# Module tests for the tracker upgrade of the CMS experiment at HL-LHC


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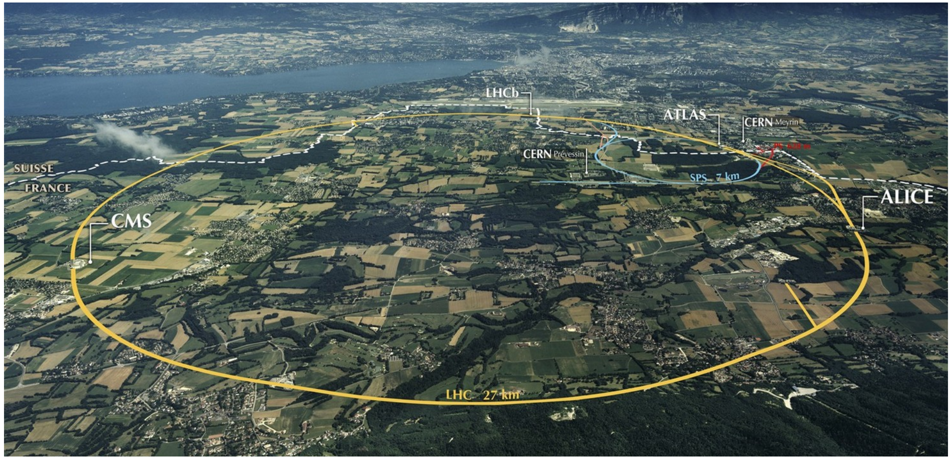
CMS Compact Muon Solenoid


# Contents

# Introduction

# The Large Hadron Collider (LHC)

- Put the Standard Model to the test
- Bunches of particles crossing at a frequency of 40 MHz (crossing every 25 ns)
- High Luminosity phase of the LHC (HL-LHC) starting in 2029
- Target luminosity of $5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$
  → Statistically limited processes

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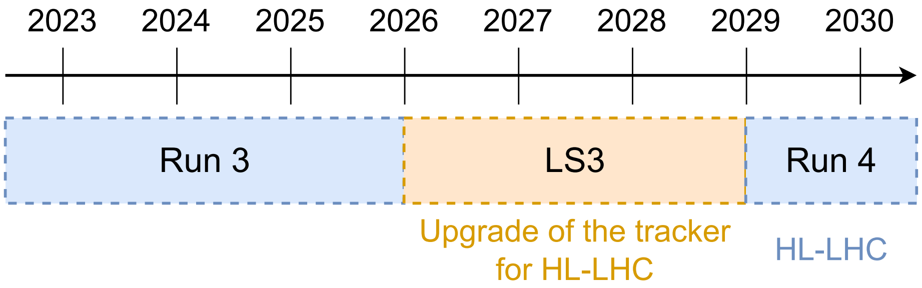
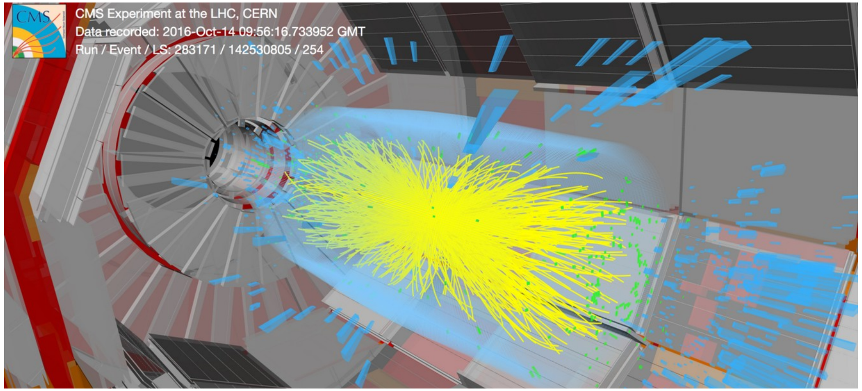


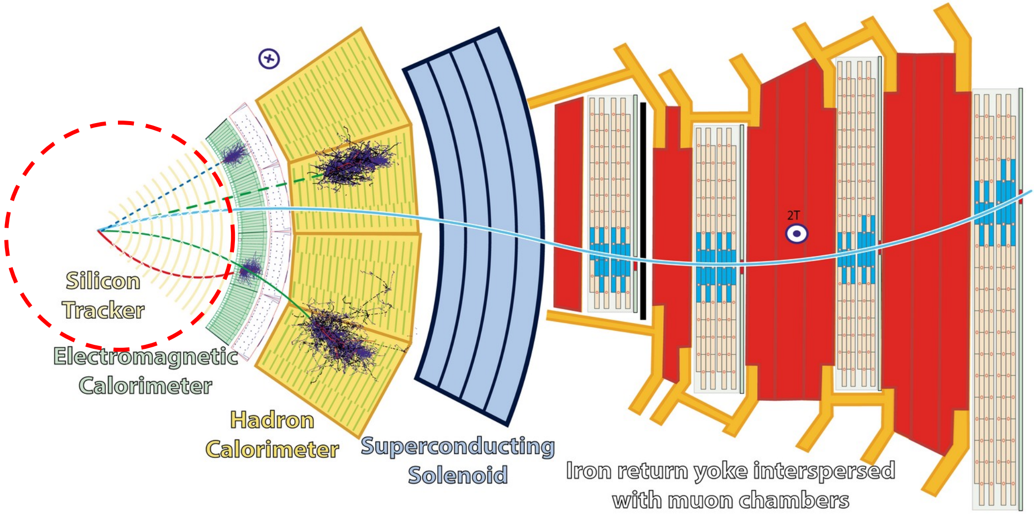
# The Compact Muon Solenoid (CMS) detector

- General-purpose detector located at a collision point

- New conditions:
  - More <u>simultaneous collisions:</u> 50 → 200
  - Higher <u>radiation dose</u>

→ Tracker entirely replaced

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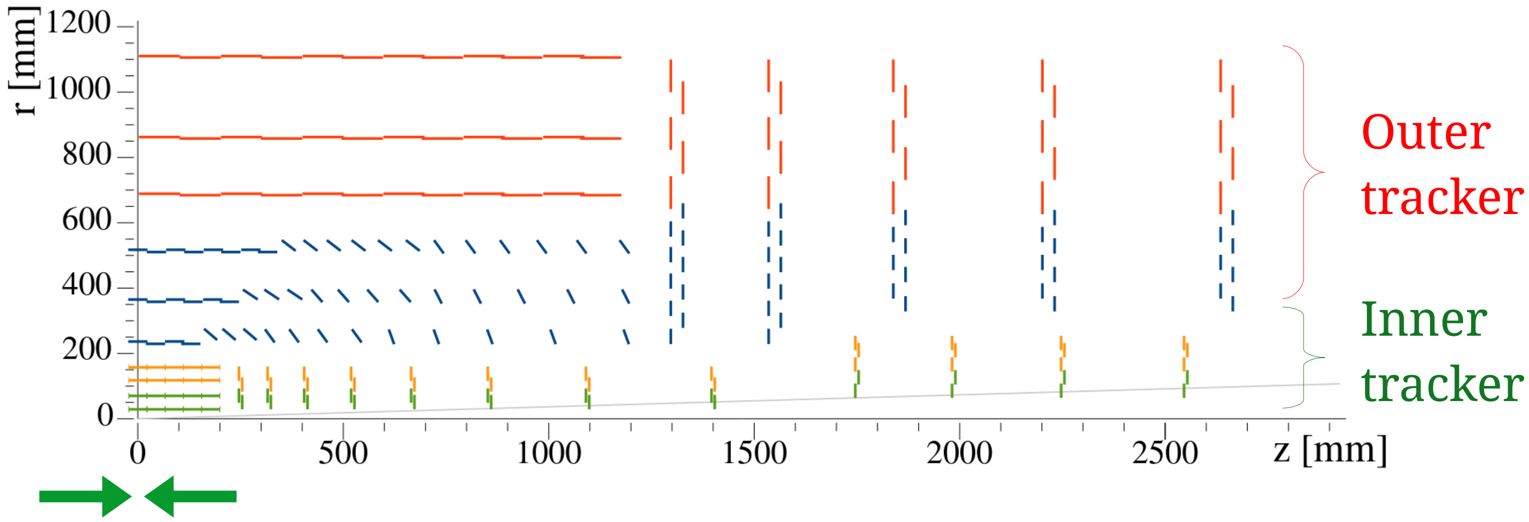
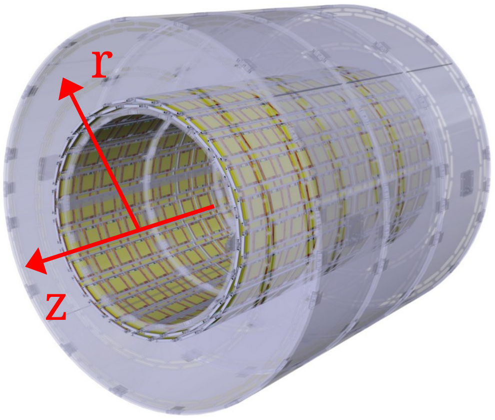
# Upgrade of the silicon tracker

