Novel Detectors and Technology R&D

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with the help of:

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Preliminary caveat

One of the main goals of the HL-LHC ECFA workshop is to **find synergies between different LHC experiments**, and possible follow-up in terms of common R&D.

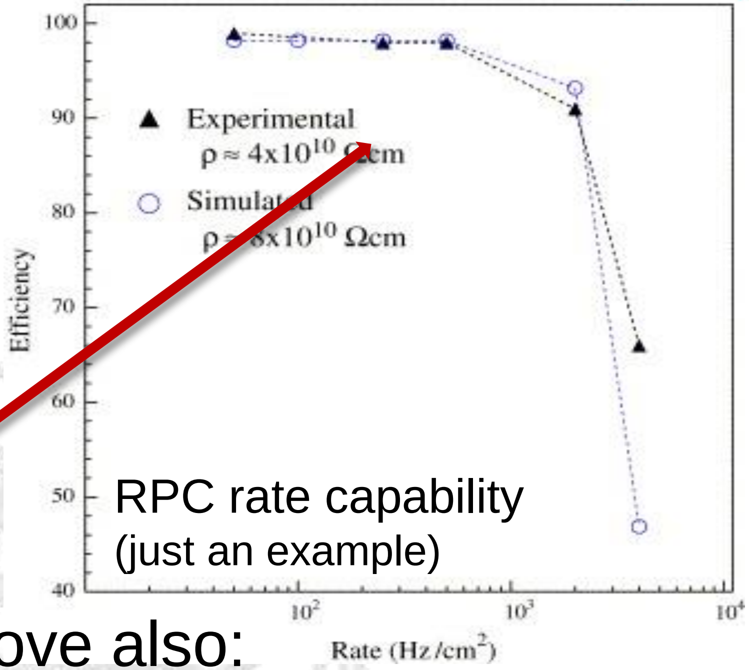
Therefore the approach of this talk will not be

- **"experiment-oriented":**
  - ✓novel detectors in ATLAS
  - ✓novel detectors in CMS
  - ✓… then ALICE, then LHCb

- **but "detector-oriented":**
  - ✓GEMs in CMS, ALICE and LHCb
  - ✓Micromegas in ATLAS
  - ✓Thin-Gap Chambers in ATLAS
  - ✓improved RPCs in CMS, ATLAS

Why do we need “new” detectors during Phase II?

- All detectors foreseen for post-LS3 **should stand a rate capability higher than the present**
  - ✓Because installed in high-η regions (typically endcaps, close to the pipe)
  - ✓From 1 kHz/cm^2 → 5-10 kHz/cm^2



RPC rate capability
(just an example)

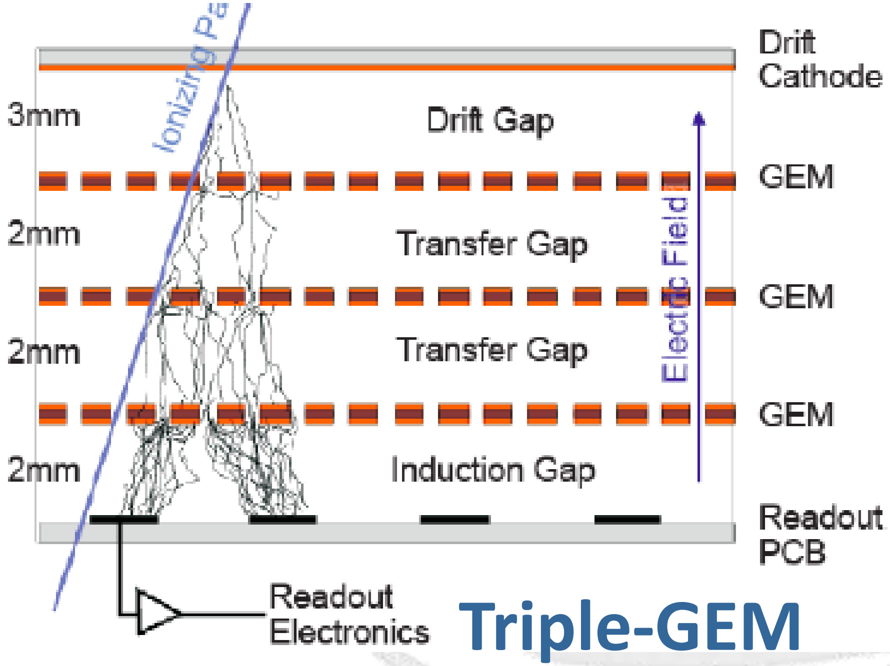
- In addition it could be needed to improve also:
  - ✓Spatial resolution – from O(1 cm) → O(1-0.1 mm)
    - Mandatory in case of trigger requirements, see K. Hoepfner’s talk
  - ✓Time resolution – from O(1 ns) → O(100 ps)
    - Useful for background rejection (and else)

Given requirement on rate capability,

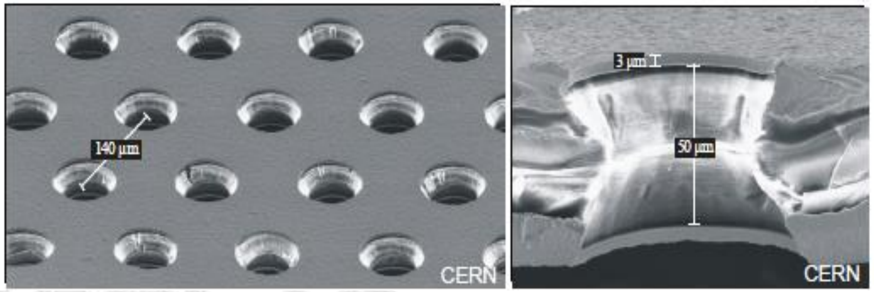
choice of the technology will be driven by the physics case:

- ✓plus robustness, cost, ease of construction, etc.

GEMs: Principles of operation



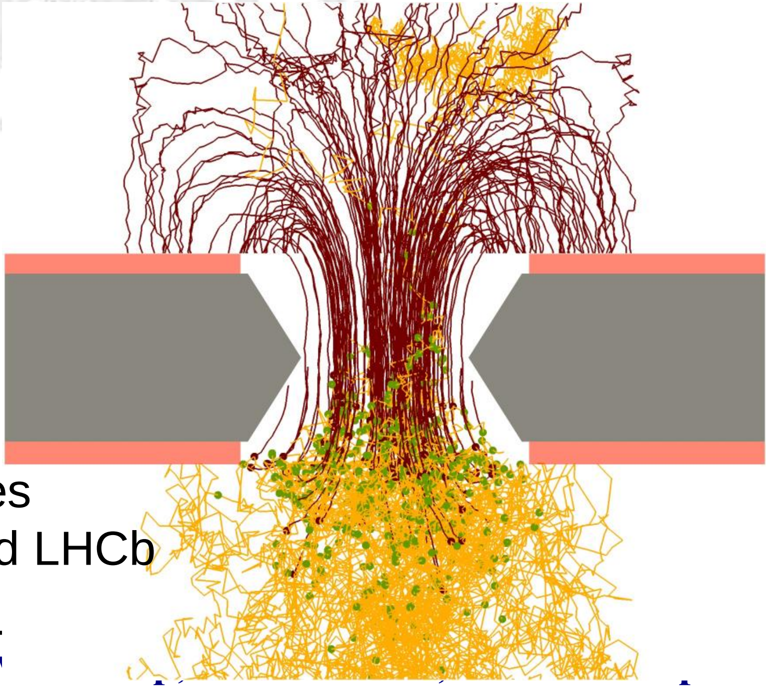
Gas Electron Multipliers (GEMs) are made of a copper-kapton-copper sandwich, with holes etched into it



Electron microscope photograph of a GEM foil

Triple-GEM

Invented by F. Sauli in 1997

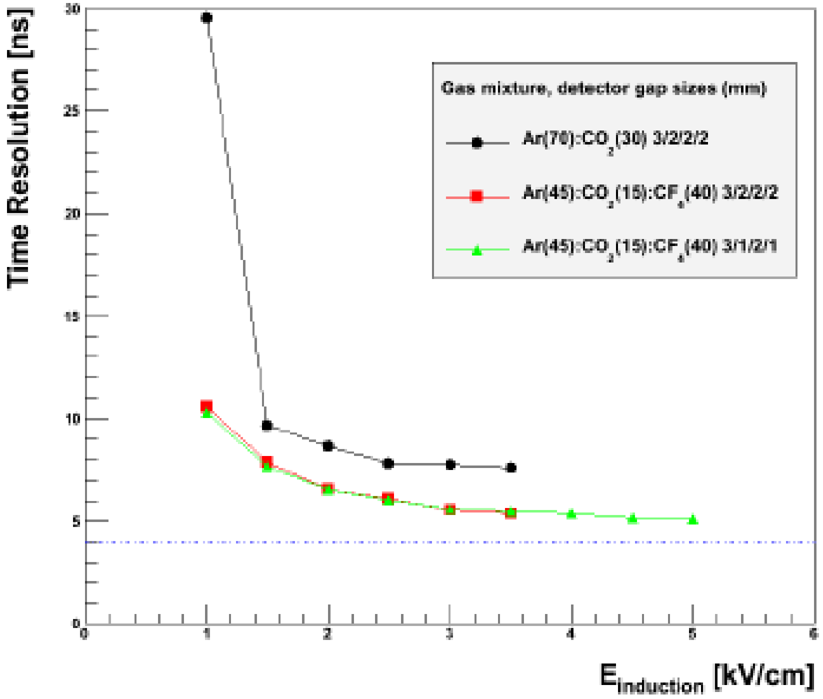


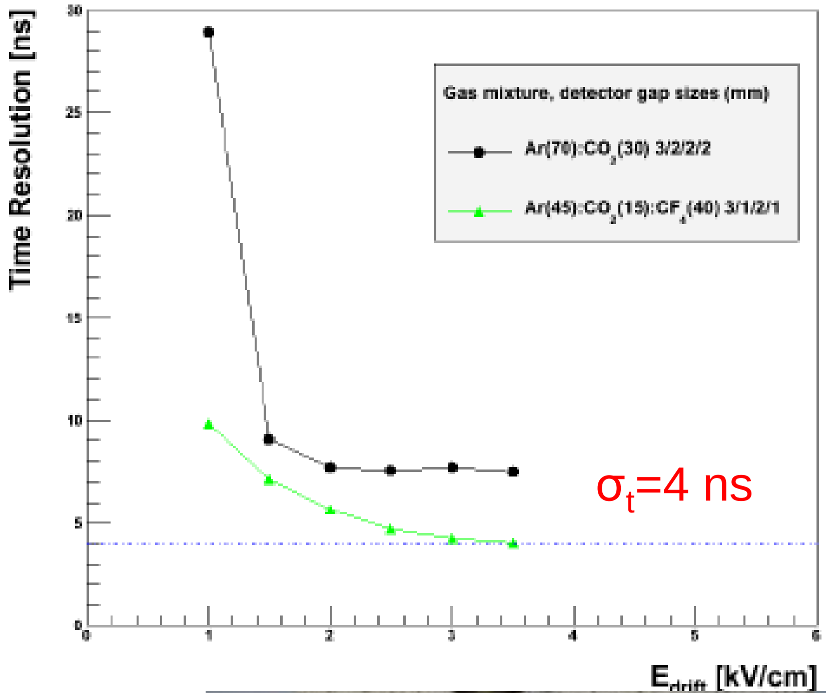
Main characteristics:

- ✓ Excellent rate capability: up to $10^5/cm^2$
- ✓ Gas mixture: $Ar/CO_2/CF_4$ – not flammable
- ✓ Large areas ~1 m x 2m with industrial processes
- ✓ Long-term operation in COMPASS, TOTEM and LHCb

GEMs for CMS: performance

Timing studies



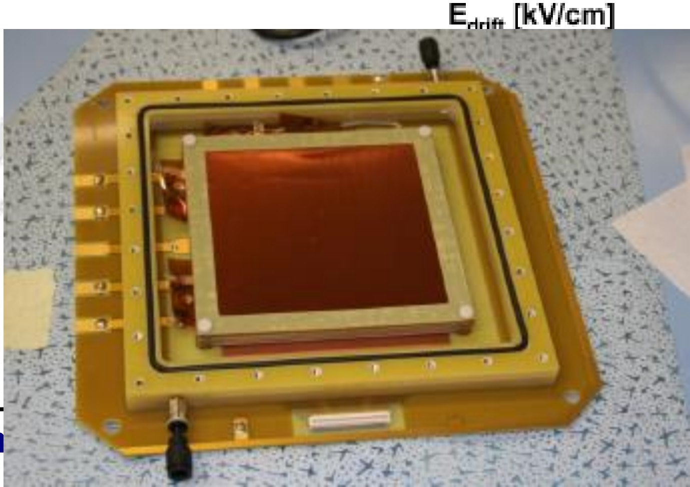


First small size prototypes (2010):

