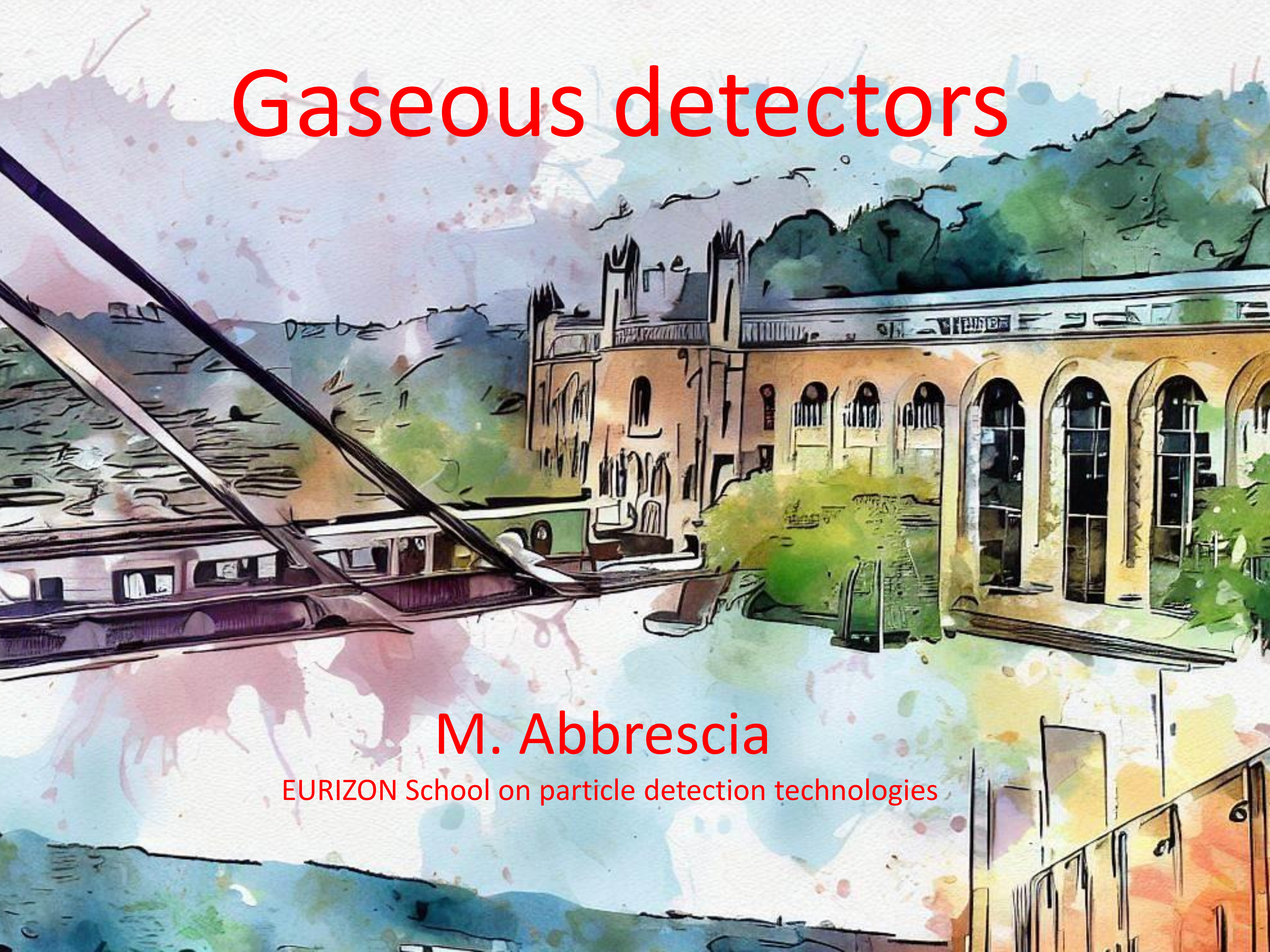


Gaseous detectors

M. Abbrescia

EURIZON School on particle detection technologies

Choice of the gas filling

1. **Noble gases** are preferentially used due to the absence of vibrational and rotational states → **ionization dominates.**

(Polyatomic gas have non-ionizing de-excitation modes available)

→ Possible electron multiplication at low electric field

→ Choose cheap noble gases with low ionization potential

Expensive and rare

Gas	ρ (g/cm³) (STP)	I_0 (eV)	W_i (eV)	dE/dx (MeVg⁻¹cm²)	n_t (cm⁻¹)
H_2	$8.38 \cdot 10^{-5}$	15.4	37	4.03	9.2
He	$1.66 \cdot 10^{-4}$	24.6	41	1.94	7.8
N_2	$1.17 \cdot 10^{-3}$	15.5	35	1.68	56
Ne	$8.39 \cdot 10^{-4}$	21.6	36	1.68	39
Ar	$1.66 \cdot 10^{-3}$	15.8	26	1.47	94
Kr	$3.49 \cdot 10^{-3}$	14.0	24	1.32	192
Xe	$5.49 \cdot 10^{-3}$	12.1	22	1.23	307
CO_2	$1.86 \cdot 10^{-3}$	13.7	33	1.62	91
CH_4	$6.70 \cdot 10^{-4}$	13.1	28	2.21	53
C_4H_{10}	$2.42 \cdot 10^{-3}$	10.8	23	1.86	195

The drift velocity depends very strongly on the nature of the gas, namely on the detailed structure of the elastic and inelastic electron-molecule cross-sections. Sometimes it saturates at high electric fields.

Choice of the gas filling

If only a noble gas is used to fill the counter, it can operates at relatively low gains ($M \approx 10^3$ - 10^4) before entering the permanent discharge regime

When the avalanche forms, excited Ar atoms are created, which can return to the ground state only emitting UV photons

- The energy of these photons can be sometimes larger than the energy needed to extract electrons from the cathode walls (7.7 eV for copper)
- Photoelectrons can be extracted from the walls, which cause farther ionization of the gas

Possible spurious delayed pulses due to ions neutralizing on the cathode

- Ar+ ions reaching the cathode are neutralized and extract an electron from the walls
- The neutral Ar atom is produced in an excited state, decays emitting UV photons
- An additional electron can also be extracted from the wall

Both processes induce spurious delayed pulses

Use of quencher gases

The problem is solved by adding to noble gas percentages of other polyatomic gases, usually called "quenchers"

✓Gas quencher molecules have non-radiative (rotational and vibrational) mode and can absorb UV photons in a wide energy range.
- CH_4 absorbs photons between 7.9 and 14.5 eV
- Other polyatomic gases used are freons, CO_2, BF_3, C_4H_{10}, etc.

✓Polyatomic gases dissipate energy by elastic collisions

Sometimes quenchers can dissociate resulting in simpler molecules, sometimes harmful to the detector, like HF → aging

Even small quantities of quencher allow to operate these detectors up to gain of 10^6 without discharges.

Use of quencher gases

Also electronegative gases are used as quenchers, like many freons (CF_3Br), ethyl-bromide (C_2H_5Br), etc. which help operate detectors at high gain without discharges.

- They are characterized by an electron capture mean free path that is less than typical anode-cathode distance (≈ 1 cm) and larger than avalanche size (few μm)

- These gases capture electrons possibly extracted at the cathode forming negative ions, preventing the formation of spurios delayed avalanches

- Also these gases can dissociate, sometimes forming solid or liquid polymers which can deposit on the electrodes, altering their properties
→Malter effect, where the E field close to the electrode is distorted, causing undesired discharges
→Aging effects (one of the main issues in all particle detectors)

Proportional counters

A cylindrical geometry is adopted

- The anode is a thin wire, on the cylinder axis
- The cathode is the metallic wall of the cylinder

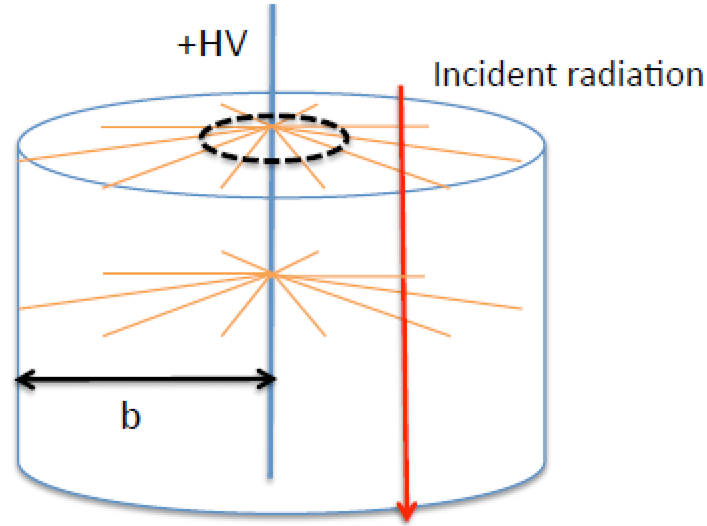
In most part of the counter, the electric field is not enough to trigger avalanche processes

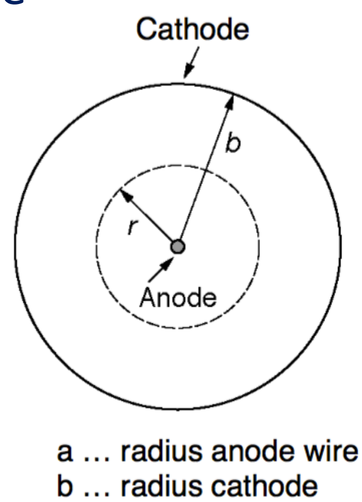
- Electrons drift toward the anode
- Ions drift toward the cathode

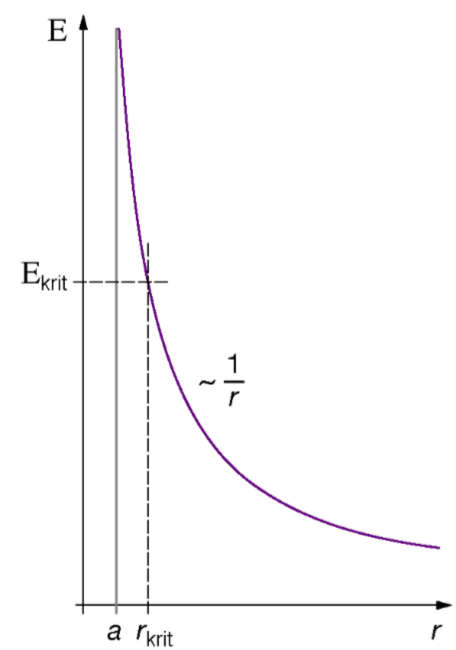
When electrons get close to the wire (usually at a few wire radii), the electric field becomes intense enough to trigger multiplication processes

- A drop-like avalanche develops, with electrons in front and ions left behind
- Due to diffusion, the avalanche surrounds the wire

Electrons are collected at the anode, while positive ions keep drifting toward the cathode

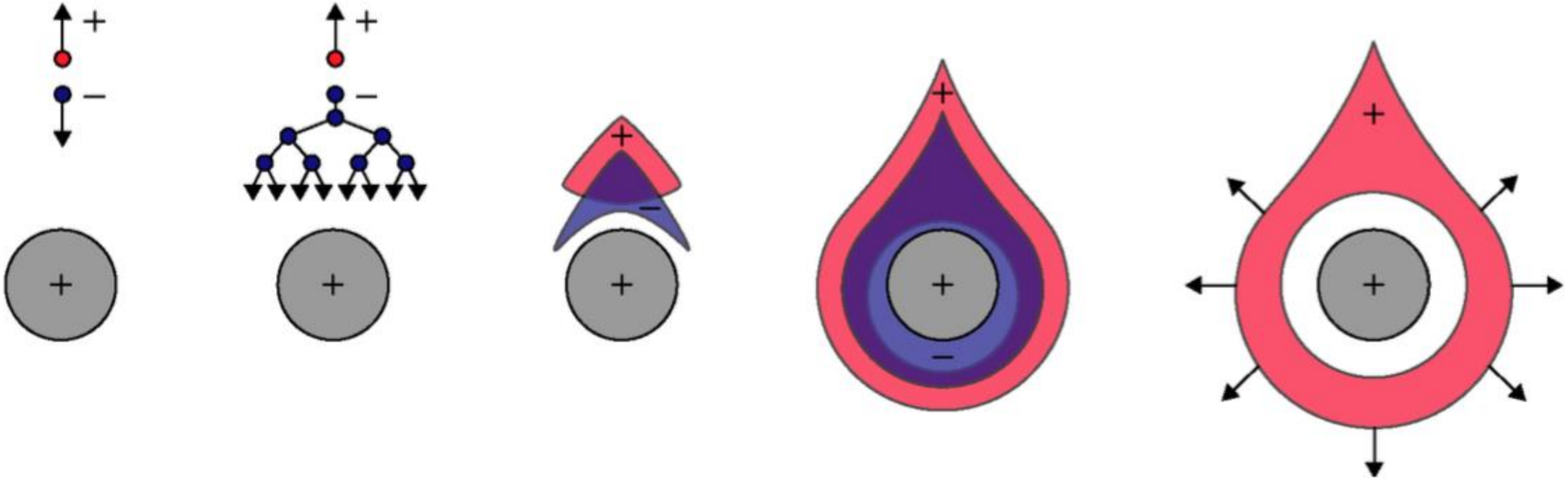






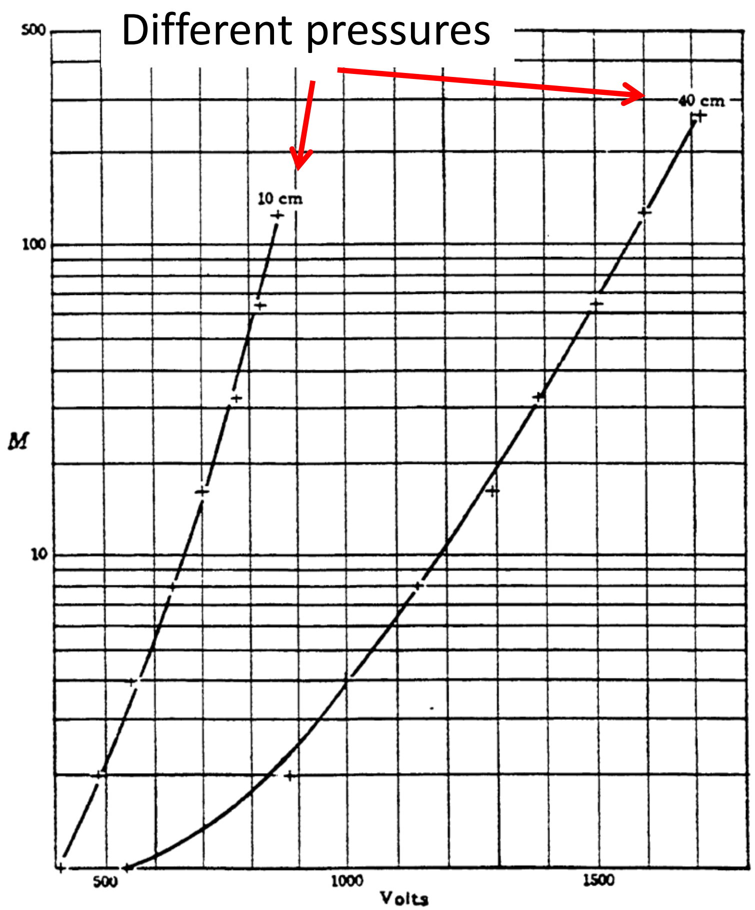
Avalanche development close to the wire

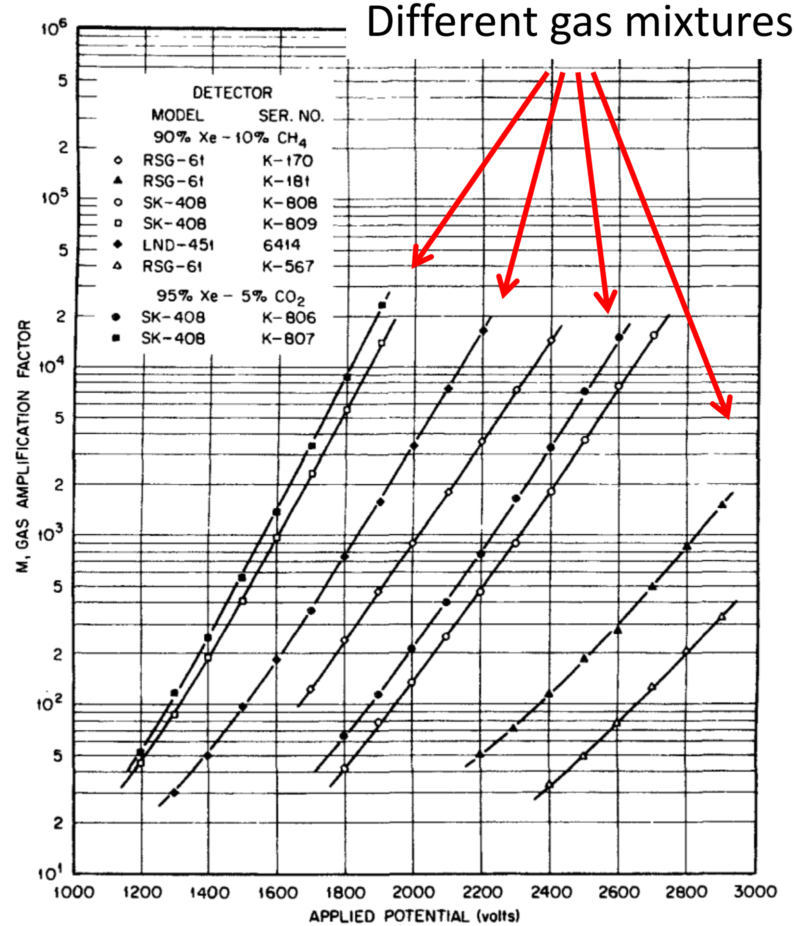
Time development of an avalanche near the wire of a proportional counter



a) a single primary electron proceeds towards the wire anode,
b) in the region of increasingly high field the electron experiences ionizing collisions (avalanche multiplication),
c) electrons and ions are subject to lateral diffusion,
d) a drop-like avalanche develops which surrounds the anode wire,
e) the electrons are quickly collected, while the ions begin drifting towards the cathode generating the signal at the electrodes.

Gain in proportional counters

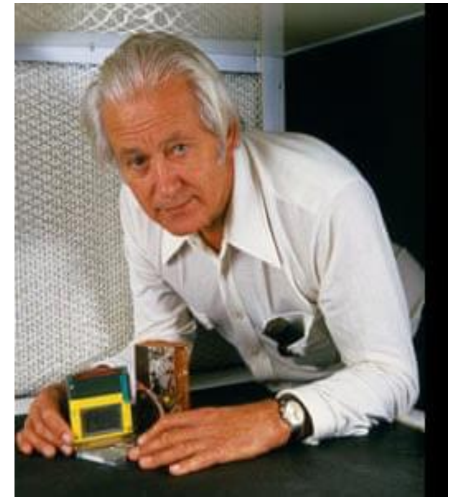




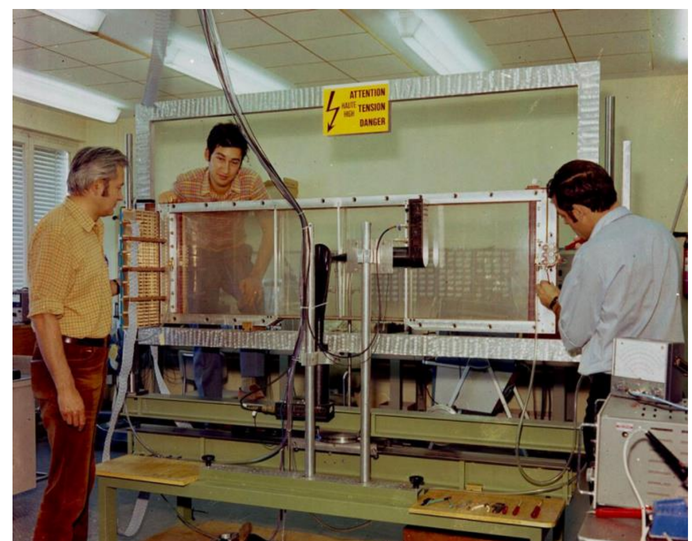
Comparison between predictions (lines, Diethorn formula) and experimental results (points)

Multi-wire proportional chambers

The invention of the Multi Wire Proportional Chamber (MWPC) by Georges Charpak in 1968 was a game changer, earning him the 1992 Nobel Prize in Physics. Suddenly, experimenters had access to large-area charged particle detectors with millimeter spatial resolution and staggering MHz-rate capability. Crucially, the emerging integrated-circuit technology could deliver amplifiers so small in size and cost to equip many thousands of proportional wires.

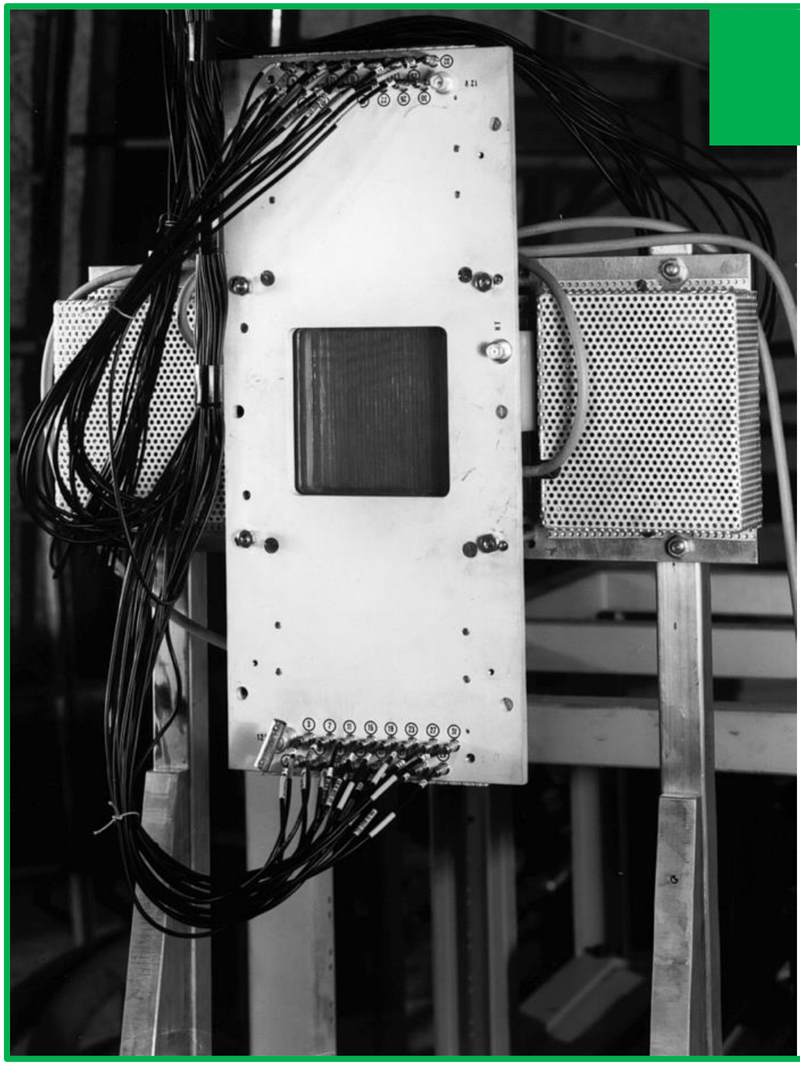


This ingenious and deceptively simple detector is relatively easy to construct. The workshops of many university physics departments could master the technology, attracting students and "democratising" particle physics. So compelling was experimentation with MWPCs that within a few years, large detector facilities with tens of thousands of wires were constructed […].



C.W. Fabjan, CERN courier, March 22nd 2019

Examples of MWPCs

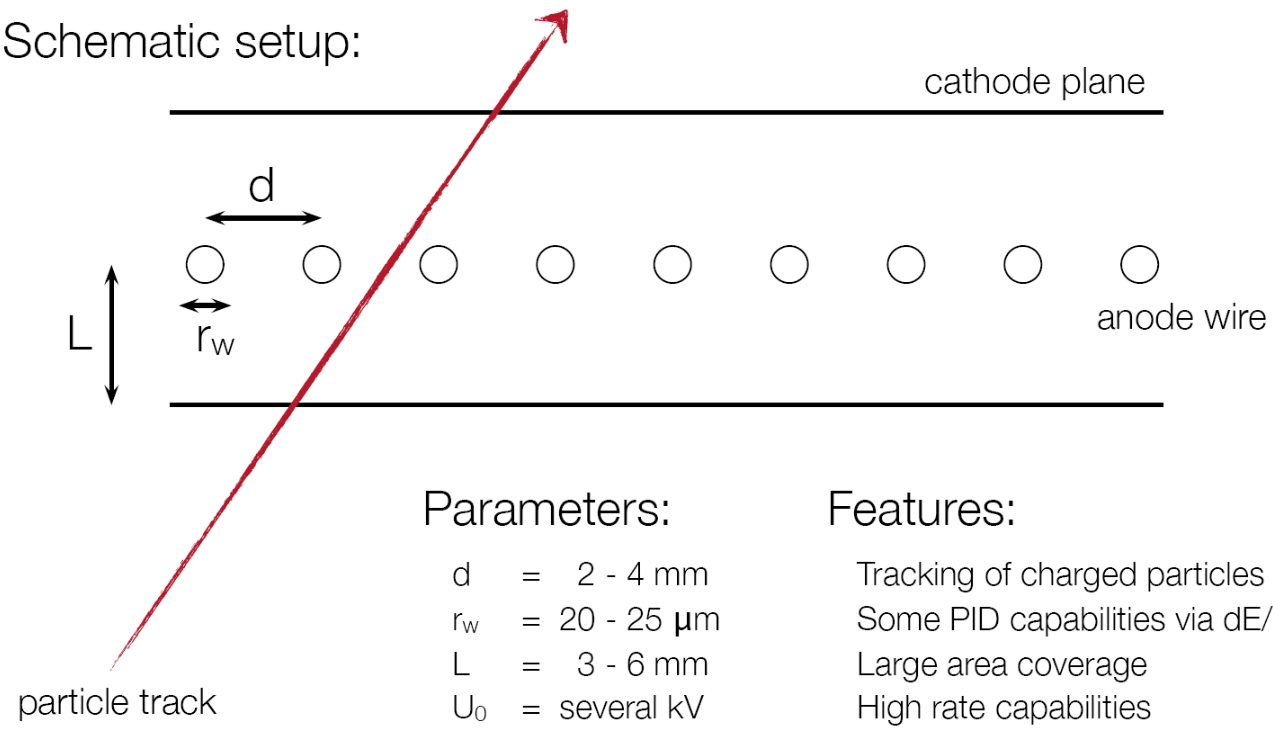


First prototype of MWPC
(Charpak 1968)

A telescope of MWPCs

Multi-Wire Proportional Chambers (MWPC)

Schematic setup:



Parameters:

d	=	2 - 4 mm
r_w	=	20 - 25 μm
L	=	3 - 6 mm
U_0	=	several kV

Total area: O(m^2)

Features:

Tracking of charged particles
Some PID capabilities via dE/dx
Large area coverage
High rate capabilities

A MWPC consists in **a set of anode wires**, equally spaced and kept at the same potential, simmetrycally placed in between two cathode planes

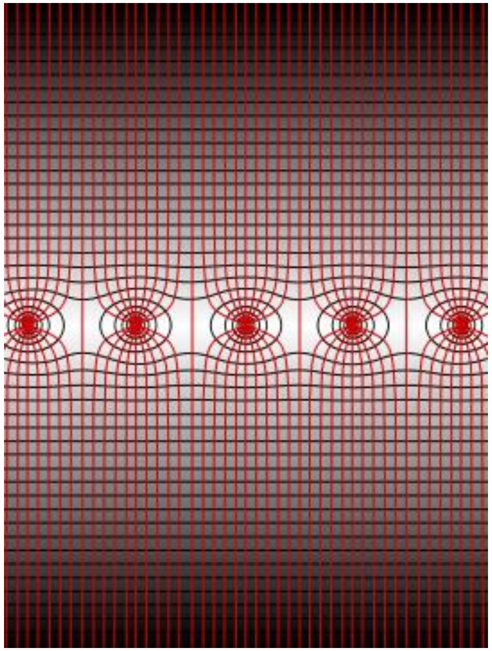
-In first prototypes anodes were grounded and the cathode were kept at negative potential

- **Each wire acts as an independent proportional counter**

-Distance between the planes usually is 3-4 time wire pitch

Multi Wire Proportional Chambers

- E field essentially uniform in most of the detector
- It becomes very intense close to the anode
  - Avalanche
- Every anode wire is connected to an amplifier and the signals can be processed electronically.



Diameter of anode wires 10 – 50 μm
Distances between wires 1 – 5 mm
Each wire connected to an amplifier
Typical gas amplification in MWPC is 10^5

Position resolution:
Depends on wire distance
e.g. for d = 2 mm
By simply using the wire position

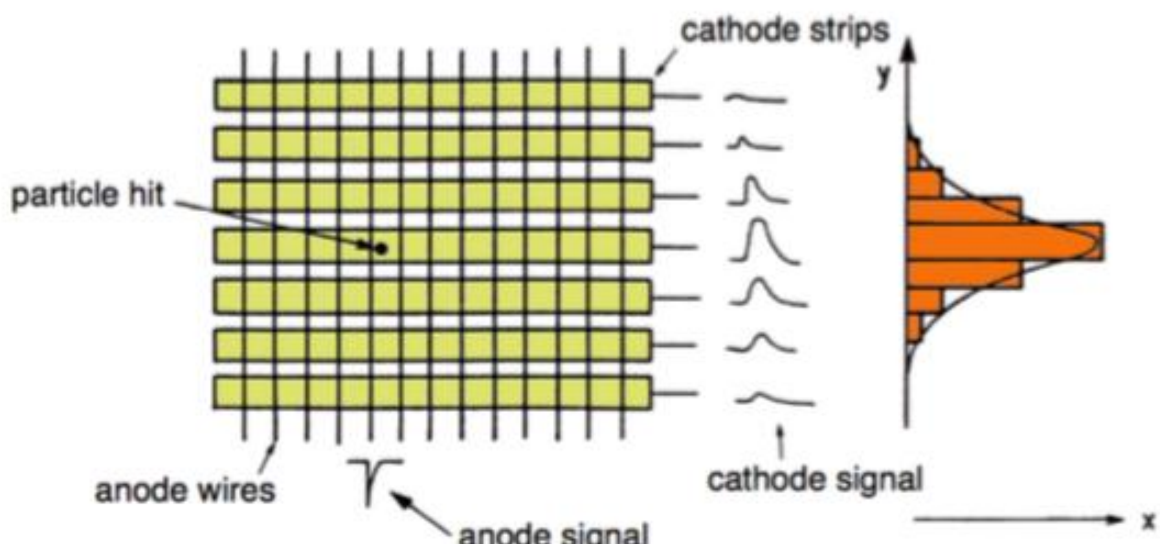
$$\sigma(x) = \frac{d}{\sqrt{12}} = 577\ \mu m$$

Multi Wire Proportional Chamber as Cathode Strip Chamber

A MWPC can only measure the coordinate perpendicular to the wires. No position measurement along the wires.

If the cathode is segmented, perpendicular to the wires, the signal induced can be used to determine the second coordinate.

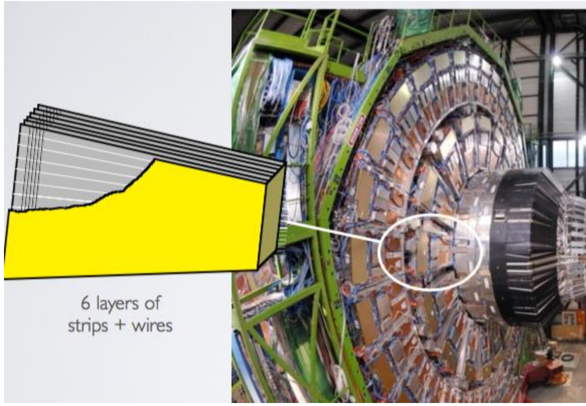
Employing a center of charge calculation a position resolution of 50 µm is achievable.

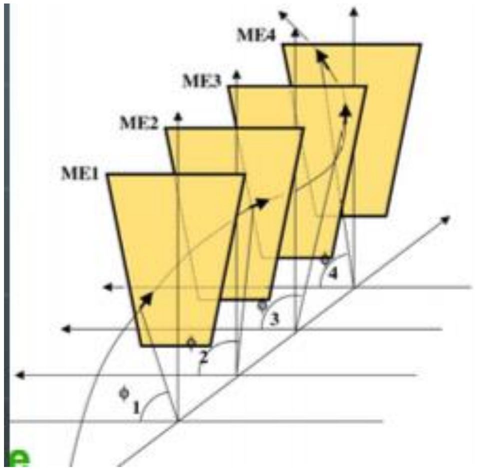


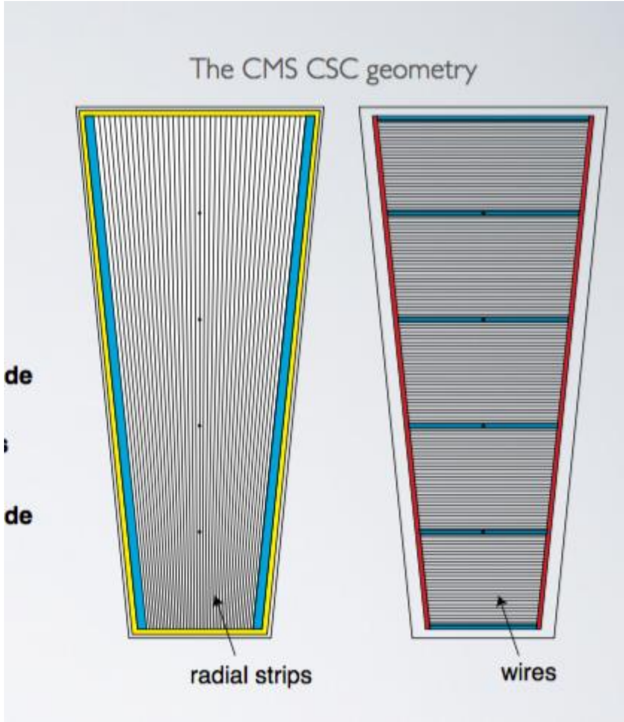
C. Grupen, *Teilchendetektoren*, B.I. Wissenschaftsverlag, 1993

CSC: example from CMS

The 4 Endcap CMS stations are equipped with CSCs Each CSC has 6 gas gaps and with 6 layer of strips (radial) and wires.



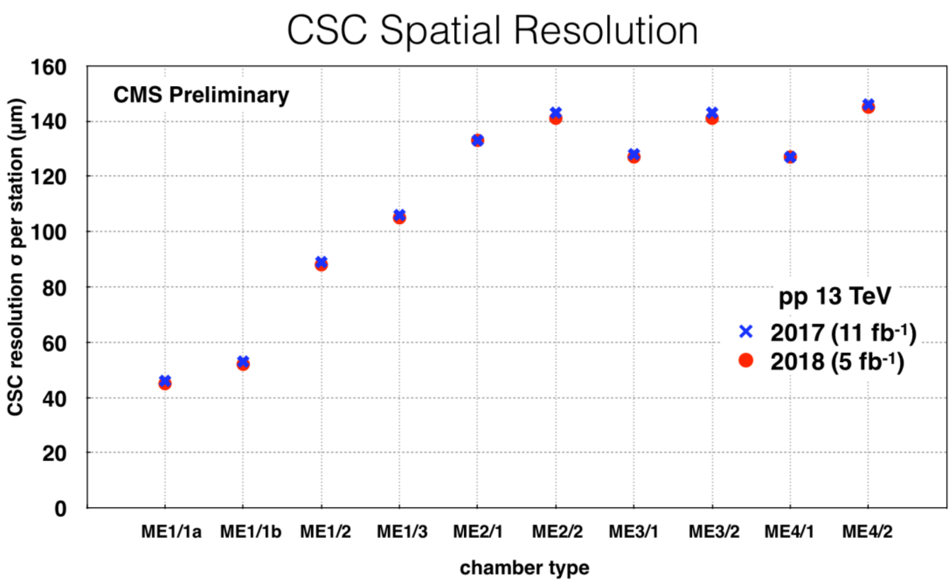




The main goal of CSCs is to define the bending angle of muon in the magnetic field of steel disks → crucial a good space resolution in direction perpendicular to the radius of a disk.

CSC chosen due to presence of high and inhomogeneous magnetic field and high particle rates.

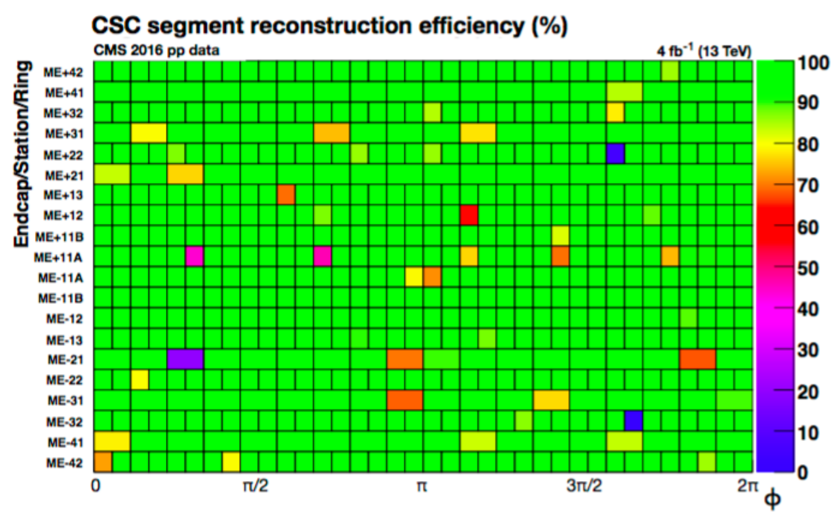
CMS CSC performance



CSC station spatial resolution :

- Between 40–140 μm (depending by the strips pitch)
- stable performance

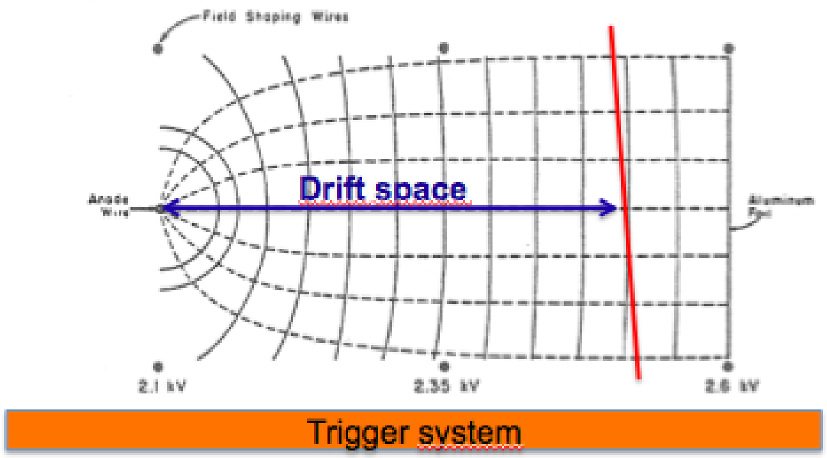
Segment reconstruction efficiency



Drift Chambers

Drift chambers are wire chamber with a long path:

1. Charged particle traversing the gas produce ionization
2. Electrons drift to the anode wire
3. Electrons close to the wire give rise to avalanche multiplication processes



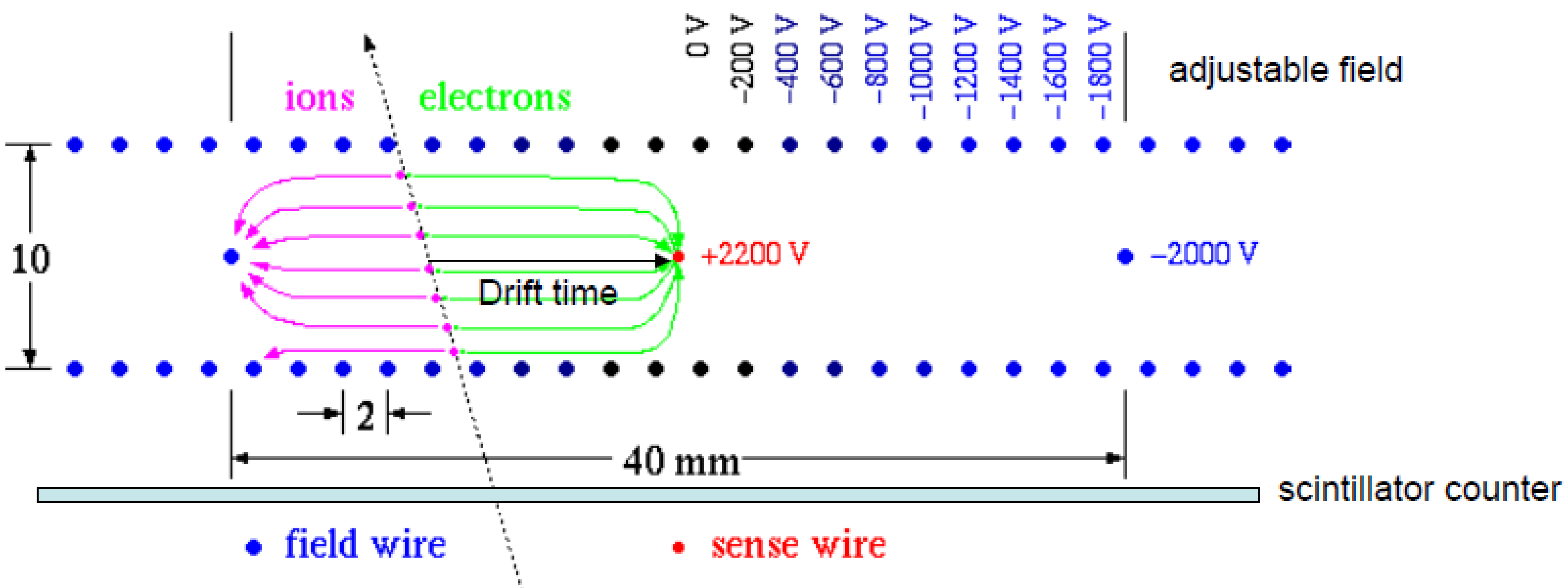
- Hit position defined by the linear relation between the drift velocity (about 50 μm/ns) and the time of arrival on the anode wire

$$x = v \cdot \Delta t$$

- The electric field has to be homogeneous and the drift velocity constant and known.
- Compared to MWPC: fewer wires and electronic channels, higher precision, but lower rate capability

Drift chambers

- A drift chamber (DC) consists of a region of moderate electric field, followed by a proportional counter
- Electrons produced by an ionizing particle at time t_0 migrate towards the anode, where the avalanche multiplication occurs at time t_1
- The position of the ionizing particle can be inferred by the space-time relationship: $x = \int_{t_0}^{t_1} w(t)dt$
  - In case of constant drift velocity: $x = w(t_1 - t_0)$
- The drift region is obtained with a set of cathode wires kept at increasing potentials

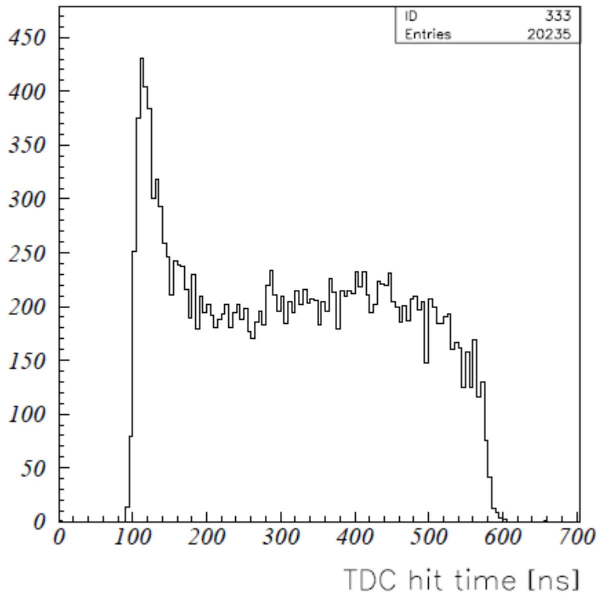


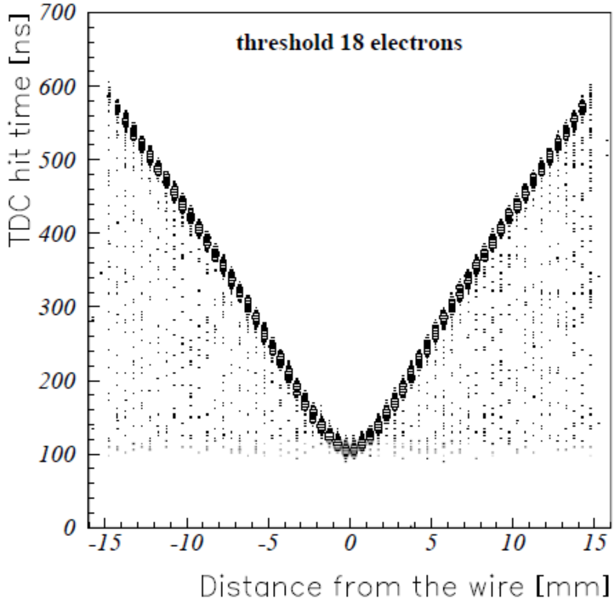
Position measurements

- The position resolution of a DC depends on:
  - Knowledge of the space-time relationship
  - Diffusion of electrons in the gas (intrinsic accuracy) ➔ $\sigma_x \propto \sqrt{x}$
- The space-time relationship can be measured by recording the time spectrum of a uniformly distributed beam of particles:

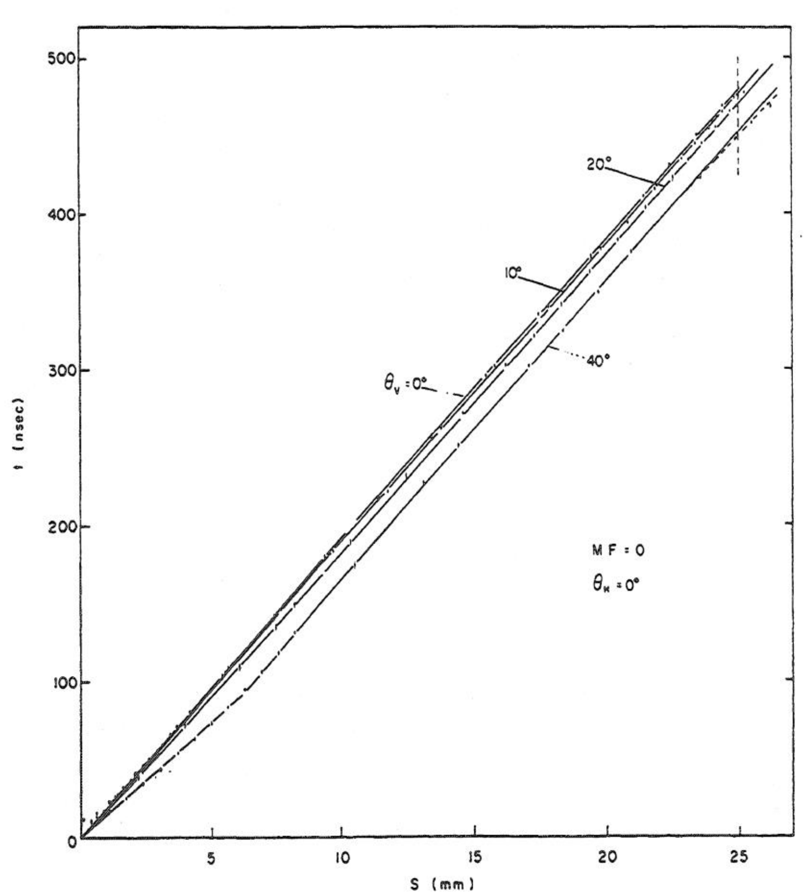
$$\frac{dN}{dt} = \frac{dN}{ds} \times \frac{ds}{dt} = kw(t) \Rightarrow \int \frac{dN}{dt} dt = k \int w(t)dt = ks(t)$$

a)Example of time spectrum obtained with a drift tube exposed to a uniform beam of particles
b)Example of space-time relationship





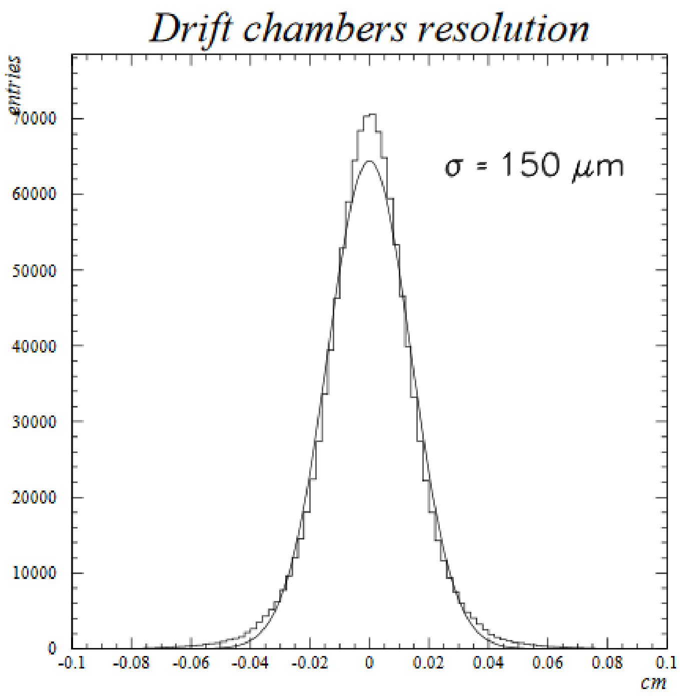
Space-time relationship



- The plot shows the space-time relationship for a drift chamber exposed to a uniform beam of minimum ionizing particles, crossing the chamber with different incidence angles
- Usually the space-time relationship is calculated by means of dedicated simulation codes (Garfield) which describe electron and ion transport in gases

Position resolution studies

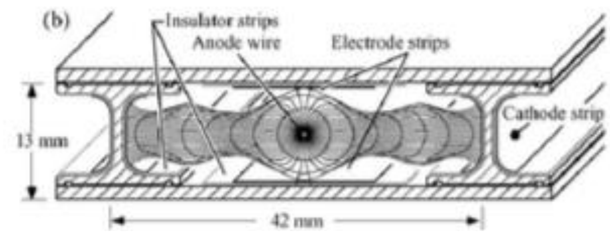
The position resolution is usually studied with a telescope of drift chambers
-The drift chamber under investigation is placed in the middle of the telescope
- The resolution is evaluated by studying the differences between the measured and fitted coordinates (with the other chambers)

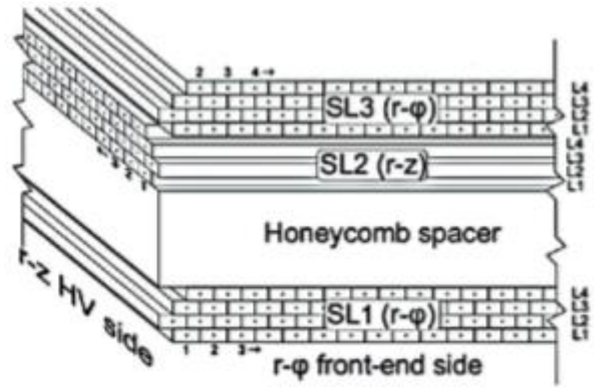


The plot shows an example of a distribution of the residuals between the fitted and reconstructed positions

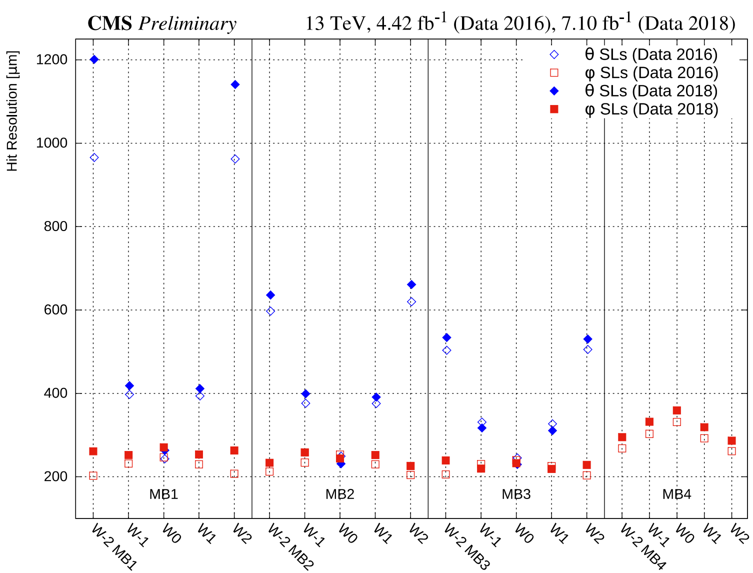
CMS Drift Chambers

- CMS barrel station are equipped by DTs
- The basic detector unit is a drift cell: a gas-filled tube with rectangular cross-section
- Four layers of tubes define **DT SuperLayers (SL)**
- DT chamber is done by two SLs with wires parallel to the beam direction, measuring muon position in the bending plane of the magnetic field and one in the longitudinal plane.





