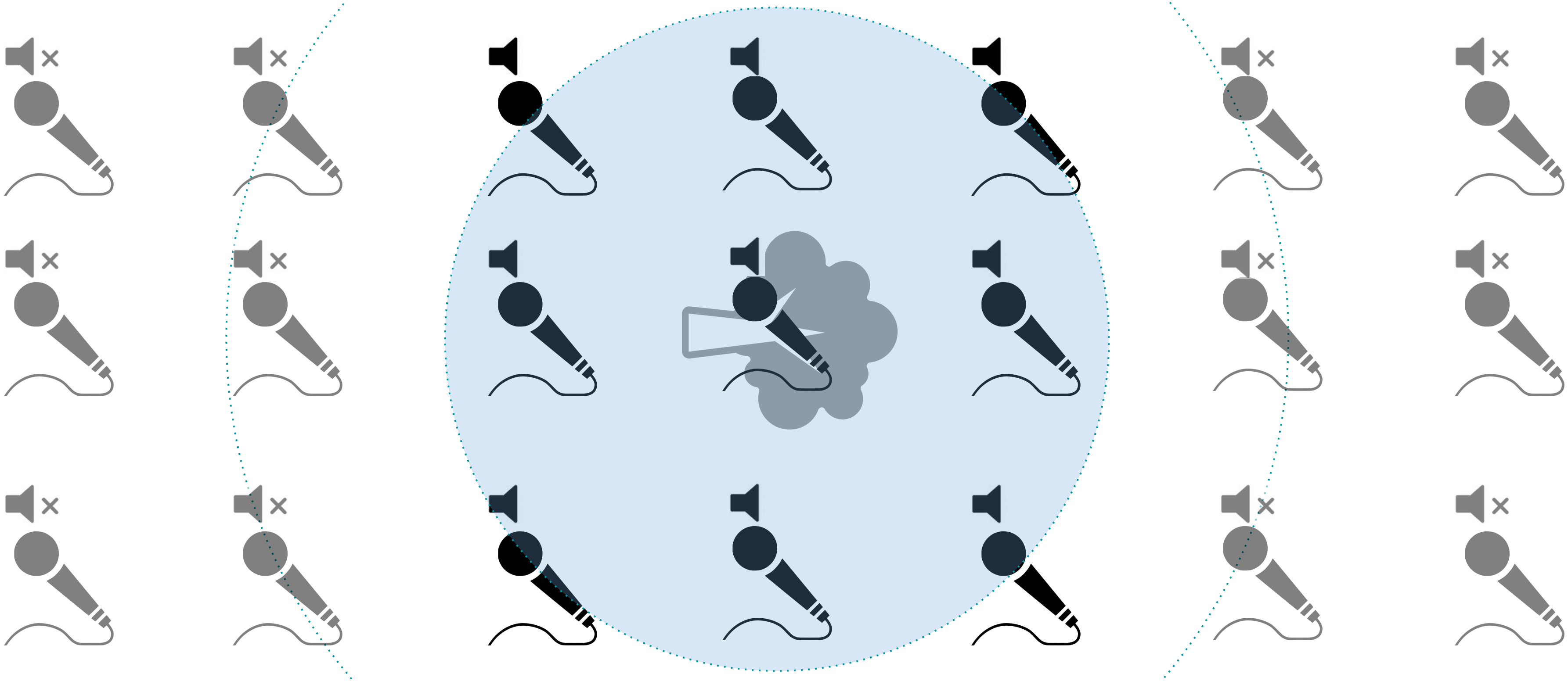
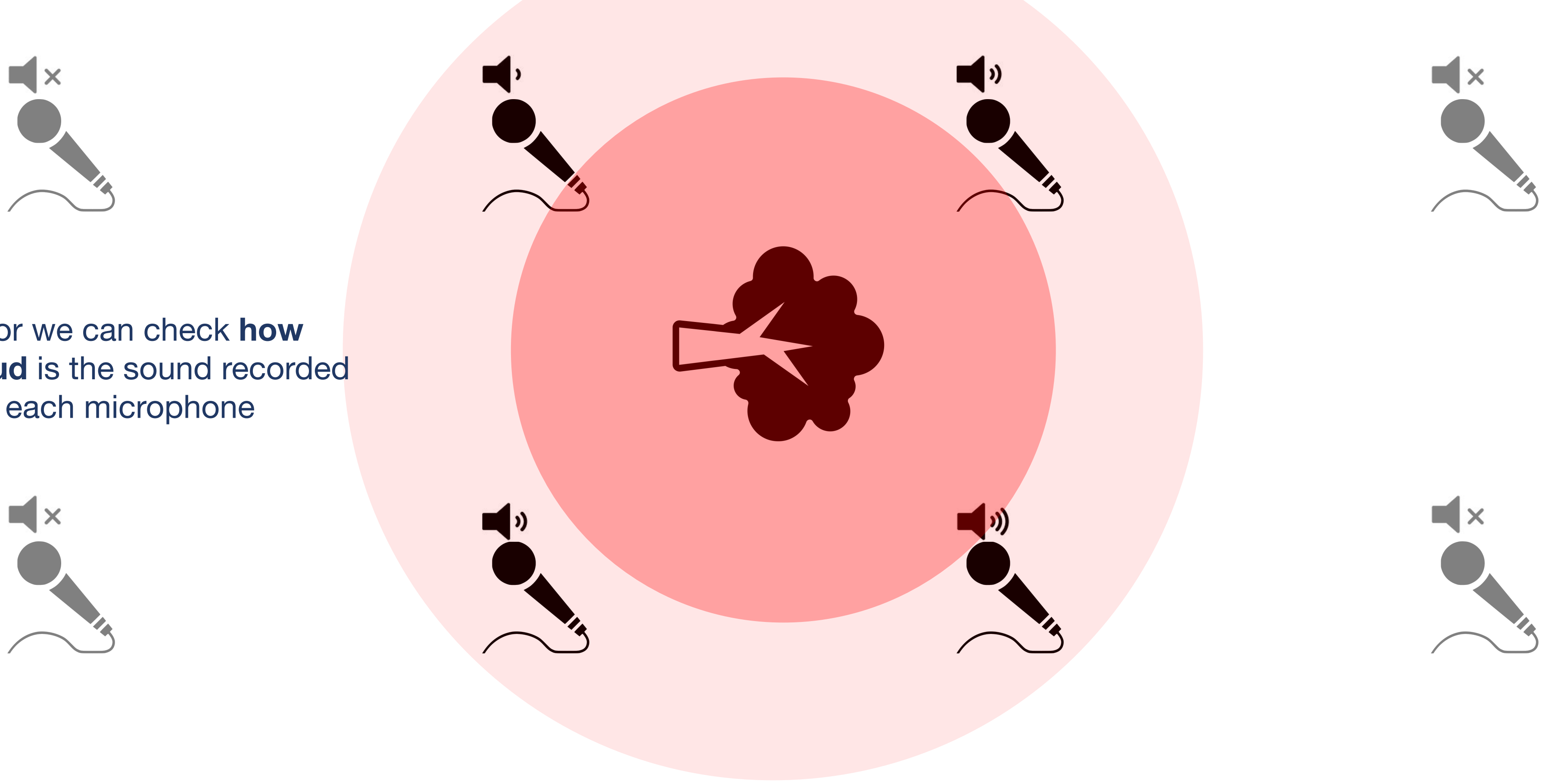


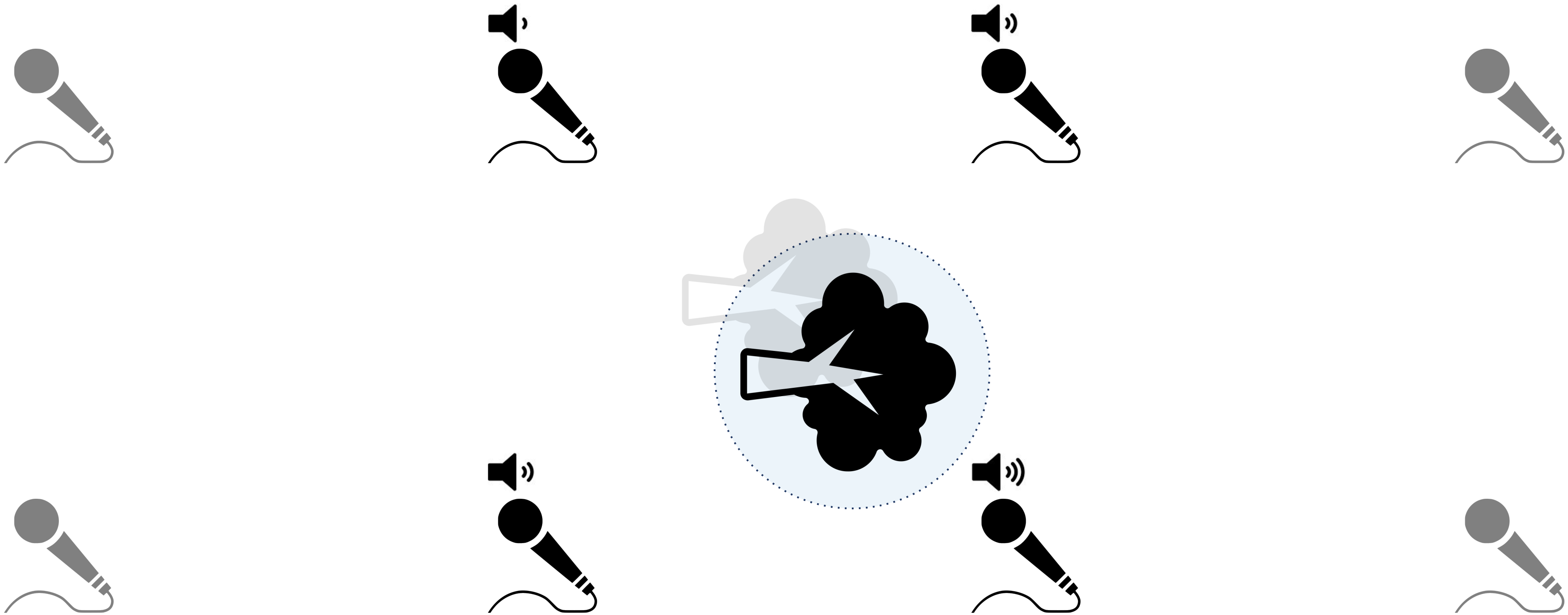
We can **increase spatial resolution** by adding **more detectors**

A tree in the forest

…or we can check **how loud** is the sound recorded by each microphone

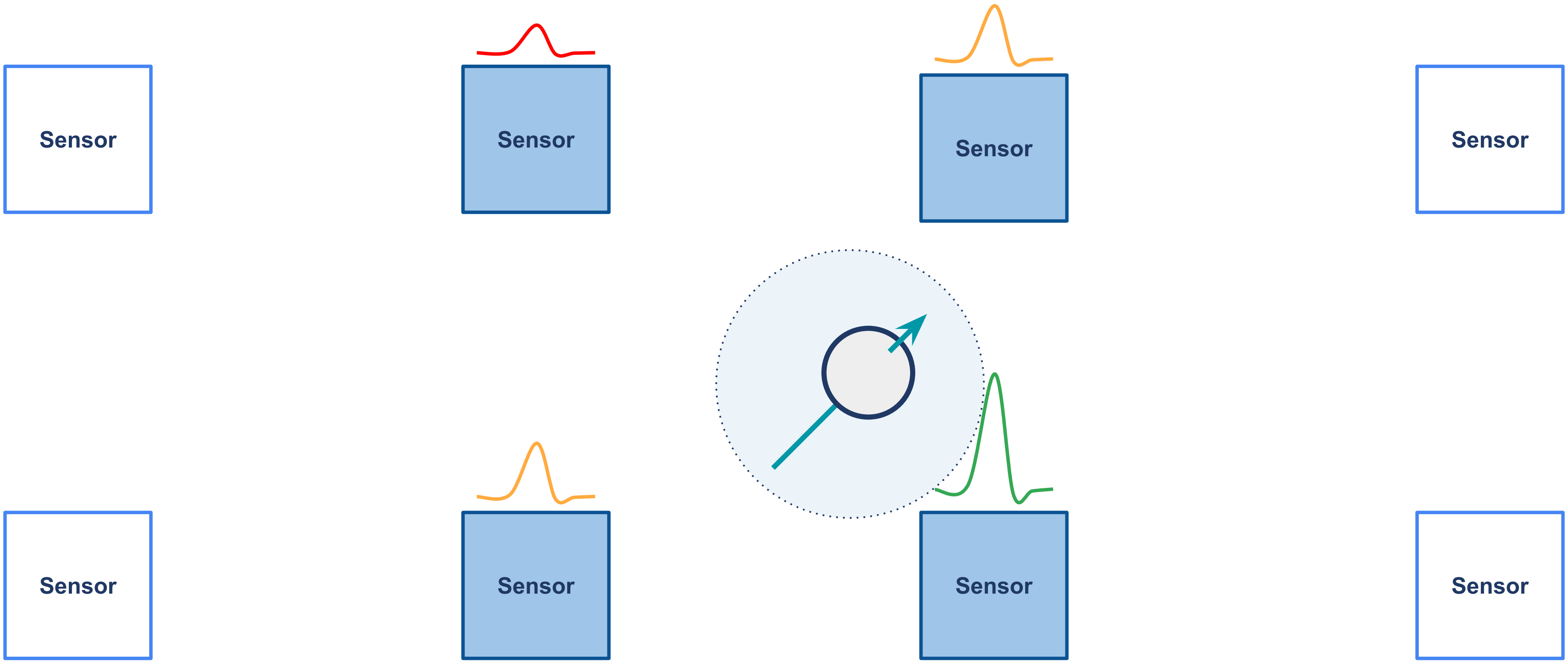


A tree in the forest



If each detector gives a **proportional response**, we can better interpolate the result (**Center of Gravity** method)

