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in Particle & Astroparticle Physics

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Muon Detection

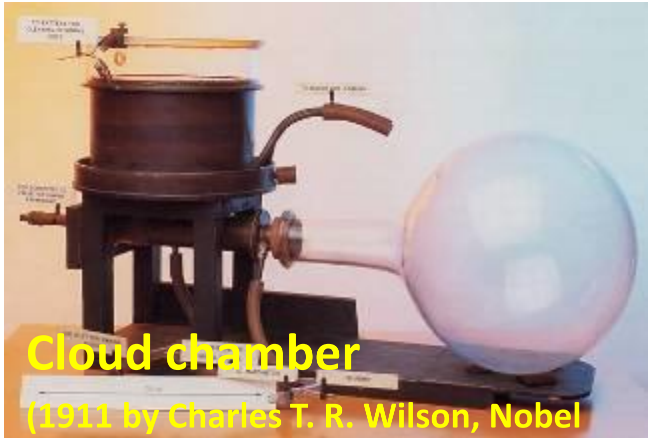
The detector technologies.

LECTURE 3

Very early detectors

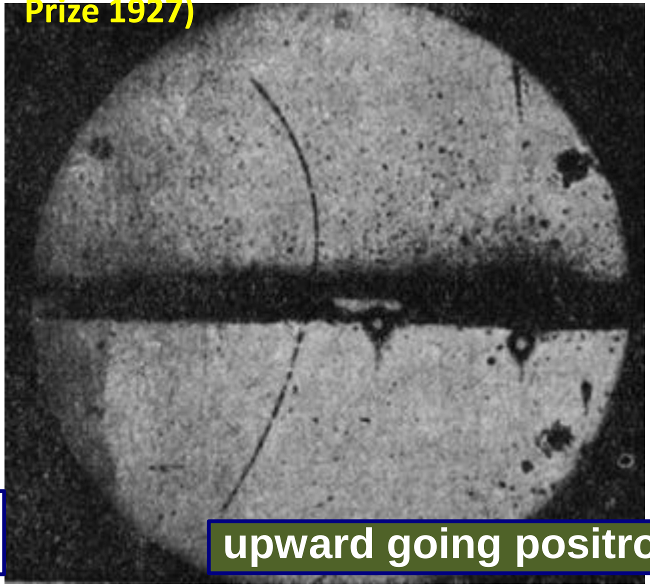
- The very early detectors like cloud chambers (or later bubble chambers used saturated water vapour in which small droplets developed that could be photographed. They were originally developed to study the formation of rain clouds

- These type of detectors were used until the 1980ies. They did what today's huge detectors do in a single device. They measured everything, however, with limits.
- They were good (actually great) for single track measurements but could not contain high energy showers.
- In addition, they were slow and very manpower intense to analyse the photographs.



Cloud chamber

(1911 by Charles T. R. Wilson, Nobel Prize 1927)



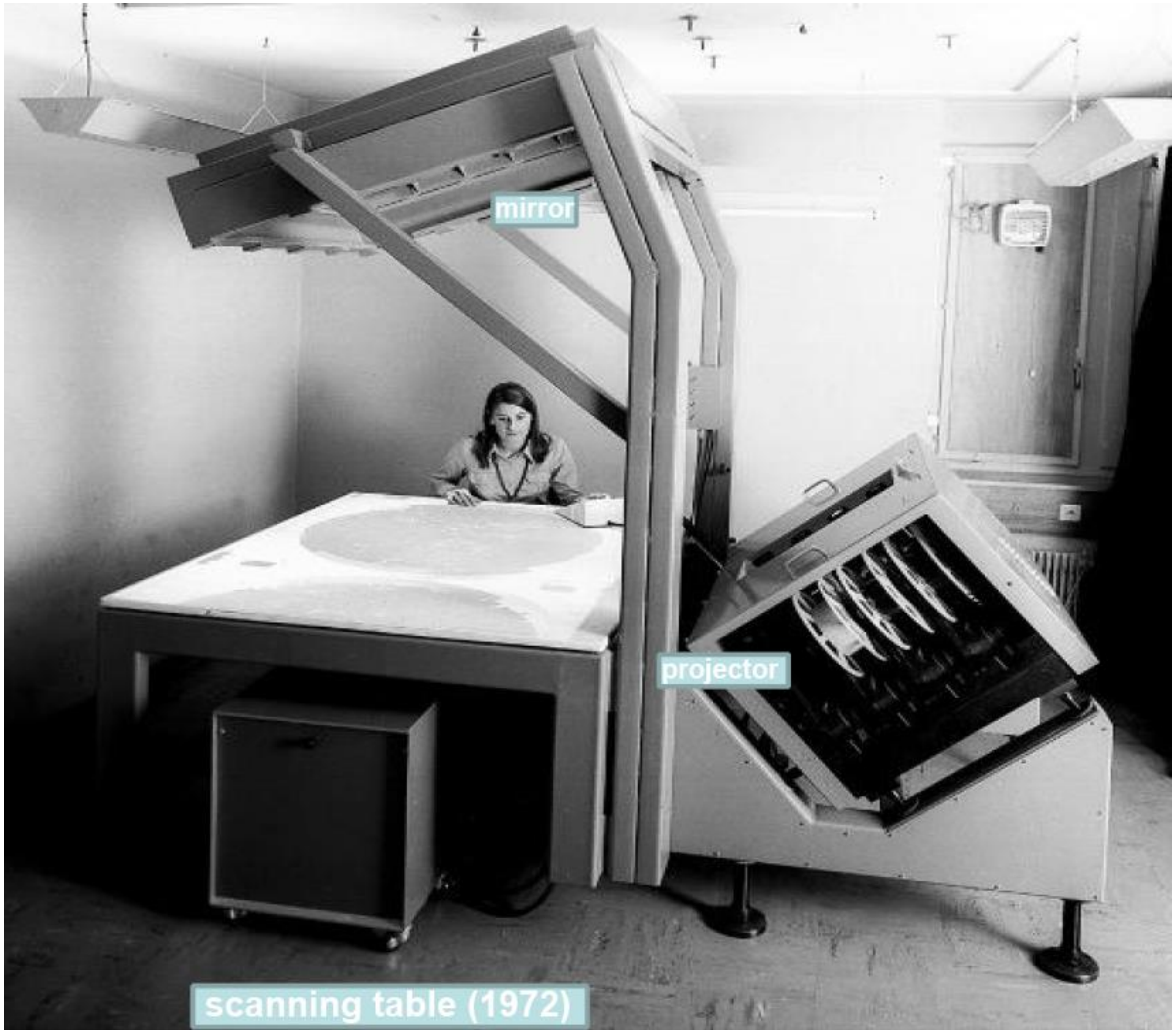
upward going positron

Was used for the discovery of the positron (1932 by Carl Anderson, Nobel Prize 1936) and the μ)

The last bubble chamber at CERN (BEBC)

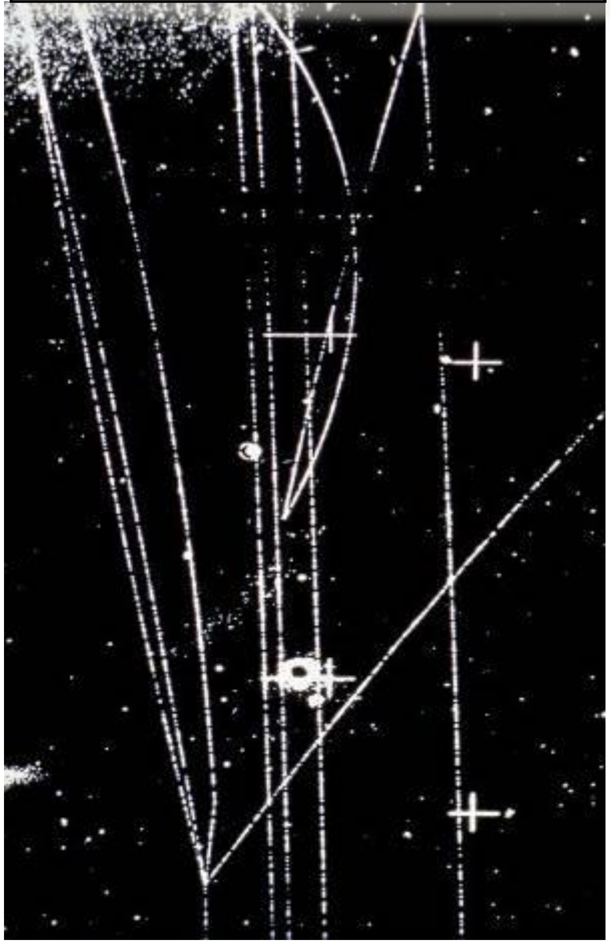
The hydrogen acted as a target (for incoming particles) and as a detector

Scanning Photographs

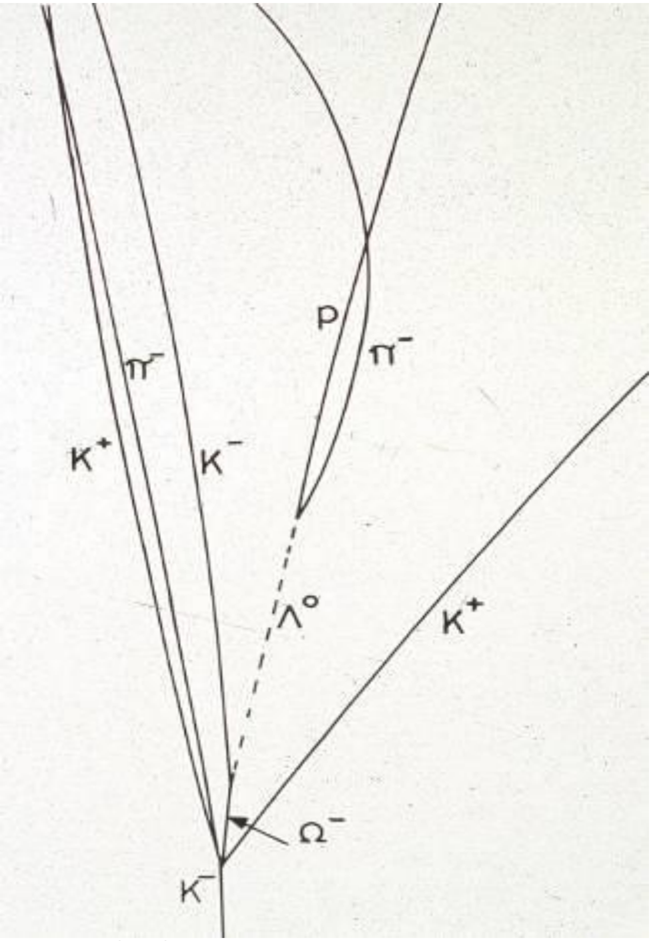


Particle colliding with a proton in liquid hydrogen

- A "Bubble Chamber"

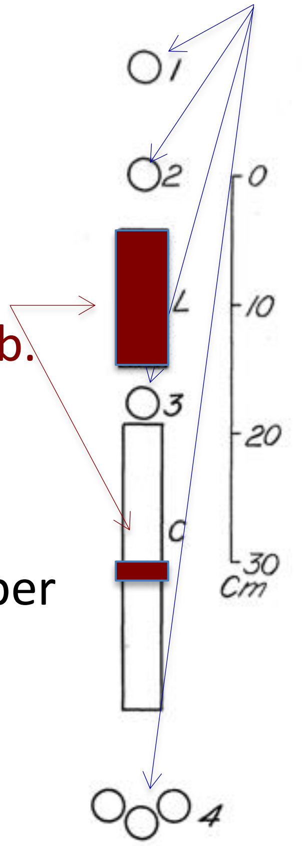


Many people employed to look through these photos to understand what happened!



The early detectors, cont'd

- The other type of detector that was used in the muon discovery experiment were Geiger tubes, they served as triggering device.
- Tubes are still heavily used as muon detectors, however, in the form of drift tubes (see later)



Geiger tubes

Lead absorb.

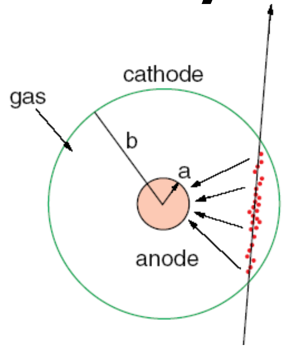
Cloud chamber

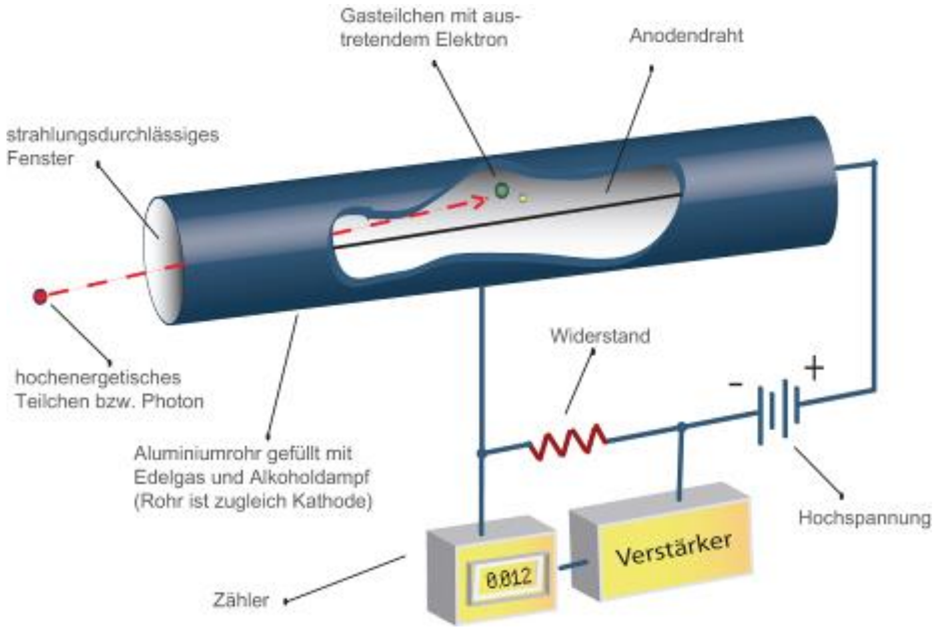
FIG. 1. Geometrical arrangement of apparatus.

Street & Stevenson, PhysRev. 52(1937)1003

Geiger-Müller counter (1928)

- Tube filled with inert gas + organic vapour
- High voltage between wire and tube
- Central thin wire (20 – 50 µm)





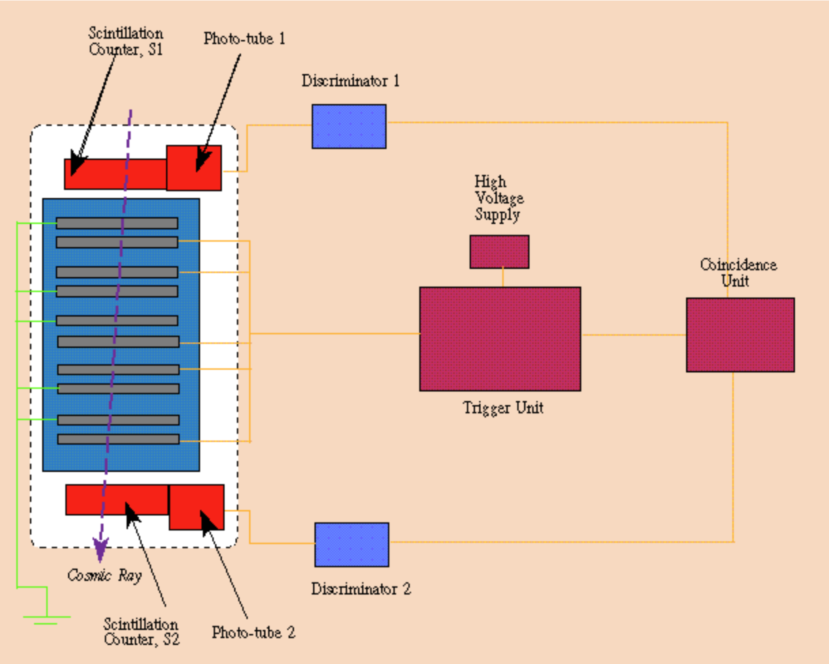
- Charged particle ionizes the gas, the electrons move to towards the anode wire, the ions towards the tube wall.
- Strong increase of the field close to the wire
- When E>10 kV/cm the electrons start ionizing themselves the gas, leading to an electron avalanche and a measurable signal on the wire
- The organic substances act as “quencher”

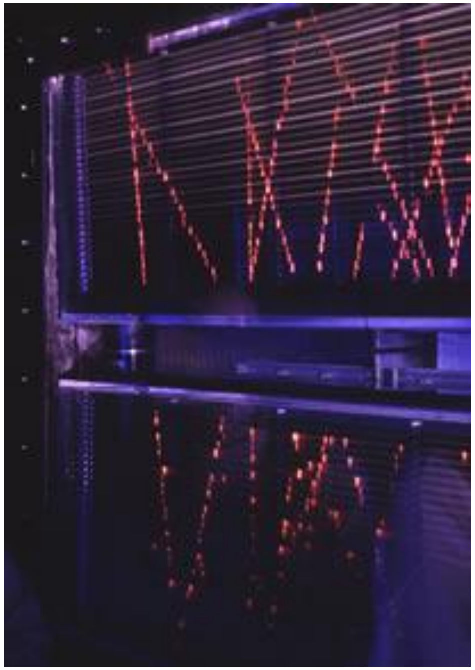
A big step forward – spark chambers

- The third type of detector that we have met is the spark chamber that played a crucial role in the discovery of the muon neutrino in 1962.
- Pairs of metal plates are connected to a HV potential of several 10 kV creating a strong electrical field between the plates. Charged particles passing across the plates ionize the gas and create a conducting trace that leads to a spark between the two plates which is then photographed.