✓Custom made HV divider for standard triple-GEM

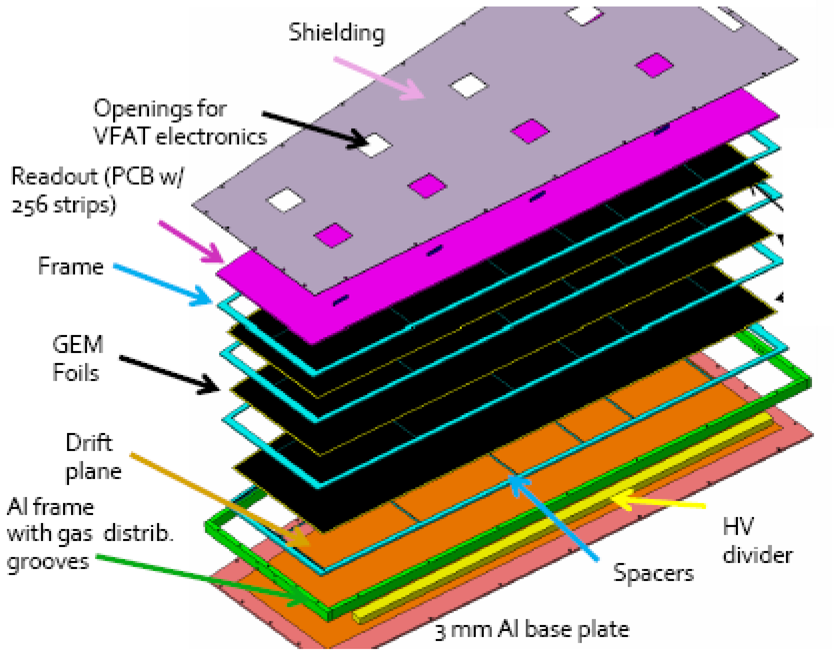
✓Clear effect of gas mixture, and induction and drift fields

✓Timing resolution of 4 ns reached

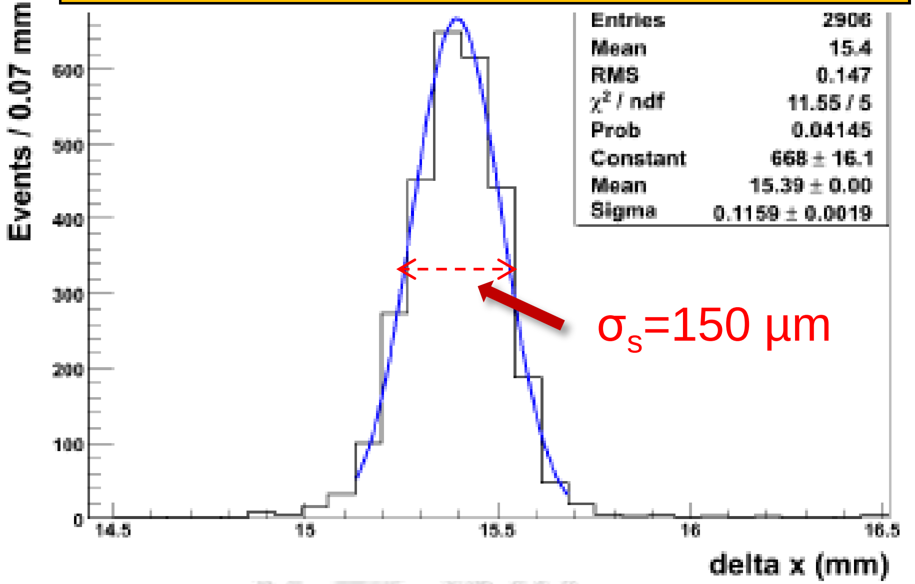


GEMs for CMS: performance

Position resolution (full size prototypes)

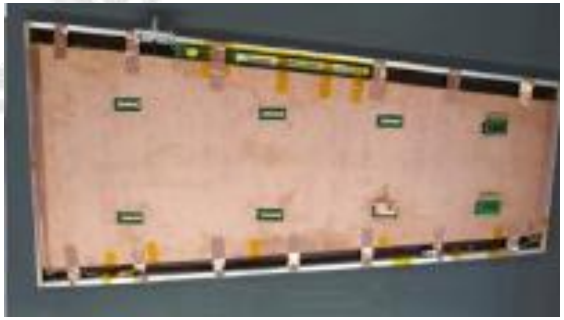


Δx_{hit} measurement :
Tracker GEM vs. CMS full-size GE1/1



σ_s=150 µm

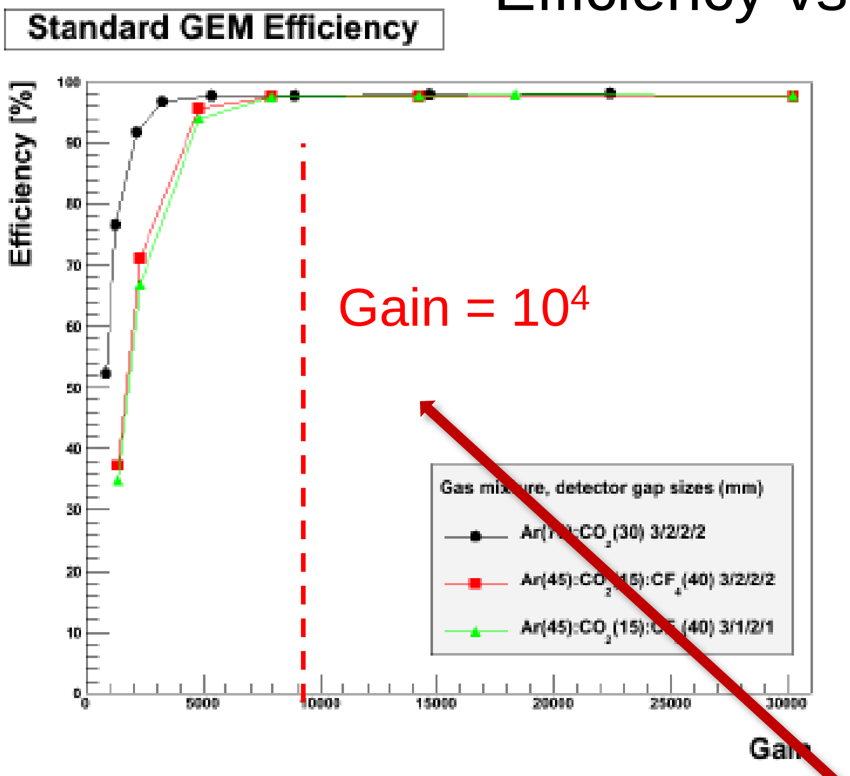
- ✓**Largest GEM built at that time (2011)!:**
  Active area 990 x (220-445) mm^2
- ✓Gap sizes: 3/2/2/2 mm
- ✓Single mask foils with spacer frames
- ✓35 HV sectors per GEM foil, ~ 100 cm^2 each
- ✓1024 channs, 4 η partitions, 2 columns; 0.8-1.6 mm strip pitch



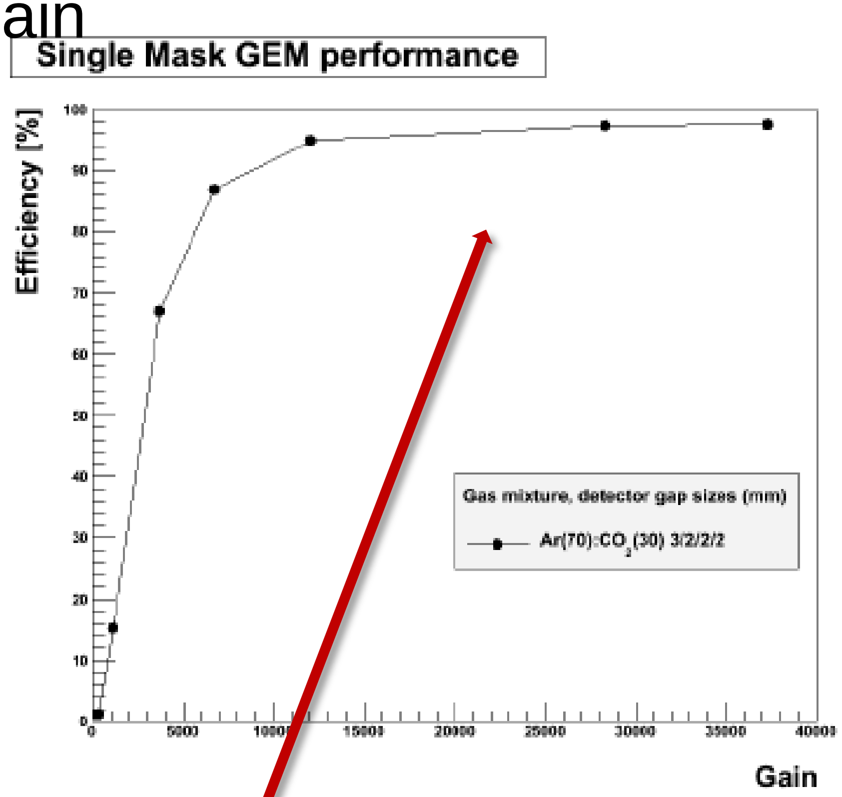
GEMs for CMS: performance

Efficiency vs. gain

Standard GEM Efficiency



Single Mask GEM performance



- ✓Full efficiency at low "single GEM" gain:
  - ✓ negligible sparking probability
- ✓comparison (and validation) between double and single mask techniques

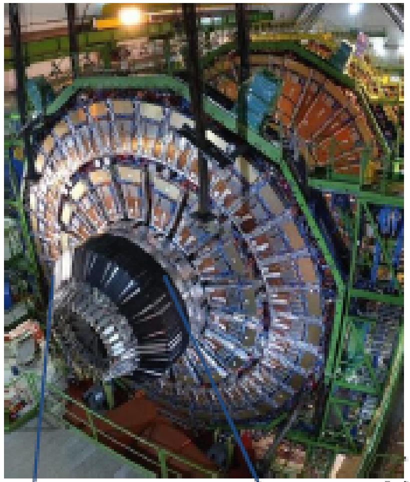
Now, the 4th detector generation built

R&D for a High-η Trigger and Tracking Detector for CMS, SLHC RD10.02

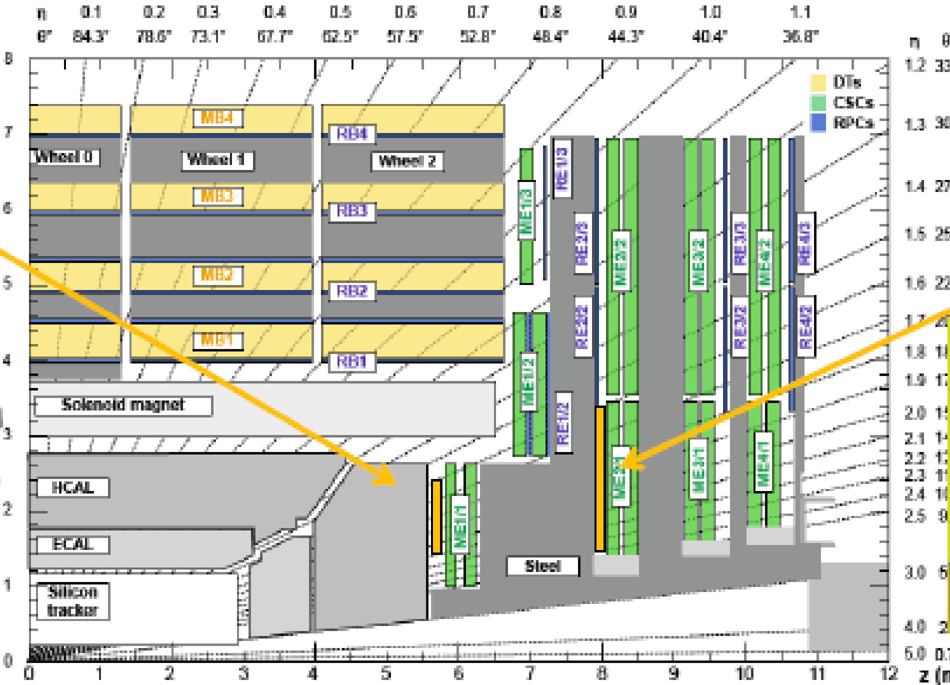
The CMS GEM project

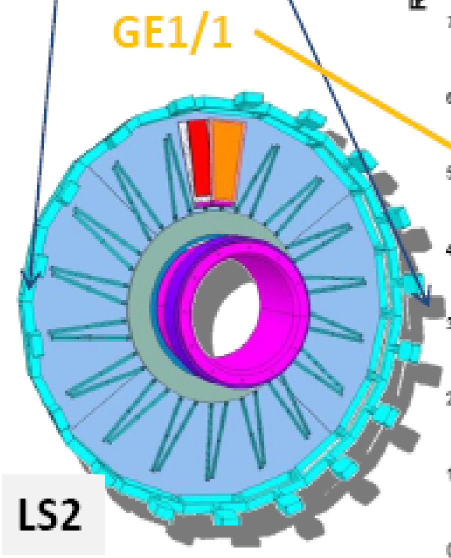
Install triple-GEM detectors (double stations) in 1.6 < | η | < 2.1-2.4 endcap region

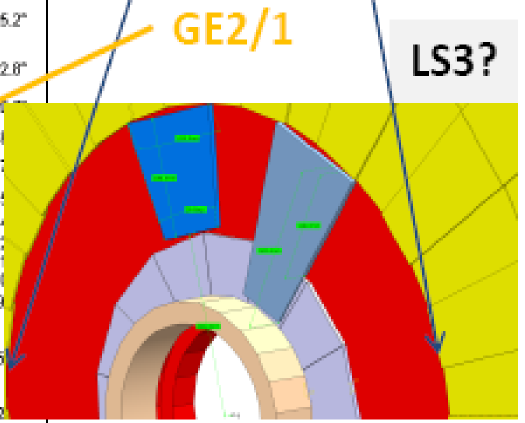
- ✓Restore redundancy in muon system for robust tracking and triggering
- ✓Improve L1 and HLT muon momentum resolution to reduce or maintain global muon trigger rate
- ✓Ensure ~ 100% trigger efficiency in high PU environment