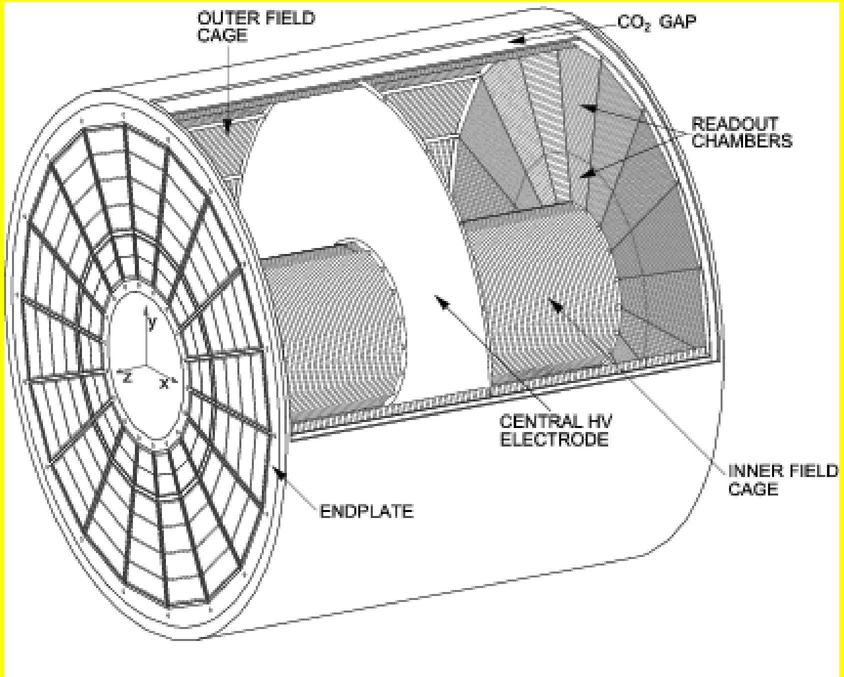
- **Gas mixture : 85% Ar + 15% CO_2**



- hit resolution in rϕ : 200 to 250 µm
- hit resolution in rz : 400 to 600 µm

Time Projection Chambers

- The TPC is a cylindrical or square field cage filled with a detection medium
  - The medium can be a gas or a liquid
  - Liquid targets are used for neutrino detectors
- Charged particles produce tracks of ionization electrons that drift in a uniform electric field towards a position-sensitive amplification stage which provides a 2D projection of the particle trajectories
- The third coordinate is calculated from the arrival times of the drifted electrons
  - The start for this drift time measurement is usually derived from an external detector

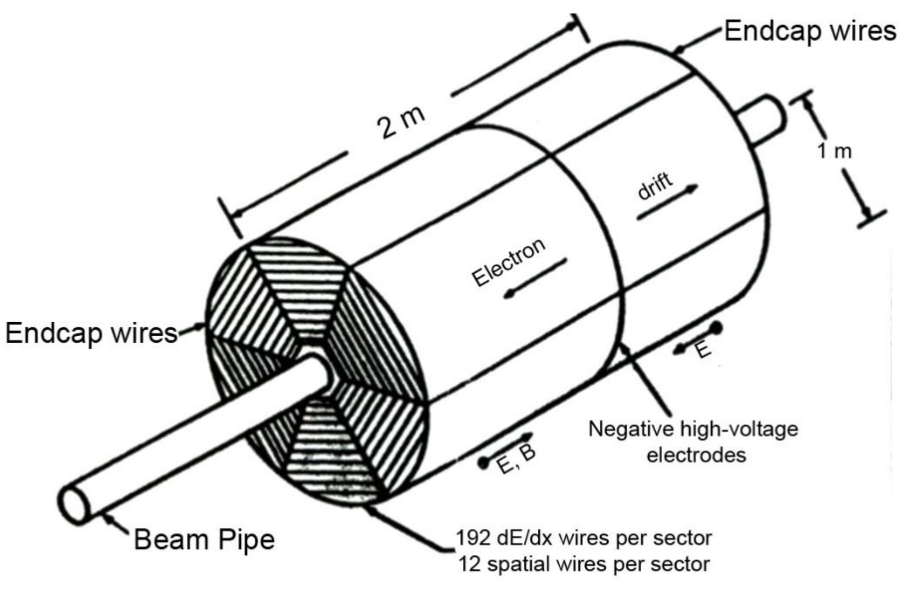


Schematic view of the ALICE TPC. The drift volume is a cylinder of 5m diameter

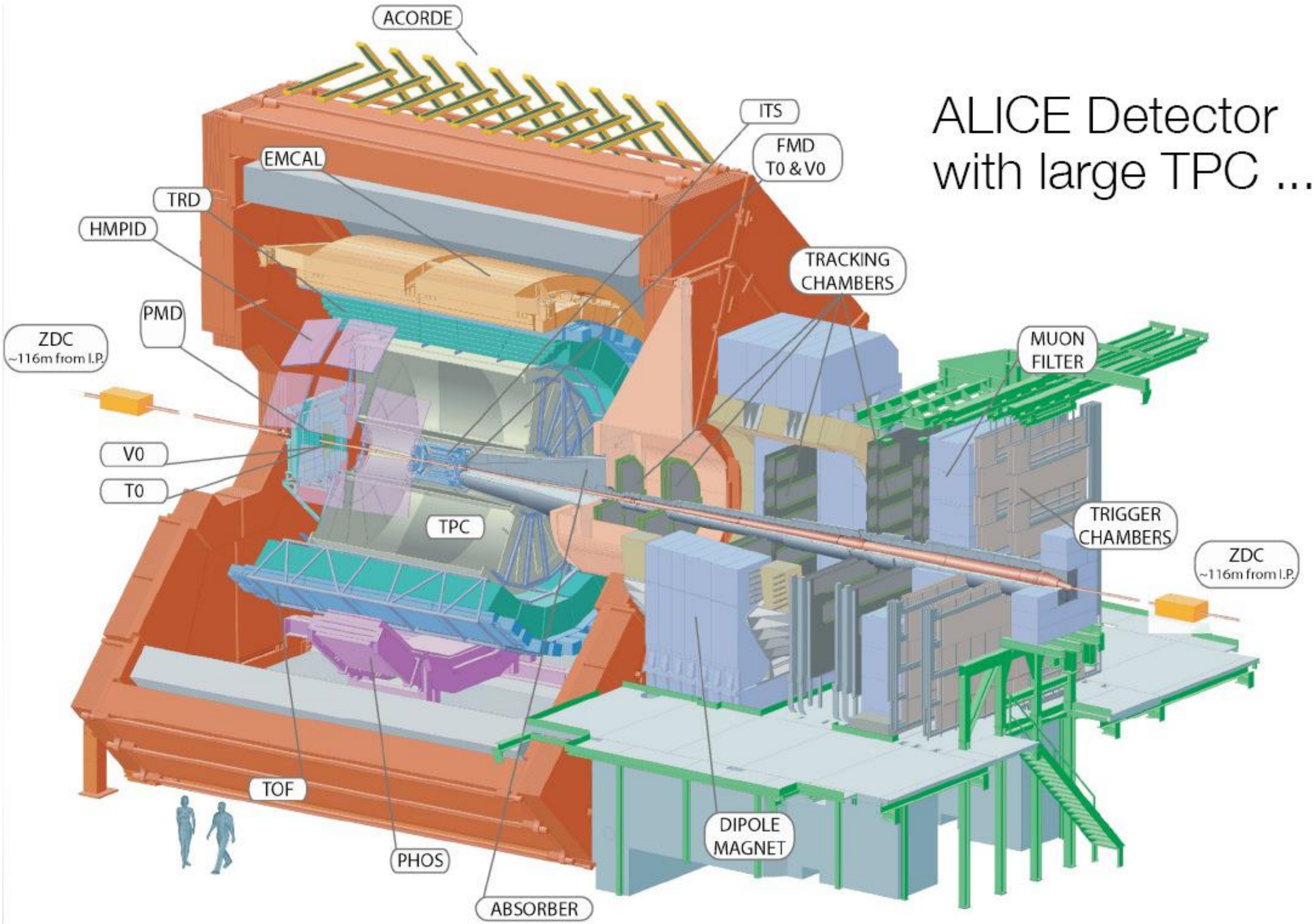
Time Projection Chambers

- The first TPC was developed by D. Nygren in 1978 for the PEP-4 experiment at SLAC
- It consisted of 2 contiguous cylindrical cells of a few m^3
  - The electric and magnetic fields are parallel to the axis
- Electrons drift towards the endcaps, equipped with proportional wires and cathode pads to reconstruct the (r, φ) coordinates
  - Resolution of $200\mu m$ on the x and y coordinates
- The z coordinate is reconstructed from the drift time
  - Resolution of $200\mu m$ on the z coordinate

Scheme of the TPC used in the PEP-4 experiment



ALICE TPC


ALICE Detector
with large TPC ...
ACORDE
ITS
FMD
T0 & V0
EMCAL
TRD
HMPID
TRACKING
CHAMBERS
PMD
ZDC
~116m from I.P.
MUON
FILTER
V0
T0
TPC
TRIGGER
CHAMBERS
ZDC
~116m from I.P.
TOF
DIPOLE
MAGNET
PHOS
ABSORBER

ALICE TPC

Length: 5 meter
Radius: 2.5 meter
Gas volume: 88 m^3

Total drift time: 92 μs
High voltage: 100 kV

End-caps detectors: 32 m^2
Readout pads: 557568

159 samples radially
1000 samples in time

Gas: $Ne/CO_2/N_2$ (90-10-5)
Low diffusion (cold gas)

Gain: > 10^4

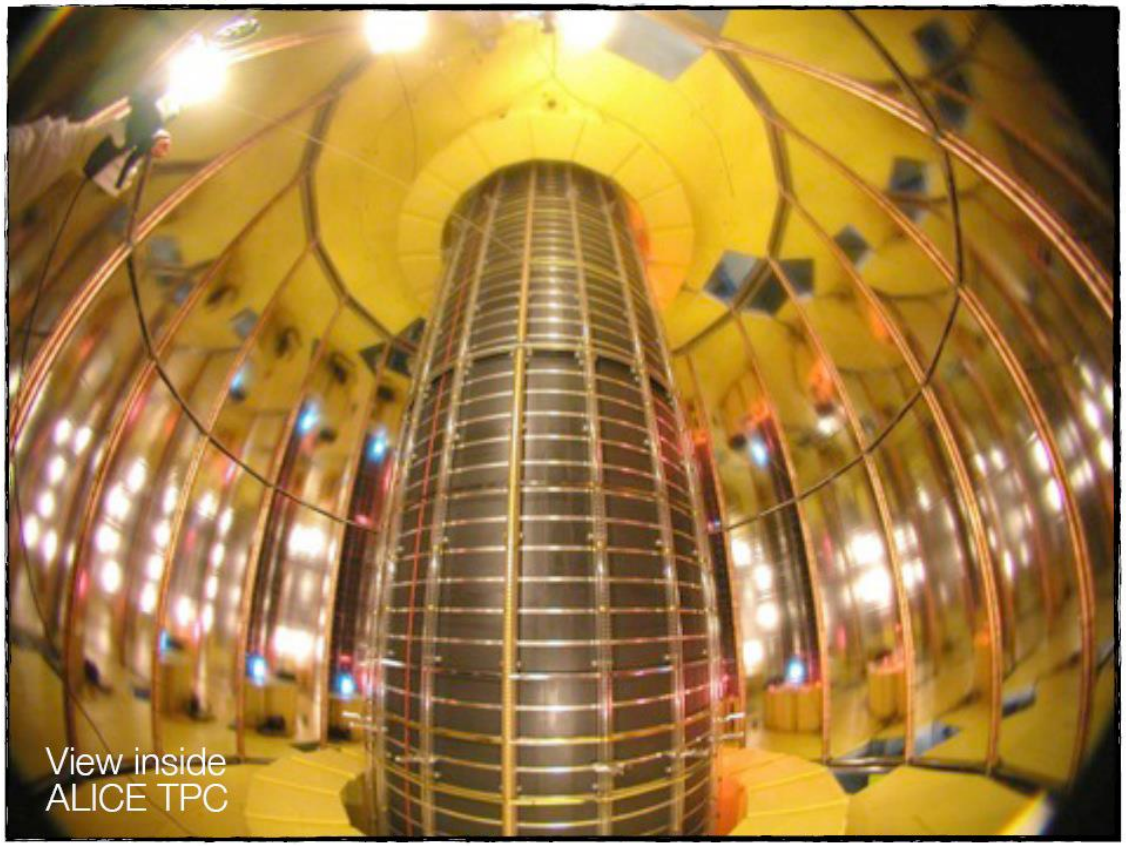
Diffusion: $\sigma_t = 250\ \mu m$
Resolution: $\sigma \approx 0.2$ mm

$\sigma_p/p \sim 1\%$ p; $\varepsilon \sim 97\%$
$\sigma_{dE/dx}/(dE/dx) \sim 6\%$

Magnetic field: 0.5 T

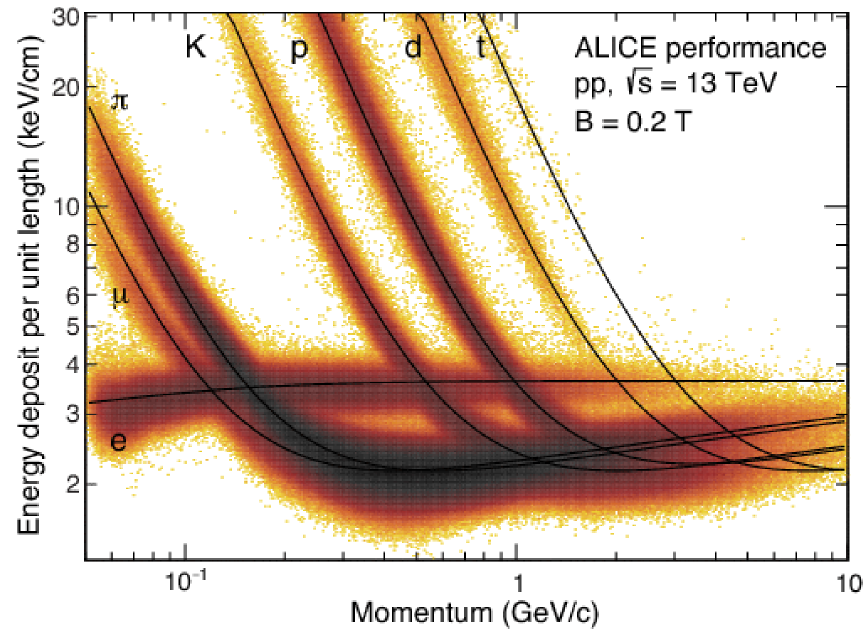
Pad size: 5x7.5 mm^2 (inner)
6x15 mm^2 (outer)

Temperature control: 0.1 K
[also resistors ...]



Particle Identification with TPCs

- Identification of the charged particles crossing the TPC is possible by simultaneously measuring their momentum and their dE/dx
- The momentum and the charge sign are calculated from a helix fit to the particle trajectory
- The dE/dx is estimated from many charge measurements along the particle trajectory (e.g. one measurement per anode wire or per row of readout pads)
  - The measured values are corrected for the effective length of the track segments and for variations of the gas temperature and pressure
  - The most probable value of the corrected signal amplitudes provides the best estimator for the specific energy deposit

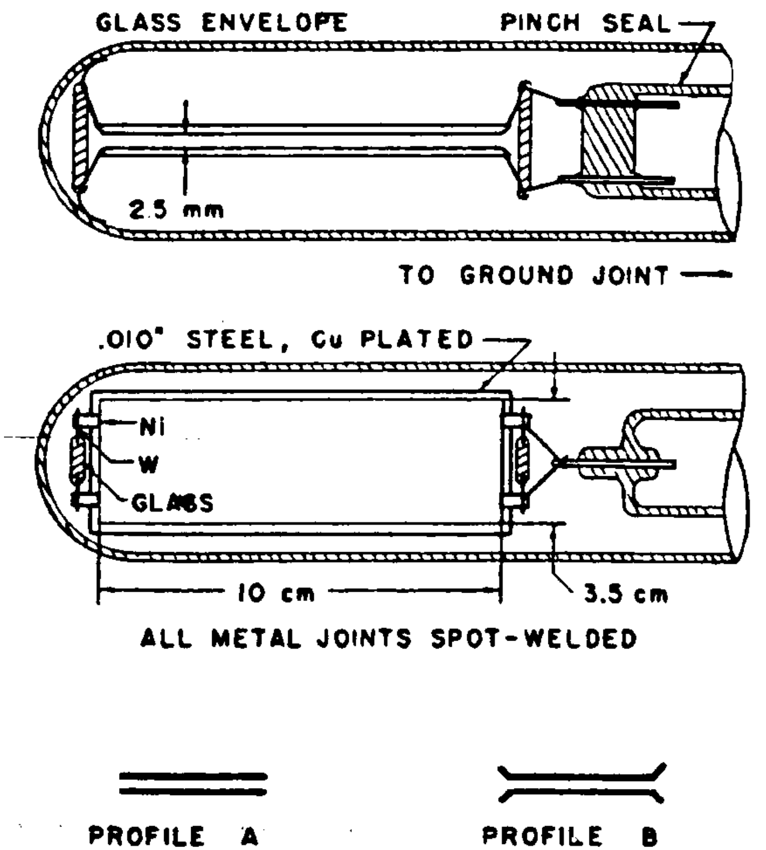


Now let's go back to the planar geometry

Remember: in principle detectors with planar geometry can achieve a quite good time resolution due to the absence of the jitter in the drift time

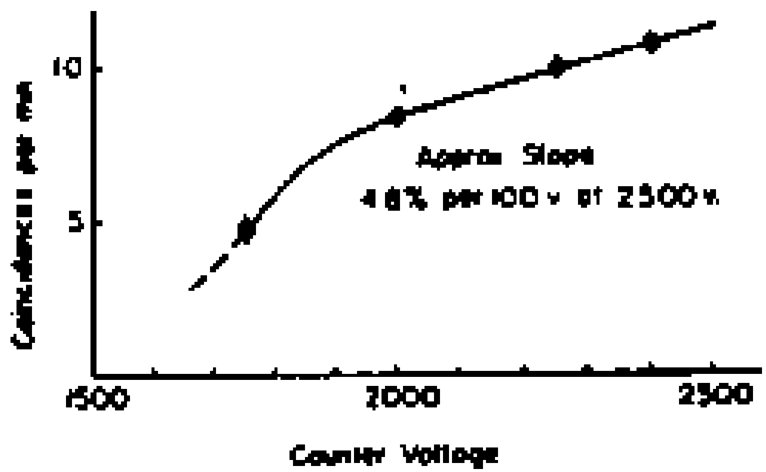
Keufell's Parallel Plate Chambers

Basically, planar capacitors, with metal electrons, dating 1949

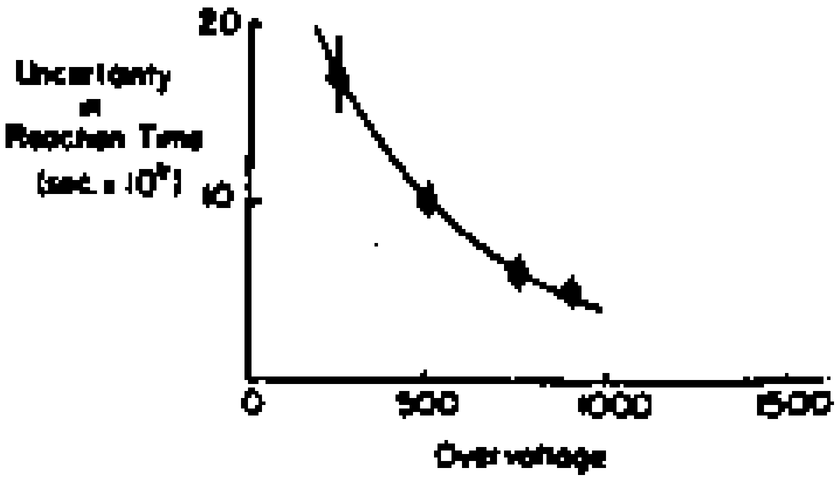


First prototype made in Molibdenum disks, later on Keufell used Cu or Iron plated with Cu. d=2.5 mm, A= 35 cm2

Gas mixture: xilene p_{parz} = 6 mmHg
argon p_{tot} = 0.5 Atm



Keufell’s Parallel Plate Chambers



Around 1 ns time resolution:

→ world record at the time!

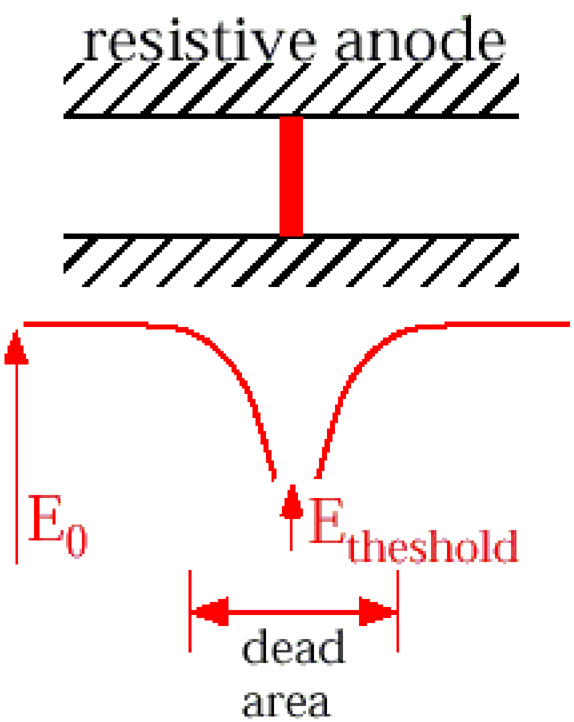
But: Life time of the detector: few months, limited by discharges setting up first in a point, then all over the detector plate surfaces.

Need to introduce auto-quenching mechanisms

Resistive Plate Chamber

Self-extinguishing mechanism

The arrival of the electrons on the anode reduces the local electric field and therefore the discharge is extinguished. During the discharge the electrodes behave like insulators.



Avalanche duration related to the drift velocity and Townsend coefficient

Time constant for re-charging up related to the RC constant of the RPC elementary cell

η = α-β = effective Townsend coefficient

$$t_{dis} = \frac{1}{h v_d} » 10ns$$

$$t_{REC} = r e_0 \left(e_r + \frac{2d}{g} \right) \approx 10ms$$

$\tau_{dis} << \tau_{rec}$

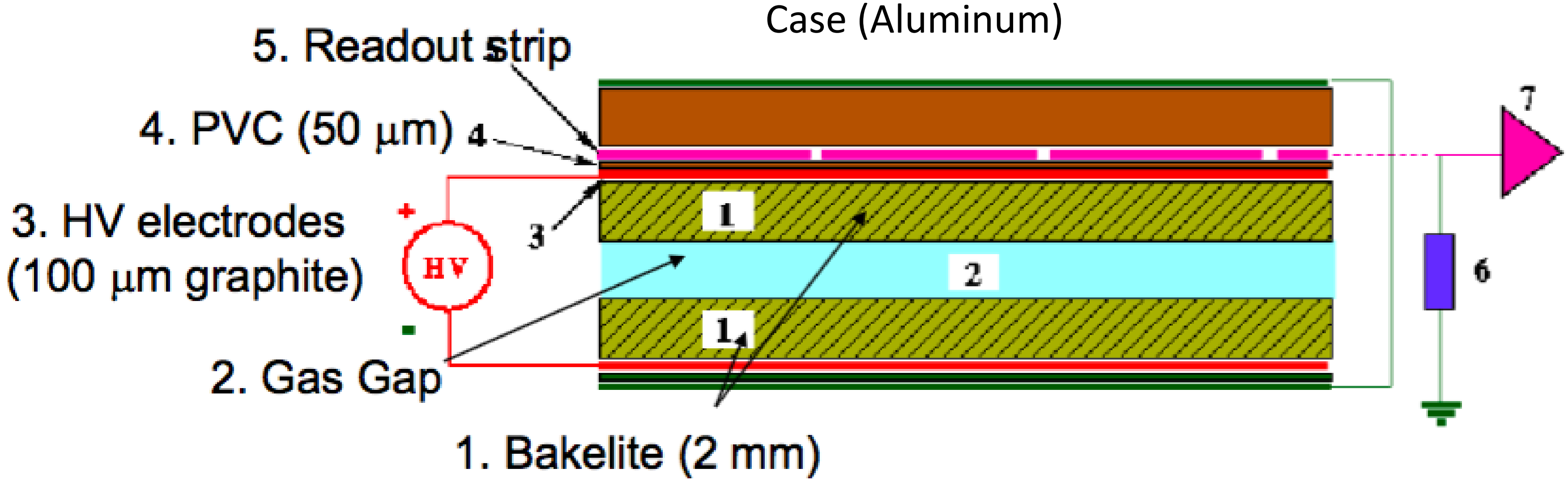
RPC basic elements

Gas mixture:
Argon, Iso-butane and Freon
at P ≈ 1 Atm

High Voltage contact: graphite coating on electrode outer surfaces

Pick up strips are used to collect the signal: **Al/Cu, ~cm**

Case (Aluminum)



Resistive Electrodes (ρ≈10^{10}-10^{12} Ωcm): High Pressure Laminates (HPL) "Bakelite" made by Kraft paper impregnated with melamine/phenol resins.
Internal electrode surface covered with a thin linseed oil layer (~µm)

Applications of the 1st generation RPCs

The first generation of RPC detectors was used in several HEP experiments:

'85: Nadir – 120 m^2 (Triga Mark II – Pavia)

'90: Fenice – 300 m^2 (Adone – Frascati)

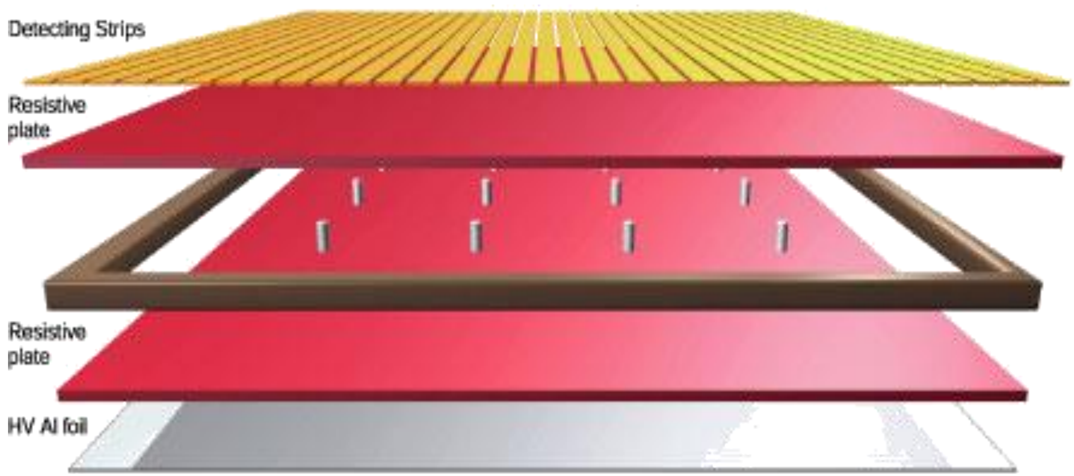
'90: WA92 – 72 m^2 (CERN SPS)

'90: E771– 60 m^2; E831 – 60 m^2 (Fermilab)

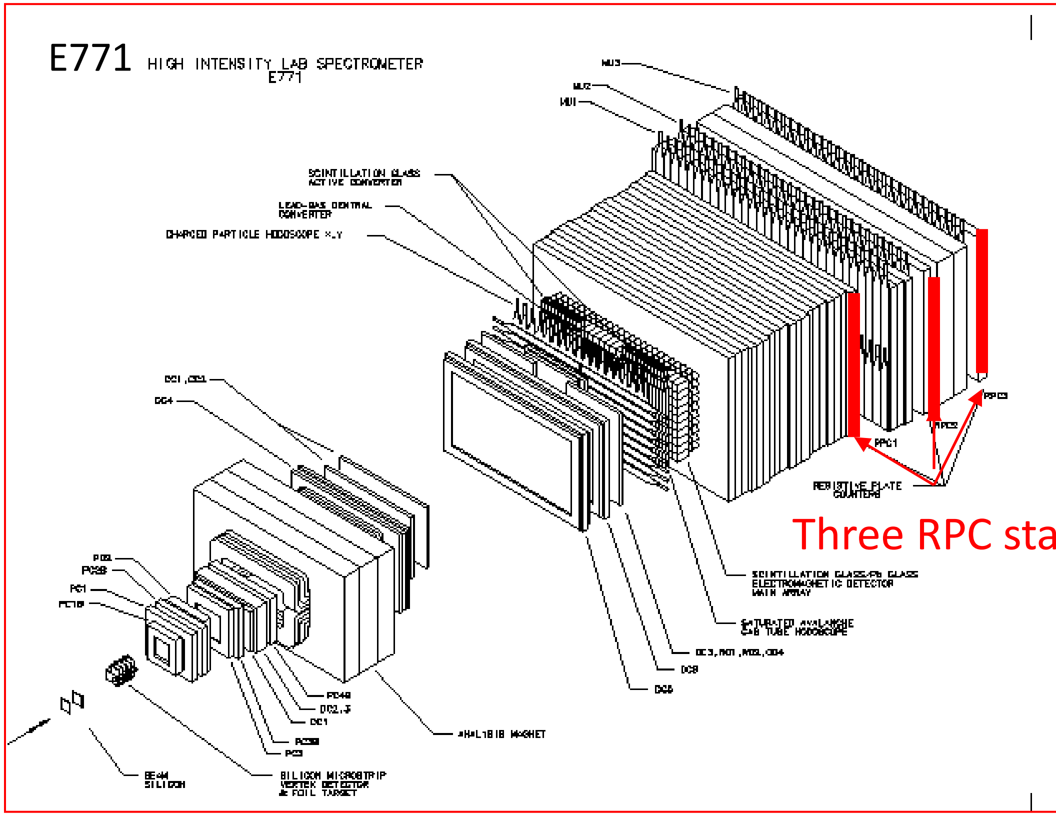
1994-1996: L3 – 300 m^2 (CERN-LEP)

1996-2002: BaBar – 2000 m^2 (SLAC)

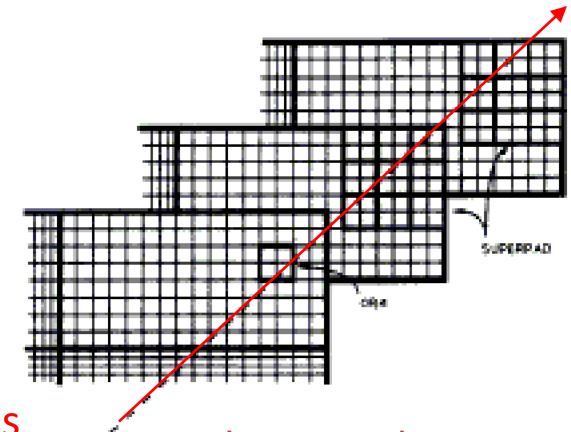
Very large area of muon detection



The E-771 experiment

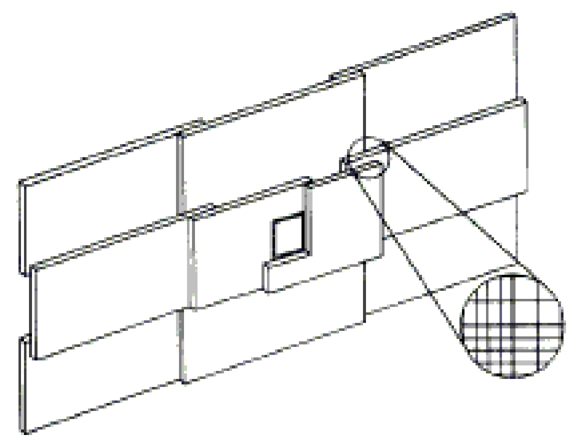


Three RPC stations



A triple coincidence to identify and track μ

The RPC system **did not cover** the zone around the beam



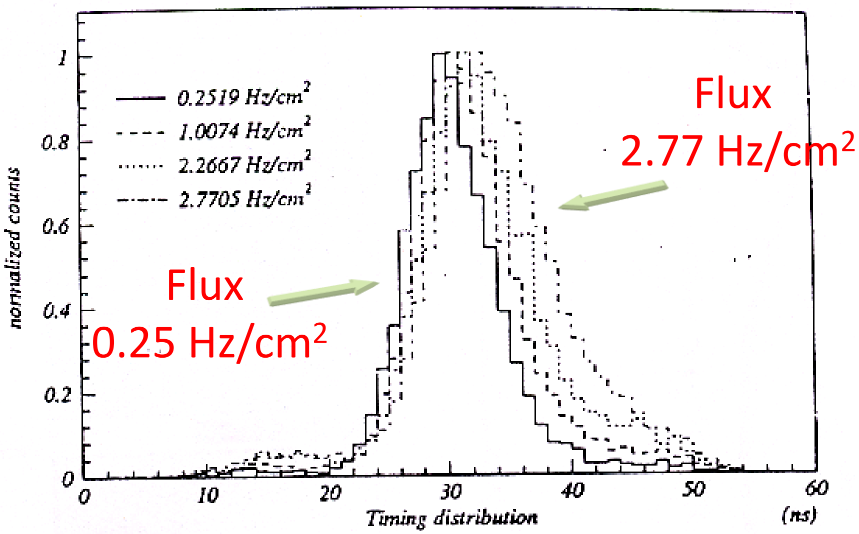
Superimposed RPCs, with pad readout

Streamer mode (Ar-isobutane-Freon)

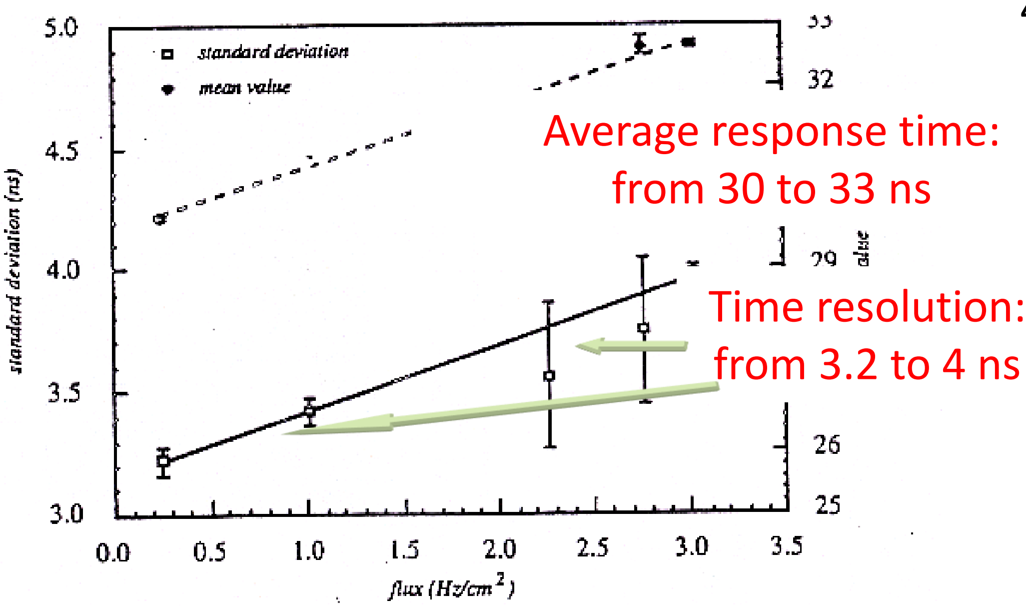
HV 8 kV

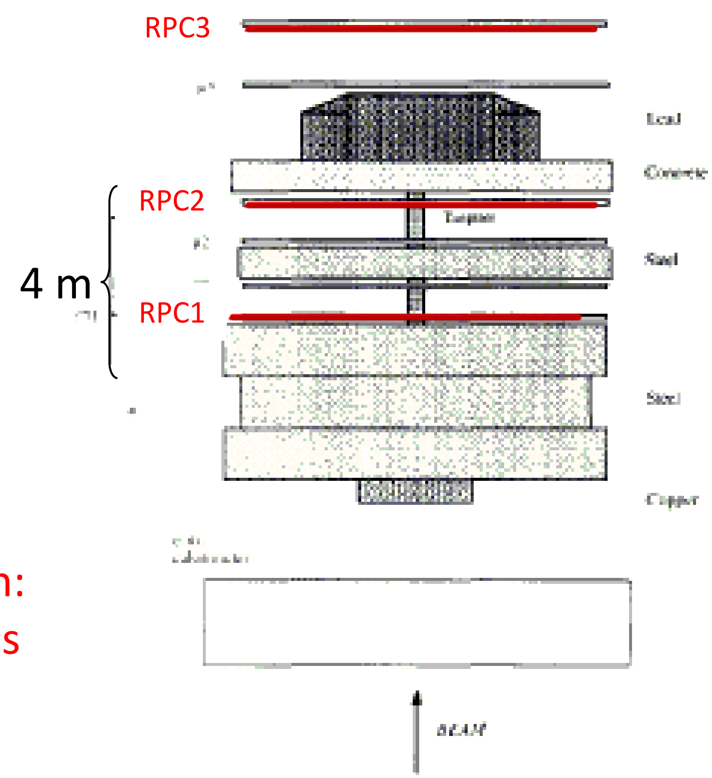
Maximum efficiency: 97%

E-771: first hints of rate capability issues

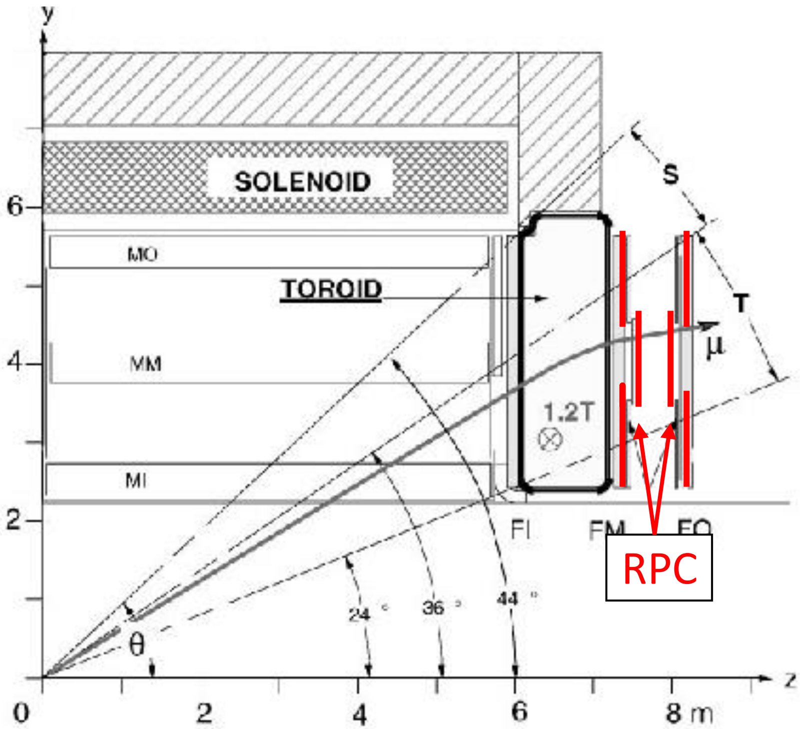


It was the first experiment were performance variations due to the flux of particles impinging on RPCs were noticed and put in evidence.



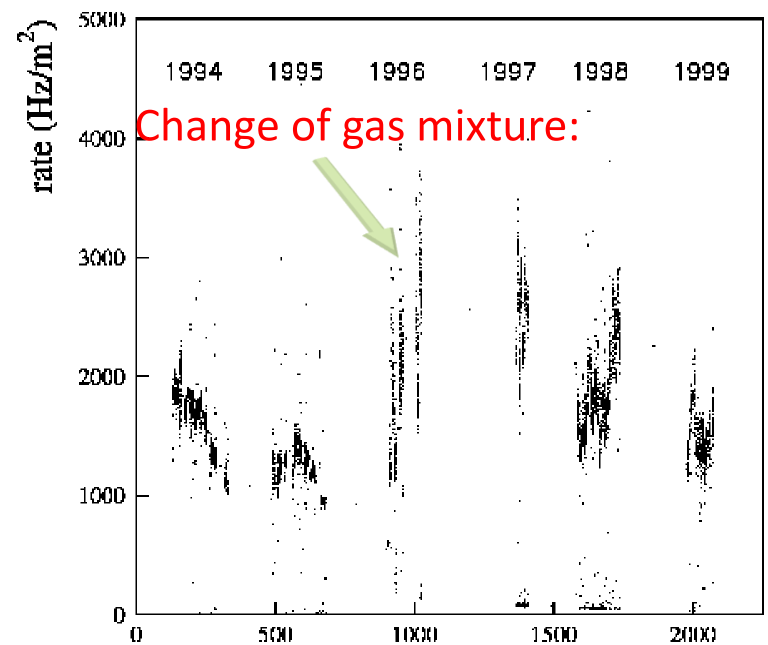


The L3 experiment at LEP



Two layers of RPCs, each divide in 3 sections, trapezoidal in form and with different dimensions, superimposed at the edges.

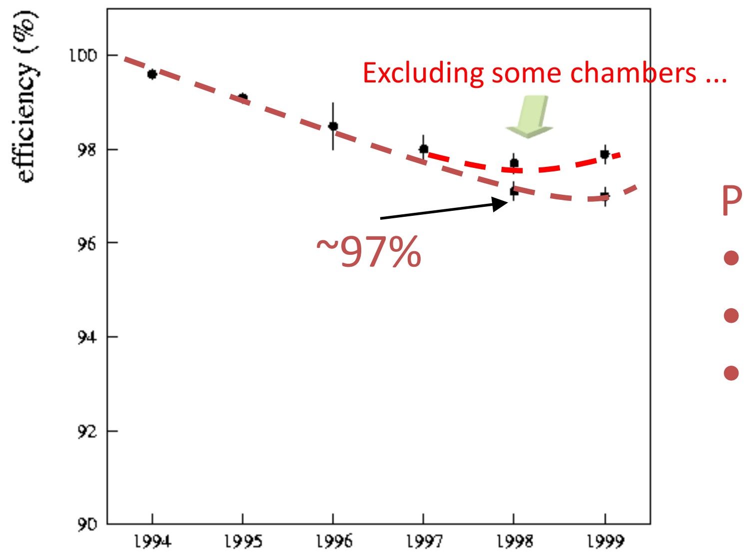
192 double gap RPC
total area > 300 m^2
6144 strips, 29 mm strip pitch



Bakelite: $\rho \sim 2 \times 10^{11}\ \Omega$cm
Gas: mixture
Argon/isobutane/CF3Br (58/38/4) up to 1996   Argon/isobutane/C2H2F4 (59:35:6) thereafter

Operating for 7 years (since 1994) in streamer mode

The L3 experiment at LEP



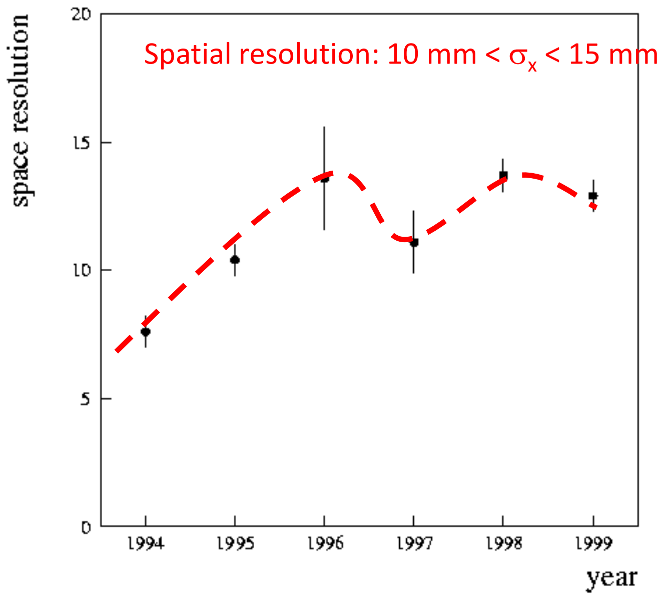
Chamber performance studied using:

$Z \rightarrow \mu^+ \mu^-$

Problems:

- electronic failures (large currents at high rate)
- increase of the chambers in some chambers
- gas leaks

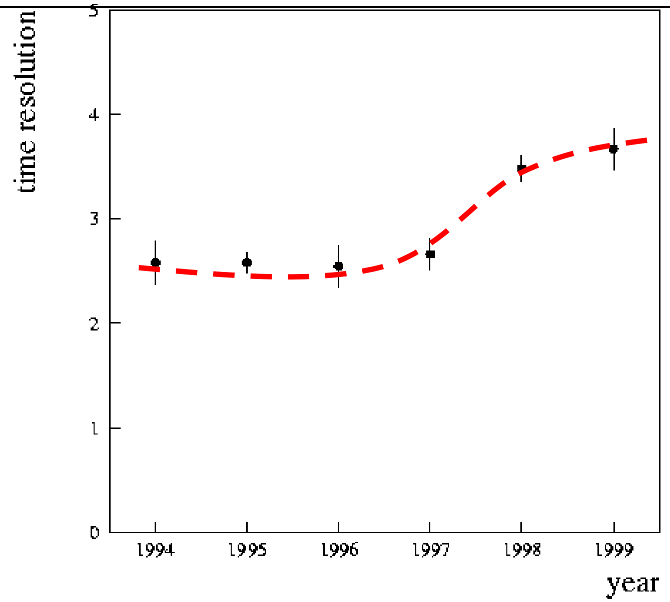
No big problems
but
slow worsening of the performance



Expected:

$$\frac{L}{\sqrt{12}} \approx 8.3\text{mm}$$

Around 1.5-2 strips fired per track



Marcello Abbrescia - Universitá di Bari, Italy

Significance of the fist generation of the RPC

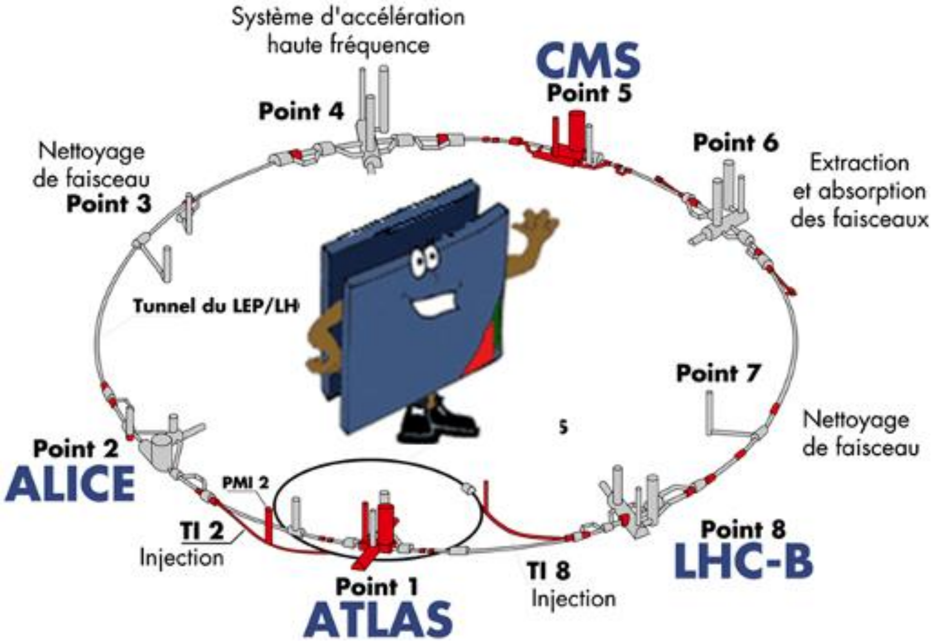
Why the RPCs were extensively used in HEP?

- **Golden parameter:** the time resolution (≈1 ns)
- **Good spatial resolution:** limited by strip dimensions
- **High muon efficiency** of the order of > 96% and **long term stability**
- **The cost** of RPC is much smaller as compared to other fast detector (like the scintillators)
- It is **easy** to construct and operate
- Simple signal pick up and readout system (just "strips")
- Two dimensional readout (x and y)

BUT

rate capability < 50 Hz/cm^2

RPCs at LHC



New detector need to sustain the expected background condition for 10 LHC year!