A tree in the forest

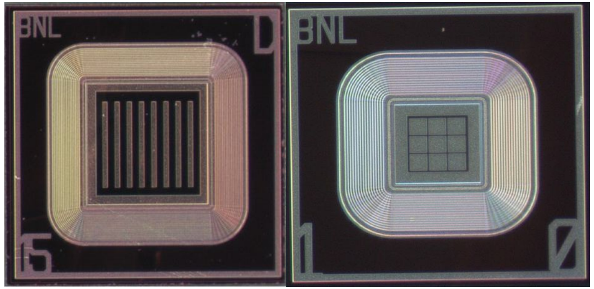


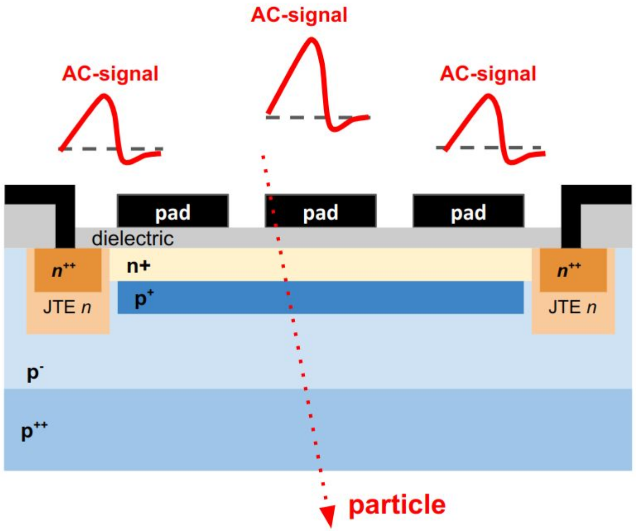
Can we do the same **for particles**?

The **AC-LGAD** paradigm

AC-LGAD

- **AC-**coupled **L**ow **G**ain **A**valanche **D**etector
- **Silicon** detector proposed in 2015

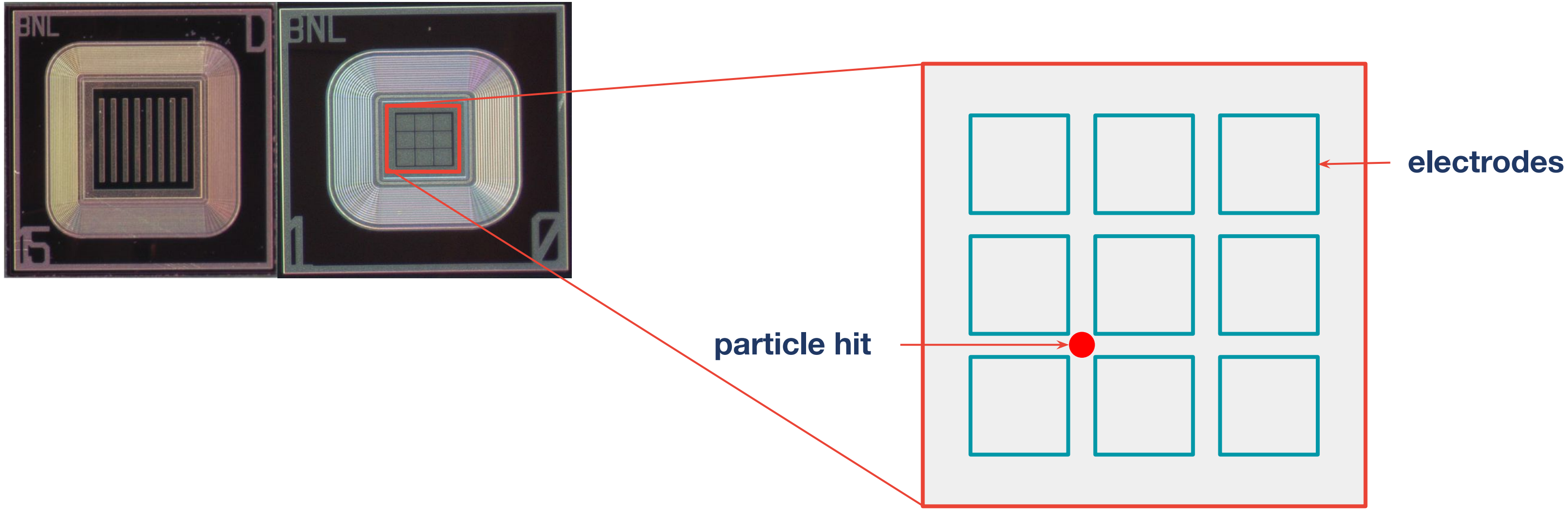




The **AC-LGAD** paradigm

AC-LGAD

- **Excellent time resolution** (LGAD-like) thanks to **internal gain**
- **Excellent space resolution** thanks to Signal Sharing



Shared signal seen by pads

The **AC-LGAD** paradigm

AC-LGAD

- **Excellent time resolution** (LGAD-like) thanks to **internal gain**
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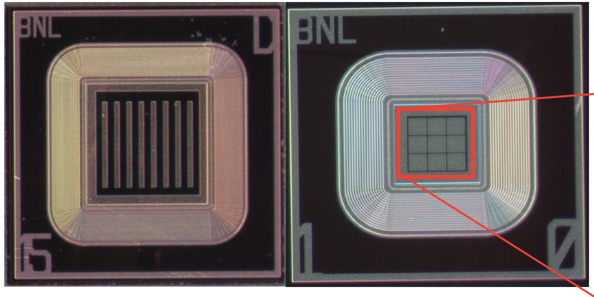
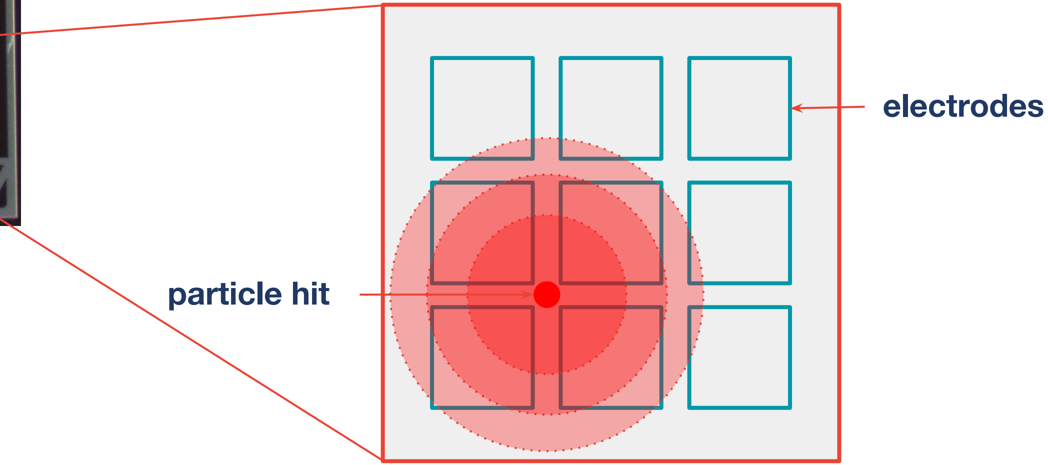


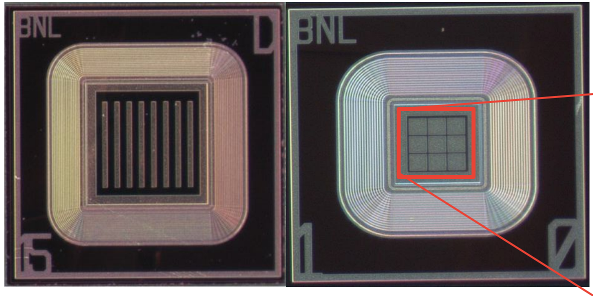


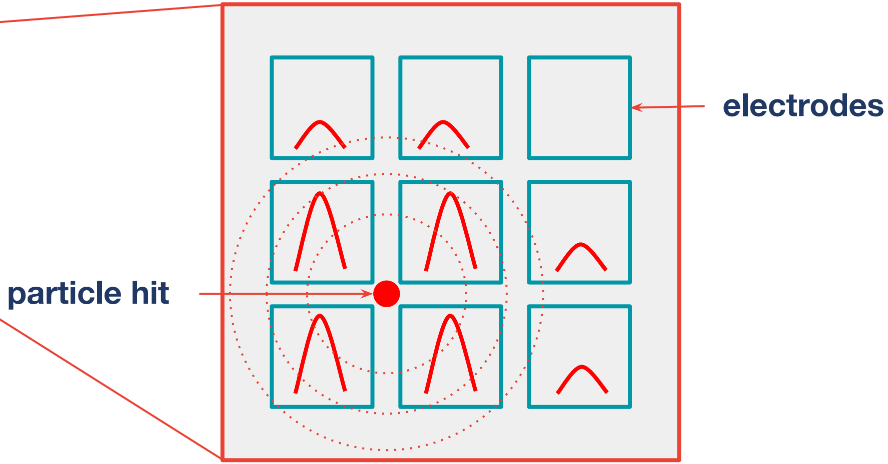
Shared signal seen by pads

The **AC-LGAD** paradigm

AC-LGAD

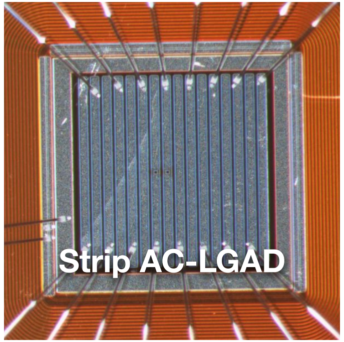
- Signal **shared among multiple pads** (pixels/strips)
- Pad response **proportional to distance** to interaction
- Allows for **high spatial resolution** with low granularity

