High-rate and fine space resolution RPCs operated with eco-gases

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on behalf of Task 13.2.3 collaboration

CERN, Gangneung Wonju, Ghent, INFN-BA, INFN-BO, INFN-LNF, INFN-TO, INFN-TOV, MPI Munich, USTC

3rd AIDA-2020 annual meting
Bologna, 24-27 April 2018

Motivations tasks and strategy

- Almost 10000 RPCs have been installed for the experiments at LHC
  - An established standard: Gas, Material, Internal structure.
- A new challenge: a new generation of RPCs for HL-LHC and beyond, with the overall simplicity of the old standard

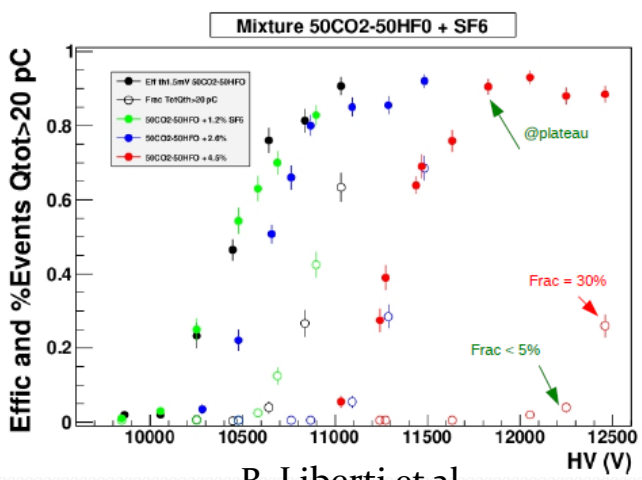
- **Targets:**
  - Rate capability → tens of kHz/cm^2
  - 6x packing factor for installing in narrow spaces
  - Space-time resolution up to → 0.2 ns x 100 mm
  - Ability to run with inexpensive and eco-compatible gases

- Parallel studies by ATLAS and CMS groups, both on new RPCs and new eco-compatible gases

Research of a new gas mixture

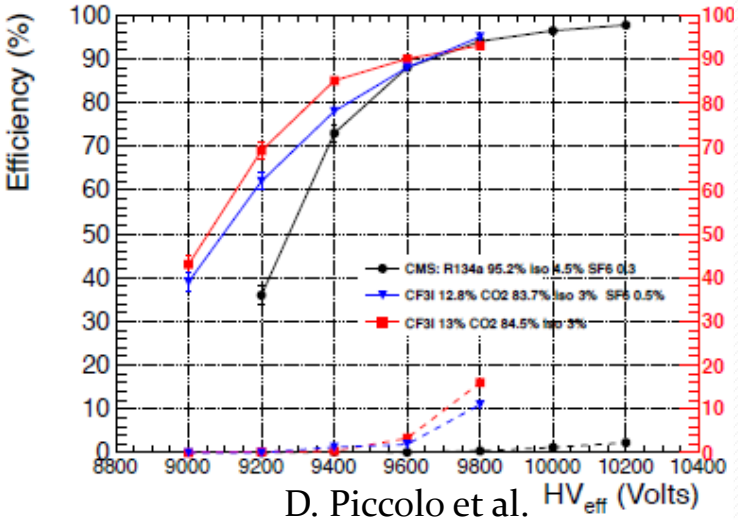
- The European Community has prohibited the production and use of gas mixtures with Global Warming Power > 150 (GWP(CO_2) = 1)
- $C_2H_2F_4$ is the main component of the present RPC gas mixture:
  - GWP($C_2H_2F_4$) = 1430, GWP(SF_6) = 23900, GWP(iC_2H_{10}) = 3.3
  - $C_2H_2F_4$ and SF_6 Crucial to ensure a stable working point in avalanche
- To test molecules similar to $C_2H_2F_4$ but with lower GWP
- HFO=1234ze (1,3,3,3-Tetrafluoropropene) has been identified as a possible choice
- No aging test has been performed yet on HFO!

CO2-HF0 plus SF6 series GWP=700



B. Liberti et al.

CF$_3$I BASED GAS MIXTURES



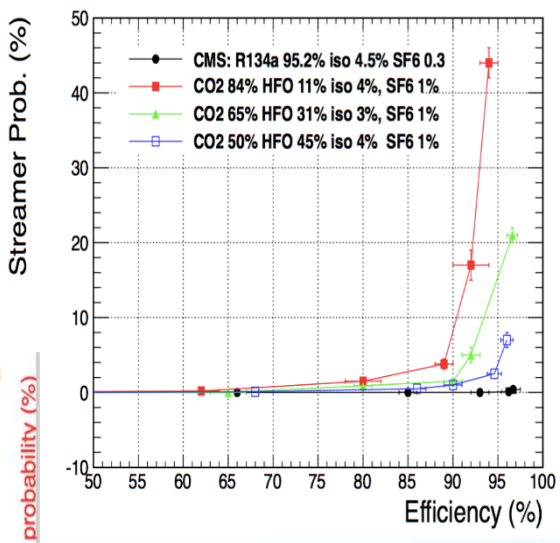
D. Piccolo et al.

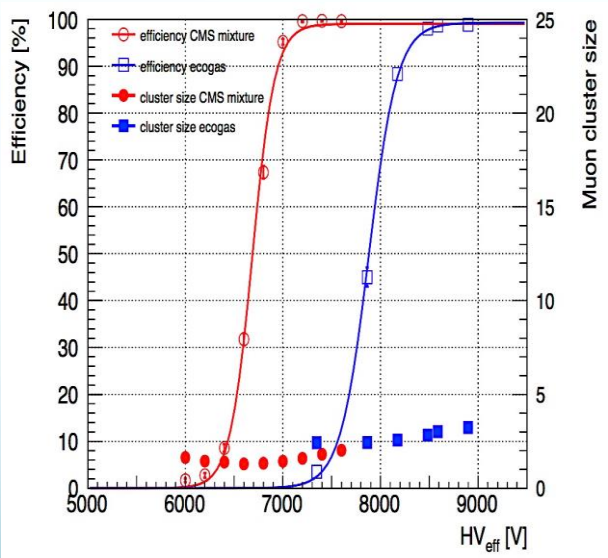
New RPC Eco-gas mixture: R&D status

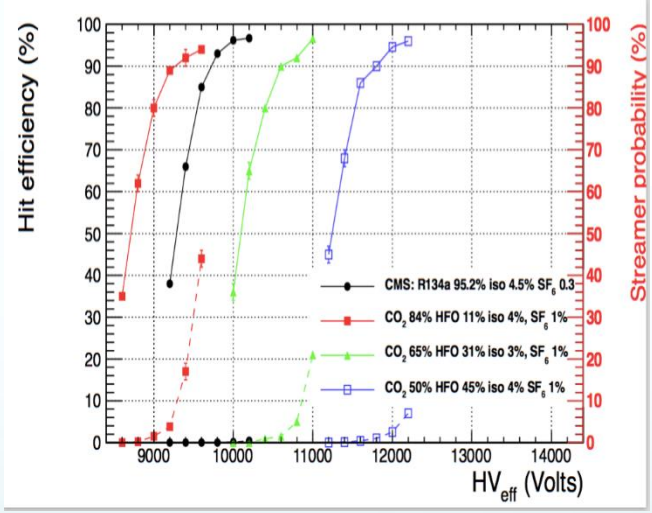
G. Pugliese

R&D ongoing in collaboration with **RPC ATLAS group:**

- HFO based gas **mixture** showed promising results on standard single-gap RPC: streamer probability < 2% at > 90% of efficiency, with an High Voltage working point < 12 kV.





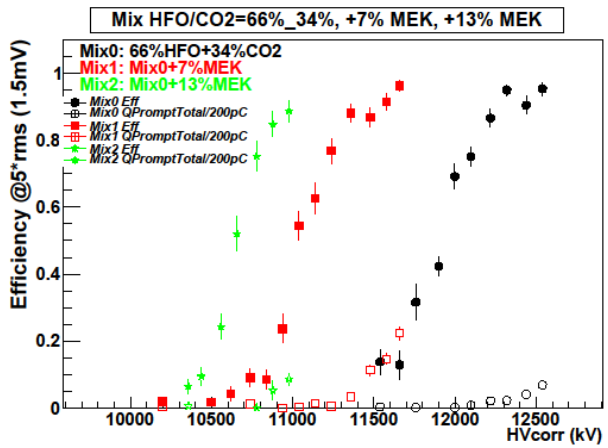


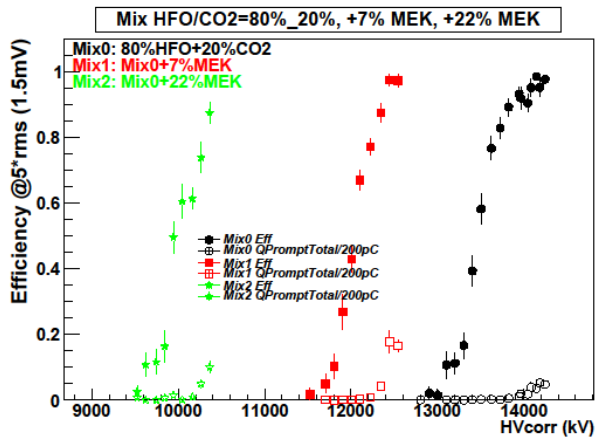
- HFO-based mixtures (**50% of HFO, 45.2% of CO_2, iso 4.5, 0.3 SF_6**) tested on iRPC (mounting ATLAS FE): **efficiency is consistent with standard gas mixture, with a shift in the working point of 1.3 kV**

