Simulation Study of Resistive Plate Chambers with $C_3H_2F_4$-based Gas Mixtures

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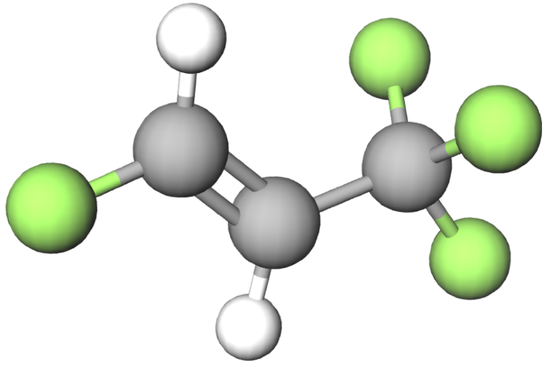
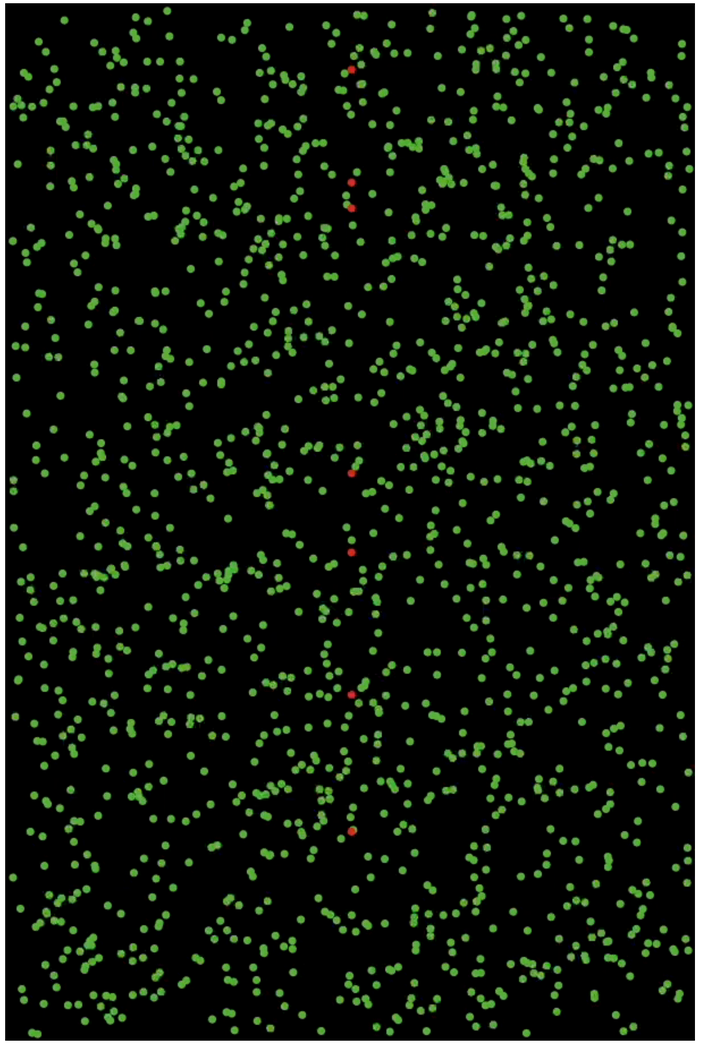
Outline

- **Thanks to an iterative procedure based on unfolding electron swarm parameters of $C_3H_2F_4$, a set of electron collision cross sections is now available**
  - methodology
  - results
- **REFF simulation**
  - results
  - limitations
  - future developments (also for multigap RPCs)



animation

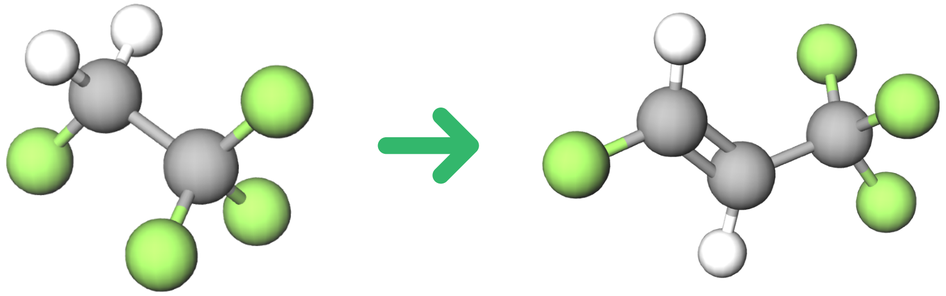


Motivation

“Striving to be the first climate-neutral continent” –European Green Deal

The hydrofluoroolefine **$C_3H_2F_4$** has been subject to a **growing interest for gaseous particle detectors and gaseous voltage insulating applications** thanks to its Global Warming Potential that is lower than 1

In Resistive Plate Chambers:



$C_2H_2F_4$ → $C_3H_2F_4$

First studies:

- “Eco-friendly gas mixtures for RPCs based on Tetrafluoropropene and Helium”, Abbrescia M. *et al* (2016)
- “Characterization of RPC operation with new environmental friendly mixtures for LHC application and beyond”, Guida R. *et al* (2016)

…nowadays, a number of R&D studies are still on-going

Motivation: a **complete set of scattering cross sections for electrons in $C_3H_2F_4$** that allows reliable predictions of electron transport coefficients and reaction rates in order to **optimize the $C_3H_2F_4$-based gas mixtures for RPCs, currently under test**

Boltzmann Transport Equation

Numerical solvers or Monte Carlo simulations

Boltzmann transport equation

electron collision cross sections

$$\frac{\partial f}{\partial t} + \vec{v} \cdot \nabla_r f + \vec{a} \cdot \nabla_v f = C[f]$$

electron swarm parameters

such as:
- electron drift velocity
- longitudinal and transverse diffusion coefficients
- effective ionization rate coefficient

$f(\boldsymbol{r}, \boldsymbol{v}, t)$ = electron distribution function
$\boldsymbol{v}$ = vector of electron velocity
$\boldsymbol{a}$ = vector of electron acceleration ⟶ if $\mathbf{H} = 0$, $\boldsymbol{a} = -e\mathbf{E}/m_e$
$C[f]$ = collision operators (all relevant information for electron-gas interactions)

If the electron motion is assumed nearly isotropic, f can be expanded in terms of Legendre polynomials of $cos(\theta)$ and truncated after the second term (TTA approximation):

$$f(z, v, t, \theta) = f_0(z, v, t) + f_1(z, v, t)\, cos(\theta)$$

Boltzmann Transport Equation

Numerical solvers (TTA):
BOLSIG+
(fast)

Numerical solvers or Monte Carlo simulations

Monte Carlo simulations (MC):
METHES or MAGBOLTZ
(precise)

Boltzmann transport equation

electron collision cross sections

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electron swarm parameters

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Boltzmann transport equation

electron collision cross sections

$$\frac{\partial f}{\partial t} + \vec{v} \cdot \nabla_r f + \vec{a} \cdot \nabla_v f = C[f]$$

electron swarm parameters

Inverse problem

For most of the gases, the electron swarm parameters can be easily measured while the measurement of their electron collision cross sections is extremely more challenging

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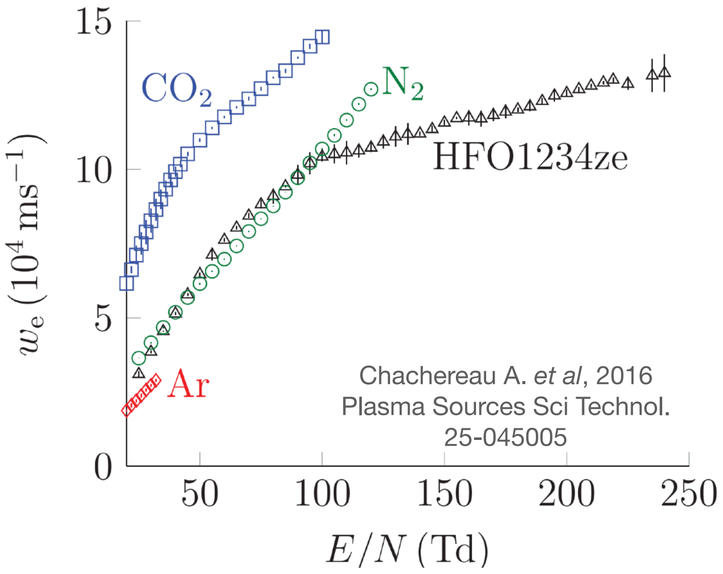
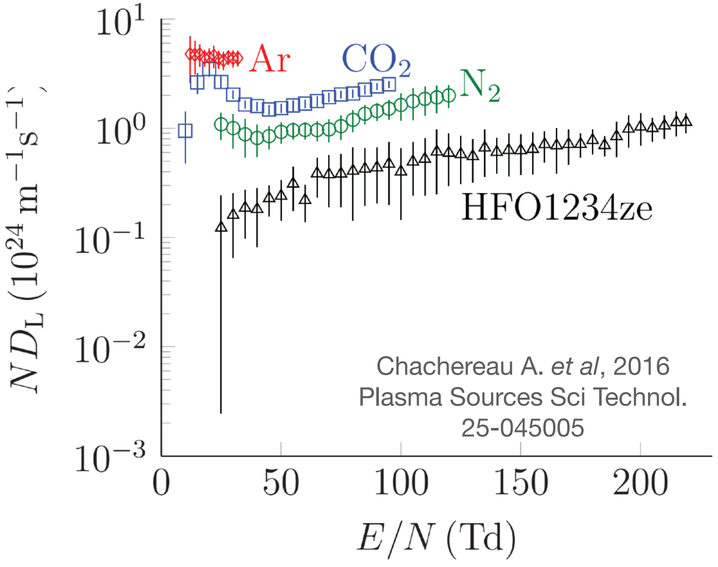
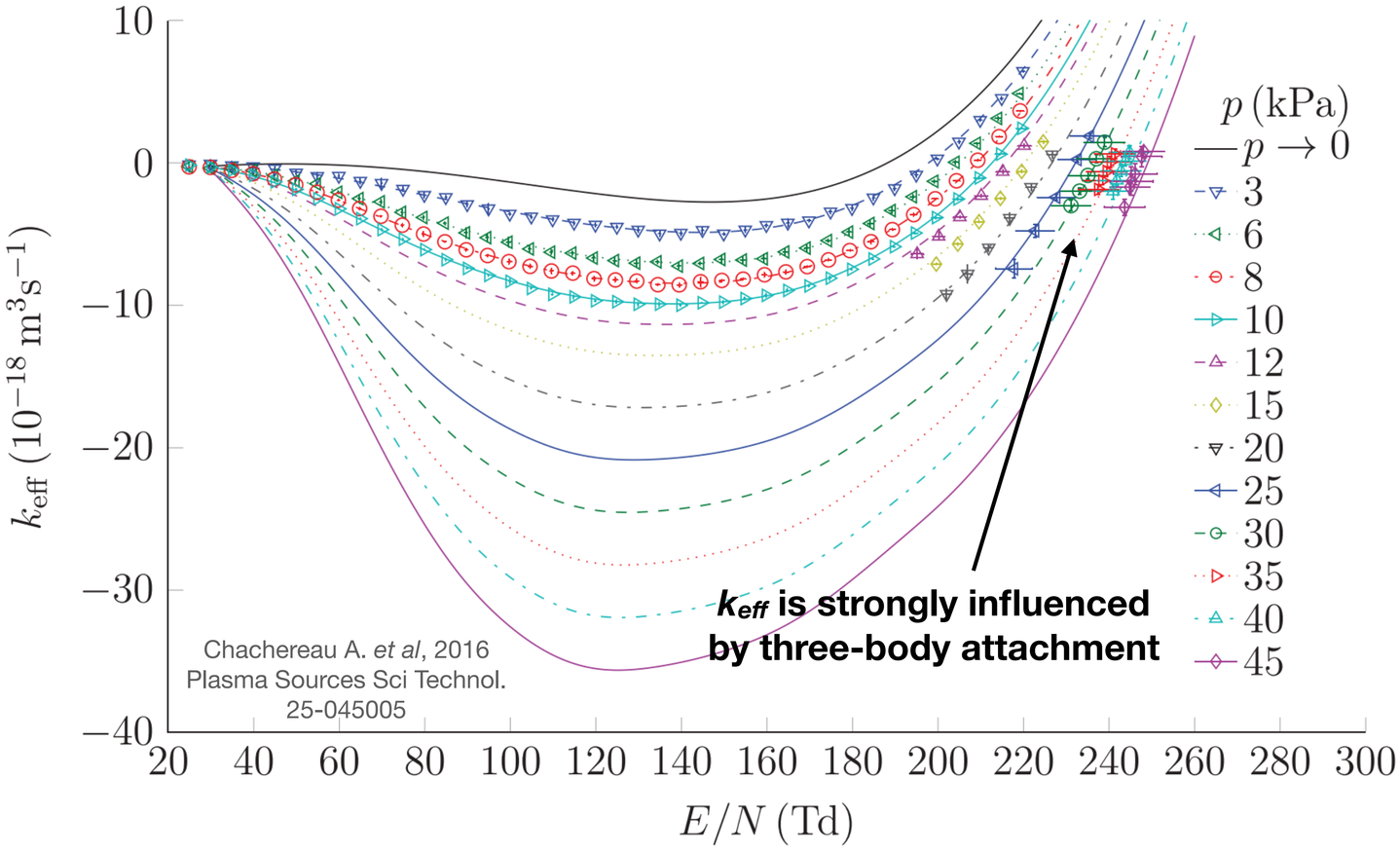
Unfolding the electron swarm parameters of $C_3H_2F_4$ is needed to obtain its electron collision cross sections

