



The ecological transition of the EEE experiment

The EEE experiment



11 deg Latitude

3 Multigap Resistive Plate Chambers (MRPCs) to detect and track cosmic muons with the aim to study Extensive Atmospheric Showers.

55 EEE Stations in school buildings
5 at INFN sections
2 at CERN

62 EEE telescopes

✓ **Low trigger rate:**

on the average ≈ 30 Hz per telescope

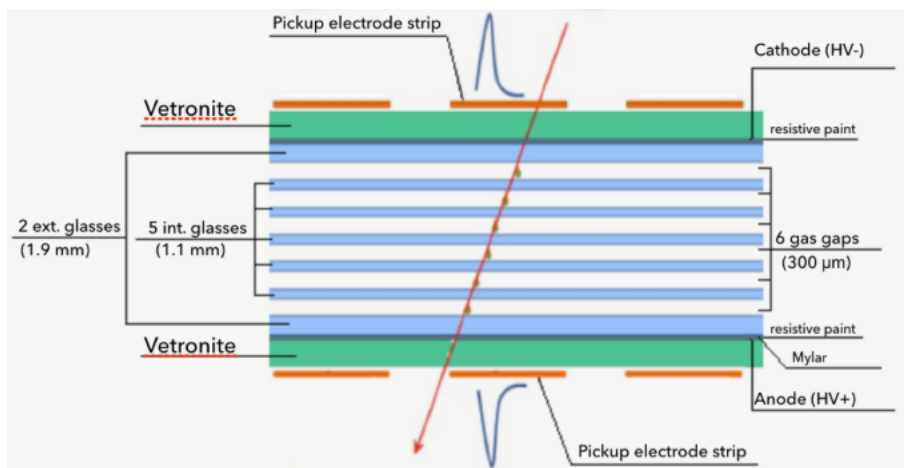
✓ **Large size, low cost MRPCs:**

1.58×0.82 m², readout copper strips;

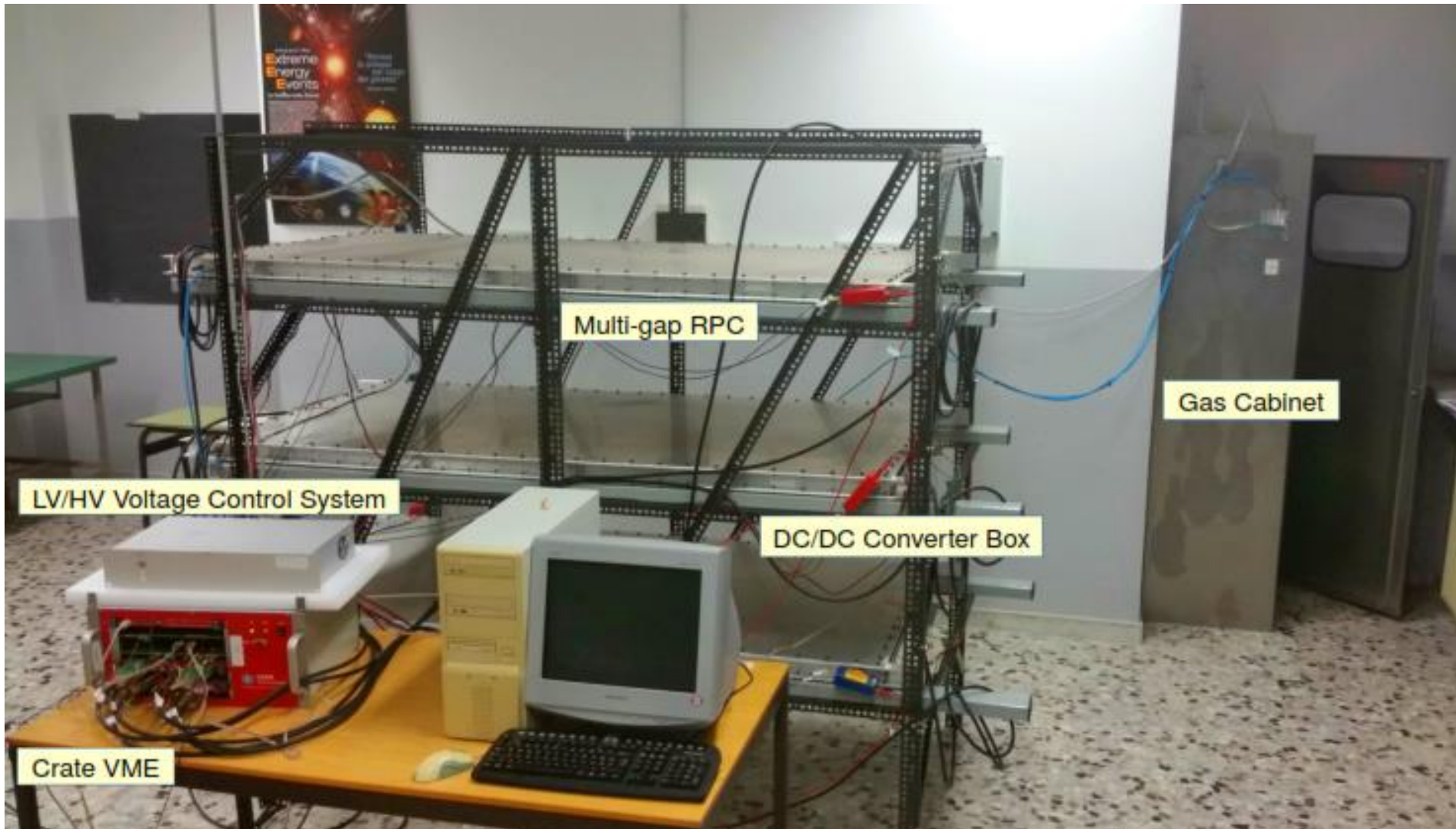
✓ **6 gas gaps: 300 μ m, spaced by fishing line**

From 2018: 55 new Chambers \rightarrow 250 μ m gaps:

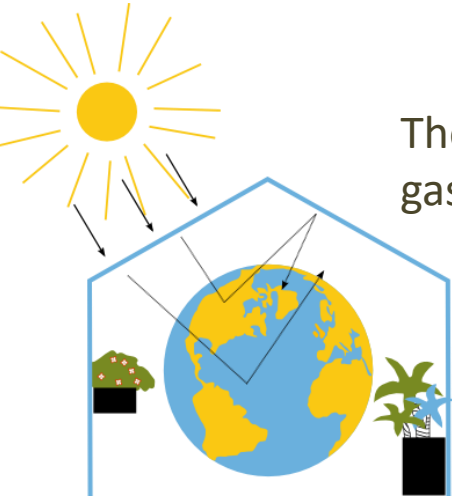
✓ **A mixture of C₂H₂F₄ (R134a) and SF₆ 98/2** flowed in daisy chain at atmospheric pressure, with a flow of ≈ 2 -3 l/h



The EEE telescopes



The GAS issue in EEE



The Global Warming Potential measures the « **greenhouse effect** » of a gas normalized to CO₂.

Mixture used in the EEE MRPCs :

R134a /SF₆ 98/2 → GWP ≈1880

62 telescopes with a flow of 2 l/h → ≈ 10⁶ l/year



**EEE strategies to reduce the greenhouse gas emissions
from the EEE MRPC array**

The EEE Collaboration has started 3 important actions:

- Gas flow reduction
- Gas recirculation system
- Eco-friendly gas mixtures

EEE gas flow reduction campaign

The flow reduction campaign started in September 2019 → stopped in March 2020

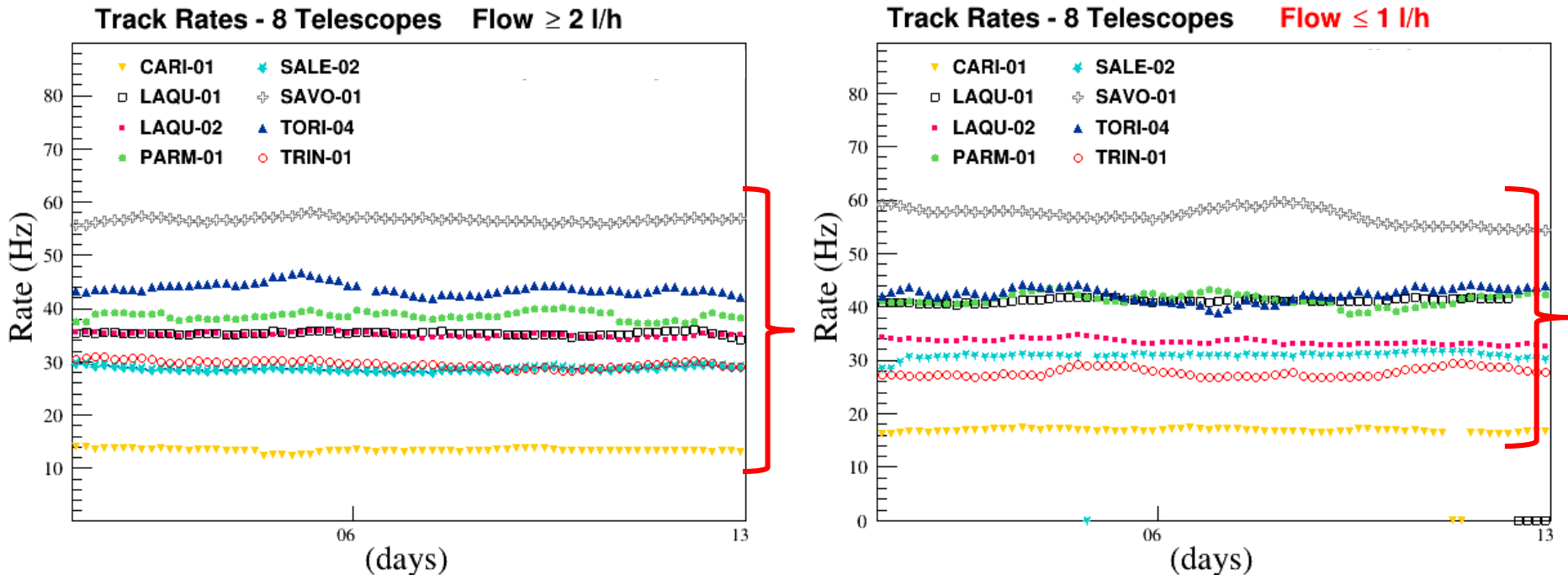
from 2-3 l/h → 1 l/h

When about 60% of the EEE telescopes was able to operate with a ≈ 1 l/h gas flow



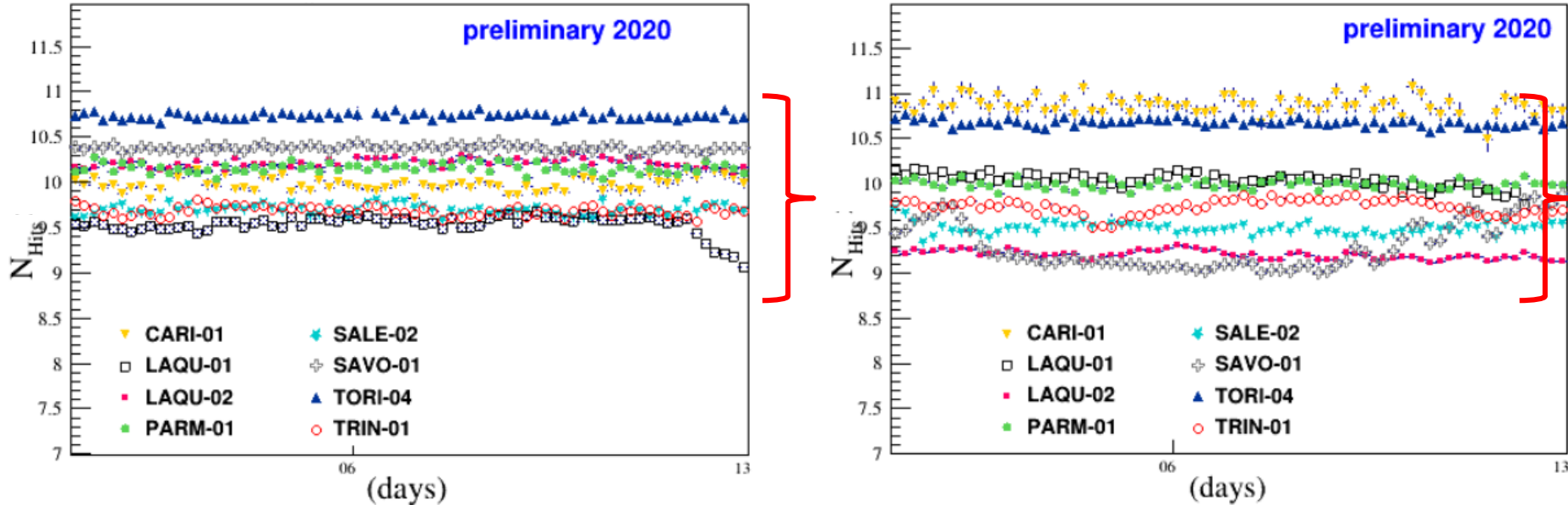
The MRPCs for tracking cosmic muons can operate at a lower flow, and their performance is not affected by flow reduction

Muon track rate: comparison before/after



Gas flow reduction campaign

Strip multiplicity (whole telescope): comparison before/after



Remarkable stability considering the different conditions in: **Temperature, external pressure, efficiency fluctuations** in a time lapse of **a year between the two data samples**.

<i>Average value</i>	<i>Flow ≥ 2 l/h</i>	<i>Flow ~ 1 l/h</i>
Time Resolution σ_t	237 ± 67 ps	238 ± 40 ps
Longitudinal Res. σ_x	1.48 ± 0.04 cm	1.4 ± 0.1 cm
Trasversal Res. σ_y	0.92 ± 0.01 cm	0.93 ± 0.05 cm

Spatial and Time resolutions not affected by gas flow reduction.

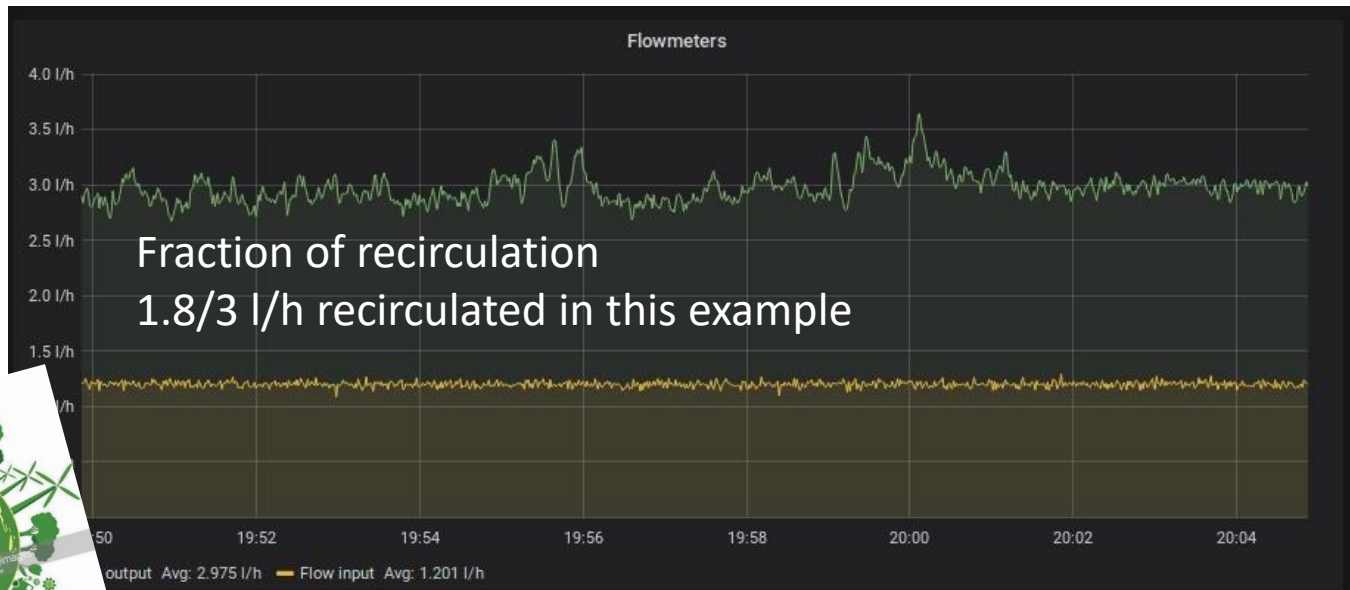
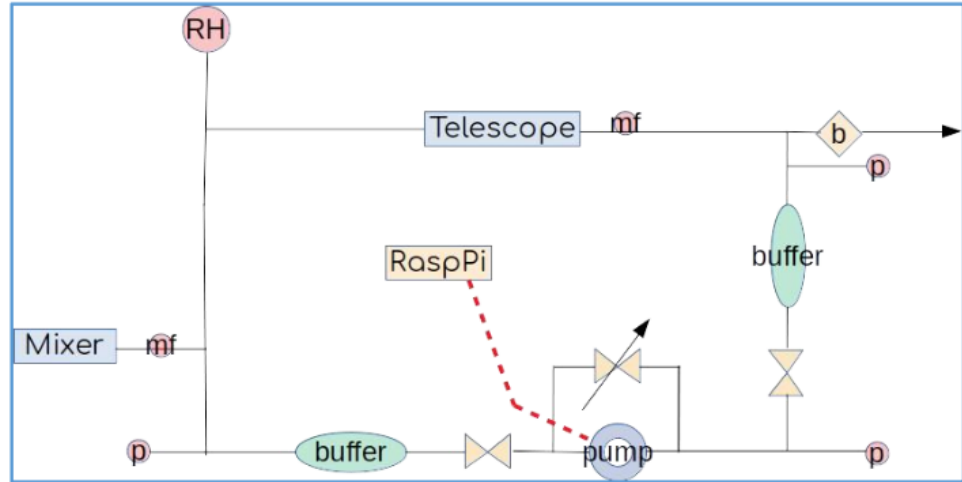
The EEE gas recirculation system prototype

A recirculation system was installed and studied on a EEE Telescope at CERN

* thanks to CERN Gas Group

OUR GOAL:

A simple, small, easy-to-use, low cost system to be eventually installed in each EEE Station



At present the prototype can reuse a flow fraction $\approx 60\%$

Some numbers on equivalent CO₂ production

1 EEE telescope uses about 1 l/h of C₂H₂F₄/SF₆ 98/2 gas mixture
→ **8760 liters per year** (when continuously operating, h24, even during August, Christmas, etc.)

