Gaseous detectors in particle physics

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All types of GASEOUS DETECTORS rely on the same principles

- A charged particle (or a photon) ionizes gas atoms/molecules along its track

- An electric field transports electrons (and ions) towards electrodes, electrons are multiplied in a strong electric field

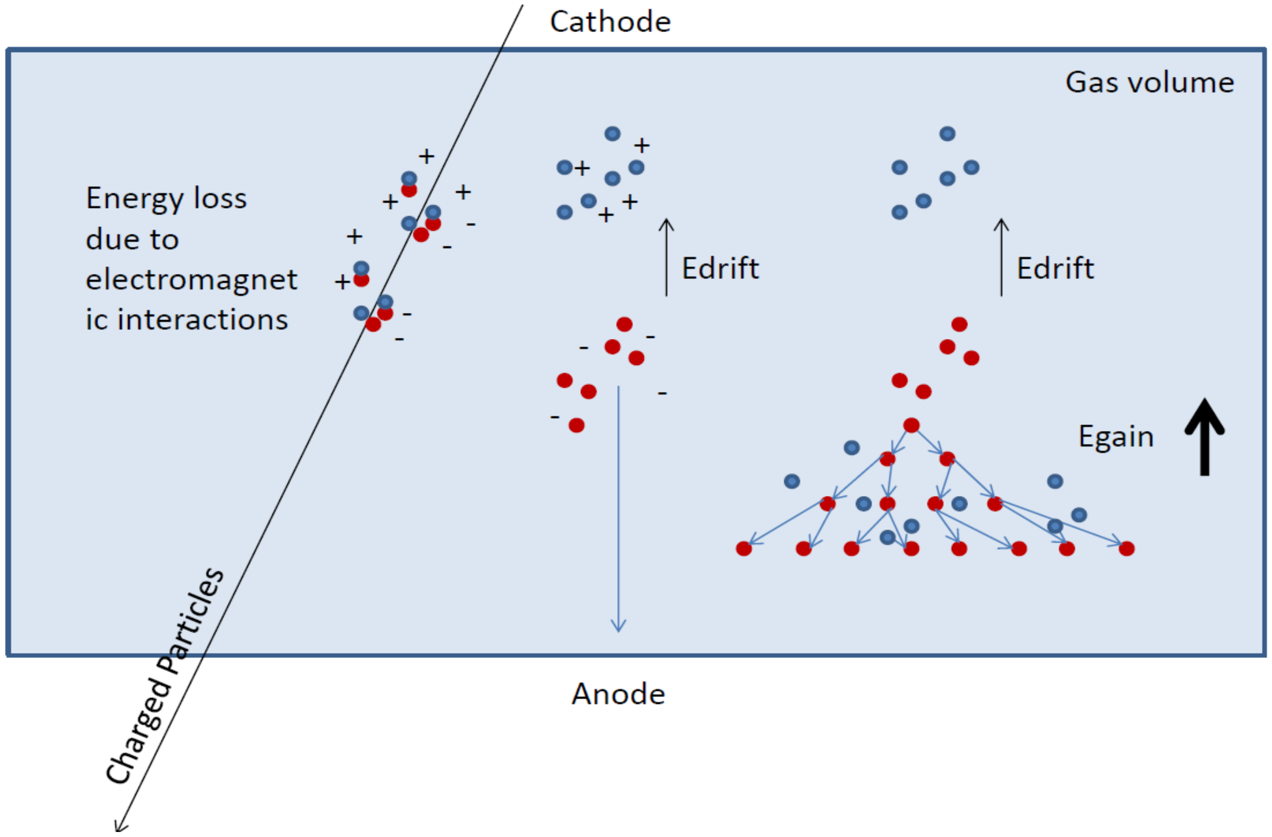
- The motion of electrons and ions induces a current on the readout electrodes

A typical gas detector working

Charged particles traversing matter leave **excited atoms**, **electron-ion pairs (gases)** or **electrons-hole pairs (solids)**

Excitation:
The photons emitted by the excited atoms in transparent materials can be detected with photon detectors like photomultipliers or semiconductor photon detectors.

Ionization:
By applying an electric field in the detector volume, the ionization electrons and ions are moving, which induces signals on metal electrodes. These signals are then read out by appropriate readout electronics.

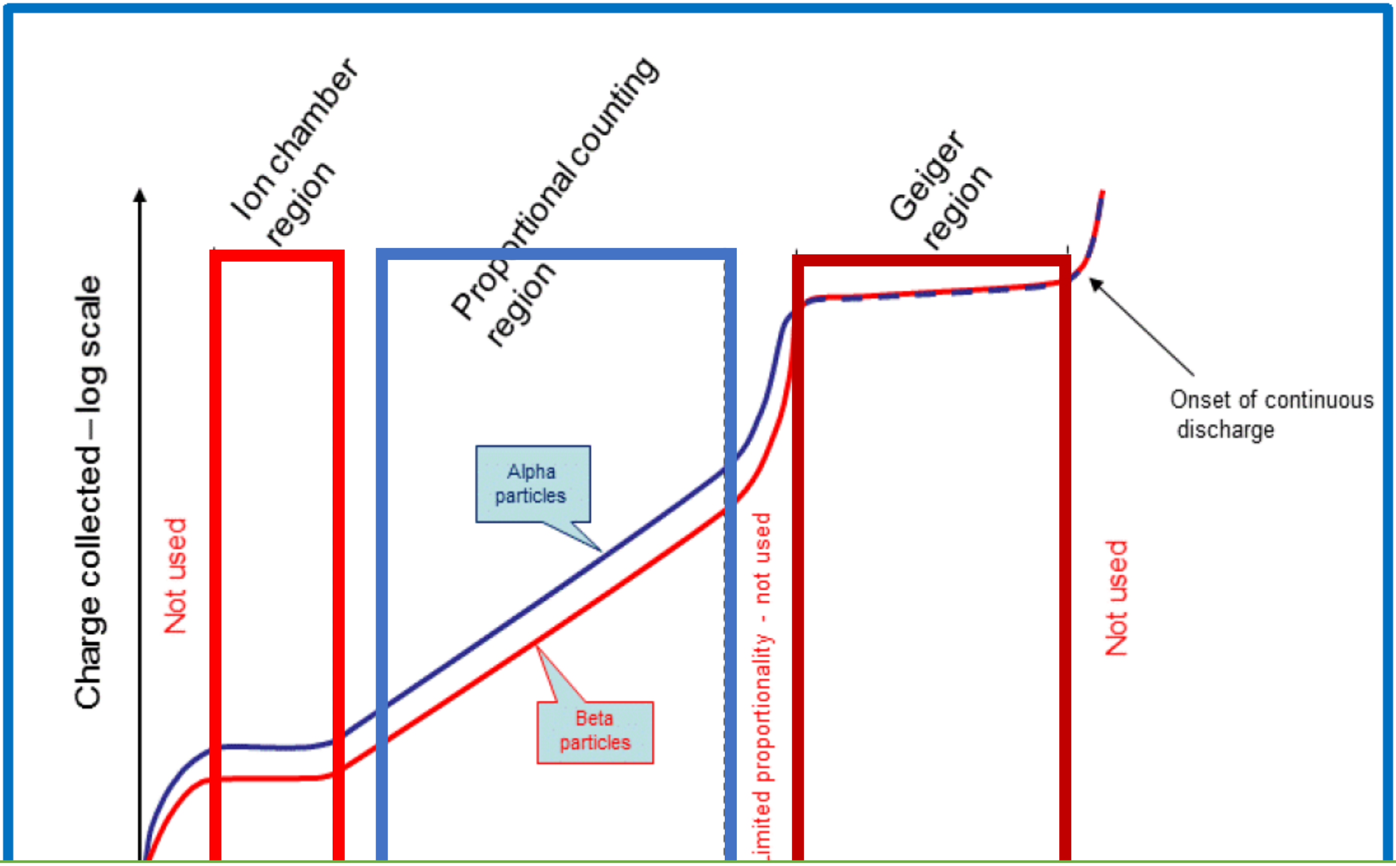


Working region

Ionization chambers operate at a low voltage, → no gas multiplication takes place.

Pros:
- ✓ Good uniform response to gamma radiation
- ✓ Accurate overall dose reading
- ✓ Sustains very high radiation rates

Cons:
- ➢ Very low electronic output



In Proportional counters the output current pulse generated is proportional to the energy deposited by the radiation. The Wire chamber is an example of proportional counter used as a research tool.

Pros:
- ✓ Can measure energy of radiation and provide spectrographic information
- ✓ Can discriminate between alpha and beta particles
- ✓ Large area detectors can be constructed

Cons:
- ➢ Anode wires delicate
- ➢ Time resolution limited by distance between the wires

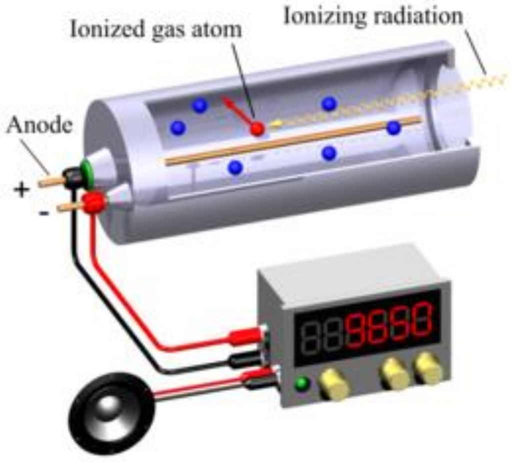
Geiger-Müller tubes operate at higher voltage: each electron-ion pair creates an avalanche. UV photons are produced and create multiple avalanches which spread along the anode wire.

Pros:
- ✓ Cheap, robust detector with a large variety of sizes and applications
- ✓ Large output signal from tube
- ✓ Can measure overall gamma dose

Cons:
- ➢ Cannot measure energy of radiation
- ➢ High dead time → does not sustain high radiation rates
- ➢ Sustained high radiation levels will degrade fill gas

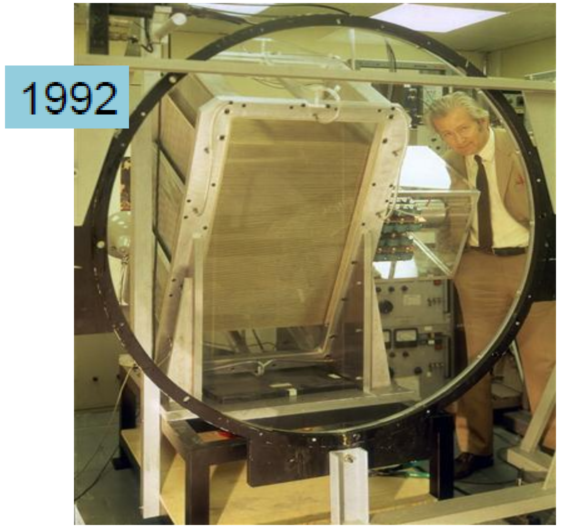
Gaseous detectors

Gaseous detectors have been used for more than 100 years in atomic, nuclear and particle physics



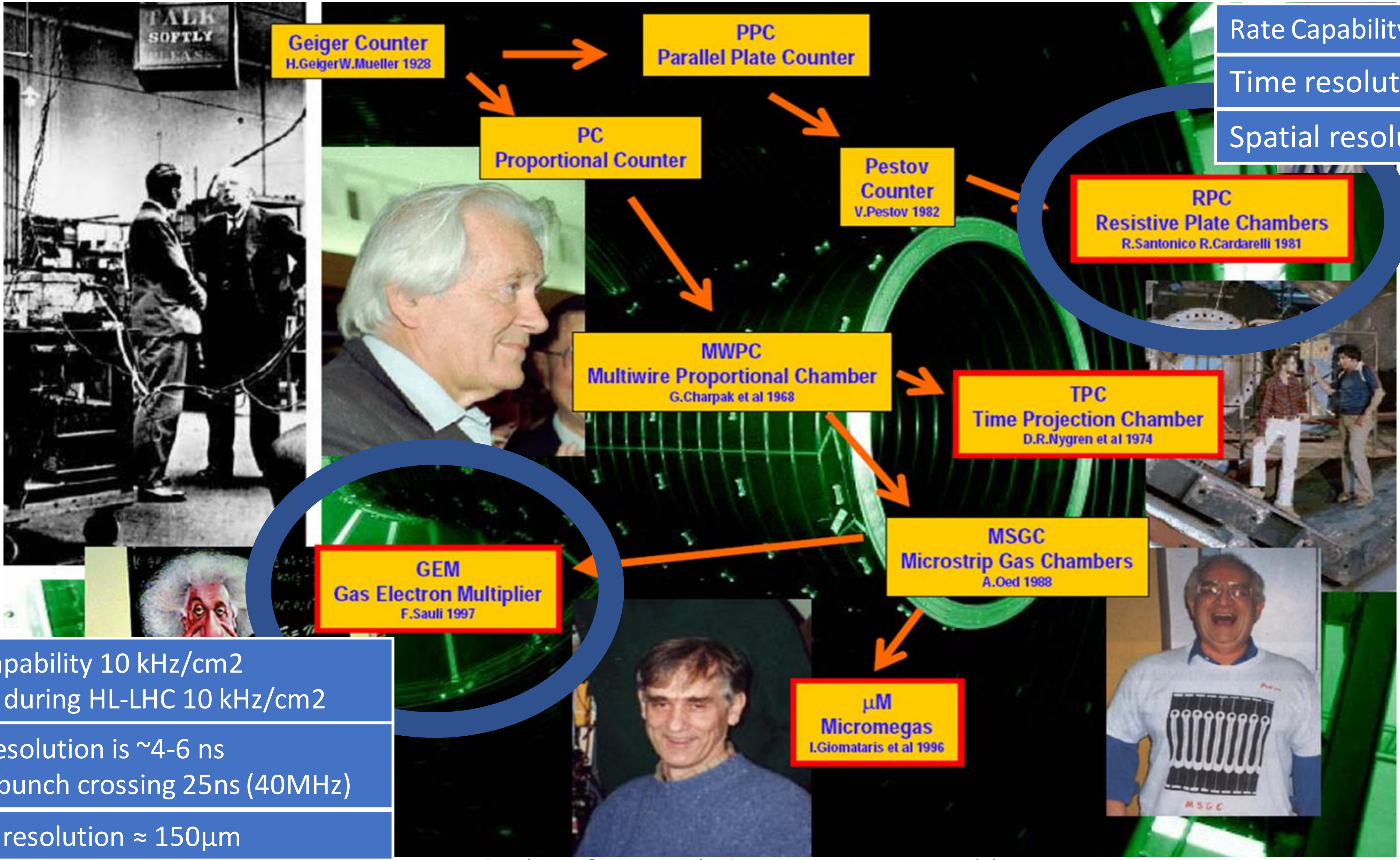
- 1908- First application of a wire counter for studying natural radioactivity - An electrical method of counting the number of α particles from radioactive substances, Rutherford E, Geiger H., Proc. Royal Soc., A81 (1908)141.

- 1928 Geiger-Müller: The sensitivity to single electrons was achieved- Geiger H, Müller W., Physik. Zeitschr., Vol.XXIX (1928) 839



- 1968 G. Charpak- invented the Multiwire Proportional Chamber (MWPC) - Charpak G, et al., NIM 62(1968)262. which allowed the homogeneous coverage of large areas and the reconstruction of space points and tracks.

Gaseous detectors



Rate Capability ≈ 1k Hz/cm2

Time resolution ≈ 1.5 ns

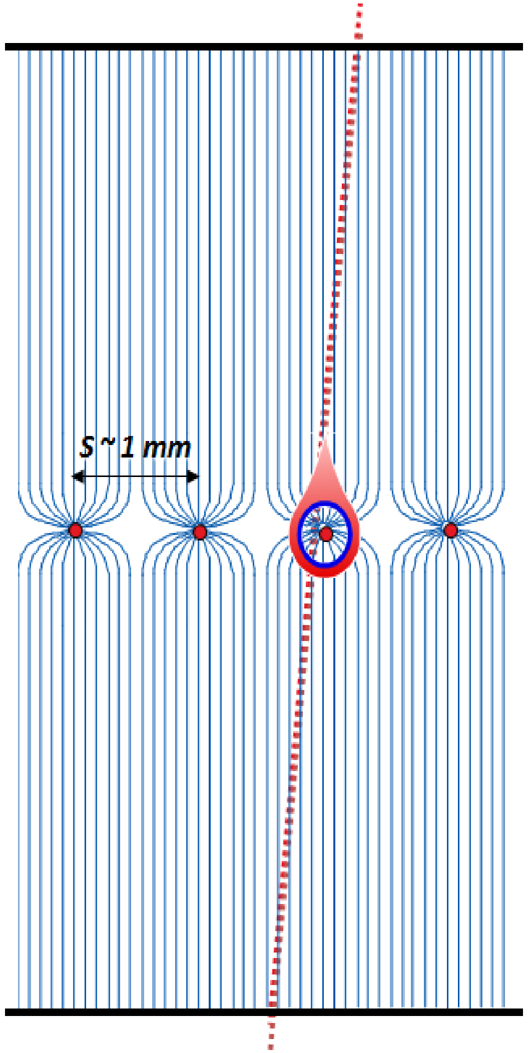
Spatial resolution ≈ 1 cm

Rate capability 10 kHz/cm2
@CMS during HL-LHC 10 kHz/cm2

Time resolution is ~4-6 ns
@LHC bunch crossing 25ns (40MHz)

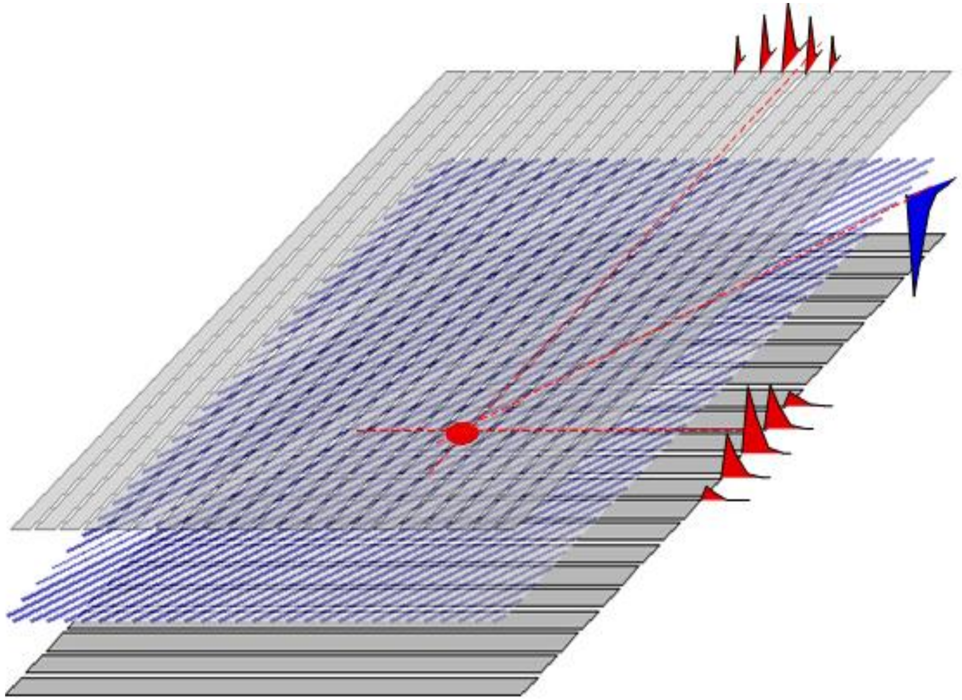
Spatial resolution ≈ 150µm

MWPC

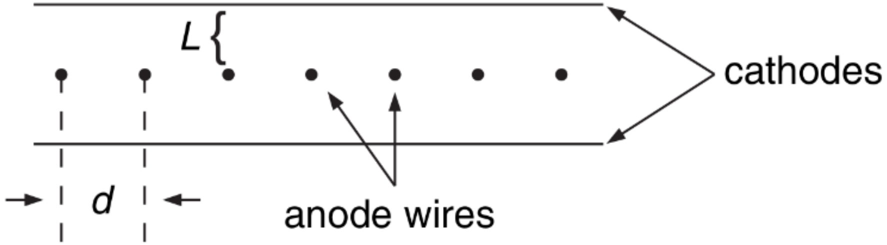


High-rate MWPC with digital readout:
Spatial resolution is limited to $s_x \sim s/\sqrt{12} \sim 300\ \mu m$

TWO-DIMENSIONAL MWPC READOUT CATHODE INDUCED CHARGE (Charpak and Sauli, 1973)



G. Charpak at al., NIM 62 (1968) 202



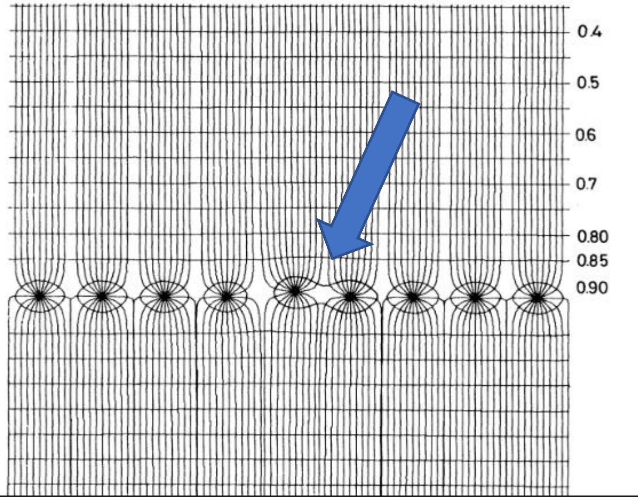
typical values:

- $d \sim 2$ - 5 mm
- $L \sim 5$ - 10 mm
- $r_i \sim 20$ - 25 µm
- $U_0 \sim 1$ - 5 kV

MWPC to MSGC

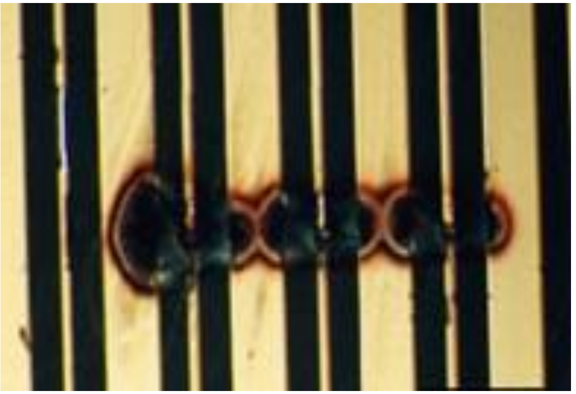
MWPC

- **Complicated MWPC construction (high geometric precision, stability,...)**
- **Wires age, can be destroyed by discharges**

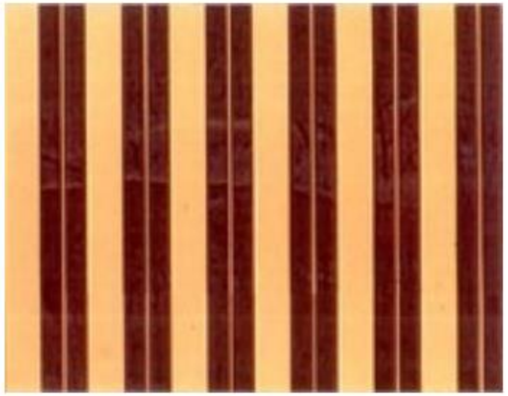


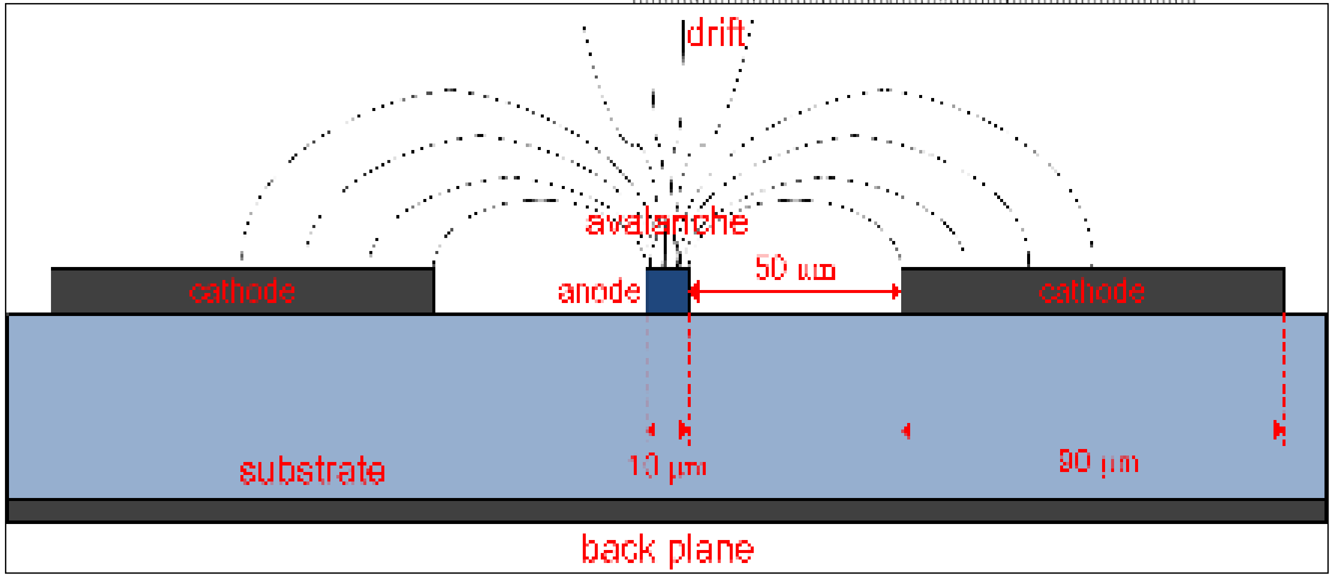
- **Microstrip are introduced to go away from wire detectors**
- **MWPC dimensions reduced by a factor 10**
- **Short ion drift, high rate capability, good resolution**

Discharges destroy anode structure.



