# Test-beam with the cyclotron CYRCé for the upgrade of the CMS tracking detector

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dépasser les frontières

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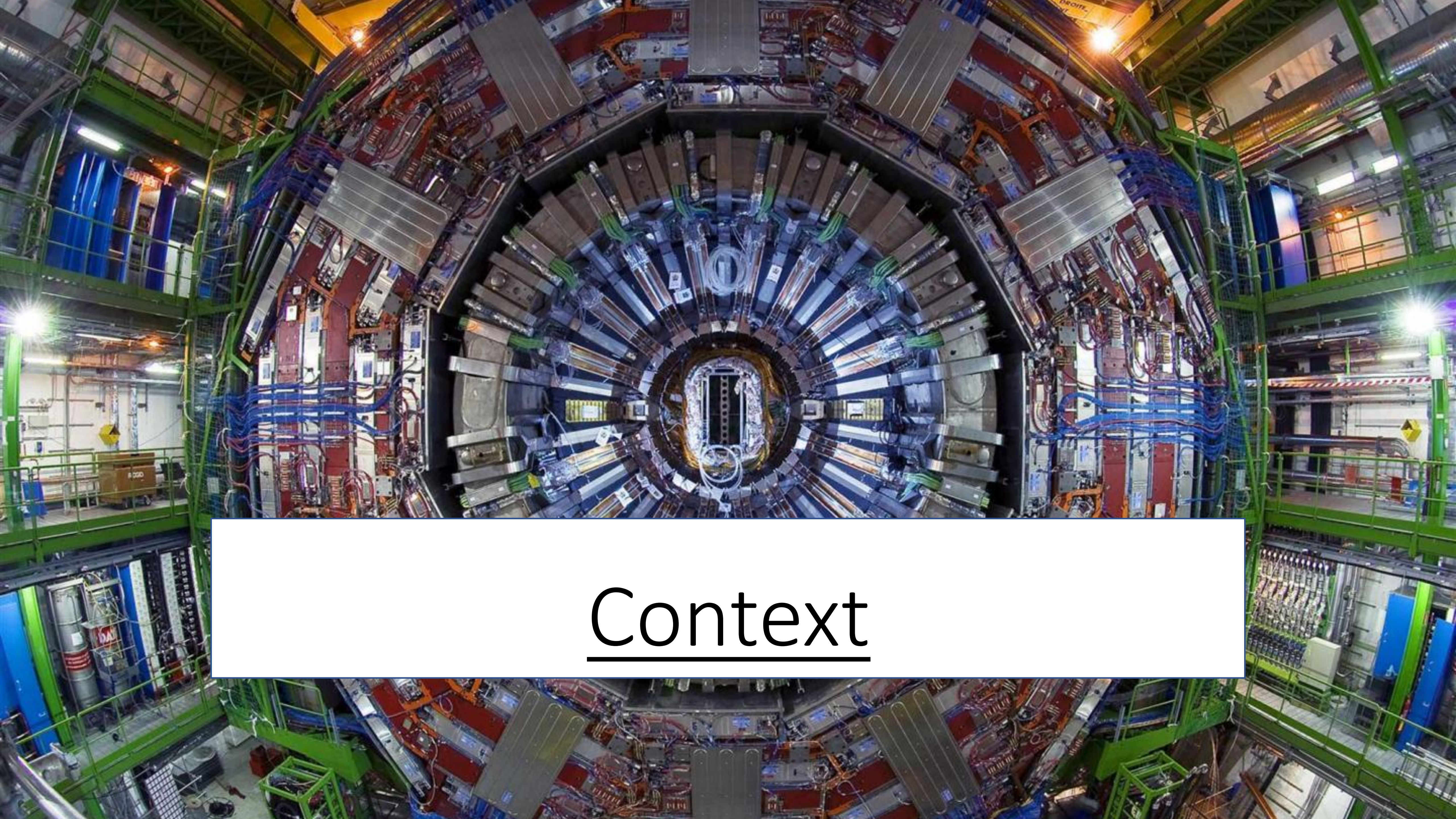
# Summary

- Context
  - The LHC and CMS
  - Upcoming upgrade
- Experimental aspects
  - What is a tracker
  - The modules
  - CMS line at cyclotron CYRCé
- Calibration, beam tests and results



# Context

# LHC and CMS

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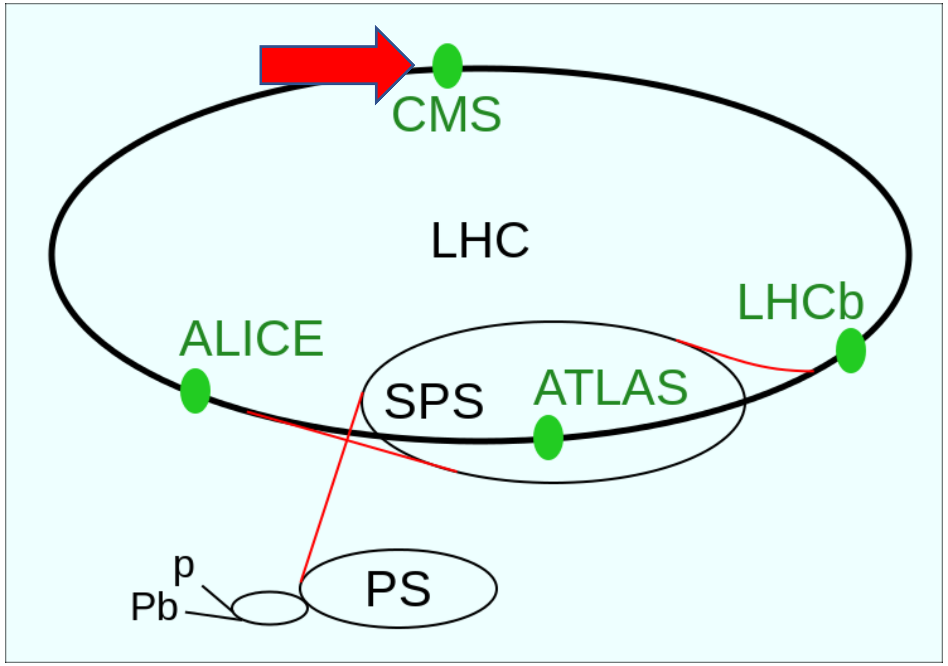
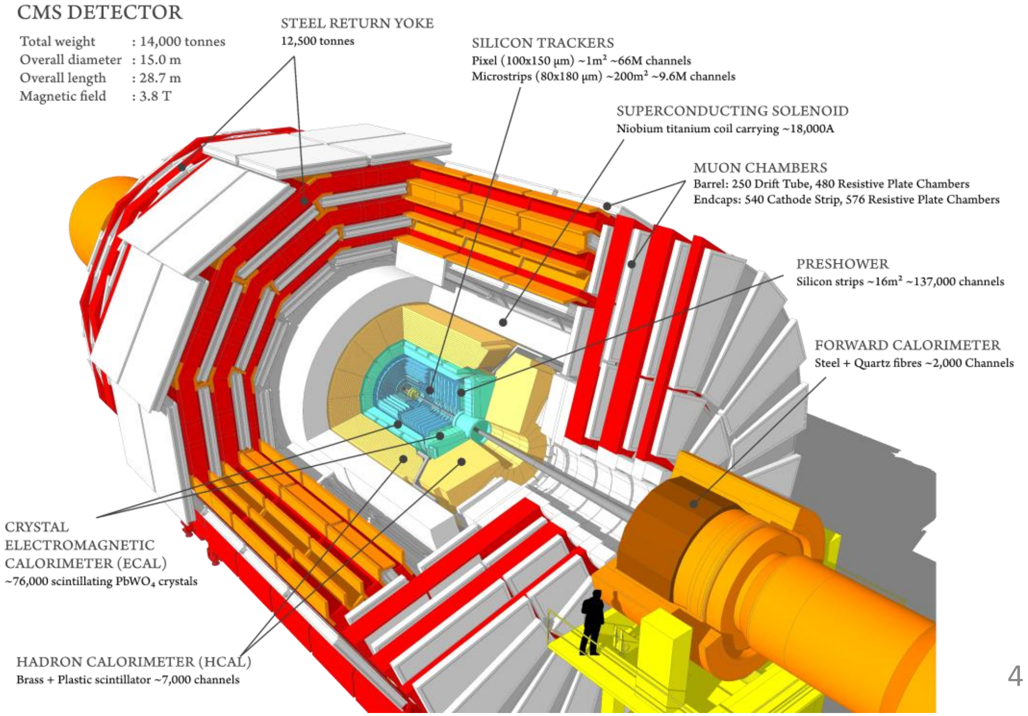
- LHC (Large Hadron Collider): E~14TeV, ($10^{11}$) protons crossing every 25ns
- CMS (Compact Muon Solenoid): detector used for particle physics researches