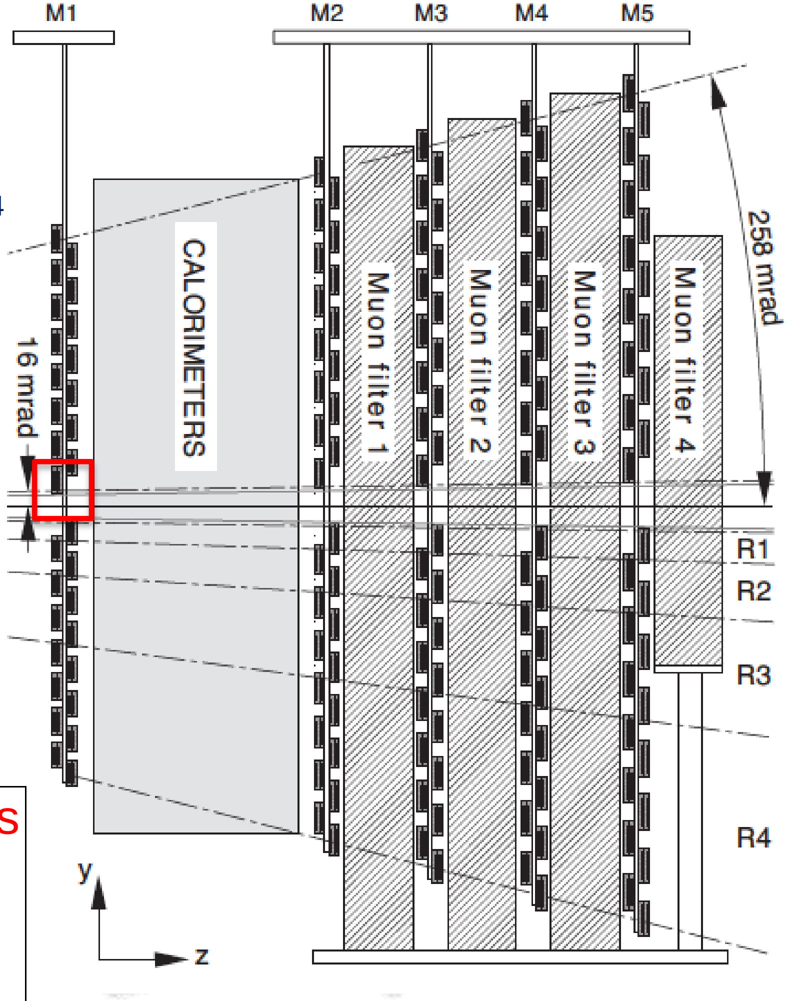
A new VFAT3 based FE electronics, developed to fully profit from GEMs performance, is an important part of the project (M. Ishino’s talk)







GEMs for the LHCb Muon Detector



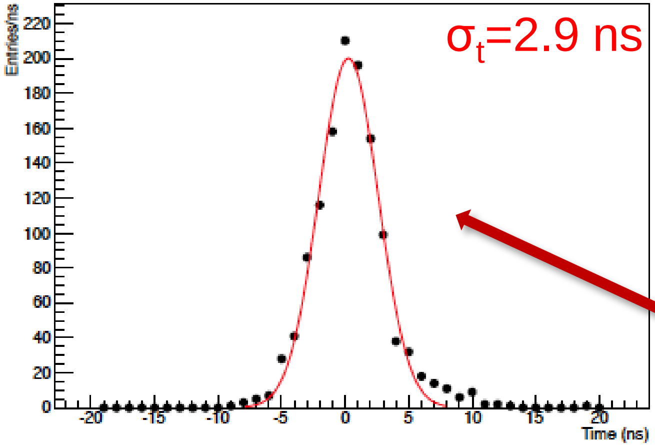
LHCb Muon Group made a long and detailed R&D on GEM based detectors. Main innovations were:

- ➢The use of a high yield, “fast” gas mixture based on CF_4
  - ✓very high detection efficiency;
- ➢The use of stretched GEM
  - ✓a simpler and reliable assembly procedure.

✓The Muon System, is composed of five stations (M1-M5). The full system comprises 1380 chambers (mostly MWPC).

✓Internal part of M1 (R1) is currently **equipped with 12 GEM based detectors** (made by two OR-ed Triple-GEM Chambers).

Thanks to the good performance achieved, LHCb was the first LHC experiment to use GEMs.



Time resolution of a (Double) triple-GEM detector using a $Ar/CO_2/CF_4$ 45/15/40 gas mixture with logically-ORed pad readout (from beam tests).

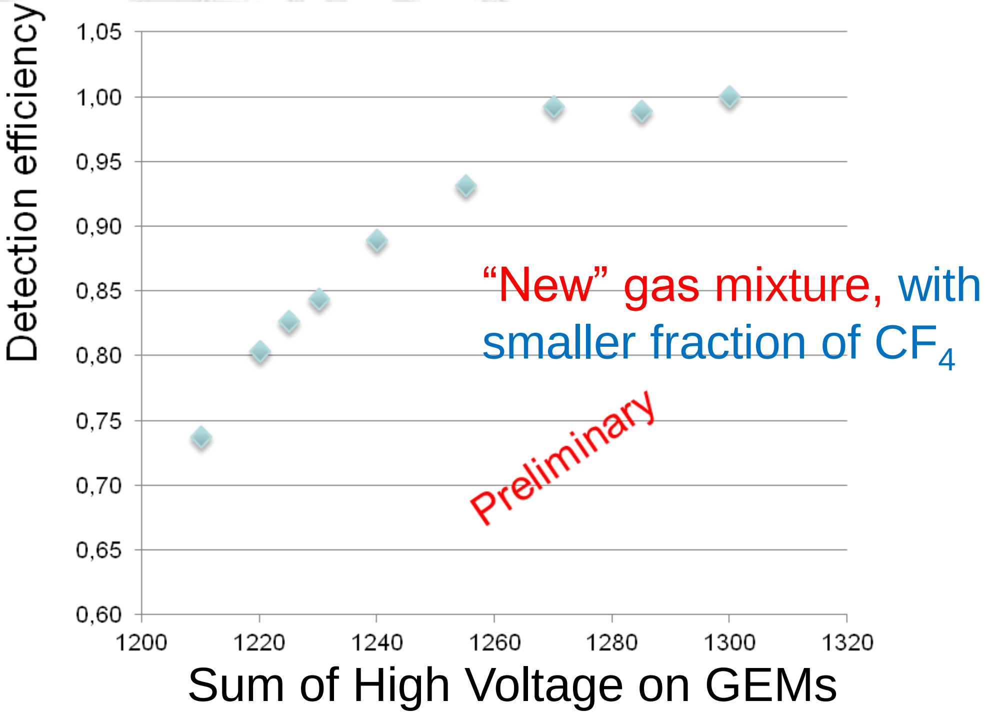
LHCb R&D on gases

In HL conditions, the station M1 will be removed. In the internal regions of M2, at a luminosity of 10^{33} cm^2 s^{-1} , particle rates of the order of 100 kHz/cm^2 are foreseen

substitute the four-gap MWPC in the hottest regions of M2 with GEM detectors

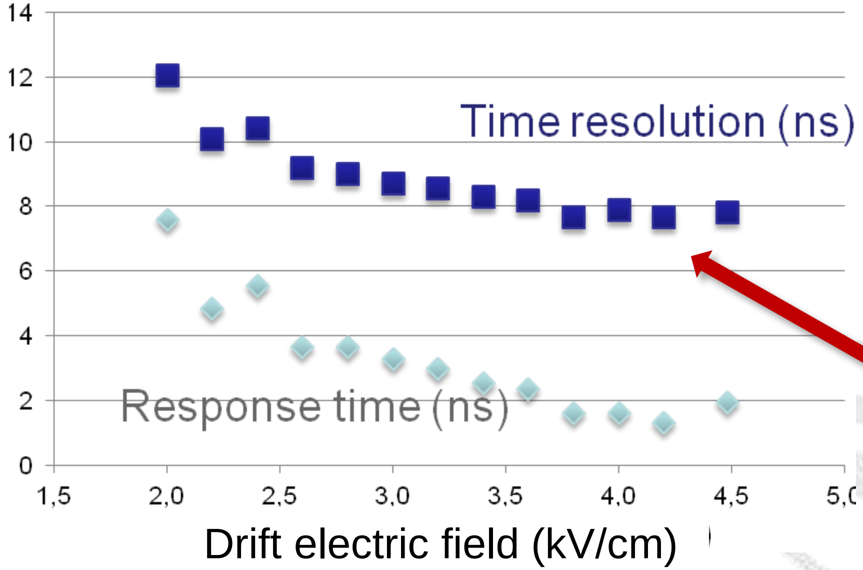
To minimize the impact of such a choice, using the same gas mixture in use for MWPC ($Ar/CO_2/CF_4$ 40/55/5) is being investigated.

- ✓ The use of a small fraction of CF_4 (5% instead of 45%) reduces the electron drift velocity and might spoil the GEM detector time resolution;
- ✓ What would happen to the performance of the GEM detectors?
- ✓ An R&D to study the performance GEM Detectors with the new gas mixture is going on.



"New" gas mixture, with smaller fraction of CF_4

Optimization of parameters



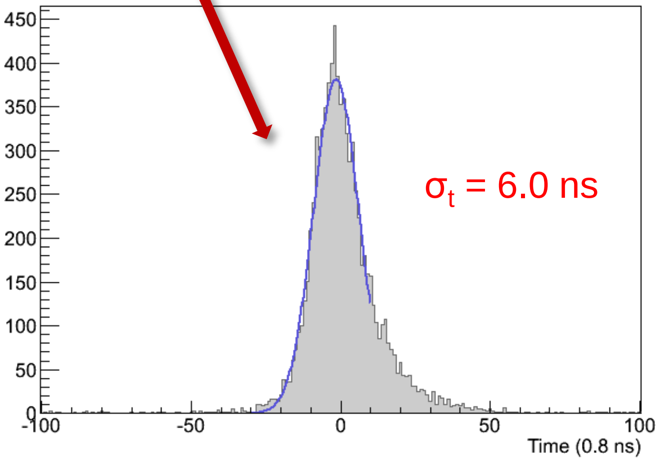
An important parameter for operating on LHC is the detection efficiency in a 25 ns window;

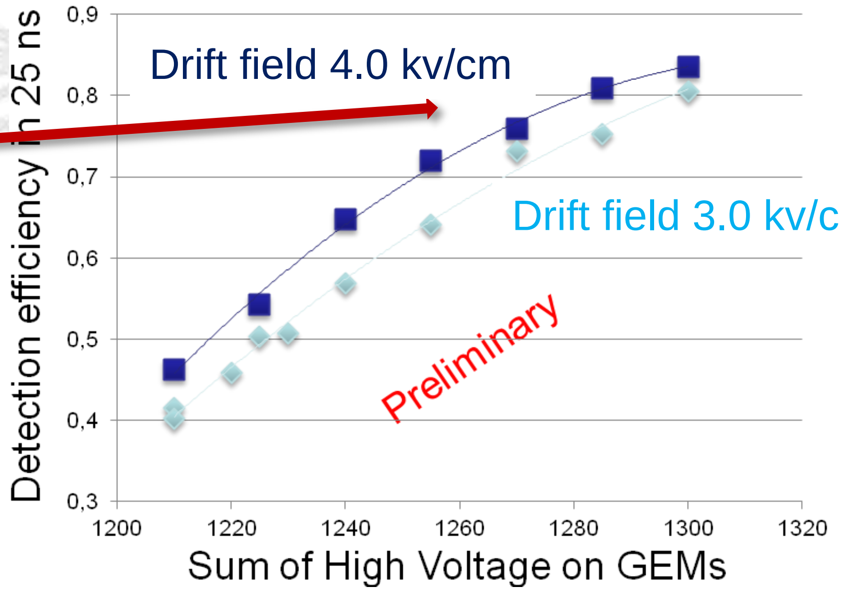
✓This parameter is related to the time resolution of the detector which is inversely proportional to the drift velocity in the drift gap

For a drift field around 4 kV/cm the drift velocity is maximized and the time resolution is optimized

“New” gas mixture, with smaller fraction of CF_4

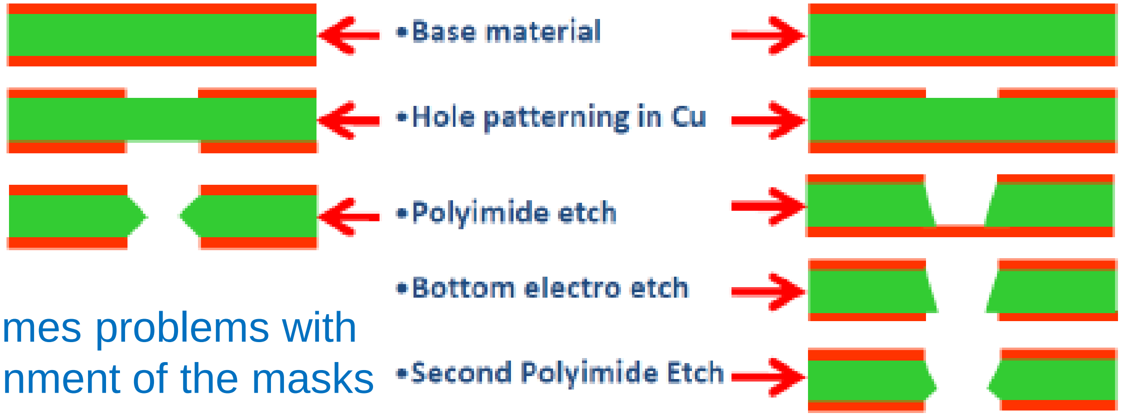
A resolution of about 6 ns was obtained for the (single) triple-GEM detector resulting in a 84% efficiency in a 25 window ns