Since the densities of C₂H₂F₄ = 4.25 kg/m³ and of SF₆ = 6.17 kg/m³, this corresponds to inject into the atmosphere, each year:

36.5 kg of C₂H₂F₄ and 1.1 kg of SF₆

However, the Global Warming Power (GWP) of C₂H₂F₄ is 1430 the one of CO₂ (namely 1 ton of C₂H₂F₄ injected warms the Earth like 1430 of CO₂), and GWP(SF₆) = 23900

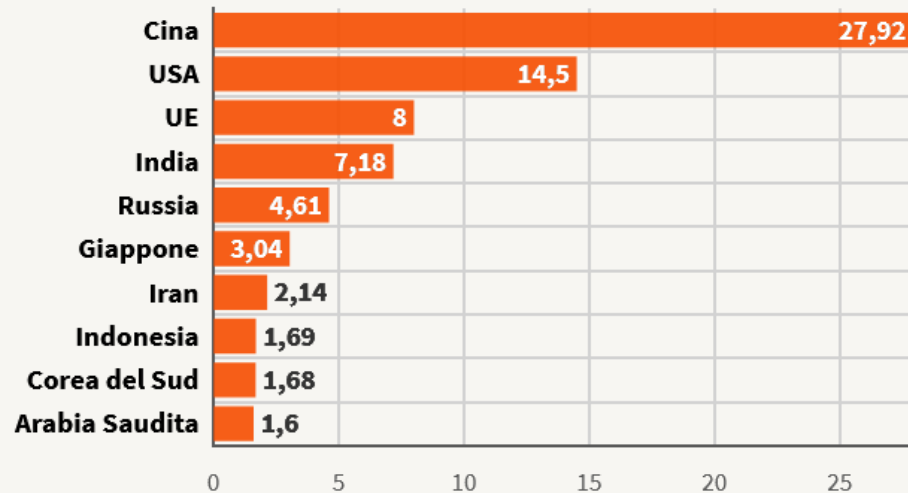
So, one EEE telescope injects into the atmosphere gas, for a GWP equivalent to **78.5 tonnes of CO₂ per year:**

36.5 kg x 1430 + 1.1 kg x 23900 = 52200 kg + 26300 kg = 78500 kg

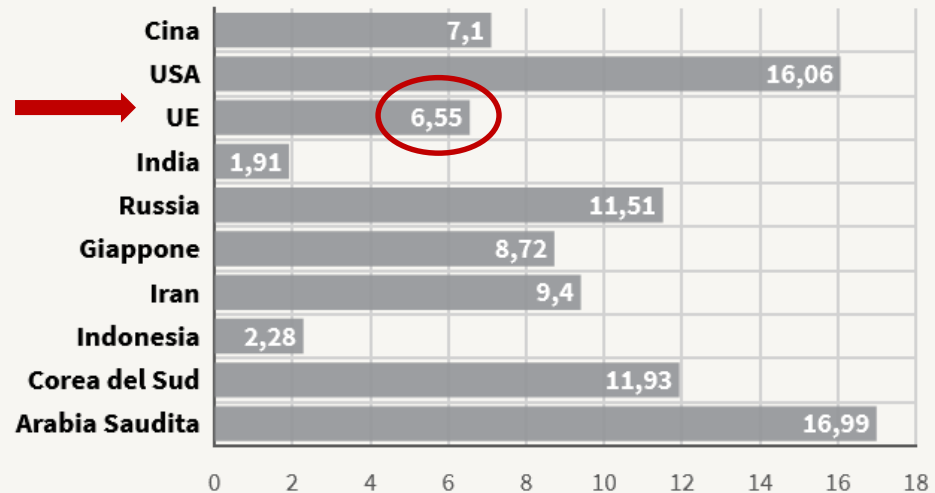
Amount of CO₂ produced in the world

■ QUOTA PERCENTUALE SUL TOTALE ■ TONNELLATE PER CAPITA

QUOTA PERCENTUALE SUL TOTALE



TONNELLATE PER CAPITA



An EU citizen injects about **6.55 tons/year** in the atmosphere
→ One EEE telescope roughly emits the CO₂ equivalent to **12 (twelve) people**

New ecofriendly mixtures in EEE: a BIG problem

For the EEE telescopes we are limited to:

- **Use binary mixtures**, since we have just two flowmeters
 - Not possible (too expensive to add another mass flowmeter to the whole EEE network)
 - An easier solution could be found using **ternary or quaternary mixtures**
- Mixtures that have a **working point close to the present**, < 20 kV
 - Not possible (too expensive) to replace the present HV power supply in the whole network

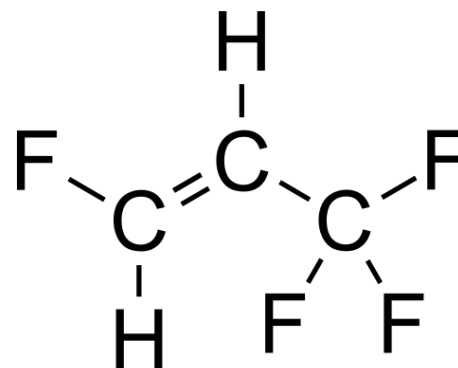
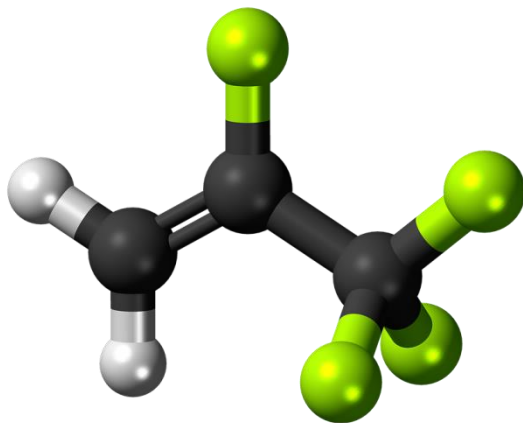


The new EEE **binary** gas mixture must have:

- ✓ a **low GWP**
- ✓ guarantee **spatial and time resolutions compatible with physics**
- ✓ must be **safe** (we cannot use hydrocarbons)
- ✓ must have a **similar cost** wrt. present one

Basic trendlines in EEE

- Research trendlines are concentrated around the idea of replacing:
- $C_2H_2F_4$ (GWP=1430) \rightarrow $C_3H_2F_4ze$ (GWP=4)
- SF_6 (GWP=23900) \rightarrow CO_2 (GWP=1) or He (GWP<1)



- $C_3H_2F_4ze$ (HFOze for the sake of brevity) is the most similar molecule to $C_2H_2F_4$ but with a low GWP;
- He and CO_2 are used to reduce the operating voltage with respect to pure HFO \rightarrow main drawback: less quenching with respect to standard mixture

Would it be a solution?

A mixture made out of $C_3H_2F_4$ /He 50/50 would have **GWP=2.5**

→ An EEE telescope would inject in the atmosphere a gas whose GWP would be equivalent to **89.5 kg/year of CO_2**

→ This would roughly correspond to the CO_2 injected yearly by **0.014 human beings living in the EU.**

The EEE collaboration started:

-a series of tests at the:

- Rende, Pisa sites → HFO/He

- Bologna, CERN sites → HFO/ CO_2



Once the tests completed on HFO/He mixtures, standard data taking (with the telescope **completely filled** with new gas mixture) started both in Rende and Pisa, for several months now.

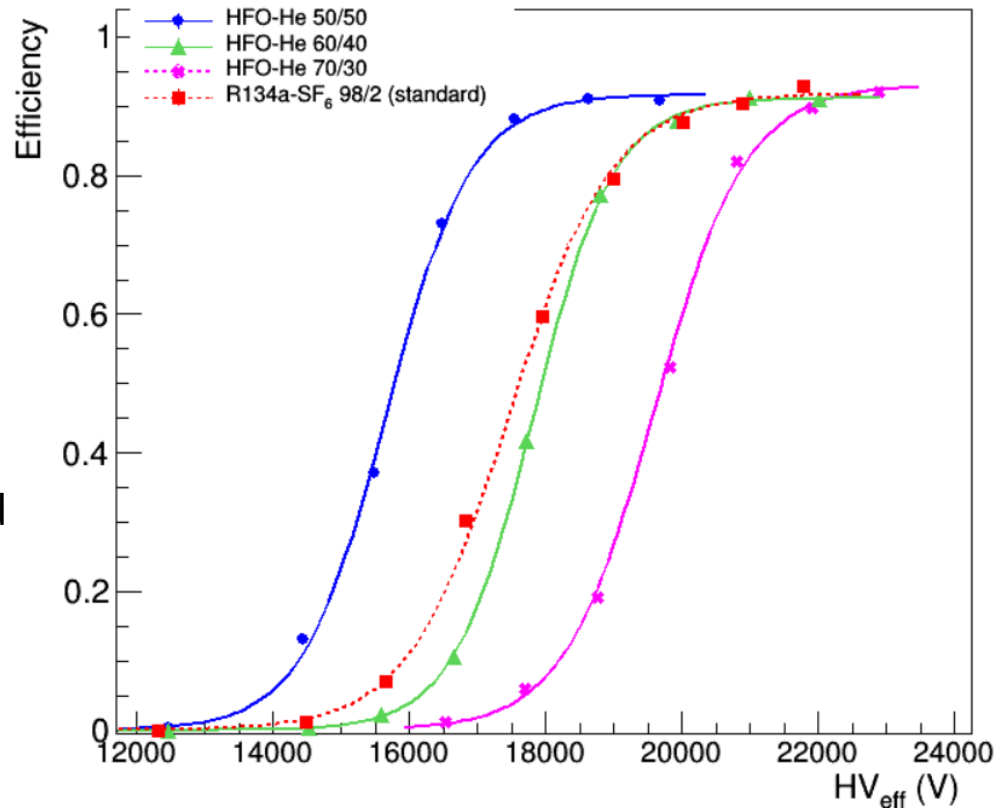
Rende tests on HFO/He

Basic idea is that **He does not take part in the multiplication processes**



It reduces the partial pressure of the active mixture component, and **the effective operating voltage**.

At Rende, telescope made of 10 years old 300 μm chambers, two used for trigger and tracking, the other filled with the new mixture.



