Performance studies of RPC detectors operated with eco-friendly gas mixtures

EP-DT-FS Gas Team

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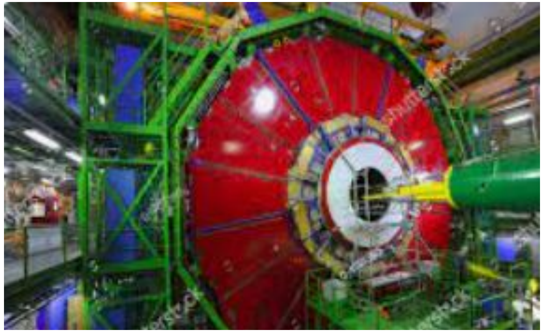
Resistive Plate Chamber Detectors (RPCs)

Widely employed **gaseous detectors** at **CERN LHC** experiments as muon trigger for the excellent time-spatial resolution

CMS

ATLAS

ALICE



Responsible for an important amount **of CERN's experiments GHG emissions** due to leaks at detector level

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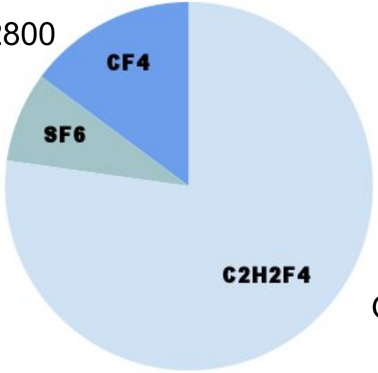
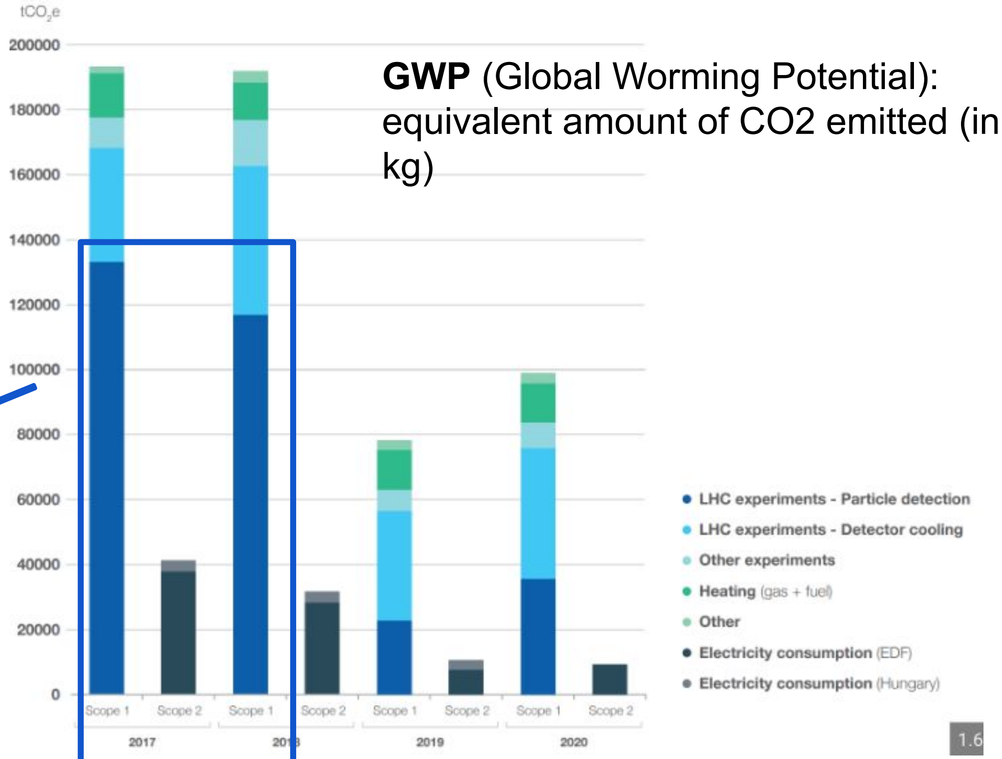
RPCs GHG emissions: why bother?

CERN's greenhouse gas emissions (scope 1) are mostly related to the use of various fluorinated gases (F-gases) for particle detection and detector cooling in large LHC experiments. During **Run 2 ~85%** of GHG emission from particle detectors came from **RPCs**

RPC emissions



GWP (Global Worming Potential): equivalent amount of CO2 emitted (in kg)



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RPCs GHG emissions: how to reduce them?

GHGs are used because of their outstanding properties for good detector operation.
CERN strategies to reduce GHG emissions in particle detection experiments:

- Gas Recuperation
- Alternative Gases → **GOAL** : find a **low GWP** gas mixture for the current RPC systems without changing the infrastructure
- Gas recirculation

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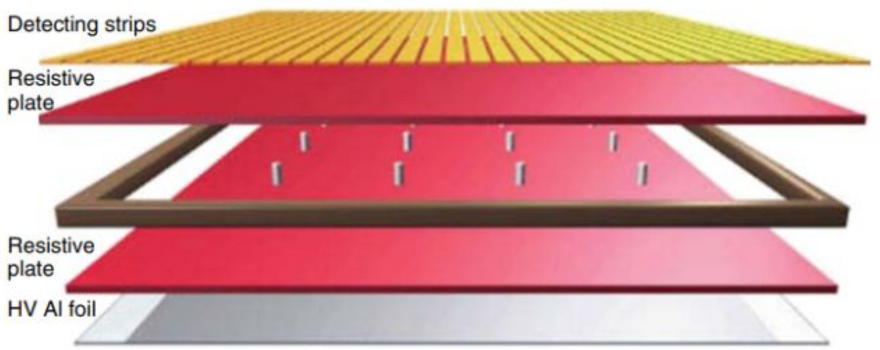
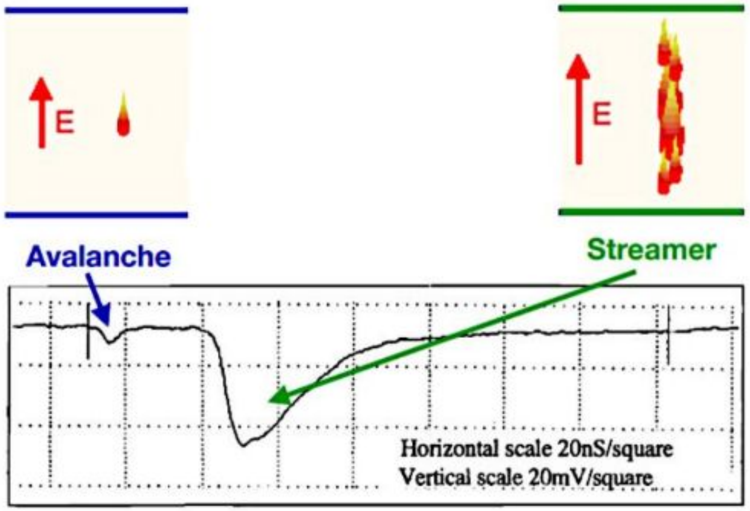
Resistive Plate Chamber Detectors



RPCs exploit **Townsend's avalanche** mechanism due to **gas ionization**



Main detector parameters

Efficiency, currents, cluster size, time resolution, streamers, charge

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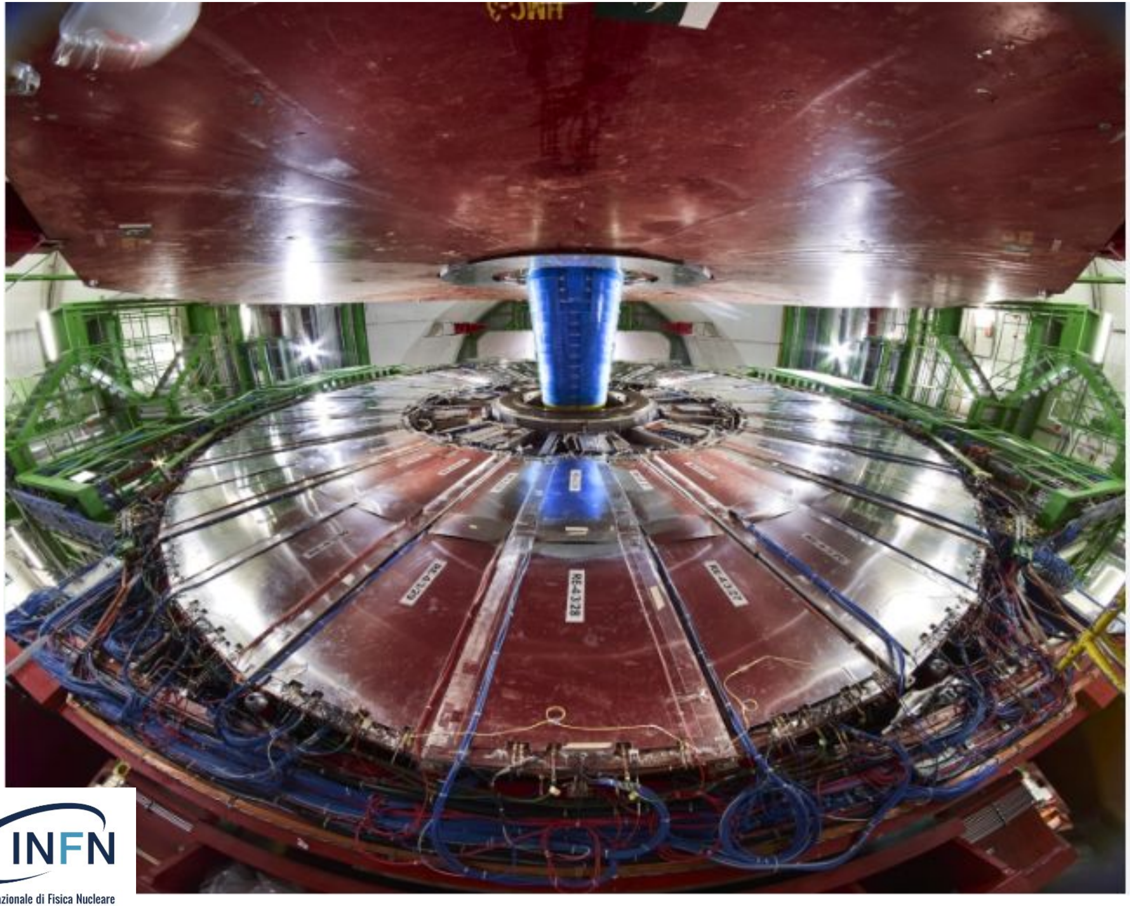
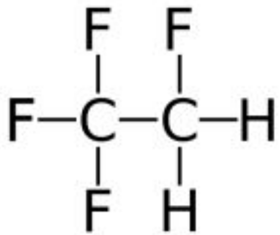
Resistive Plate Chamber Detectors



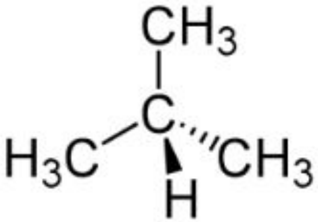
Standard Gas Mixture (STD)



95.2 %

R134a $(C_2H_2F_4)$

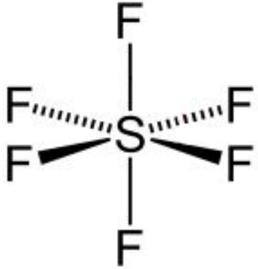
Easy to ionize



4.5 %

Isobutane (i-C_4H_{10})

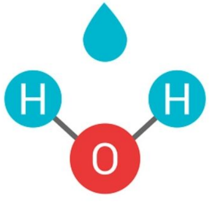
Photon quenching



0.3 %

Sulfur hexafluoride (SF_6)

Highly electronegative



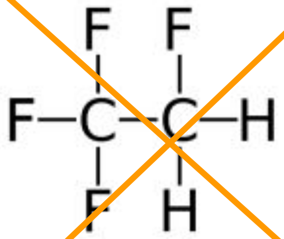
H_2O

0.7 %

constant electrodes resistivity

Standard Gas Mixture (STD)

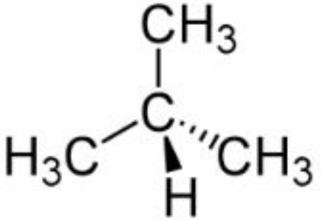
High GWP!!



95.2 %

R134a $(C_2H_2F_4)$

GWP : 1430

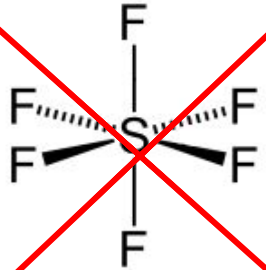


4.5 %

Isobutane (i-C_4H_{10})

GWP : 3.3

High GWP!!