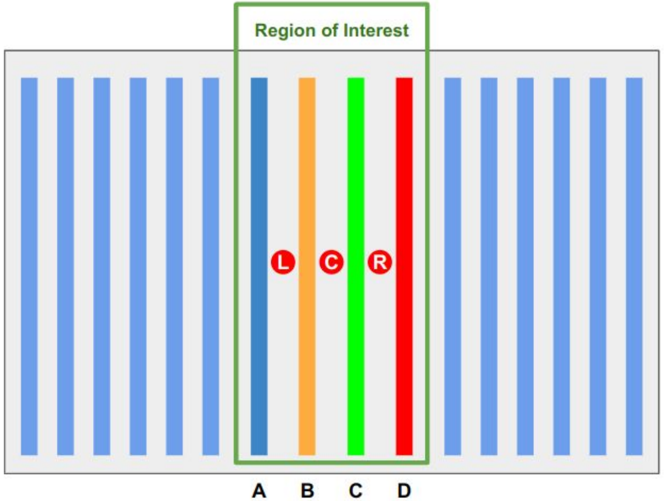




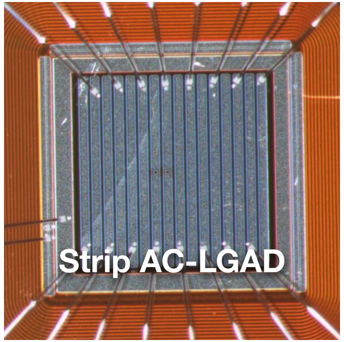
Shared signal seen by pads

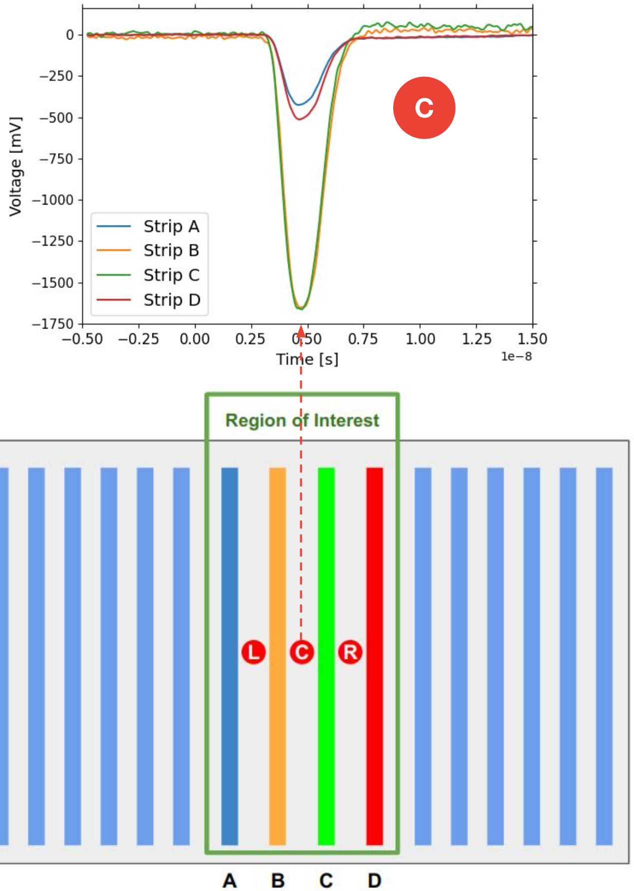
Signal sharing



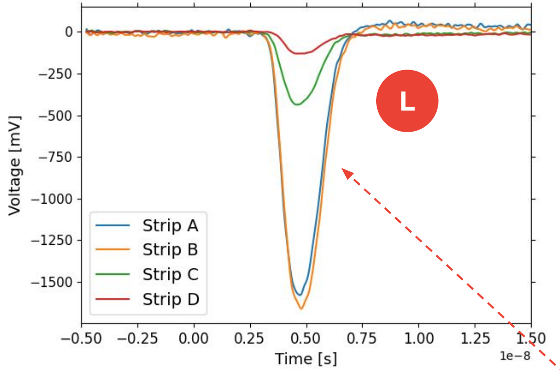


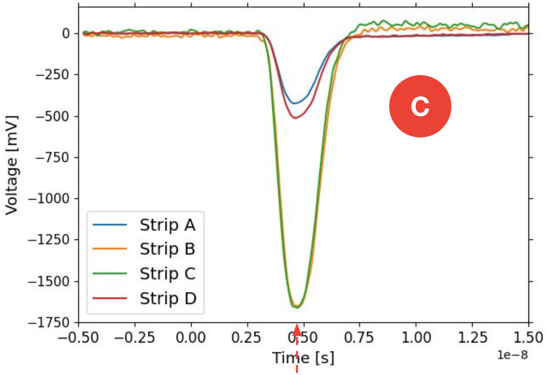
Signal sharing

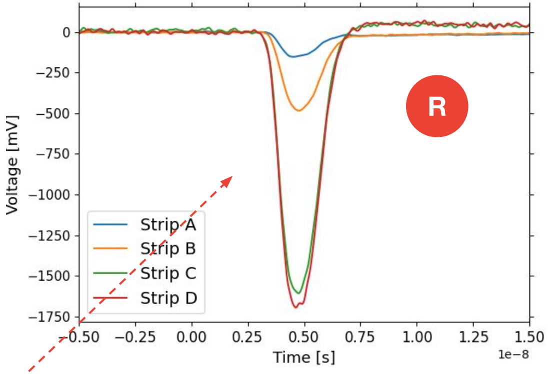


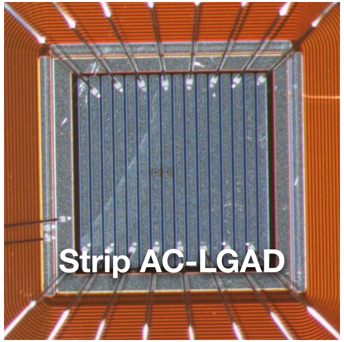


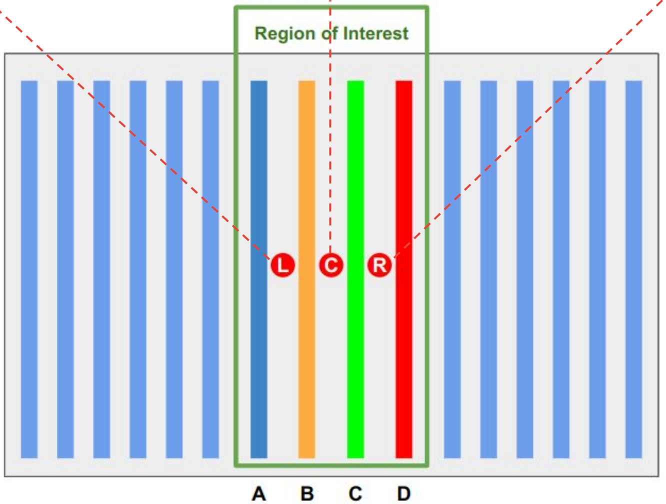
Signal sharing





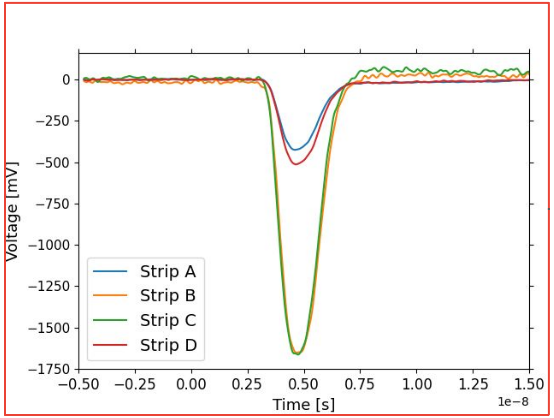






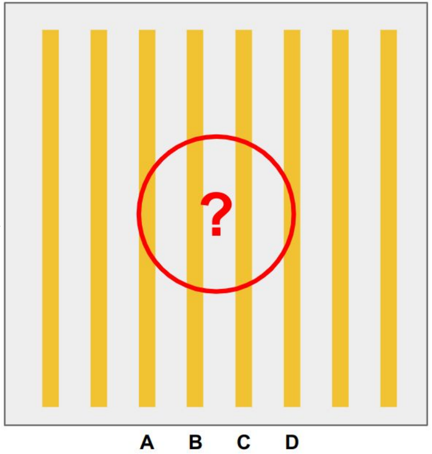
AC-LGAD - **Calibration**

Shared Signal

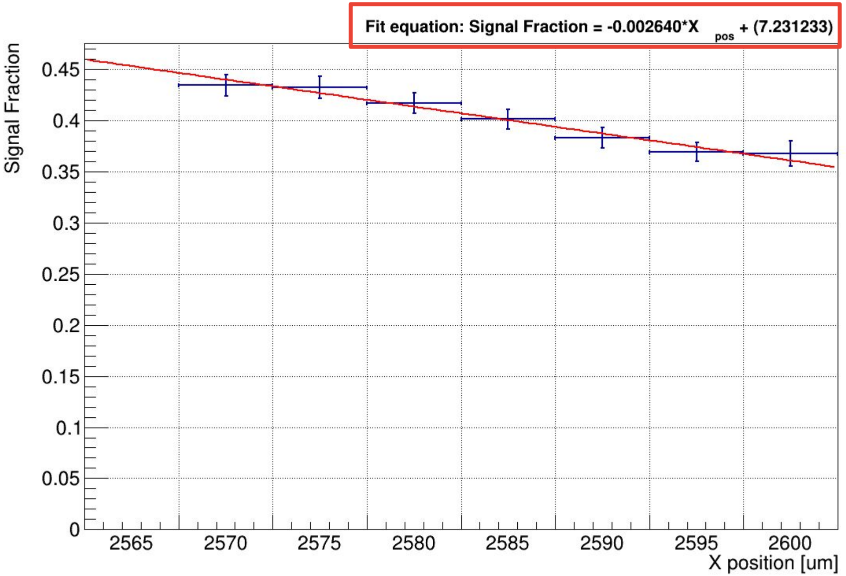


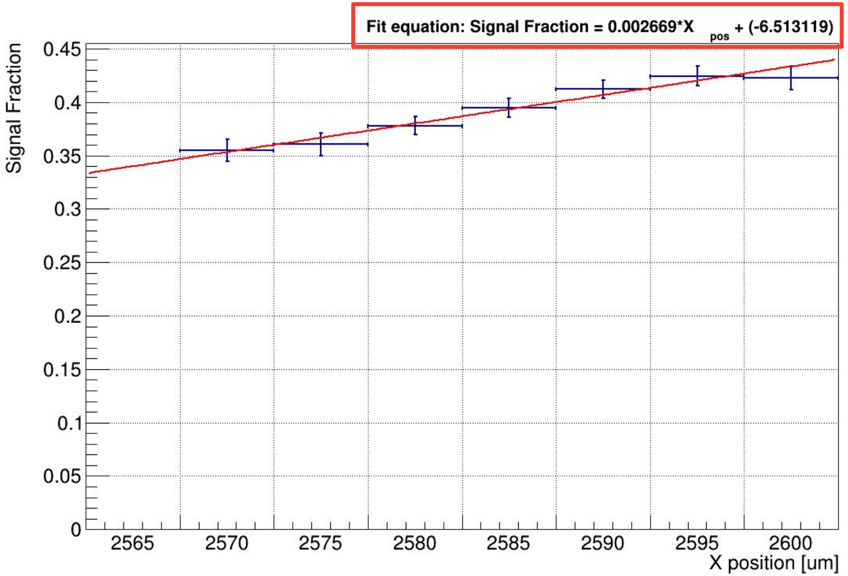
???

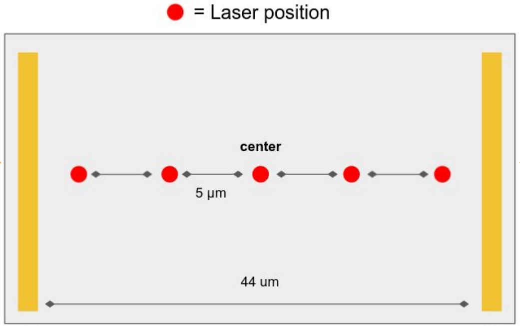
Reconstructed position



AC-LGAD - **Calibration**



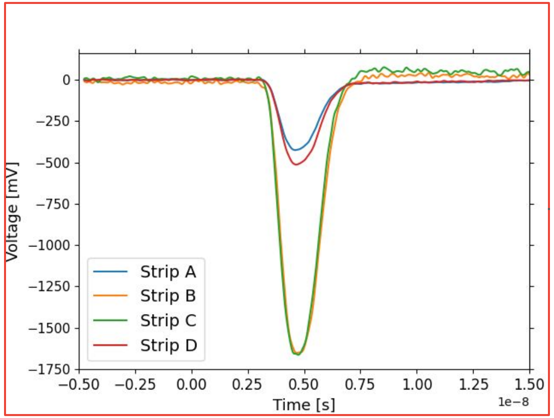




Use data points and laser position information (x^{Laser}) to find **calibration parameters** for each strip

AC-LGAD - **Calibration**

Shared Signal

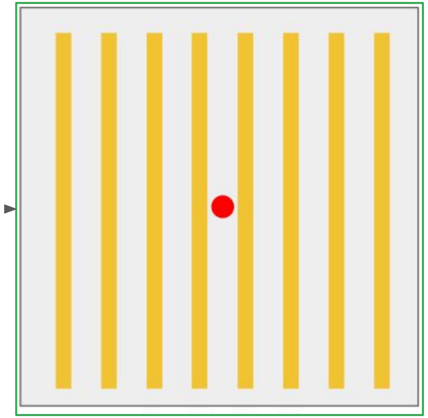


Calibration

$$\chi^2 = \sum_{i=strips} \left(\frac{m^i * x + q^i - f^i}{\sigma^i} \right)^2$$

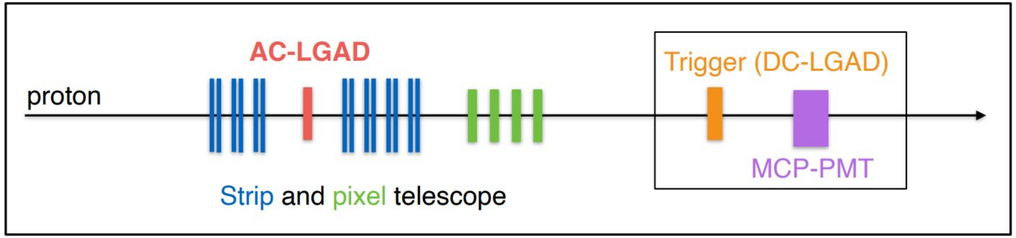
- x: laser position
- m^i, q^i: calibration params
- f^i: amplitude fraction observed by i^{th} strip

