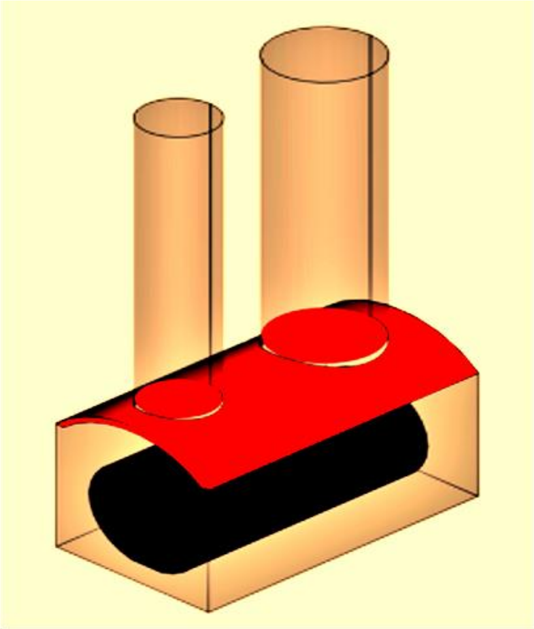
Operation of 1 mm HPL RPCs with low-GWP gas mixtures

Aashaq Shah
Cavendish Laboratory, University of Cambridge

On behalf of the ANUBIS Collaboration



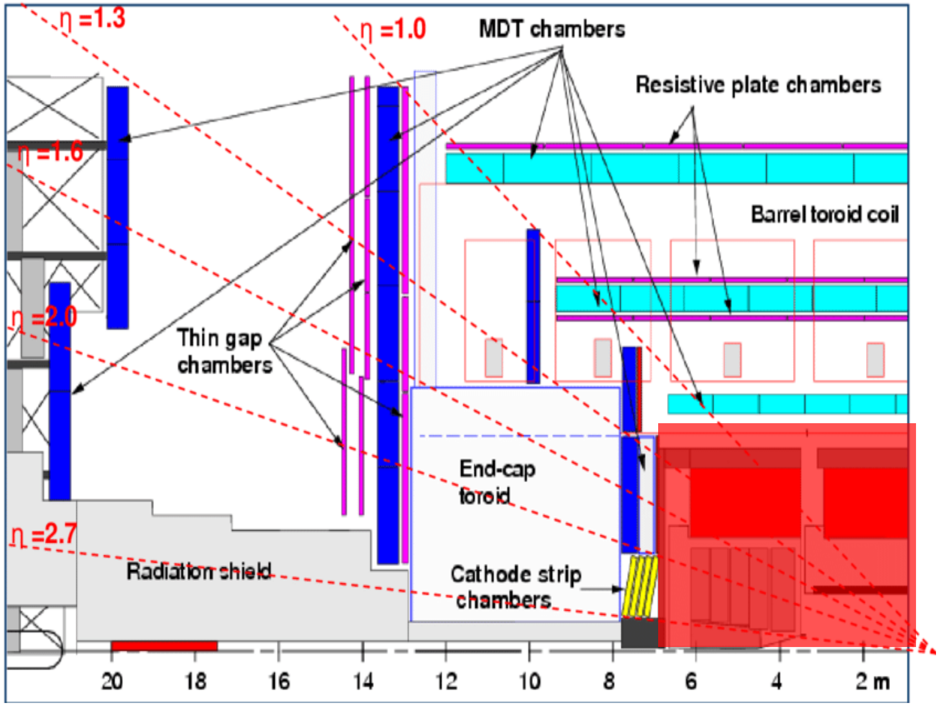
**XVII International Conference on Resistive Plate Chambers and Related Detectors (RPC2024),
9-13 Sep. 2024, Santiago de Compostela, Spain**

Introduction

Why to look for eco-friendly or low GWP gases?

- OK - Climate change a global concern
- Greenhouse Gas (GHG) emissions one of the major contributing factors
- GHG from where, are HEP experiments also contributing?
- LHC experiments for particle detection used
  ~135 ktCO_2 eq. (2017)
  ~119 ktCO_2 eq. (2018)
  ~101 ktCO_2 eq. (2022) (CERN Env. report)
- ATLAS and CMS RPC contributing mainly

- **Should HEP Experiments STOP?**
  Hmmm - ?



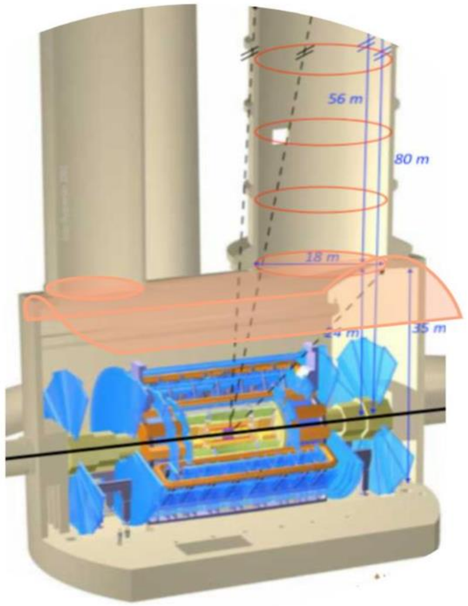
A schematic side-view of the ATLAS Muon Spectrometer systems, showing the different chamber technologies.

ANUBIS and its interest

ANUBIS – AN Underground Belayed In-Shaft search experiment

See other talks: ANUBIS: future large-scale application of RPC detector
: Insights from the proANUBIS demonstrator using Run 3 LHC collision data

- ANUBIS intending to use RPC's
  - › Next generation of RPC → ATLAS Phase II technology
- A large detector volume, will require a lot of (detectors) gases…
  - › Active gas gap area ~ 9800 m^2
    Volume ~ 9.8 m^3



ANUBIS: ATLAS underground cavern ceiling - large detector area needed

- Normally RPC being operated with Freon-based gas mixture
  - › 95% of $C_2H_2F_4$, 4.5% of iC_4H_{10} and 0.3% of SF_6
- **Problem**: These systems are of the "once through" type, in which the exit gas is **vented to the atmosphere** (the gas can be recycled too (but very costly))

The focus of this talk

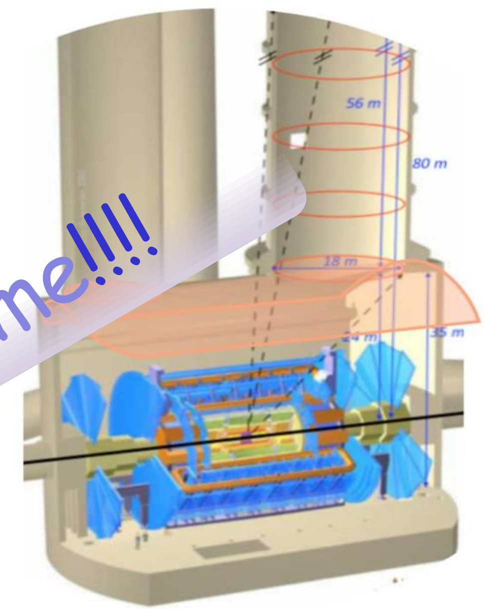
- › **Share ongoing activities and mitigation measures being undertaken by ANUBIS Collaboration**

ANUBIS and its interest

ANUBIS – AN Underground Belayed In-Shaft search experiment

See other talks: ANUBIS: future large-scale application of RPC detector
: Insights from the proANUBIS demonstrator using Run 3 LHC collision data

- ANUBIS intending to use RPC's
  - Next generation of RPC → ATLAS Phase II technology
- A large detector volume, will require a lot of (detectors) gases…
  - Active gas gap area ~ 9800 m^2
    Volume ~ 9.8 m^3



ANUBIS: ATLAS underground cavern ceiling - large detector area needed

- Normally RPC being operated with Freon-based gas mixture
  - 95% of $C_2H_2F_4$, 4.5% of iC_4H_{10} and 0.3% of SF_6
- **Problem**: These systems are of the "once through" type, in which the exit gas is **vented to the atmosphere** (the gas can be recycled too (but very costly))

Relatively new players in the game!!!!

The focus of this talk

- **Share ongoing activities and mitigation measures being undertaken by ANUBIS Collaboration**

ANUBIS for GHG mitigation

- The ANUBIS is committed to European guidelines for the use of F-gases
- Implementing/following CERN F-gas mitigation strategies
- Implementing strict QC criteria for gas tightness and validation of gas gaps (for now and more towards future)
- Optimisation of current technologies and replacement with more environmentally friendly gases
  - Includes attention to operation and monitoring
  - Shorter plans replacing F-gases with CO_2,which has a substantially lower GWP
  - Longer plan to investigate environmentally friendly gas mixtures

R&D on Low GWP gases: Ongoing efforts

Produced recently prototype 50 cm x 50 cm RPCs following ATLAS Phase II design (with different FE board)

- Gas gaps constructed from resistive electrodes made of **high-pressure phenolic-melaminic laminate (HPL - bakelite)** with a high resistivity of approximately 10^{10} **Ωcm**. (prefabricated Gas gaps from GTE, Italy)

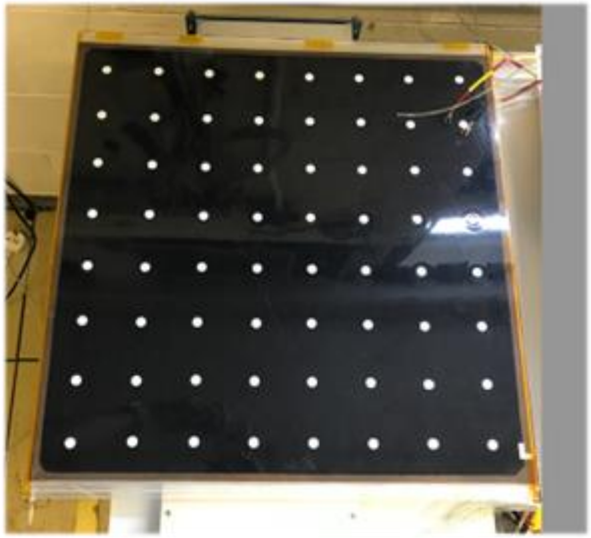
- The thickness remains 1 mm, with uniform spacing maintained by polycarbonate pillars, designed at 1 mm thick and 10 mm in diameter. The matrix pitch 7 cm x 7 cm to ensure structural stability.

- The internal gas distributor based on the ATLAS BIS78 gas gap type design. Gas distributors along two sides of the gas volume, gas inlets/outlets located at the corners.

- The Bakelite electrode thickness 1.2 mm

- Graphite electrode resistivity ~ close to 350 kΩ/□;

- High voltage connection with 1 mm diameter with 18 kV-rated wire



Prototype 50 cm x 50 cm gas gap

R&D on Low GWP gases: Ongoing efforts

Produced recently prototype 50 cm x 50 cm RPCs following ATLAS Phase II design (with different FE board)

- Gas gaps constructed from resistive electrodes made of **high-pressure phenolic-melaminic laminate (HPL - bakelite)** with a high resistivity of approximately 10^{10} **Ωcm**. (prefabricated Gas gaps from GTE, Italy)

- The thickness remains 1 mm, with uniform spacing maintained by polycarbonate pillars, designed at 1 mm thick and 10 mm in diameter. The matrix pitch 7 cm x 7 cm to ensure structural stability.

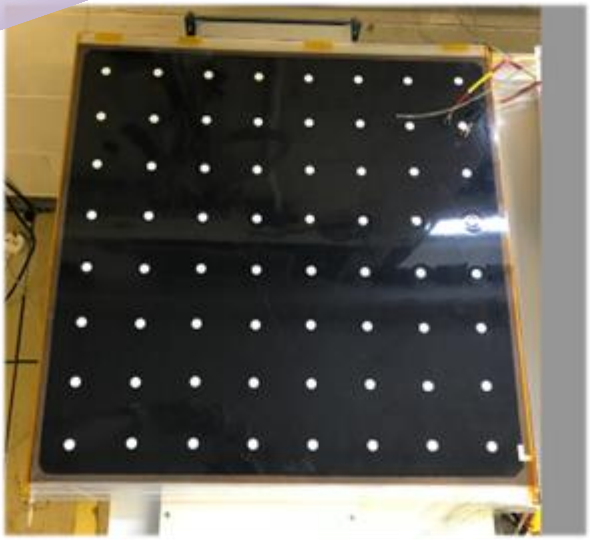
- The internal gas distributor based on the ATLAS BIS78 gas gap type design. Gas distributors along two sides of the gas volume, gas inlets/outlets located at the corners.