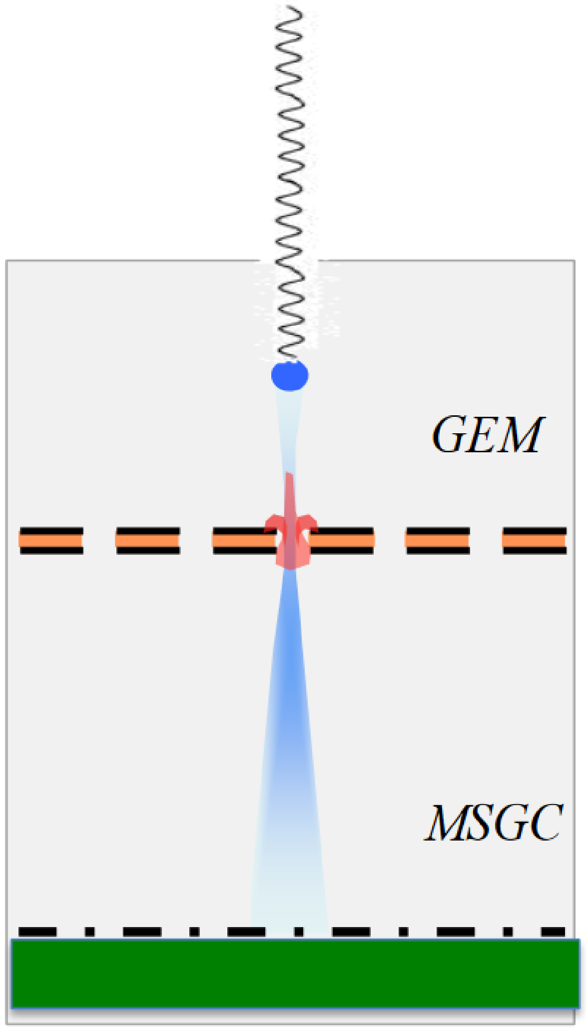
A. Oed, 1988 MSGC





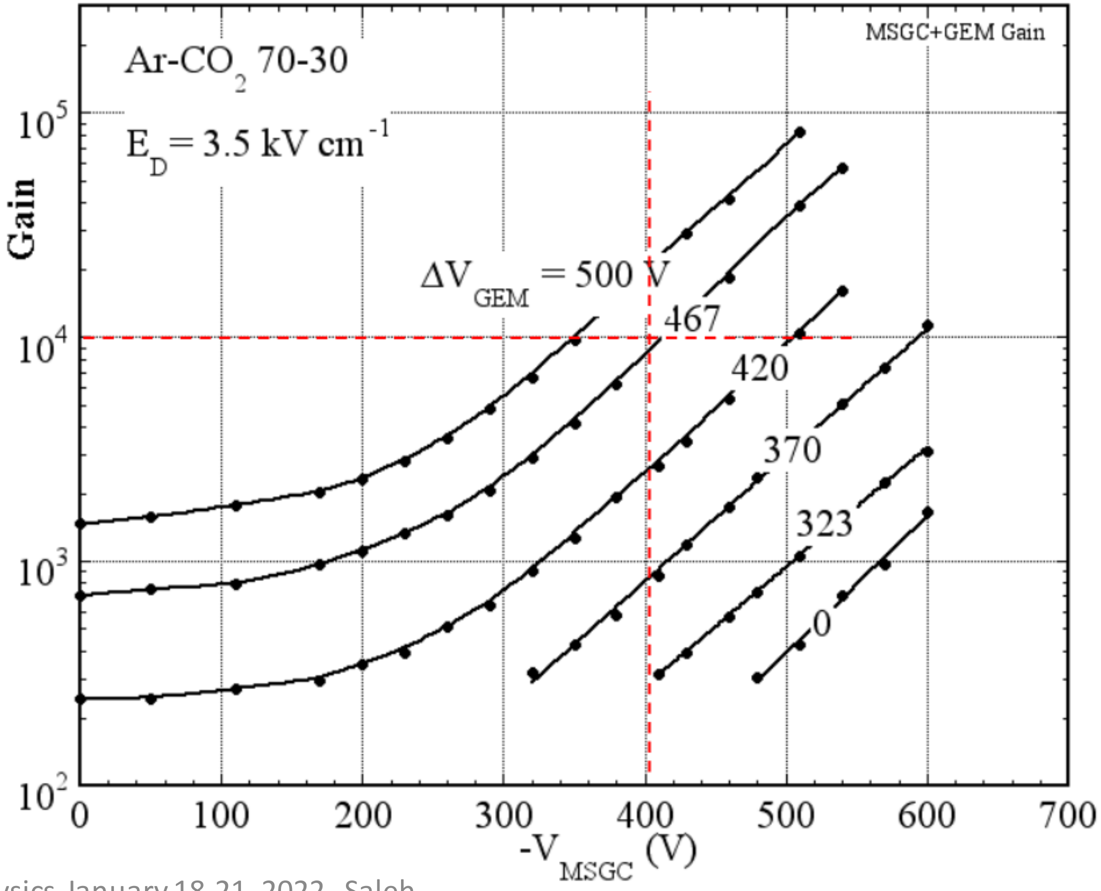
MSGC to GEM detector

MSGC WITH GEM PREAMPLIFIER



R. Bouclier et al, Nucl. Instr. and Meth. A396(1997)50

COMBINED GAIN CURVES



Gas Electron Multiplier

Nuclear Instruments and Methods in Physics Research A 386 (1997) 531–534

NORTH-HOLLAND ELSEVIER

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Letter to the Editor

GEM: A new concept for electron amplification in gas detectors

F. Sauli

CERN, CH-1211 Genève, Switzerland

Received 6 November 1996

Abstract

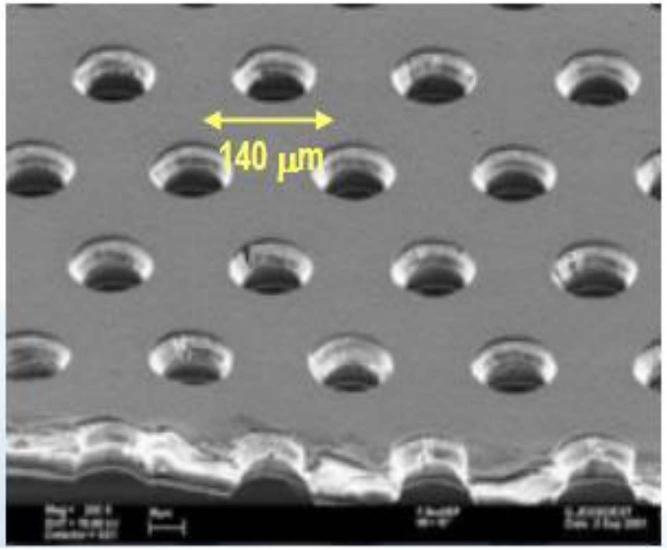
We introduce the gas electrons multiplier (GEM), a composite grid consisting of two metal layers separated by a thin insulator, etched with a regular matrix of open channels. A GEM grid with the electrodes kept at a suitable difference of potential, inserted in a gas detector on the path of drifting electrons, allows to pre-amplify the charge drifting through the channels. Coupled to other devices, multiwire or microstrip chambers, it permits to obtain higher gains, or to operate in less critical conditions. The separation of sensitive and detection volumes offers other advantages: a built-in delay, a strong suppression of photon feedback. Applications are foreseen in high rate tracking and Cherenkov Ring Imaging detectors. Multiple GEM grids assembled in the same gas volume allow to obtain large effective amplification factors in a succession of steps.

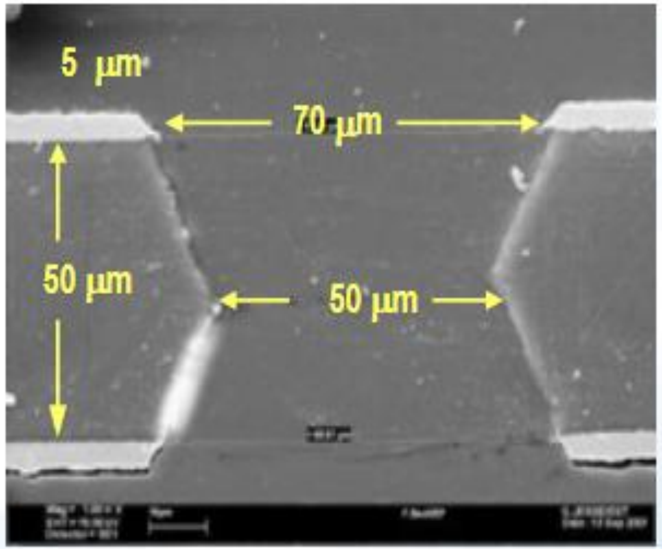
GEM foil and field

High density micromoles, in presence of intense electric field is a source of charge amplification.

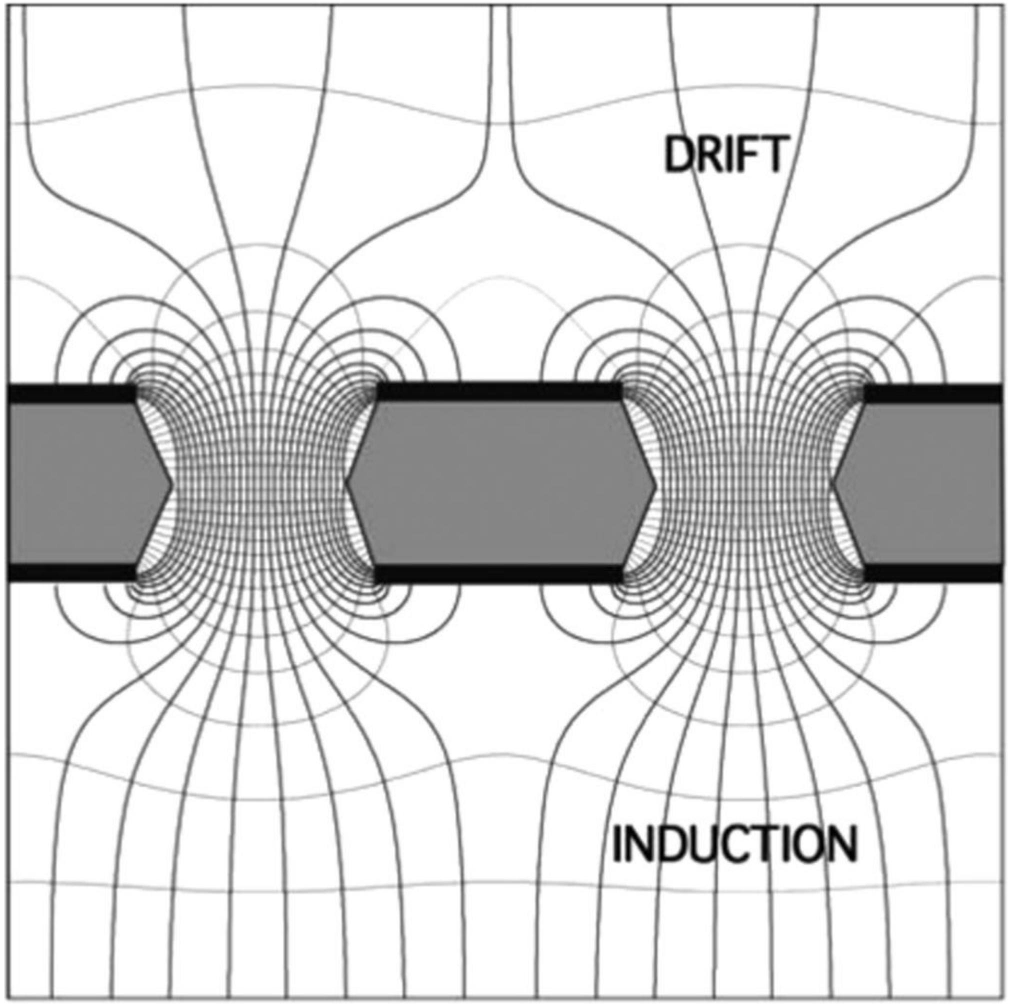
- 50 µm Kapton
- 5 µm Cu
- Bi-conical

Holes are formed by Photolithography





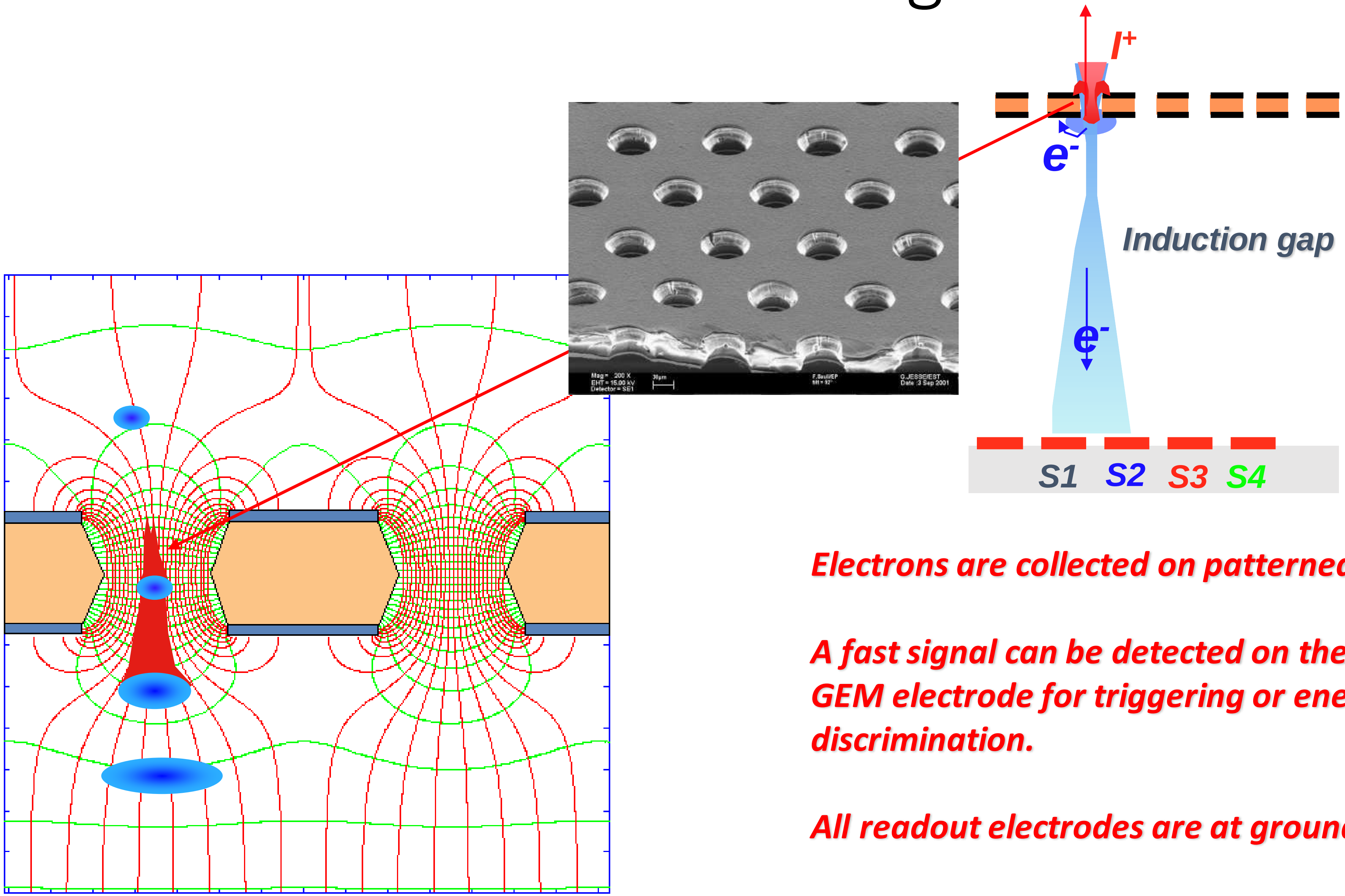
F. Sauli, 1997



300-500 V

60-100 kV/cm

GEM working



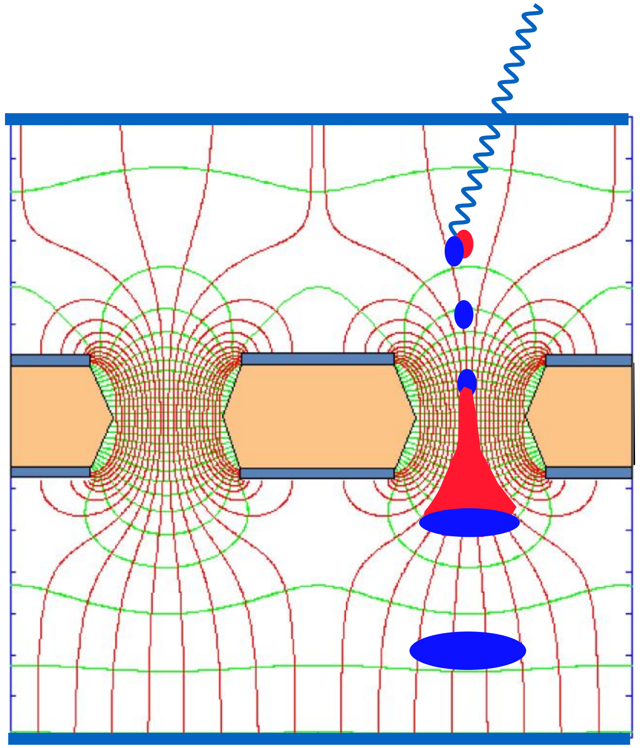
Electrons are collected on patterned readout board.

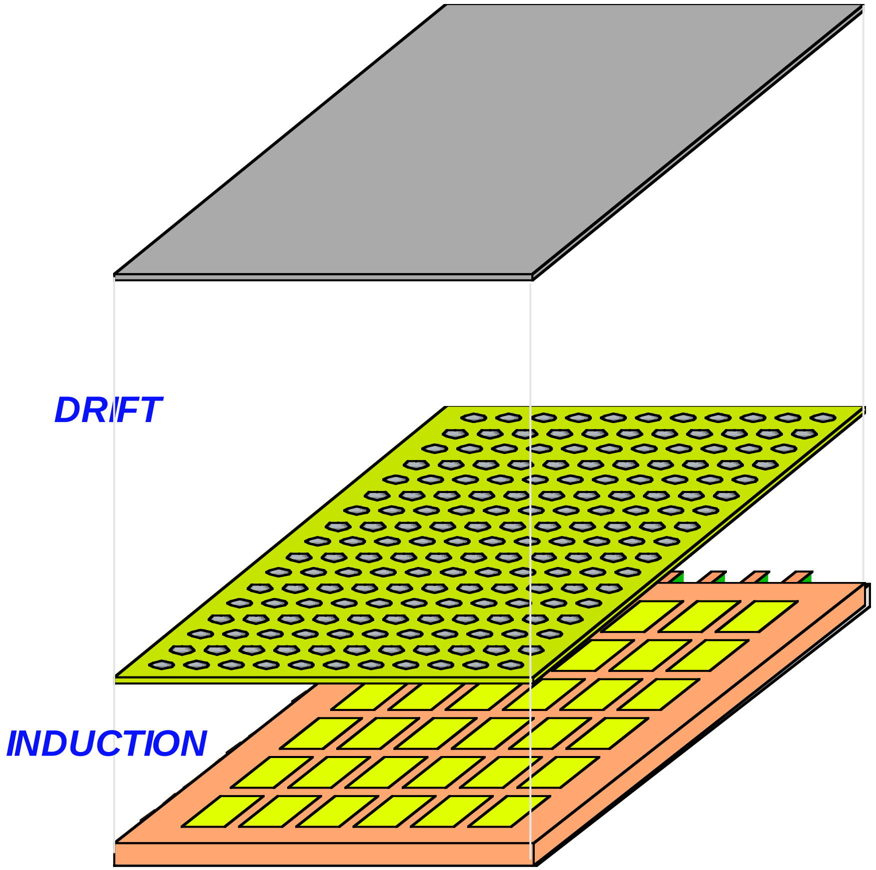
A fast signal can be detected on the lower GEM electrode for triggering or energy discrimination.

All readout electrodes are at ground potential.