Electron Swarm Parameters of $C_3H_2F_4$



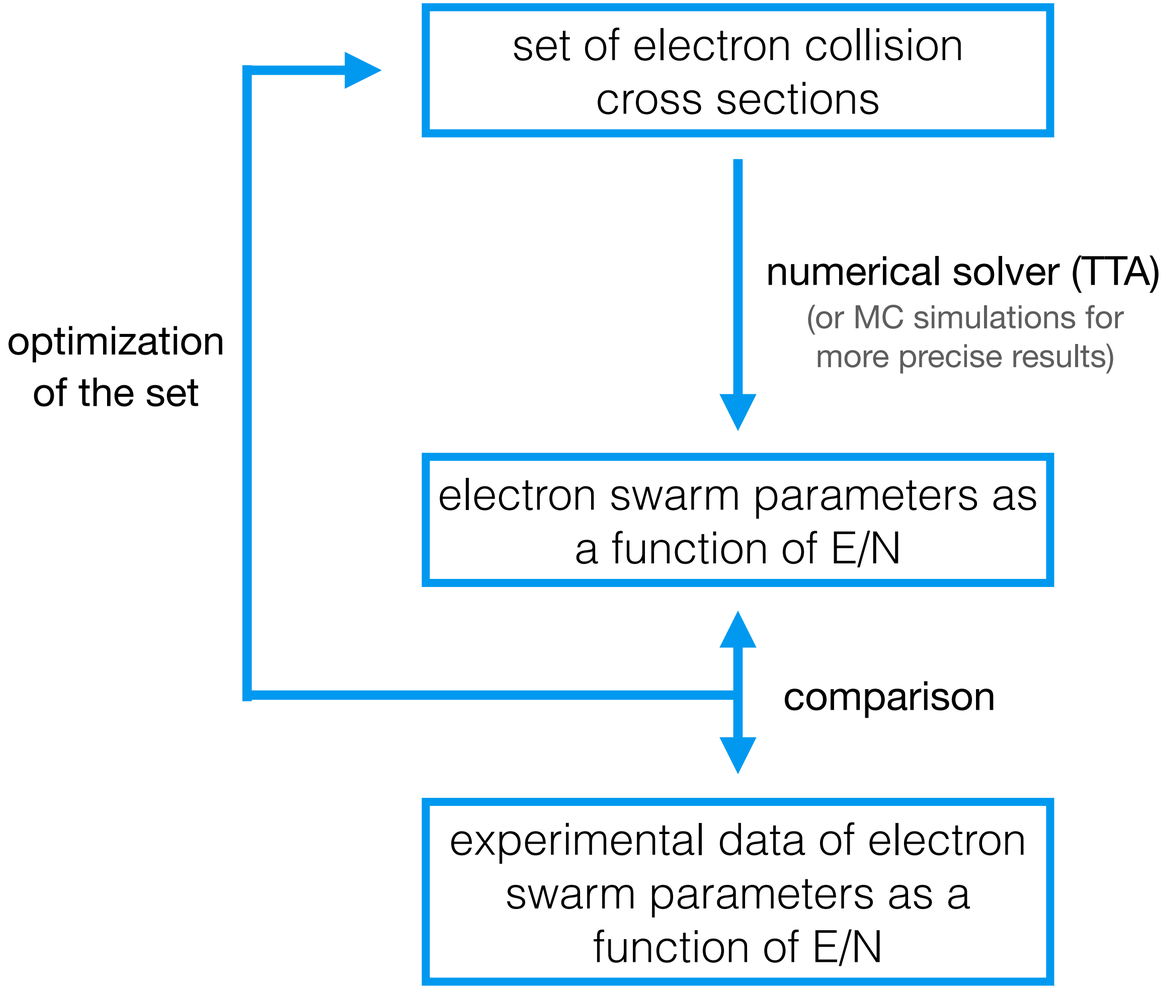




Measurements of electron swarm parameters are also available for $C_3H_2F_4$-based gas mixtures with the addition of CO_2, Ar or N_2:

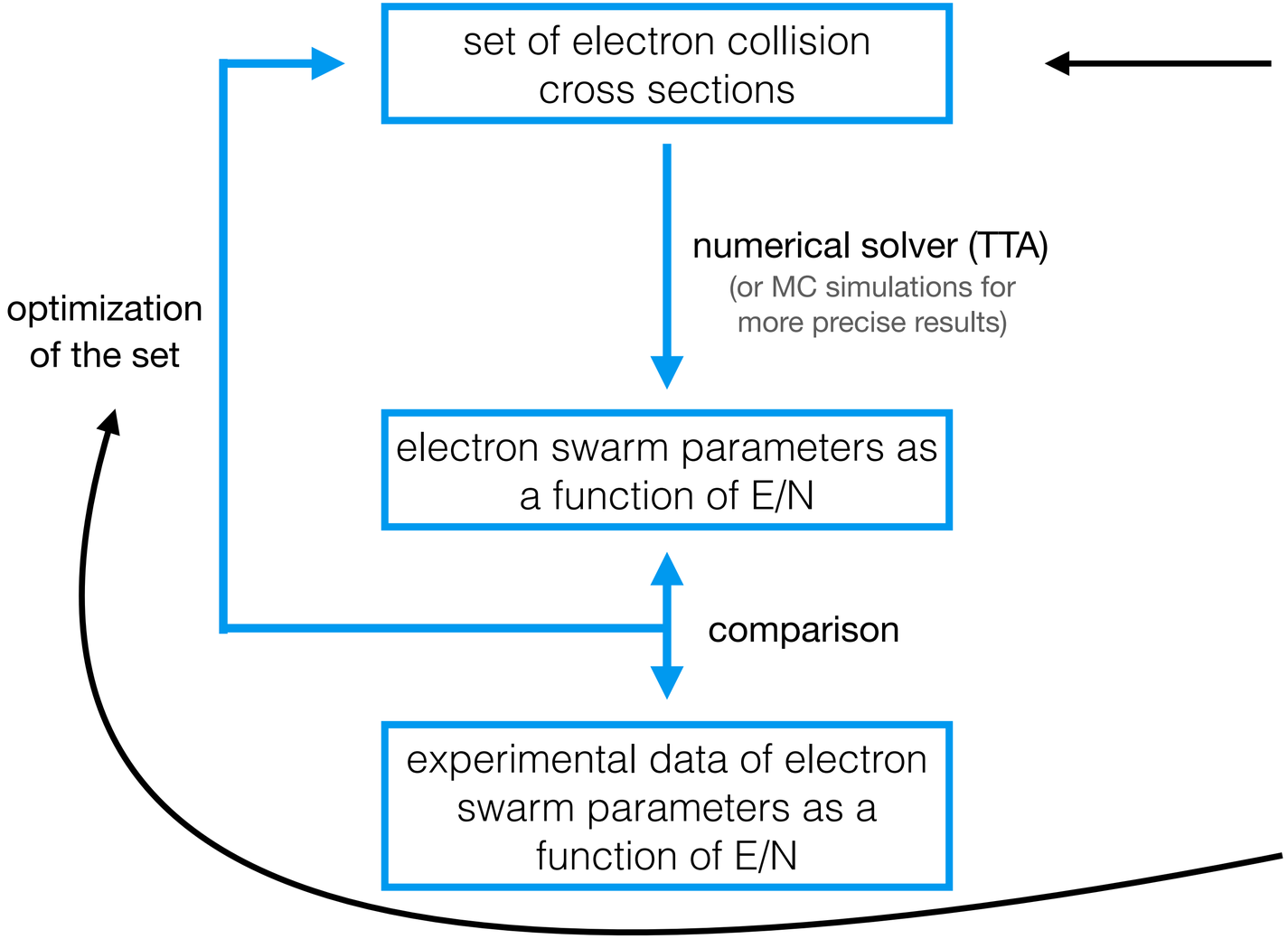
Chachereau A. and Christian F., "Characterization of HFO1234ze mixtures with N_2 and CO_2 for use as gaseous electrical insulation media", ISH 2017

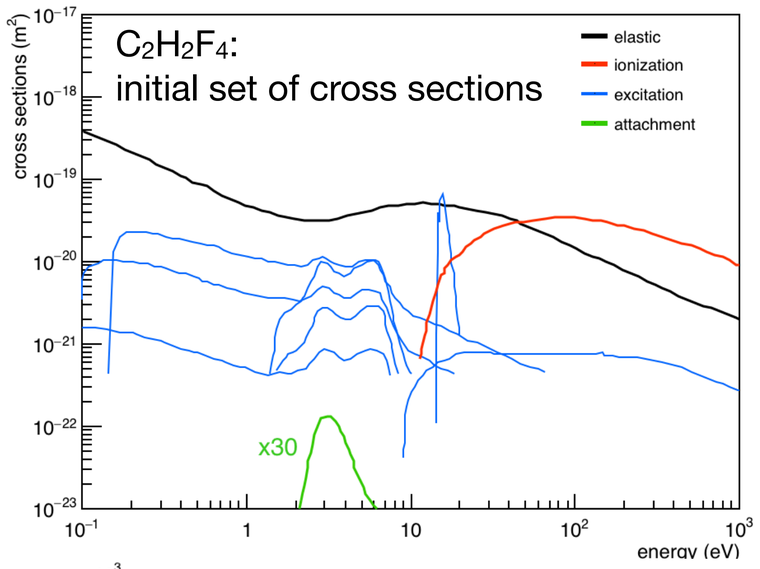
Unfolding of Electron Swarm Parameters

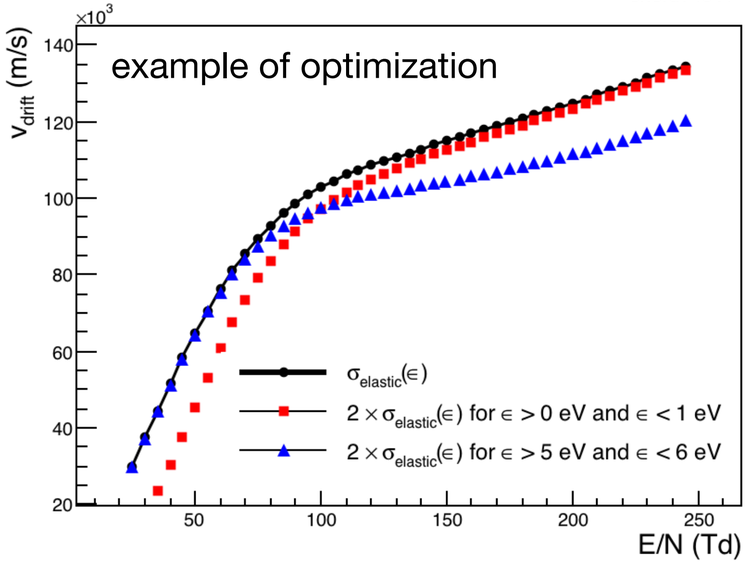


The discrepancies between the electron swarm parameters, calculated by a trial set of cross sections, and the experimental data are progressively minimized

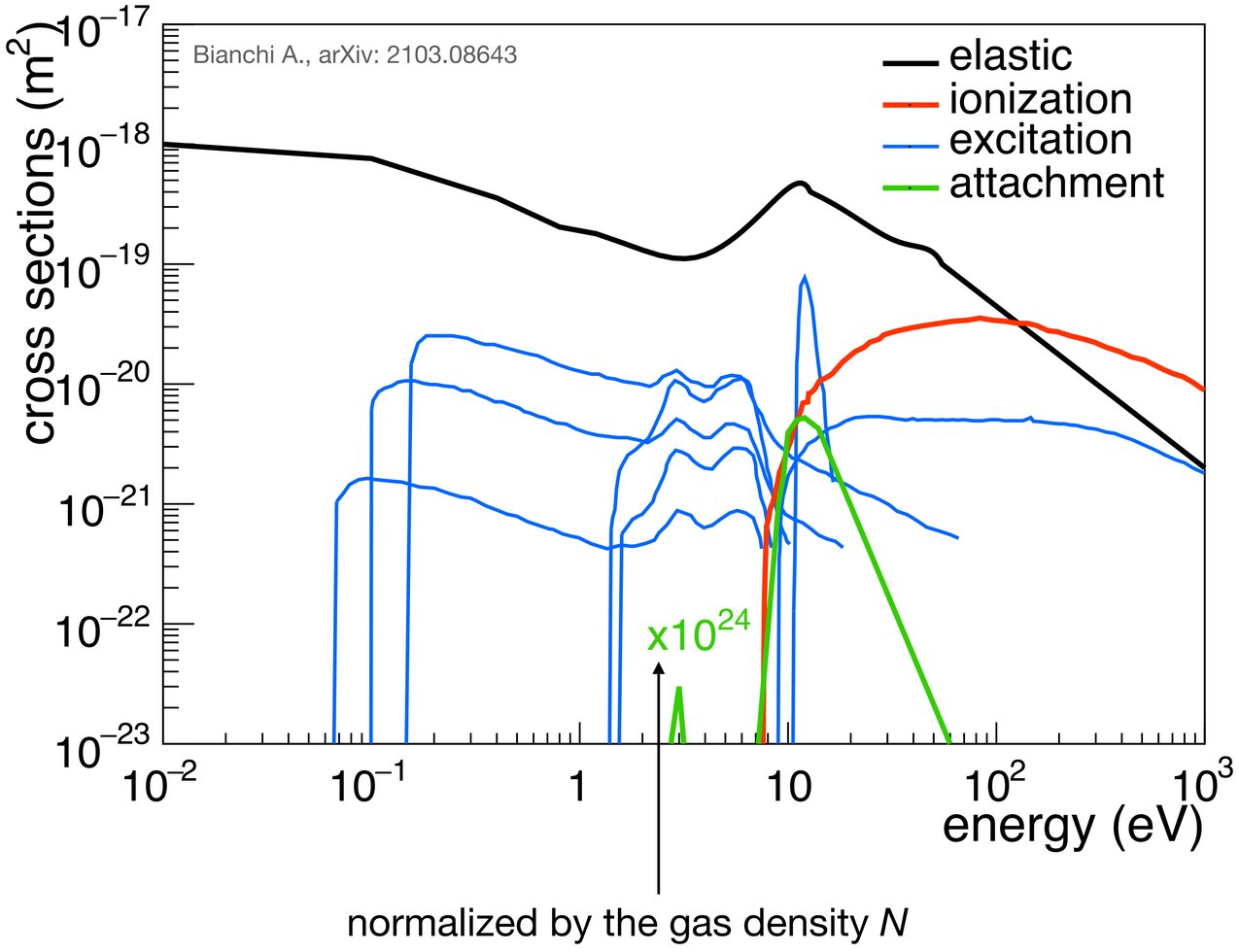
Unfolding of Electron Swarm Parameters







Electron Collision Cross Sections of $C_3H_2F_4$



The stable capture of electrons can occur in $C_3H_2F_4$ by:

$$e^- + C_3H_2F_4 \rightarrow A^- + B$$

dissociative attachment

or

$$(C_3H_2F_4)^* + C_3H_2F_4 \rightarrow (C_3H_2F_4)^- + C_3H_2F_4$$

collisional stabilization

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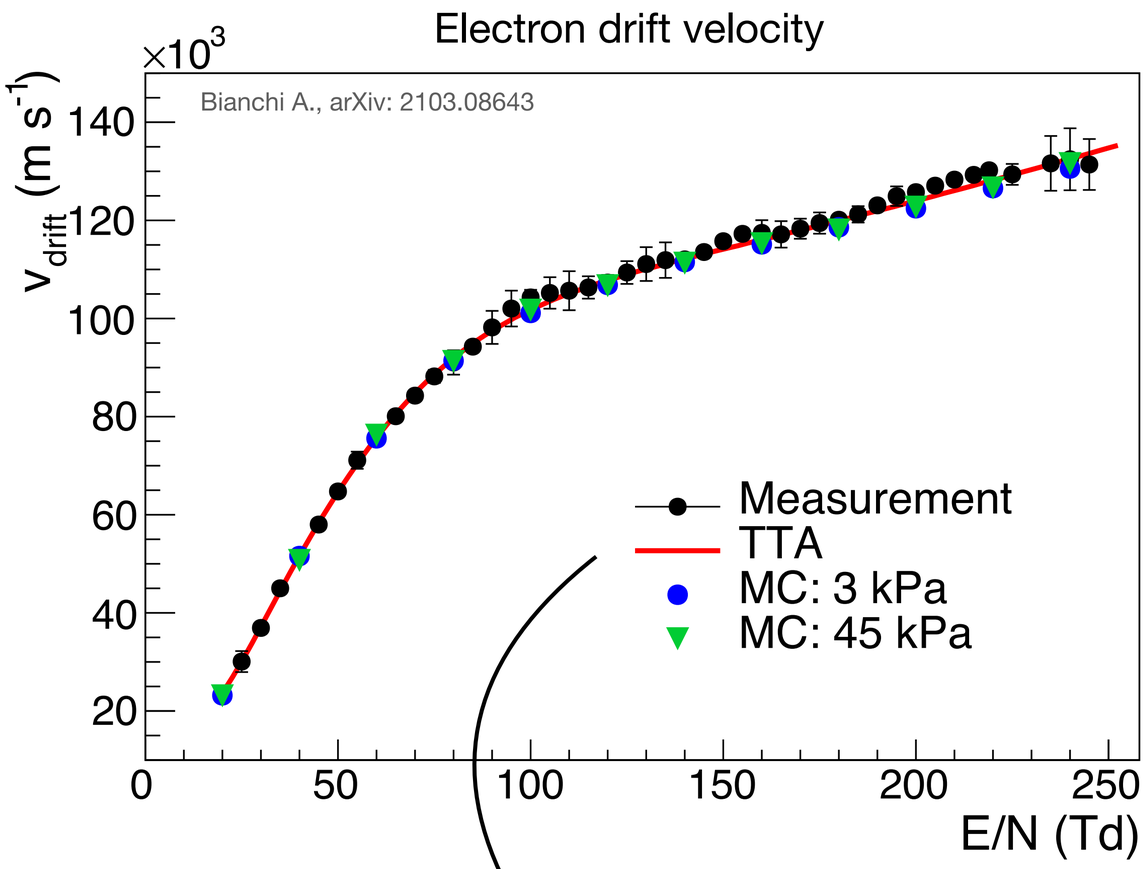
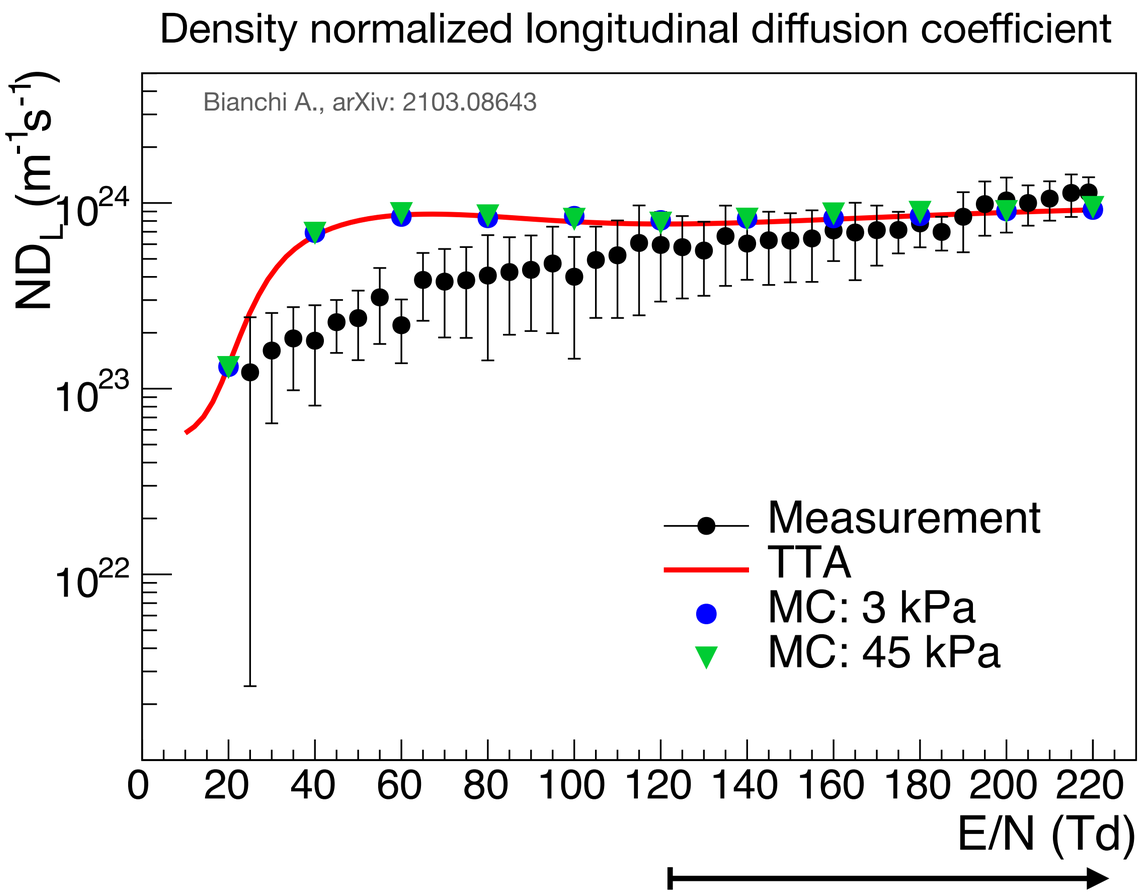
the probability of collisional stabilization process (three-body attachment) depends on the collision rate of $C_3H_2F_4$ and hence the gas density *N*

Pure $C_3H_2F_4$

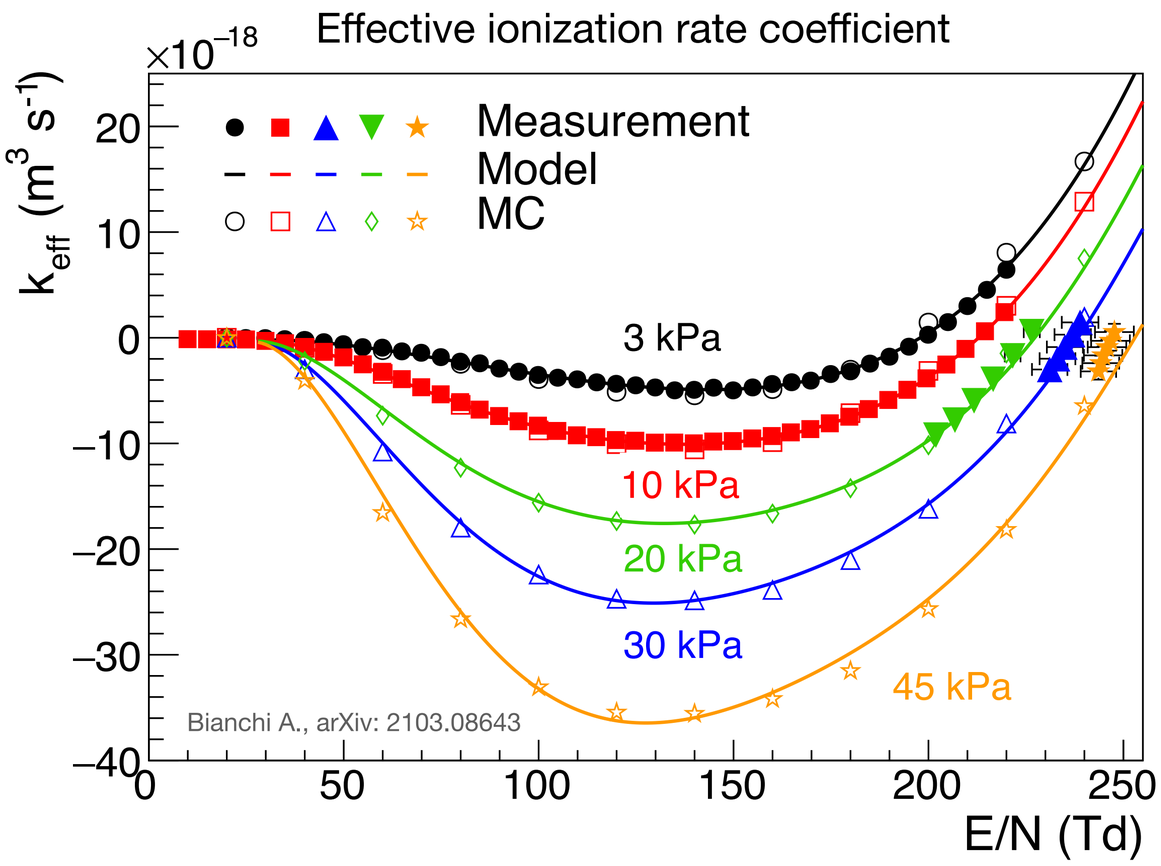


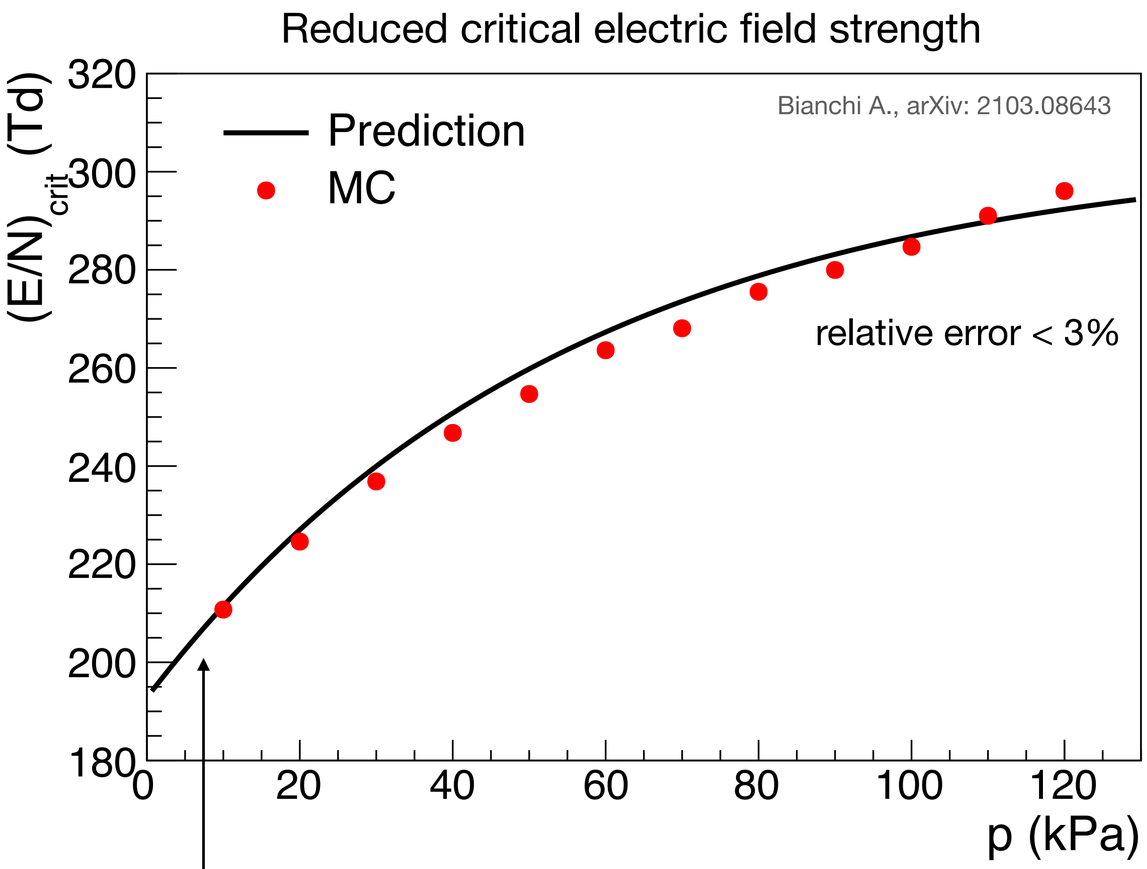


TTA: numerical solver (BOLSIG+)
MC: Monte Carlo simulation (METHES)