- The Bakelite electrode thickness 1.2 mm

- Graphite electrode resistivity ~ close to 350 kΩ/□;

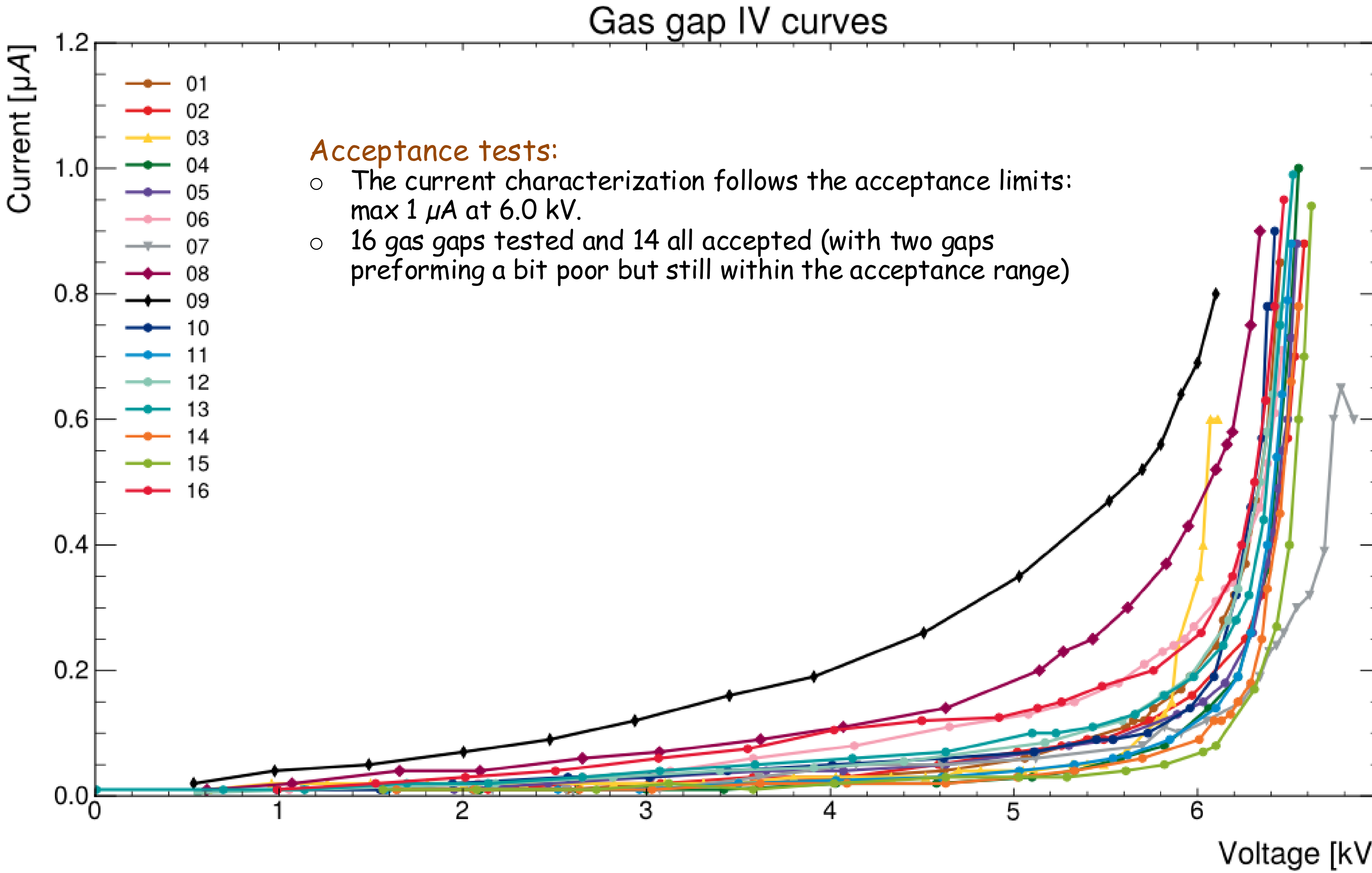
- High voltage connection with 1 mm diameter with 18 kV-rated wire

Just starting....!!!!



Prototype 50 cm x 50 cm gas gap

R&D on Low GWP gases: Ongoing efforts



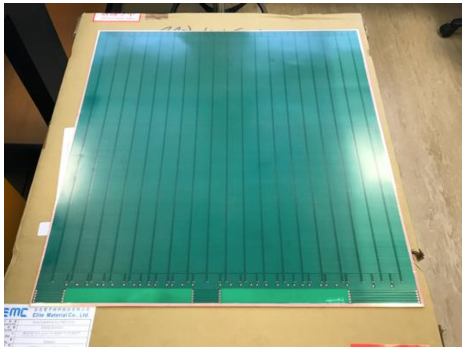
Acceptance tests:

- The current characterization follows the acceptance limits: max 1 μA at 6.0 kV.
- 16 gas gaps tested and 14 all accepted (with two gaps preforming a bit poor but still within the acceptance range)

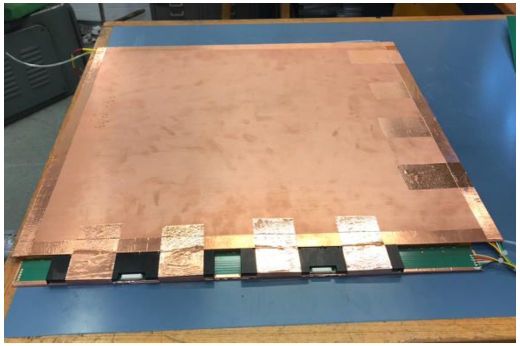
R&D on Low GWP gases: Ongoing efforts

- Strip panels designed at Cambridge University and fabricated within the UK
- The panels were prepared by sandwiching a thin layer of low density material – Forex between a panel and a copper ground plane
- RPC assembled by sandwiching gas gaps between X and Y-strip panels
- Front End boards (8 channel) developed by ATLAS for BIS78 project were used (here covered by 3D printed casing to prevent it from getting damaged)

Strip Panel

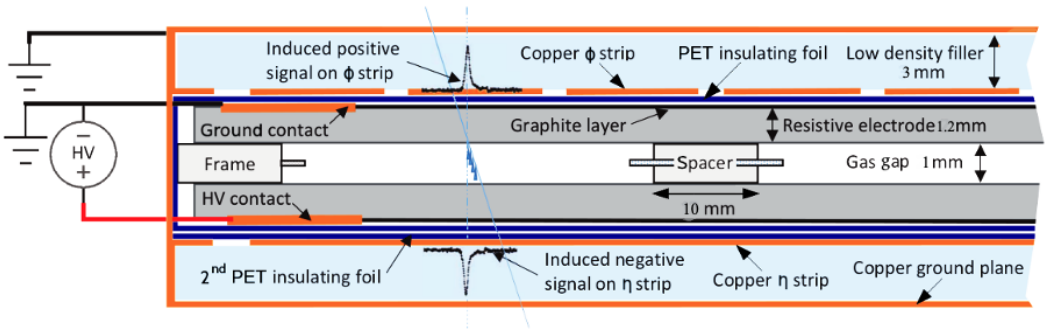


Prototype RPC



FE boards used

	Standard RPC	Current RPC
FEE		
Effective threshold	1mV	0.5mV
Power consumption	30 mW	6 mW
Technology	GaAs	BJT Si + SiGe
Discriminator	Embedded	Separated
TDC embedded	No	No
Detector		
Gap Width	2 mm	1 mm
Operating voltage	9600 V	5800 V
Electrode thickness	1.8 mm	1.2 mm
Time resolution	1 ns	0.4 ns



Modified from arXiv: 2103.01029

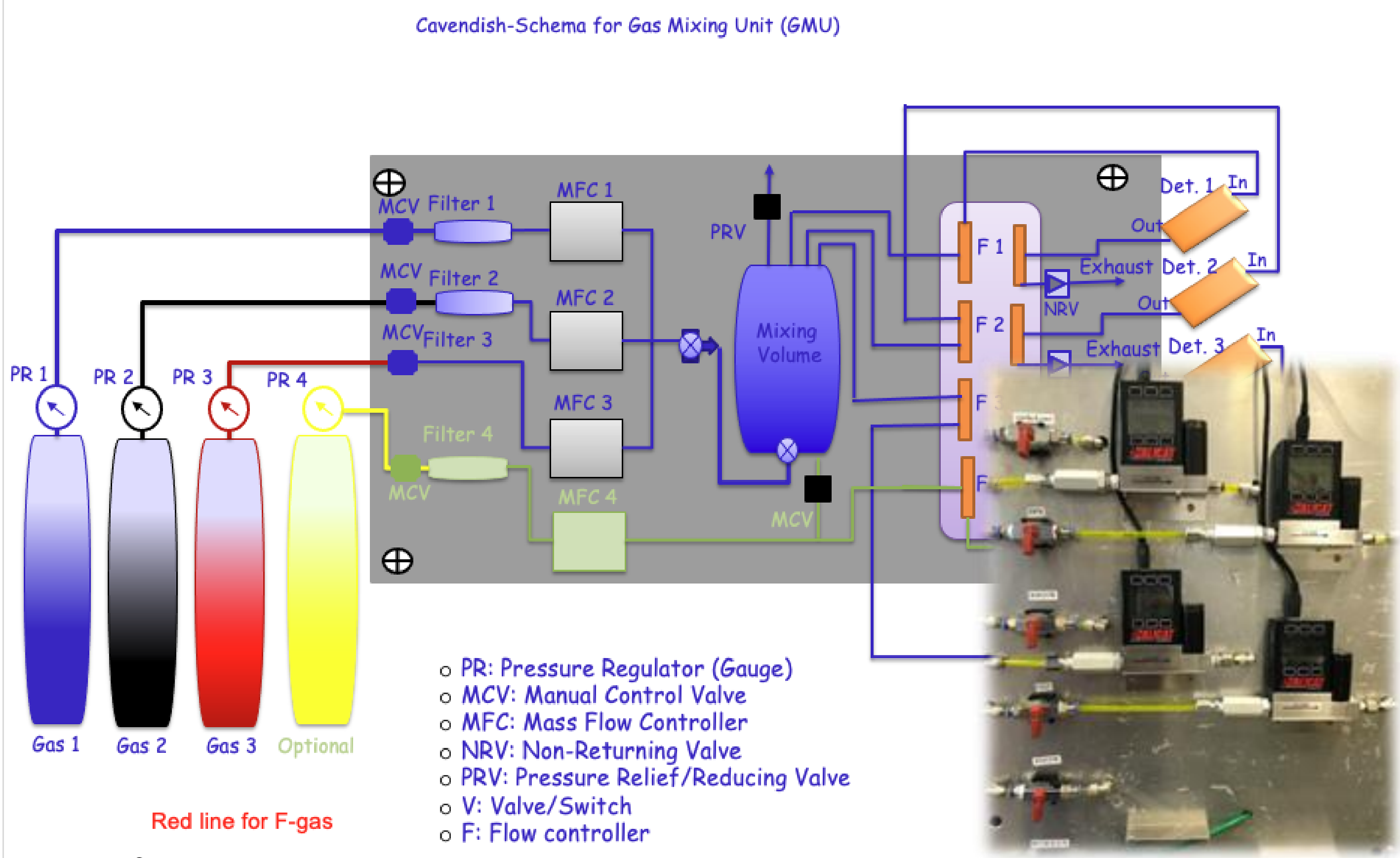
R&D on Low GWP gases: Ongoing efforts

Dedicated Gas mixing System

- Gas mixing system with four MFCs from Alicat allowing to use different gases
- Additionally, equipped with a couple of rotameters

Dedicated DAQ system

- Commercial components such as TDCs from CAEN
- Trigger boards (OR, SOR) designed at Cambridge University (similar to what is used for proANUBIS)



Gas mixing system

Gas MFC panel

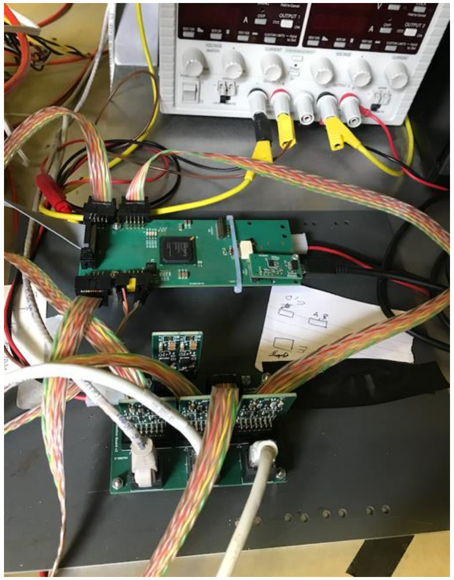
RPC detector and associated DAQ setup

R&D on Low GWP gases: Ongoing efforts

Test setup

- Scintillator/s size 50 cm x 50 cm, each having two Silicon Photomultipliers (SiPM) to read the output signal and to reduce the dark count rate
- Scin. Setup uses an FPGA board to generate the coincidence of trigger pulses/muons

- Measurements performed using one RPC and two scintillators for the calculating the efficiency
- Utilised (later) RPC self trigger mode with proANUBIS like DAQ setup