Starting from HFO and CO_2 binary mixtures

We could not get NovecTM 5110 fluid, very promising eco-compatible substitute of SF6, so we decide to try some interesting molecules which are available at environmental temperature and pressure in liquid state :

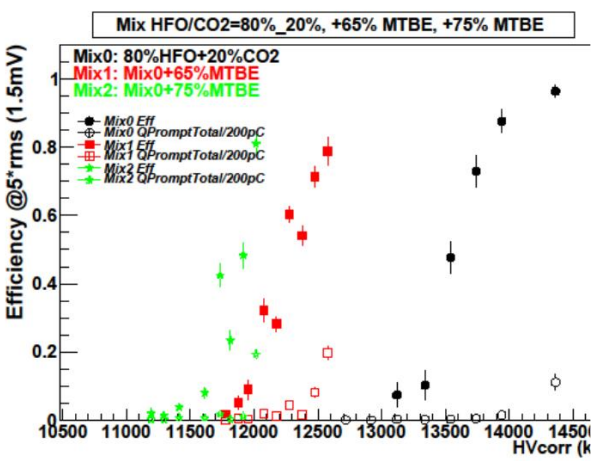
B. Liberti, RPC 2018, Puerto Vallarta, Jalisco State, MEXICO

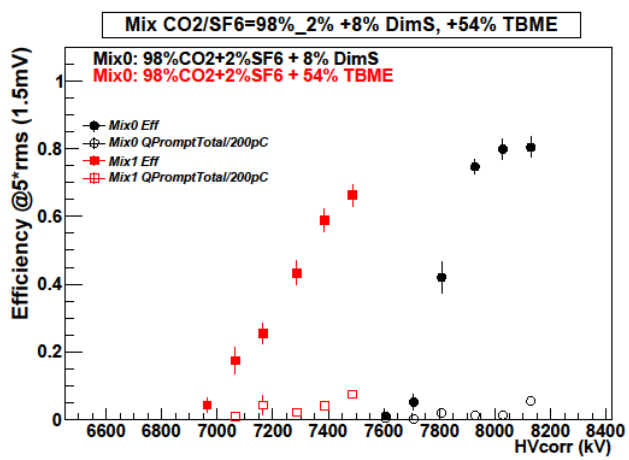




1) Ethylmethylketone (MEK)

- Difficult to handle with these molecules, because of high vapor pressure, leading to vapor condensation





- The HV working point is lowered, but the average total prompt charge increases for equivalent efficiency

2) Methyl Tert-Butyl Ether

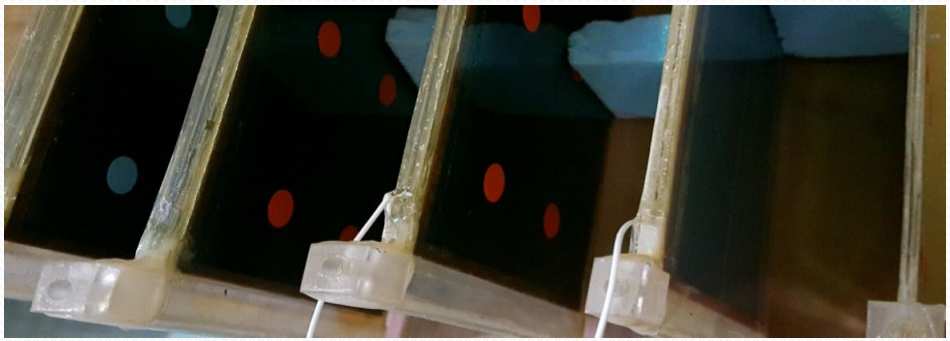
3) Dimethyl Sulfide

R&D for the new ATLAS RPCs

Main challenges: higher rate capability, better aging, smaller dimensions, reliability and efficiency, eco gas compatibility

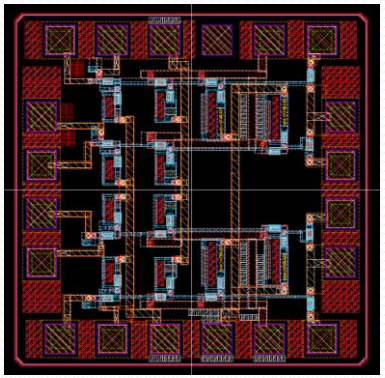
New Gas Gap

- Thinner gas gap (2 mm → 1 mm)
- Thinner electrodes (1.8 mm → 1.2 mm)
  - Lower detector weight
  - Thinner supports allowed
  - More efficient signal collection
  - Almost halve the applied HV
  - Improved charge distribution
  - Double time resolution



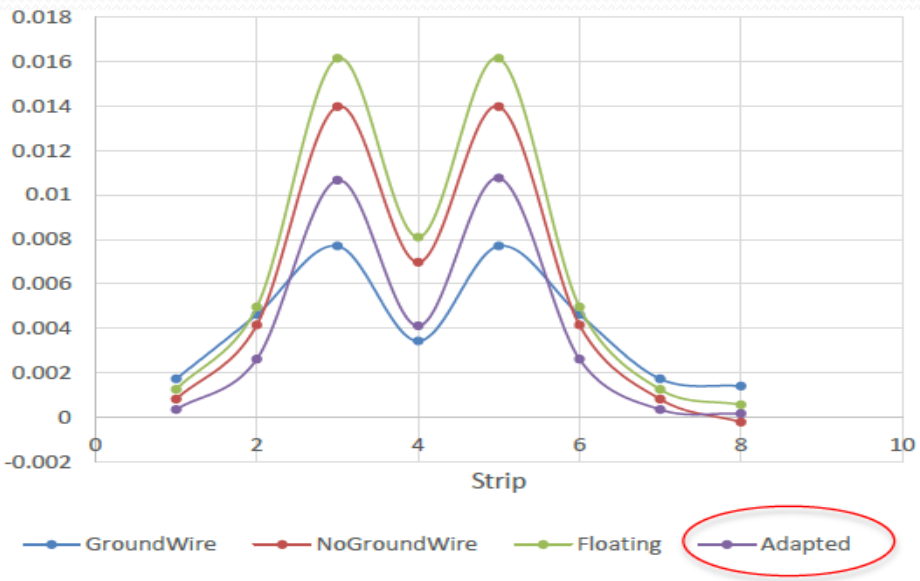
New FE

- SiGe BiCMOS instead of Si
  - Higher rate capability
  - Radiation hardness
  - Better space-time resolution
  - Inexpensive high performance low power FE
  - All in one ASIC with amplifier, discriminator, TDC and serializer



New ATLAS Readout strips

- Cross-talk simulation studies
  - **Best Result**: with ground wire and adapted impedances
- Panels of fiberglass, with 25 mm copper strips along with their respective ground wires
- Both the strips and the ground wire are adapted from the front-end and back-end side with an impedence
- FE solded directly on the panel



Readout strips, 25mm width, with 27.4Ohm to GND on the readout end,and 24.3Ohm on the other end

Ground wire,1mm width, and 1mm gap between the wire and strip. The match resistor of both end is 100Ohm

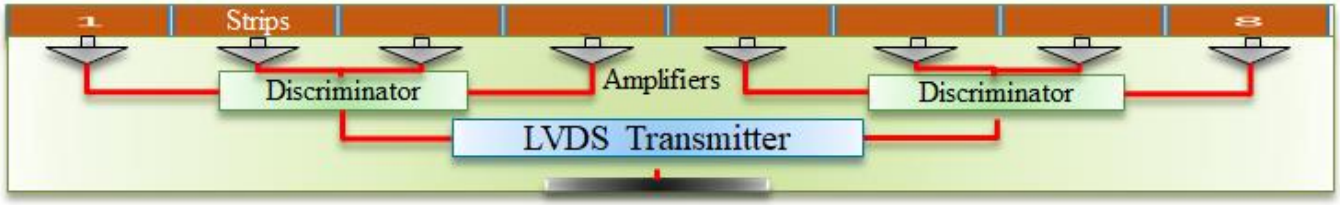
Blank for FE Board

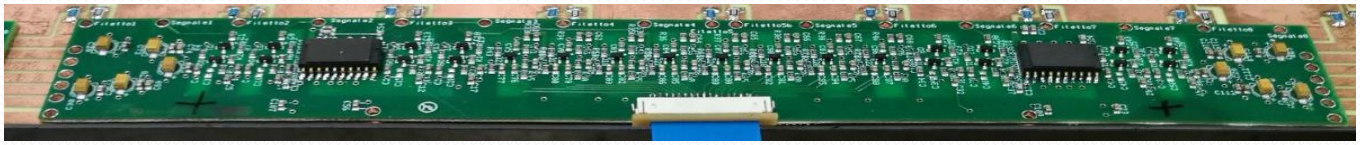
Ground

Power Line for FE Board

New ATLAS Front End board

8-channels Front-End Board composed by a new Amplifier, a full-custom ASIC Discriminator and an LVDS transmitter.