RPCs are usually operated in this range

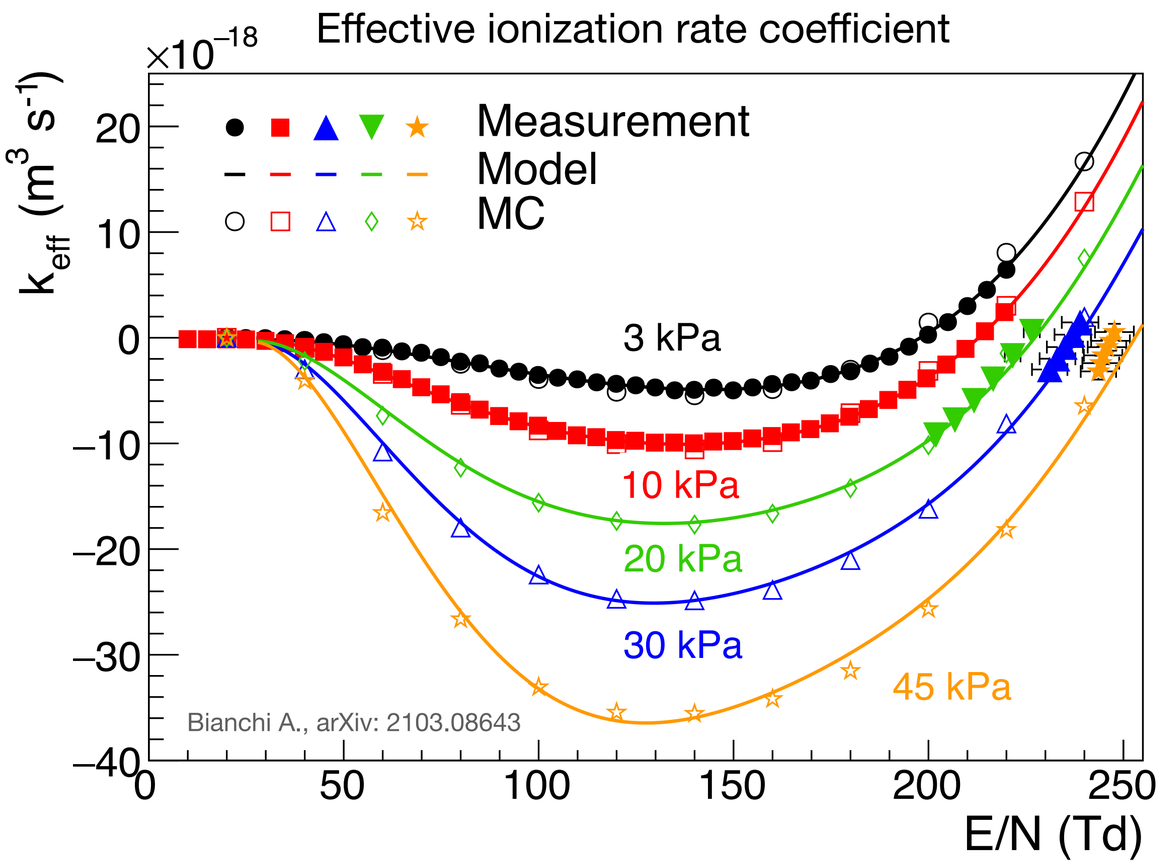
Pure $C_3H_2F_4$

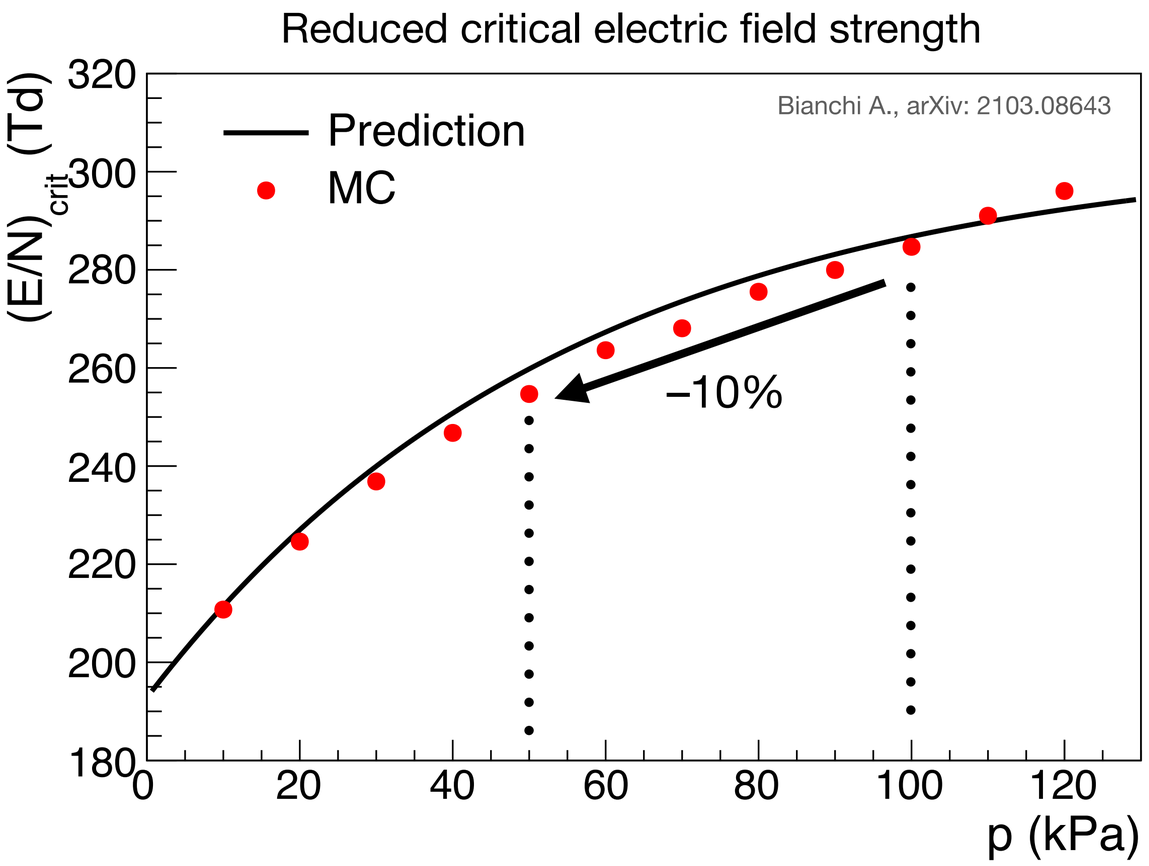




Koch *et al.*'s model: $(E/N)_{crit} = 305\,\mathrm{Td} \cdot \left(1 - \exp\left(-\frac{p + 55\,\mathrm{kPa}}{55\,\mathrm{kPa}}\right)\right)$

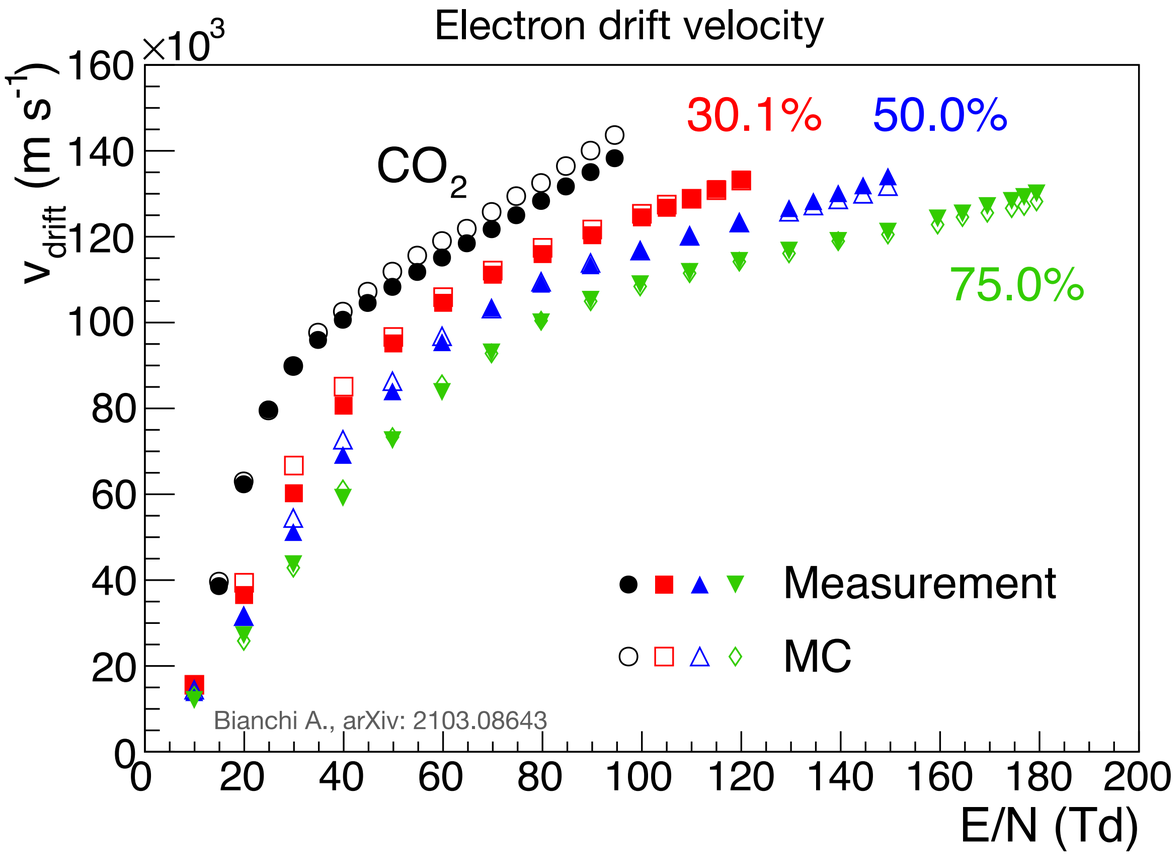
Pure $C_3H_2F_4$

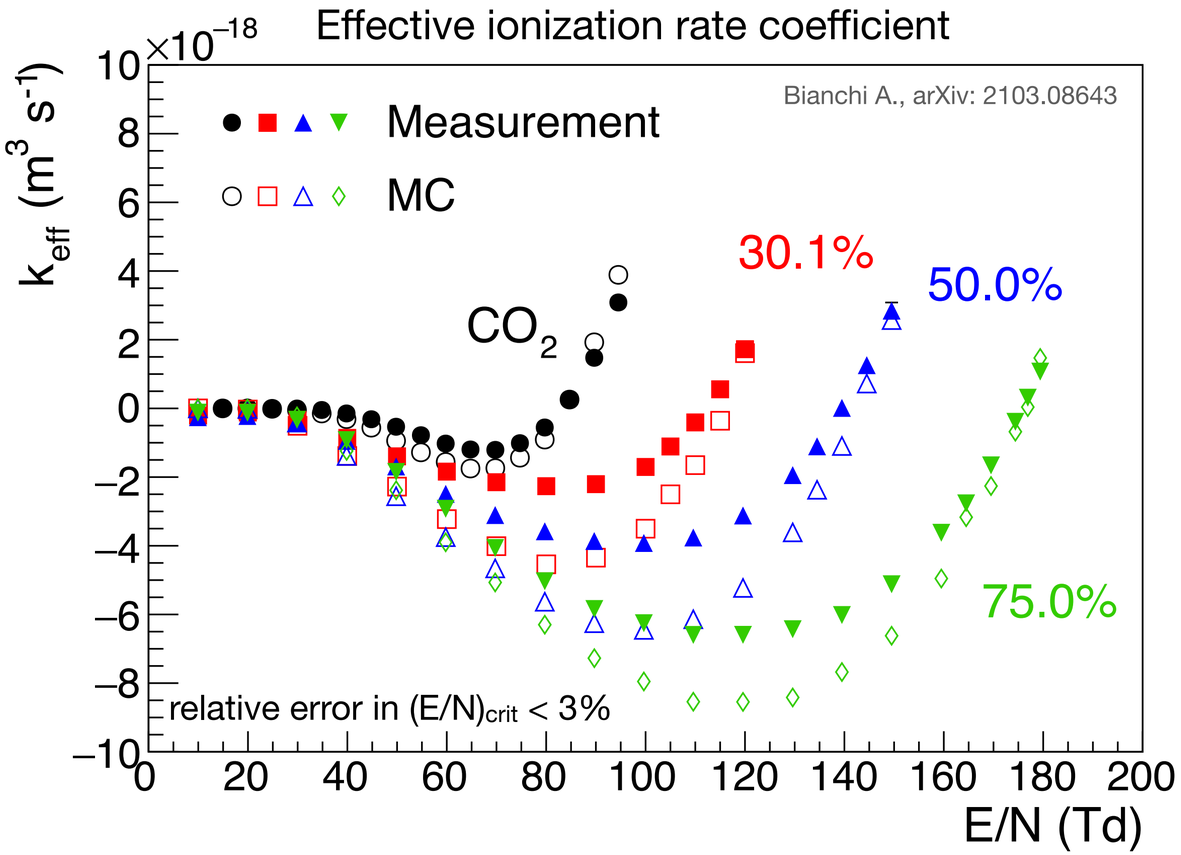




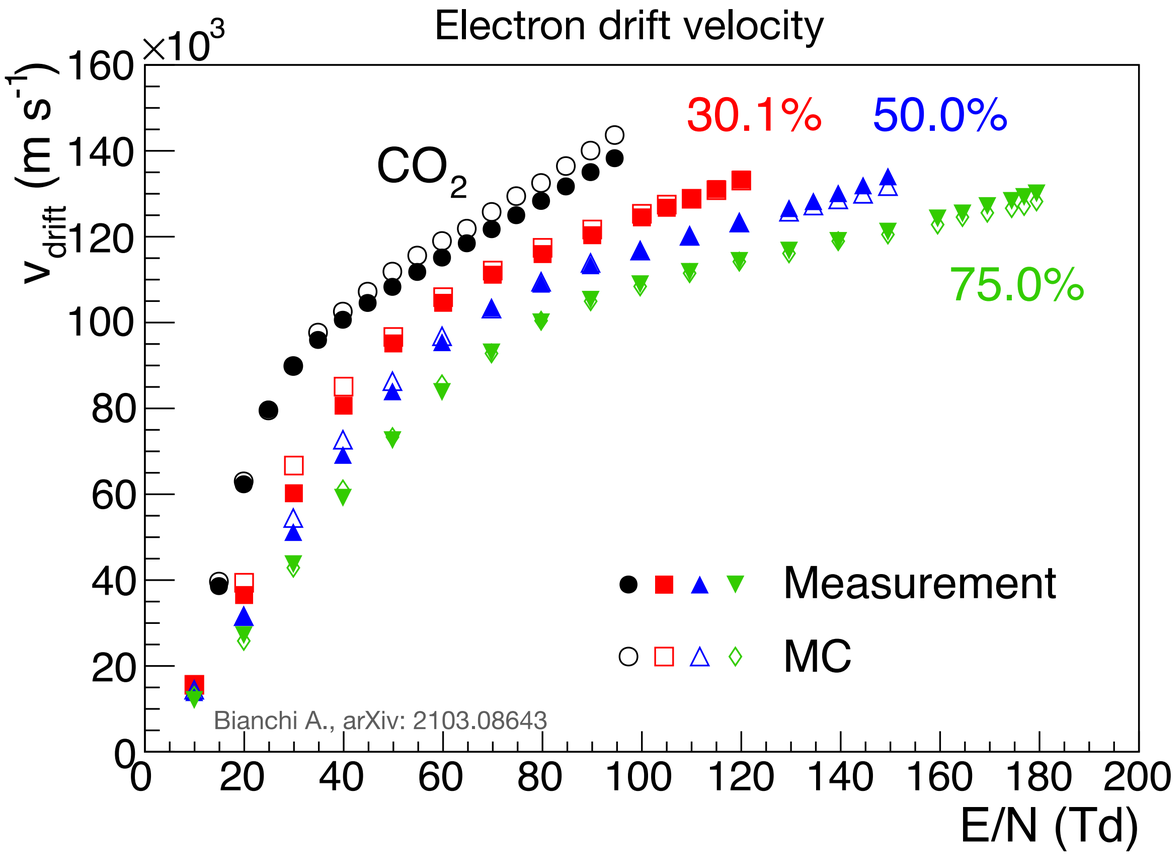
50% $C_3H_2F_4$ + 50% inert gas: $(E/N)_{crit}$ = 250 Td → **−10%**