0.3 %

Sulfur hexafluoride (SF_6)

GWP : 22800

Research lines

The study of alternatives gases to

R134a | **SF6** | **CH4**

Several requirements must be satisfied for a new gas mixture :

- **HV cables**, **electronics** and **detectors** themselves must **not** be **changed**
- **Not flammable**
- **Not toxic**

European Union Regulations

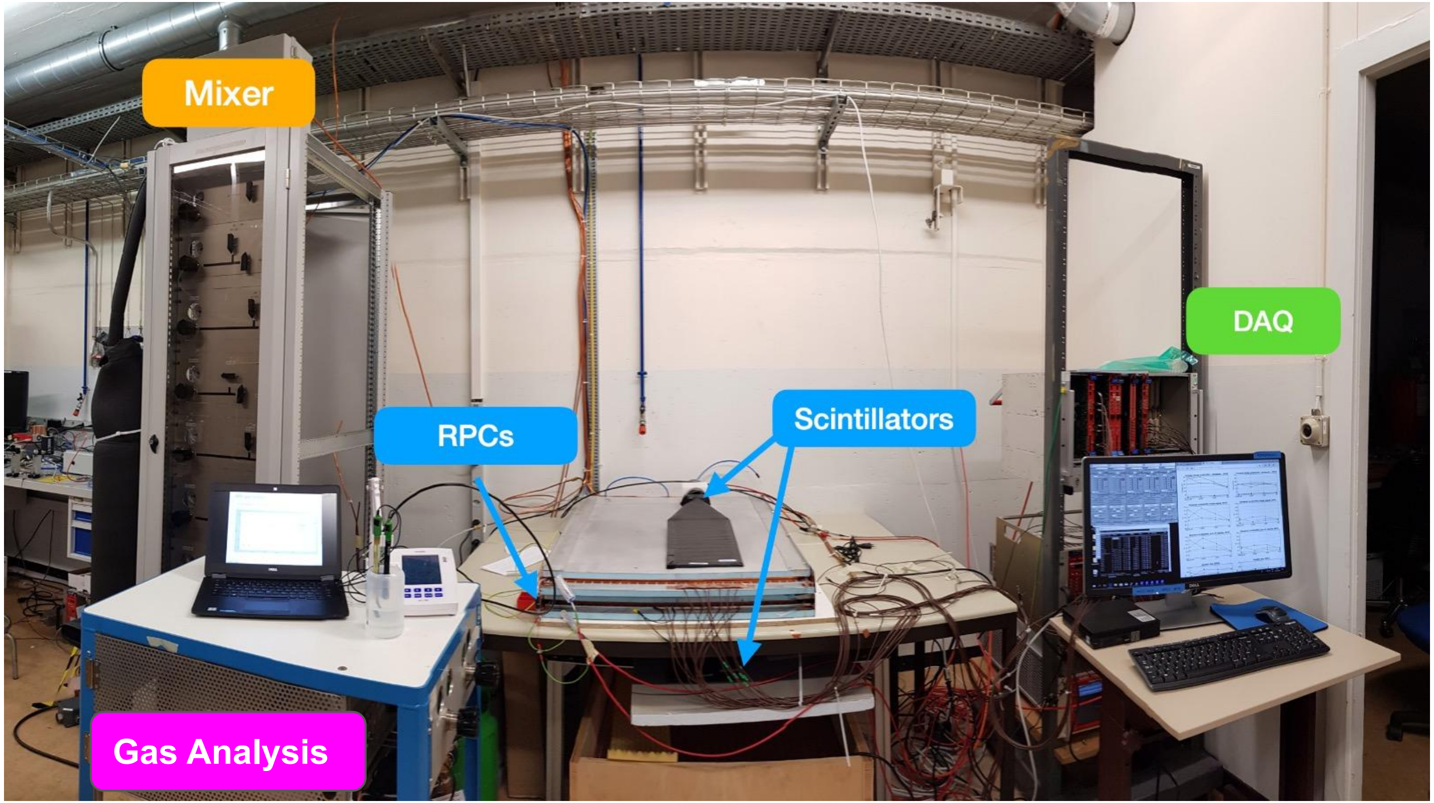
Starting from 1st January 2015

- Limiting the total amount of the 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.
- Require regular and certified check controls on leaks for existing equipments.
- Require a recovery of the gases at the end of the equipments life.

Laboratory experimental Set Up

Cosmic Muons

- **Gas Mixing Unit** : up to 6 different gases
- **3 RPCs** : single gap 2 mm, read out strips 2 cm
- **DAQ** : CAEN digitizer 1730, resolution 0.122 mV/ADC, sampling 500 MS/s
- **Data Analysis**
- **Gas Analysis** : Gas Chromatograph and Mass Spectrometer



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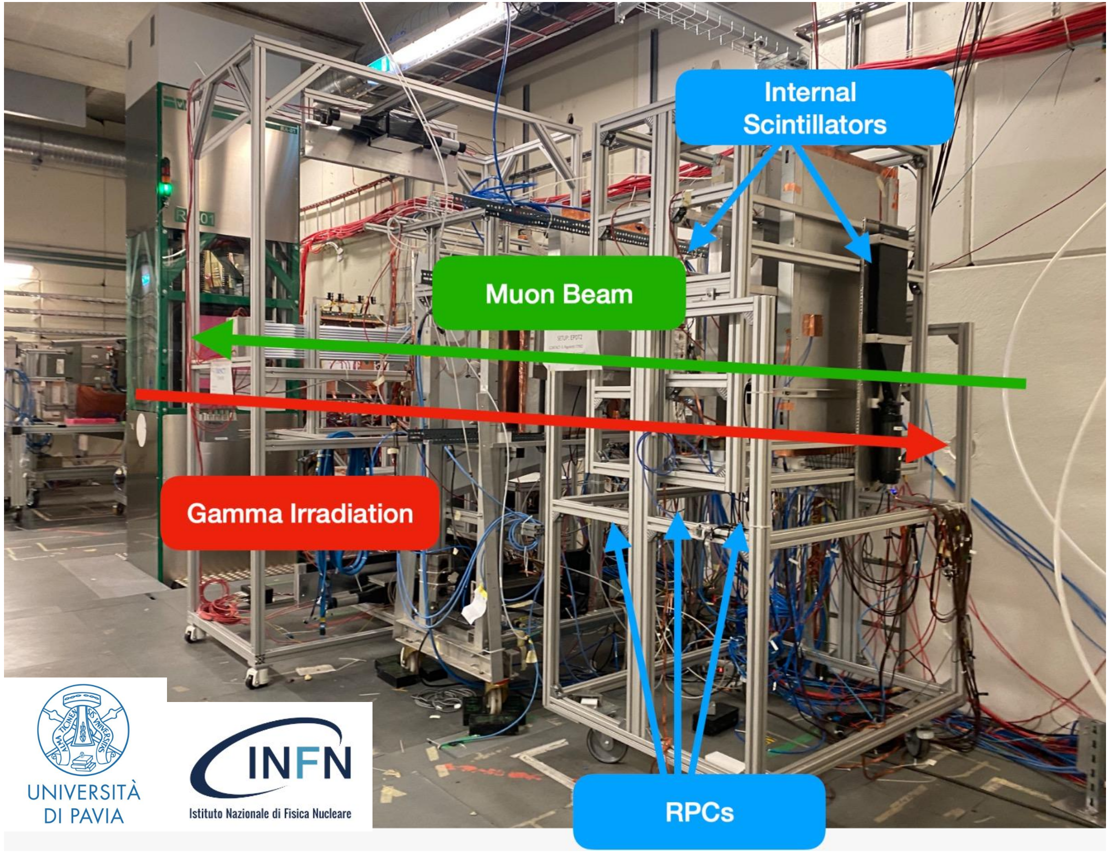
Experimental Set Up
Gamma Irradiation Facility (GIF ++)

SPS Muon Beam



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Performance studies under LHC-like conditions

- Gas System
- 3 RPCs of 2 mm single gap
- 2 Scintillators
- 12.5 TBq 137Cs provides gamma irradiation background
- Small replica of the background expected at HL-LHC
- PB filters allow different attenuation factors (ABS)

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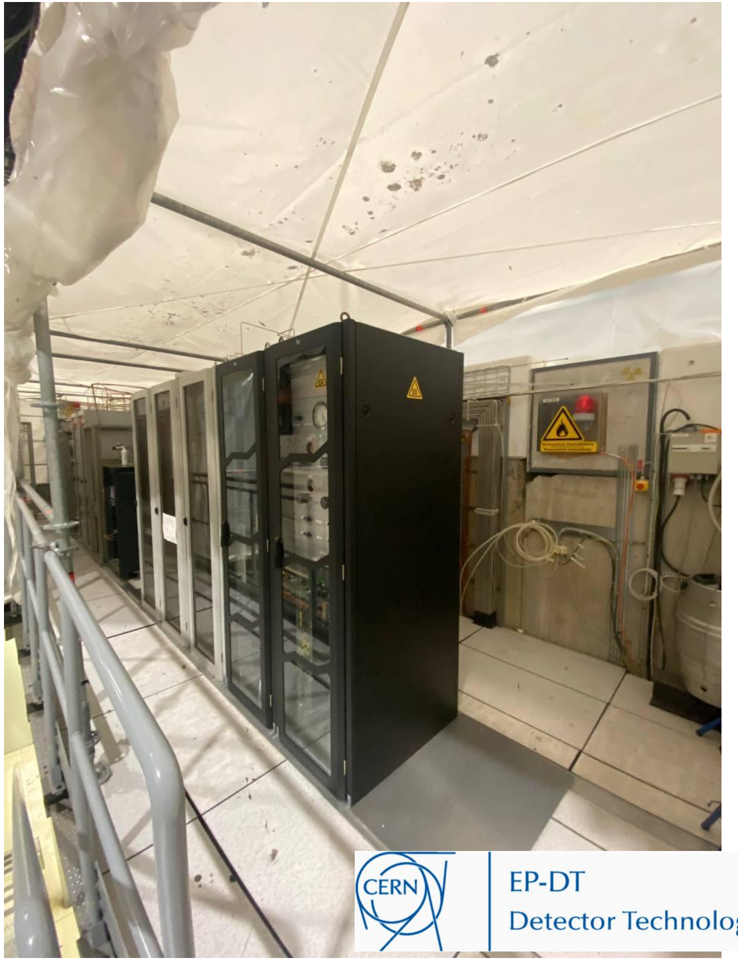
Experimental Set Up - Gas system



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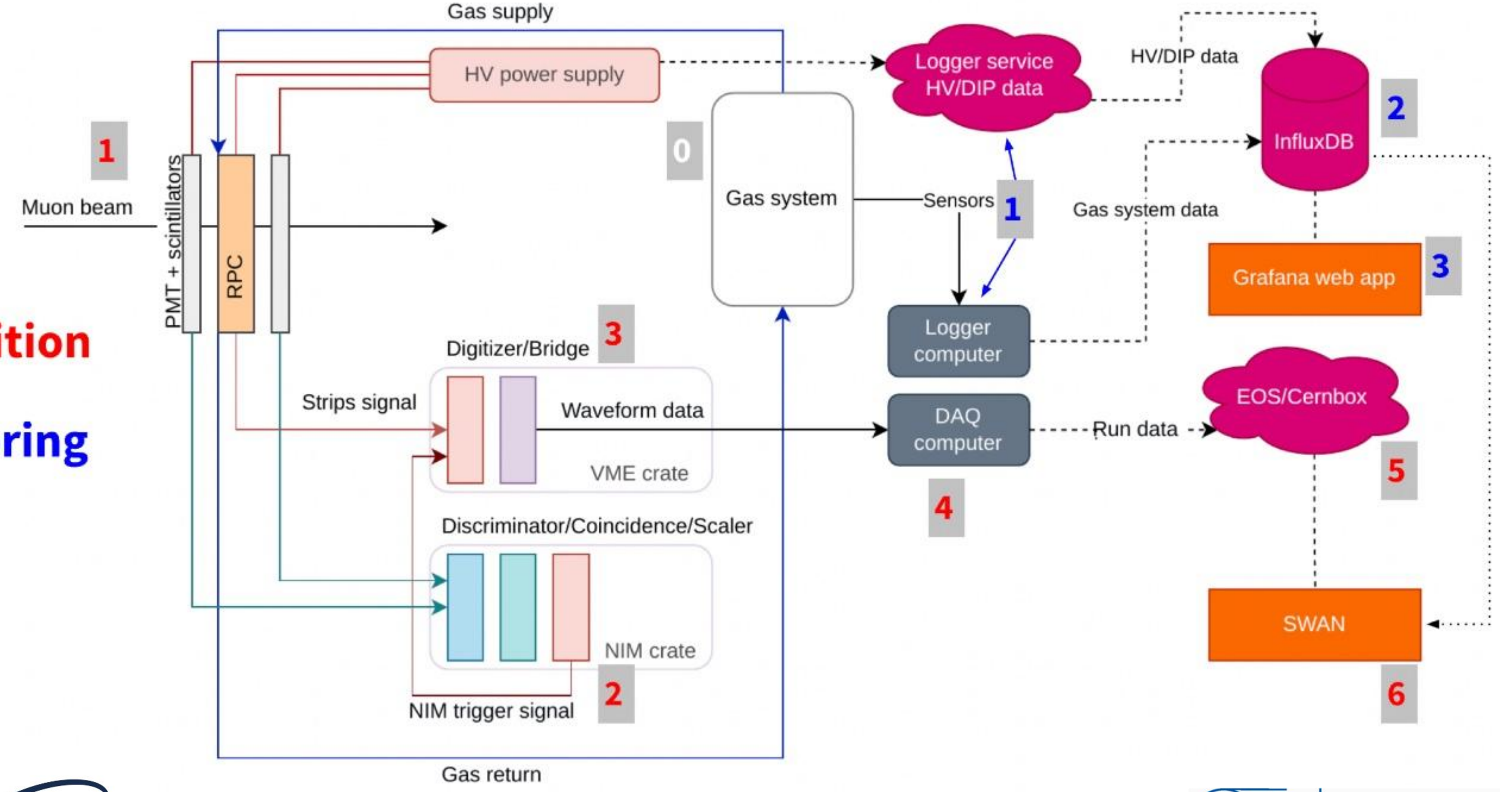
Scheme of the Set up and Data Analysis