GEM Readout option

AMPLIFICATION AND TRANSFER SINGLE GEM DETECTOR:

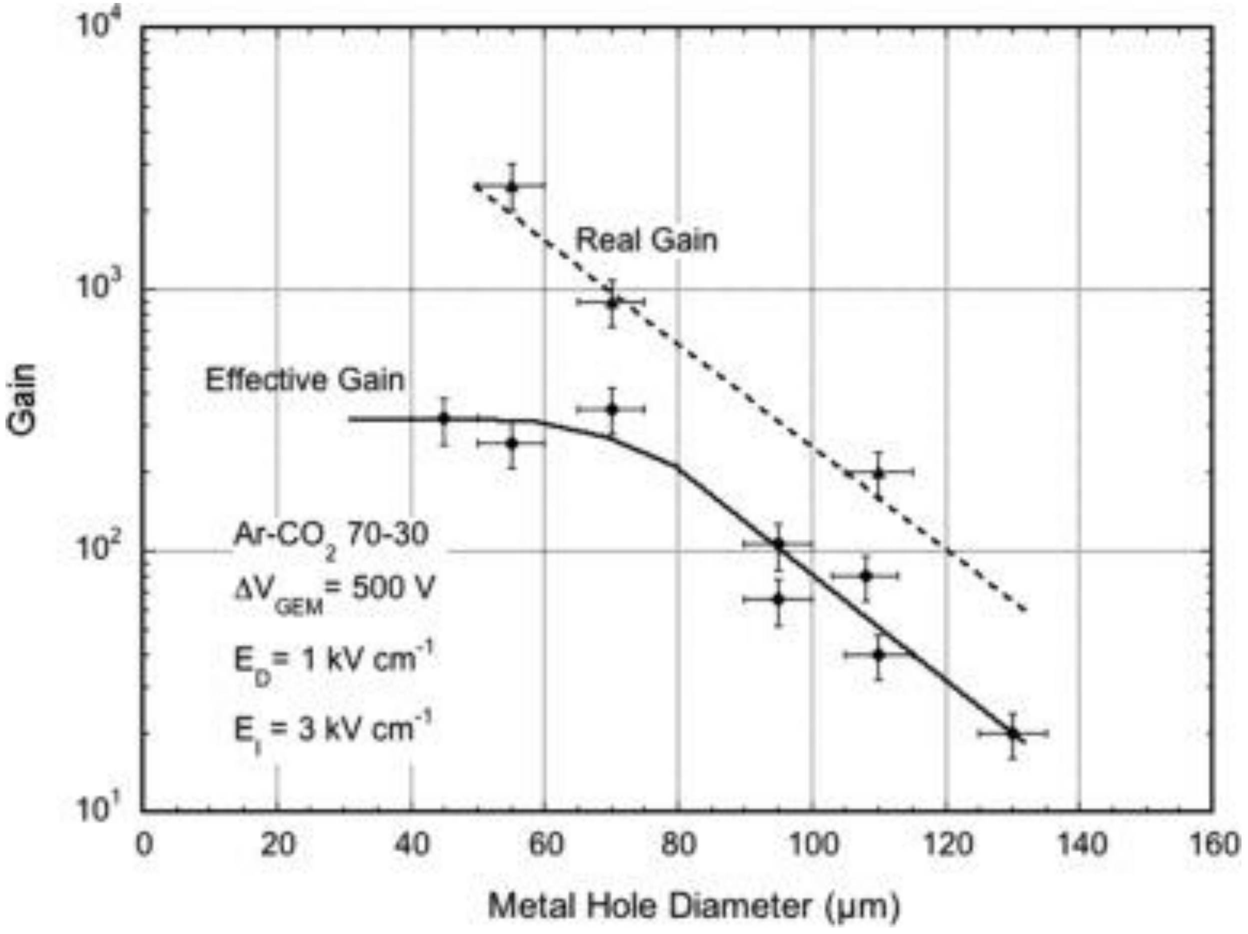




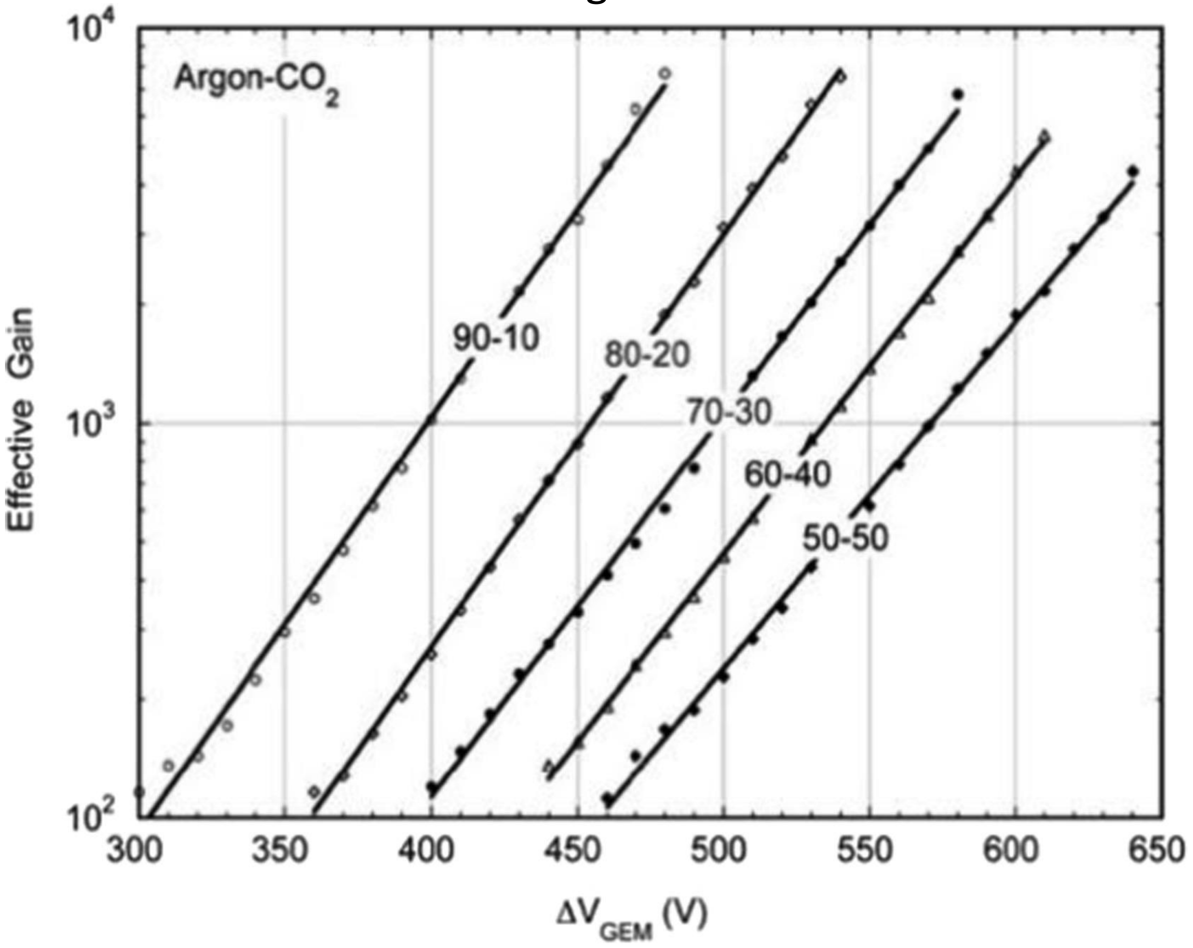
Holes and gas effect the detector performance

Single GEM

F. Sauli NIM in Physics Research A 805 (2016) 2-24



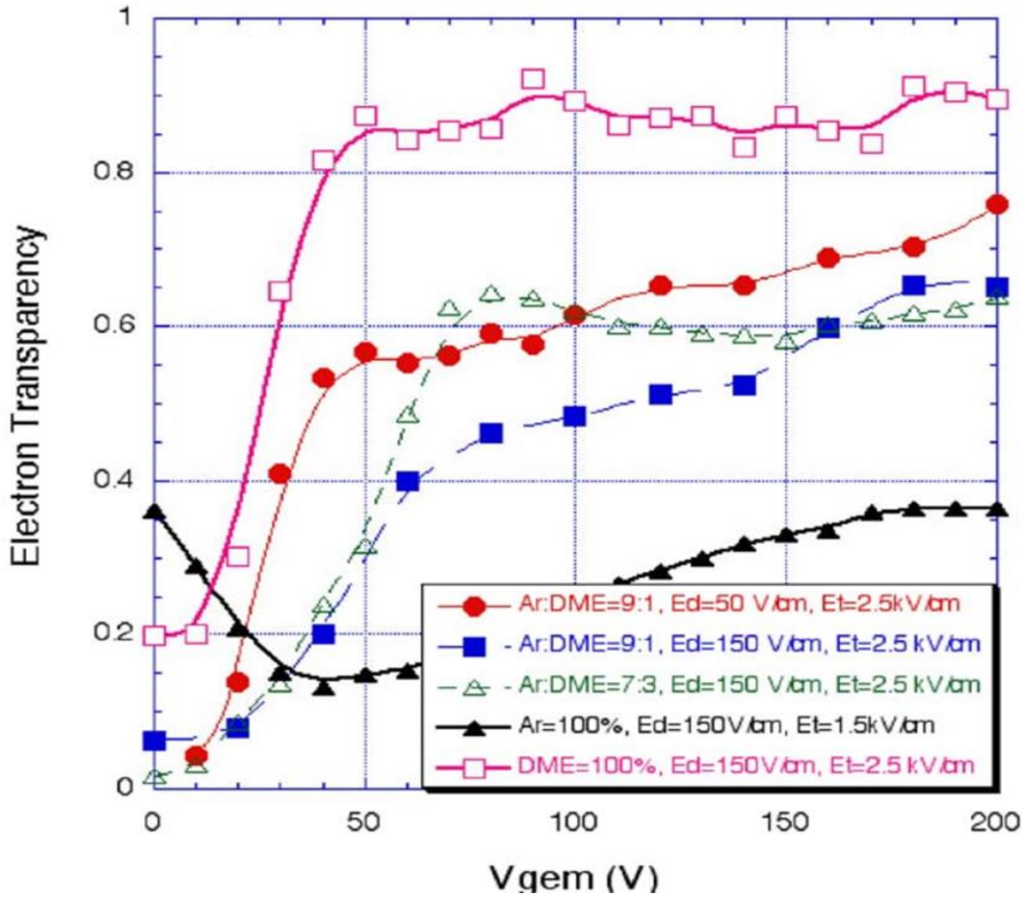
Single GEM



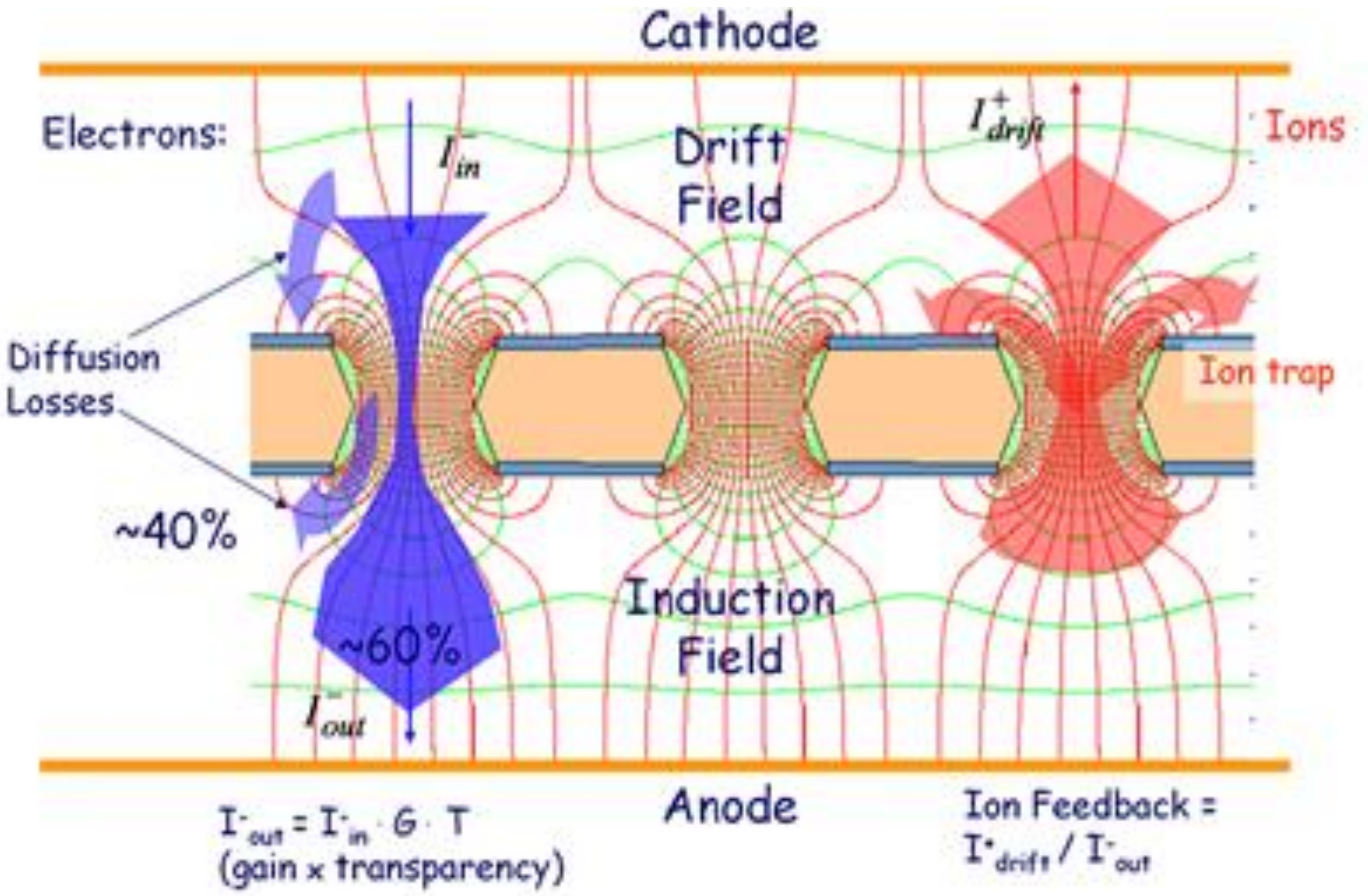
GEM foil holes dimensions and gas mixture are very crucial for the detector performances

Electrons and Ions propagation in the GEM

Electron transparency is measured by computing the ratio of the current on the readout electrode to the total electron current (sum of GEM upper, GEM lower and readout plane electrode)



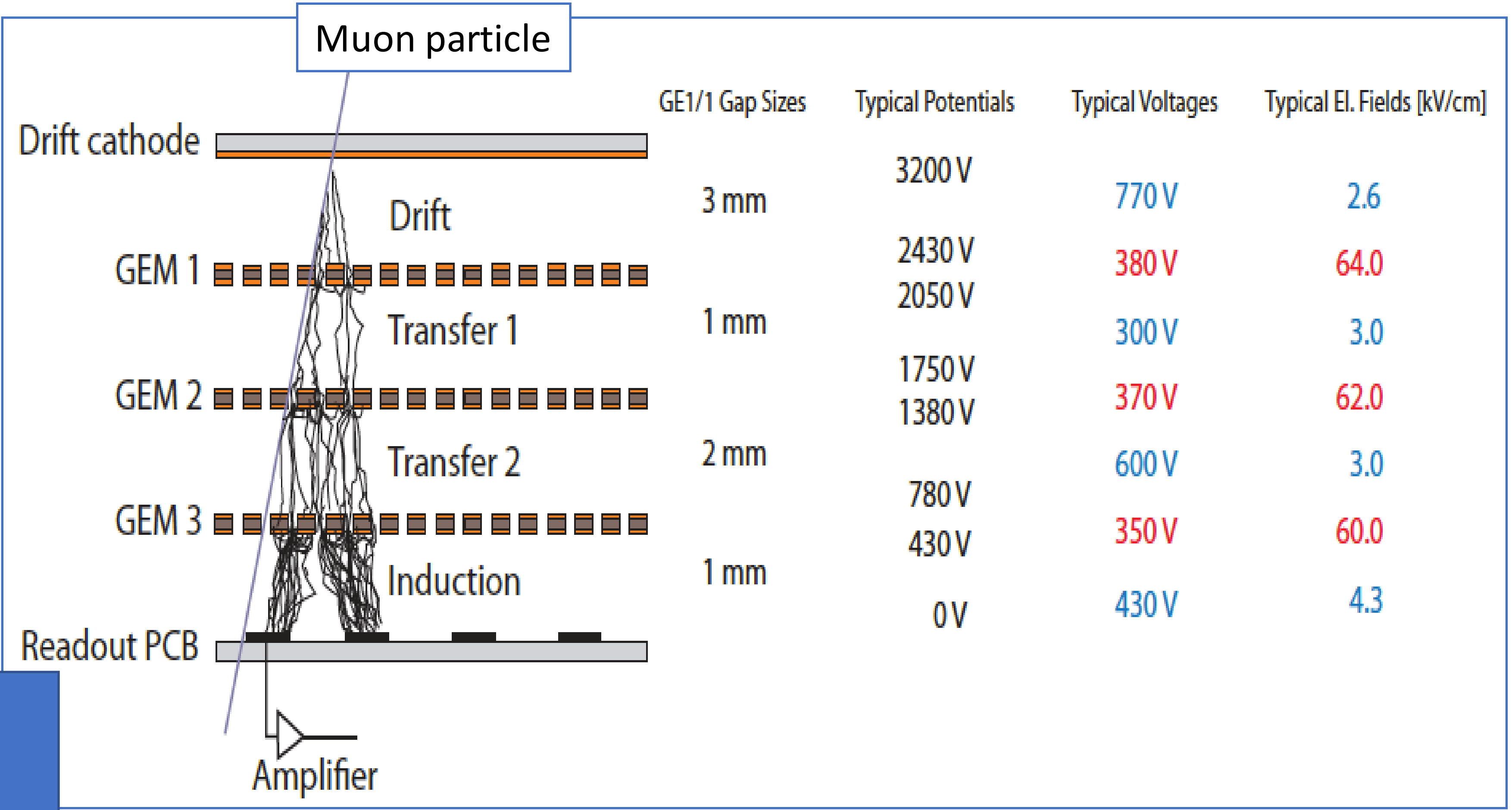
P.S. Barbeau et al. NIM in Physics Research A 525 (2004) 33



Triple GEM detector operating principle

- Potential difference applied on copper sides either through a divider or through independent HV channels
- Electric field between foils drift of electrons towards the underlying foil.
- High electric field inside holes avalanche multiplication of electrons entering the holes.
- Signal collected with appropriate electronics

CMS GEM TDR 2015

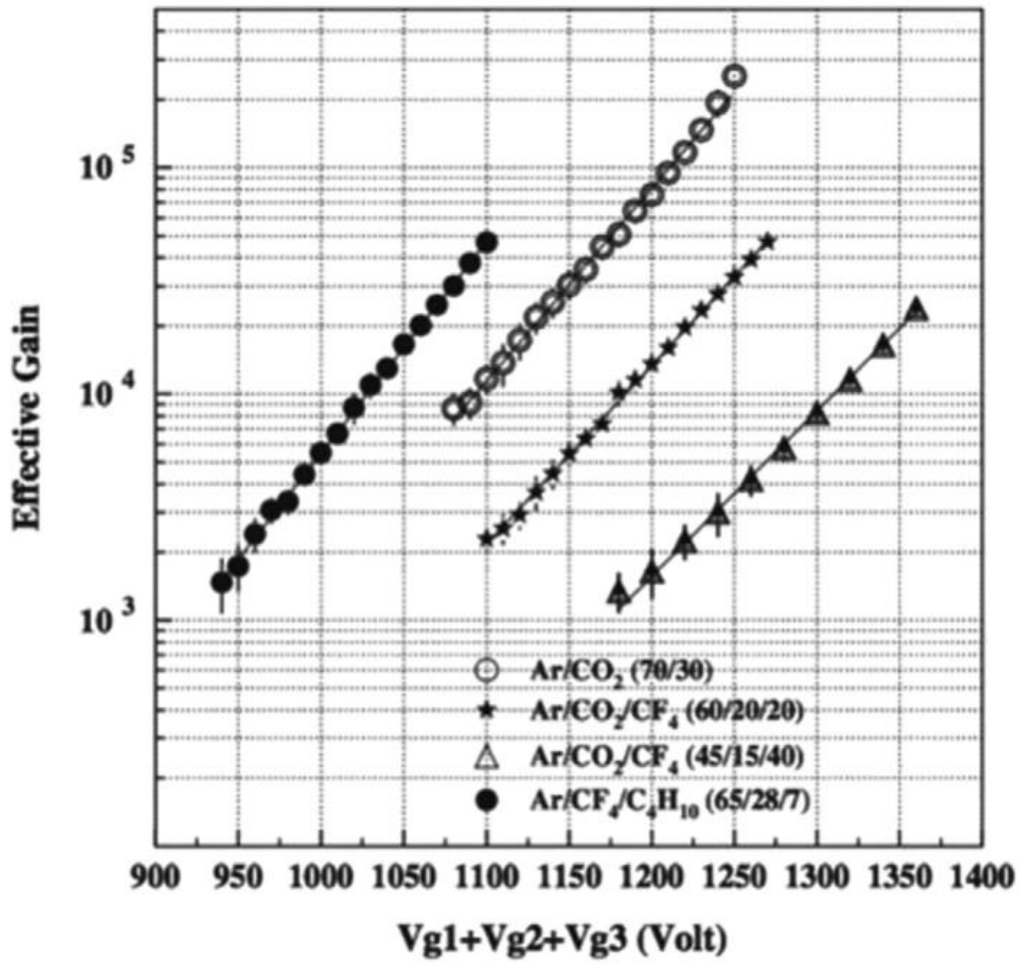


Muon detection efficiency > 97 %

Gas gain $=10^4$

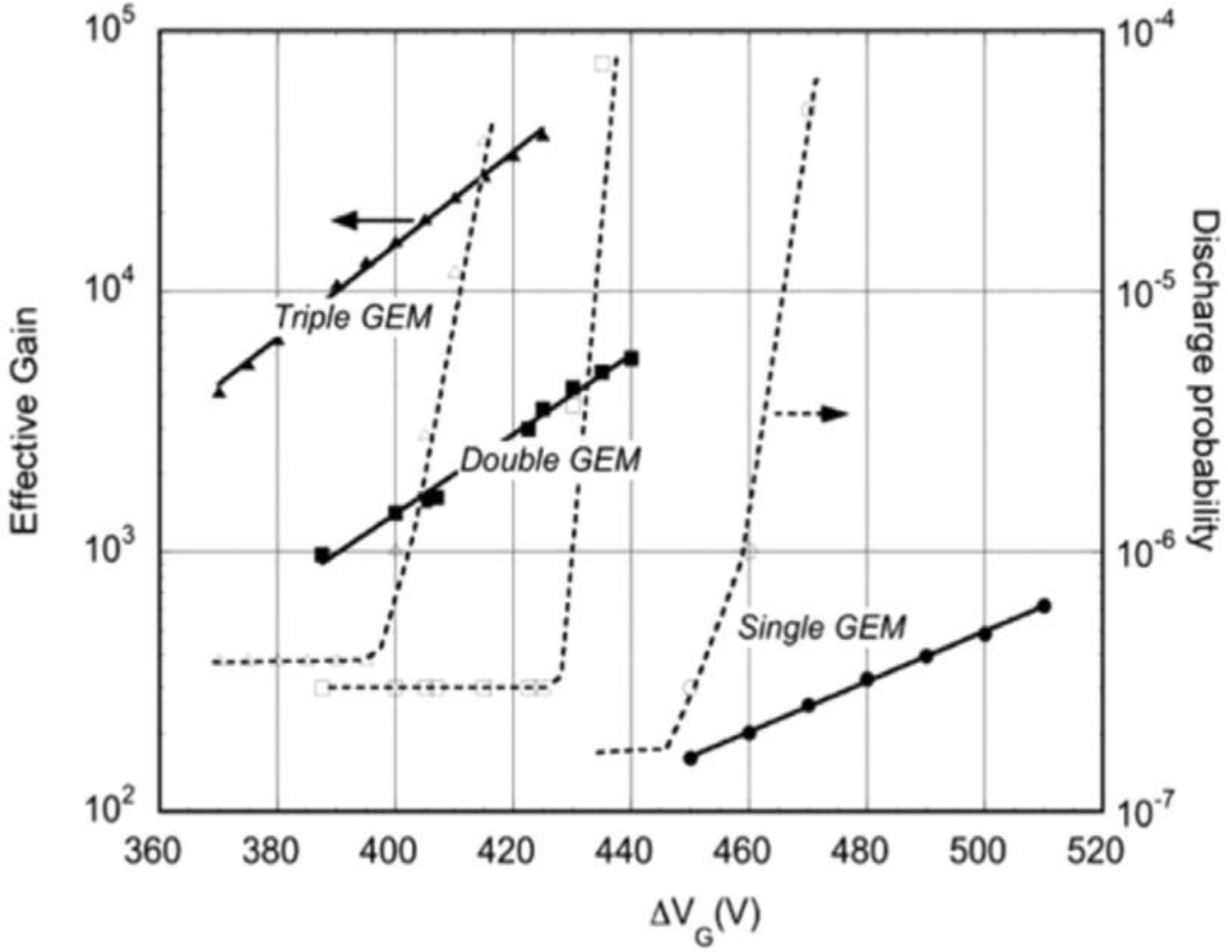
Timing resolution is = 4 ns

Triple GEM performance



F. Sauli NIM in Physics Research A 805 (2016) 2-24

Ar: CO2 70:30

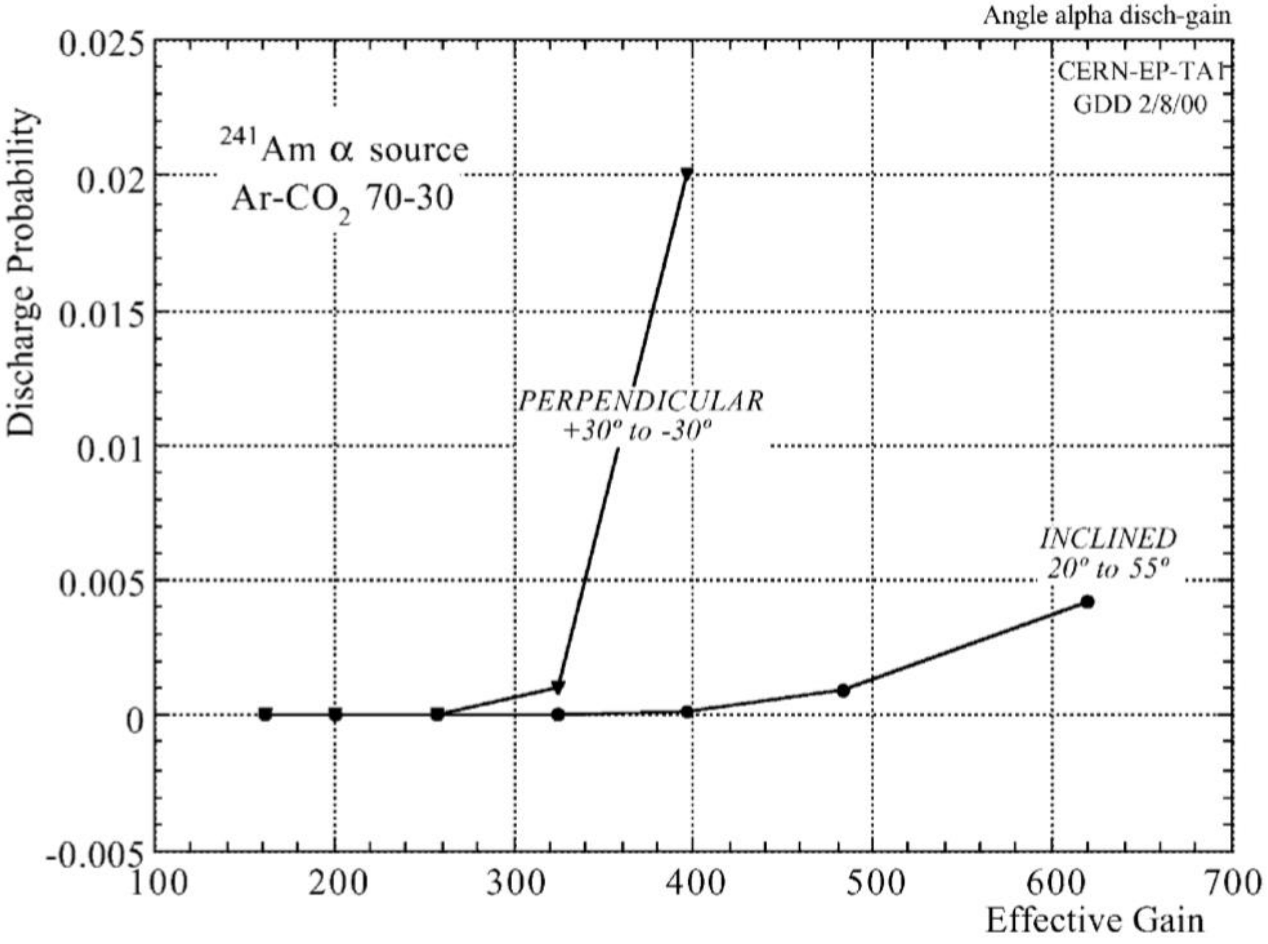


Discharged Probability

Discharge probability is the ratio between the observed frequency of breakdowns and the source rate

The decrease in discharge voltage is a reflection of the increasing avalanche size for multiple devices

- Maximum gain and discharge probability depend on the charge sharing between cascaded multipliers.
- The discharge probability depends strongly on the angle of tracks.