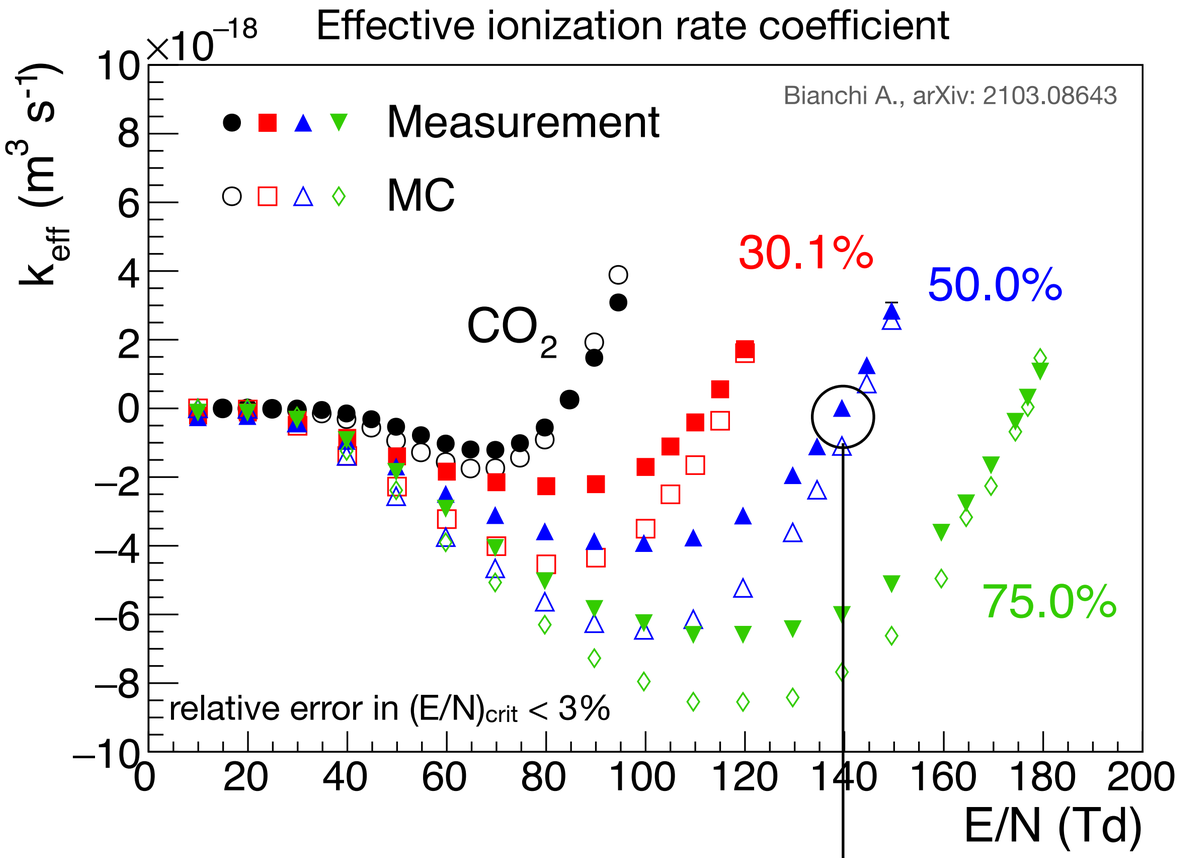
$C_3H_2F_4$-based Gas Mixtures with CO_2





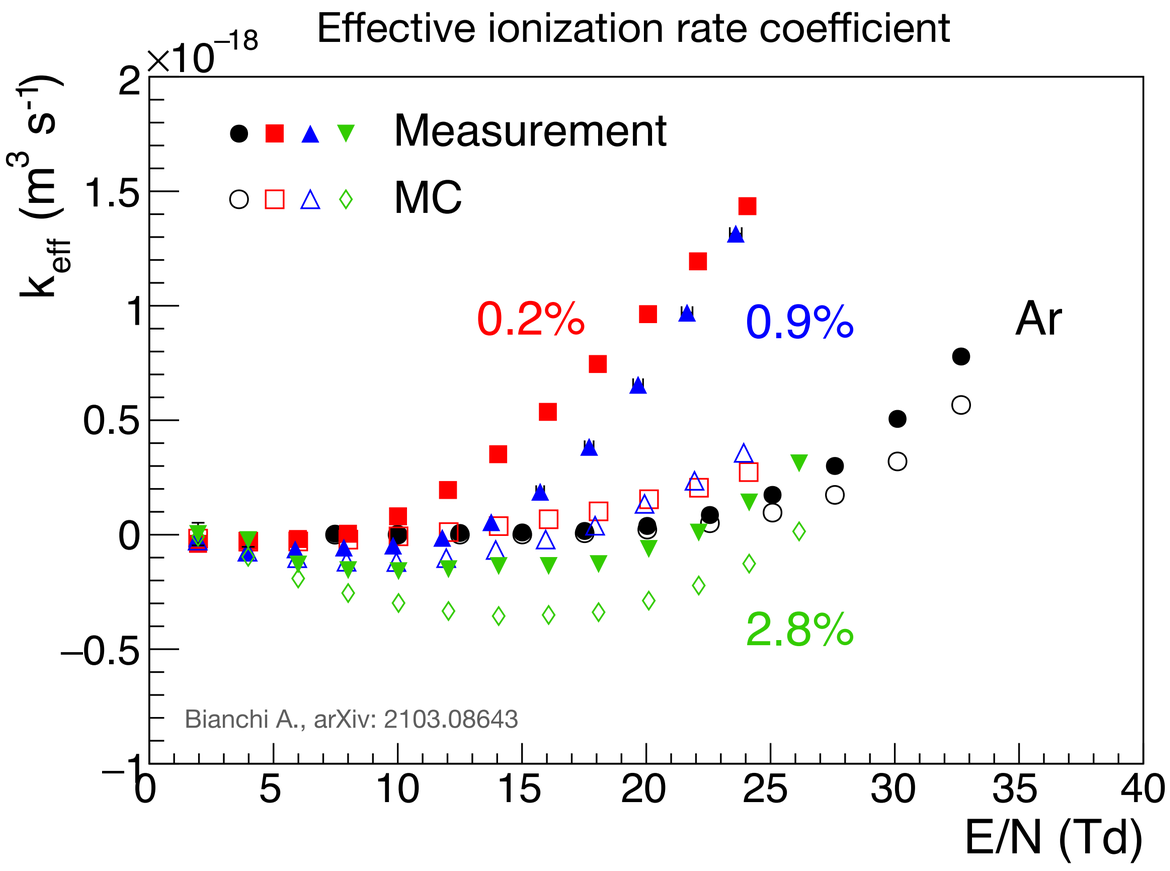
$C_3H_2F_4$-based Gas Mixtures with CO_2





50% $C_3H_2F_4$ + 50% CO_2: $(E/N)_{crit}$ = 140 Td → **–50%**

$C_3H_2F_4$-based Gas Mixtures with Ar



Significant differences between calculations and measurements → **Penning effect** between excited states of Ar and neutral molecules of $C_3H_2F_4$

REFF Simulation

electron collision cross sections → Townsend coefficients (α and η)

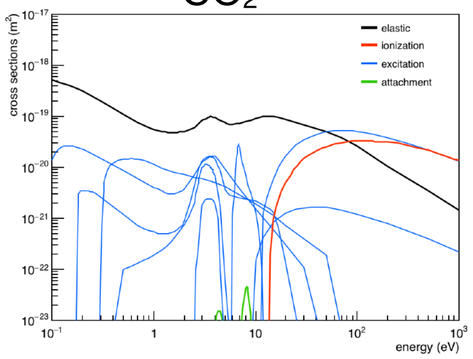
primary clusters (HEED) → Townsend coefficients (α and η)

Townsend coefficients (α and η) → Output: RPC efficiency vs HV

primary clusters (HEED) → Output: RPC efficiency vs HV

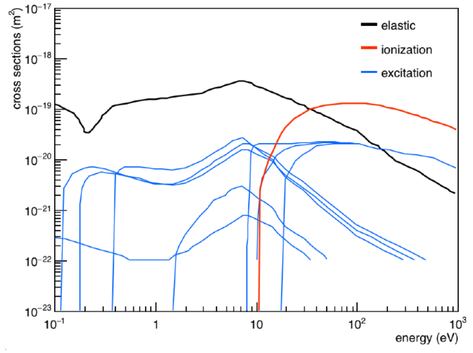
The REFF simulation is a simplified method to evaluate the efficiency curve of RPCs as a function of the high voltage (HV) with different gas mixtures

CO_2



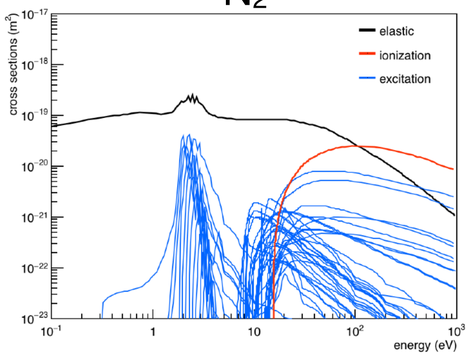
+

$i\text{-}C_4H_{10}$

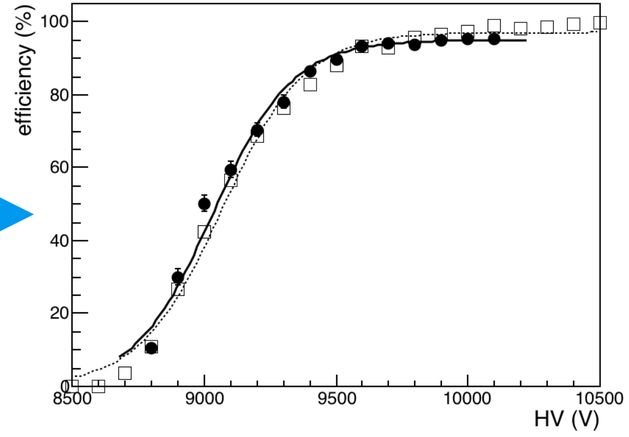


+

N_2



→

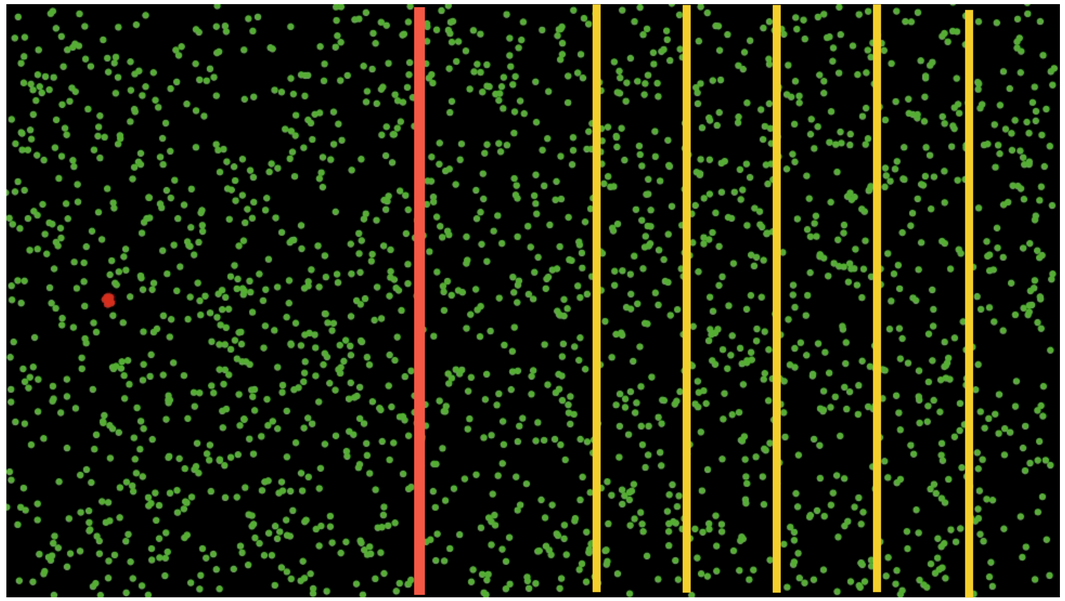


REFF Simulation

electron collision cross sections → Townsend coefficients (α and η)