Reconstructed position

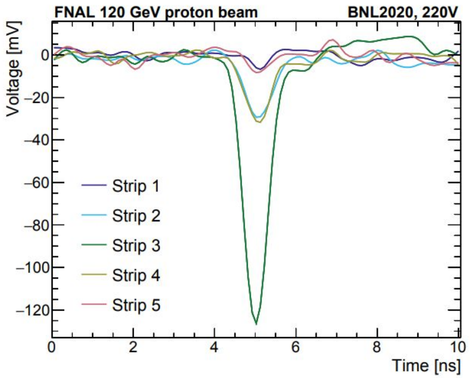


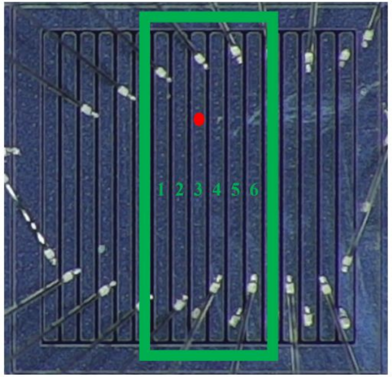
Measurement of space resolution

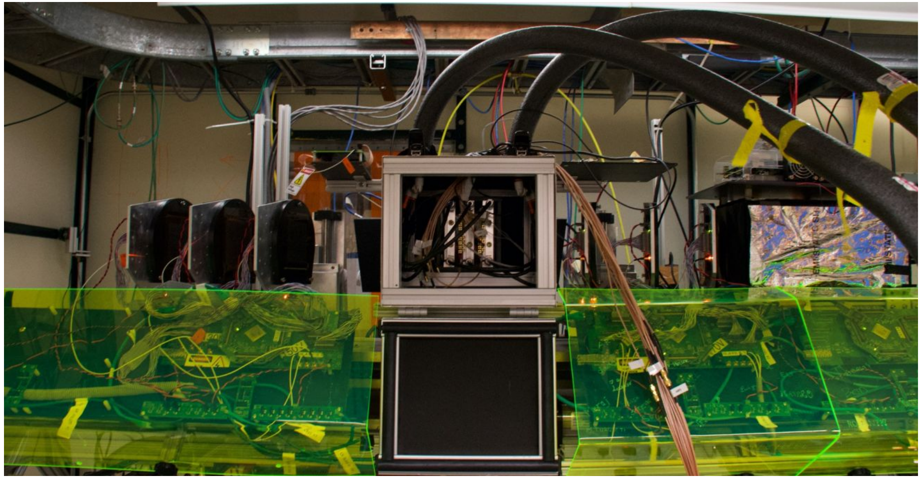
Space resolution for MIPs measured at protons test beam @**FermiLab Silicon Telescope** using beam of 120 GeV protons



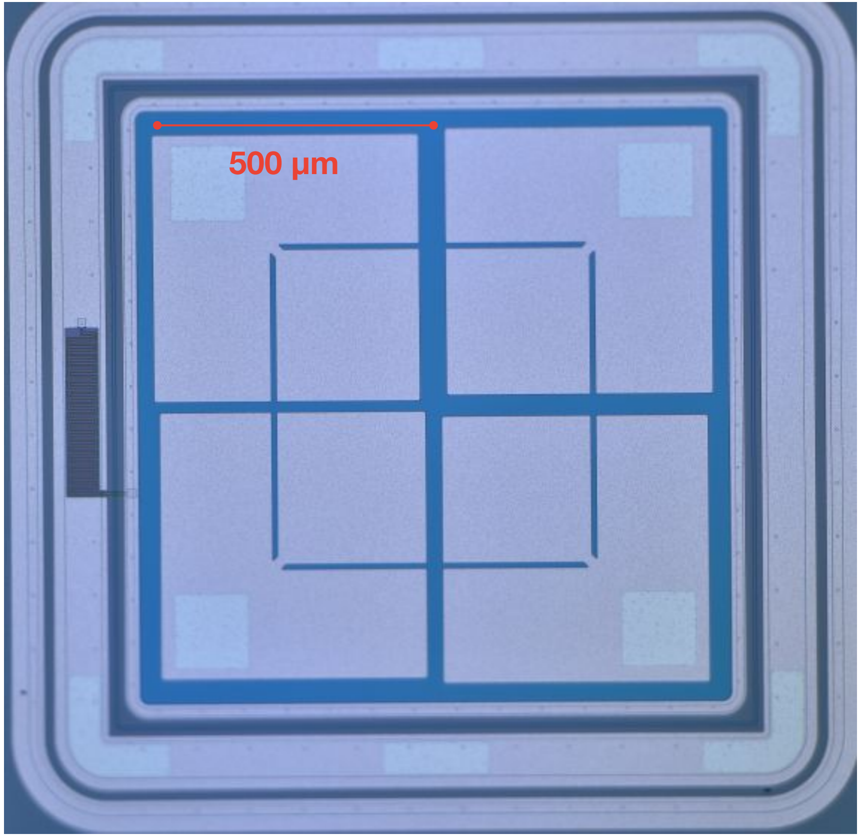
Signal sharing depends on electrode geometry (pitch, gap size) and resistivity of n+ layer (tunable)







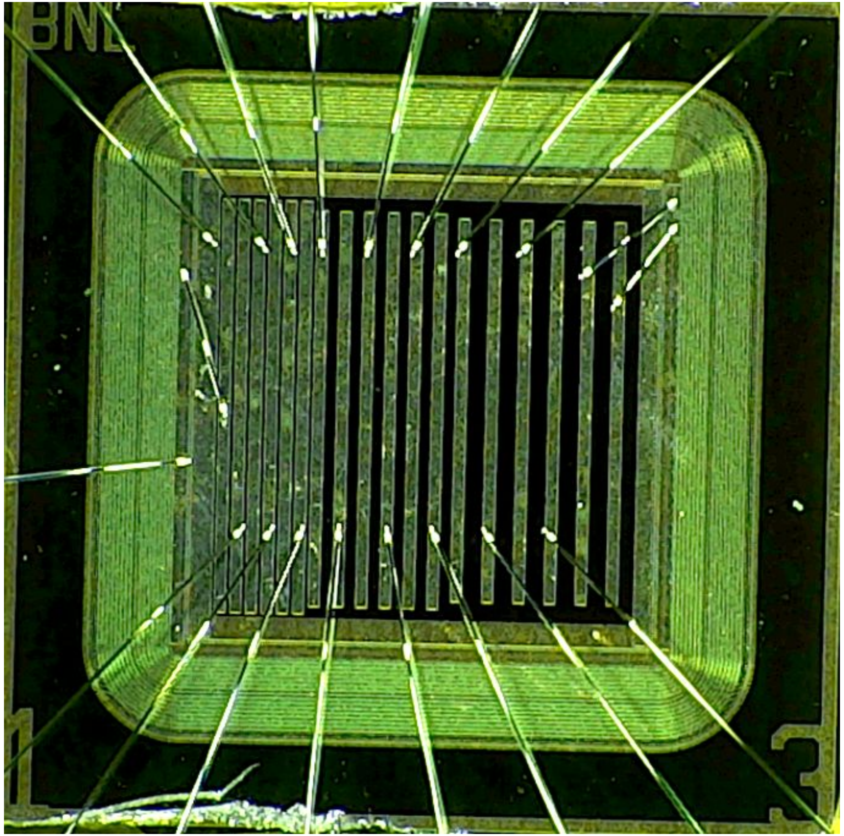
Spatial resolution



Sensor name	Pitch [um]	Space resolution [µm]	Time resolution [ps]
Hamamatsu “B-2”	500	24 ± 1	27 ± 1
Hamamatsu “C-2”	500	22 ± 1	30 ± 1

R. Heller et al.,Characterization of BNL and HPK AC-LGAD sensors with a 120 GeV proton beam, JINST 17 (2022)

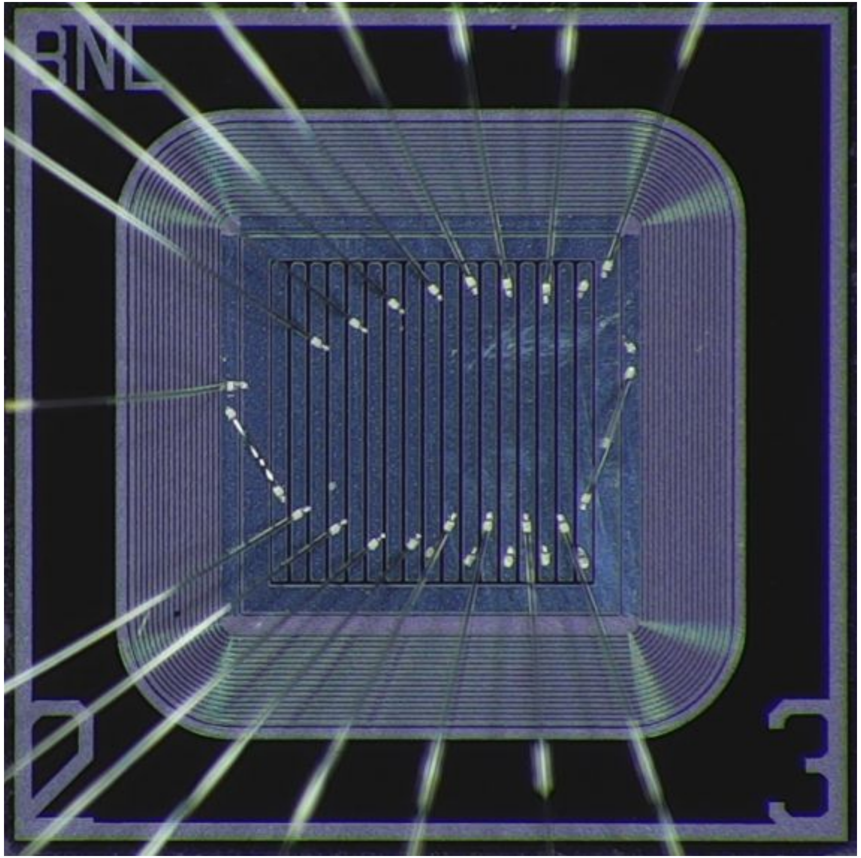
Spatial resolution



Sensor name	Pitch [um]	Space resolution [µm]	Time resolution [ps]
Hamamatsu “B-2”	500	24 ± 1	27 ± 1
Hamamatsu “C-2”	500	22 ± 1	30 ± 1
BNL “Wide”	200	≤ 9	30 ± 1
BNL “Medium”	150	≤ 11	33 ± 1
BNL “Narrow”	100	≤ 9	32 ± 1

R. Heller et al.,Characterization of BNL and HPK AC-LGAD sensors with a 120 GeV proton beam, JINST 17 (2022)

Spatial resolution



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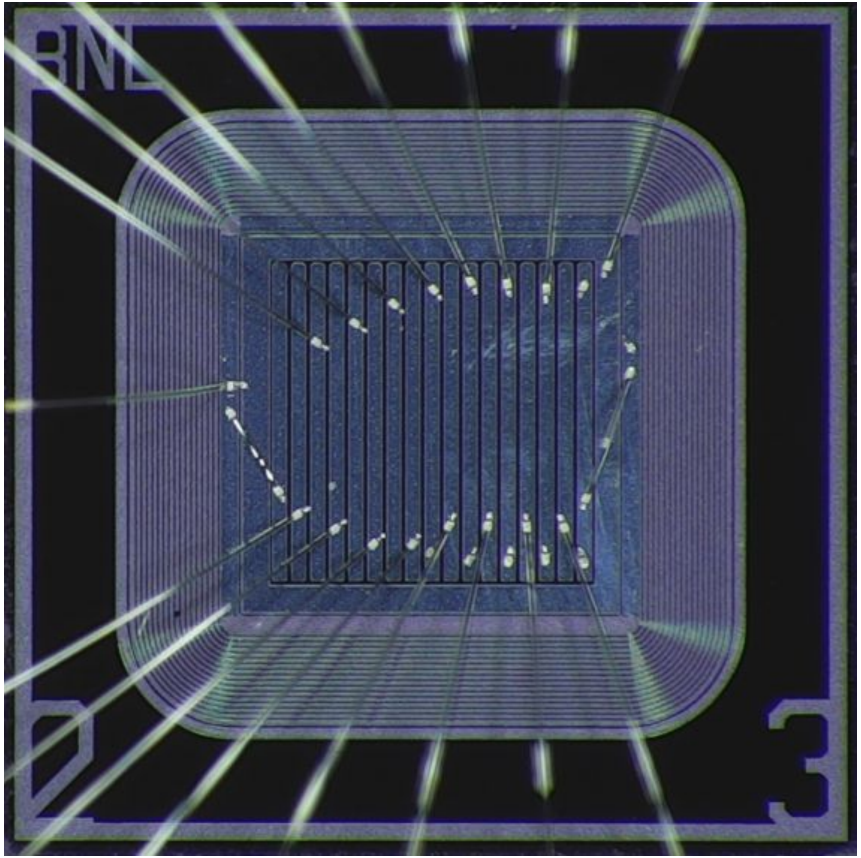
BNL “Narrow”	100	≤ 9	32 ± 1
BNL “100”	100	≤ 6	29 ± 1

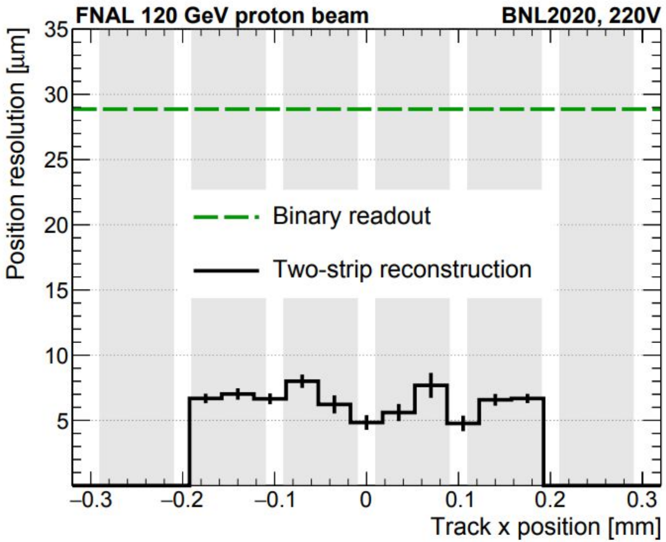
R. Heller et al.,Characterization of BNL and HPK AC-LGAD sensors with a 120 GeV proton beam, JINST 17 (2022)

Spatial resolution



Binary readout:
Space resolution limited by sensor pitch/√12 *

Proportional readout:
Space resolution improves by a factor ~5 using the same number of pads



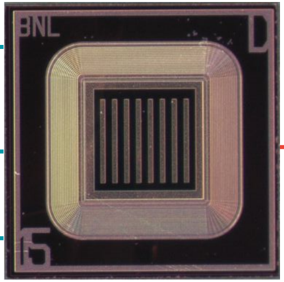
AC-LGADs as 4D detectors

AC-LGAD = excellent 4D capabilities

Space resolution < 6 um achievable using AC-LGAD technology.