- Enhanced radiation tolerance, higher granularity, and compatibility with <u>very high rates</u>




Collison point

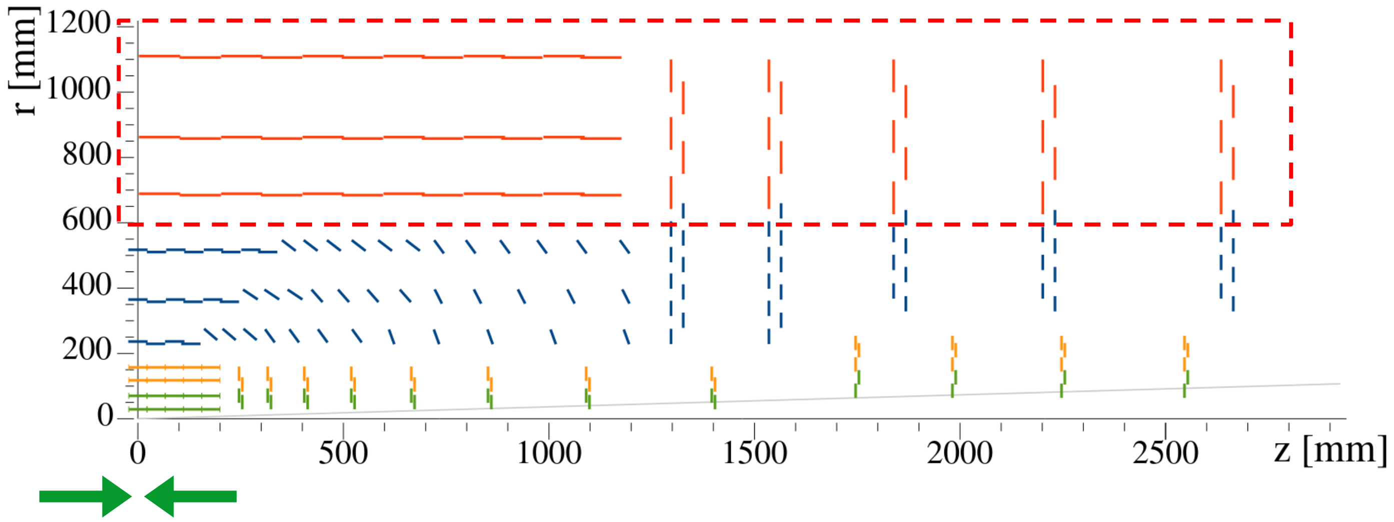
One quarter of the new tracker layout

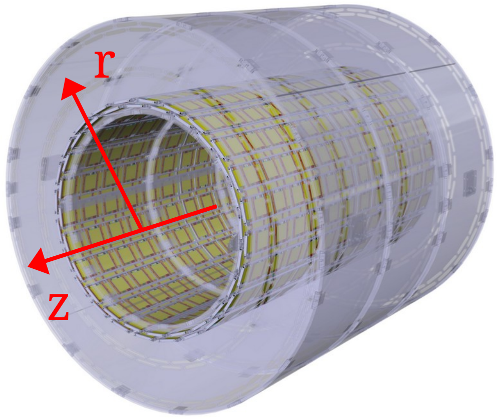
*From [1]*

# Upgrade of the silicon tracker

- Enhanced radiation tolerance, higher granularity, and compatibility with <u>very high rates</u>

Tested modules



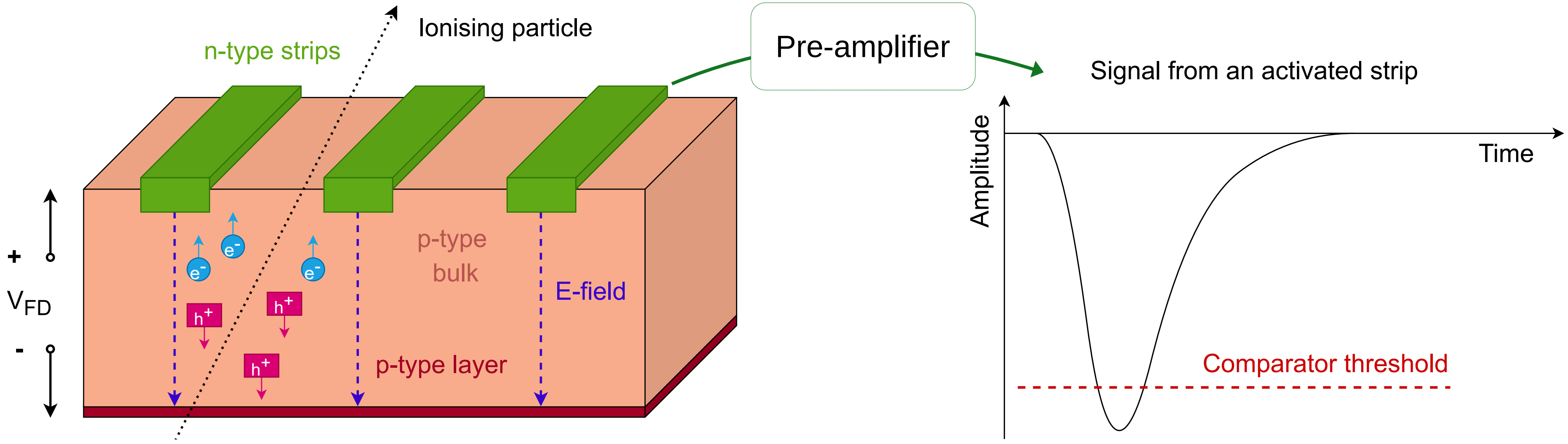

*From [1]*

Collison point

One quarter of the new tracker layout

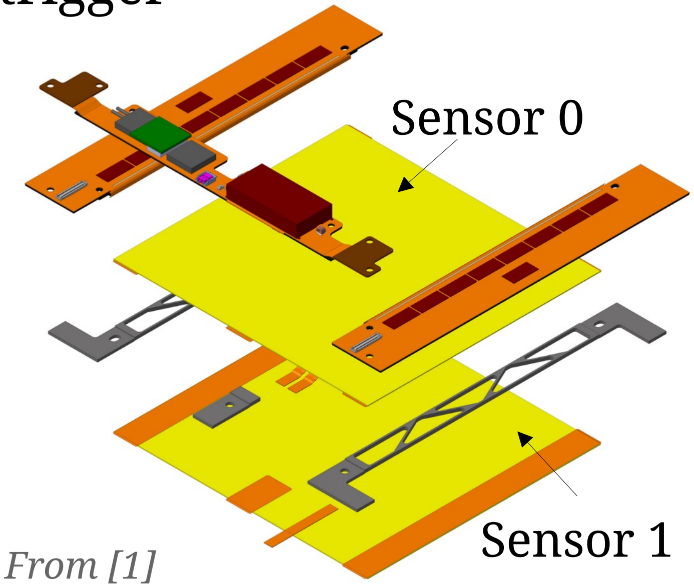
# Charge collection in a strip silicon sensor

- The number of activated strips depends on the charge generated by the energy deposition of the particle. Which depends on the energy via the Bethe-Bloch formula

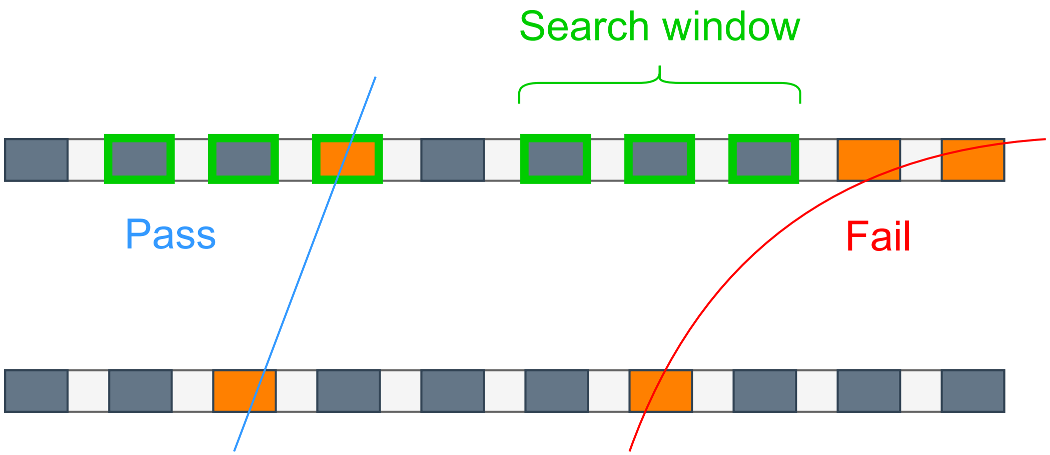


# The 2S modules

- Not all collisions happening inside the detector can be recorded and stored: Trigger system, 40 MHz → 750 kHz
- New modules will provide tracking information to the first stage of trigger