# High-Luminosity LHC

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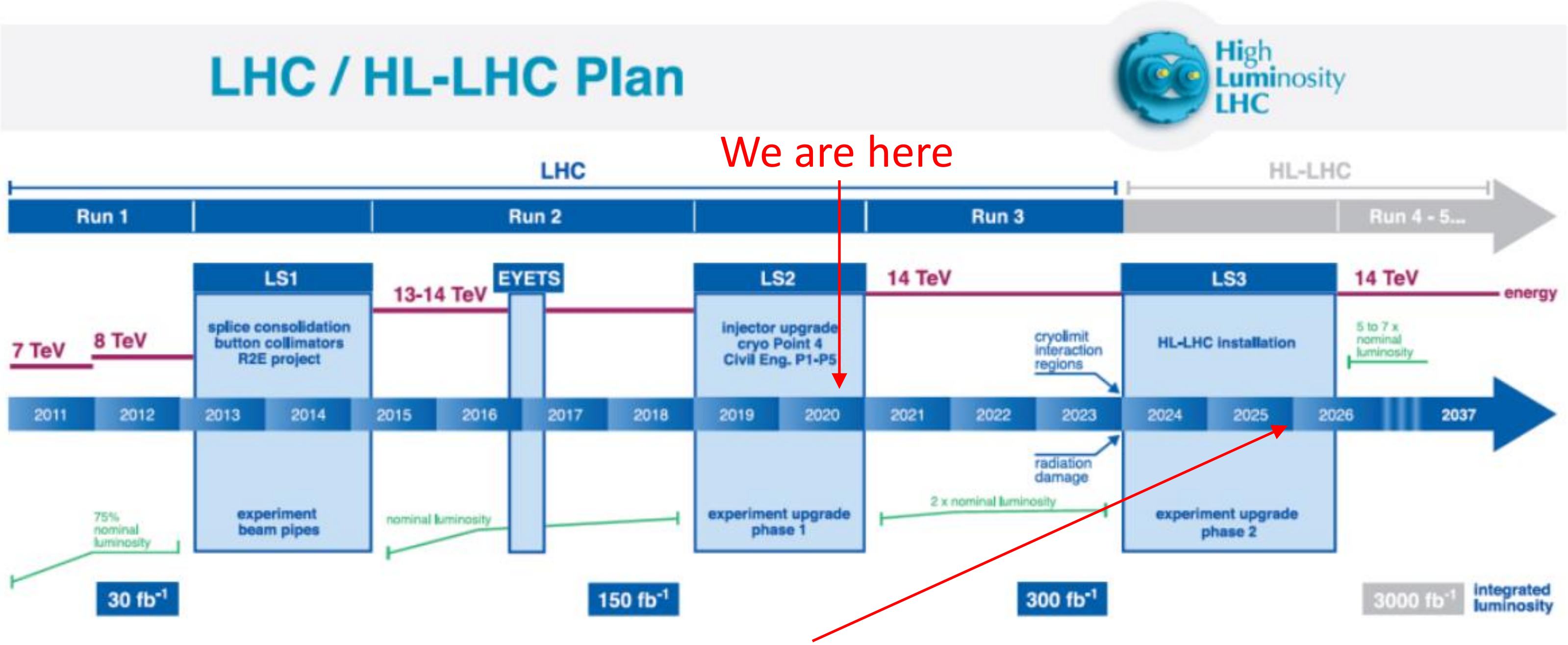
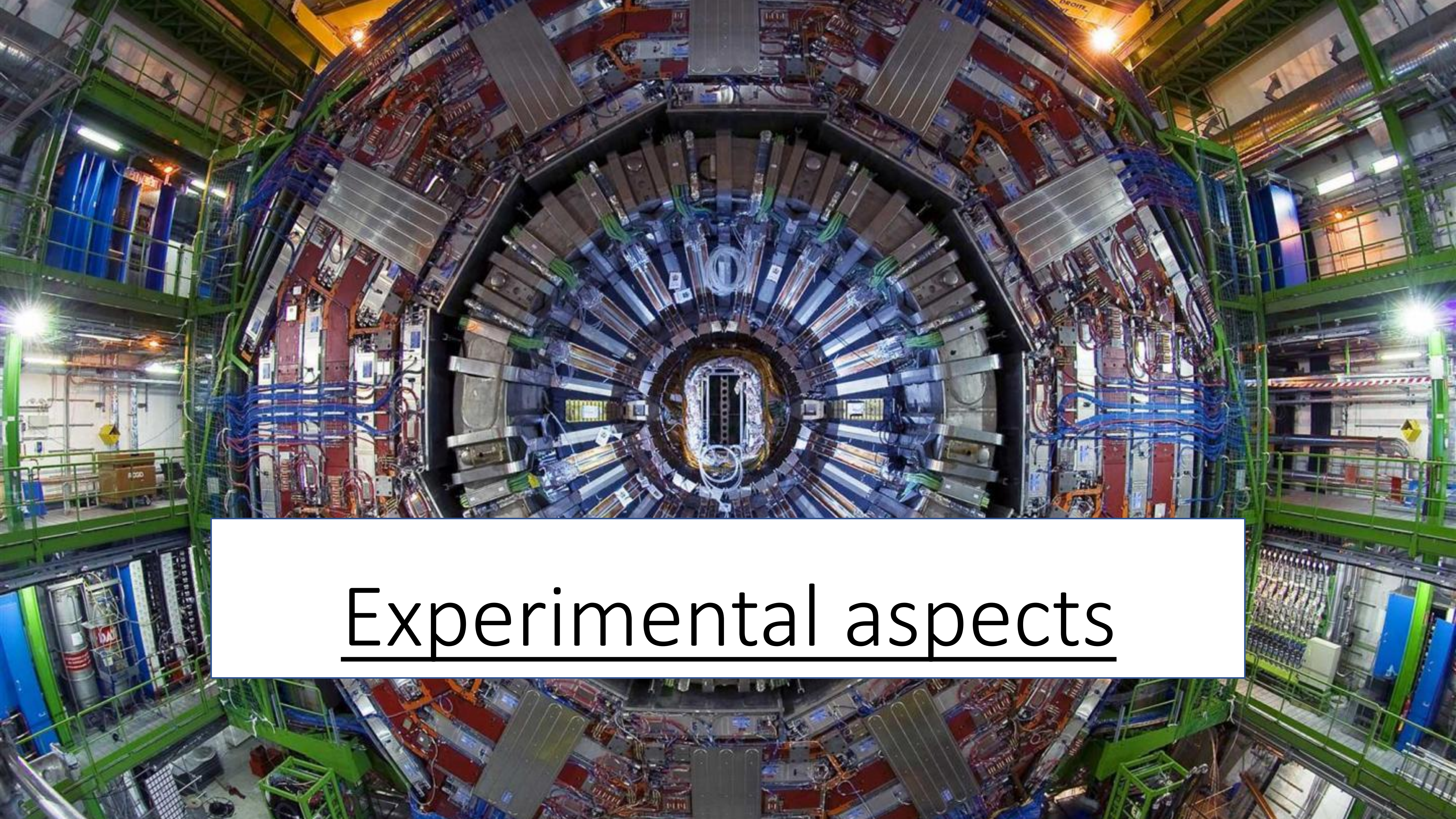



2026: LHC -> HL-LHC (luminosity up to 5 or 7 times the nominal luminosity)

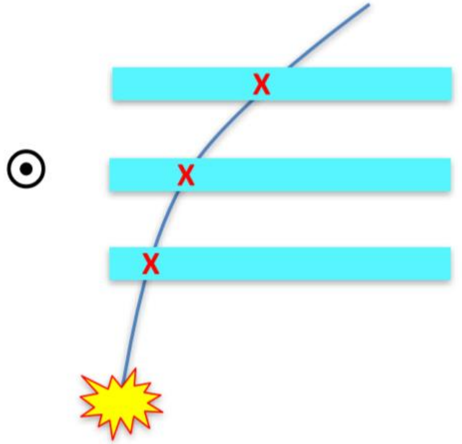
New challenges: trackers will contribute to L1 -> fast electronics needed, they will also have to resist to a way greater amount of radiation



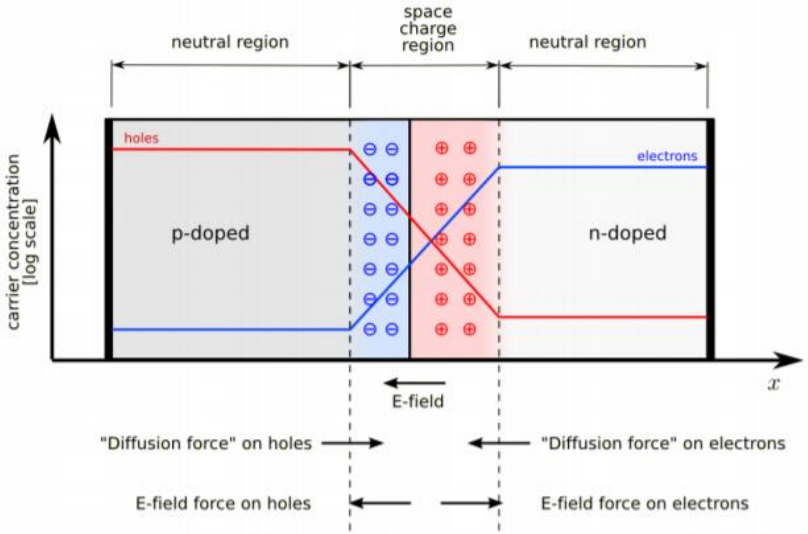
# Experimental aspects

# What is a tracker ?

- The charged particle will pass through many layers of detection and « hit » the different modules (here in silicon, semi-conductor)
- It will be deflected thanks to a magnetic field: $p_T = qBR$
- Electric signal of the particle: « amplified » by the help of a p-n junction