Detector requirements:

- **Maximum rate* ≈ 300 - 500 Hz/cm^2**
- **Improved time resolution (<ns) for TOF applications**

**** at the nominal LHC luminosity $10^{34} cm^{-2} s^{-1}$***

2^{nd} generation of "classic" RPC

In late '90, a new generation of RPC was developed:

- **New working mode: *Avalanche mode (saturated avalanche)***
- New gas mixture: Freon-based mixture
- Total charge ~ 20-40 pC (from 0.1 – 1 nC)
    - lower current in the detector → better longevity

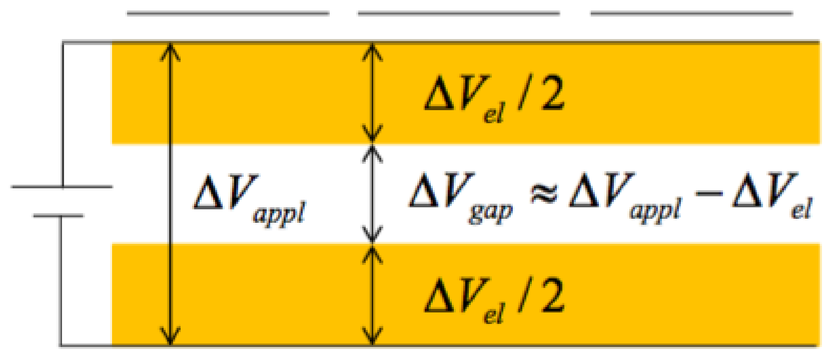
- **New electronics** in order to transfer a large fraction of the amplification from the gas to the electronics

→ **good rate capability ~ 500 Hz/cm^2 with high efficiency (> 95%) and stable conditions for 10 LHC years**

The issue of the rate capability

In the static condition the voltage applied to the chamber DV_{gap} is entirely transferred to the gas.
But, in the presence of a φ flux of particle, which creates a current I, the voltage inside the gas gap is reduced:

$$DV_{gap} = DV_{appl} - RI = DV_{appl} - DV_{el}$$



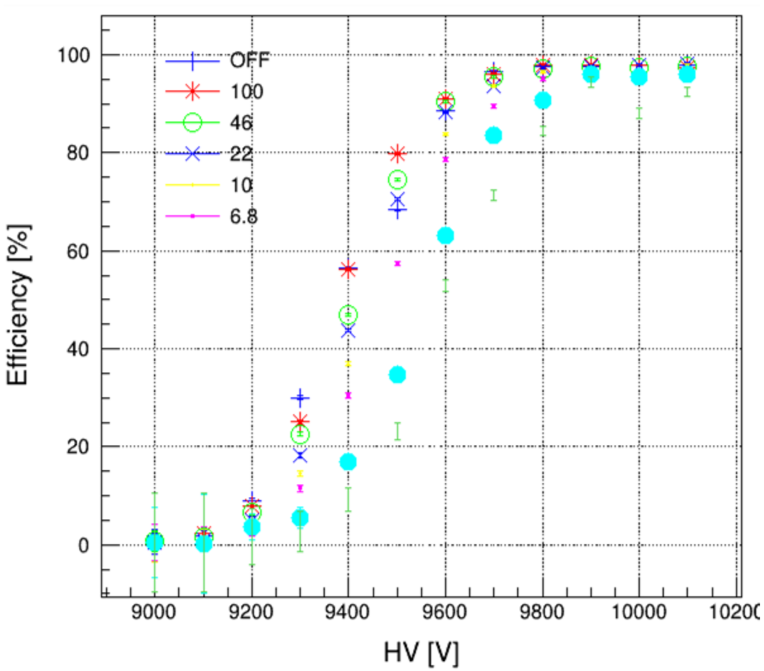
$$DV_{el} = r\ d\ F\ \langle Q \rangle$$

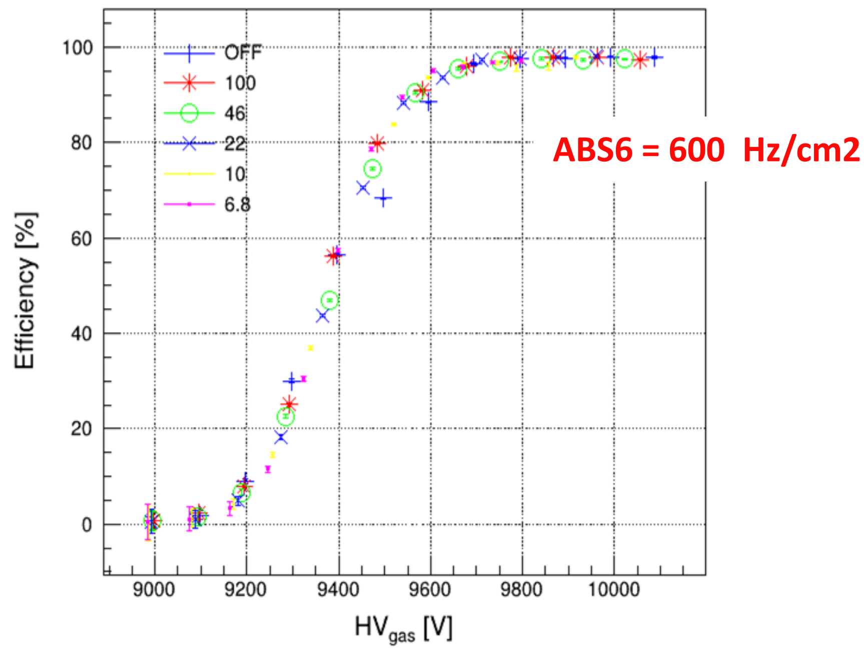
- r: Electrode resistivity
- d: Electrode thickness
- F: Particle flux counts/cm^2
- $\langle Q \rangle$: Average charge/hits

➢ To increase the rate capability (i.e the particle flux) the relevant parameters are **<Q>, ρ, d**

Experimental results

Chamber efficiency as a function of HV_{gas} does not depend on the electrodes resistance once that ΔV_{el} has ben get ridden of : the operation regime of the detector is invariant with respect to ΔV_{gas}



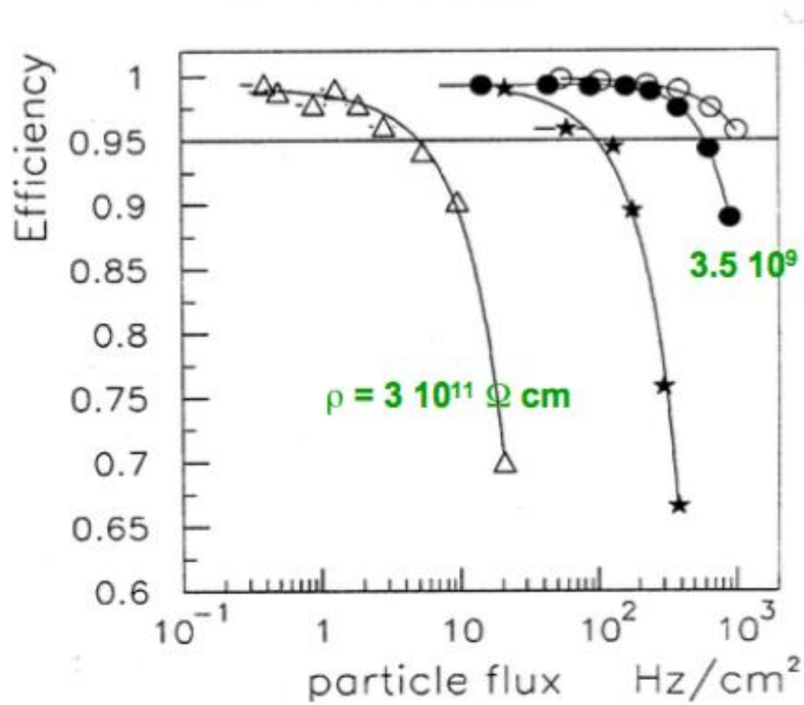


$$DV_{gap} = DV_{appl} - DV_{el} = DV_{appl} - r\ d\ F\ <Q>$$

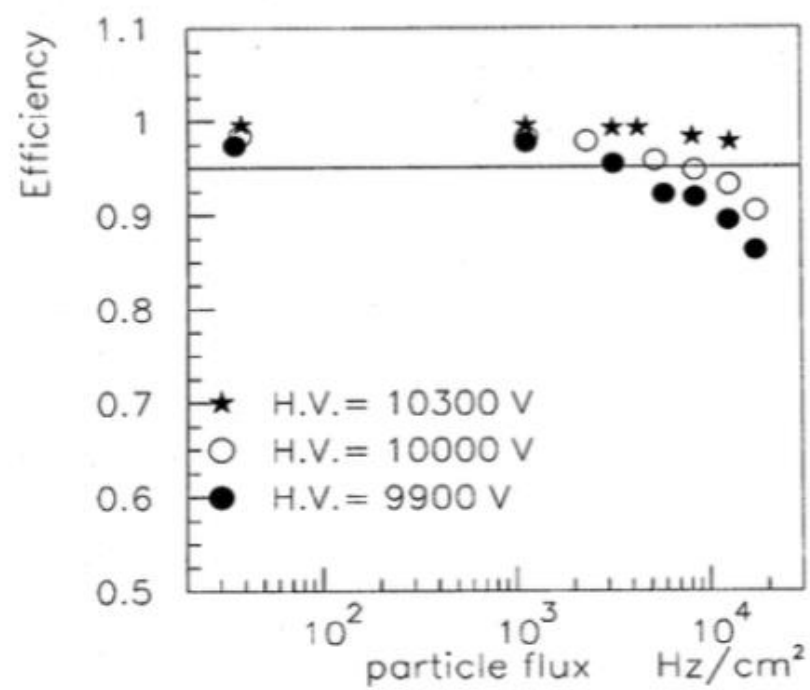
Change of the Operation mode

Average charge ~ 20-40 pC in Avalanche mode - 0.1 – 1 nC in streamer

STREAMER MODE:



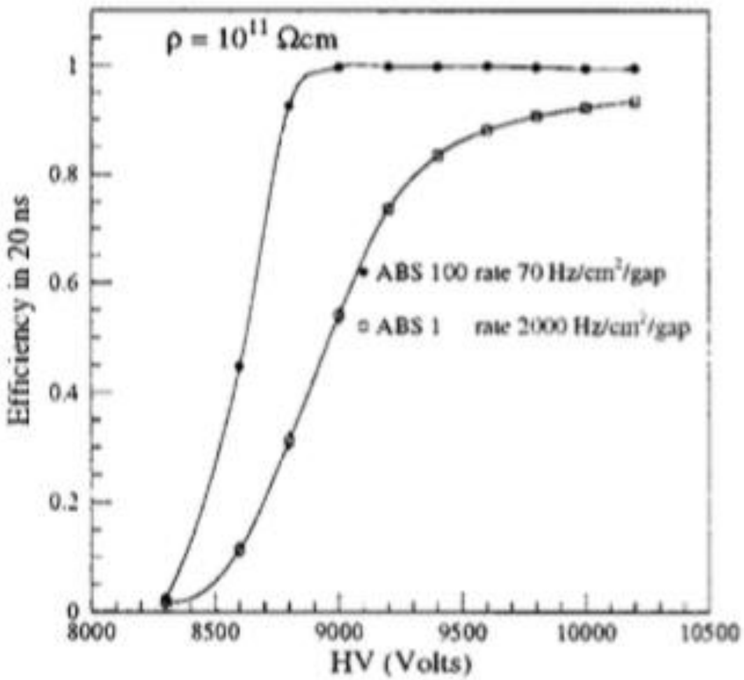
AVALANCHE MODE:

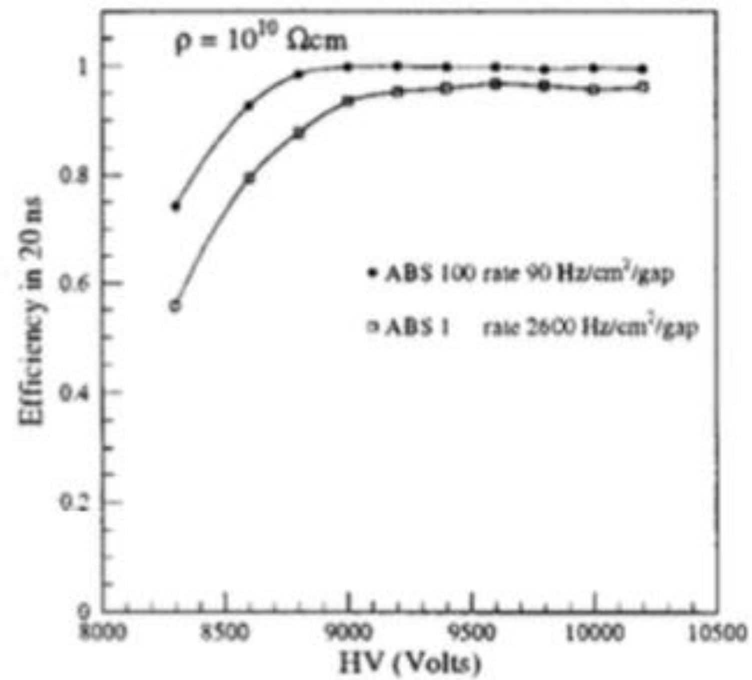


R. Arnaldi et al, Nucl. Physics B (Suppl) 78 (1999) 84

$$\Delta V_{gap} = \Delta V_{appl} - \Delta V_{el} = \Delta V_{appl} - \rho\, d\, \Phi \langle Q \rangle$$

Reduced resistivity





M. Abbrescia et at. NIM, 434 (1999), 244-253

$$DV_{gap} = DV_{appl} - DV_{el} = DV_{appl} - r \; d \; F \; \langle Q \rangle$$

A new gas mixture

$C_2H_2F_4$ (95.4%), Iso-butane = 4.5%, SF_6 = 0.3 %

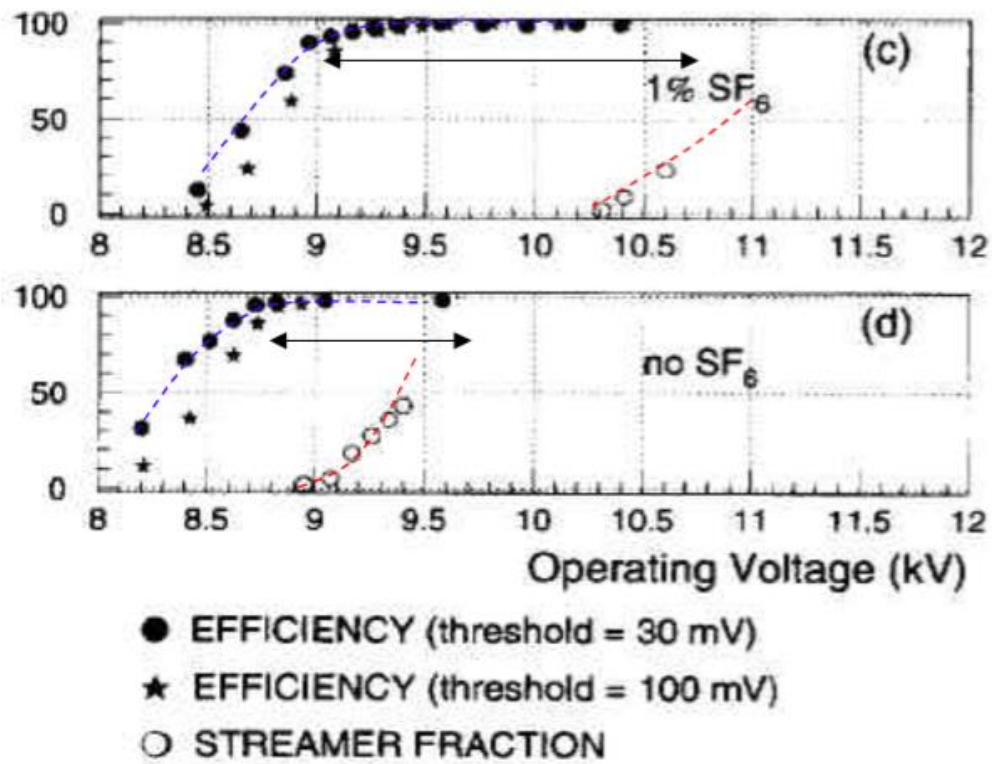
In a streamer mode, the main gas components should provide a robust first ionization signal and a large avalanche multiplication for a low electric field→ **Argon based gas mixture (λ = 2.5 mm^{-1})**

In avalanche mode, the main component has to have high primary ionization but with small free path for electron capture. The high electronegative attachment coefficient limits the avalanche electron number → **Freon ($C_2H_2F_4$) based gas mixture (λ = 5 mm^{-1})**

Plus....a "**quenching gas**" like the **iso-butane** which has an high probability for absorbing ultra violet photons

A new gas mixture

… and a **strong electronegative** gas the **SF6** is also used to control the excess number of electrons and extends the separation between streamer and avalanche

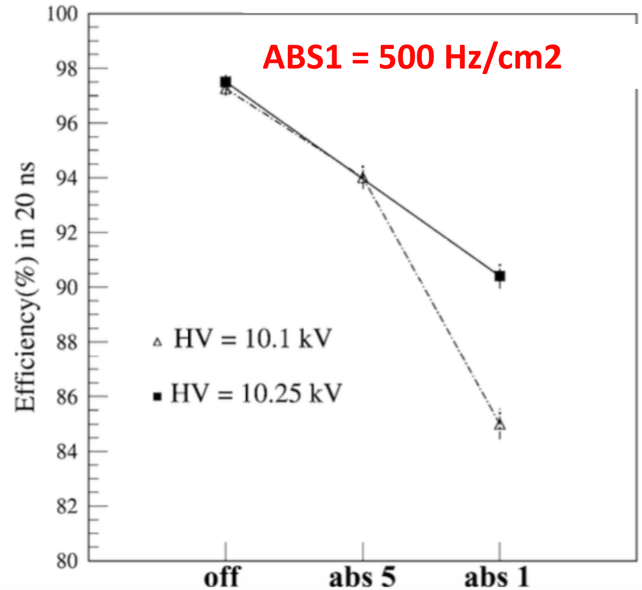


R. Santonico, Scient. Acta XII N2(1997)1
P. Camarri et al, Nucl. Instr. and Meth. A414(1998)317

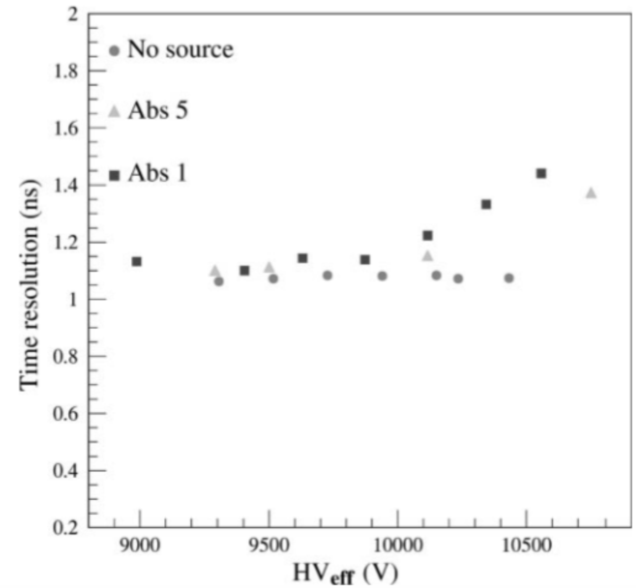
2nd generation RPC: Performance

AB5 = 300 Hz/cm2

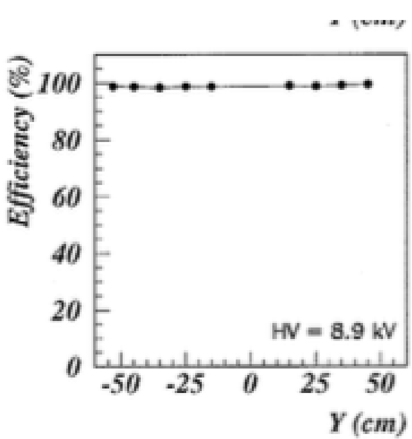
ABS1 = 500 Hz/cm2

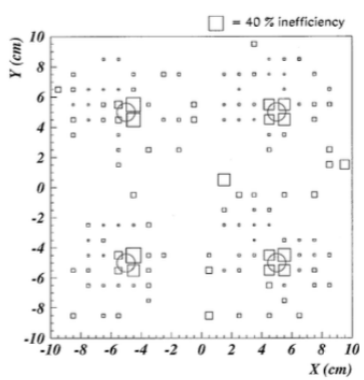


Efficiency vs gamma hits rate



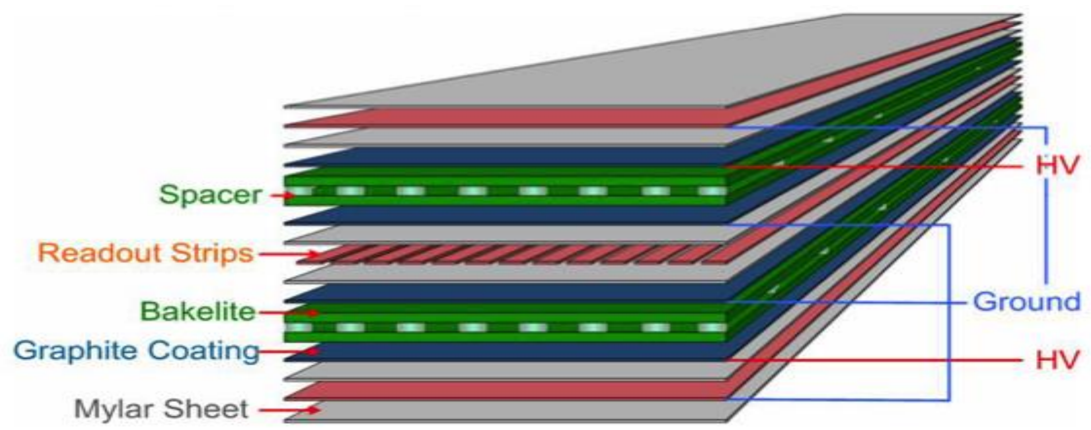
Time resolution vs HV at different gamma background

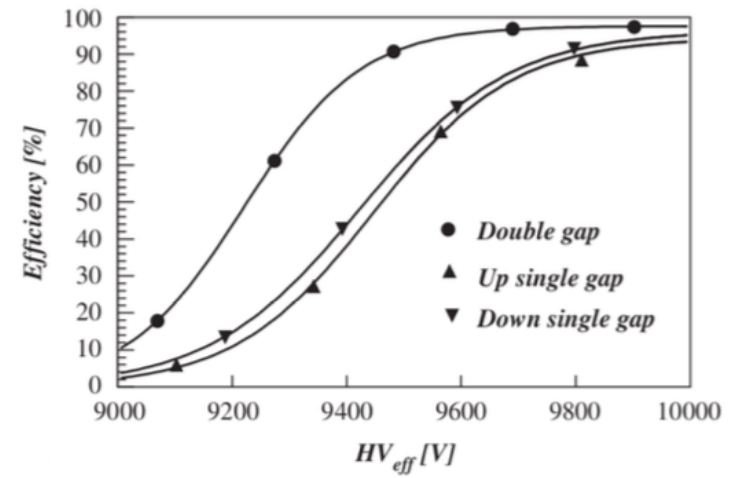




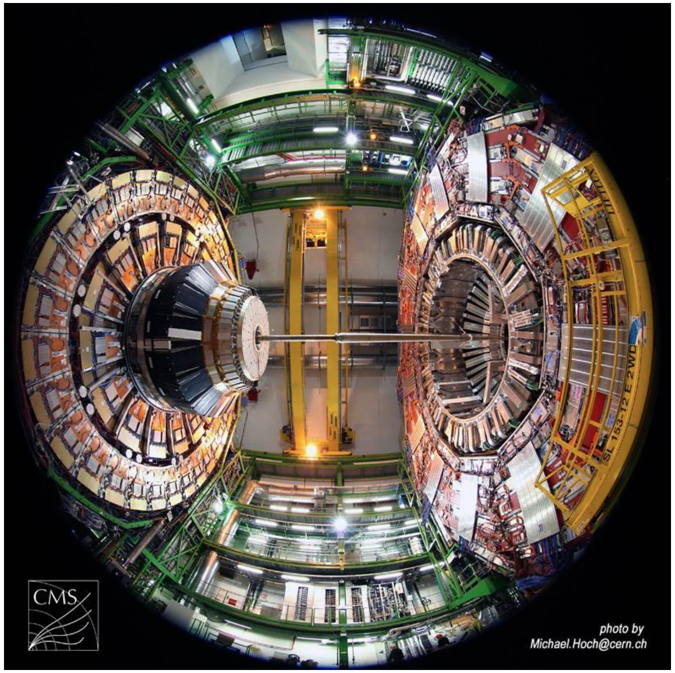
Uniform efficiency!

CMS RPC design

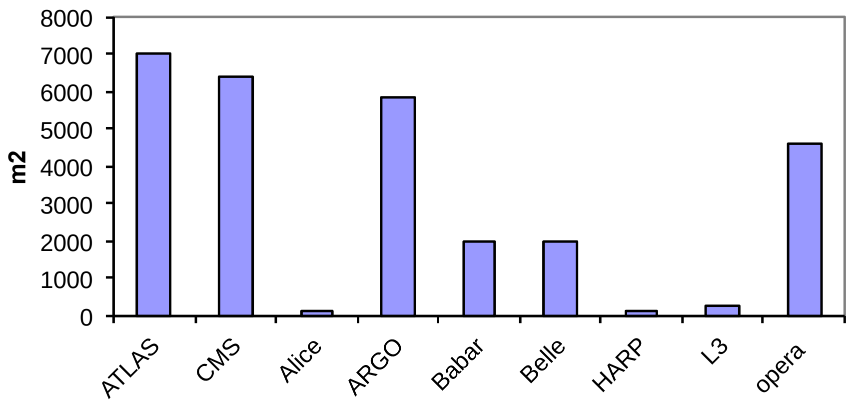




- **1056** chambers covering eta region up to 1.8
- Sensitive layers area: **3.200 m^2**
- **Double gaps: 2mm gas gap width**
- **Working in avalanche mode**
- **Bakelite** bulk resistivity: $\rho = 2 - 5 \times 10^{10}\ \Omega$cm
- **Gas Mixture** 95.2% $C_2H_2F_4$+4.5% i-C_4H_{10}+ 0.3%SF_6
- **Strip read-out:** 2 ÷ 4 cm
- **Charge per hit ≈ 20-30 pC**



RPC CMS construction



- CMS is one of the largest experiments equipped with RPC.

Key of the success:

→ An "industrial approach"

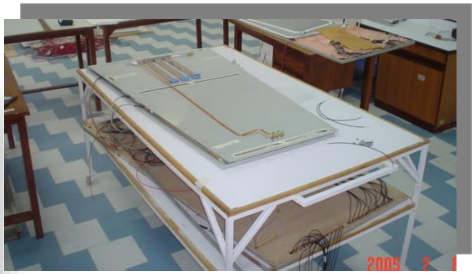
→ Quality control and acceptance criteria

World Wide RPC production

RPC mass production started in **early 2000**:

- **HPL:** PanPla (Italy)
- **Gaps:** General Tecnica (Italy) for the Barrel and Korea University for Endcap
- **Chambers** built and tested in several sites in Europe and Asia
- **Detector installation from 2004-2008**

Barrel Station

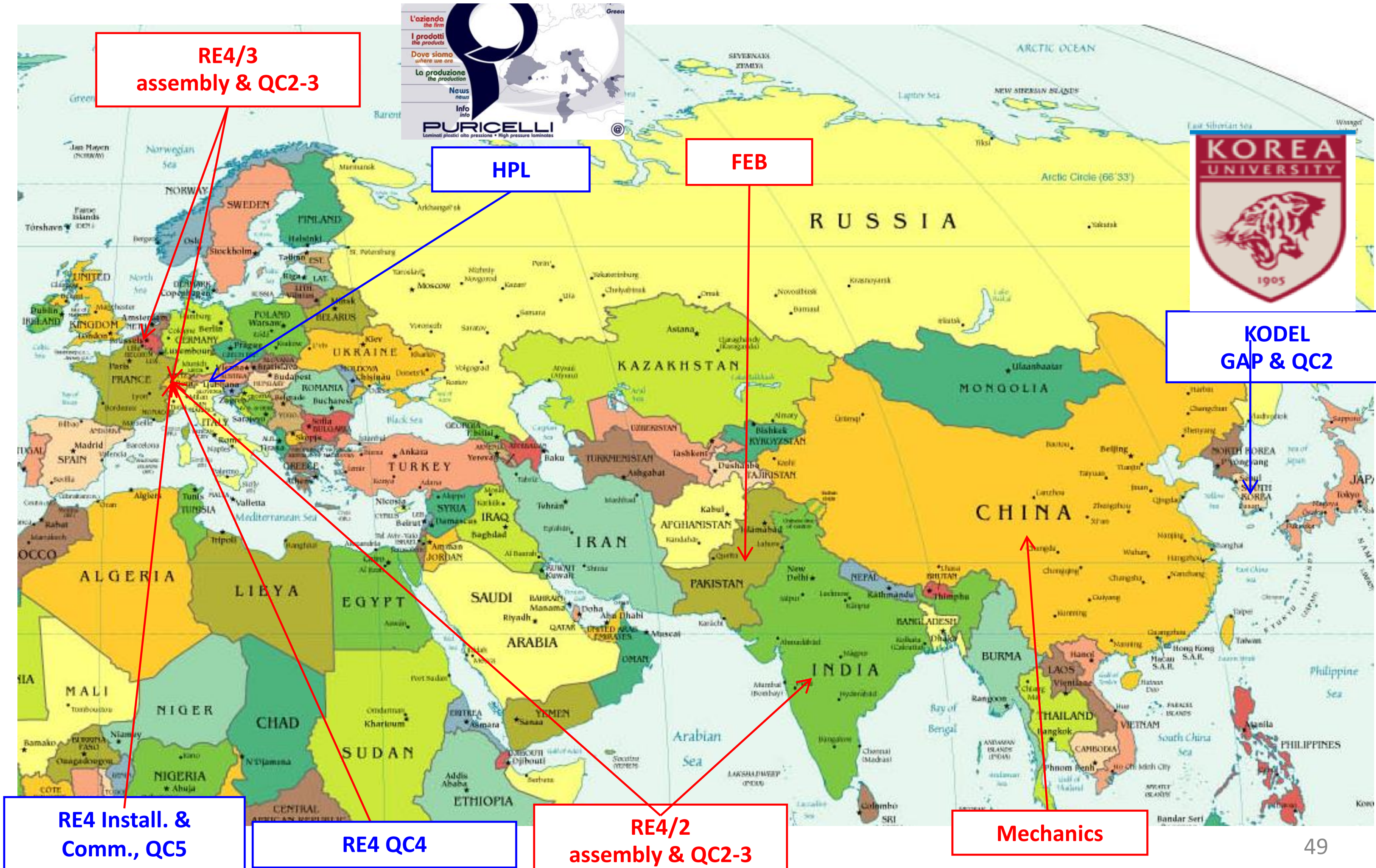


Forward Station

RE4 stations construction and installation in 2012-14:

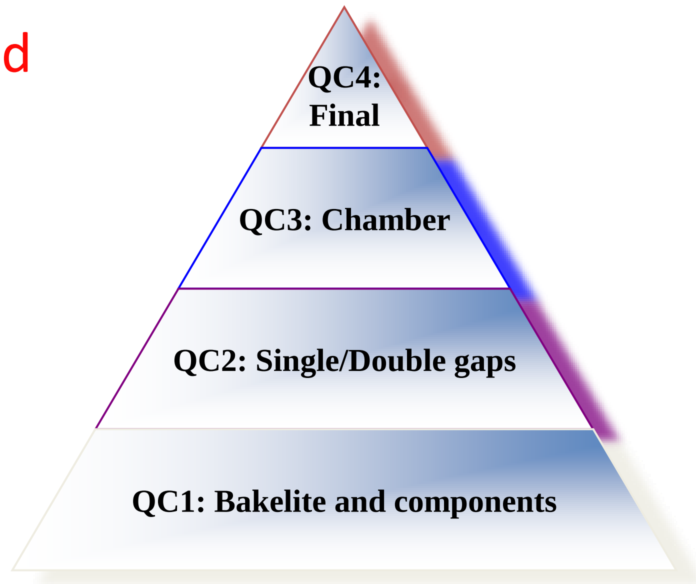
- **HPL:** Puricelli (Italy)
- **Gaps:** Korea University
- **Chambers:** India, Belgium and CERN

World Wide RPC production:
RE4 CMS example



CMS RPC mass production

Key point: well defined Quality Control and Acceptance Criteria

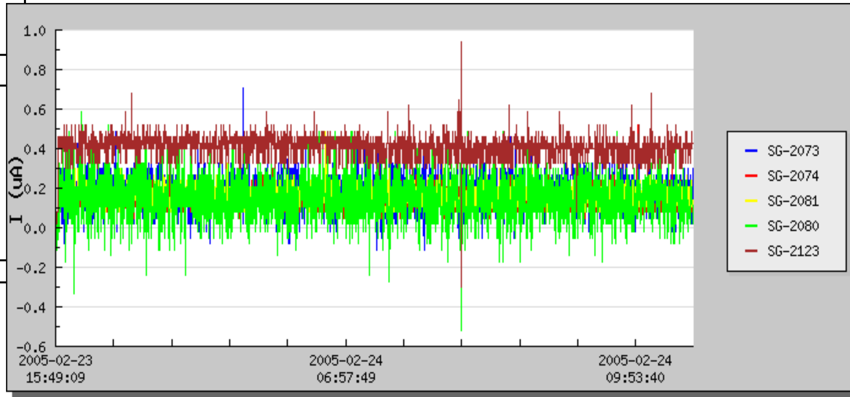


Final chamber tests:
- Gas leak, connectivity, dark current tests
- Long term detector stability test

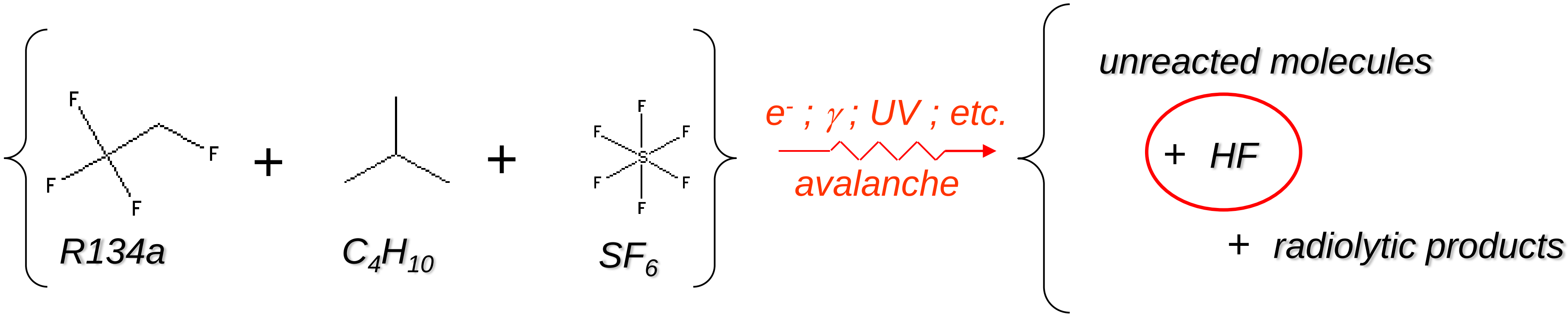
Chamber Assembly and tests
- Visual inspection, gas tightness, dark current test, connectivity test
- Performance study with cosmic muons

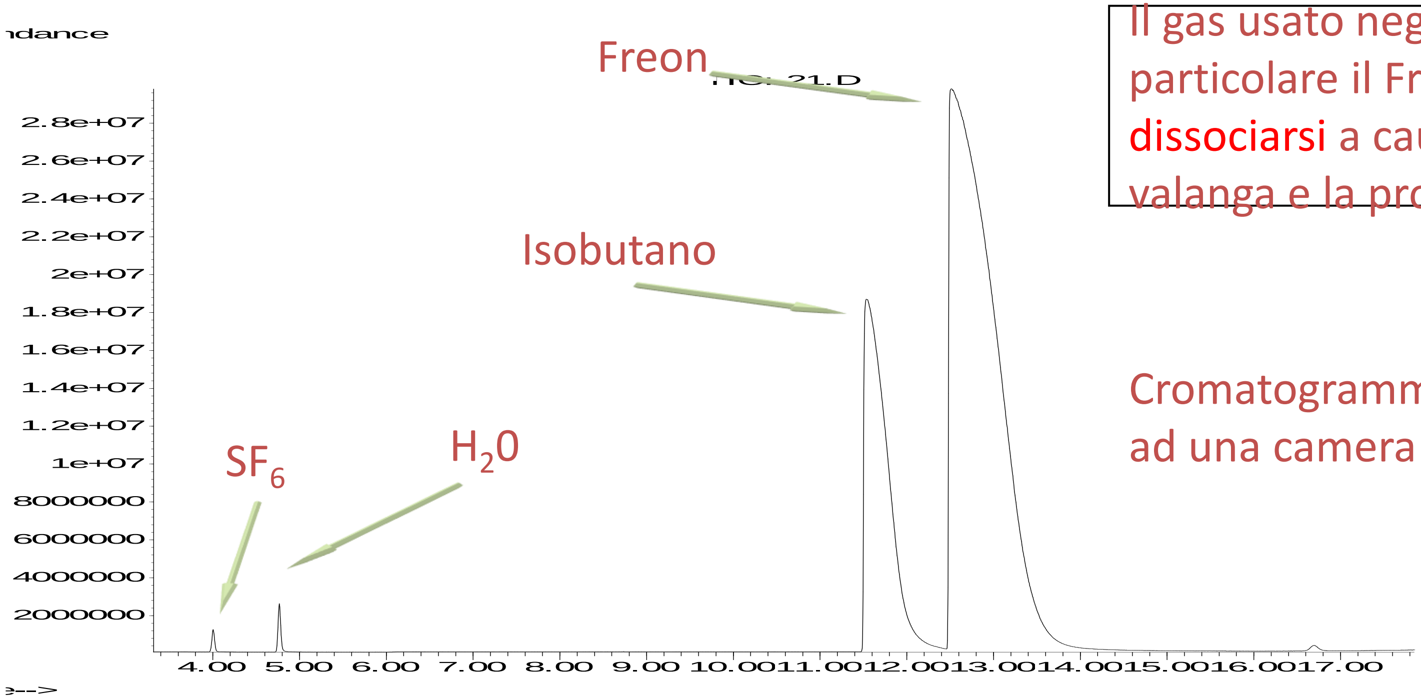
Gaps and Double production test
- Visual inspection, gas tightness and spacer test
- Electrical and dark current, resistivity measurement

HPL production test: surface inspection, HPL resistivity
FEB test: PCB electrical integrity, FEB calibration, FEB +PCB calibration



Gas issues





Il gas usato negli RPC (ed in particolare il Freon) può in parte dissociarsi a causa dei processi di valanga e la produzione di UV

Cromatogramma del gas in ingresso ad una camera

Gas issues

Chromatograph of the gas in output from one chamber

Perfluoro and hydrofluoro compounds

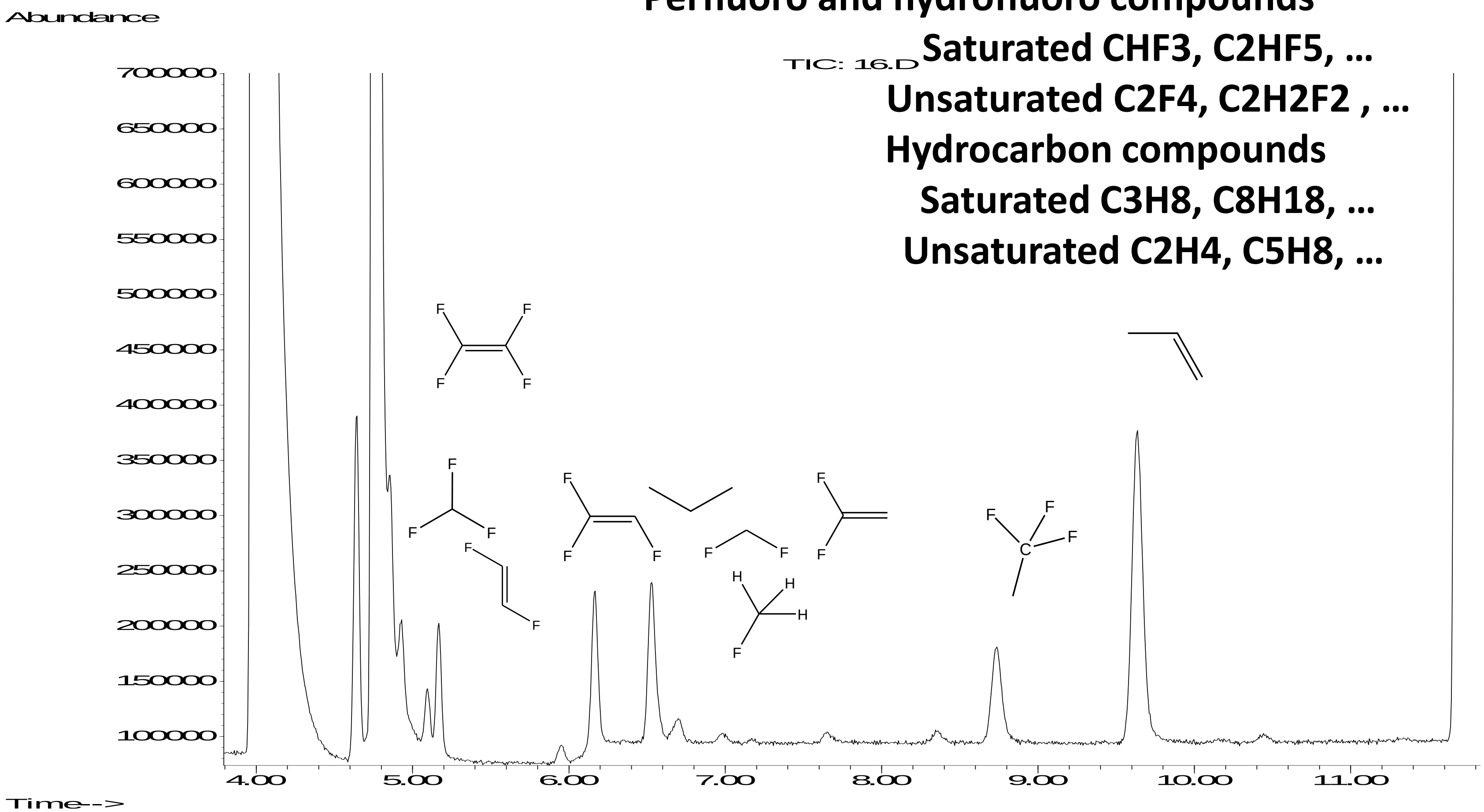
Saturated CHF_3, C_2HF_5, …

Unsaturated C_2F_4, $C_2H_2F_2$, …

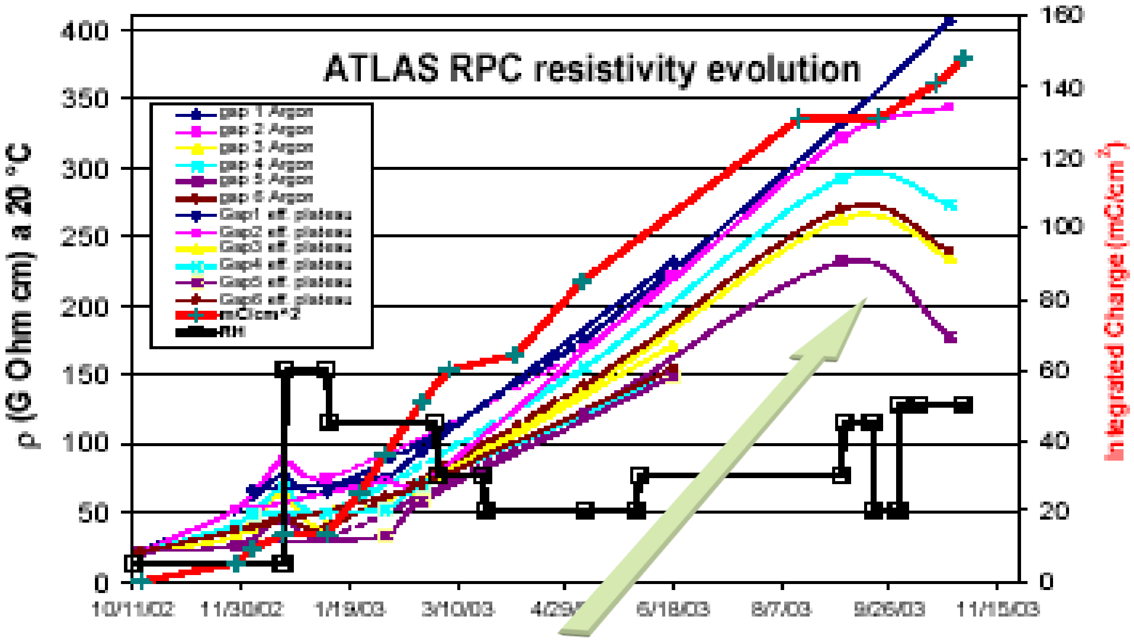
Hydrocarbon compounds

Saturated C_3H_8, C_8H_{18}, …

Unsaturated C_2H_4, C_5H_8, …



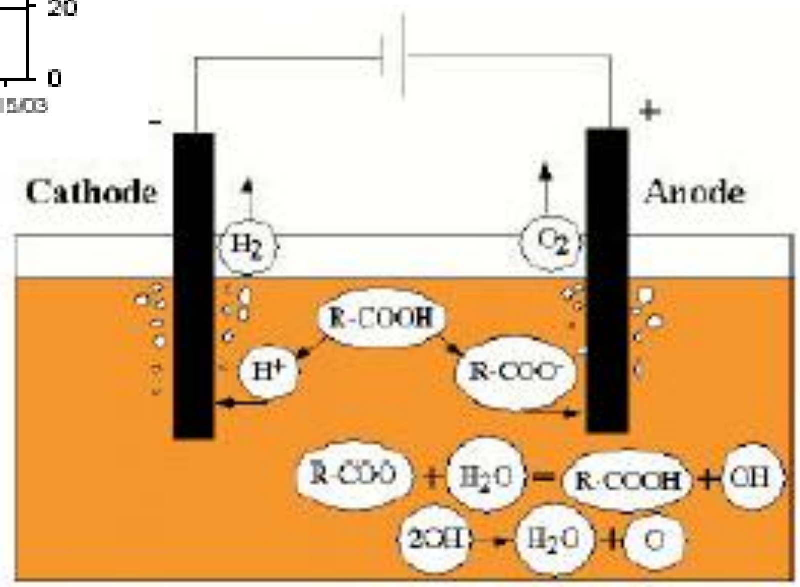
Water vapour issue



Bakelite resistivity has been experimentally found to depend on the amount of water vapour added to the mixture.

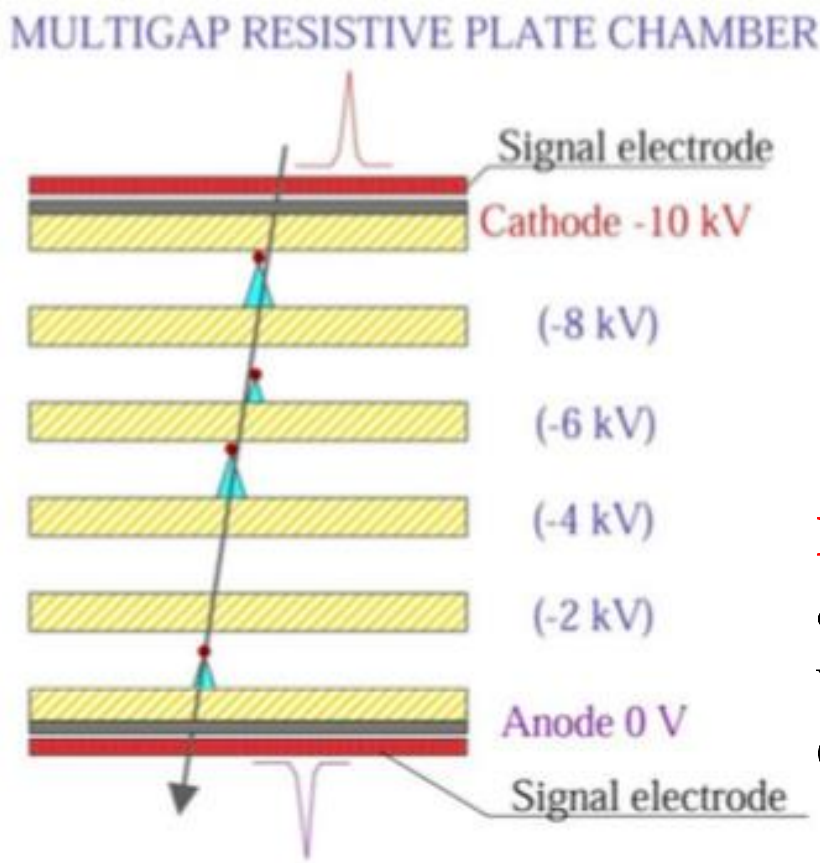
Time where the gas mixture was added with water vapour

Conduction mechanism in bakelite is ionic, and therefore needs water to be sustained (J. Vavra)



Multi-gap RPCs

Multi-gap RPCs: developed by C. Williams for the ALICE experiment

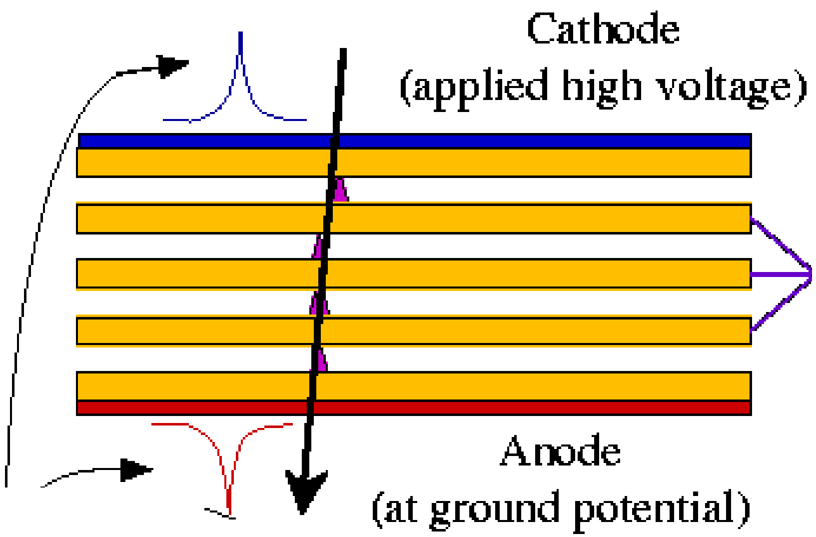


The **key point** to improve the timing is to use very thin gas gaps, in a multi-gap structure, to compensate the reduced primary ionization in the gas (high inefficiency).

Design: the multi-gap is characterized by a number of floating (glass) electrodes whose potentials scales in such a way to equalize the field in all gaps.

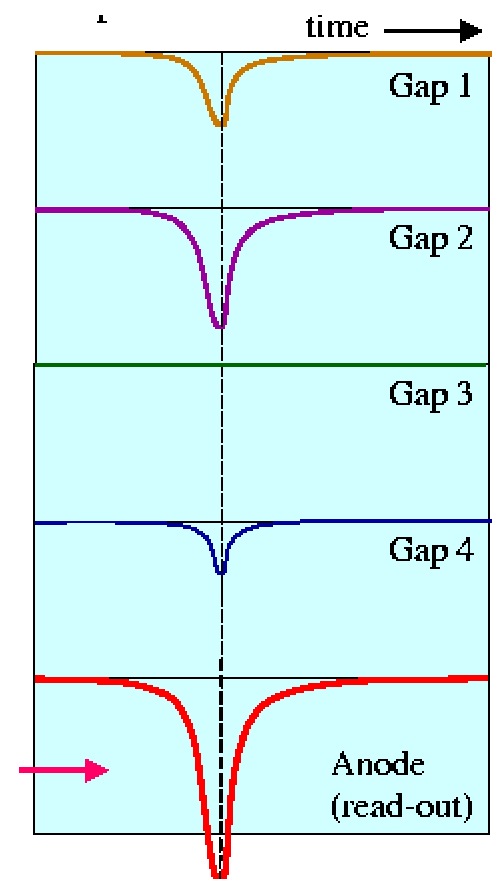
Compared with the single gap design the average charge induced on the pick up electrodes does not change but gives a narrower charge distribution

Multi-gap RPCs



The intermediate planes are left electrically floating

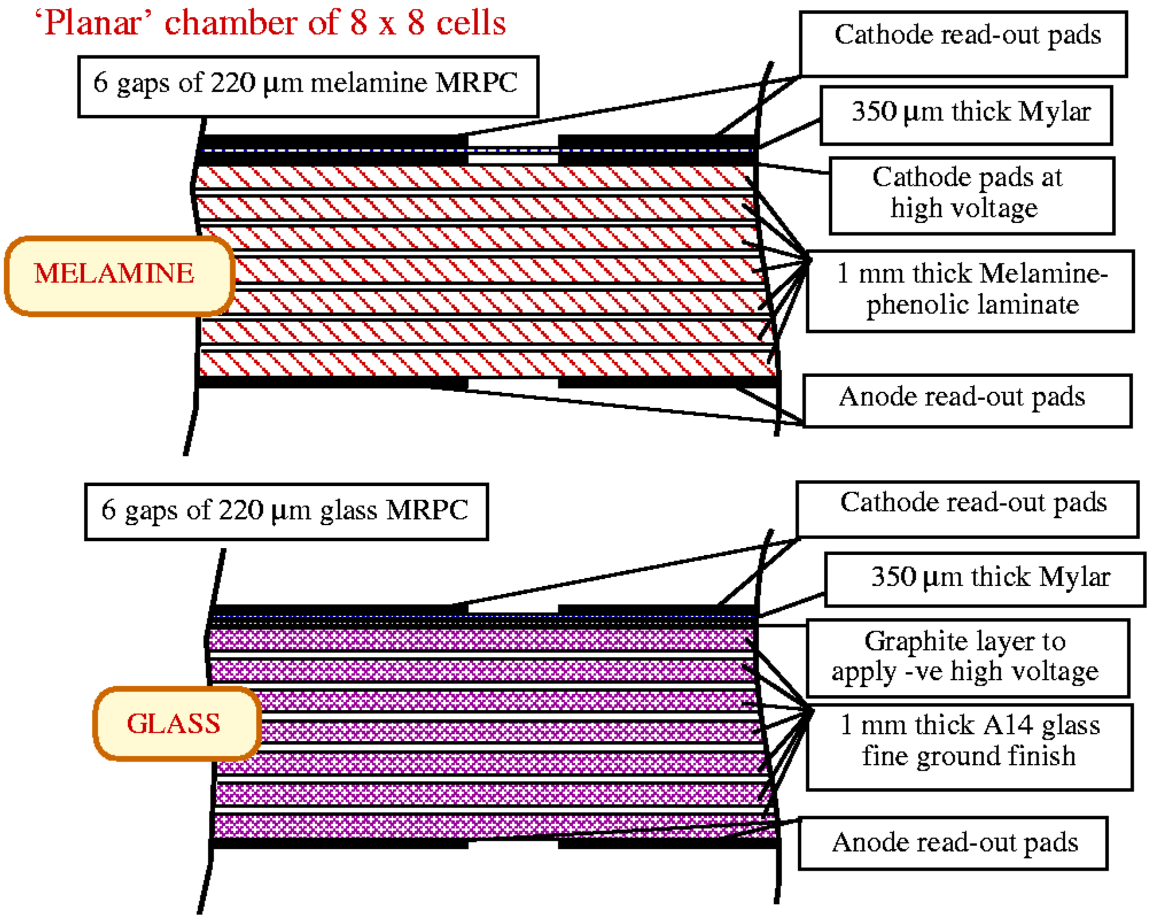
The intermediate planes are transparent to the induced signals



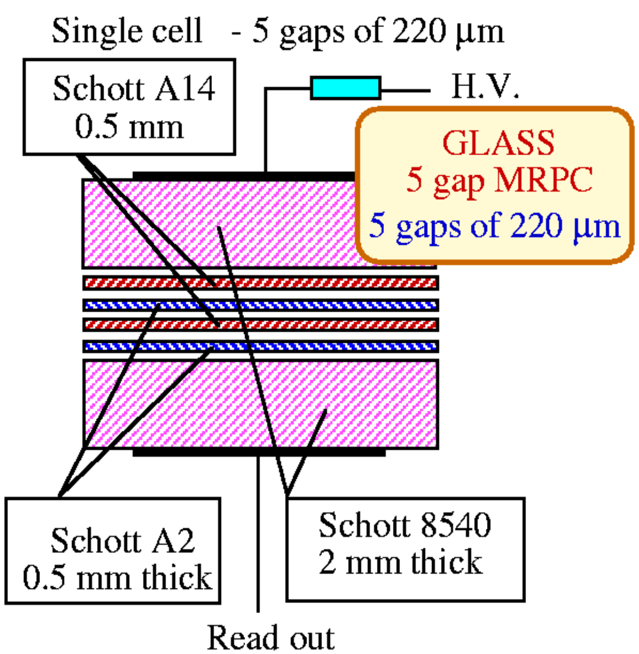
Avalanches in the various gaps take place (approximately) at the same time

The total signal is the analog sum of the signal from the various gaps

Possible configurations



Built with glass, bakelite, ceramics.