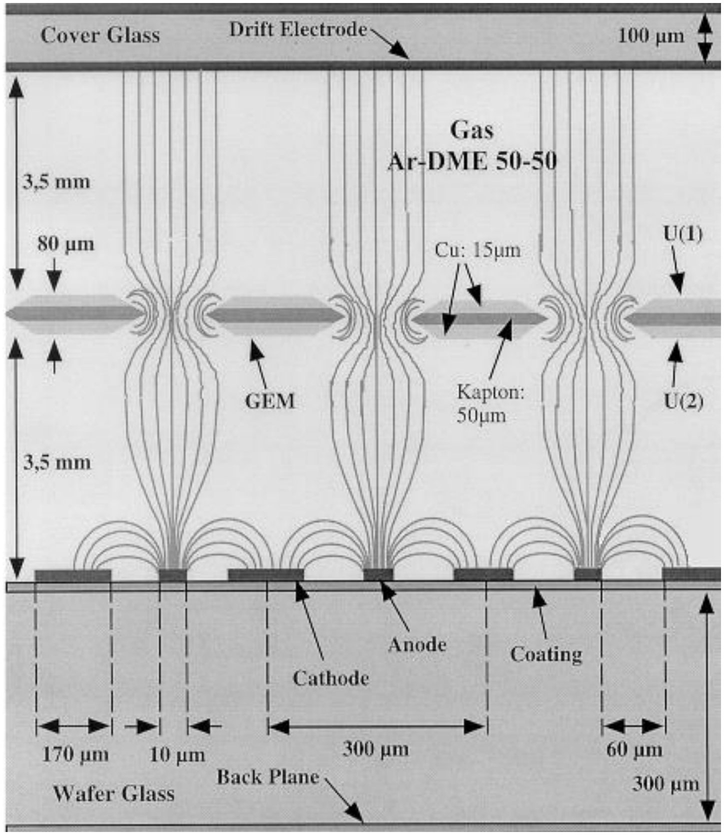


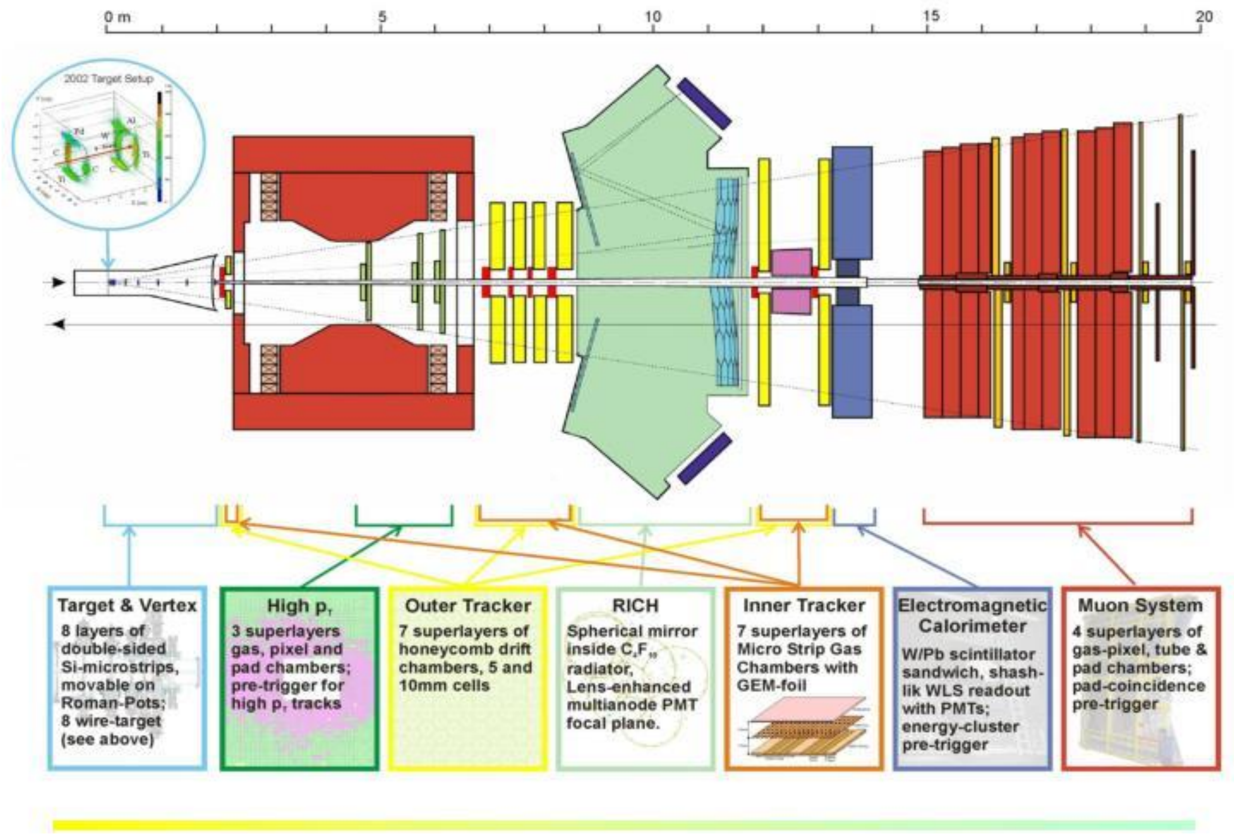
S. Bachmann et al. / NIM in Physics Research A 479 (2002) 294

GEM as a tracking detector at HERA-B

- (1999-2003)- The Inner Tracker (ITR) consists of Micro-Strip Gaseous Chambers (MSGC) combined with Gas Electron Multiplier foils (GEM).

- The MSGCs are made up of alkali-free glass plates coated with an 60-nm-thick amorphous carbon layer and a golden strip pattern.



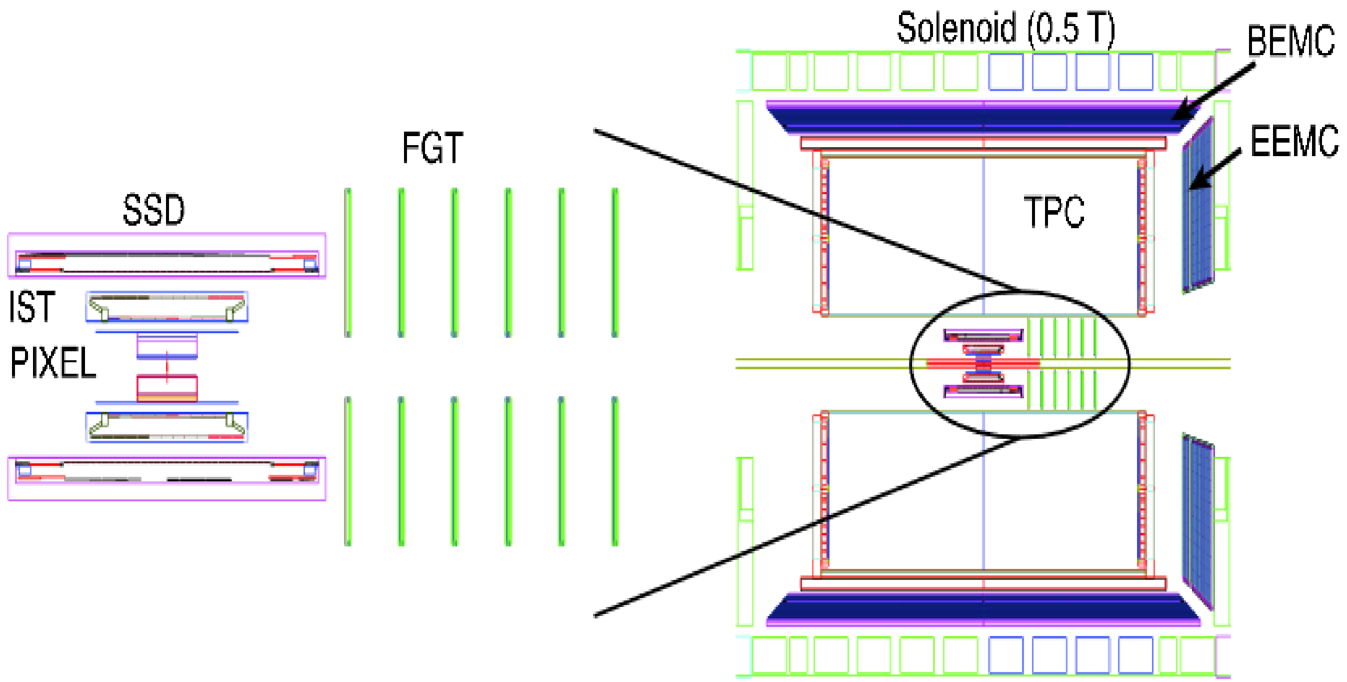


T. Hott/NIM. in Phys. Res. A 408 (1998) 258–265

GEM as a tracking detector in STAR

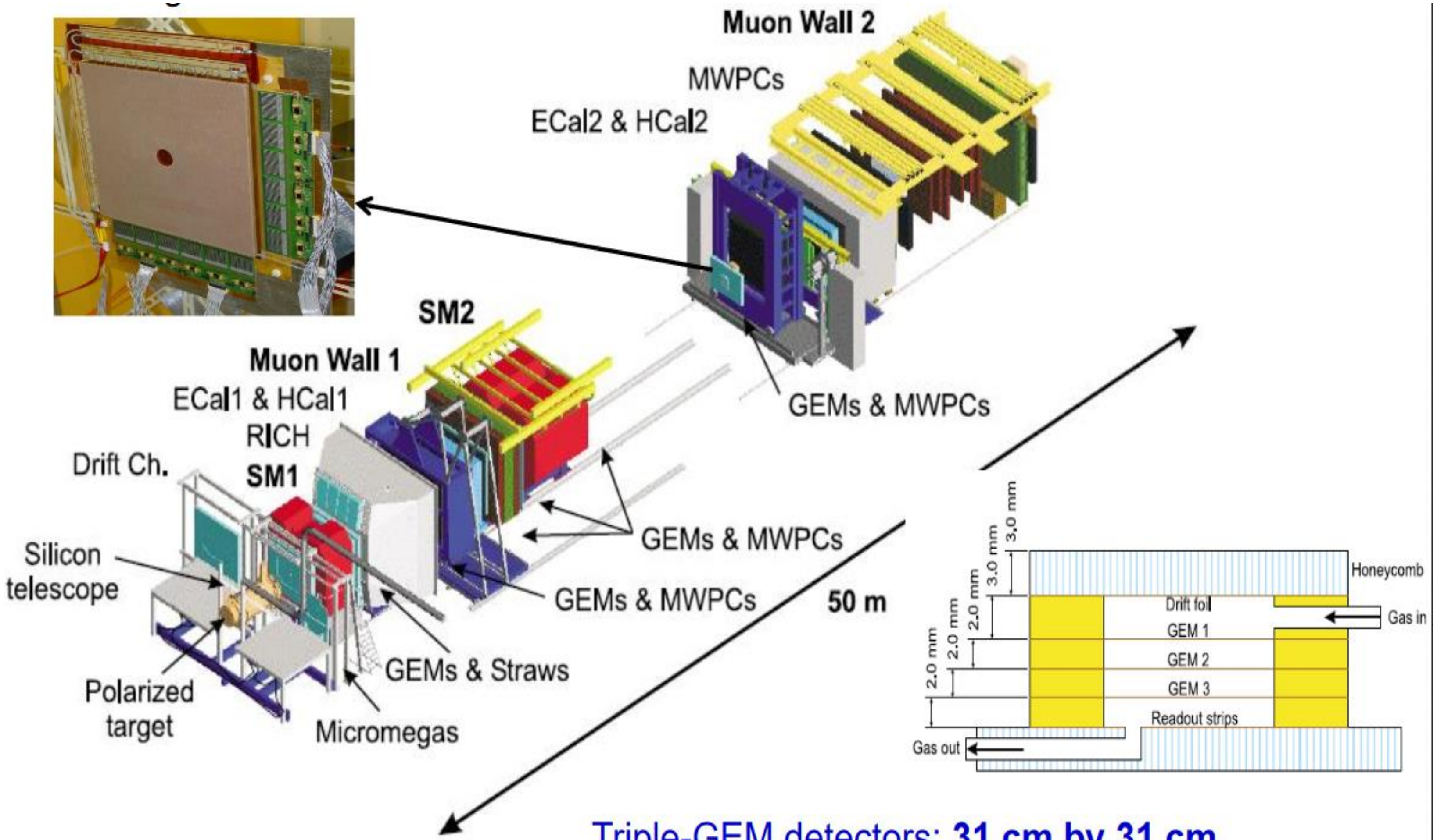
The **STAR detector** (for Solenoidal Tracker at RHIC) is one of the four experiments at the Relativistic Heavy Ion Collider (RHIC) in Brookhaven National Laboratory, United States.

- The baseline design of the Forward GEM Tracker FGT consists of 6 triple GEM disks along the beam direction.
- The GEM disks sit inside the inner field cage of the main time projection chamber TPC.
- The GEM detector disks are constructed from four quarter sections.



GEM as a tracking detector at COMPASS

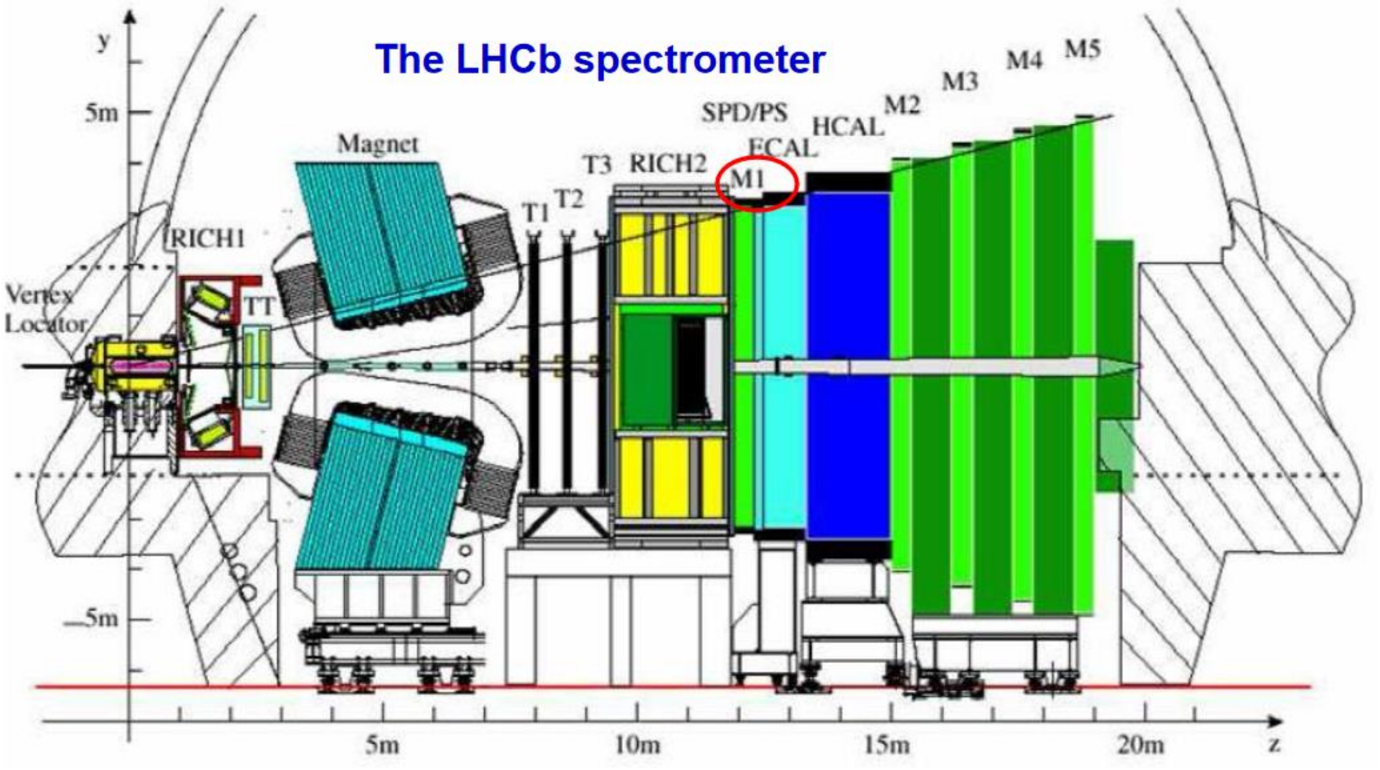
COMPASS (Comon Muon and Proton Apparatus for Structure and Spectroscopy) has been installed at the Super Proton Synchrotron accelerator (SPS) at CERN and began data taking in summer 2001.

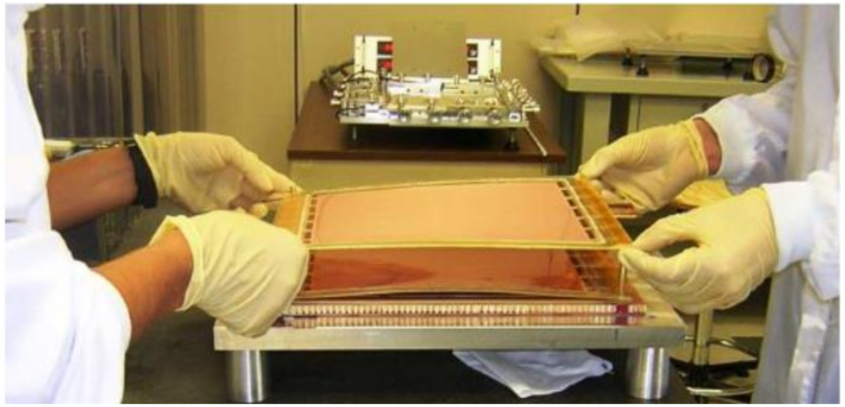


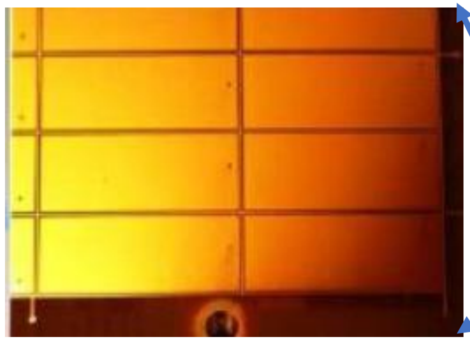
Triple-GEM detectors: **31 cm by 31 cm**

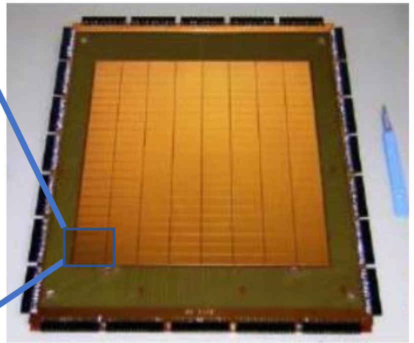
GEM as a trigger detector at LHCb

Triple GEM installation in the first muon station (M1R1)



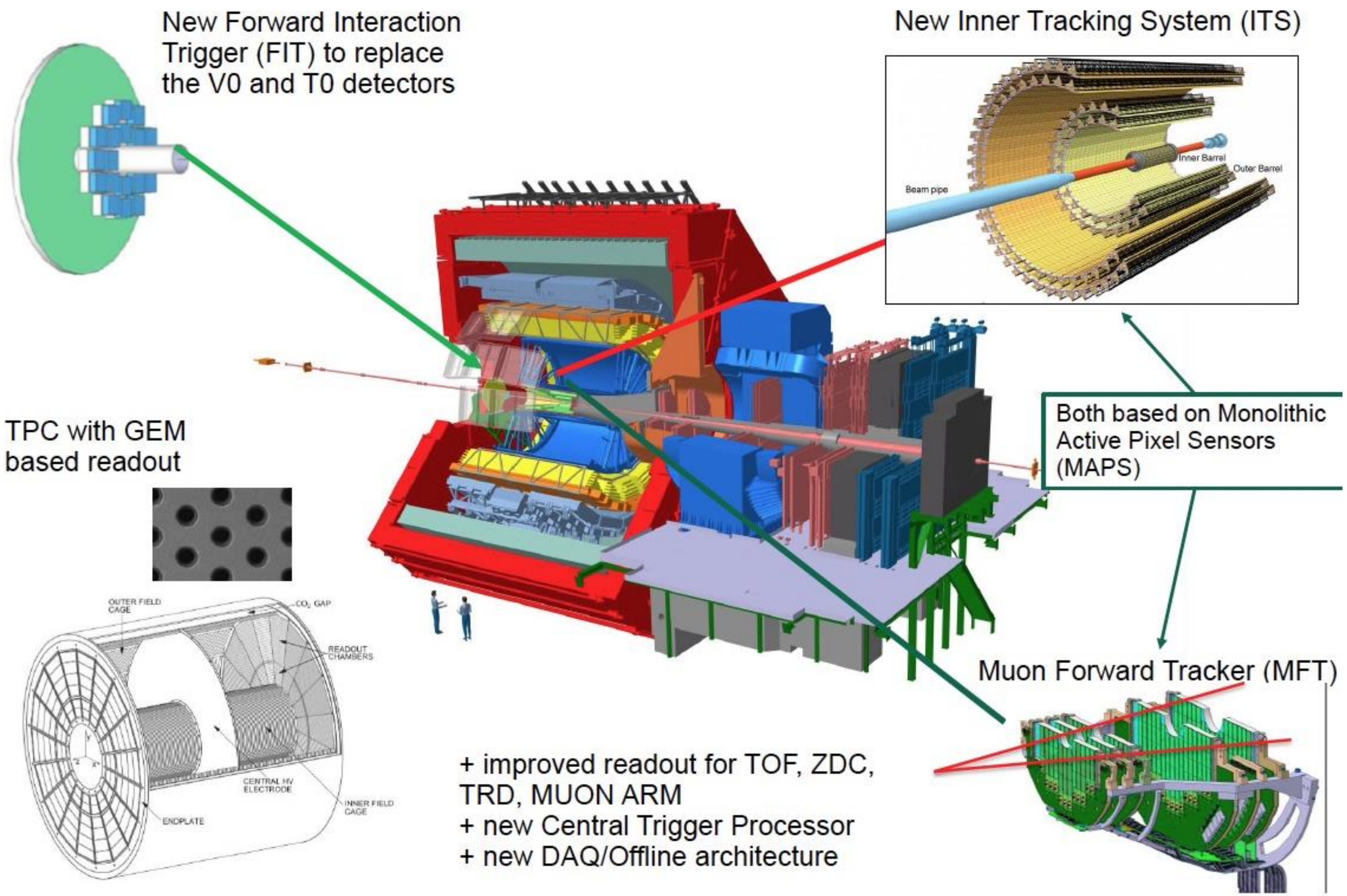






Triple GEM with an area of 20cm by 24 cm,
Readout: 8*24 gold plated pads
(size 25 mm by 10 mm).