To avoid saturation, HV is only applied for a few ms, triggered, e.g., by a coincidence in two scintillators.

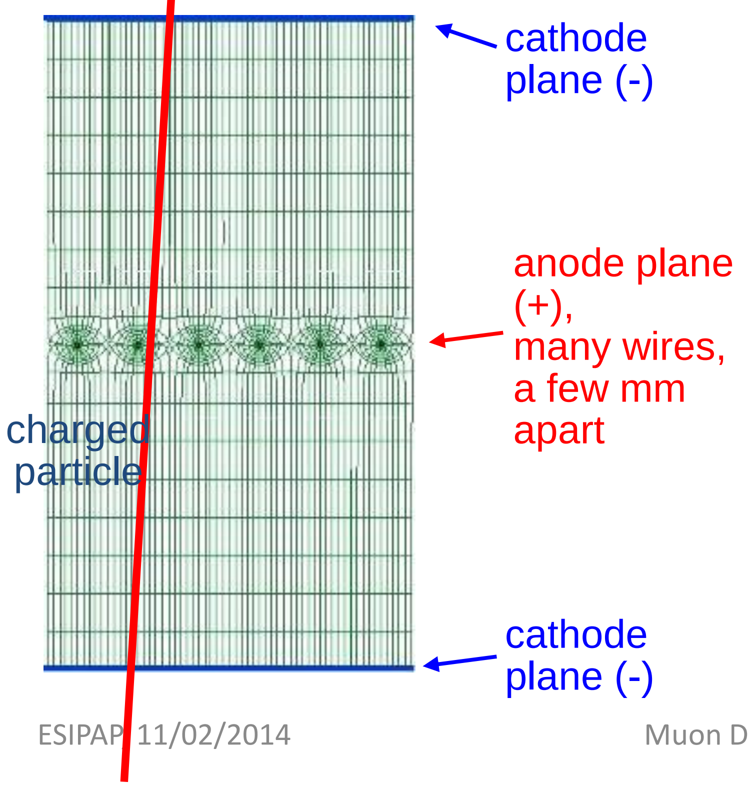
Spark chambers were used in the 1960ies and 70ies





Multiwire proportional chamber

- Invented in 1968 by Georges Charpak (Nobel Prize 1992)
- A simple idea, generalizing the Geiger-Müller tube to a multi-channel setup, without the internal tube walls.



cathode plane (-)

anode plane (+), many wires, a few mm apart

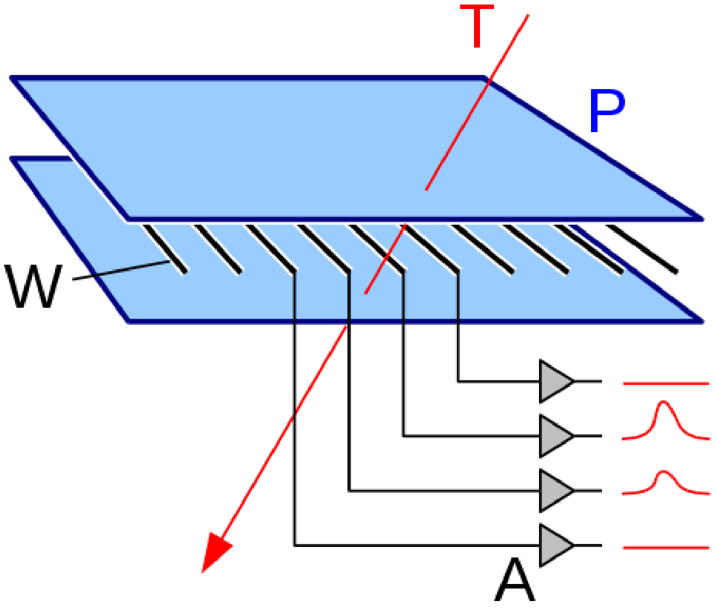
charged particle

cathode plane (-)

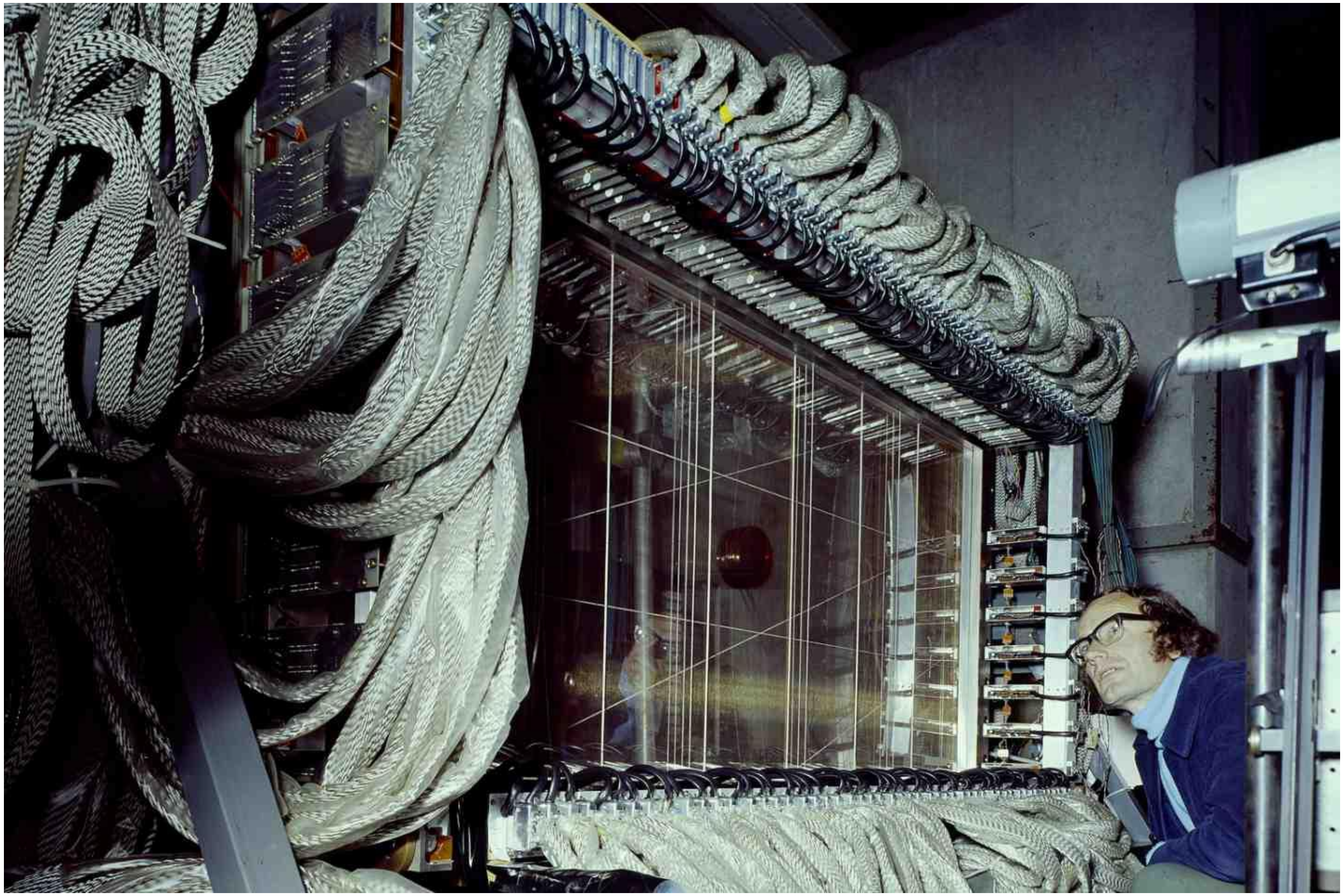
Multiwire proportional chamber II

- The invention of the MWPC chamber revolutionized the field, very quickly wire chambers were used all over
- It opened the door for constructing large area (and volume) tracking detectors.
- The accuracy that can be reached with MWPCs is a function of the wire distance, typical wire distances are d=1–2 mm

  $\sigma_x = d/\sqrt{12} \approx 300\ \mu m$ (for d=1 mm)
- Another limitation with the original MWPC was that the fact that wires measure only one coordinate



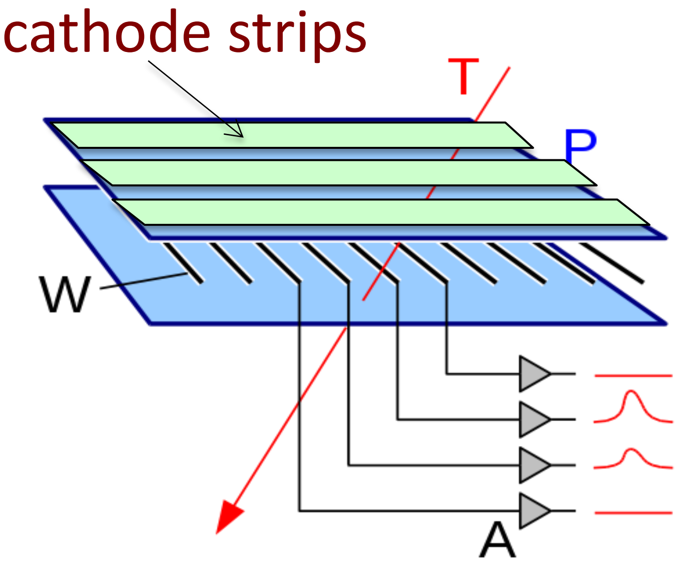
MWPC of NA2 muon detector (1977)

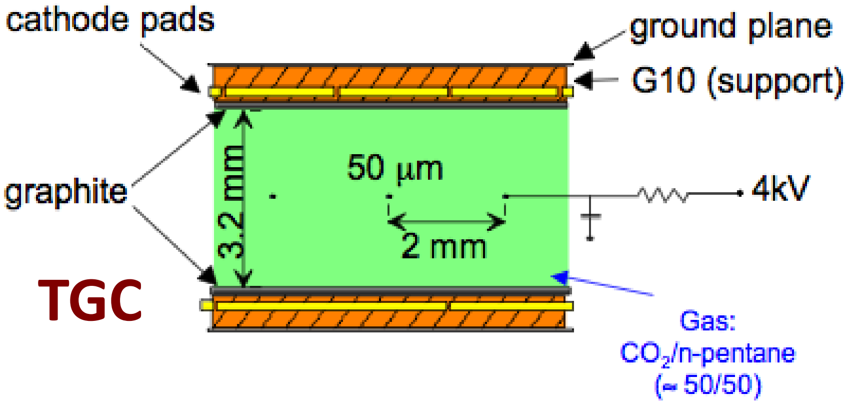


MWPC and 2nd coordinate

Several approaches to extract the 2nd coordinate from MWPCs were used

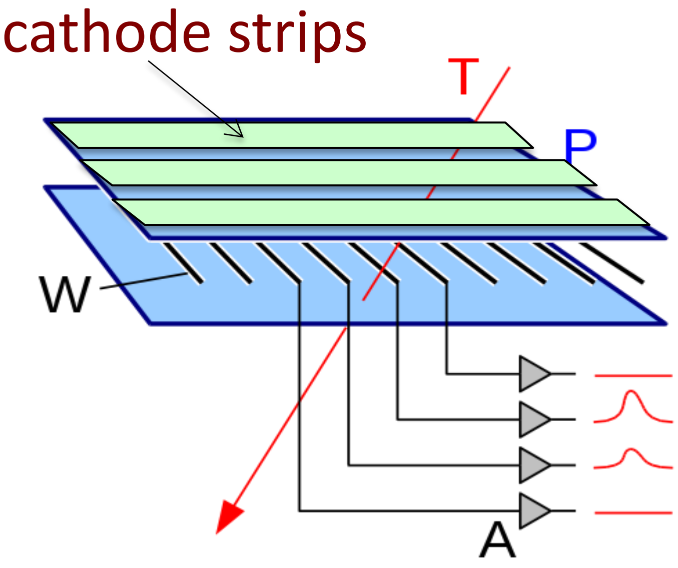
- Crossed wire planes, restricted to small areas and low occupancy (ghost tracks)
- Charge division: resistive wires read out from the two sides
- Time division: comparing the signal arrival time at the two wire ends
- Segmented cathode planes, picking up the induced signal, leading to a number of variants of the MWPCs, still today heavily in use
  - Cathode Strip Chambers (CSCs)
  - Thin Gap Chambers (TGCs)

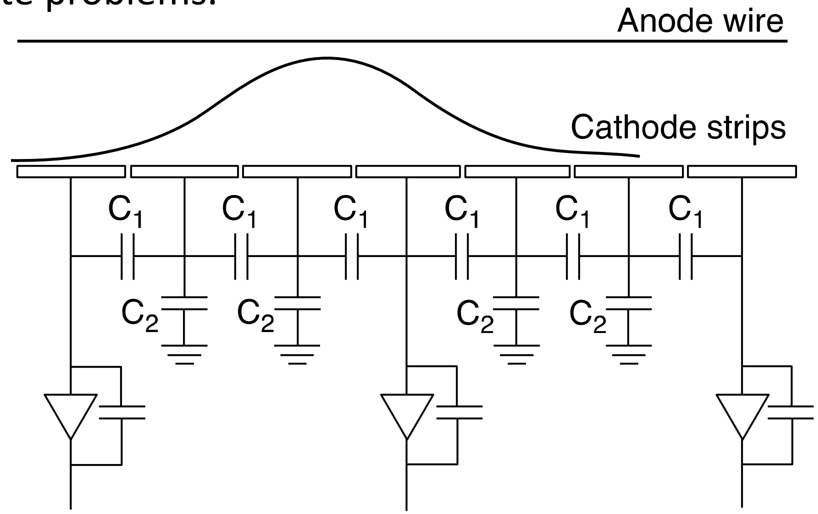


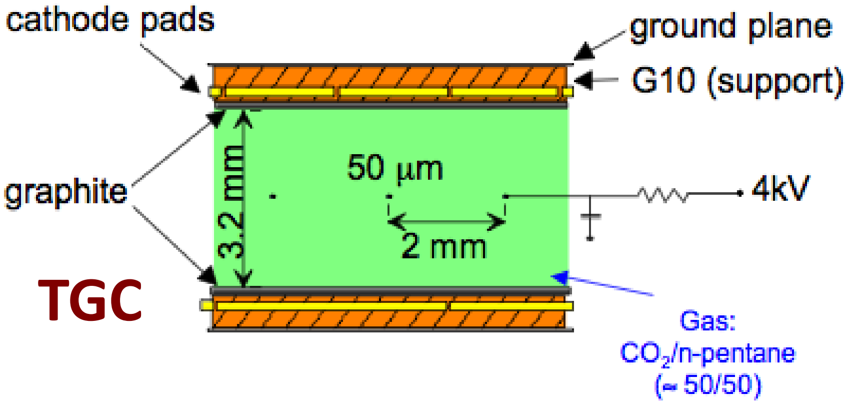


Charge interpolation

- With the introduction of the pick-up electrodes separated by an insulator and a layer of graphite two problem of the MWPCs got solved, the limited spatial resolution and the rate limitations.
- The charge (from the avalanche on the wire) that gets induced on the cathode strips is spread out and usually extends over several strips. By charge interpolation spatial resolutions much better than the $d/\sqrt{12}$ can be achieved.
- The graphite layer, inside the active gas volume, serves to transport the ions out of the detector, thus reducing the rate problems.







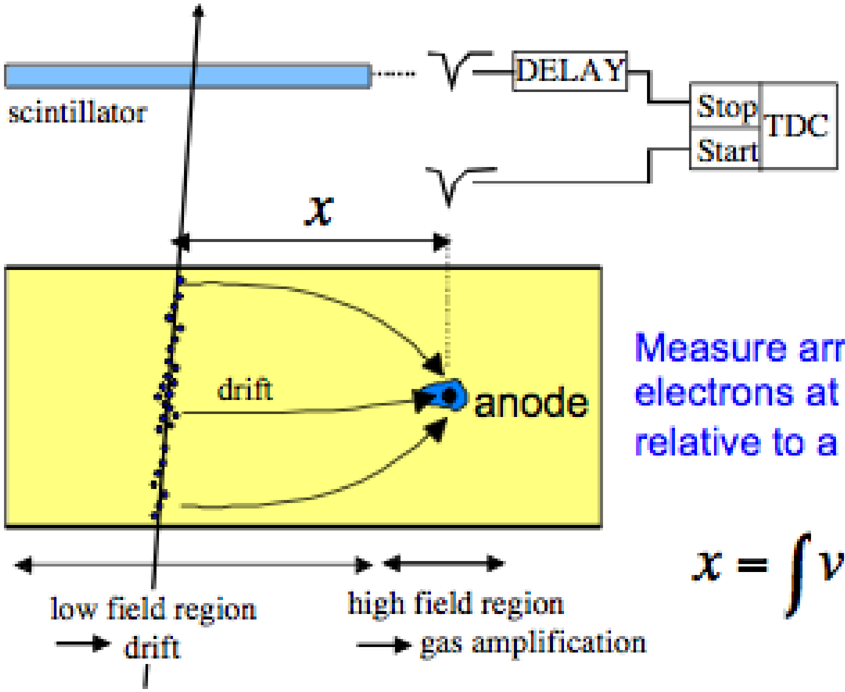
Drift chambers

A natural evolution of the MWPC was the drift chamber, it solved a number of shortfalls of the MWPCs.