Common items

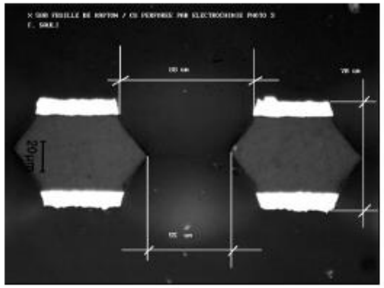
Single side etching technique



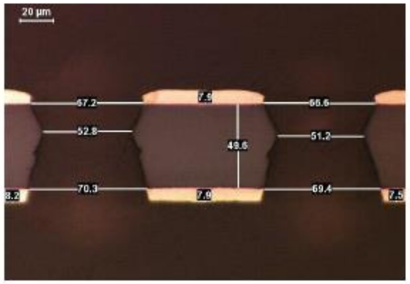
- Base material
- Hole patterning in Cu
- Polyimide etch
- Bottom electro etch
- Second Polyimide Etch

Overcomes problems with the alignment of the masks

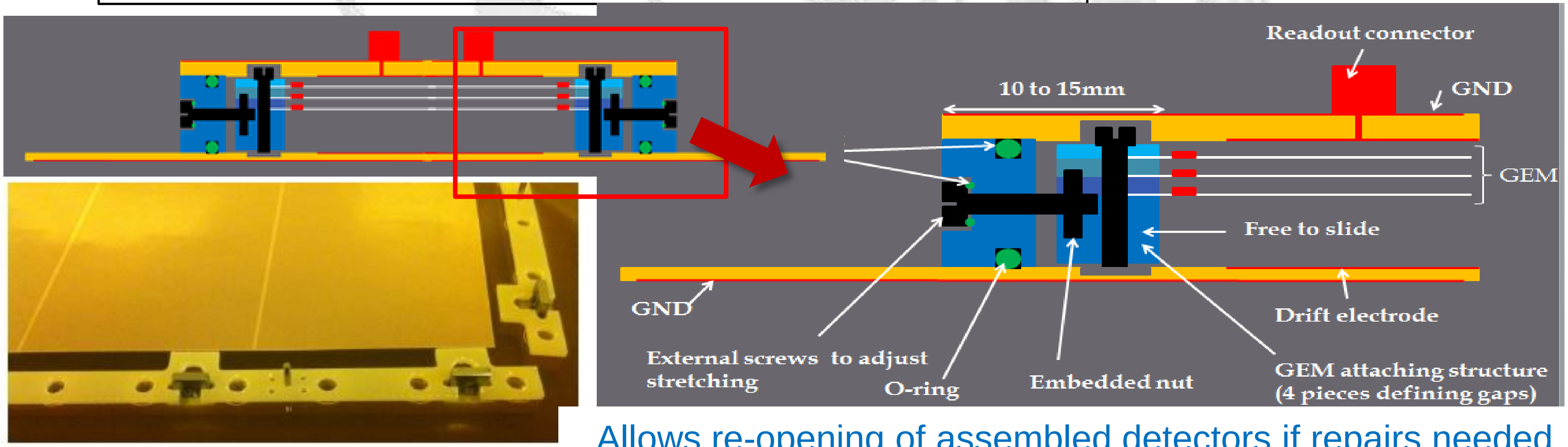
Achieved 40x40cm^2



Achieved 200x60cm^2



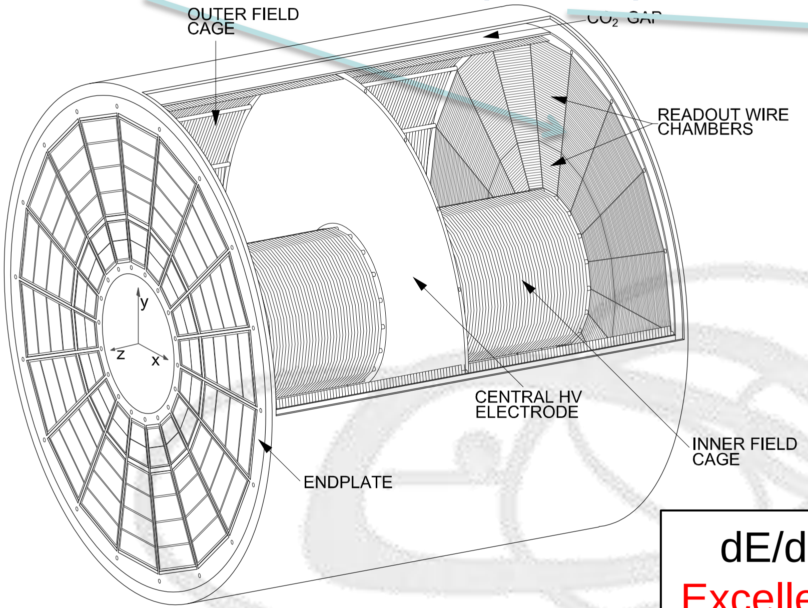
Stretching assembly technique without spacers (CERN)

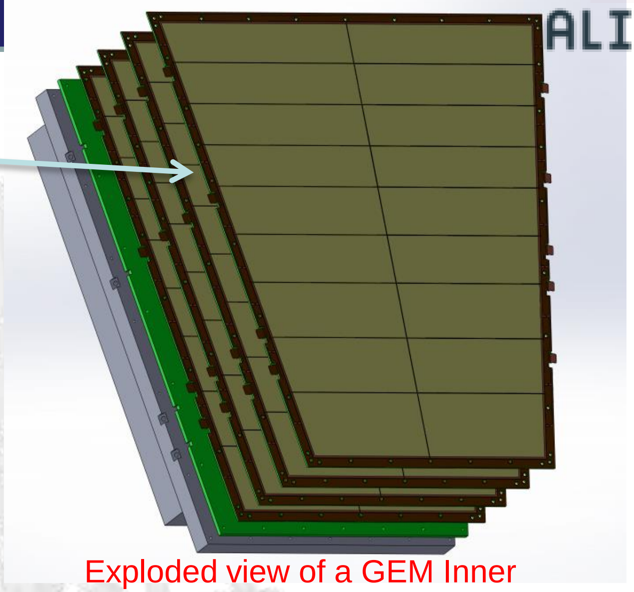


Allows re-opening of assembled detectors if repairs needed

ALICE TPC upgrade with GEMS

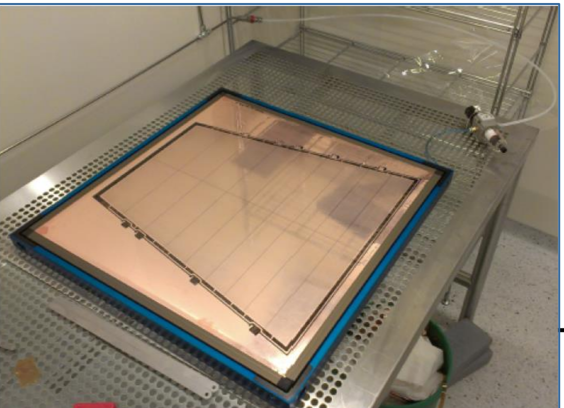
Replace wire chambers with quadruple-GEMs





Exploded view of a GEM Inner Readout Chamber (IROC)

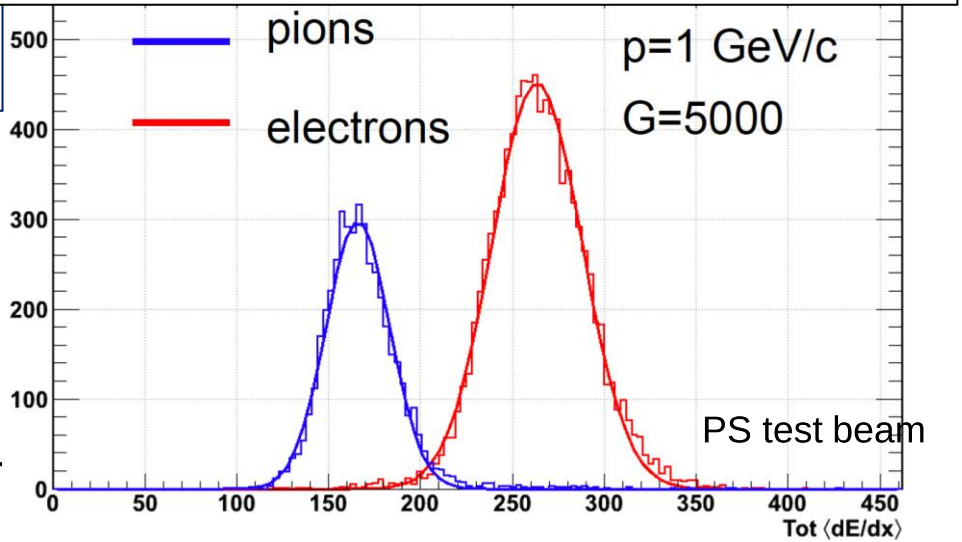
Because of ion backflow in the field cage MWPC not compatible with 50 kHz operation



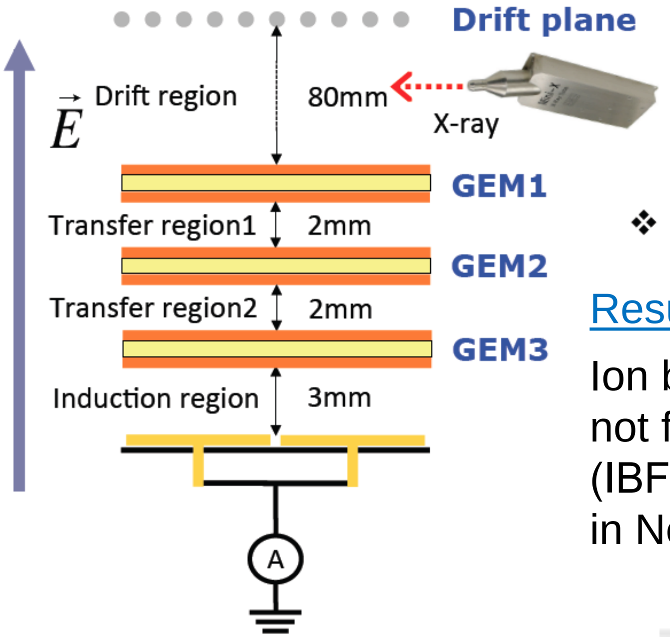
Choice of quadruple-GEM detectors to minimize ion backflow

dE/dx spectrum of 1GeV/c electrons and pions

Excellent TPC performance maintained with GEMs



Ongoing R&D – ion backflow

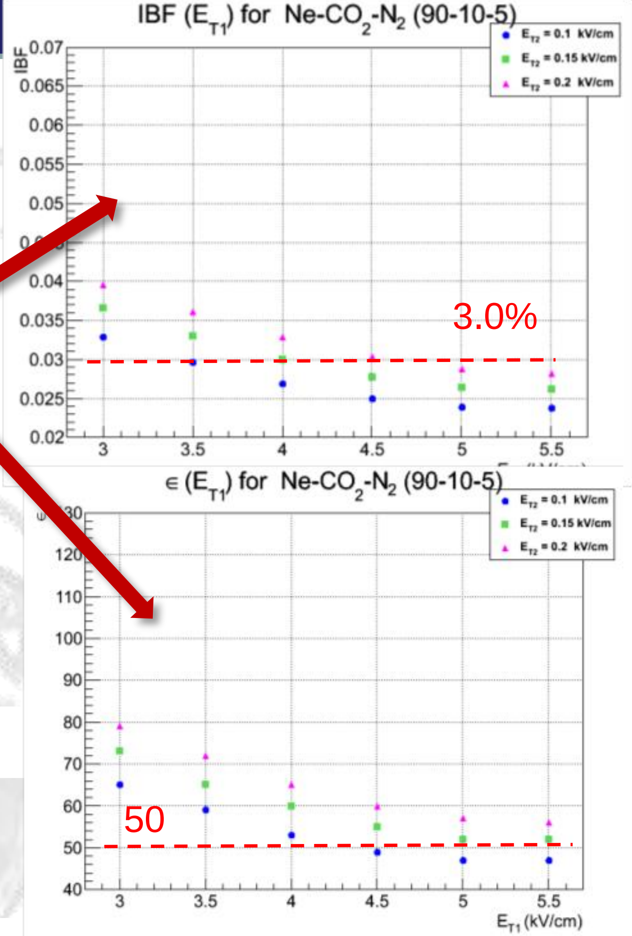


❖ ε : number "back-drifting" ions per electron reaching the GEM stack

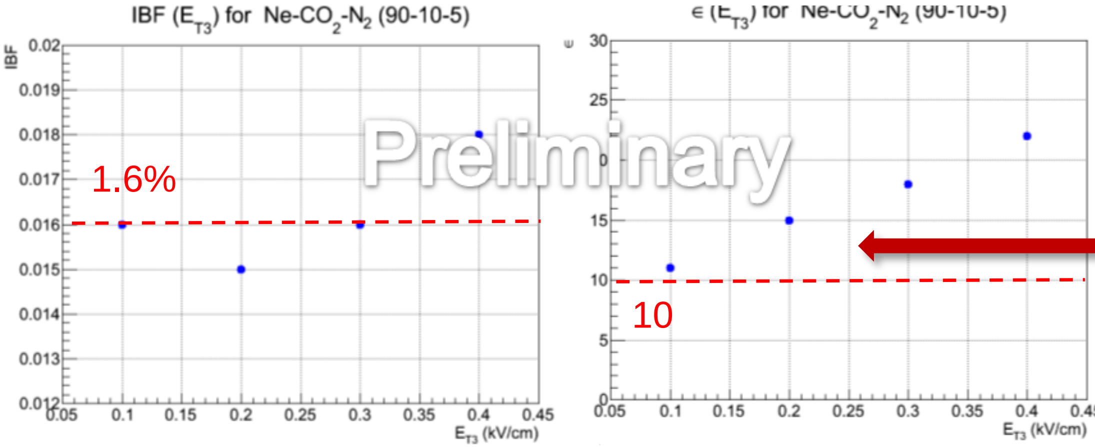
IBF=$I_{drift}/I_{readout}$

Results for triple-GEM

Ion back-flow (IBF) and ε do not fulfill ALICE requirements (IBF ≤ 1%, ε ≤ 10 at gain 2000 in Ne-based mixture)