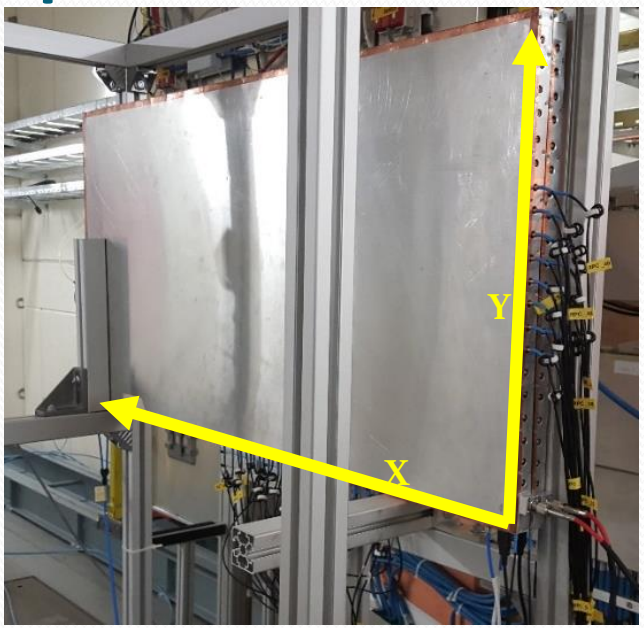


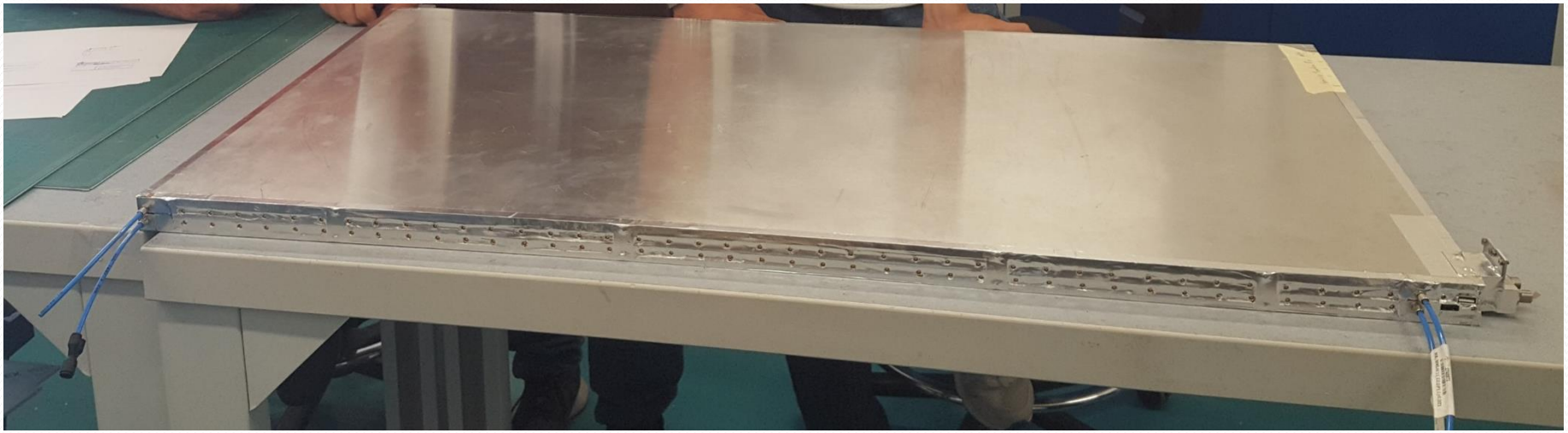
Amplifier	
Technology	Si BJT
Voltage Supply	3-5 V
Sensitivity	2-4 mV/fC
Noise	1700 e^- RMS
Input impedance	100-50 Ohm
Bandwidth	10-100 MHz
Power consumption	10 mW/ch
Rise time input	300-600 ps
Radiation hardness	10 kGy, 10^{13} n/cm^{-2}

Discriminator	
Technology	SiGe BiCMOS
Voltage Supply	3-3 V
Threshold	3-200 mV
Input impedance	100 Ohm
Bandwidth	500 MHz
Power consumption	10 mW/ch
Rise time input	300 ps
Radiation hardness	10 kGy, 10^{13} n/cm^{-2}
Minimum duration nput pulse	0.5 ps
Double pulse separation	1 ns

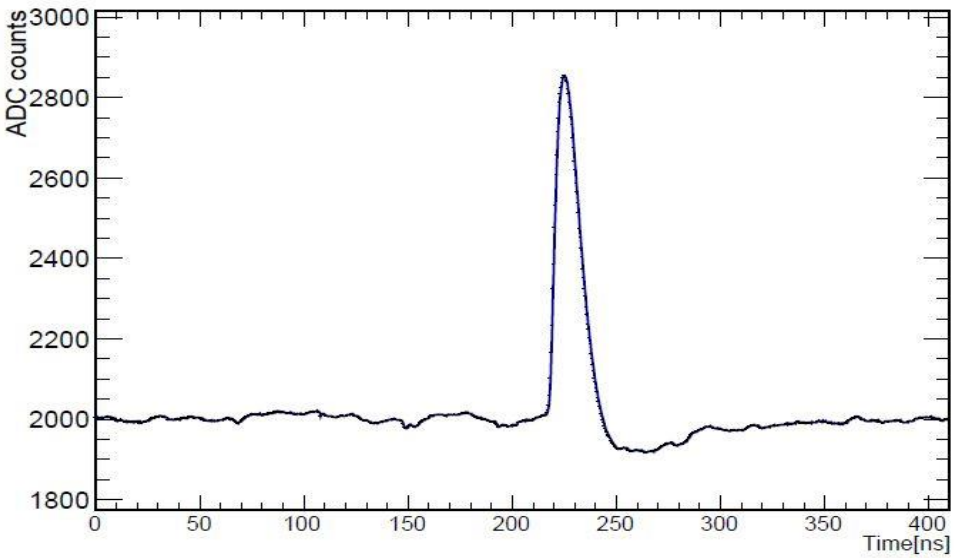
High rate test on a multiplet

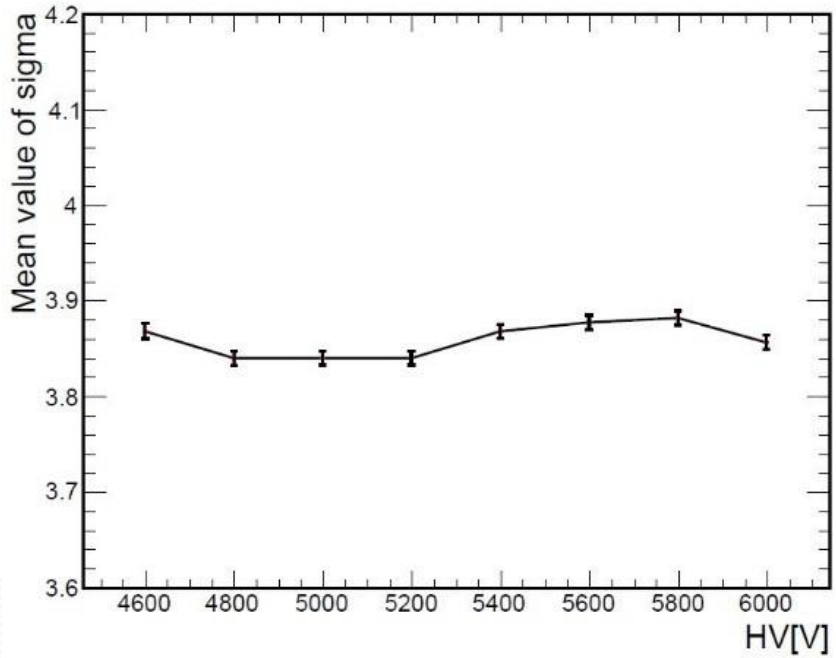
- Intermediate size RPC made by 2 mono-gaps 50x100 cm² with full X-Y readout with the new amplifier
- Gas gap 1 mm, electrodes 1.2 mm
- Beam tests in 2016-2017 at CERN GIF++
- Muon beam, plus photons from a ^{137}Cs source
- Trigger from 2 scintillators 12x12 cm²