-Acquisition

-Monitoring

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Data Analysis

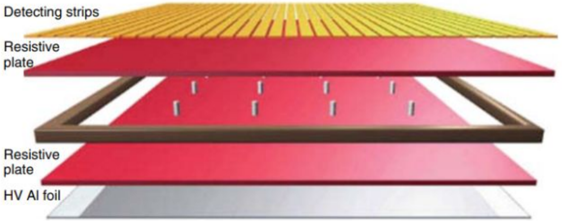
Signal → raw data of 520 samples collected by a single read out strip [adc -> mV]

Event → simultaneous recording of the signals over different strips by a single trigger

Acquisition → data collected at an HV point

Run → data collected over multiple HV points

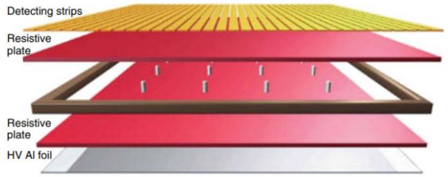
Main detector parameters



Event →

- **Avalanche signal** : < 10^8 electrons (< 19 pC)
- **Streamer signal** : > 10^8 electrons (> 19 pC)
- **Cluster size** : the maximum number of adjacent strip hit by the same particle
- **Time resolution** : computed as the difference of the arrival time with respect to the external trigger

Main detector parameters



Acquisition →

- **Efficiency** : the probability of a particle to be detected when hitting the detector
- **Streamer Probability** : number of detected streamers/number of all detected particles

Run →

- **Maximum Efficiency**
- **Knee** of the efficiency curve : voltage value corresponding to 95% of the efficiency max
- **Working Point** : knee + 150V
- **Cluster Size** and **Time resolution** evaluated at WP

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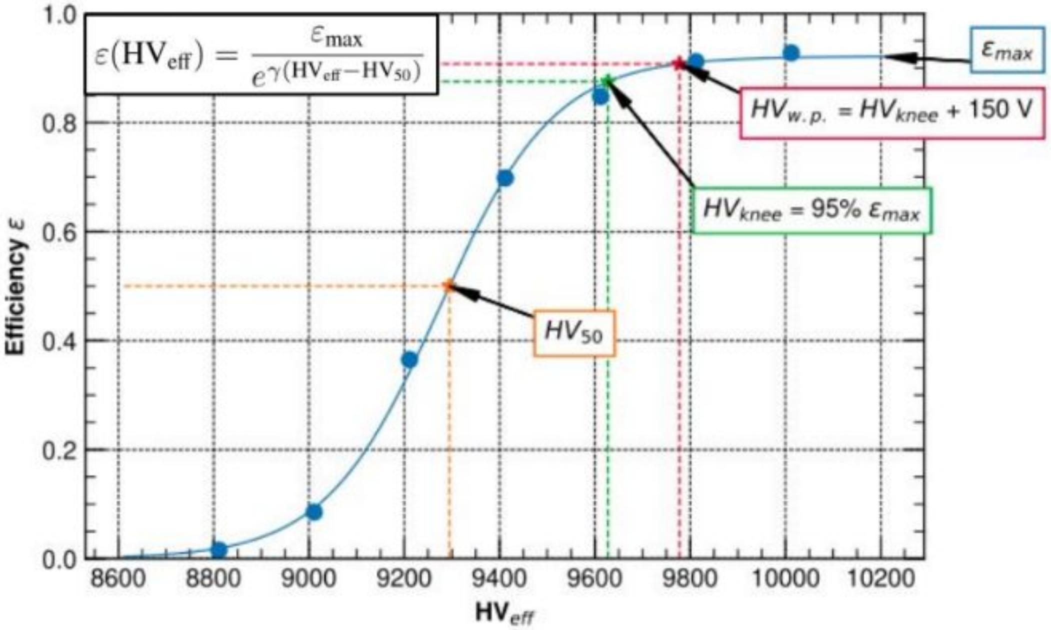
Fit efficiency curve

For each run about 10 voltage point are collected.

The **fit** of the **efficiency curve** is realized with the formula :

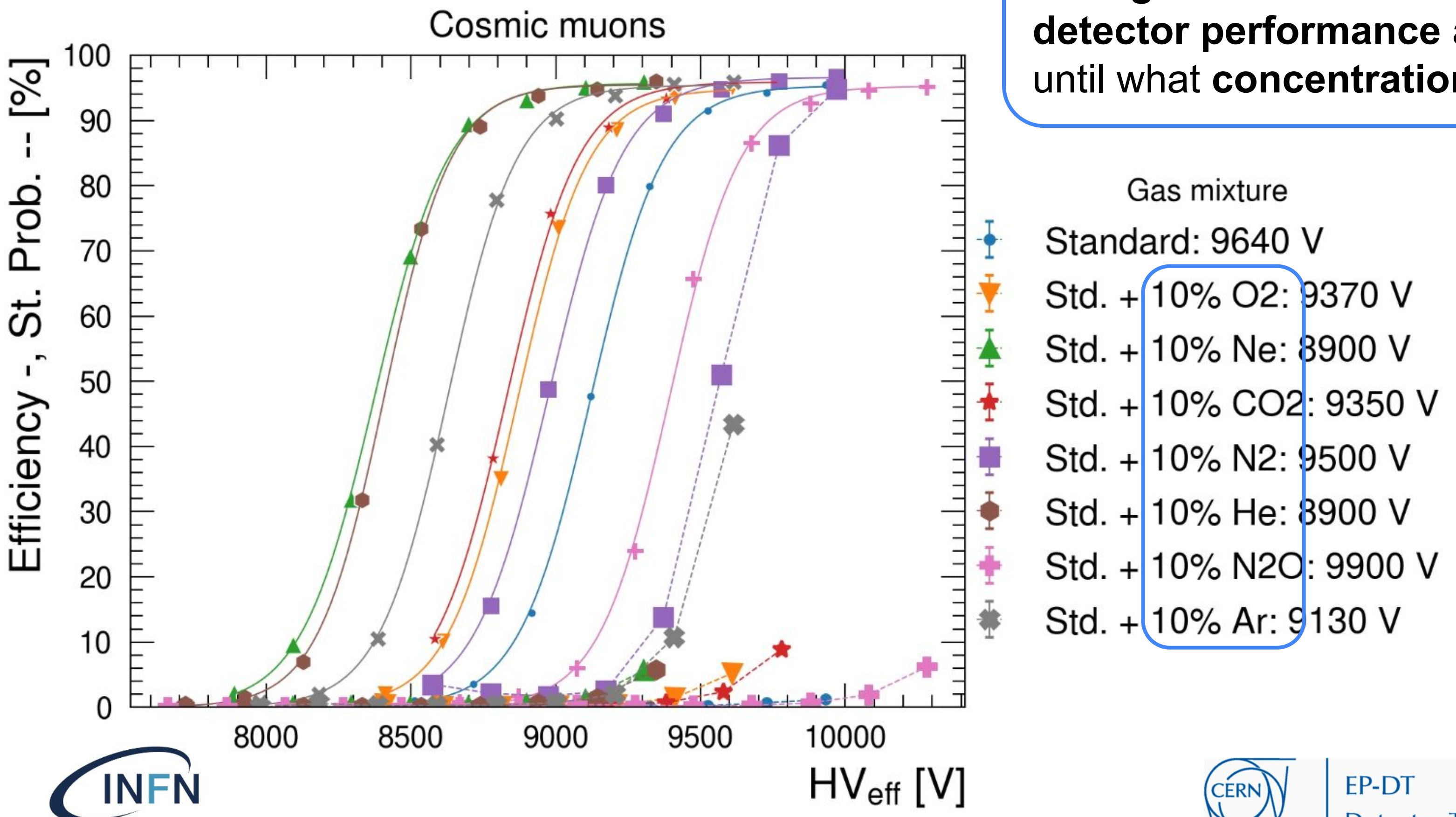
$$\epsilon = \frac{\epsilon_{max}}{1 + e^{-\lambda(HV_{eff} - HV_{50})}}$$

- HVeff is the applied voltage
- HV50 is the voltage at 50% efficiency



Investigation of inert gases

The aim : check if adding an **inert gas** could **affect detector performance** and until what **concentration**



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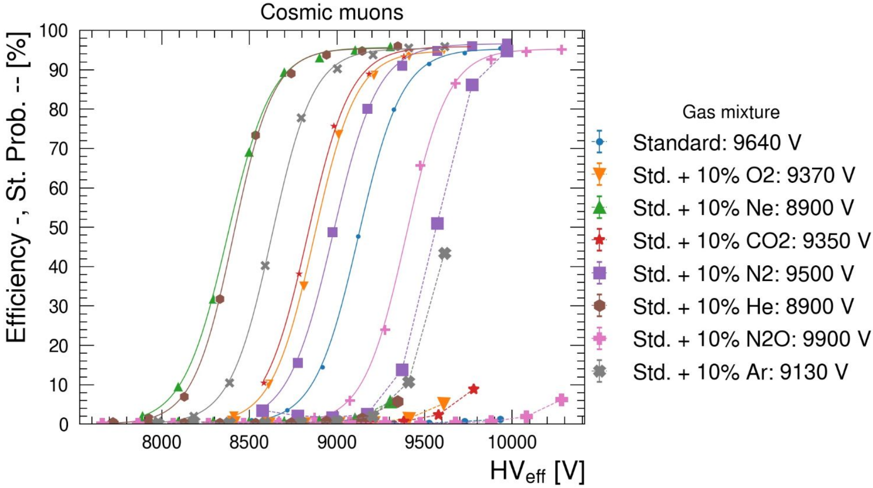
Investigation of inert gases

- **He** : could be a good alternative, but it can't be used at LHC because it's a problem for PMT in the cavern
- **Ne** : WP 900 V lower than STD WP, but it has a restricted availability and high market price
- **O2** : good results for WP and SP, but is a comburant. A slow drift trends for current was observed, it could be related to the high number of oxidation reactions when the detector operates at full efficiency



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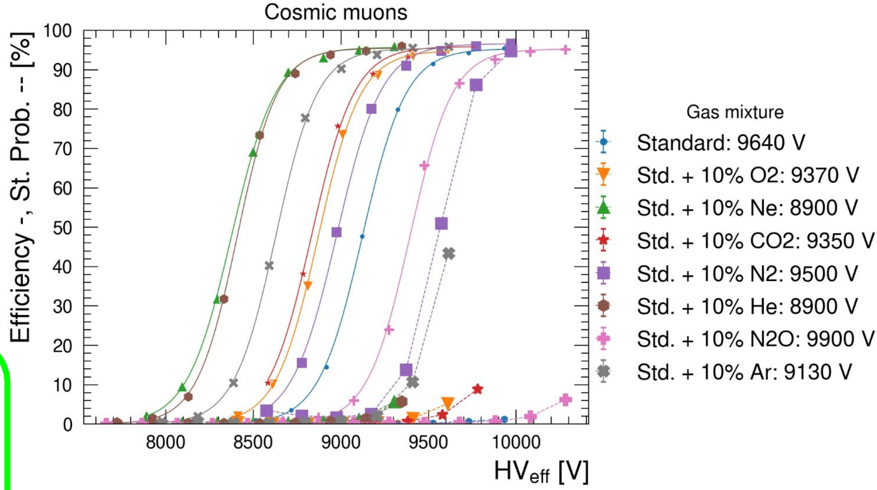
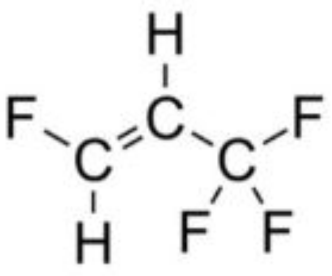
Investigation of inert gases

- **N2** : 10% concentration results in 35% of streamers at WP
- **N2O** : stable performance but WP 300 V higher than STD WP. Difficult to use in higher concentrations
- **CO2** : quencher gas, but it shows a different energy range of photon absorption when compared to i-C4H10 in the RPCs



Tested alternatives to R-134a



R-1234ze (HFO)

GWP : **6**

Higher Working Point,
Streamer Probability, currents

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Raise CO2 concentration **lowering R-134a** percentage

Lower Working Point
Similar properties **to STD** gas mixture

Higher currents

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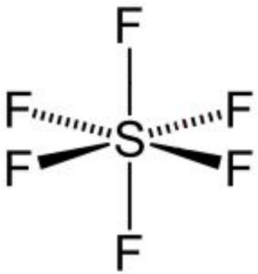
Tested alternative to SF6



