Resistive Plate Chamber for the Muon apparatus

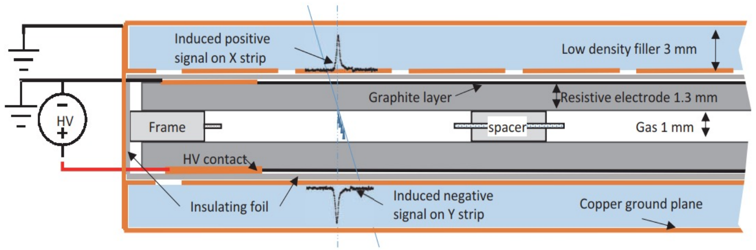
Acknowledge

Many thanks to Bencivenni, Giacomelli, Laktineh, Lee, Poli Lener, Ramos for useful discussions and support.

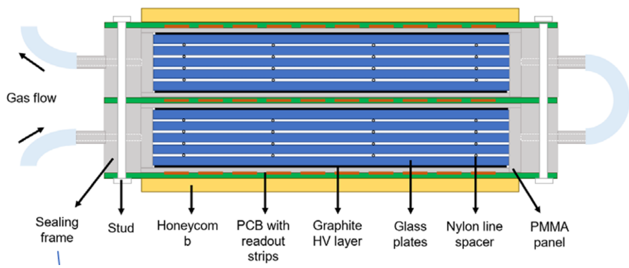
On behalf of the RPC community and participants to RPC 2024

RPC2024 conference outlook

Standard RPC



Multigap RPC



Statement from prof. Santonico RPC 2024

Overview of future RPC perspectives

Further relevant RPC evolutions/applications are achievable in a relatively straight way at the level of large are chambers and complex systems

➢Multigap-RPCs have still a relevant growth potential for large area ToF system with the goal of few picoseconds resolution

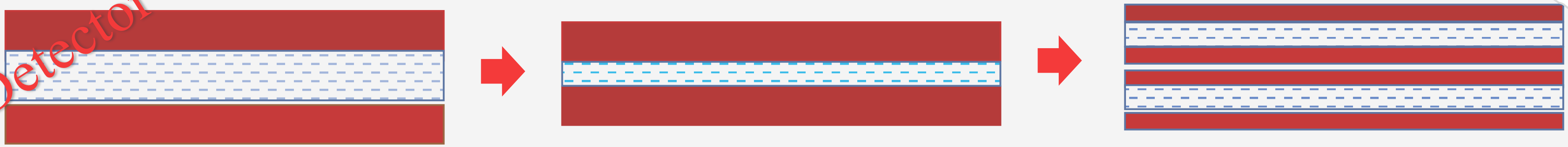
➢Standard RPCs with twin gap configuration can track muons with stace x time resolution of 100 µm x 100 ps at the rate of 10^4/ cm2

➢"Cylindrical RPCs" (see A. Rocchi talk) can operate at high pressure overcoming the 10 millibar limit of planar RPC. Particularly important for operating in free space (zero external pressure)

➢Several practical applications are achievable. Muon tomography of very large objets is a very interesting one

Evolution of “standard RPC”

Detector

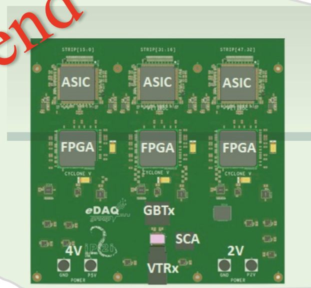


Decrease gas gap

Decrease electrode thickness

Double gap concept, decrease the charge on a single gap, study new electrodes

Fron-end

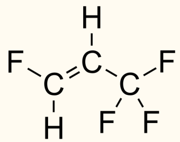


Gap size (mm)	Amplifed Efficiency @ plateau knee	Op. Voltage for amplified signal (V)	Average input prompt charge (pC)
2	90%	9660	0.4
1	90%	6010	0.2
0.5	77%	3780	0.11

Improve front end to achieve order 10 fC threshold sensitivity and low noise

Operation

Study Eco-friendly mixtures

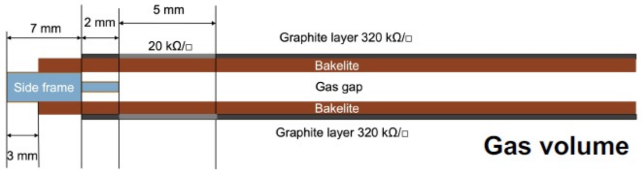


The ATLAS RPC upgrade for LHC

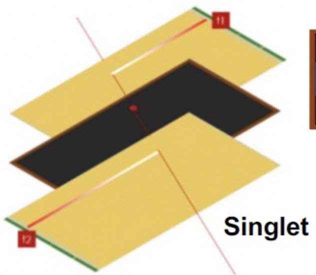
New gap layout

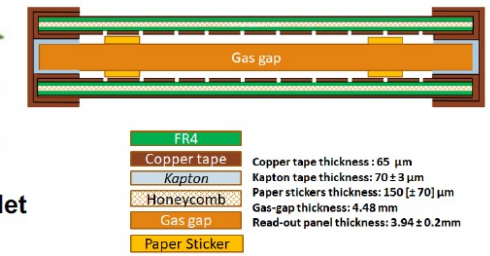
- New thin-gap RPCs (1 mm)
- Improved time resolution (0.4 ns) for time-of-flight measurements

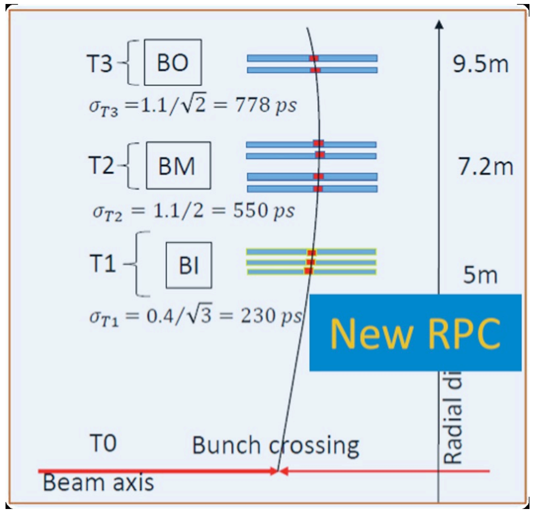
- Gas-gap thickness: reduced from 2 mm to 1 mm.
- Electrode thickness: reduced from 1.8 mm to 1.4 mm