Working principle of a tracker



# CMS tracking detector for the HL-LHC: the new modules

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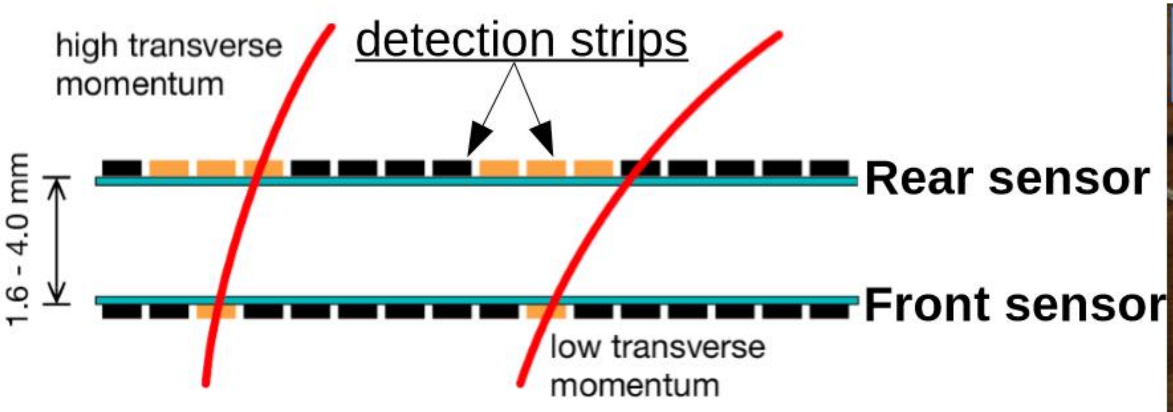
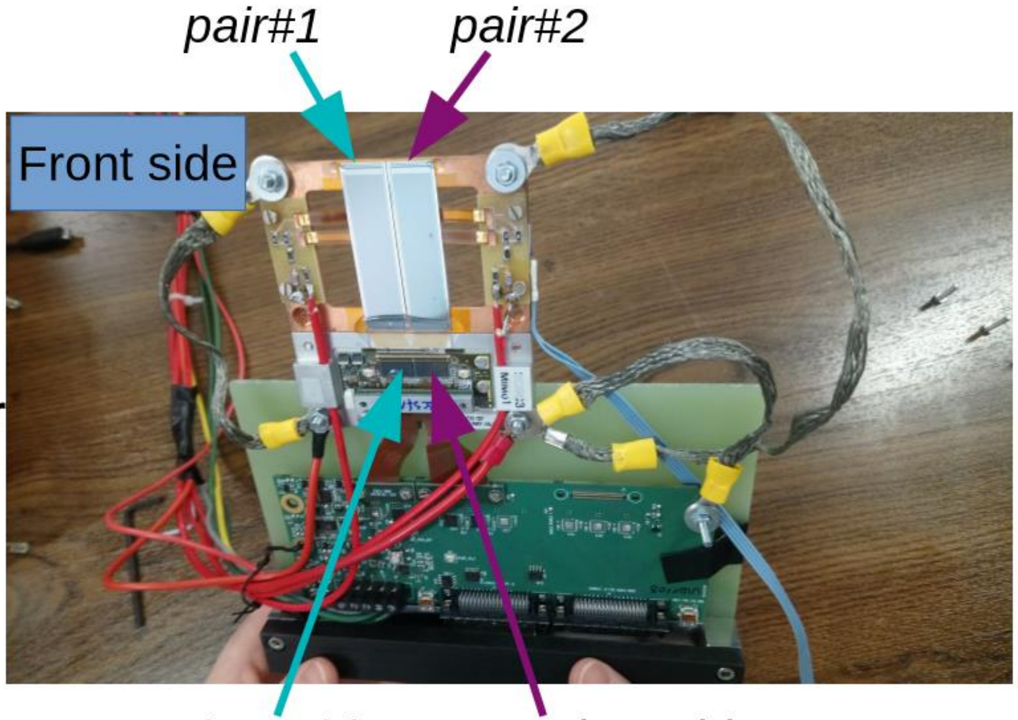



127 detection strips per sensor

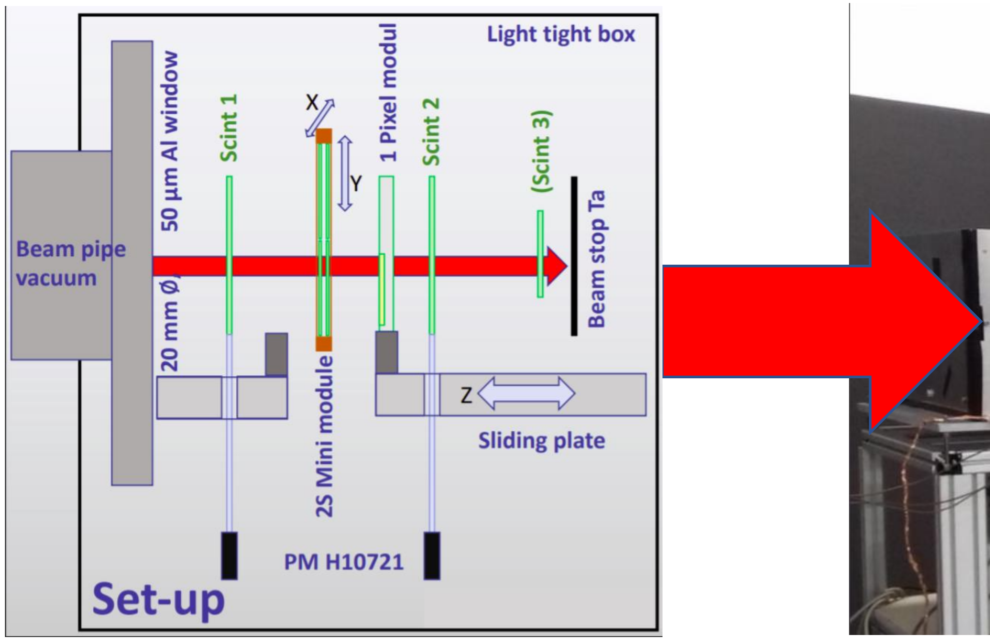
1 readout chip per pair of sensors

We are working with 2 pairs of sensors

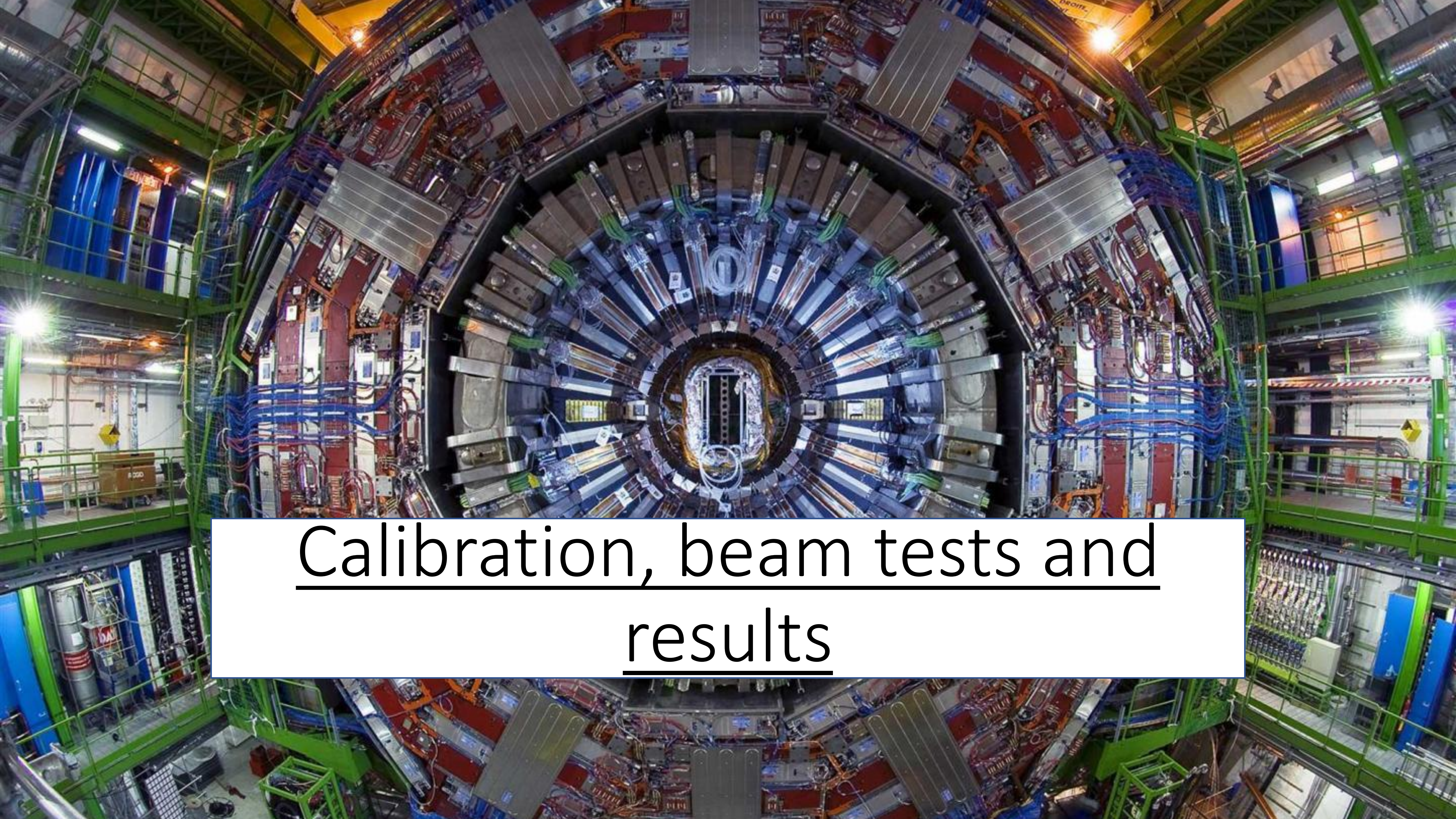


# CMS line at cyclotron Cyrcé

- Proton beam at 25 MeV
- Quadrupoles acting like lenses on the beam
- Steerer to control the direction of the beam (left/right, up/down)