Offline event selection based on data from the 2 trigger chambers:

- β of reconstructed particle in the 0.85-1.25 range
- extrapolated intercept point within the fiducial area on test chambers
- track zenithal angle $\theta < 25$

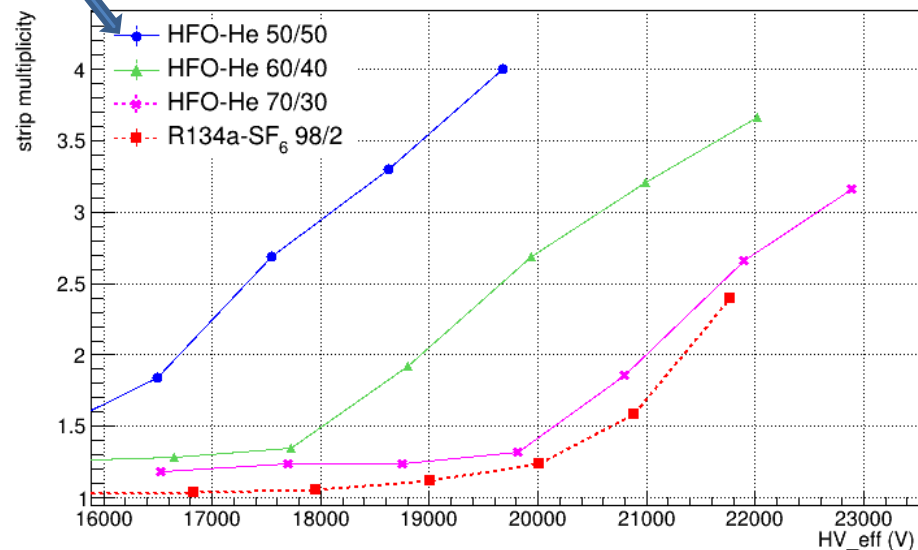
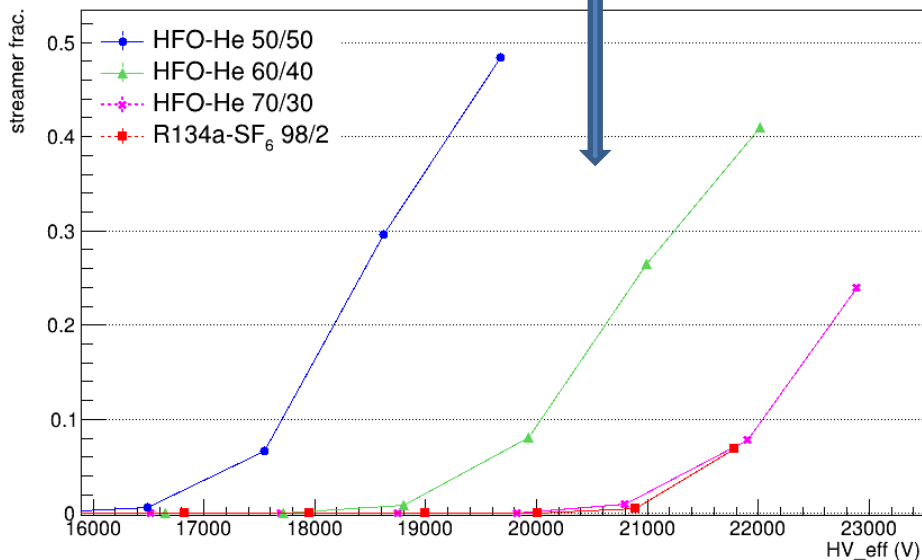
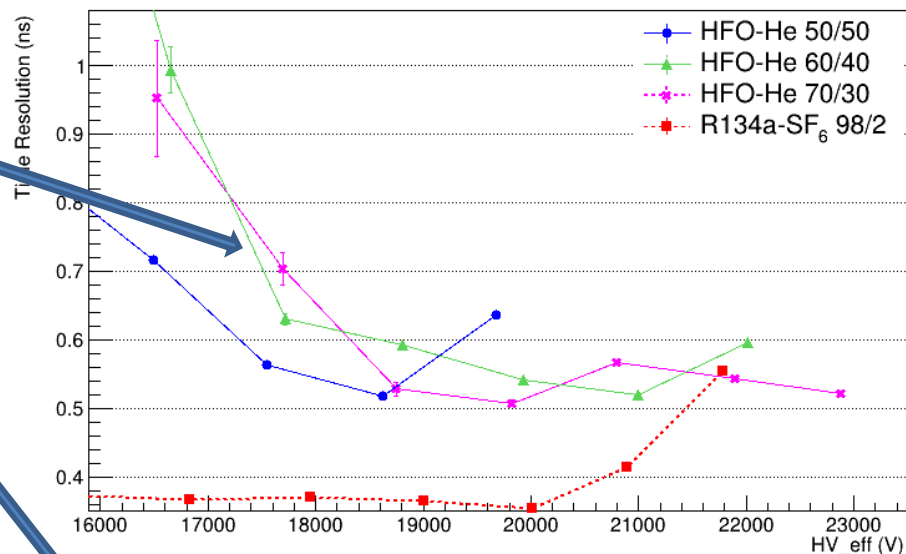
Chamber considered efficient if a cluster is found within 10 cm from the extrapolated intercept point.

Rende tests with HFO/He

Time resolution: generally worse wrt. standard mixture (lower electron drift velocity)

Strip multiplicity: generally larger wrt. standard mixture (lower electron drift velocity)

Streamer fraction: generally larger wrt. standard mixture (less quenching)



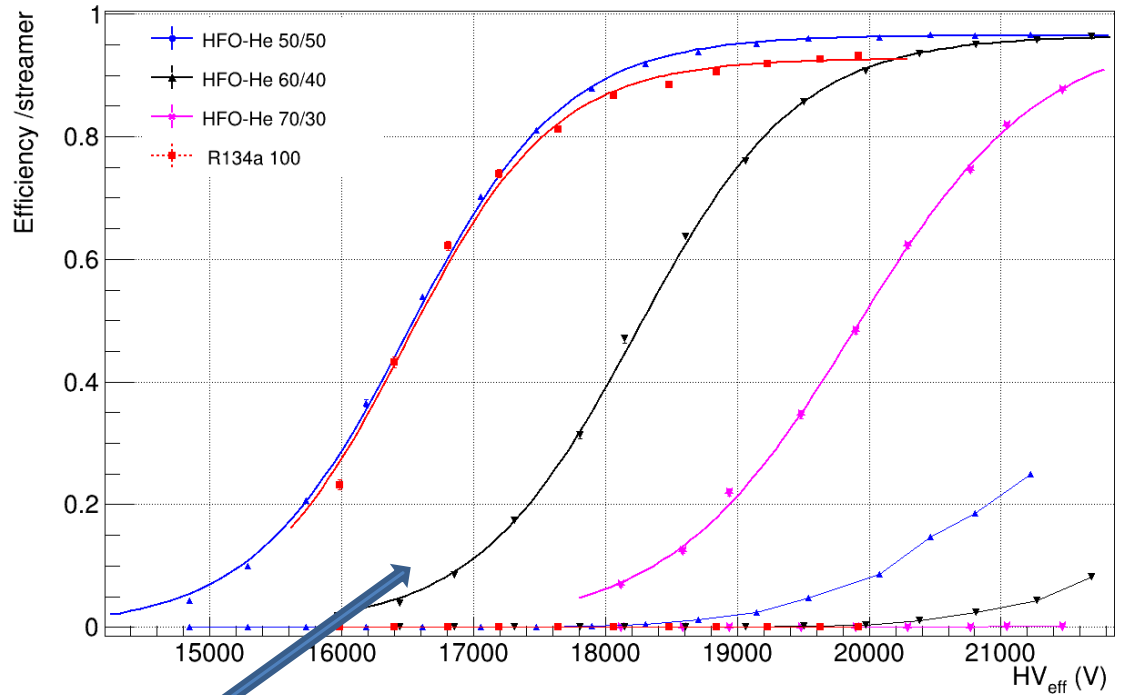
Pisa tests with HFO/He

In Pisa performed similar tests to Rende:
For “historical” reasons comparison done to a mixture TFE 100.



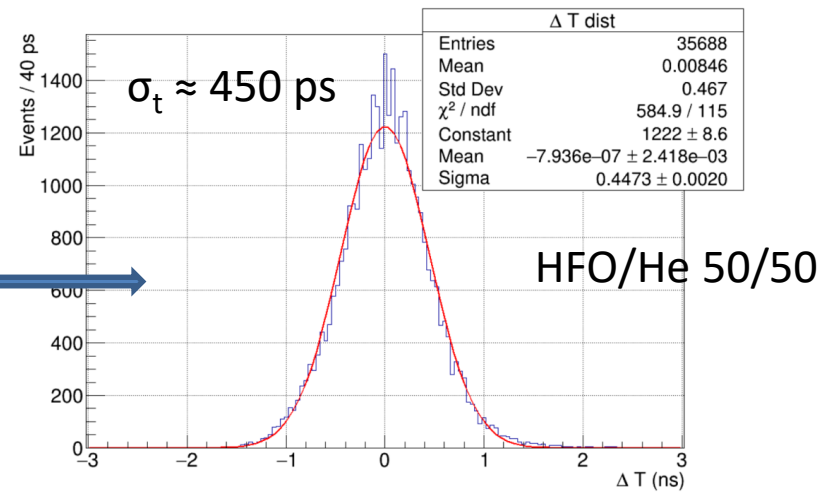
✓ HFO/He 50/50 give similar results wrt. TFE 100