1 mm gap



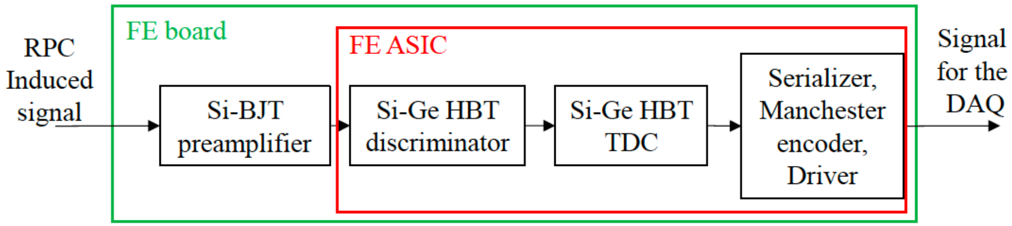


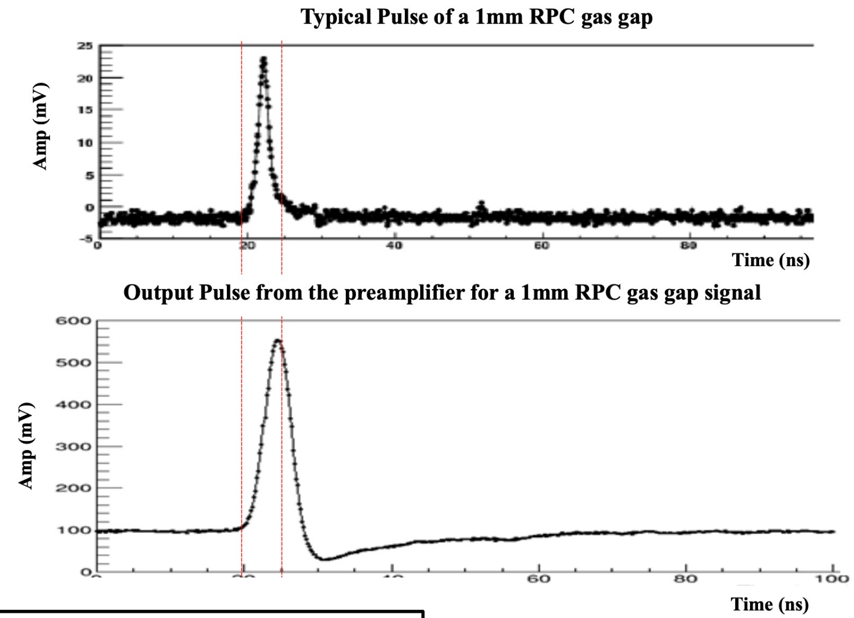


Courtesy of Paolo Camarri

The ATLAS RPC upgrade for LHC

The FE electronics is realized in a mixed technology of Silicon BJT for the discrete component preamplifier and a full custom ASIC in IHP Silicon-Germanium BiCMOS technology.





New electronics

1. Minimum Threshold of 0.3 mV
2. Detectable signal of *1-2 fC*

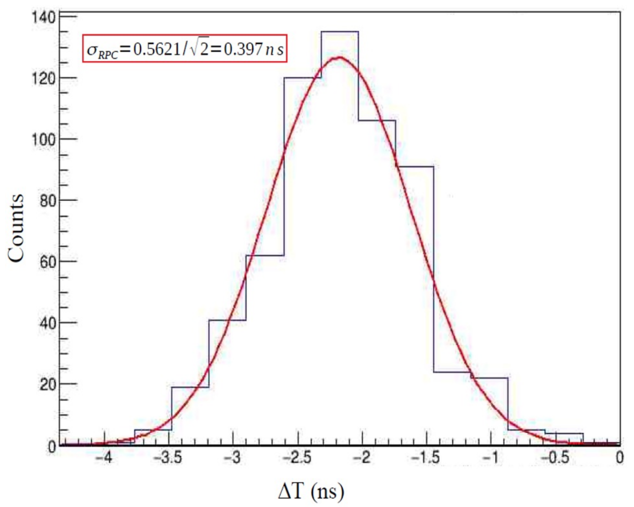
Reduction of **factor 10** in the charge produced inside the gas gap wrt the ATLAS RPCs currently installed → **Rate capability up to 10 kHz/cm²**

Published on JINST **15** (2020) no.11, C11010

Courtesy of Luca Pizzimento

The ATLAS RPC upgrade for LHC

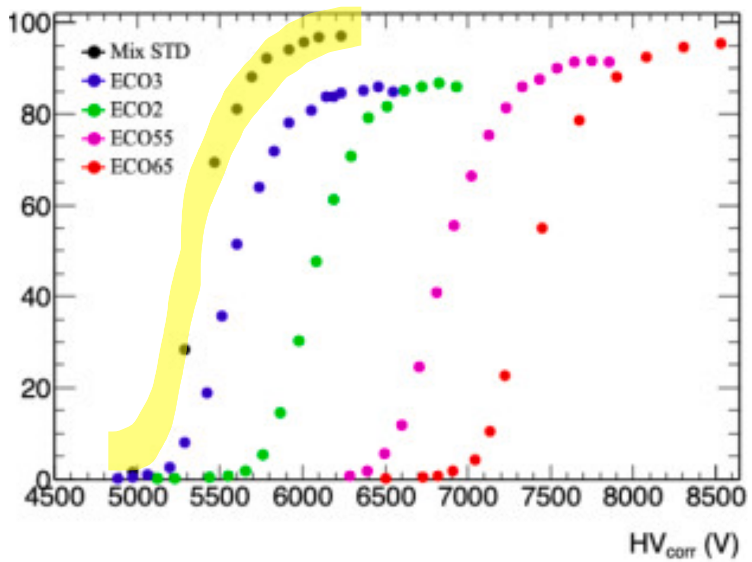
Timing



Time resolution applying the time walk correction ~ 330 ps with a mono-gap RPC

Performance of the BIS78 RPC detectors: a new concept of electronics and detector integration for high-rate and fast timing large size RPCs
ATLAS Collaboration - Luca Pizzimento (Rome U., Tor Vergata and INFN, Rome3)

Efficiency

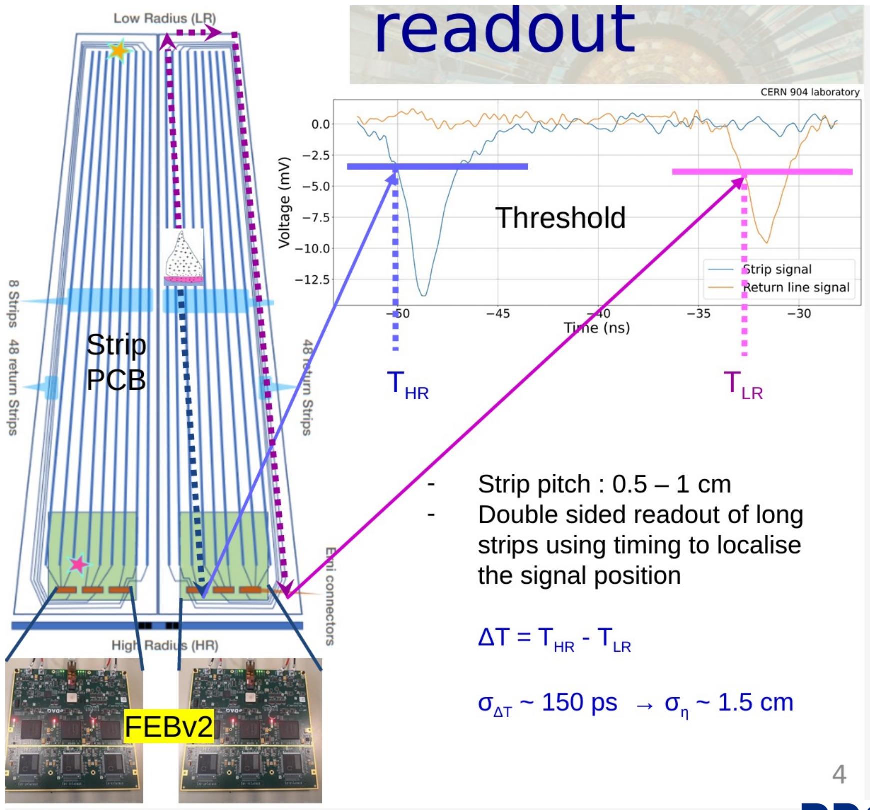


Performance of new generation of Resistive Plate Chambers operating with alternative gas mixtures
Nucl.Instrum.Meth.A 1066 (2024) 169580
Giorgia Proto, N. Bangaru, F. Fallavollita, O. Kortner, H. Kroha