Can be improved tweaking construction parameters (doping, pitch, etc)!!!

Signal Sharing



Time resolution < 30 ps limited by Landau Noise.

Can be improved with thinner sensors (first results are encouraging!)

Internal Gain

Chapter **IV**

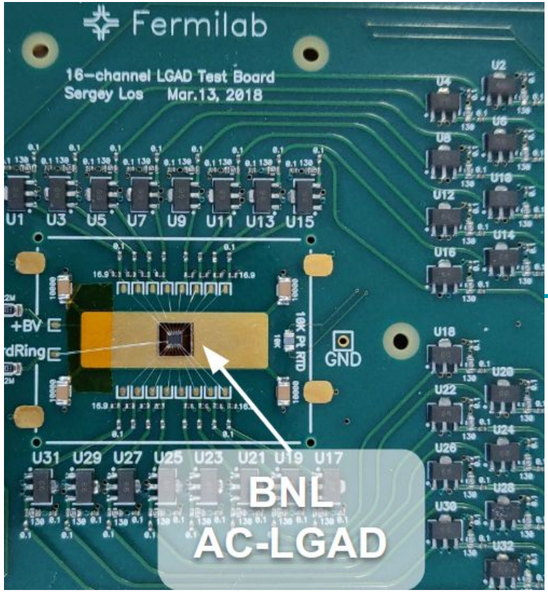
A particle mess
We need more time
A tree in the forest

A real 4D detector

A real 4D detector

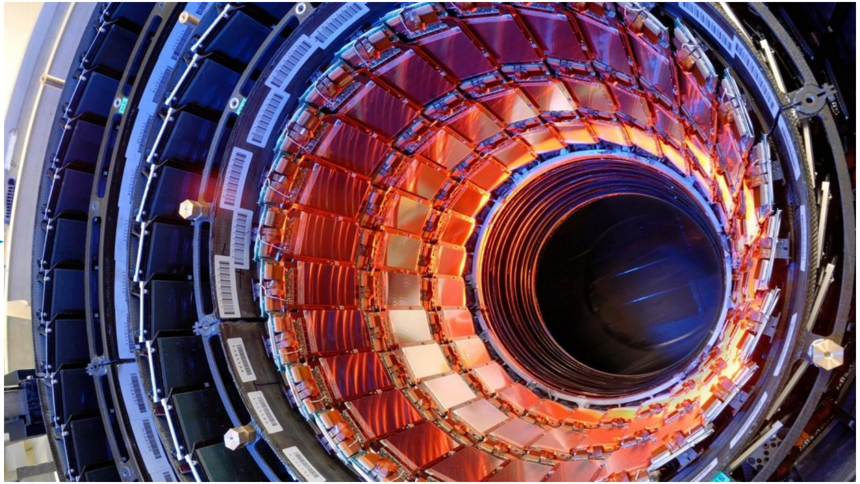
"Lab" setup

AC-LGAD read-out using **custom discrete electronics** and **oscillocopes**



Real 4D detector

In large-scale systems we need to evaluate AC-LGADs when coupled to **read-out chip (ROC)**

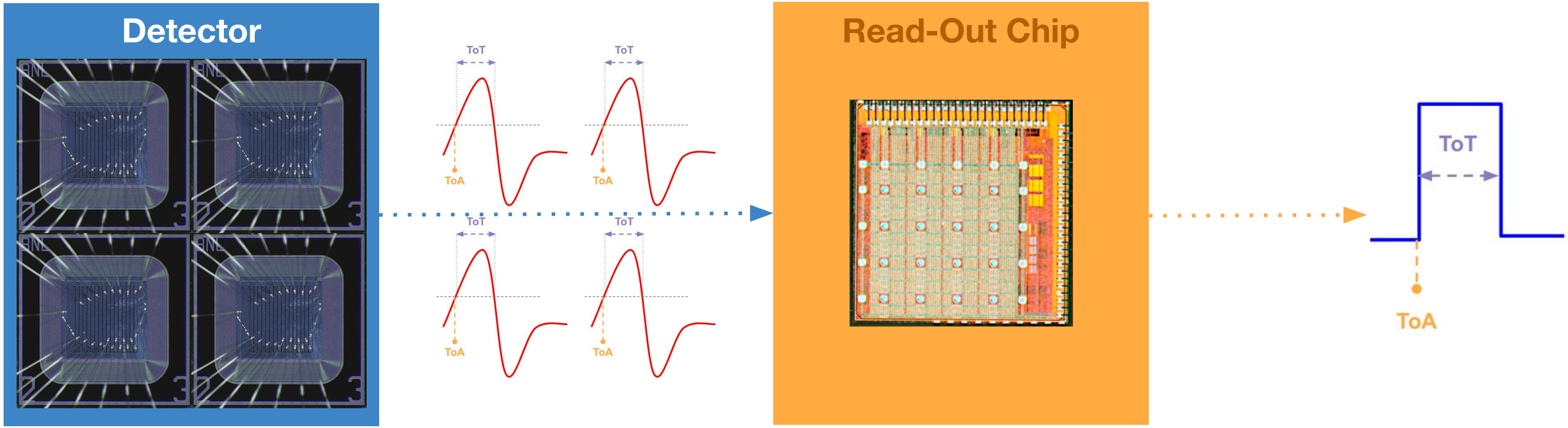


The CMS strip-inner tracker, barrel region

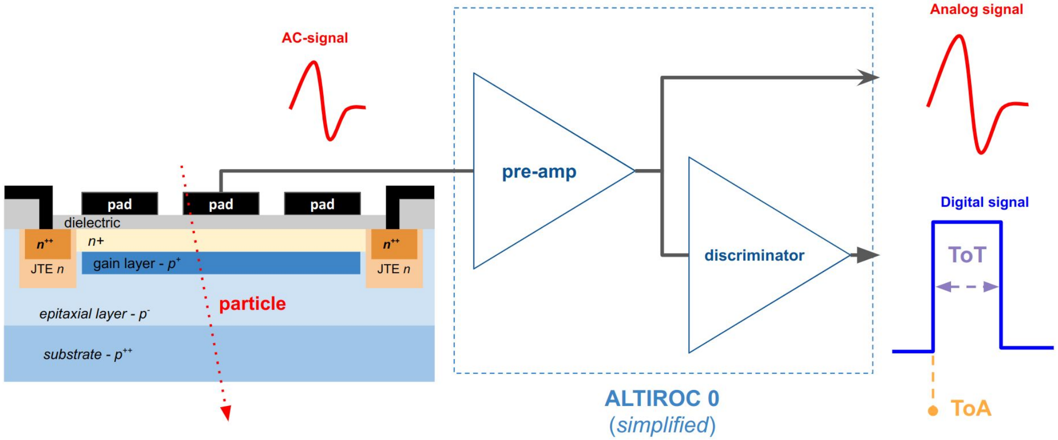
A real 4D detector

Reasons for ROC:

- **Scalable** solution
- Acquire signal from multiple ($O^{6 - 9}$) sensors
- **Digitalize** important parameters of signal (ToA, ToT, etc)
- Pack everything neatly



Reading out AC-LGADs



ATLAS **L**GAD **TI**MING **ROC**

Designed for **LGAD signals** for ATLAS High-Granularity Timing Detector (HGTD)

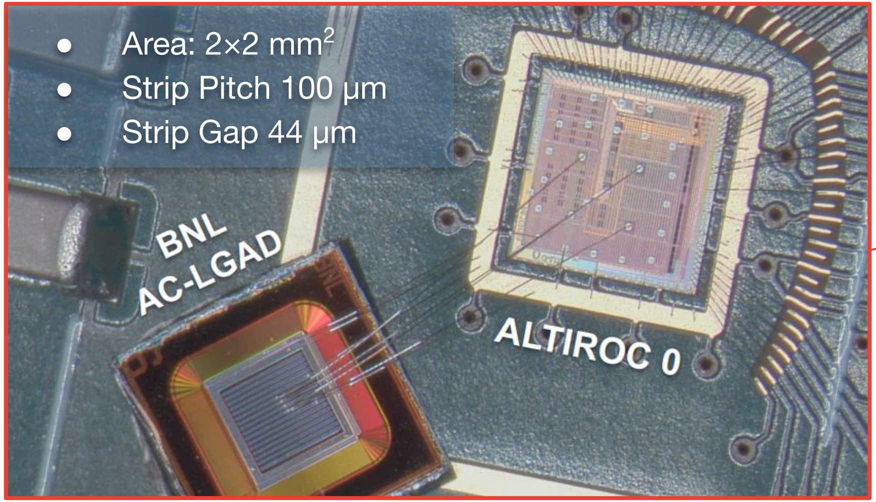
Outputs two signals per read out strip:

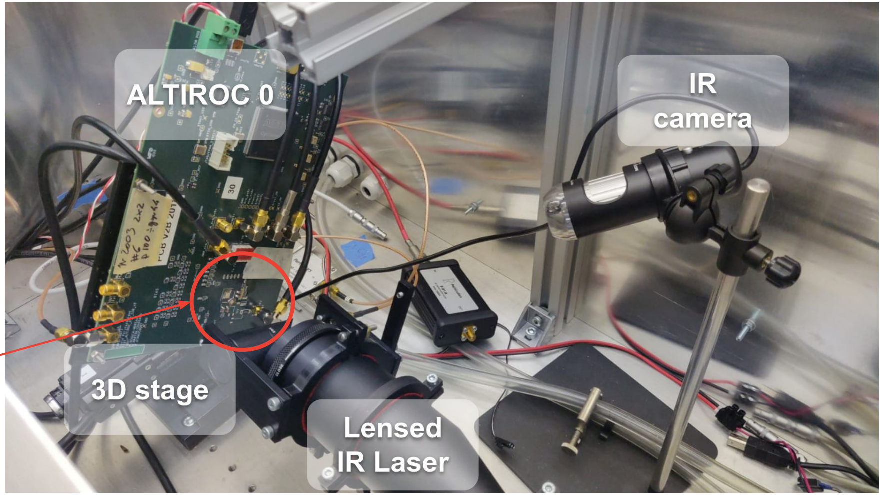
- **Analog signal** (via Voltage Pre-amp)
- **Digital signal** (via Discriminator)

Our questions:

1. Is it possible to read out AC-LGADs using a chip?
2. Can we access AC-LGAD **Signal Sharing** capabilities?
3. What is the **impact on Signal Sharing**?
4. Can we exploit ALTIROC **digital signal**?