Electrical noise

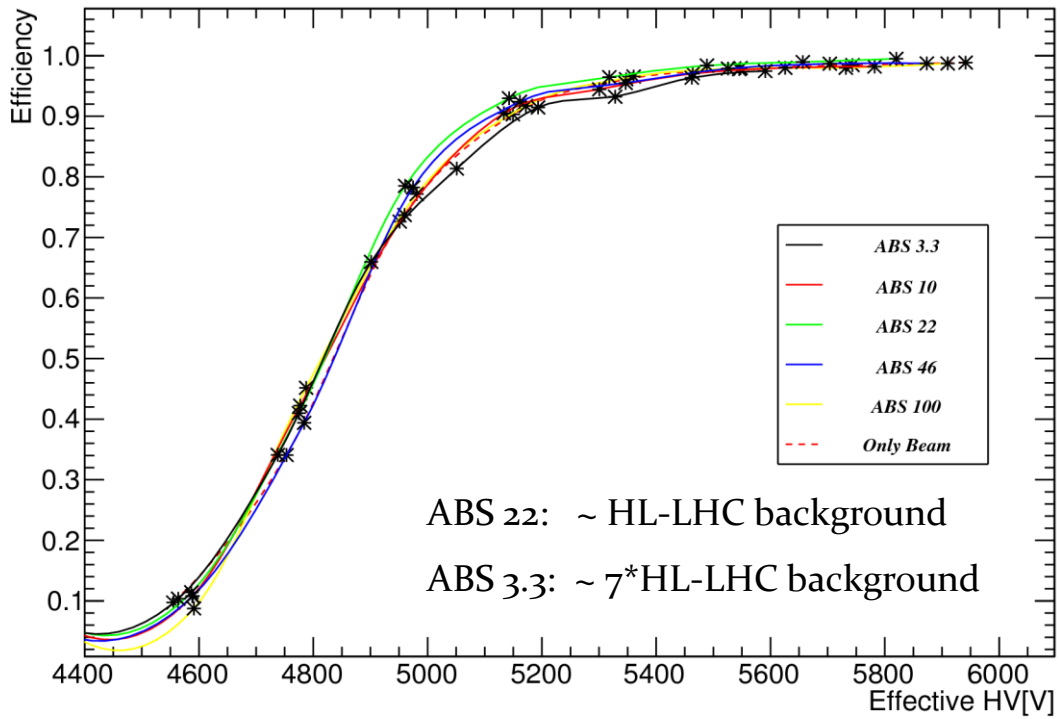




- Electrical noise measured in terms of standard deviation of the baseline distribution.
- Analysis is done using only pure beam data.
- Standard deviation almost stable between 3.8 V and 3.9 V

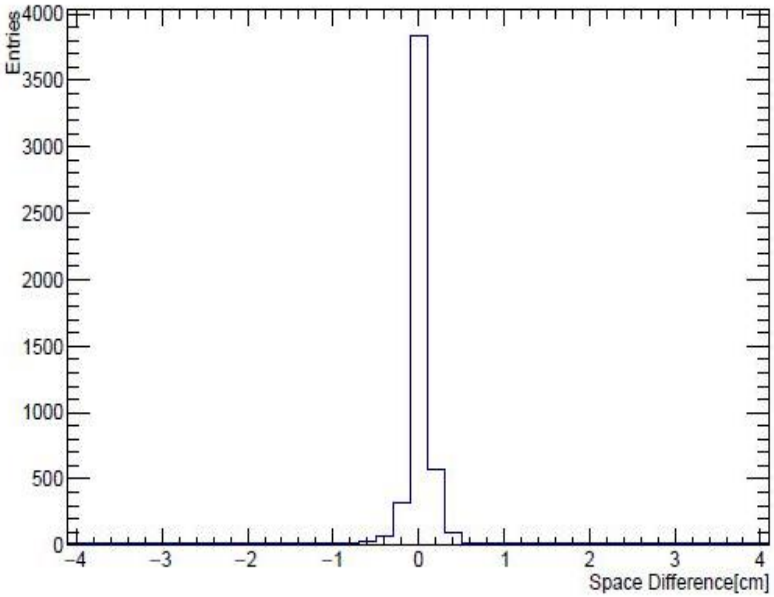
Efficiency at high rate

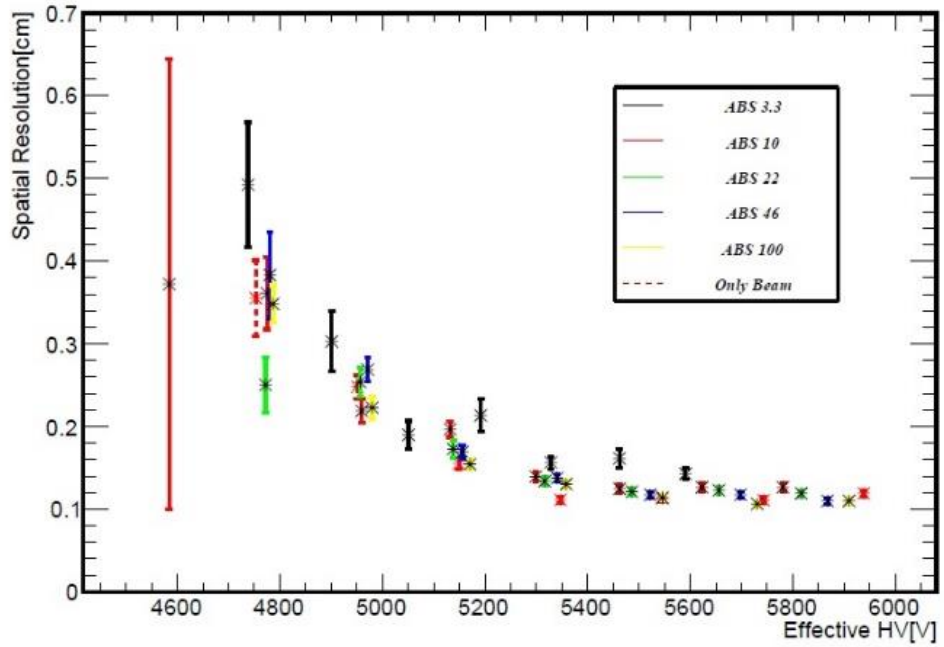
- Use 1 chamber as monitor and calculate the efficiency of the other chamber.
- An efficient hit must be correlated in time (20 ns) and space (± 1 strip) with the monitor hit on both X-Y views



- Different values of absoption factor on a radiactive ^{137}Cs source, simulating the photon background of HL-LHC
- Working point: 5400 V (95% efficiency)
- ~98% efficiency in plateau region

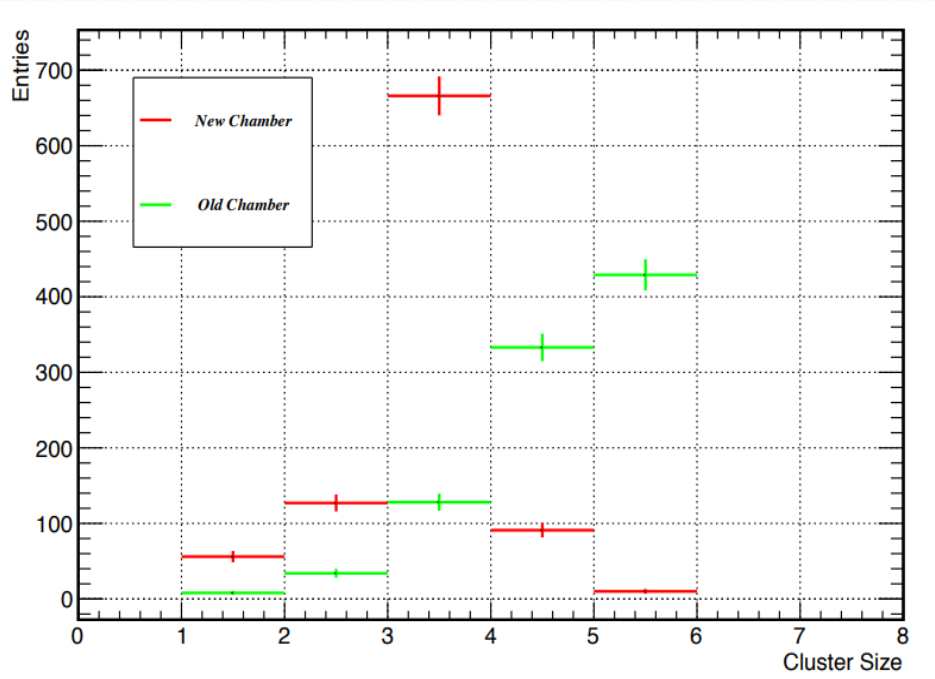
Spatial resolution





- Hit position determined through the «center of gravity» method, using the amplitude of the signals in the strips as imput
- Spatial resolution obtained dividing by a factor $\sqrt{2}$ the standard deviation of the hit position difference between the two RPC detectors
- **Spatial resolution of 1 mm** on both X-Y planes, read homogeneously by two sets of orthogonal strips