Different concentrations of

Sulfur hexafluoride (SF_6)

NOVEC 4710

Highly **electronegative**

GWP : **2100**

May **react** with **water**

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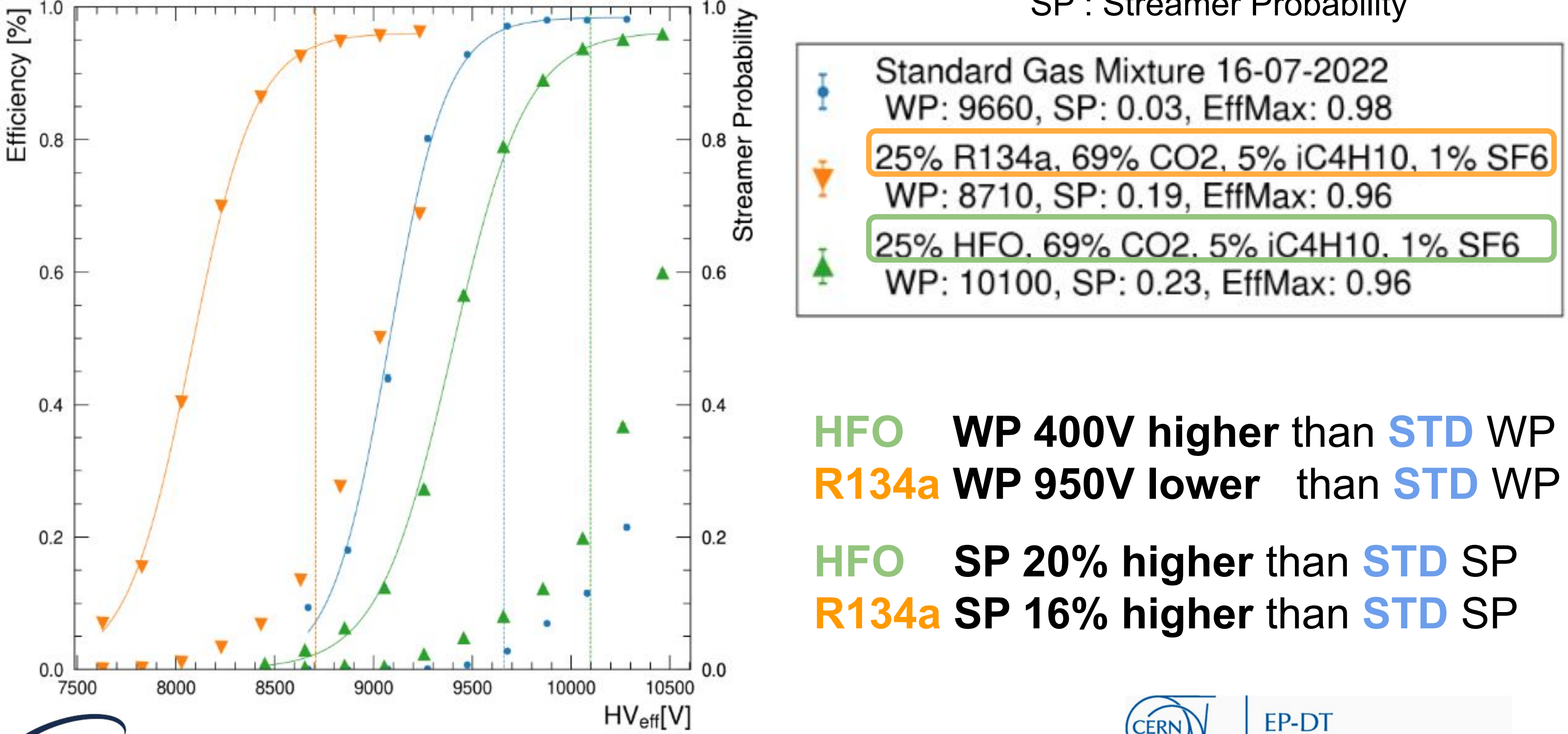
Test Beam Results and Analysis

R-134a VS HFO

WP : Working Point
SP : Streamer Probability



HFO **WP 400V higher** than STD WP
R134a **WP 950V lower** than STD WP

HFO **SP 20% higher** than STD SP
R134a **SP 16% higher** than STD SP

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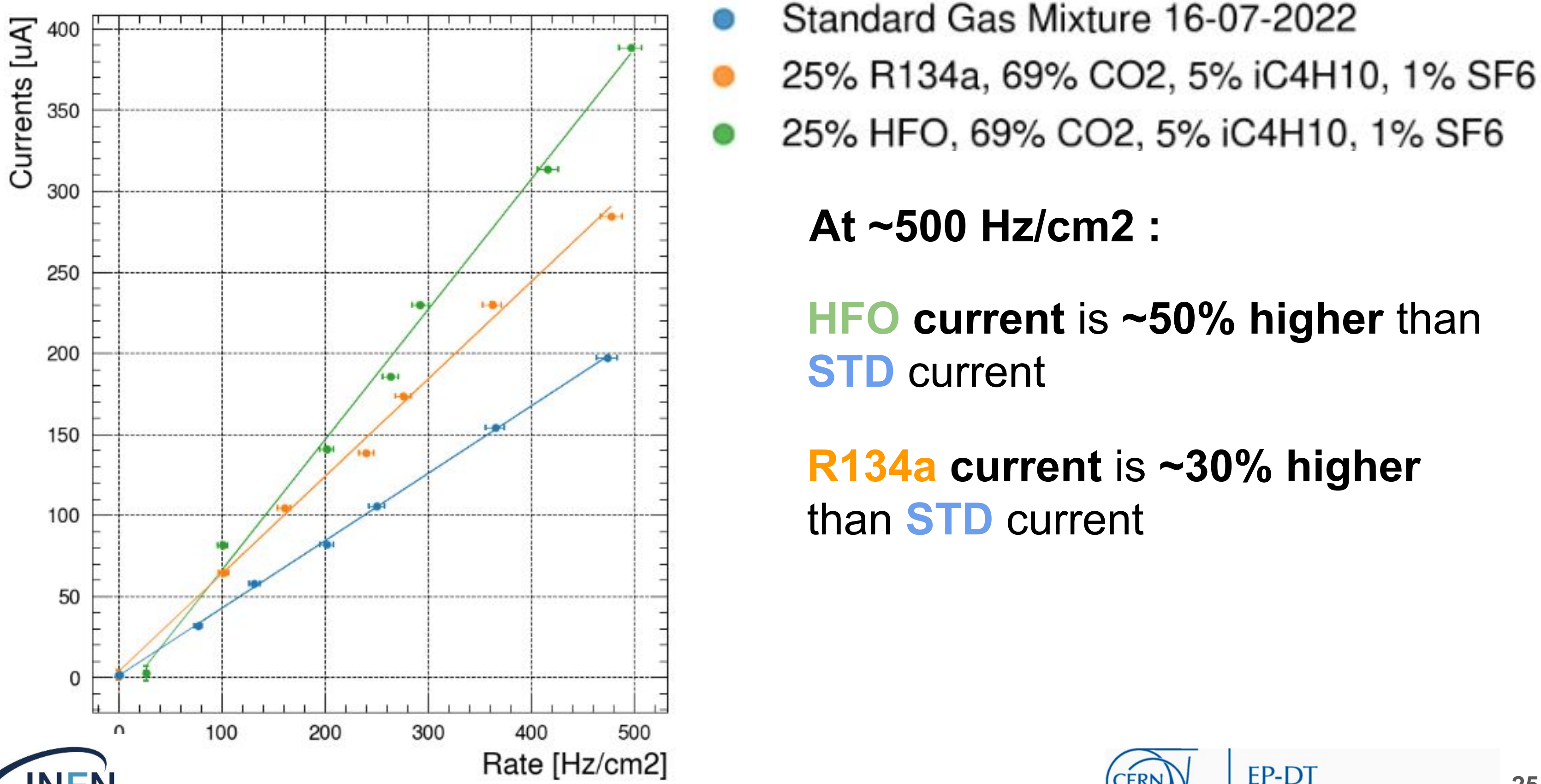
Test Beam Results and Analysis

R-134a VS HFO



At ~500 Hz/cm2 :

HFO current is **~50% higher** than **STD** current

R134a current is **~30% higher** than **STD** current

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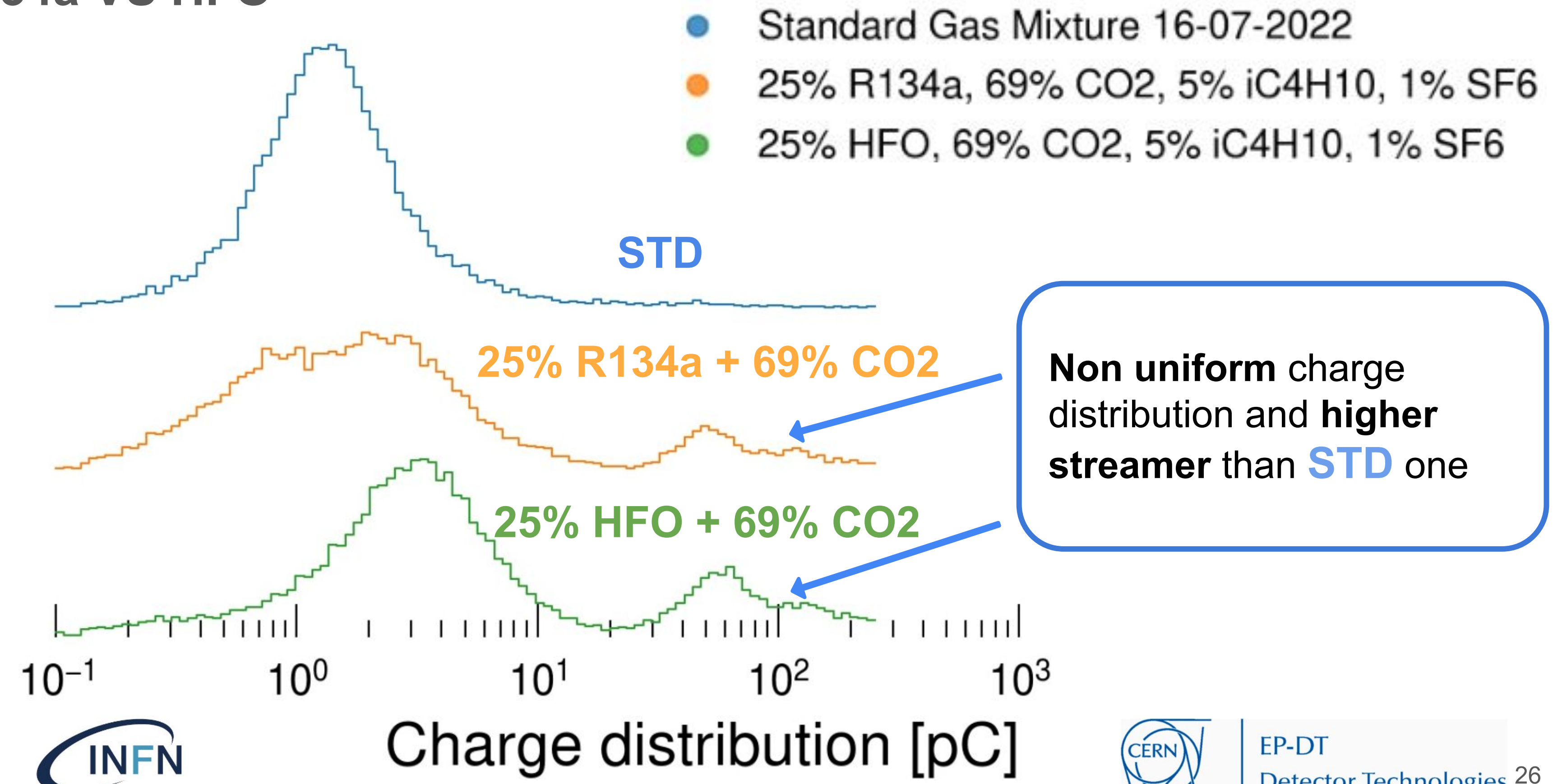
Test Beam Results and Analysis