The CMS RPC upgrade for LHC

- Gas-gap thickness: reduced from 2 mm to 1.4 mm.
- Sub-ns time resolution
- High background capability up to 2 kHz/cm^2
- Innovative FEB with low sensitivity threshold (below 50 fc)

1.4 mm gap



- Double side strip readout for XY recostruction
- FEB based on ASIC petiROC2C, specially designed by OMEGA group

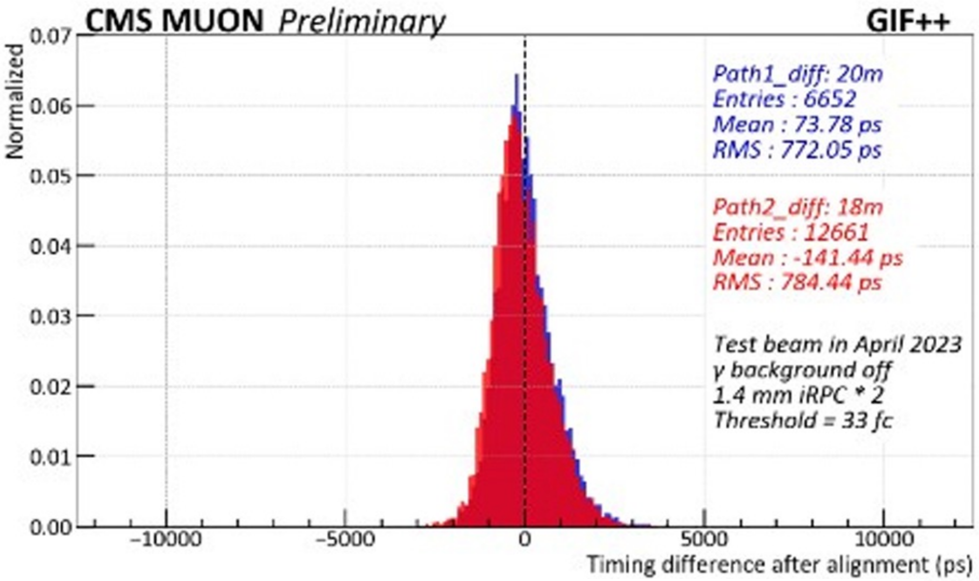
Courtesy of Maxime Gouzevitch

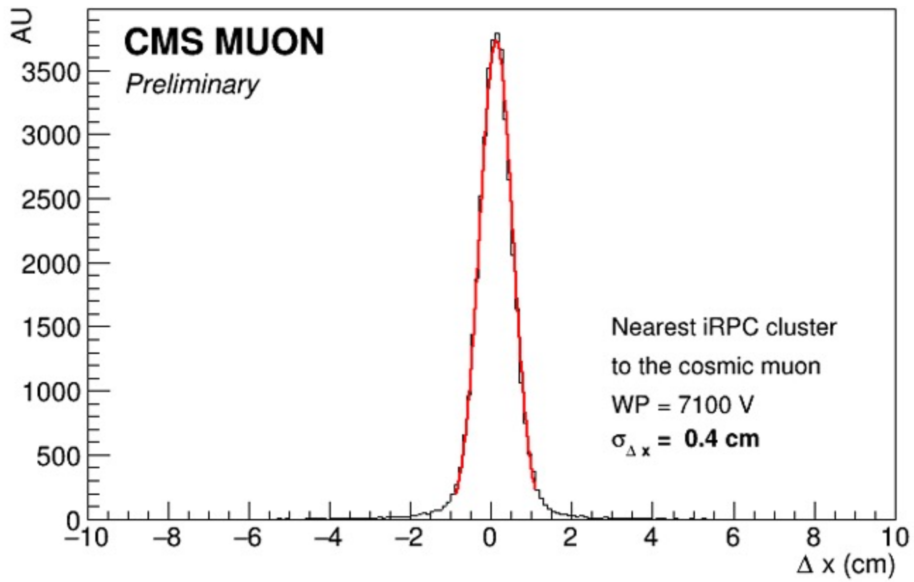
The CMS RPC upgrade for LHC

Timing

Absolute time resolution of a two chambers system: 780 ps

Space resolution on x coordinate

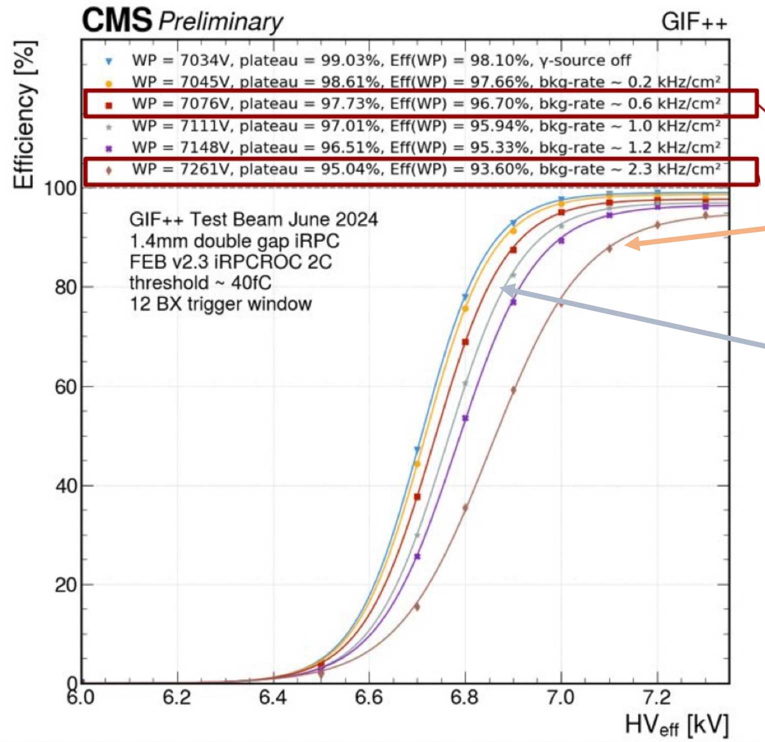




780 ps → per chamber 780/√2 ~ 550 ps

Courtesy of Maxime Gouzevitch

The CMS RPC upgrade for LHC



Efficiency plateau at 2.3 kHz/cm^2 background rate.

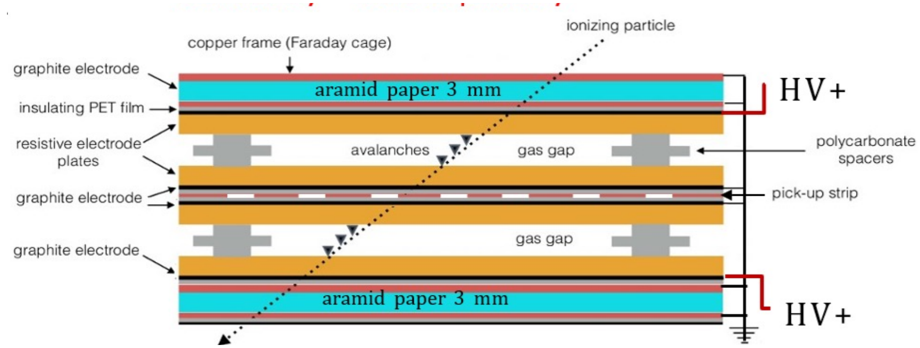
Efficiency plateau at 1.0 kHz/cm^2 background rate.