✓ HFO/He 60/40 give similar results wrt. TFE/SF₆ 98/2 (Rende) → expected



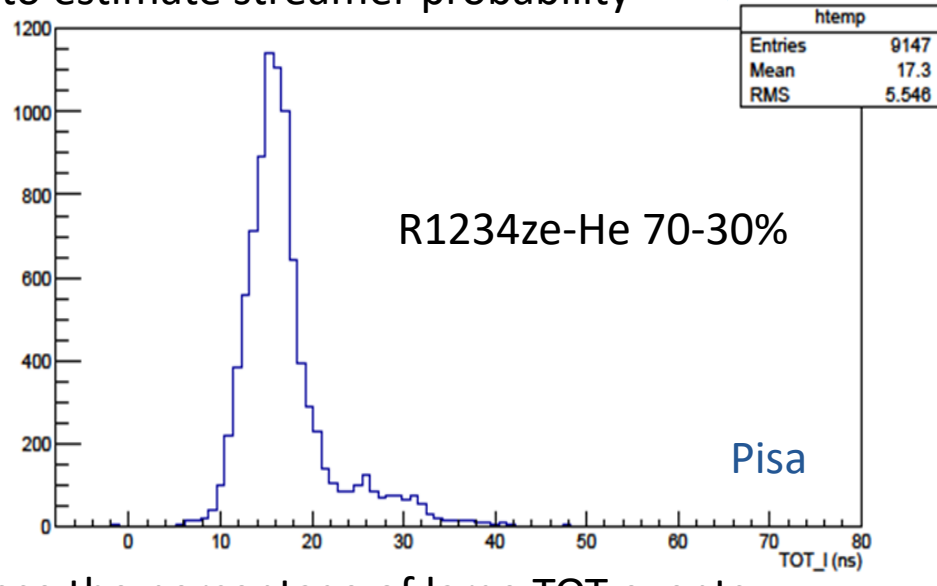
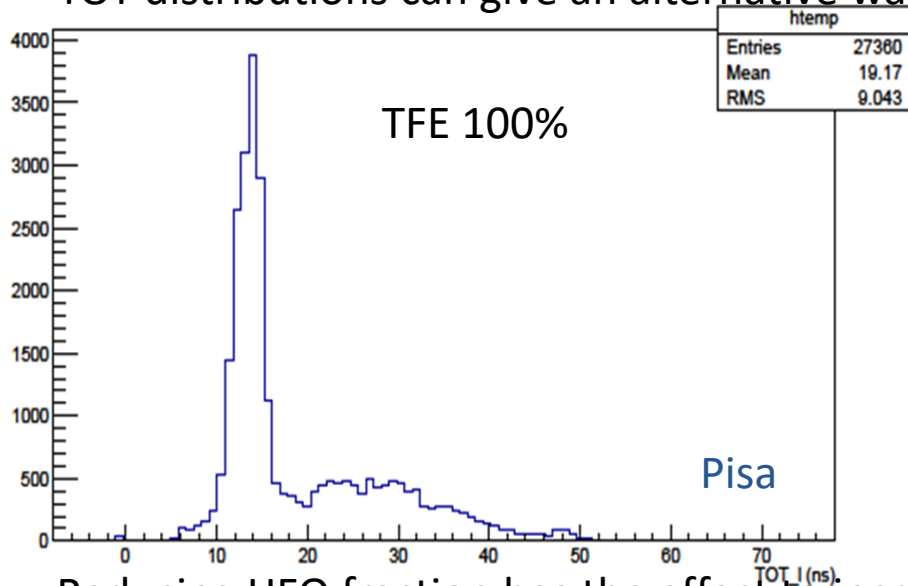
Efficiency and streamer fraction

Time distributions



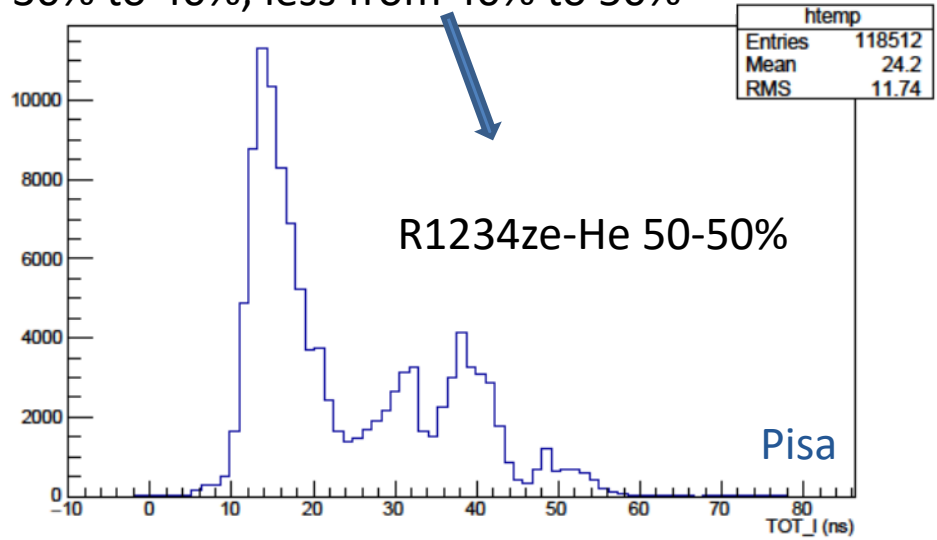
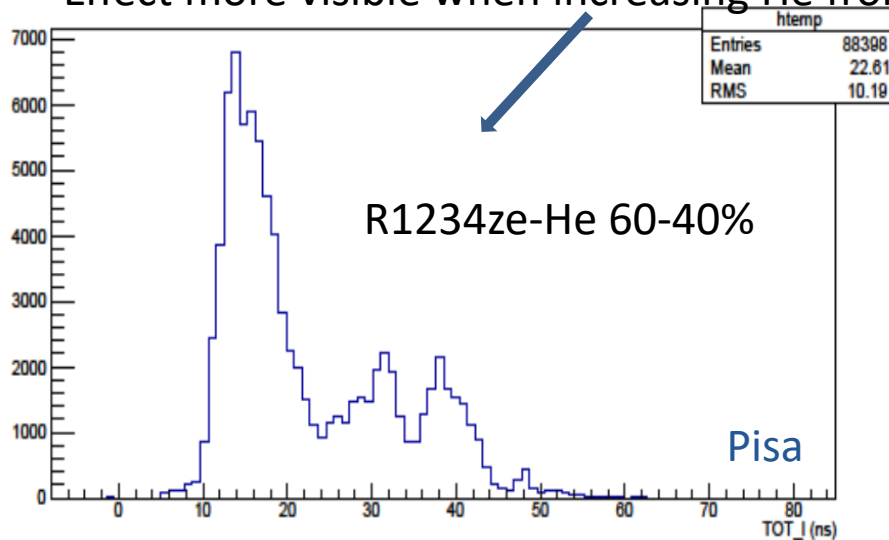
Time Over Threshold comparison

TOT distributions can give an alternative way to estimate streamer probability



Reducing HFO fraction has the effect to increase the percentage of large TOT events

- Effect more visible when increasing He from 30% to 40%, less from 40% to 50%



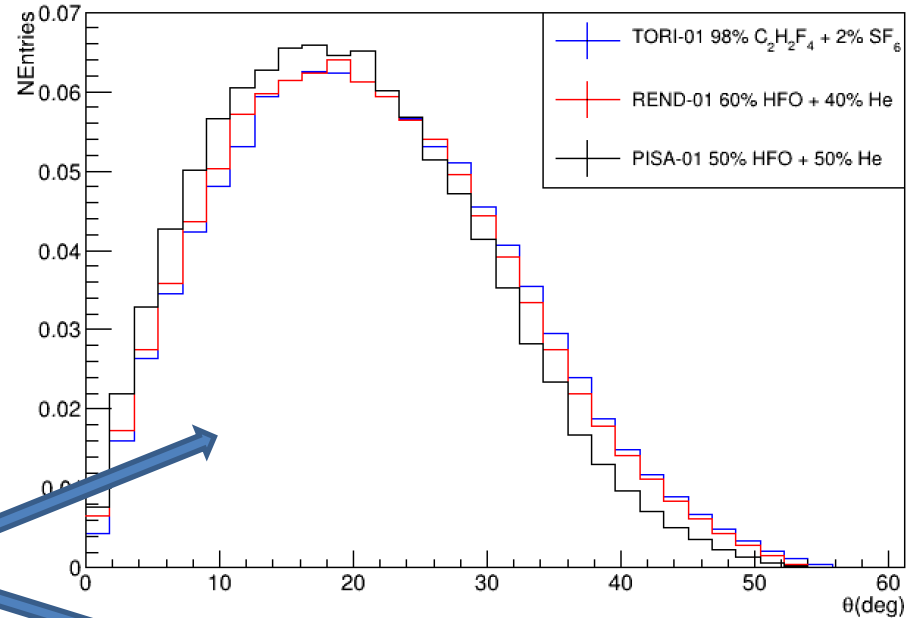
Long term data taking with HFO/He

All three chambers of both telescopes (Rende and Pisa) filled with HFO/He mixtures in different percentages