R-134a VS HFO

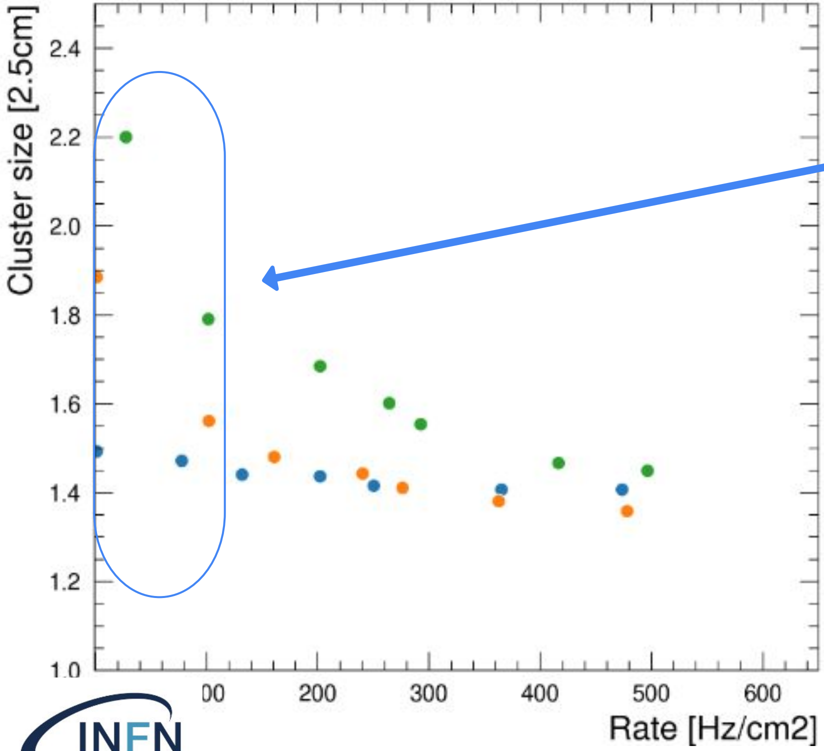


Non uniform charge distribution and **higher streamer** than **STD** one

Test Beam Results and Analysis

R-134a VS HFO

- Standard Gas Mixture 16-07-2022
- 25% R134a, 69% CO2, 5% iC4H10, 1% SF6
- 25% HFO, 69% CO2, 5% iC4H10, 1% SF6



HFO cluster size higher than **STD** one
No good tricking properties at **low rate**

Gas mixture	Time resolution
Standard	2.05 ns
25% R134a + 69% CO_2	1.80 ns
25% HFO + 69% CO_2	1.86 ns

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CO2 as alternative to R134a

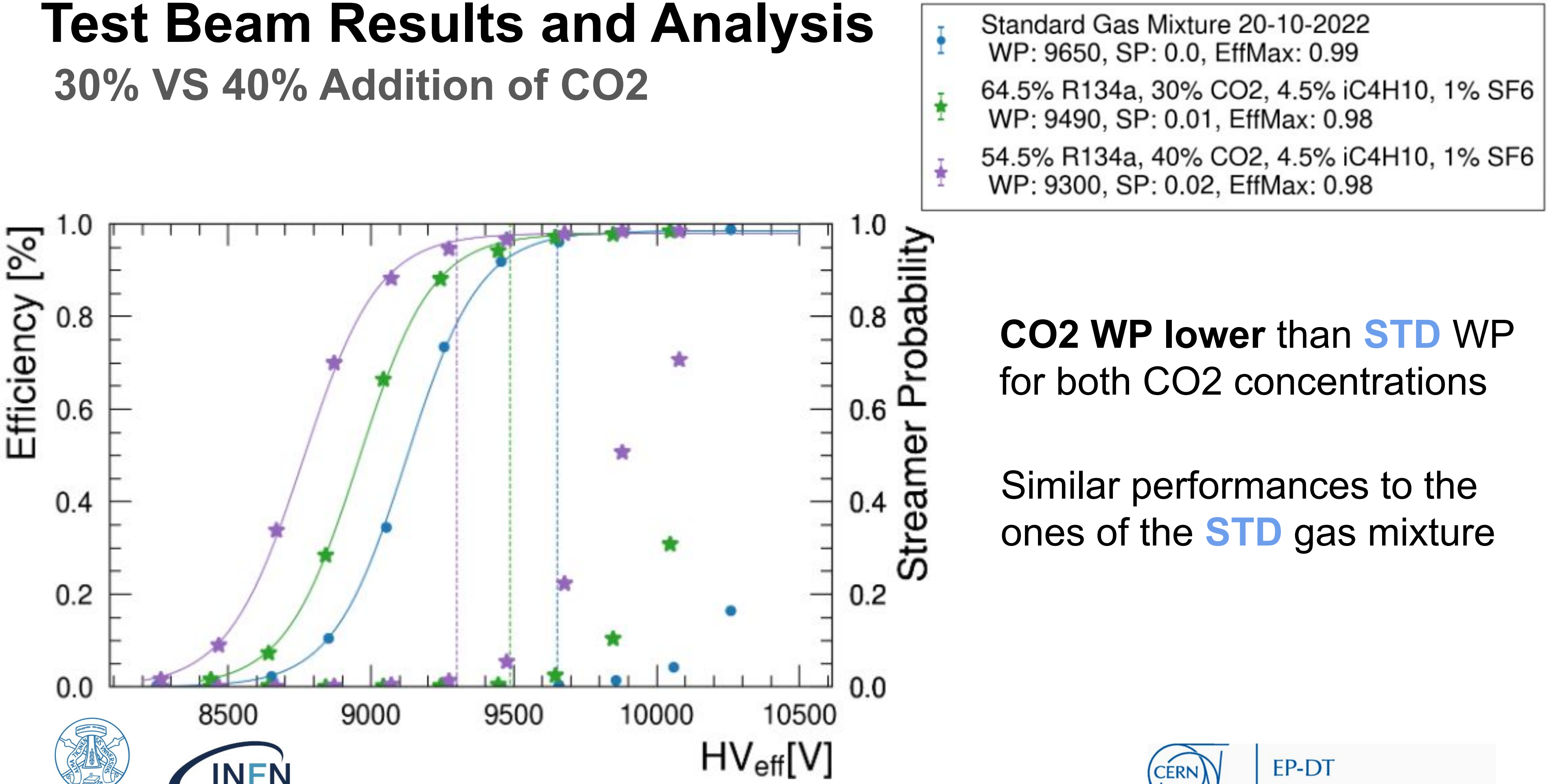
30% VS 40% Addition of CO2 + 1%SF6

Previous studies conducted by the gas group showed that an increased amount of SF6 up to 0.6% and 0.9% in the CO2 based gas mixture could help to suppress the streamer signals

Here the link of the studies :
https://doi.org/10.1016/j.nima.2023.168088

Test Beam Results and Analysis

30% VS 40% Addition of CO2



CO2 WP lower than **STD** WP for both CO2 concentrations

Similar performances to the ones of the **STD** gas mixture

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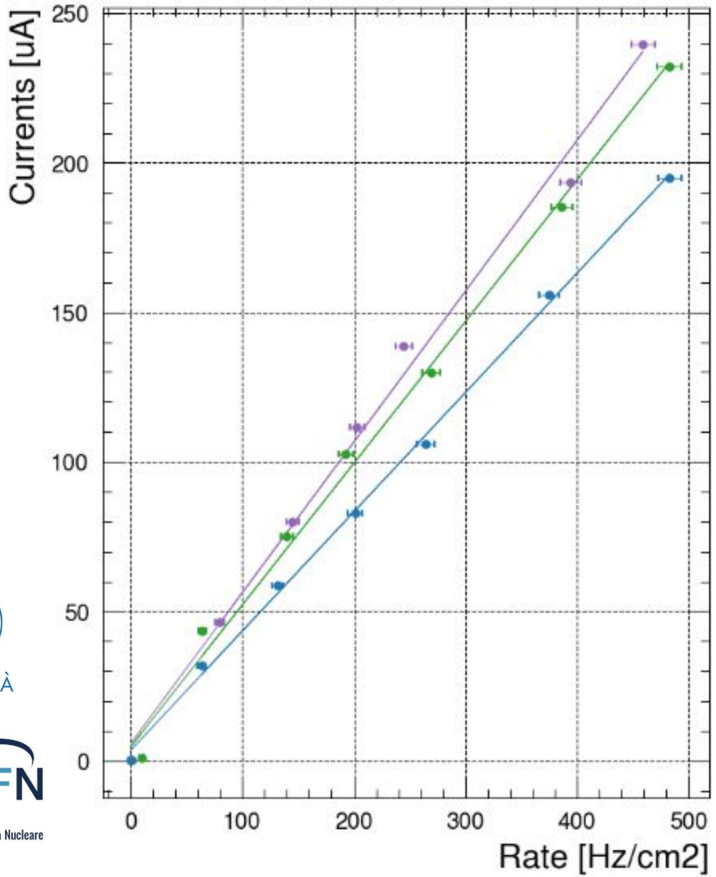
Test Beam Results and Analysis

30% VS 40% Addition of CO_2



At ~ **400 Hz/cm2 currents** are ~ **15% higher** than **STD** current

A reduced amount of CO_2 reduces the currents

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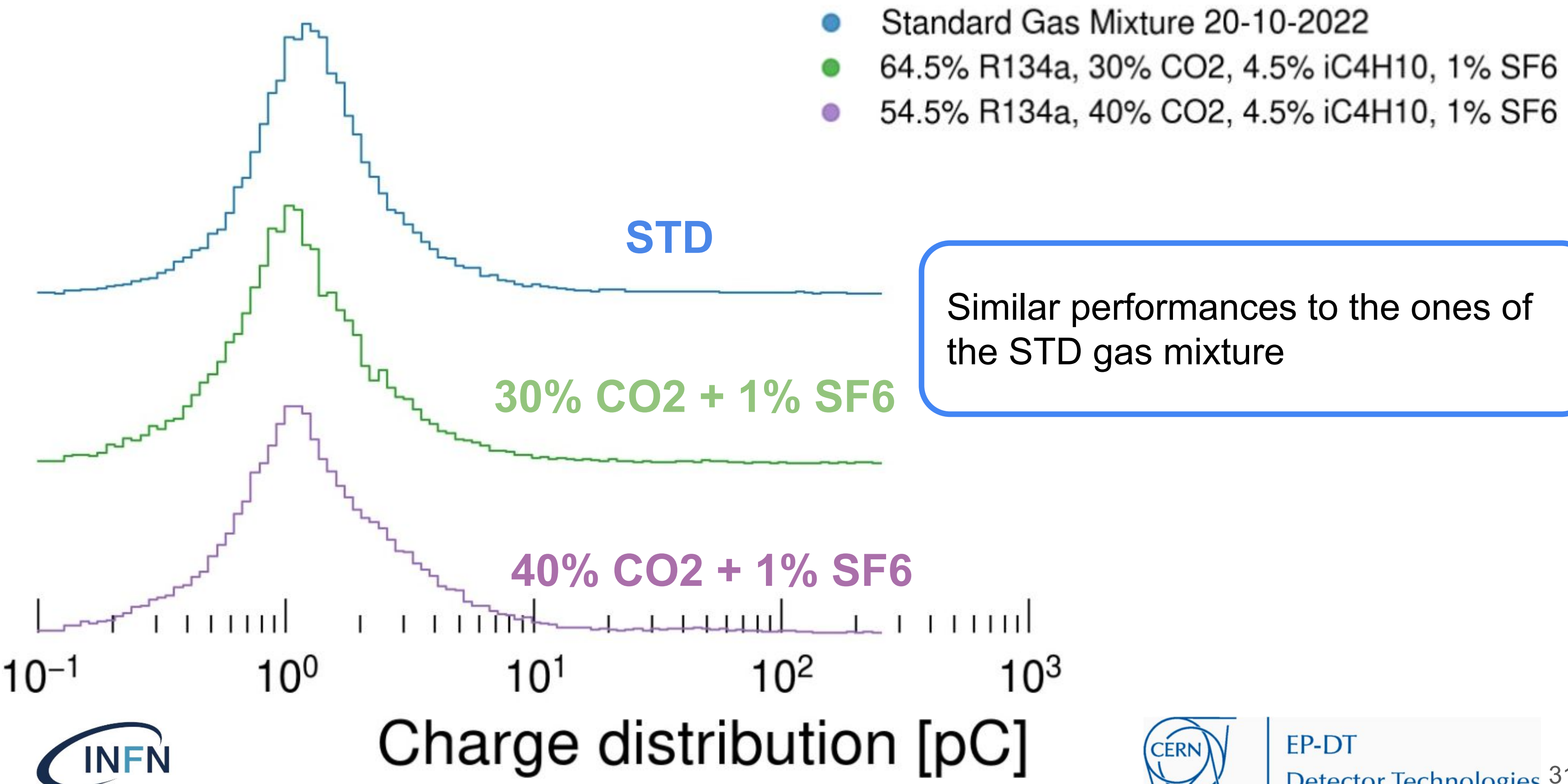
Test Beam Results and Analysis