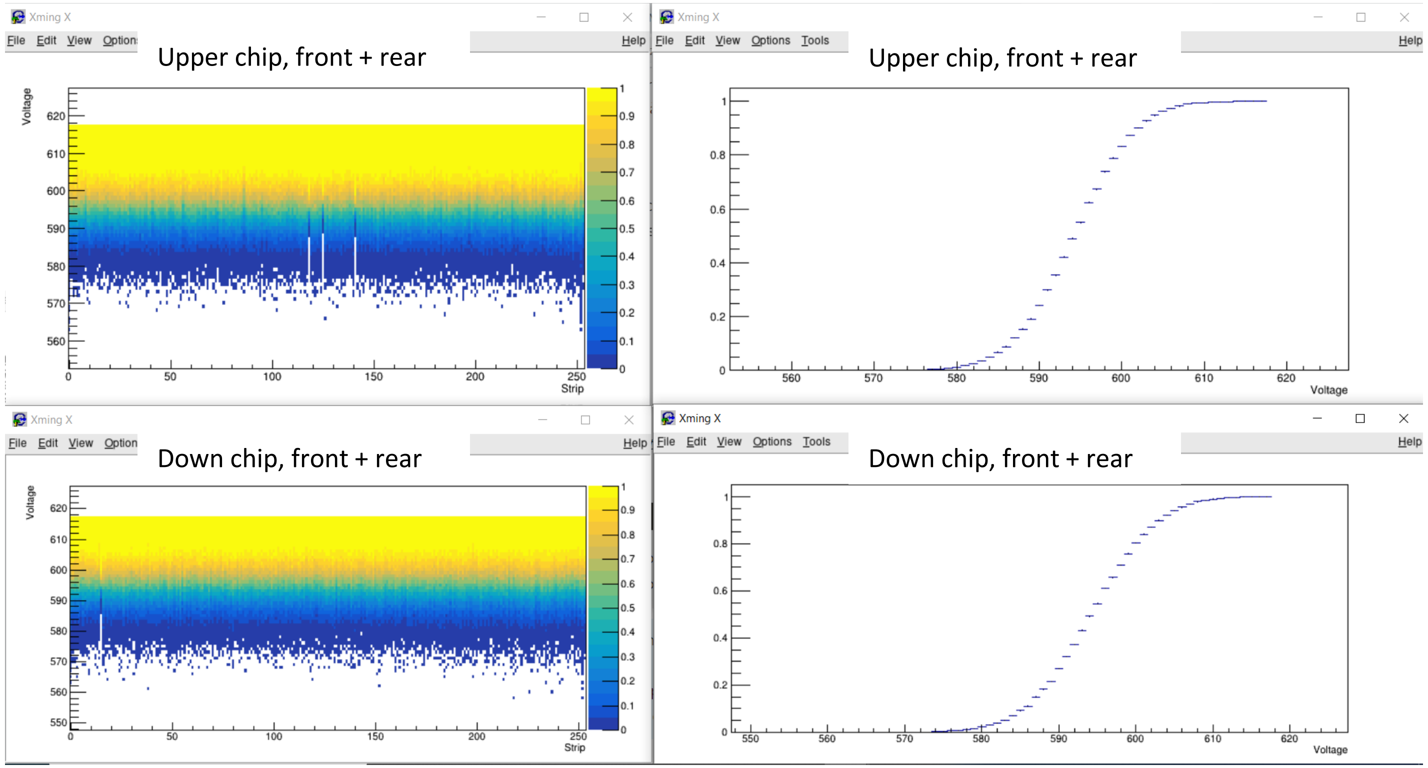

# Calibration, beam tests and results



# Calibration



- Measure of the electrical noise as a function of the applicated voltage for each detection strip
- Gives us the detection threshold
- S curves centered on the pedestal previously chosen




Example of S curves at 400V

# Observations: high voltage and calibration

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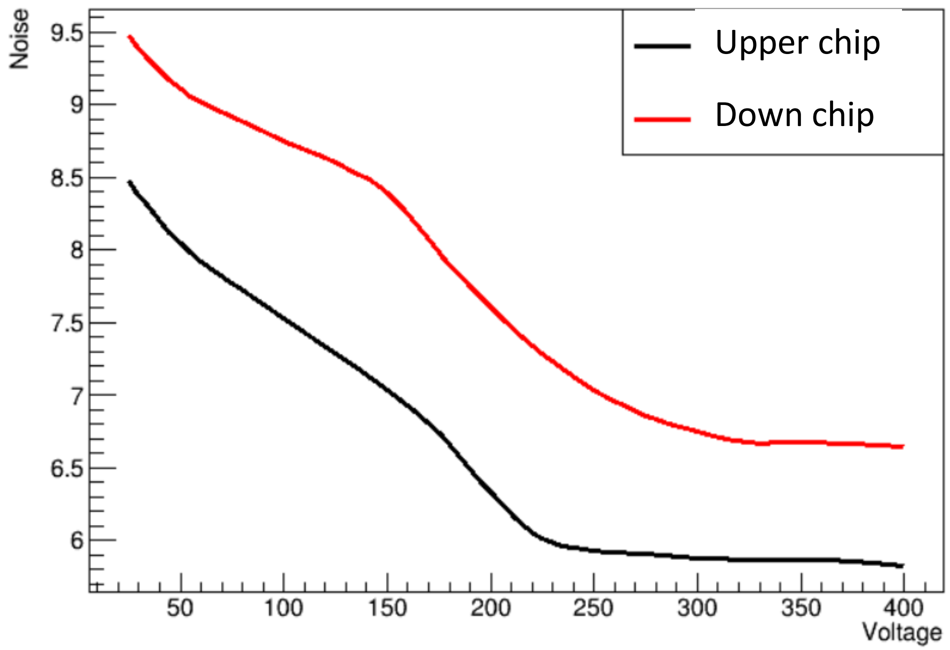
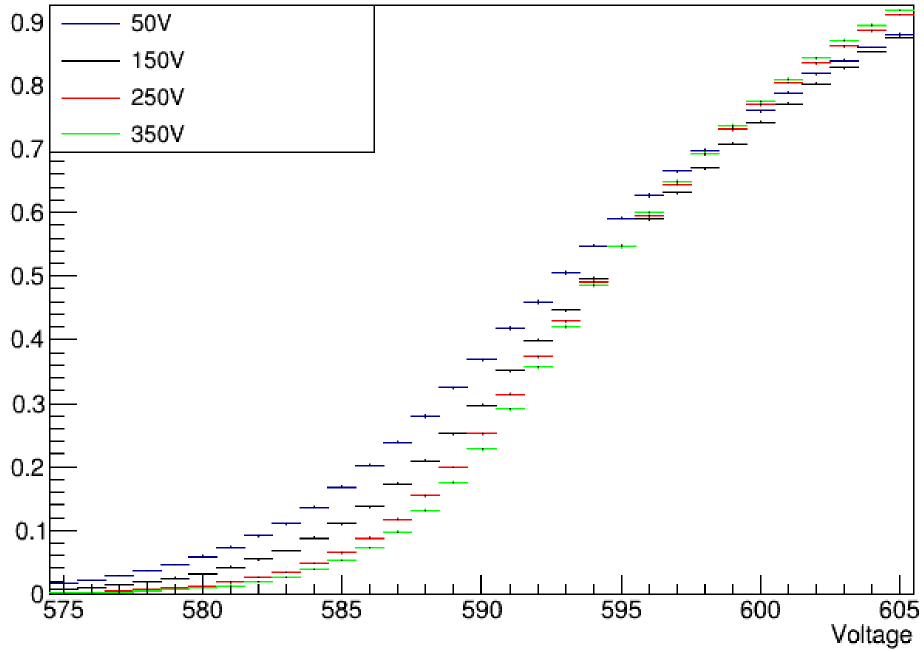
Evolution of the electrical noise as we increase the high-voltage




Evolution of the S curve as we increase the high-voltage



# Beam test: the quadrupoles

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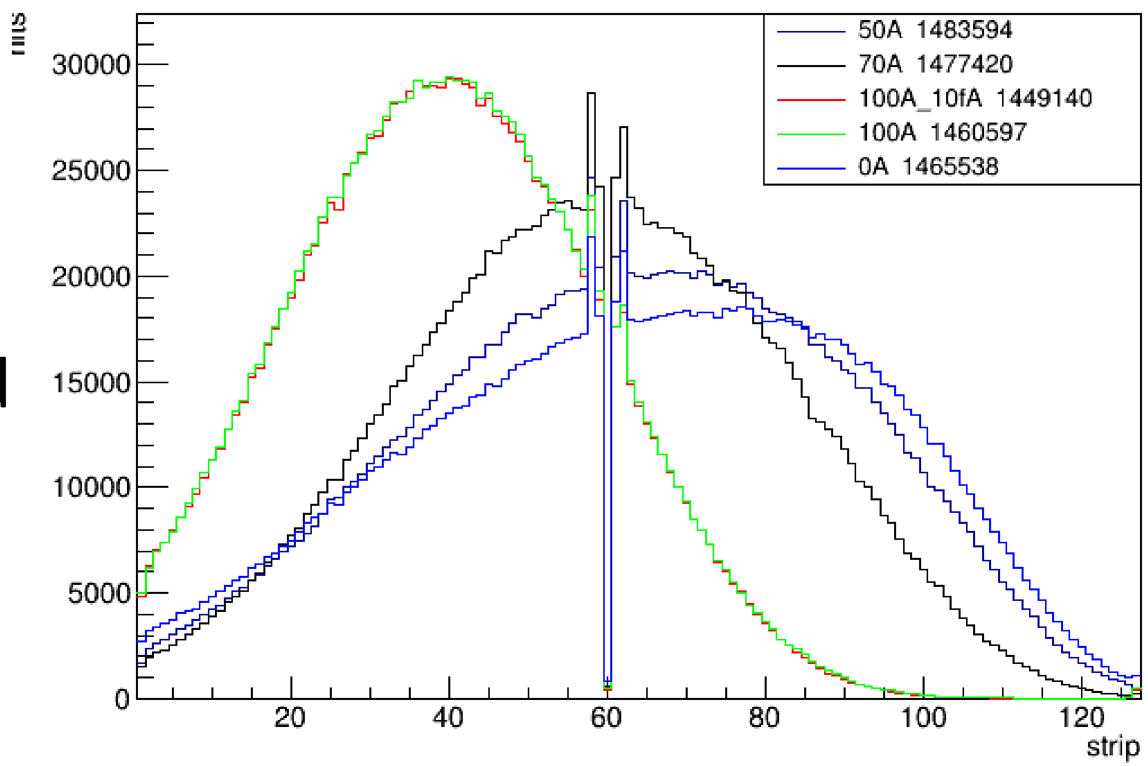
- Number of hits on each detection strip
- Beam collimated by the quadrupoles
- Low intensities: beam shifted downwards ?