Cluster size

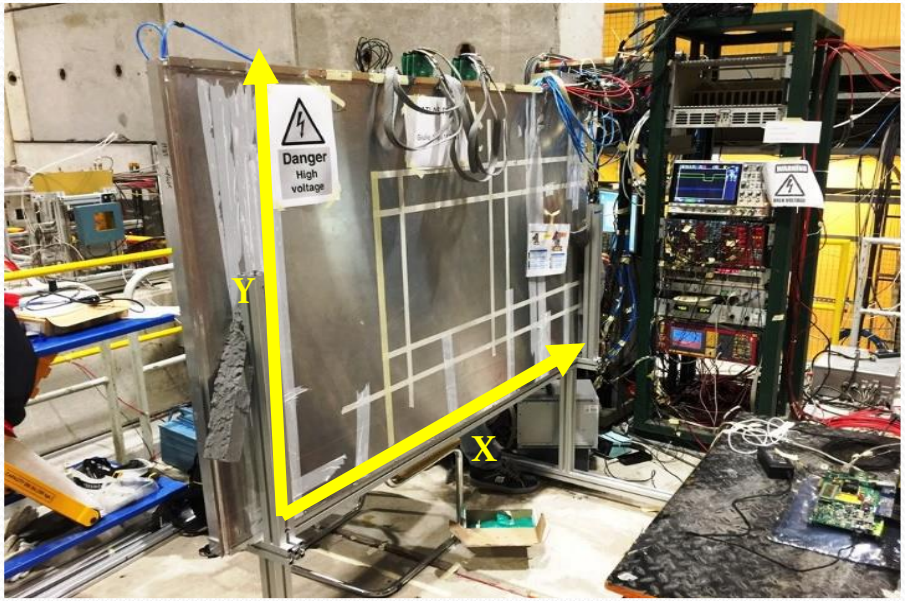


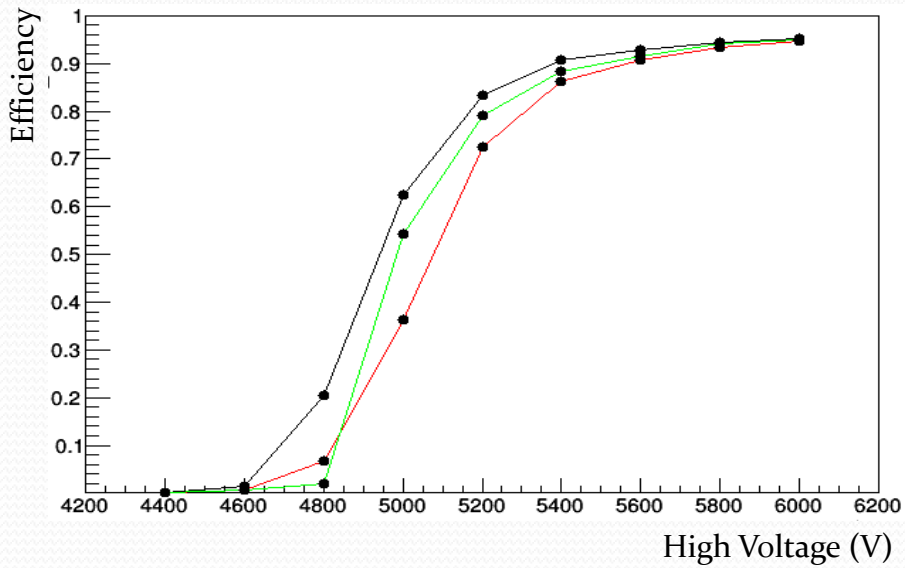
- The cluster size measured on the doublet was higher than expected (5)
  - delayed hits from the gap and strip plane couplings
  - cluster size 1-2 can be found removing these delayed hits
  - Reason: not optimized values of the graphite resistivity

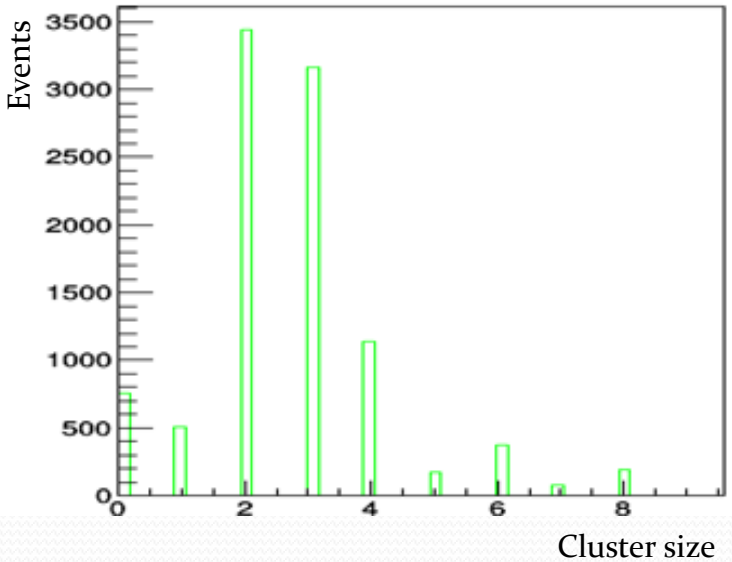
- A new mono-gap 50x100 cm² with different graphite resistivity (620 kΩ/■ instead of 120 kΩ/■) added in 2017 to the doublet, making a triplet
  - Cluster size in the new mono-gap is 3.
  - 620 kΩ/■ is the new reference value for graphite resistivity

Test with new FE

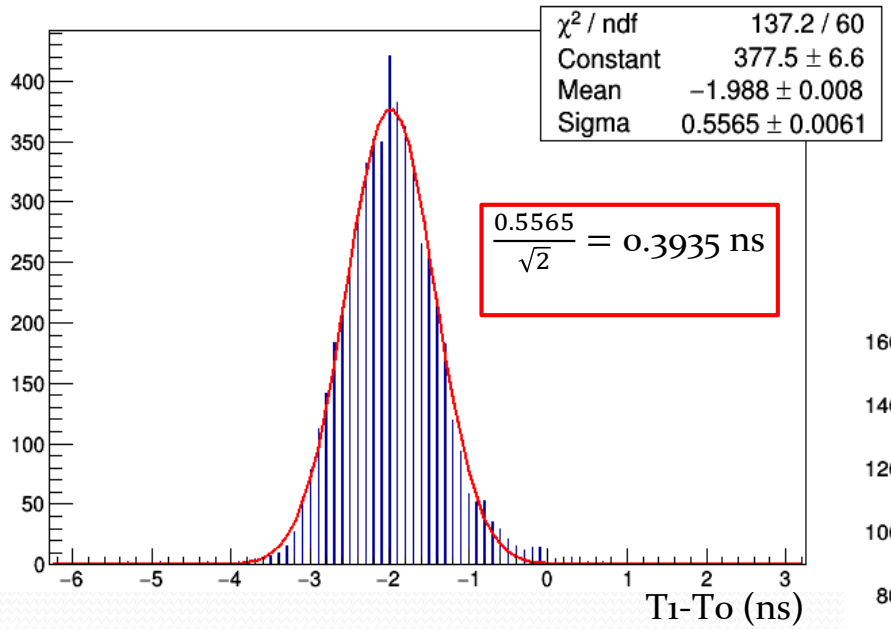
- Large size RPC made by 3 mono-gaps of size 180x120 cm²
- Full X-Y readout with new FE
- Gas gap 1 mm, electrodes 1.2 mm
- Beam test in October 2017 at CERN North Area (H8)
- Muon beam
- Trigger from 2 scintillators 10x10 cm²



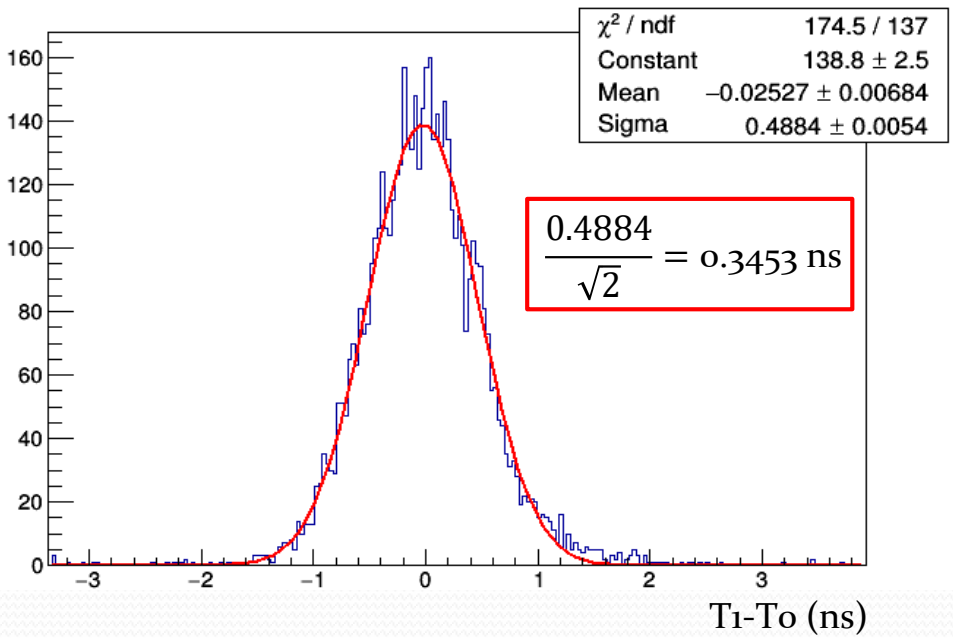




Time resolution with new FE



Applying time-walk corrections



Time resolution obtained dividing by a factor $\sqrt{2}$ the standard deviation of the difference between the time measurements of two different gaps.