primary clusters (HEED) → Output: RPC efficiency vs HV

animation

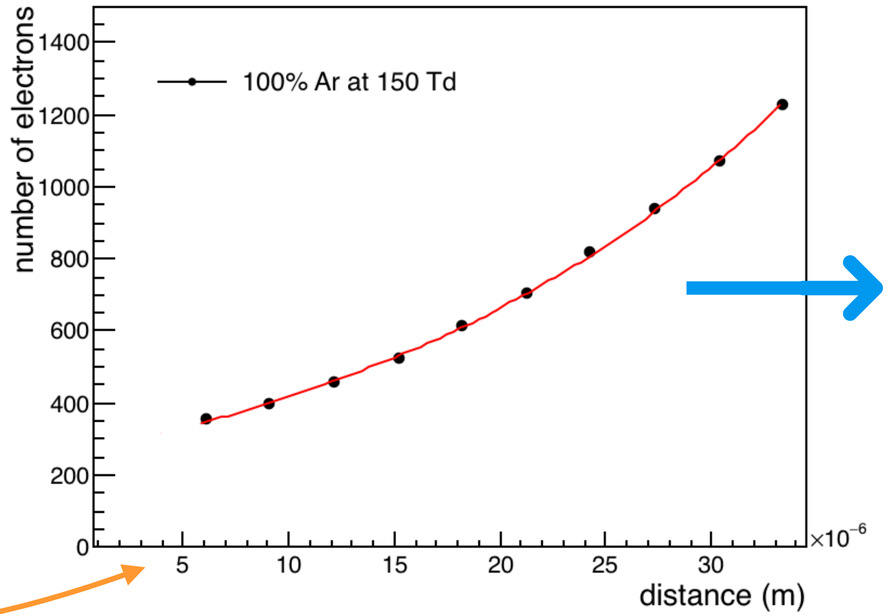


qualitative representation

steady-state

virtual planes

Number of electrons as a function of distance

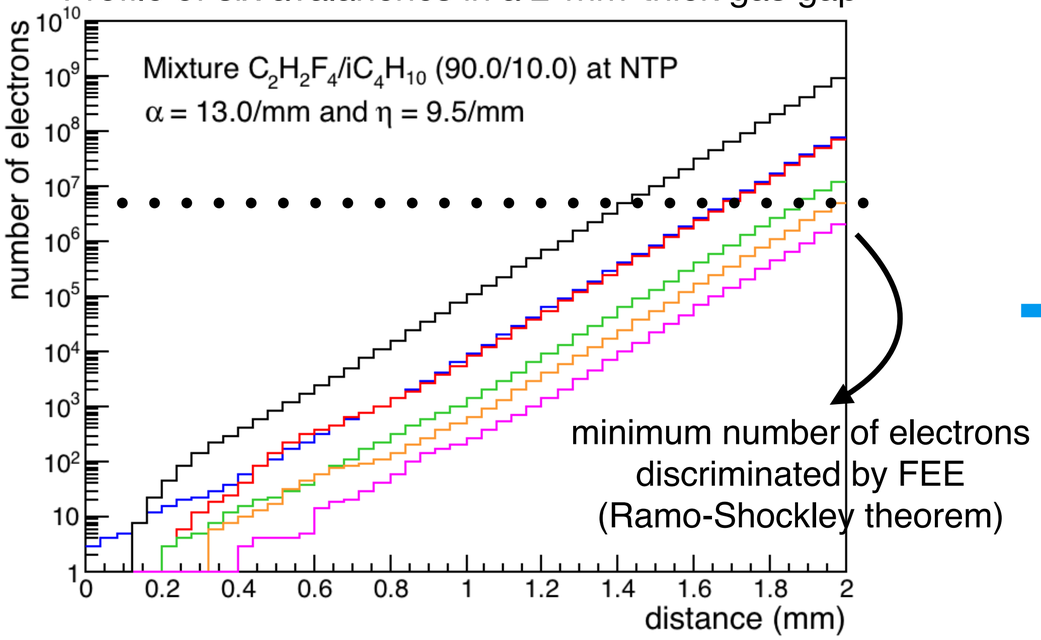


Townsend coefficients (α and η)

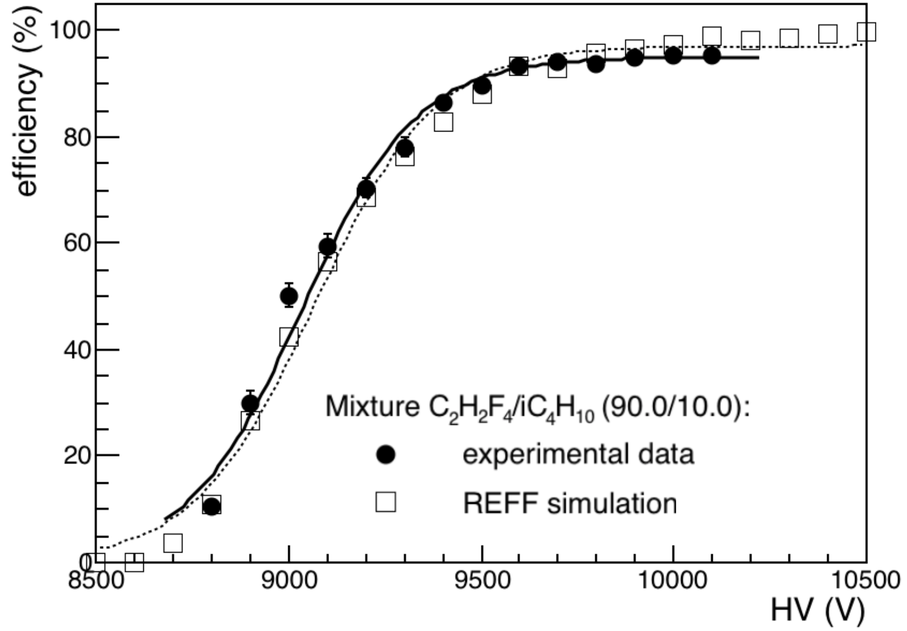
REFF Simulation

electron collision cross sections → Townsend coefficients (α and η) / primary clusters (HEED) → Output: RPC efficiency vs HV

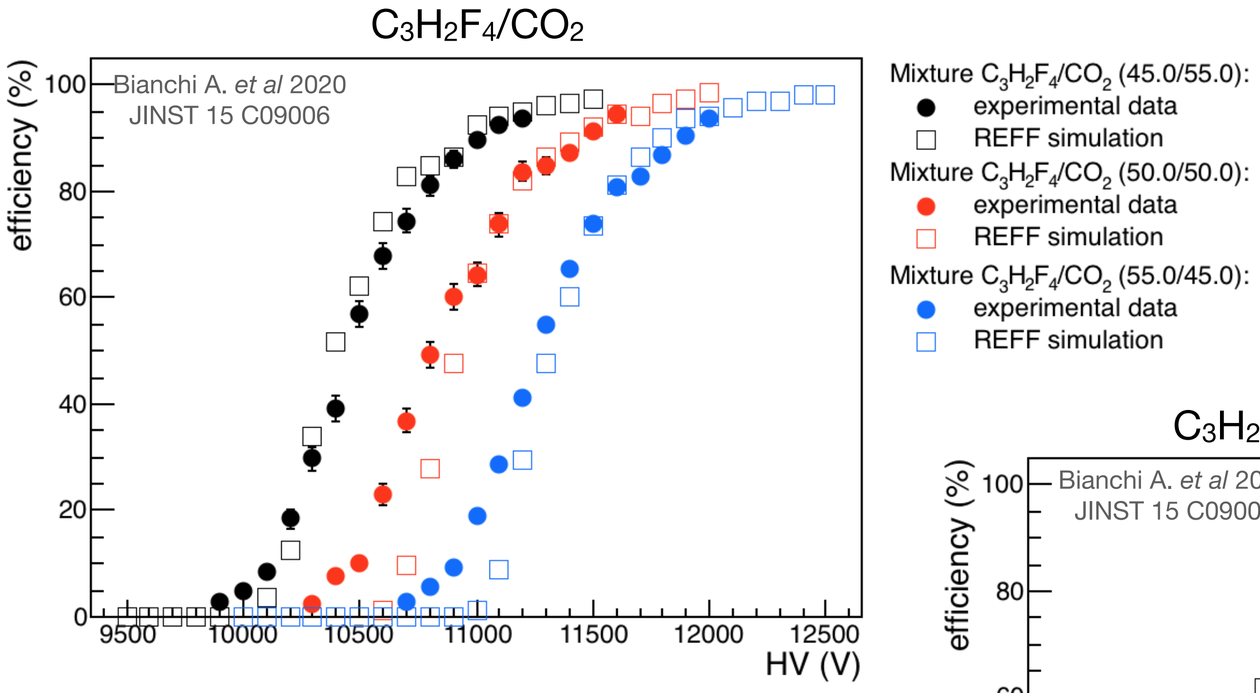
Profile of six avalanches in a 2-mm-thick gas gap

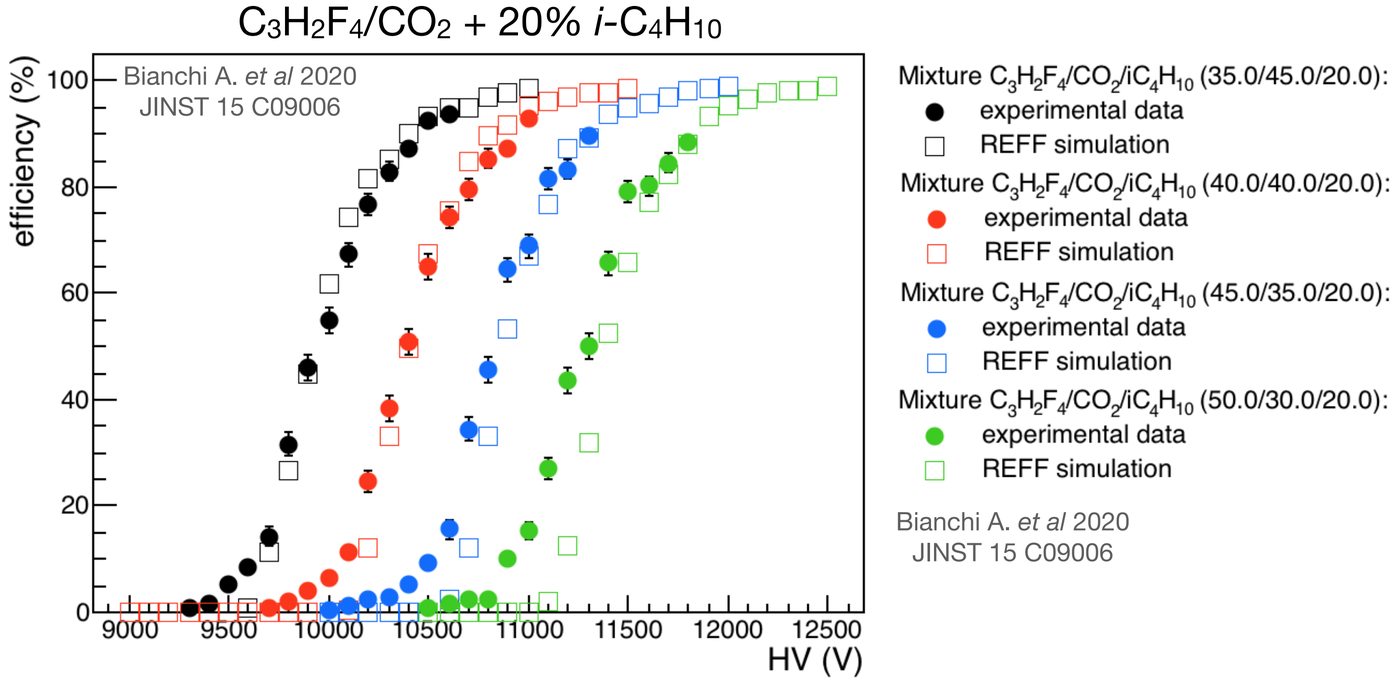


RPC efficiency as a function of the high voltage (HV)