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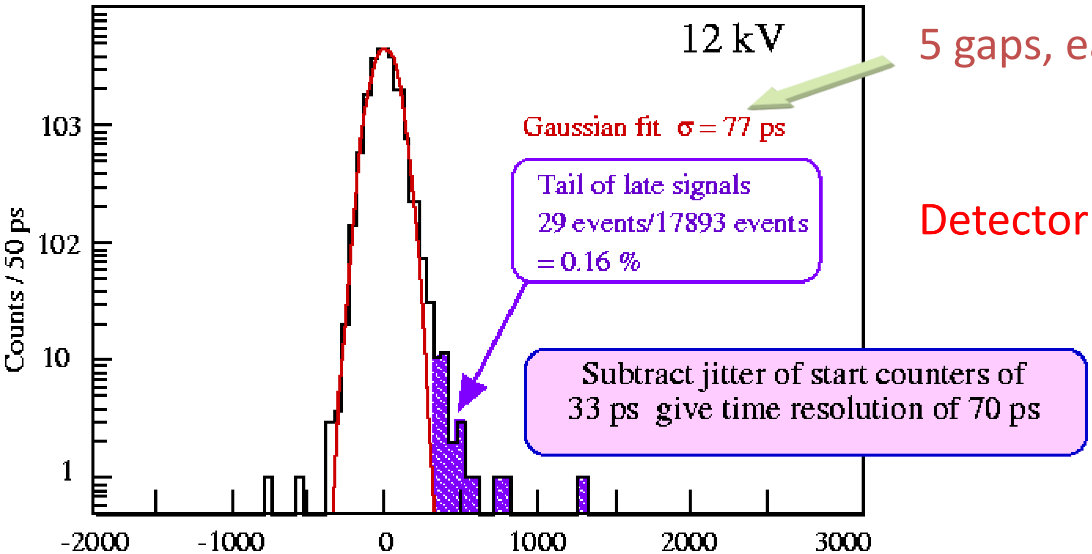
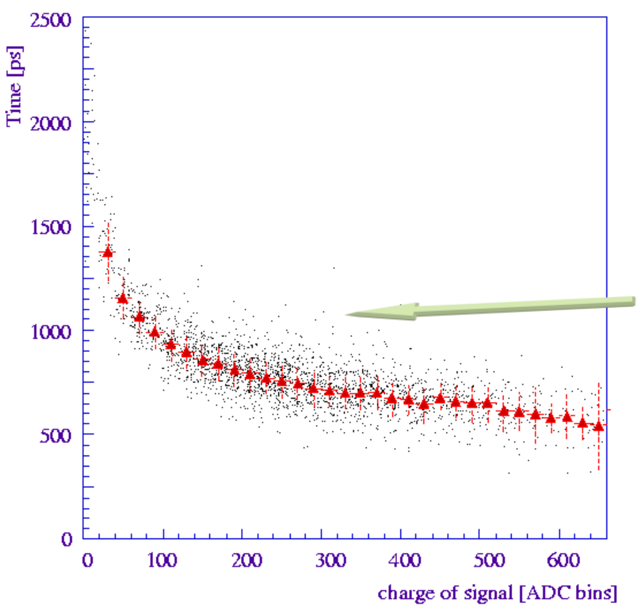
MRPC time resolution

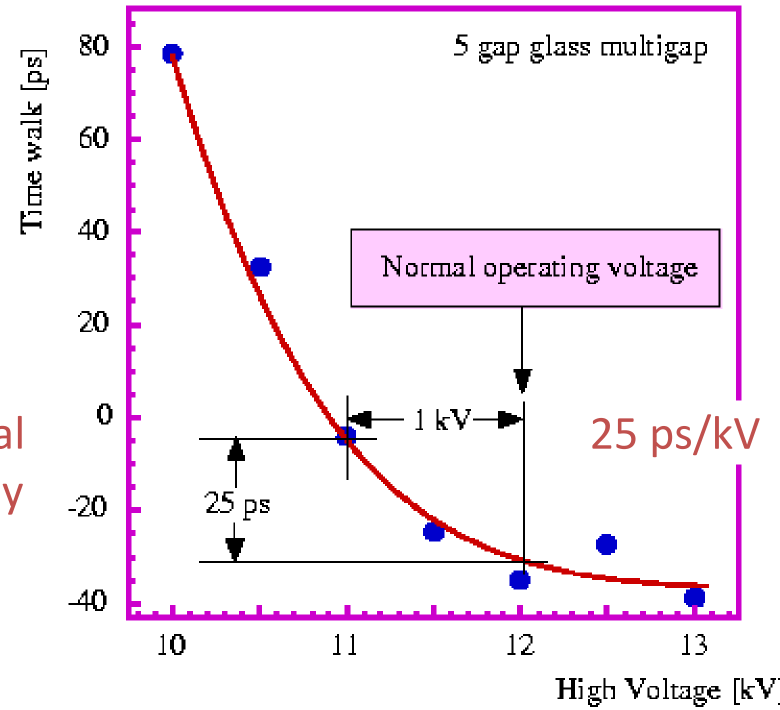


5 gaps, each 220 μm thick

Detector time resolution ≈ 50 ps



Correction: signal amplitude - delay



25 ps/kV

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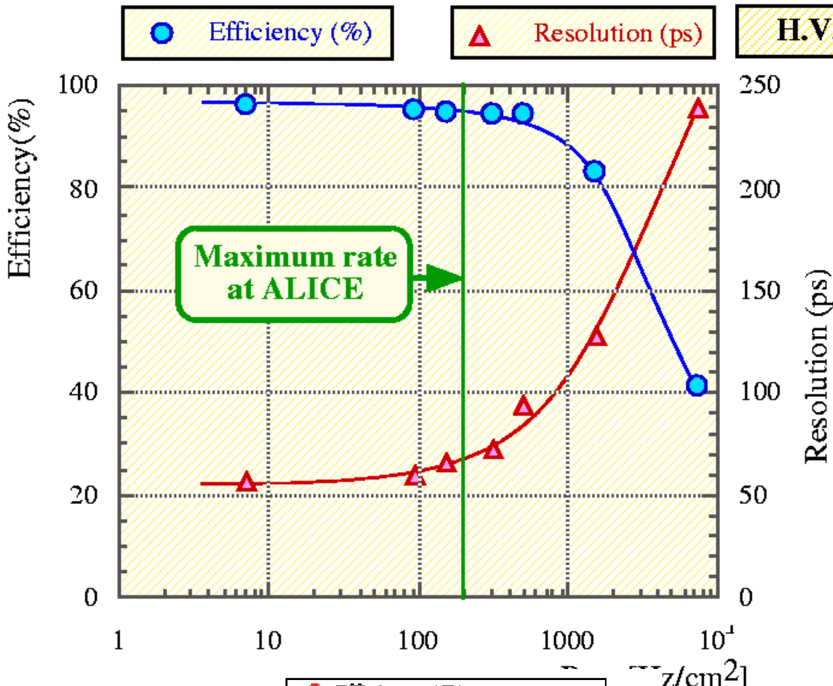
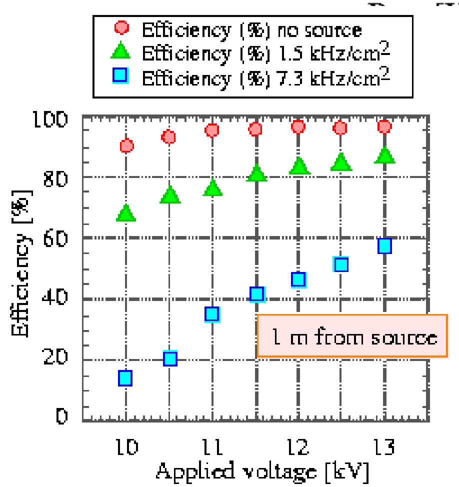
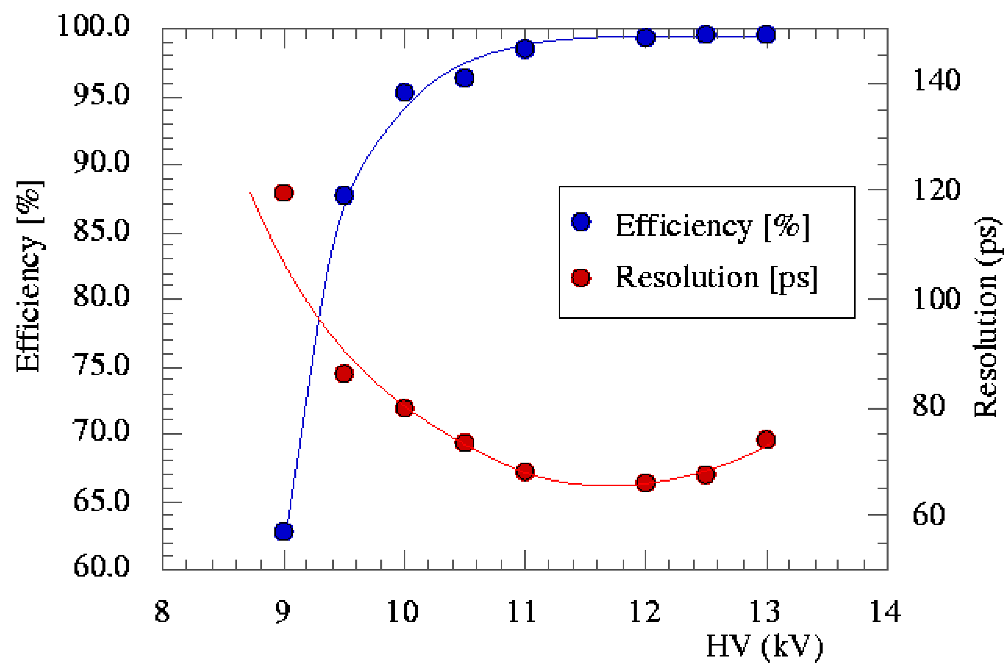
Rate capability



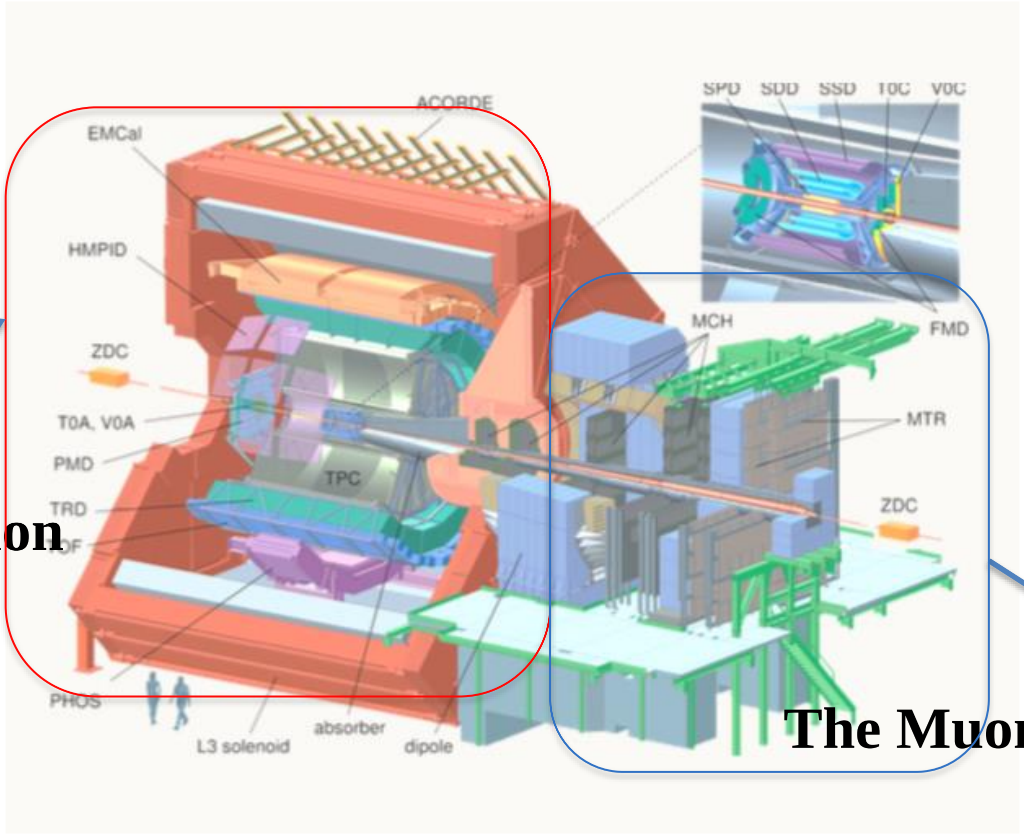


Efficiency measured in conditions of increasing background.



ALICE

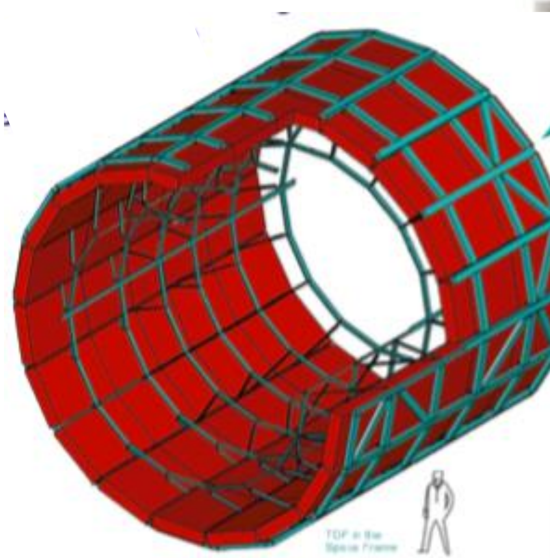
ALICE (A Large Ion Collider Experiment) is specialized in the detection of signatures of the Quark-Gluon Plasma state @ Heavy-ion collisions at ultra-relativistic energies (5.5 GeV). It is composed by two groups of detectors:



The Barrel region

The Muon Spectrometer

The Barrel region: ALICE TOF



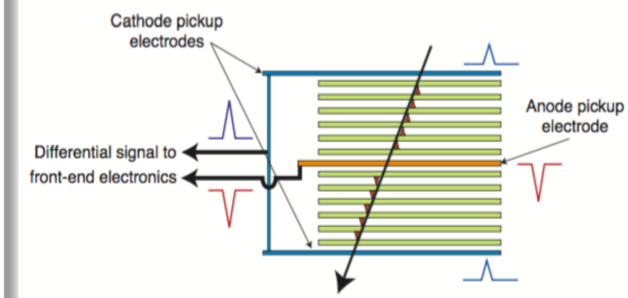
In the barrel region, charged particles in the intermediate momentum range (from 1 GeV/c to a few GeV/c) are identified by the **Time Of Flight (TOF) detector.**

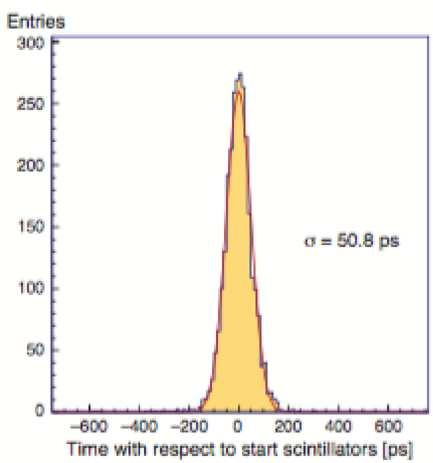
The TOF s a large area detector covering a cylindrical surface of 141 m^2 with an inner radius of 3.7 m, a pseudo-rapidity interval [-0.9,+0.9] and full azimuthal coverage.

MRPC for the ALICE TOF

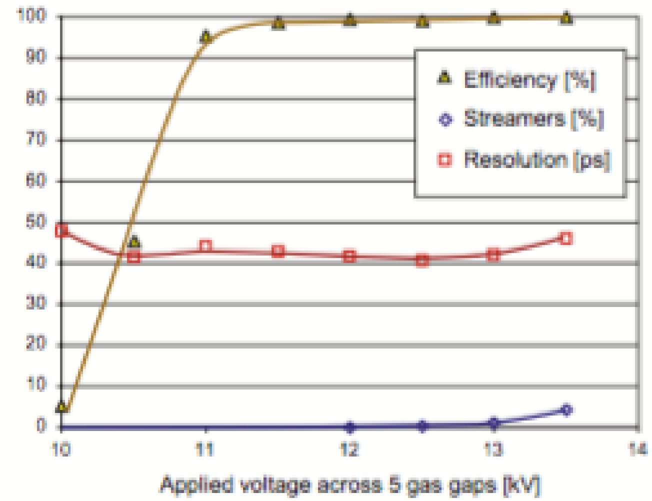
The TOF system is made of 1593 Multigap Resistive Plate Chamber (MRPC)

- Each MRPC consists of 2 stacks of glass, each with 5 gas gaps of 250 μm; with an active area of 7.4×120 cm^2
- Electrodes: high resistivity (≈10^{13} Ωcm) float glass, 0.4 mm thick
- 96 readout pads of 2.5 × 3.5 cm^2





Performance results

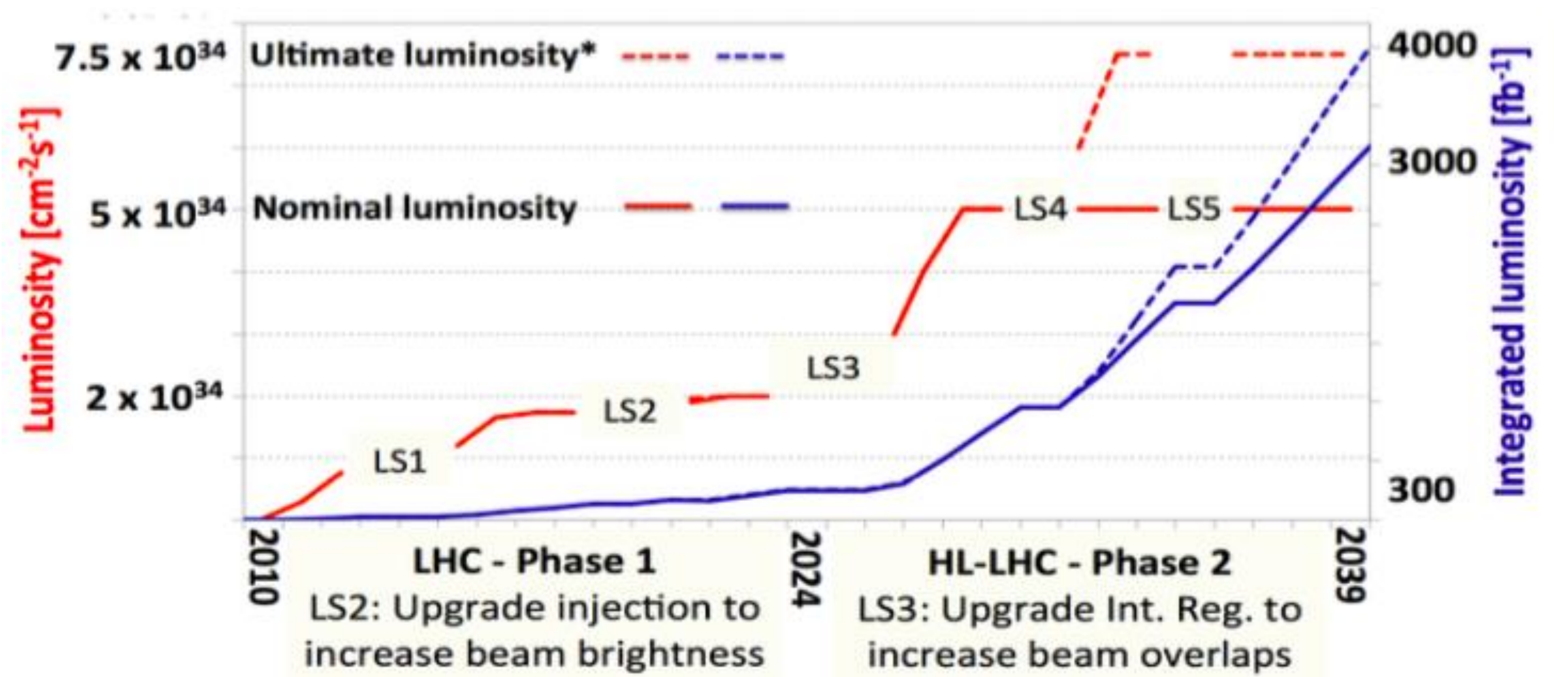


The time resolution of the TOF MRPC is in the 50 ps range. A typical efficiency and time resolution plateau as a function of the high voltage is more than 2 kV long before the onset of streamers, with efficiency reaching 99.9 %.

3th generation of RPC

New challenge: the HL-LHC

*"**Europe's top priority** should be the **exploitation** of **the full potential of the LHC**, including the high luminosity upgrade of the machine and the detectors with a view to collecting 10 times more data than in the initial design, by around 2030"*

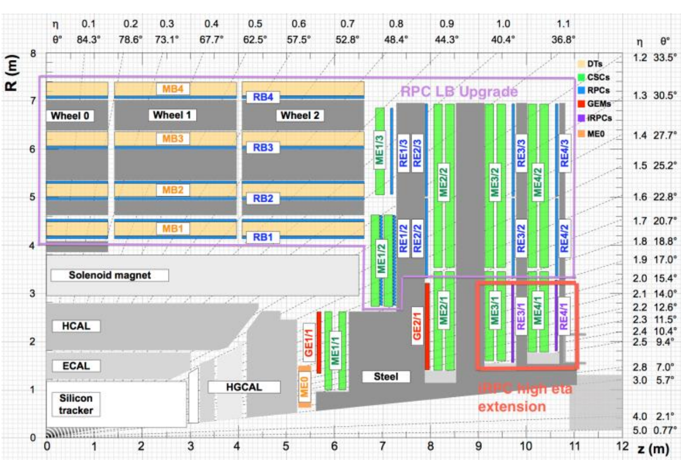


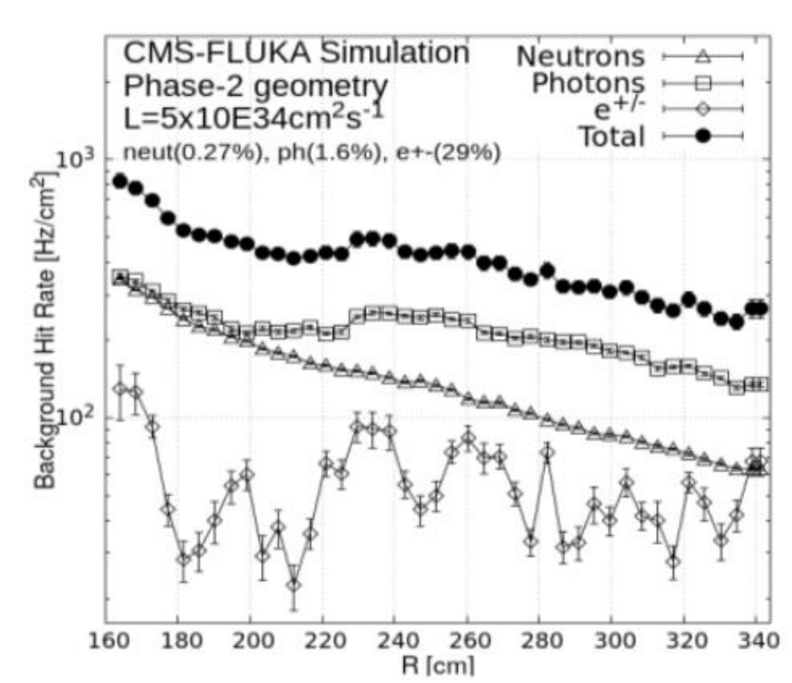
We are here

The challenges for the RPC systems in the LHC experiments

- ➢ Confirm muon system performance at HL-LHC conditions: the RPC systems have to run at **5 times the expected LHC intensity** and for **30 years (instead of 10)**

- ➢ New RPC chambers needed to extend the CMS muon coverage up to $|\eta| < 2.8$ or to improve the trigger perfomance (ATLAS)
  - ➢ **Rate capability ≈ 1-2 kHz/cm²**





Further improve of the rate capability

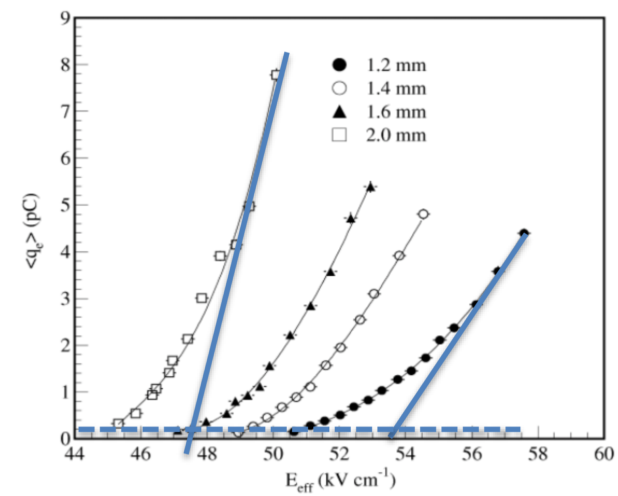
All relevant detector improvement factors have been investigated **to improve rate capability:**

- Reduced electrode resistivity
- **New detector geometry: gas gap and electrodes thickness**
- New Front-End electronics

The key points is to reduce:

- the charge
  - thinner gas gaps: from 2 mm to 1 mm
  - lower electronics threshold

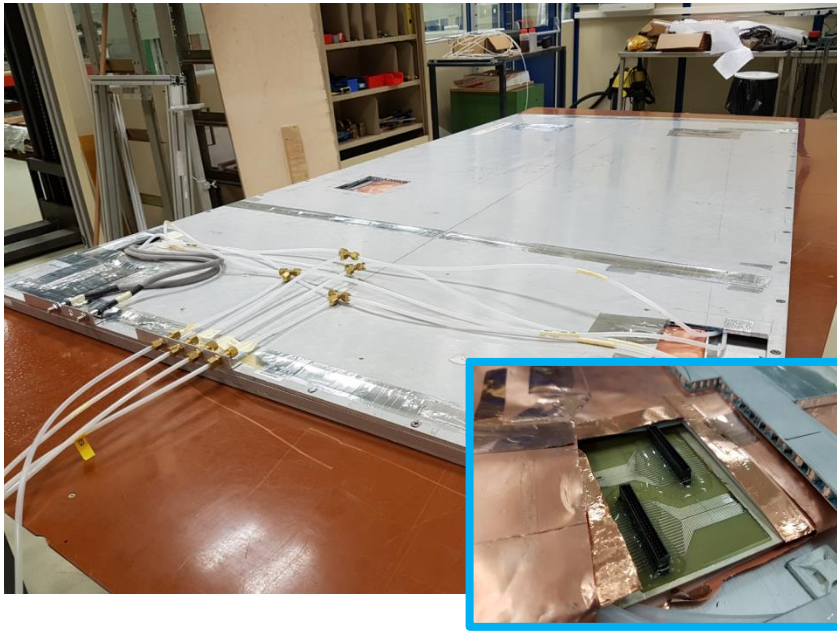
- Thinner electrodes: from 2 mm to 1mm

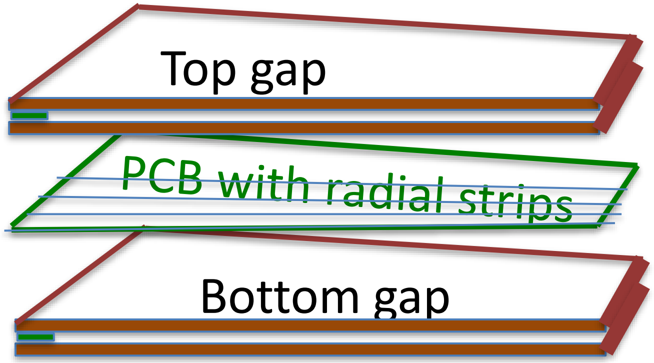


$$DV_{el} = r \; d \; F \; <Q>$$

CMS improved RPC: new 2D design

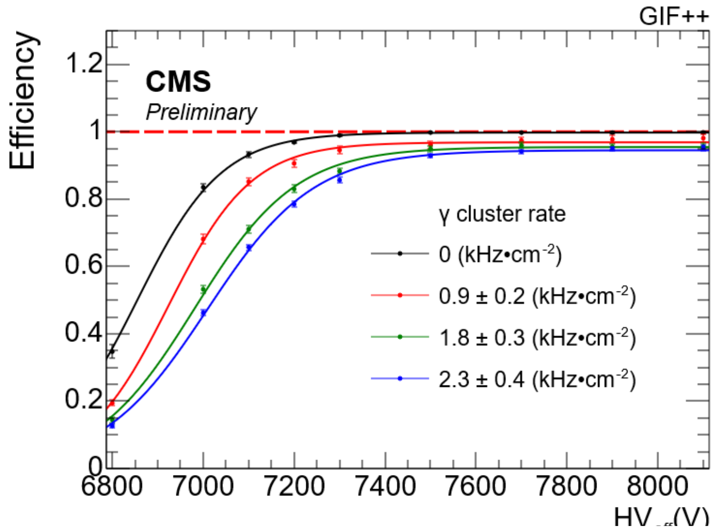
	iRPC	RPC
High Pressure Laminate thickness	1.4 mm	2 mm
Num. of Gas Gap	2	2
Gas Gap width	1.4 mm	2 mm
Resistivity (Ωcm)	$0.9 - 3 \times 10^{10}$	$1 - 6 \times 10^{10}$
Charge threshold	50 fC	150 fC
η segmentation	2D readout	3 η partitions





2D readout design:
Readout Strips (with a pitch ≈*0.6÷1.0* cm) are readout from both-ends and connected to a new Front-End Boards equipped with a TDC

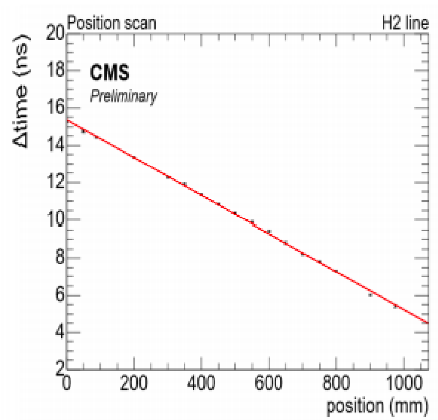
CMS improved RPC: new 2D design



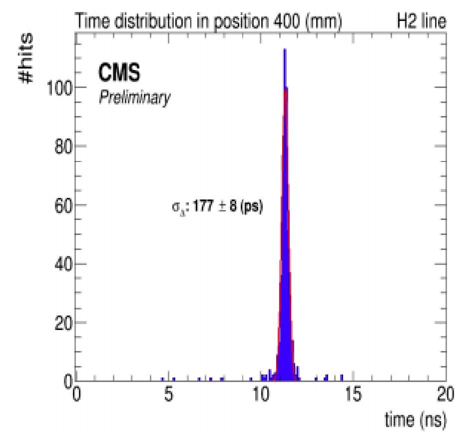
It has been proved:

- rate capability of 2 kH/cm2
- Spatial resolution along y coordinate 1.4cm

Final validation of the new FEB ongoing..



Uniformity in H2 using DESY table



Along-strip time resolution and space resolution ση ~ 1.4 cm

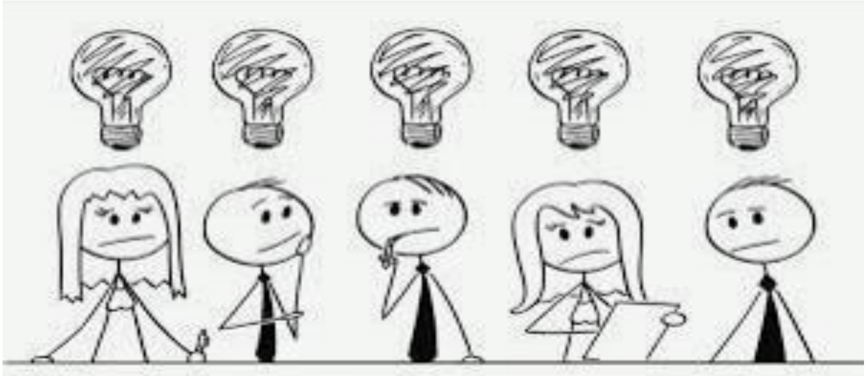
The eco-gas problem

We need to replace the R134a and SF_6 with more ecological gases, namely with a much lower GWP → limit the green house effect.

Difficult problem: gases are **the core of gas-filled detectors**

-It's like I would ask you to replace silicon in electronic devices (including smartphones, computers, TV sets, etc.) with another material, BUT:

- with the **same performance**
- at the **same cost**
- without **changing anything** of the rest of electronic circuits



A green choice

Note that EU is progressively banning greenhouse gases:

- but they are still allowed for research applications

- $C_2H_2F_4$ and SF_6 are still allowed by law to be used at CERN experiments

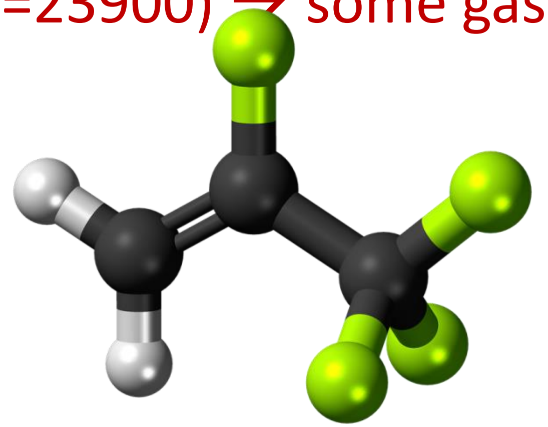
- nevertheless the green choice of the CERN community (and others) was to start asap research on ecofriendly gas mixtures

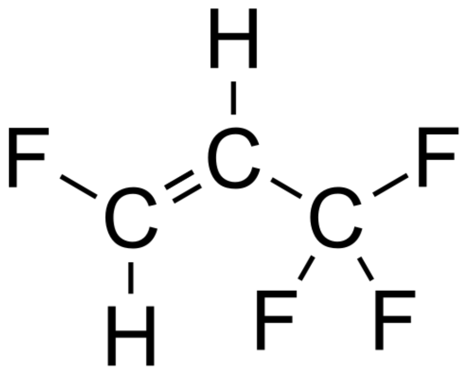
The smart (!?) idea

All high energy experiments (CMS, ATLAS, ALICE, LHCb, etc.) have started an intense R&D program to find suitable gas mixtures

-Practically all research trendlines are concentrated around the idea (by a smart guy) of replacing:

- $C_2H_2F_4$ (GWP=1430)→ $C_3H_4F_4$ze (GWP=4)
-Adding some CO2 to reduce the operating voltage
- SF_6 (GWP=23900) → some gas still to be found





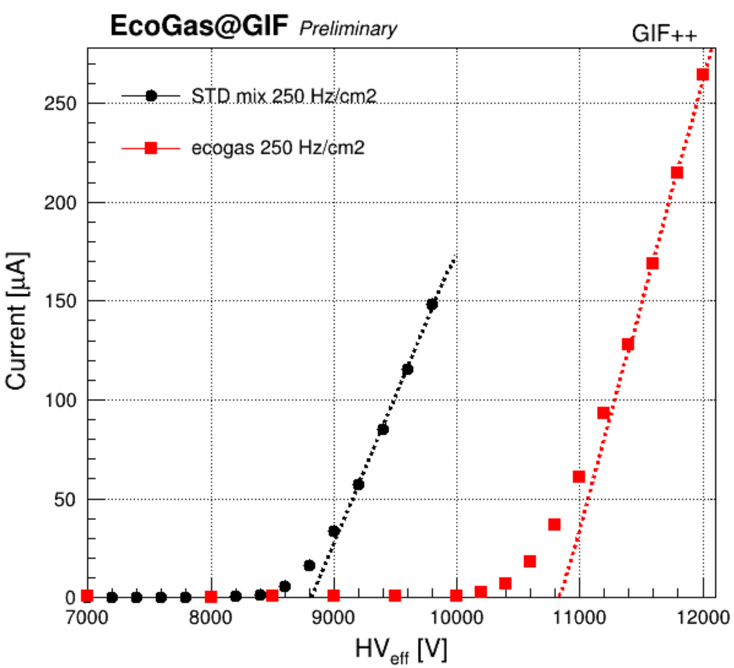
$C_3H_4F_4$ze is the most similar molecule to $C_2H_2F_4$ but with a low GWP

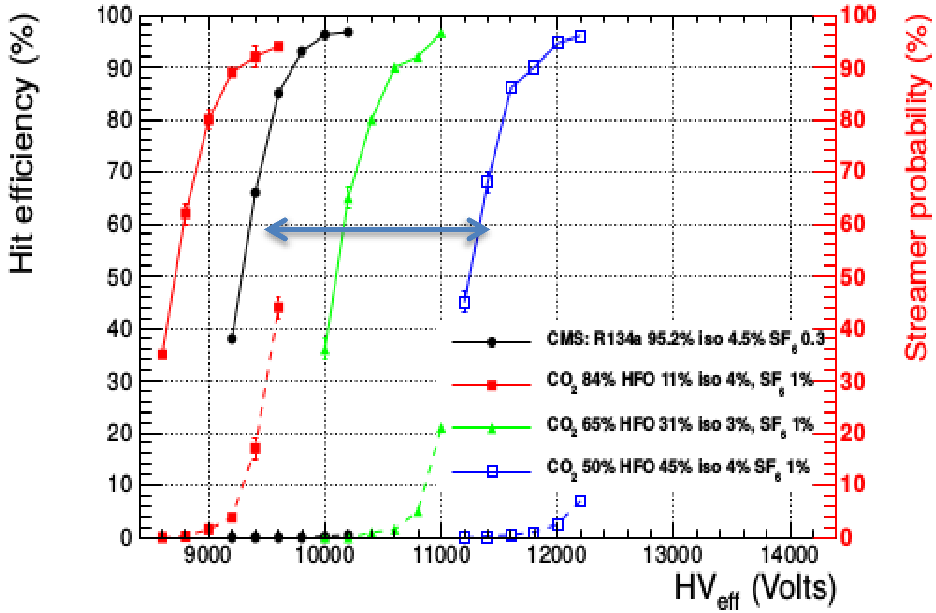
Eco-gas mixtures

Validation of a **new ecological RPC gas mixture** started in GIF++ since April 2019.

- Five RPCs (2 CMS, 1 ATLAS, 1 ALICE, 1 EP-DT) are under test.
- One eco-gas mixture based on HFO 1234ze ($C_3H_2F_4$) (45%HFO, 50%CO_2, 1SF_6, 4%C_4H_{10}) under study

2 kV of HV shifts @ 250 Hz/cm2 between the eco-gas was measured





Detector performance stability ongoing …

Conclusions

- Gaseous detectors were extremely successful in the past, and promise to be even more successful and wide spread in the future
- They are a fascinating topic to study, but, above all, there is so much work still to be done...

by YOU!

Contact information

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- University of Bari, Italy

-Email: marcello.abbrescia@uniba.it, marcello.abbrescia@ba.infn.it,

-Please do not hesitate to contact me for any information, request of additional material, or just a nice scientific discussion.

Relevant bibliography

F. Sauli: **Principles of operation of multiwire proportional and drift chambers**, CERN Yellow Reports, CERN 77-09, 1977. - 92 p., 10.5170/CERN-1977-009

A. Peisert and F. Sauli: **Drift and diffusion of electrons in gases : a compilation (with an introduction to the use of computing programs)**, CERN Yellow Reports, CERN 84-08, 1984. - 127 p.

F. Sauli: **Gaseous Radiation Detectors: Fundamentals and Applications**, Cambridge University Press July 2014, ISBN: 9781107337701 , hUps://doi.org/10.1017/CBO9781107337701

Glenn F. Knoll **Radiation Detection and Measurement, 4th Edition, Wiley ed.** ISBN: 978-0-470-13148-0, September 2010 864 Pages

W. Leo, "**Techniques for Nuclear and ParLcle Physics Experiments: A How-to Approach",** Springer-Verlag, ISBN-13: 978-3540572800 , ISBN-10: 3540572805

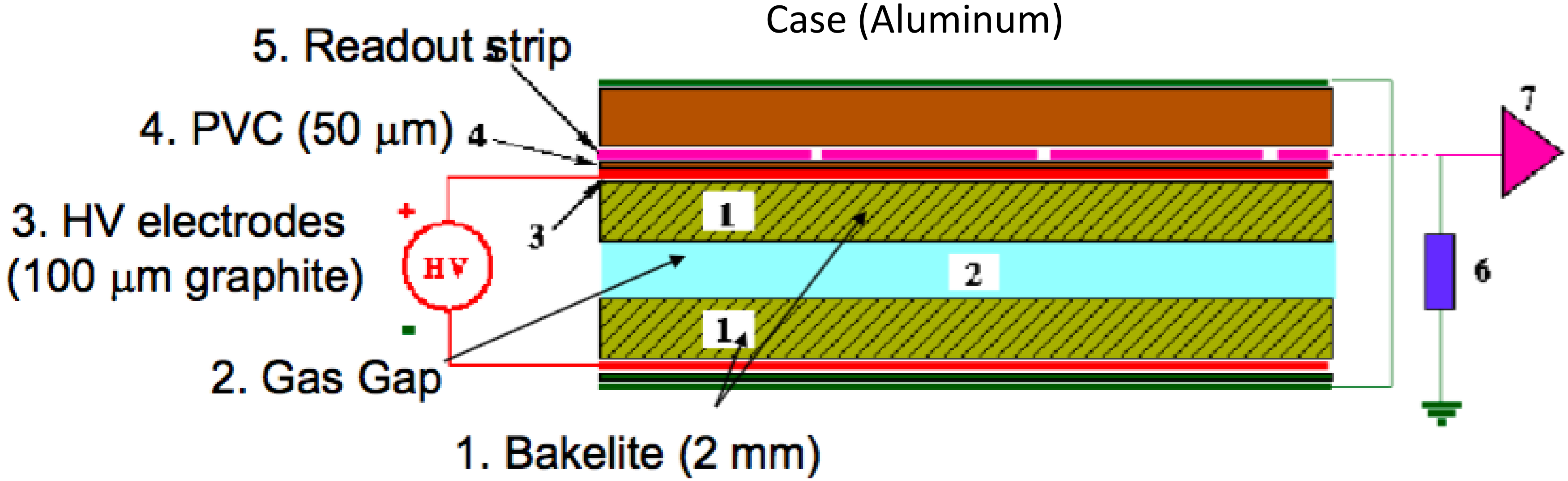
Walter Blum, Werner Riegler, Luigi Rolandi, **Particle Detection with Drift Chambers**, Springer-Verlag 2008, ISBN: 978-3-540-76683-4

RPC basic elements
(as in the 1st generation)

Gas mixture:
Argon, Iso-butane and Freon
at P ≈ 1 Atm

High Voltage contact: graphite coating on electrode outer surfaces

Pick up strips are used to collect the signal: **Al/Cu, ~cm**

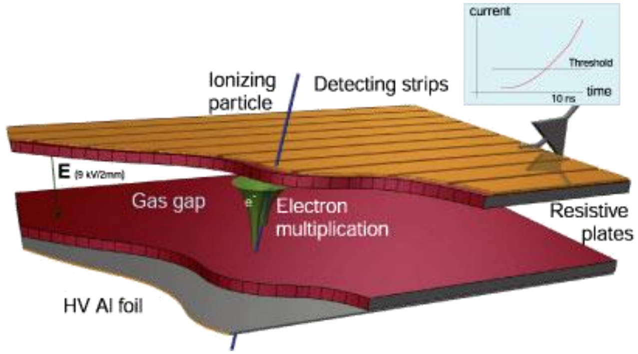


Resistive Electrodes (**ρ≈10^{10}-10^{12} Ωcm**): **High Pressure Laminates (HPL)** "Bakelite" made by Kraft paper impregnated with melamine/phenol resins.
Internal electrode surface covered with a **thin linseed oil layer (~µm)**

Brief History of the Resistive Plate Chamber

- 1981: **1st generation** R. Santonico published the [paper "Development of Resistive Plate Counters``, Nucl. Instrum. Meth. N.187]()

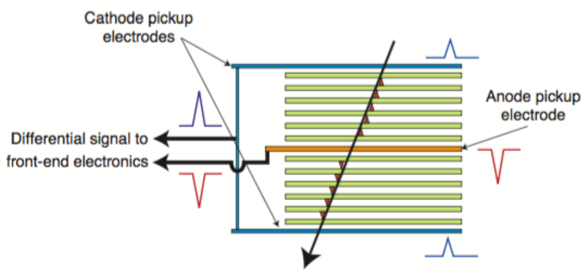
Operated in **streamer mode** with an **Argon** based mixture
Performance: time resolution ≈ 1ns Efficiency > 96%
Rate Capability ≈ 50 Hz/cm2



- 1992: **2nd generation** of RPC detector was developed for the LHC experiments (installed in ATLAS, CMS and ALICE).

Operated in **avalanche mode** with a **Freon** based mixture
Performance: time resolution ≈ 1 ns Efficiency > 96%
Rate Capability ≈ 500 Hz/cm2

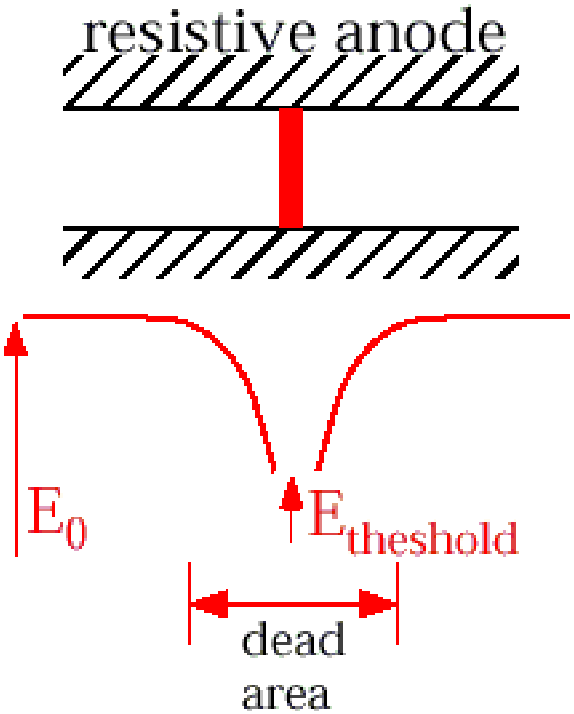
- 1995: **Multi-gap RPCs** developed by C. Williams (installed in ALICE and other experiments).



Operated in **avalanche mode** with a **Freon** based mixture
Performance: time resolution ≈ 60 ps Efficiency > 96%

- 2015: **3nd generation of** RPC developed for HL-LHC

Resistive Plate Chamber



Discharging time linked to drift velocity and multiplication factor

Time constant for recharge related to the RC constant of the RPC elementary cell

$\eta = \alpha - \beta$ = effective Townsend coefficient

$$t_{dis} = \frac{1}{\eta v_d} \approx 10ns$$

$$t_{REC} = \rho \varepsilon_0 \left(\varepsilon_r + \frac{2d}{g} \right) \approx 10ms$$

$\tau_{dis} \ll \tau_{rec}$

Self-extinguishing mechanism

The arrival of the electrons on the anode reduces the local electric field and therefore the discharge will be extinguished.

During the discharge the electrodes behave like insulators.

Why Electrodes are “cured” with linseed oil ?

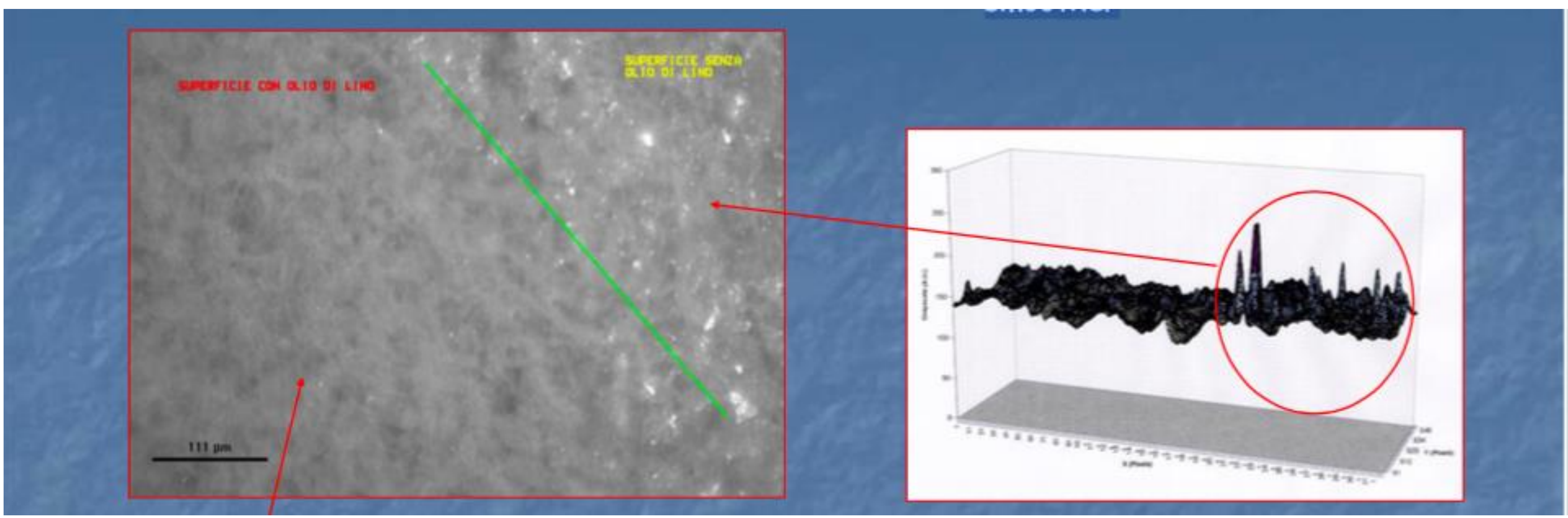
Linseed oil (If you look on Wikipedia..)

The Linseed oil is used as a painting medium. It was a significant advantage in the technology of oil painting!

Mixture of triglycerides, formed by one molecule of glycerol and three molecules of linear fatty acids. The oil is cured forming a hard stable film because of oxidation followed by polymerization.

