Environment-friendly gas mixtures for Resistive Plate Chambers: an experimental and simulation study

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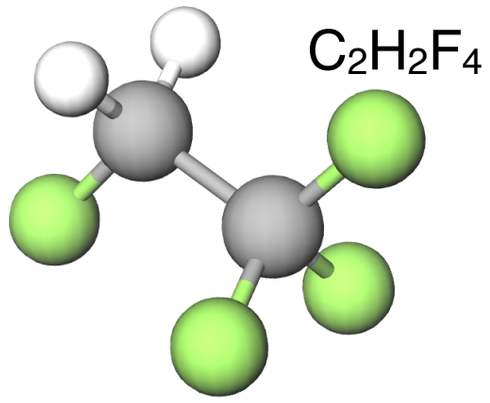
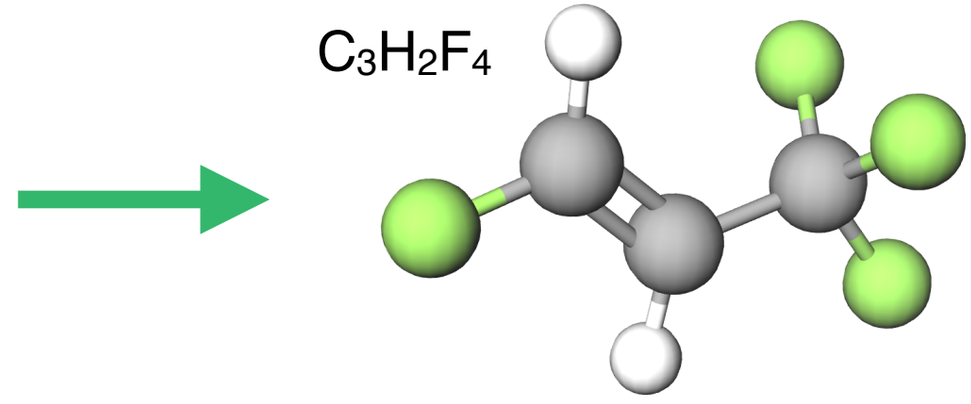
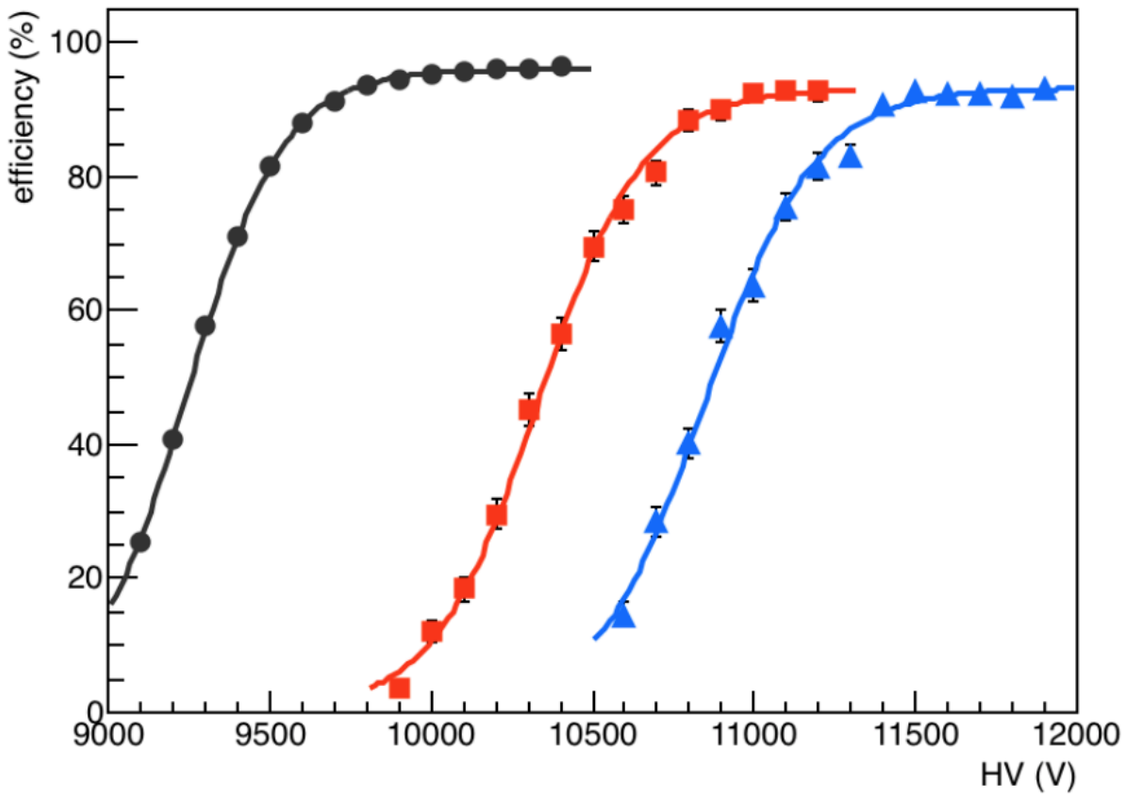
Outline

- **Search of environment-friendly gas mixture**
  - experimental approach
  - simulation approach

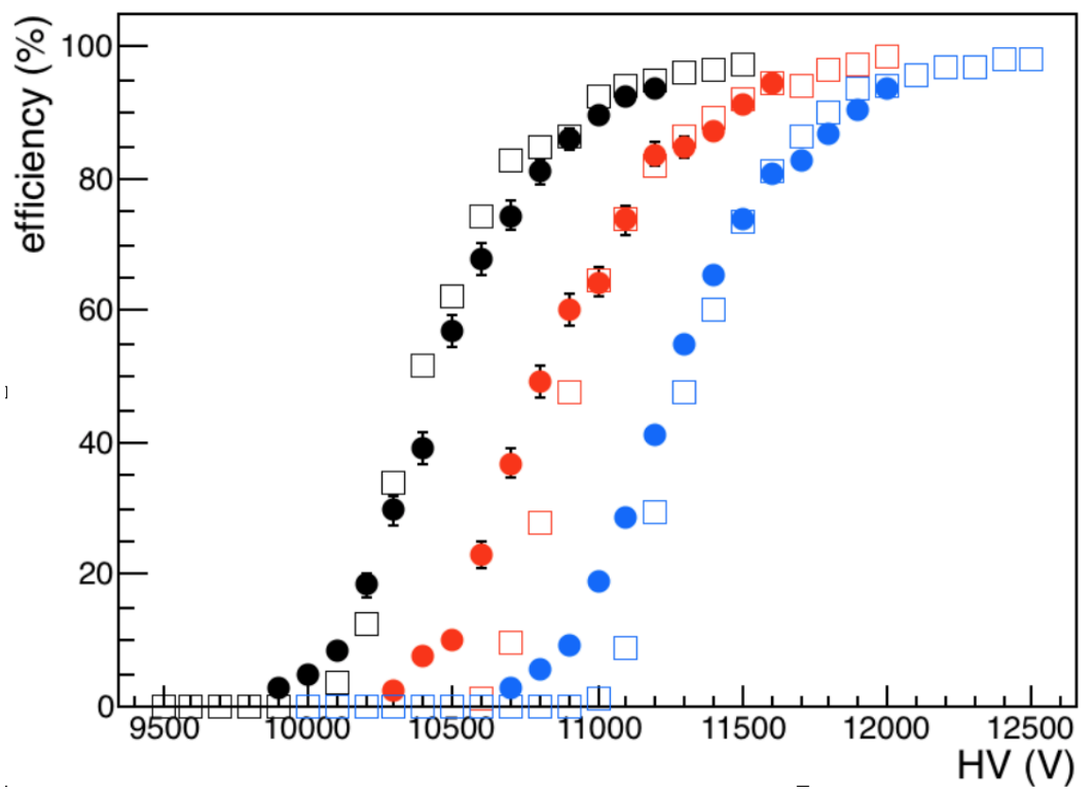




measurements



simulations



R&D studies on ALICE muon RPCs

"I want Europe to become the first climate-neutral continent in the world by 2050"
Ursula von der Leyen — European Commission

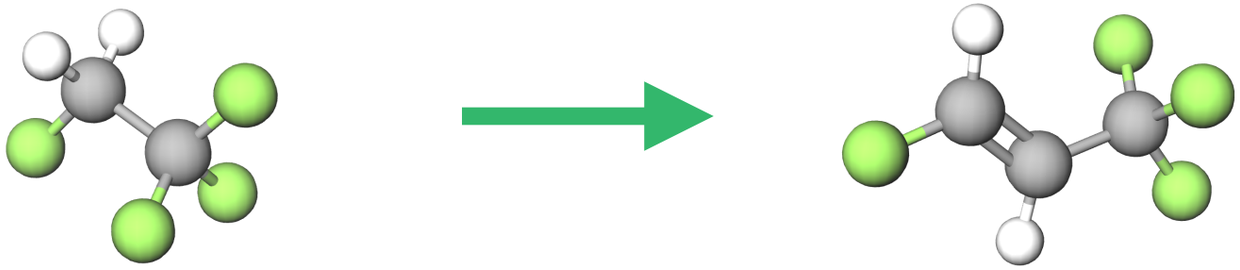
- Recent European regulations have imposed the reduction of the emissions of fluorinated greenhouse gases (e.g. $C_2H_2F_4$) since January 2015
- CERN has elaborated a number of strategies to reduce greenhouse gas emissions

Motivation for R&D studies on a new gas mixture for RPCs:

- **reduce greenhouse gas emissions** in the atmosphere
- **cost saving**: $C_2H_2F_4$ is being phased out by EU regulations → **limited future availability and possible rise of prices in the coming years**

Properties of $C_3H_2F_4$

95% of the total GWP of the RPC mixture is due to the presence of $C_2H_2F_4$, therefore:



$C_2H_2F_4$ $C_3H_2F_4$

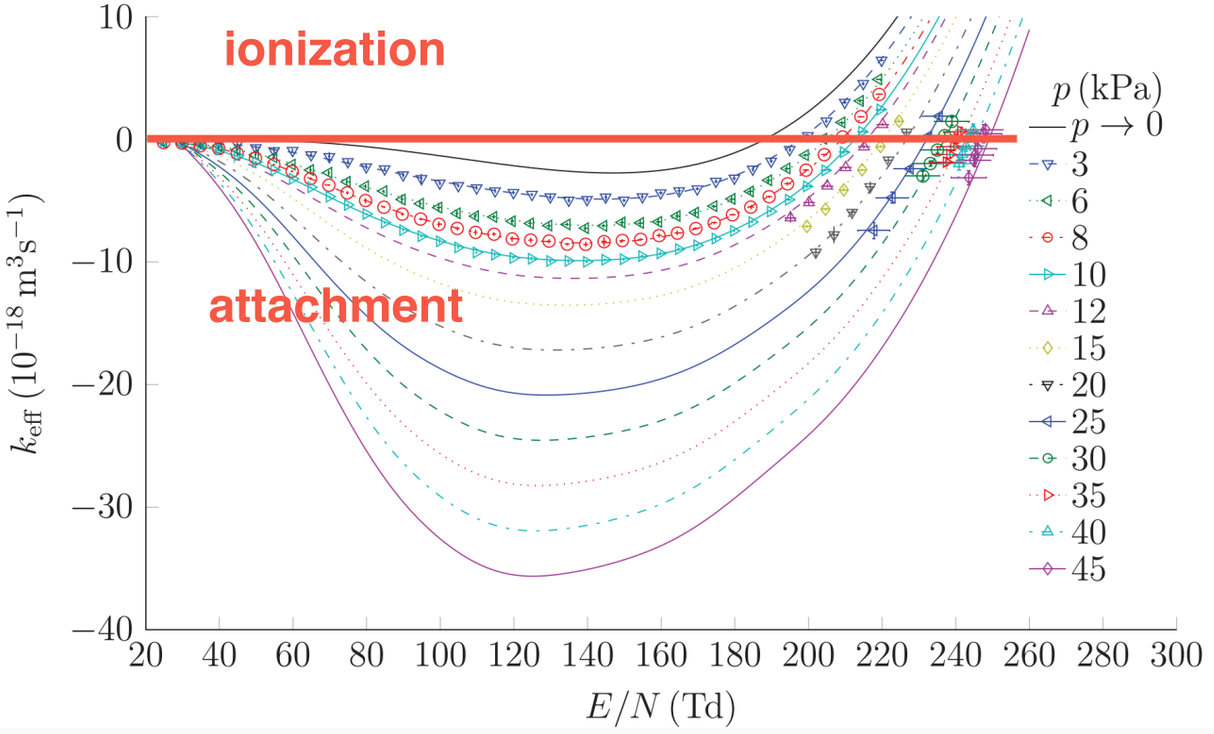
Some references:
M. Abbrescia *et al* 2016 *JINST* **11** P08019
R. Guida *et al* 2016 *JINST* **11** C07016
B. Liberti *et al* 2016 *JINST* **11** C09012
A. Bianchi 2019 *JINST* **14** C09003

Tetrafluoropropene $C_3H_2F_4$ (HFO1234ze(E)):

- HFO1234ze(E) is **not flammable** at room temperature and its **GWP = 7***
- Products of the atmospheric oxidation of HFO1234ze(E) have negligible environmental impact
  → Javadi, M. S., et al., Atmospheric Chemistry and Physics, 2008
- N_p = ~90/cm and E_{ion} = ~9 eV
  → simulation by Saviano, G., et al., *JINST* 13.03, 2018
- the **strong electron attachment makes $C_3H_2F_4$ a promising gas for electric insulation**
  → Rabie M., et al., *Environmental science & technology* 52.2, 2018

*5th Intergovernmental Panel on Climate Change (IPCC) has revised this value: GWP < 1

Effective ionization rate coefficient as a function of the reduced electric field:



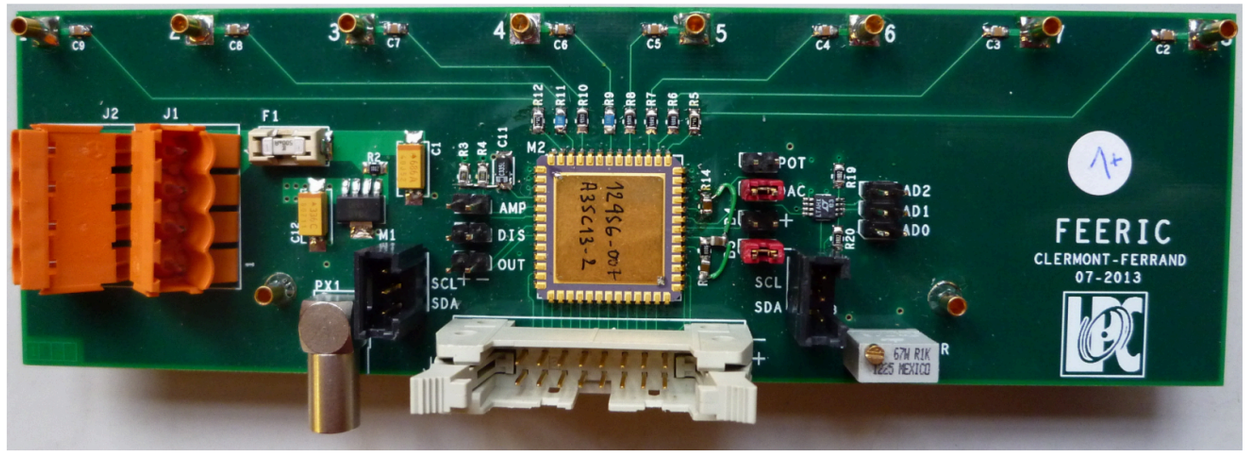
Chachereau A., et al, *Plasma Sources Science and Technology* 25.4, 2016.

Pressure dependence of k_{eff} is a typical indication of **three-body attachment**

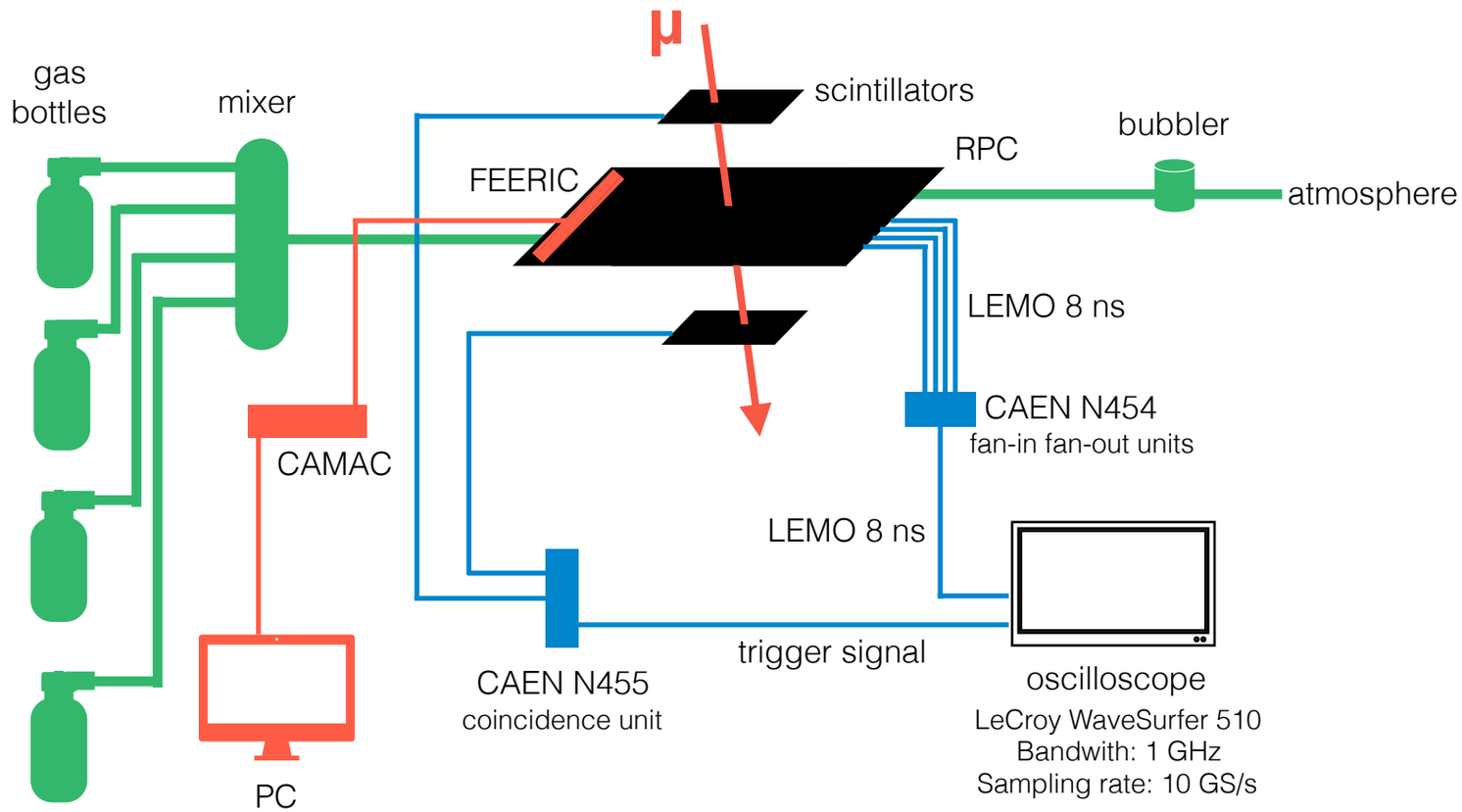
Experimental set-up

R&D studies on eco-friendly gas mixtures:

- small-size (50 x 50 x 0.2 cm^3) RPC inside a Faraday cage
- trigger: three scintillators coupled with photomultipliers
- HV is applied with temperature and pressure correction (p_0 = 1000 mbar and T_0 = 20 °C)
- possibility to mix at maximum 4 different gases with H_2O vapor
- signals in read-out strips (2 x 50 cm^2) **discriminated by FEERIC front-end electronics and acquired by oscilloscope**
- FEERIC amplifies signals (input charge range = 0.1÷1 pC)



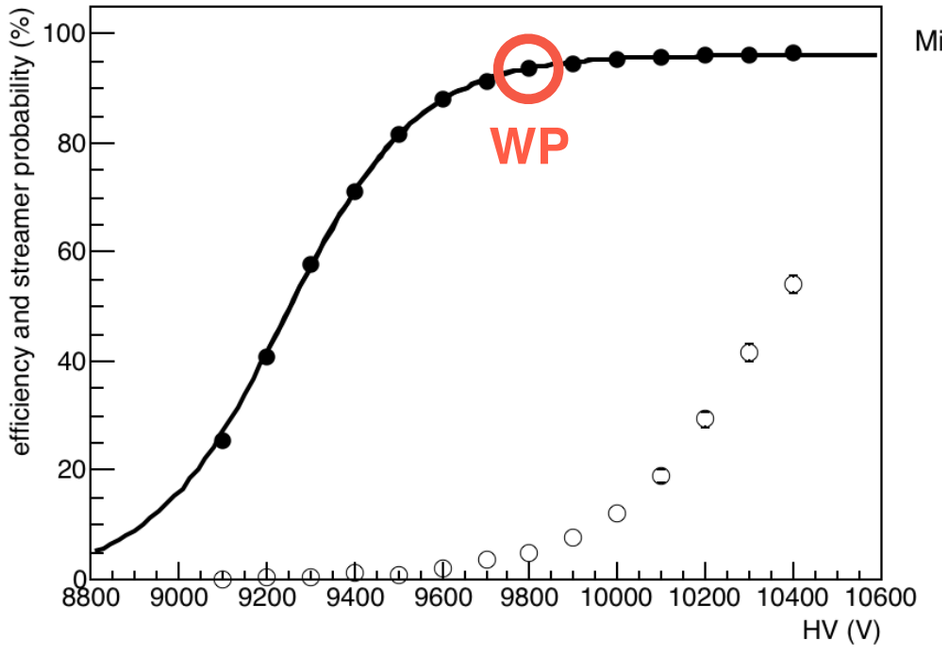
Dupieux P. et al., *Upgrade of the ALICE muon trigger electronics*, JINST 9.09 (2014)



total trigger area: ~6 x 6 cm^2

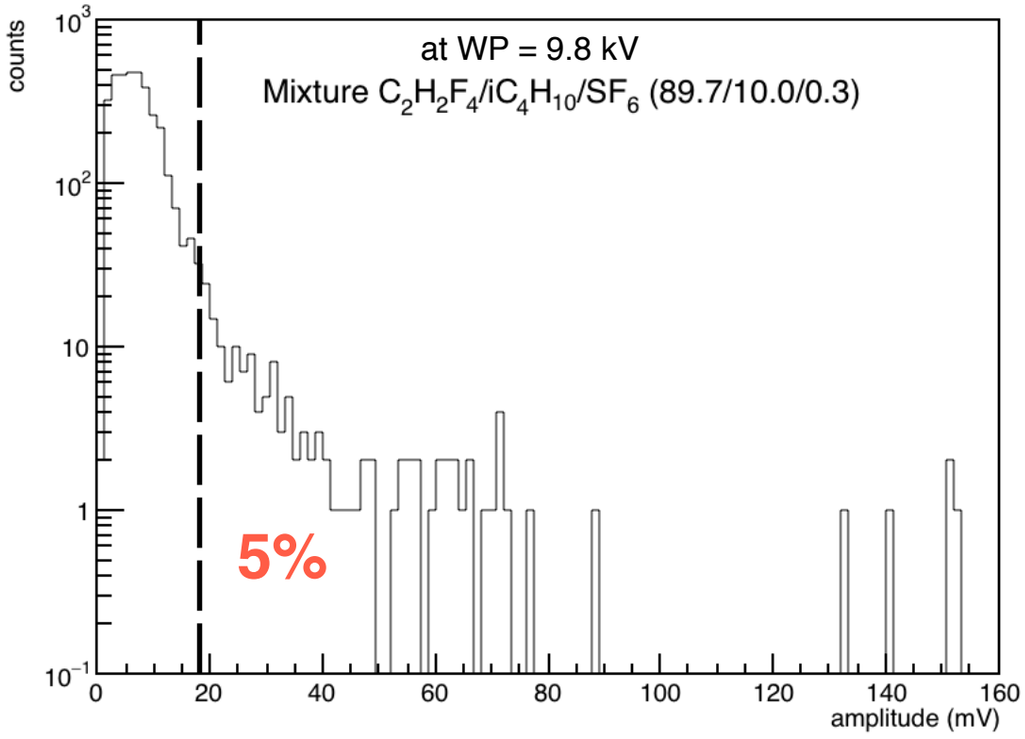
Characterization with ALICE mixture

Efficiency and large signal probability with ALICE mixture, which is used as reference:



Mixture $C_2H_2F_4/iC_4H_{10}/SF_6$ (89.7/10.0/0.3):

- efficiency
- streamer probability



Thresholds used for the analysis:

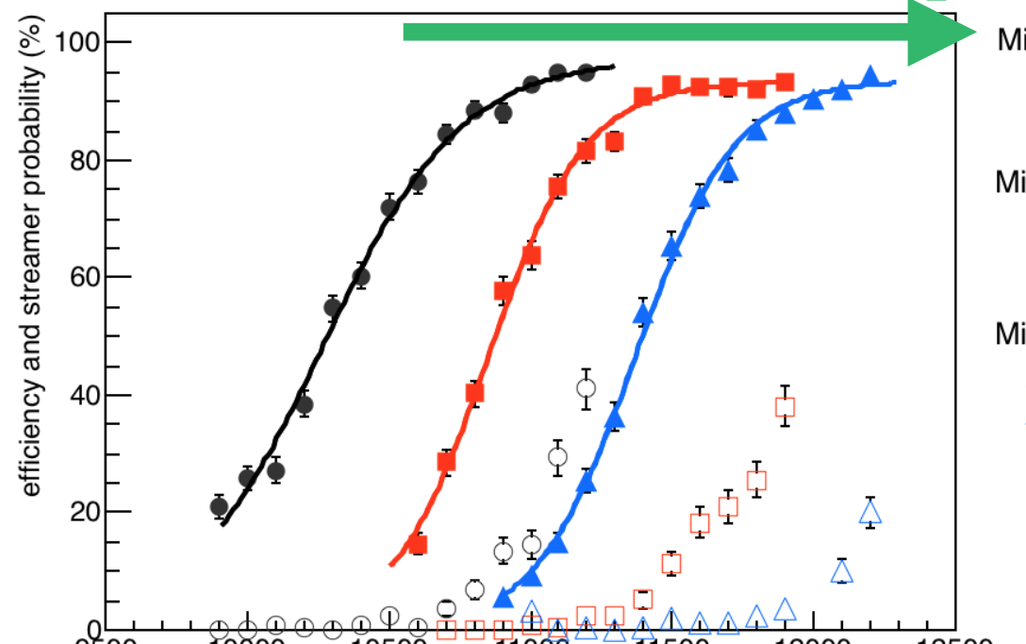
- **efficiency (FEERIC response)**:
  $Q_{induced}$ = **~130 fC** (70 mV after amplification)
- **streamer probability**:
  amplitude (by the oscilloscope) > 18 mV
  (threshold used to tag 5% largest signals)

The new gas mixture with low GWP has to provide similar detector performance as the current one with the standard ALICE mixture

Systematic study: gas mixtures with $C_3H_2F_4$ and CO_2 has been carried out with the addition of *i*-C_4H_{10} and SF_6
Methodology: changing the fractions of **two gas components out of four** at a time, evaluating how their ratio affects the performance of the RPC → paper: A. Bianchi *et al.* 2019 *JINST* **14** P11014

Ratio between $C_3H_2F_4$ and CO_2/*i*-C_4H_{10}

$C_3H_2F_4$↑ and CO_2↓

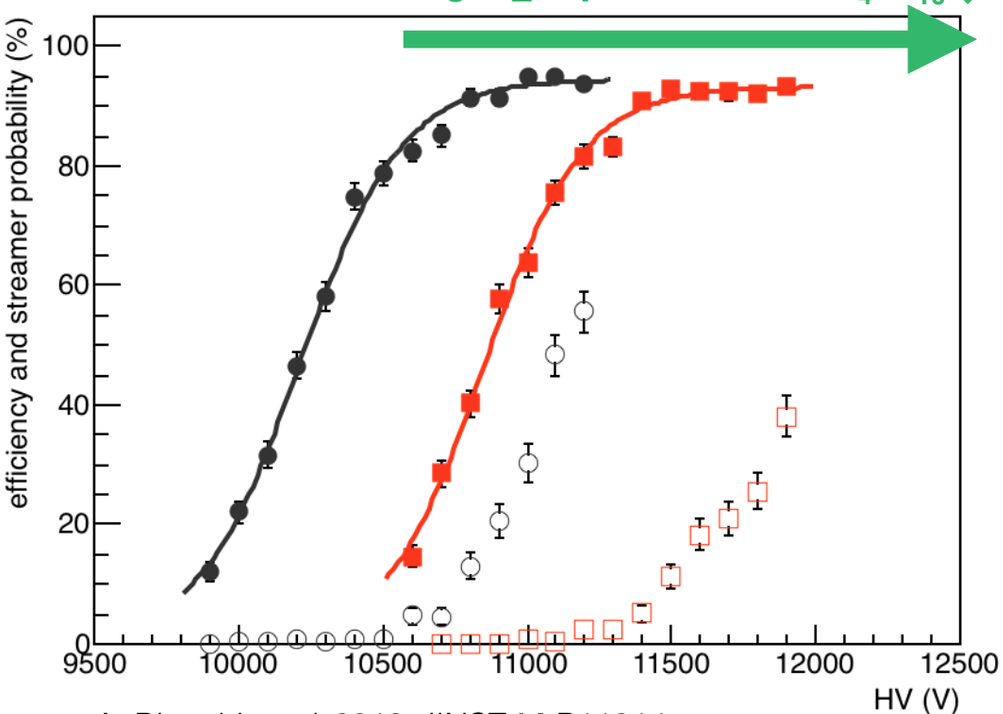


A. Bianchi *et al.* 2019 *JINST* **14** P11014

If the fraction of $C_3H_2F_4$ is increased and CO_2 or *i*-C_4H_{10} is decreased:

- the working point turns out to be shifted towards higher voltages
- no significant variation on the streamer probability

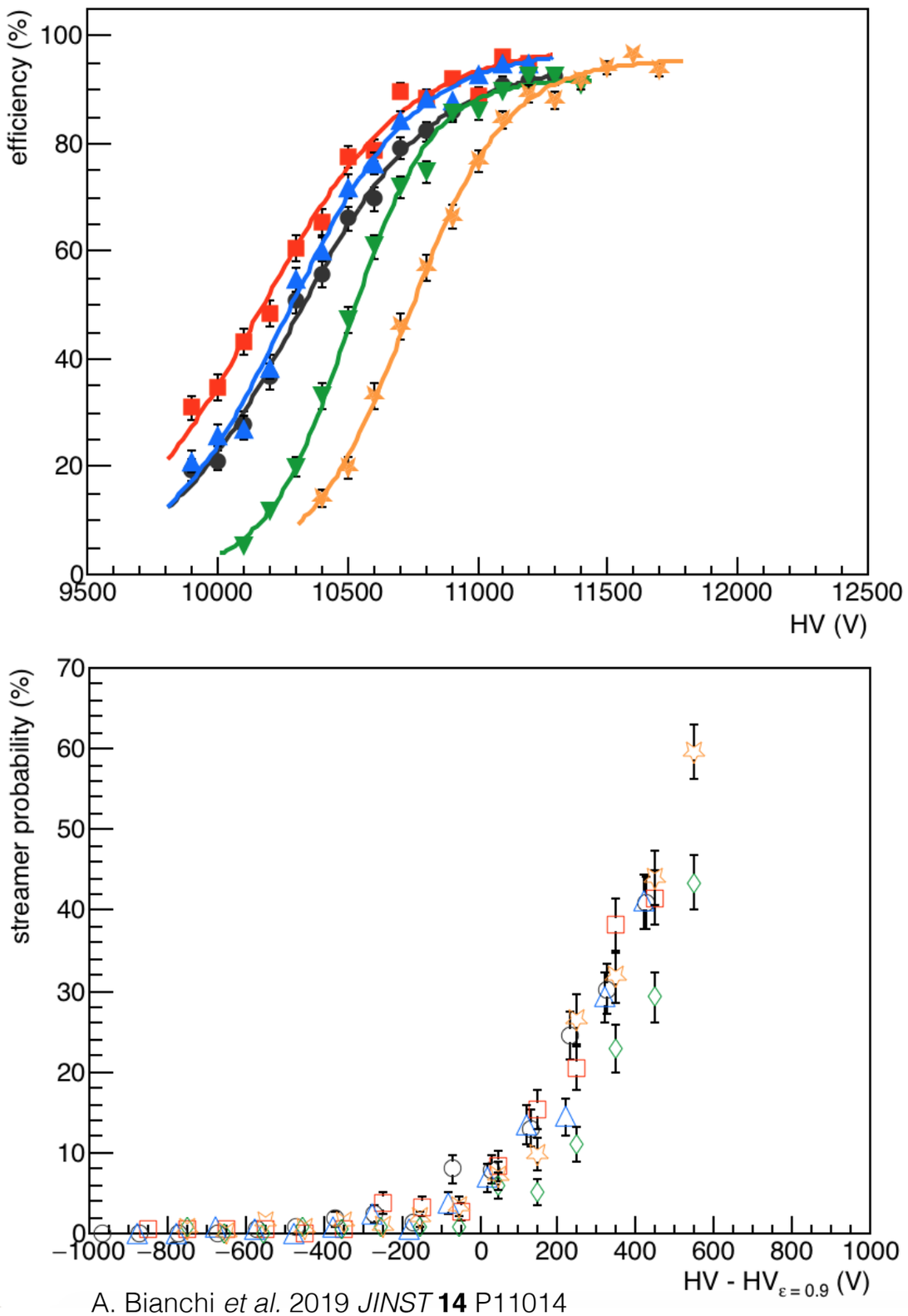
$C_3H_2F_4$↑ and *i*-C_4H_{10}↓



A. Bianchi *et al.* 2019 *JINST* **14** P11014

Strong dependence between the concentration of $C_3H_2F_4$ and the working point

Ratio between CO_2 and i-C_4H_{10}



Mixture $CO_2/C_3H_2F_4/iC_4H_{10}/SF_6$ (65.5/33.5/0.0/1.0):
- efficiency
- streamer probability

Mixture $CO_2/C_3H_2F_4/iC_4H_{10}/SF_6$ (60.5/33.5/5.0/1.0):
- efficiency
- streamer probability

Mixture $CO_2/C_3H_2F_4/iC_4H_{10}/SF_6$ (55.5/33.5/10.0/1.0):
- efficiency
- streamer probability

Mixture $CO_2/C_3H_2F_4/iC_4H_{10}/SF_6$ (50.0/34.0/15.0/1.0):
- efficiency
- streamer probability

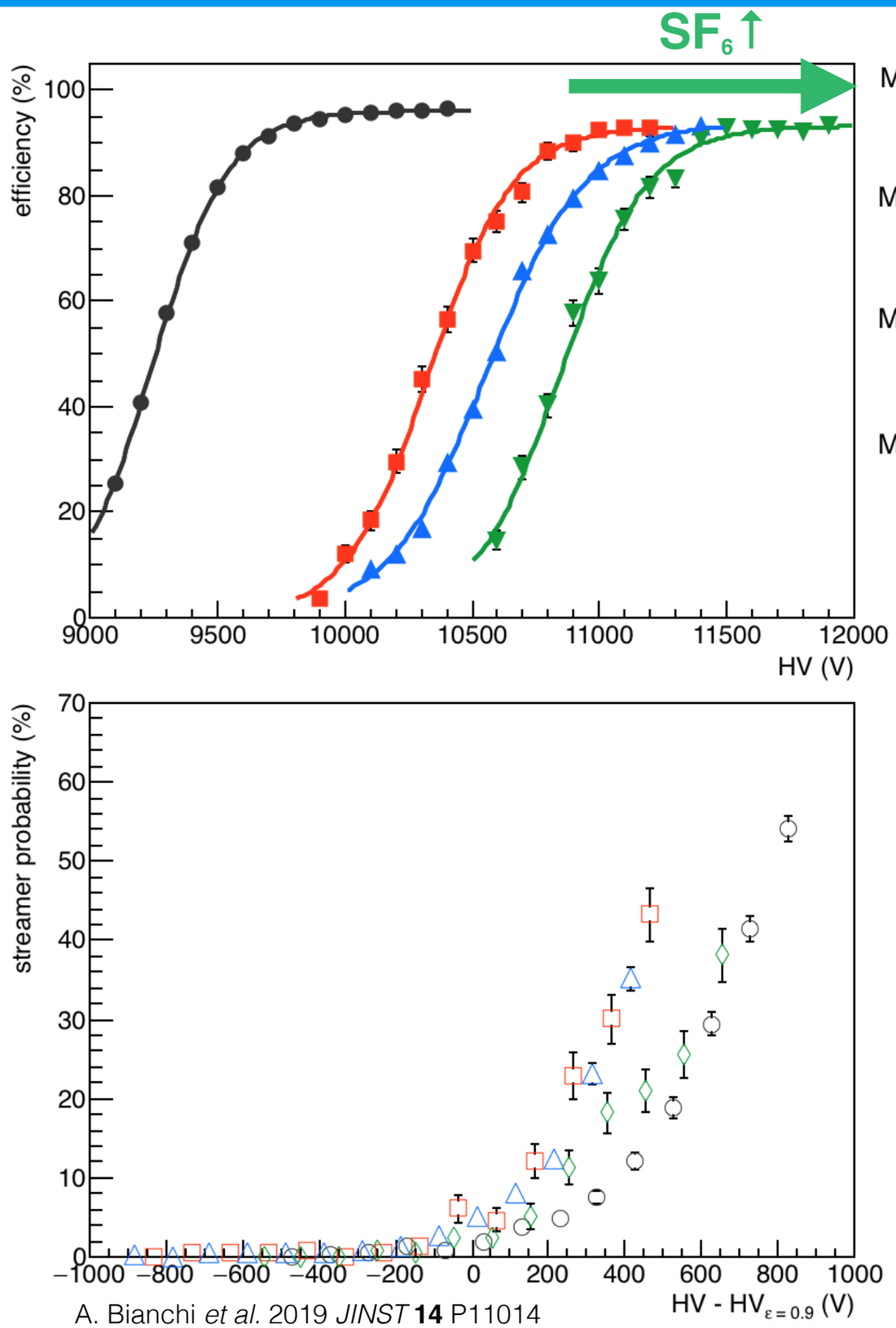
Mixture $CO_2/C_3H_2F_4/iC_4H_{10}/SF_6$ (44.5/34.5/20.0/1.0):
- efficiency
- streamer probability

i-C_4H_{10} ↑ and CO_2 ↓

A. Bianchi *et al.* 2019 *JINST* **14** P11014

- The **working point does not vary monotonically**
- **Streamer probability is very similar in all cases**, with the possible exception of 15% i-C_4H_{10}
- The **reduction of i-C_4H_{10} (flammable) is desirable** for safety and practical reasons, but it seems that reducing i-C_4H_{10} would result in less steep turn-on of the efficiency, which is a drawback