Courtesy of Jules Vandenbroeck, Mehar Ali Shah

R&D: glass phenolic laminate (Roma2)

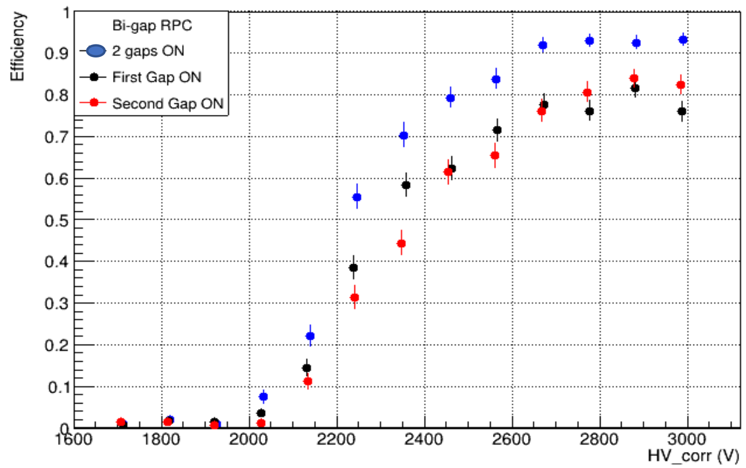
Phenolic glass properties:

- Electrical Resistivity, Average value: 2-4 x 10^{12} Ω cm
- Dielectric Constant, Average value: 5.10
- Dielectric Breakdown, Average value: 30000 V



Detector features

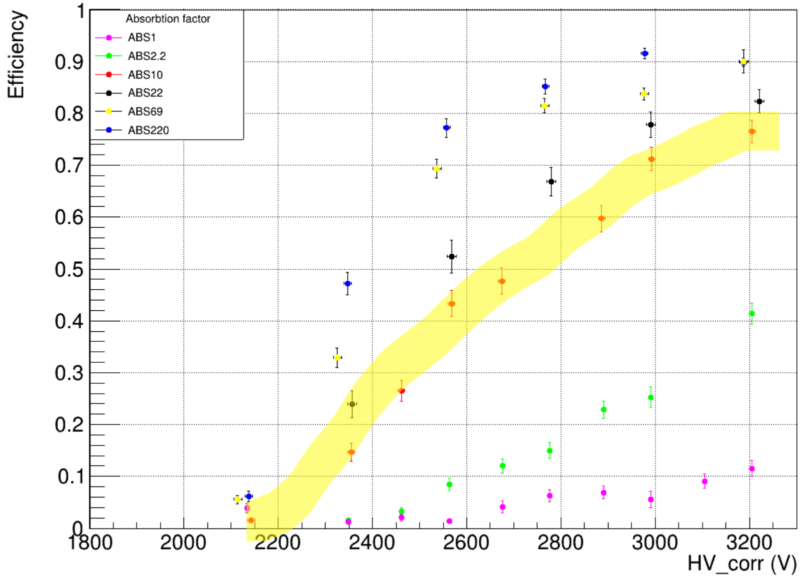
- Gap configurations: 2 parallel/single gap
- Electrode thickness: 0.4 mm
- Gas-gap thickness: 0.2 mm
- Active surface: 8 cm x 30 cm
- Spacer lattice: 3 cm x 3.5 cm
- Electrode material: phenolic glass



Courtesy of Alessandro Rocchi

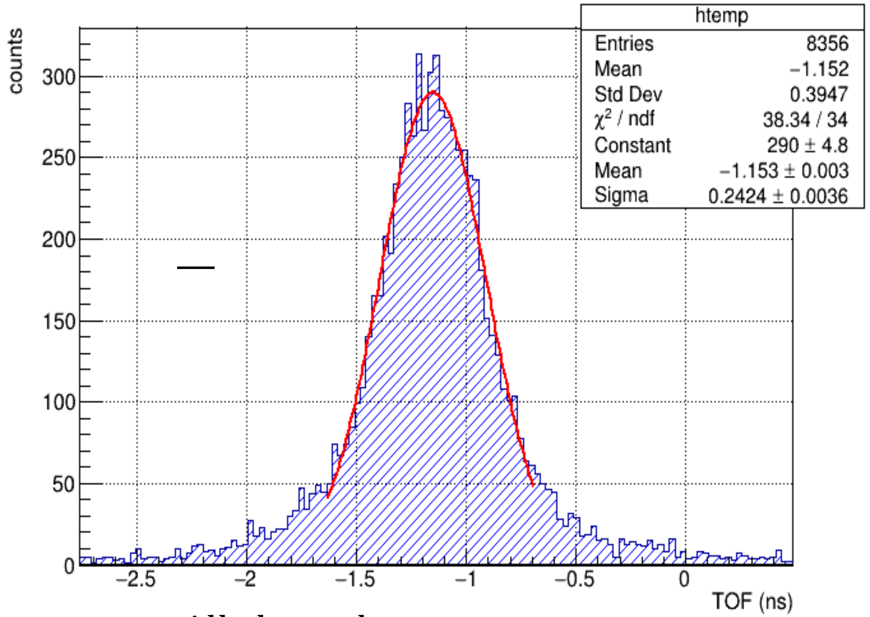
R&D: glass phenolic laminate (Roma2)

Rate capability at GIF++



A rate capability of approximately **2 kHz/cm²** (ABS 10) **at 75% efficiency is observed**

Time resolution on the H8 beam line



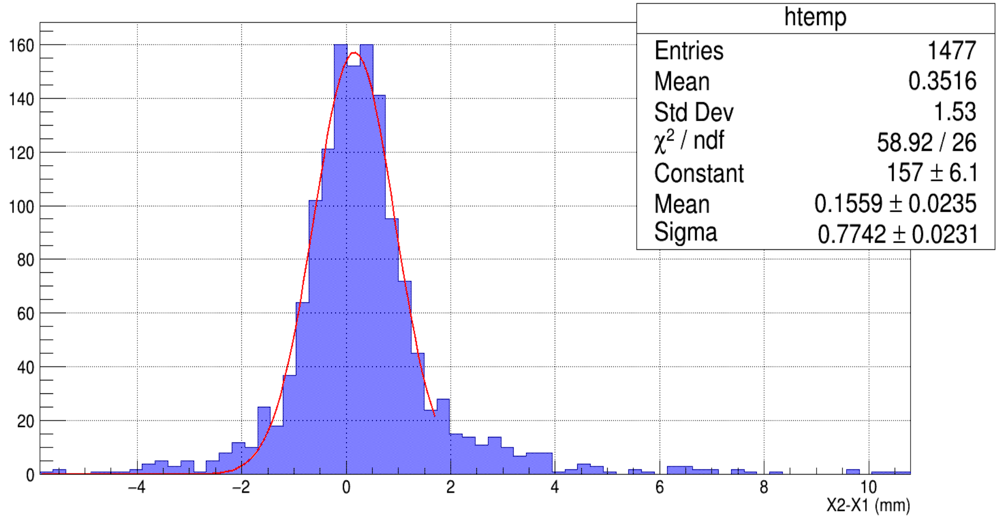
All channels

$$\sigma_t = \frac{\sigma}{\sqrt{2}} = 170\ ps$$

Courtesy of Alessandro Rocchi

R&D: glass phenolic laminate (Roma2)