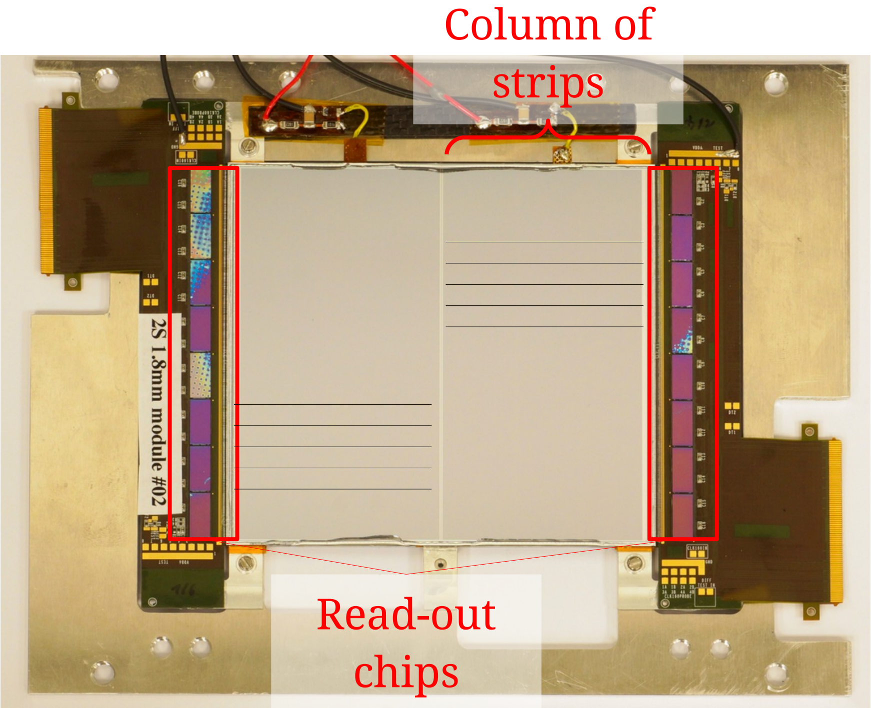



*From [1]*



# Front-end electronics

- The read-out chips (CBC) will provide the $p_T$ discrimination logic

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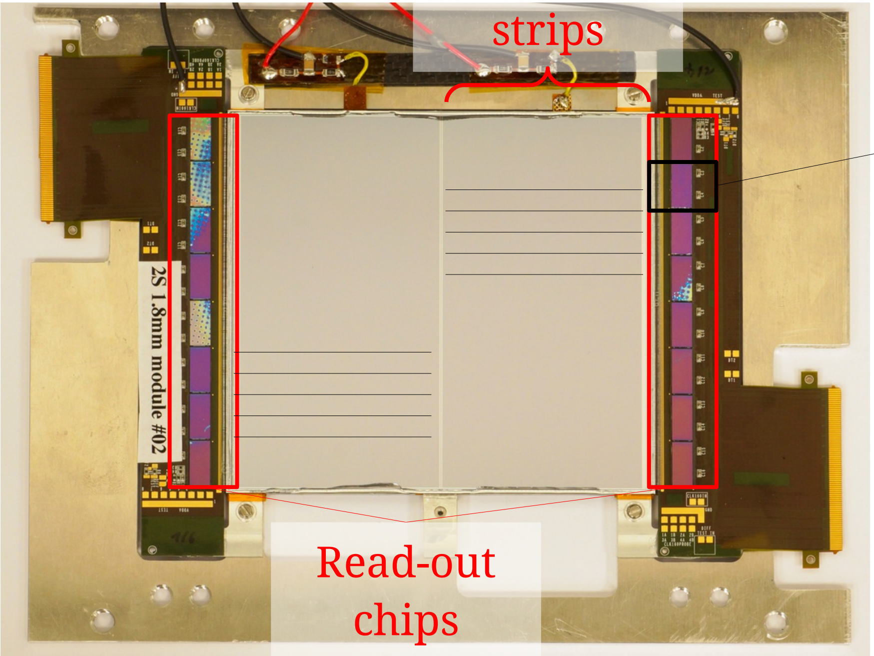


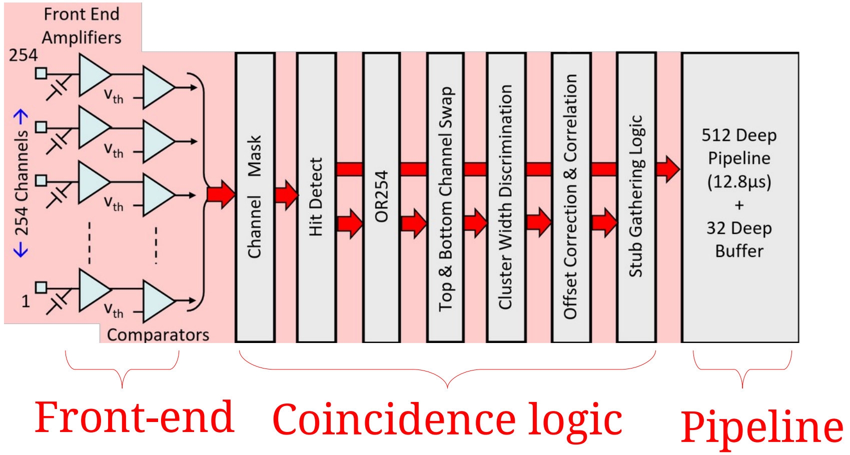


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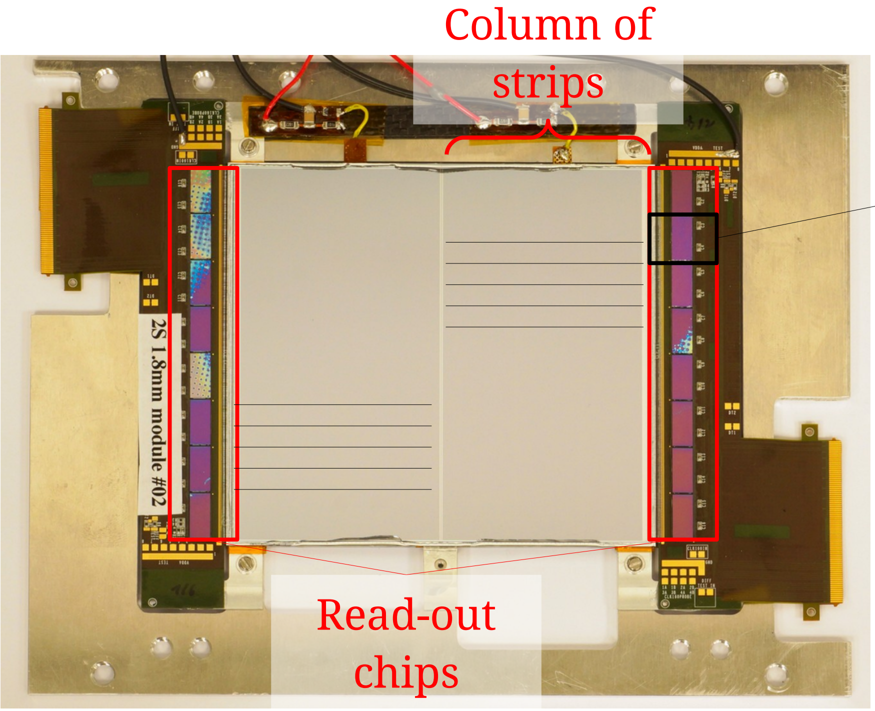


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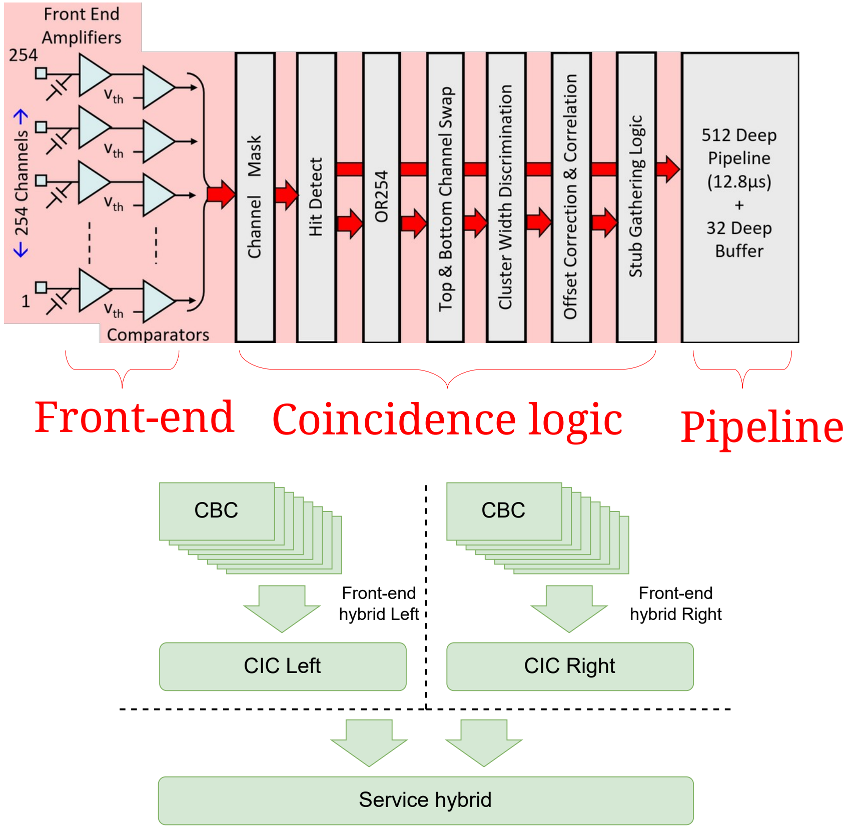