Linseed oil makes the surface smoother

The smoother the surface, the lower the intrinsic noise of the detector

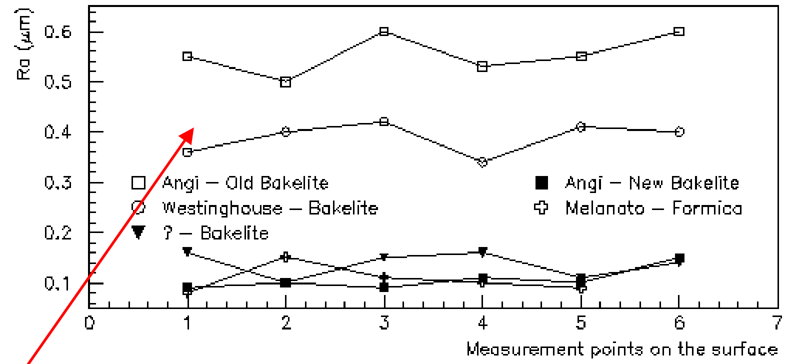


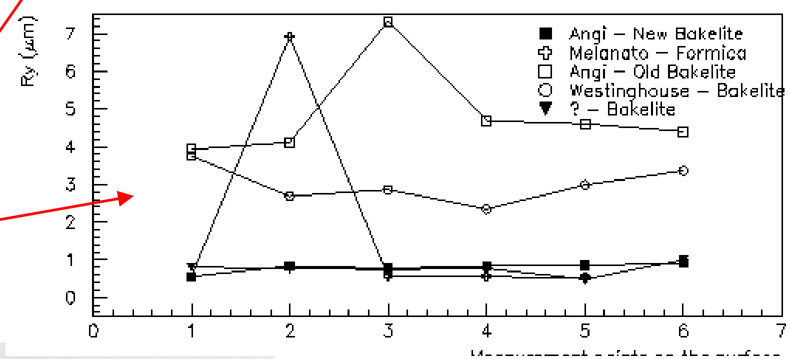
Comparison among not-oiled, oiled and smoother surfaces RPC

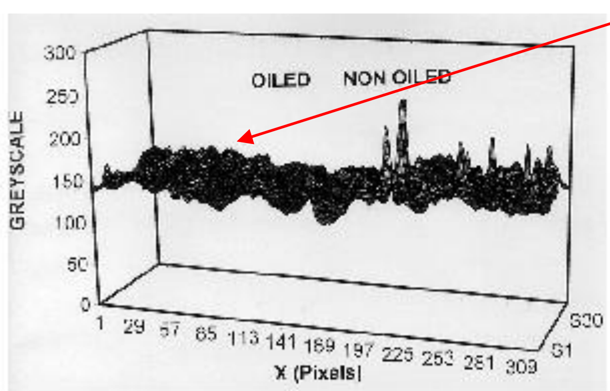
Direct measurements of surface roughness

-mono-dimensional

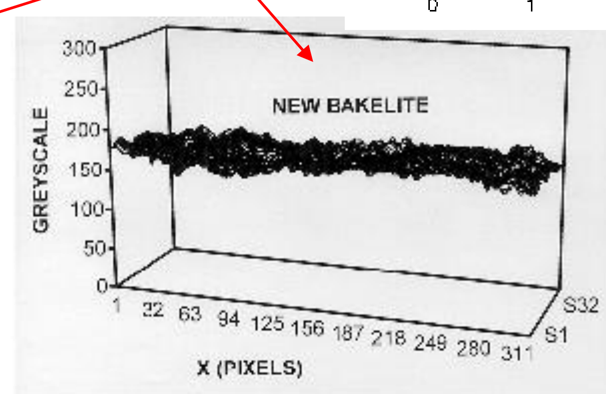
- bi-dimensional





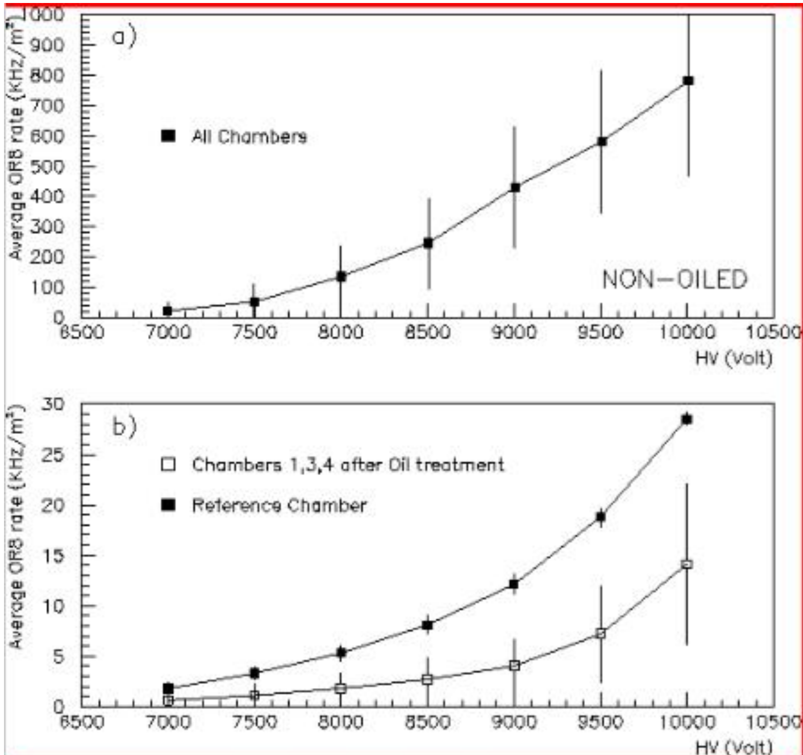


a)

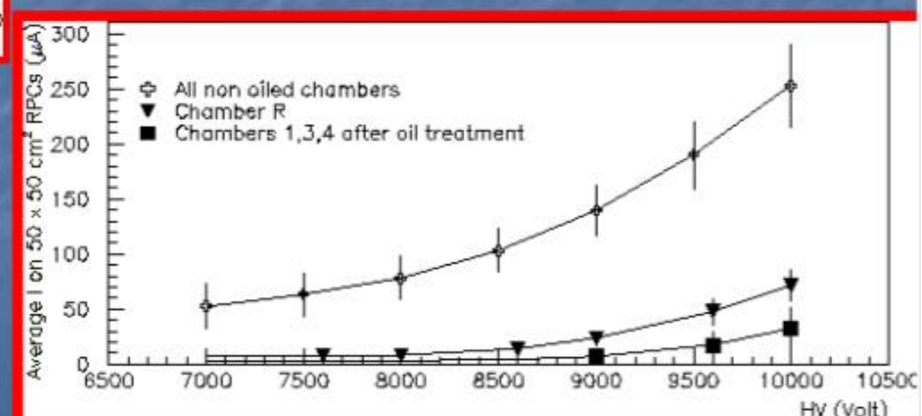


b)

RPC: the linseed Oil



Reduced Currents and Noise rate

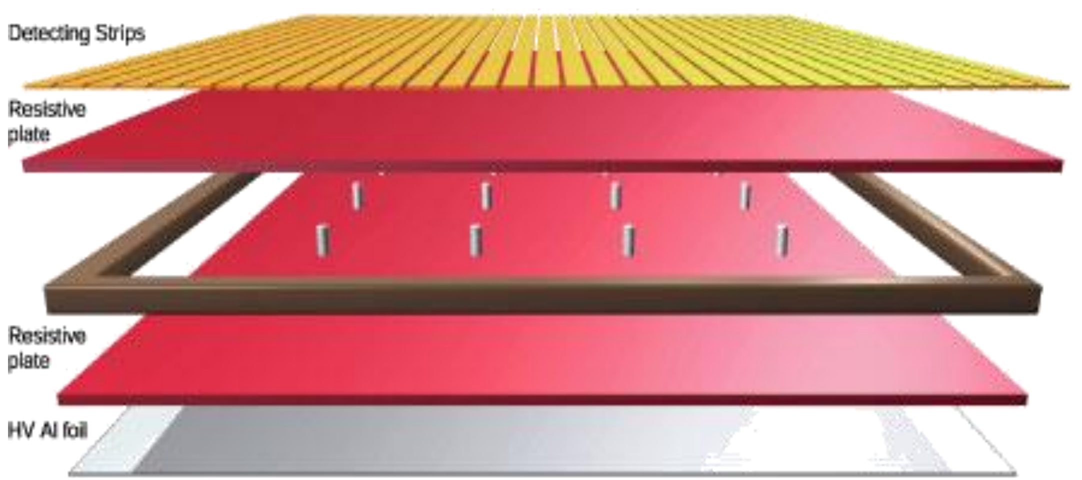


Applications of the 1st RPC generation

The first generation of RPC detectors has been used in several HEP experiments:

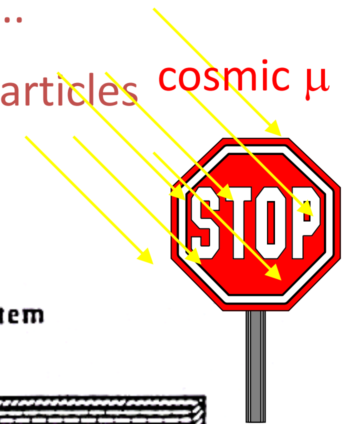
'85: Nadir – 120 m^2 (Triga Mark II – Pavia)
'90: Fenice – 300 m^2 (Adone – Frascati)
'90: WA92 – 72 m^2 (CERN SPS)
'90: E771– 60 m^2; E831 – 60 m^2 (Fermilab)
1994-1996: L3 – 300 m^2 (CERN-LEP)
1996-2002: BaBar – 2000 m^2 (SLAC)

Very large area of muon detection



Experiments using RPCs

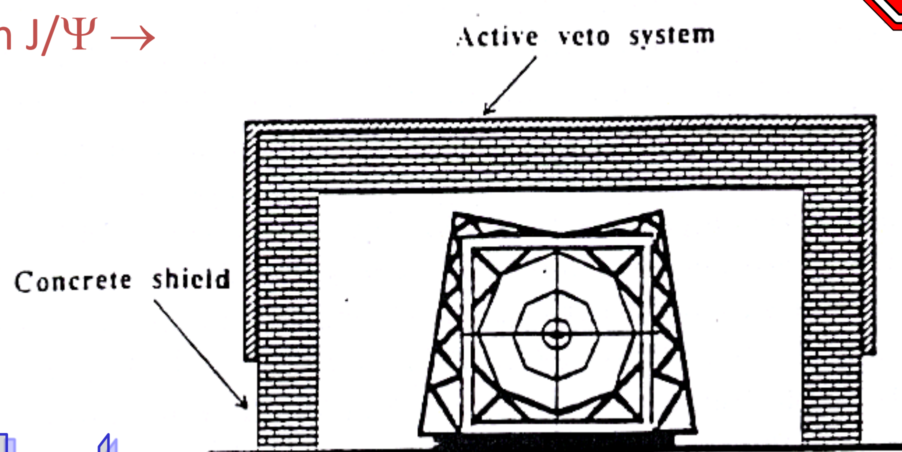
1st generation RPCs were immediately used in many physics experiments...



Veto

Nadir: 120 m^2 of double gap RPCs used as a veto on cosmic particles in an experiment on neutron-anti neutron oscillations

Fenice: 300 m^2 of RPC used as a cosmic vet in the reaction $J/\Psi \rightarrow$ n-n bar at Adone



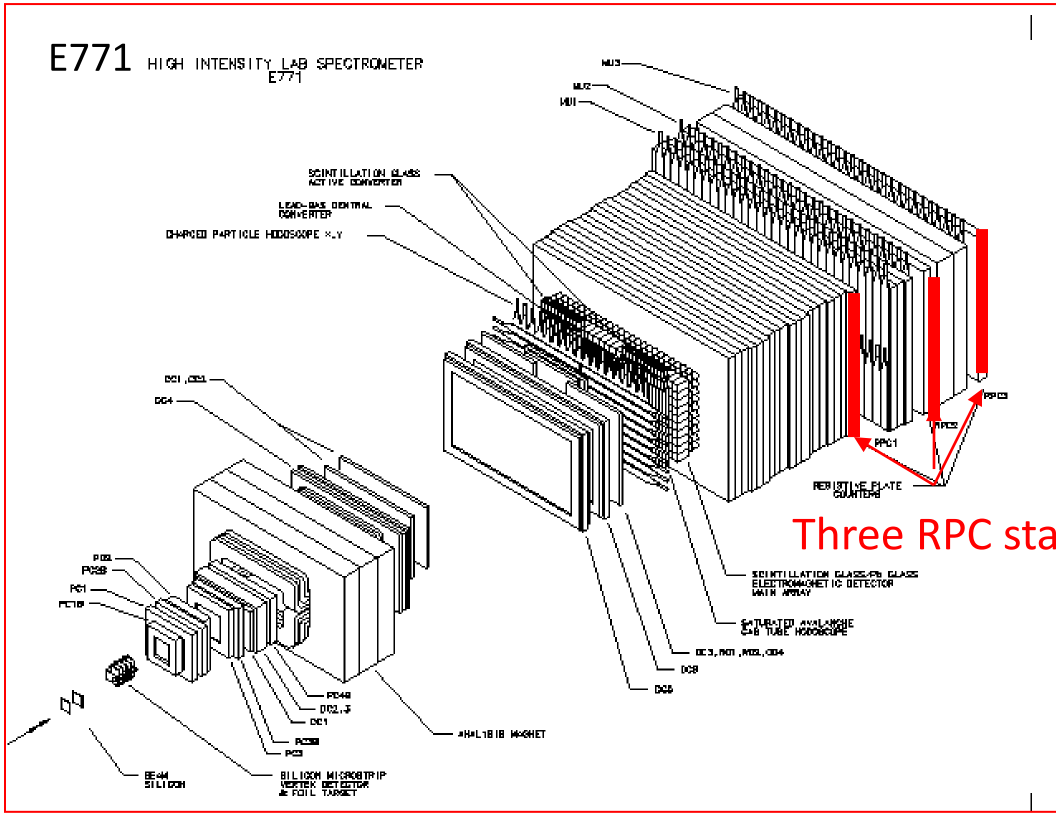
Operated in streamer mode
(Ar-isobutane-Freon)
HV 7-8 kV
Veto efficiency: 97-99%/plane

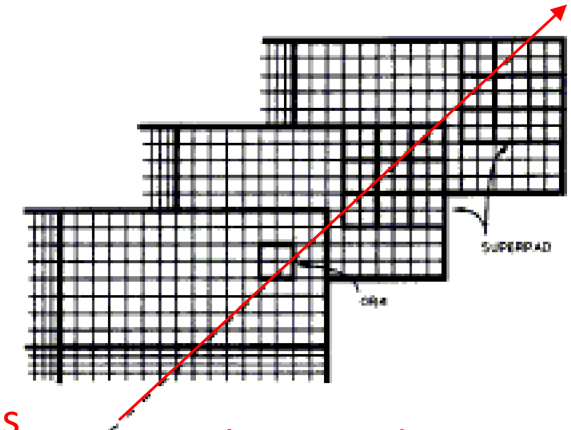
Trigger and tracking at accelerators

WA92: 72 m^2 of RPC used as trigger on μ events with high p_t in semi-leptonic decays of the B (SPS at CERN)

E771: 60 m^2 of RPC used as trigger and tracking come trigger on μ events with hig p_t in semi-leptonic decays of the B (Fermilab)

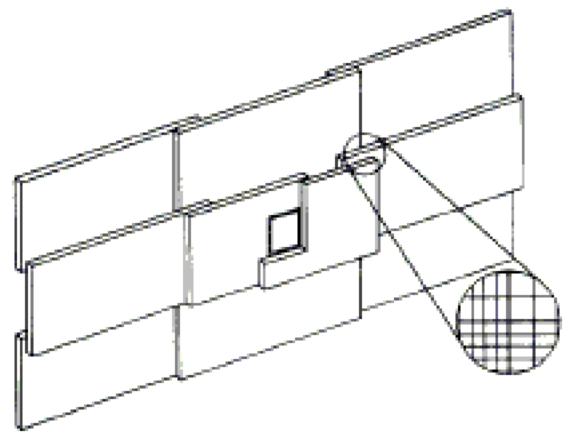
The E-771 experiment





A triple coincidence to identify and track μ

The RPC system did not cover the zone around the beam



Superimposed RPCs, with pad readout

Streamer mode (Ar-isobutane-Freon)
HV 8 kV
Maximum efficiency: 97%

ARGO-YBJ

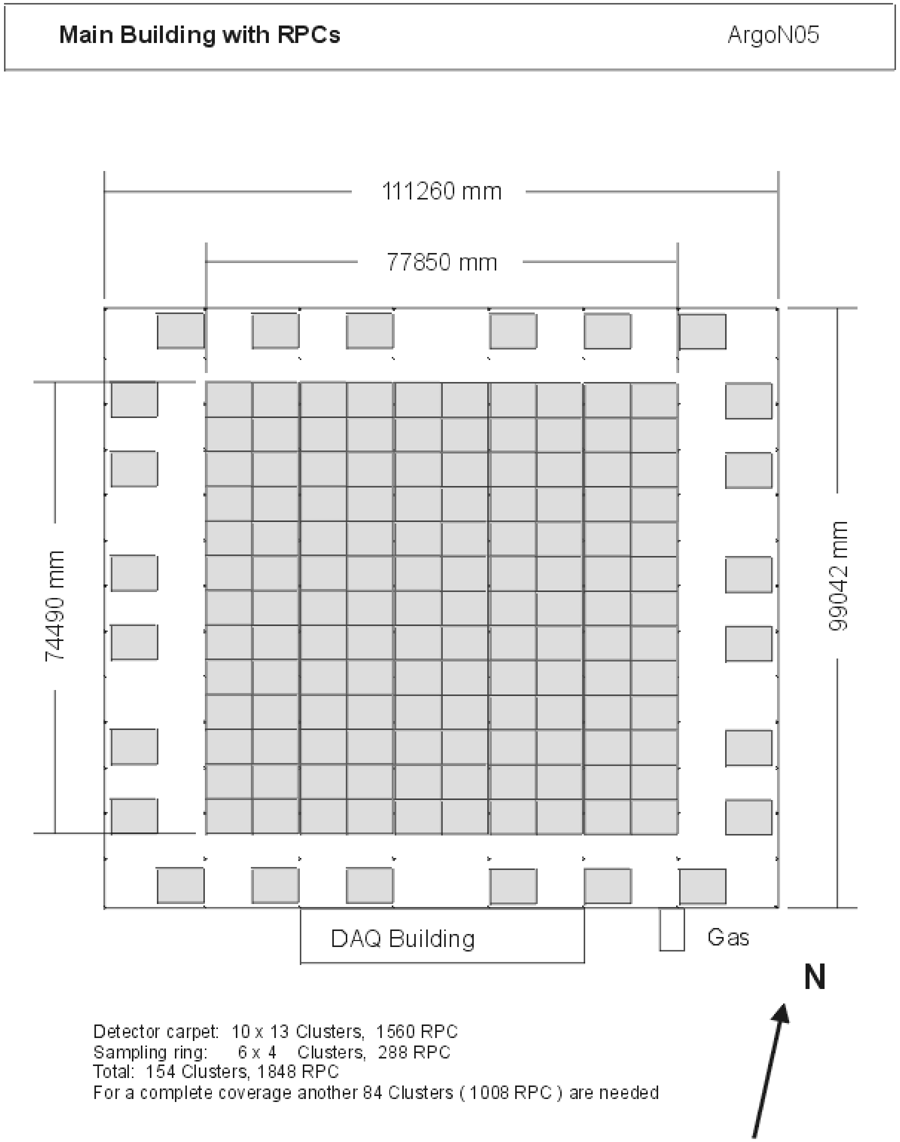
Argo Panopte (who sees everything) is described as being very strong, since he had 100 eyes and was capable to sleep with only 50 of his eyes closed-

ARGO-YBJ (Astrophisical Radiation with Ground based Observatory at YangBaJiing, Tibet) did never sleep.

Experiment to study with high efficiency and sensitivity Extensive Air Showers with energy > 100 GeV

- γ Astronomy ~ 100 GeV
- Diffuse γ rays
- γ-Burst
- Ratio p/p bar
- Spectrum of the primaries
- Physics of Sun and atmosphere

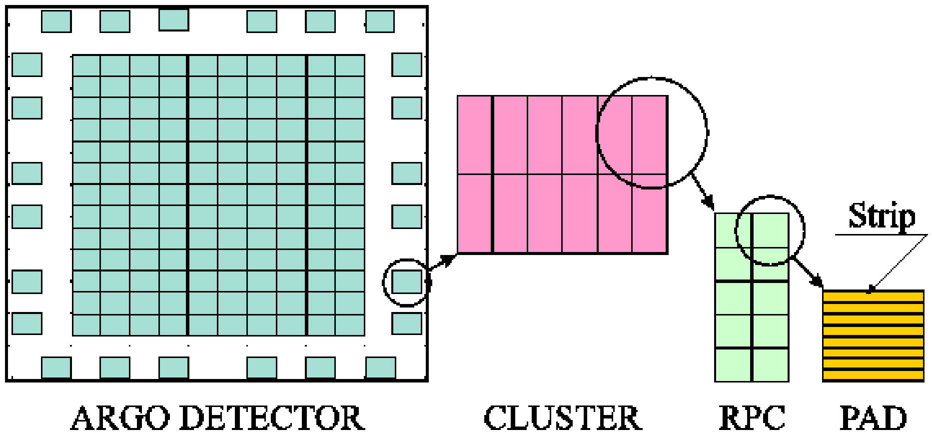
ARGO-YBJ



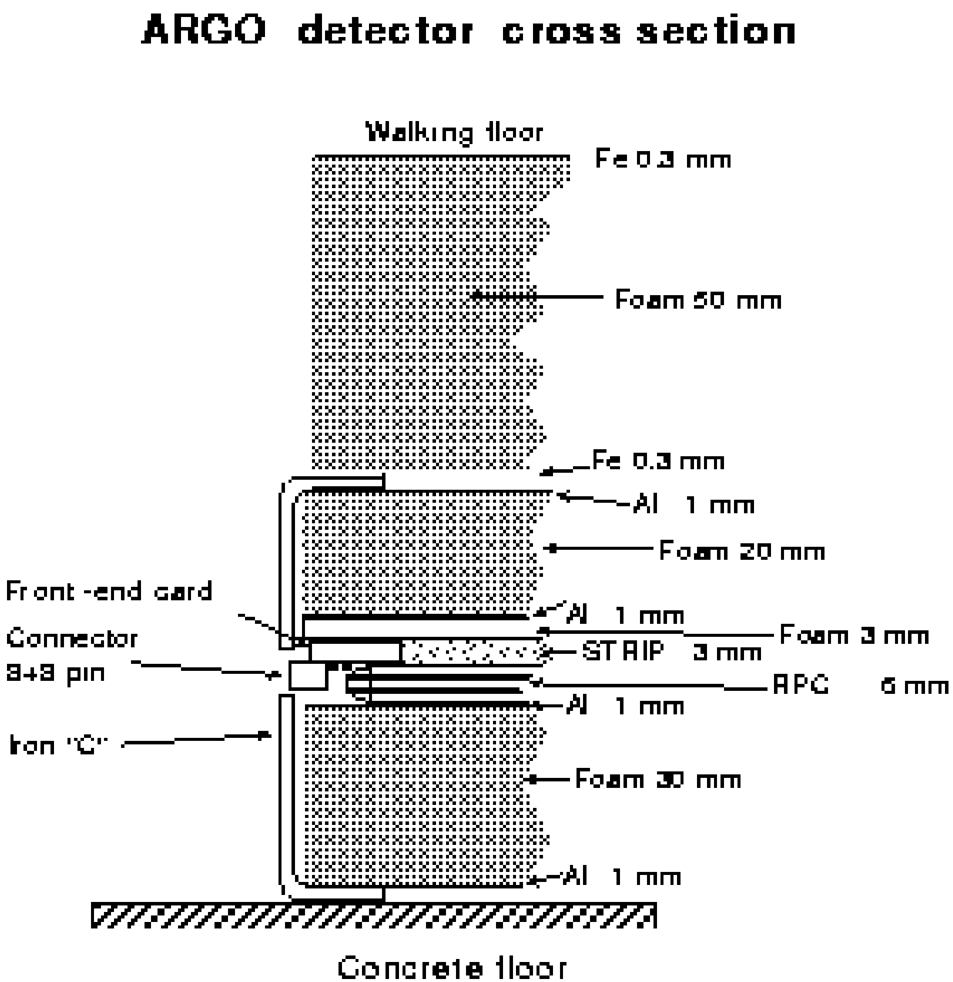
78 x 74 m^2 covered with RPCs

In addition a guard ring with partial cover up to 100 x 100 m^2

"RPCs chosen because their low cost, large active area, excellent time and spatial resolution, easy of integration as a large system."



ARGO-YBJ



Single gap RPCs
Volume resistivity > 5 10^{11} Ωcm
Area: 126 x 285 cm^2

Aluminium strips 6 x 56 cm

Fast-OR of16 strips defining a PAD

10 pads (56 x 60 cm^2) covering a chamber (in total 18480 pads)

Streamer mode

Gas:
15% Argon,
10% Isobutane
75% Tetrafluoroethane $C_2H_2F_4$

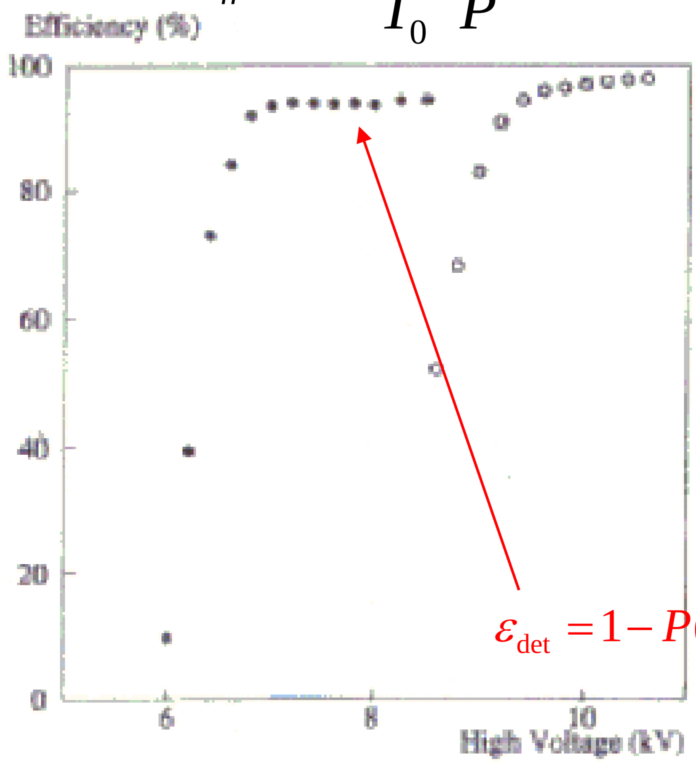
Use of converters to increase the number of hits/event.

ARGO-YBJ

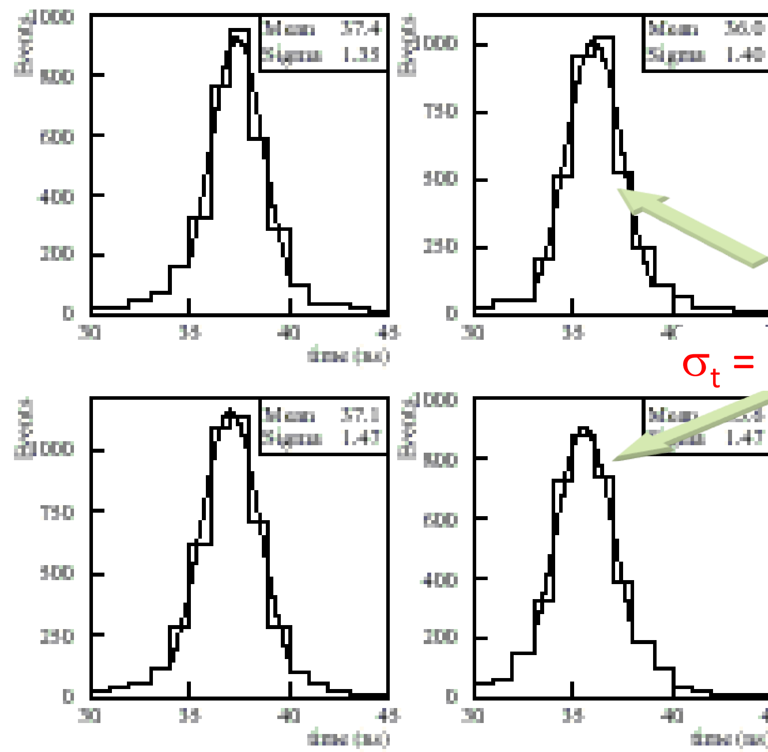
Operating at 4300 m above sea level

Low pressure ~ 600 mbar

$$V_{eff} = V_0 \frac{T}{T_0} \frac{P_0}{P}$$



$$\varepsilon_{\det} = 1 - P(0) = 1 - e^{-\bar{n}}$$

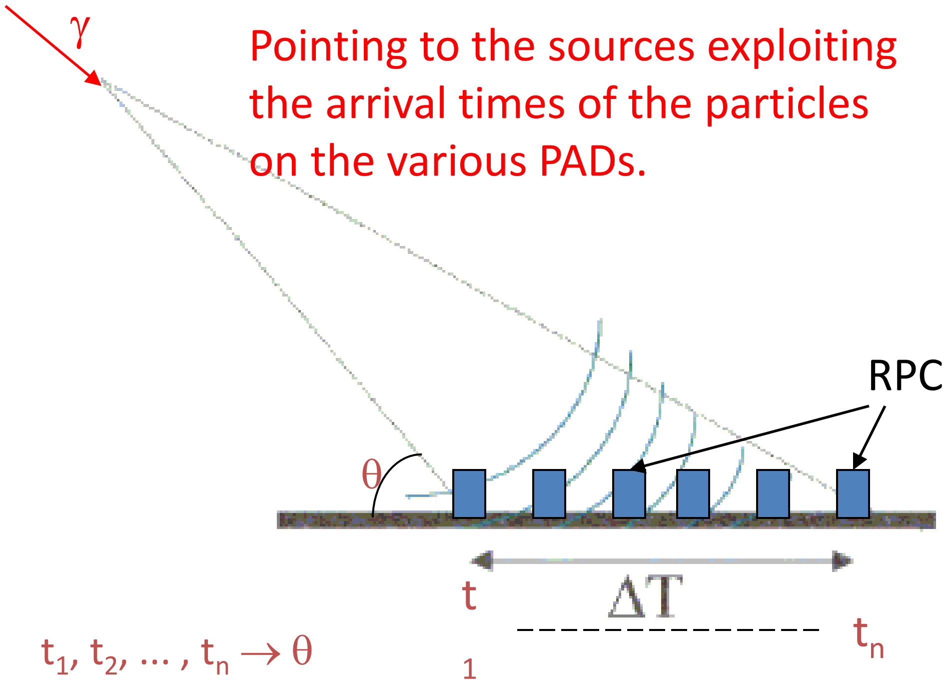


σ_t = 1.45 ns

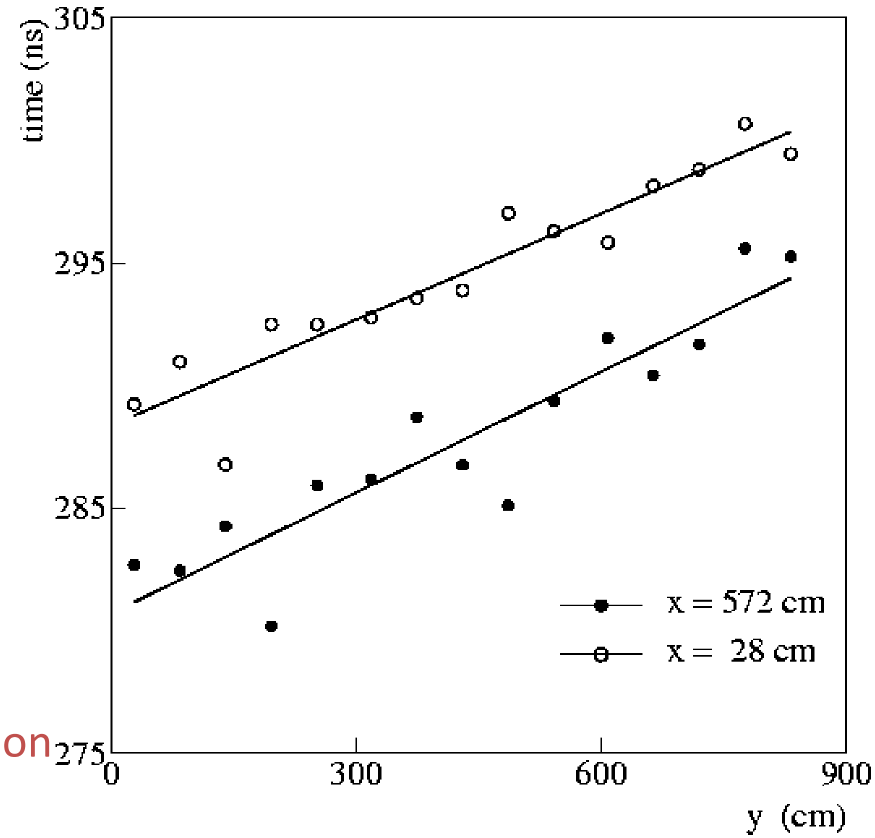
Time resolution

ARGO-YBJ

Pointing to the sources exploiting the arrival times of the particles on the various PADs.



$t_1, t_2, \dots, t_n \rightarrow \theta$

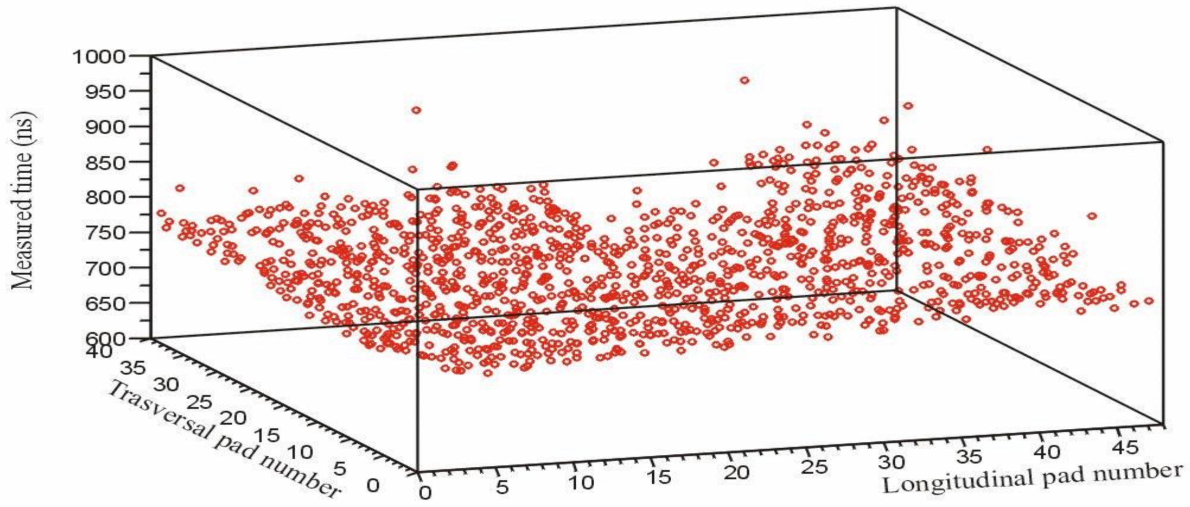


Interesting application where good time resolution is essential for a good tracking

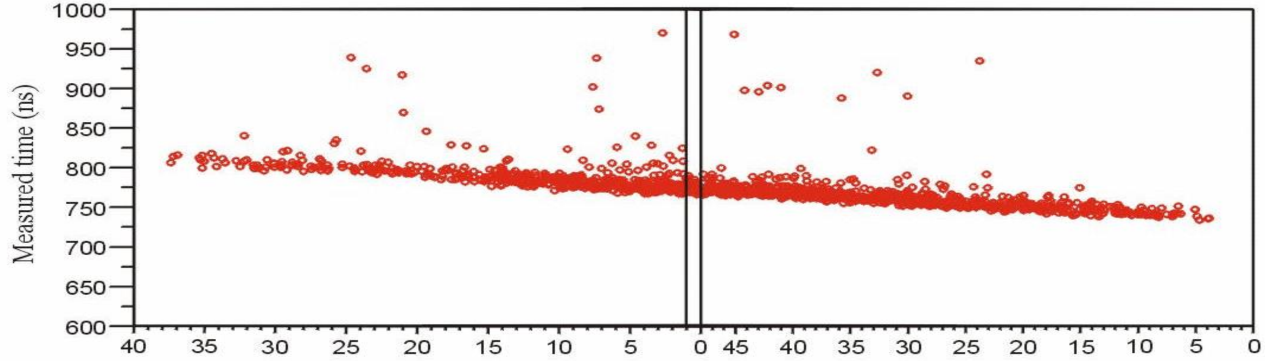
Δt_{RPC} ~ 1-2 ns $\rightarrow \Delta\theta$ = 1 mrad

$$\frac{Signal}{Background} \propto \frac{1}{(\Delta\theta)^2}$$

ARGO-YBJ



Picture of an event on 16 clusters



The same event from such a point of view
to appear as a plane

Significance of the fist generation of the RPC

Why the RPCs have been extensively used in several HEP experiments?

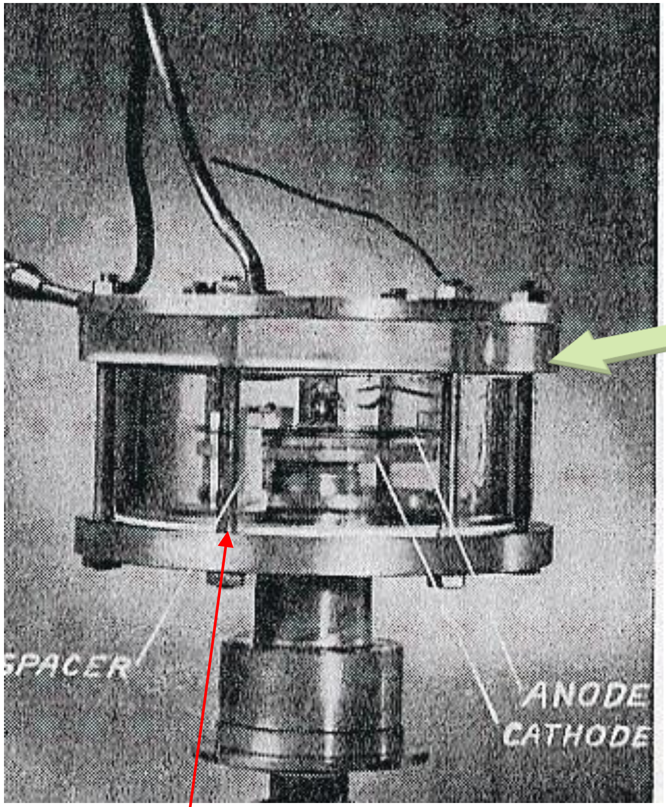
- **Golden parameter:** the time resolution (≈1 ns)
- **Good spatial resolution:** limited by strip dimensions
- **High muon efficiency** of the order of > 96% and **long term stability**
- **The cost** of RPC is much smaller as compared to other fast detector (like the scintillators)
- It is **easy** to construct and operate
- Simple signal pick up and readout system (just “strips”)
- Two dimensional readout (x and y)

BUT

rate capability < 50 Hz/cm^2

Le PPC di Madansky e Pidd

Sviluppati immediatamente dopo le PPC di Keuffel

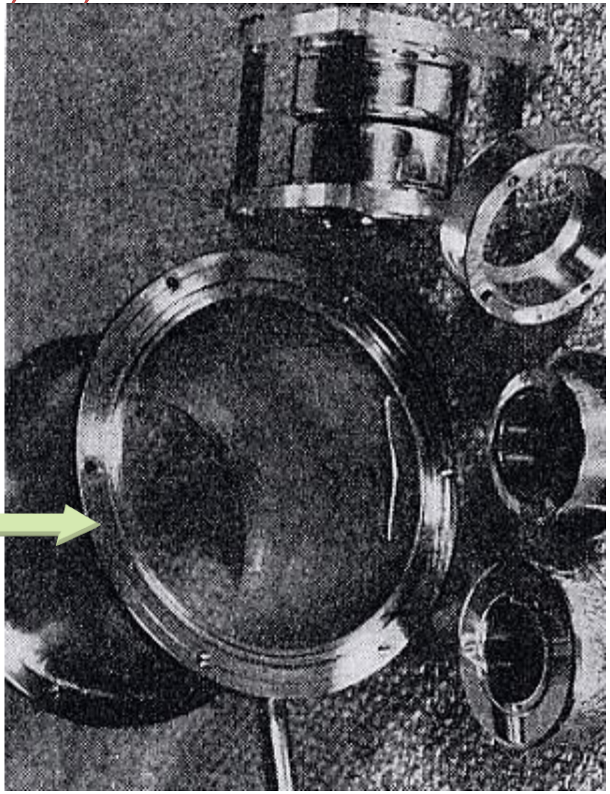


uso di spaziatori di materiale isolante

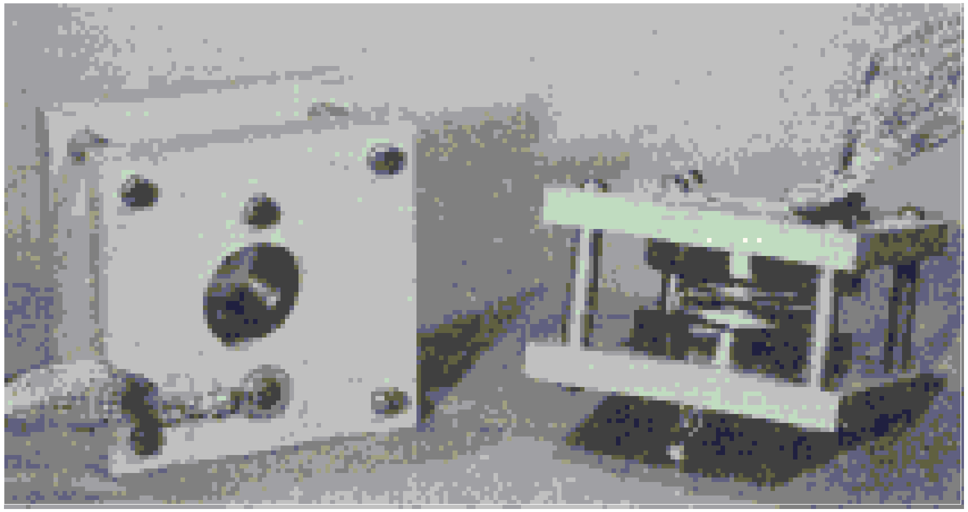
Elettrodi circolari
Anodo in Rame di dimensioni diverse: da 1 a 8 cm
Catodo in Cu, Al, Au, Pt, Pb, etc.

distanza tra gli elettrodi variabile tra 0.5 e 5 mm

Variante: entrambi gli elettrodi in fogli di rame, spessore 3 mm, tesi "come la pelle di un tamburo" su un'intelaiatura di qualche cm di di...



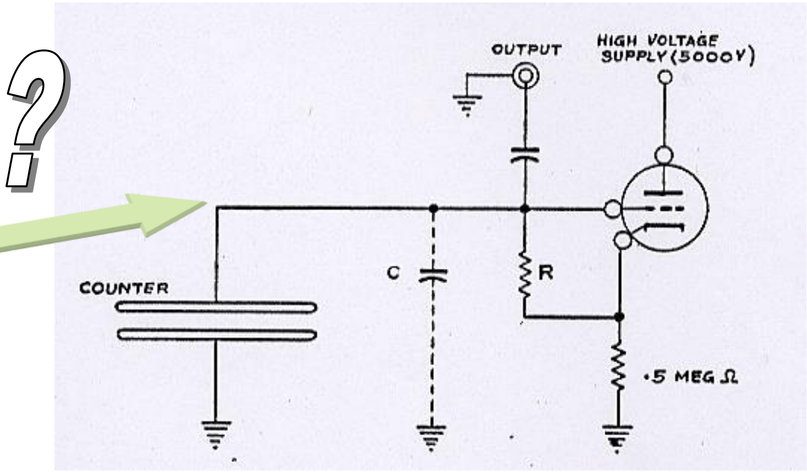
Le PPC di Madansky e Pidd



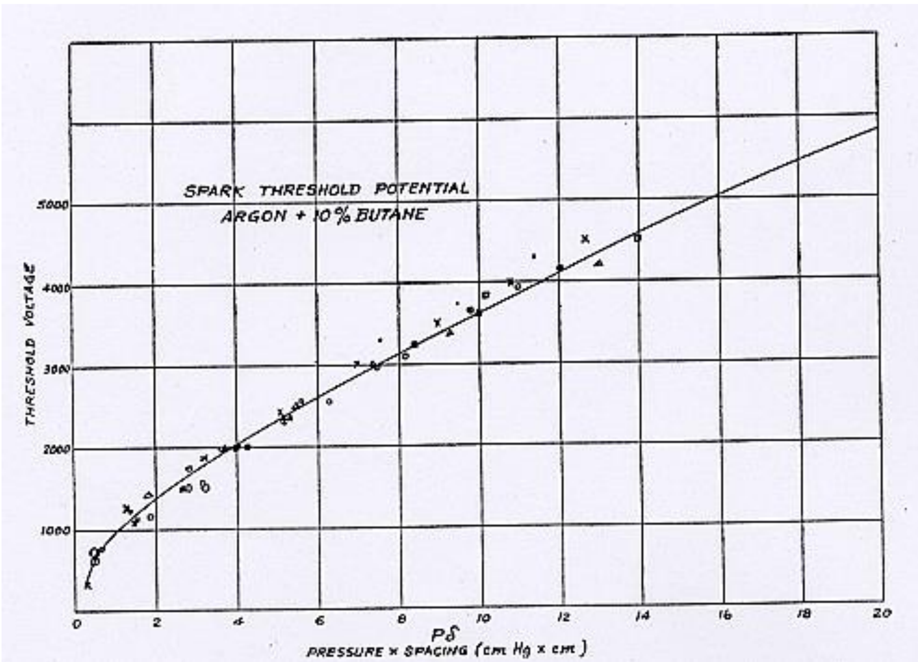
"il parallelismo degli elettrodi influisce sull'uniformita' del campo elettrico (dichiarato entro lo 0.2%), sulla massima sovratensione permessa, ed, in generale, sulle prestazioni dei rivelatori"

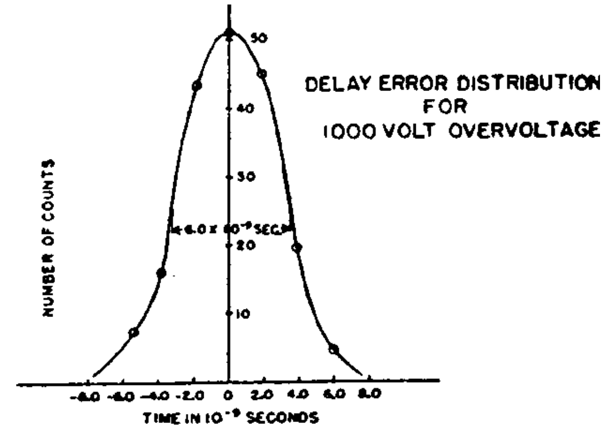
miscela: 90% Argon, 10% iso-butano
pressione: studio sistematico tra 10 e 150 mmHg

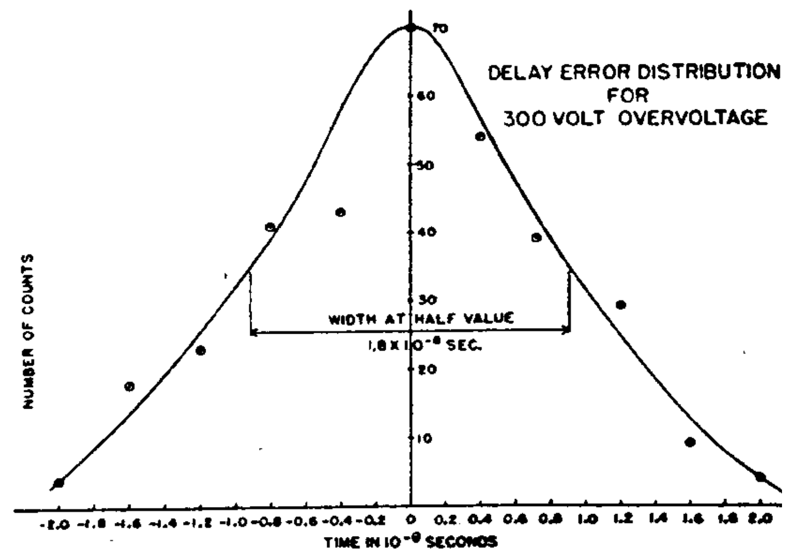
L'applicazione delle PPC passera' attraverso lo sviluppo di elettronica sempre piu' sofisticata: sia per le lettura del segnale, che per l'accegnimento-spegnimento del rivelatore



Le PPC di Madansky e Pidd







Prestazioni:

- segnali: ~ 100 V (su 50 Ω)
- periodo di spegnimento: 0.1 - 0.001 s
- efficienza ~ 98% per particelle β
- risoluzione temporale: 6-18 ns, per sovratensione tra 300 e 1000 V

Il problema del "quenching" (3)

• Al contrario di cio' che avviene nei rivelatori a filo centrale, nei rivelatori a piani paralleli, una scarica perdura fino a quando la tensione applicata dall'esterno non viene in qualche modo rimossa.

• L'intero volume del rivelatore e' attivo nei riguardi dello sviluppo di una scarica; essa tendera' a propagarsi verso l'esterno mediante fotoionizzazione UV e ionizzazione secondaria.

•Anche gli elettrodi contribuiscono a questo effetto: elettroni ritardati vengono emessi dal catodo, sui cui viene raccolta la carica positiva in ~ 100 µs (after effect).

Quanto rapidamente puo' essere ristabilita la HV fra gli elettrodi del rivelatore, dopo la scarica, senza causare conteggi spuri?

Si puo':

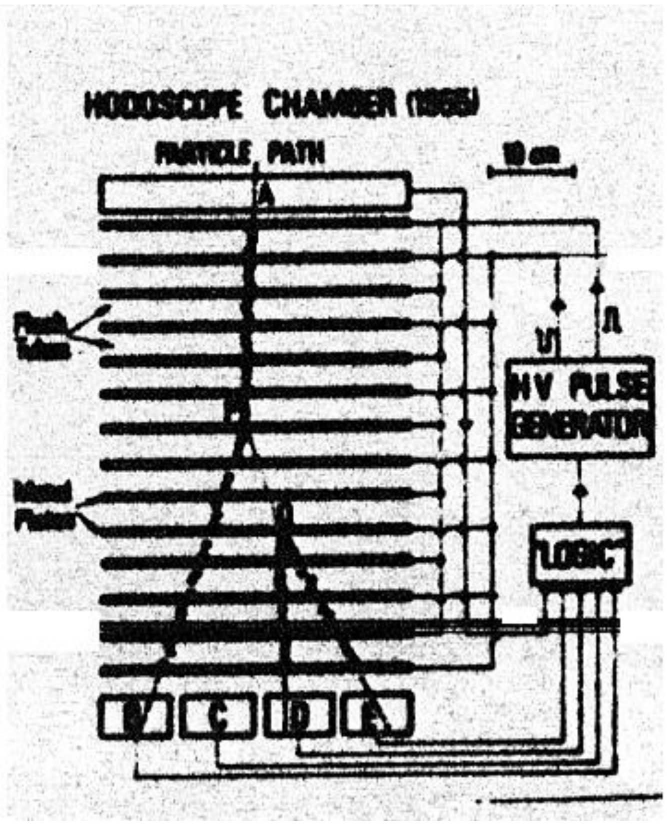
1. Dopo il passaggio di una particella ionizzante, rimuovere la tensione applicata per un certo tempo (0.01 - 0.05 s) → circuiti di spegnimento (Franzinetti e Bella, Focardi, Torelli, Rubbia ...)

2. Applicare la tensione solo in coincidenza con il passaggio della particella ionizzante

La frequenza massima di rivelazione delle particelle e' quindi limitata: devo evitare le spurie ed, inoltre, il tempo di ricarica e' correlato alla costante di tempo RC del sistema (compresi i piatti ...)