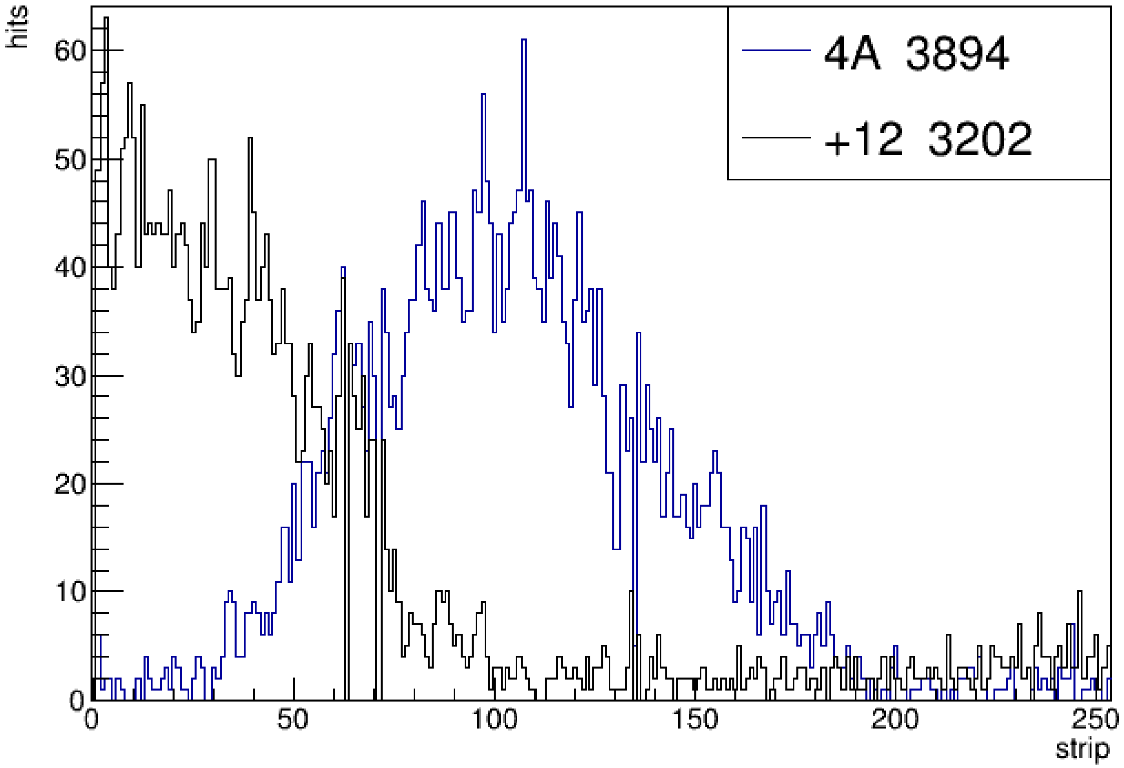
Upper chip, front sensor



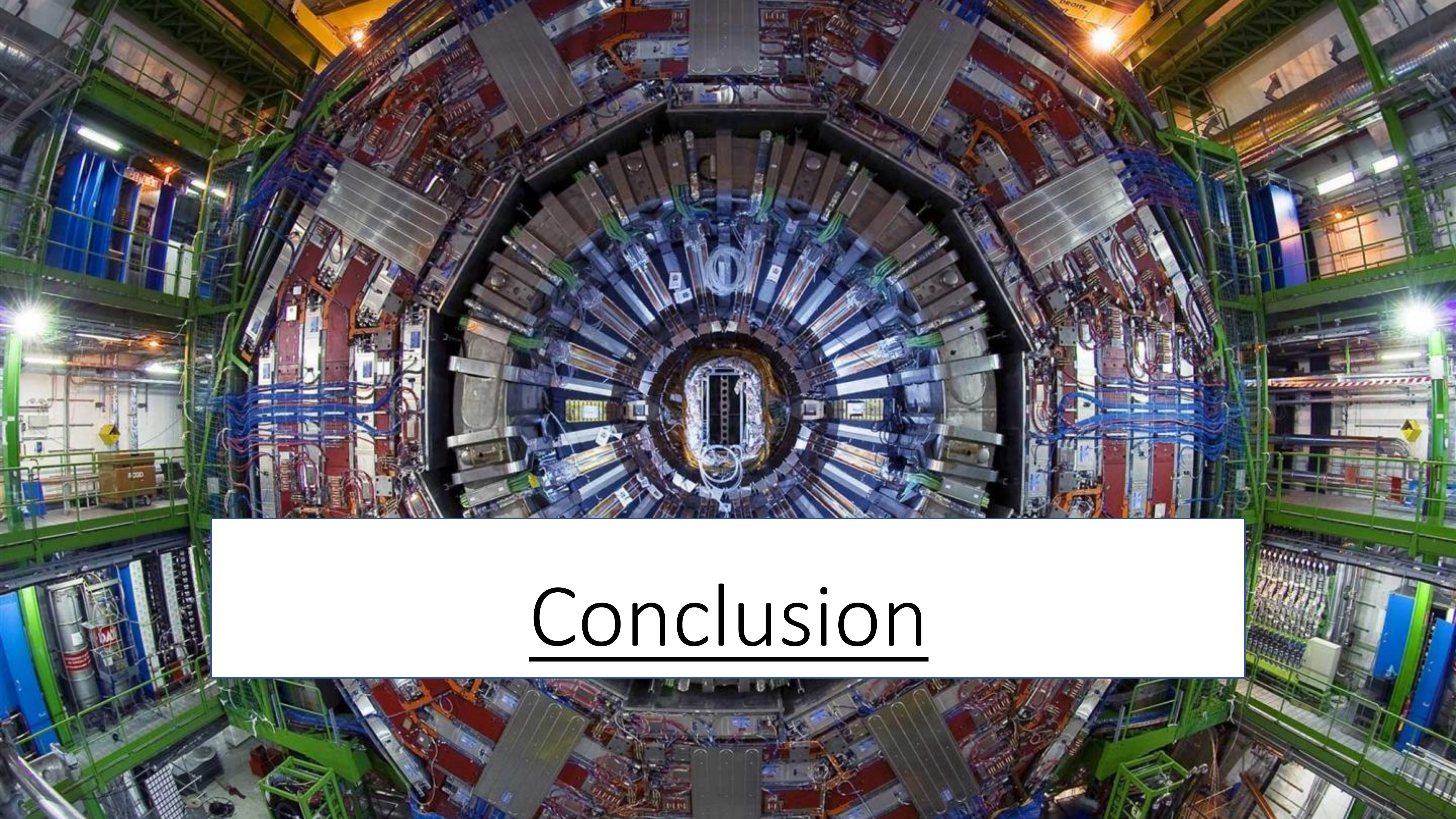
# Beam test: the steerer

- Vertical position of the beam for two different intensities of the steerer: -4A and +12A
- Other intensities have been tested
- Steerer intensity increased -> Beam shifted upwards

Rear sensor, up and down chips



# Conclusion



# What did I do ? Why is it important ?

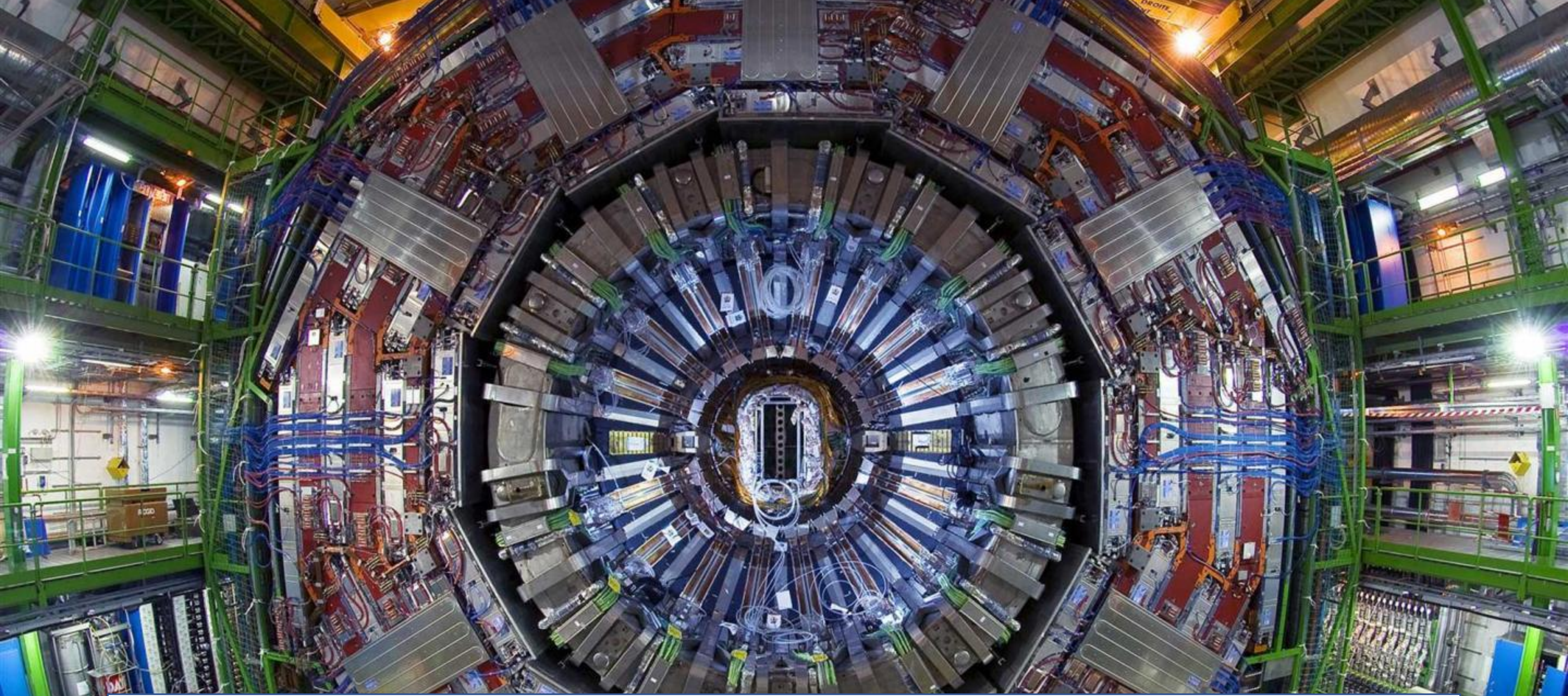
- At CYRCé:
  - Calibration of the new modules at different voltages (-> avoid bias due to noise)
  - Beam tests with many different settings (-> learn about the behavior of the beam and the modules' response)
  - Recordings of data from the beam tests
- At the office:
  - Analysis of data recorded at CYRCé
  - Writting codes to help and ease the analysis, make comparisons and highlight important phenomena
- During the quarantine:
  - Theory
  - This presentation

# What did I learn ?

- At CYRCé:
  - How beam tests actually look like
  - How are physicists of the CMS team preparing to the HL-LHC upgrade
  - How do silicon detection modules work
- At the office:
  - How to interprete different types of data
  - How to analyse these data using ROOT
  - How to program using ROOT tool (in C++ language)