First studies: T. Bressani, G. Charpak, D. Rahm, C. Zupancic (1969)

First operation of a drift chamber: A.H. Walenta, J. Heintze, B. Schürlein (NIM 92 (1971) 373)

- By measuring the arrival time of the signals on the wire the distance between track and wire is determined
- Using this technique spatial resolutions much below 100 µm have been achieved
- At the same time the number of wires in a drift chamber is drastically reduced compared to a MWPC
- Drift distances can extend to several cm; the drift chambers of the WA1 neutrino detector of Lecture 1 had a drift space of 3 cm and a wire distance of 6 cm.



Measure arrival time of electrons at sense wire relative to a time t_0.

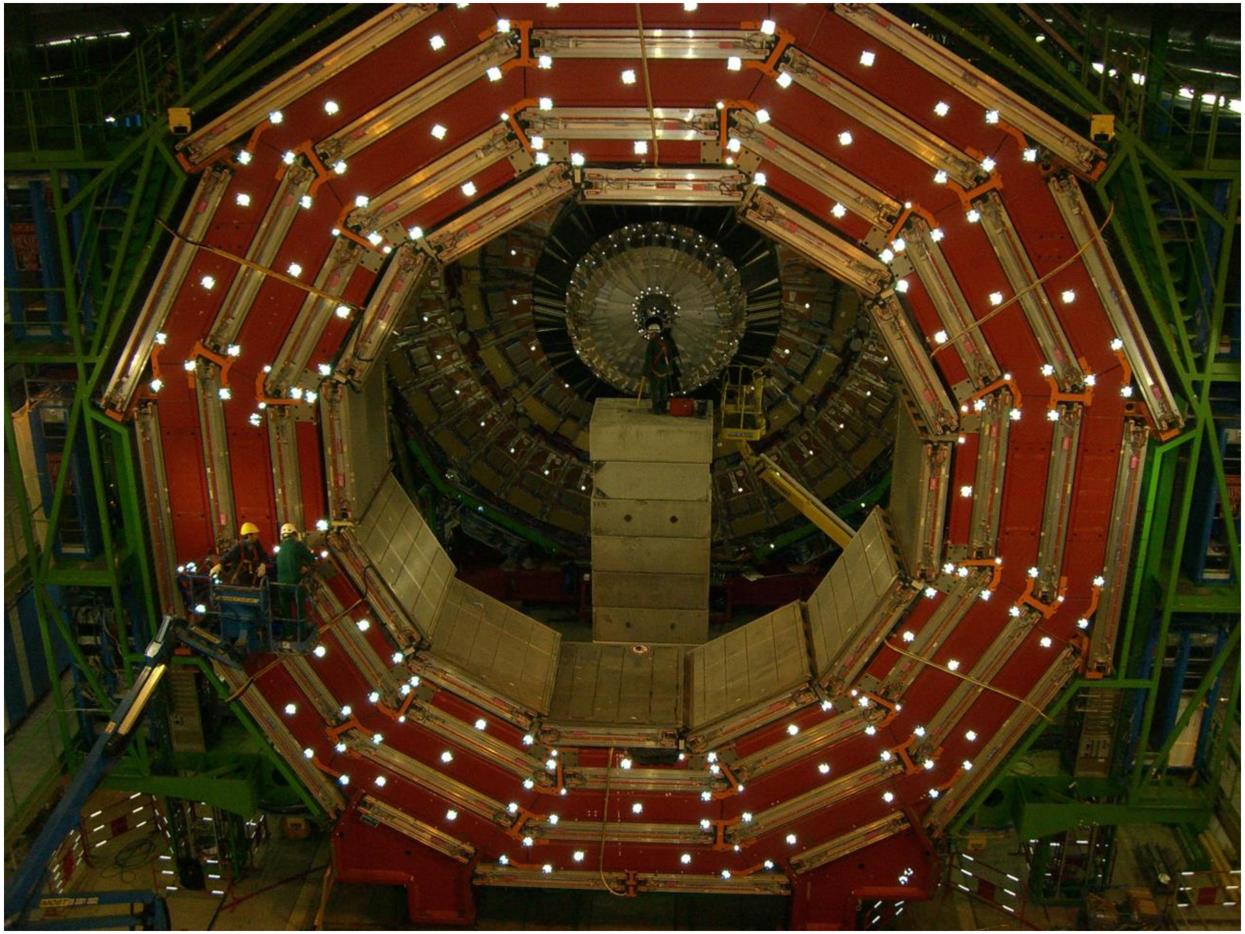
$$x = \int v_D(t)\,dt$$

CMS barrel muon system

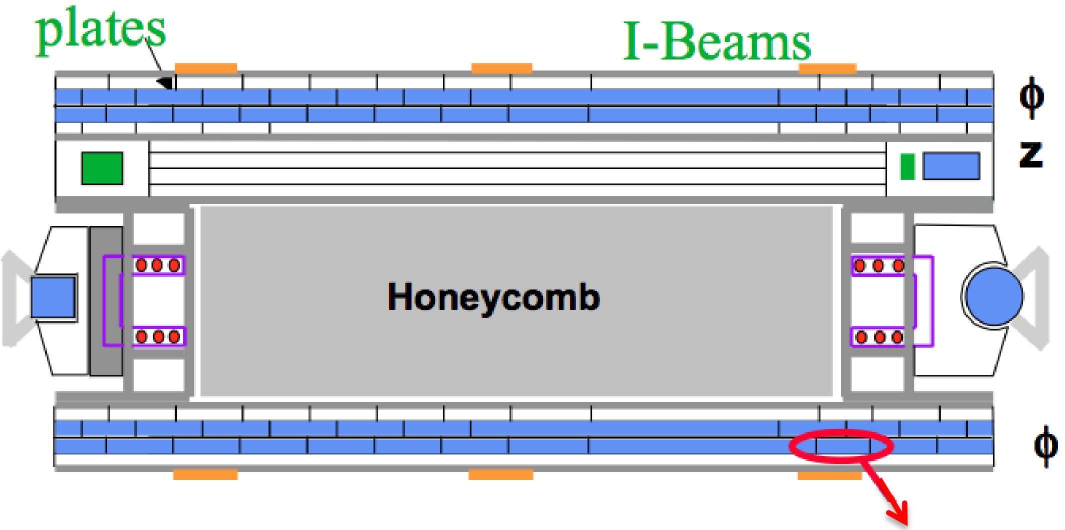
Drift chamber/RPC packages in the barrel

- Tracking & triggering
- 4 measurement stations
- 8 layers in phi, 4 layers in z/station

Cathode Strip Chambers (CSC) and RPCs in the end-caps

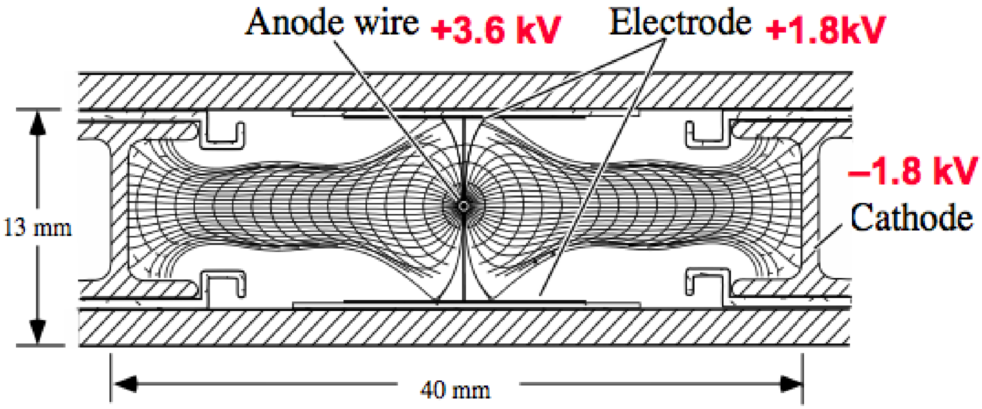


The CMS drift cells



2 superlayers in ϕ
1 superlayer in z

Each superlayer has 4 layers of drift-tubes

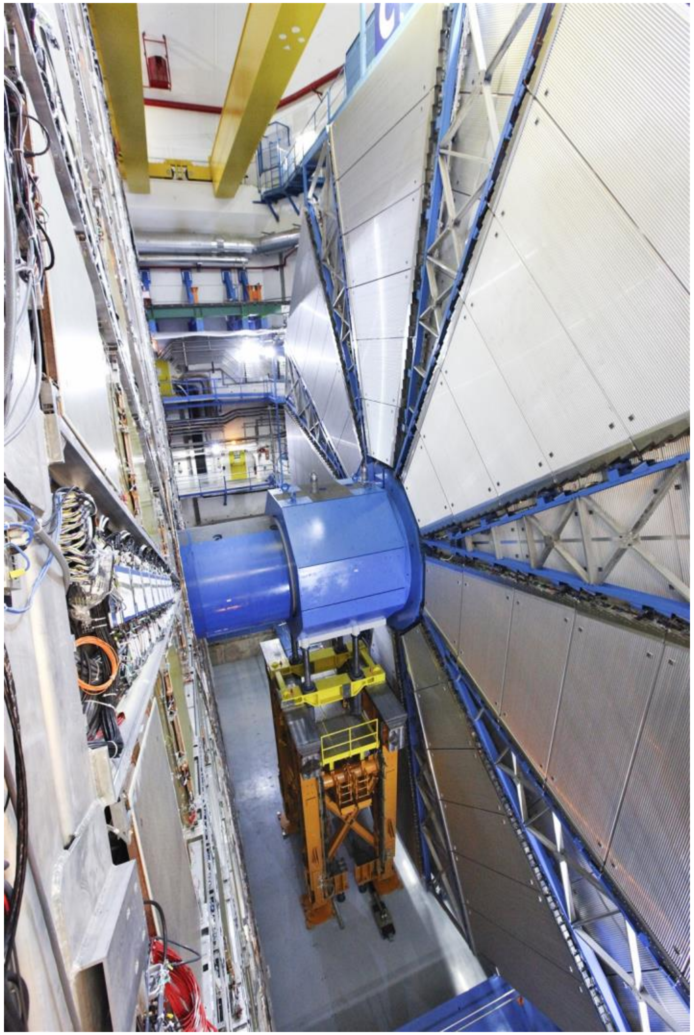


Operated with Ar:CO_2 mixture
400 ns maximum drift time
250 µm resolution/cell

The ATLAS drift tubes

It looks as if we are back to the good old Geiger-Müller tube. Almost.
Applying the drift chamber concept to a single tube makes all the difference

- In ATLAS 375 000 drift tubes are used as precision muon detectors, arranged in 1200 chambers, each consisting of 6 or 8 tube layers.
- They cover an area of about 5500 m^2.
- The largest chambers employ drift tubes of >7 m length.

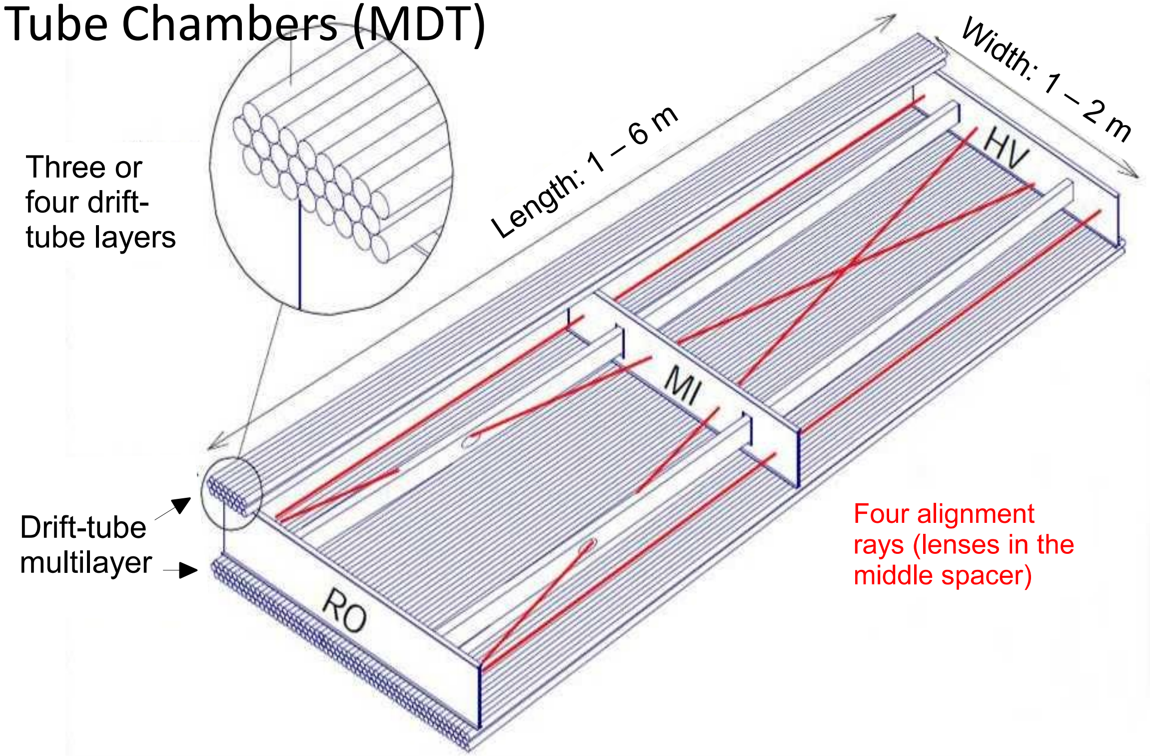


A sector of the ATLAS MDT Big Wheel

Composed of 30 mm Drift tubes

The ATLAS drift tubes

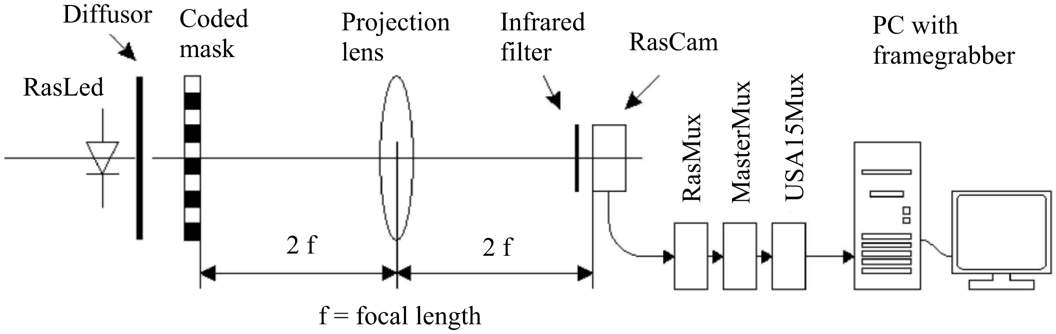
- The drift tubes are arranged in 1200 chambers, each consisting of 6 or 8 tube layers. Typical chamber dimensions are 2 x 4 m^2 in area and 0.5 m high.
- The deformation of the chambers being monitored, we call them Monitored Drift Tube Chambers (MDT)



Alignment

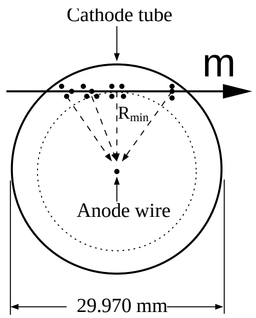
- The ATLAS muon chambers have been constructed with extremely high precision
  - The drift tubes were located to typically 10–15 µm (rms)
- An in-plane monitoring system (RASNIK) installed in each chamber is used to follow any deformation of the chambers during installation and operation within a few µm
- The RASNIK was installed during construction and is periodically readout
- The location of one chamber with respect to the other is achieved by a grid of optical monitoring lines throughout the detector