Space resolution with the charge centroid method



$$\sigma_S = \frac{0.77}{\sqrt{2}} mm = 0{,}543 \pm 0{,}016\, mm$$

Perspective for tracking – timing – high-rate capability

Reduce the graphite resistivity

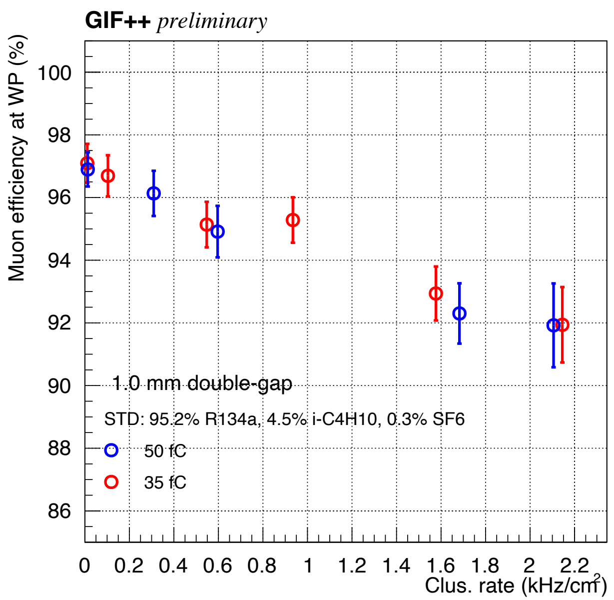
Reduce the strip pitch

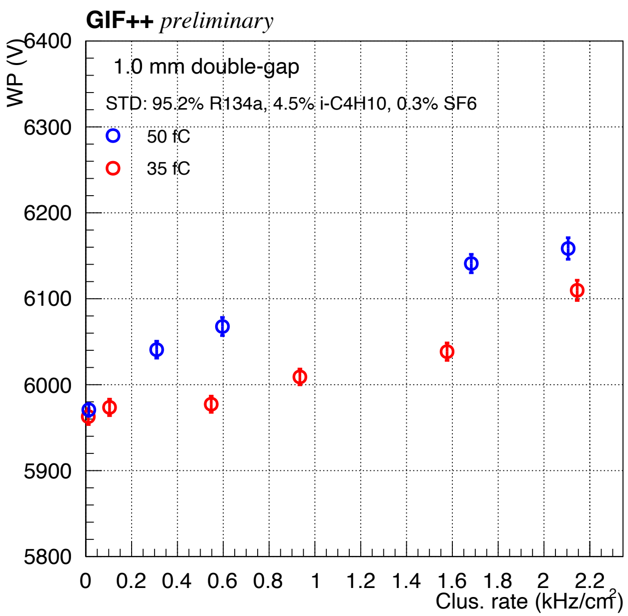
Reduce the phenolic glass resistivity by optimizing production processes and selection.

Courtesy of Alessandro Rocchi

R&D: 1 mm gas gap (Bari-KODEL)

- Double gap HPL equipped with CMS front-end
- 1 mm gap thick and 1.4 electrode thick





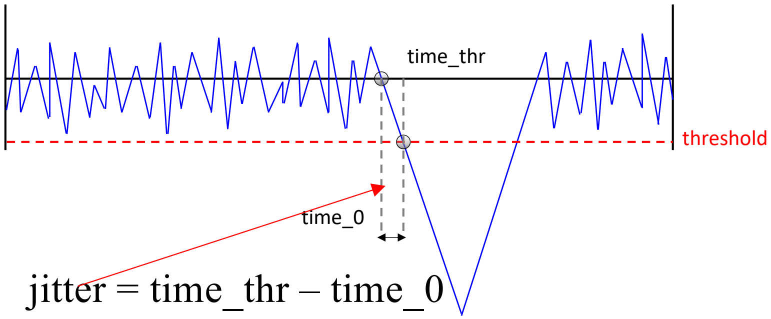
- 92% efficiency up to ~ 2.2 kHz/cm^2
- Working point average ~ 6 kV

Courtesy of D. Ramos

R&D: 500 μm Glass RPC (Bari-KODEL)

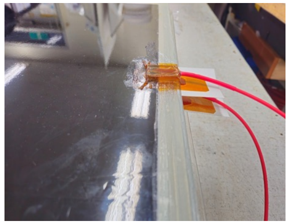
50x50cm² prototype double gap glass RPC with gas thickness of 500 um under test for fast timing RPC prototype.

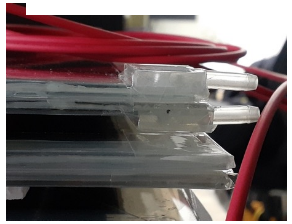
Preliminary signal study by using CAEN digitizer DT5742, strip PCB 5 mm pitch and cosmic trigger

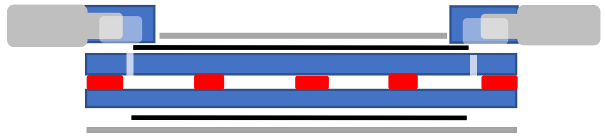


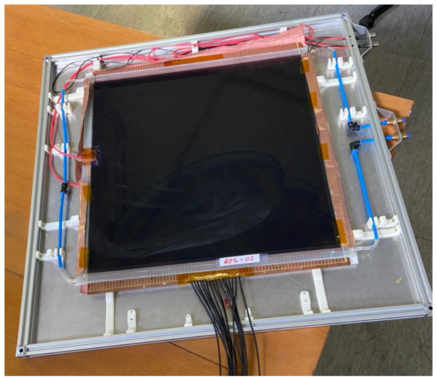
Study jitter distribution @ 4 kV with standard CMS mixture

Preliminary: 220 ps









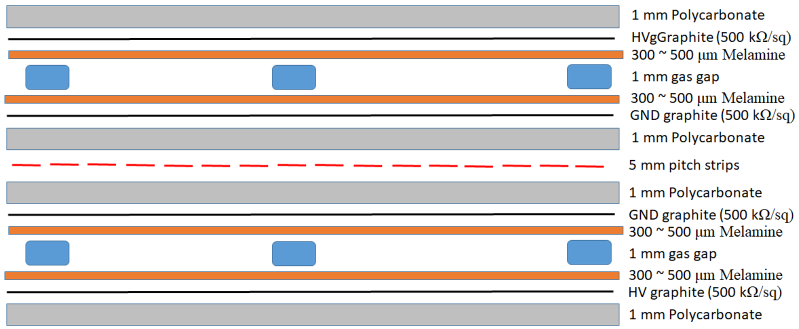
Courtesy of D. Ramos

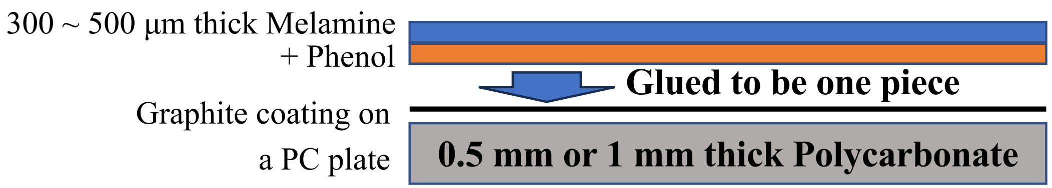
R&D: new melamine electrodes (KODEL)

New RPC electrode material (Melamine sheet):

- Thinner gas gap volumes to achieve a better time resolution (~ 300 ps or better)
- 2 mm thick gas volume RPCs → 1 mm thick gas volume RPCs
  → In next R&D, 0.5 mm thick gas volume RPCs
- Thinner RPC electrode for higher rate capability (> 5 kHz cm^{-2})
- Hopefully NO oil varnishing needed
- Why NOT soda-lime glass instead? (commonly used for timing RPCs)
- Resistivity ~ 10^{12} Ωcm → Too high to be used at high-rate environment
  → The rate capability at best ~ 1 kHz cm^{-2}
- Too fragile to make large sized trigger RPC gaps


Thin melamine sheets (ρ ~ 1.5 x 10^{11} Ω cm) and polycarbonate sheet to support the gas gaps