GEM at ALICE



New Forward Interaction Trigger (FIT) to replace the V0 and T0 detectors
New Inner Tracking System (ITS)
Beam pipe
Inner Barrel
Outer Barrel
TPC with GEM based readout
Both based on Monolithic Active Pixel Sensors (MAPS)
OUTER FIELD CAGE
CO_2 GAP
READOUT CHAMBERS
CENTRAL HV ELECTRODE
INNER FIELD CAGE
ENDPLATE
Muon Forward Tracker (MFT)
+ improved readout for TOF, ZDC, TRD, MUON ARM
+ new Central Trigger Processor
+ new DAQ/Offline architecture

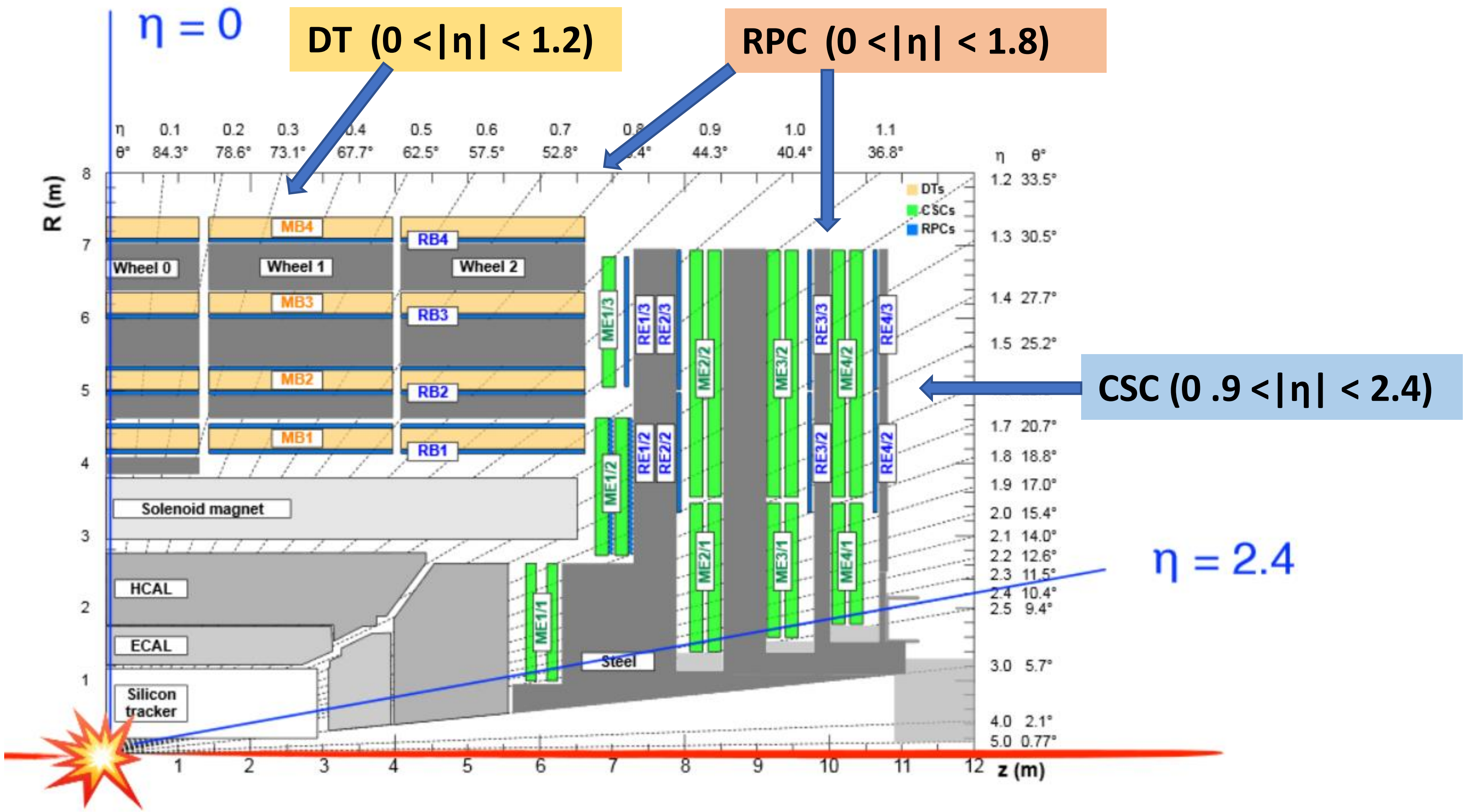
GEM at CMS Muon system

Technologies are chosen for different regions based on the particle rates and magnetic field.

Pseudo-rapidity= $\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$

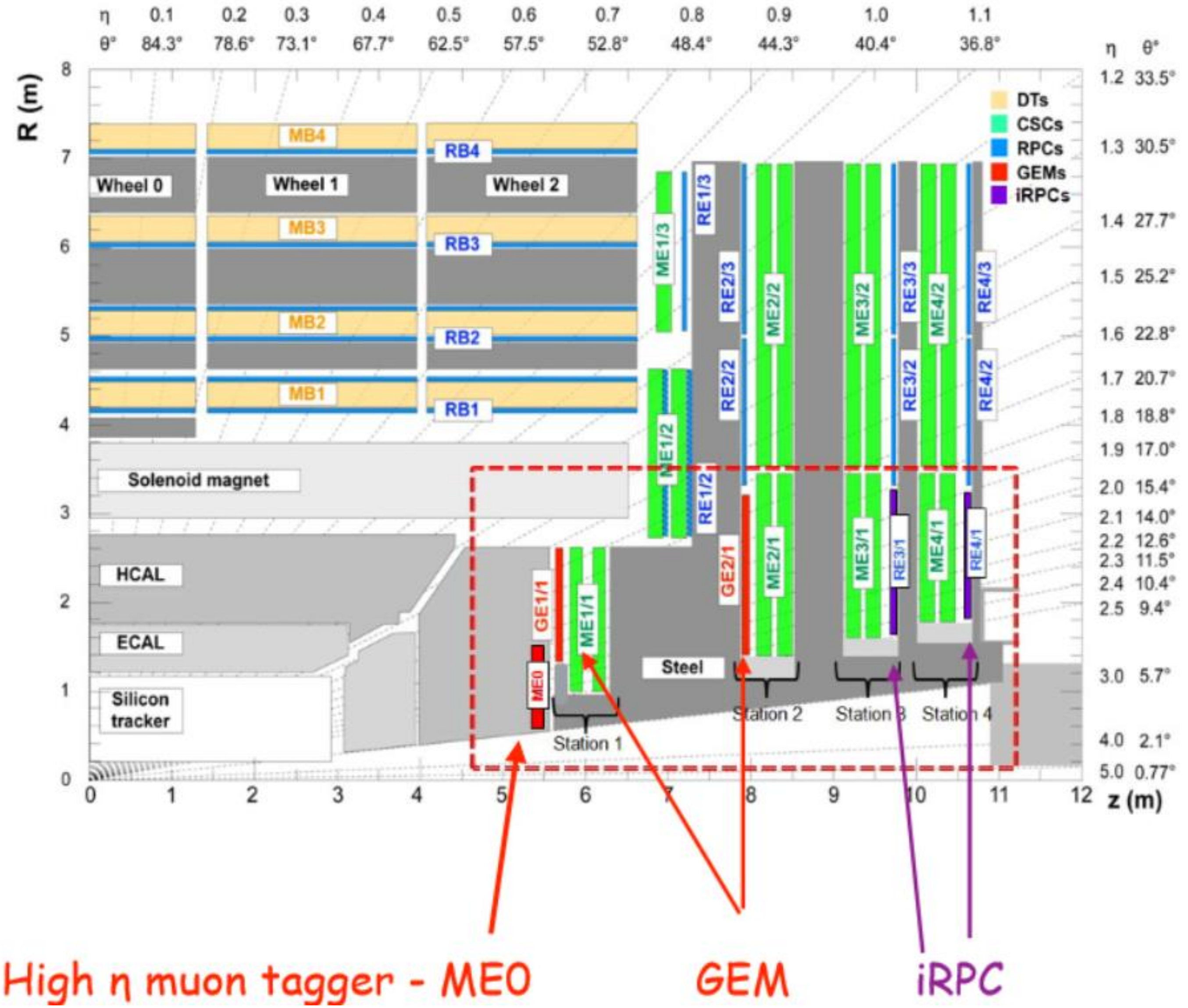
The trajectory of a muon passes 4 stations, 2 types of detectors (**except for the high η region**)

250 Drift tube chambers
172,000 channels
468 Cathode strip chambers
500,000 channels
912 Resistive plate chambers
160,000 channels
Total area ~ 6000 m² ie like a football field



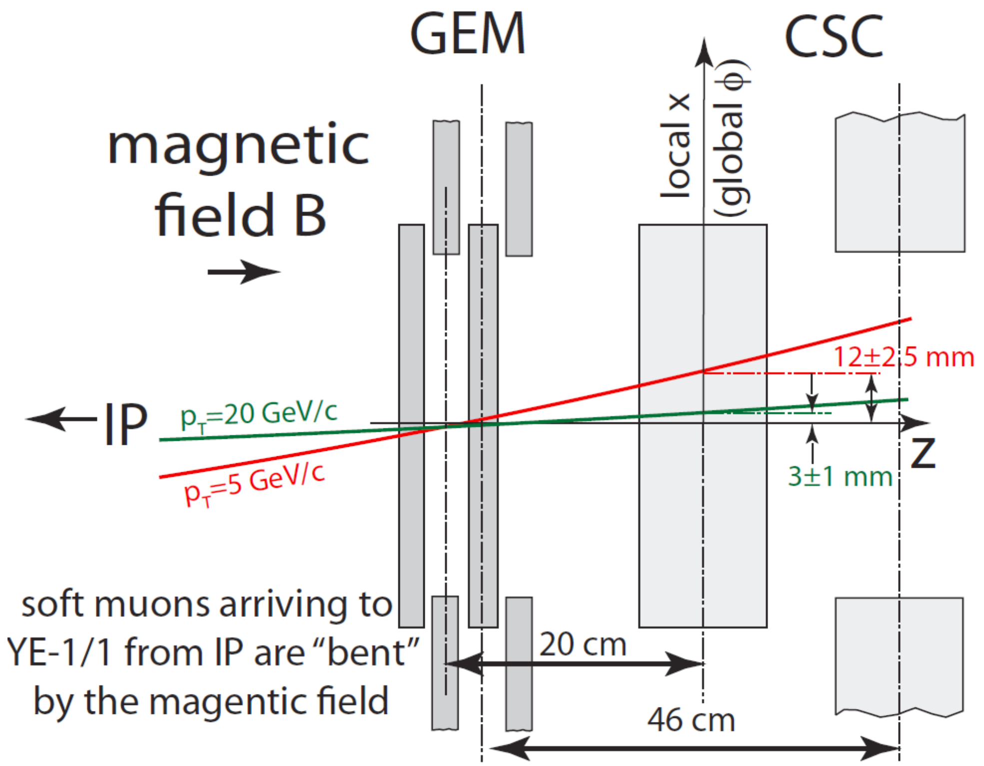
Muon system Upgrade

- ❑ High rate from random hits
- ❑ Low magnetic field => small bending of muon trajectory.
- ❑ Despite harsher environment, this region has fewer hits measurement as of today 1.8 < |η| < 2.4 covered only by CSC



GE1/1 Project motivation

L1 muon-trigger momentum resolution can be improved by measuring the bending angle with CSC+GEM

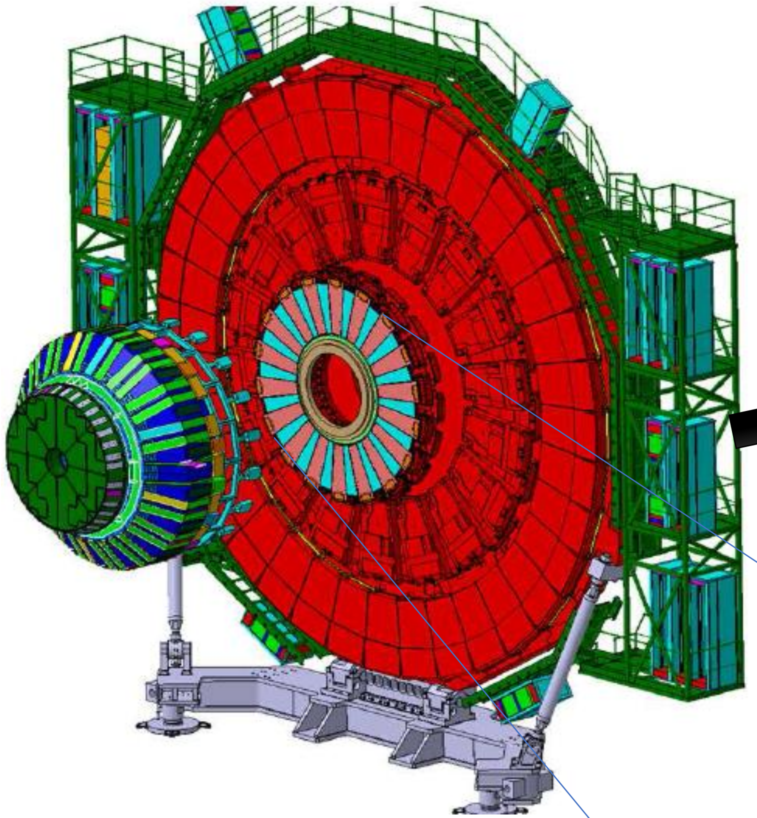


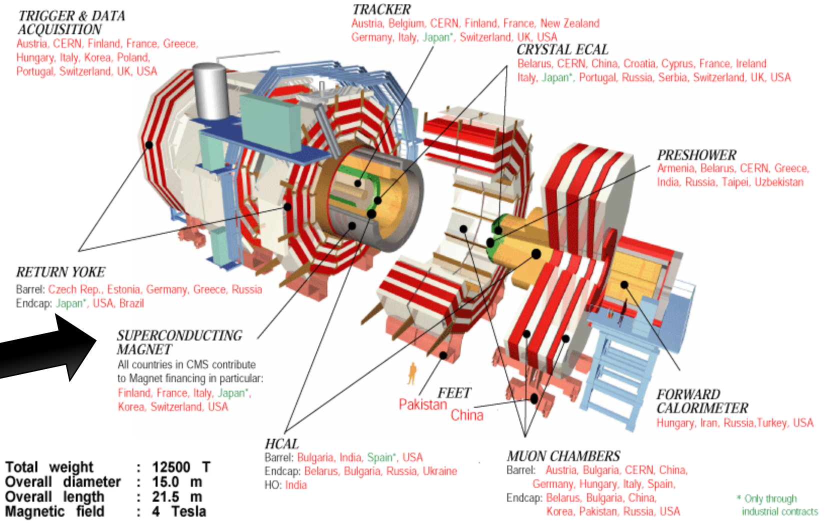
	p_T=5 GeV	p_T= 20 GeV
YE-1/1	12 cm	3 cm

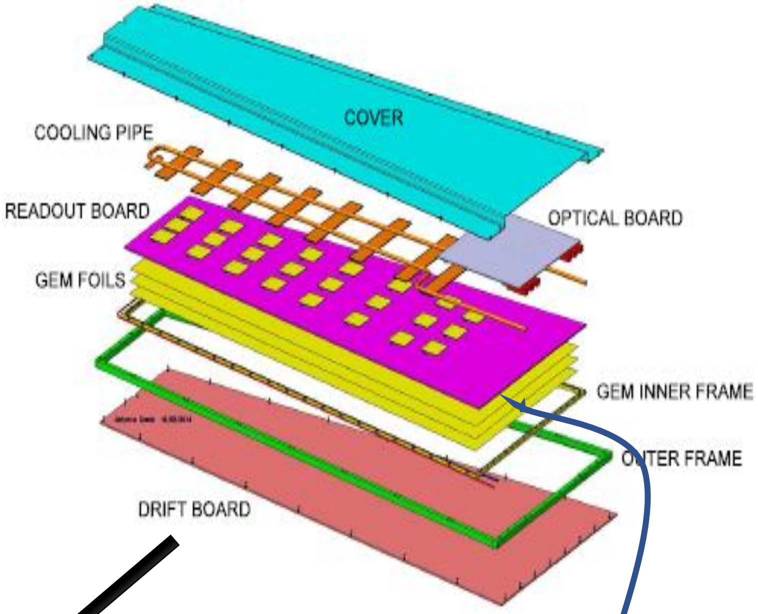
Measurement of the bending angle with a pair of a CSC and a GEM chamber, illustrating discrimination between lower and higher momentum muons.

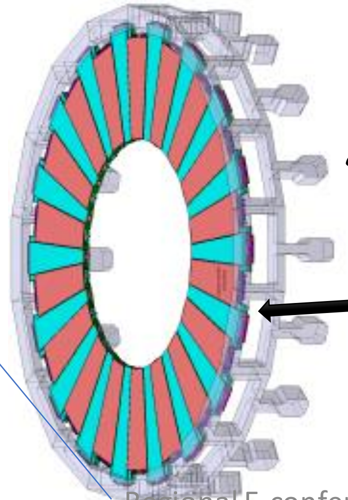
The GE1/1 upgrade provides an effective solution to the trigger rate problem and allows CMS to preserve its excellent muon triggering capabilities in the range |η| <2.2 until the LS3 and beyond.

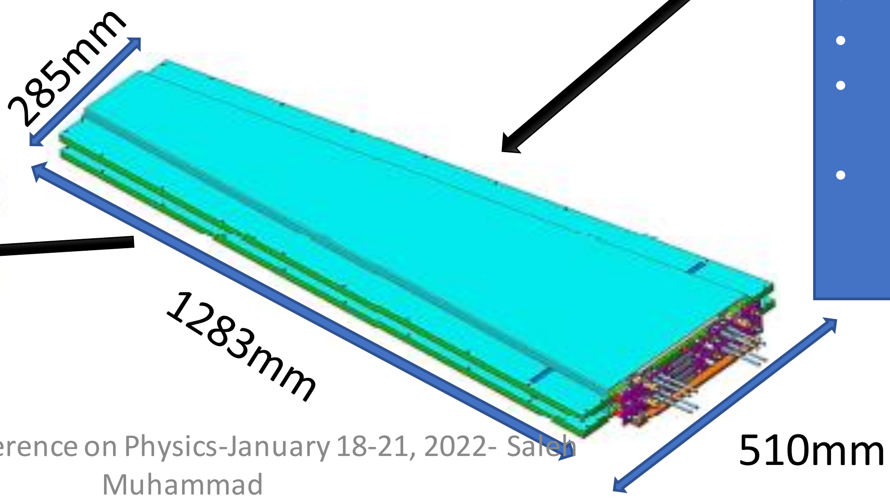
GE1/1 Project for CMS







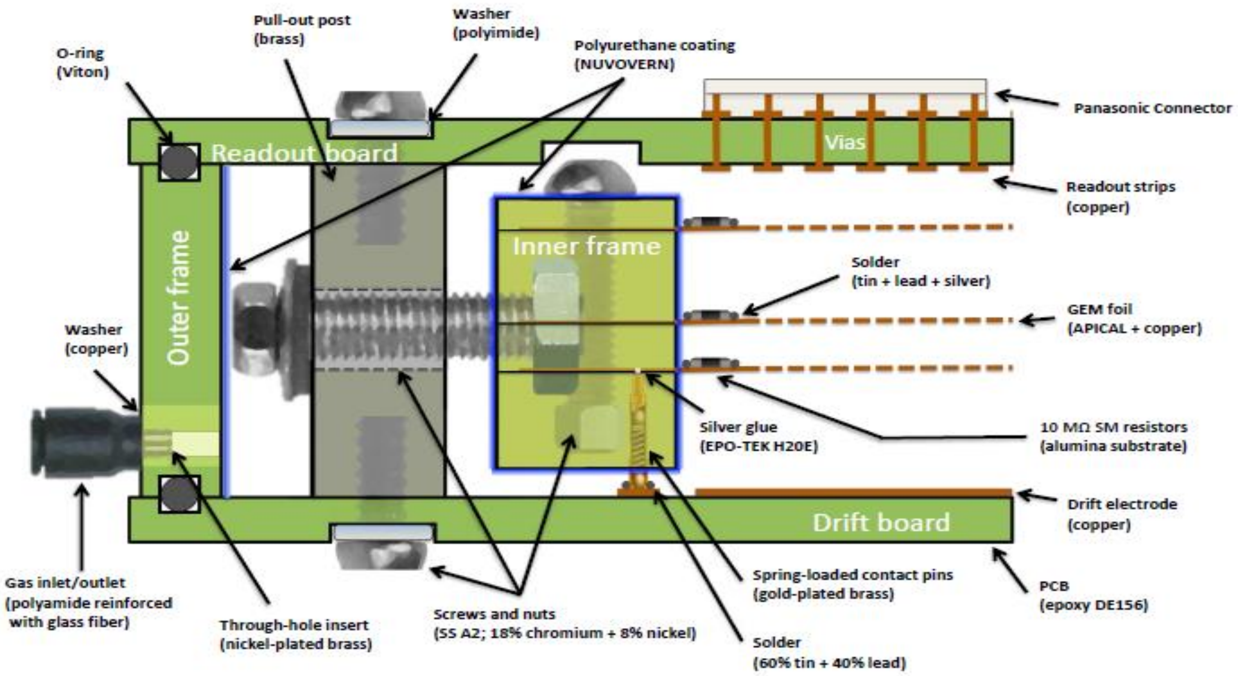


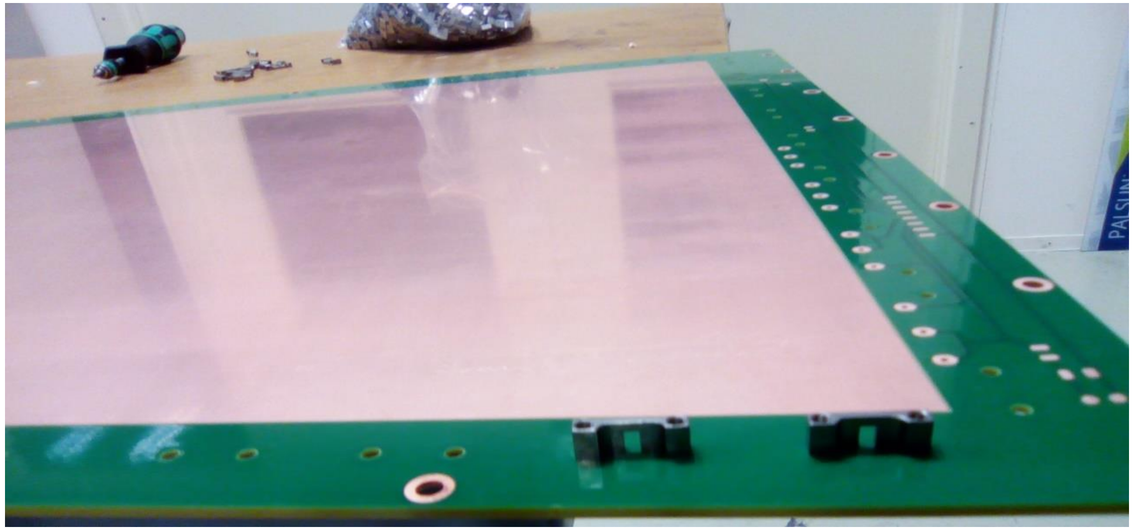


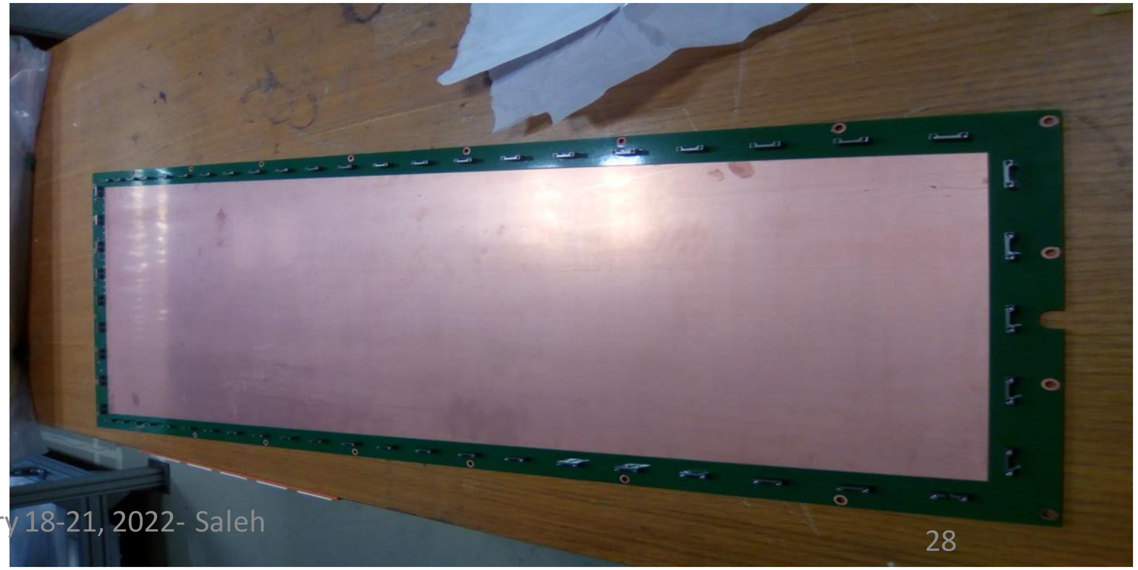
- Kapton + Copper 60µm thickness
- 1 to 2 mm spaces
- High dense micro holes (~ 75 holes/mm²)
- Intense electric field ~ 64 KV/cm at 380V PD, inside the holes produce charge amplification