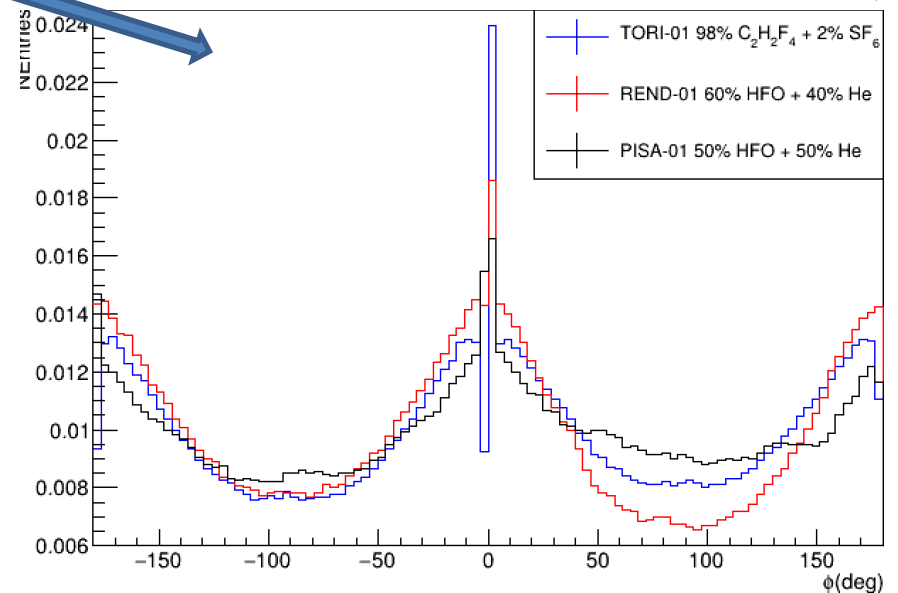
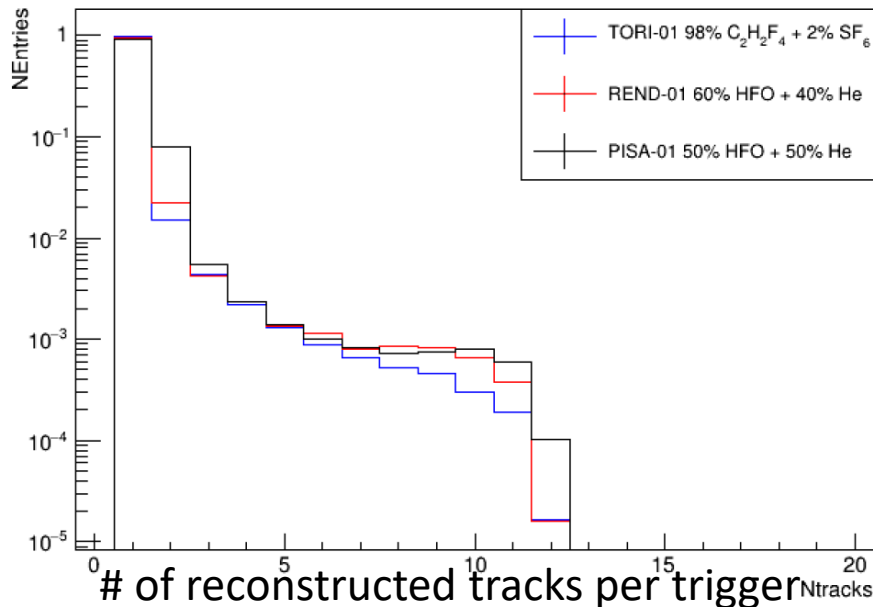
Data taking going on:

-since beginning of 2022 and continuing at Rende (HFO/He 60/40)

-Since March 2022 and stopped in June 2022 for an electronic problem at Pisa (HFO/He 50/50)



Muon tracks angular distributions



Data taking with HFO/He

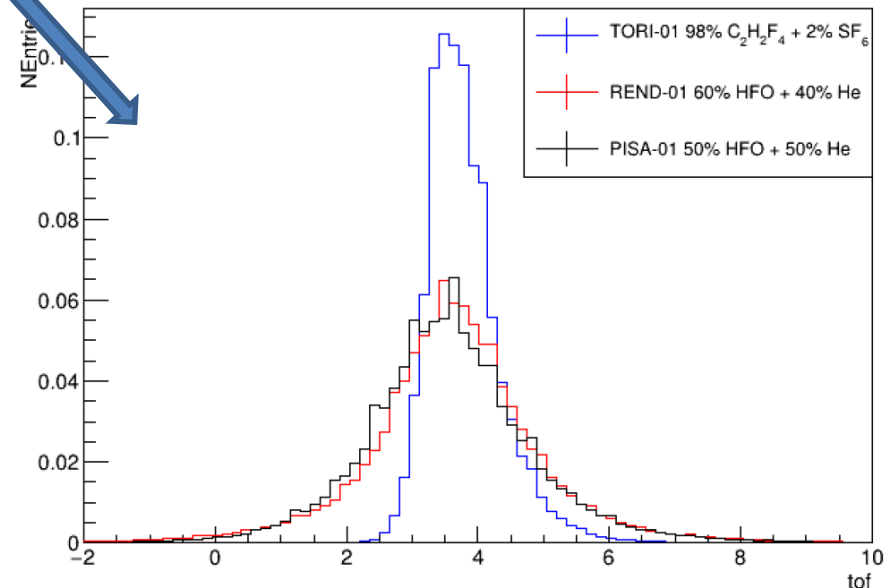
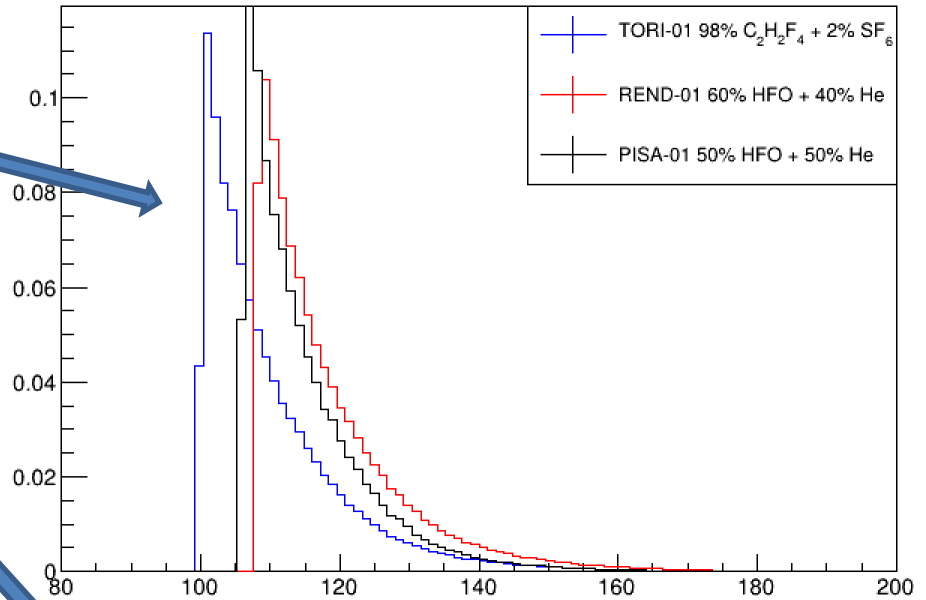
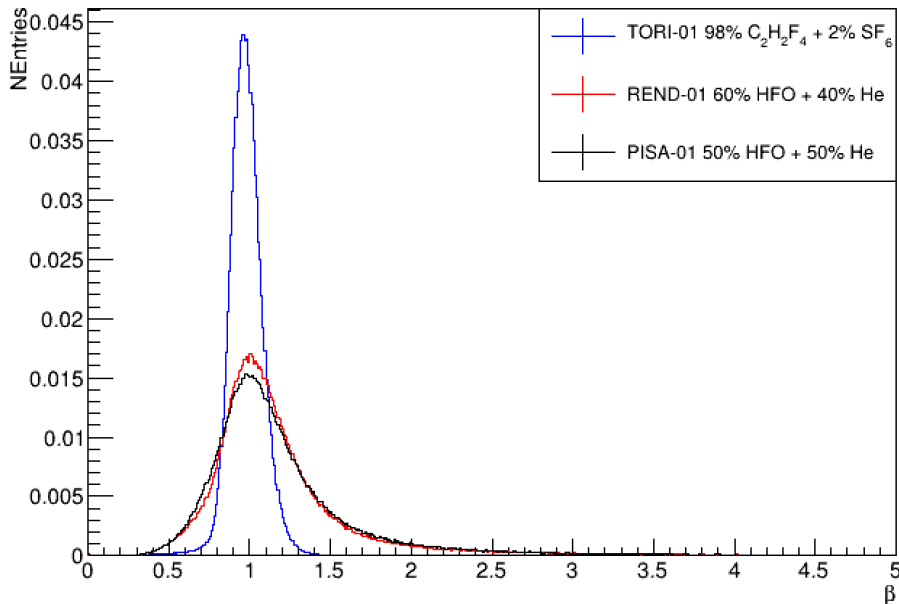
Reconstructed muon track length:

- Minimum track length related to distance between top and bottom chambers: TO 1 m, RN and PI 1.05 m

Time Of Flight between top and bottom chambers:

- Larger distribution due to worse time resolution

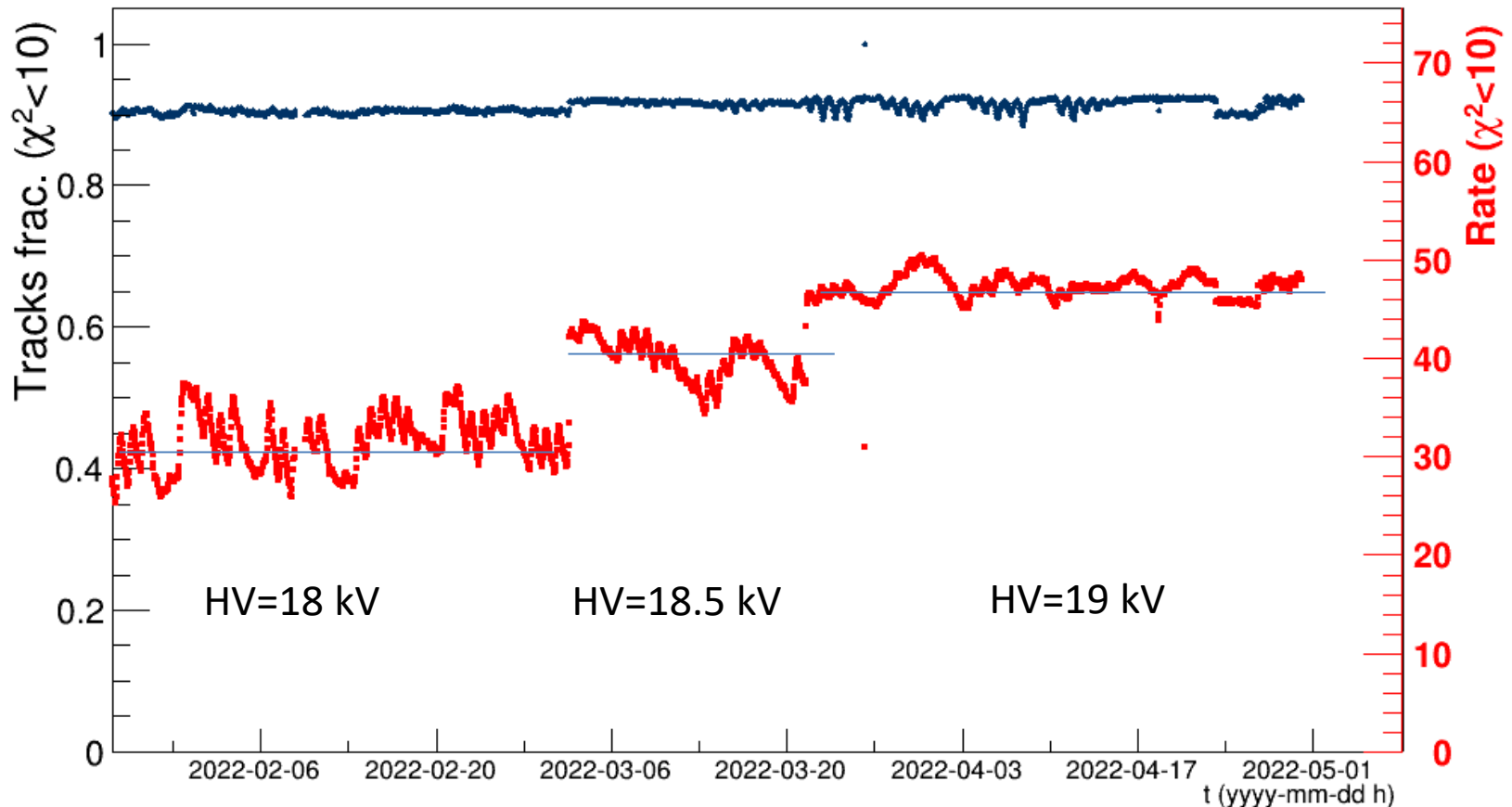
β of reconstructed muon tracks



Long term data taking with HFO/He

REND-01

HFO/He 60/40



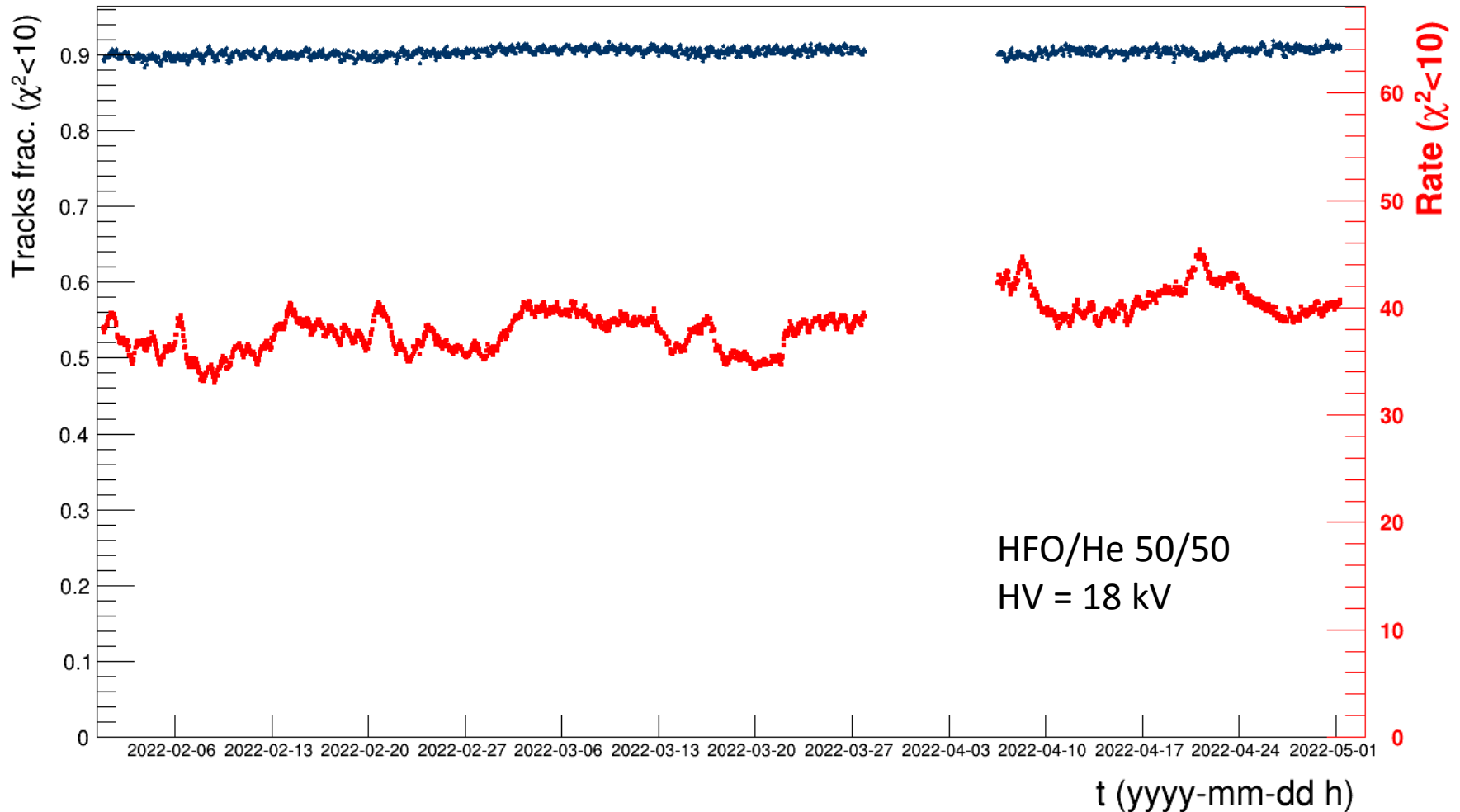
Oscillations due to **temperature variations** inside the hut where the telescope is located

- Oscillations reduced when HV deeper in the efficiency plateau

Apart from that, **remarkable stability**

Long term data taking with HFO/He

PISA-01



Tests with HFO/CO₂

Tests with both 300 (older) and 250 (newer) μm chambers

- **CERN and Bologna**

In general a slightly lower efficiency measured with HFO/CO₂ mixtures

- Evident with HFO/CO₂ 40/60

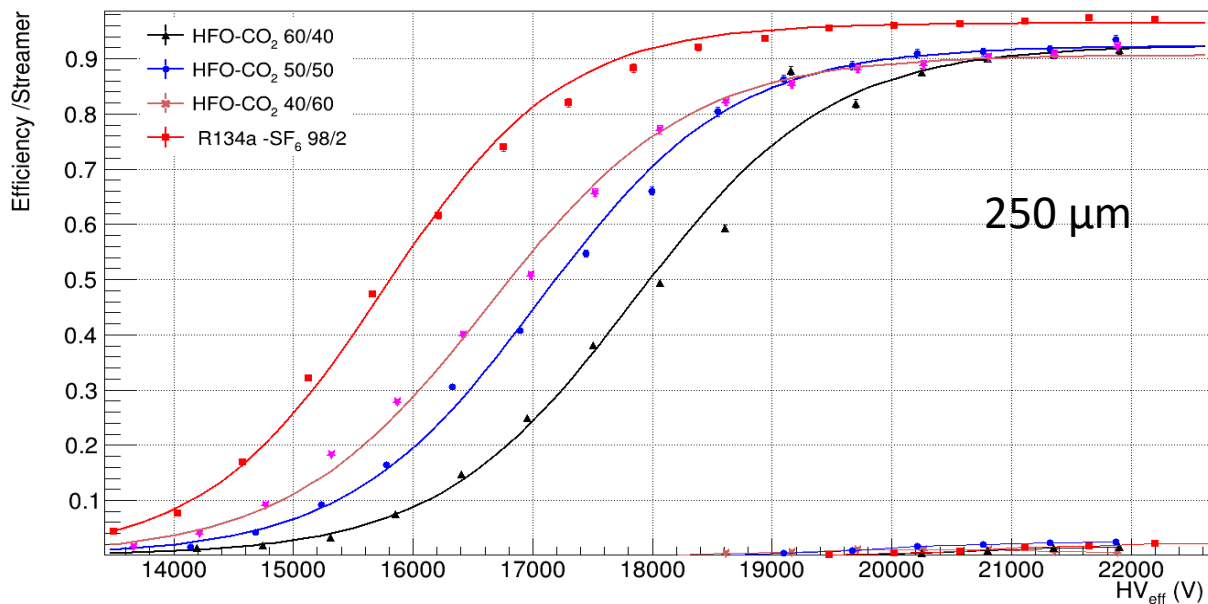
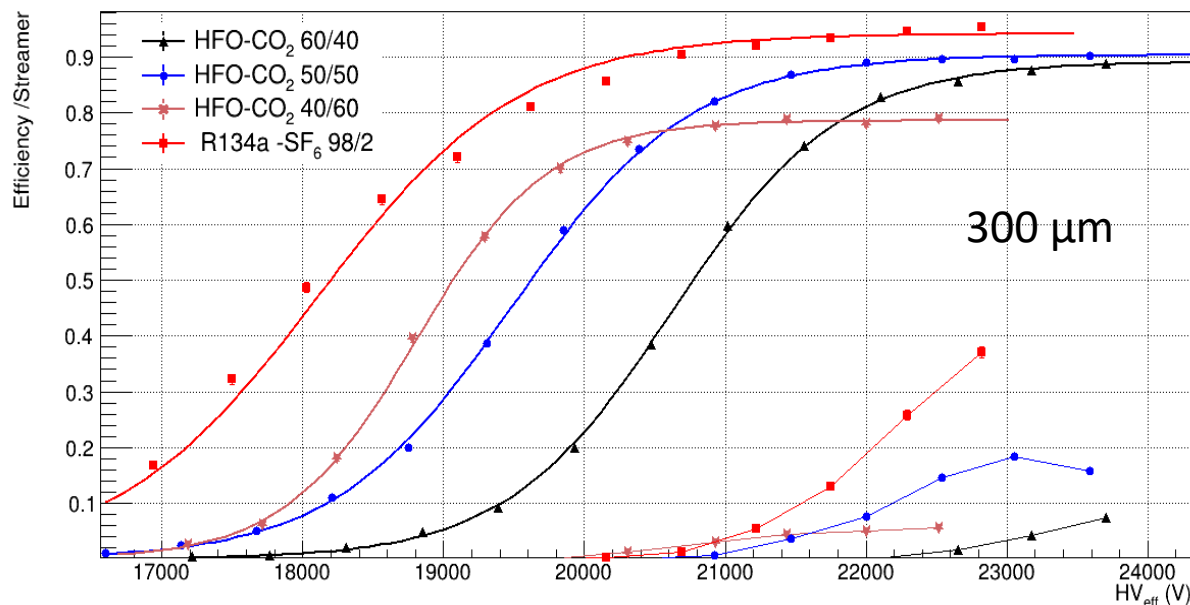
Higher working point wrt. to HFO/He mixtures (with same percentage of HFO)