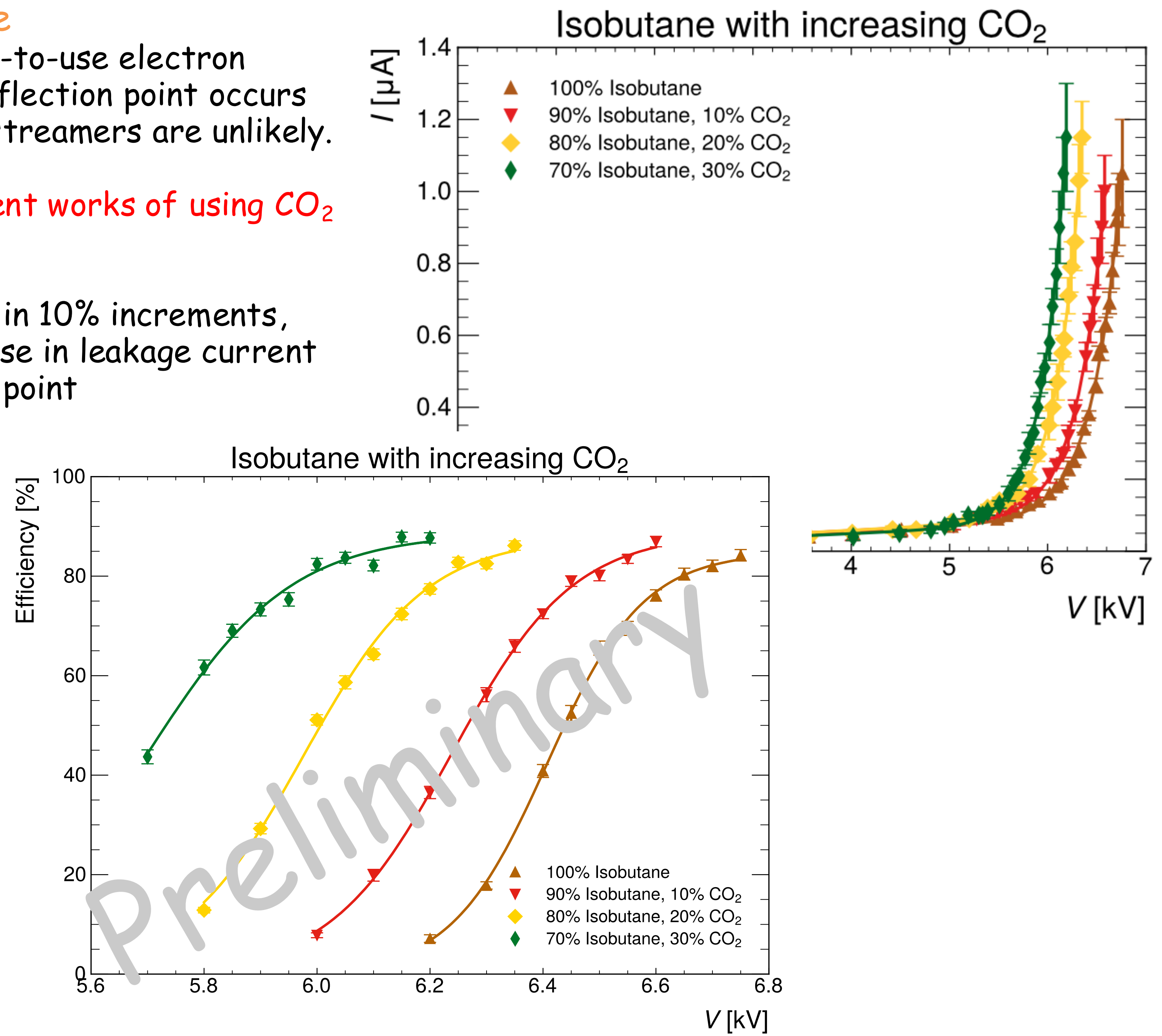
FPGA based trigger logic unit used to generate scintillator coincidence logic

RPC plus Scintillator coincidence setup

R&D on Low GWP gases: Ongoing efforts

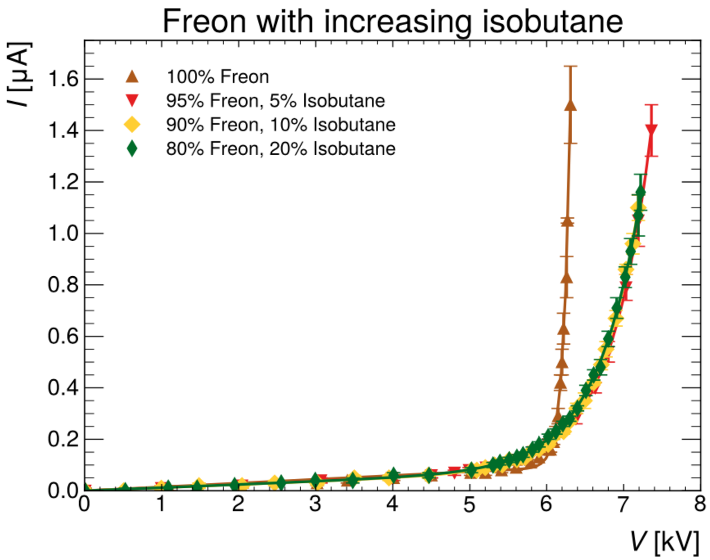
Tests with Isobutane

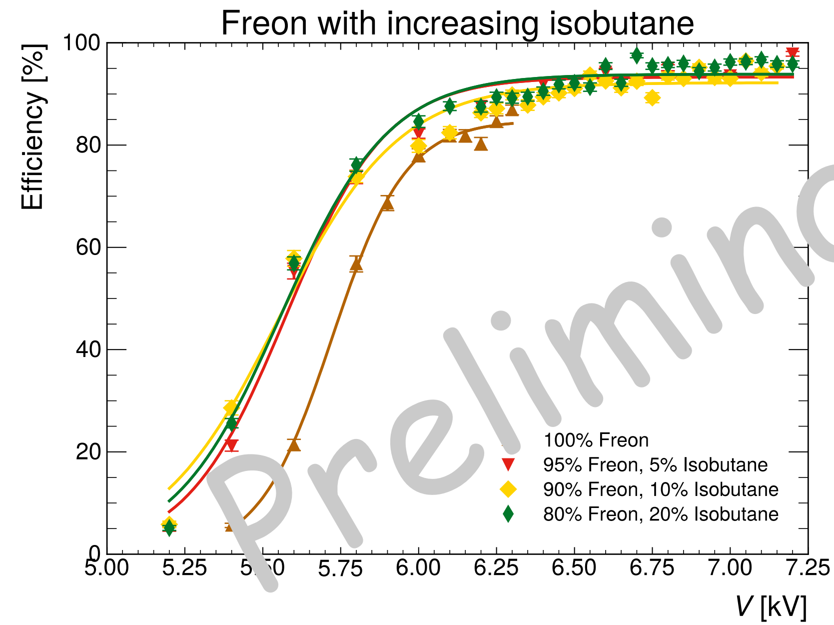
- Isobutane is an easy-to-use electron quencher gas: the inflection point occurs at high voltage and streamers are unlikely.
- Inspired by the recent works of using CO_2 based mixtures
- The addition of CO_2 in 10% increments, resulted in an increase in leakage current above the inflection point

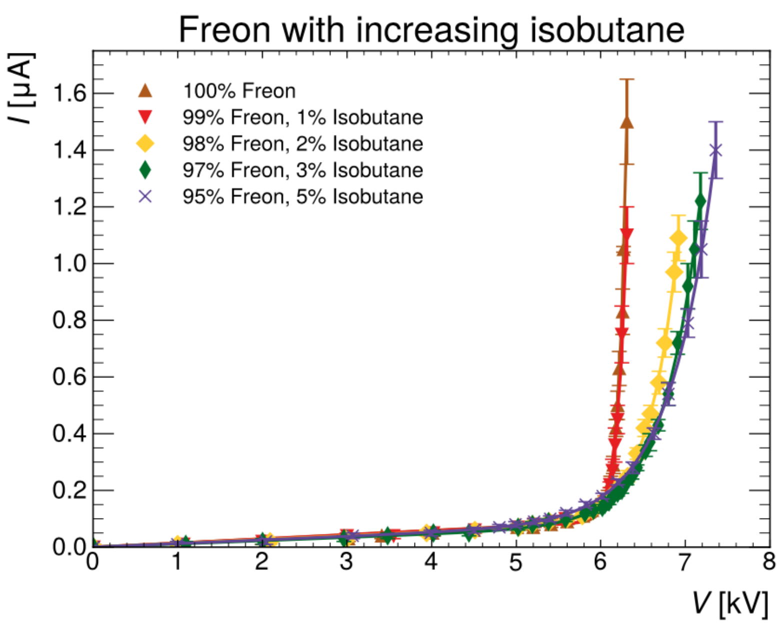


- Estimated by: T. Adolphus
- New Student working and better results after proper alignment, etc

R&D on Low GWP gases: Ongoing efforts







Students: T. Adolphus

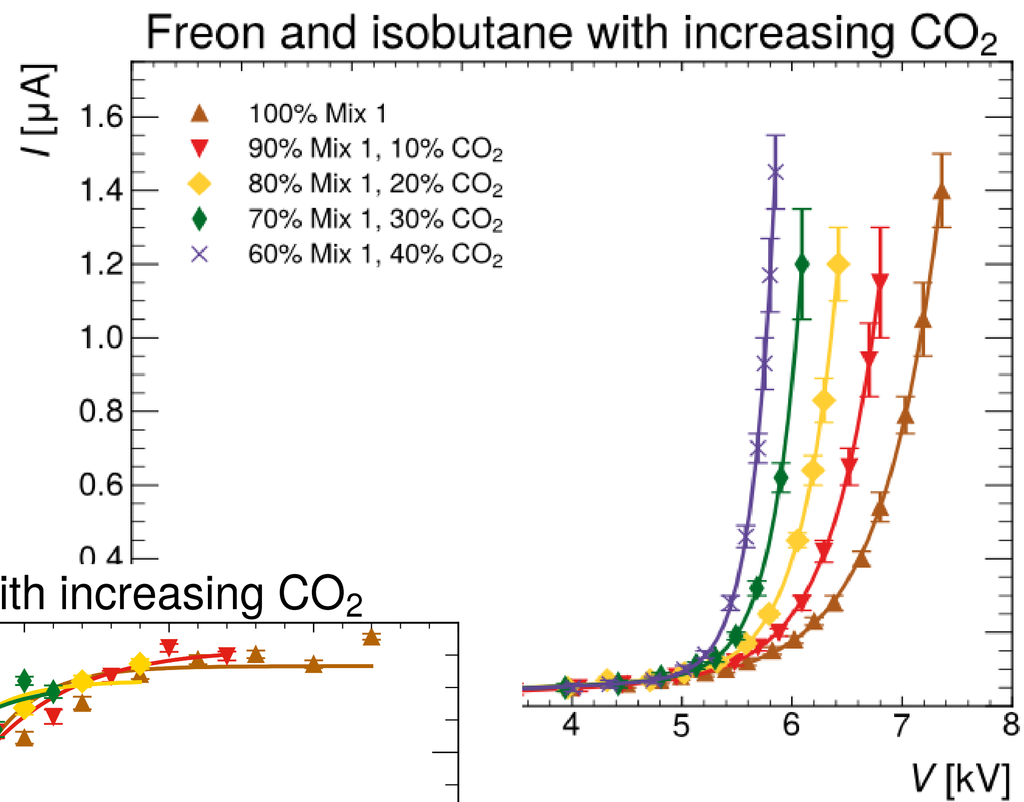
Tests with Freon with additions of Isobutane

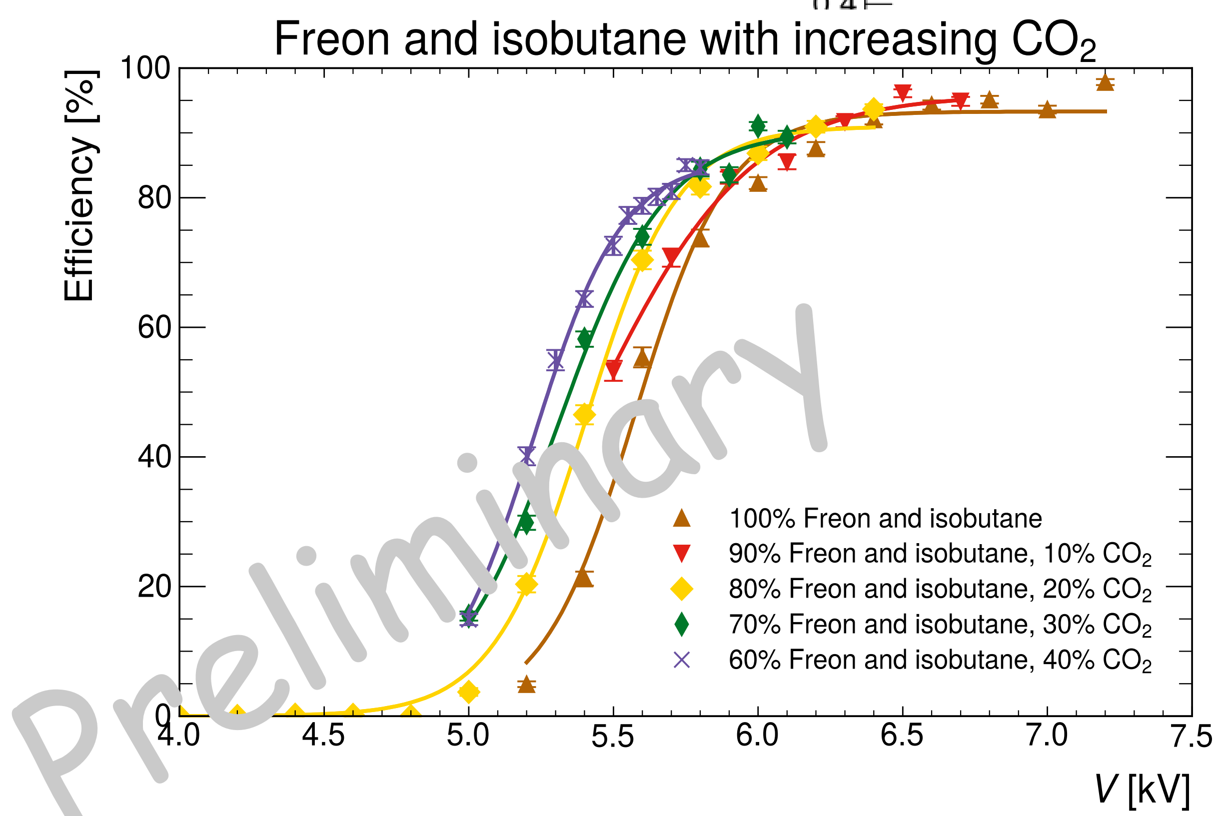
- Adding isobutane in low concentrations showed a 'switch-like' effect: for a 1% isobutane added, the IV curve compared to pure freon was virtually unchanged.
- The IV curves for higher concentrations, 3% above, were separate to this but all overlaid on top of each other
- Increasing the concentration of isobutane above 3% to as high as 20% had no further effect on the shape of the IV
- Isobutane could be reduced from 5% to 3