30% VS 40% Addition of CO_2



Similar performances to the ones of the STD gas mixture

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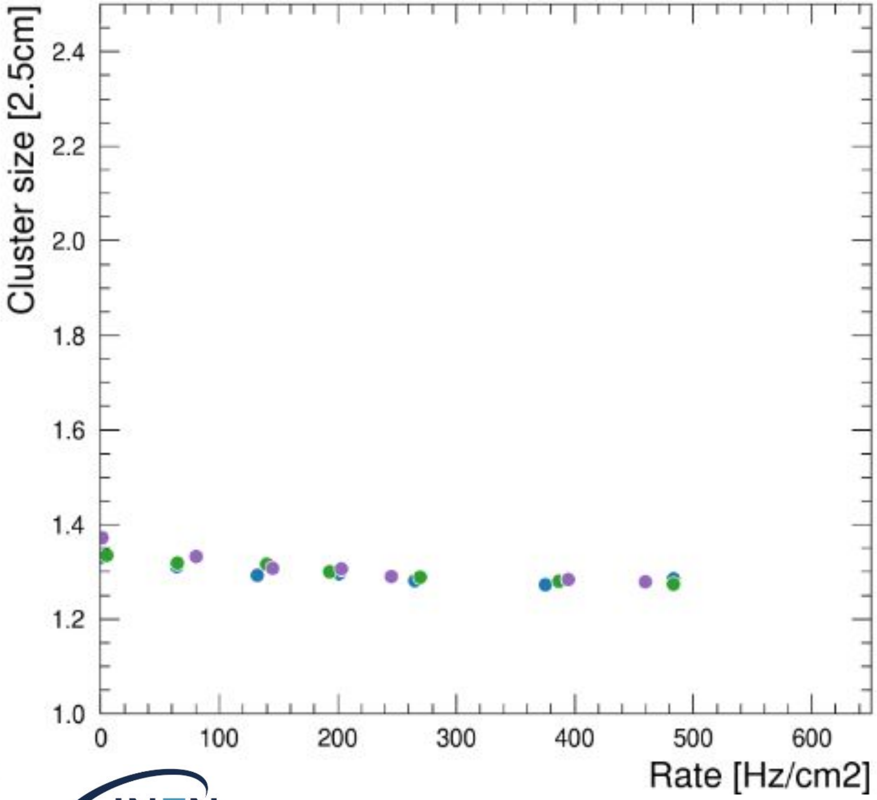
Test Beam Results and Analysis

30% VS 40% Addition of CO2



- Standard Gas Mixture 20-10-2022
- 64.5% R134a, 30% CO2, 4.5% iC4H10, 1% SF6
- 54.5% R134a, 40% CO2, 4.5% iC4H10, 1% SF6

Similar performances to the ones of the STD gas mixture

Gas mixture	Time resolution
Standard	1.62 ns
30% CO_2 + 1% SF_6	1.45 ns
40% CO_2 + 1% SF_6	1.45 ns

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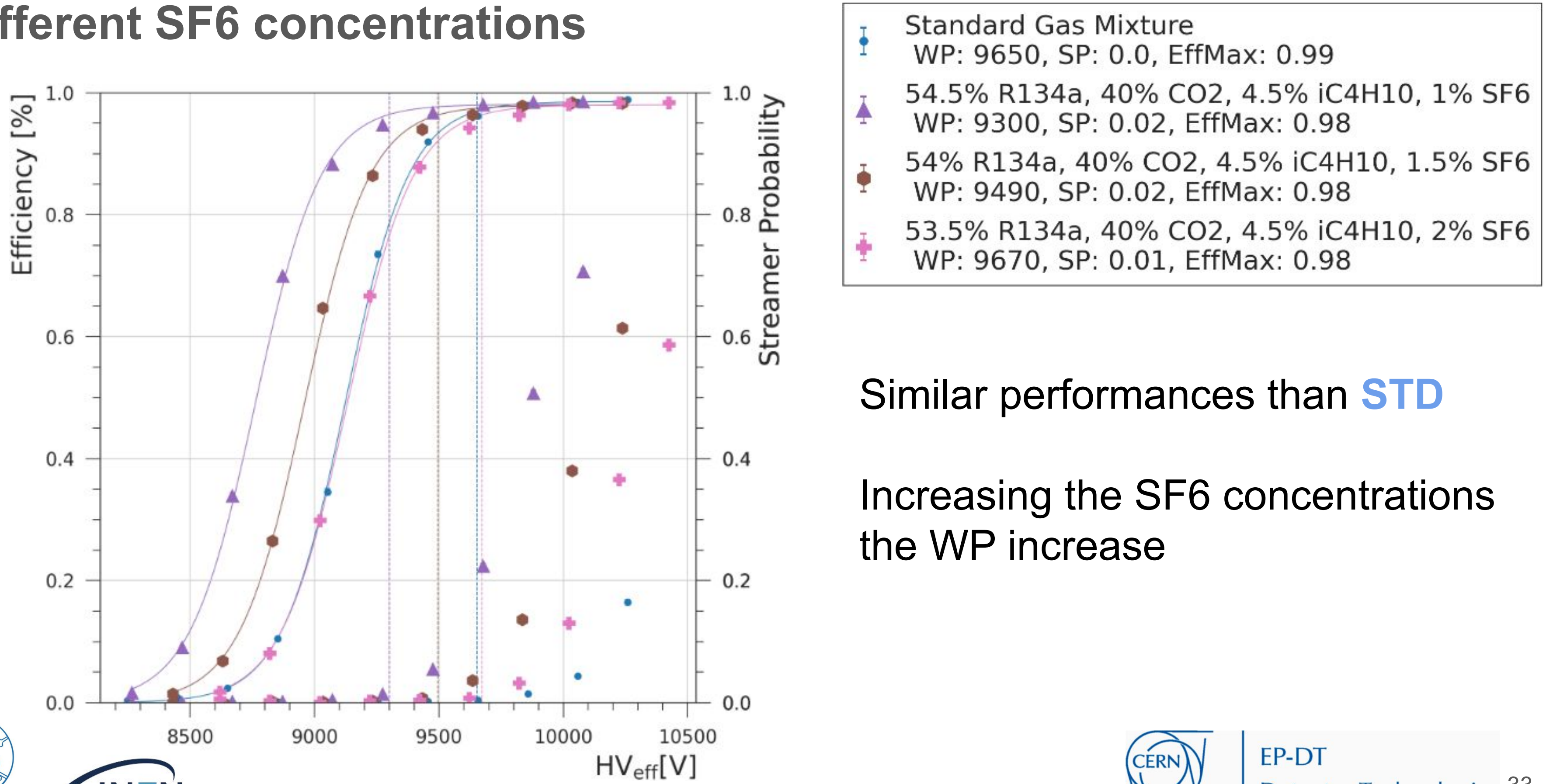
Test Beam Results and Analysis

Different SF6 concentrations



Similar performances than **STD**

Increasing the SF6 concentrations the WP increase

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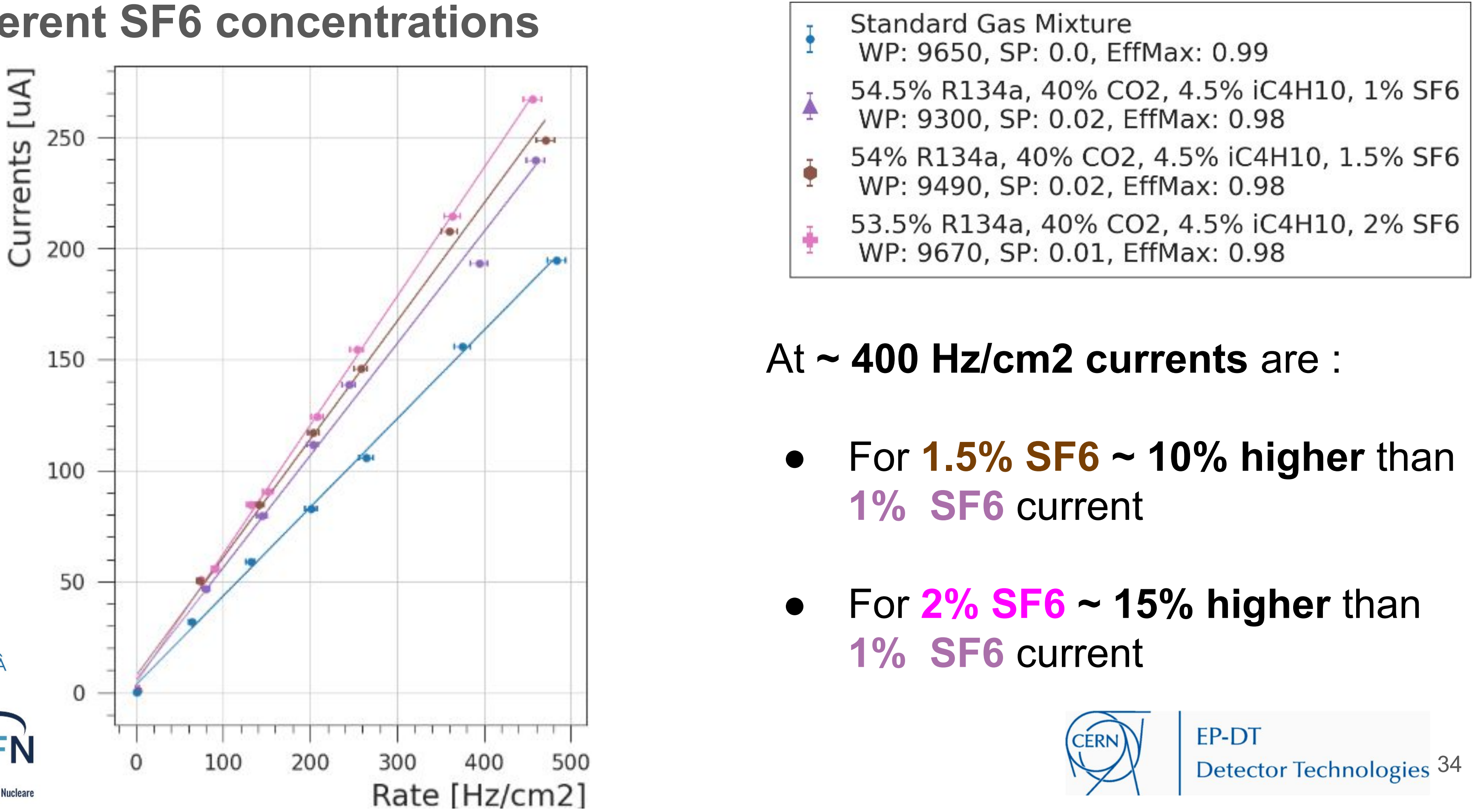
Test Beam Results and Analysis

Different SF6 concentrations



At ~ **400 Hz/cm2 currents** are :

- For **1.5% SF6** **~ 10% higher** than **1% SF6** current
- For **2% SF6** **~ 15% higher** than **1% SF6** current

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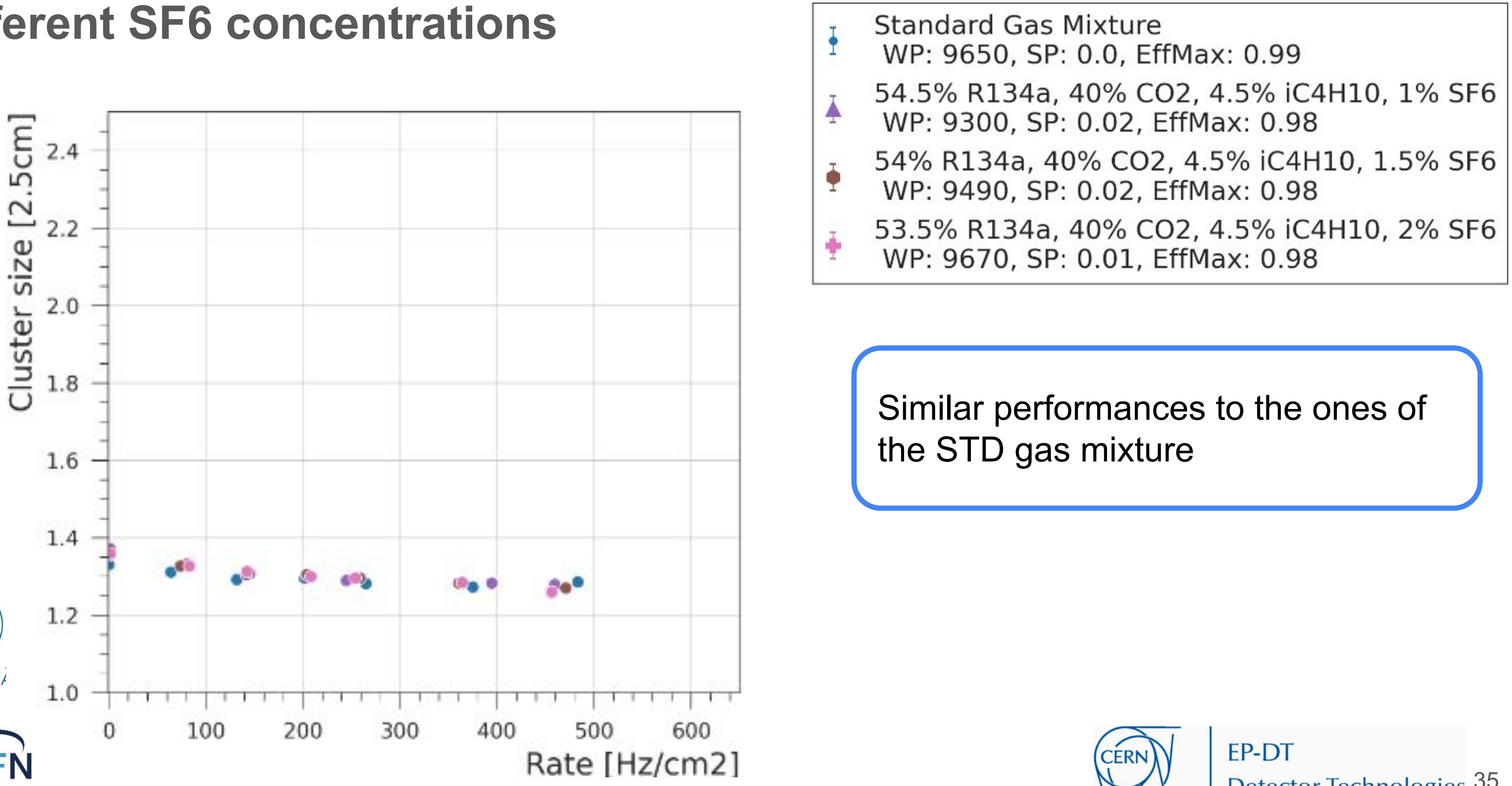
Test Beam Results and Analysis