# Course of the internship

Objective: validate the performance of a pre-production version of a 2S module in high rates condition

- Participation in the beam tests at CYRCé :
  11/03 – 22/03 & 22/04 - 26/04
  → Preparation and manipulation of the module on the setup
  → Working with the software interface for data taking

- Analysis of the recorded data:
  → Implementation in C++/ROOT
  → Discussion with members of the collaboration

# Experimental setup

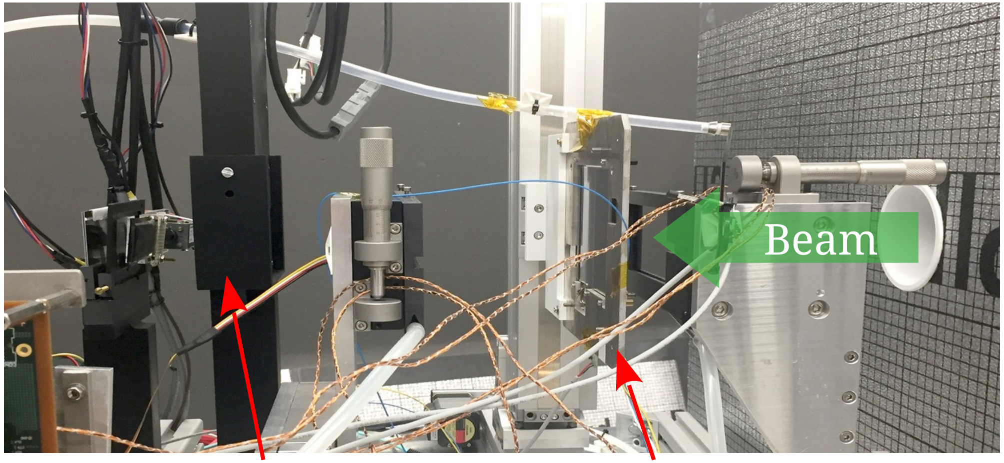
# The CYRCé cyclotron

Beam line dedicated to irradiation of sensors for tracker upgrade

- Beam of 25 MeV protons at adjustable intensities: from 1 fA to 100 nA

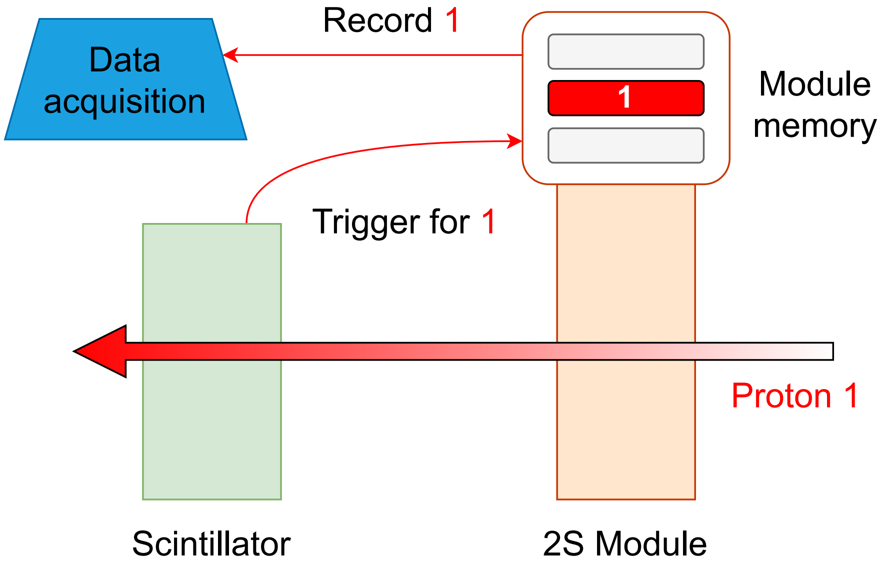
- Bunches of proton delivered at 85 MHz, frequency divided by 2: 42.5 MHz

# Setup inside the experimental box



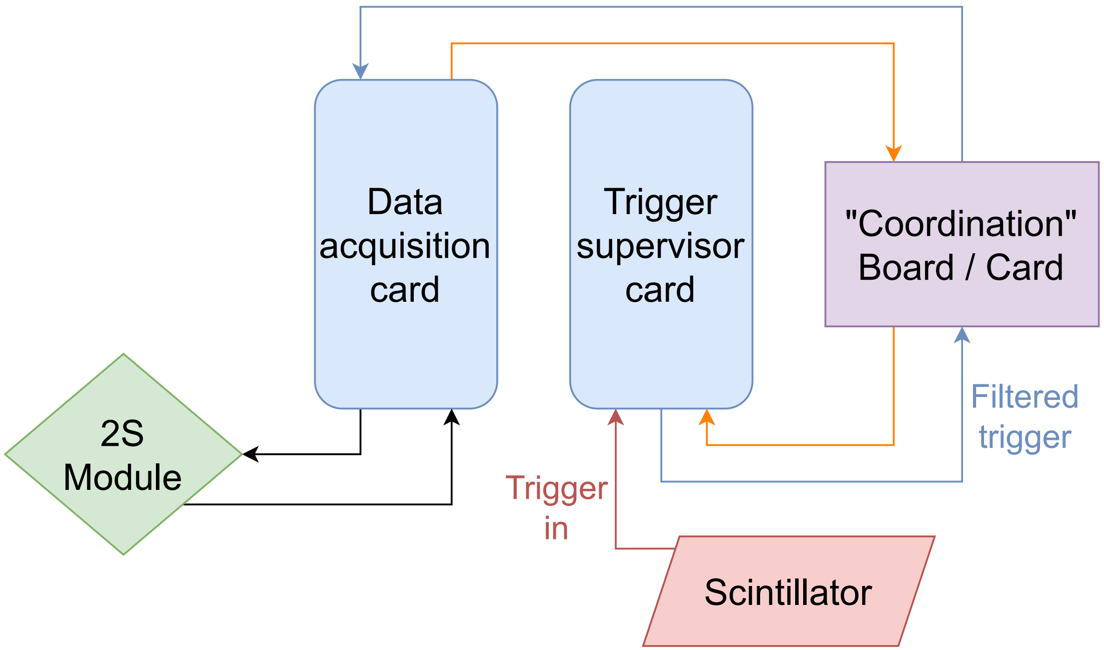

Scintillator

Detector under test:
2S module




- Monitoring temperature and humidity to avoid damage to the silicon sensors

# Data acquisition system

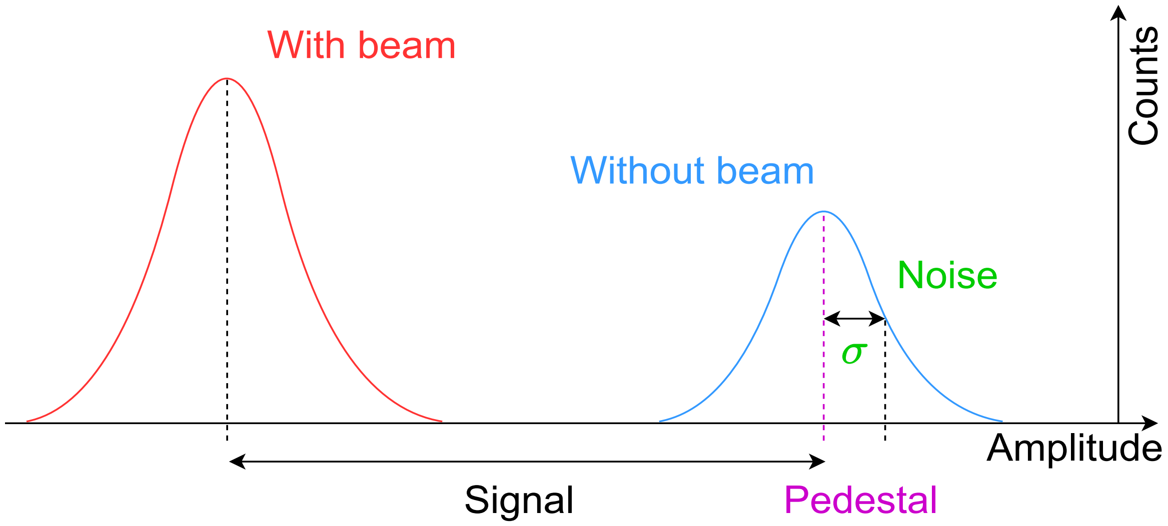


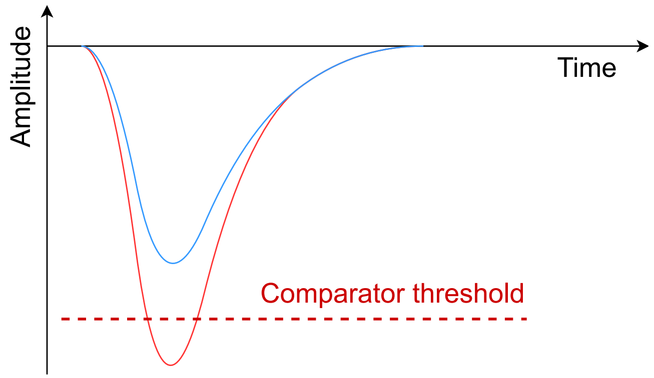

- The signal from the scintillator is filtered by a trigger supervisor system to keep the events compatible with a 40 MHz clock