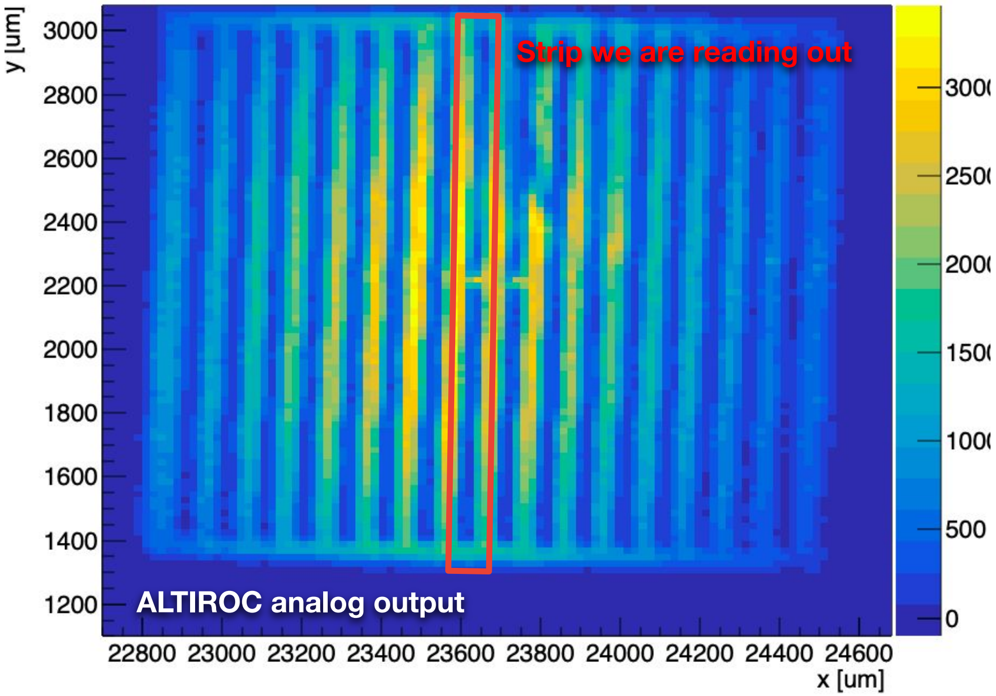
Reading out AC-LGADs





- ALTIROC setup adapted to **Transient Current Technique** (TCT) station
- Characterization performed with **IR laser** injecting charge onto AC-LGAD
- We can point the IR laser at specific locations on the sensor with 1um precision

Reading out AC-LGADs

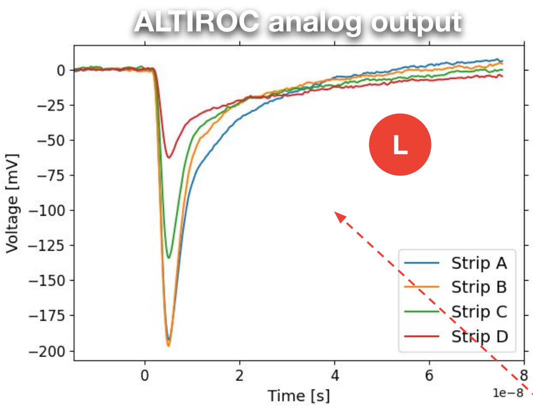


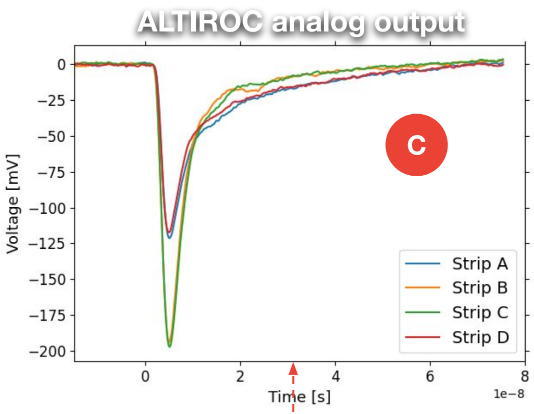
- Colour indicates integral charge of the **signal from ALTIROC analog output**
- Signal can be **seen at ~2 strips of distance (signal sharing)**

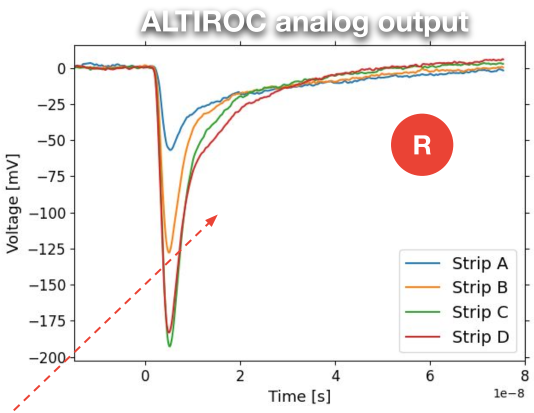
Our questions:

1. Is it possible to read out AC-LGADs using ALTIROC? **YES**
2. Can we access AC-LGAD Signal Sharing capabilities? **MAYBE**
3. What is the **impact on Signal Sharing**?
4. Can we exploit ALTIROC **digital signal**?

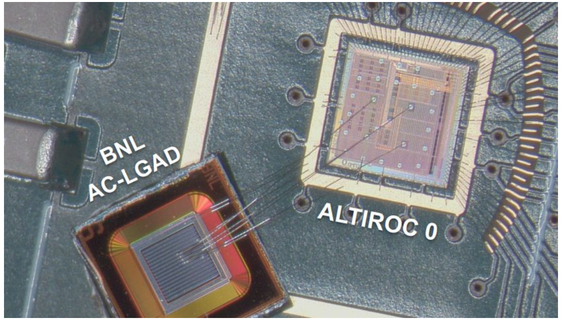
Signal sharing using ALTIROC

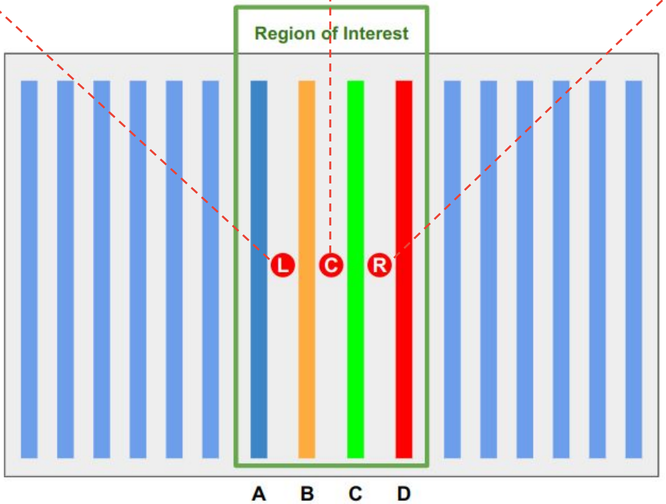




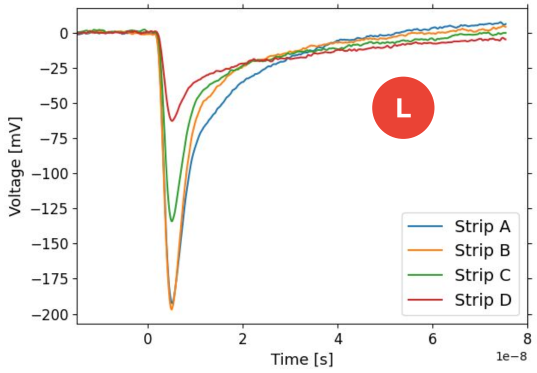


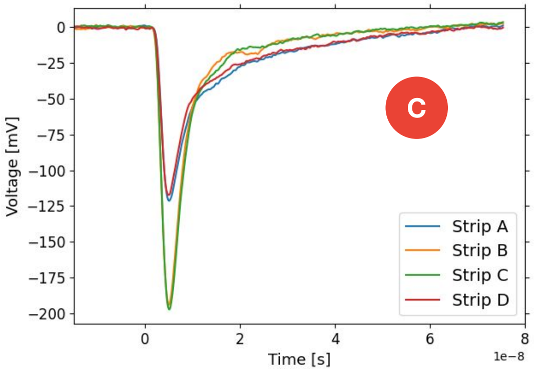
Device under test

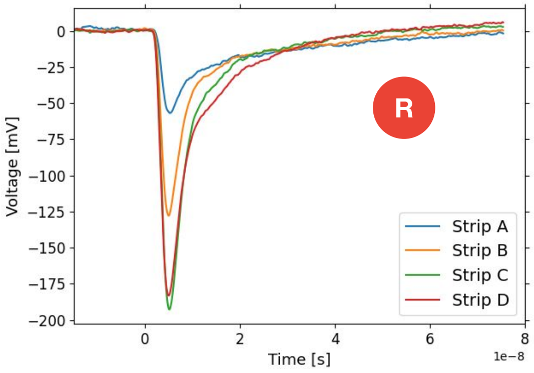




Signal sharing using ALTIROC





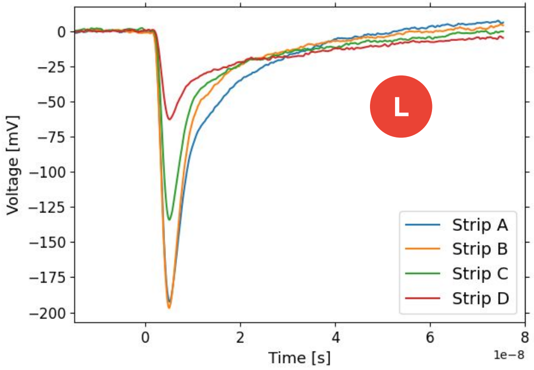


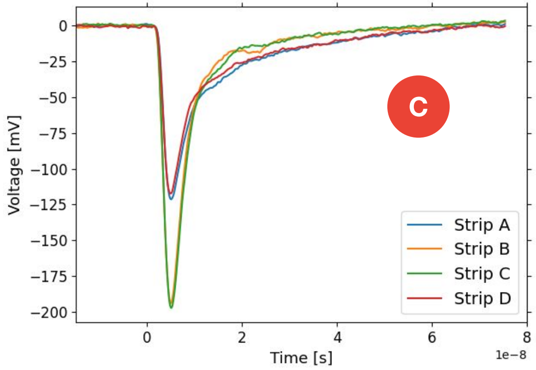
Our questions:

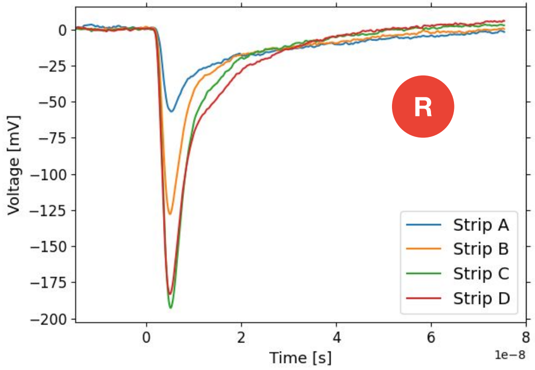
1. Is it possible to read out AC-LGADs using ALTIROC?
2. Can we access AC-LGAD Signal Sharing capabilities?
3. What is the **impact on Signal Sharing**?
4. Can we exploit ALTIROC **digital signal**?

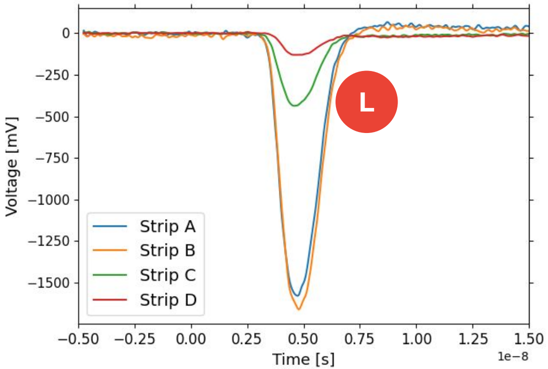
Signal sharing using ALTIROC

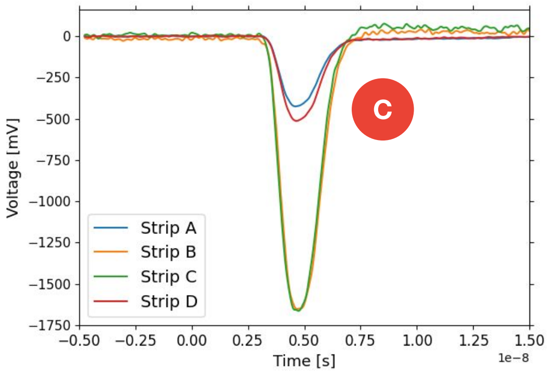
ALTIROC 0

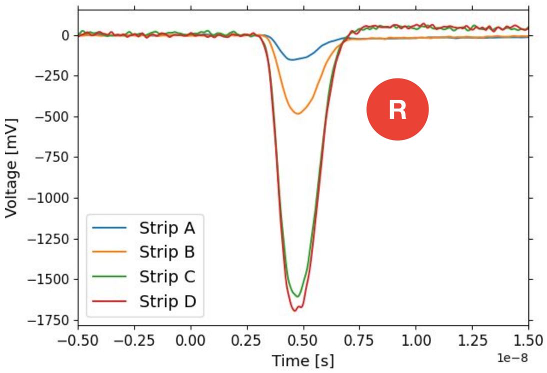






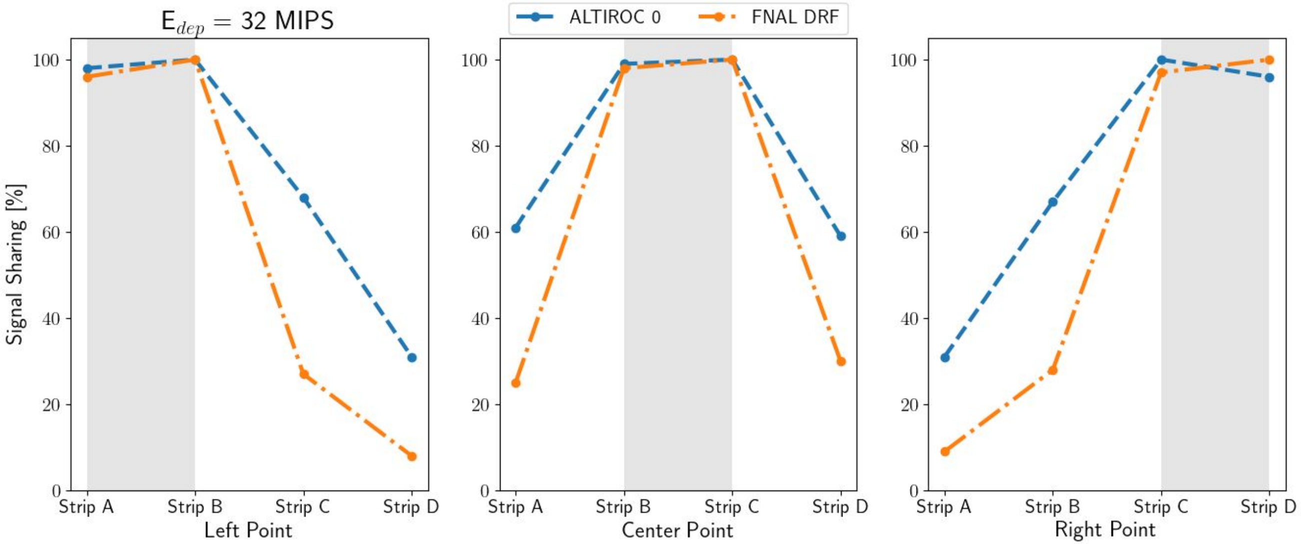






Discrete electronics

Signal sharing using **ALTIROC**



$$\text{Signal Sharing}_i\ [\%] = \frac{A_i}{A_{highest}}$$

Measured difference in signal sharing profile on first order due to **different input impedance** of ALTIROC 0 and the discrete component board