# Prospects

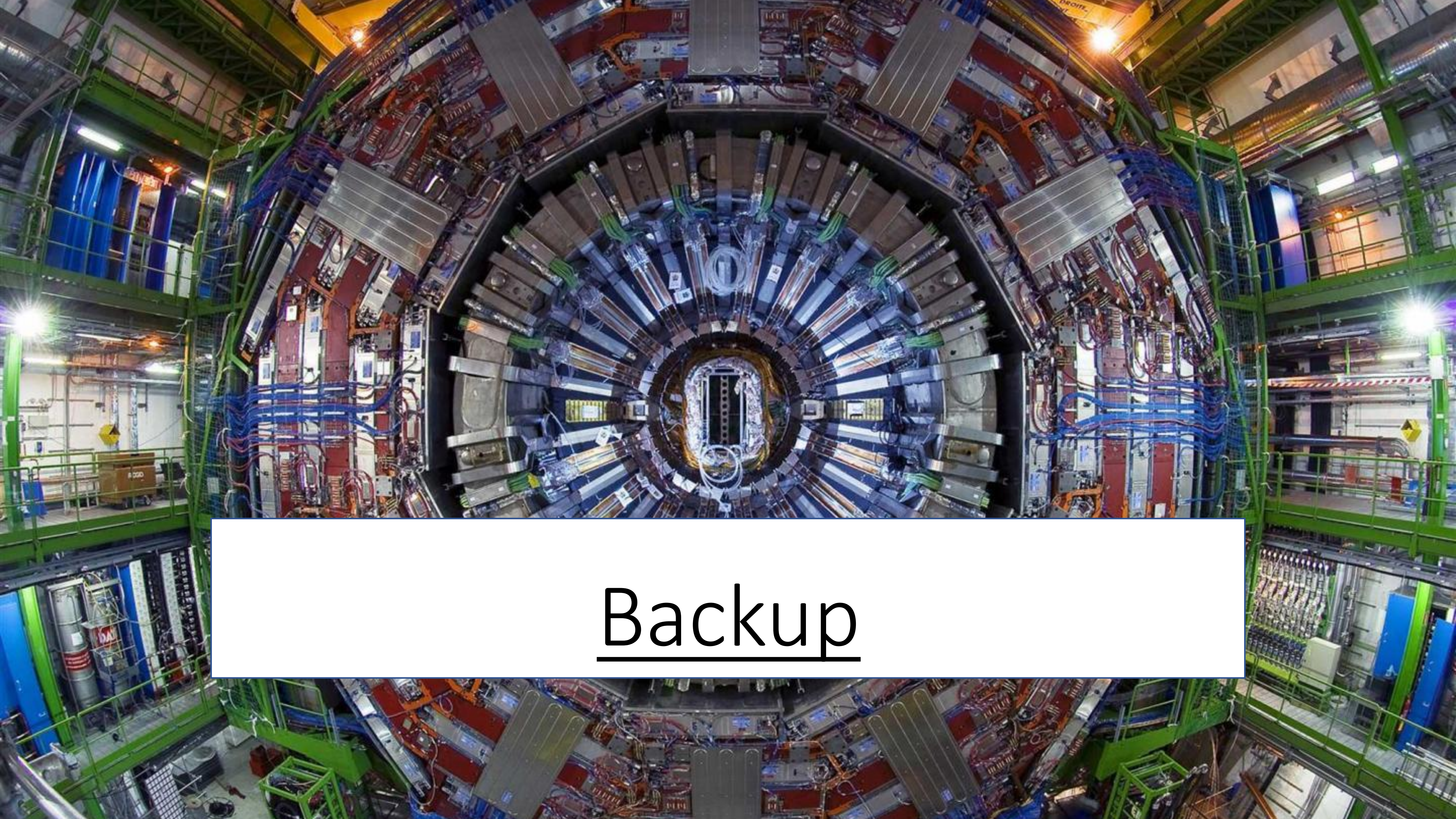
- What could have been done or could be done in the future ?
  - Beam tests with higher rates
  - Tests with several modules
  - Try to get a better sight of the beam’s profile by having it more centered on the modules



Thanks for listening !

# References

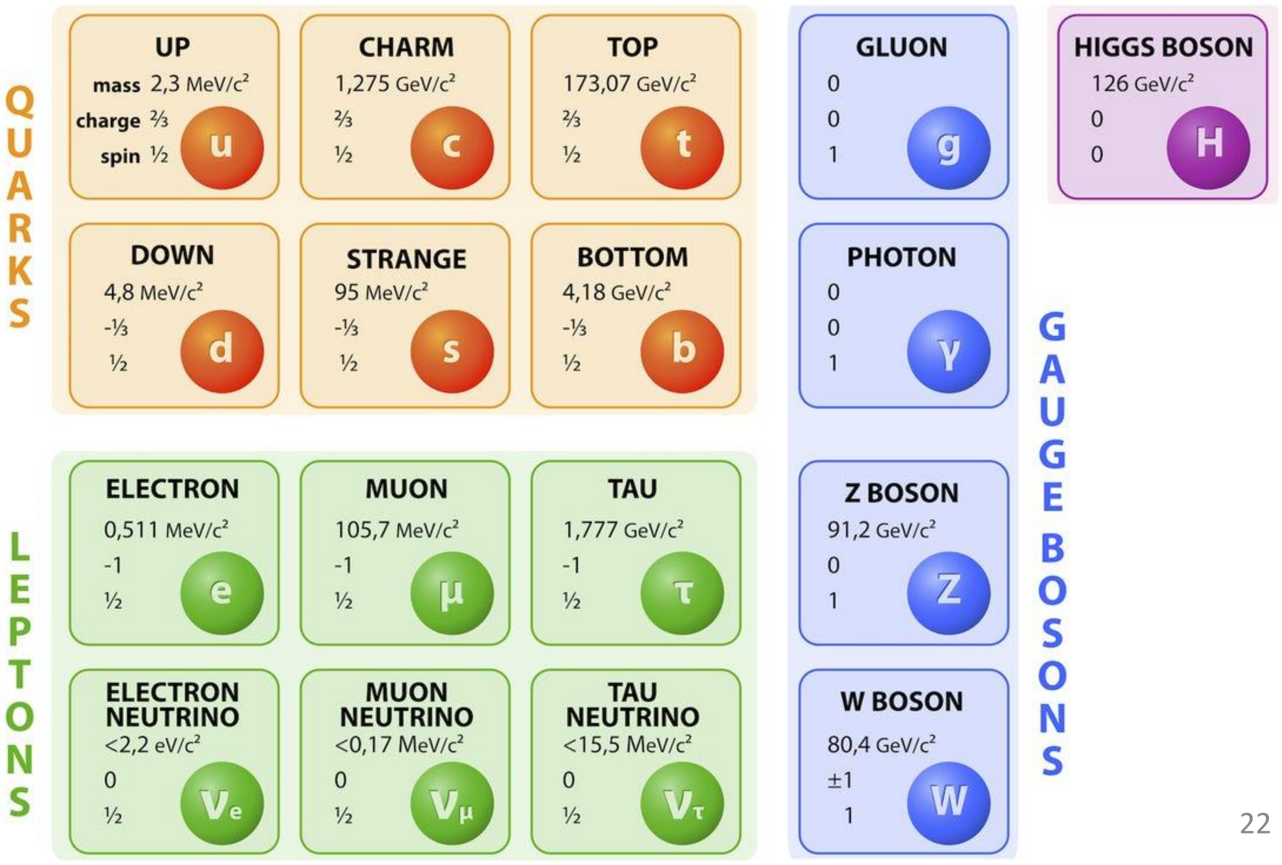

- CMS line at CYRCé:
  - *Test beam facility at CYRCé for high particle rate studies with a CMS Upgrade module: design and simulation*, P. Asenov, 2019
  - *Test-beam and irradiation facility at the 25 MeV proton cyclotron CYRCé at Strasbourg*, U. Goerlach, 2020
- CMS tracker system for Phase II:
  - *Firmware development and characterization of CMS Phase II outertracker prototype modules*, L. Dehennin, 2018
  - *Development of a Macro-Pixel sensor for the Phase-2 Upgrade of the CMS experiment*, D. Schell, 2019
  - *Design and Commissioning of a Temperature-Controlled Readout Station for CMS 2S Modules*, N. Thamm, 2019



# Backup

# The standard model of particle physics

- Quarks and leptons: Components of matter
- Gauge bosons: Interaction carriers
- Higgs boson: Generates the other particles' mass
- Fundamental propreties: mass, charge, spin



# Collisions: probing matter, producing particles

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- Energy: higher is the energy of the particle, higher is its momentum, lower is its De Broglie's wavelength (which is the scale we are going to probe)
- Luminosity: number of events per second and per cross section (which is linked to the probability it has to happen)

De Broglie's wavelength with respect to the momentum:

$$\lambda_B = \frac{h}{p}$$

Luminosity:

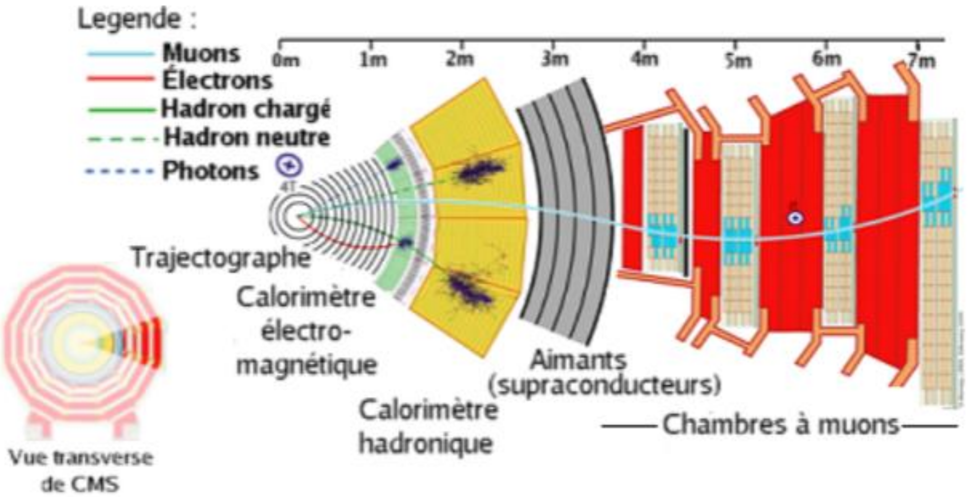
$$L = \frac{1}{\sigma}\frac{dN}{dt}$$

Examples:

$$\lambda \sim 10^{-15}\ \text{m} \implies p \sim 123\ \text{MeV} \implies E \sim 1\ \text{GeV for a proton.}$$
$$\lambda \sim 10^{-18}\ \text{m} \implies p \sim 123\ \text{GeV} \implies E \sim 123\ \text{GeV for a proton.}$$
$$E = 7\ \text{TeV} \implies p \sim 7\ \text{TeV for a proton} \implies \lambda \sim 10^{-20}\ \text{m.}$$