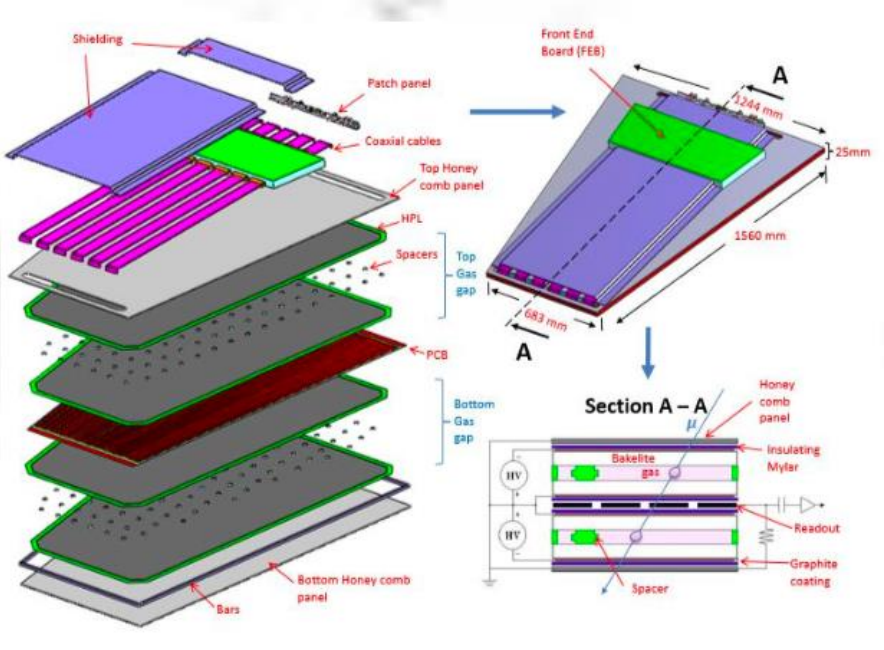
Best result ever with a 1 mm RPC!

CMS Improved RPC

G. Pugliese

Detector Design and specifications

	New RPC
High Pressure Laminate thickness	1.4 mm
Num. of Gas Gap	2
Gas Gap width	1.4 mm
Resistivity (Ωcm)	0.9 - 3 x 10^{10}
Charge threshold	50 fC
η segmentation	2D readout



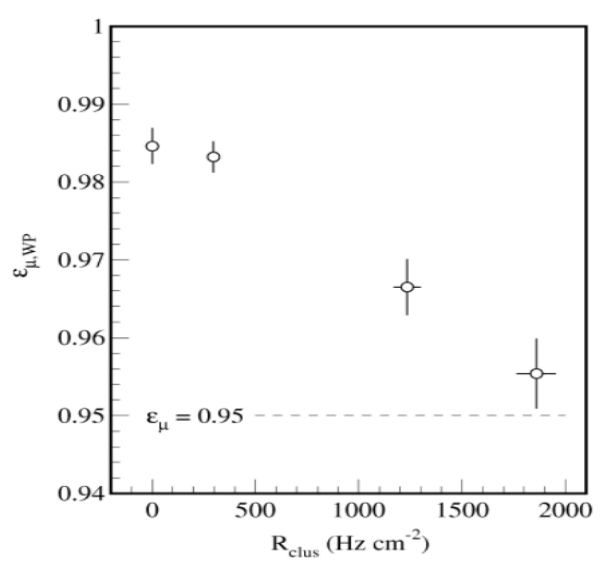
New readout schema:

one PCB with radial strips inserted between the two gaps. Coaxial cables connects the strips to the FEB. Both ends strips will be readout.

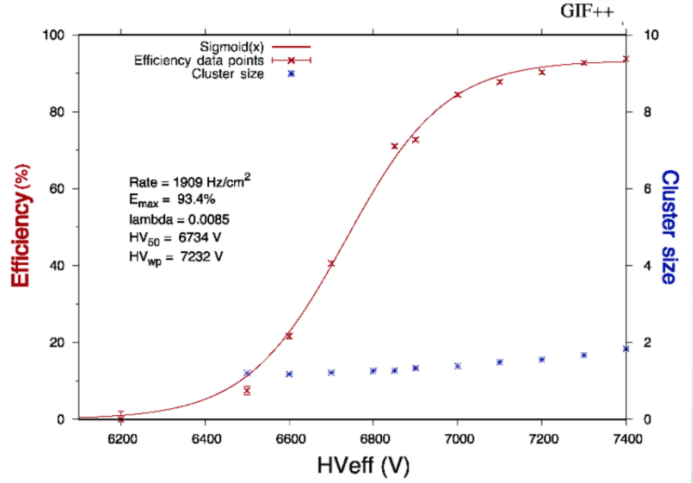
1 cm pitch strip

CMS Detector Validation (small and large scale)

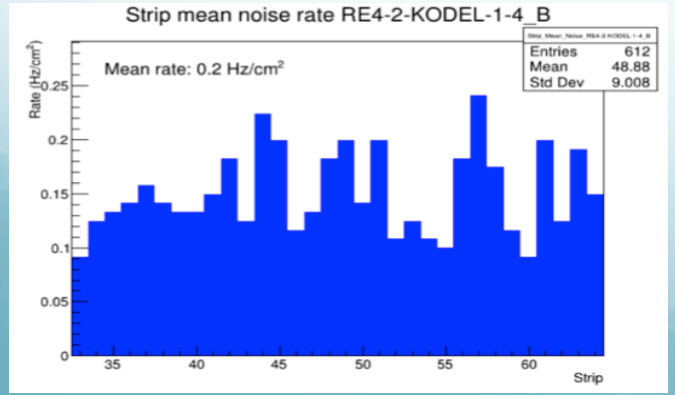
G. Pugliese



- **Small (66x36 cm^2) iRPC prototypes** tested in February 2017 at KODEL with cosmic muons and γ source up to ≈2kHz/cm^2: at maximum background efficiency dropped 3%



- **Large (166x92 cm^2) iRPC prototypes** tested in June 2017 at GIF++ with muons beam: confirmed efficiency ≈ 94% for maximum background



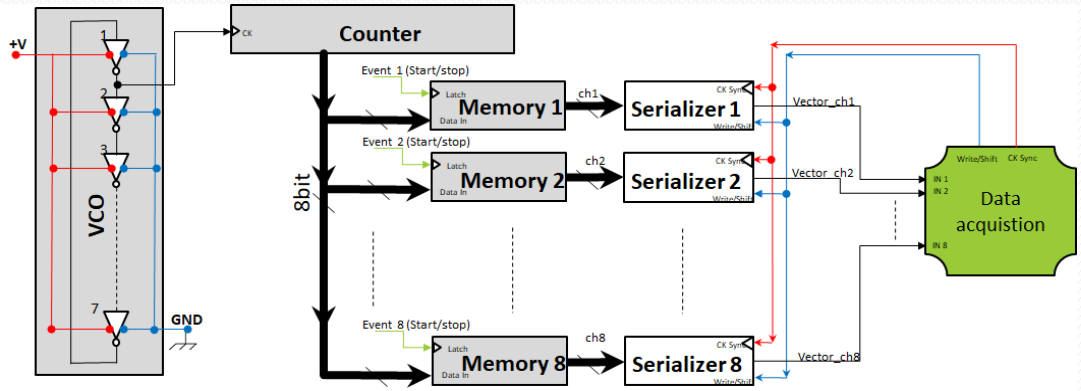
Intrinsic noise ≈ 0.2 Hz/cm^2

Conclusions

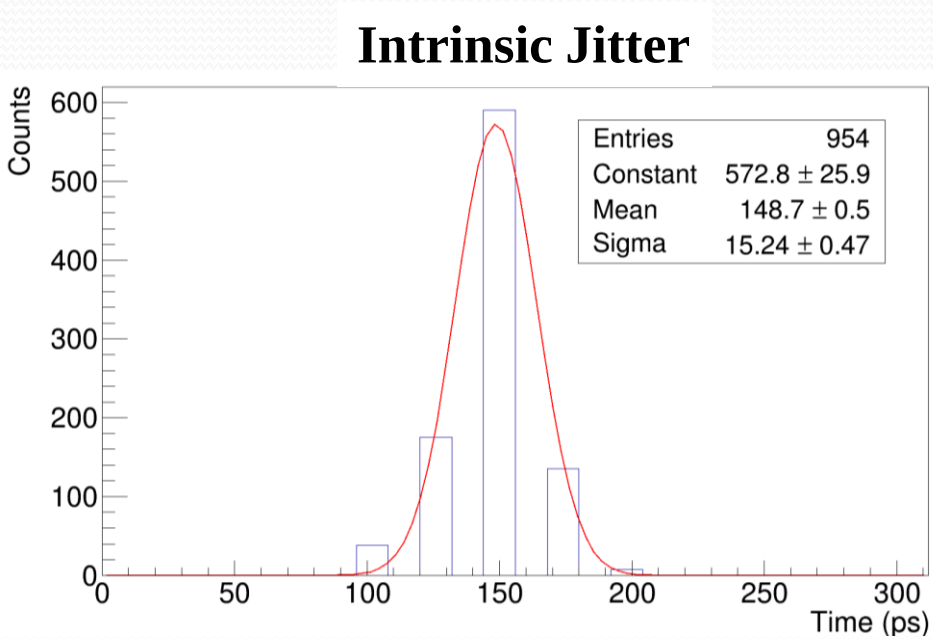
- Combined ATLAS and CMS R&D on eco-gas is still on going
  - An aging test on HFO-mixtures is needed
- New standards for RPCs in adronic colliders
- ATLAS RPC: 3 monogaps 1 mm thick
  - ~98% efficiency in plateau region with HL-LHC photon background (600 Hz/cm^2)
  - Working point: 5400 V
  - Minimum cell in the phase-space: 1 mm^3 x 0.35 ns
  - Tests performed with small (50x100 cm^2) and large (180x120 cm^2) size prototypes
- CMS RPC: 2 monogaps 1.4 mm thick
  - 94% efficiency with maximum photon background
  - Tests performed with small (36x66 cm^2) and large (92x166 cm^2) size prototypes