GE1/1 detector assembly

By adopting stretching technique instead of glow assembly time reduced from week(s) to two hours per chamber and problem of dead region is also solved



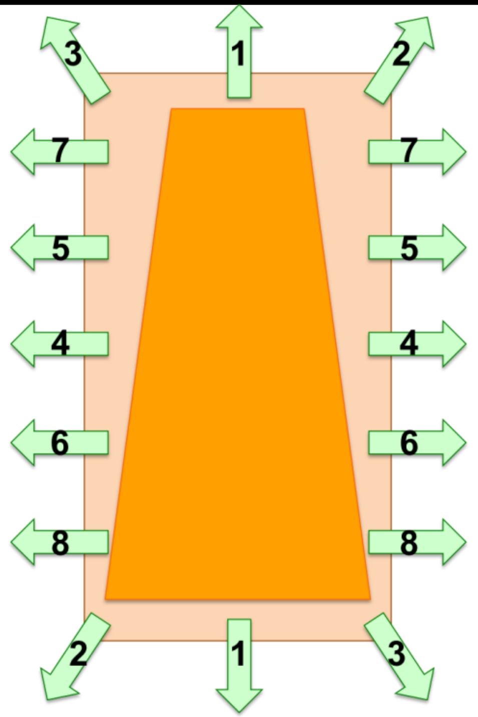




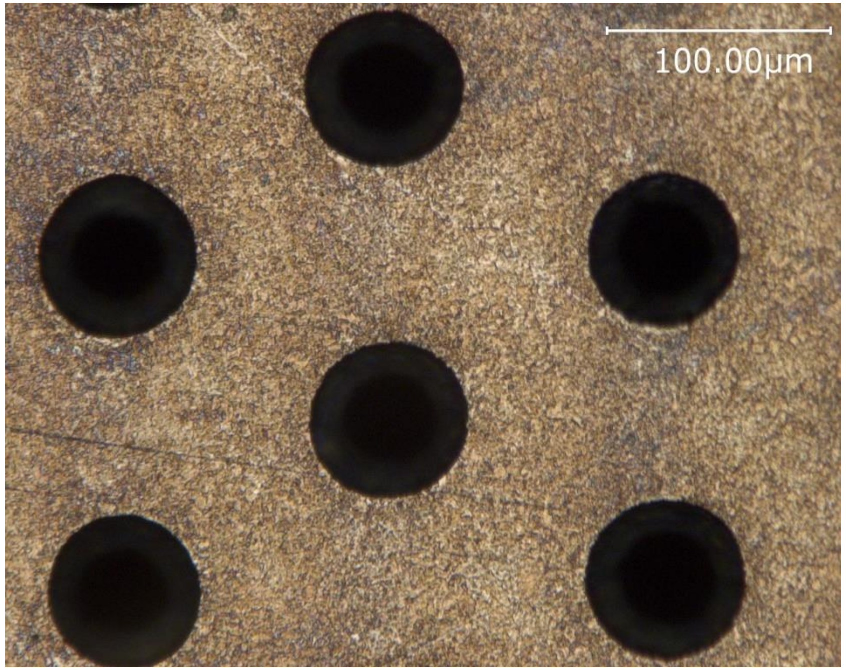
Type	Number of pull out
Short	55
Long	62

GE1/1 foil material structure

GEM foil consist of kapton (50 μm) coated with copper on both by 5 μm on each side and perforated with high density of holes.

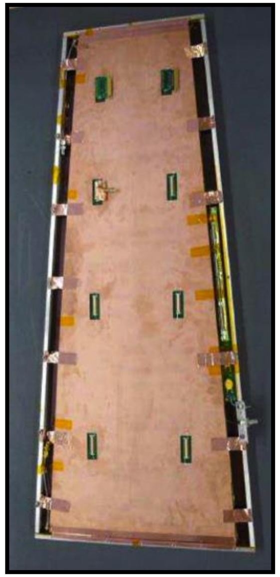
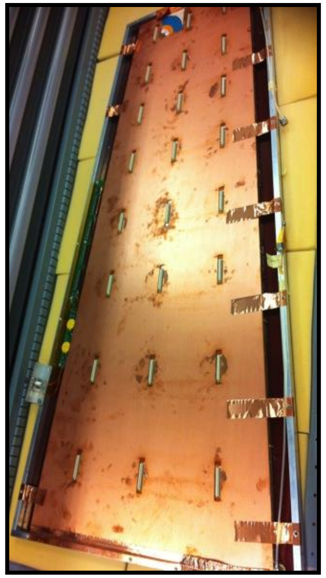
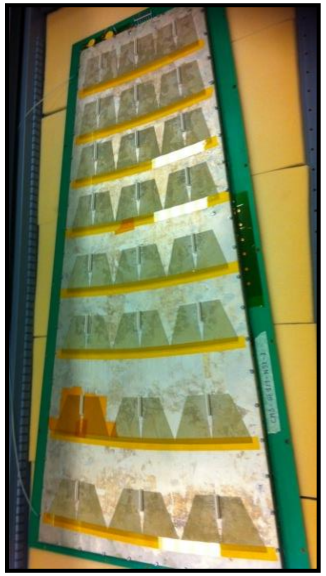


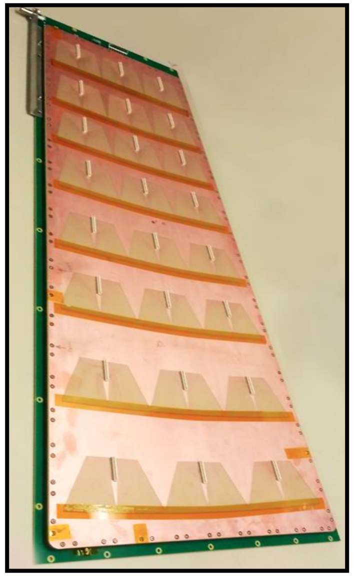
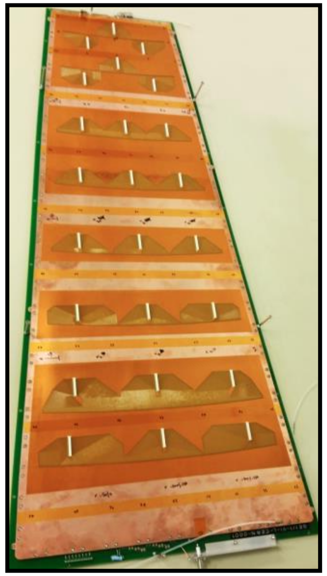
- 70 μm holes diameter
- 140 μm holes pitch
- Distance among the GEM foils is 1 and 2 mm and must be kept with a 50 μm precision in order not to have gain non-uniformity



Three GEM foils stack need to STRETCH in order to maintain the uniform gaps (1 mm) among the foils in the area of about 0.4 m^2

GE1/1 detector R & D phases

2010 2011 2012 2013 2014 2015

R&D phases

Toward production phase

GE1/1-I
- -> first 1m-class GEM detector ever built
- -> single-mask technology
- -> 99x(22-45) cm^2
- -> 1024 readout channels
- -> gap config. 3/2/2/2
- -> use of spacer grid and glue

GE1/1-II
- -> Optimization of the electric field configuration
- -> single-mask technology
- -> 99x(22-45) cm^2
- -> 3072 readout channels
- -> gap config. 3/1/2/1
- -> use of spacer grid and glue

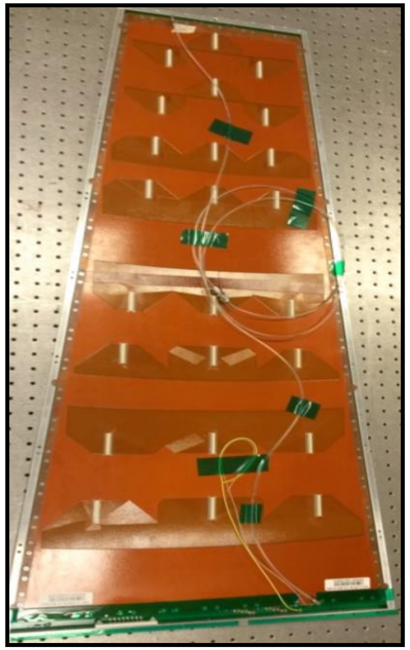
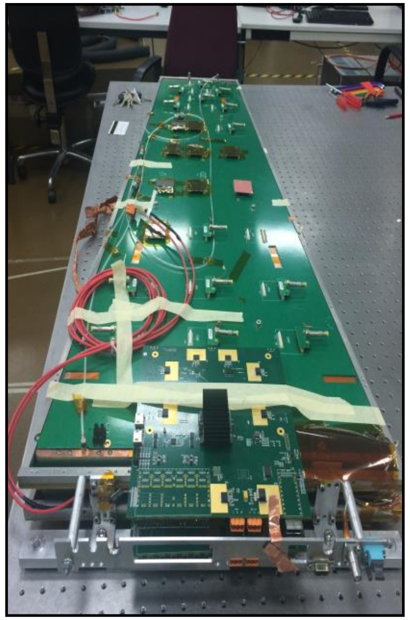
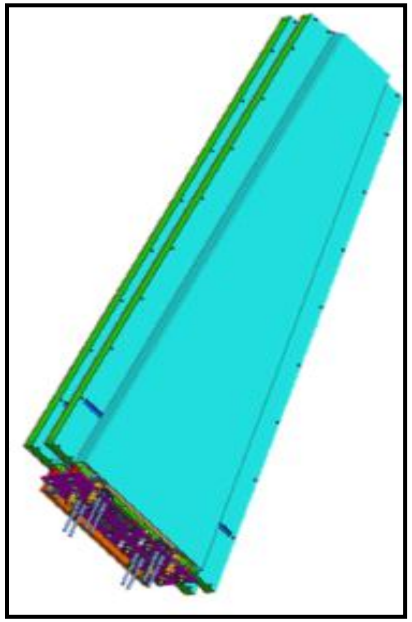
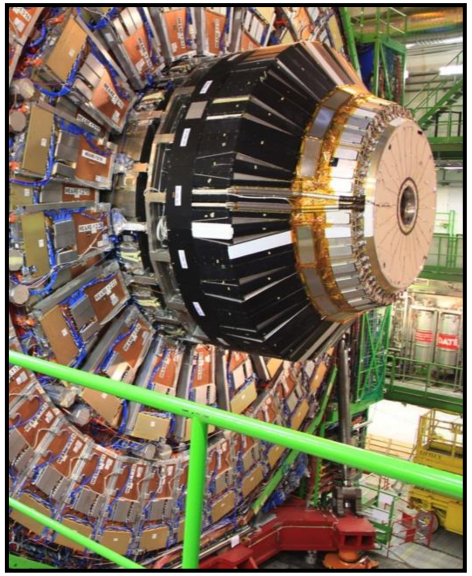
GE1/1-III
- -> first use of the self-stretching technique
- -> single-mask technology
- -> 99x(22-45) cm^2
- -> 3072 readout channels
- -> gap config. 3/1/2/1
- -> No spacers but glue on the external frame

GE1/1-IV
- -> Optimization of the mechanics and assembly
- -> single-mask technology
- -> 99x(22-45) cm^2
- -> 3072 readout channels
- -> gap config. 3/1/2/1
- -> No glue/no spacers

GE1/1-V
- -> Optimization of the mechanics
- -> stretching apparatus inside the gas volume
- -> single-mask technology
- -> 99x(22-45) cm^2
- -> 3072 readout channels
- -> gap config. 3/1/2/1
- -> No glue/no spacers

GE1/1-VI
- -> Optimization of the mechanics
- -> single-mask technology
- -> design for long and short detectors
- -> 99x(22-45) cm^2
- -> 120x(20-50) cm^2
- -> 3072 readout channels (new mapping)
- -> gap config. 3/1/2/1
- -> No glue/no spacers

GE1/1 supper chamber

GE1/1-X (LS2)

GE1/1-VII (slice test)
- ***Optimization of the mechanics***
- ***Optimization of the grounding***
- ***Optimization of the HV distribution***
- ***Single-mask technology***
- ***3072 readout channels***
- ***gap config. 3/1/2/1***
- ***No glue/no spacers***

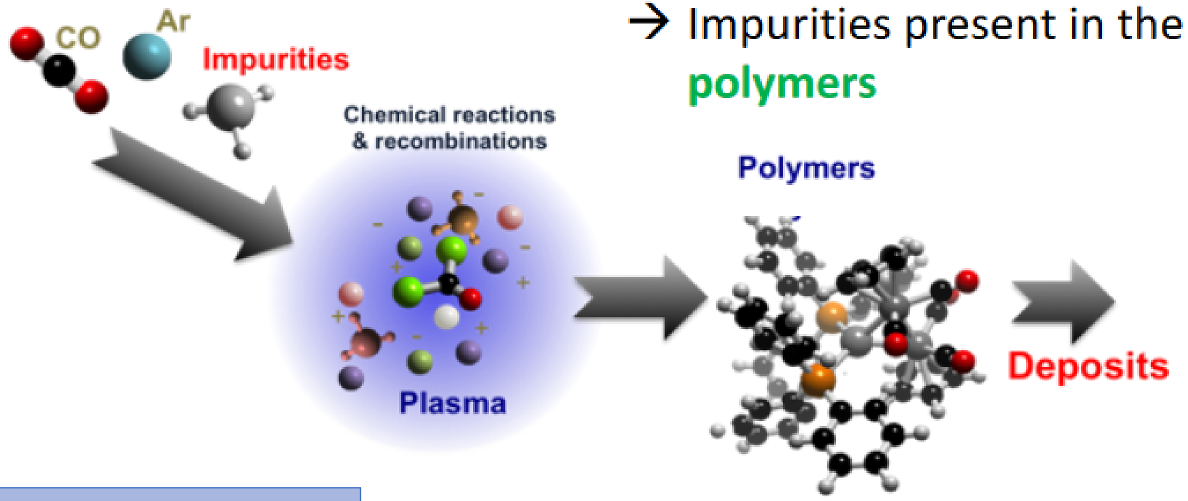
- ***GE1/1 chamber assembly and certification***
- ***Super chamber mechanics optimization***
- ***First test with final front-end electronics***

- ***GE1/1 super chamber assembly and certification with final front-end electronics.***

- ***GE1/1 super chambers installation in P5.***
- ***Installation and cabling of all super chambers***
- ***Commissioning in situ with cosmic muons***
- ***Super chamber characterization in situ with cosmic muon***

Aging

Classical Aging:



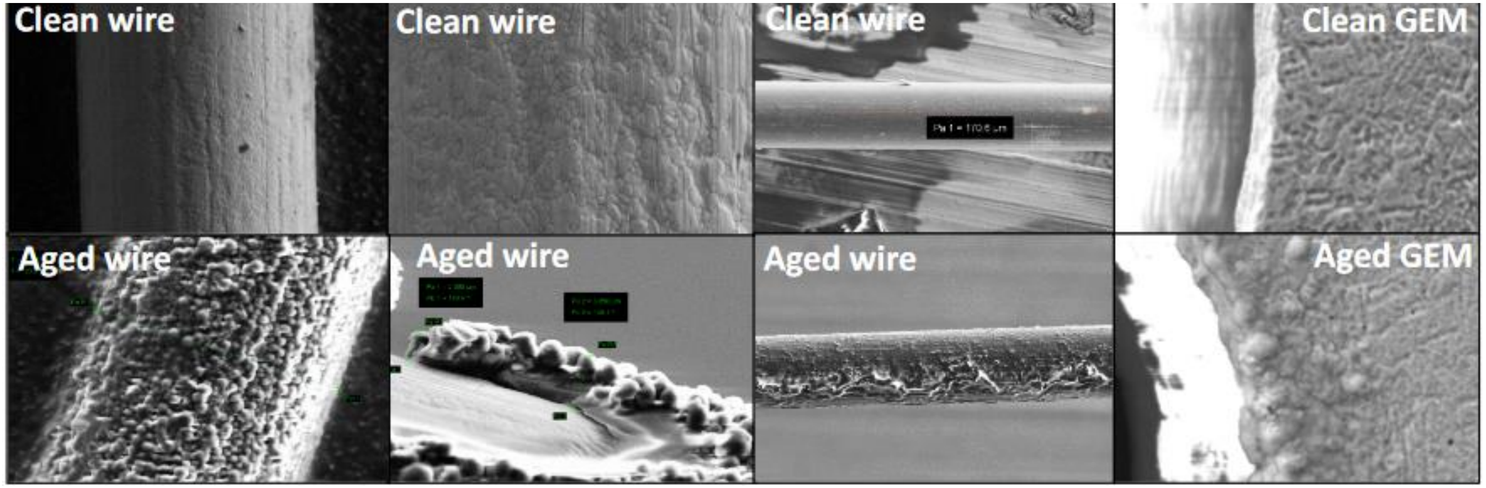
→ **Plasma polymerization** can take place during the amplification, inside the electron avalanche

→ Impurities present in the gas can dissociate et re-combine as **polymers**

→ Polymers can then **build up** on the amplification structure, disturbing the electric field, causing HV stability, causing leakage current, defects, discharges etc …

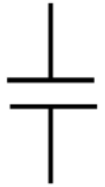
→ **Slow process**, but will keep going everytime a particle crosses the detector

Plasma Polymerization is a **process in which organic and inorganic polymers are deposited from a monomer vapor** by the use of an electron beam, ultraviolet radiation, or glow discharge.



Discharge

A GEM is a foil of insulating material (PI) coated on both sides with a thin layer of copper à large capacitor



GEM foils typically have a capacitance of several nf (several tens of nf for the largest ones)

When operating at nominal gain, the voltage across a GEM foil is typically 400-450 V

The energy stored in the foil is given by

$$E = \frac{1}{2} \times C \times V^2$$

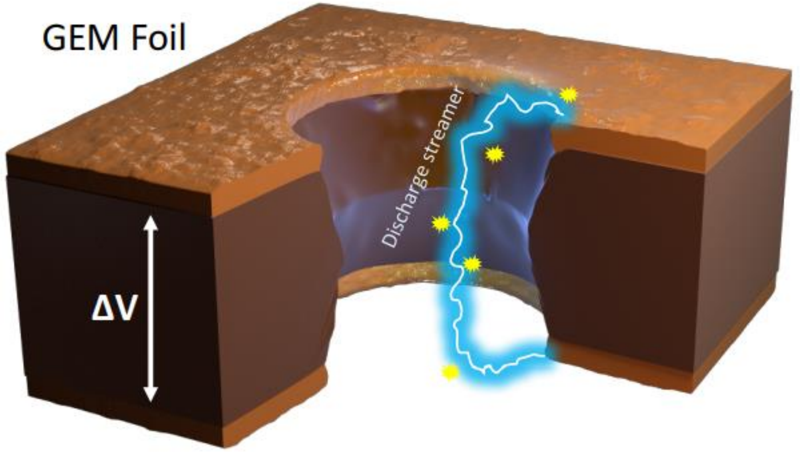
Where C is the capacitance and V the voltage

$$E = \frac{1}{2} \times 10\, nF \times 450V^2 \sim \mathbf{1\ mJ}$$

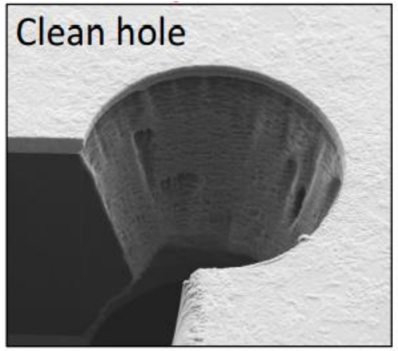
In the world of microscopic objects, 1 mJ is something big !

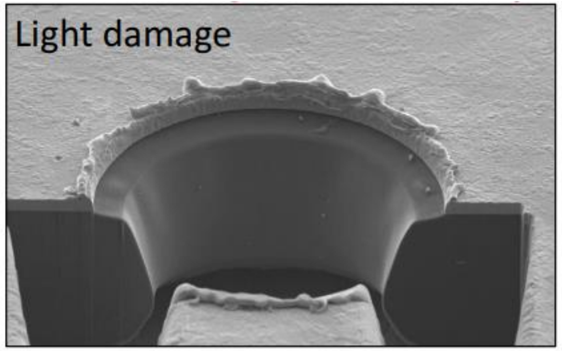
During the operation, a GEM hole may become conductive (because of defects, dust, or the presence of too many free charges in the gas)

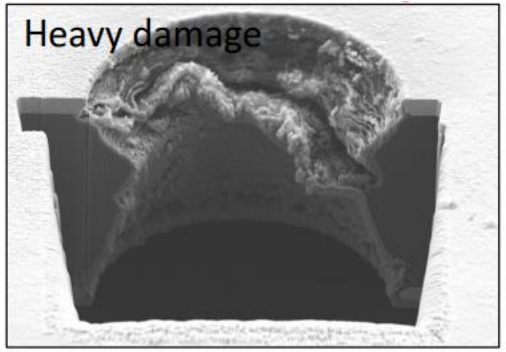
- In that case, the charge stored in one of the GEM electrode can be transferred to the other electrode
- During this transfer, a lot of energy is involved and may damage the inside structure of the GEM holes, provoke the evaporation of the thin copper layer, melt the insulating material etc …