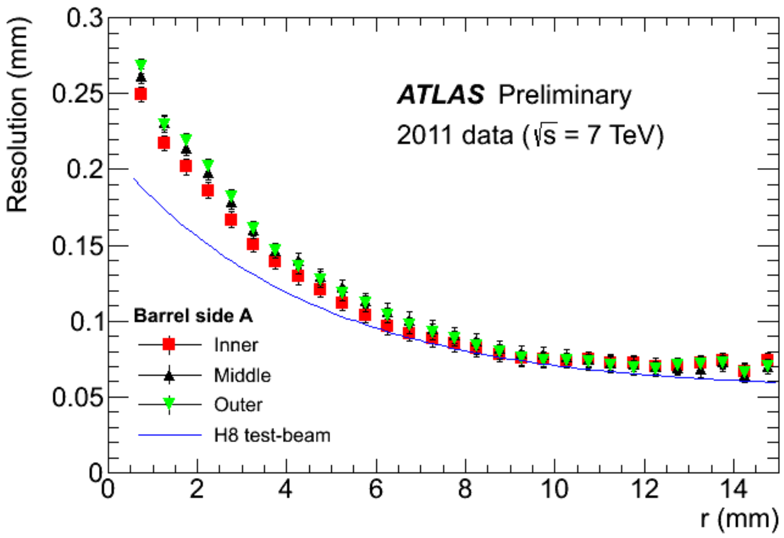
RASNIK principle

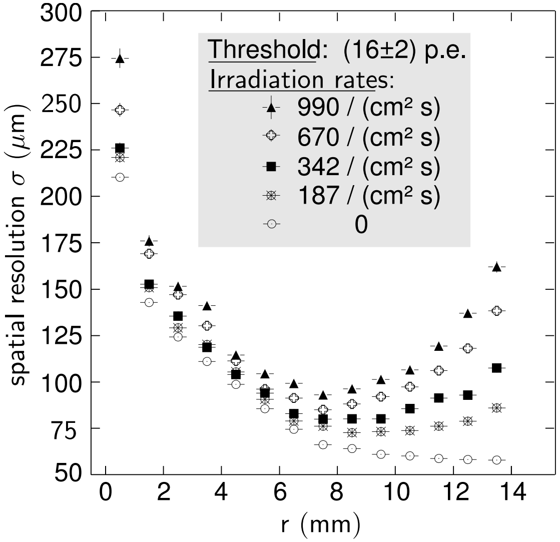


The ATLAS MDTs

- The MDT tubes have a diameter of 30 mm, the anode wire is 20 µm thick.
- The tubes are operated with an Ar:CO_2 (93:7) gas mixture at 3 bar absolute pressure.
- By measuring the signal arrival time the distance of the track to the wire can be determined with a resolution of O(100 µm) per tube (except close to the wire)

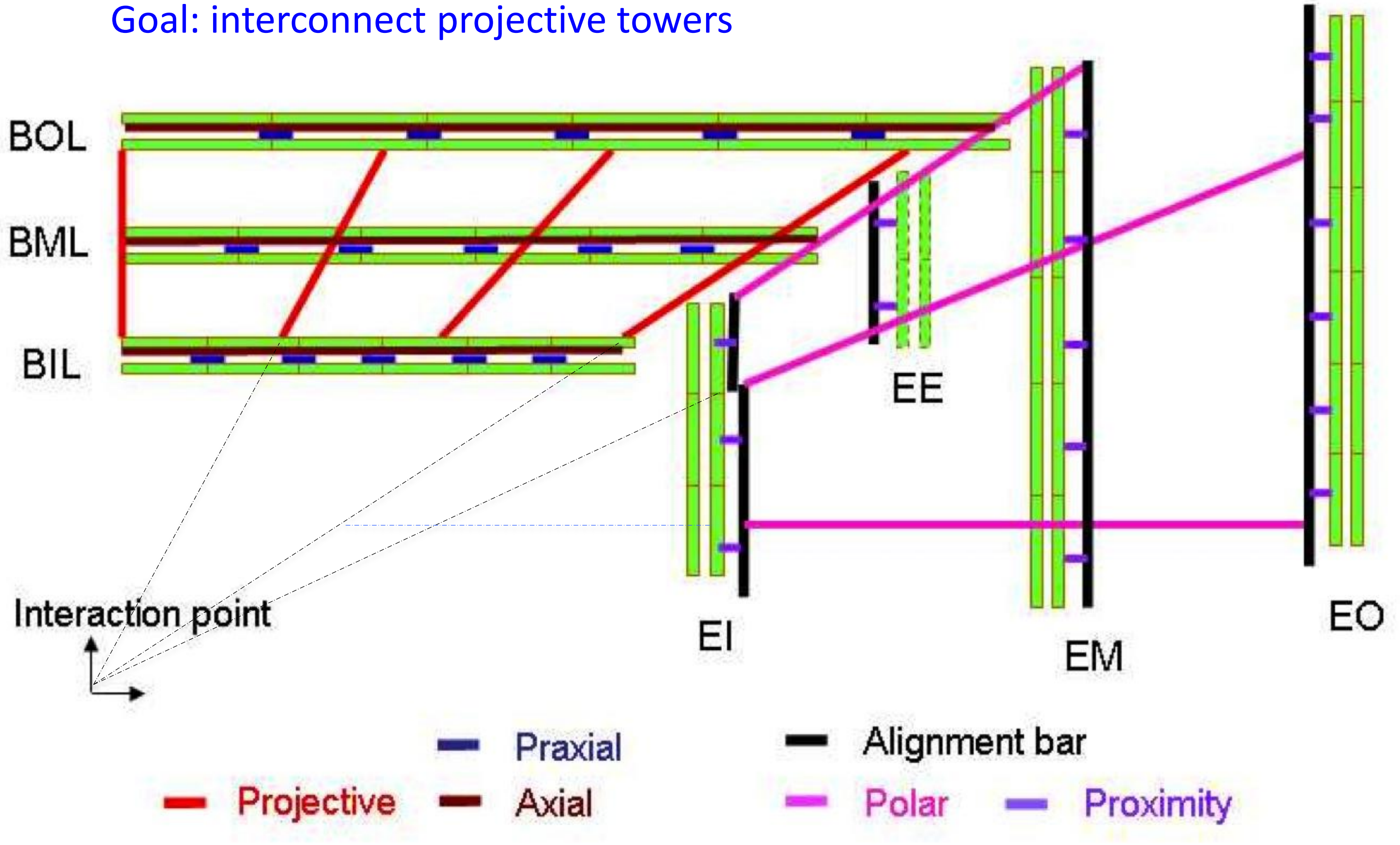






The ATLAS muon alignment system

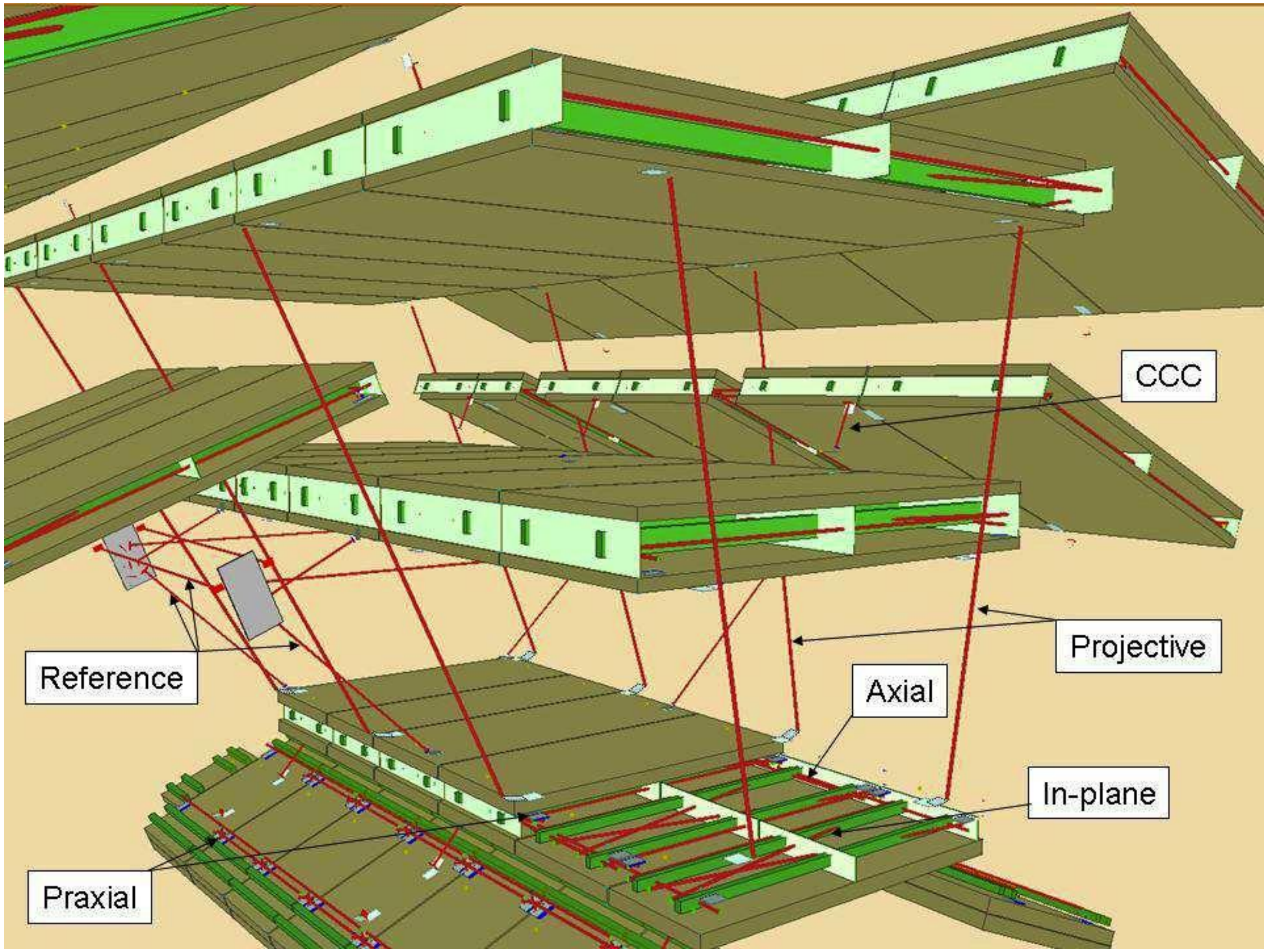
Goal: interconnect projective towers



The ATLAS muon barrel alignment

Only the chambers in the odd sectors (between coils) are projectively ‘aligned’.

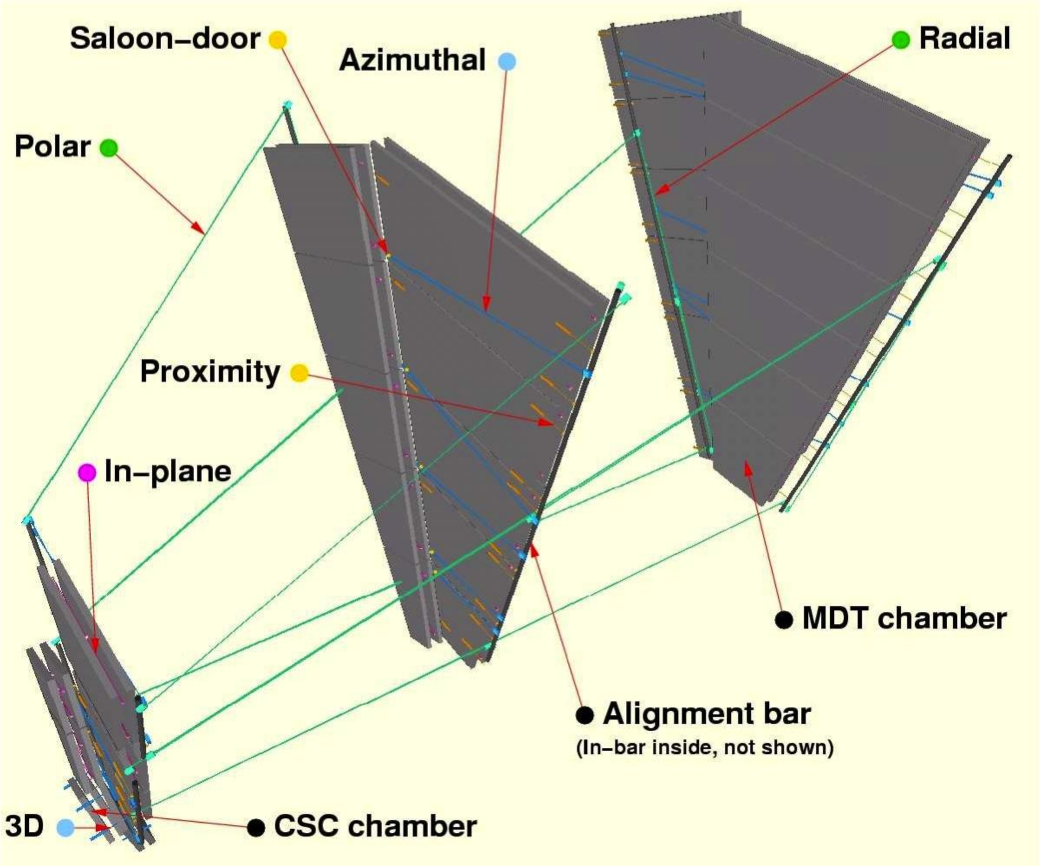
The chambers of the even sectors are aligned with tracks through chamber overlaps



The ATLAS muon end-cap alignment

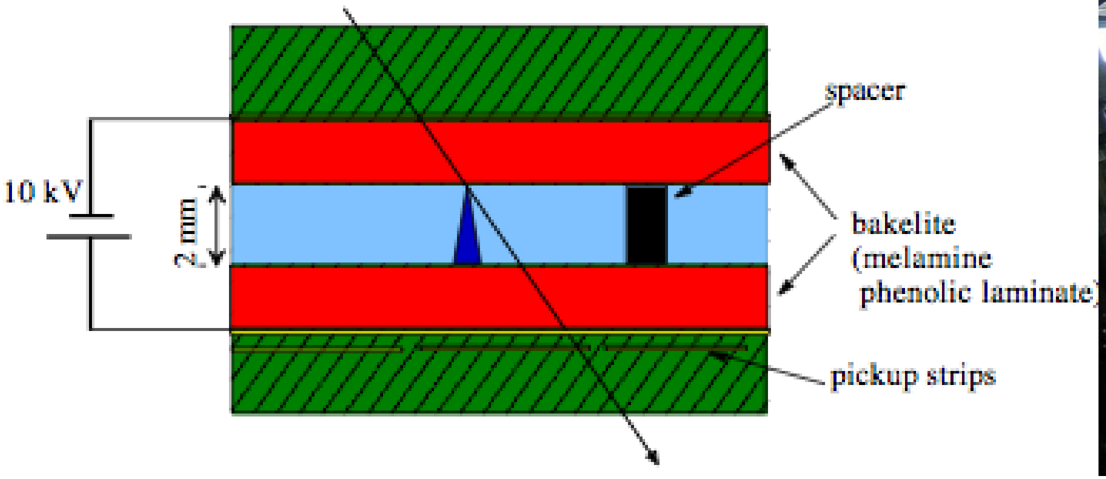
A set of alignment bars, optically interconnected, creates an external reference system.

Azimuthal optical lines monitor the relative position of the chambers to these bars.



Resistive Plate Chambers (RPC)

- RPCs are heavily used in CMS and ATLAS as trigger detectors, plus in many other experiments … as TOF detectors taking advantage of their superb time resolution
- They are parallel-plate detectors without wires, similar to the spark chambers
- They are operated at typically 5 kV/mm either in streamer or avalanche mode
- Gas: $C_2H_2F_4$:iC_4H_{10} :SF_6 (96.7:5:0.3)

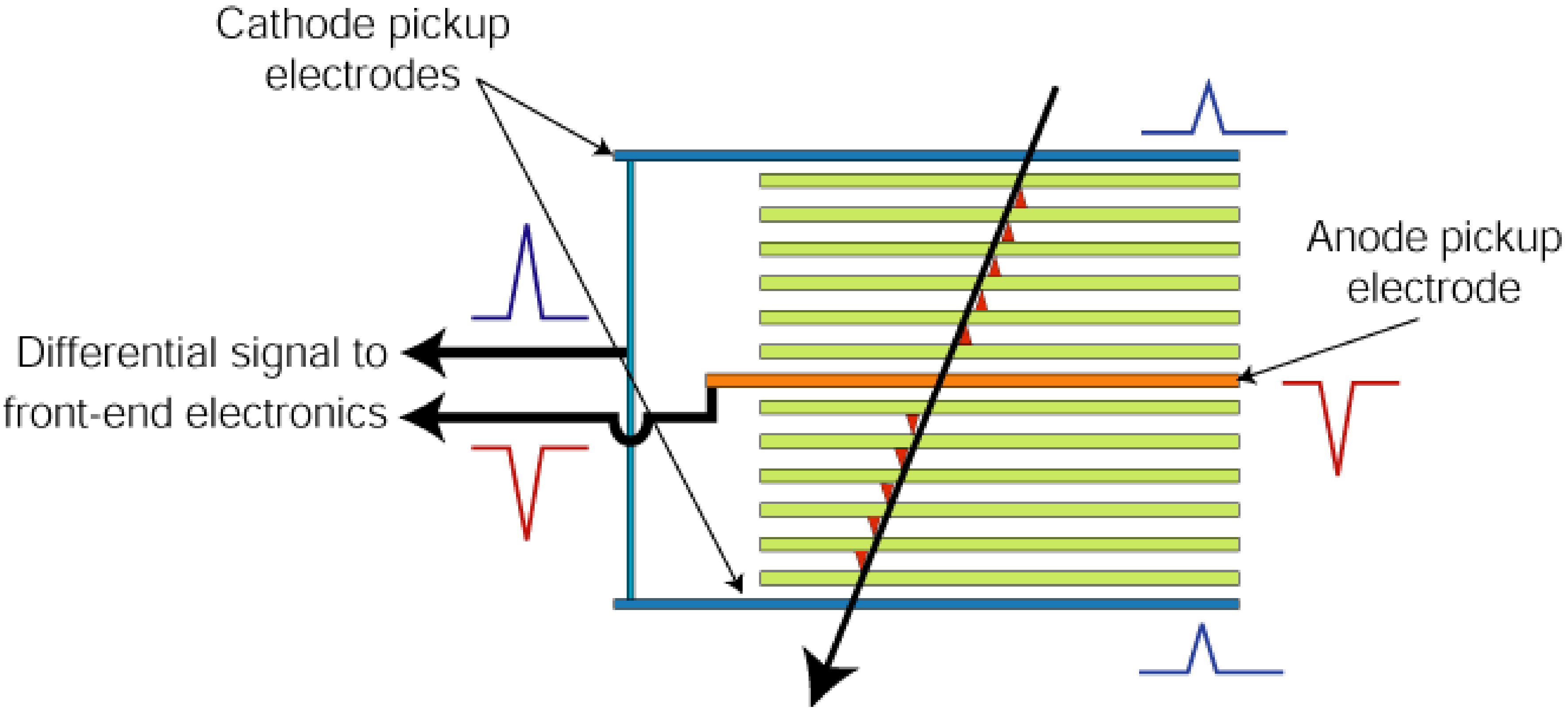



RPCs installed on the CMS detector

RPC con’t

- RPCs are robust detectors, they have no wires to break
- The signal formation happens in the conversion gap as soon as the ionization electrons amplify and the avalanche develops. The signal is induced instantly on the readout strips placed on the outside of the resistive plates. RPCs are therefore fast detectors and achieve time resolutions in the ns range (or better)
- In standard RPCs the resistive plates are bakelite with a bulk resistivity of $\approx 10^{10}$ Ohm/cm (CMS, ATLAS, Babar, …)
- In multi-gap timing RPCs glass plates (with a bulk resistivity of $\approx 10^{12}$ Ohm/cm) are more commonly used
- The weak point of the RPCs is their rate limitation owing to the high bulk resistivity in the resistive plates, leading to local charging up, followed by a loss of efficiency.
- RPCs are considered safe up to rates of about a few kHZ/cm^2