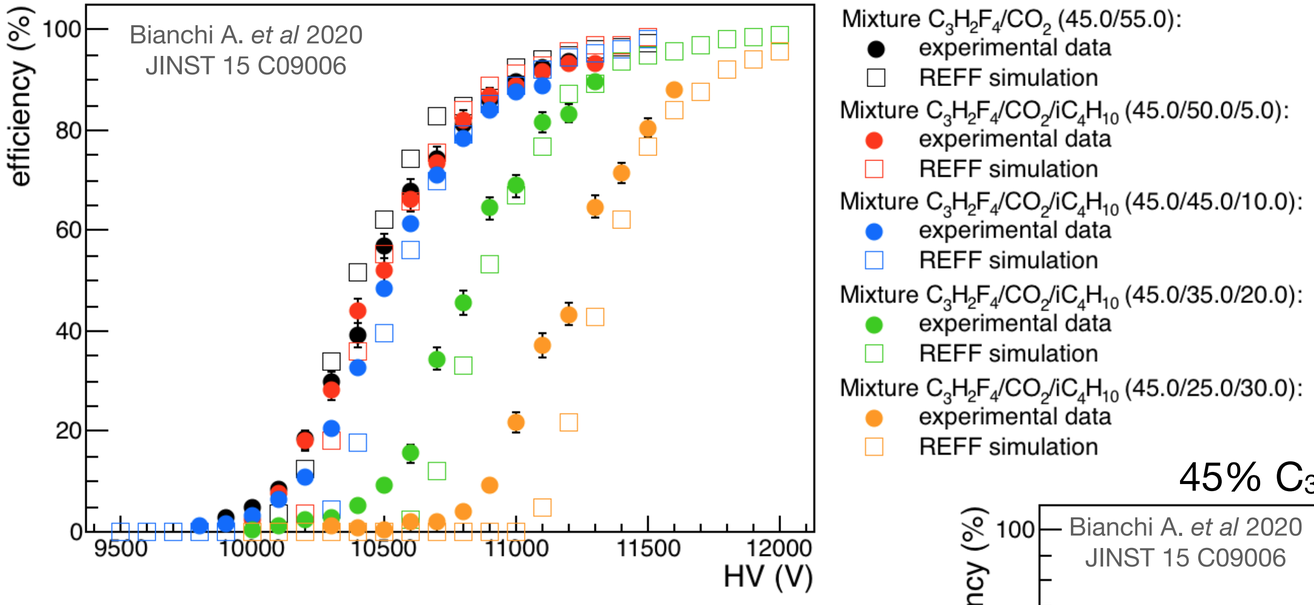
REFF Simulation Results





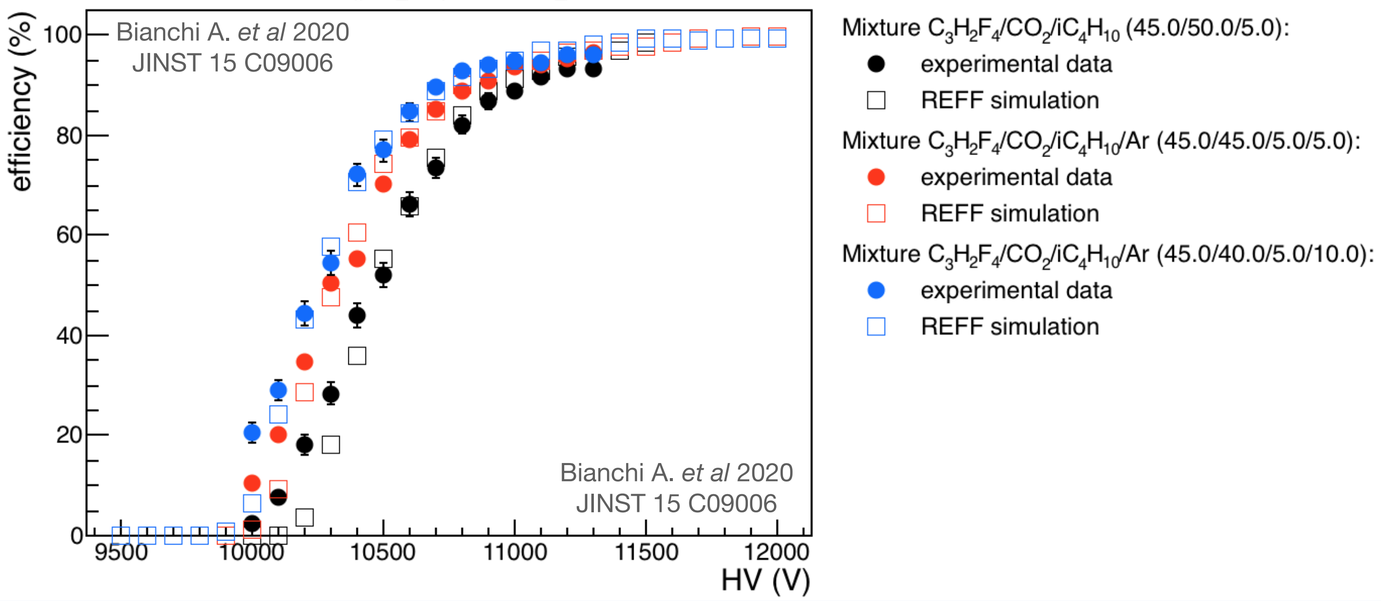
REFF Simulation Results

45% $C_3H_2F_4$ + CO_2/*i*-C_4H_{10}

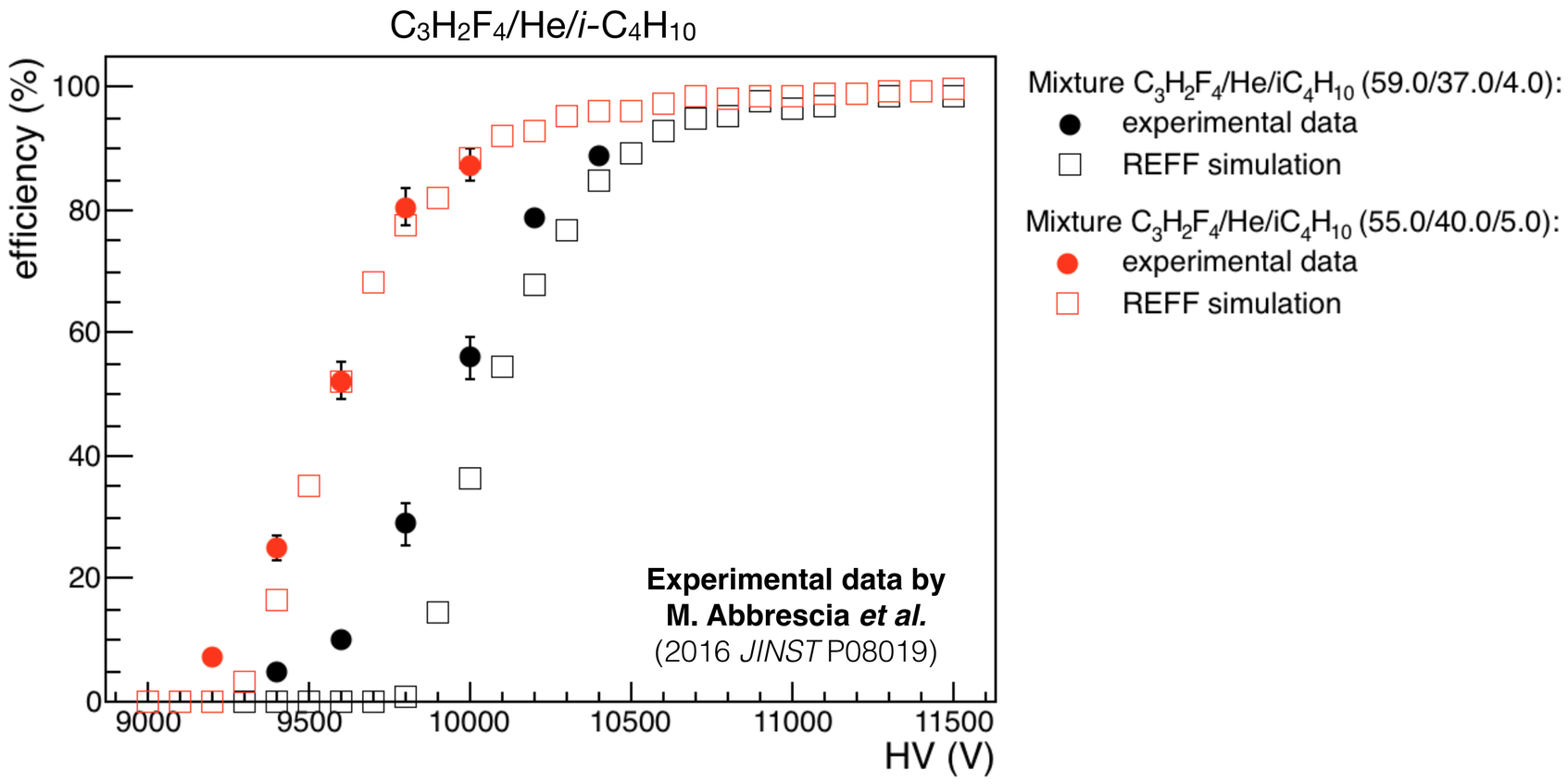


Good results are also obtained in $C_3H_2F_4$-based gas mixtures with the addition of **O_2** or **N_2**

45% $C_3H_2F_4$ + CO_2/Ar

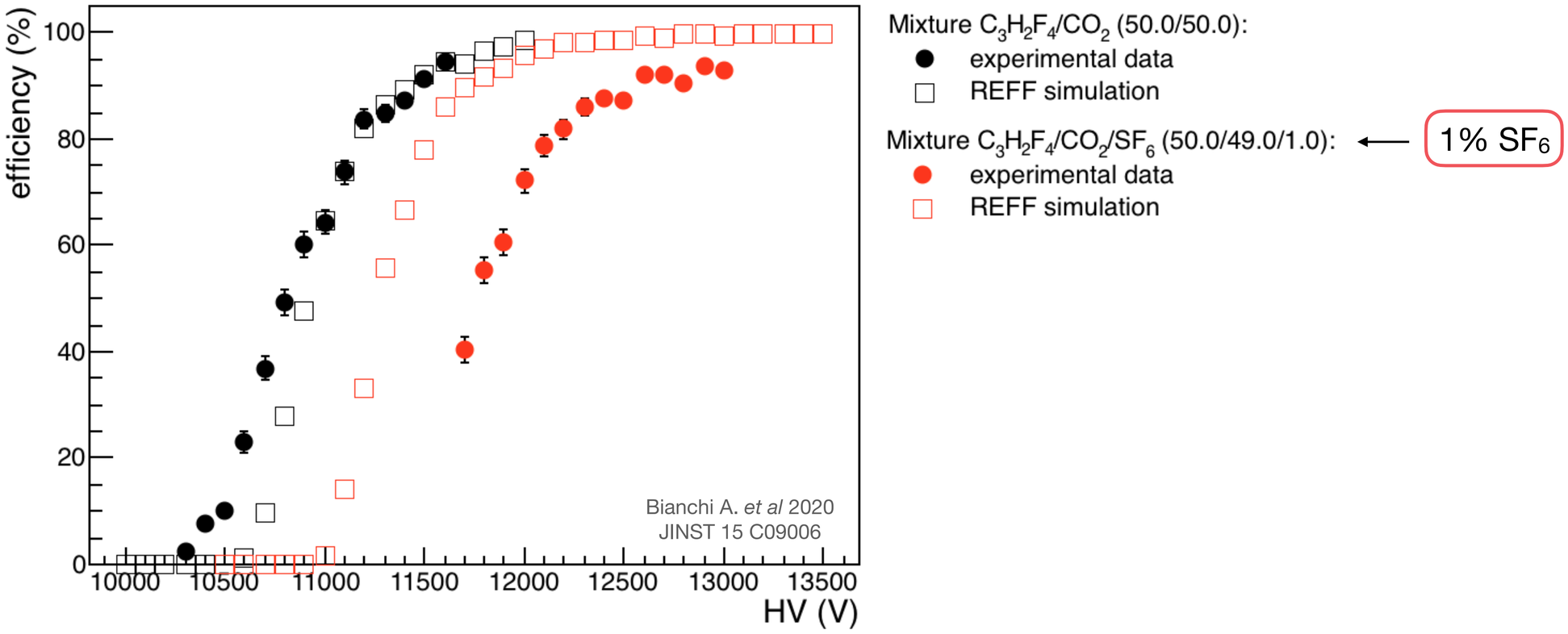


REFF Simulation Results



The discrimination threshold is of ~300 fC while it was ~130 fC in the previous cases

Limitation of REFF Simulation

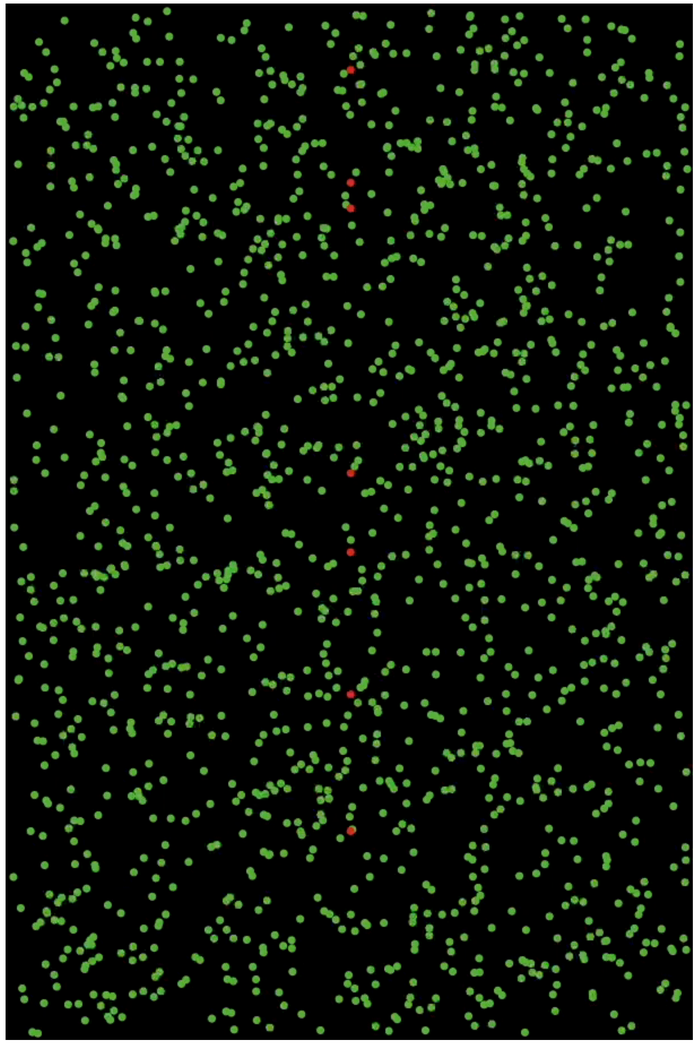


Limitations of REFF simulation have been found in presence of SF_6. Potential future improvements:

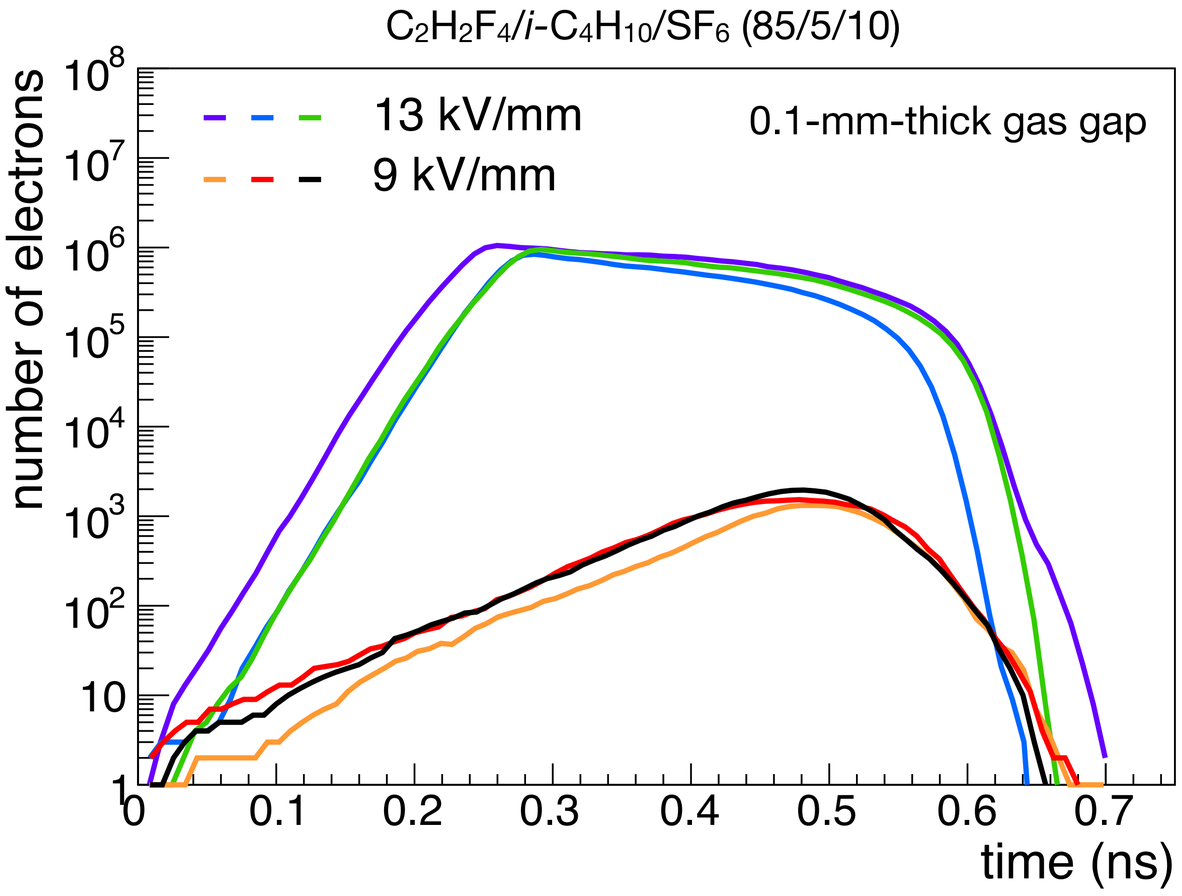
- other different sets of cross sections of SF_6 should be tested (at the moment, only MAGBOLTZ database is used for SF_6)
- space-charge effects are not still implemented in the simulation