R&D on Low GWP gases: Ongoing efforts

CO_2 addition to Freon and Isobutane

- Increasing CO_2 concentration causing the critical voltage to lower and the avalanche regime to steepen





Students: T. Adolphus

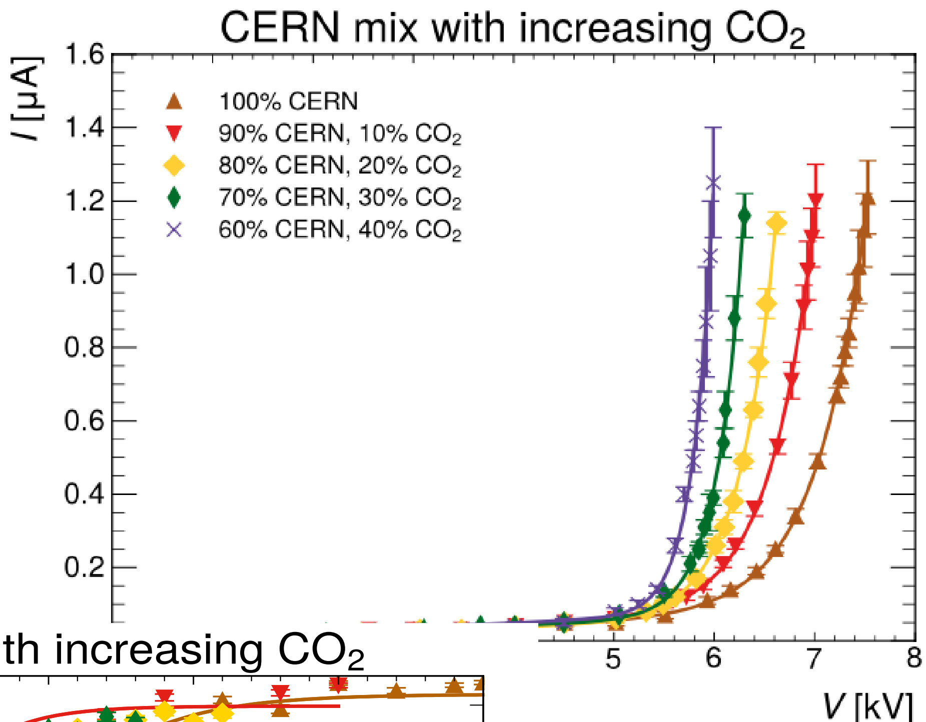
R&D on Low GWP gases: Ongoing efforts

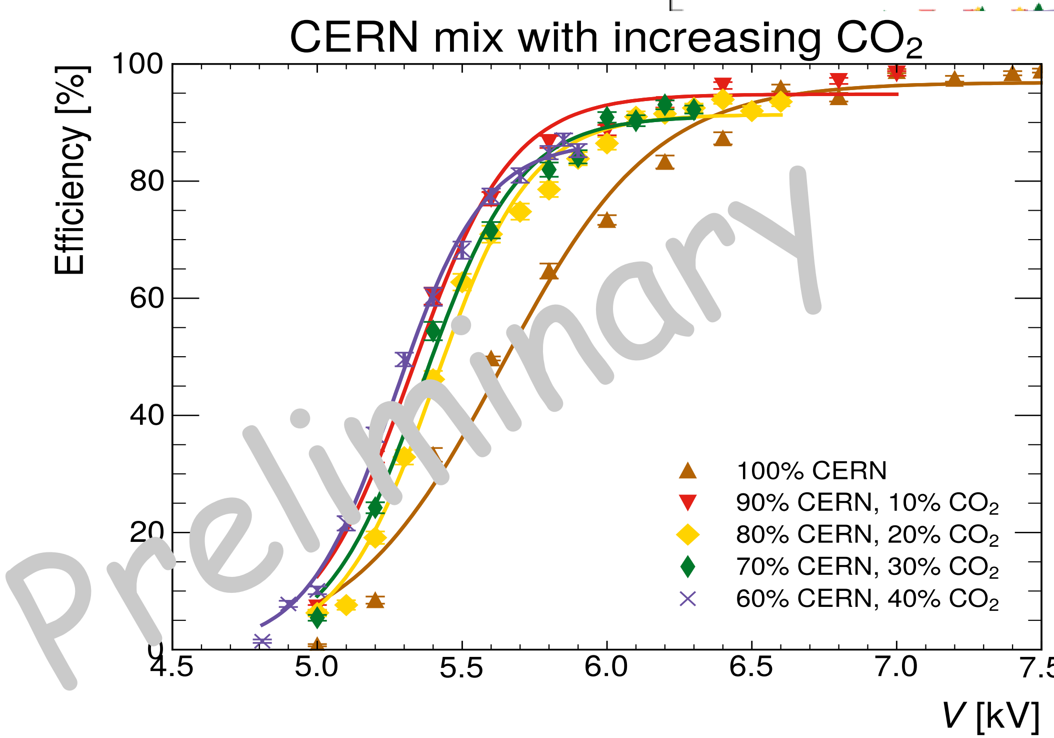
CO_2 addition to CERN mixture

- ATLAS mixtures changed from:
  $C_2H_4F_4$ 94.7%, i-C_4H_{10} 5%, SF_6 0.3%
  to
  $C_2H_4F_4$ 64%, CO_2 30%, i-C_4H_{10}+ 5%, SF_6 1%

- Mixture foresees a **~14%** reduction of the Global Warming Potential (GWP)

- Current tests considered on
  CERN mix: $C_2H_4F_4$ 94.7%, i-C_4H_{10} 5%, SF_6 0.3% with
  $C_2H_4F_4$ 64.7%, CO_2 __%, i-C_4H_{10}+ 5%, SF 0.3% and here it has been called as CERN mix





T. Adolphus

Summary….

- Exploring new gas mixtures and working towards performance evaluation, cluster distribution formation and streamer probabilities, etc
- Preliminary tests presented as a part of the eco-gas R&D and more work to be carried out ….!

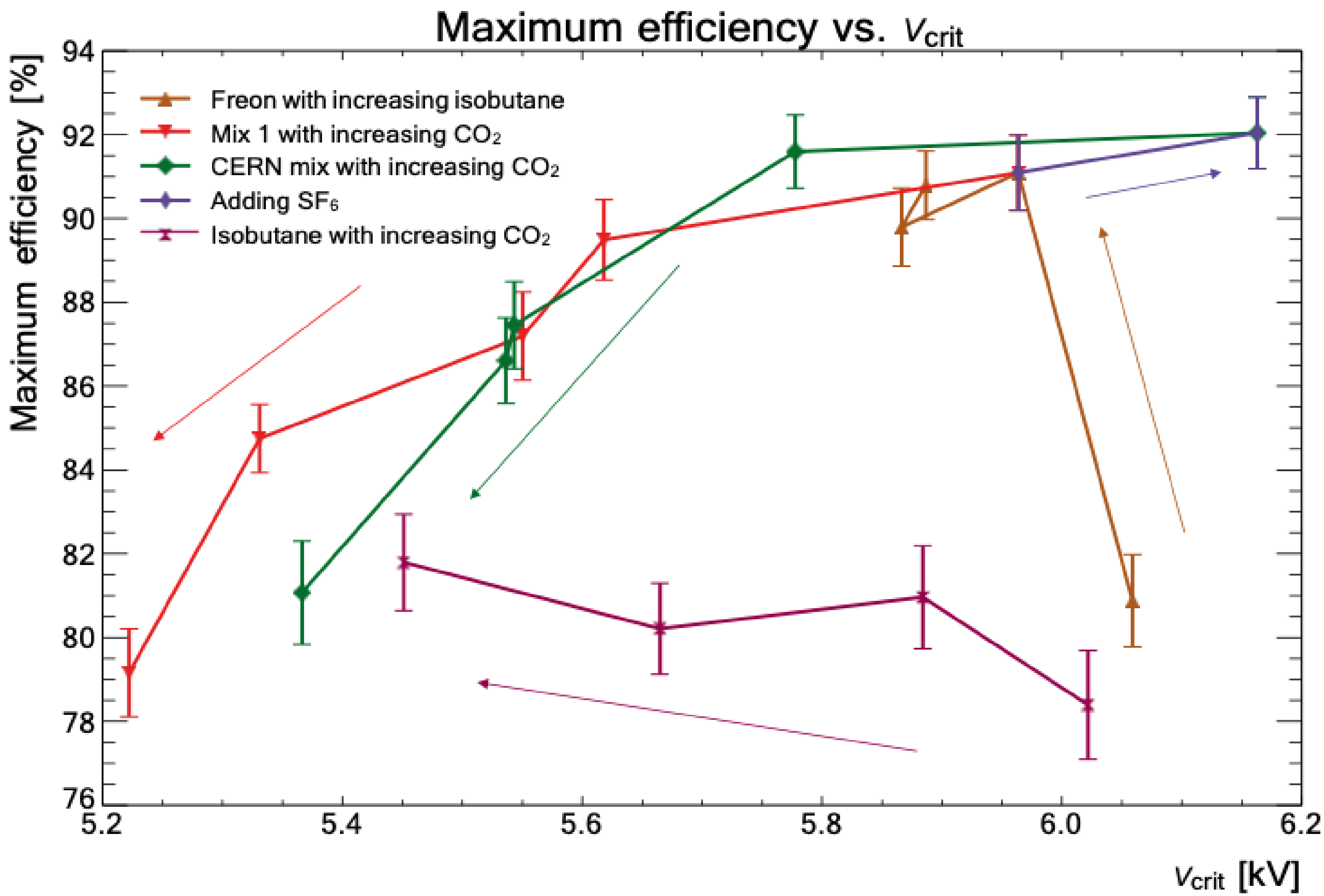
Eco-friendly ANUBIS, ….and the work will continue for it!

Just starting…!!!!

Thank you

Back-Up

Uncorrected, ~3% eff. to be added to account the difference in the scintillator Vs area

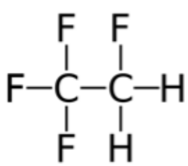


ANUBIS and the need for eco-friendly gases

- Currently, RPC being operated with Freon-based gas mixture
  - > 95% of $C_2H_2F_4$, 4.5% of iC_4H_{10} and 0.3% of SF_6

- **Problem**: These systems are of the "once through" type, in which the exit gas is **vented to the atmosphere** (the gas can be recycled too (but very costly))

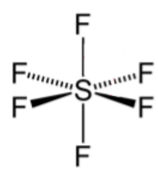
GWP 1430



$C_2H_2F_4$

Containment of charge
Rate capability

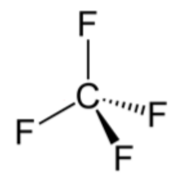
GWP 22800



SF_6

Electronegative: limiting charge development

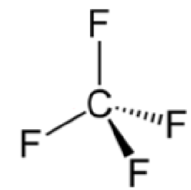
GWP 7390



CF_4

Time resolution
Gas Electron Multiplier (GEM); phased out

GWP 8860



C_4F_{10}

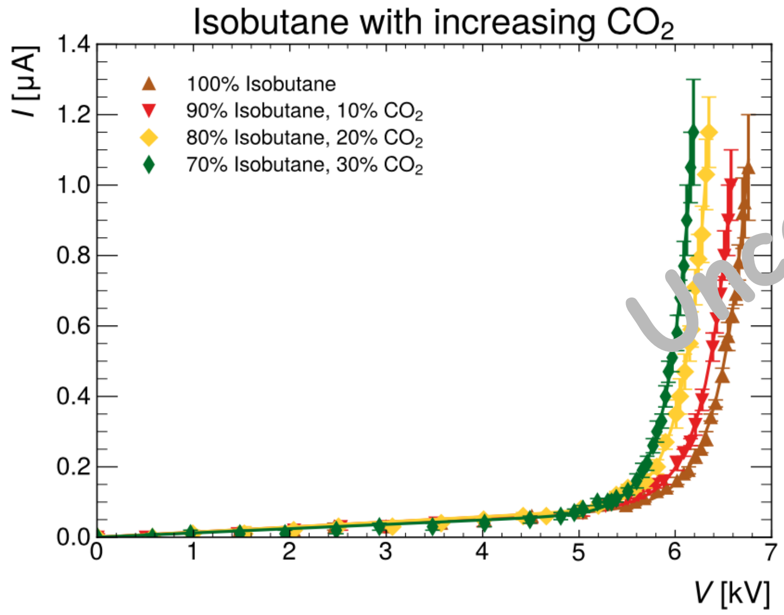
Cherenkov radiator
Ring-imaging Cherenkov detector (RICH)