# Calibrations : detection threshold

- The pedestal (or baseline) value is the average output obtained without the beam irradiating the module

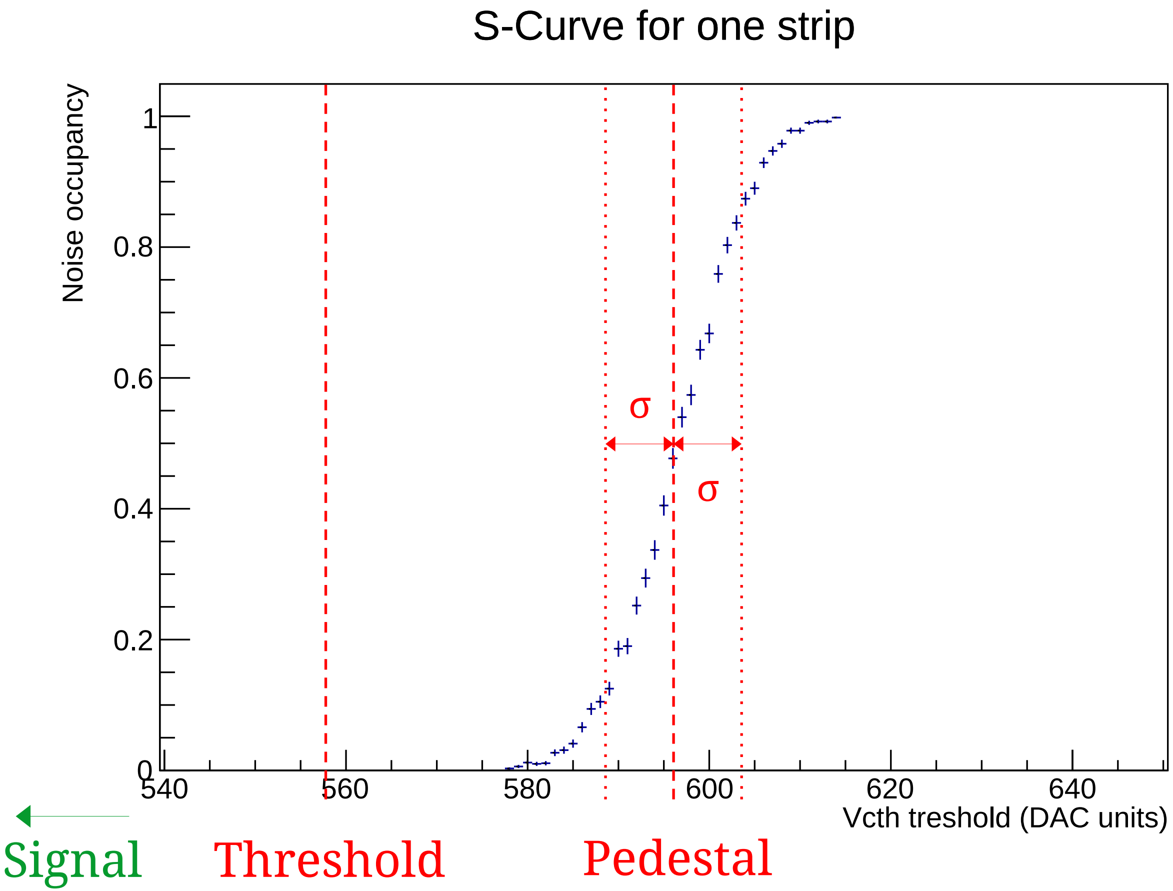
- The noise are the fluctuations around the pedestal



# Calibrations : detection threshold

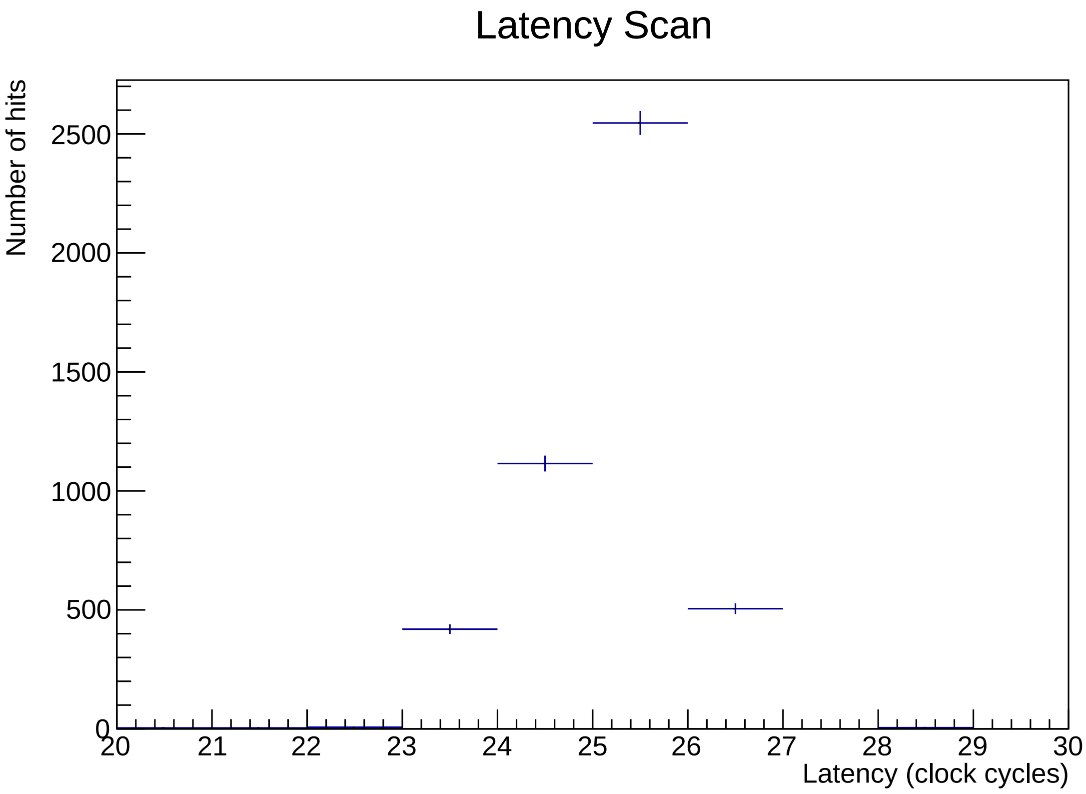
- The pedestal and noise can be determined from an S-curve
- The threshold is set to detect signals 5σ above the pedestal
- Expressed in *Vcth* DAC units, a lower *Vcth* value corresponds to a higher threshold