Our questions:

1. Is it possible to read out AC-LGADs using ALTIROC?
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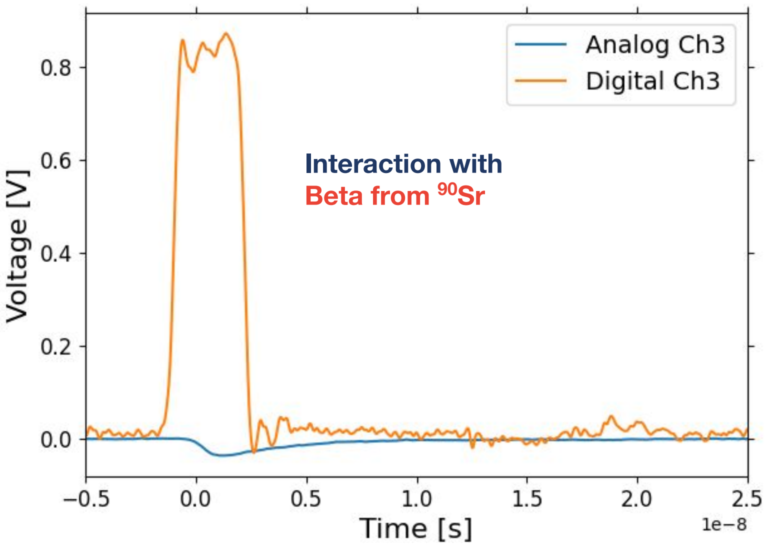
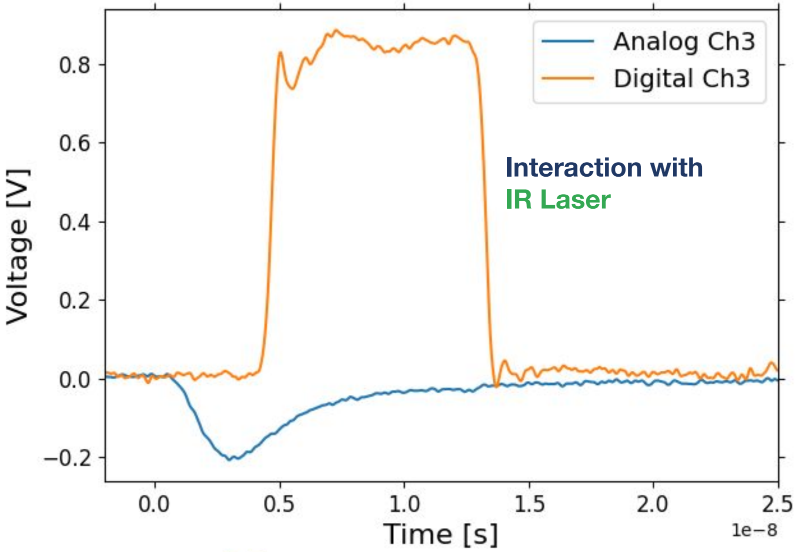
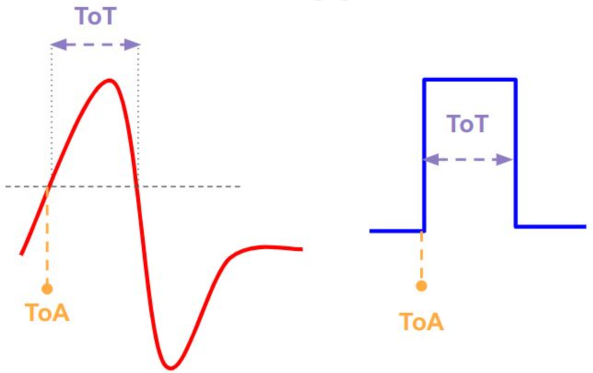
3. What is the **impact on Signal Sharing**?
4. Can we exploit ALTIROC **digital signal**?

AC-LGAD Signal digitalization

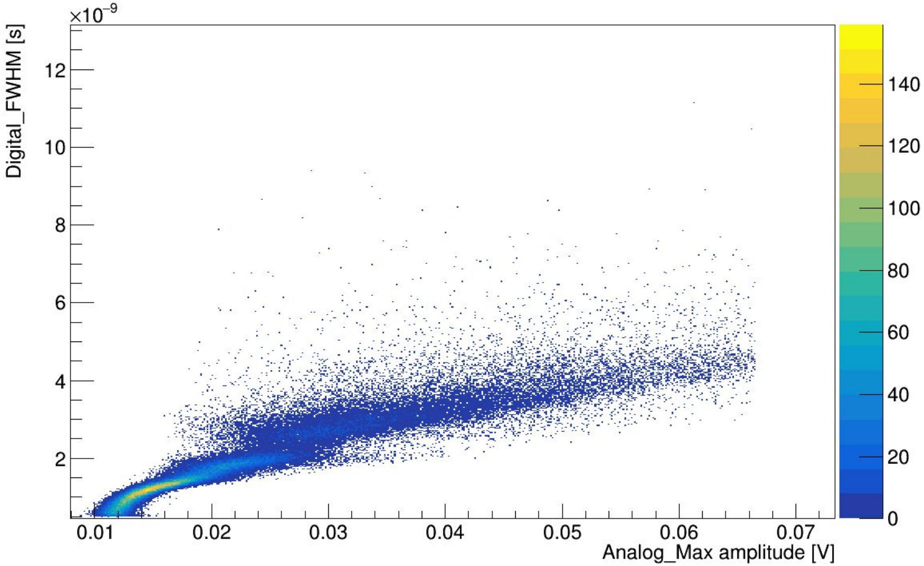




- Width (FWHM) of the digital signal proportional to **Time-over-Threshold** (ToT) of the Analog Signal
- Can use Analog **signal amplitude** as proxy for ToT



AC-LGAD Signal digitalization



- Interaction with **beta particles** leaves a **long tail of deposited energies** (Landau)
- Univocal dependence (~linear) on the analog signal amplitude/deposited energy

Our questions:

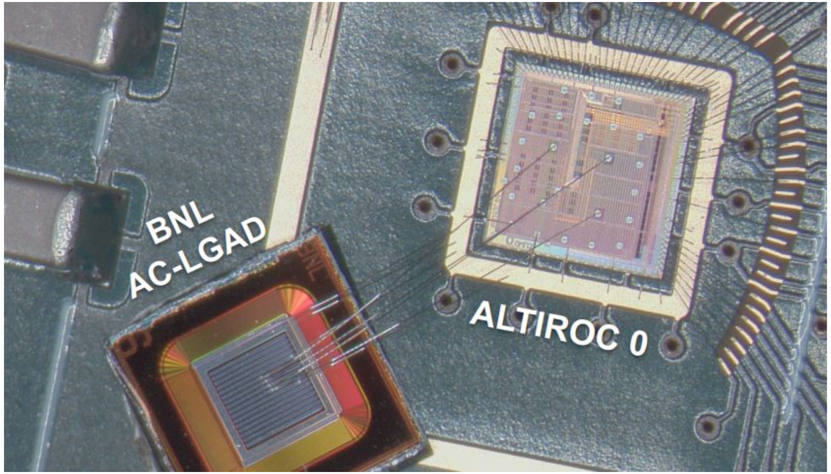
1. Is it possible to read out AC-LGADs using ALTIROC?
2. Can we access AC-LGAD Signal Sharing capabilities?
3. What is the **impact on Signal Sharing**?
4. Can we exploit ALTIROC **digital signal**?

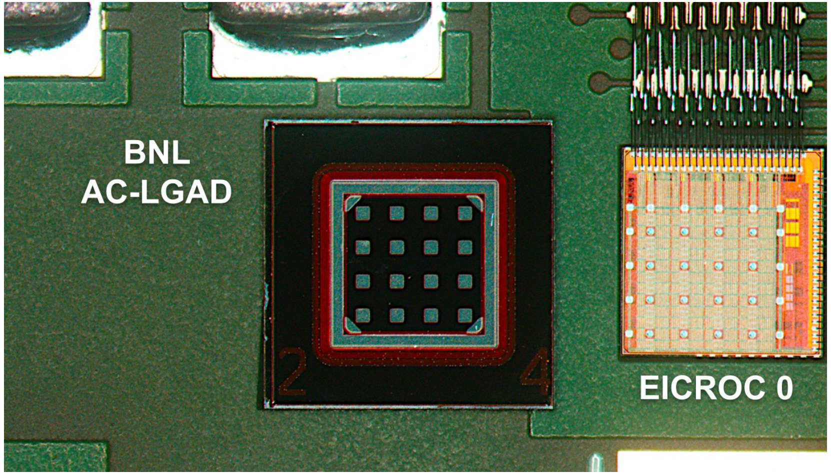
Need dedicated readout chip supporting signal sharing!

First readout of AC-LGAD using ASIC!

G.D'Amen et al., Signal formation and sharing in AC-LGADs using the ALTIROC 0 front-end chip, JINST 17 2022

A **readout ASIC** for 4D detectors





ALTIROC 0

TARGET SENSOR	DC-LGAD
PIXEL SIZE	1.3×1.3 mm2
CHANNELS	4
PIXEL CAPACITANCE	4 pF
TDC (TOT)	8bit/10bit

EICROC 0

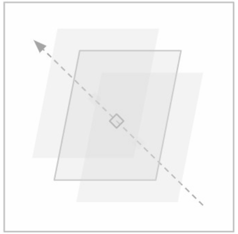
TARGET SENSOR	AC-LGAD
PIXEL SIZE	0.5×0.5 mm^2
CHANNELS	16
PIXEL CAPACITANCE	0.5 pF
ADC (Amplitude)	8bit/10bit

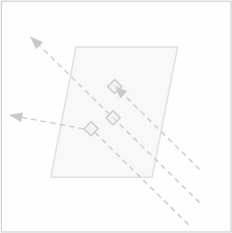
Chapter **V**

The next step

Tackling the **future**

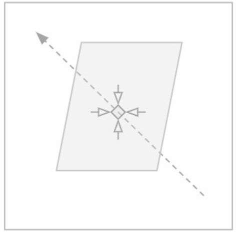
Time resolution
Driven by: Hadronic Colliders

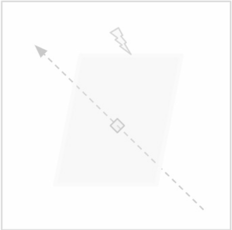




Material budget
Driven by: Muon Colliders, Leptonic Colliders

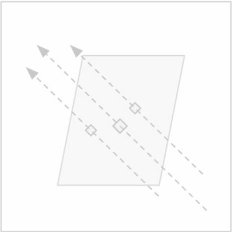
Space resolution
Driven by: Hadronic and Leptonic Colliders

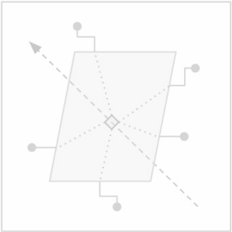




Power consumption
Driven by: Leptonic Colliders (background)