Variation of SF_6



A. Bianchi *et al.* 2019 *JINST* **14** P11014

Mixture $C_2H_2F_4/iC_4H_{10}/SF_6$ (89.7/10.0/0.3):
- efficiency
- streamer probability

Mixture $CO_2/C_3H_2F_4/iC_4H_{10}/SF_6$ (50.0/39.7/10.0/0.3):
- efficiency
- streamer probability

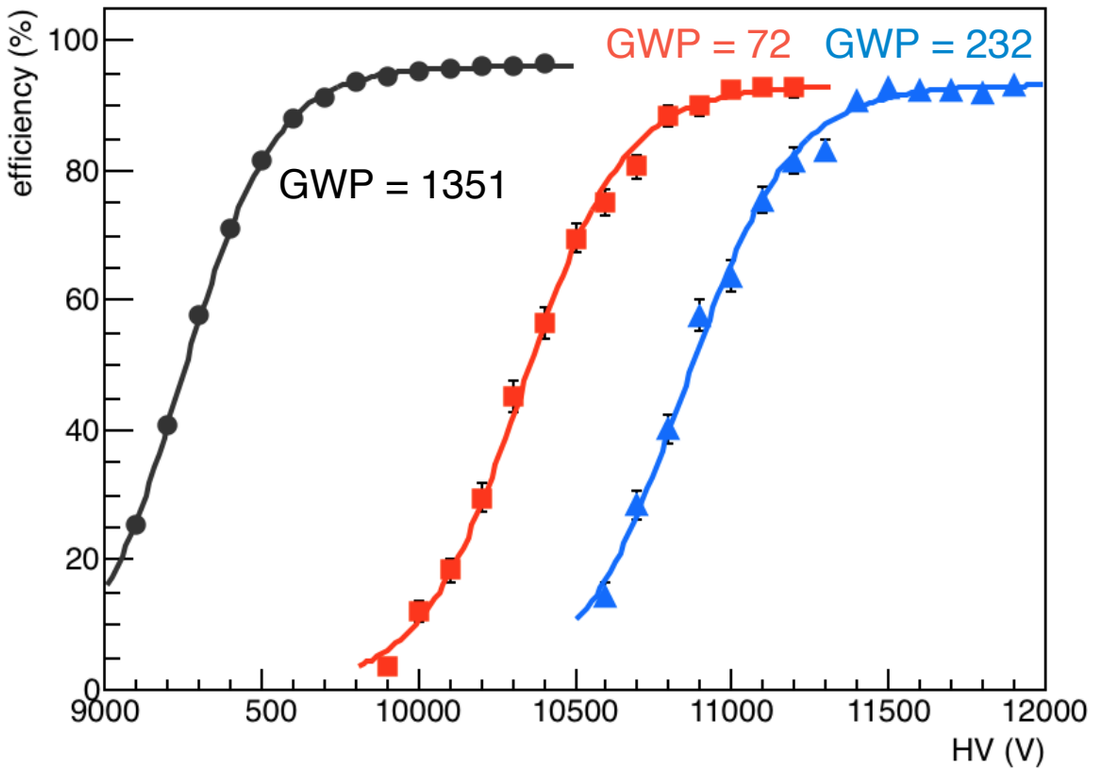
Mixture $CO_2/C_3H_2F_4/iC_4H_{10}/SF_6$ (50.0/39.4/10.0/0.6):
- efficiency
- streamer probability

Mixture $CO_2/C_3H_2F_4/iC_4H_{10}/SF_6$ (50.0/39.0/10.0/1.0):
- efficiency
- streamer probability

A small variation on the concentration of SF_6 leads to an important effect on the working point: the shift of the working point is ~500 V from 0.3% to 1.0% SF_6

No significant variations in the streamer probability are observed if SF_6 is increased from 0.3% to 0.6%, while **the suppression of streamers is slightly higher with 1.0% SF_6**

Promising gas mixtures with low GWP



A. Bianchi *et al.* 2019 *JINST* **14** P11014

Mixture $C_2H_2F_4/iC_4H_{10}/SF_6$ (89.7/10.0/0.3):
- ● efficiency
- ○ streamer probability

Mixture $CO_2/C_3H_2F_4/iC_4H_{10}/SF_6$ (50.0/39.7/10.0/0.3):
- ■ efficiency
- □ streamer probability

Mixture $CO_2/C_3H_2F_4/iC_4H_{10}/SF_6$ (50.0/39.0/10.0/1.0):
- ▲ efficiency
- △ streamer probability

50% CO_2, 39.7% $C_3H_2F_4$, 10% *i*-C_4H_{10}, 0.3% SF_6 :

- GWP: 72 (~20 times lower than the GWP of ALICE mixture)
- the working point is quite close to the working point of the ALICE RPCs during LHC Run 1 and Run 2 (~1.0 kV)
- the streamer probability is not as low as in the current ALICE mixture

50% CO_2, 39% $C_3H_2F_4$, 10% *i*-C_4H_{10}, 1% SF_6 :

- GWP: 232 (~5 times lower than the GWP of ALICE mixture)
- the working point is higher (~1.5 kV)
- the streamer probability is similar to the ALICE mixture, although slightly higher

→ in both cases, values of cluster size are similar to those obtained with the ALICE mixture

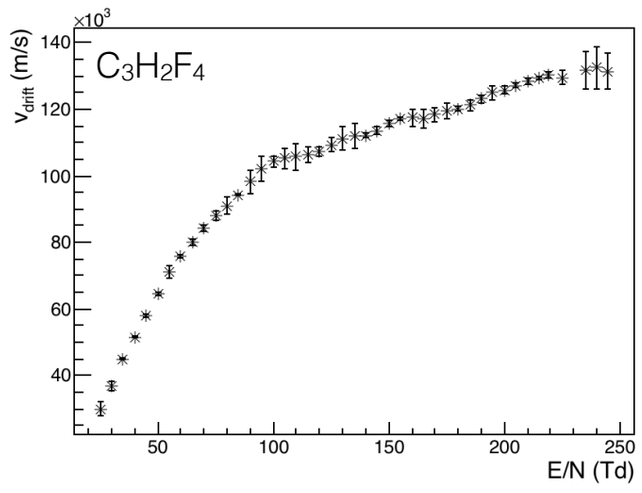
→ more details in A. Bianchi *et al.* 2019 *JINST* **14** P11014

Simulations of RPC performance

Reliable simulations of electron transport parameters in $C_3H_2F_4$-based gas mixtures turn out to be extremely useful to optimize the RPC performance, but also for:

- different experiments with different operational conditions (ATLAS/CMS or ALICE)
- different types of RPCs (different gas gap width, multi-gap, etc.)
- different types of gaseous detectors (i.e. GEM)

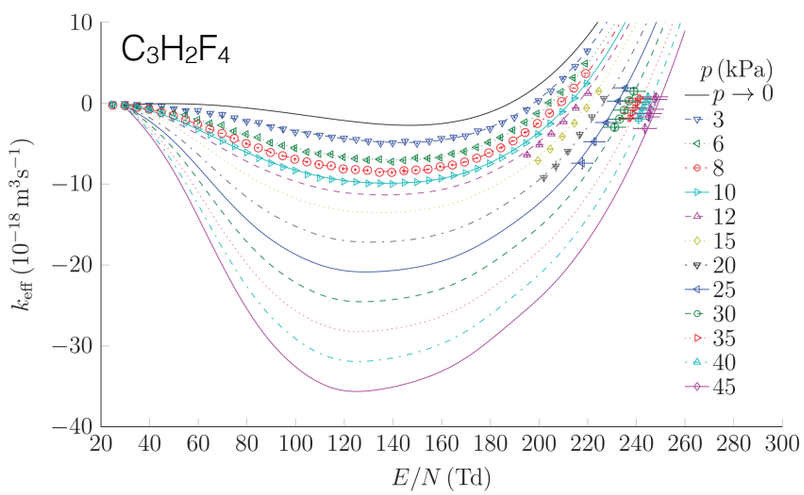
ETH Zurich: A. Chachereau *et al.*, 2016
Plasma Sources Sci. Technol. **25** 045005



Numeric solvers (fast)
or
Monte Carlo simulations (precise)

reduced electric field (E/N)

electron collision cross sections → **Boltzmann transport equation** → transport coefficients and reaction rates