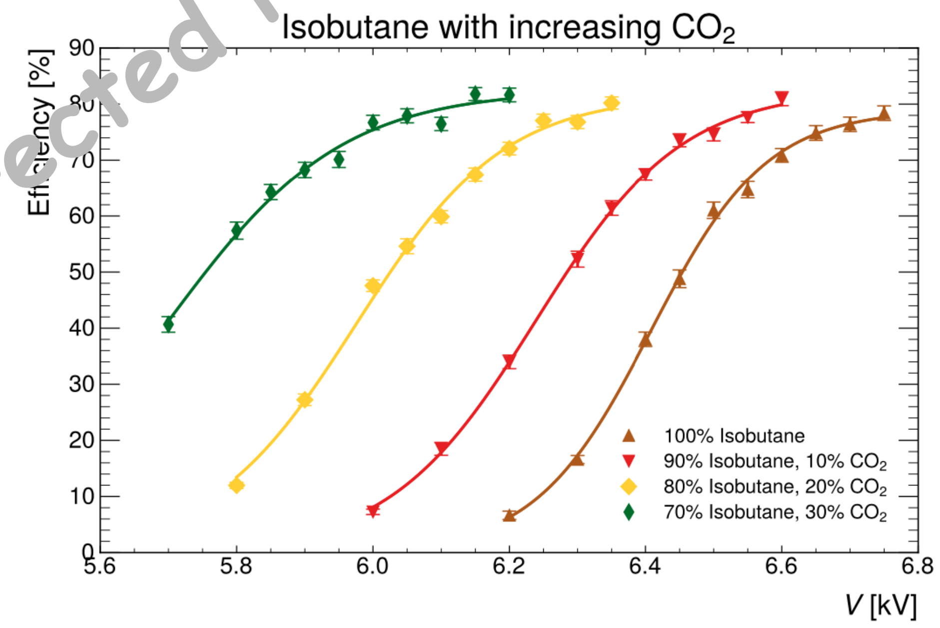
Resistive Plate Chamber (RPC)

Mitigation of aging phenomena
Cathode Strip Chamber (CSC)
Multi Wire Proportional Chamber (MWPC)

- ANUBIS going to use RPCs but looking for alternative and eco-friendly solutions

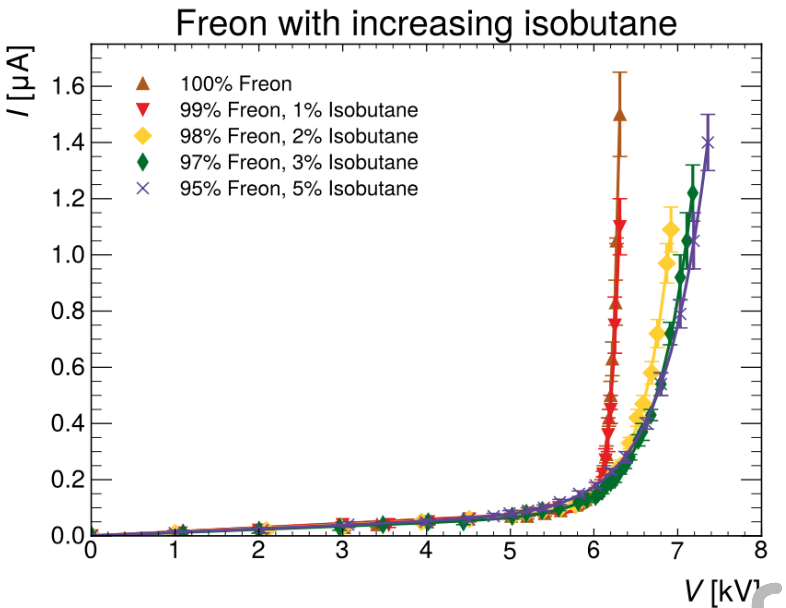
Eco-gas R&D: preliminary tests

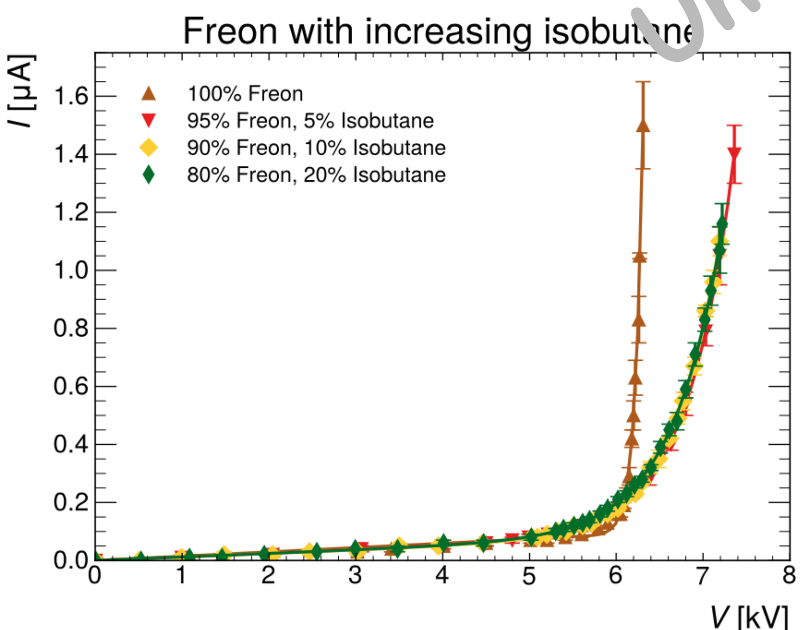


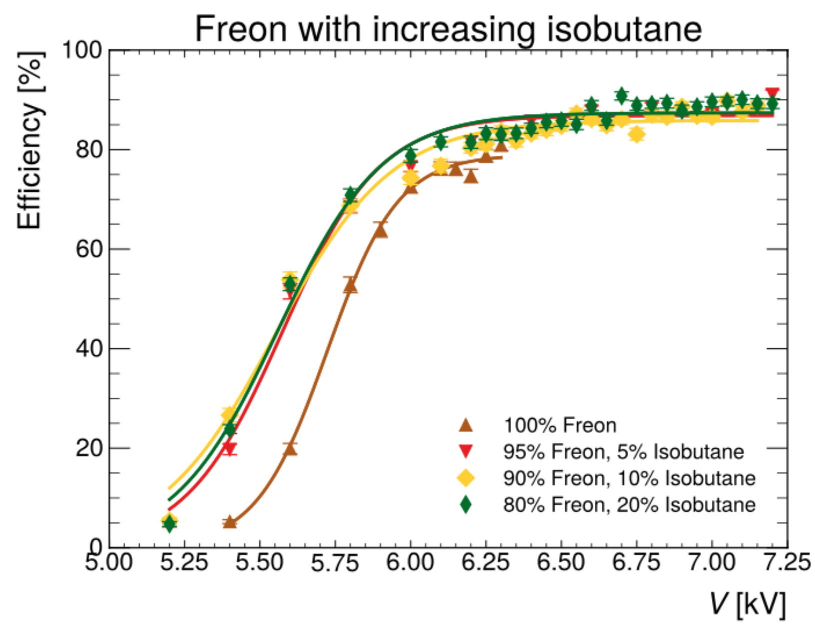


Uncorrected results

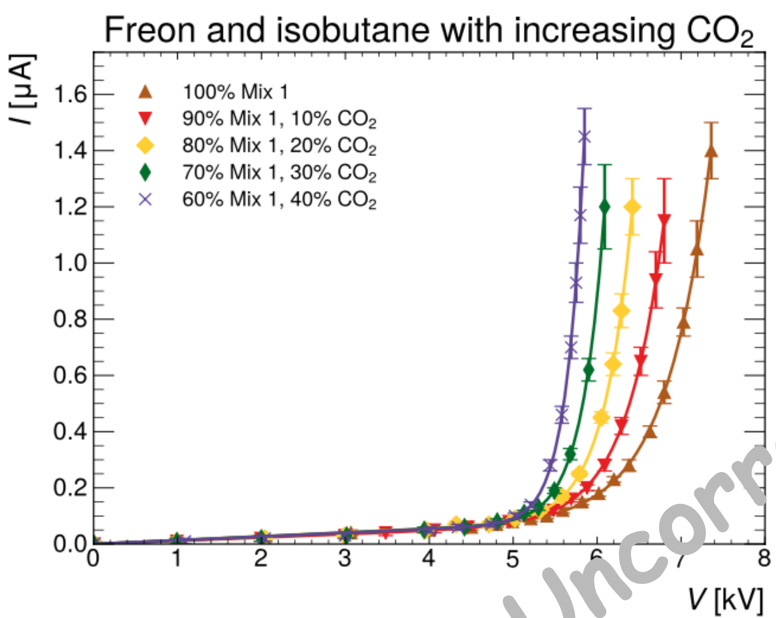
Adding Credits

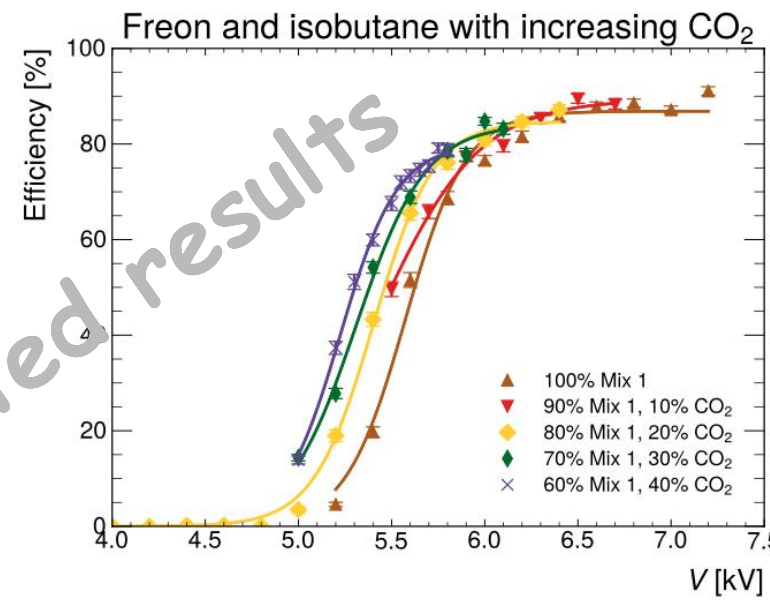




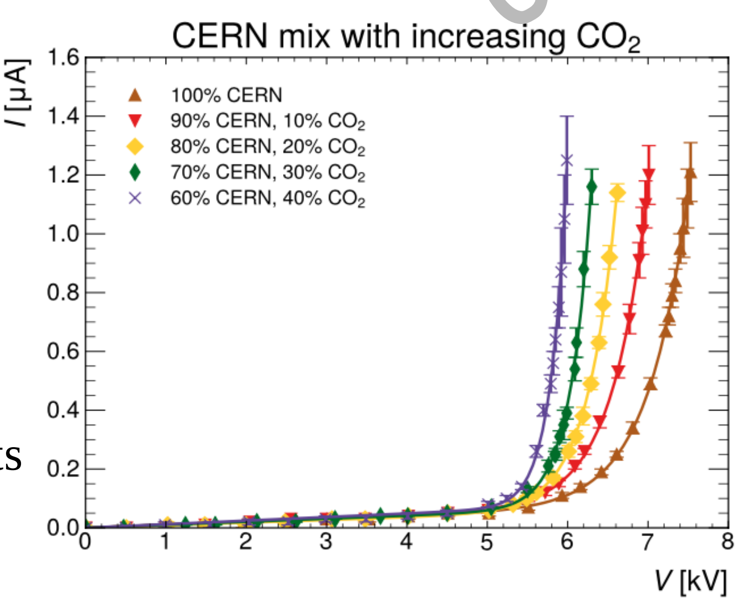


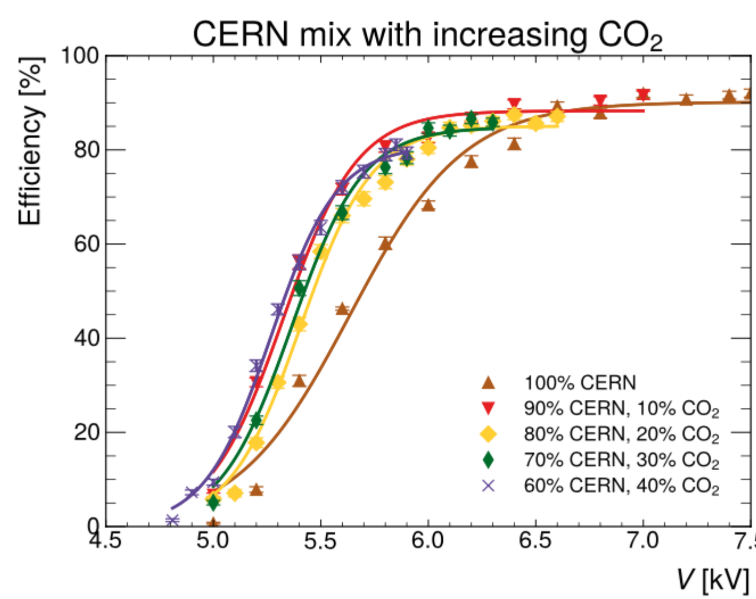
Adding Credits





Adding Credits



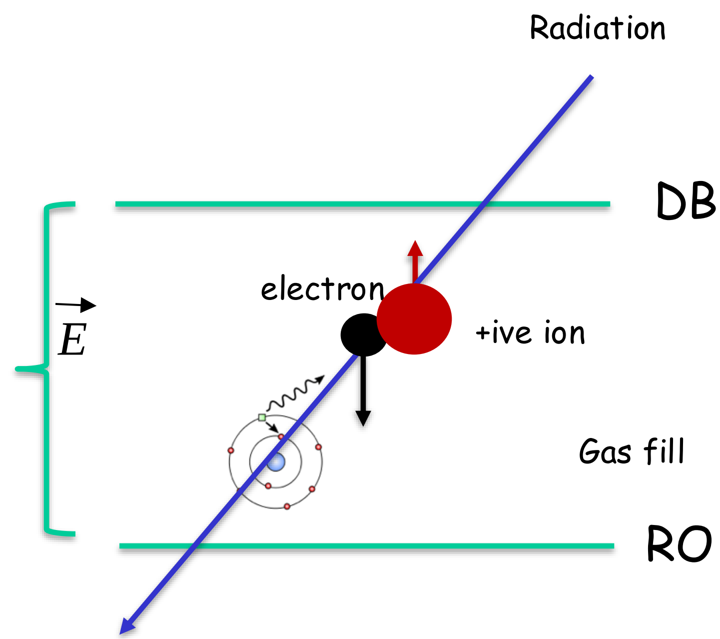


GHGs in HEP experiments: operation of Gaseous detectors

- Main gas for ionization density

- Addition of ***quench*** gas such as methane, CO_2, etc. to suppress the photon-induced effects

- Basic properties of a fill gas can be changed significantly by small concentrations of a second gas, leading to better proportionality, improved fluctuations and energy resolution, etc.