Radiation hardness
Driven by: Hadronic and Muon Colliders

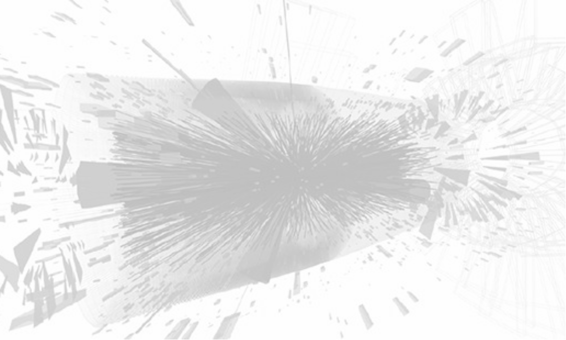




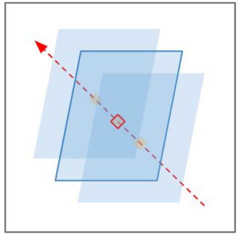
DAQ bandwith
Driven by: All Colliders

Tackling the **future**

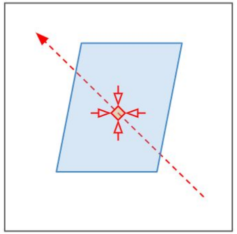
AC-LGAD technology can deliver **excellent 4D performances**



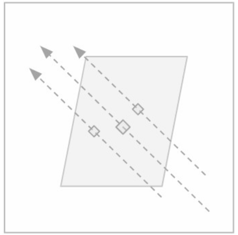
Time resolution
Driven by: Hadronic Colliders

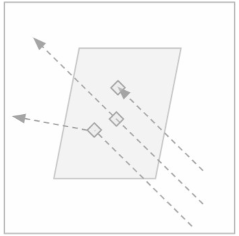


Space resolution
Driven by: Hadronic and Leptonic Colliders

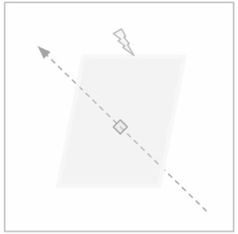


Radiation hardness
Driven by: Hadronic and Muon Colliders

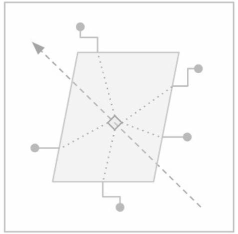




Material budget
Driven by: Muon Colliders, Leptonic Colliders



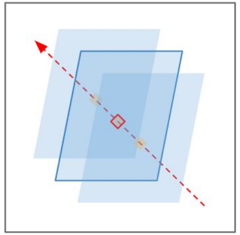
Power consumption
Driven by: Leptonic Colliders (background)



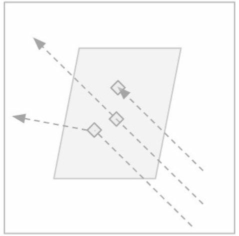
DAQ bandwith
Driven by: All Colliders

Tackling the **future**

Time resolution
Driven by: Hadronic Colliders

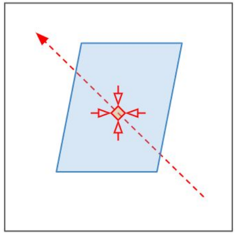


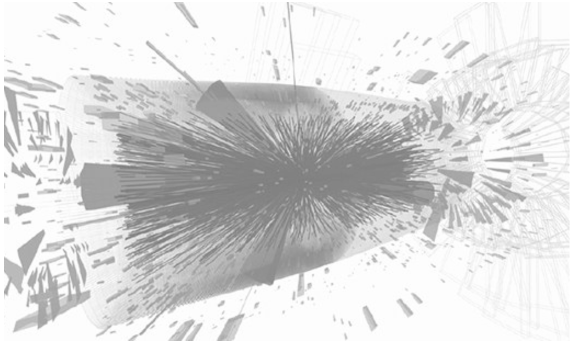
New **extrinsic/compound semiconductors** can withstand extremely high fluences

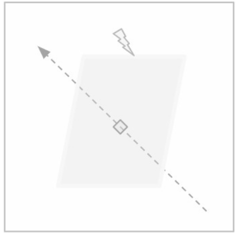


Material budget
Driven by: Muon Colliders, Leptonic Colliders

Space resolution
Driven by: Hadronic and Leptonic Colliders

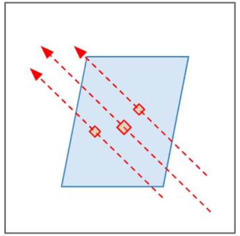


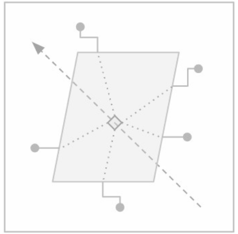




Power consumption
Driven by: Leptonic Colliders (background)

Radiation hardness
Driven by: Hadronic and Muon Colliders

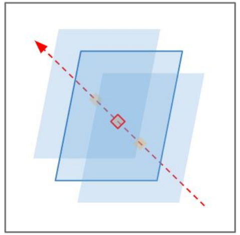




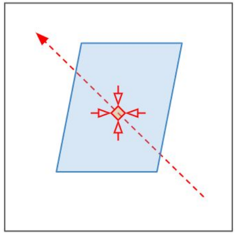
DAQ bandwith
Driven by: All Colliders

Tackling the **future**

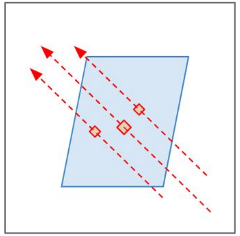
Time resolution
Driven by: Hadronic Colliders



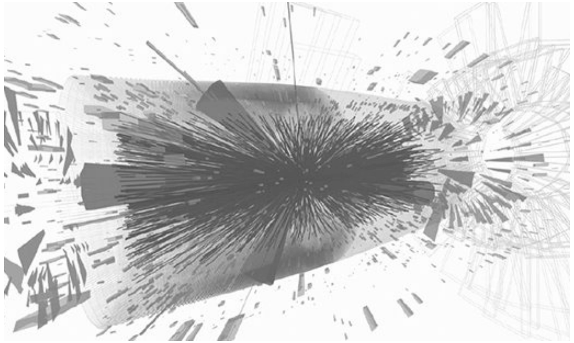
Space resolution
Driven by: Hadronic and Leptonic Colliders

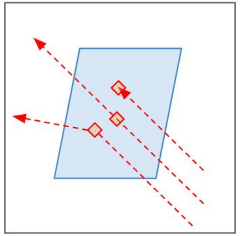


Radiation hardness
Driven by: Hadronic and Muon Colliders

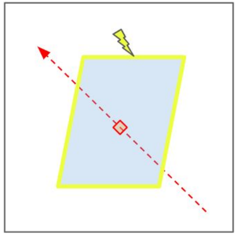


Monolithic sensors could considerably decrease material budget and power consumption

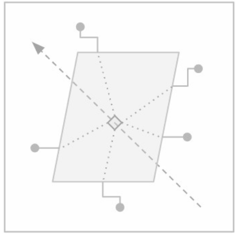




Material budget
Driven by: Muon Colliders, Leptonic Colliders



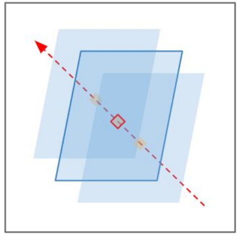
Power consumption
Driven by: Leptonic Colliders (background)



DAQ bandwith
Driven by: All Colliders

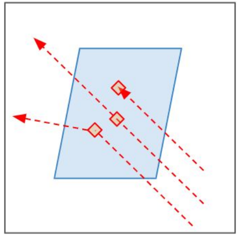
Tackling the **future**

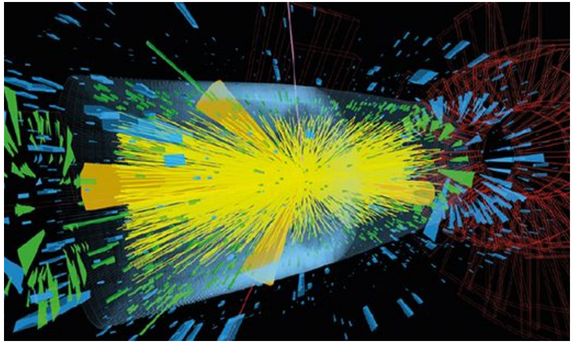
Time resolution
Driven by: Hadronic Colliders



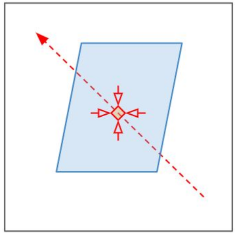
New ML methods can be implemented in hardware to make online DAQ and reconstruction more efficient

Material budget
Driven by: Muon Colliders, Leptonic Colliders





Space resolution
Driven by: Hadronic and Leptonic Colliders



Power consumption
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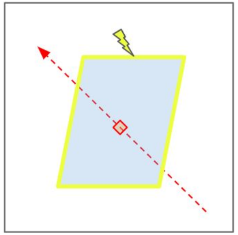
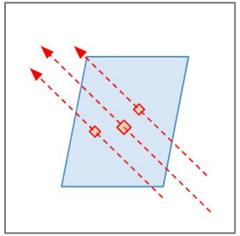
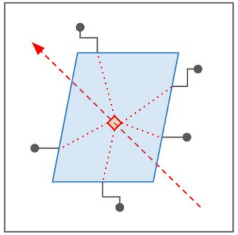


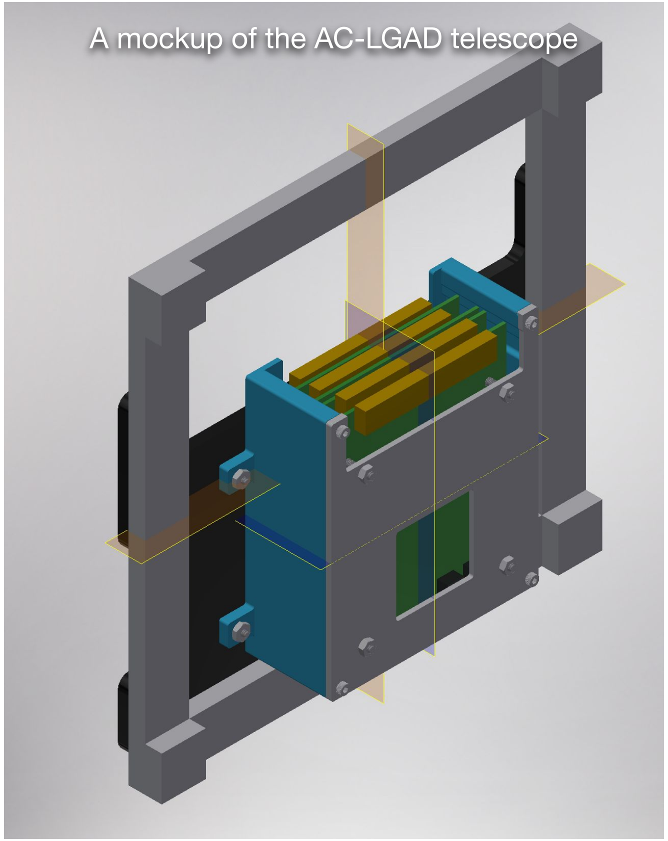
Radiation hardness
Driven by: Hadronic and Muon Colliders



DAQ bandwith
Driven by: All Colliders



The **AC-LGAD Telescope**

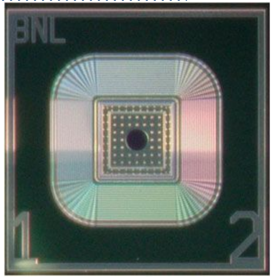


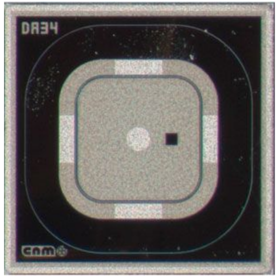
Thank you for C-R.Deane for the project of the support structure

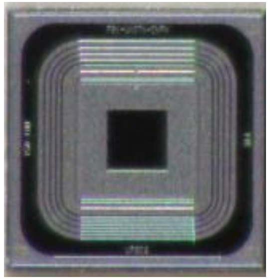
- Based on **AC-LGAD technology**
- **Portable** and **modular telescope**
- **Baseline** for future 4D studies and developments
- **First test beam** scheduled for Sept 2023 (tomorrow…) at BNL Tandem Van De Graaf

Recap and Future Outlook

- Next generation of accelerators will pose several experimental challenges; this requires a **new generation 4D detector**
- AC-LGAD paradigm is a **prime candidate for 4D reconstruction** thanks to its fast timing and signal sharing capabilities
- A new detector requires a **dedicated readout system: enter EICROC!**
- We need to **drive advancements** in Material Science, Machine Learning, Detector Design to face what's coming next!







Thank you for your attention

Aknowledgements

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- N. Seguin-Moreau

from the **OMEGA-CNRS-Ecole Polytechnique** for the ALTIROC and EICROC designs

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- S. Kita
- T. Imamura
- K. Hara

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- T. Kersten

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- L. Serin
- P.-K. Wang

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- A. Apresyan
- R. Heller
- C. Madrid

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