# Calibrations : latency

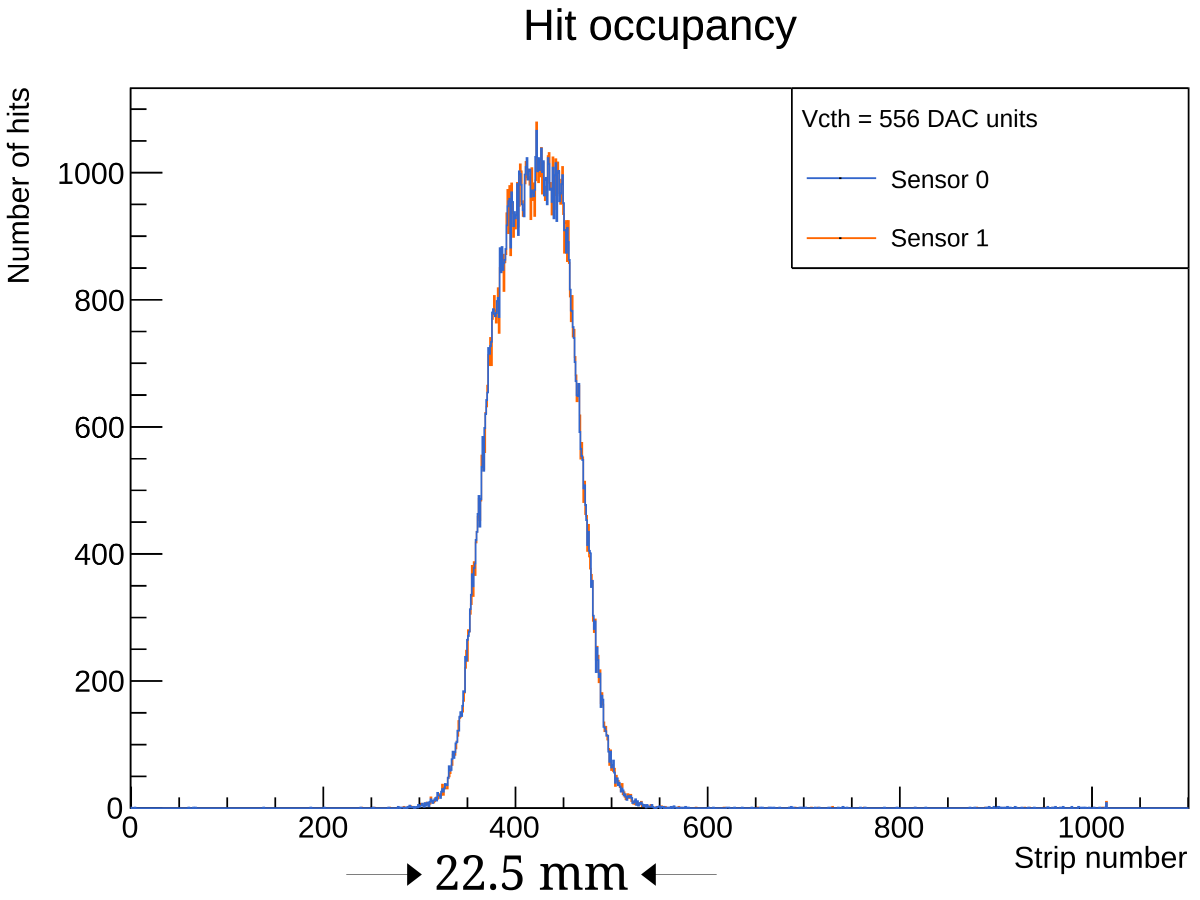
- The latency: delay between the detection of a proton by the scintillator and the reception of the trigger signal by the module

- Expressed in 40 MHz clock cycles (units of 25 ns)



# Results

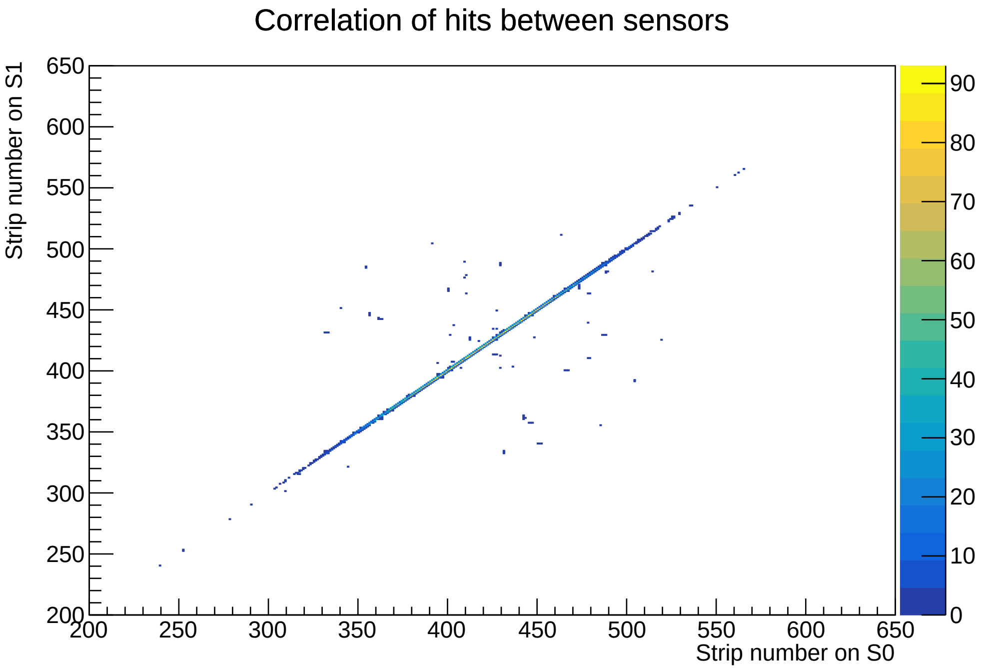
# Beam profile

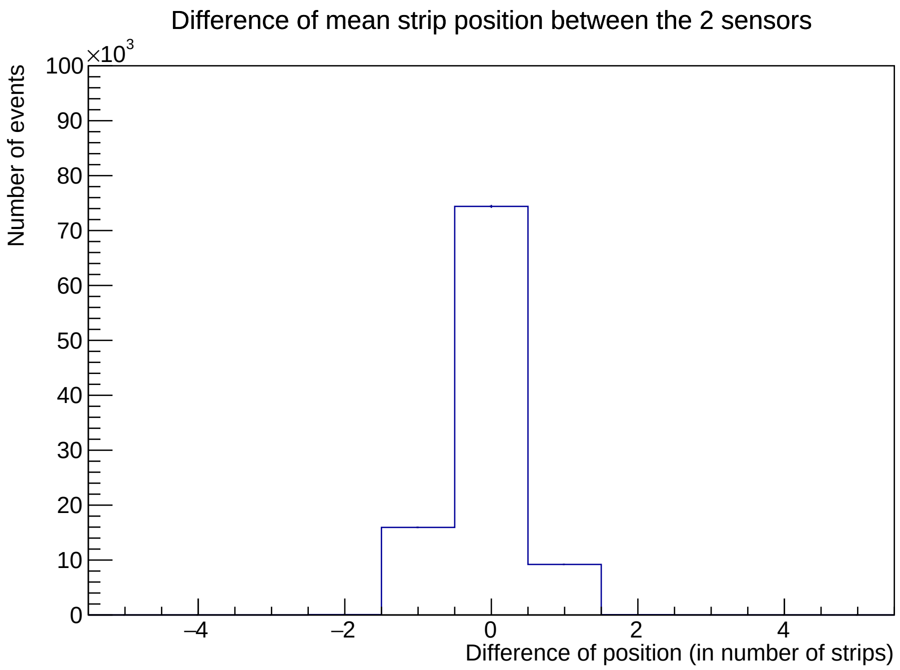



- Beam hitting 250 strips: spreading on two read-out chips

- Beam profile as expected from beam line diagnostics

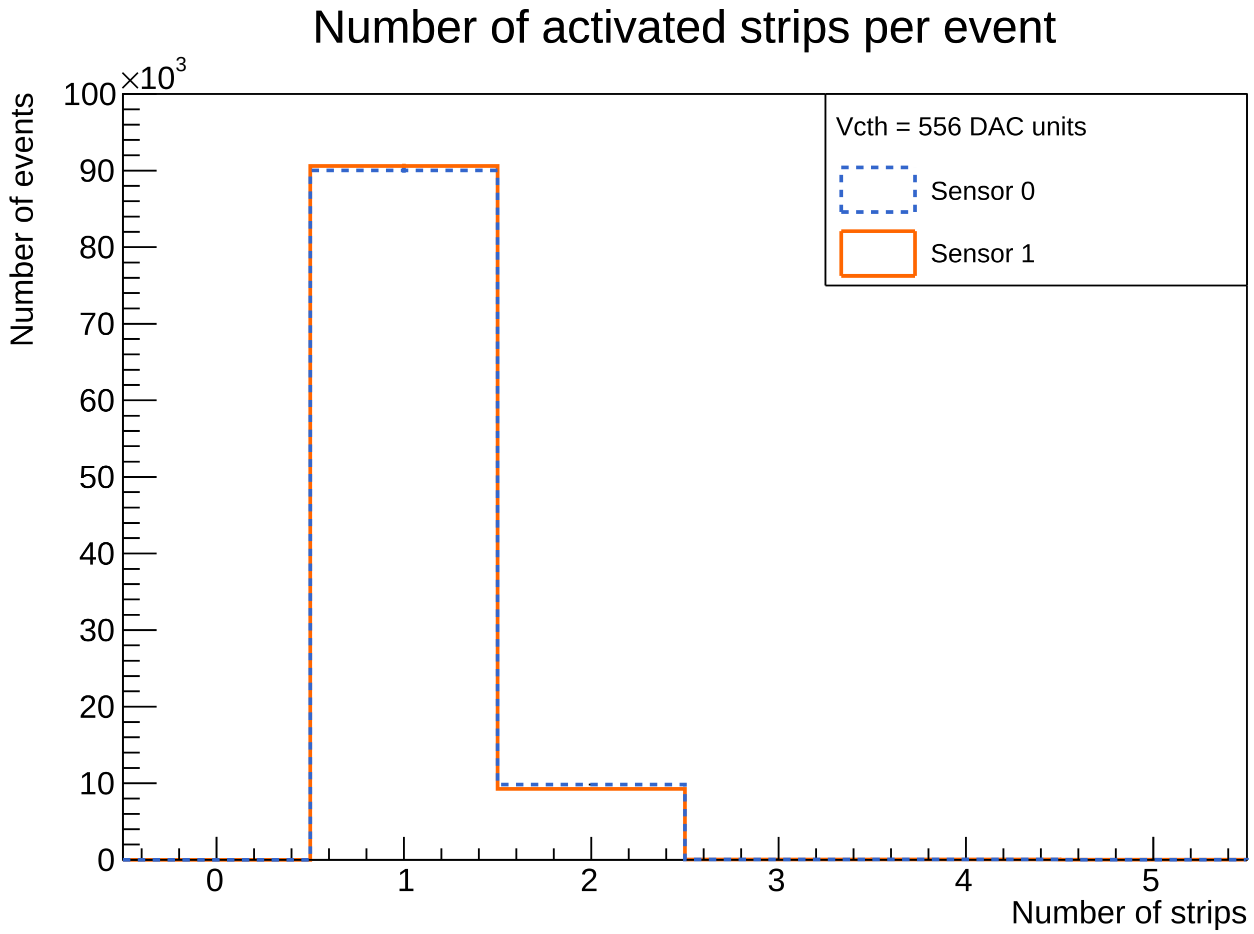
# Correlation of hits between the two sensors