Different SF6 concentrations



Similar performances to the ones of the STD gas mixture

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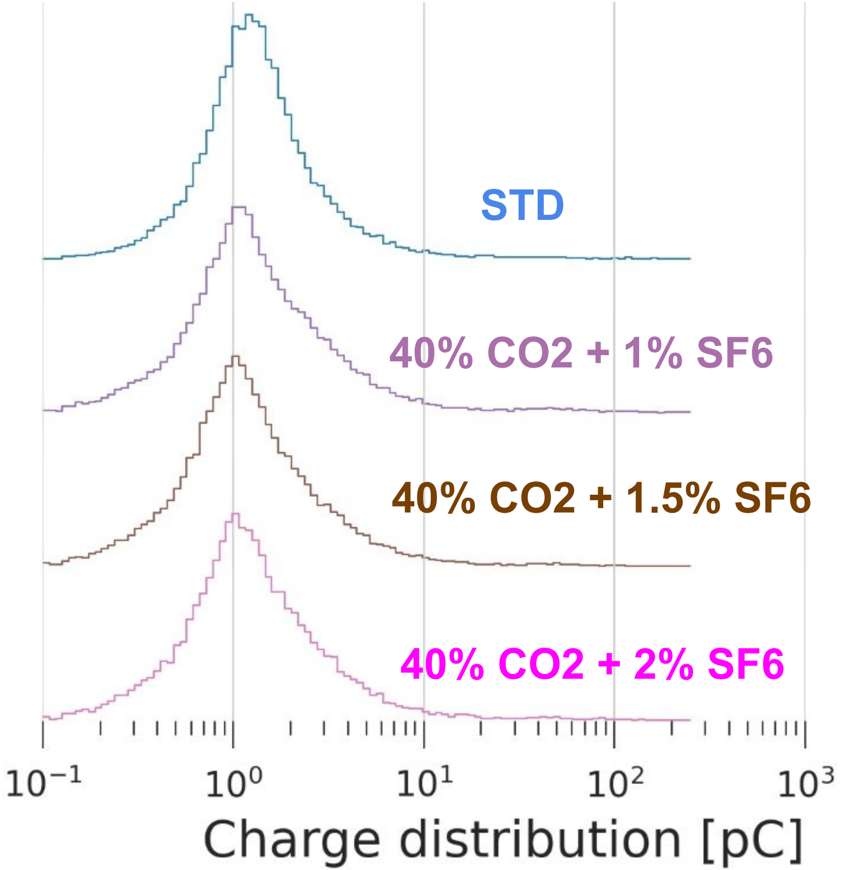
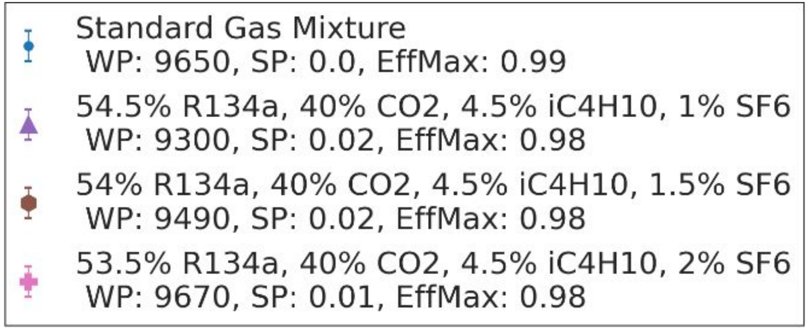
Test Beam Results and Analysis

Different SF6 concentrations





No significant **variation** in the **charge distribution and streamer signal increasing the SF6** concentration more than 1%

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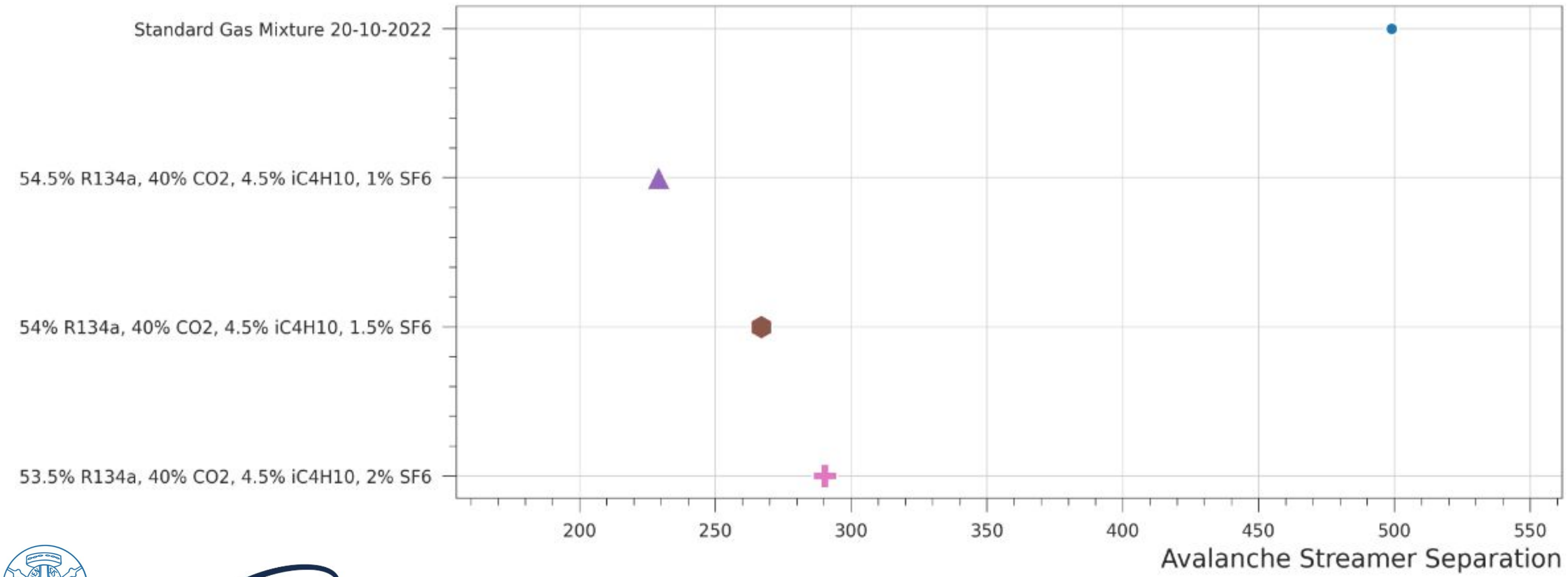
Test Beam Results and Analysis

Different SF6 concentrations

Avalanche streamer separation : difference in voltage between the WP and the voltage at which the SP is 10%



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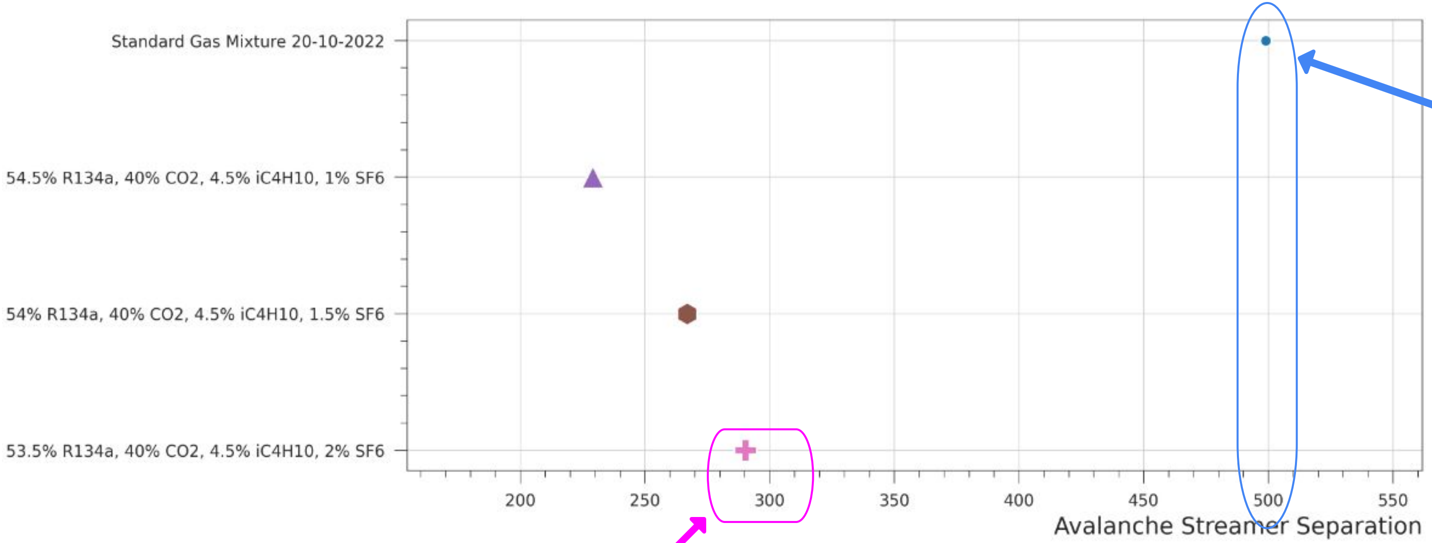
Test Beam Results and Analysis

Different SF6 concentrations

An **increased** amount of **SF6** could help **suppress the streamer signals**



The **STD** the best avalanche-streamer separation

The **2% SF6** show the highest separation among the gas mixtures tested

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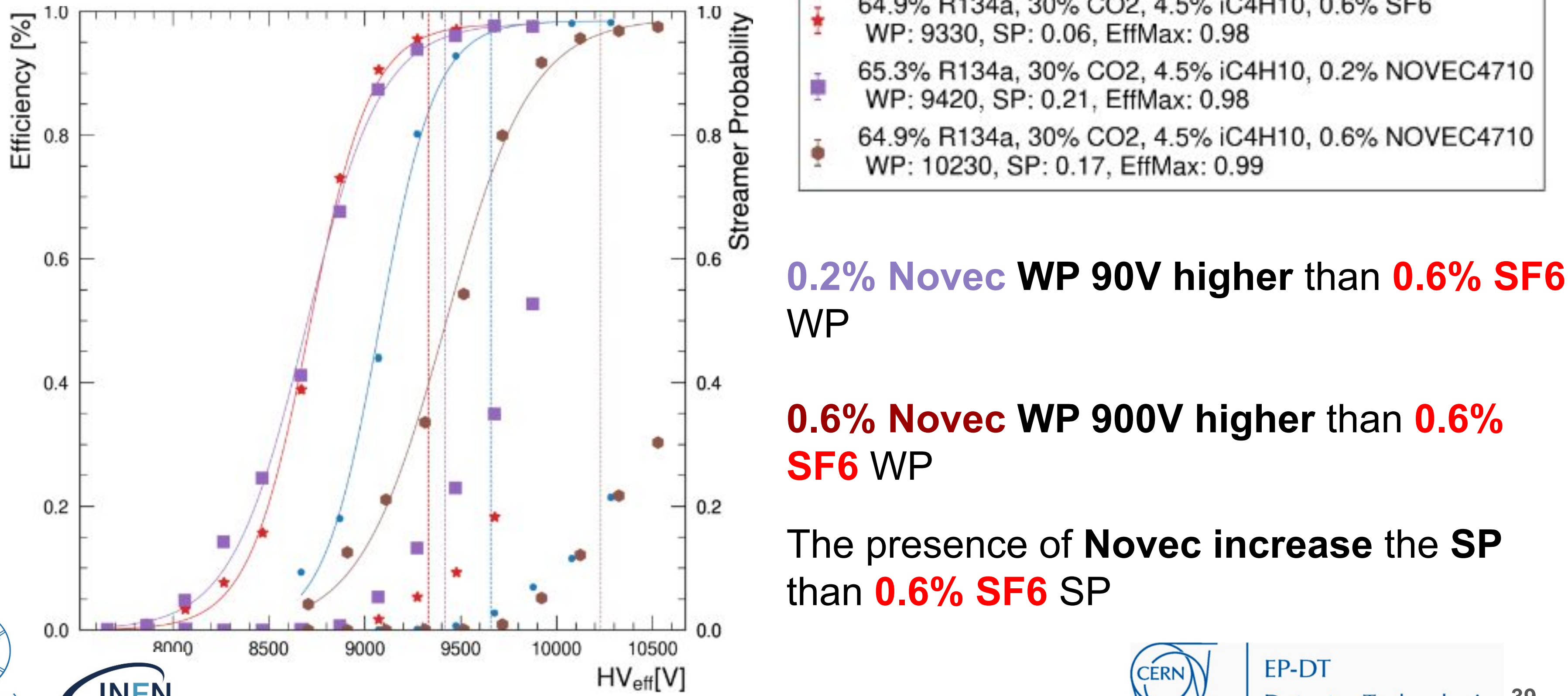
Test Beam Results and Analysis