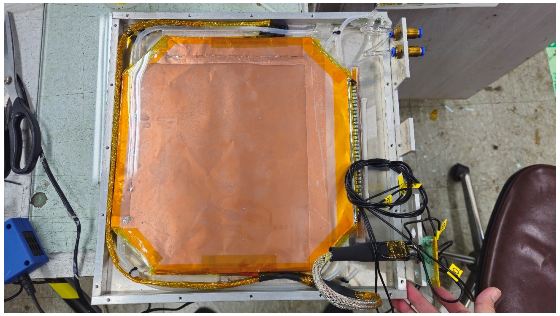
Courtesy of K. Lee

R&D: new melamine electrodes (KODEL)

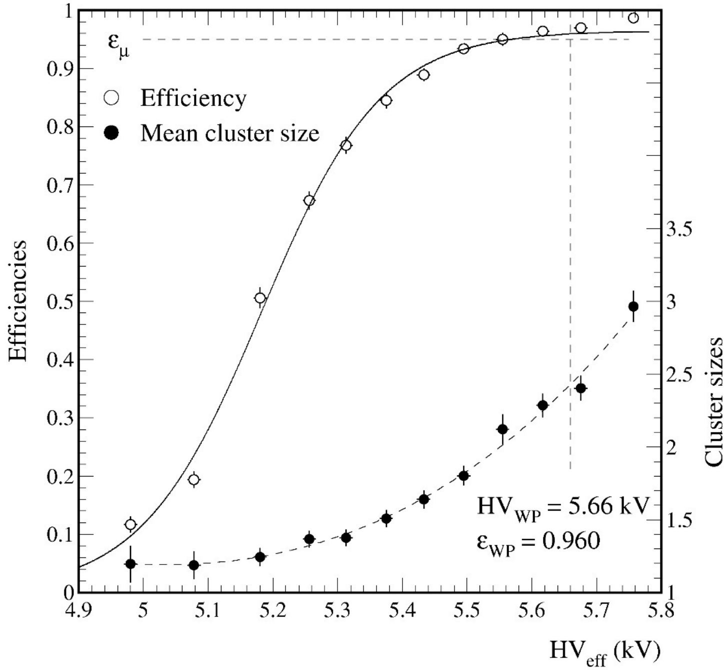
Small 1-mm thick gas-volume double-gap RPC made of 500 µm-thick melamine-based sheets

- Active area of the detector: 26.4 x 26.4 cm^2
- Strip pitches
  - ✓ 5 mm to address a 1 ~ 2 mm position resolution
  - ✓ 11 mm for typical RPC triggers
- Surface resistivity of graphite ~ 500 kΩ/sq
- Absence of good front-end-electronics with a time resolution better than 100 ps

→ Unable to check the time characteristics of the detectors



11 mm pitch strips (read only 24 strip among 32 strips)
Digitization threshold = 0.33 mV (~ 50 fC)
HV_{WP} = HV(abs 95%) + 100 V = 5.71 kV
Efficiency @HV_{WP} = 0.972, ε_{max} = 0.990
Mean cluster size @WP = 2.5
Noise rate ~ 10.8 Hz cm^2 @ 23.1 °C

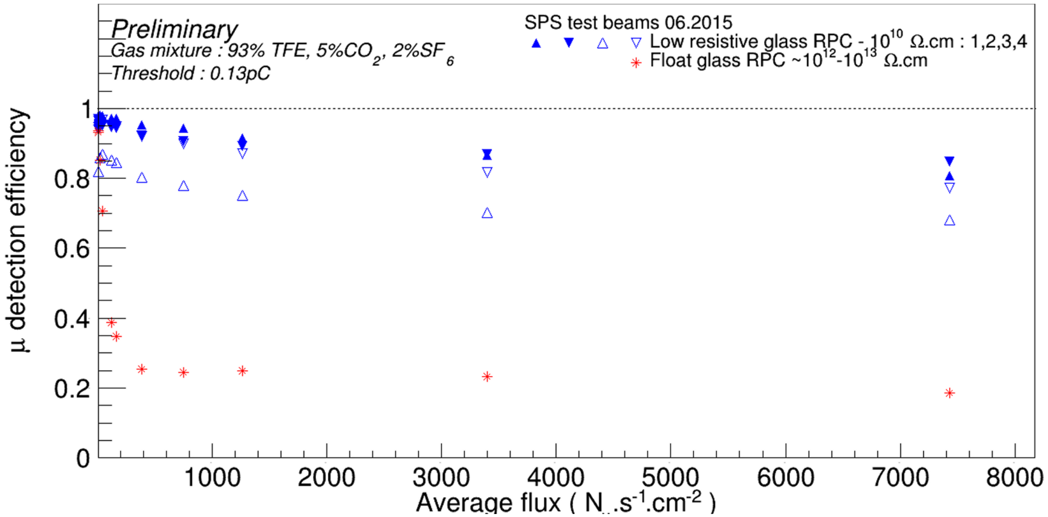


Courtesy of K. Lee

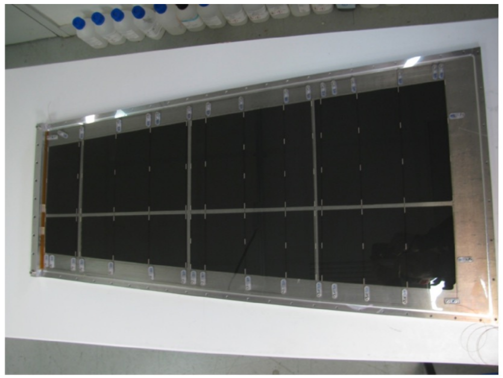
R&D: glass electrodes (Lyon, Tsinghua)

Standard glass RPC have low-rate detection capability (a few hundreds of Hz/cm^2)

Tsinghua has developed a low resistive glass 10^{10} $\Omega \cdot$ cm (doped glass with metal components) and a very high surface uniformity, with a roughness below 10 nm



Limitation (30 cm x 30 cm) is a problem



REF. F. Lagarde et al 2016 JINST 11 C09006

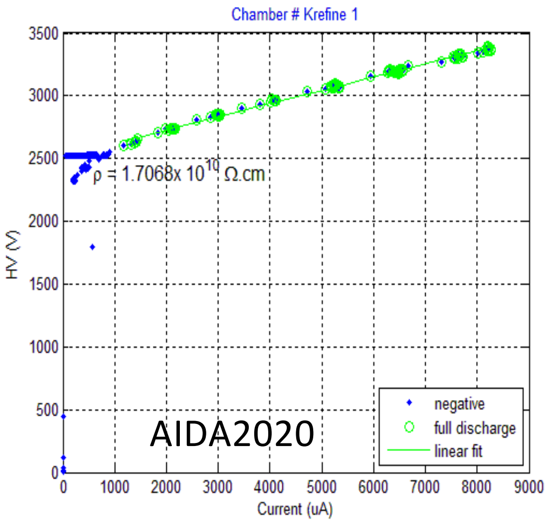
Courtesy of I. Laktineh

R&D: plastic electrodes (Lyon)

PVdF and **PEEK** are very stable and chemically inert thermoplastic

New kind of PVdF developed with the help of PolyOne (Germany). Doped with CNT we achieved a bulk resistivity of $10^{11\text{-}12}$ Ω cm.

New charged PEEK developed with the help of Krefine (Japan). Doped with BC a bulk resistivity of $10^{8\text{-}9}$ Ω cm was achieved.



A few small detectors were made using doped PVdF plates of 2-3 mm thickness. An excellent efficiency is obtained with cosmic, but resistivity is not low enough for reaching high rate.