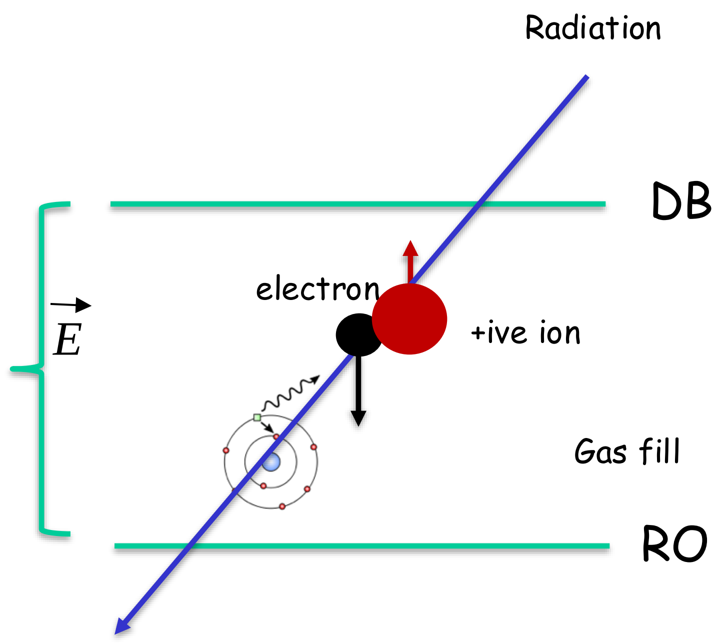
- High-efficiency applications for the detection of gamma-ray photons by absorption within the gas, the heavier inert gases (krypton or xenon) are sometimes substituted

- In applications where the signal is used for coincidence or fast timing purposes, gases with high electron drift velocities (CF_4) are preferred

- **Experiments use different gas mixtures mainly due to their properties necessary for optimal detector performance and long term operation**

GHGs in HEP experiments: operation of Gaseous detectors

- Main gas for ionization density
- Addition of ***quench*** gas such as methane, CO_2, etc. to suppress the photon-induced effects
- Basic properties of a fill gas can be changed significantly by small concentrations of a second gas, leading to better proportionality, improved fluctuations and energy resolution, etc.



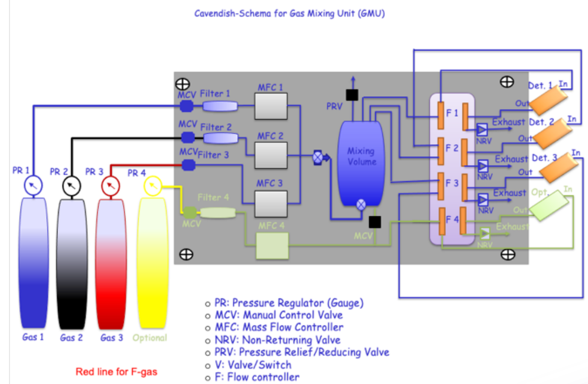
- **Experiments use different gas mixtures mainly due to their properties necessary for optimal detector performance and long term operation**

Ongoing R&D activities at Cavendish: Long term goals

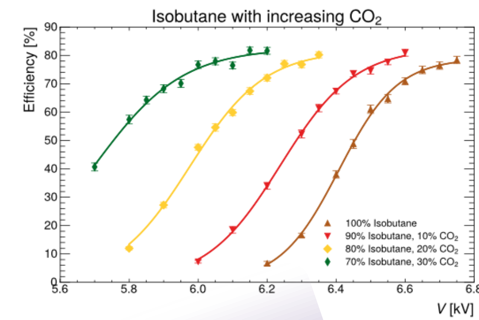
Long term goals: Search for eco-friendly gas mixtures for HEP experiments in general and for ANUBIS in particular

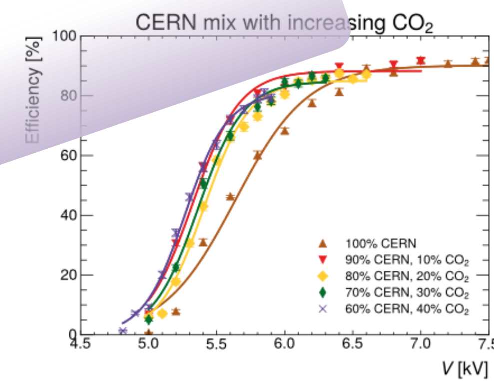
RPC detector and associated DAQ setup

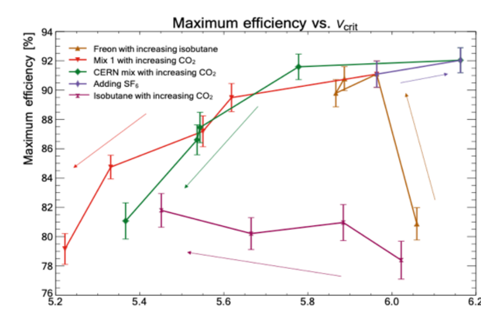
Gas mixing system



Some studies by our project students



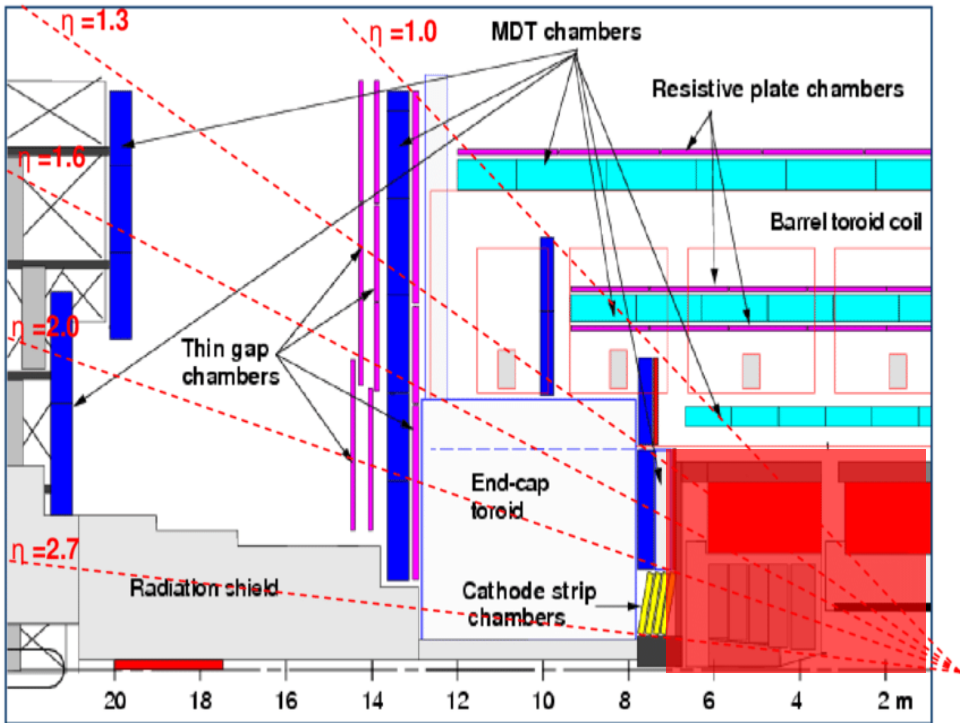




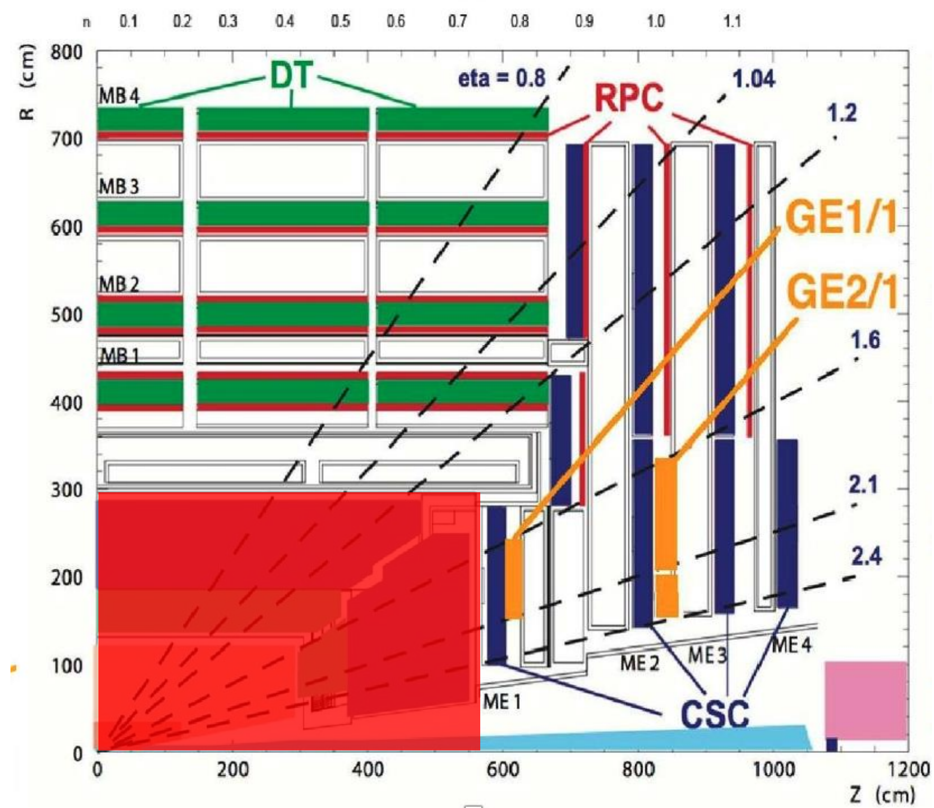
Just a beginning…!!!!

Thank you!