Results for quadruple-GEM stack-up with GEM-#3 with x2 pitch



Preliminary results with quadruple-GEM chambers are very promising (in the ballpark of the target value)

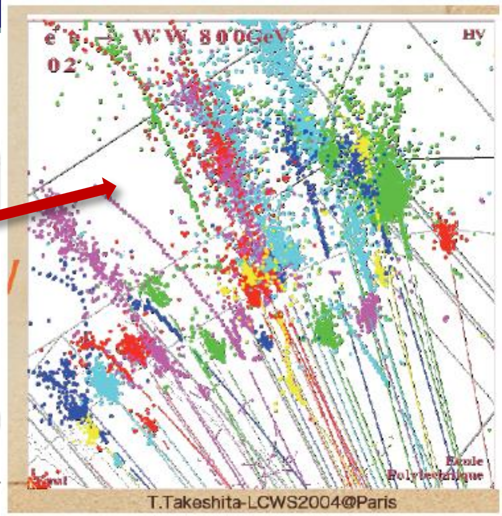
✓Further optimization in progress

GEMs for calorimetry

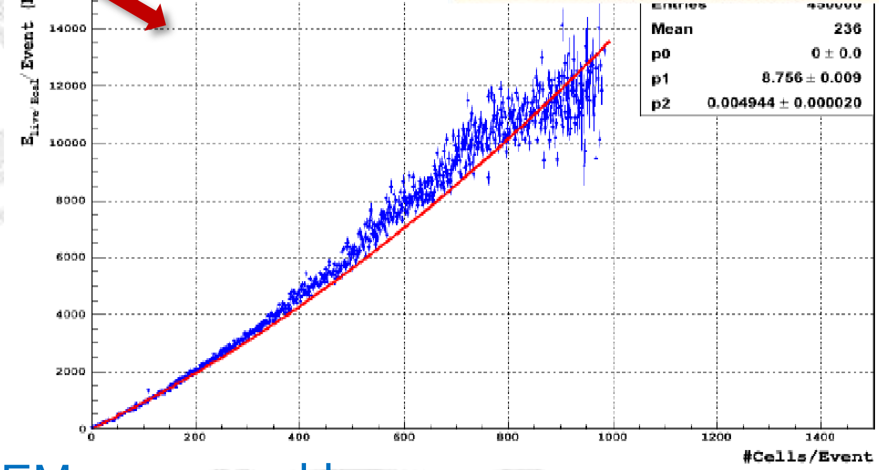
Proposed a few years ago in the ILC framewok (synergies…)

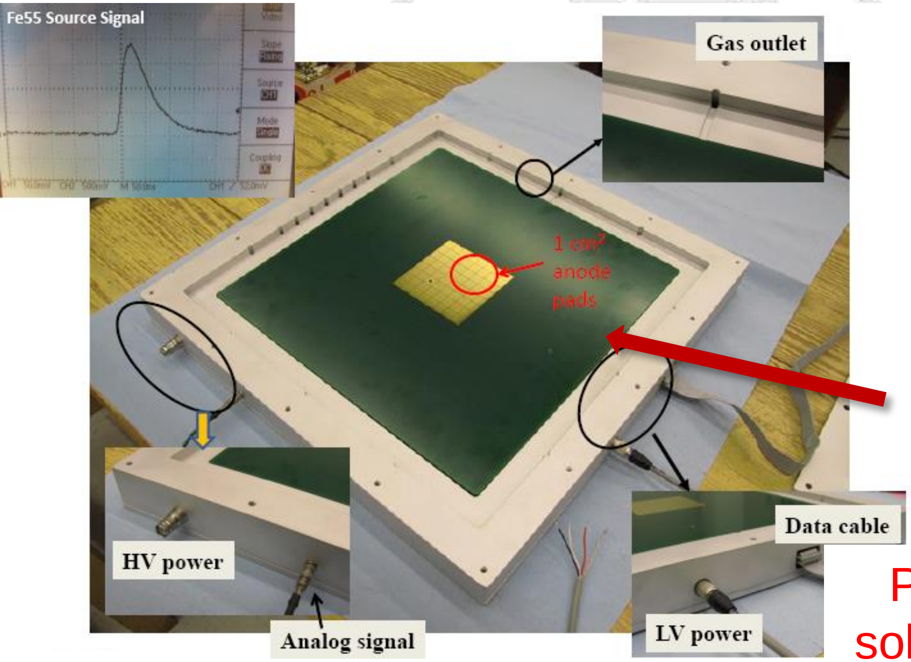
Digital calorimetry approach:

- ✓ Cell is either ON or OFF
- ✓ High granularity for charged particle tracking
- ✓ Good correlation between particle energy and numbers of cells hits
- ✓ Requires development of Particle Flow algorithm



T.Takeshita-LCWS2004@Paris





GEMs proposed because:

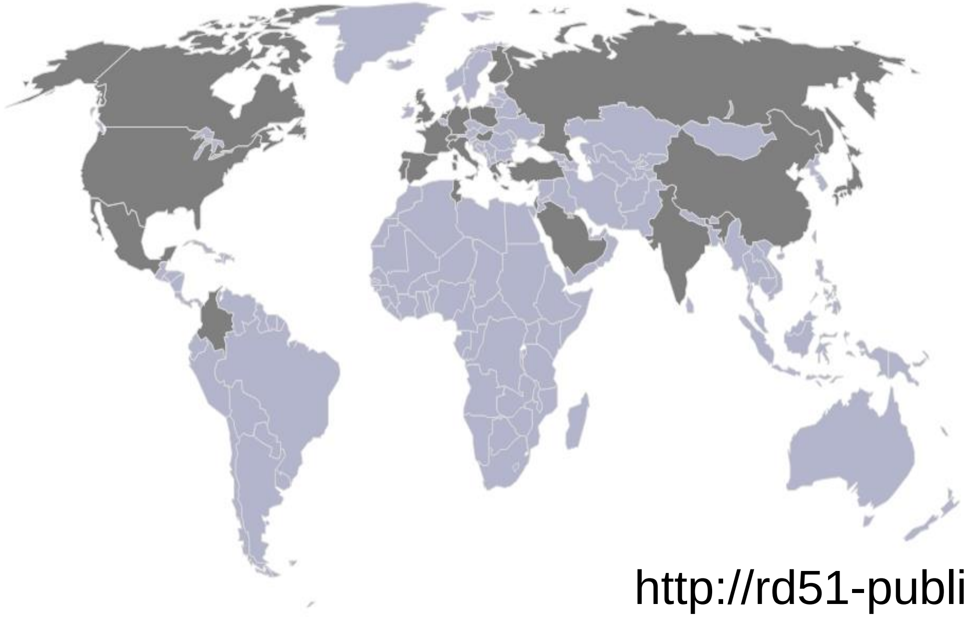
- ✓ Easy to implement small (~1x1 cm^2 cells)
- ✓ Fast and robust

Potentially quite interesting to find integrated solutions among calorimetry and muon systems

A perfect example of cross-fertilization: RD51 collaboration

RD51 MPGD Collaboration

~450 Authors from 75 Institutes from 25 Countries



Motivation and Objectives

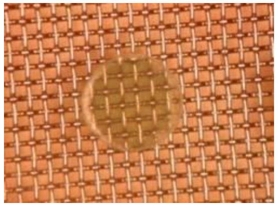
World-wide coordination of the research in the field to advance technological development of Micropattern Gas Detectors.

✓Foster collaboration between different R&D groups; optimize communication and sharing of knowledge/experience/results concerning MPGD technology within and beyond the particle physics community

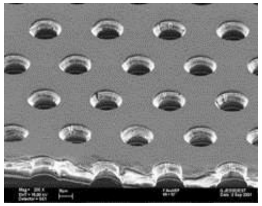
✓Investigate world-wide needs of different scientific communities in the MPGD technology

✓Optimize finances by creation of common projects (e.g. technology and electronics development) and common infrastructure (e.g. test beam and radiation hardness facilities, detectors and electronics production facilities)

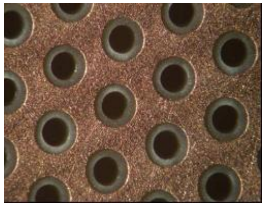
http://rd51-public.web.cern.ch/rd51-public/Welcome.html



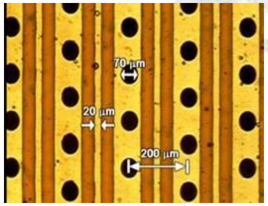
MicroMegas



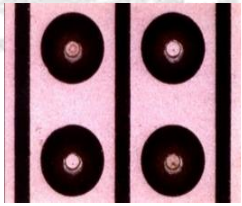
GEM



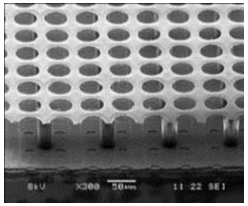
THGEM



MHSP



MicroPIC

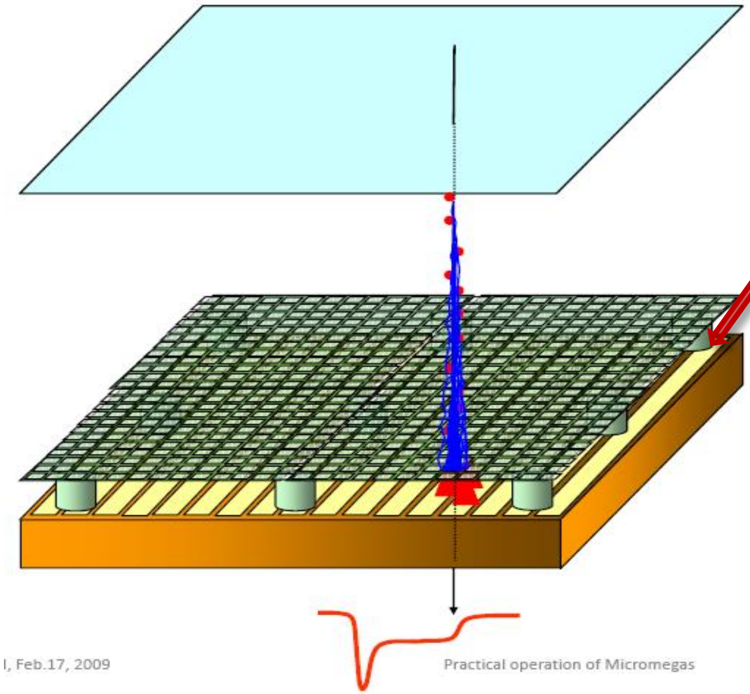


Ingrid

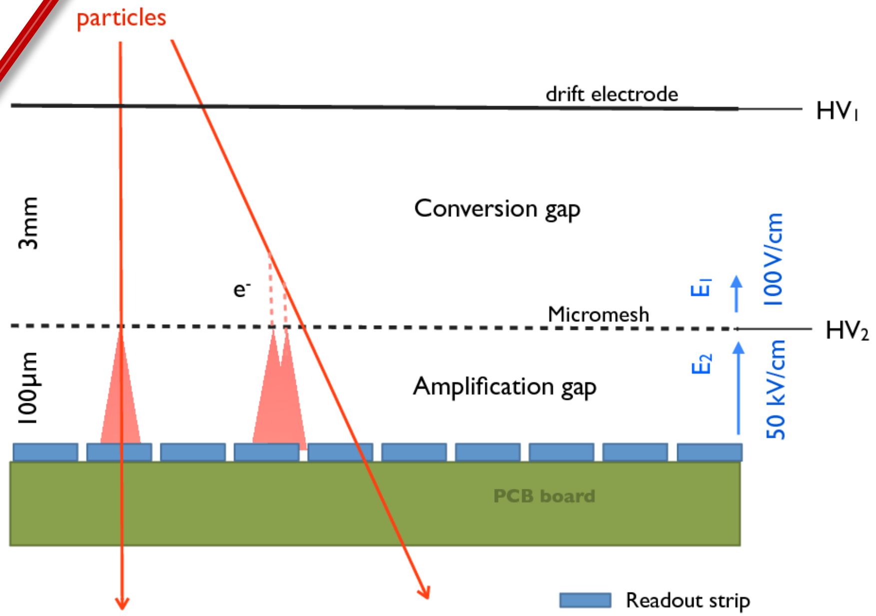
MMs: Principles of operation

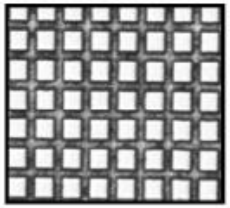
Y. Giomataris, PH. Rebourgeard, JP. Roberts and G. Charpak, NIM A 376 (1996) 29

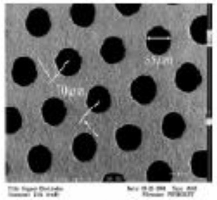
Micromegas (MMs) are parallel-plate chambers where the amplification takes place in a thin gap, separated from the conversion region by a fine metallic micro-mesh, supported by 50-100 µm insulating pillars.