Plates made with charged PEEK were produced reaching $10^{8\text{-}9}$ Ω cm which could allow reaching rates of hundreds of kHz/cm^2, but some homogeneity issues are still there.

More efforts and funding are needed to finalize this material.

Courtesy of I. Laktineh

R&D: Sustainable RPC operation

Eco-friendly mixtures requirements: Low GWP, low toxicity, not flammable, detector performance comparable with standard one. Actions:

- Replace $C_2H_2F_4$ with HFO
- Addition of CO_2
- SF_6 still needed but studies on replacement on going

HFO moves the operating voltage (WP) at much higher values, so the the addition of CO_2 helps in limiting this increase. For thin gap RPC (es. sub-mm gaps), this might be less important

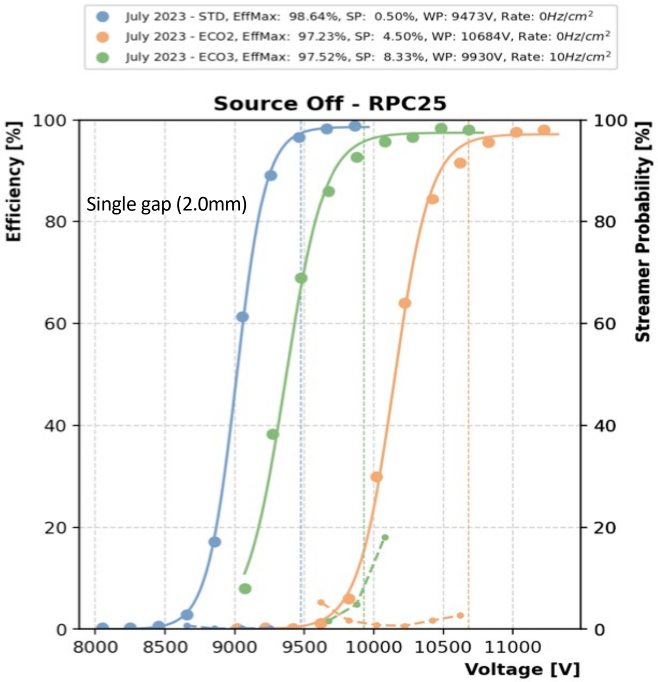
	TFE (%)	HFO (%)	CO_2 (%)	iC_4H_{10} (%)	SF6 (%)	GWP	CO_2e (g/l)*
STD	95.2	-	-	4.5	0.3	1485	6824
ECO2	-	35	60	4	1	476	1522
ECO3	-	25	69	5	1	527	1519
Density (g/l)	4.68	5.26	1.98	2.69	6.61	-	-
GWP	1430	7	1	3	22800	-	-

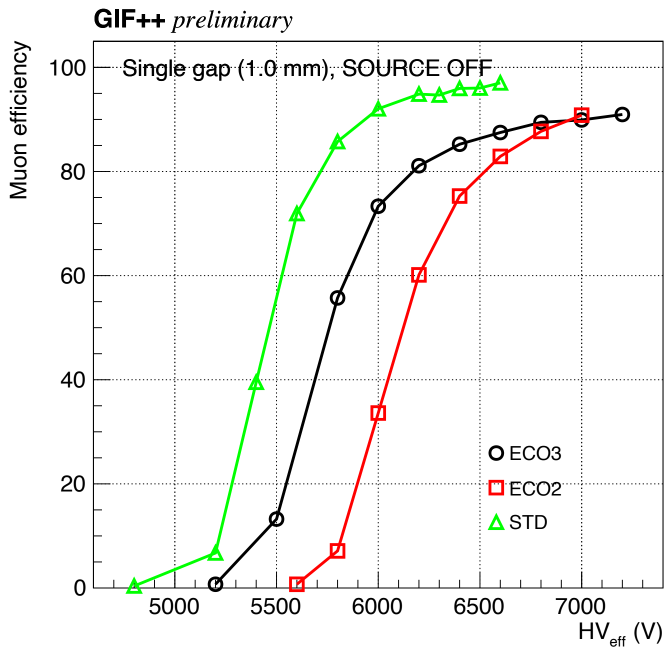
*GWP with respect to CO_2, and their CO_2e, in grams, for one litre of mixture

Courtesy of RPC EcoGas@GIF++ collaboration

R&D: Sustainable RPC operation

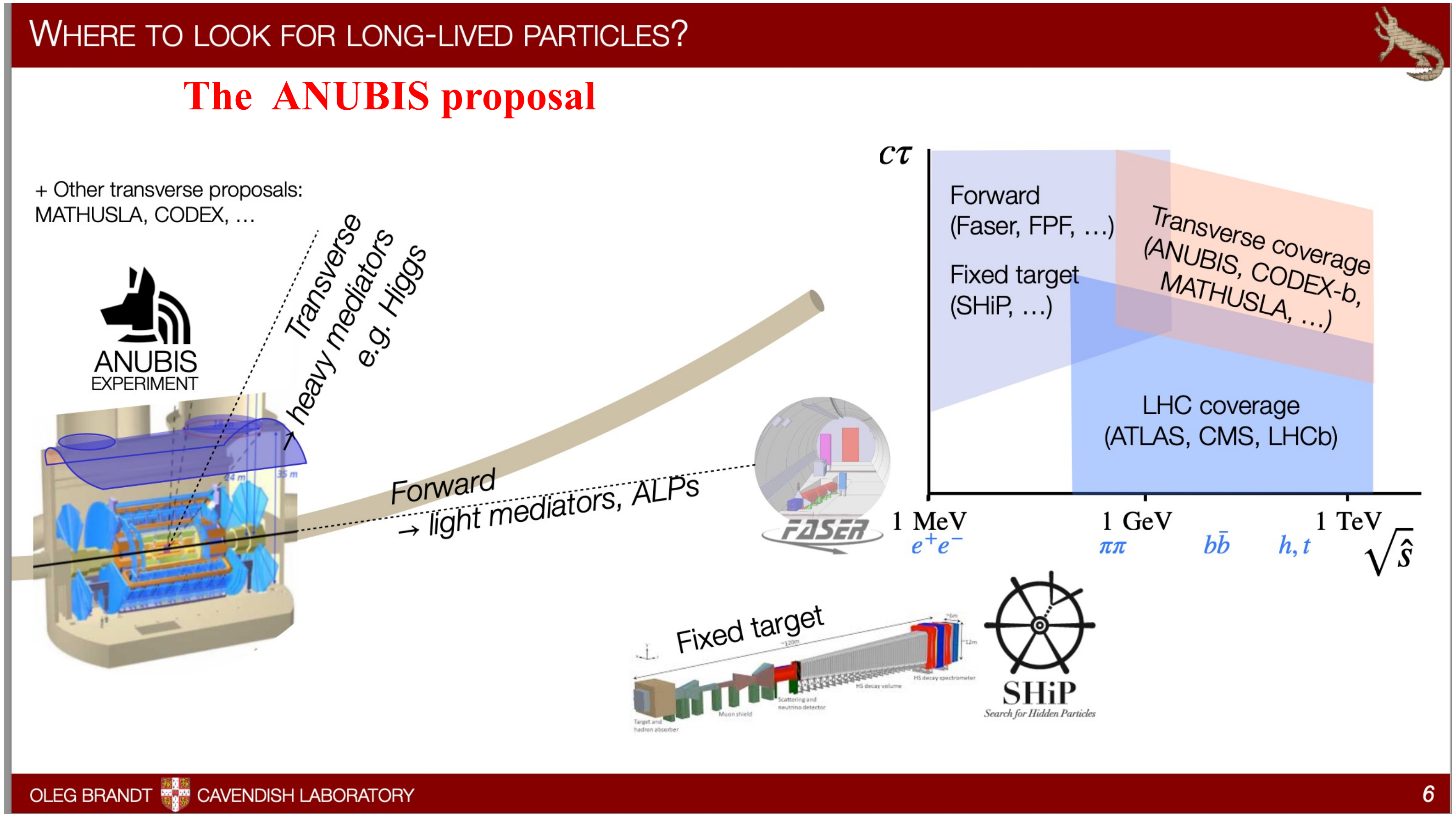
Efficiency single gap HPL RPC   2mm vs 1mm