An example: Gaseous detectors in ATLAS and CMS



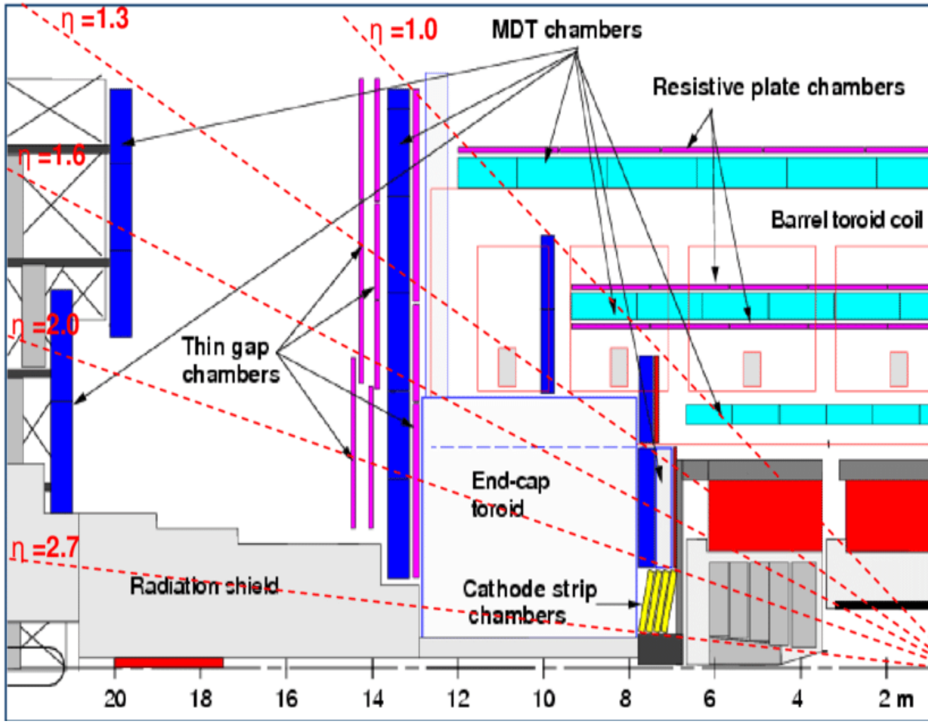
ATLAS



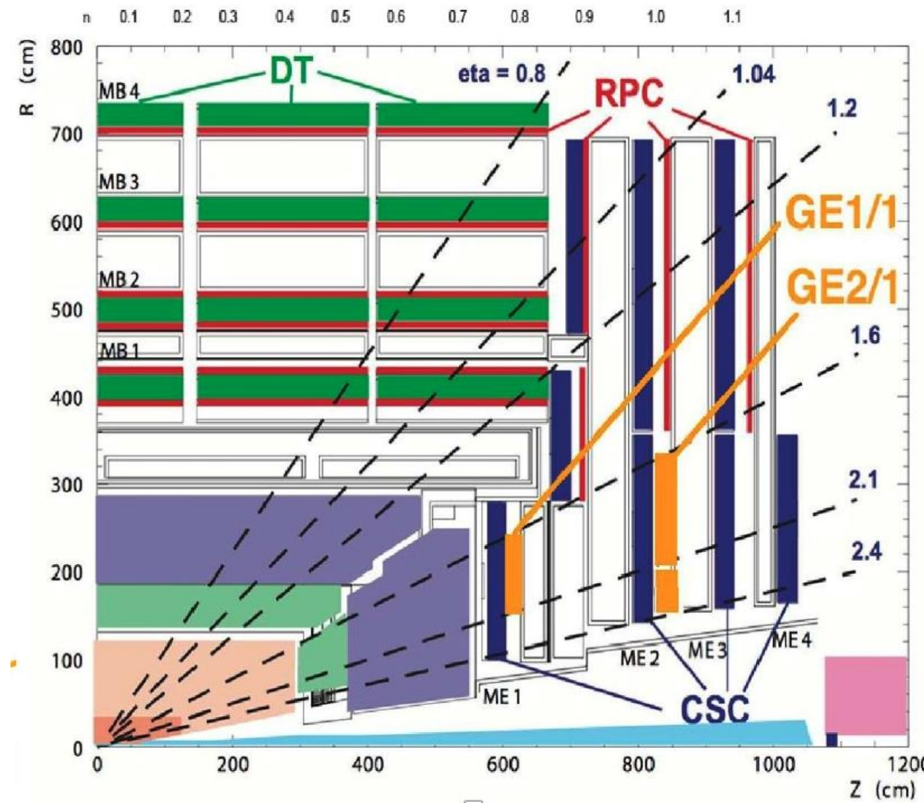
CMS

A schematic side-view of the ATLAS and CMS Muon Spectrometer systems, showing the different chamber technologies. A cross-section through a quarter of the detector in the z-y plane is shown

Use of GHGs in HEP: Gaseous detectors in ATLAS and CMS



ATLAS



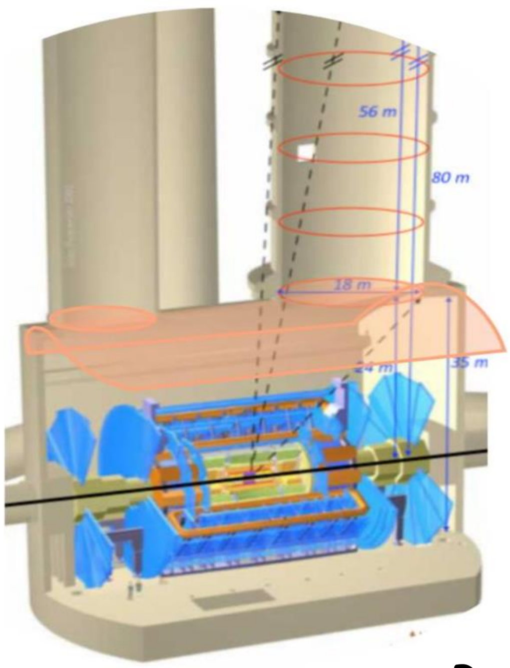
CMS

A schematic side-view of the ATLAS and CMS Muon Spectrometer systems, showing the different chamber technologies. A cross-section through a quarter of the detector in the z-y plane is shown

ANUBIS and its interest

ANUBIS – AN Underground Belayed In-Shaft search experiment

- Proposal to search for LLPs at LHC CERN
  - Instrument the ceiling of the ATLAS Cavern at Point-1
  - Ceiling approximately 20 m away from the ATLAS IP
  - Include stations in the two service shafts (PX14, PX16)



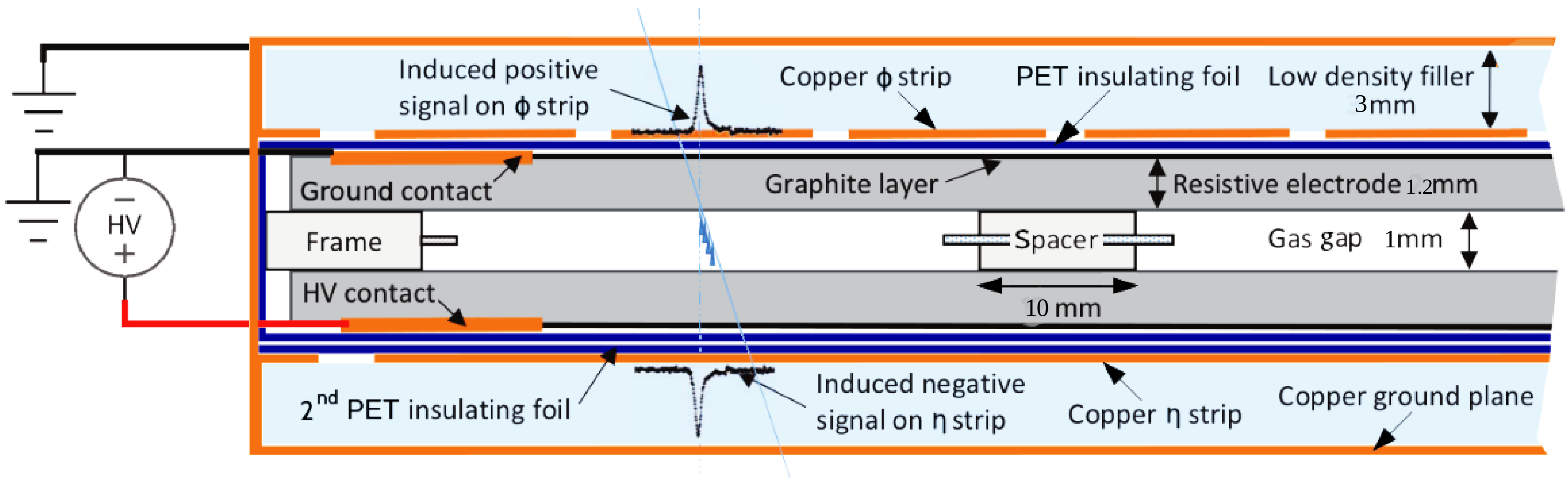
Use of RPCs →

RPC's @ CERN BB5

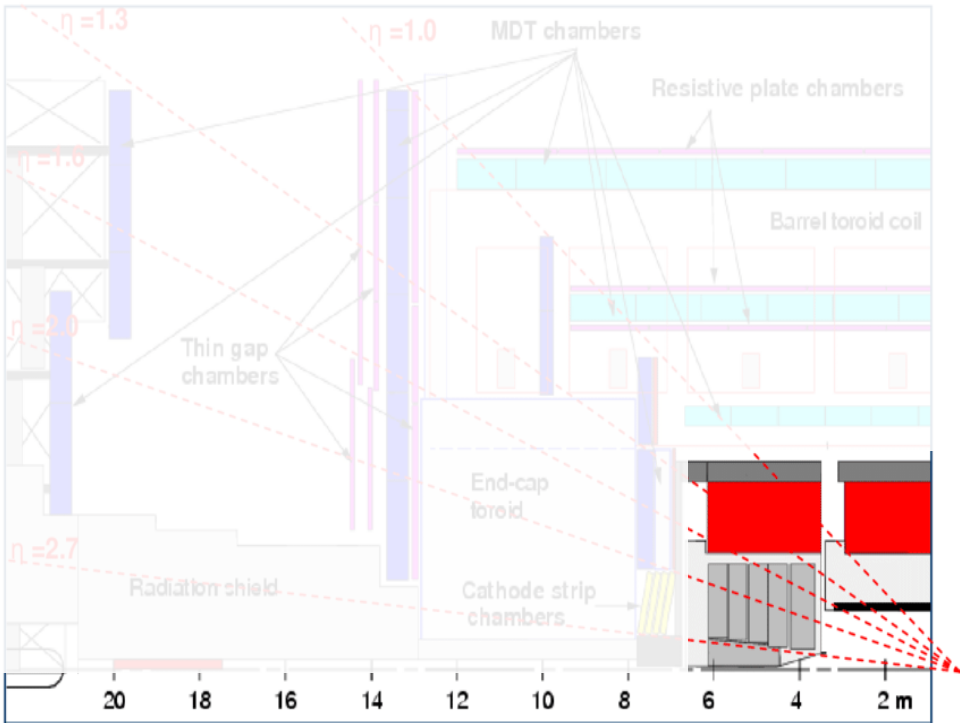
Proposal arXiv:1909.13022

Updates: https://twiki.cern.ch/twiki/bin/view/ANUBIS

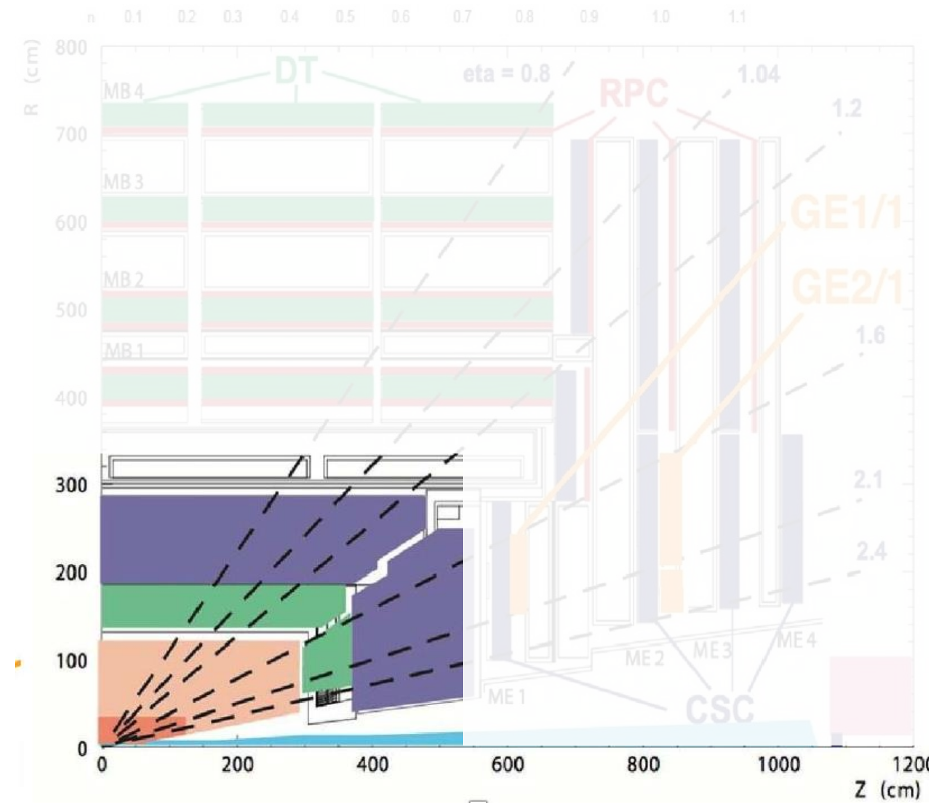
Recent work: DOI: 10.22323/1.449.0051


Induced positive
signal on ϕ strip
Copper ϕ strip
PET insulating foil
Low density filler
3mm
HV
Ground contact
Graphite layer
Resistive electrode 1.2mm
Frame
Spacer
Gas gap 1mm
HV contact
10 mm
2nd PET insulating foil
Induced negative
signal on η strip
Copper η strip
Copper ground plane

Use of GHGs in HEP: Gaseous detectors in ATLAS and CMS



ATLAS



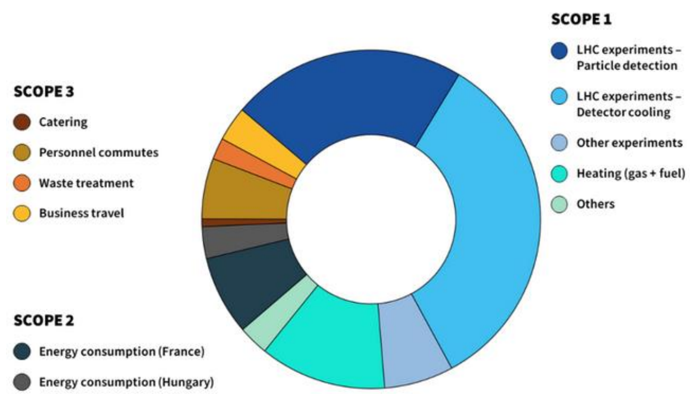
CMS

A schematic side-view of the ATLAS and CMS Muon Spectrometer systems, showing the different chamber technologies. A cross-section through a quarter of the detector in the z-y plane is shown

GHG emissions at CERN: how much?