Backup

TDC prototype



- TDC prototype in SiGe BiCMOS technology, with a time resolution of 100 ps.
  - Perfect resolution to enhance the characteristics of the new thin RPCs
  - Time Over Threshold measurements



- TDC intrinsic jitter (ultimate precision limit)

$$\sigma_{vco} = \frac{\sigma}{\sqrt{2}} = 10.77\ ps$$

Starting from HFO and CO2 binary mixtures

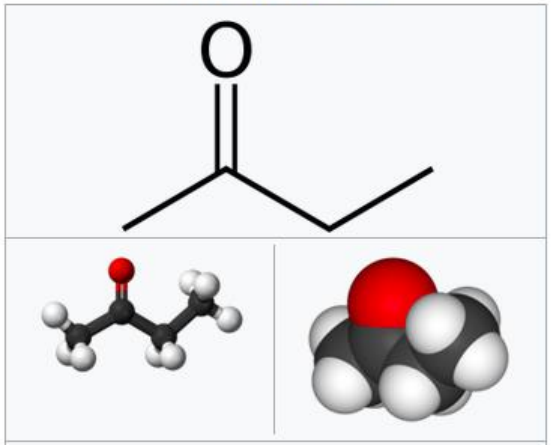
... we could not get NovecTM 5110 fluid, very promising eco-compatible substitute of SF6, so we decide to try some interesting molecules which are available at environmental temperature and pressure in liquid state :

1) Ethylmethylketone or MEK
2) Methyl tert-Butyl ether or MTBE
3) Dimethyl Sulfide

1) Ethylmethylketone or MEK

Names
Preferred IUPAC name
Butan-2-one[2]
Other names
Ethyl methyl ketone[2]
Methyl ethyl ketone (deprecated[2])
MEK
2-Butanone
Methylpropanone
Ethylmethylketone
Methylacetone

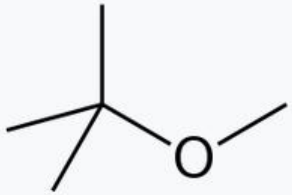
Butanone[1]

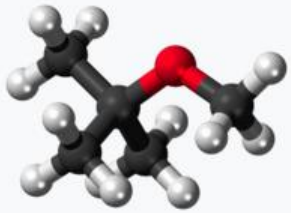


Properties	
Chemical formula	C_4H_8O
Molar mass	72.11 g·mol^{-1}
Appearance	Colorless liquid
Odor	mint or acetone-like[3]
Density	0.8050 g/mL
Melting point	−86 °C (−123 °F; 187 K)
Boiling point	79.64 °C (175.35 °F; 352.79 K)
Solubility in water	27.5 g/100 mL
Vapor pressure	78 mmHg (20°C)[3]
Acidity (pK_a)	14.7
Magnetic susceptibility (χ)	-45.58·10^{-6} cm^3/mol
Refractive index (n_D)	1.37880
Viscosity	0.43 cP

2) Methyl tert-Butyl ether or MTBE

Methyl *tert*-butyl ether





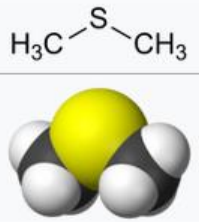
Names	
IUPAC name	2-Methoxy-2-methylpropane
Other names	Methyl *tertiary*-butyl ether; Methyl *tert*-butyl ether; Methyl *t*-butyl ether; MTBE; *tert*-Butyl methyl ether; tBME; *tert*-BuOMe

Properties	
Chemical formula	$C_5H_{12}O$
Molar mass	88.15 g·mol^{-1}
Density	0.7404 g/cm³
Melting point	−109 °C (−164 °F; 164 K)
Boiling point	55.2 °C (131.4 °F; 328.3 K)
Solubility in water	42 g/L (20 °C)[1]
Viscosity	0.36 cP at 25 °C

Hazards	
NFPA 704	
Flash point	−33.0 °C (−27.4 °F; 240.2 K)

3) Dimethyl Sulfide

Dimethyl sulfide



Names	
Preferred IUPAC name	(Methylsulfanyl)methane[1]
Other names	(Methylthio)methane[1] Dimethyl sulfide[1]

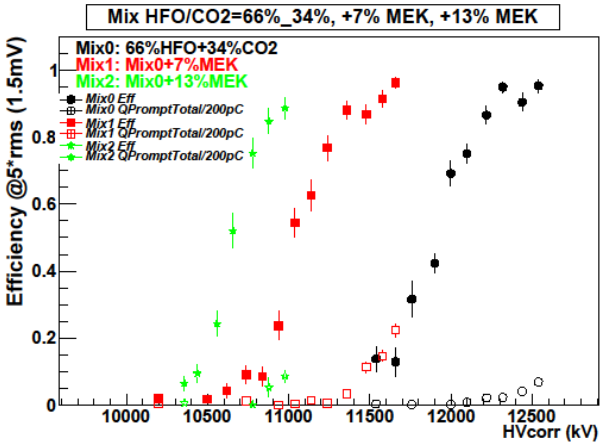
Properties	
Chemical formula	C_2H_6S
Molar mass	62.13 g·mol^{-1}
Appearance	Colourless liquid
Odor	Cabbage, sulfurous
Density	0.846 g cm^{-3}
Melting point	−98 °C; −145 °F; 175 K
Boiling point	35 to 41 °C; 95 to 106 °F; 308 to 314 K
log *P*	0.977
Vapor pressure	53.7 kPa (at 20 °C)
Magnetic susceptibility (χ)	-44.9·10^{-6} cm^3/mol
Refractive index (n_D)	1.435

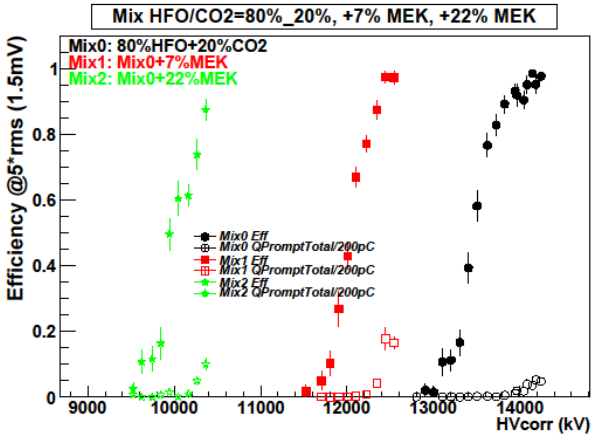
Thermochemistry	
Std enthalpy of formation ($\Delta_f H^{\ominus}_{298}$)	-66.9--63.9 kJ mol^{-1}
Std enthalpy of combustion ($\Delta_c H^{\ominus}_{298}$)	-2.1818--2.1812 MJ mol^{-1}
Hazards	
Safety data sheet	osha.gov
GHS pictograms	
GHS signal word	**DANGER**
GHS hazard statements	H225, H315, H318, H335
GHS precautionary statements	P210, P261, P280, P305+351+338
Flash point	−36 °C (−33 °F; 237 K)
Autoignition temperature	206 °C (403 °F; 479 K)
Explosive limits	19.7%

Starting from HFO and CO_2 binary mixtures

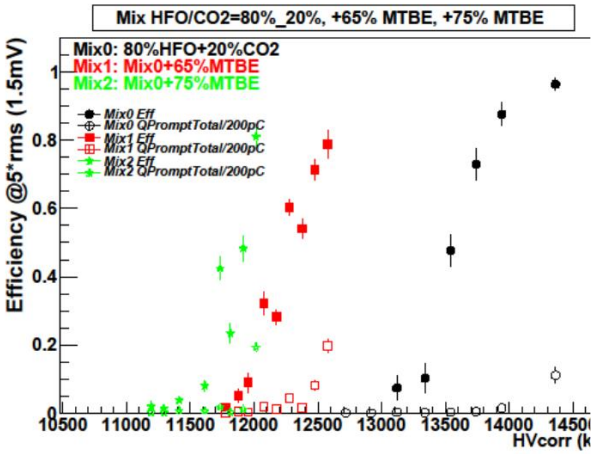
We could not get NovecTM 5110 fluid, very promising eco-compatible substitute of SF6, so we decide to try some interesting molecules which are available at environmental temperature and pressure in liquid state :