- As expected from multiple scattering effect, the position can differ up to 1 strip

# Number of activated strips per event




- Large energy deposition by 25 MeV protons: Expecting 3 ~ 4 activated strips per event from previous results

- Peak at 1 strip per event

# Detector efficiency

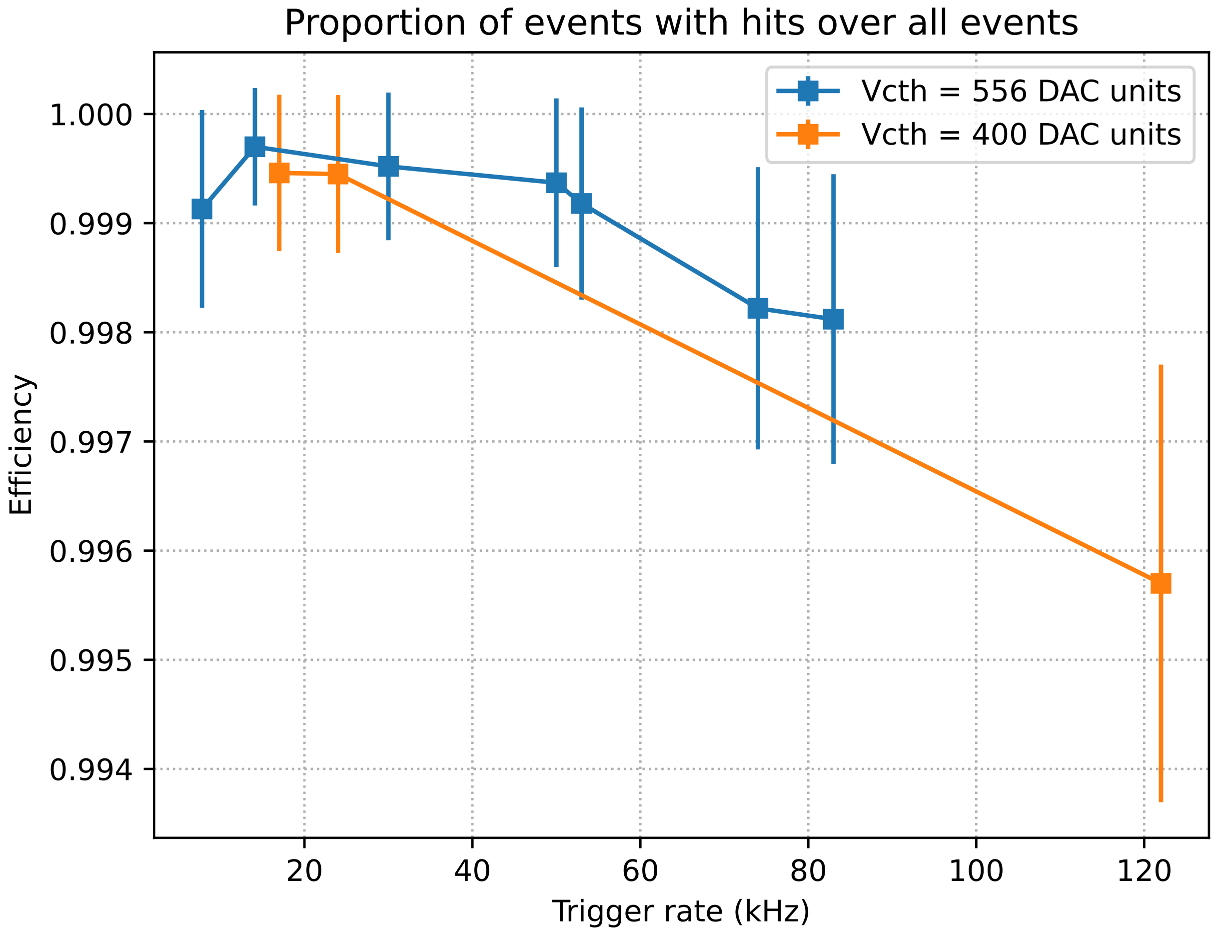
- Increasing gradually the intensity of the beam, and so the rate
  → Test the module up to high rates (~ 750 kHz)

- Assess the efficiency of the module as function of the trigger rate

$$E = \frac{number\ of\ events\ with\ recorded\ hits}{total\ number\ of\ triggered\ events}$$

- The test was done for two threshold values

# Detector efficiency




- Above 99 % for this range of rate
- Decreasing with trigger rate for the higher threshold
- Problem limiting data taking to ~ 100 kHz

# Conclusion

# Discussion

- Other facilities observed the same problem with the data acquisition system
  → Once the problem is fixed, the tests will be performed again

- Unexpected low number of activated strips per events: problem of threshold calibration
  → More systematic tests to better understand the impact of the threshold on the number of activated strips

# Conclusion

- Learn the functioning of a module and the associated data acquisition system and conduct beam tests

- Current data acquisition system is not suitable for high rates tests

- Efficiency of the module above 99 % for the range of accessible rates

→ Another series of tests with the fixed data acquisition system

# References


- [1] K. Klein et al, 2017, *‘ The Phase-2 Upgrade of the CMS Tracker ’*

- [2] W. Adam et al, 2020,
  *‘ Beam test performance of prototype silicon detectors for the Outer Tracker for the Phase-2 Upgrade of CMS ’*

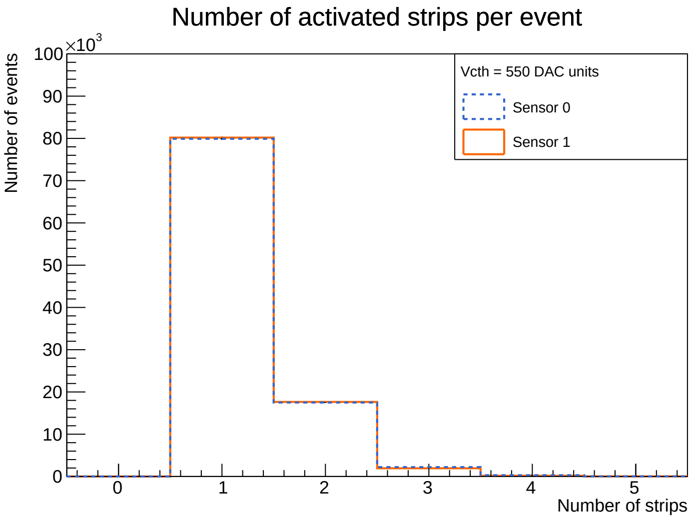
- [3] Frank Hartmann, 2017,
  *‘ Evolution of Silicon Sensor Technology in Particle Physics ’*

- [4] H. Kolanoski, N. Wermes, 2020,
  *‘ Particle Detectors: Fundamentals and Applications ’*