Space Charge Effects in REFF Simulation

animation



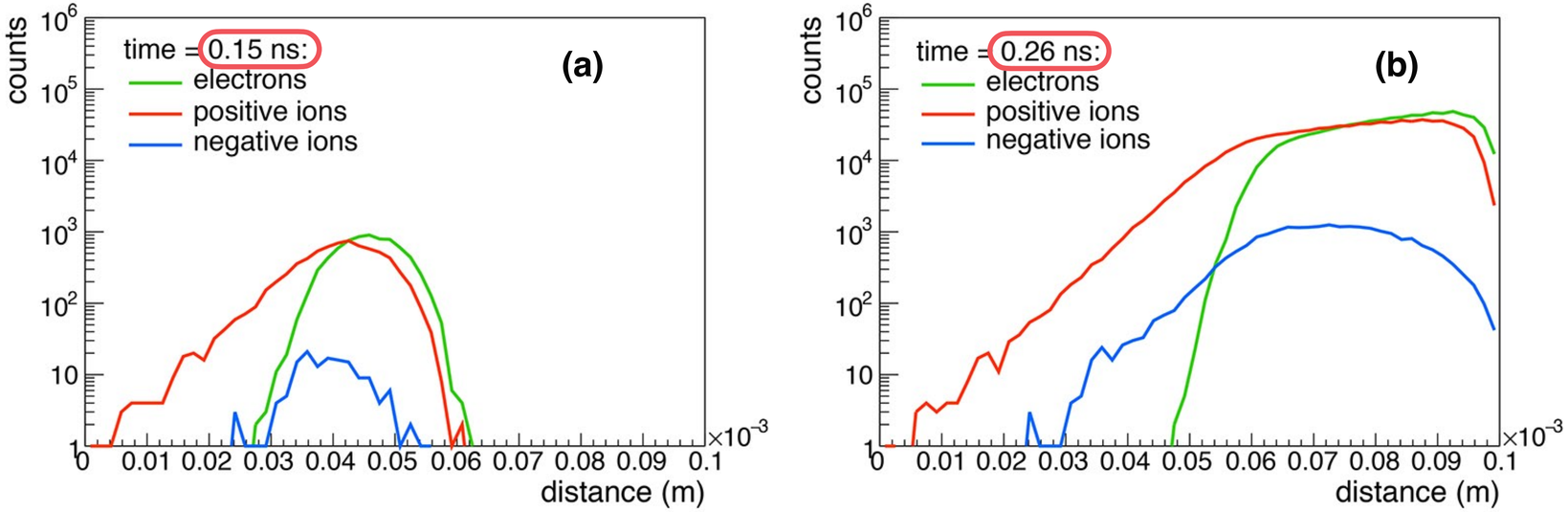
qualitative representation



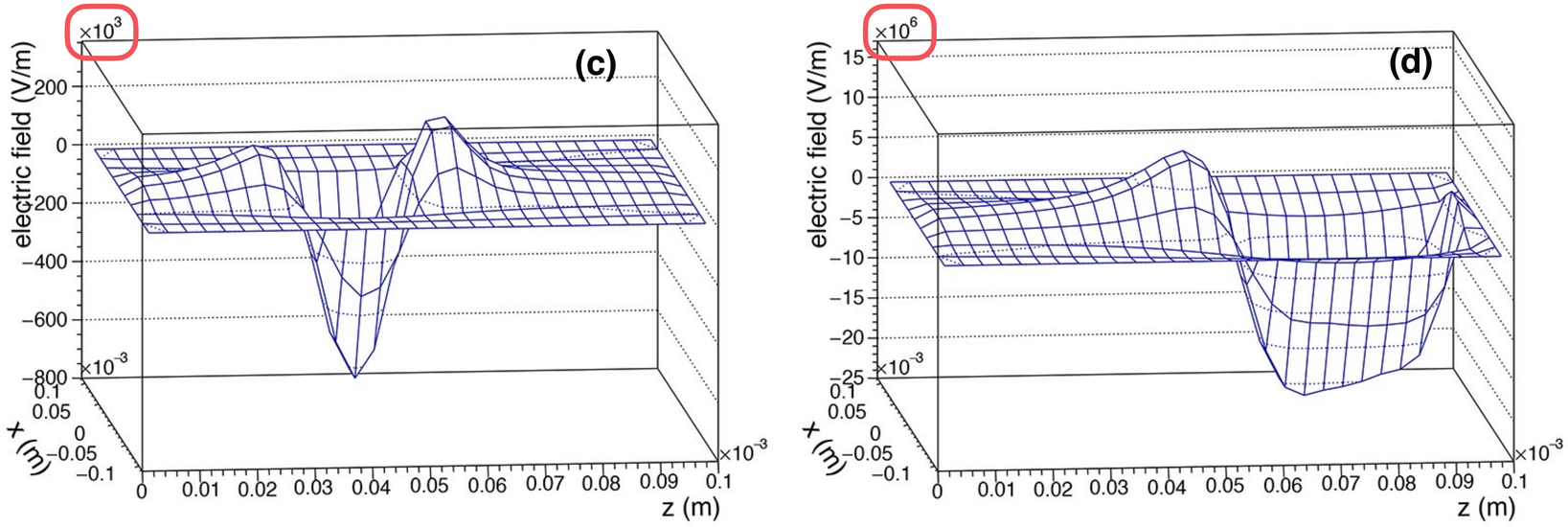
Space Charge Effects in REFF Simulation

14 kV/mm

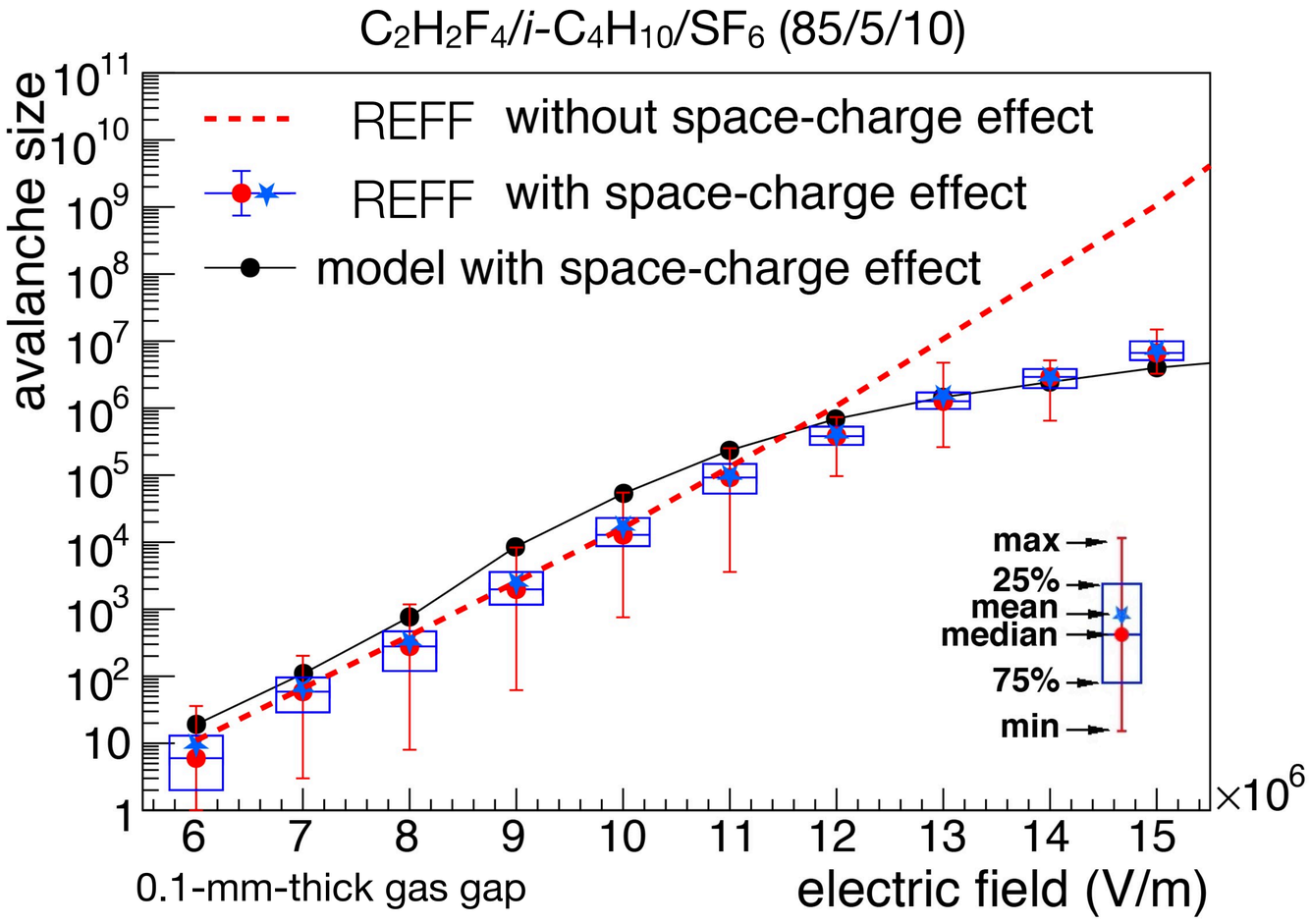
0.1-mm-thick gas gap



space charge electric field



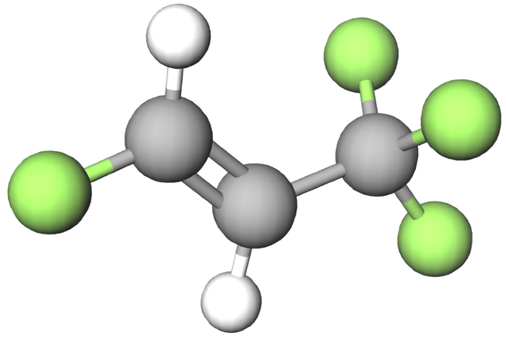
Space Charge Effects in REFF Simulation



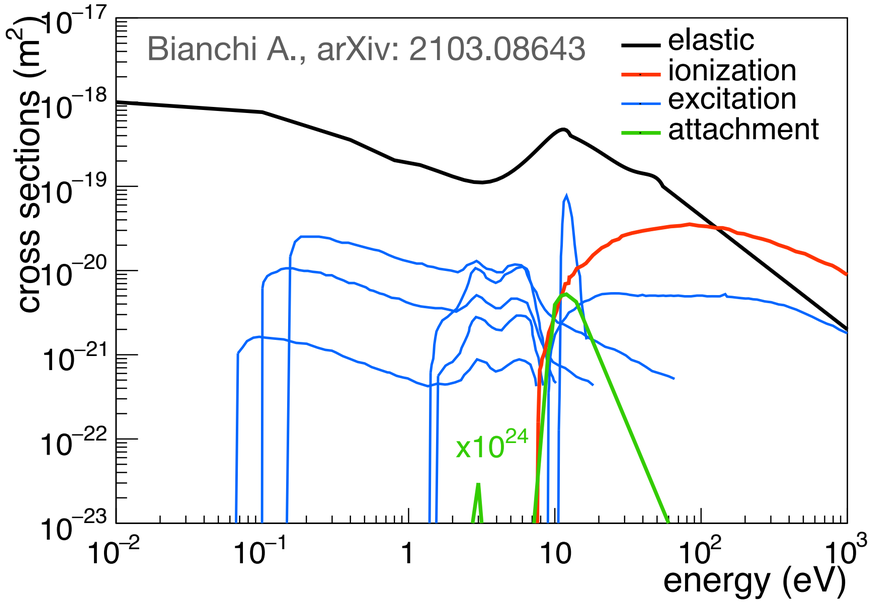
At the moment, only multi-gap RPCs have been simulated

Conclusions and Perspectives

- **Growing interest in $C_3H_2F_4$ for gaseous detectors and voltage insulating applications**
  - thanks to a well-known iterative procedure, **a set of electron collision cross sections for $C_3H_2F_4$** is obtained by unfolding electron swarm parameters
  - the dependence of **three-body attachment** rate with the gas density is implemented while further work needs to be done for the **Penning effect** in presence of Ar
  - the **set is fully validated** in pure $C_3H_2F_4$ and $C_3H_2F_4/CO_2$ gas mixtures



- **REFF simulation**
  - **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, N_2, He and low concentrations of Ar
  - some **limitations** have been found in $C_3H_2F_4$-based gas mixtures **with SF_6**
  - efforts are put in place to include the **space charge effects** in the REFF simulation



- **Perspectives**
  - novel strategy to **optimize $C_3H_2F_4$-based gas mixtures for Resistive Plate Chambers**
  - novel strategy to investigate the **positive synergy of $C_3H_2F_4$ with buffer gases for voltage insulating applications**

CERN