Slightly lower streamer probability at the same efficiency

- **Quite low with 250 μm chambers**

Analysis ongoing

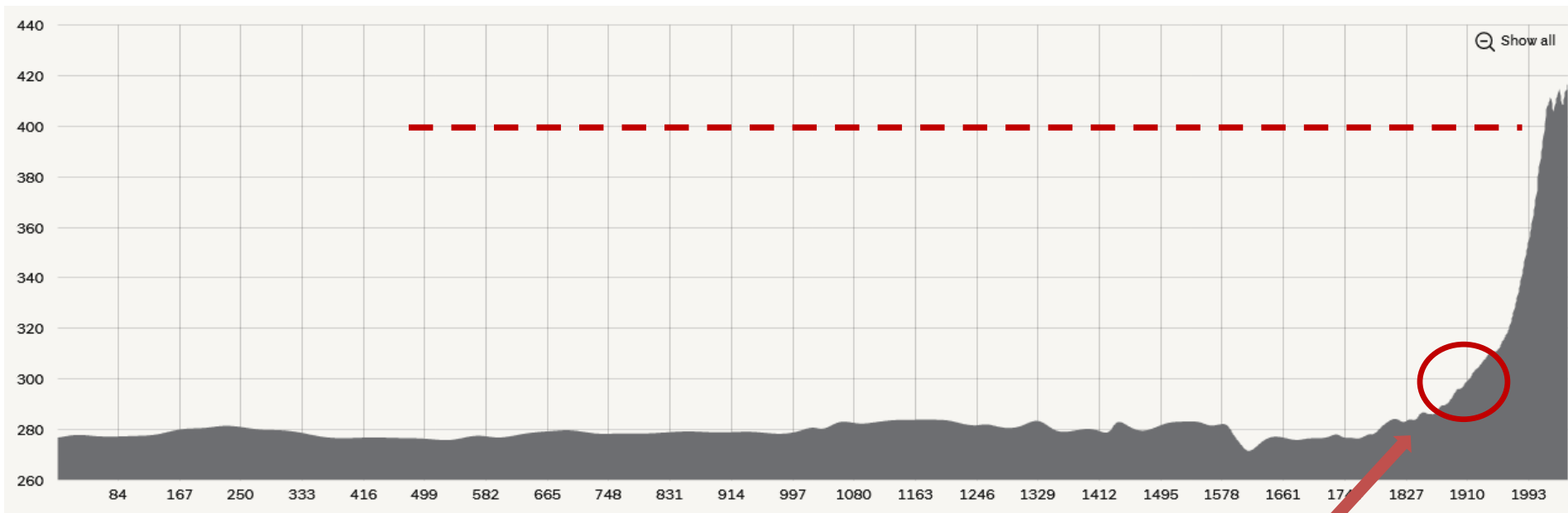
- Many tests done



Conclusions

- ✓ The EEE experiment is on the eve **of its ecological transition.**
- ✓ Tests with HFO/He mixtures completed satisfactorily
 - ✓ Reasonable efficiency at low HV;
 - ✓ Larger cluster size and streamer fraction;
 - ✓ Worse time resolution.
- ✓ Long term data acquisition with telescopes completely filled with ecofriendly gas mixtures showed **performance completely satisfactory for the physics aim of the experiment**
- ✓ Other stations being equipped with new eco-friendly gas an underway for restart
- ✓ Achieved a **complete replacement of greenhouse gases with an ecofriendly gas mixture**
 - ✓ EEE is running with a fully ecofriendly gas mixture.
- ✓ Tests with HFO/CO₂ still on going

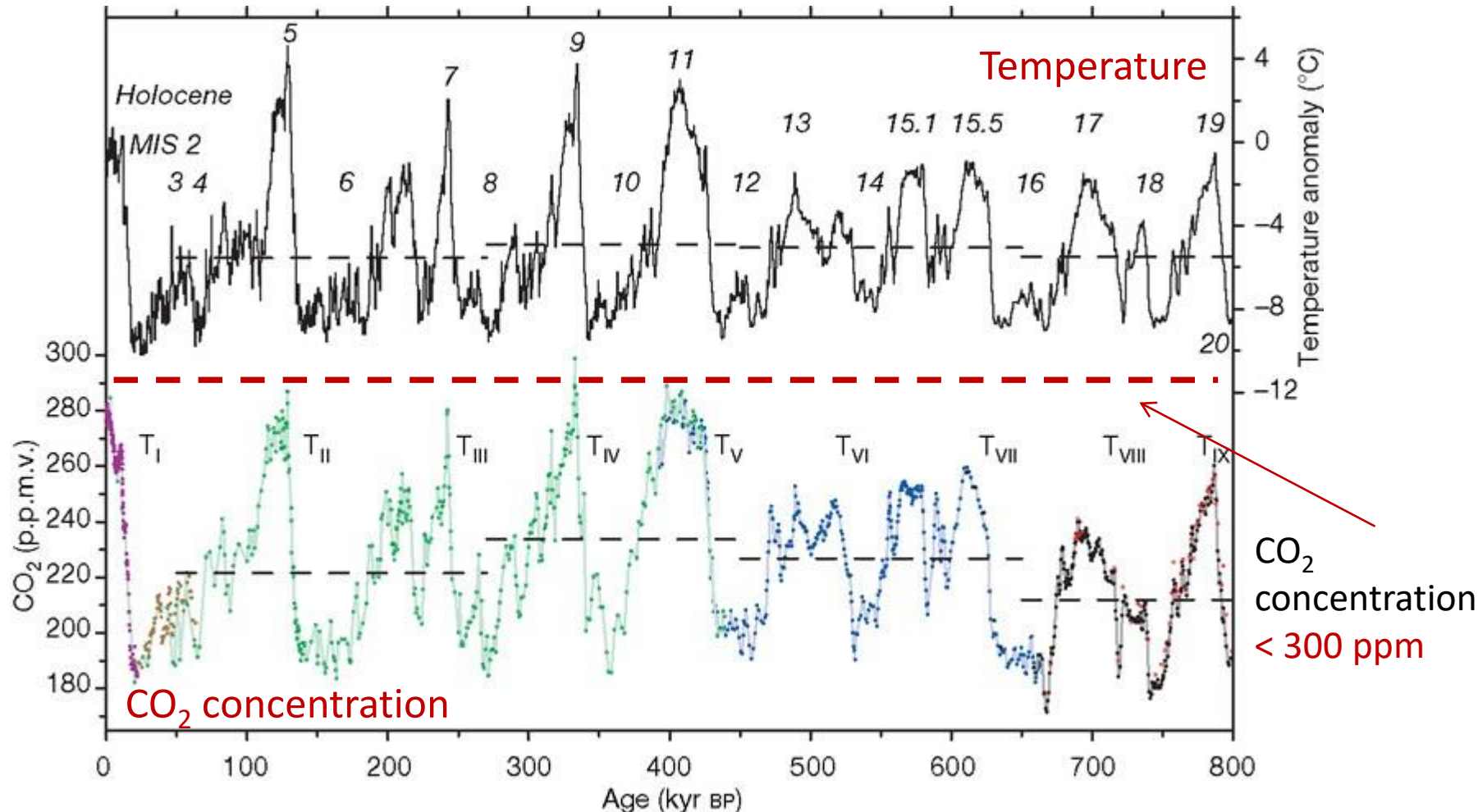
CO₂ concentration: last two thousand years



The first time in human history that atmospheric CO₂ exceeded 300 ppm was about the time the **Titanic sank (1912)** in the North Atlantic Ocean. Now, the crossover to concentrations that stay above 400 ppm CO₂ **is nearly complete**.

An interlude: CO₂ concentration: last million year

Lüthi, D., Le Floch, M., Bereiter, B. *et al.* High-resolution carbon dioxide concentration record 650,000–800,000 years before present. *Nature* **453**, 379–382 (2008). <https://doi.org/10.1038/nature06949>



We know that atmospheric CO₂ has ranged between 172 and 300 part per million (ppm) for the past 1 million years.

THE GREENHOUSE EFFECT