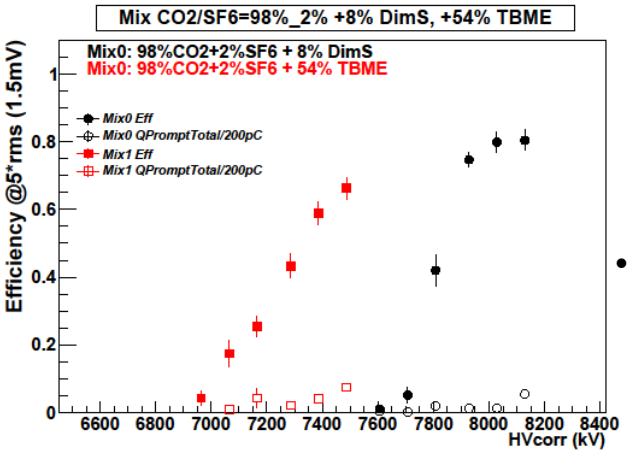
B. Liberti, RPC 2018, Puerto Vallarta, Jalisco State, MEXICO





1) Ethylmethylketone (MEK)





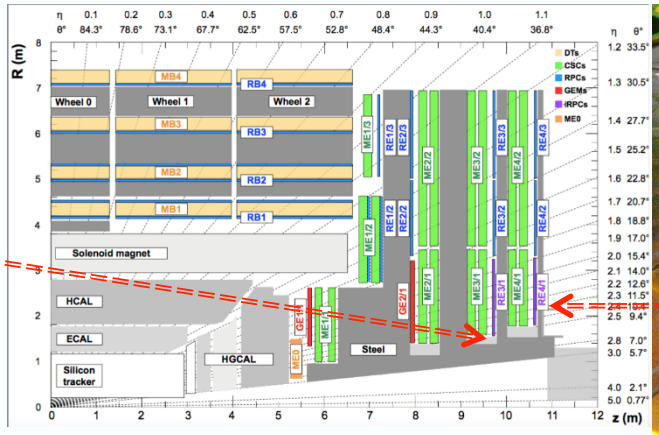
2) Methyl Tert-Butyl Ether

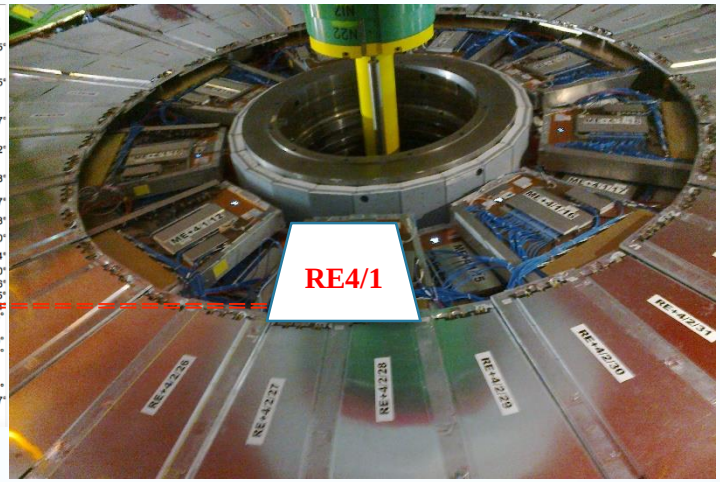
3) Dimethyl Sulfide

- MEK is able to lower the high voltage working point, the lower the higher is its concentration, and the lower the higher is HFO percentage in the binary mixture. But the average total prompt charge increases for equivalent efficiency.
- MTBE is very difficult to handle with, because of its very high vapor pressure. Because of very high currents in the gas gap, probably due to the vapor condensation, the high voltage could not be increased to achieve higher efficiency. No significant improvement for total charge with respect to lowering the working point.
- Dimethyl Sulfide is impressive with CO_2. In increasing concentration should be better studied. But in excessive concentration it diverges the gap current.

iRPC for CMS high eta completion

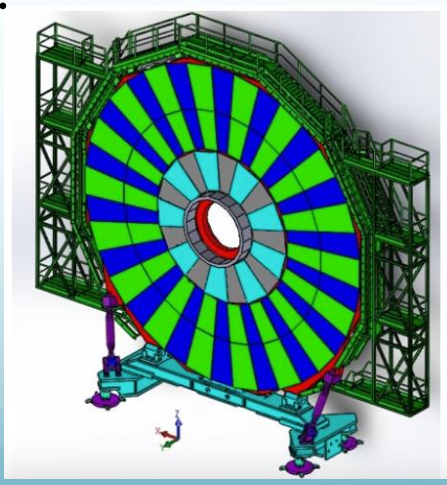
G. Pugliese

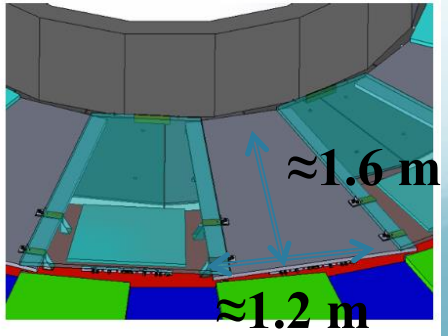




At high eta region (1.9<η<2.4), the 3th and 4th CMS muon stations will be equipped with a new generation of RPC capable of handling the challenging conditions expected at the HL-LHC.

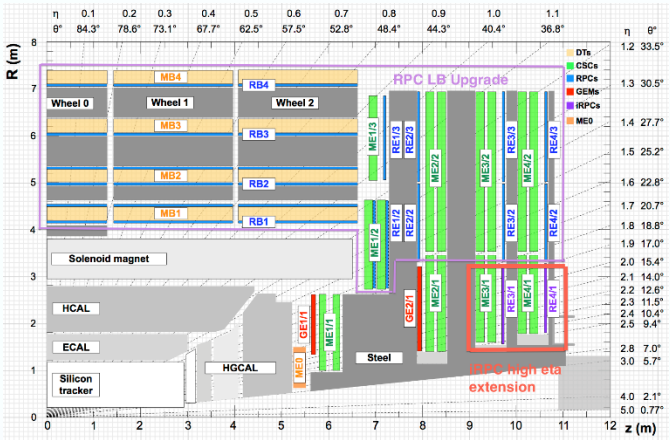
- 72 iRPC chambers
- trapezoidal shape chamber
- 20° in φ

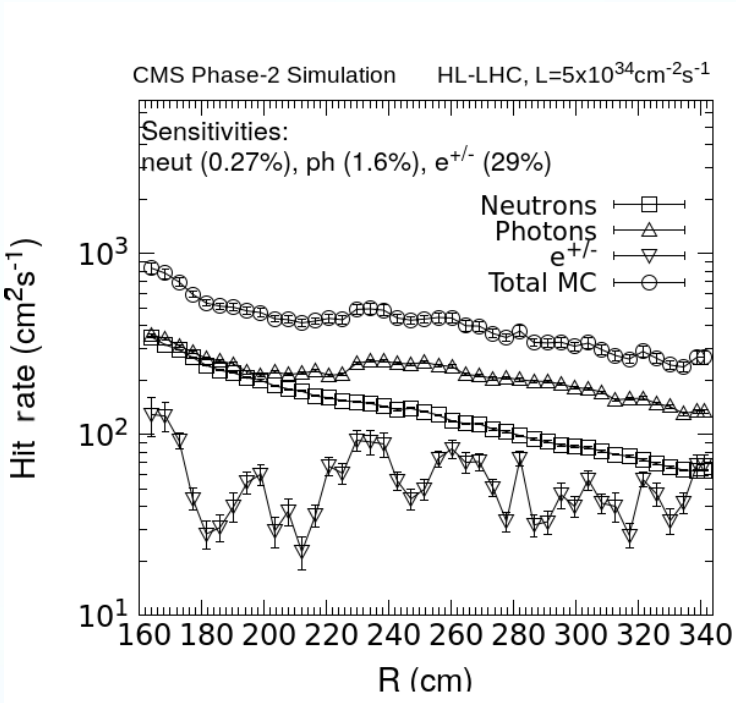




CMS 3.1 and 4.1stations requirements

G. Pugliese





Simulated Background expected rates at HL-LHC in 3.1 and 4.1 stations

	Present system	RE3/1-RE4/1
|η| coverage	0 - 1.9	1.8 - 2.4
Max expected rate (SF = 3 included)	600 Hz/cm^2	2 kHz/cm^2
Max integrated charge (SF = 3 included)	~ 0.8 C/cm^2	~ 1.0 C/cm^2
ϕ resolution	~ 0.3^0	~ 0.2^0
η resolution	~ 20 cm	~ 2 cm