Multi-gap RPCs as TOF detectors

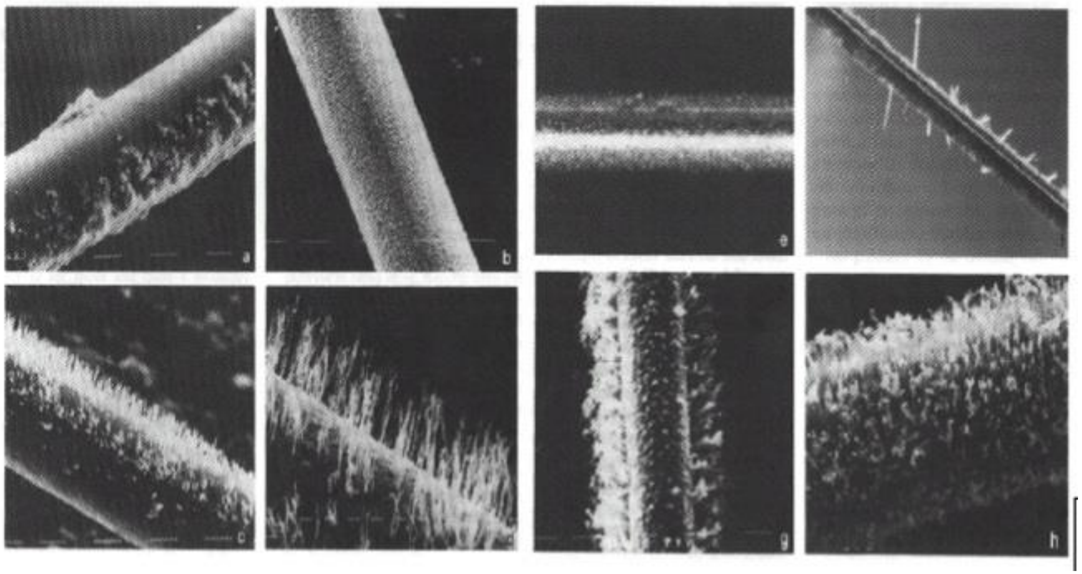


In ALICE time resolutions of 50 ps have been reached (C. Williams et al.)

Problems with wire chambers

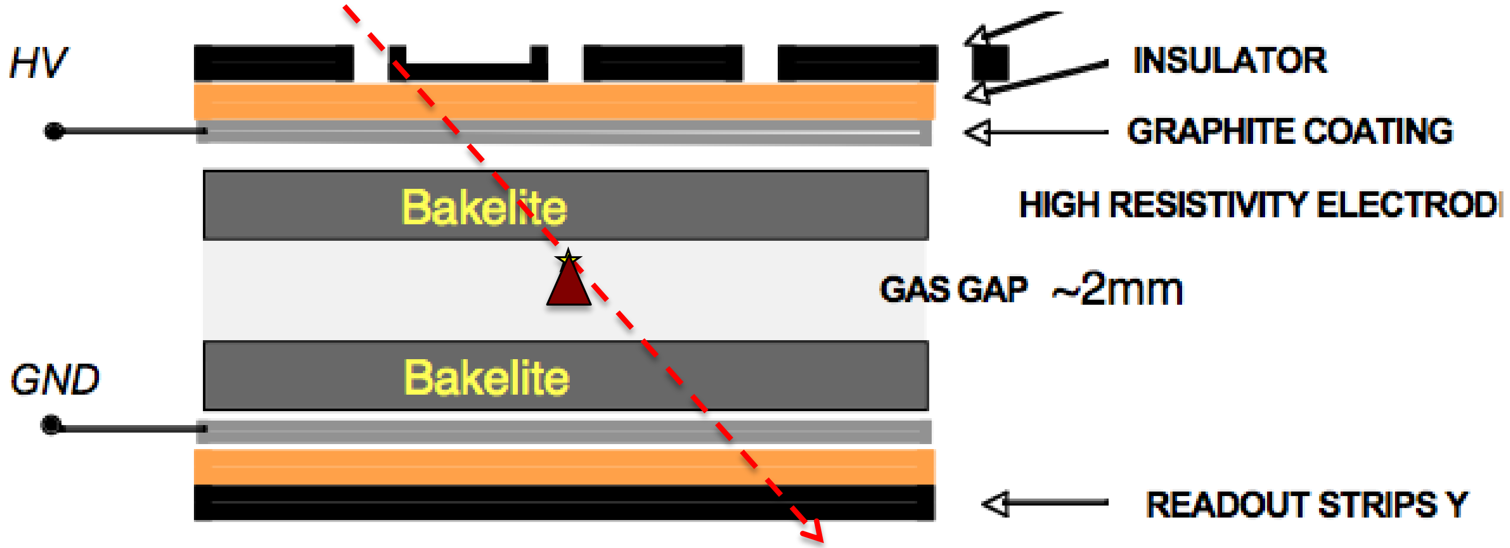
- Gas impurities or high currents may lead to the development of deposits on the wires in the form of tiny whiskers (polymerization of chemical elements in the gas)
- These may lead to HV instabilities and inefficiencies and in the worst case they may make chambers completely unusable

- Measures against ageing:
  - Careful choice of materials (no Si or similar)
  - Highest gas gas purity
  - Avoid exceedingly high currents



Problems with RPCs

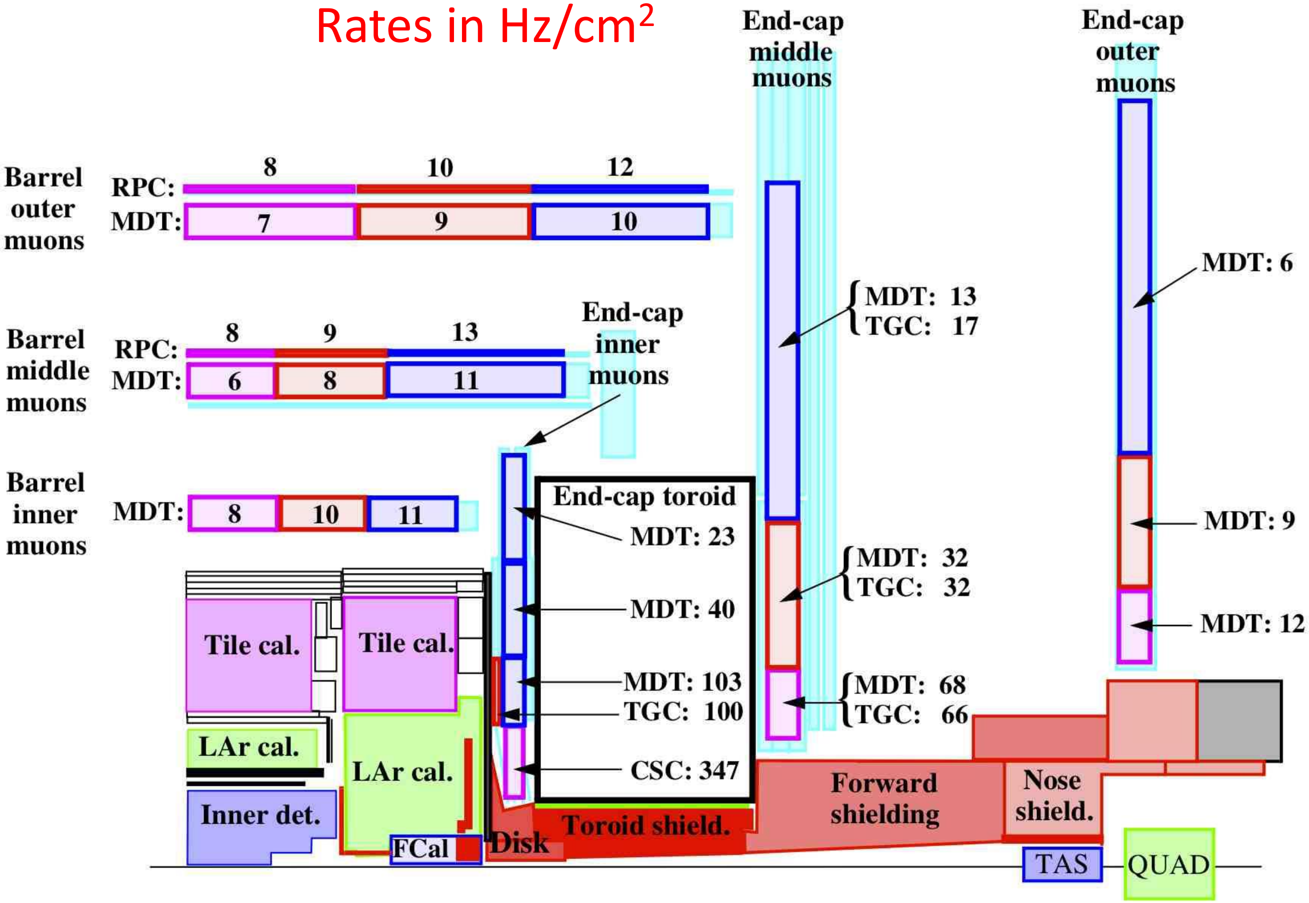
- RPCs do not suffer from deposits on the wires, however, surface impurities may lead to similar effects on the parallel surfaces, with the risk of discharges, given the high potential of 5 kV/mm between the plates.
- While RPC are extremely fast detectors, their weakness is their limited rate capability owing to the charging up of the resistive plate
- Another weak point is the moderate spatial resolution that can be reached since the exact point of conversion is not known



Future muon detectors

Count rates*) in the ATLAS Muon System at $\sqrt{s}$ = 14 TeV for L = 10^{34} $cm^{-2}s^{-1}$

Rates in Hz/cm²

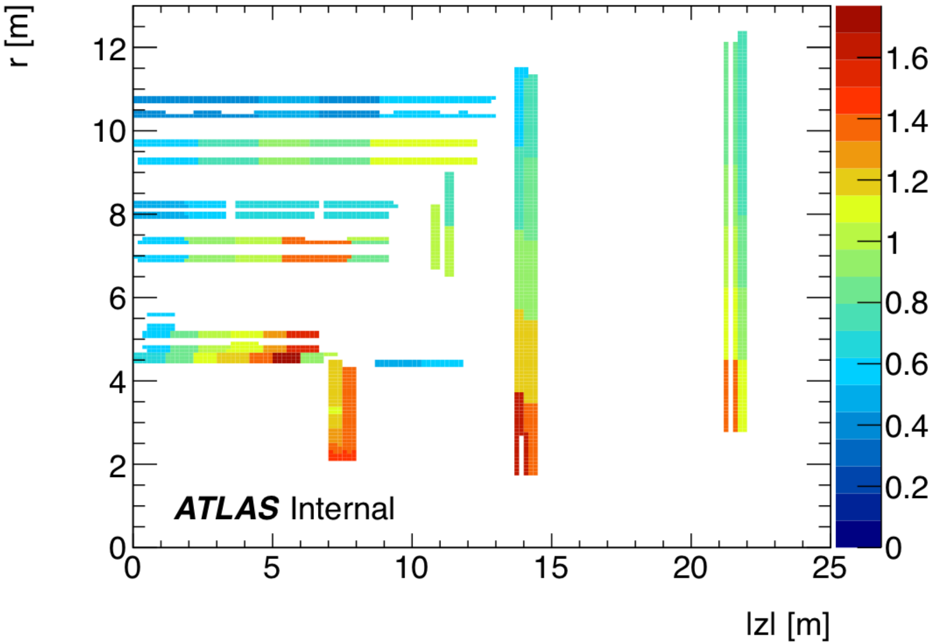


*) ATLAS Detector paper, 2008 JINST 3 S08003

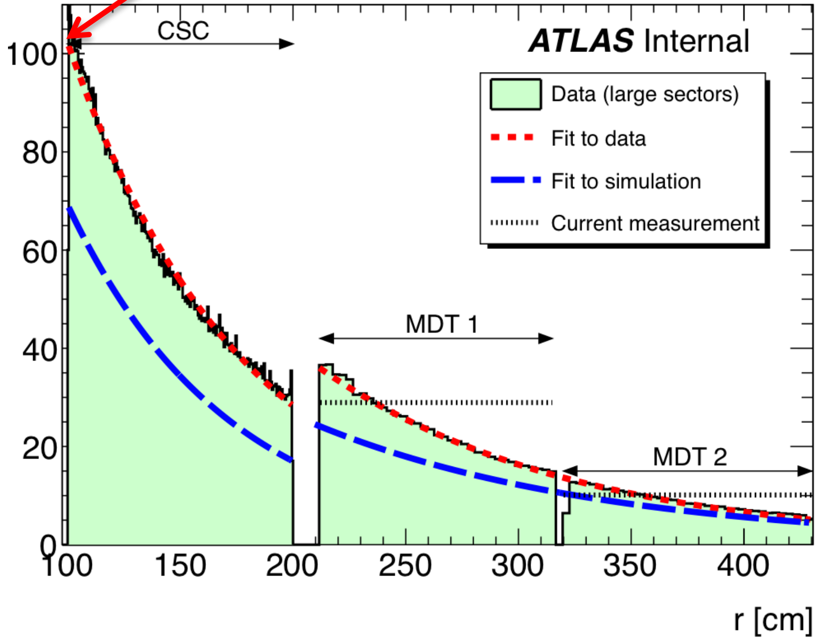
Rates: measurement vs simulation

Measured and expected count rates and in the Small Wheel detectors

Data correspond to L = 0.9 x 10^{33} $cm^{-2}s^{-1}$ at √s = 7 TeV



Ratio between MDT data and FLUGG[*)] simulation (CSC region not shown)



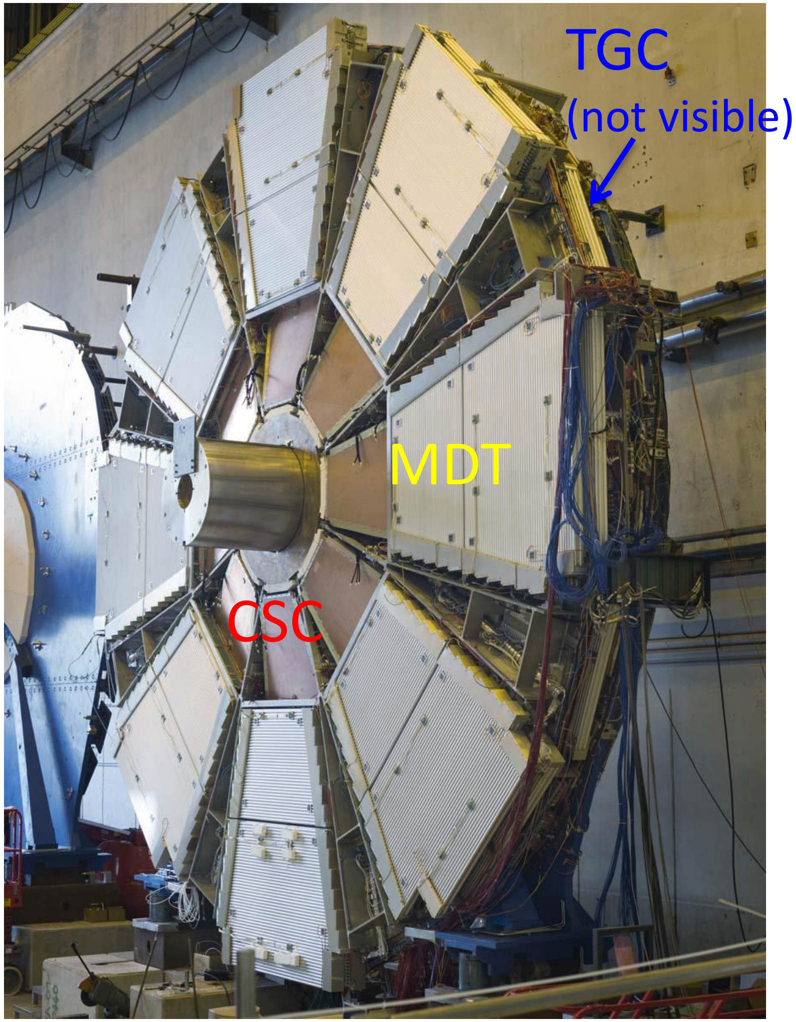
Expect: 10 kHz @ 7 x 10^{34} $cm^{-2}s^{-1}$

Rate in Hz/cm^2 as a function of radius in the large sectors

[*)] FLUGG simulation gives rates about factor 1.5 – 2 higher than old simulation

MPGDs: muon detectors for the future

- In ATLAS the first station of the end-cap muon system (Small Wheel) is most affected. In the most forward region the rates could reach up to 10–15 kHz/cm^2 at full luminosity after the LHC upgrade
- None of the currently installed detectors (MDT, CSC, TGC) can cope with such rates
- It has been decided to replace the detectors on the Small Wheel with a new generation of muon detectors: Micromegas and sTGCs.