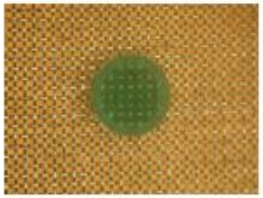

I, Feb.17, 2009

Practical operation of Micromegas




Electroformed

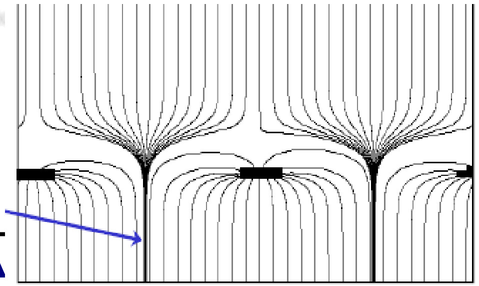

Chemically etched


Wowen


Deposited by vaporization

Different kinds of mesh

Funnel field lines:
high transparency to electrons

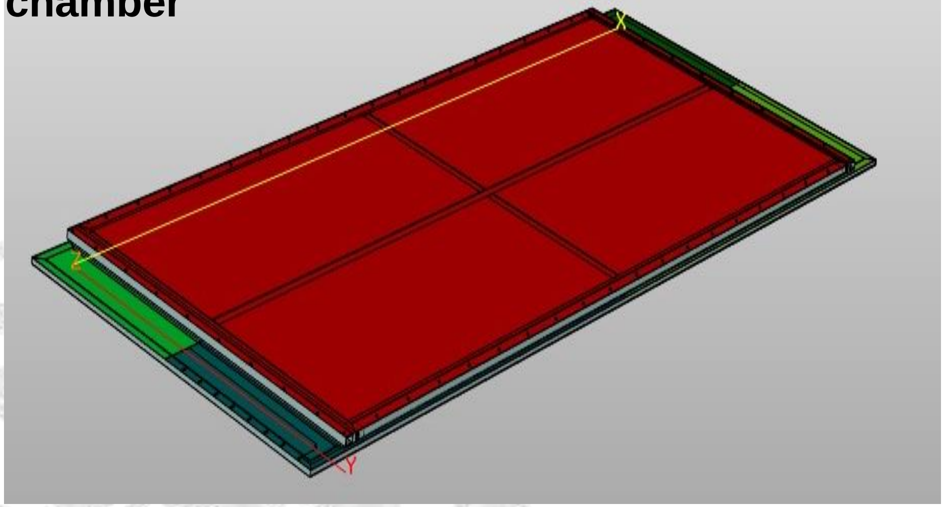


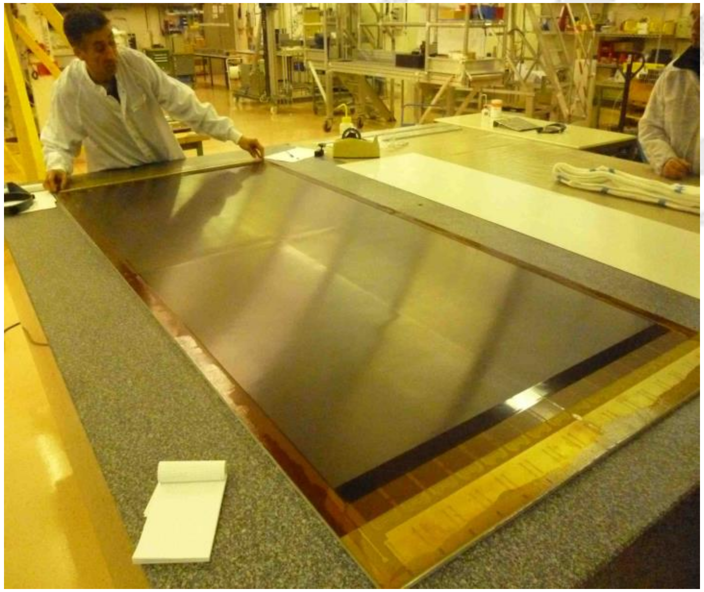
Micromegas for ATLAS

Micromegas have been chosen as precision measurement detectors (but also trigger) of the New Small Wheels of ATLAS

- ➢ First large system based on Micromegas

3D view of the first large (1 x 2.4 m^2) MM chamber





✓Detector dimensions: 1.5–2.5 m^2 per detector.

✓Combine precision and 2nd coord. measurement as well as trigger functionality in a single device

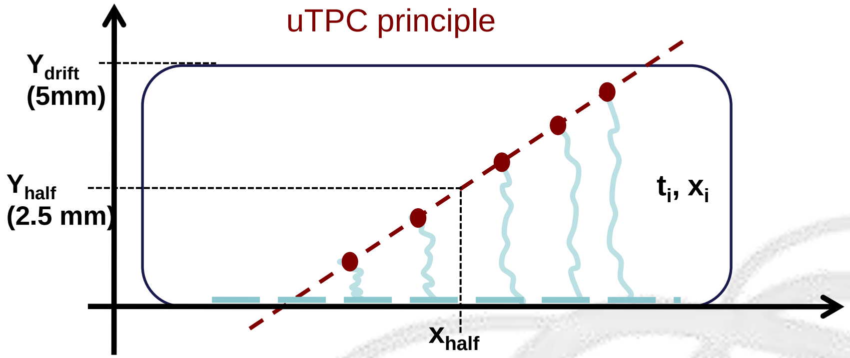
✓Each detector technology comprises eight active layers, arranged in two multilayers

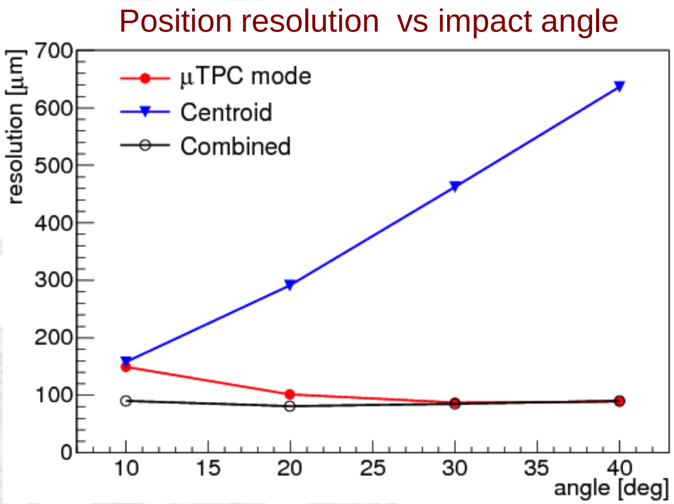
✓MM 2nd coord will be achieved by using ± 1.5° stereo strips in half of the planes.

- •2 M readout channels
- •A total of about 1200 m^2 of detection layers

Technology breakthroughs

Good spatial resolution also for inclined tracks thanks to µTPC operation mode

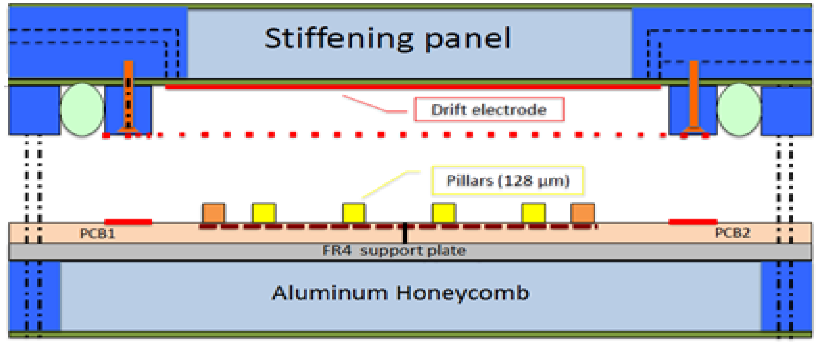


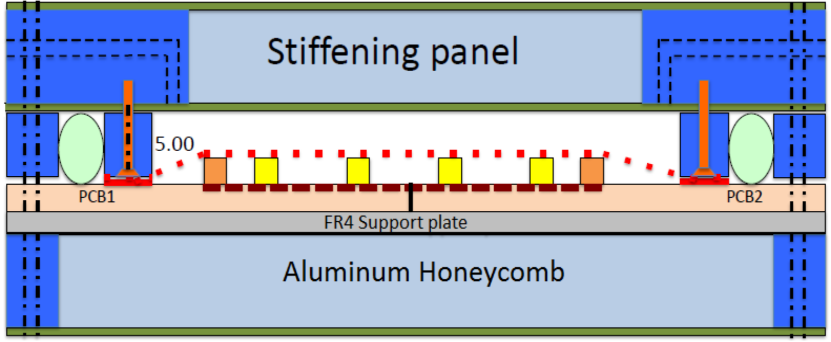


Same principle as in Time Projection Chambers, applied on a mm scale (proposed by P. Iengo)

✓ Bulk technique replaced by 'floating mesh' configuration

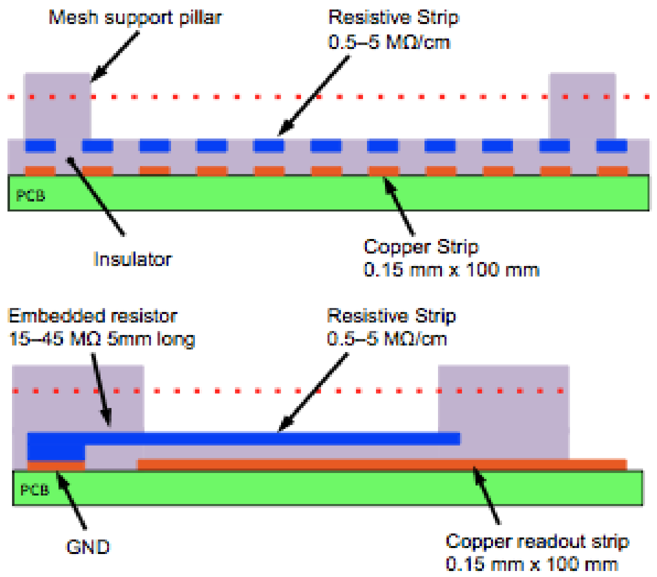
Using also pillars to keep the mesh at a defined distance from the board, the mesh is integrated with the drift-electrode panel and placed on the pillars when the chamber is closed. This allows us to build very large chambers using standard printed-circuit boards





Technology breakthroughs

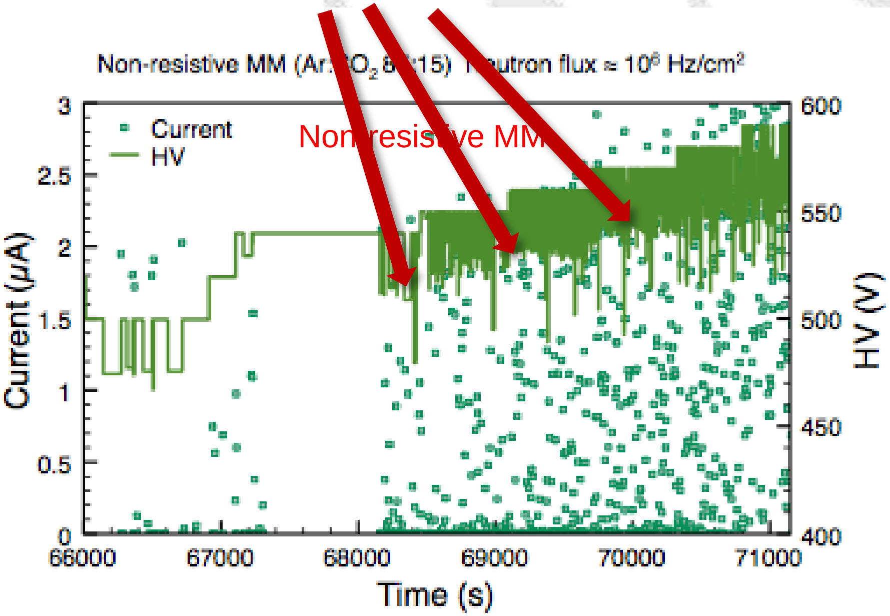
➢Resistive strips for spark immunities

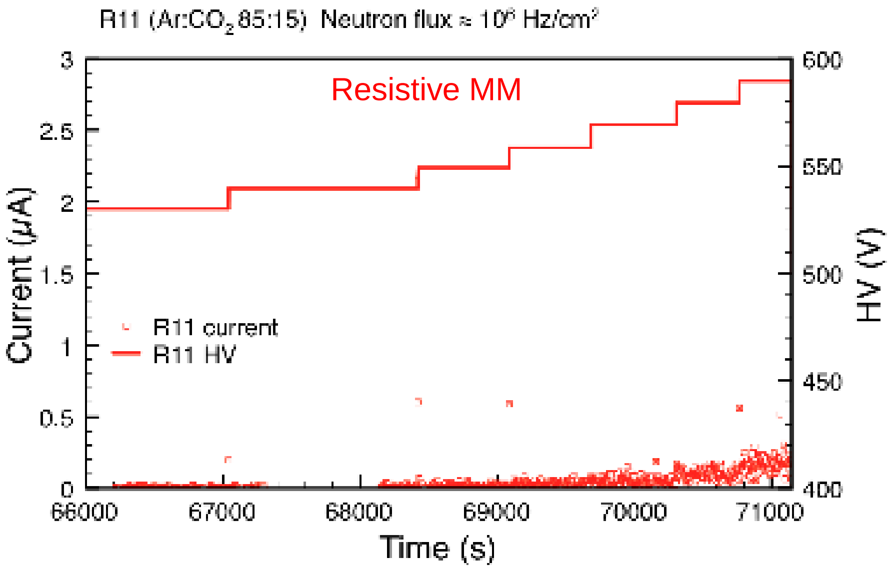


Same principle as resistive plates devices:
✓electric field is locally dumped in case of large discharge by protecting the device with resistive strips on top of the readout (conductive) strips