# How do we detect particles ?

- Trackers help us to get the momentum of a charged particle and its electrical charge thanks to its path.
- Calorimeters give us the energy lost as light by a particle passing through them.
- Particles can then be identified by looking where they are stopped, their speed, the radiation they emit or their time of flight



# How do we detect particles ? Focus on trackers

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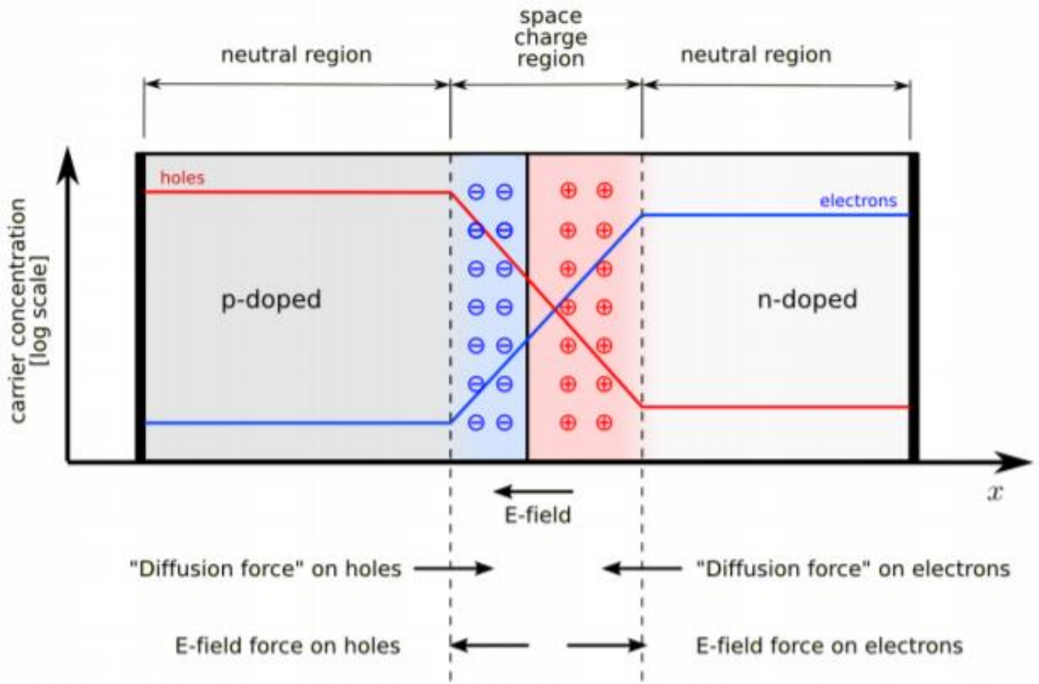
- A single particle passing through a semi-conductor produces a signal way lower than the thermal excitation of the material
- Solution: a p-n junction
- The larger is the voltage, the larger gets the depletion region



# LHC (Large Hadron Collider)

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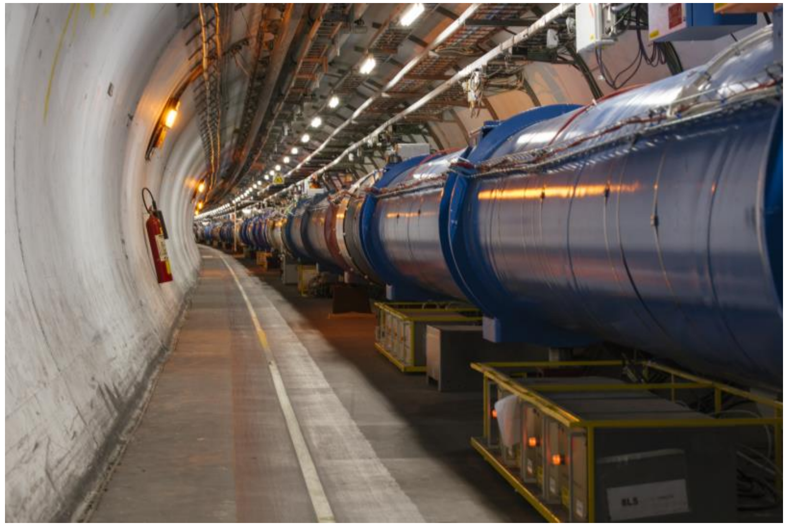
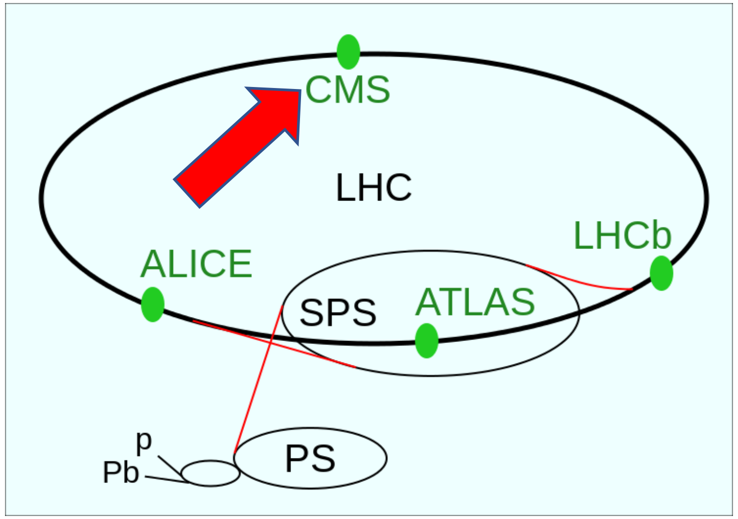
- Largest accelerator in the world (27km circular accelerator under the French-Swiss border)
- Collisions with the highest energy ever reached (~14TeV)
- Nominal luminosity high enough to make bunches ($10^{11}$) of protons cross every 25 ns (which gives a 40MHz crossing rate)



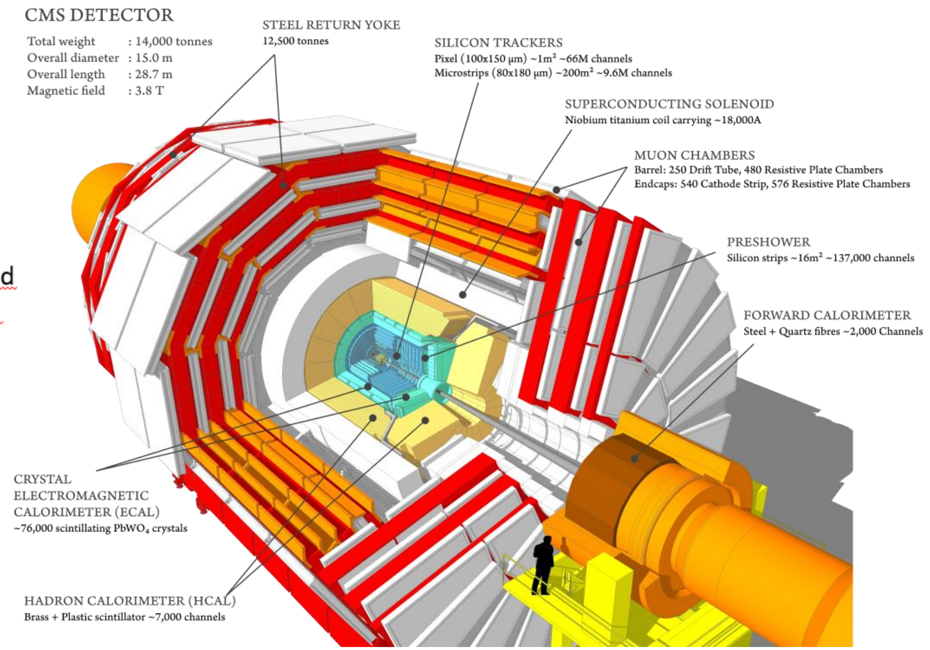


# CMS (Compact Muon Solenoid)

- Silicon trackers (microstrips, pixels)
- Superconducting solenoid
- Data acquisition:

LHC: 40M collisions every second → L1 → 100k events every second filtered in about 1µs → HLT → Aroud 1000 events per second selected and recorded

- Calorimeters (electromagnetic and hadronic)
- Return yoke and muon chambers



# Data acquisition

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- 40 million collisions of bunches per second: absolutely huge, we can’t store all of it
- L1 trigger: uses criteria on data from the calorimeters and the muon chambers to decrease the rate of recorded events to 100kHz
- HLT (High Level Trigger): uses data from other parts like the trackers to decrease again the rate down to 1kHz, selecting consistent events

LHC: 40M collisions every second → (L1) → 100k events every second filtered in about 1μs → (HLT) → Aroud 1000 events per second selected and recorded

# CMS tracking detector for the HL-LHC: our work

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- What we are doing in Strasbourg:
  - Calibration of the new silicon modules
  - Beam tests of these modules with protons accelerated by the cyclotron CYRCé (IPHC)
  - Intensity: CYRCé provides almost $10^5$ protons per second with a beam of about 10fA

CYRCé, cyclotron used at IPHC (Strasbourg)