Greenhouse gas emissions at CERN arise from the operation of the Laboratory's research facilities. The majority of emissions come from CERN's core experiments and more than 78% are fluorinated gases

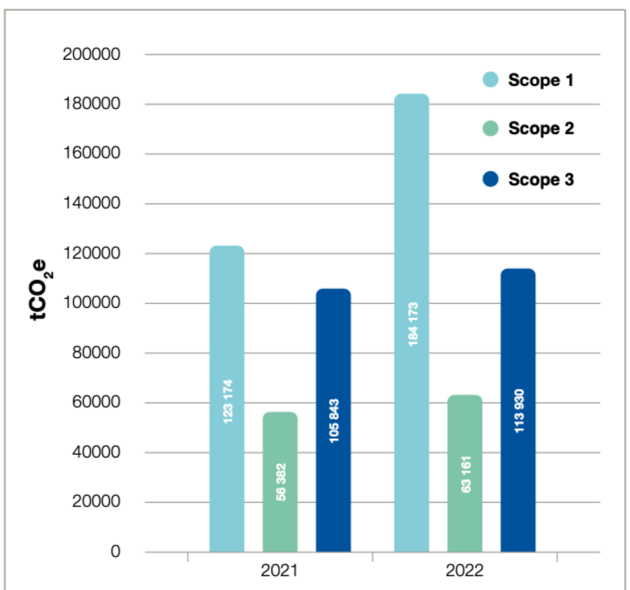
- **Scope 1** refers to the direct emissions resulting from an organisation's facilities and vehicles
- **Scope 2** refers to indirect emissions related to the generation of electricity, steam, heating or cooling purchased
- for an organisation's own use
- **Scope 3** refers to all other indirect emissions occurring upstream and downstream of an organisation's activities, such as business travel, personnel commutes, catering and procurement



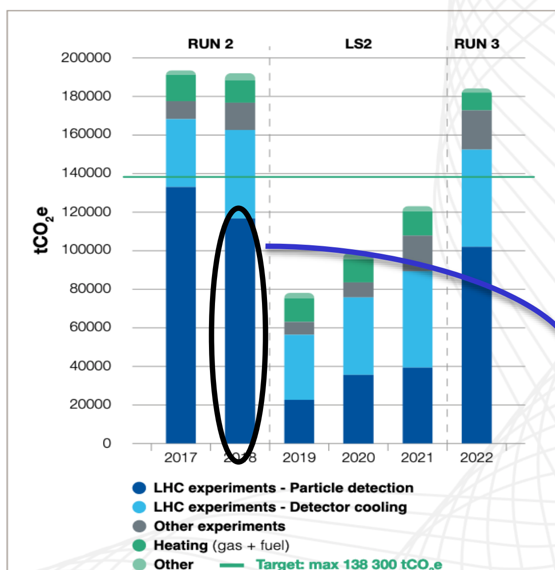
- ~90% of emissions related to large LHC experiments
- Most emissions from particle detection

GROUP	GASES	tCO_2e 2021	tCO_2e 2022
Perfluorocarbons (PFCs)	CF_4, C_2F_6, C_3F_8, C_4F_{10}, C_6F_{14}	55 921	68 989
Hydrochlorofluorocarbons (HFCs)	HFC-23 (CHF_3) HFC-32 (CH_2F_2) HFC-134a ($C_2H_2F_4$) HFC-404a HFC-407c HFC-410a HFC-507	36 557	86 211
Other F-gases	SF_6, NF_3	16 838	18 355
Hydrofluoroolefins (HFO)/HFCs	R-449 R1234ze NOVEC 649	86	199
	CO_2	13 771	10 419
Total Scope 1		123 174	184 173

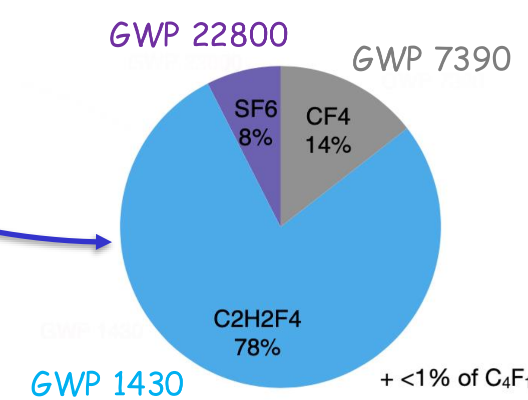
The tCO_2e values calculated based on the real consumption of the different gases, weighted by their GWP



CERN'S TOTAL SCOPE 1, 2 AND 3 EMISSIONS 2021–2022

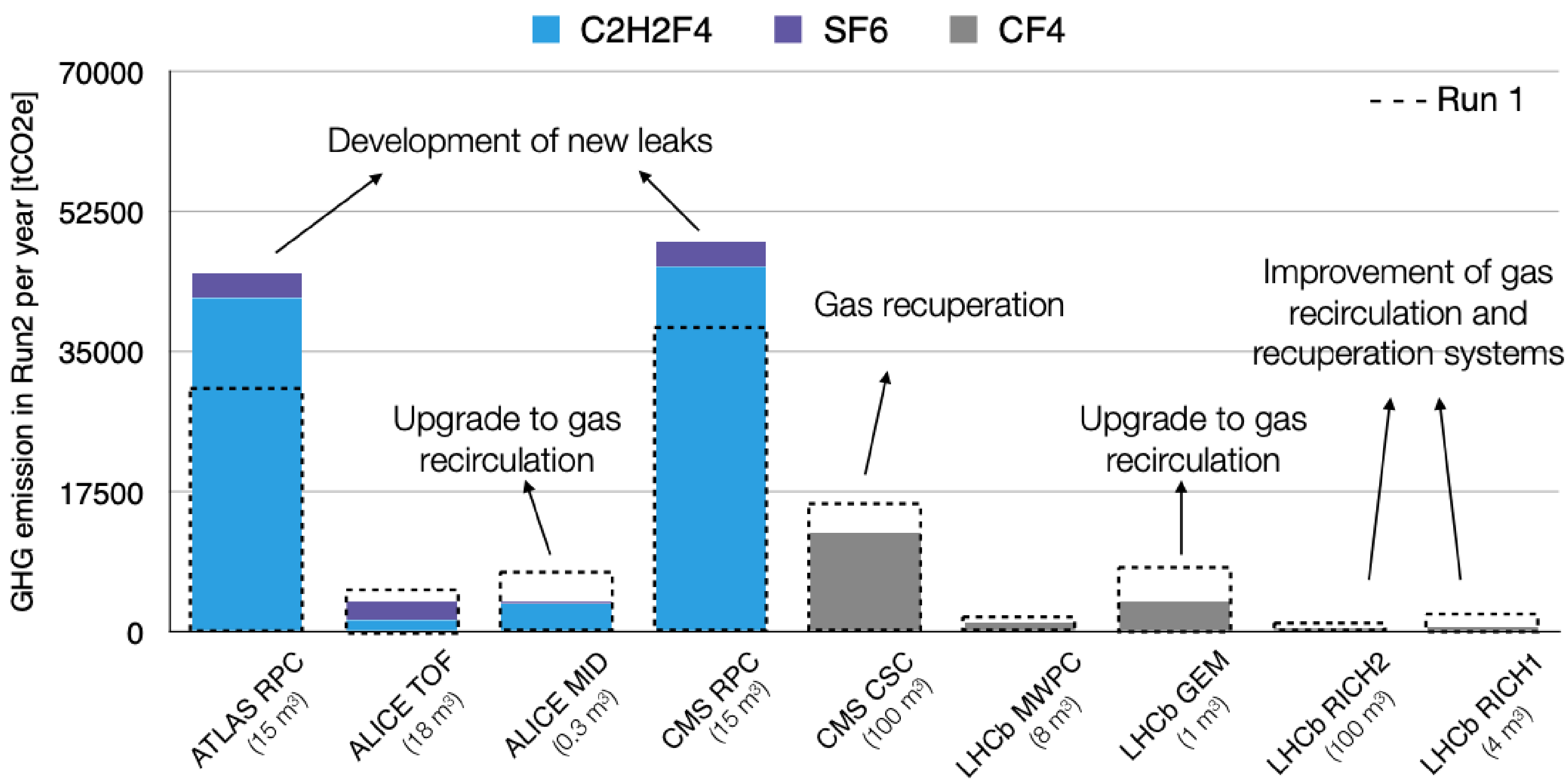


CERN SCOPE 1 EMISSIONS FOR 2017–2022 BY CATEGORY
"Other" includes air conditioning, electrical insulation, emergency generators and the fuel consumption of the CERN vehicle fleet.



[CERN Environment Report 2021-2022]

GHGs for particle detection at LHC: Run 1 Vs Run 2



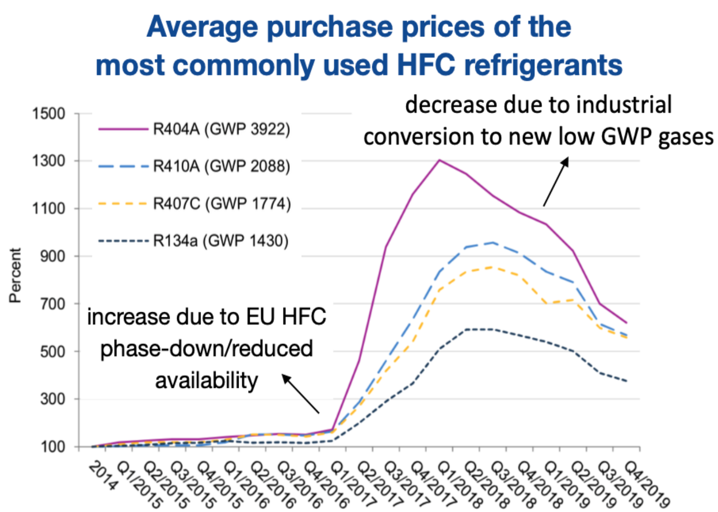
- -40% GHG emissions from Run 1 to Run 2 excluding ATLAS and CMS RPC systems
- ATLAS and CMS RPC systems: +35% increase of GHG emissions due to development of new leaks
- All other detector systems: decrease of GHG emissions from -20% to -80% from Run 1 to Run 2
- Thanks to the different gas system upgrades

The EU HFC Phase down policy

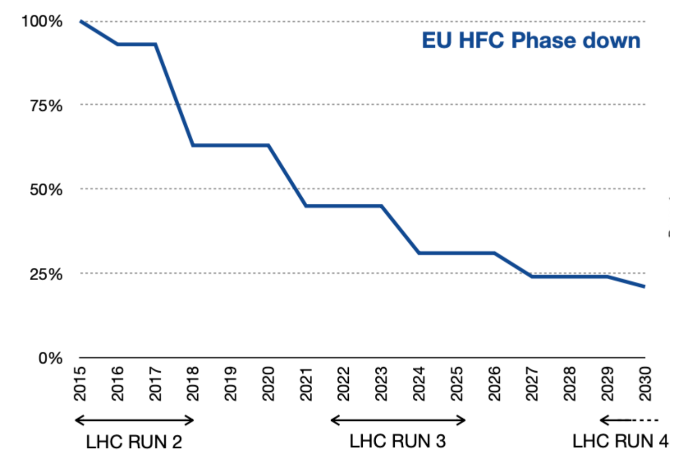
European Union "F-gas regulation"

- **Limiting the total amount** of the most important F-gases that can be sold in the EU from 2015 onwards and phasing them down in steps to one-fifth of 2014 sales in 2030
- **Banning the use** of F-gases in many new types of equipment where less harmful alternatives are widely available
- **Preventing emissions** of F-gases from existing equipment by requiring checks, proper servicing and recovery of the gases at the end of the equipment's life

Prices are increasing in EU and availability in the future is not known



Reduction of the use of F-gases is fundamental for future particle detector applications



- The search for new environmentally friendly gas mixtures is necessary to reduce GHG emissions and costs as well as to optimize detector/s performance

European Environment Agency, Fluorinated greenhouse gases 2019 report, Oko Recherche report, March 2020 J. Kleinschmidt et al.

European Regulations

- Since 2015 onwards, the European Union defined a set of regulations* aiming at reducing the GHG emissions from **fluorinated gases** with the main points summarized as:

  - Restrict the placing on the market by reducing products availability of fluorinated GHGs
  - Ban the use of GHGs where eco-friendly alternatives are already available
  - Require regular and certified check controls on leaks for existing equipment
  - Require a recovery of the gases at the end of the equipment life

*Official Journal of the EU (L 150/95), vol. 57, 20 May 2014, ISSN 1977-0677.

Studies at CERN (ATLAS muon): short term goals

- Measured the efficiency for different mixtures, the working point anticipation of 200V for the CO_2 mixtures wrt. Standard gas mixture
- For 30% and 40% CO_2 gas mixtures, observed that the current is increasing by ~20% wrt. Standard gas mixtures

ATLAS RPC system switched to Standard + 30% CO_2 mixture in August, 2023