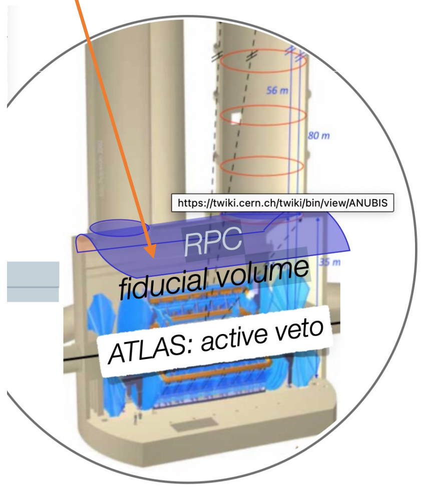


Courtesy of RPC EcoGas@GIF++ collaboration

A physics case: Long Lived Particles



Instrument with RPC the ATLAS roof



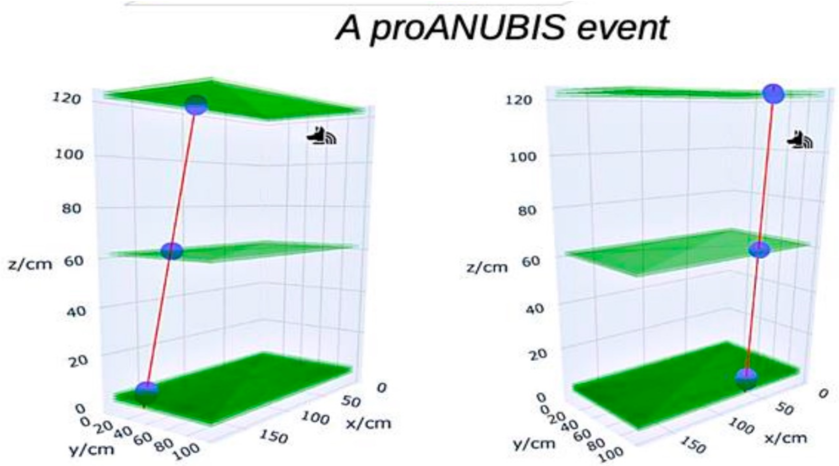
Courtesy of Oleg Brandt

A physic case: Long Lived Particles

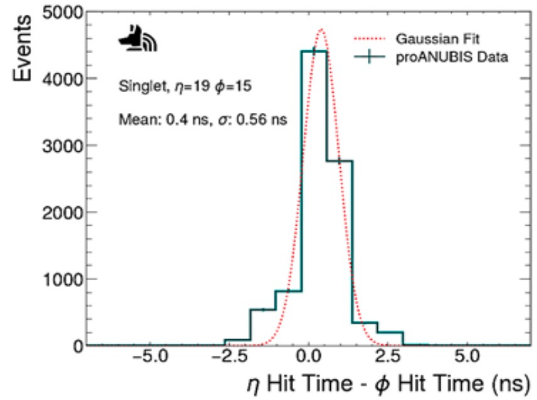
ANUBIS Detector requirements:

Parameter	Specification
Time resolution	$\delta t \lesssim 0.5$ ns
Angular resolution	$\delta\alpha \lesssim 0.01$ rad
Spatial resolution	$\delta x, \delta z \lesssim 0.5$ cm
Per-layer hit efficiency	$\varepsilon \gtrsim 98\%$

The proANUBIS demonstrator with LHC data



Two reconstructed proANUBIS tracks from 2024 LHC collision data

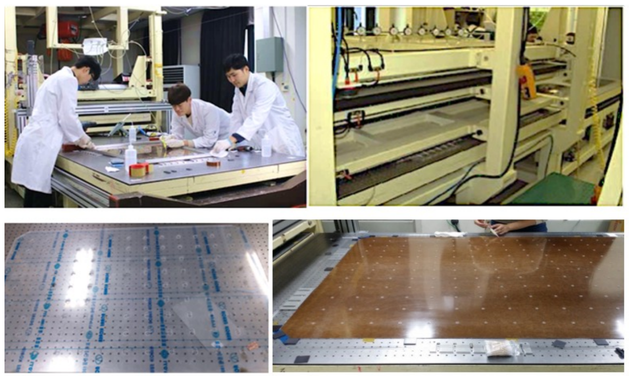


The time difference for two adjacent eta and phi planes at a particular location in the detector, corrected for systematic offsets

Courtesy of Aashaq Shah

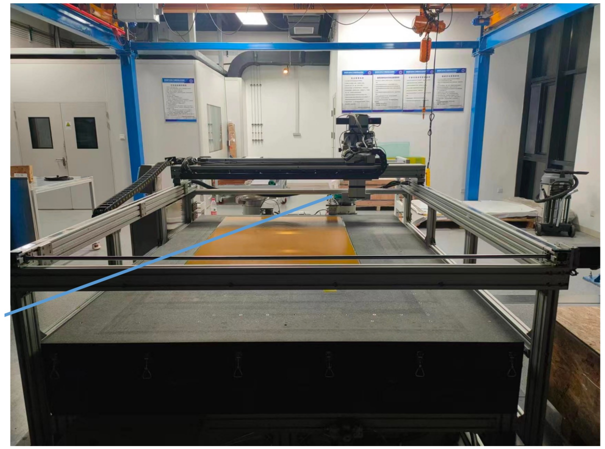
Facility productions

General Tecnica (Italy) has produced the gas gaps for ATLAS phase I and CMS Barrel. It is now producing the new ATLAS RPC gas gap for phase II. Also ready to respond to R&D requests.



KODEL@Korea University has produced the gas gaps for CMS forward (still in production). Also, the group significatively active in R&D activity. Under discussion the future of the mass production facility. Input from scientific community needed.

Facility productions (new entries)



University of science and technology of China (USTC) is undertaking a major effort to set up a gas gap production facility for the ATLAS RPC. Preparatory work is over. Ready for production.

Max Plank Institute (MPI) has recently put in operation a new facility for the ATLAS gas gap production. Also, the MPI group has started to establish two additional manufacturers:

MIRION TECHNOLOGIES
Website: https://www.mirion.com/

PTS Maschinenbau
Website: https://www.ptsmaschinenbau.com/

Conclusion

Detector performance such as: rate capability of 4-5 kHz/cm^2, time resolution of 200-300 psec, space resolution of 400-500 μm are easily achievable with the present technology for "standard RPC". Improvement of at least a factor of 2 is within reach. Inputs from community on FCC muon detector baseline are needed.

Additional R&D should be performed on novel material for electrodes and assembly procedure for thin gas gas RPC (0.2-0.5 mm)

The eco-gas puzzle needs some special effort, but there is the evidence that operation with thin gas gaps would facilitate the definition of a proper eco-friendly mixture

Several facilities are now in operation and can respond to possible call for production

DRD1 has offered a unique platform for collaborative network and could facilitate the discussion for possible FCC muon detector ideas