Replacing SF6 with Novec 4710



0.2% Novec **WP 90V higher** than 0.6% SF6 WP

0.6% Novec **WP 900V higher** than 0.6% SF6 WP

The presence of **Novec increase** the **SP** than 0.6% SF6 SP

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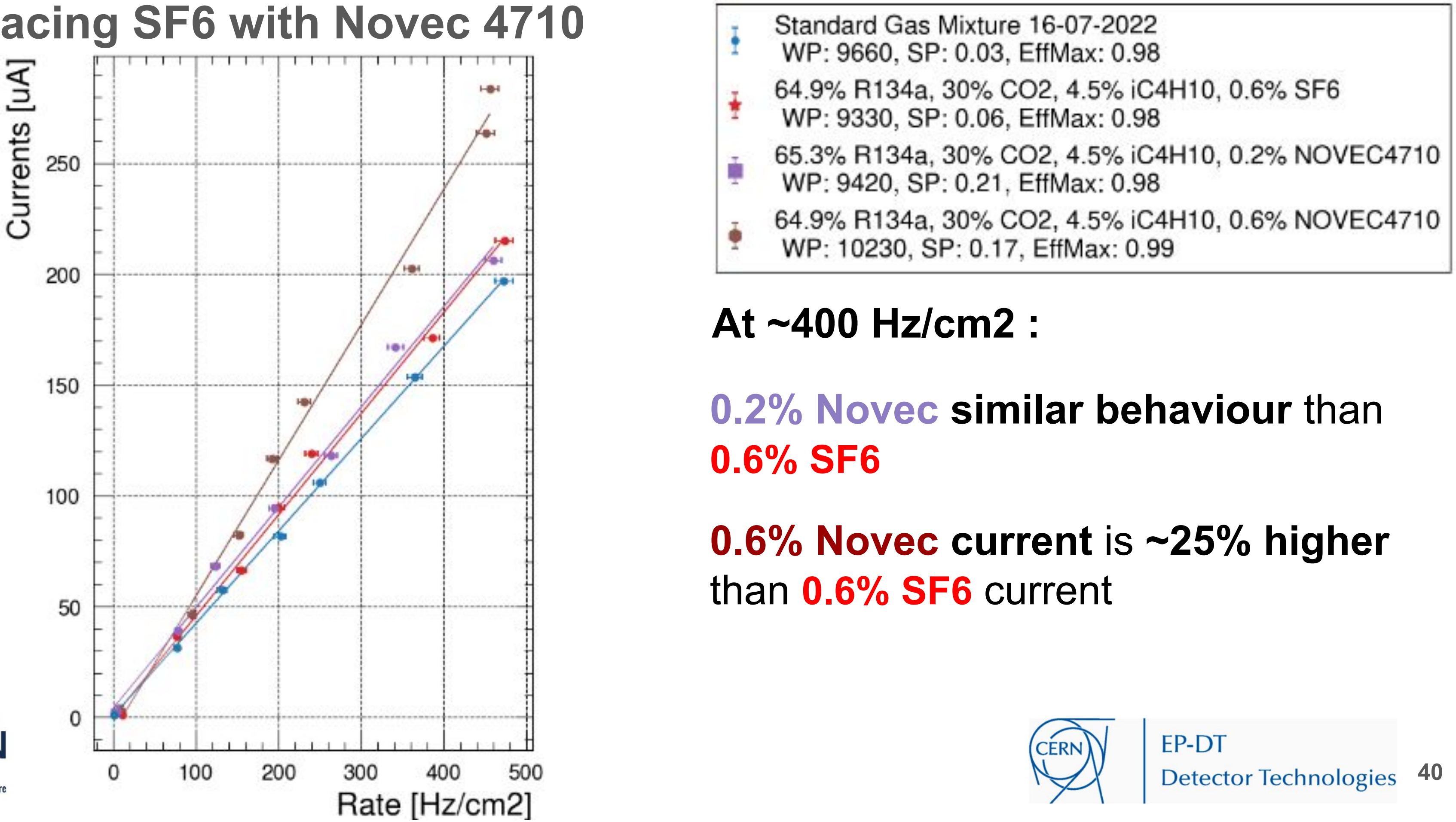
Test Beam Results and Analysis

Replacing SF6 with Novec 4710



At ~400 Hz/cm2 :

0.2% Novec similar behaviour than **0.6% SF6**

0.6% Novec current is **~25% higher** than **0.6% SF6** current

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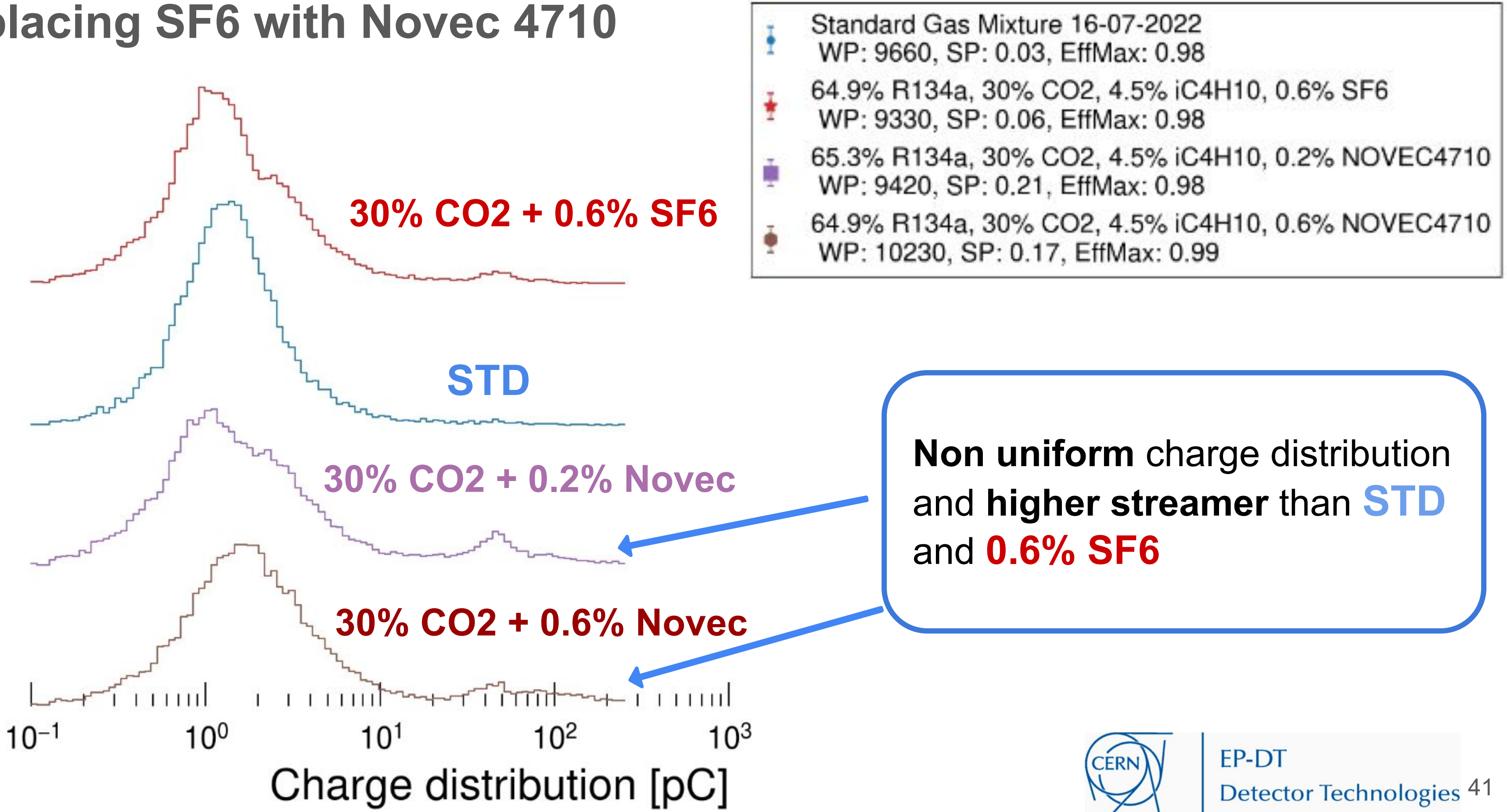

Non uniform charge distribution and **higher streamer** than STD and 0.6% SF6

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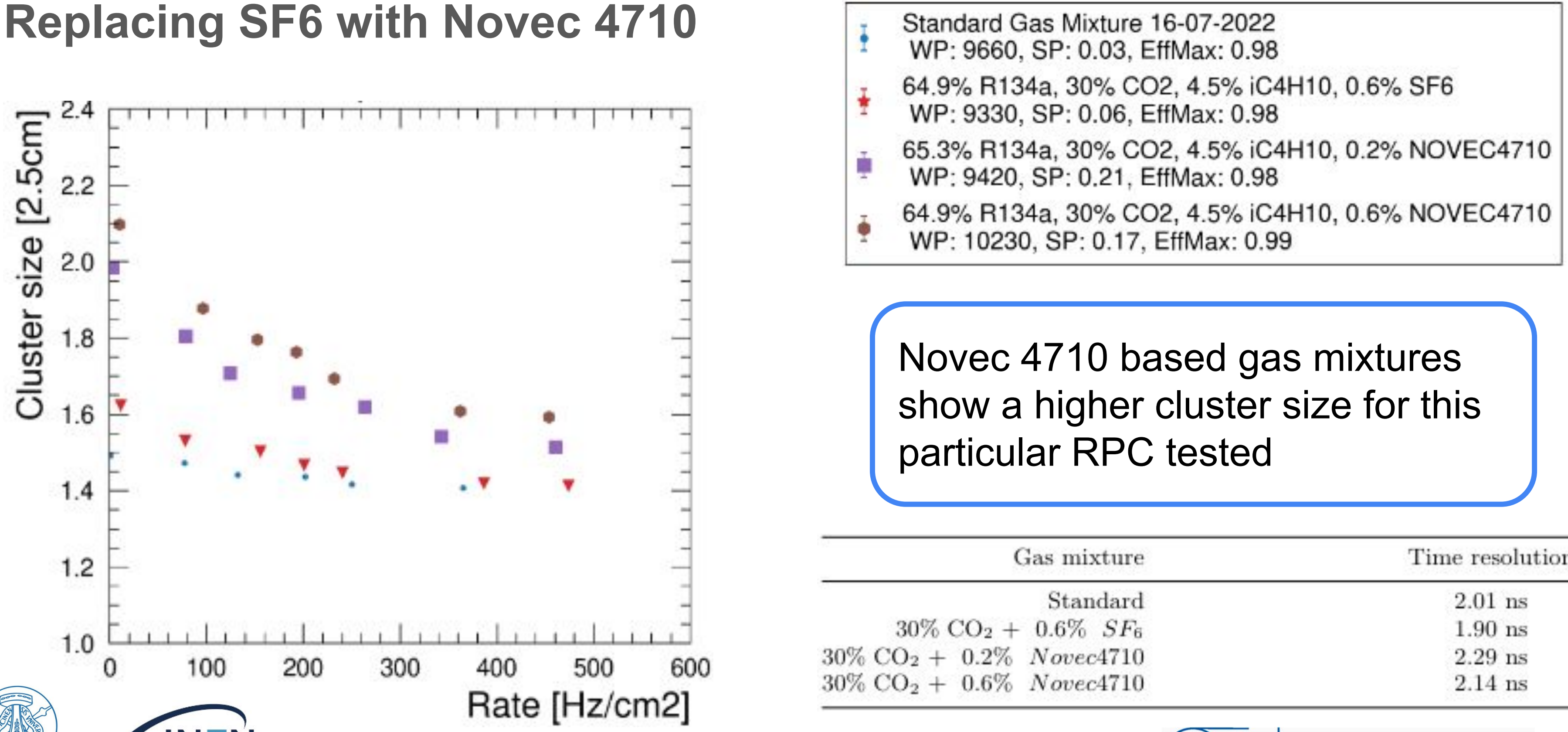

Novec 4710 based gas mixtures show a higher cluster size for this particular RPC tested

Gas mixture	Time resolution
Standard	2.01 ns
30% CO_2 + 0.6% SF_6	1.90 ns
30% CO_2 + 0.2% $Novec4710$	2.29 ns
30% CO_2 + 0.6% $Novec4710$	2.14 ns

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Conclusions

- HFO **+ CO_2** shows **higher Working Point and Currents** than R134a **+ CO_2**
- 0.2% Novec has **good performances** and similar to the STD ones
- **The increase of Novec** concentration leads to the **increase of currents**
- **Novec 4710** may **react with water,** further investigations are needed

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Conclusions

- **Lower CO_2 concentration** shows **good performances**, allowing to reduce the R134a amount

- More tests were performed with **30% CO_2 + 1% SF_6 gas mixture** and it was selected from the **Gas Team and ATLAS group** for the **aging tests**

- Since last month **30% CO_2 and 1% SF_6 Gas Mixture** has started to be used in **ATLAS RPCs at LHC experiment**

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Thank you for your attention