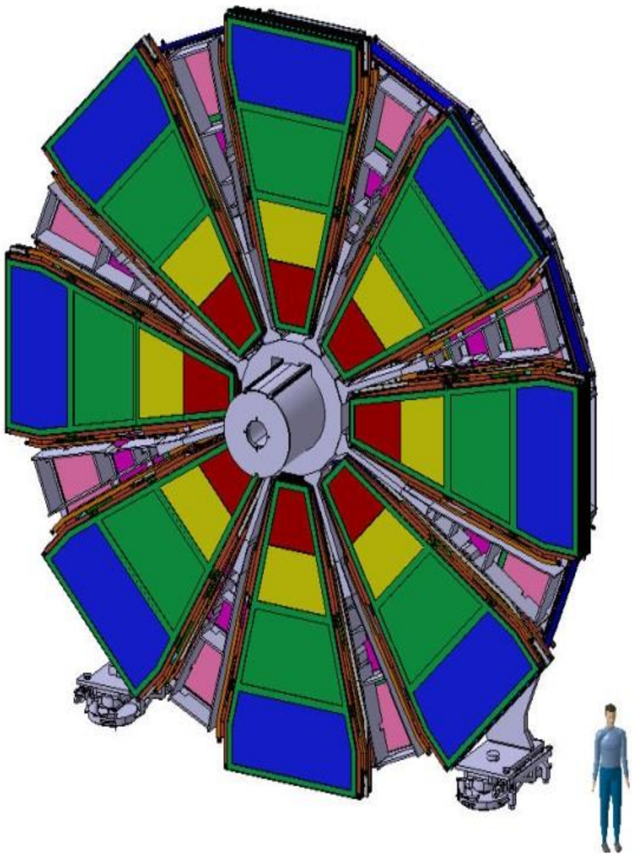
The ATLAS New Small Wheel

Two main objectives:

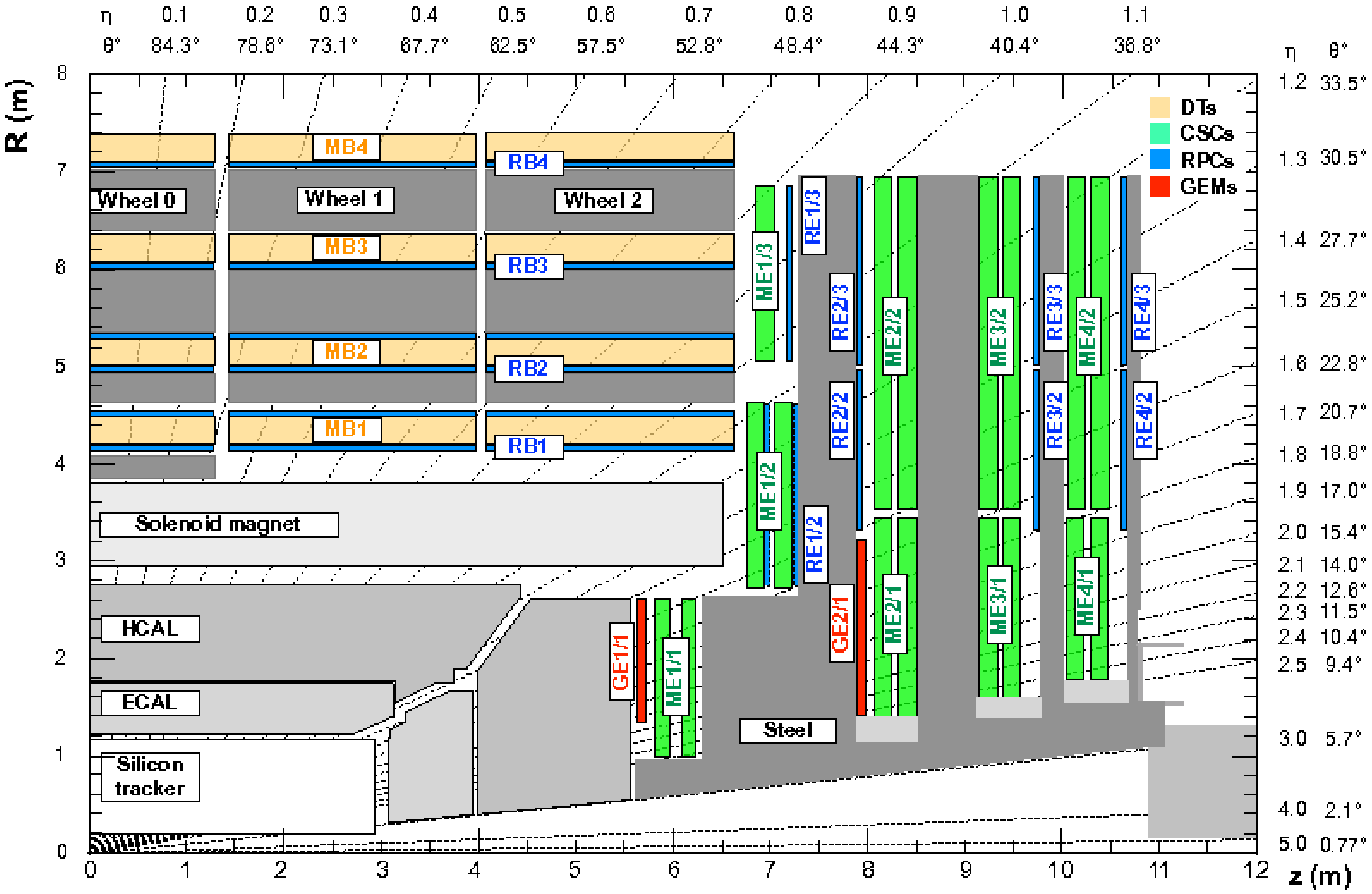
- Cope with higher rates
- Add trigger capability to the first end-cap station to fight fake triggers

Detectors:

- 8 layers of sTGCs with much finer readout (and trigger) granularity (3.2 mm compared to 20–30 mm of TGCs now installed)
- 8 layers of Micromegas (MM) with a readout strip pitch of 0.4 mm, comprising 2 M readout channels and 1200 m^2 of detector area
- Both detectors will deliver precision coordinates and LVL1 trigger information, i.e., track angle and position to confirm LVL1 candidates from Big Wheel



CMS GEM project



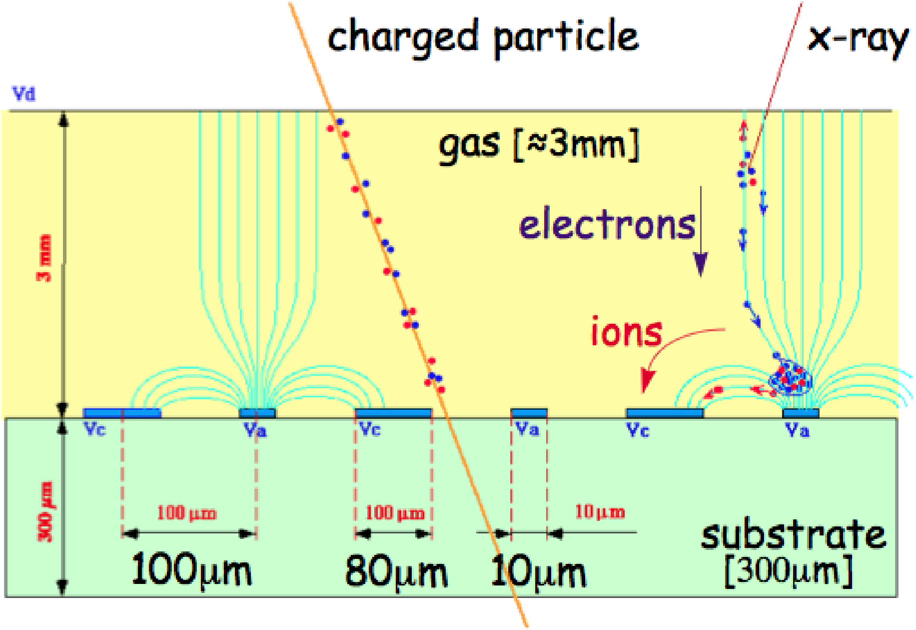
- Installation of two rings of Triple-GEM detectors in the forward direction

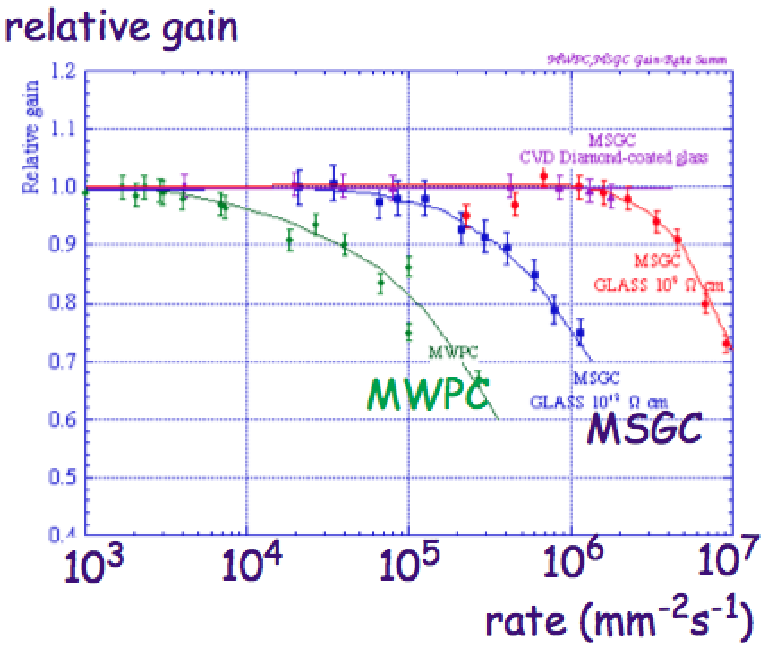
Why Micro Pattern Gaseous Detectors?

- Both MMs and GEMs fulfil a number, if not all, of requirements for the new generation of muon chambers
- They are capable of operating at very high rates, they work in magnetic fields, they are radiation hard and age well.
- Their shape and readout segmentation can be adapted to the needs. They are parallel plate structures with straight-forward field shapes.
- In particular the MMs can be operated at very low HV owing to the extremely thin amplification gap.
- Both MM and GEM have been, for years, successfully used in the COMPASS experiment as vertex detectors and demonstrated their high-rate capability.
- Both types of detectors start being industrially produced opening the field for on-the-shelf detectors.

Microstrip gaseous detectors

A. Oed, NIM A 263 (1988) 352

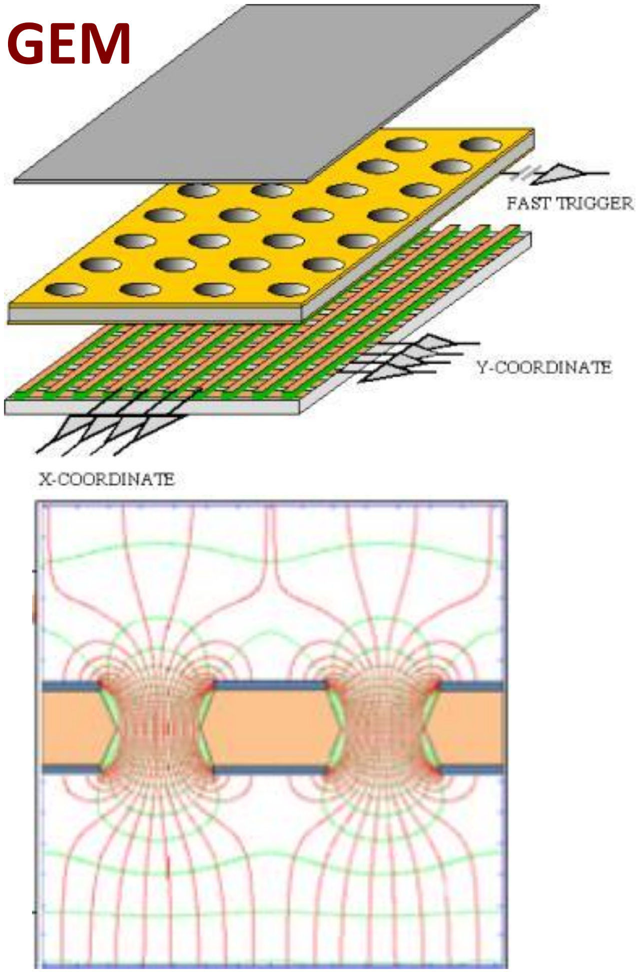




- Very precise readout structures produced using PCB technology (lithography)
- Very good spatial resolution
- No wires, small conversion (drift) gap, moderate HV
- Short ion evacuation path => high rate capability

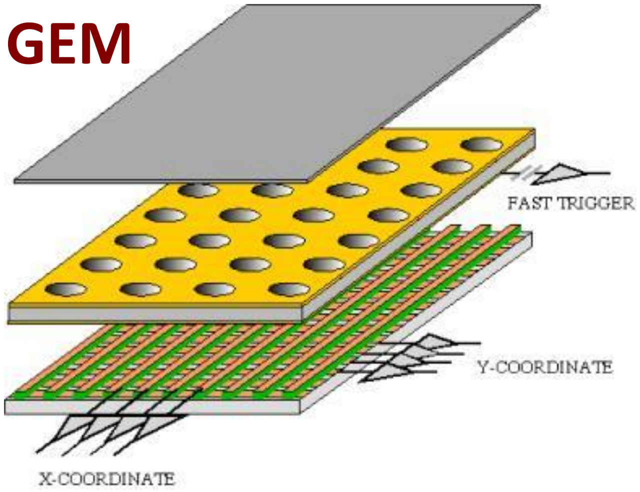
Gas Electron Multiplier (GEM)

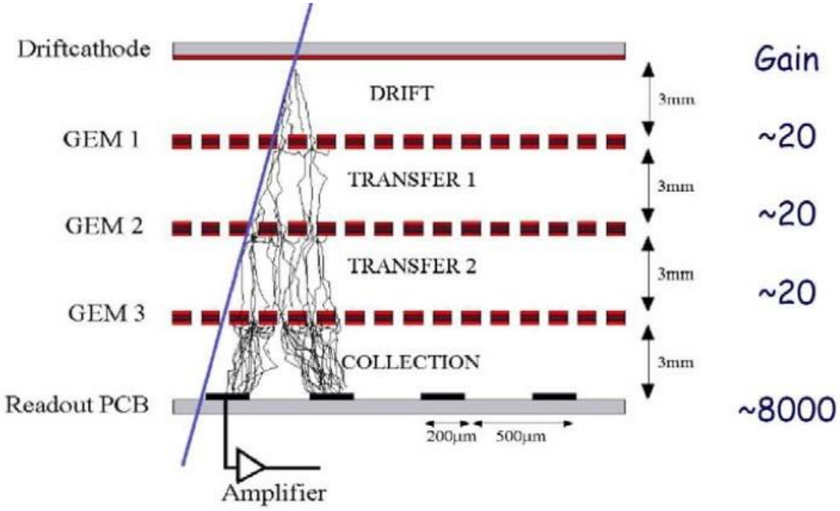
- The GEM (gas electron multiplier) was invented by F. Sauli at CERN, (R. Bouclier et al., NIM A 396 (1997) 50).
- It is a parallel plate structure with perforated Cu-clad Kapton foils. By applying a potential between conducting foil surfaces a strong field develops inside the holes
- The electron multiplication takes place in the field inside the holes
- Typical hole diameters are 70–120 µm and the Kapton foils are about 50 µm thick