Le camere a Flash

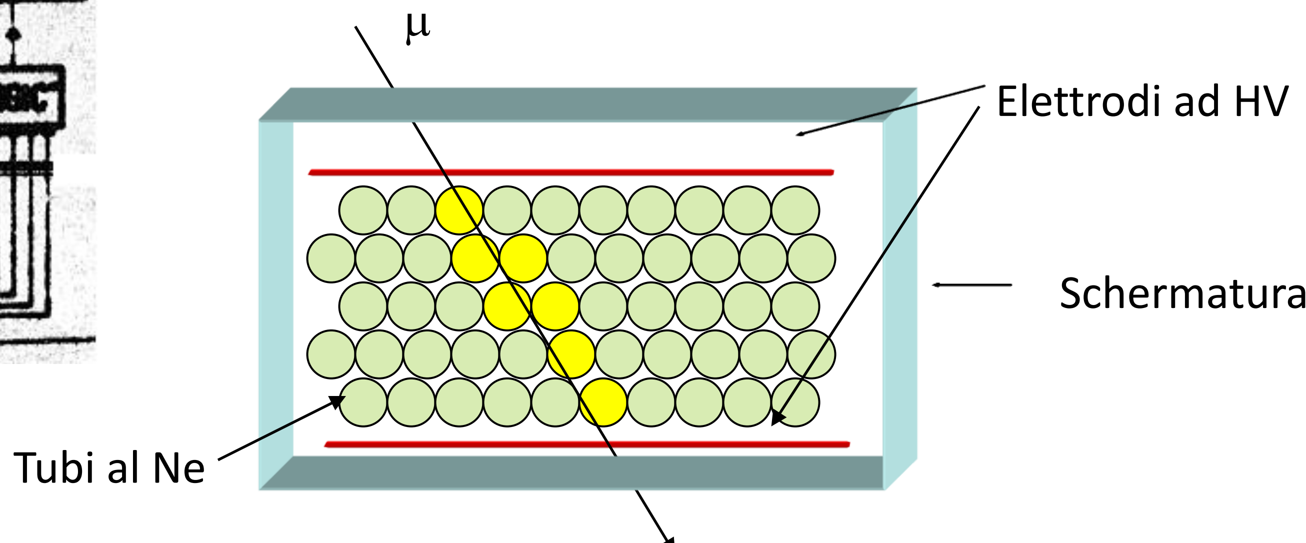
Sviluppate a Pisa dal gruppo di M. Conversi, attorno al 1955



Condensatore a piani paralleli riempito da un gran numero di tubi di vetro, diametro ~ 1 cm, senza filo centrale

Miscela di Ar o Ne a 0.5 Atm

Qualche decimo di μs dopo il passaggio della particella, applicazione di 10 kV/cm agli elettrodi di metallo, per 2 μs



Elettronica molto sofisticata

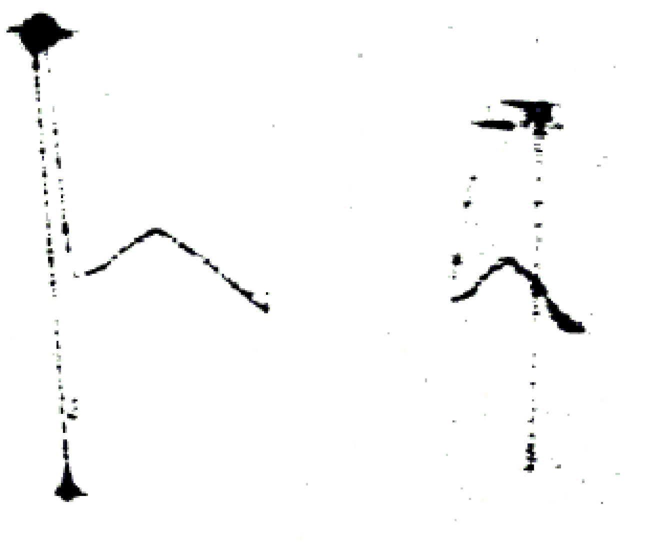
Le camere a Flash

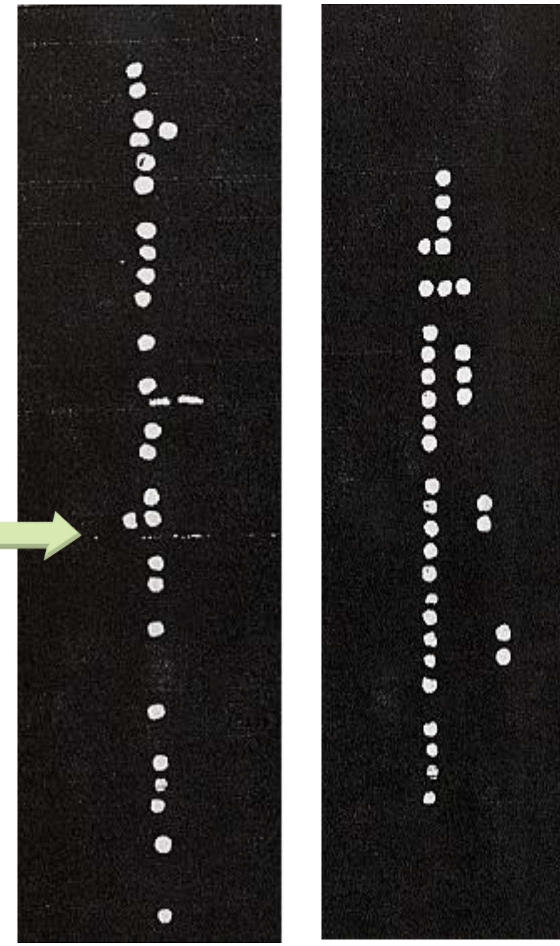
A causa della presenza del campo elettrico applicato nella regione fra le armature, sincronizzato con il passaggio di una particella ionizzante, si origina una scarica, accompagnata da emissione luminosa: gli elettroni prodotti nella valanga “accendono il neon”

Gran numero di tubi, disposti perpendicolarmente

ricostruzione 3D della traccia

Prime fotografie di μ cosmici o sciami elettromagnetici



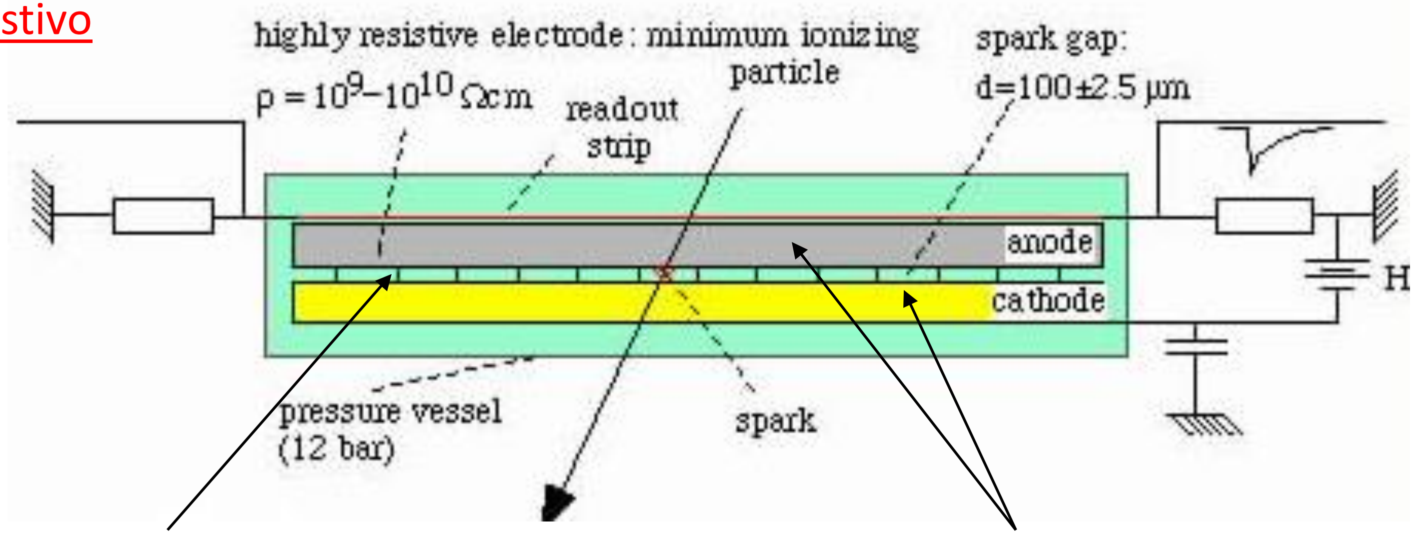


μ cosmico γ→e^+e^-

Le Planar Spark Chambers

Sviluppate da Yu. Pestov attorno al 1970, ed ancora usate attualmente

Le prime camere in cui uno degli elettrodi e' costituito non di metallo, ma da materiale resistivo



Gap tra 100 µm ed 1 mm, con una precisione di 1-5%

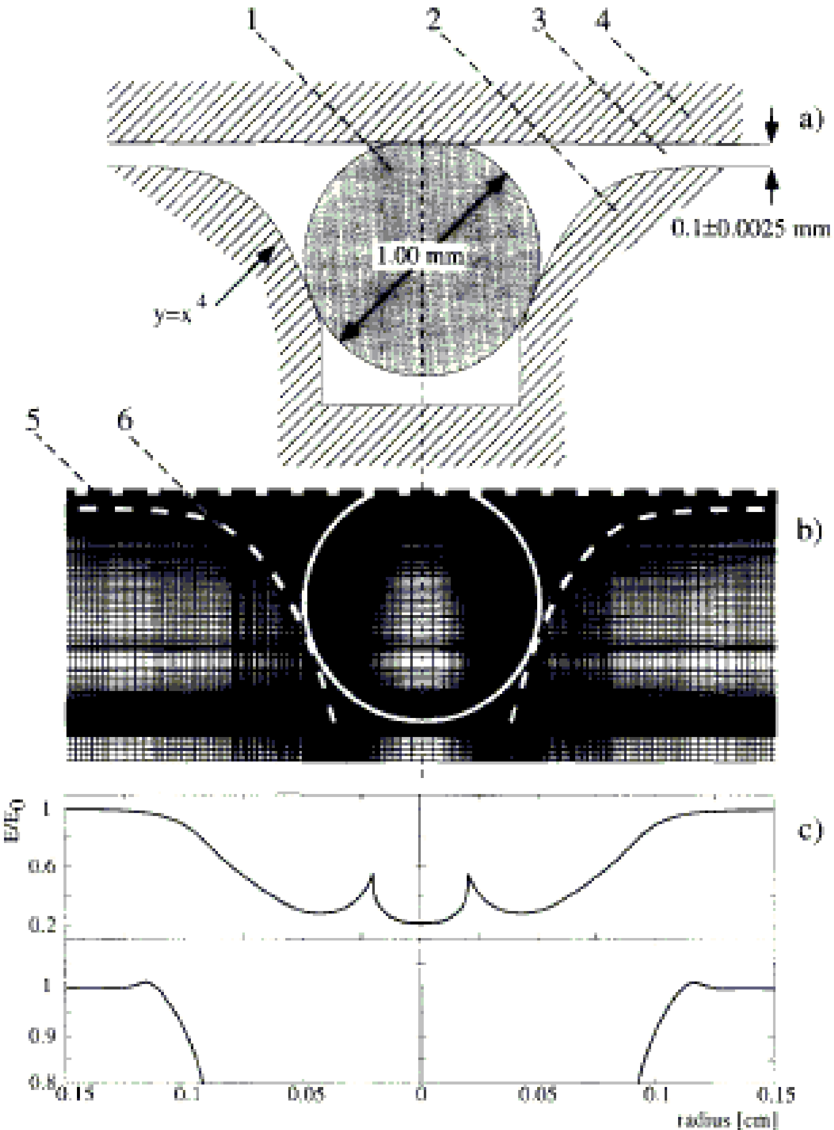
Elettrodi: catodo di vetro con pellicola di rame di 3 µm
anodo di vetro semiconduttore $\rho = 10^9 - 10^{10}$ Ωcm

Campo elettrico 2×10^4 V/cm

Risoluzione temporale ~ 50 ps

Miscela di gas a 10 Atm:
Argon-Neon, piu' gas di quenching (isobutano, etilene, butadiene, idrogeno, etere dietilico).

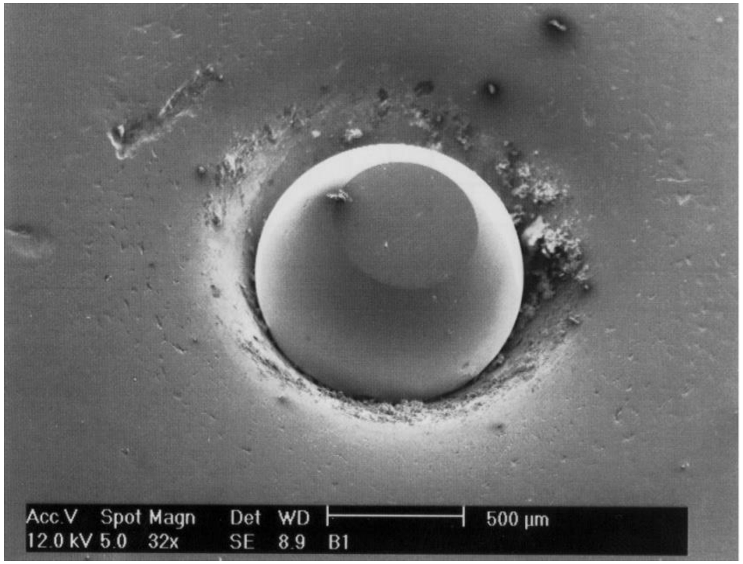
Le Planar Spark Chambers



Rivelatori "meccanicamente" <u>estremamente critic</u>

Poiche' il parallelismo e' critico:
Studio degli spaziatori molto accurato: possono perturbare il campo elettrico in maniera sostanziale

Foto di uno spaziatore in un catodo di Al



Le Planar Spark Chambers

Trattamento delle superfici degli elettrodi:

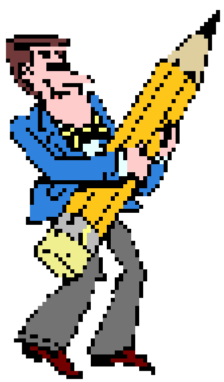
• pulizia con ossido di cerio ed acqua filtrata e deionizzata

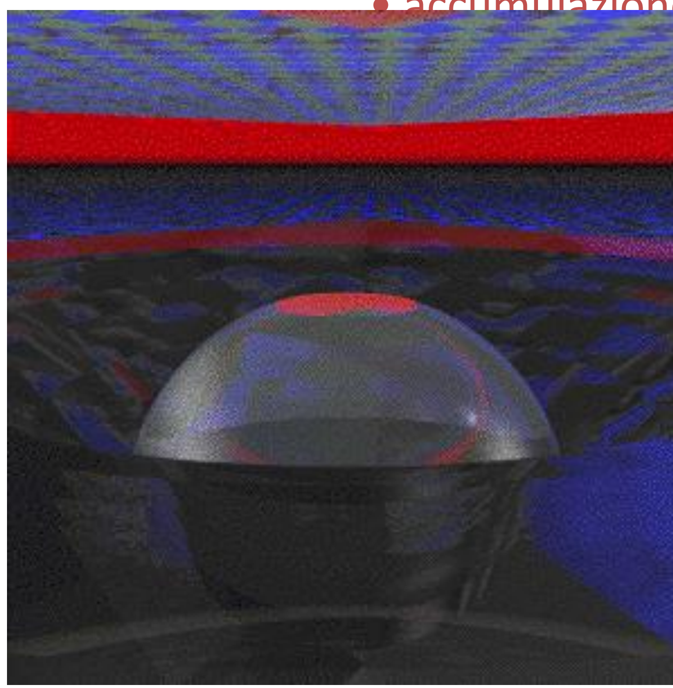
• uso di effetti di interferenza sulle superfici per individuare imperfezioni

Condizionamento:

• per una settimana si aumenta gradualmente la tensione di lavoro mentre il rivelatore e’ esposto ad una sorgente

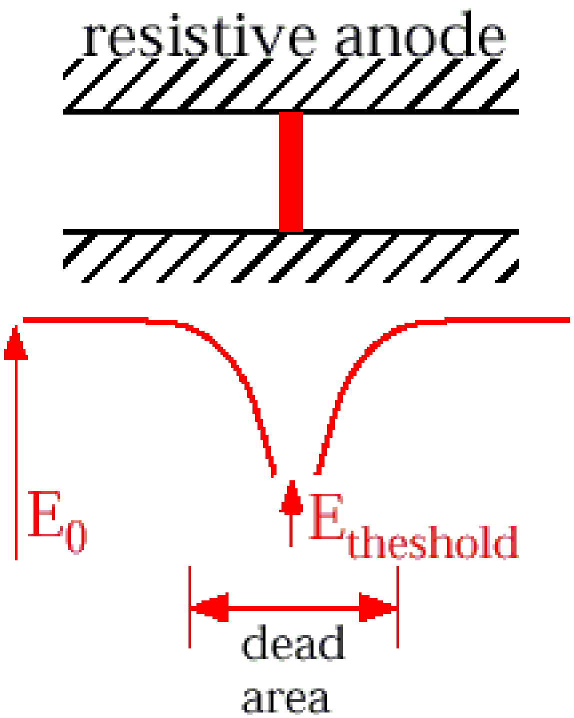
• accumulazione di 10^6 scintille per cm^2
pellicola di gas
gli elettrodi



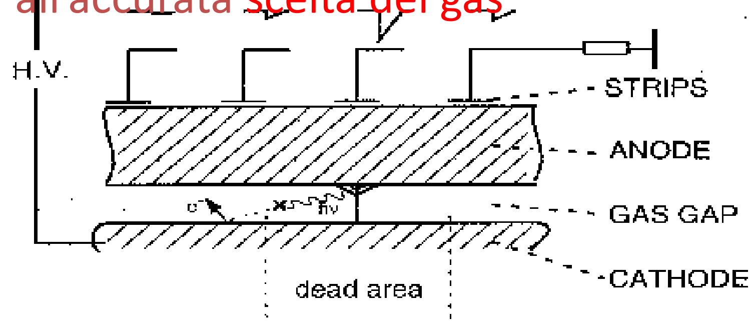


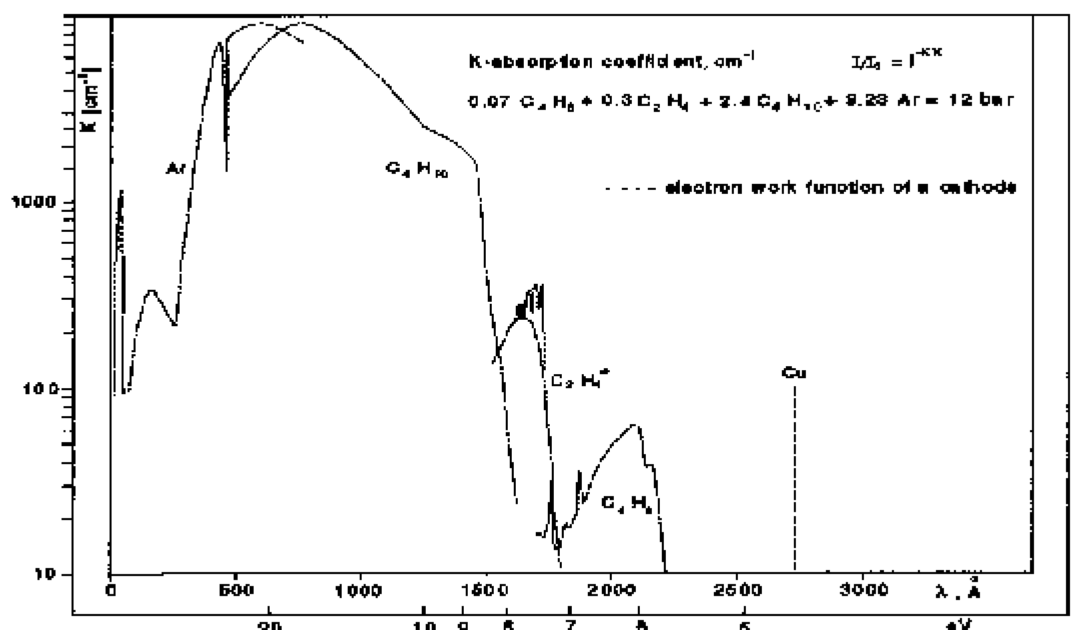
Veduta “d’artista” di uno spaziatore

Le Planar Spark Chambers



La scarica rimane (piu' o meno) localizzata grazie agli elettrodi resistivi e all'accurata scelta del gas

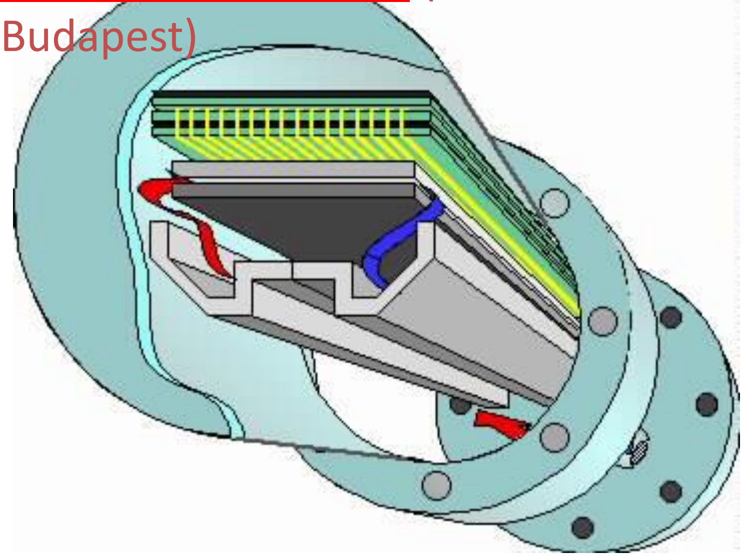


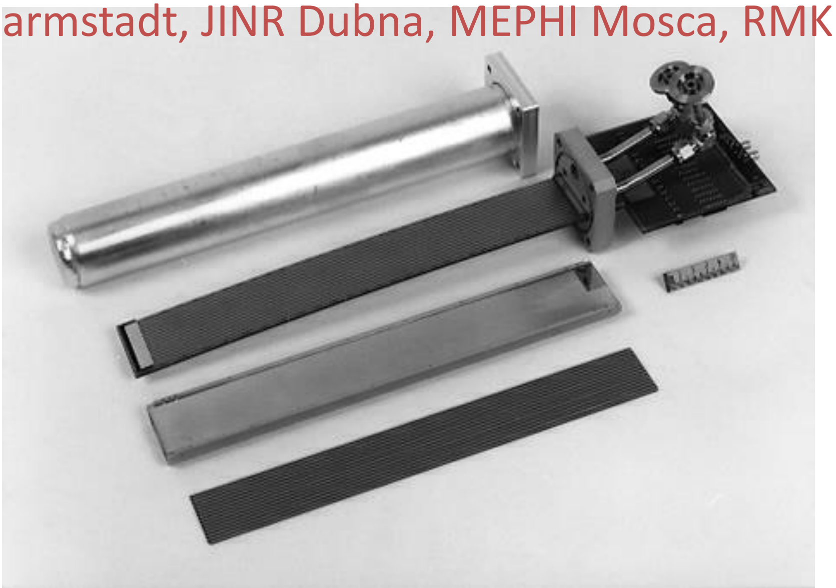


Poiche' il tempo di ricarica dell'elettrodo e' "grande" solo una zona limitata di esso viene interessata dal processo di scarica

Le Planar Spark Chambers

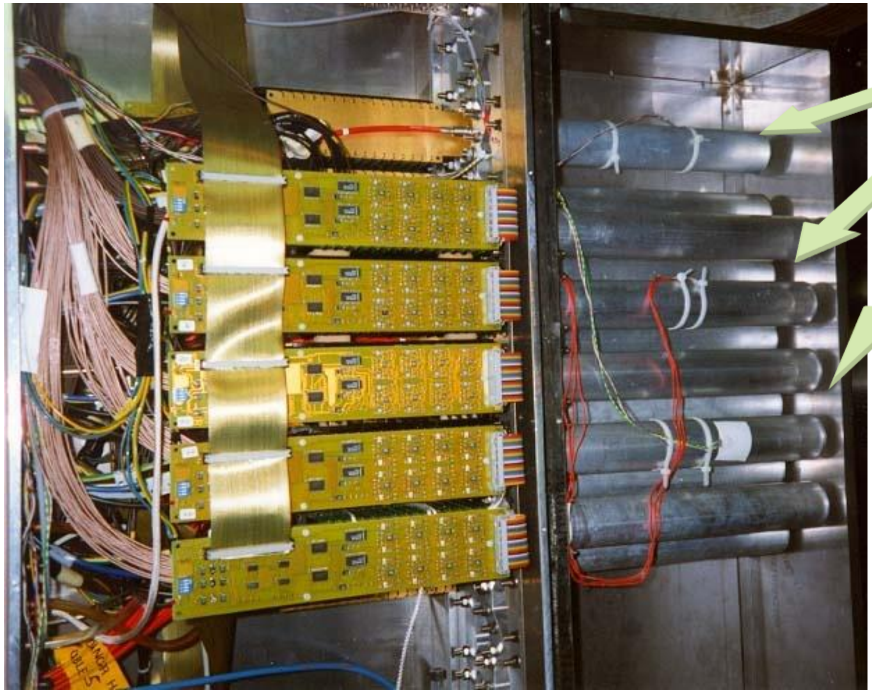
Idea di spark counters con scarica localizzata: Novosibirsk, 1971
prima applicazione ai collider e^+e^-: Novosibirsk 1982-85
continuazione dell'R&D ai collider e^+e^-: Novosibirsk, SLAC 1986-91
sviluppo degli spark counters (Pestov spark counters) per esperimenti con ioni pesanti:
PesTOF collaboration (BINP Novosibirsk, GSI Darmstadt, JINR Dubna, MEPHI Mosca, RMKI Budapest)



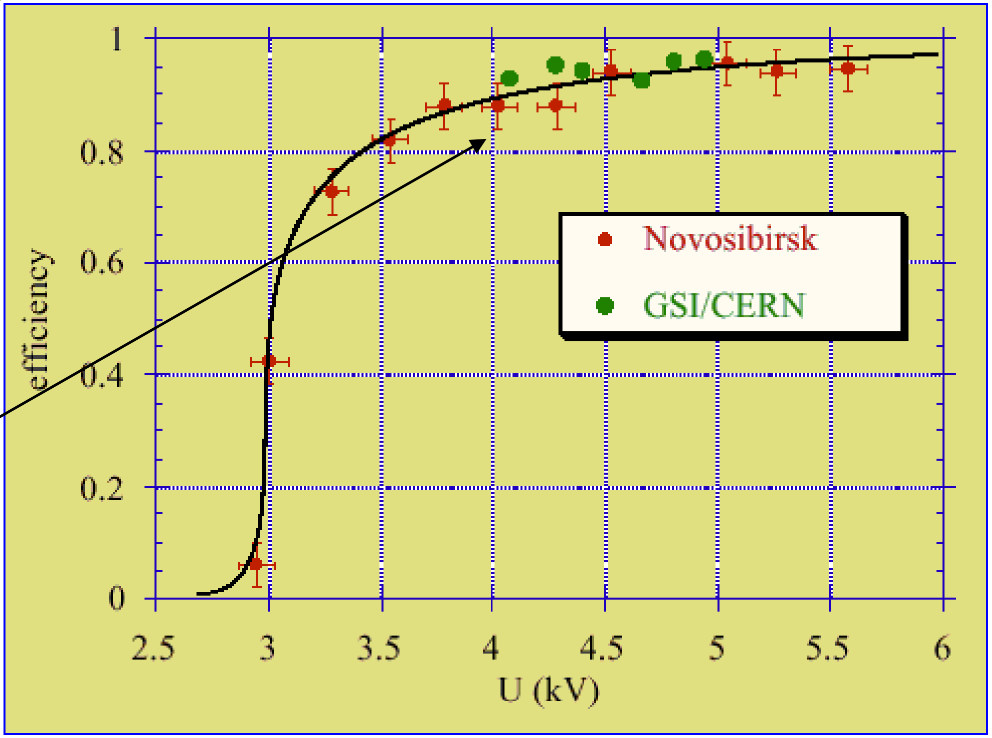


Attualmente tre grandi esperimenti hanno preso in considerazione l'uso di un grande array di spark counters:
ALICE, NA49 (CERN-SPS), FOPI al GSI

Le Planar Spark Chambers



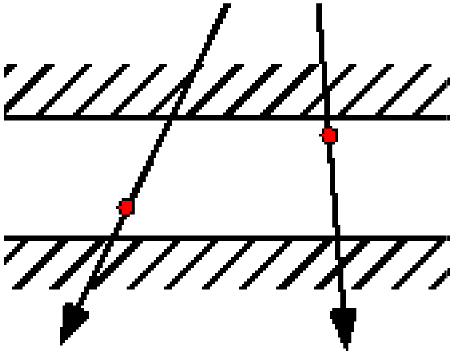
Una serie di 14 PSC ad NA49 al CERN



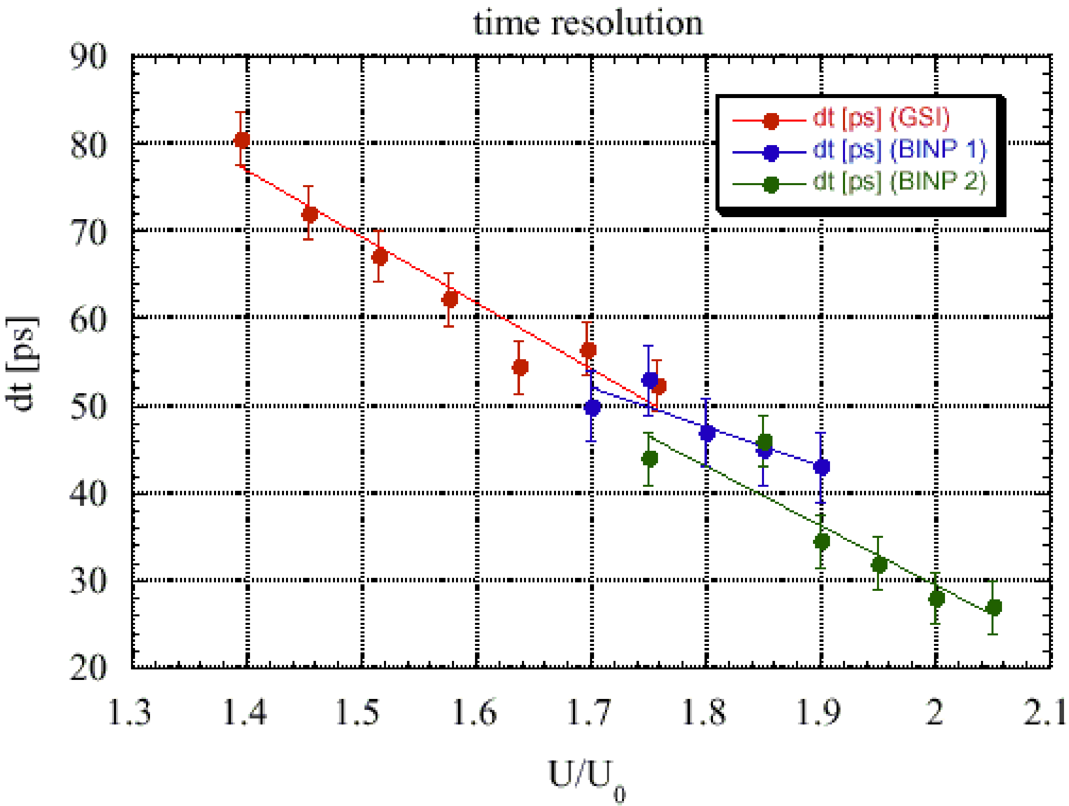
Efficienza elevata grazie al fatto che ci sono Almeno 4-5 coppie ione-elettrone nella gap (a 12 Atm)

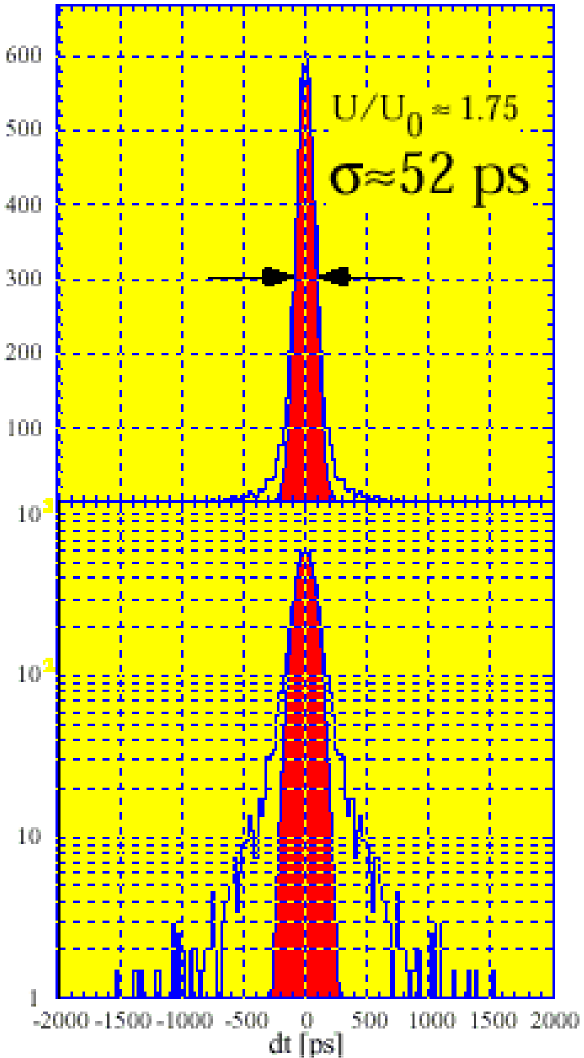
$$\varepsilon_{det} = 1 - P(0) = 1 - e^{-\bar{n}}$$

Le Planar Spark Chambers



Risoluzione temporale legata al **tempo di transito** della particella nella gap ~ ps





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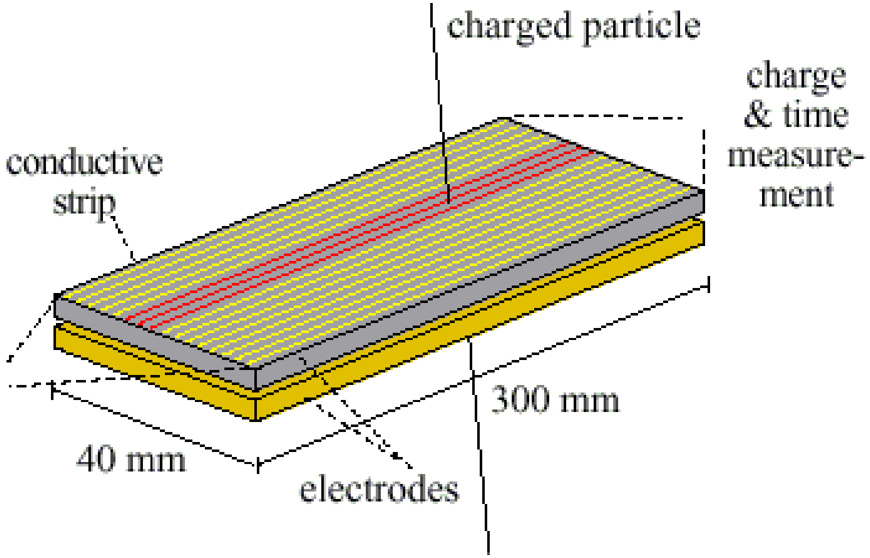
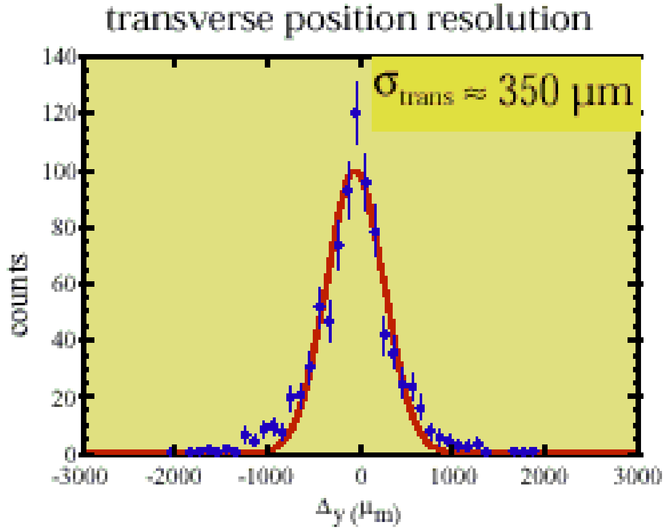
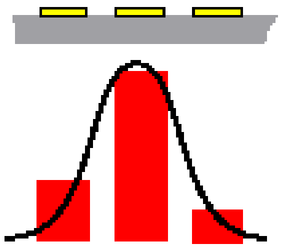
Otranto, Serra degli Alimini, 20-26 Settembre 2004

Le Planar Spark Chambers

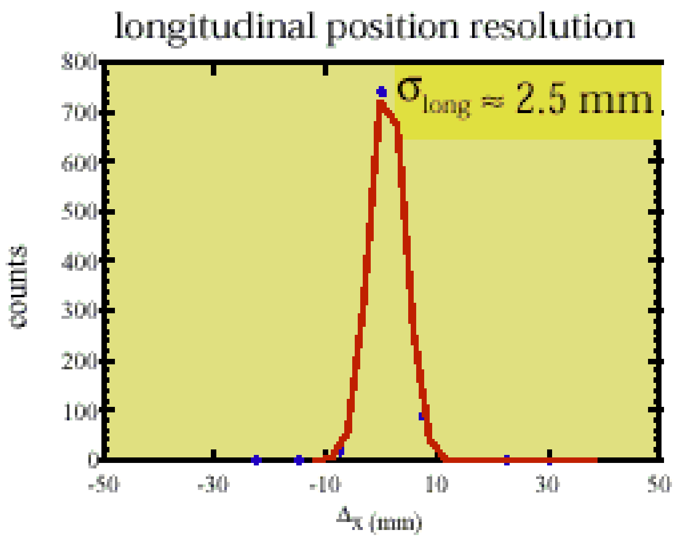






Posizione trasversale dalla media pesata della carica misurata sulle varie strip

Posizione longitudinale determinata dalla differenza dei tempi destra-sinistra (limitata dalla risoluzione temporale



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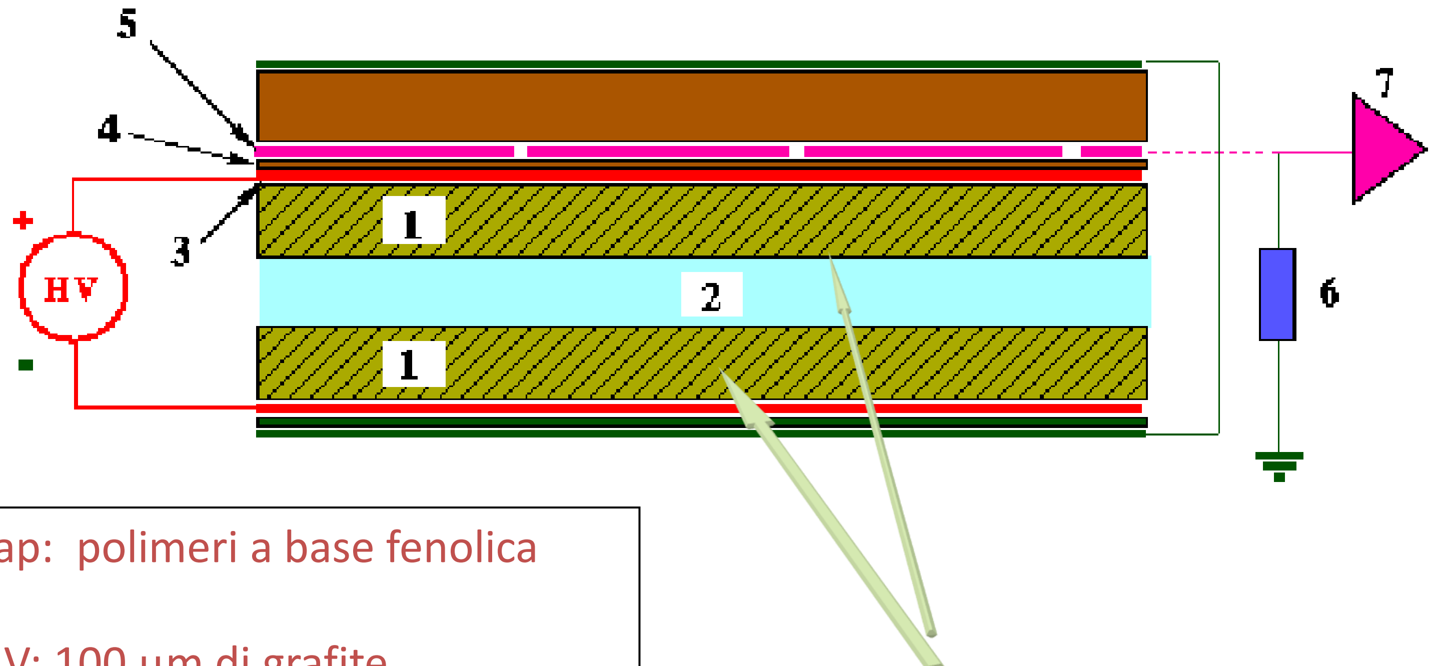
Finalmente ... Gli RPC

Sviluppati all'inzio degli anni '80 da R. Santonico (Roma)



bakelite di resisitivita' 10^{10}- 10^{12} Ωcm
trattata con olio di lino

- Piani della gap: polimeri a base fenolica
- Gap: 2 mm
- Elettrodi di HV: 100 μm di grafite
- Pressione di funzionamento: ~ 1 Atm
- Miscela di gas: 70% Ar, 29% iso-Butano, 1% Freon
- Gas flow: 0.1 vol/ora
- Dimensioni: Area: 1 x 2 m^2
  Spessore: 6 mm
- Strip di lettura in Al o Cu: larghe 1-3 cm

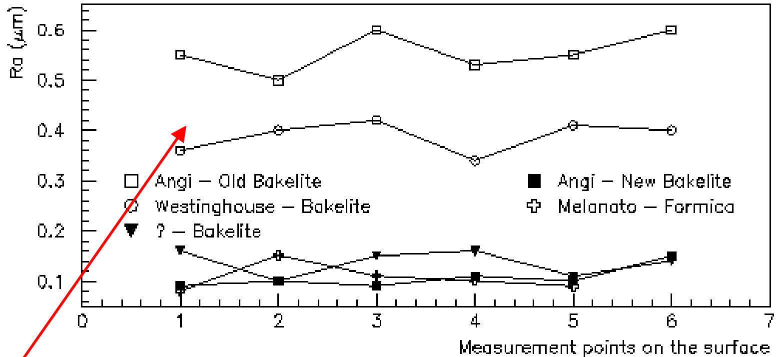
Finalmente ... Gli RPC

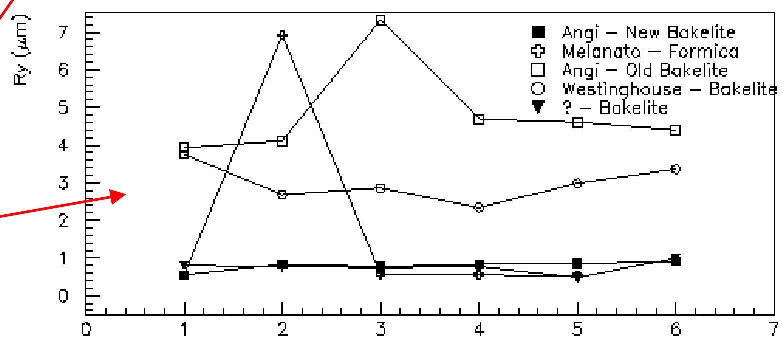
Paragone con gli scintillatori (R. Santonico):

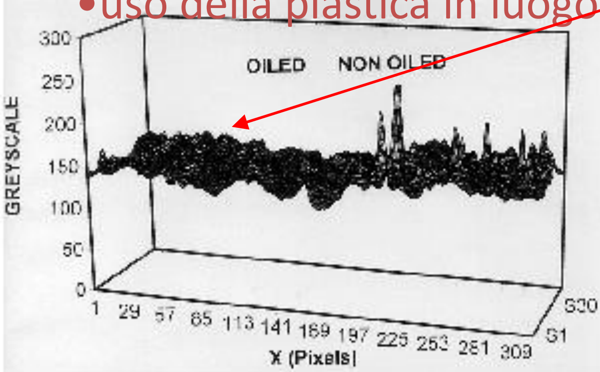
- RPC meno costosi (10^5 lire/m^2)
- Risoluzione temporale comparabile (1ns)
- Elettronica semplice
- Trasmissione del segnale su strip di lettura, cioe' bassa attenuazione su lunghe distanze
- Risoluzione spaziale determinata dalla dimensione delle strip (1-3 cm)

Rispetto alle PSC:

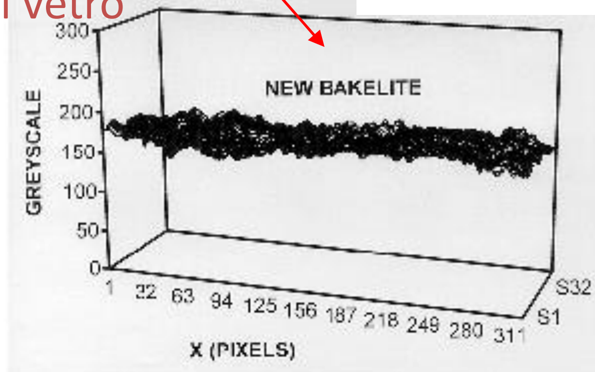
- assenza di gas ad alta pressione
- bassi requisiti di precisione nella meccanica
- uso della plastica in luogo del vetro







a)



b)

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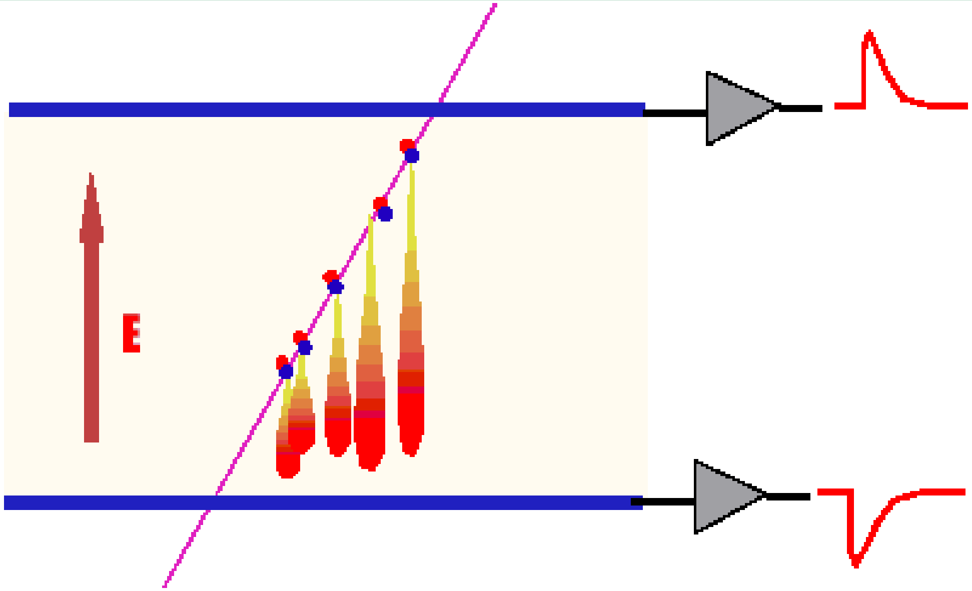
Regimi di funzionamento



Nel caso dei contatori a piani paralleli (e quindi anche degli RPC) la moltiplicazione della carica avviene in un campo elettrico uniforme

La grandezza della valanga dipende dalla distanza dall'anodo

Non e' un contatore proporzionale

Il segnale e' indotto sugli elettrodi di lettura

SPARK COUNTER

RESISTIVE PLATE CHAMBERS

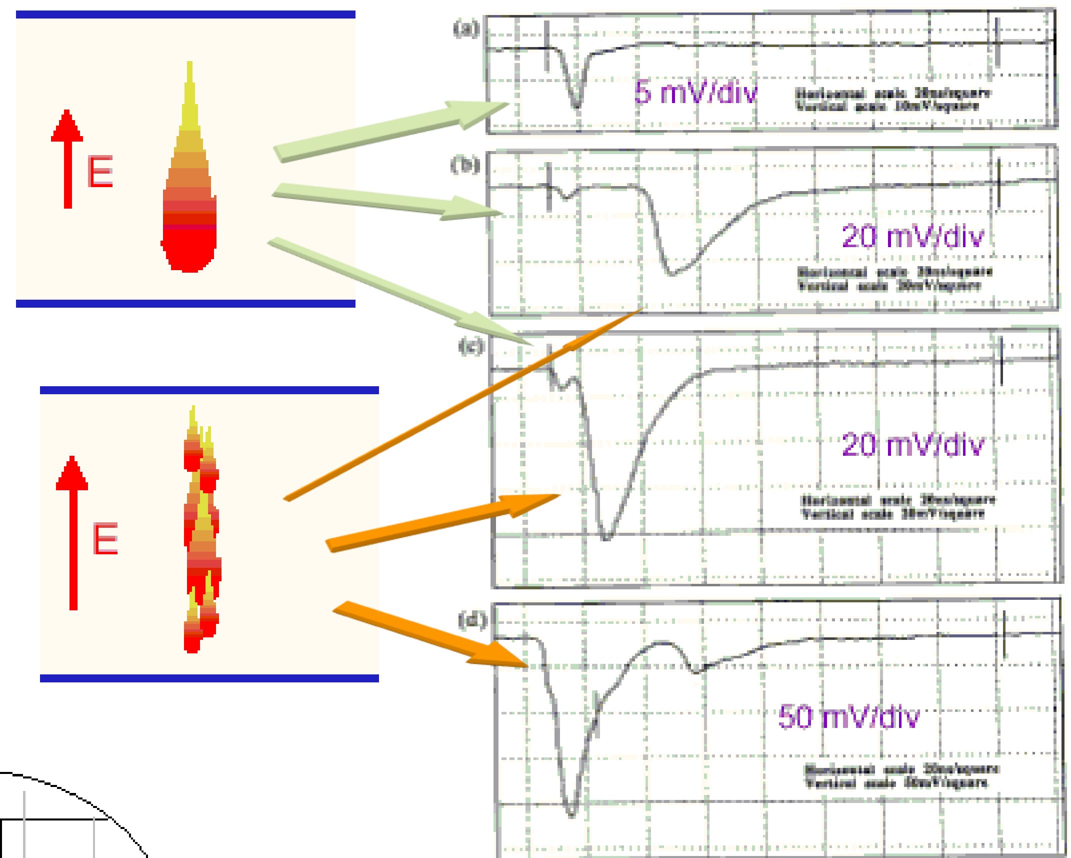
AVALANCHE CHAMBERS

A seconda della tensione applicata opera con regimi di funzionamento diverso

Regimi di funzionamento

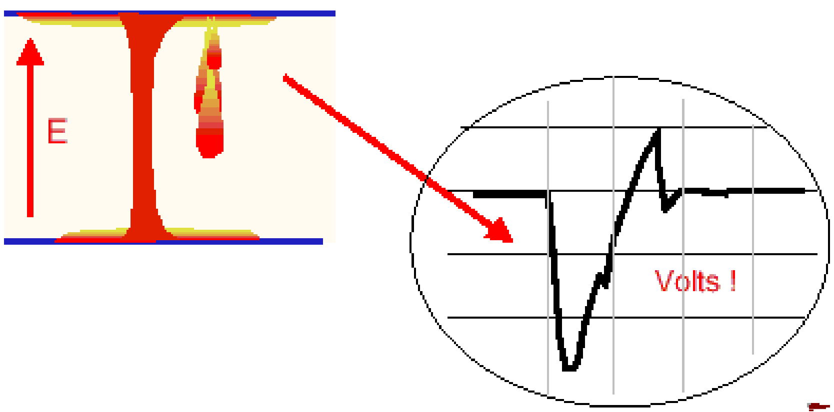
Avalanche:

Il valore del campo elettrico e' tale che l'energia acquistata dall'elettrone e' maggiore dell'energia di ionizzazione



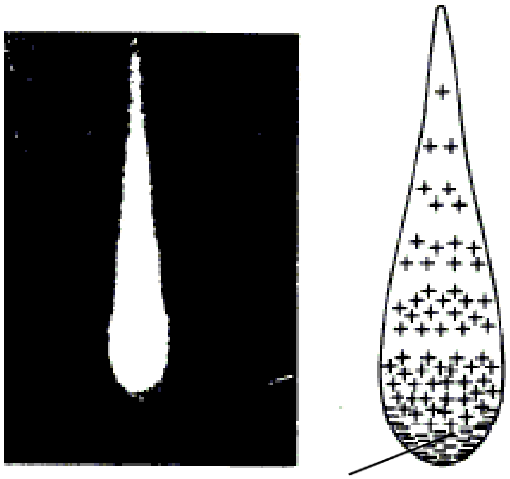
Streamer

Spark



Nota: la separazione avalanche-streamer diminuisce all'aumentare della tensione

Regimi di funzionamento



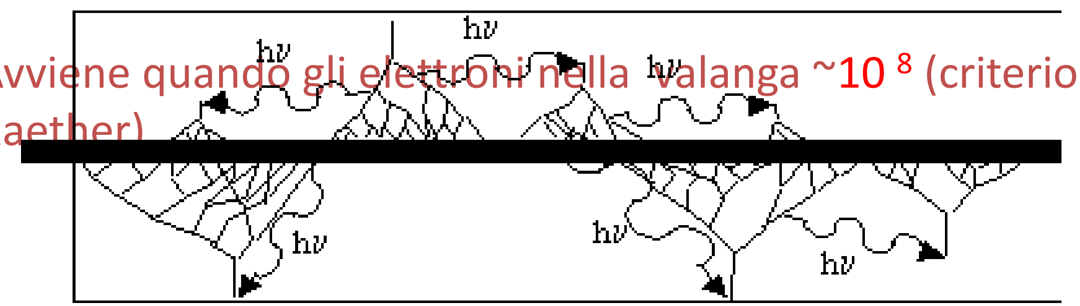
E~0 se # e^-~10^8

<u>Streamer</u>

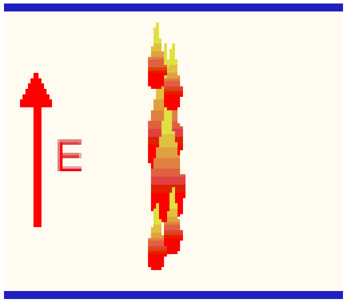
A campi elettrici piu' elevati la carica spaziale dovuta agli elettroni in testa alla valanga modifica
il campo esterno fino ad annullarne gli effetti

- Ricombinazione di e^- -ioni
- Produzione di fotoni ultavioletti
- Produzione di ulteriori valanghe da ionizzazione di ultra-violetti

Avviene quando gli elettroni nella valanga ~10^8 (criterio di Raether)



Filo centrale



Piani paralleli

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Come viene originato il segnale in un RPC?