# The modules in the experimental box

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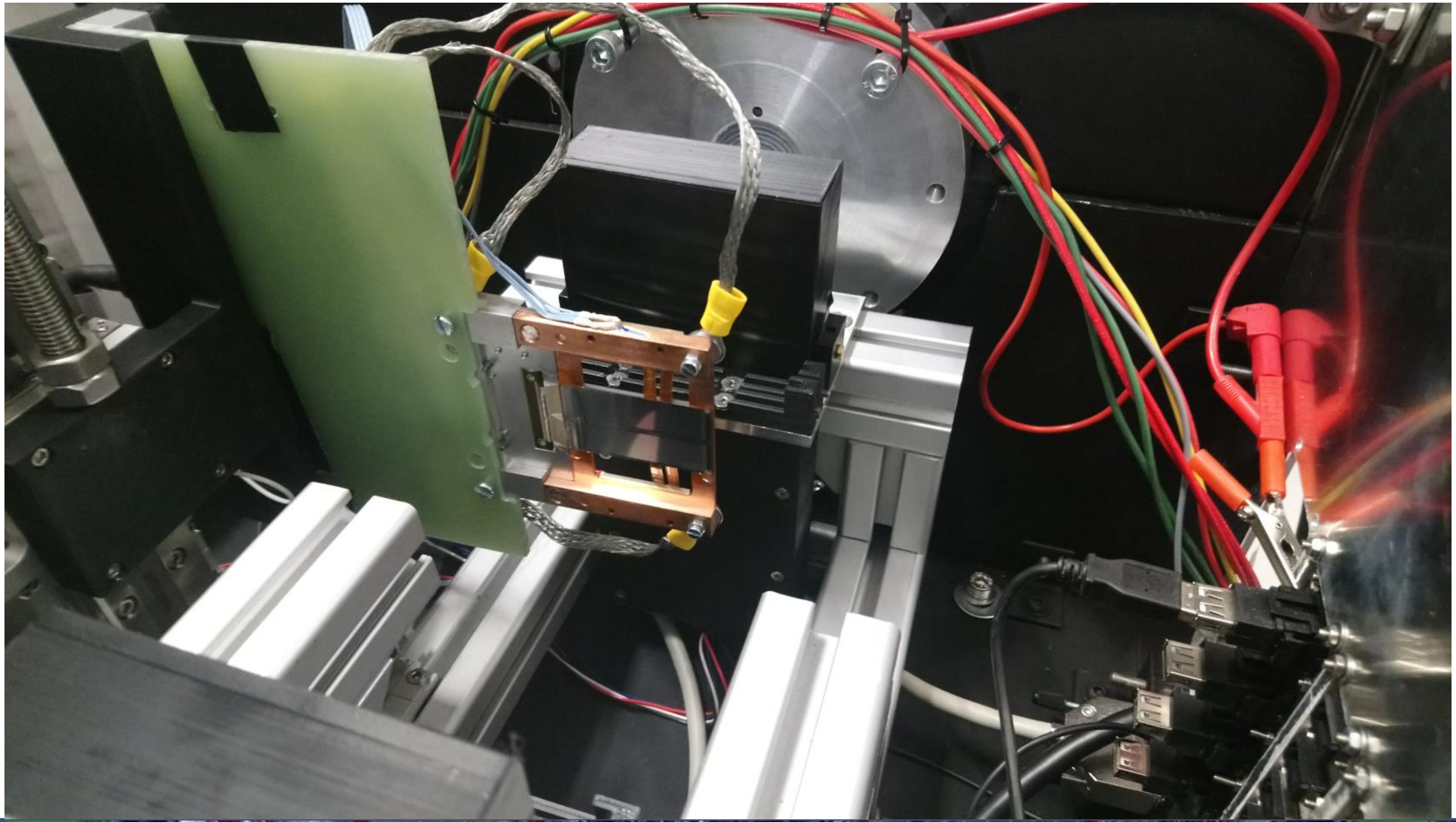

# Correlation

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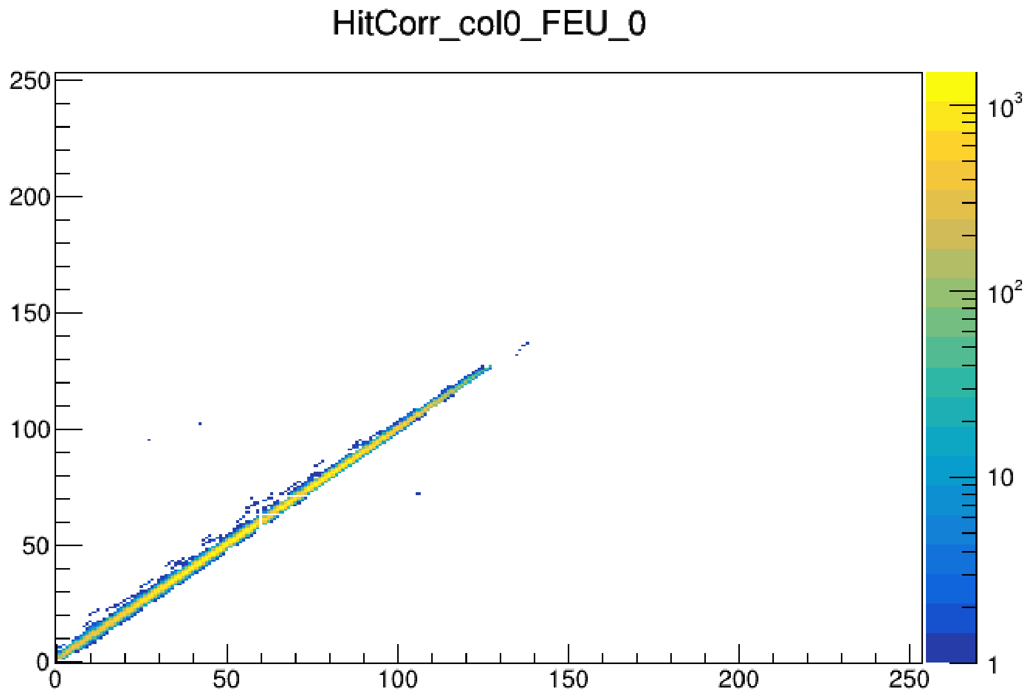
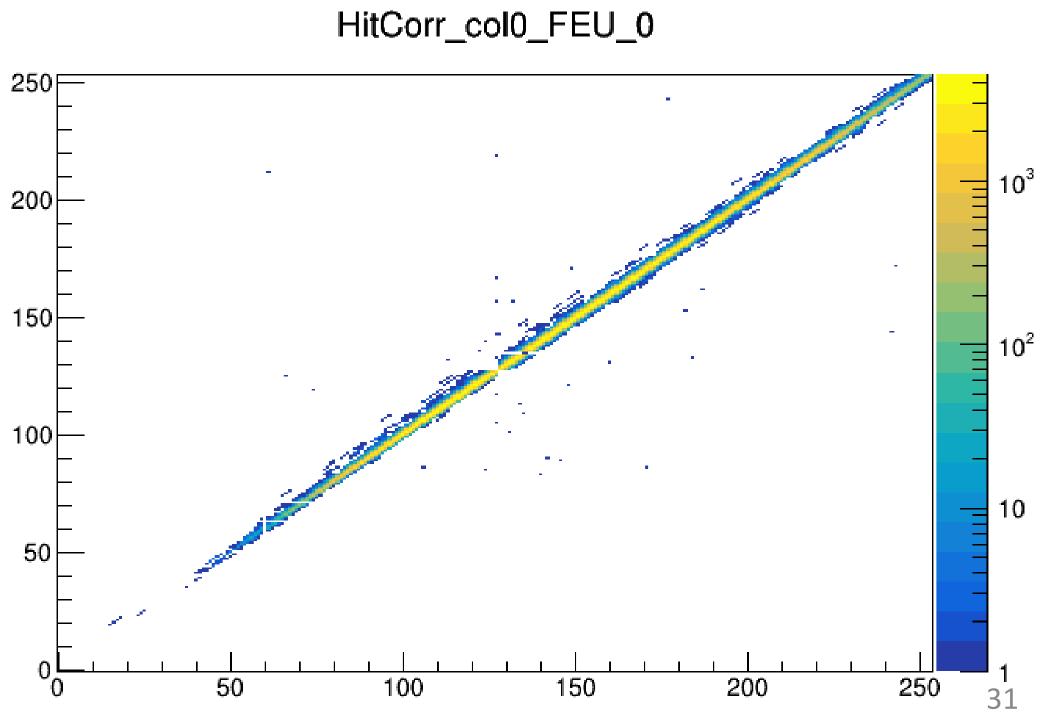
Beam test of December 2019




Beam test of July 2019



# Position of the beam

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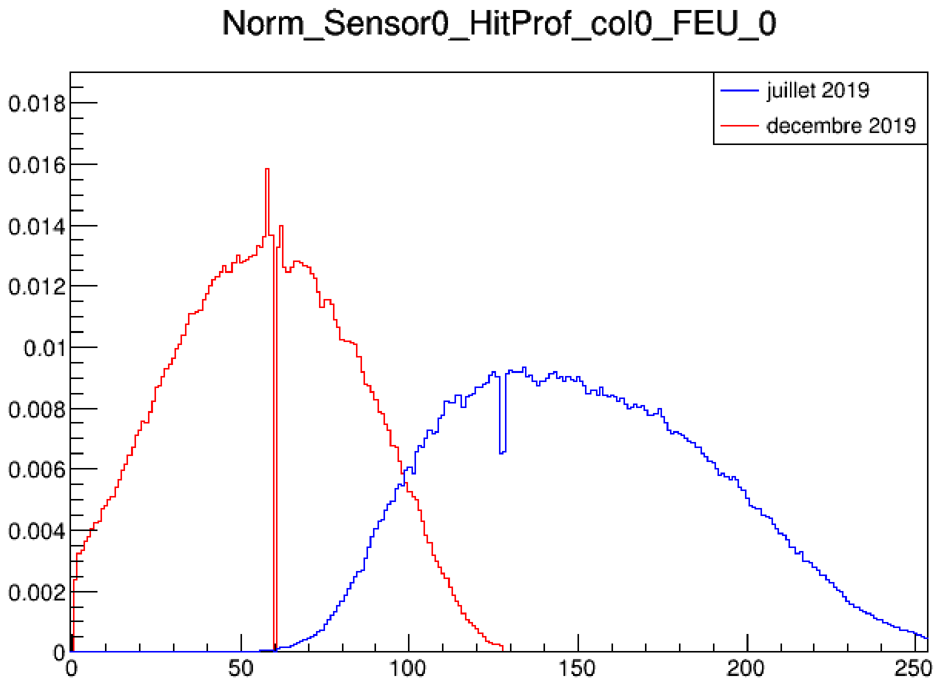
Comparison of the position of the beam recorded by the front sensor in July 2019 and in December 2019




Comparison of the position of the beam recorded by the rear sensor in July 2019 and in December 2019