GEMs

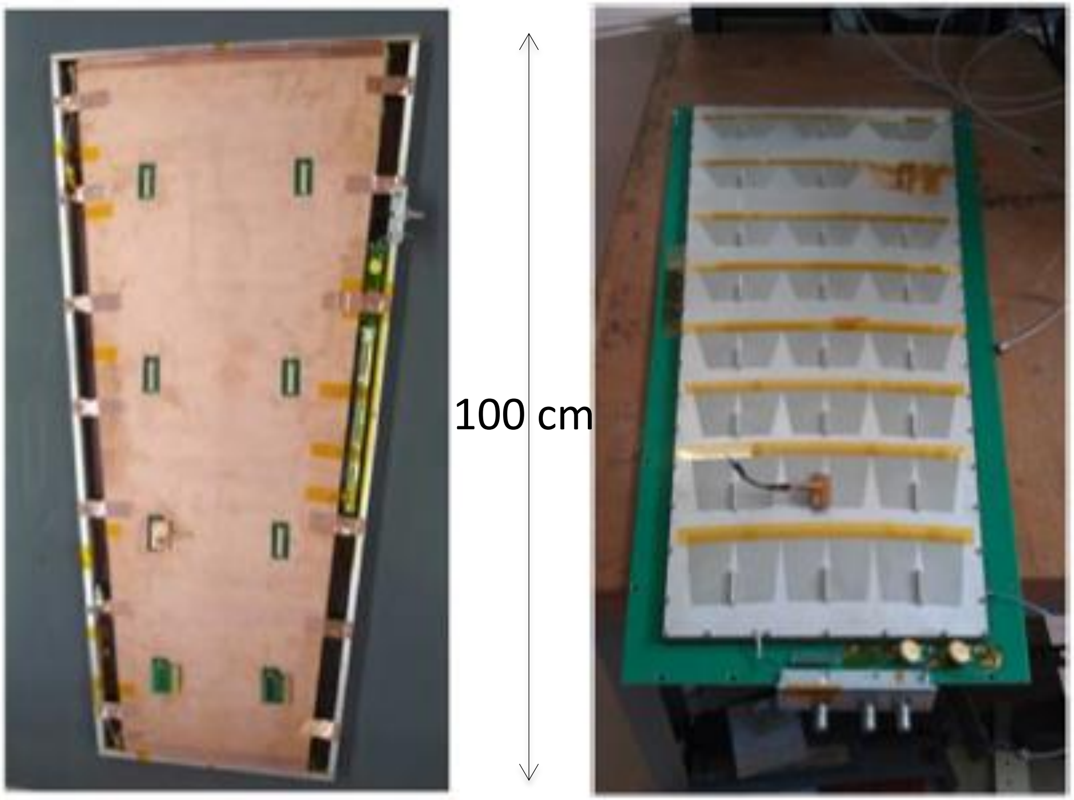
- GEMs have been successfully used in a large number of detectors and reached excellent performance in high rate environments (e.g. COMPASS, NA48, …)
- Most of the time triple-GEM structures were used to avoid HV breakdown. By keeping the amplification in each of the GEM foils low and by spreading the electron avalanche sparking can be reduced to a very low level.





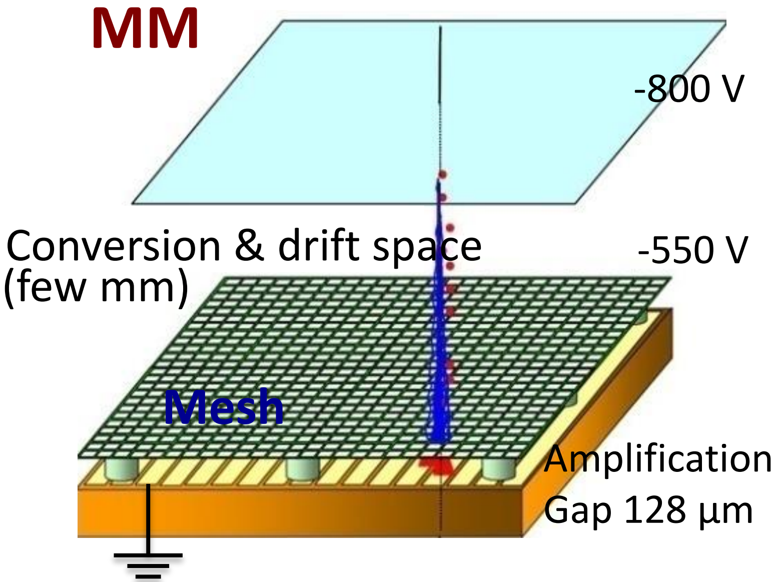
GEMs for the CMS upgrade

- CMS started about five years ago to develop detectors based on the GEM technology to be installed in the forward nose of the CMS end-caps
- They have constructed a few full-size test chambers and successfully tested them. They showed that they can operate without problems inside a magnetic field. Spatial resolutions close to 100 µm have been reported.
- 2 x 2 GEMs will be installed as demonstrator system in the 2016 shutdown in CMS.
- The full system is expected to be installed in the 2018 LHC shutdown.



Micromegas

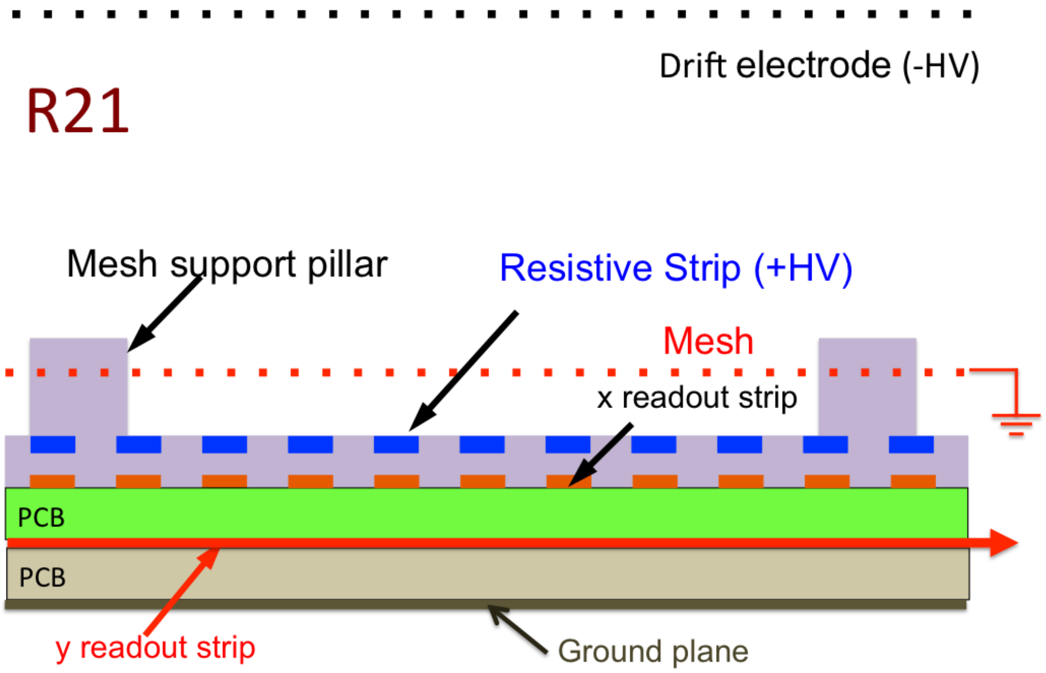
- Micromegas (I. Giomataris et al., NIMA 376 (1996) 29) are parallel-plate chambers where the amplification takes place in a thin gap, separated from the conversion region by a fine metallic mesh
- Depending on the gas a few mm of conversion gap are sufficient to achieve efficiencies close to 100%; in argon an average of 35 ionization electrons are produced in a 5 mm gap.
- The thin amplification gap (short drift times and fast absorption of the positive ions) makes it particularly suited for high-rate applications
- The weak point of the MMs were their vulnerability to sparking



The principle of operation of a micromegas chamber

Micromegas

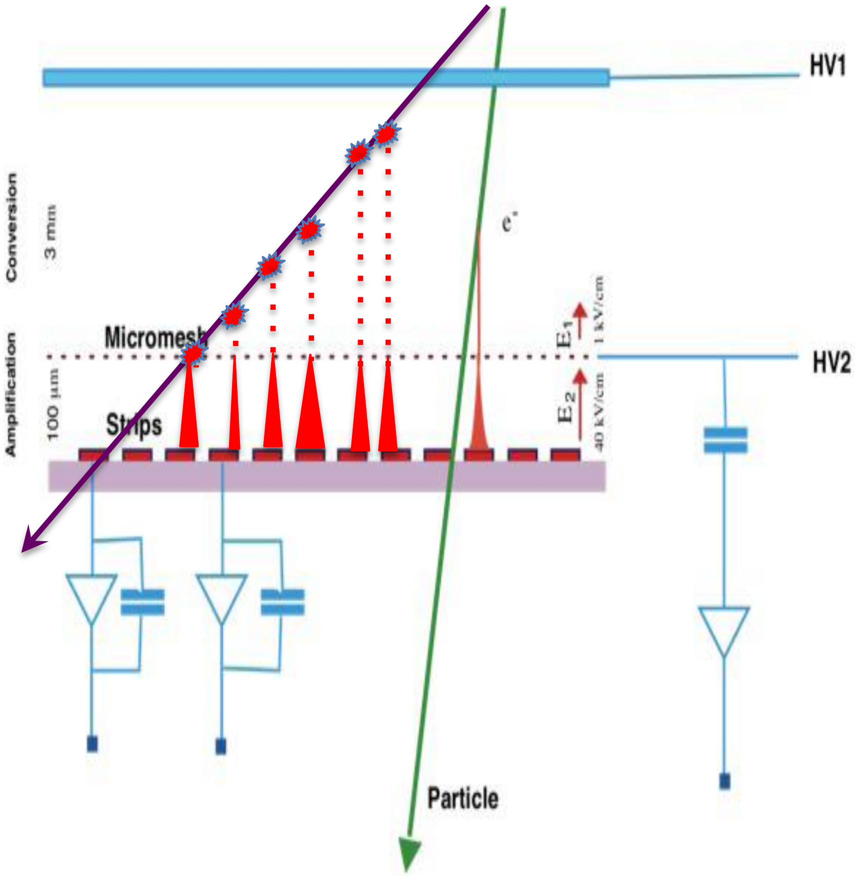
- The break-through came with the introduction of a layer of resistive strips above the readout structure, making the MMs spark tolerant without degrading their performance(T. Alexopoulos et al., NIMA 640 (2011) 110)



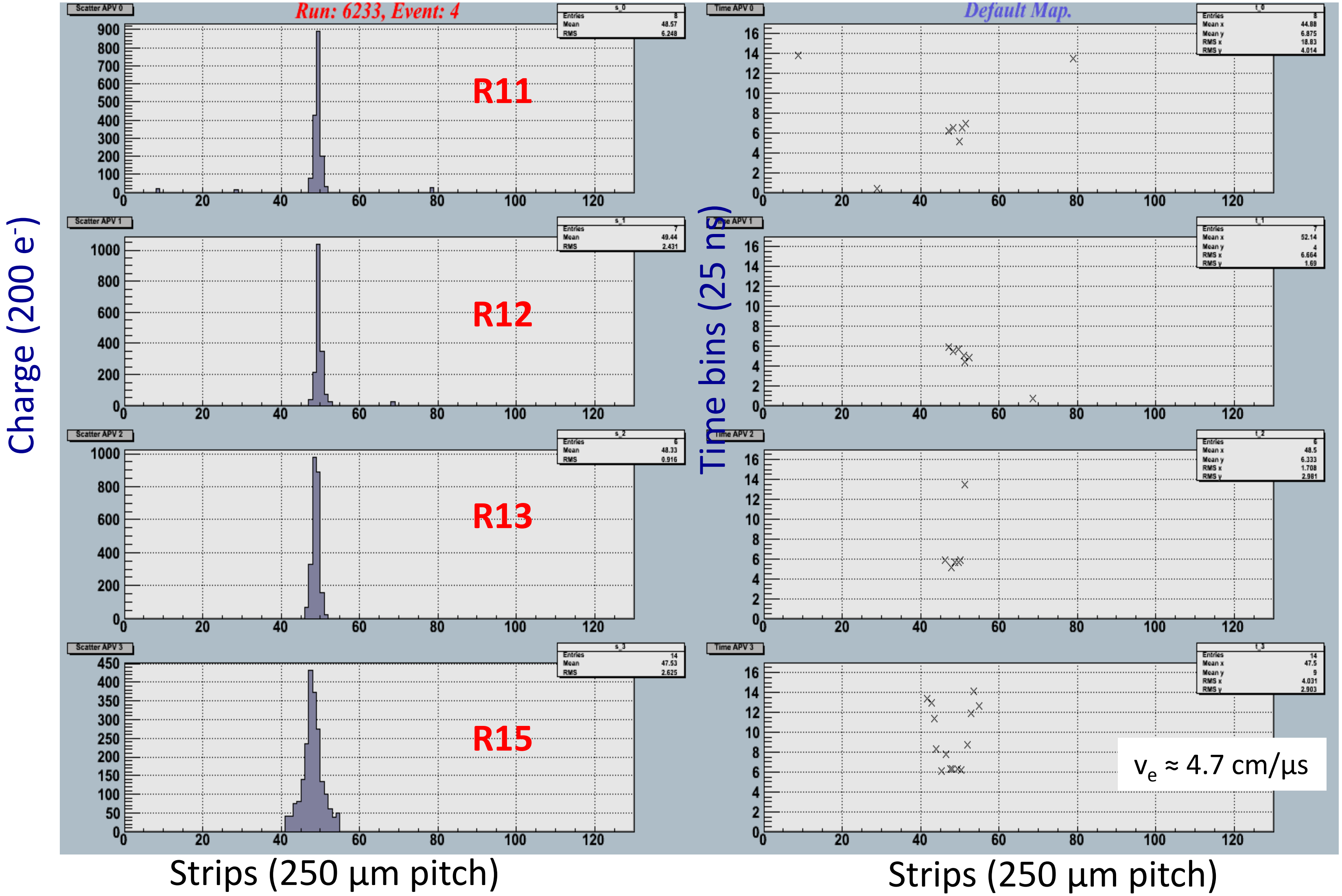
Micromegas as µTPC

- ‘Wide’ drift region (typically a few mm) with moderate electric field of 100–1000 V/cm
- Narrow (100 µm) amplification gap with high electrical field (40–50 kV/cm); a factor $E_m/E_d \approx 70–100$ is required for full mesh transparency for electrons
- With drift velocities of 5 cm/µs (or 20 ns/mm) electrons need 100 ns for a 5 mm gap
- By measuring the arrival time of the signals a MM functions like a TPC