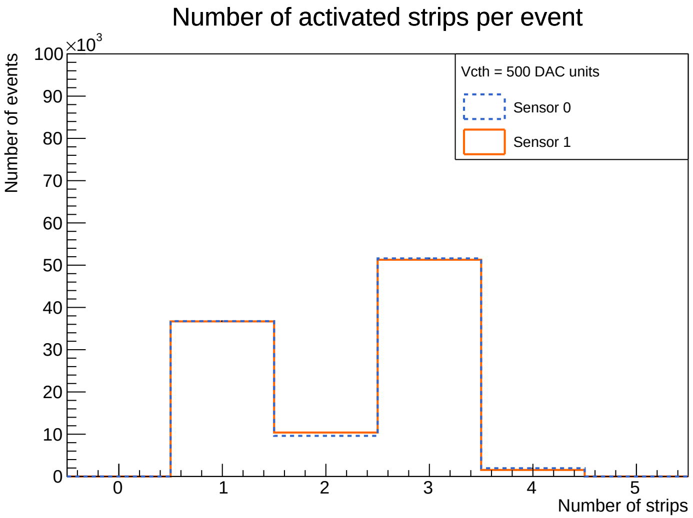
- [5] T. Ullrich, Z. Xu, 2007, *‘ Treatment of Errors in Efficiency Calculations ’*

# Backup

# Threshold scan




*Vcth* = 550 DAC Units

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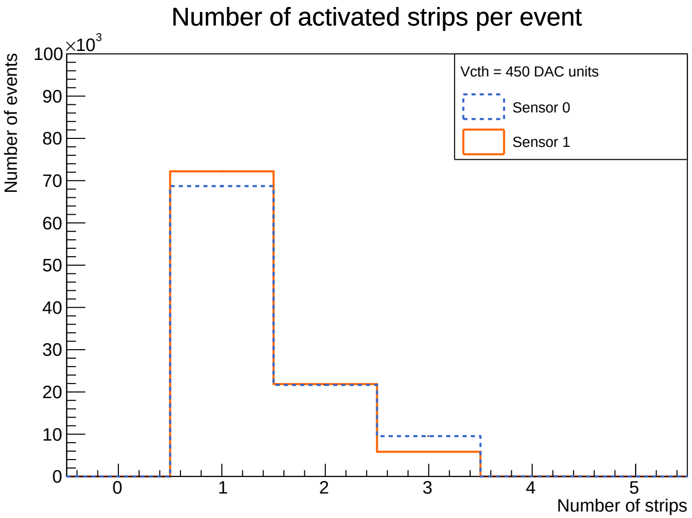
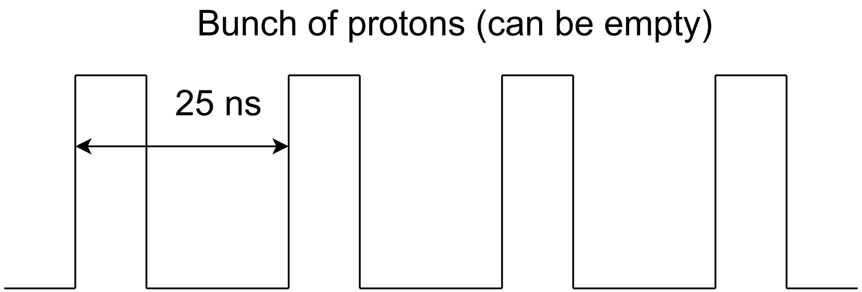



*Vcth* = 450 DAC Units

- Surprising peak at 3 activated strips per event for *Vcth* = 500 DAC units

# Bunch crossing Id

- Bunches of particles crossing at a frequency of 40 MHz (crossing every 25 ns)
  → For CYRCé, each clock cycle corresponds to a bunch of protons sent by the cyclotron



# Bunch crossing Id

- Bunches of particles crossing at a frequency of 40 MHz (crossing every 25 ns)
  → For CYRCé, each clock cycle corresponds to a bunch of protons sent by the cyclotron

- Bunch crossing Id: numerical value associated to the corresponding clock cycle

- The trigger supervisor keeps tracks of the trigger signals sent to the module by counting the bunch crossing Id

# Matching of events with the trigger supervisor

- Check that the trigger signals sent by the trigger supervisor were correctly received by the module

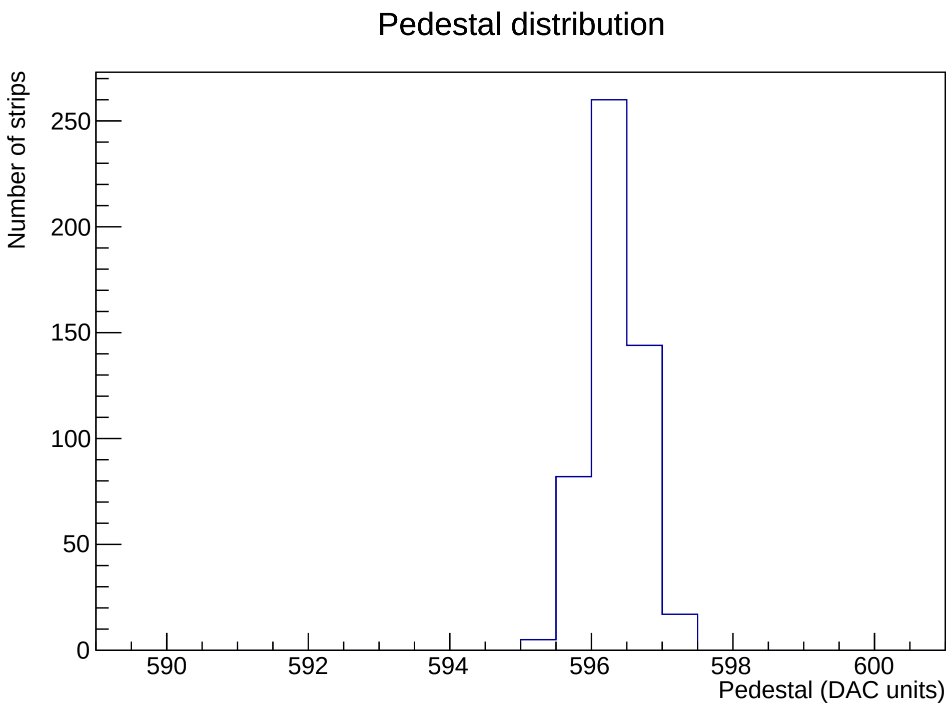
- Bunch crossing Id values counted by the trigger supervisor and the data acquisition system were matched
  → However, they are not synchronous when counting the bunch crossing Id values

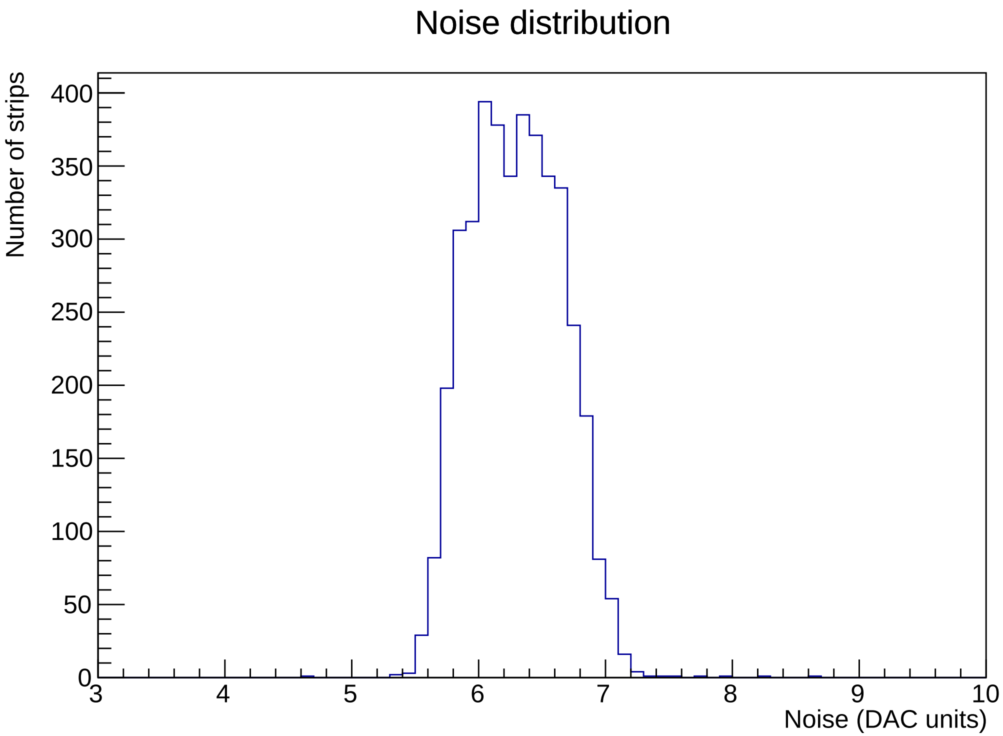
- Matching indirectly, by comparing the difference between consecutive bunch crossing Id values

# Matching of events with the trigger supervisor

| Data acquisition system | Difference | Trigger supervisor |
| --- | --- | --- |
| 208 | - | 2373 |
| ------------------------------ | 452 --- 452 | ------------------------------ |
| 660 | - | 2825 |
| ------------------------------ | 529 --- 529 | ------------------------------ |
| 1189 | - | 3354 |
| ------------------------------ | 209 --- 741 | ------------------------------ |
| 1398 | | 4095 |

# Pedestal and noise distributions



# Crate picture