Alexopulos et al., NIM A640 (2011) 110-118

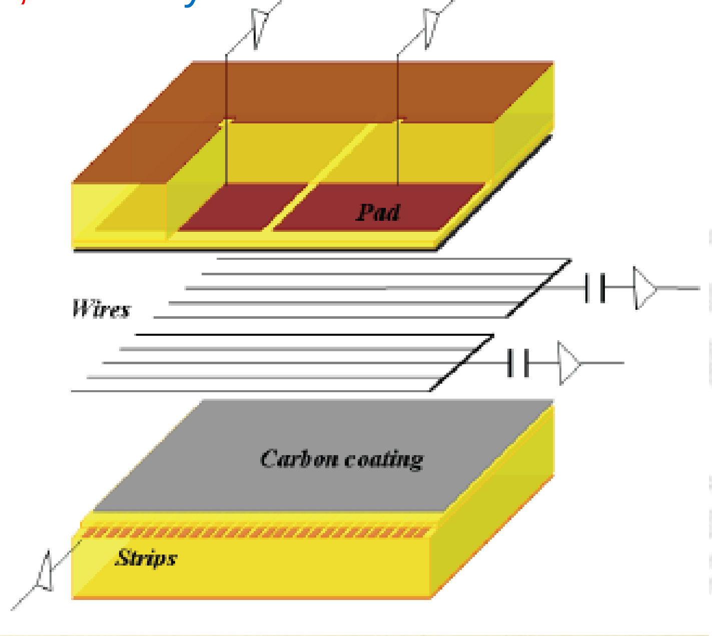
Voltage drops due to small discharges

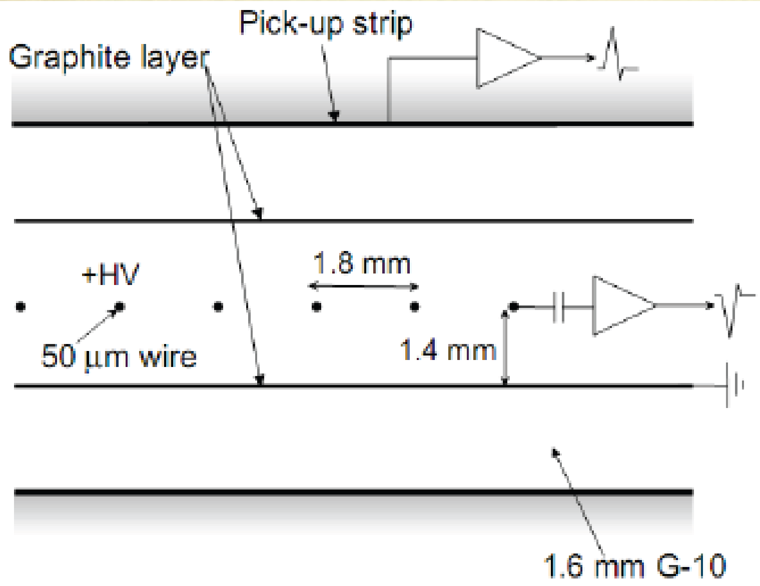




small-strips TGC for ATLAS

Second detector chosen for the New Small Wheels in ATLAS, currently used in the forward muon trigger





sTGC geometry	
Wire-carbon gap	1.4 mm
Wire-wire space	1.8 mm
Strip pitch	3.2 mm
Inter strip gap	0.5 mm
Gas mixure	CO$_2$:n-pentane (55:45)
Wire potential	2.9 kV

Not a “novel” detector – used already in OPAL, proposed for the DELPHI upgrade @ LEP

From the ~2 cm strip pitch of the TGC already in ATLAS

to 3.2 mm strips (small-strips TGCs)

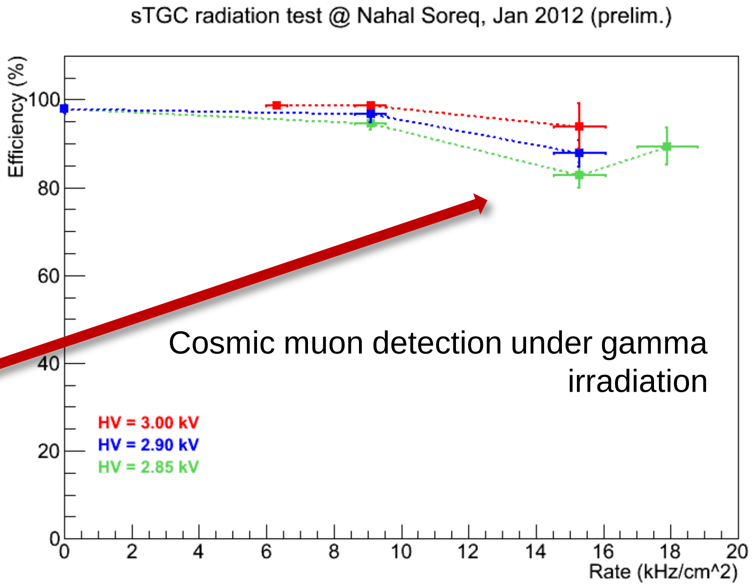
Technology improvements for sTGC

✓In large detectors, resistive cathodes (i.e. the graphite layer) set a limit to the rate capability

✓To increase rate capability, necessary to pass from present TGC cathode resistivity (1 MΩ/cm^2) to 100 kΩ/cm^2

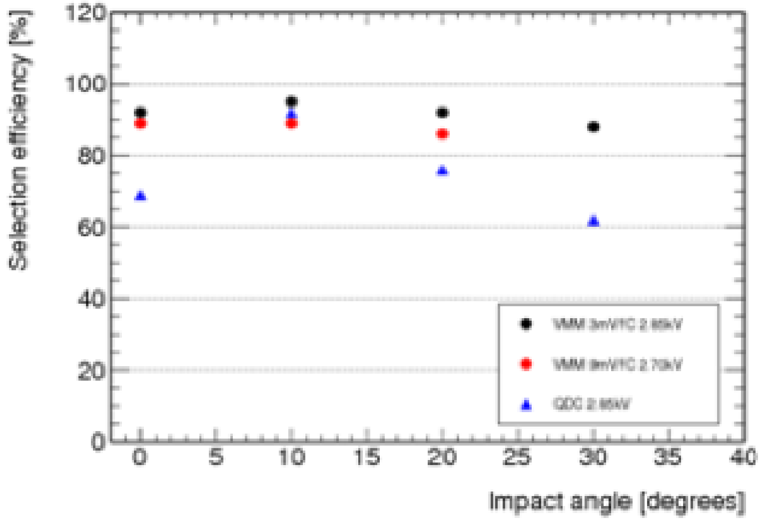
✓To keep transparency to the signal constant (proportional to RC) reduce gap between strips and cathode

Good performance even at high rate

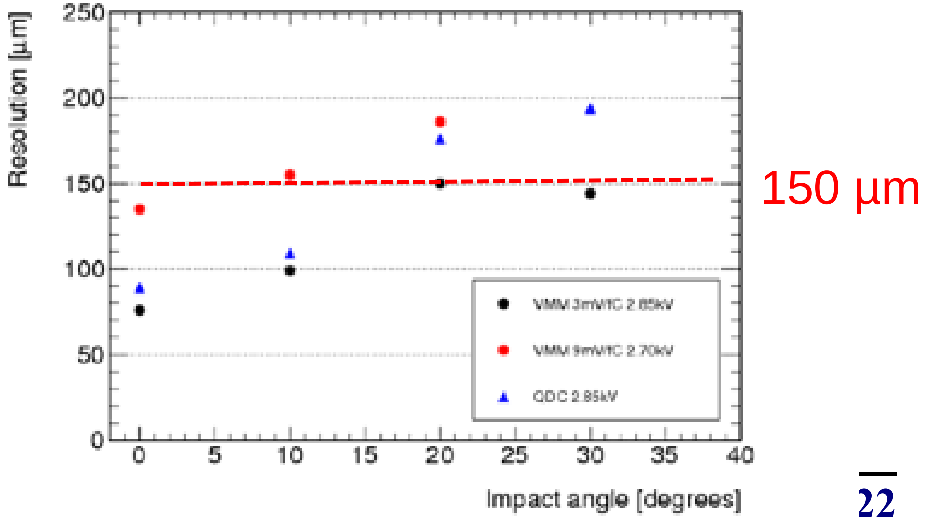

sTGC radiation test @ Nahal Soreq, Jan 2012 (prelim.)

Cosmic muon detection under gamma irradiation

Detector efficiency vs. impact angle



Position resolution vs. impact angle



150 µm

Improved Resistive Plate Chambers: Possible options

Rate capability in RPCs can be improved in many ways:

✓Reducing the electrode resistivity (to be < $10^{10}\Omega$cm)

- ➢Reduces the electrode recovery time constant $\tau \approx \rho\varepsilon$
- ➢Previous studies and (semi) theoretical considerations limit the lowest resistivity usable at $10^{7}\Omega$cm
  - ✓At this point the detector practically looses its self-quenching capabilities (behaves like having metallic plates)
  - ✓In principle a lot of room (3 orders of magnitude) to exploit
- ✓Needs important R&D on electrodes materials

✓Changing the operating conditions

- ➢reduces the charge/avalanche, i.e. transfers part of the needed amplification from gas to FE electronics (already done in 1990s!) – needs an improved detector shielding against electronic noise

✓Changing detector configuration

- ➢ Improves the ratio (induced signal)/(charge in the gap)

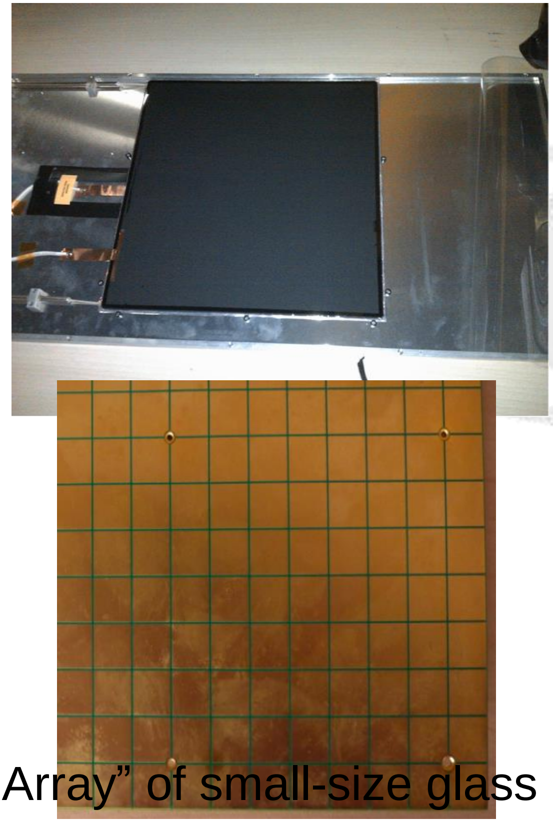
Just some of these possibilities are being explored in present R&D

R&D on glass RPCs for CMS

New “low” resisitivity (10^{10} Ωcm) glass used for high rate RPC

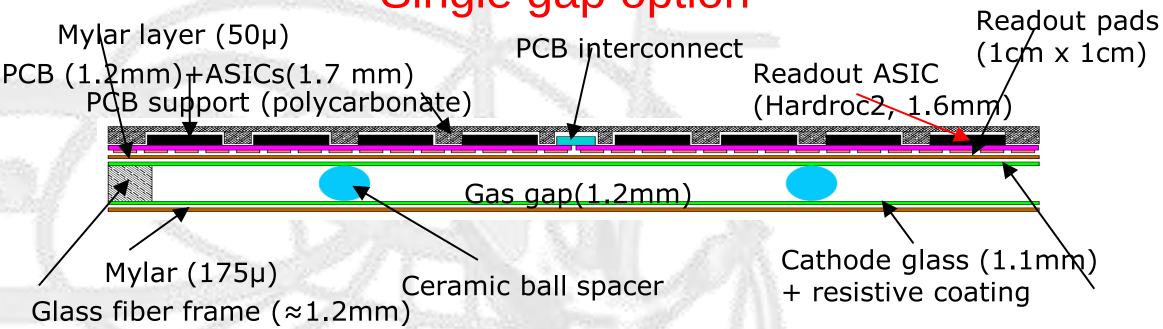
adding Aluminum, and changing the percentages of the usual ingredients

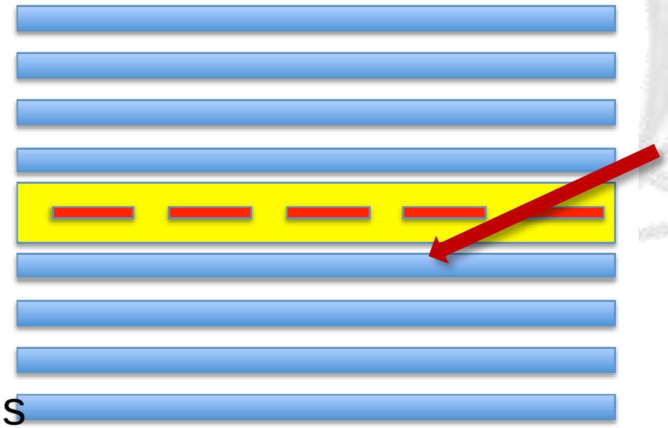
- ✓RPC rate capability depends linearly on electrode resistivity
- ✓Smoother electrode surfaces → reduces the intrinsic noise
- ✓Improved electronics characterized by lower thresholds and higher amplification



“Array” of small-size glass tiles to cover large surfaces

Single gap option





Multigap option:

- ✓a variation of the double-gap configuration used for CMS: “double triple-gaps”
- ✓High rate + high time resolution