=> Track vectors for inclined tracks

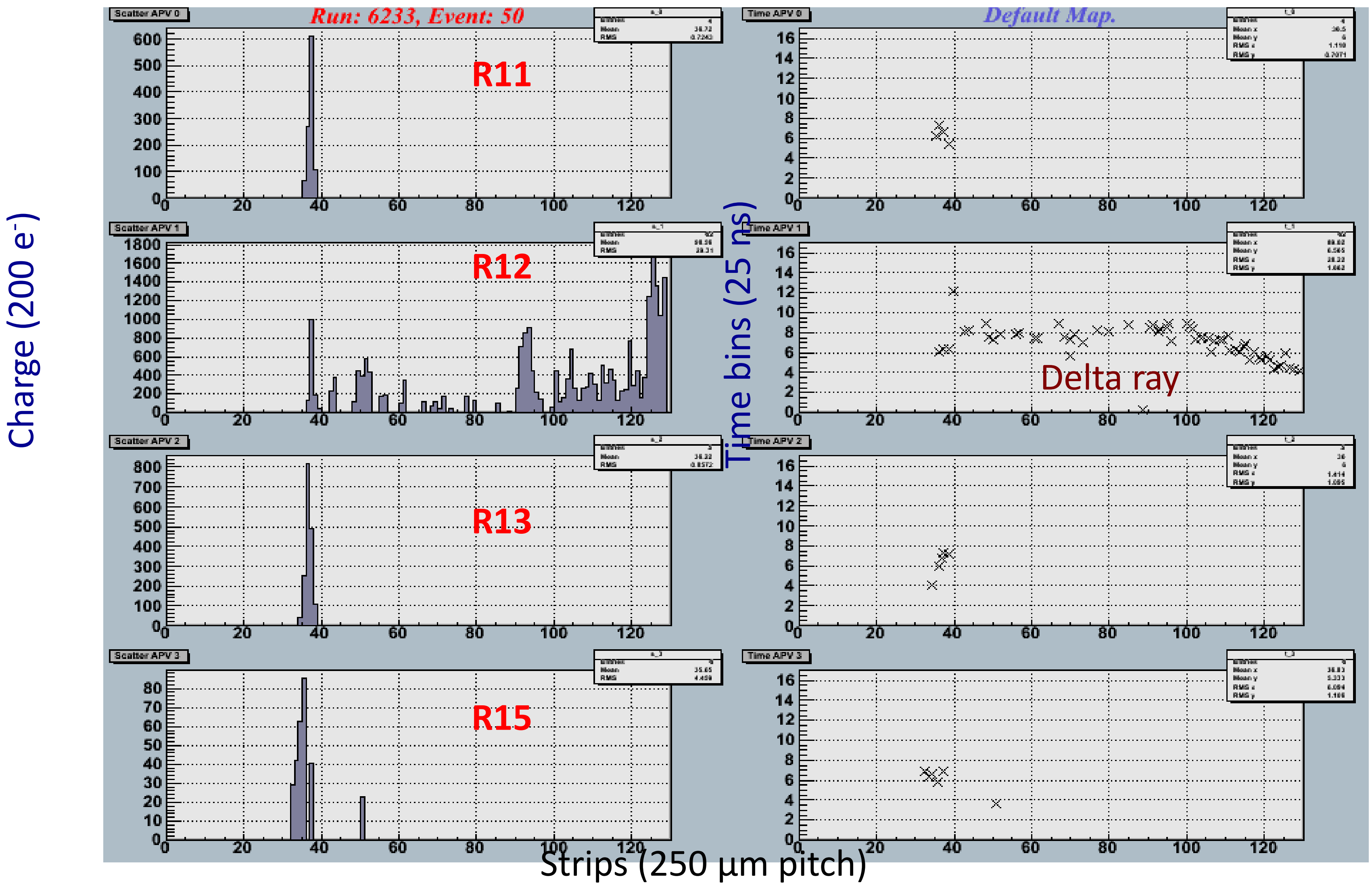


Pion track measured in four micromegas detectors

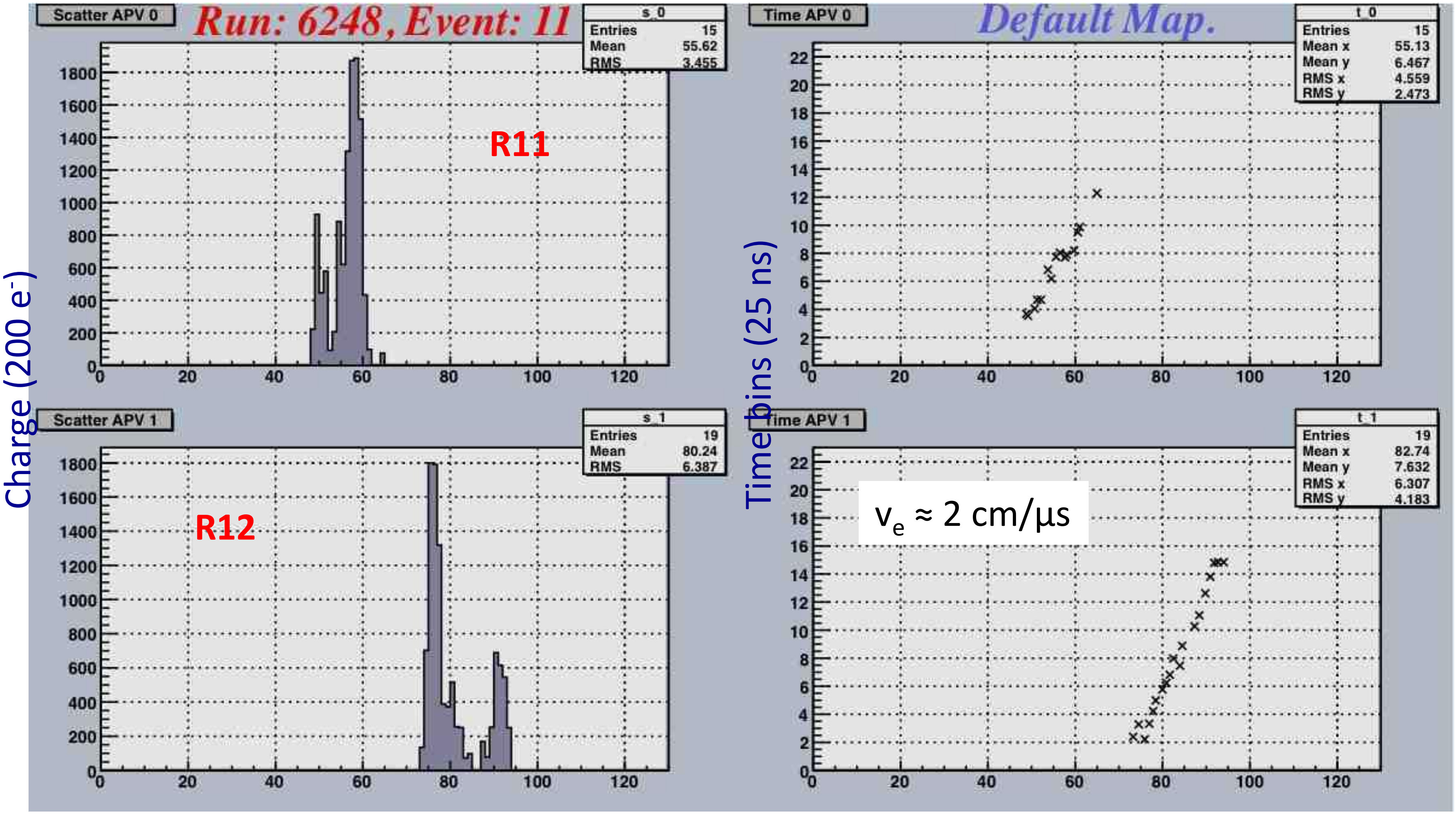


$v_e \approx 4.7$ cm/µs

Pion track measured in four micromegas detectors



Inclined tracks (40°) – µTPC



Charge (200 e$^-$)

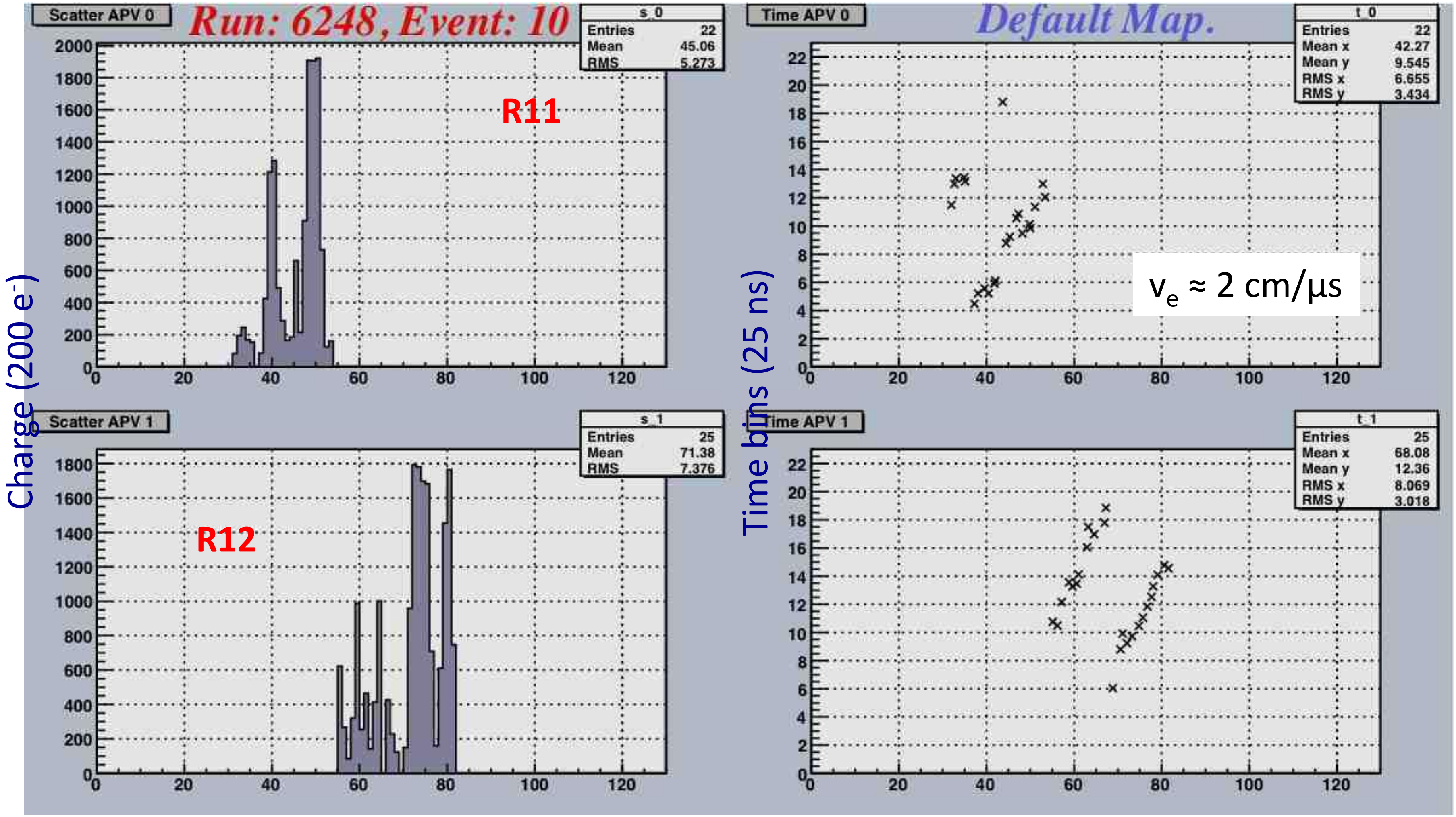
Timebins (25 ns)

R11

R12

$v_e \approx 2$ cm/µs

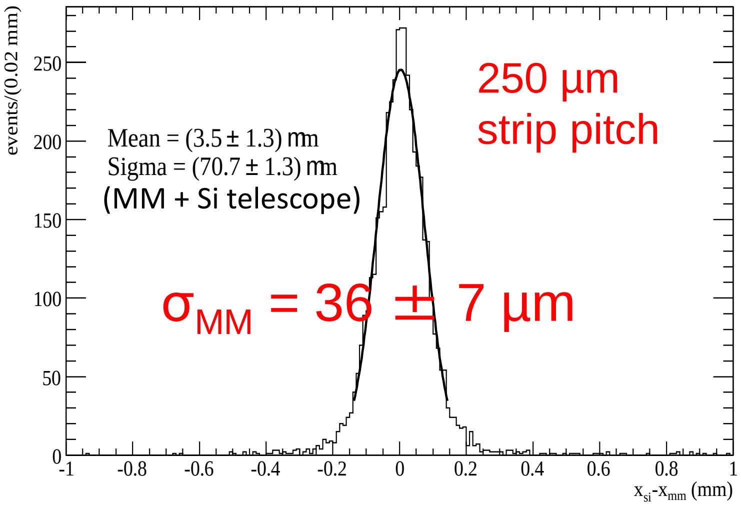
… and a two-track event



$v_e \approx 2$ cm/μs

MM performance

- Efficiency ≥99% per plane
- Gas gain: ≈10^4
- Very good spatial resolution for vertical tracks

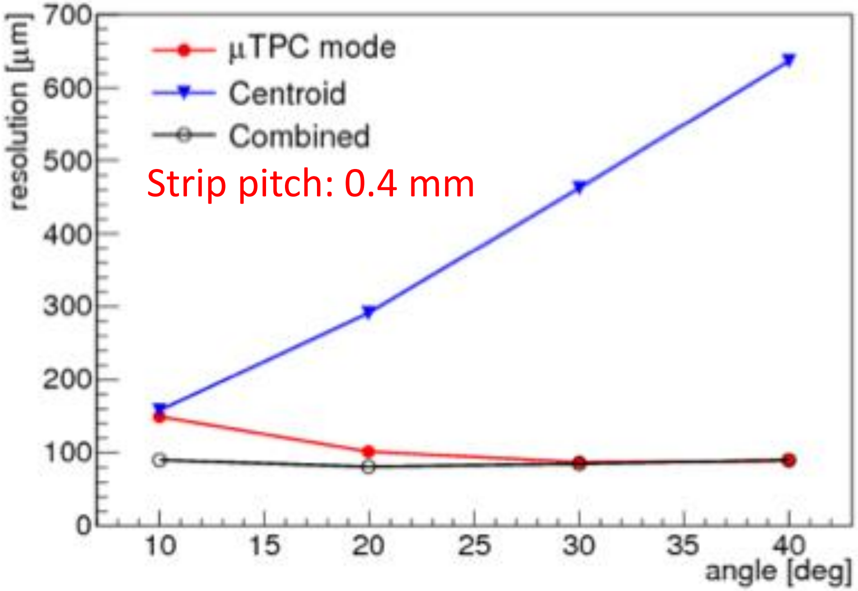


(MM + Si telescope)

250 µm strip pitch

$\sigma_{MM} = 36 \pm 7$ µm

- Spatial resolution degrades quickly with track inclination
- µTPC mode recovers resolution, combining the two leads to spatial resolutions below 100 µm independent of track angle



Strip pitch: 0.4 mm

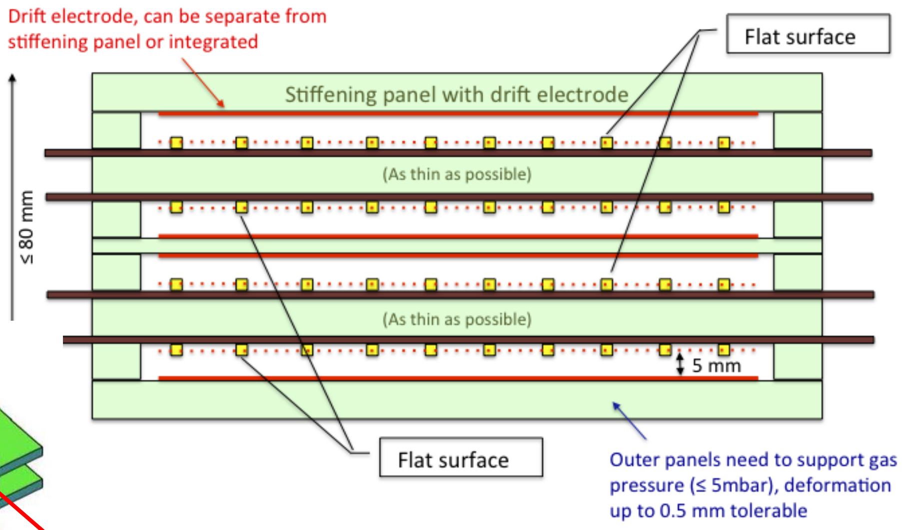
Micromegas as muon chambers

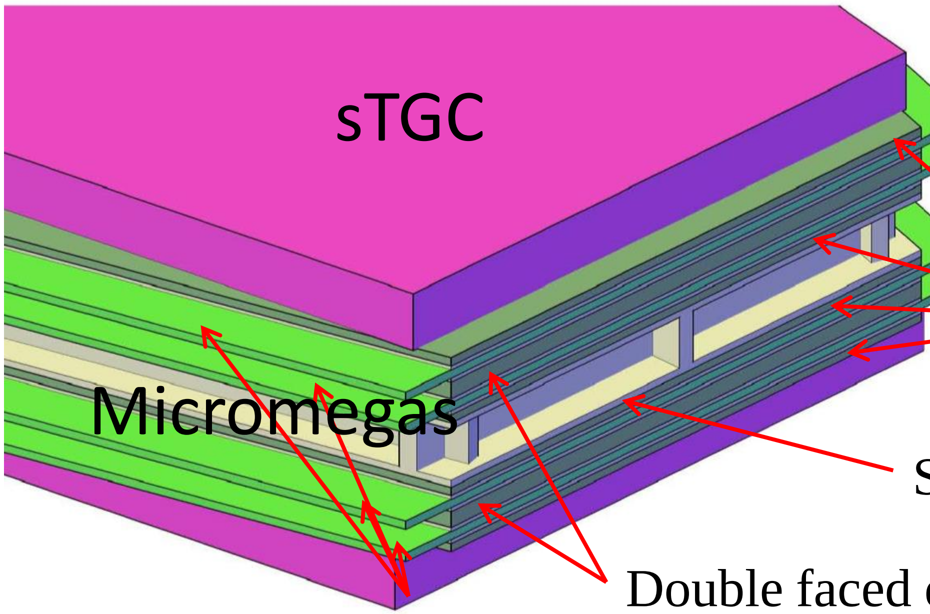
- The first large-area micromegas detector has been constructed early 2013
- Now ATLAS is preparing for Module-0 detectors for the NSW, to be constructed in the 2nd half of 2014
- 128 detector quadruplets, each 2–3 m^2 in size, will be constructed in France, Italy, Germany, Greece, and Russia, starting next year.
- Installation in ATLAS will take place in 2018/2019


15 Jan 2013

The ATLAS New Small Wheel II

Micromegas stack





Drift panel
(10 mm)

Spacer – 40 mm

Double faced drift panel (10 mm)

Read-out panel (10 mm)

Conclusions

- Muon detection started with cloud chambers (and Geiger-Müller tubes!) some 80 years ago
- The main break-through in tracking detectors came with the invention of the MWPC in the 1960ies and their variants in the following years; they are still widely used.
- A new trend came with wireless, parallel-plate chambers such as RPCs and more recently with the a large variety of MPGDs (GEMs, MMs, micropics, THGEM, …)
- MPDGs are probably the new generation of muon detectors being robust, radiation hard and showing no signs of ageing, while at the same time they are able to cope with high rates and reach excellent spatial resolution and are, at the same time, fast enough to serve as trigger detectors.