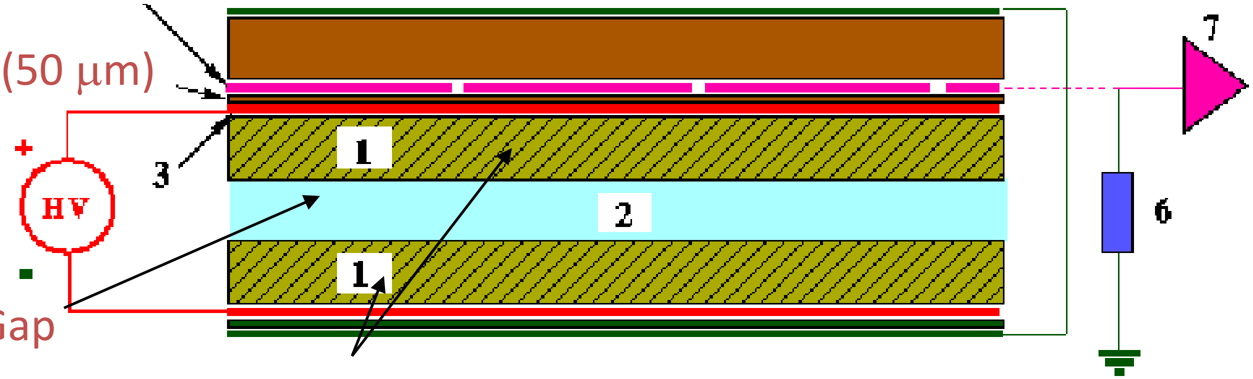
In un RPC le strip sono completamente separate (isolate) dalla gap:

5. Strip di lettura

4. PVC isolante (50 μm)

3. Elettrodi di HV (grafite 100 μm)

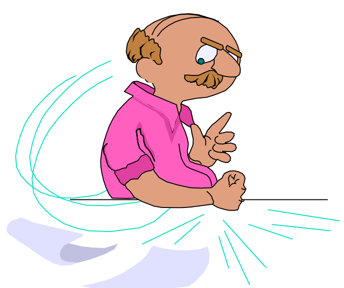
2. Gap



1. Bakelite (2 mm)

Gli elettroni della valanga o dello streamer non arrivano sulle strip:

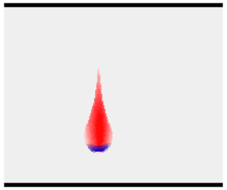
il segnale e' indotto dal movimento delle cariche (elettroni e ioni) nella gap



La dizione popolare: "raccolta della carica" e', a volte, misleadi

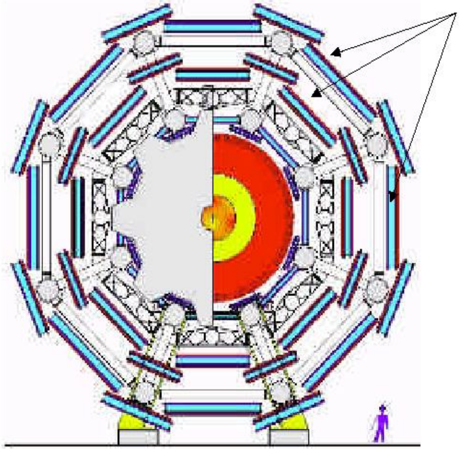
Cosa si vuole fare …

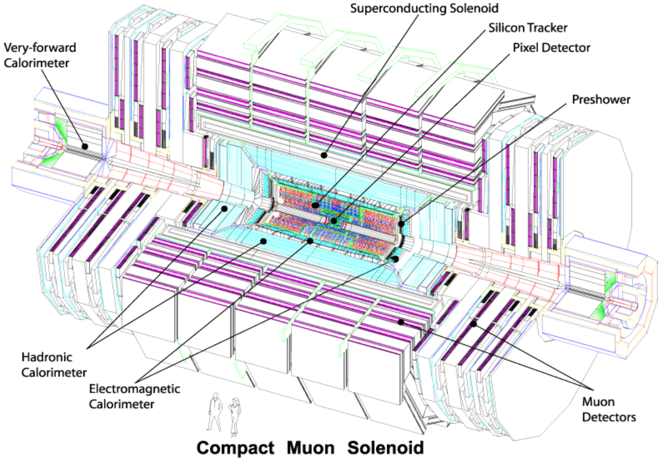
Avalanche mode



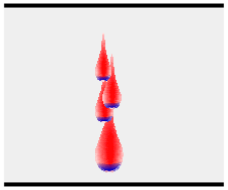
ATLAS

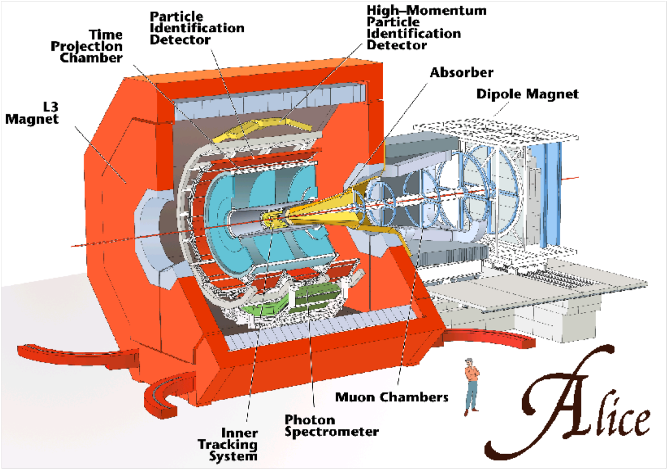
CMS



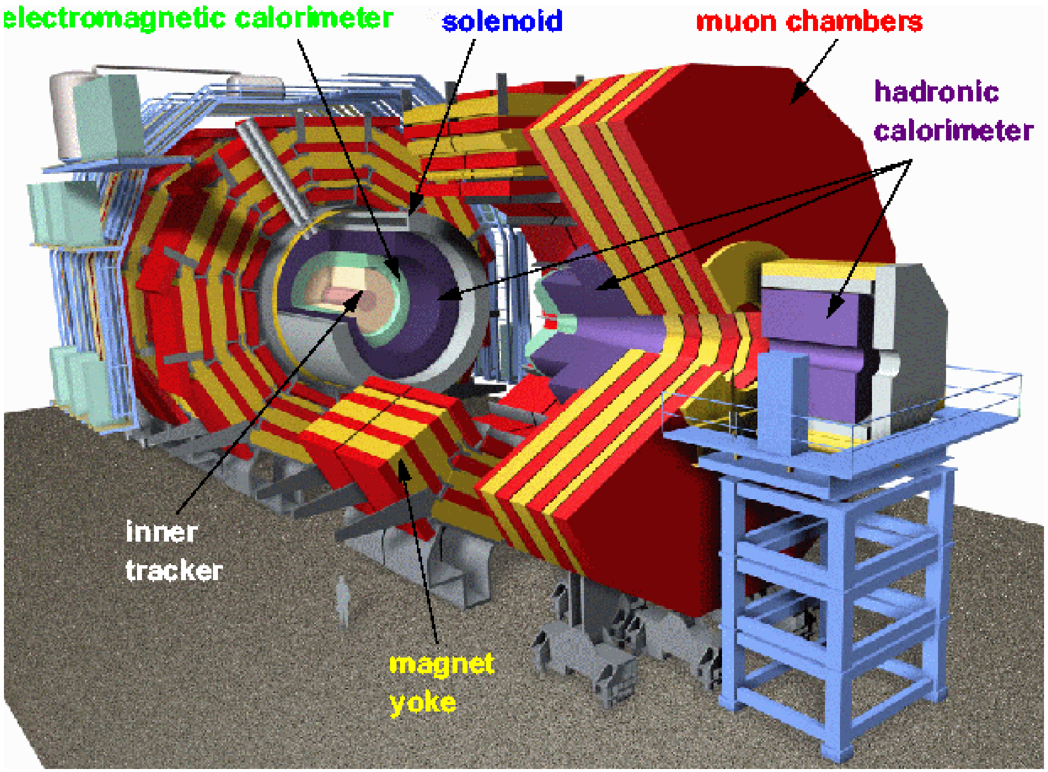


Streamer mode

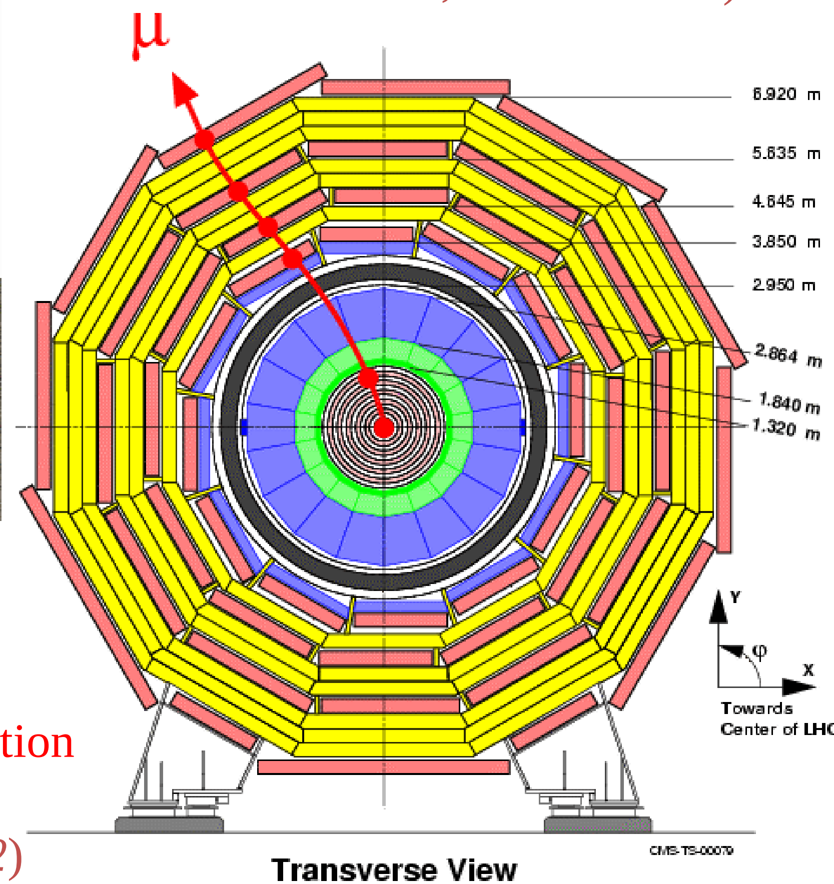




CMS



CMS sara' basato su:
"A very good redundant muon system"
(*Technical Proposal, CERN-LHCC 94-28, 15 Dec. 1999*)



Il trigger di primo livello dovra' garantire:
- Complete coverage of the solid angle
- Robustness: maximal use of available information
- Speed: decision time of the order of 1 μs

(*Letter of intent CERN-LHCC 92-3 1 Oct. 1992*)

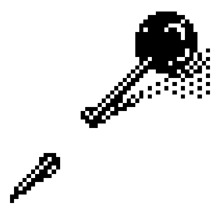
CMS (2...)

Durante 10 anni LHC produrra'

~10^{17} collisioni pp

Un'osservazione di 10 eventi "esotici" potrebbe portare a Nuova Fisica

Bisogna trovare 10 eventi tra 10^{17}



Un ago in un pagliaio?

Tipico ago:5 mm^3

Tipico pagliaio: 50 m^3

ago/pagliaio=1/10^{10}

Cercare nuova fisica ad LHC e' come cercare un ago in 1.000.000 di pagliai!

Contact information

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- University of Bari, Italy
-Email: marcello.abbrescia@uniba.it, marcello.abbrescia@ba.infn.it,
-Please do not hesitate to contact me for any information, request of additional material, or just a nice scientific discussion.

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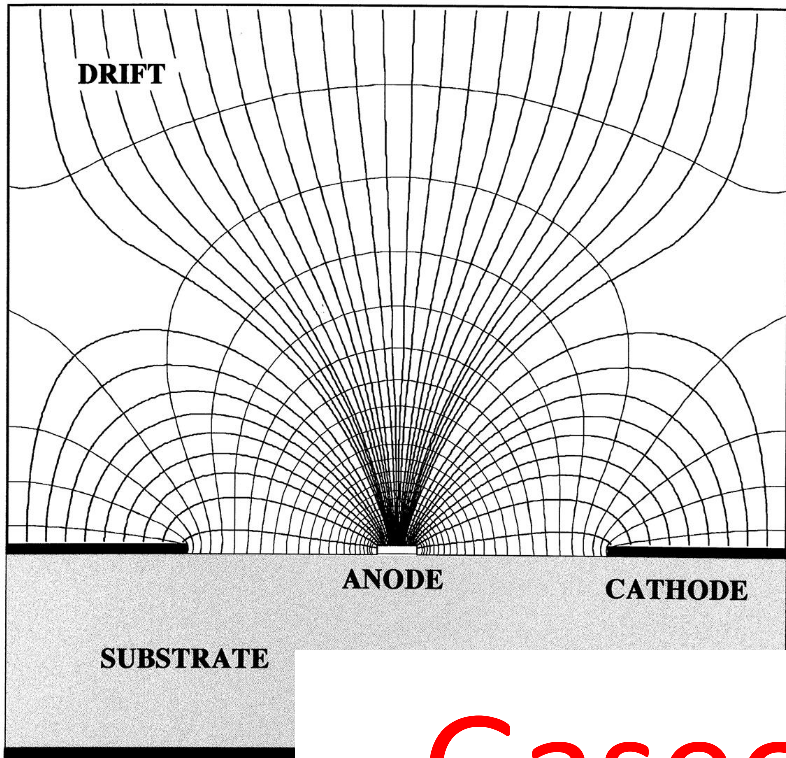
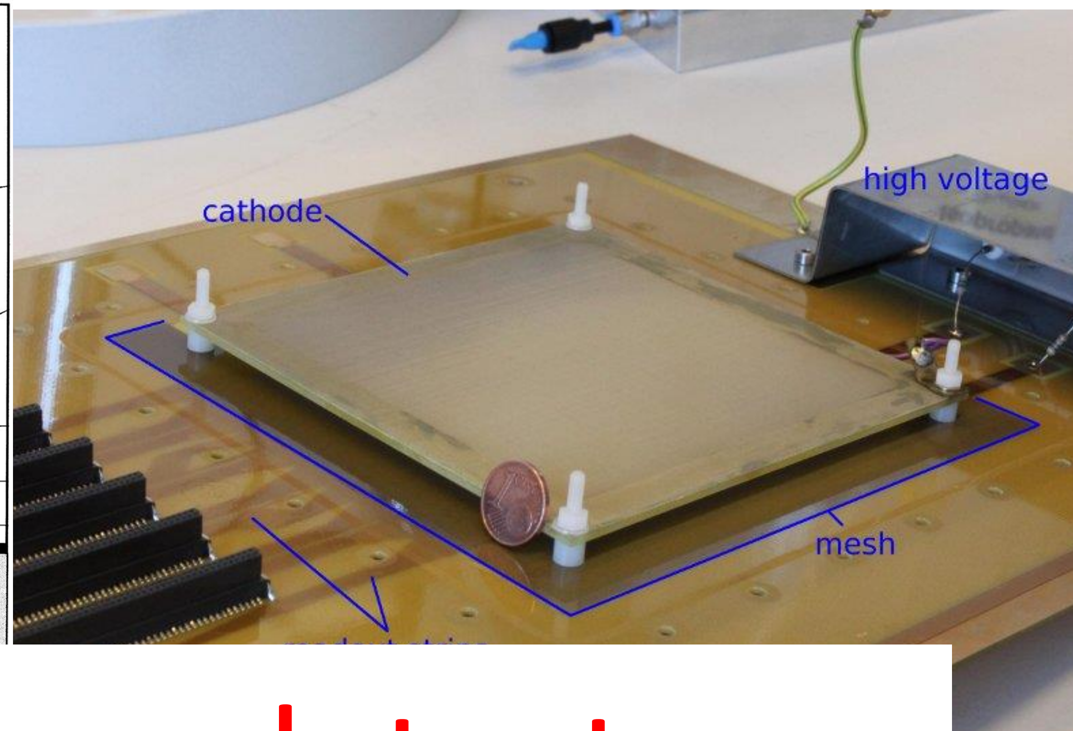
Relevant bibliography

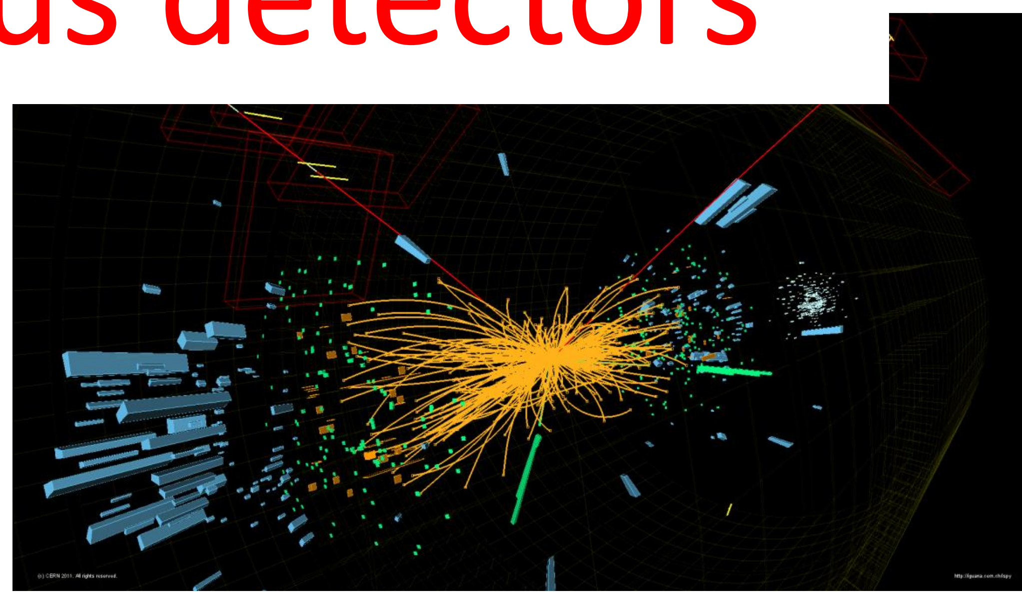
F. Sauli: **Principles of operation of multiwire proportional and drift chambers**, CERN Yellow Reports, CERN 77-09, 1977. - 92 p., 10.5170/CERN-1977-009
A. Peisert and F. Sauli: **Drift and diffusion of electrons in gases : a compilation (with an introduction to the use of computing programs)**, CERN Yellow Reports, CERN 84-08, 1984. - 127 p.
F. Sauli: **Gaseous Radiation Detectors: Fundamentals and Applications**, Cambridge University Press July 2014, ISBN: 9781107337701 , hUps://doi.org/10.1017/CBO9781107337701

Glenn F. Knoll **Radiation Detection and Measurement, 4th Edition, Wiley ed.** ISBN: 978-0-470-13148-0, September 2010 864 Pages
W. Leo, "**Techniques for Nuclear and ParLcle Physics Experiments: A How-to Approach",** Springer-Verlag, ISBN-13: 978-3540572800 , ISBN-10: 3540572805
Walter Blum, Werner Riegler, Luigi Rolandi, **Particle Detection with Drift Chambers**, Springer-Verlag 2008, ISBN: 978-3-540-76683-4





Gaseous detectors



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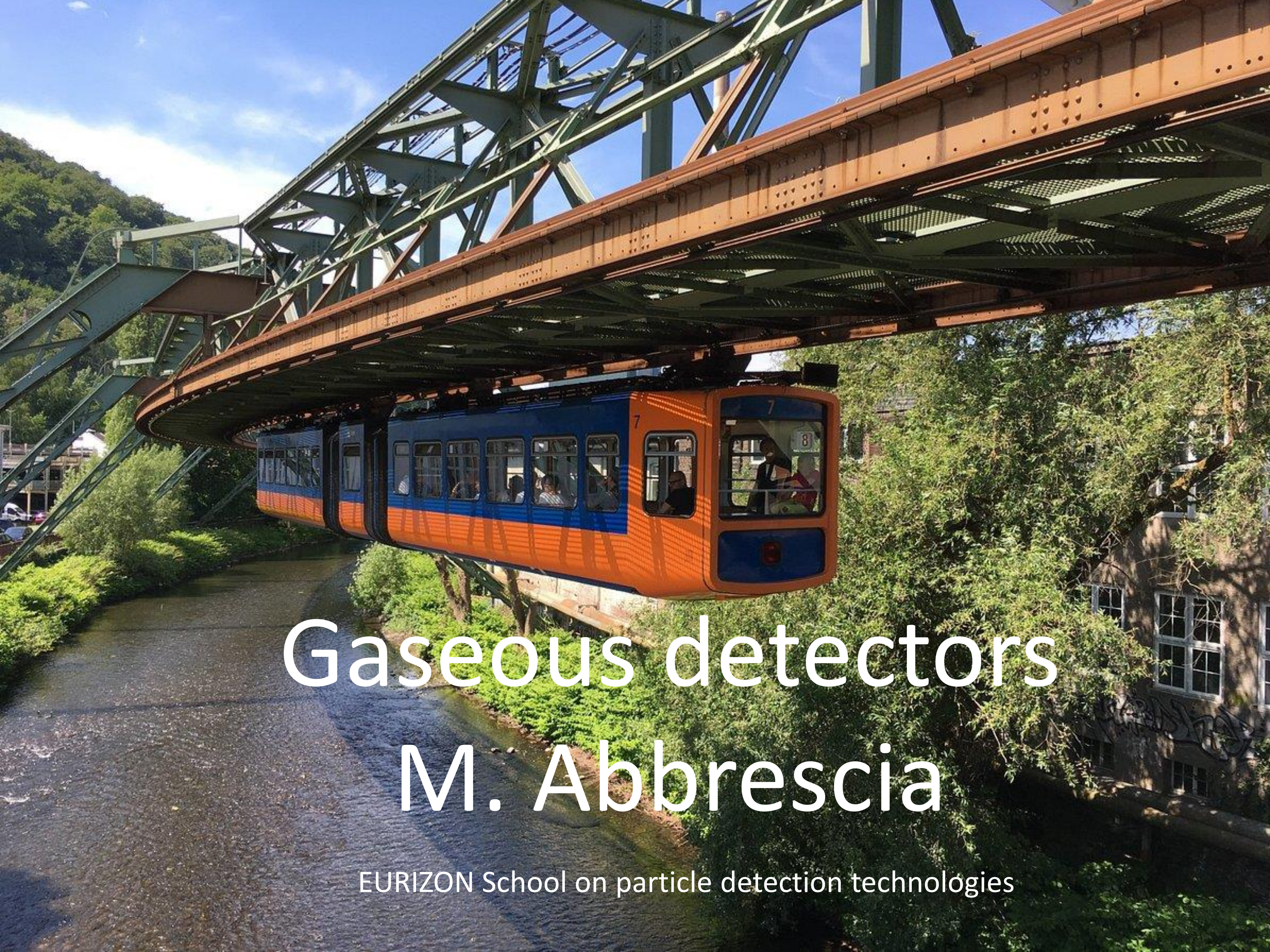
Gaseous detectors

Gaseous detectors
M. Abbrescia

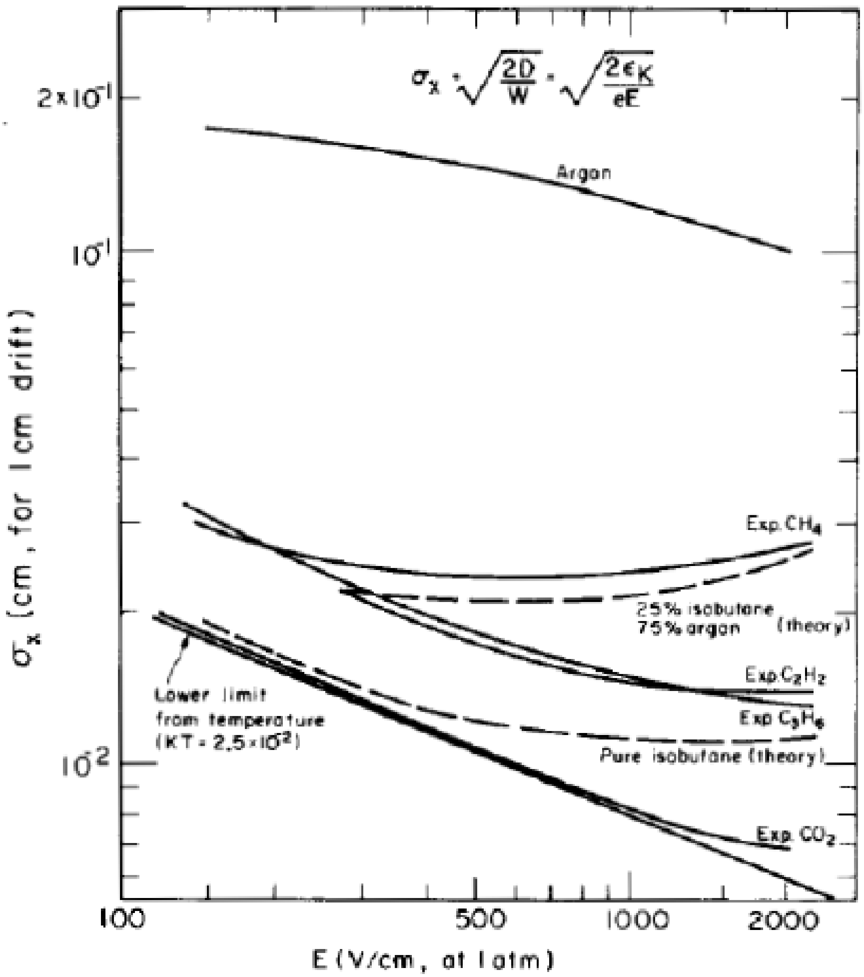
EURIZON School on particle detection technologies



Gaseous detectors
M. Abbrescia

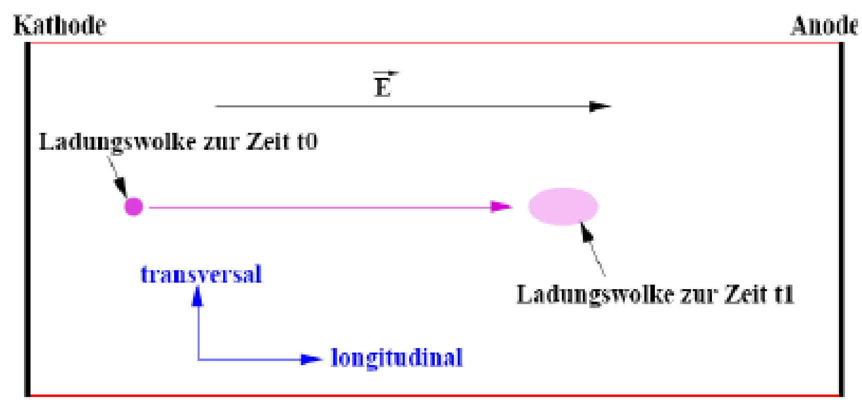
EURIZON School on particle detection technologies

Diffusion in electric fields



Drift in direction of E-field superimposed to statistical diffusion

Extra velocity influences longitudinal diffusion
Transverse diffusion not affected



E-field reduced diffusion in longitudinal direction

8

Historical background

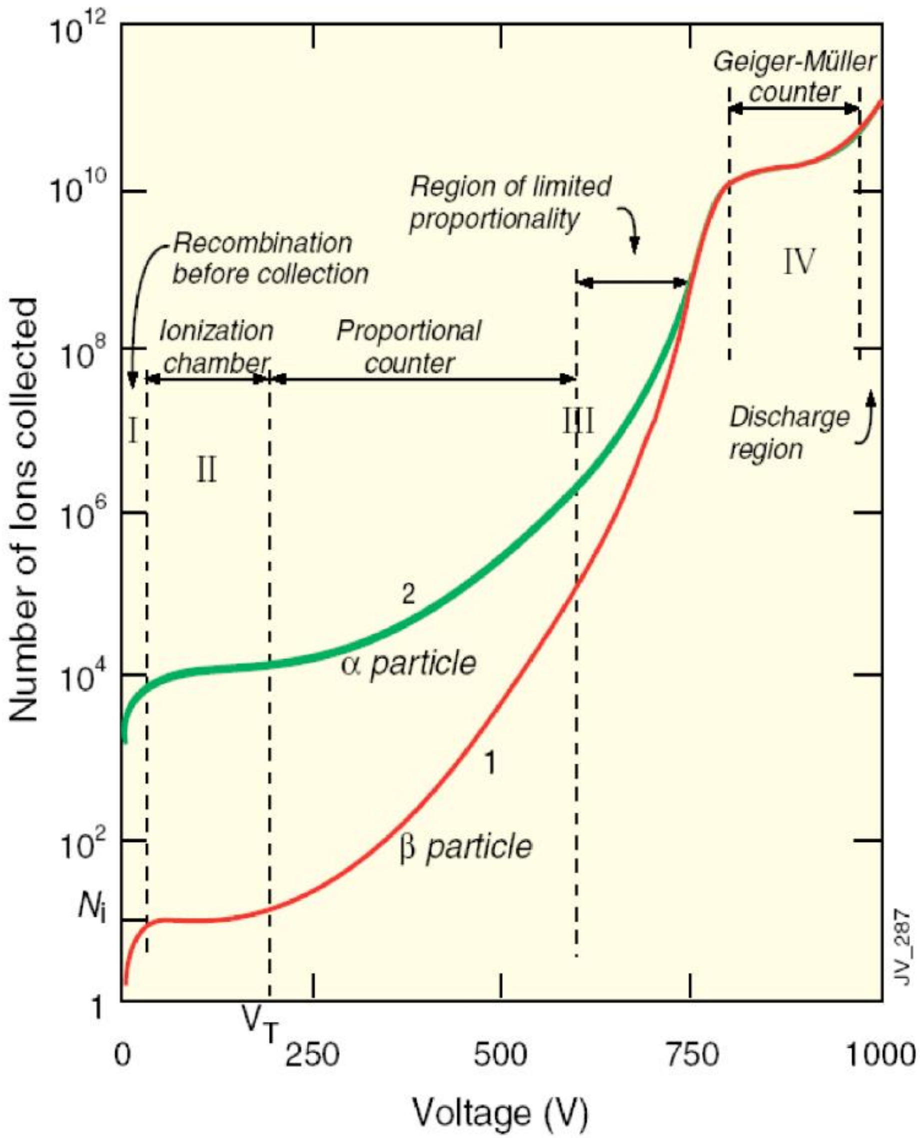
- First gaseous detector invented by Ernest Rutherford, 1908 Nobel Laureate in Chemistry, with the help of Hans Geiger → proportional counter
- Further developments by Geiger and Walther Muller permitted to detect single electrons (1928)
- Cloud chamber by Charles Thomson Wilson, Nobel Laureate in 1927 (Bubble chamber by Donald Arthur Glaser, Nobel Laureate in 1960)
- Multi-Wire Proportional Chamber, by George Charpak, Nobel Laureate in 1992
- Micro Pattern Gaseous Detectors (MPGD), beginning of 2000

… and in between many many many other detector and successes

Operational regimes of gaseous detectors

Gaseous detector operate differently depending on the voltage applied between cathode and anode:

I. Recombination
II. Charge collection (ionization chambers)
III. Proportional regime
  - proportional counters
  - limited proportionality - saturation
IV. Streamer region
  - limited streamer region
  - discharge region



Multi Wire Proportional Chamber

MWPC was developed 1968 by Georges Charpak and it was the first full electronic detector!

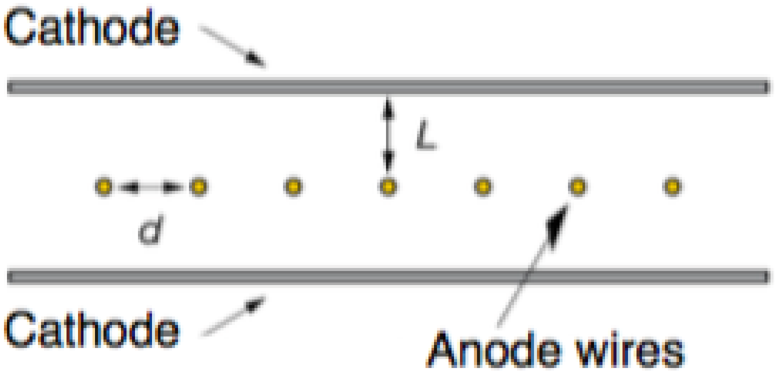
The Nobel Prize in Physics 1992 was awarded to Georges Charpak *"for his invention and development of particle detectors, in particular the multiwire proportional chamber"*.

Georges Charpak (1924-2010)

Nobelprize.org
http://nobelprize.org/physics/laureates/1992/

It consists of a set of parallel anode wires tightly spaced, between parallel cathodes

The signal is induced by the movement of e- and ions in the electric field.



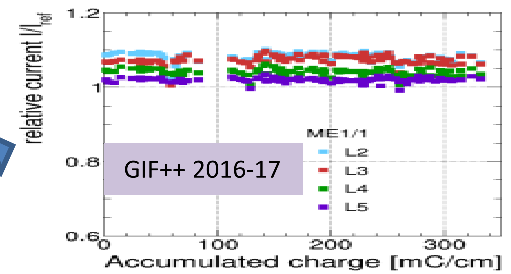
CMS CSC gas mixture

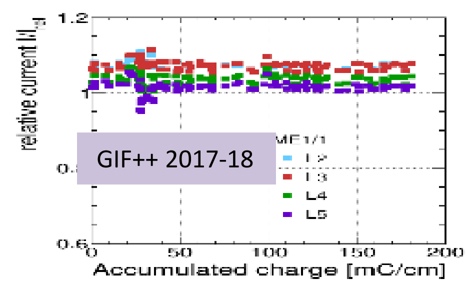
✓ **40% Ar + 50% CO_2 + 10% CF_4**

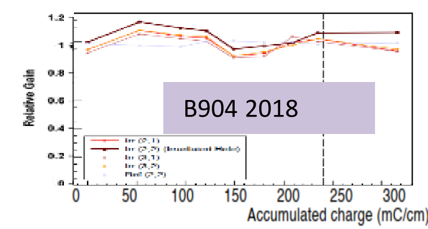
➢ CF_4 ensures good timing (higher v_{drift}), operation stability (avalanche quencher) and anti-aging properties

In view of a F-gas reduction consumption, tests have been done with reduced CF_4 concentration. They indicate stable operation and no degradation of performance is seen even after integrating the charge equivalent to HL-LHC plus a safety factor.

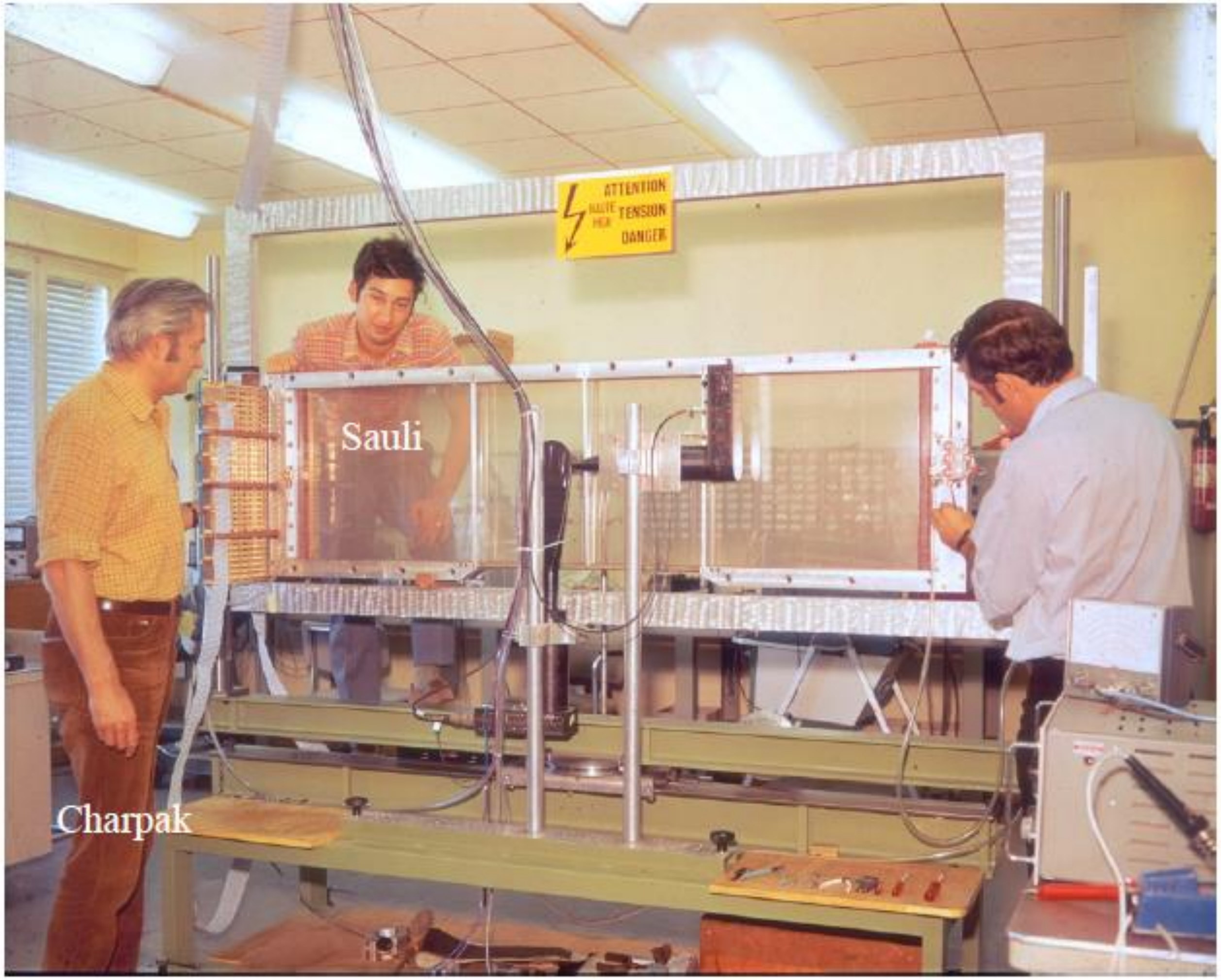
- CSCs irradiated at CERN GIF++ (2016-17) and PNPI (2016) with 10% CF_4 and Ar-CO_2 (40+50)% have shown no signs of aging up to >3x the charge of 3000fb^{-1} integrated lumi at HL-LHC
- CSC irradiated at CERN GIF++ & B904 (2017-18) with 2% CF_4 and at PNPI (2017) with 1.6% CF_4 and Ar-CO_2 (40+58)% show stable gas gain after 3-4x HL-LHC.
- CSC prototypes irradiated at CERN B904 (2018) w/o-CF_4 and Ar-CO_2 (40+60)% show stable gas gain after 3x HL-LHC



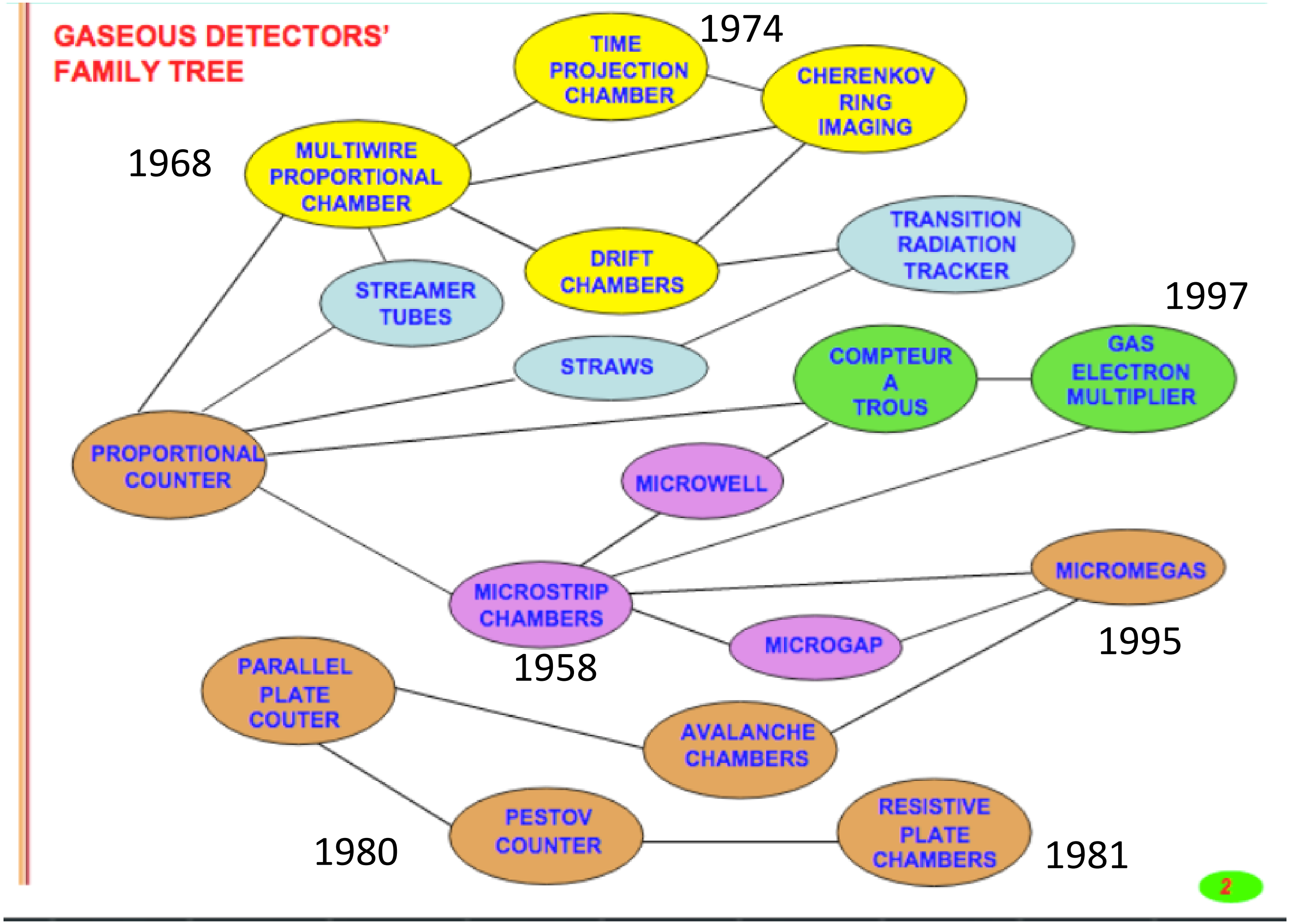




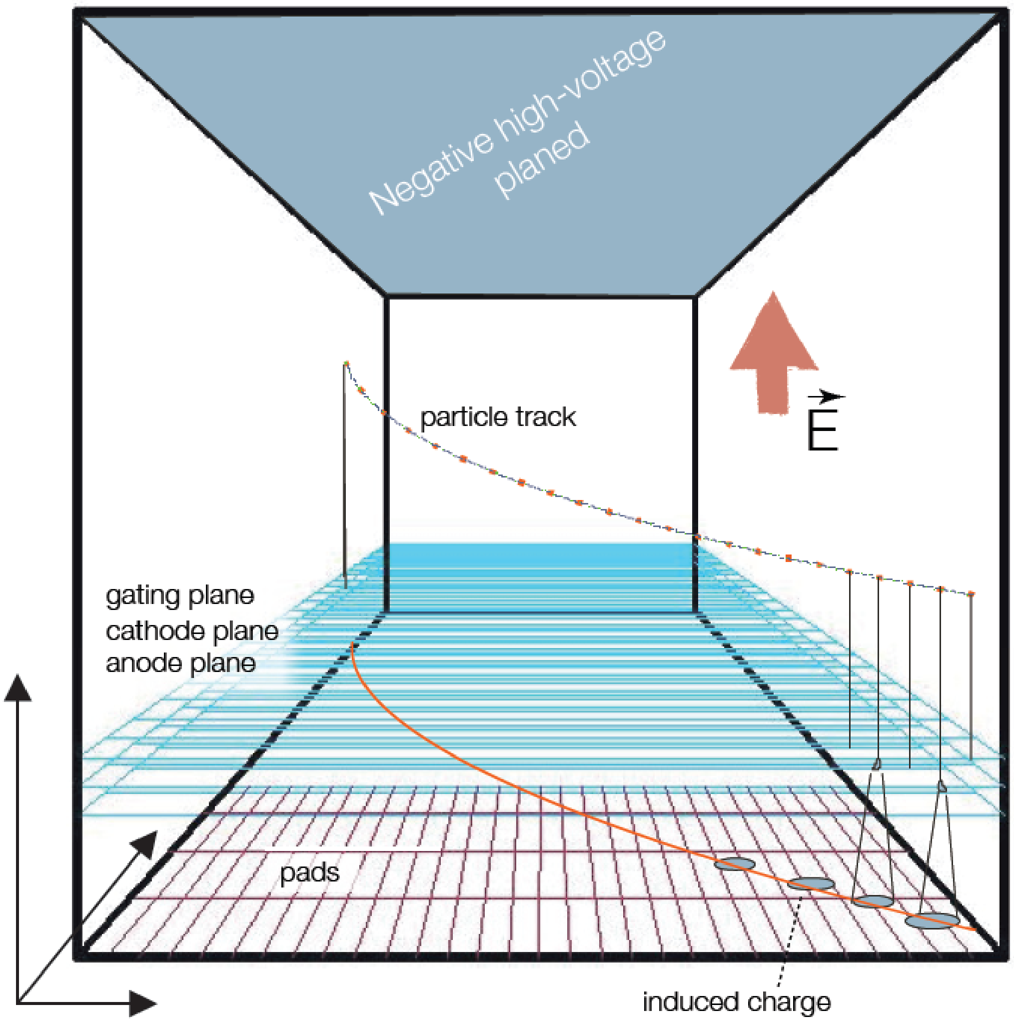
LARGE MWPC PROTOTYPE (1971)



Gaseous detectors family tree



TPCs pros and cons



Advantages:

- Complete track within one detector yields good momentum resolution
- Relative few, short wires (MWPC only)
- Good particle ID via dE/dx
- Drift parallel to B suppresses transverse diffusion by factors 10 to 100

Challenges:

- Long drift time; limited rate capability [attachment, diffusion ...]
- Large volume [precision]
- Large voltages [discharges]
- Large data volume ...
- Extreme load at high luminosity; gating grid opened for triggered events only ...

Typical resolution:

z: mm; x: 150 - 300 μm; y: mm
dE/dx: 5 - 10%

TPCs – technical solutions

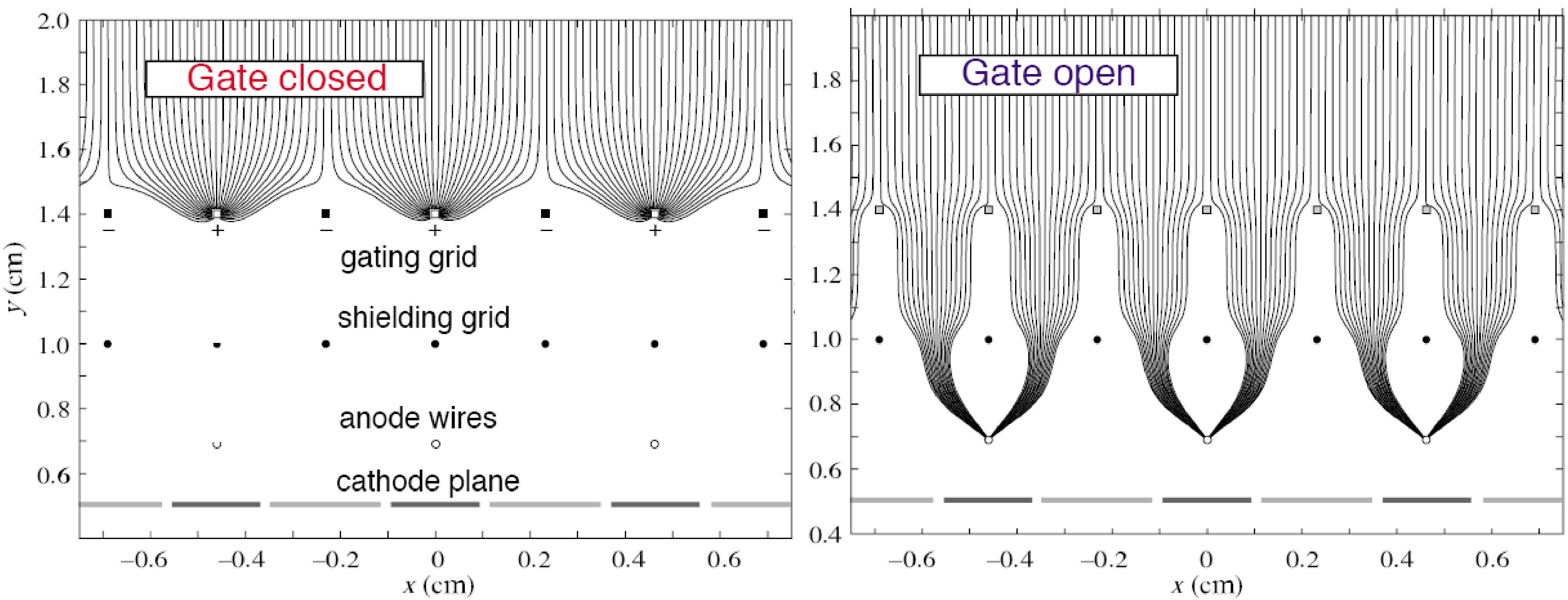
Difficulty: space charge effects due to slow moving ions change effective E-field in drift region ....

Important: most ions come from amplification region

Solution: Invention of gating grid; ions drift towards grid ...

[Also: shielding grid to avoid sense wire disturbance when switching]

Requires external trigger to switch gating grid ...



Why Electrodes are “cured” with linseed oil ?

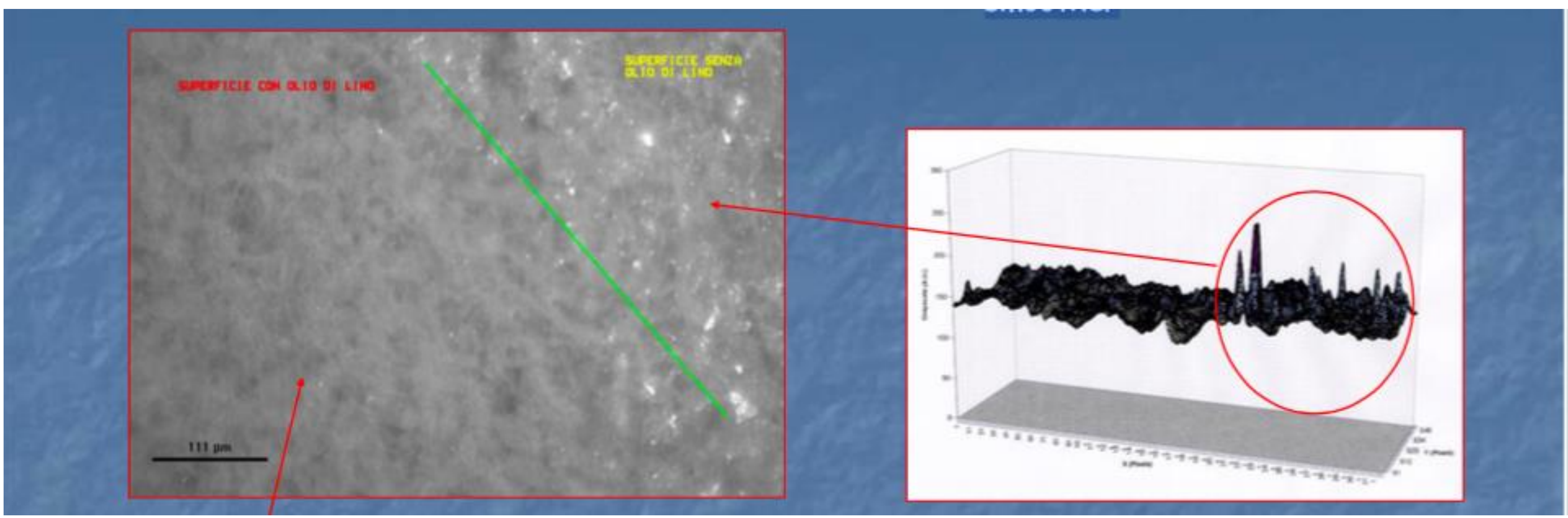
Linseed oil (If you look on Wikipedia..)

The Linseed oil is used as a painting medium. It was a significant advantage in the technology of oil painting!

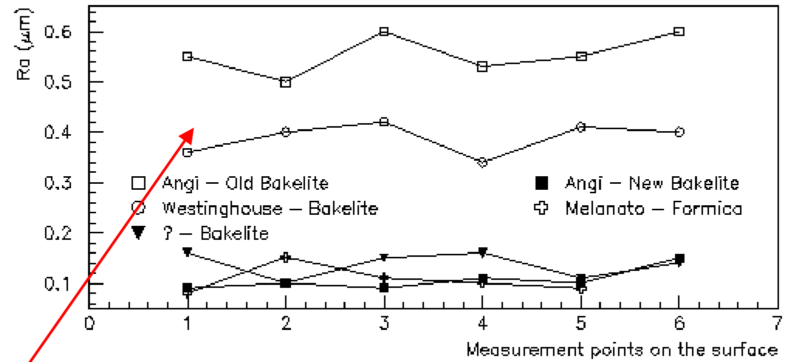
Mixture of triglycerides, formed by one molecule of glycerol and three molecules of linear fatty acids. The oil is cured forming a hard stable film because of oxidation followed by polymerization.