Irreversible damage due to discharge



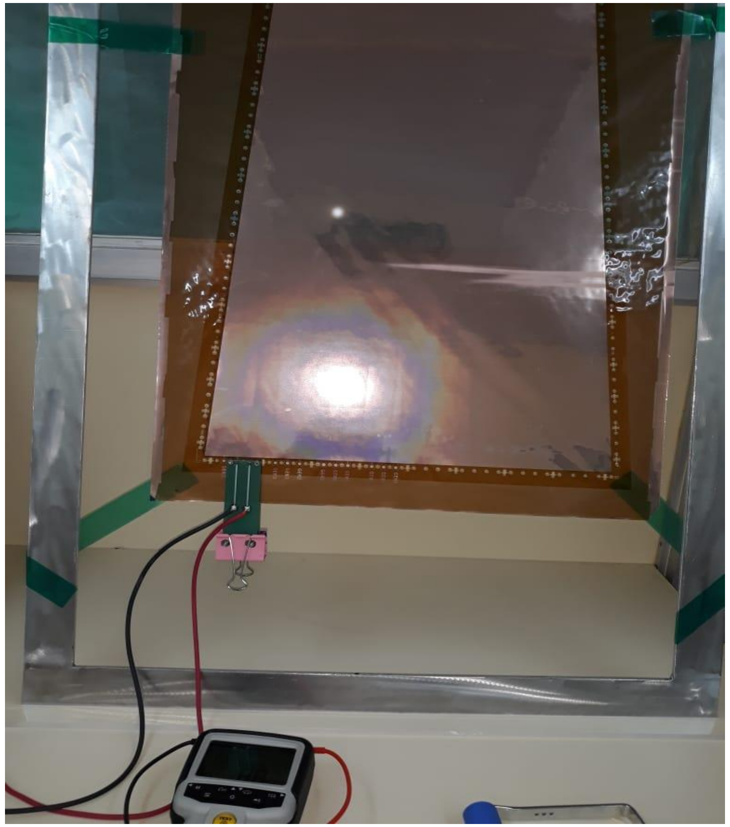


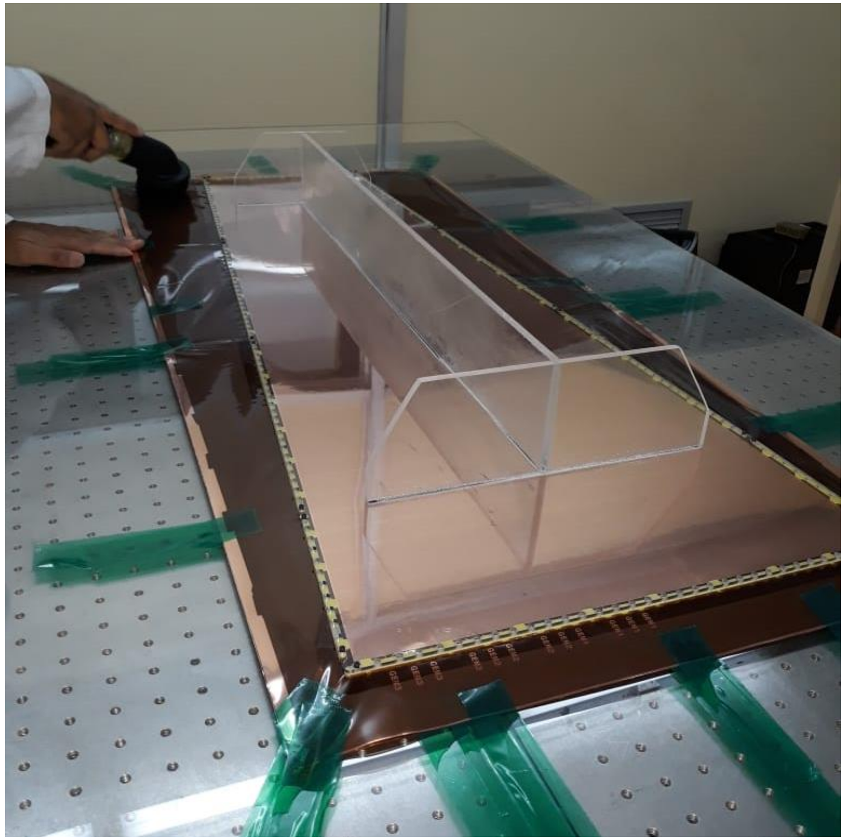


CMS GEM Collaboration

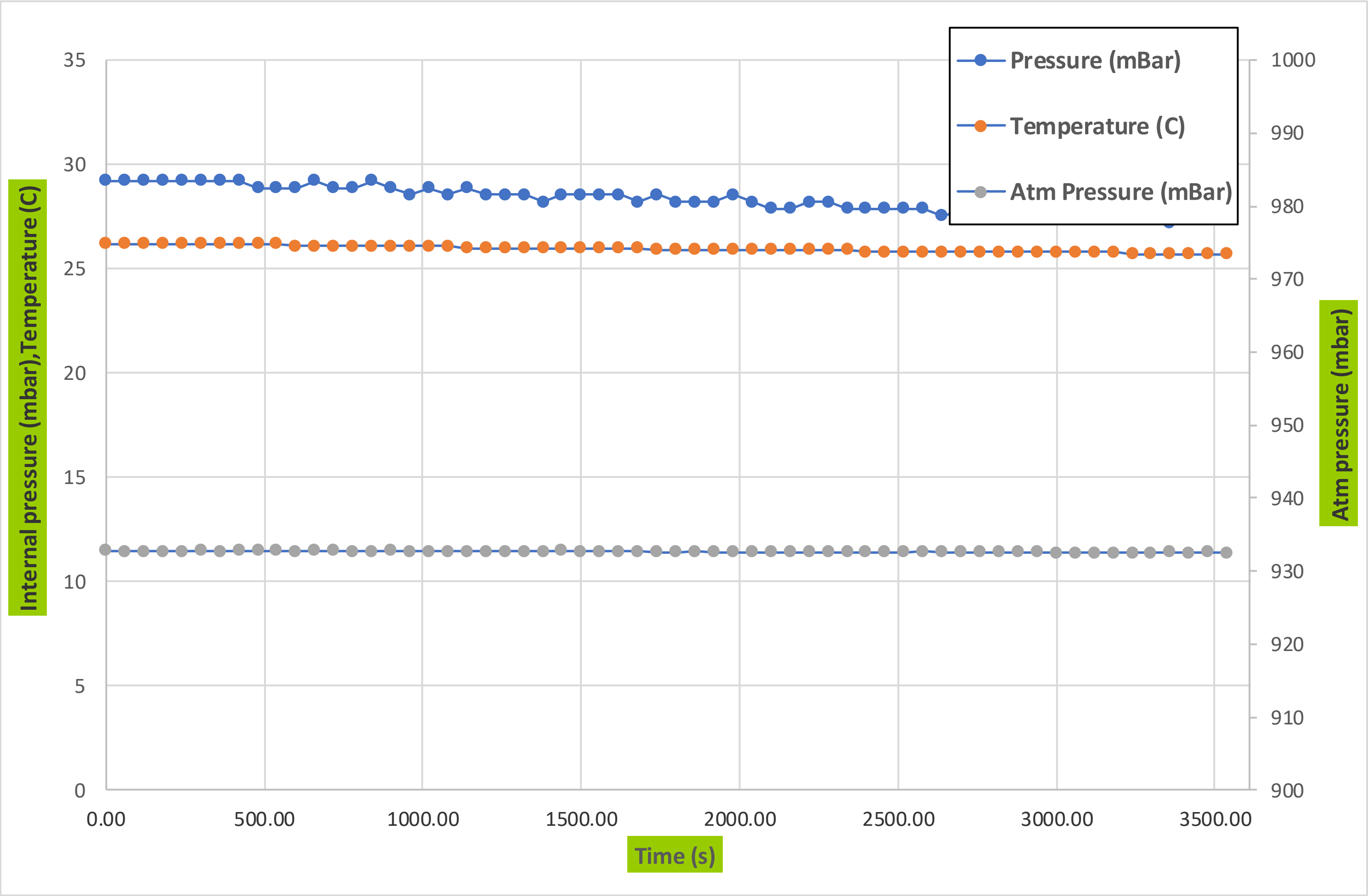
GEM lab at NCP

Detector assembly pics.

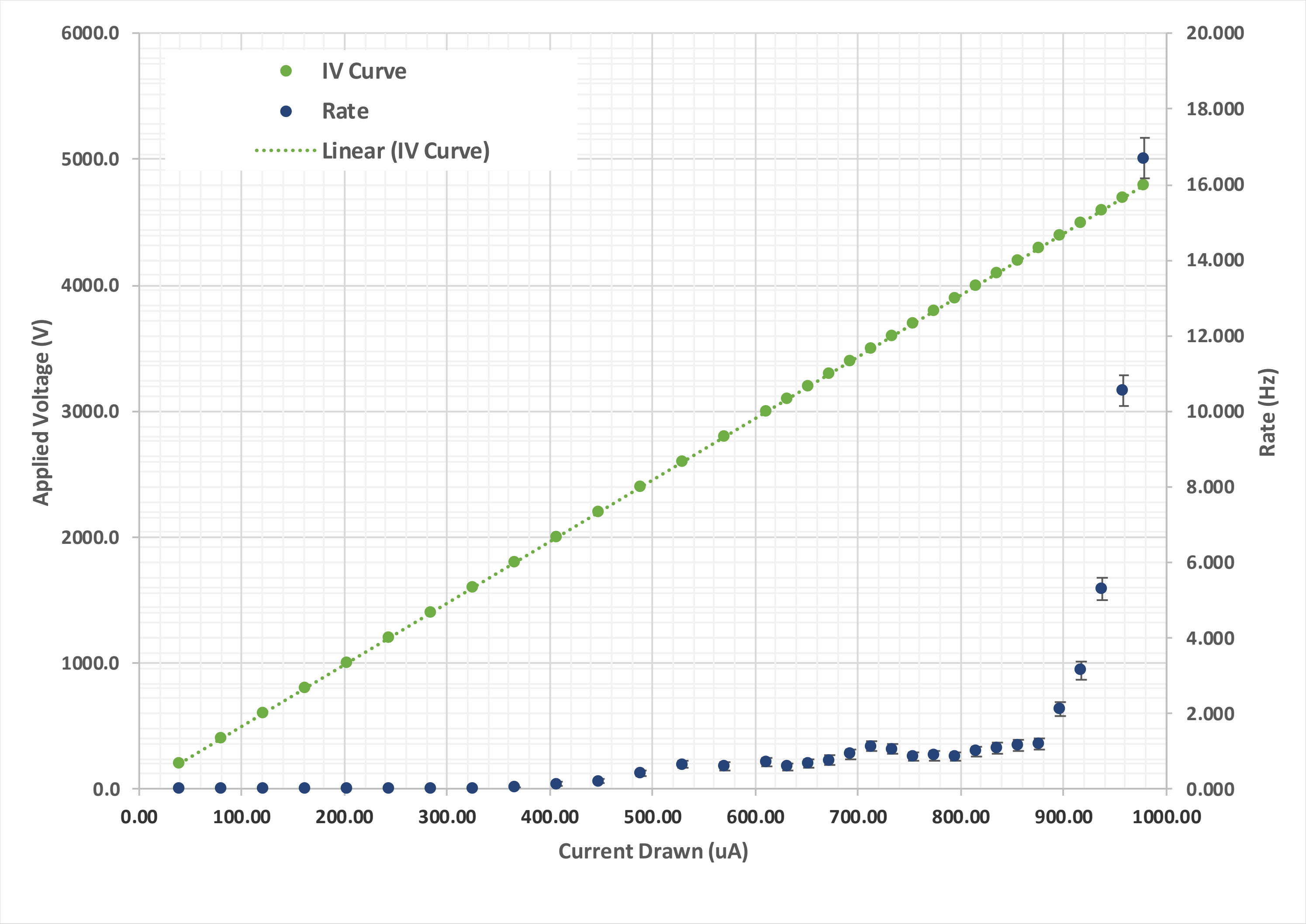




QC3-GE11-VII-S-PAK-002



QC4-GE11-VII-S-PAK-002



QC5-Effective gain

$$\text{Gain} = \frac{I}{R \times n_{prim} \times e}$$

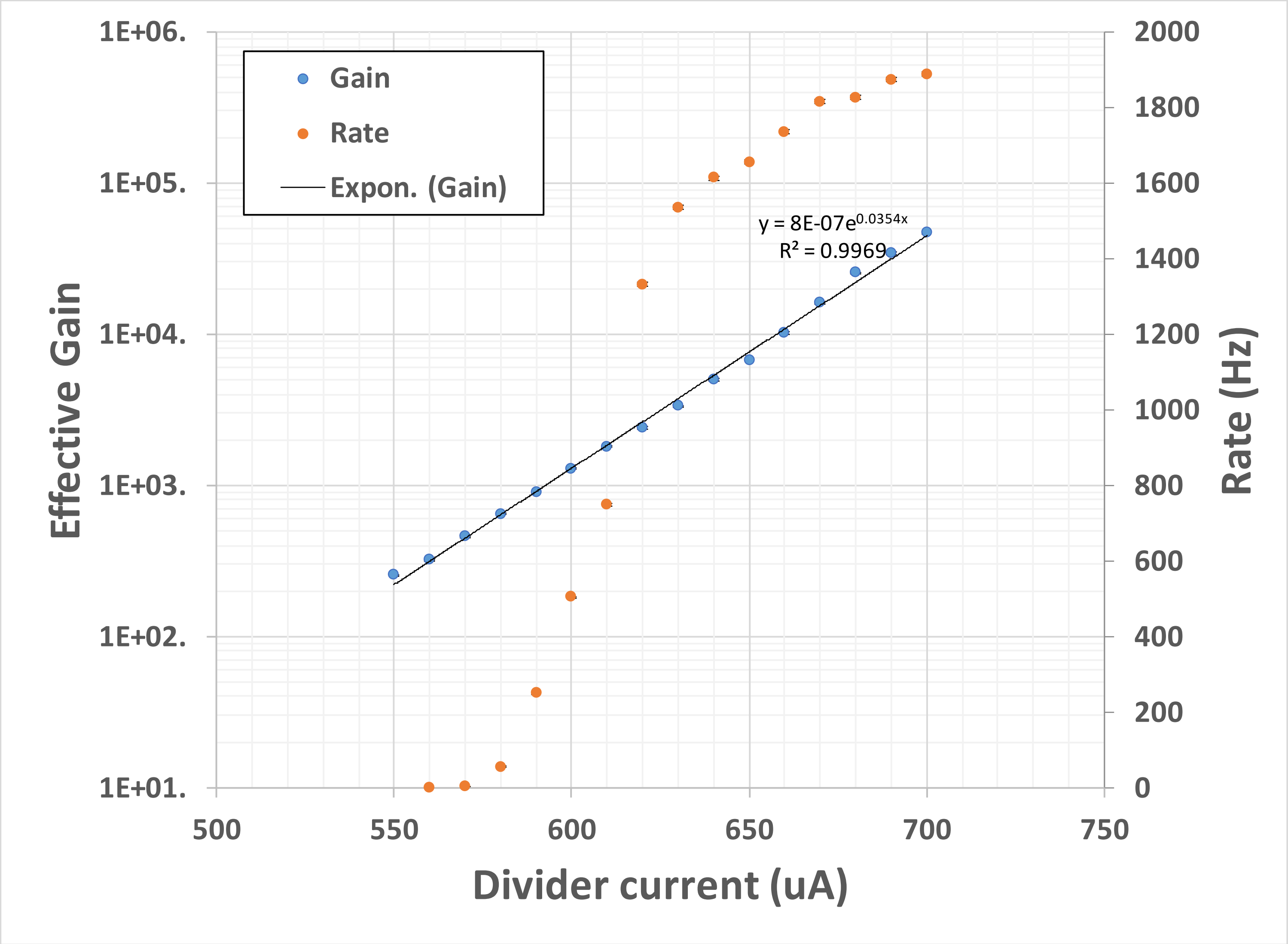
Ar/CO2 gas mixture in 70:30

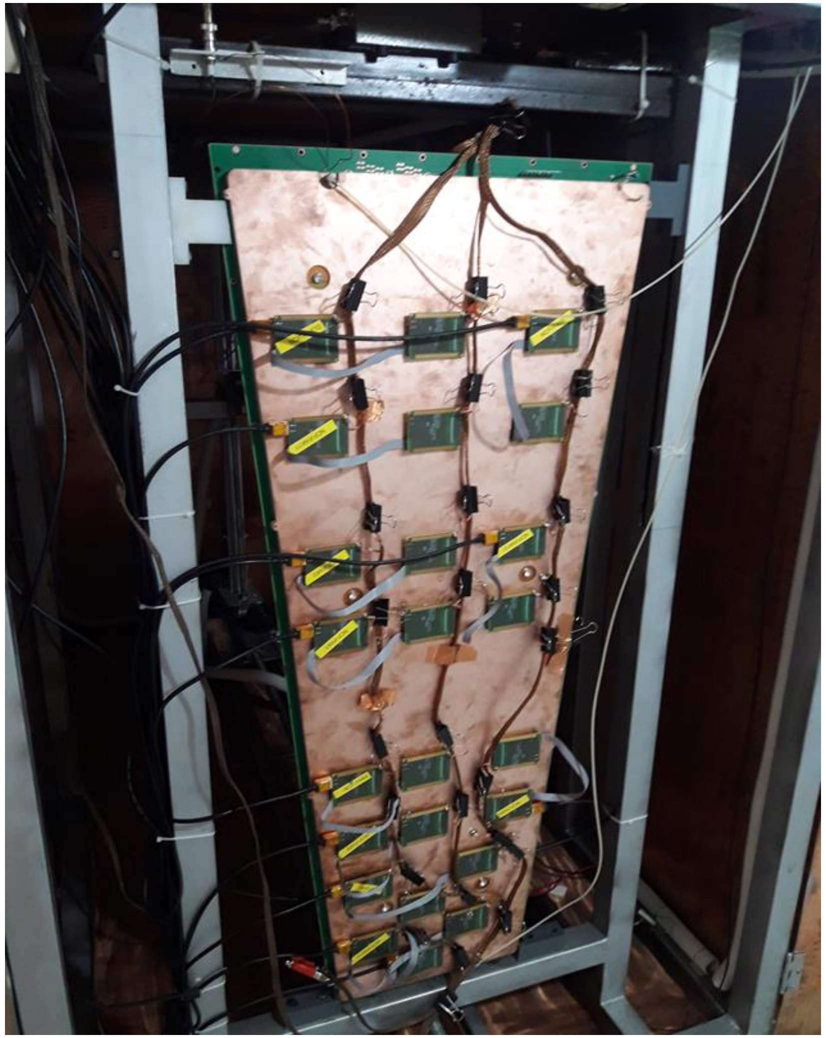
In GEM detectors Geff is smaller than gain of the GEMs, due to transparency and the losses of electrons along their drift path inside the GEM holes.

$$\frac{1}{Work\ function} = \frac{1}{\boldsymbol{W}} = \frac{\%(Ar)}{WAr} + \frac{\%(CO2)}{WCO2} = \frac{1}{27.8}$$

- I = total current collected on the anode.
- R = rate of the x-rays
- e = elementary charge of an electron
- $n_{prim} = \frac{E_{x-rays}}{W}$ = number of primary electrons created per incident particle