CMS R&D #12.01

GRPCs for CMS: performance

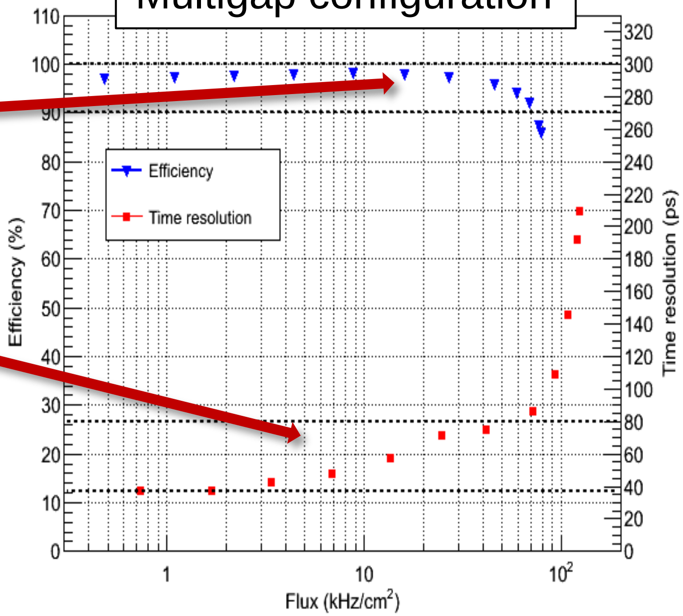
Very promising performance at localized beam tests even at high rate

✓Rate capability ~ 30 kHz/cm^2

✓Time resolution 20-30 ps

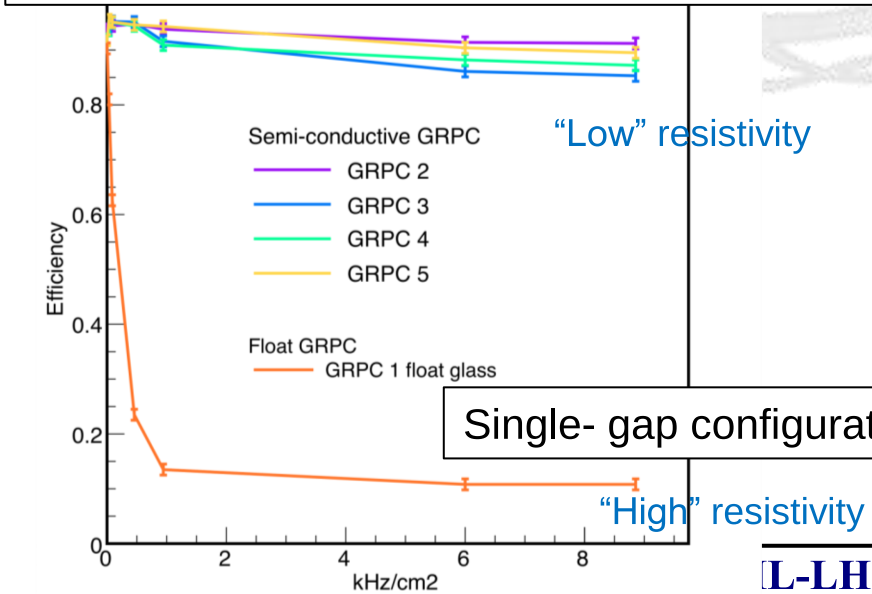
✓Caveat: localized irradiation <u>different</u> from an uniform irradiation

At the moment low resistivity GRPCs at GIF for a series of high rate and aging tests



Multigap configuration

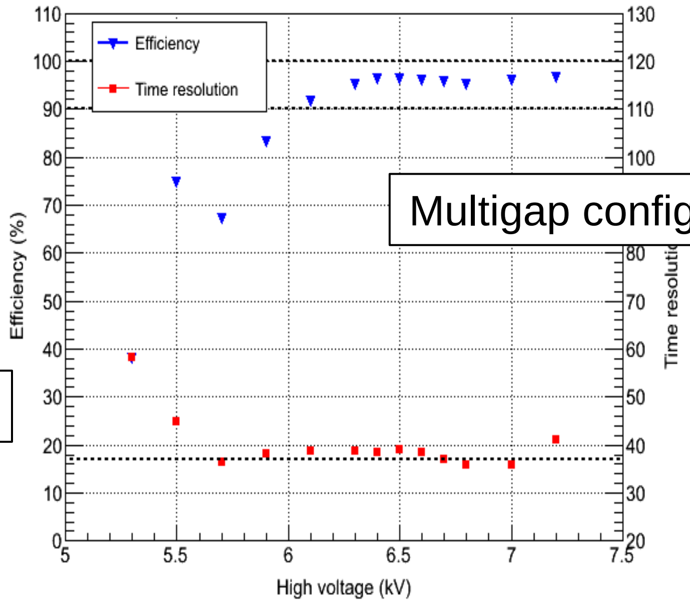
Effect of reduced resistivity on rate capability



"Low" resistivity

"High" resistivity

Single- gap configuration



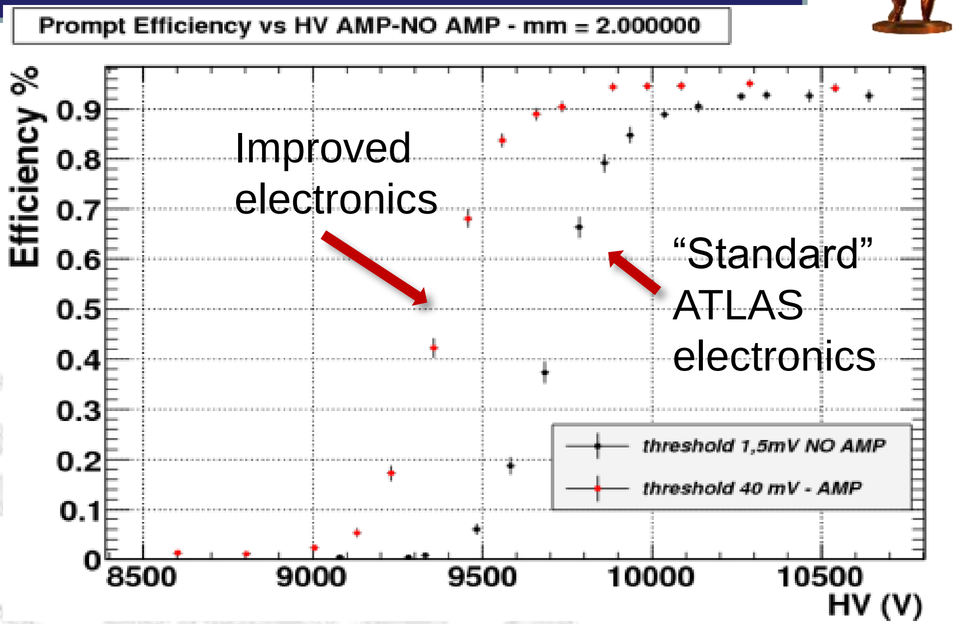
Multigap configuration

improved RPCs for ATLAS

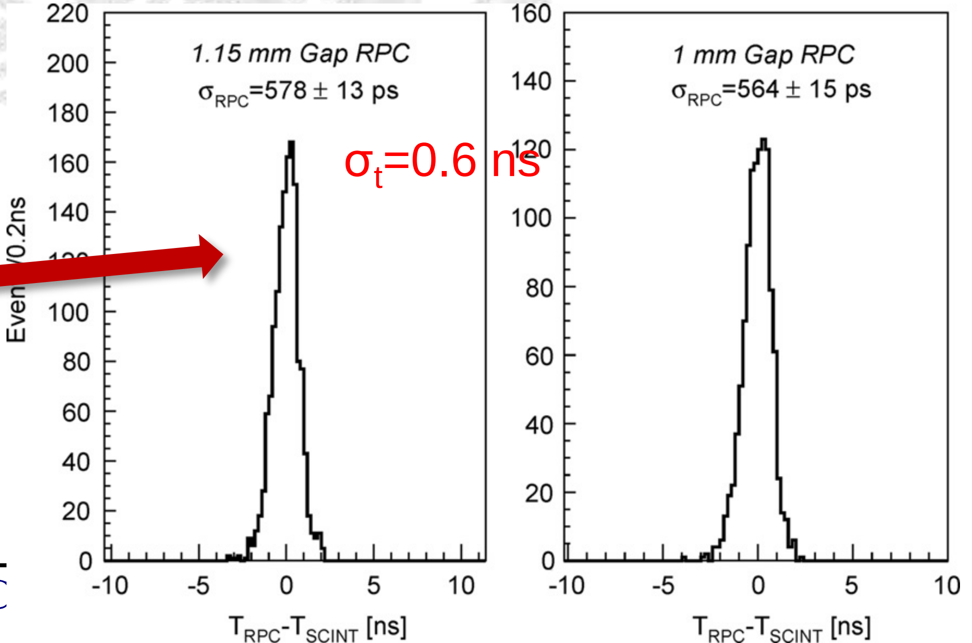
Using “standard” bakelite RPCs, but with:
✓improved electronics
✓different configuration

A shift in the efficiency curves indicates sensitivity at lower induced charge

Higher rate capability



Time resolution is (inversely) related to the gap width
(and to the number of gaps)
Reducing the gap width, a sub-ns resolution can be reached even with single or double gaps

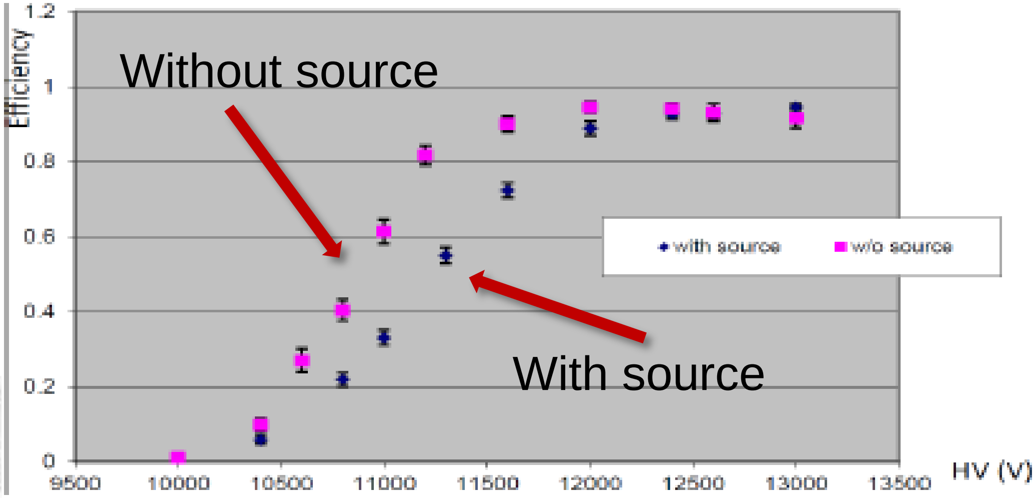


improved RPCs for ATLAS

Test at GIF, fully irradiating the chambers at about 7 kHz/cm^2

Efficiency shifted but comparable with the one measured at low rate

✓A rate capability of – or superior to – 7 kHz/cm^2 demostrated

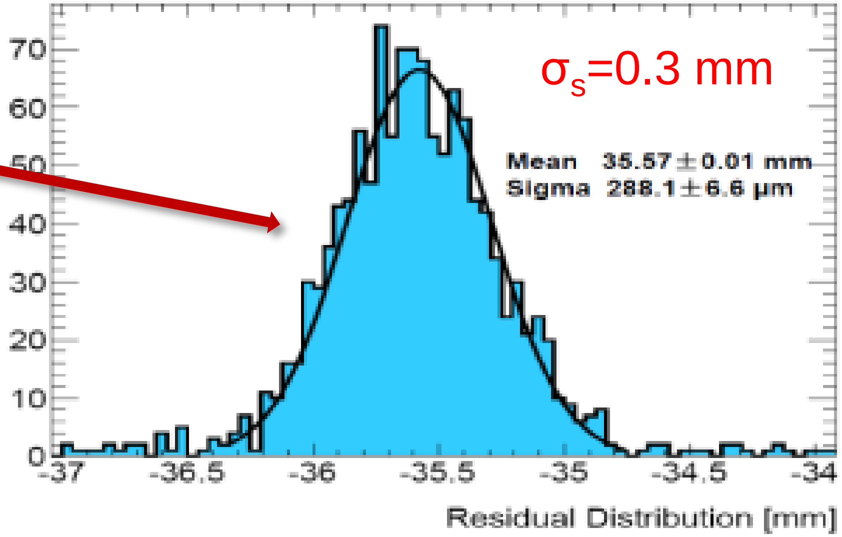


Without source

With source

Tests with small readout strips and charge centroid method:

✓Sub-mm position resolution demonstrated (dependent on strip pitch)



σ_s=0.3 mm

These are only two examples of the different possibilities studied, by many groups, to improve RPCs performance

Conclusions of this talk

- The novel detectors proposed **-including the ones I could not cite-** provide **a full range of improved characteristics** that fit nicely with the ones required for the LHC experiments at phase II

Many different scenarios can be pursued

Choice (if necessary) will be an exciting -and difficult- task!

- **Detector R&D greatly profits from cross-fertilization among different experiments and subsystems**
  - ✓GEMs in the RD51 framework is the perfect example
  - ✓Experiences like RD51 should be repeated elsewhere (i.e. iRPC)
- R&D for LHC experiments is becoming a huge collaborative effort, to be carefully planned and steered

- **A very nice group was set up for preparing this talk: thanks!**

Conclusions of the session

Conditions after LS3, in terms of instantaneous and integrated luminosity, will pose **a significant challenge for the muon systems** of the LHC experiments.

Strategies to cope with the new conditions are being developed, so that their performance remains stable despite increased pile-up, luminosity, background

Present expectations are that most of the **existing detectors should survive** for the whole HL-LHC period:

- ✓**new detectors should be installed in the most critical regions** to ensure performance stability or possibly improve it, particularly in terms of acceptance;
- ✓**trigger and readout electronics will have to be upgraded,** by profiting of the new standards developed in industry;
- ✓**testing facilities**, for the existing detectors and the new ones, **are mandatory.**

New detectors with improved performance promise to satisfy the requirements for the muon systems of the post LS3 scenarios, even if R&D is still needed.

Synergies - like the ones developed for preparing this set of talks - are essential for optimizing the tight resources, in terms of people and money, allocated to this task while ensuring a smooth operation and a safe data taking to the LHC experiments.