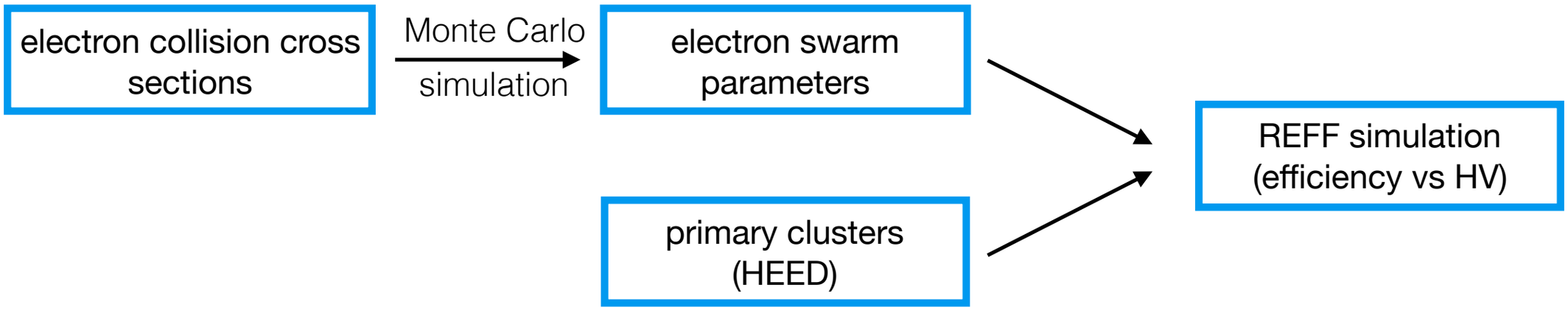


Inverse problem

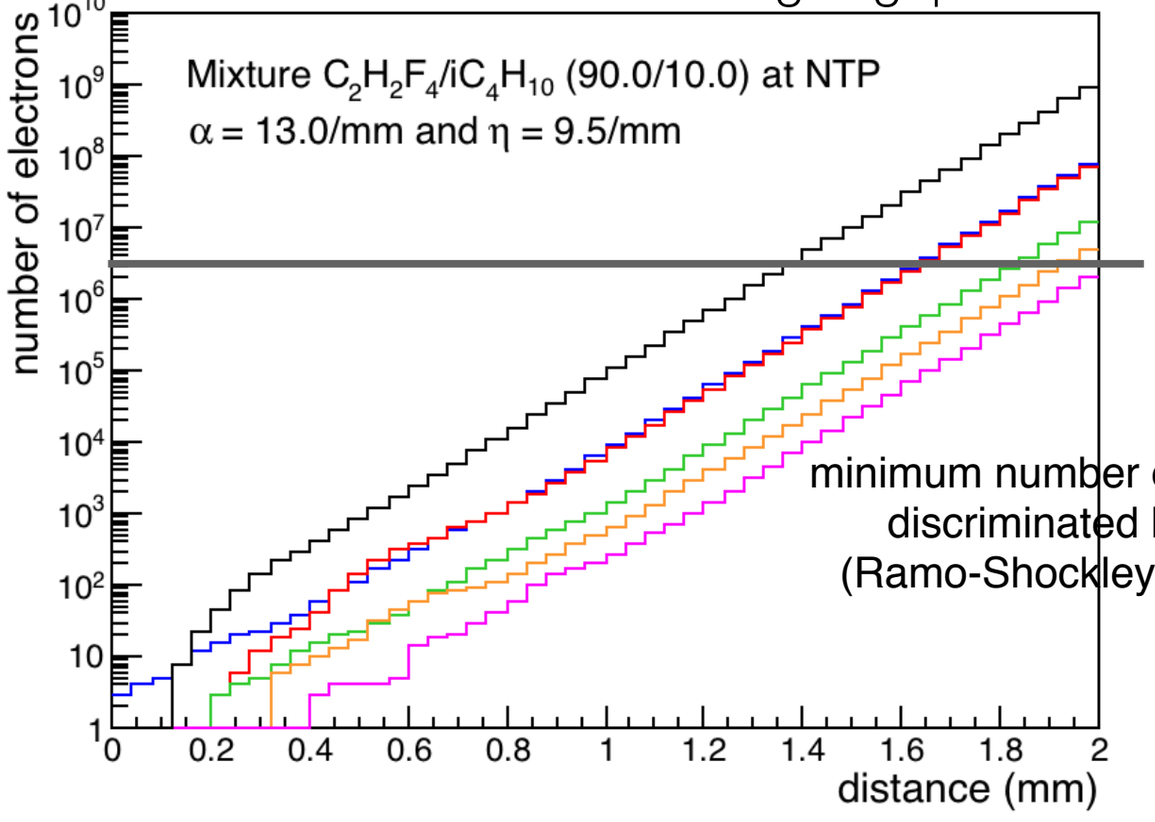
Electron collision cross sections of $C_3H_2F_4$ are obtained by unfolding its electron swarm parameters

REFF simulation

The REFF (RPC EFFiciency) simulation implements a simplified method to evaluate the efficiency curve of RPCs with different gas mixtures

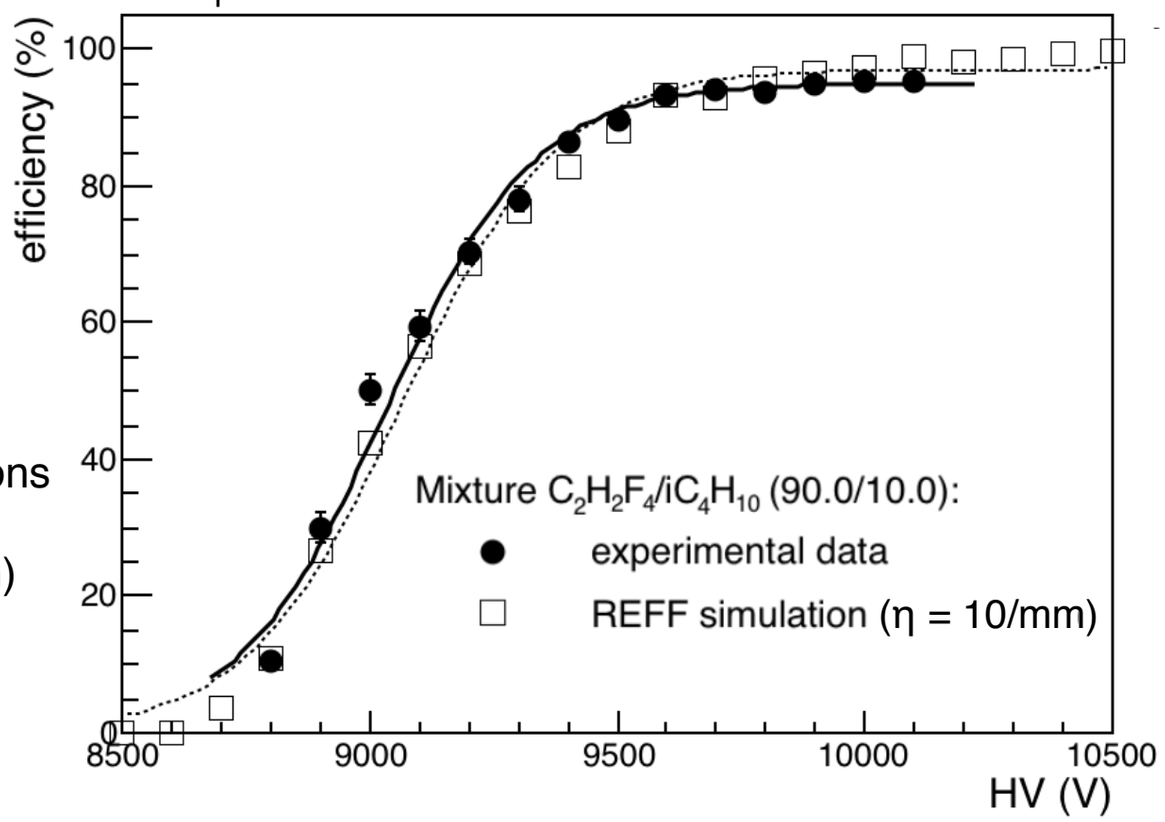


Profile of 6 avalanches in the gas gap:



minimum number of electrons discriminated by FEE (Ramo-Shockley theorem)

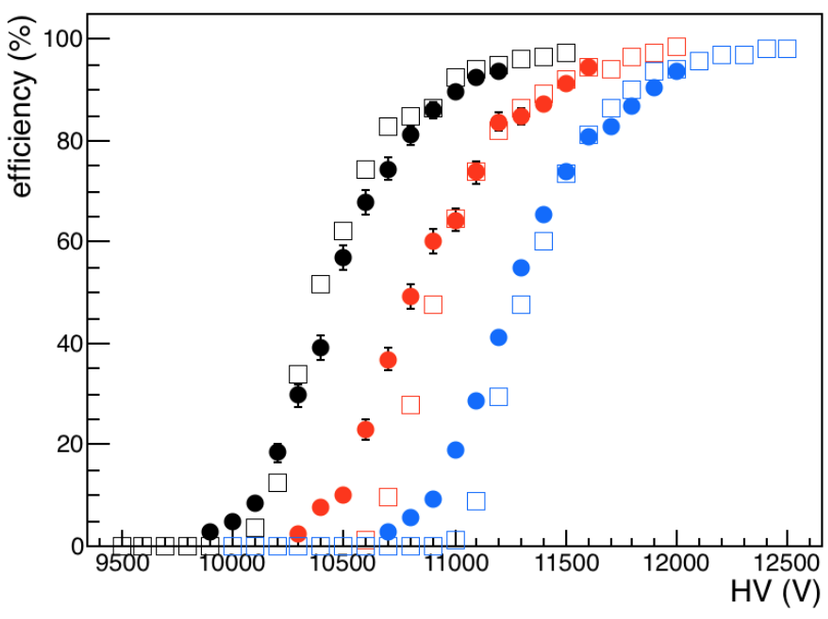
Output:

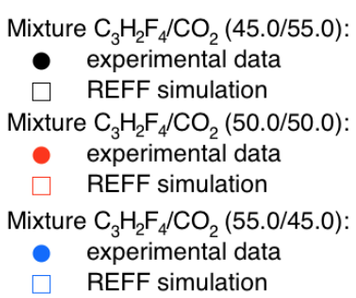


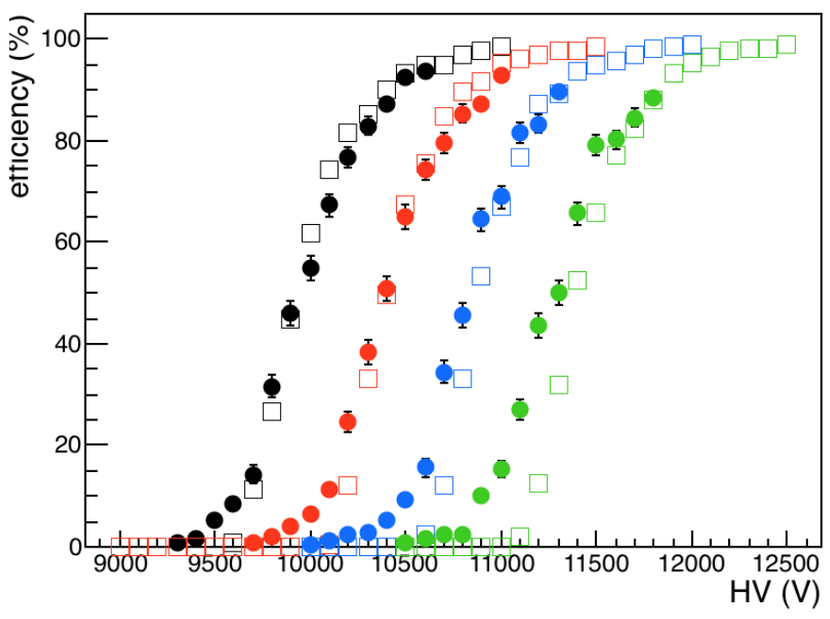
At the moment, no implementation of space charge effects.

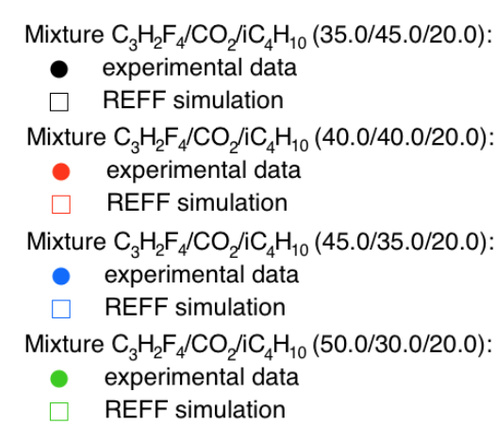
Results of REFF simulation

Variation of the ratio between $C_3H_2F_4$ and CO_2 without *i*-C_4H_{10} and with 20% *i*-C_4H_{10}:

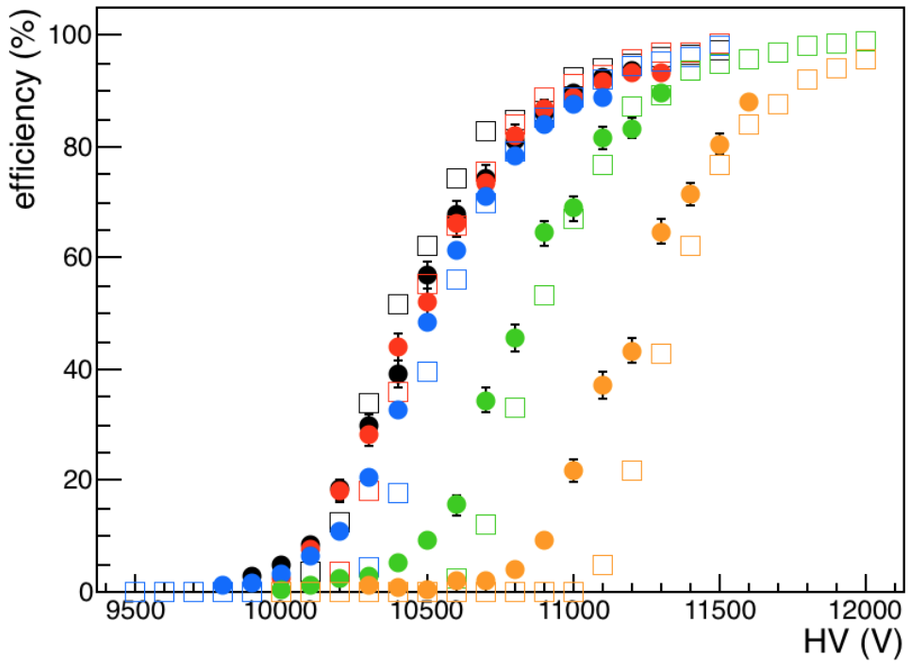


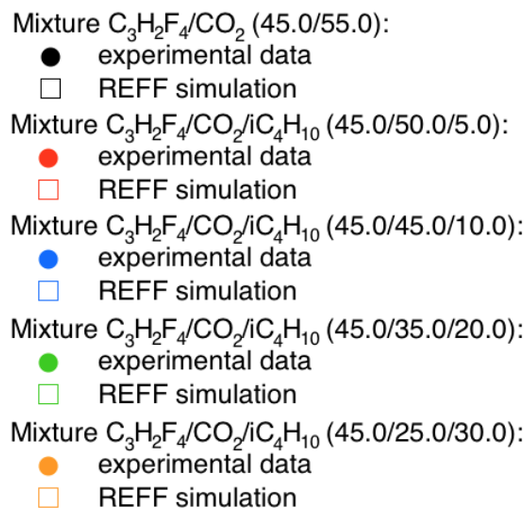






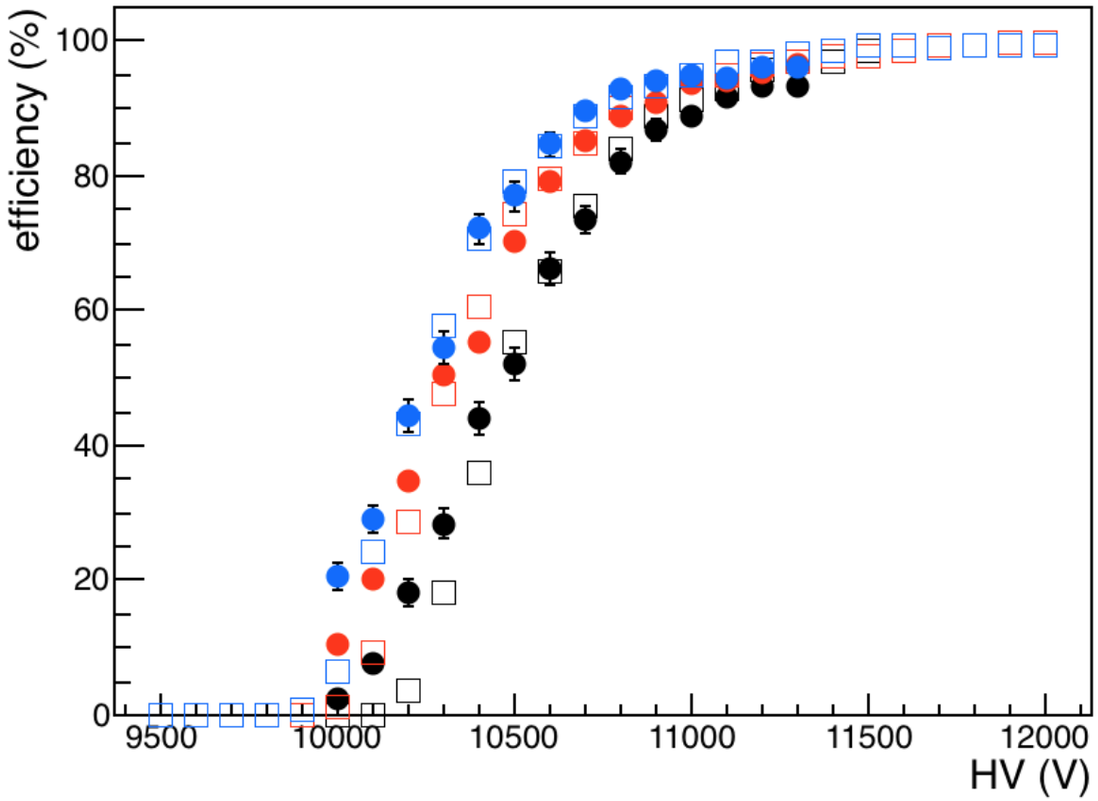
Variation of the ratio between CO_2 and *i*-C_4H_{10} while $C_3H_2F_4$ fraction is kept constant at 45%:





Results of REFF simulation

Variation of the ratio between CO_2 and **Ar** with 45% $C_3H_2F_4$ and 5% *i*-C_4H_{10}:

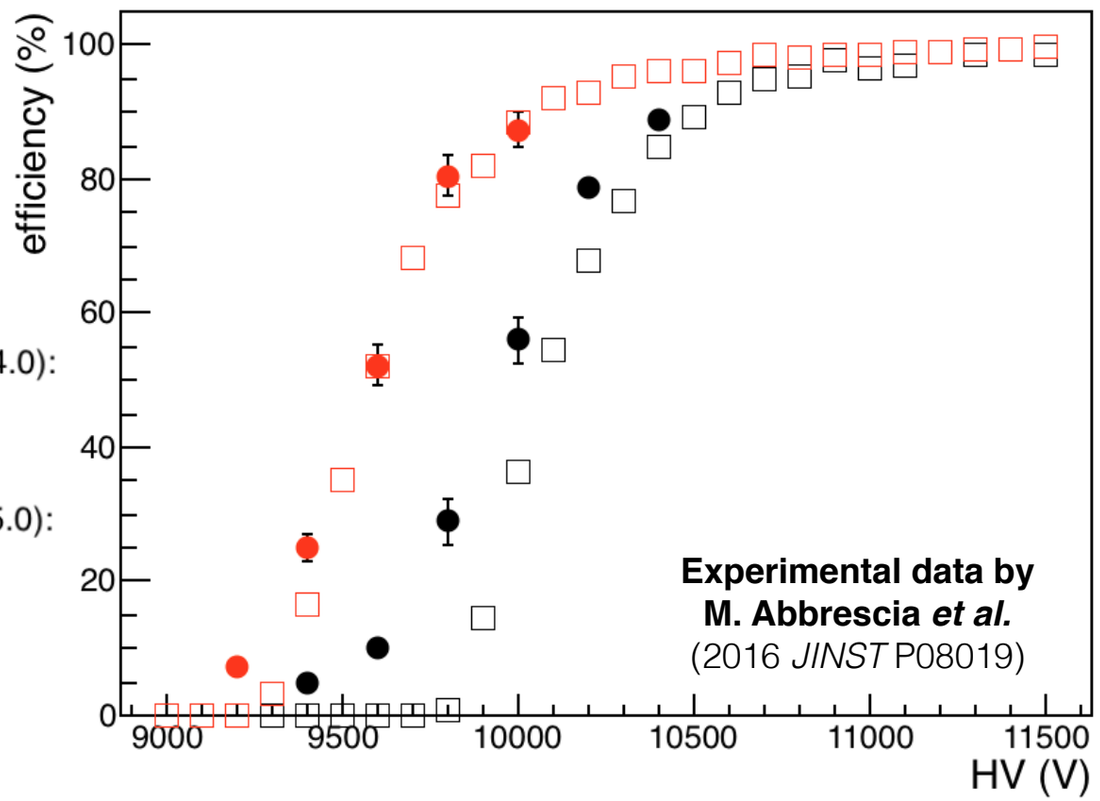


Mixture $C_3H_2F_4/CO_2/iC_4H_{10}$ (45.0/50.0/5.0):
- experimental data
- REFF simulation

Mixture $C_3H_2F_4/CO_2/iC_4H_{10}$/Ar (45.0/45.0/5.0/5.0):
- experimental data
- REFF simulation

Mixture $C_3H_2F_4/CO_2/iC_4H_{10}$/Ar (45.0/40.0/5.0/10.0):
- experimental data
- REFF simulation

Gas mixtures with $C_3H_2F_4$, *i*-C_4H_{10} and **He**:



Discrimination threshold of ~300 fC while it was ~130 fC in the previous cases

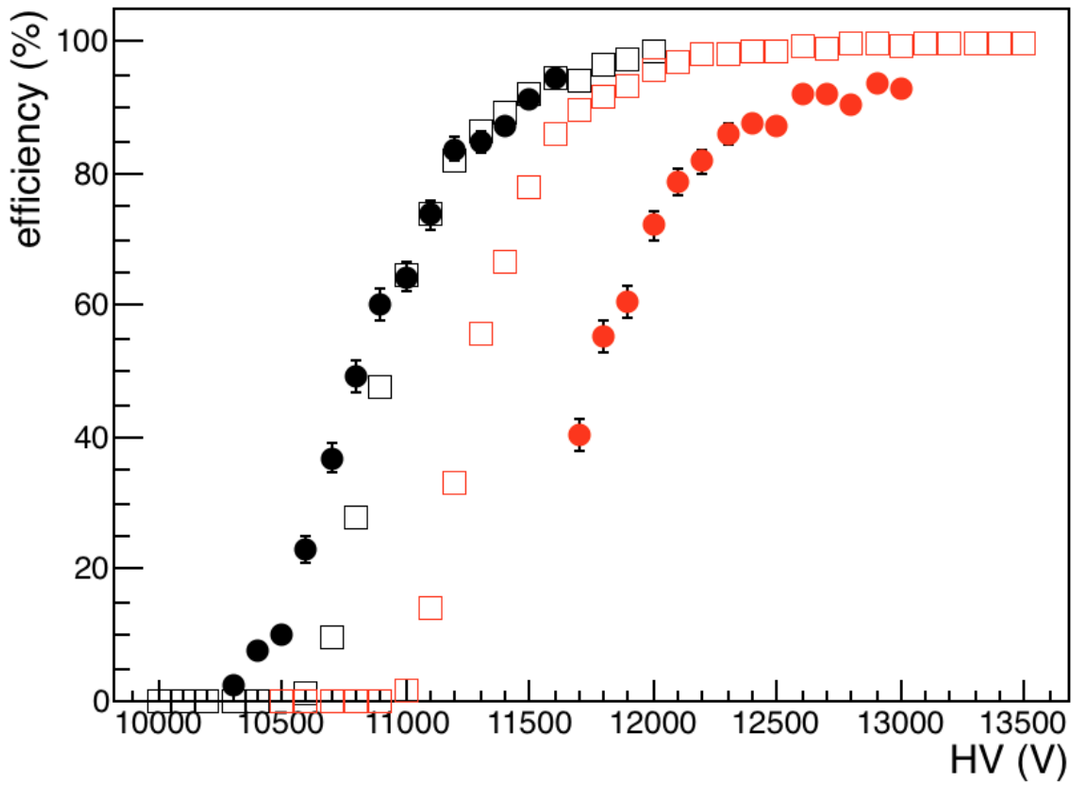
Mixture $C_3H_2F_4/He/iC_4H_{10}$ (59.0/37.0/4.0):
- experimental data
- REFF simulation

Mixture $C_3H_2F_4/He/iC_4H_{10}$ (55.0/40.0/5.0):
- experimental data
- REFF simulation

Good results are also obtained with gas mixtures of $C_3H_2F_4$, CO_2 and **O_2**

Limitations of REFF simulation

Gas mixtures with $C_3H_2F_4$ and CO_2 at same concentrations with and without SF_6:



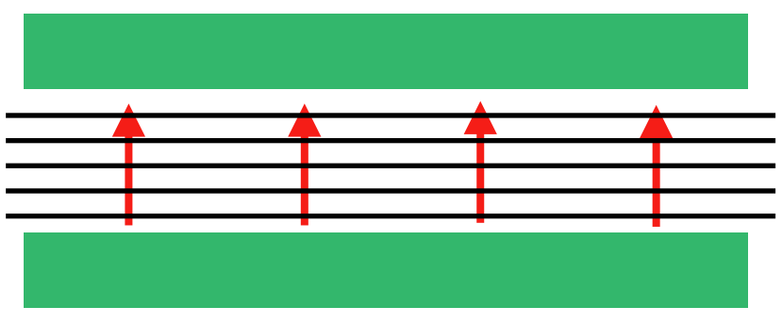
Mixture $C_3H_2F_4/CO_2$ (50.0/50.0):
- experimental data
- REFF simulation

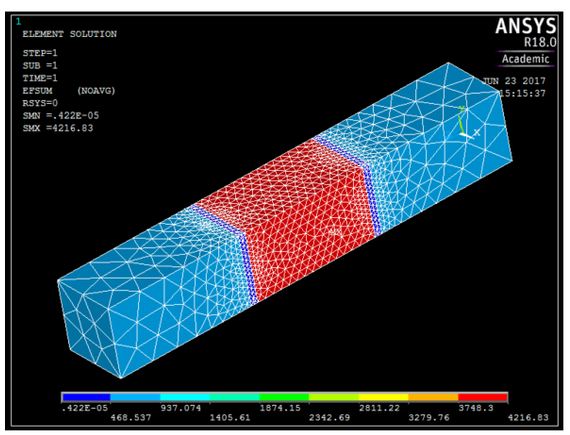
Mixture $C_3H_2F_4/CO_2/SF_6$ (50.0/49.0/1.0):
- experimental data
- REFF simulation

Some limitations of REFF simulation have been found in presence of SF_6. Possible future improvements:

- other different sets of cross sections of SF_6 can be tested for the simulation
  → for now, MAGBOLTZ database is used
- space-charge effects are not still implemented in the simulation (C. Lippmann's approach or FEM)

C. Lippmann's approach:
"1.5D model"
(gas gap in slides)





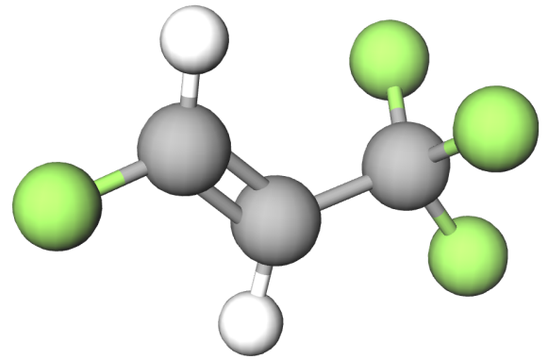
Finite element method (ANSYS)

Conclusions and outlook

- **R&D on eco-friendly gas mixtures:**

  → goal: to have a eco-friendly gas mixture (at least with a low GWP)

  → **$C_3H_2F_4$ is a possible candidate** to substitute $C_2H_2F_4$, thanks to its low GWP



- **Characterization of mixtures with $C_3H_2F_4$:**
  - strong dependence between the working point of the detector and the concentration of $C_3H_2F_4$
  - direct replacement of $C_2H_2F_4$ with $C_3H_2F_4$ is not suitable (working point > 14 kV) → the **addition of CO_2** to $C_3H_2F_4$-based gas mixtures is required to operate at lower voltages
  - **promising $C_3H_2F_4/CO_2$-based mixtures with *i*-C_4H_{10} and SF_6:**

    GWP reduced by a factor 5-20

- **Simulation of RPC efficiency:**
  - **reliable predictions** of the RPC efficiency in **$C_3H_2F_4$-based gas mixtures with** the addition of ***i*-C_4H_{10}, CO_2, O_2, Ar, He**
  - some **limitations** have been found for $C_3H_2F_4$-based gas mixtures with the addition of **SF_6**
  - **future developments** of the REFF simulation, including **space charge effects**, could improve the agreement between experimental data and simulation results

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Characterization of tetrafluoropropene-based gas mixtures for the Resistive Plate Chambers of the ALICE muon spectrometer

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