QC5-effective gain -GE11-VII-S-PAK-002

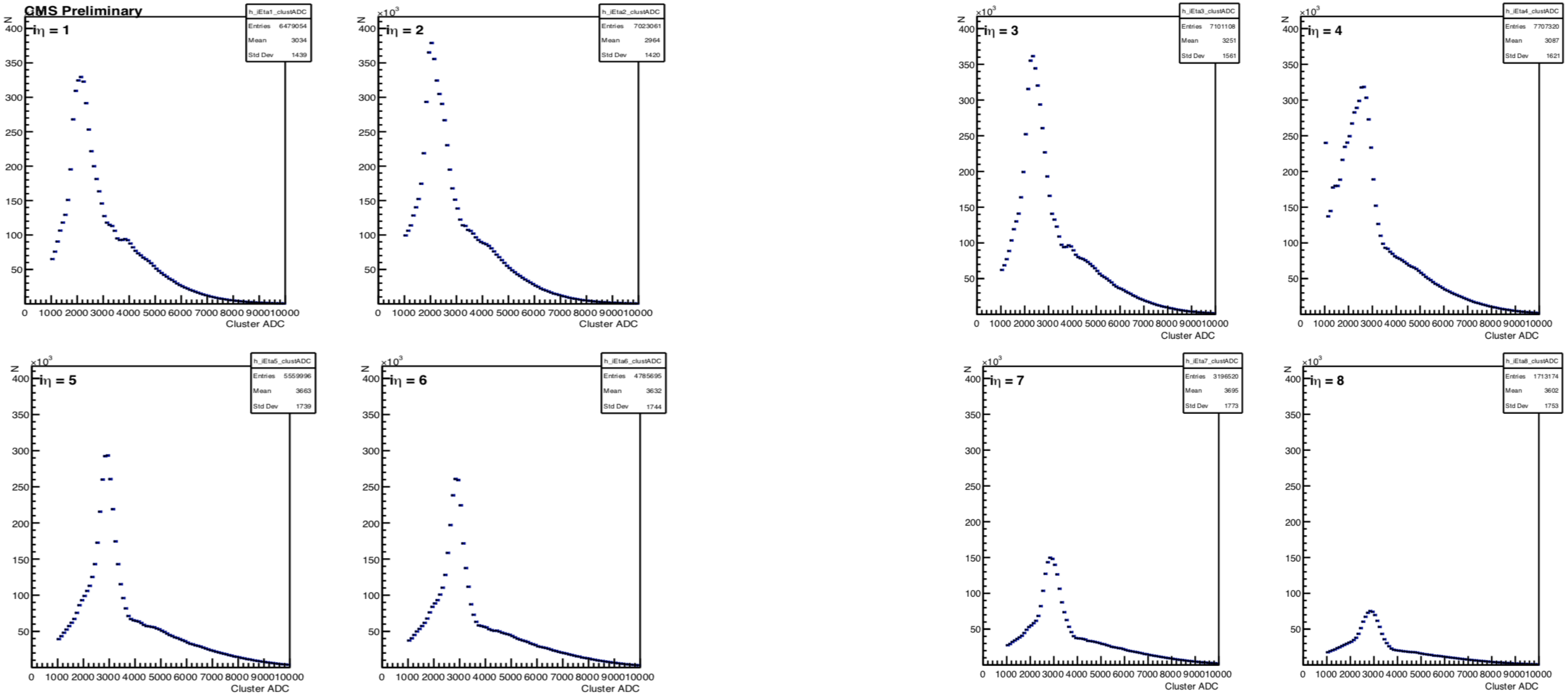




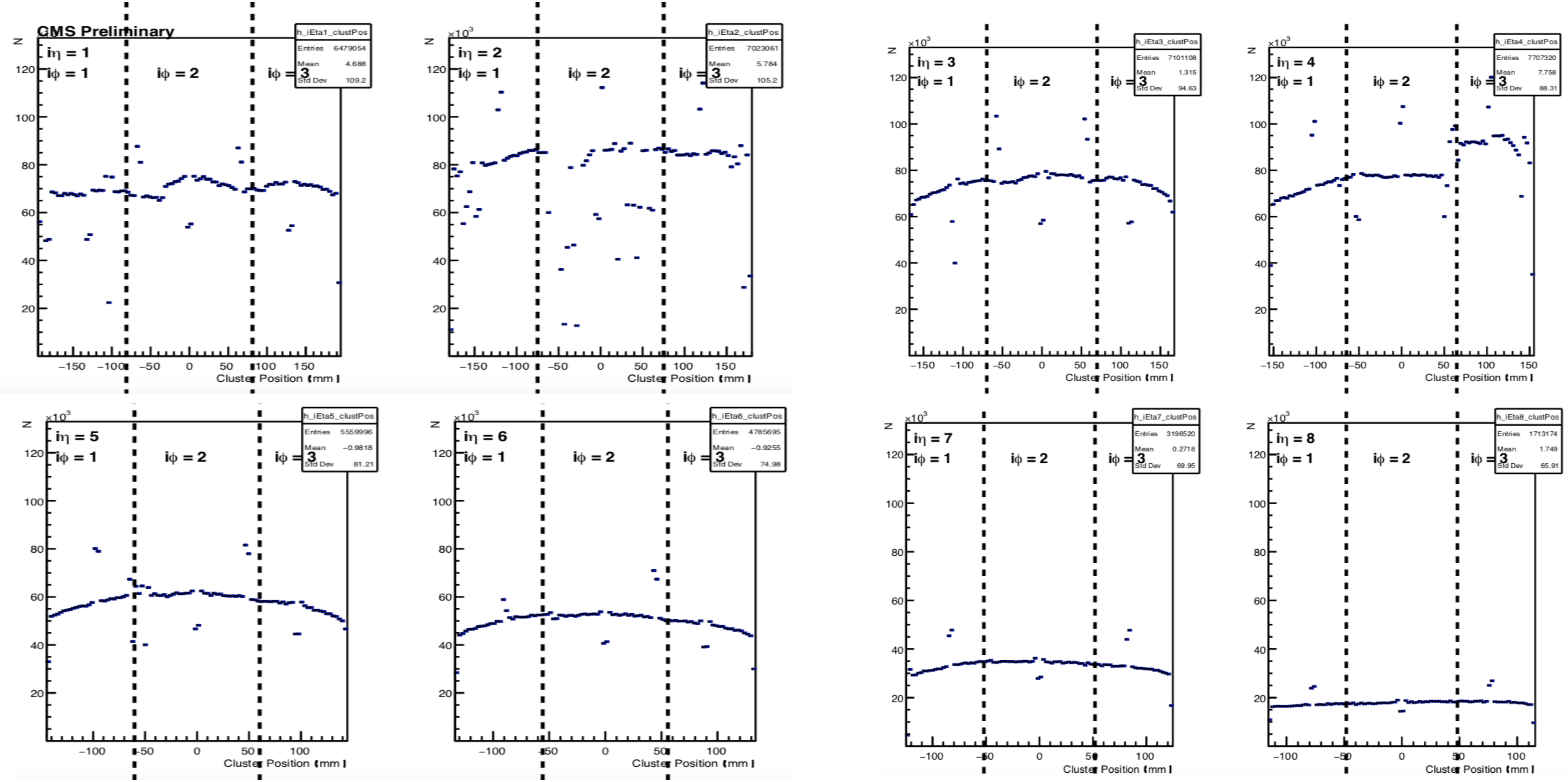
Response uniformity

GE11-VII-S-PAK-0002 Data : 10 MEvents

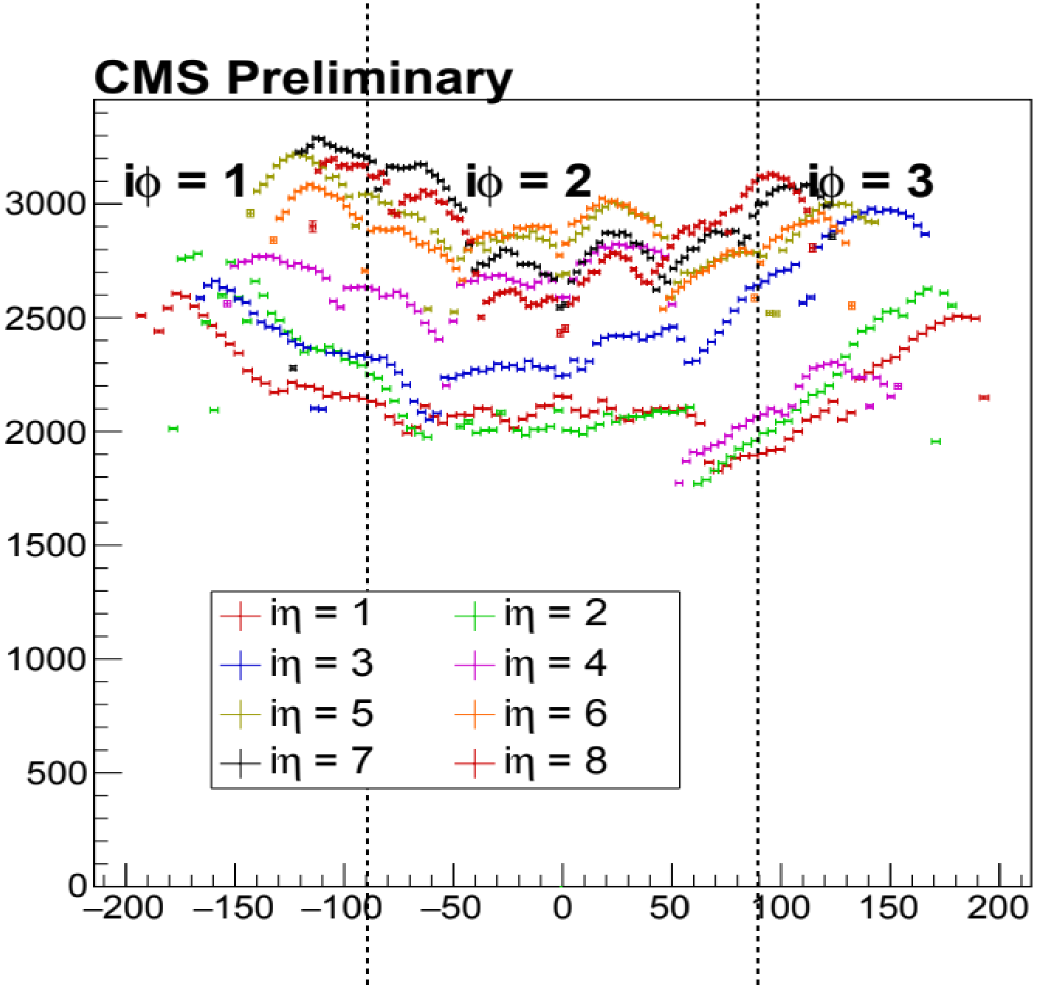
Cluster ADC All eta



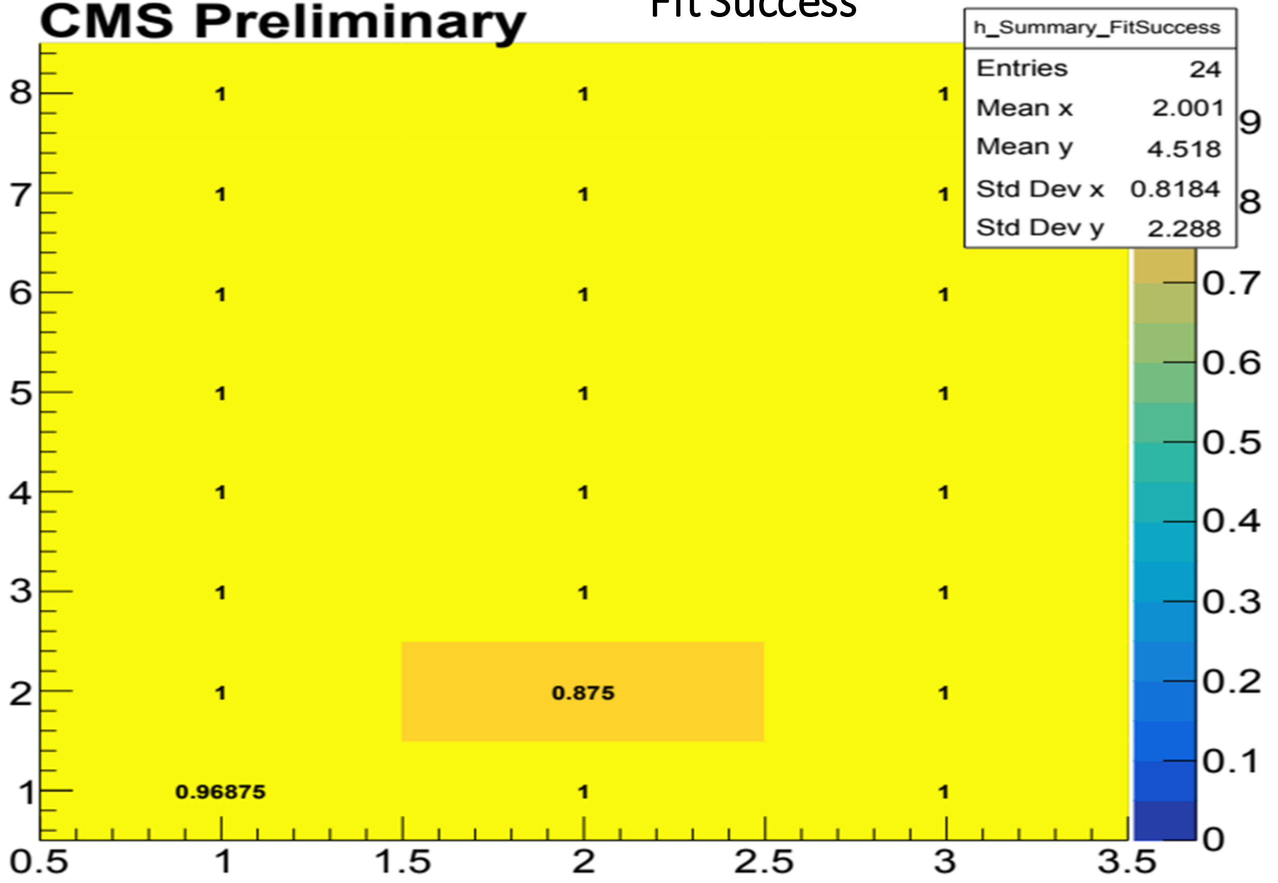
Cluster Position All eta



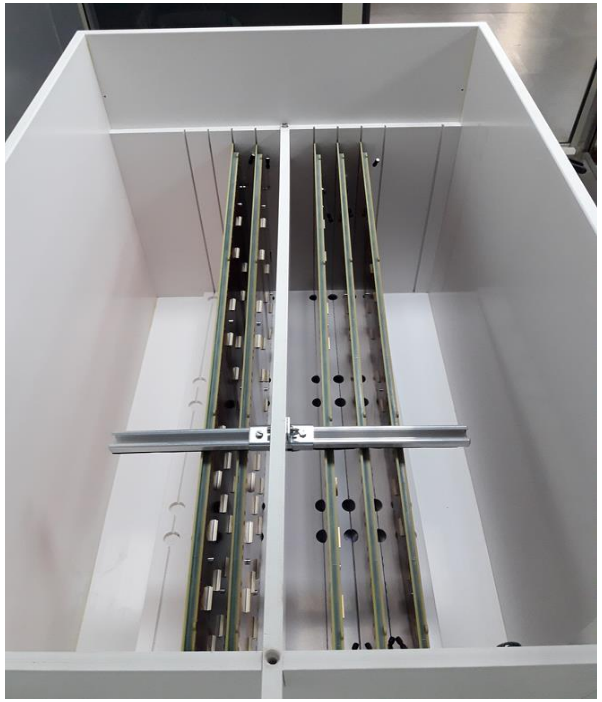
Response FitPk Pos. All eta

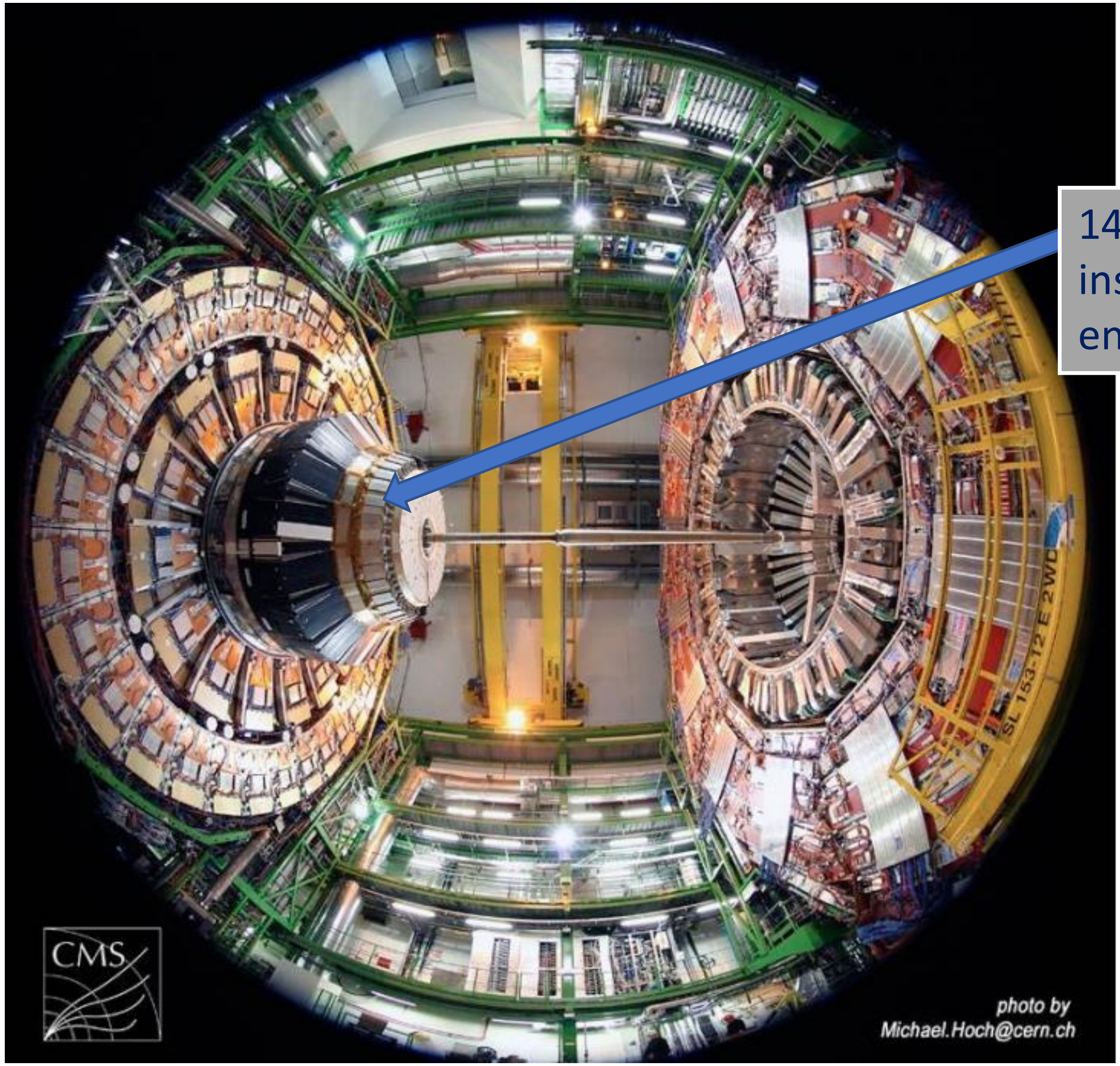


Fit Success



GEM detectors shipped from NCP to CERN to install@ CMS





144 GEM detectors are installed at CMS endcap regions

Resistive Plate chamber (RPC)

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

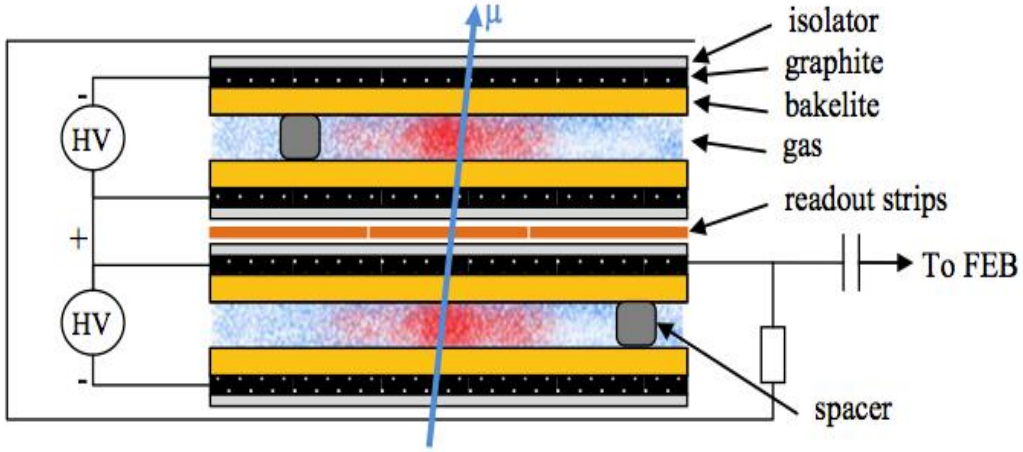
Operated in **streamer mode** with an Argon based mixture Performance: time resolution ≈ 1ns, Efficiency > 96%, Rate Capability ≈ 50 Hz/cm2

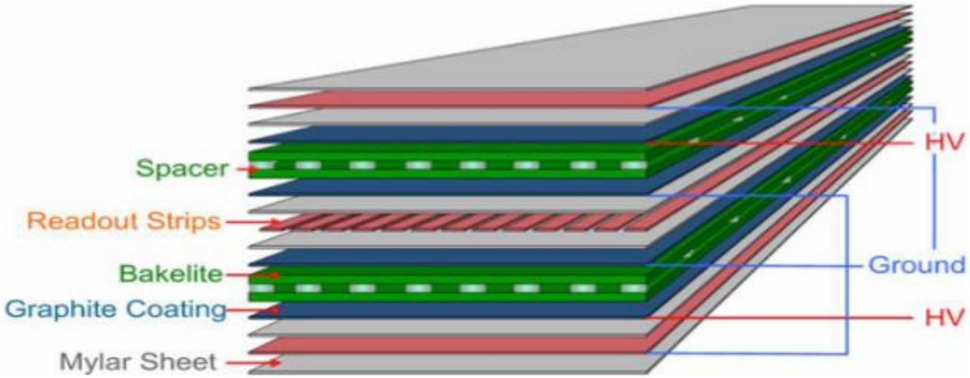
1992: 2nd generation of RPC detector was developed for LHC experiments (installed in ATLAS, CMS and Alice)

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

2015: 3rd generation of RPC developed for HL-LHC Operated in **streamer mode** with an Argon based mixture Performance: time resolution ≈ 1ns Efficiency > 96% Rate Capability ≈ 50 Hz/cm2

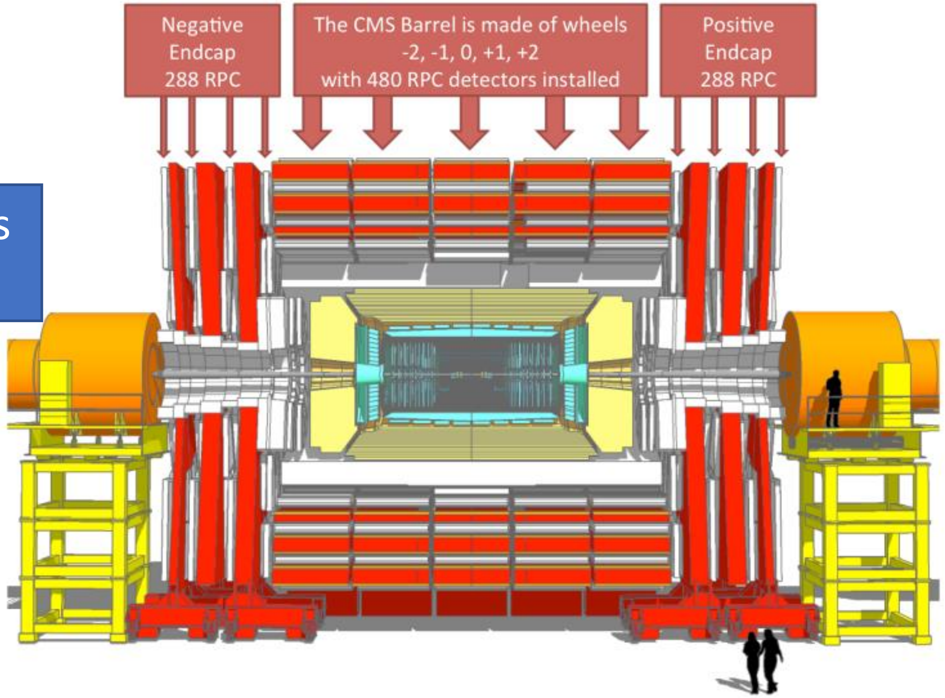
Operated in **avalanche mode** with a Freon based mixture Performance: time resolution ≈ 1ns, Efficiency > 96%, Rate Capability ≈ 500 Hz/cm2





RPC@ CMS

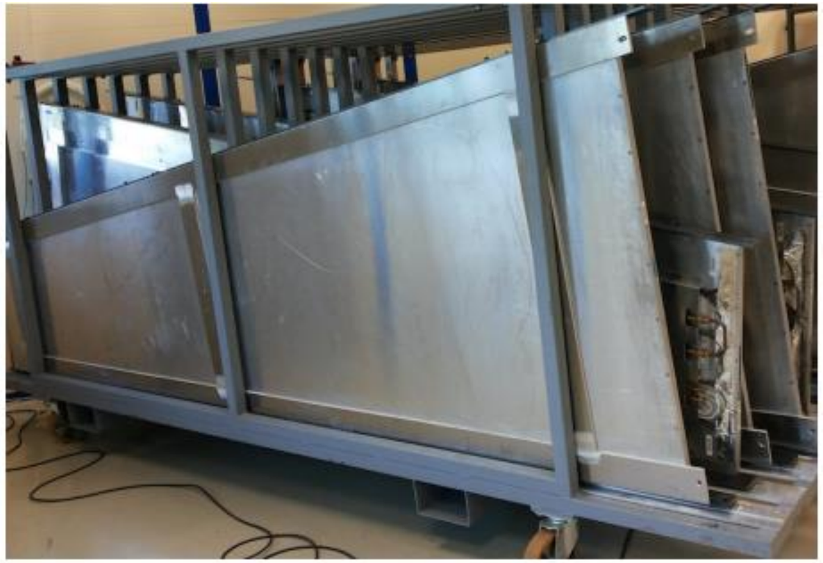
1056 RPCs in total



- **1056** chambers covering eta region up to 1.8
- Sensitive layers area: **3.200 m²**
- **Double gaps: 2mm gas gap width**
- **Working in avalanche mode**
- **HPL** 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**

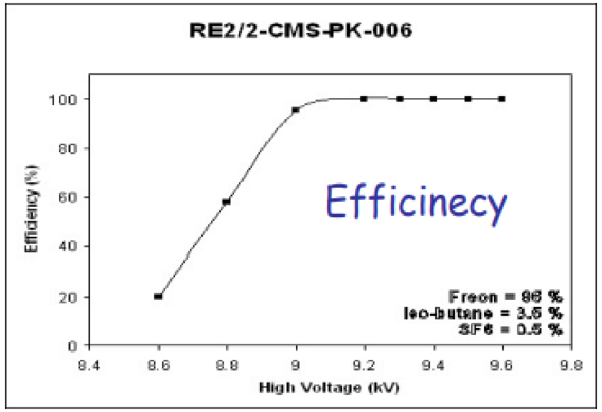
BARREL

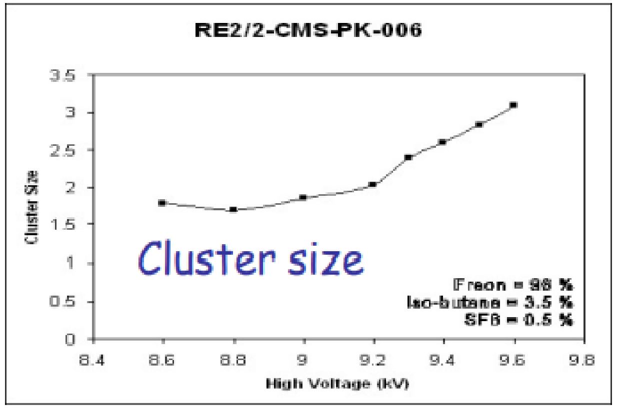
ENDCAP



Endcap RPC and NCP contributions

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

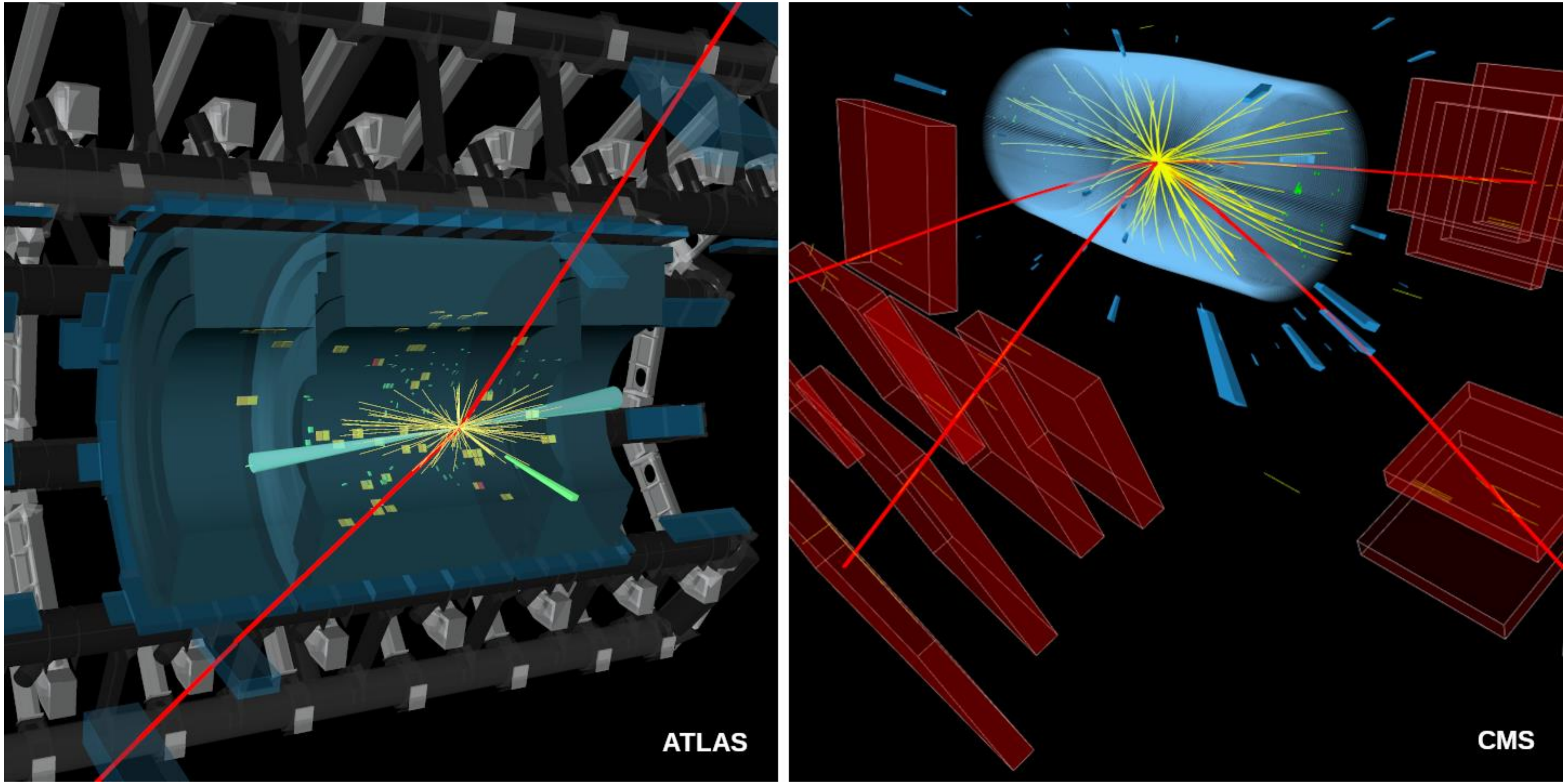




RPCs Lab at NCP

RPCs at CMS

PP collision events display



Collision events recorded by ATLAS (left) and CMS (right), used in the search for rare Higgs boson transformations. Image © CERN

Gaseous detectors have proven to work efficiently at high rate, low material budget, in the big experiments to discover the particles