Linseed oil makes the surface smoother

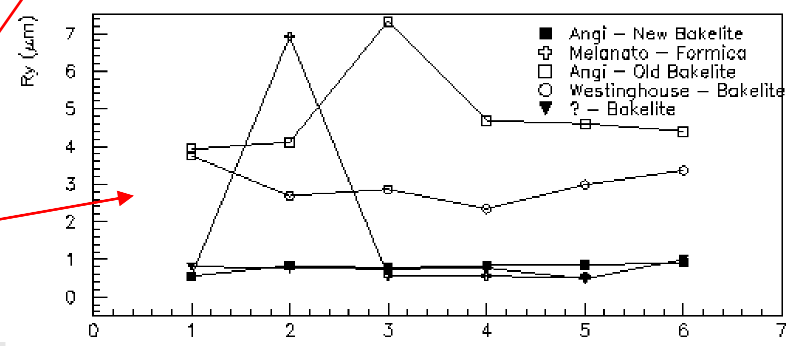
The smoother the surface, the lower the intrinsic noise of the detector

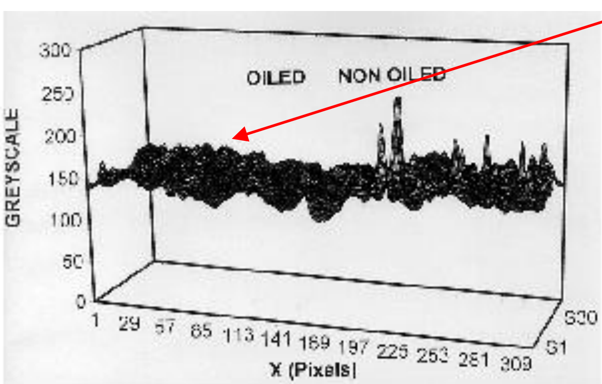


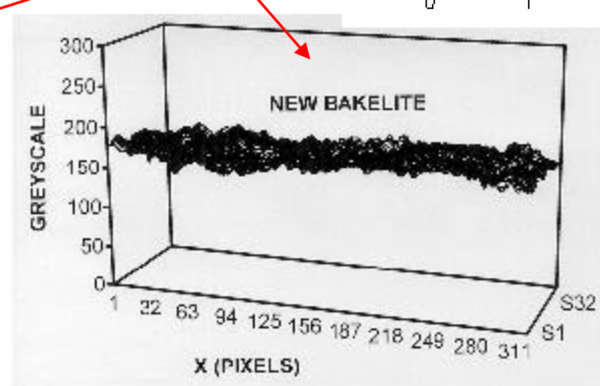
Comparison among not-oiled, oiled and smoother surfaces RPC



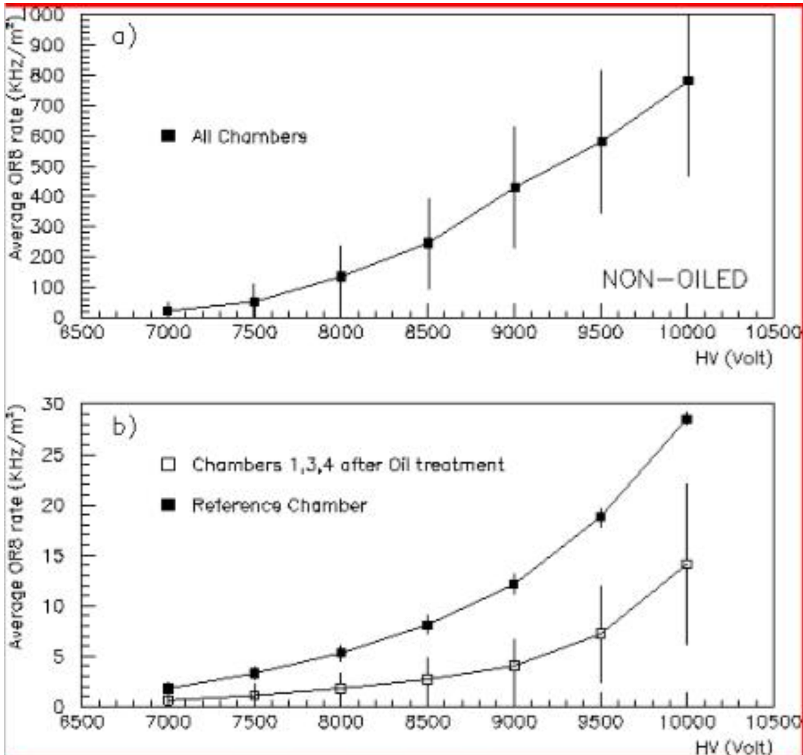
Direct measurements of surface roughness
-mono-dimensional
- bi-dimensional



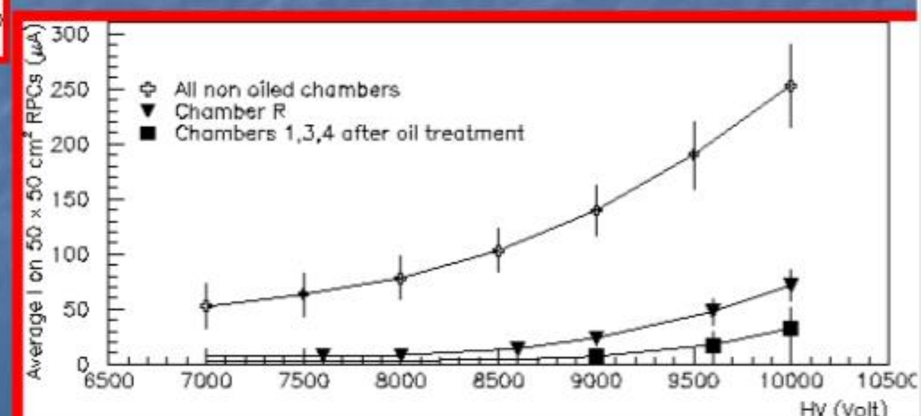
a) 

b) 

RPC: the linseed Oil

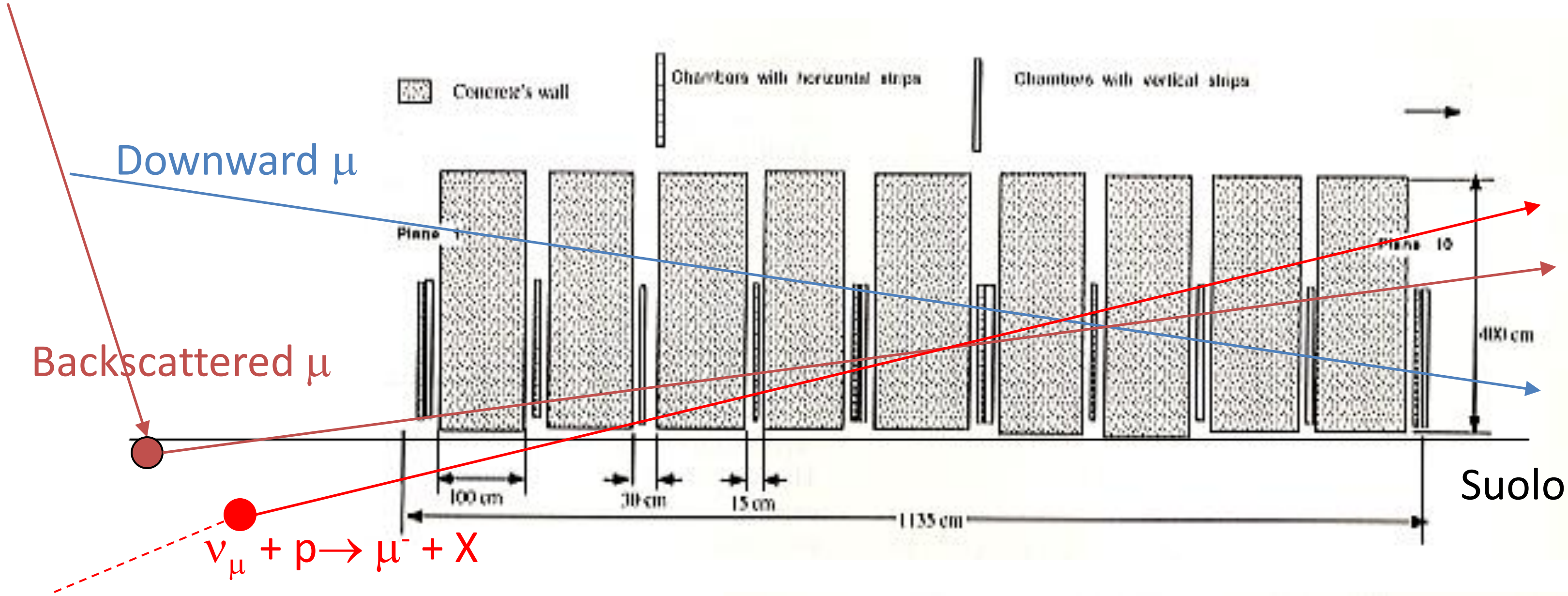


Reduced Currents and Noise rate

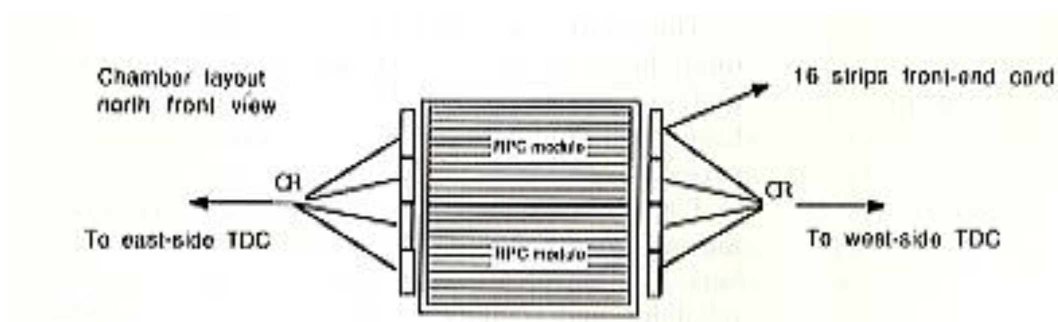


MINI: first experiment fully implemented with RPCs

MINI: telescope for atmospheric (and backscattered) μ: 64 m^2 of single gap RPC



Operating from since 1990 to 1996



10 stations, equipped with 14 chambers
8 chambers with horizontal strips
6 with vertical strips

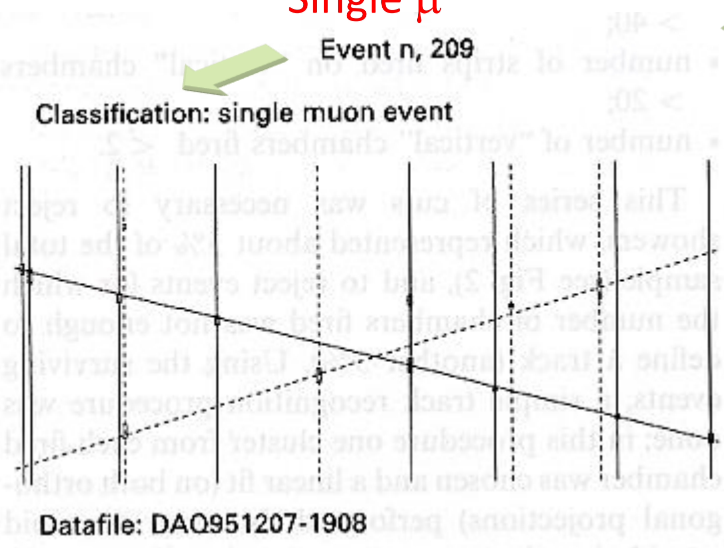
⇨ Precise tracking!

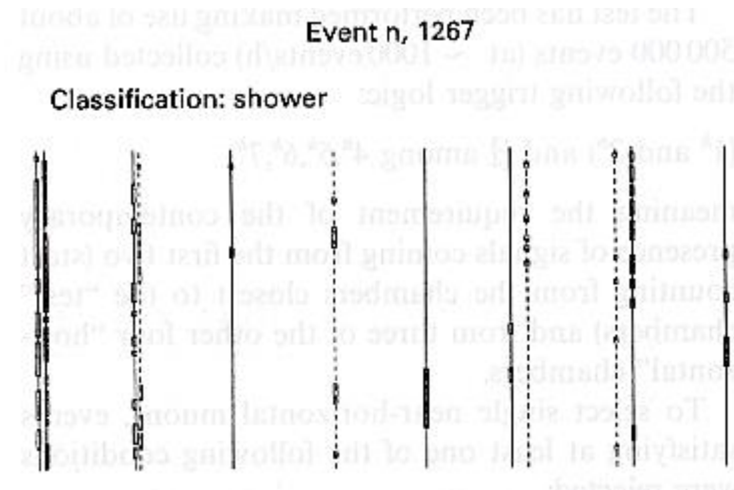
MINI

3D event reconstruction

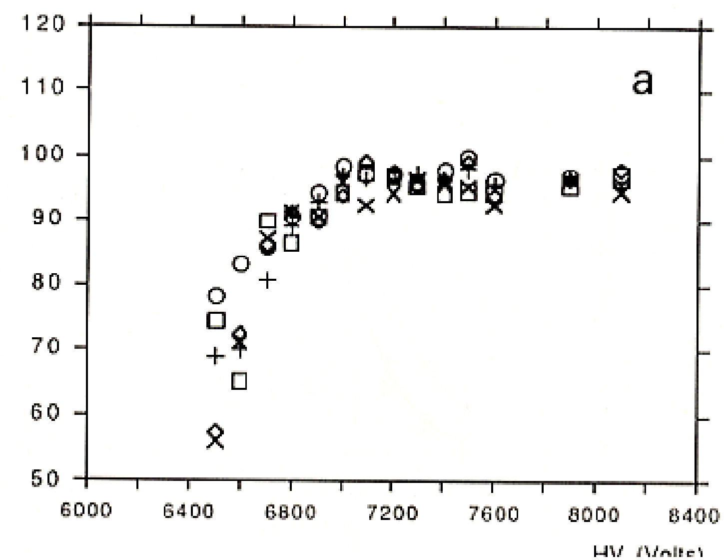
Atmospheric shower

Single μ





Lateral and upper view superimposed

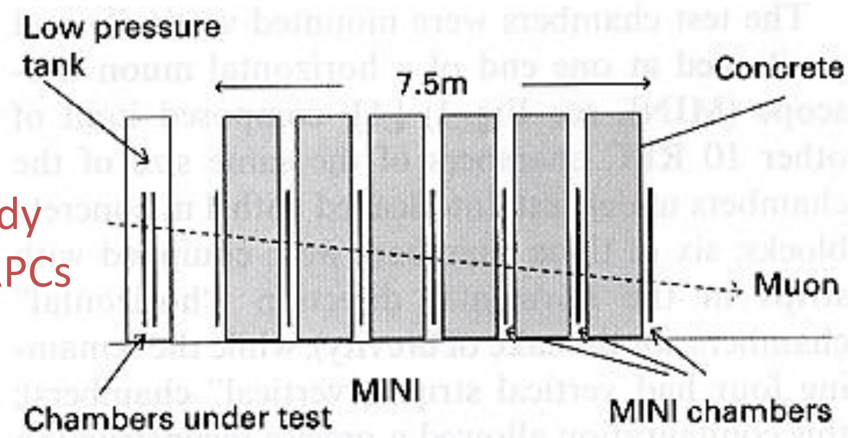


MINI was used both for physics and for studies on RPC performance

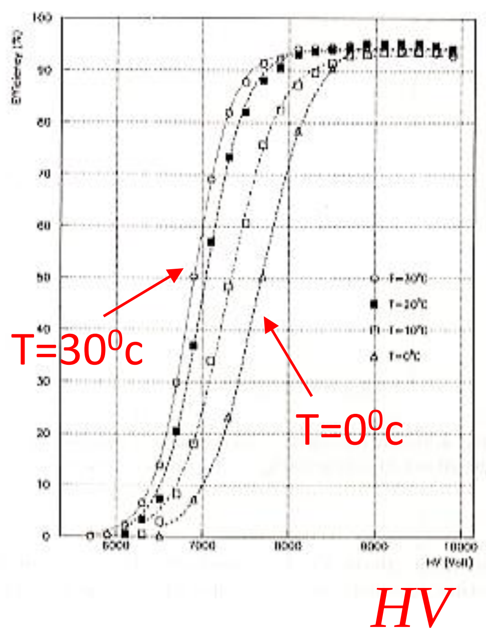
Efficiency uniformity

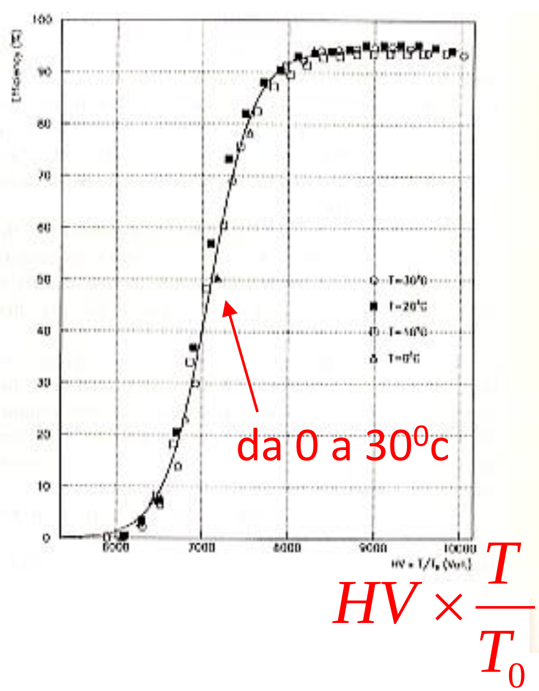
MINI

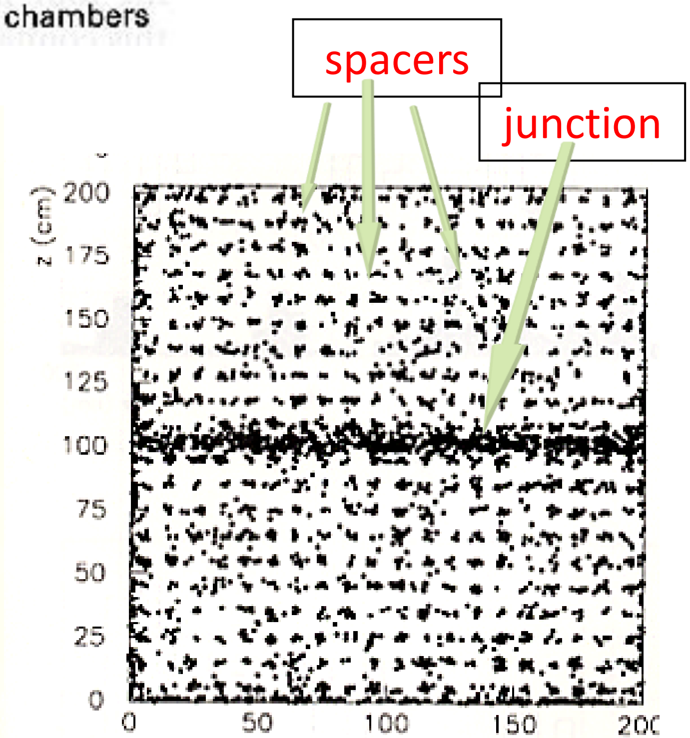
MINI was used to study the performance of RPCs vs. T and p



Prima "radiography" of a chamber suing cosmic μ (ineffciency points due to the spapcers and junctions)







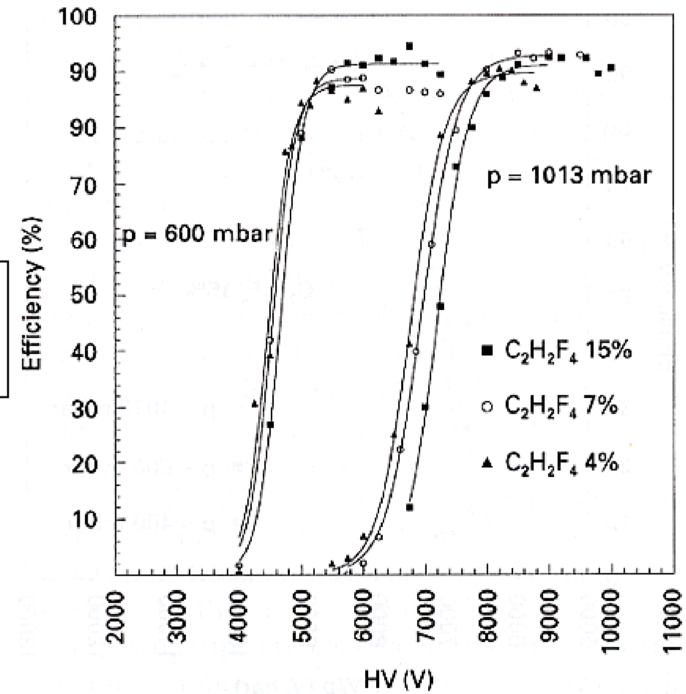
MINI

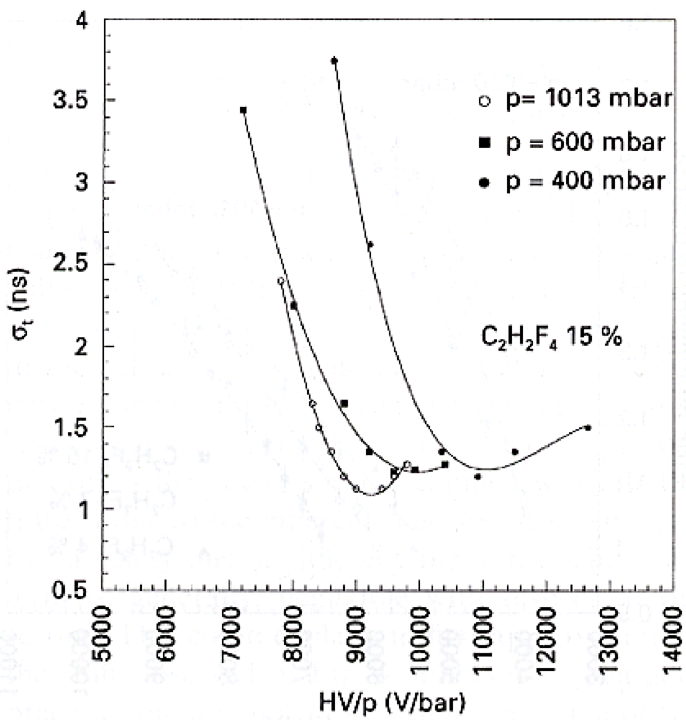
One of the most interesting results from MINI was checking that RPCs can operate at reduced pressure (down to 400 mbar)

Not trivial, dealing with gaseous detectors...

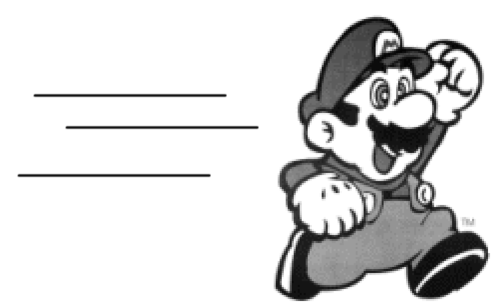
Less primary pairs

Change in the mean free path, gas density ...





“Pilot” experiment for ARGO-0



Marcello Abbescia - Universitá di Bari, Italy

ARGO-YBJ

Argo Panopte (who sees everything) is described as being very strong, since he had 100 eyes and was capable to sleep with only 50 of his eyes closed-

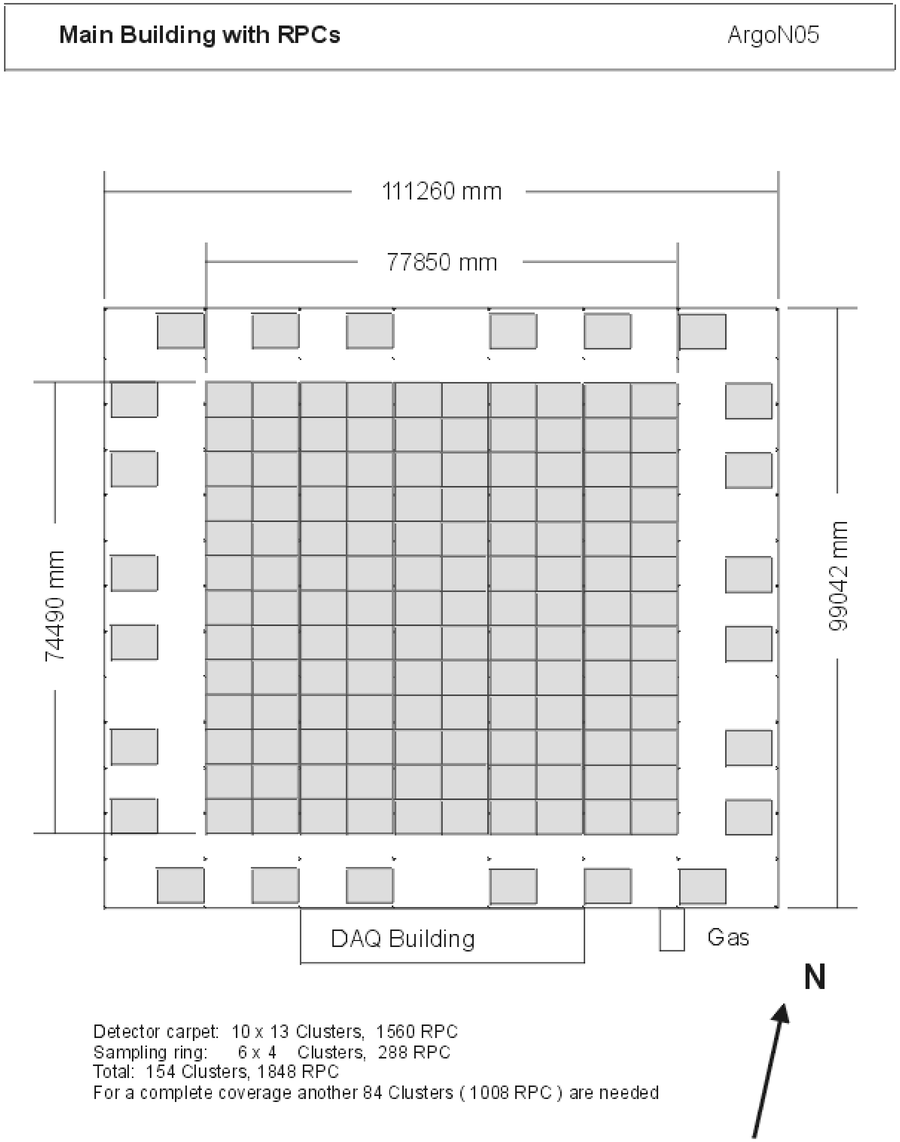
ARGO-YBJ (Astrophisical Radiation with Ground based Observatory at YangBaJiing, Tibet) did never sleep.

Argo–YBJ

Experiment to study with high efficiency and sensitivity Extensive Air Showers with energy > 100 GeV

- γ Astronomy ~ 100 GeV
- Diffuse γ rays
- γ-Burst
- Ratio p/p bar
- Spectrum of the primaries
- Physics of Sun and atmosphere

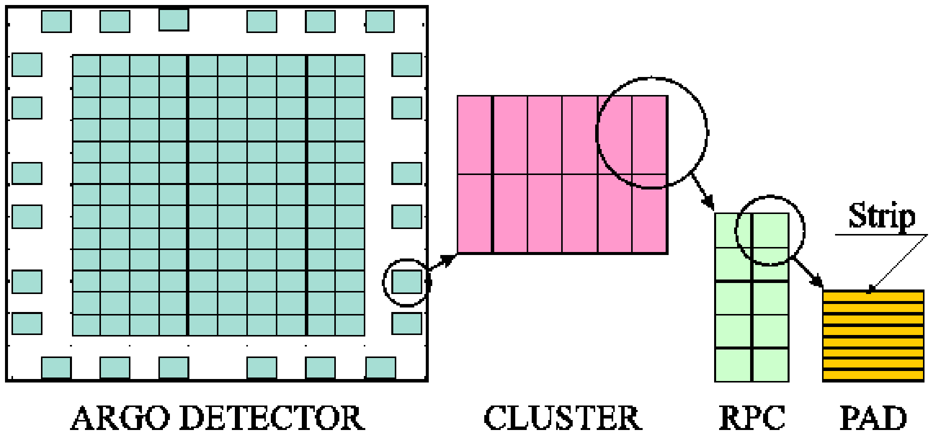
ARGO-YBJ



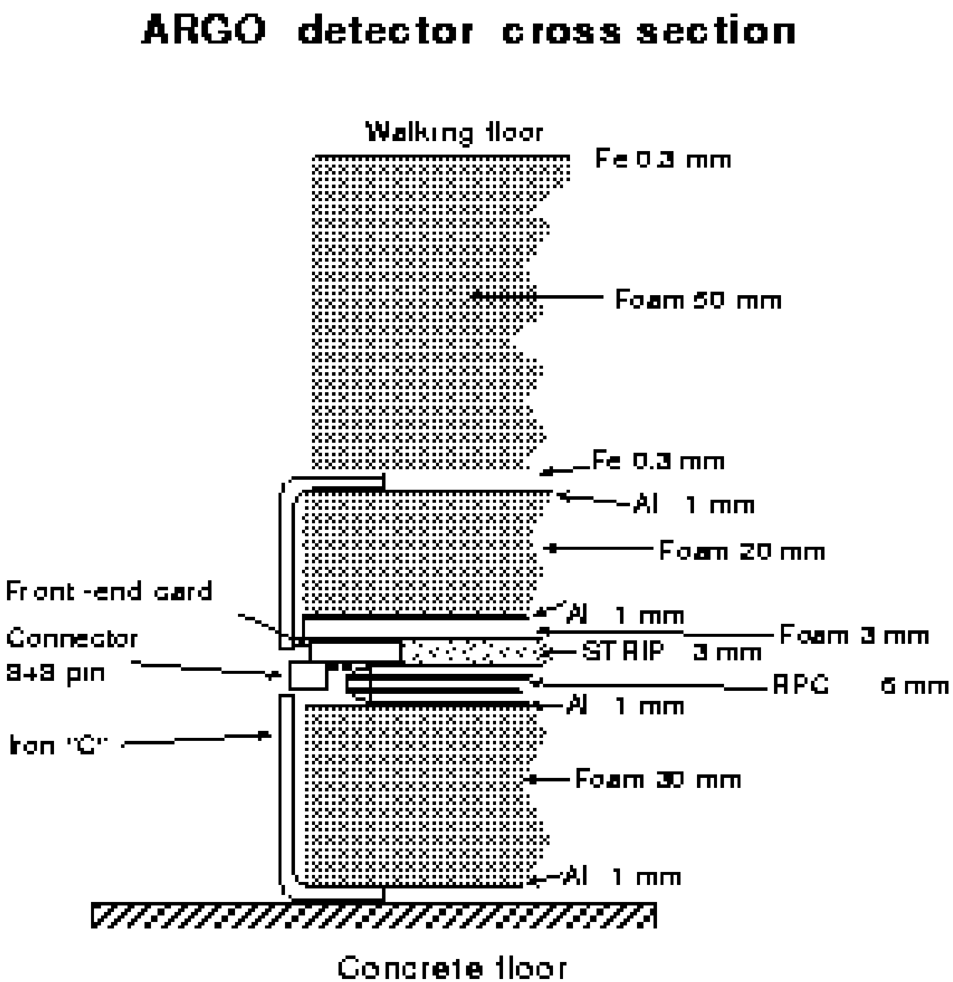
78 x 74 m^2 covered with RPCs

In addition a guard ring with partial cover up to 100 x 100 m^2

“RPCs chosen because their low cost, large active area, excellent time and spatial resolution, easy of integration as a large system.”



ARGO-YBJ



Single gap RPCs
Volume resistivity > 5 10^{11} Ωcm
Area: 126 x 285 cm^2

Aluminium strips 6 x 56 cm

Fast-OR of16 strips defining a PAD

10 pads (56 x 60 cm^2) covering a chamber (in total 18480 pads)

Streamer mode

Gas:
15% Argon,
10% Isobutane
75% Tetrafluoroethane $C_2H_2F_4$

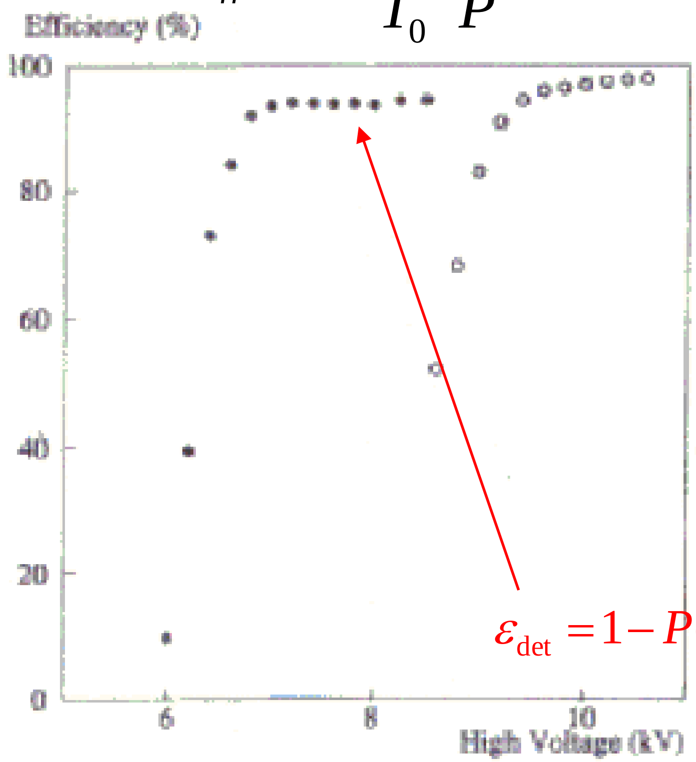
Use of converters to increase the number of hits/event.

ARGO-YBJ

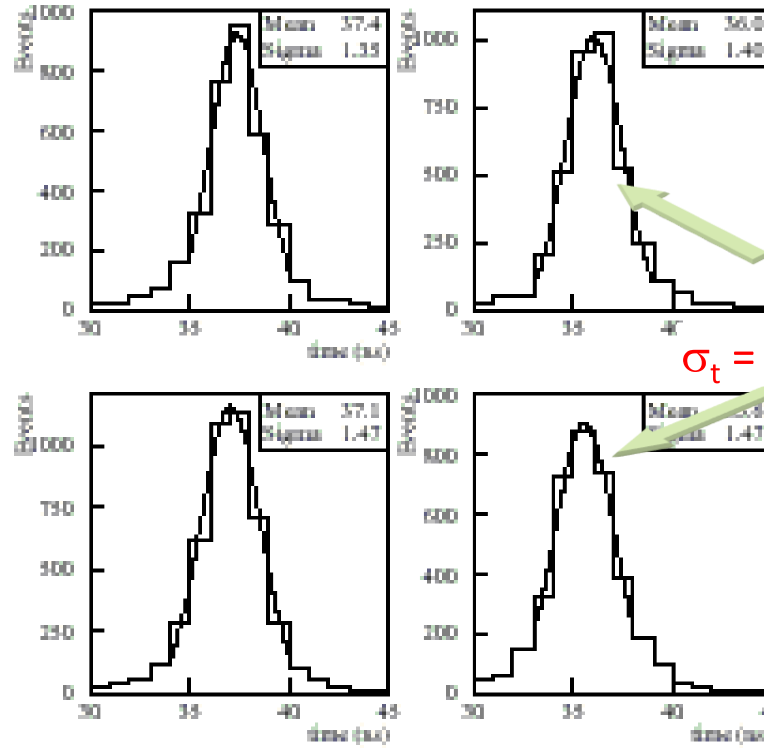
Operating at 4300 m above sea level

Low pressure ~ 600 mbar

$$V_{eff} = V_0 \frac{T}{T_0} \frac{P_0}{P}$$



$$\varepsilon_{\text{det}} = 1 - P(0) = 1 - e^{-\bar{n}}$$

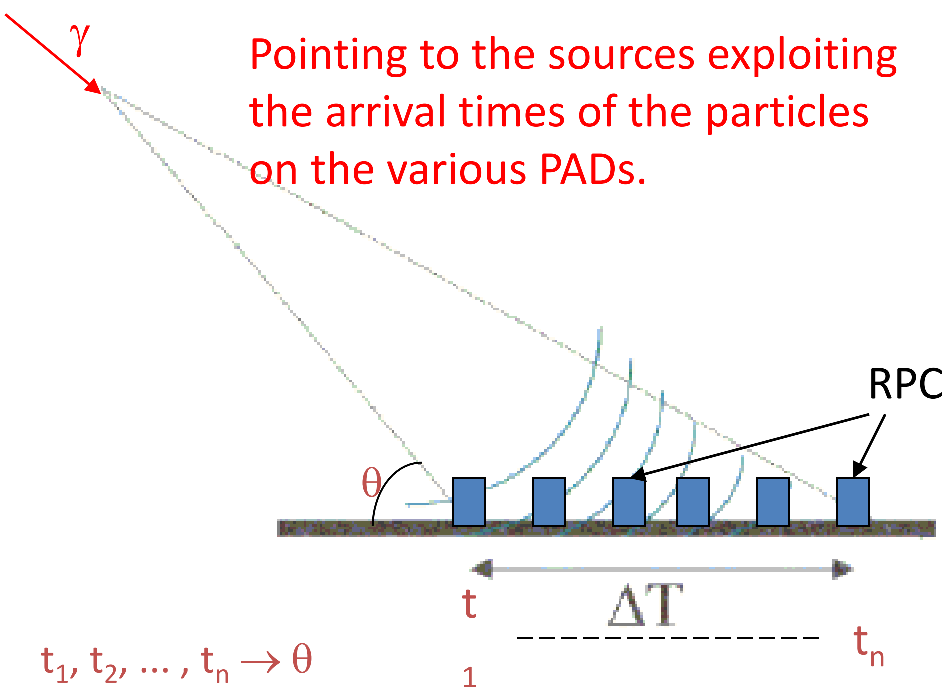


σ_t = 1.45 ns

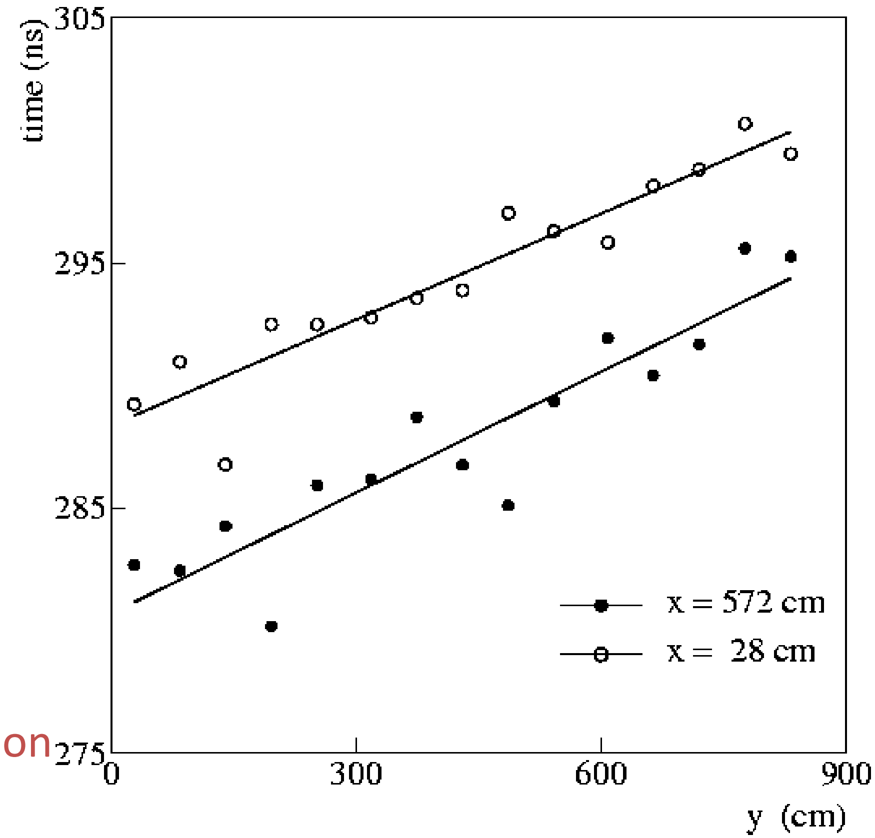
Time resolution

ARGO-YBJ

Pointing to the sources exploiting the arrival times of the particles on the various PADs.



$t_1, t_2, \ldots, t_n \rightarrow \theta$



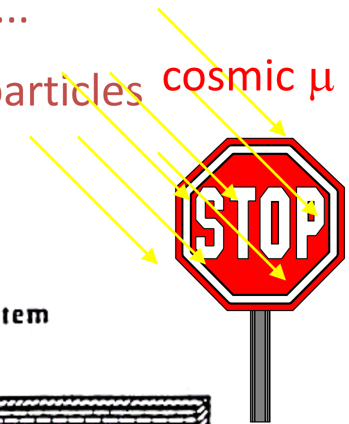
Interesting application where good time resolution is essential for a good tracking

$\Delta t_{RPC} \sim$ 1-2 ns $\rightarrow \Delta\theta$ = 1 mrad

$$\frac{Signal}{Background} \propto \frac{1}{(\Delta\theta)^2}$$

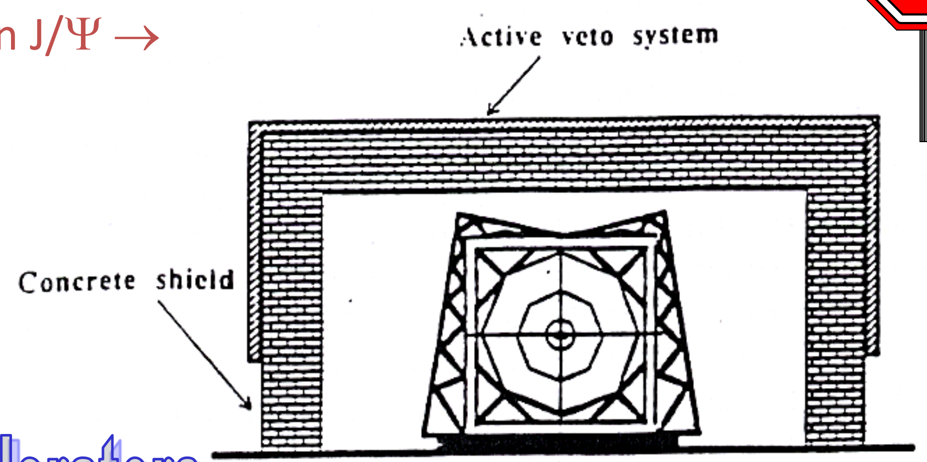
Experiments using RPCs

1st generation RPCs were immediately used in many physics experiments...



Veto

- Nadir: 120 m^2 of double gap RPCs used as a veto on cosmic particles in an experiment on neutron-anti neutron oscillations
- Fenice: 300 m^2 of RPC used as a cosmic vet in the reaction $J/\Psi \rightarrow$ n-n bar at Adone

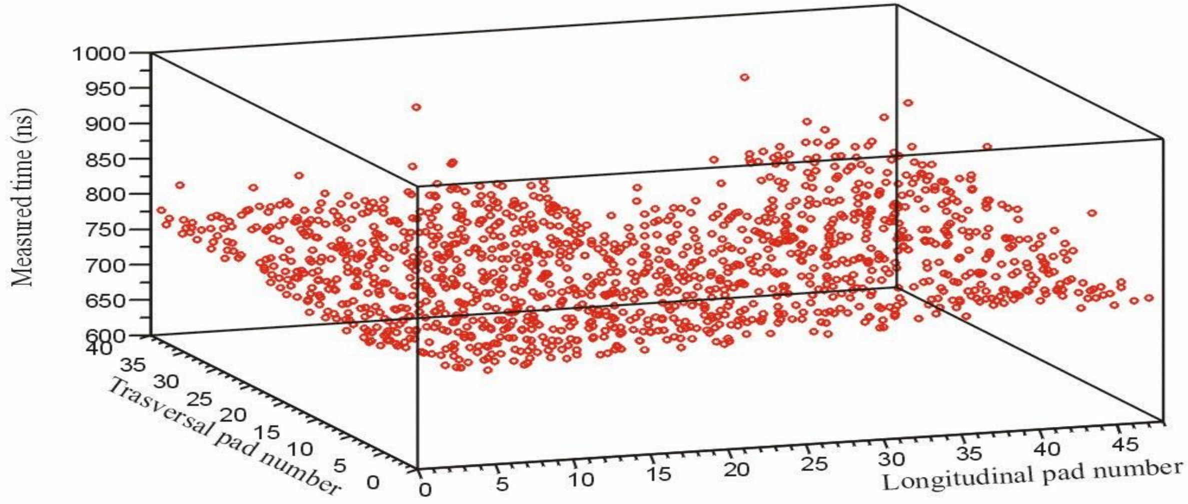


Operated in streamer mode (Ar-isobutane-Freon) HV 7-8 kV Veto efficiency: 97-99%/plane

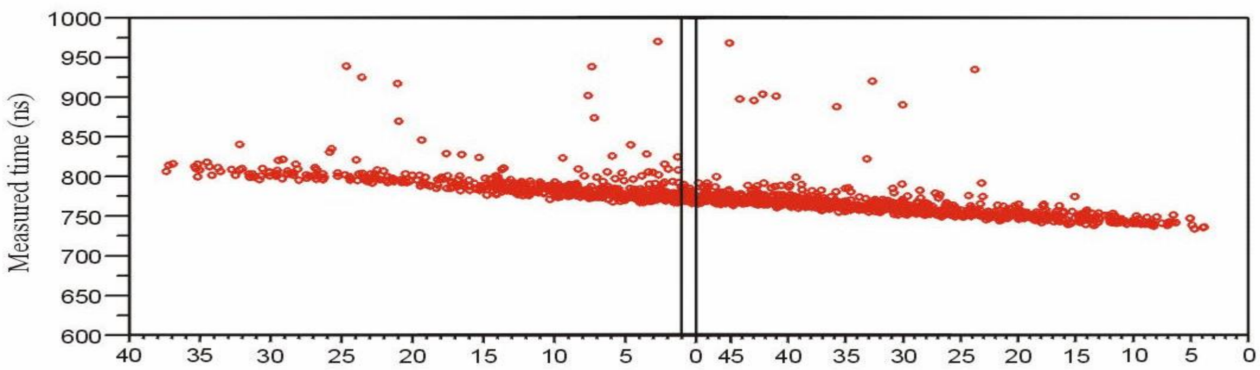
Trigger and tracking at accelerators

- WA92: 72 m^2 of RPC used as trigger on μ events with high p_t in semi-leptonic decays of the B (SPS at CERN)
- E771: 60 m^2 of RPC used as trigger and tracking come trigger on μ events with hig p_t in semi-leptonic decays of the B (Fermilab)

ARGO-YBJ



Picture of an event on 16 clusters



The same event from such a point of view
to appear as a plane

NCP contribution on CMS R&D

Pakistan was actively involved in the CMS RPC project since the R&D phase

- **PK-01/99** 400*400 mm^2 double gap RPC, Italian bakelite 1999. (non-oiled)
  PK-02/00 Full size RE2/2 chamber, tested at GIF in 2000, phenolic bakelite gaps fabricated in Italy ($\rho \approx 10^{10}\Omega$, not-oiled)
- **PK-03/01** Full size RE2/2 chamber, tested at GIF in 2001,melaminic bakelite gaps ($\rho \approx 10^{10}\Omega$, not-oiled)
- **PK-04/02** Full size RE2/2 chamber, tested at GIF in 2002, gaps supplied from Korea ($\rho \approx 10^{10}\Omega$ cm, not oiled)
- **PK-05/03** Full-size RE2/2, tested at GIF in 2003, gaps supplied from Korea ($\rho \approx 10^{10}\Omega$ cm, oiled))

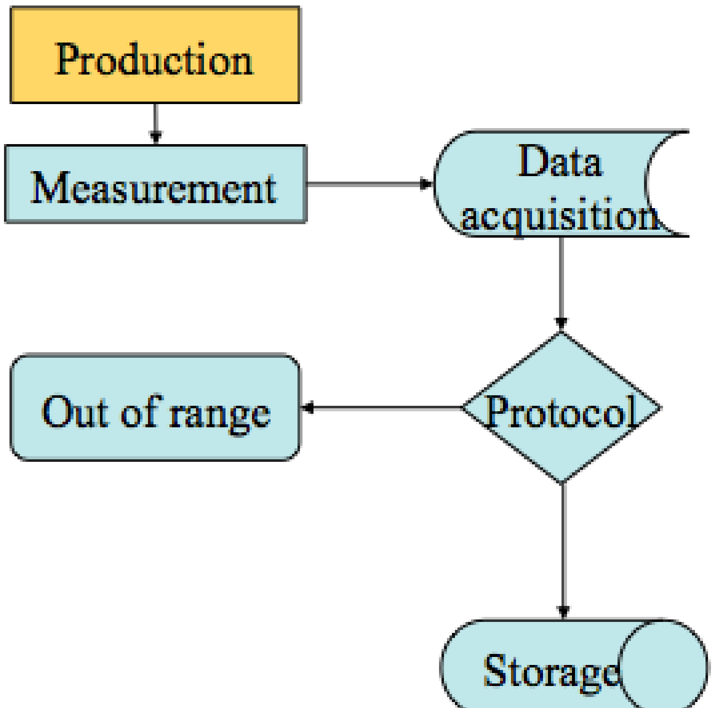
1999 (400*400 mm^2)

2000 Full Size

2003 Full Size

Bakelite quality control

CMS example



Bulk resistivity ρ

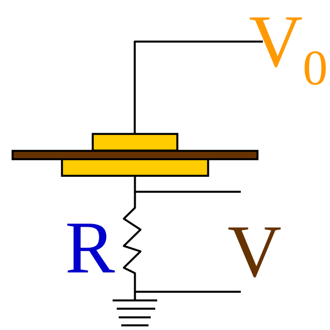
Determines the time constant of an elementary RPC cell and the rate capability

Average roughness R_a

It is related to the quality of the surface. A small R_a reduces spontaneous discharges which might affect the RPC rate capability

Dielectric constant ε_r

It is related to τ and to the average fast charge q_e of a single avalanche



$$\rho = k\ V_0/(V/R)$$

k = geometrical factor (98.17)

V_0 = 500 V

R = 10 or 100 kΩ

CMS RPCs production @ NCP

66% of Endcap chambers (288 + 10 % contingency) have been produced in NCP lab…

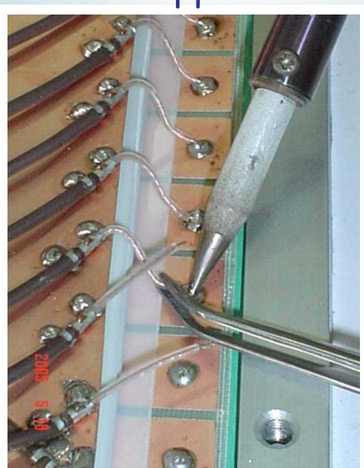
Gas leak test, Spacer test and HV vs Dark Current test on the gas gaps

Copper sheet

Gas pipes at inlet

Readout strips sheet

Assembly Procedure



Soldering

Mounting of FEBs

Conclusions: the RPC from 1981 to nowadays

The RPC are gas detector are extensively used in several experiments
A lot of progress on detector performance done:

- **Rate capability** from 10 Hz/cm^2 to 30000 Hz/cm^2
- **Time resolution** from 1 ns to 50 ps
- **Space resolution** from 1 cm to 0.01cm
- Stable detector performance at LHC experiment

- ….while keeping the same simple structure which always allowed to scale the detector to large surfaces

The Secret?

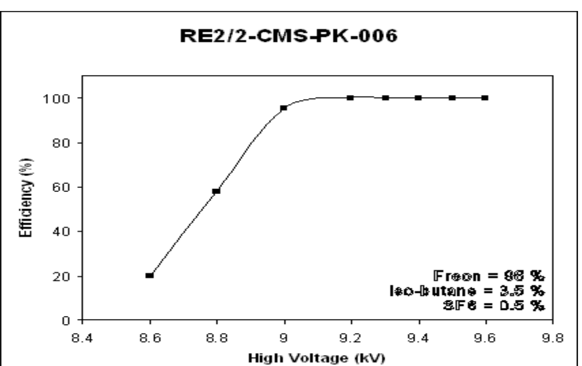
- Right choice of materials and electronics
- Severe QC and AQ during construction
- Continuously monitoring of the detector performance during the LHC operation and maintenance during the LHC showdown

Looking forward for future applications of the RPCs

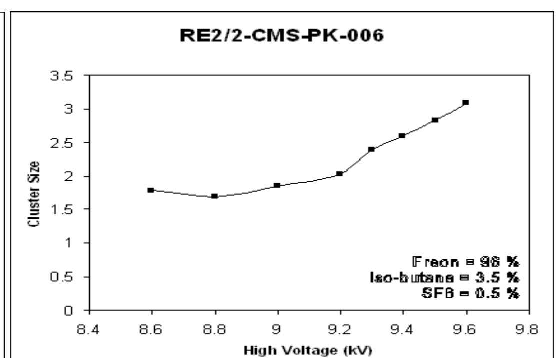
CMS RPCs validation @ NCP

… tested in NCP cosmic test lab….

…and Shipped to CERN



Efficiency



Cluster size