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Improved criterion to numerically estimate streamer probabilities of RPCs for environmentally friendly gas mixtures

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XVII Conferences on Resistive Plate Chambers and Related Detectors, Santiago de Compostela

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Motivation

Requirement for an eco-friendly alternative mixture for trigger RPCs

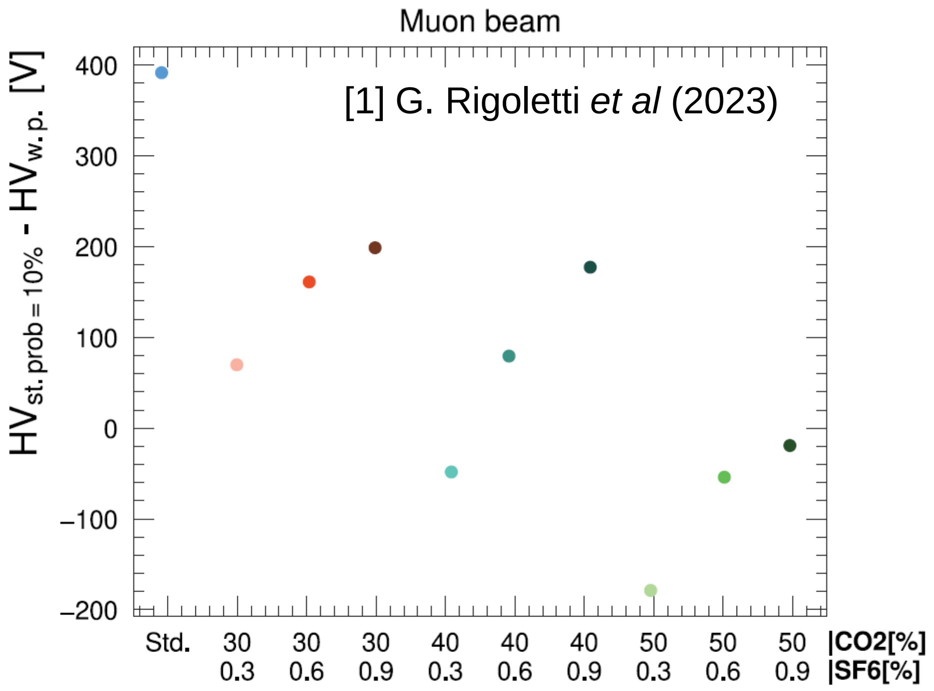

Fig. 6. Avalanche-streamer separation with muon beam for the standard gas mixture and the gas mixture with 30%, 40%, 50% of CO_2 in combination with 0.3%, 0.6%, 0.9% of SF_6.

We all agree: R134a, strong GHG, part of F-gas regulation needs eco-friendly replacement

The critical requirement for an alternative mixture:

- Suppression of discharges
  - Slowing down the ageing process
  - Reducing the *dead-time*

Yet, no numerical tool to predict the avalanche-streamer separation

- Prediction of inception; no need for detailed simulation
- Promising numerical optimization techniques to tune for %

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Discharges in RPCs

Slow breakdown: Townsend discharge, Paschen law [2]
- Linseed oil-coated Bakelite: UV insensitive [3]
- Isobutane: large UV absorption cross-section [4]

Fast breakdown: Streamer criterion
- Single avalanche: typically $10^6 - 10^8$ electrons [5, 6, 7]
- Photo-ionization driven, diffusion-driven, …
  → **enhanced by large space-charge fields**

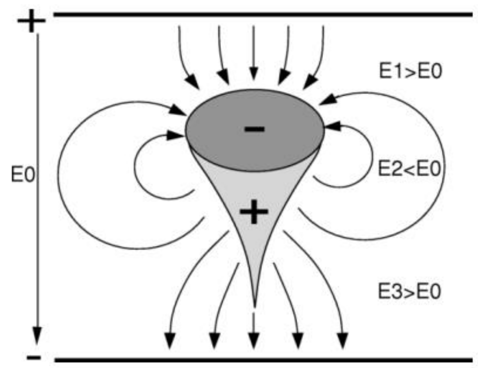

Figure: Space-charge field distortion of a single avalanche. [8]

Definition: Improved streamer inception criterion

A multi-electron avalanche transitions to a critical avalanche if its space-charge field exceeds a fraction *k* of the background field,

$$\max_{\mathbf{x},\,t} E_{sc}(\mathbf{x}, t) \geq kE_0 \Rightarrow \text{inception}$$

Setup

Based on experimental setup given by G. Rigoletti et al [1]

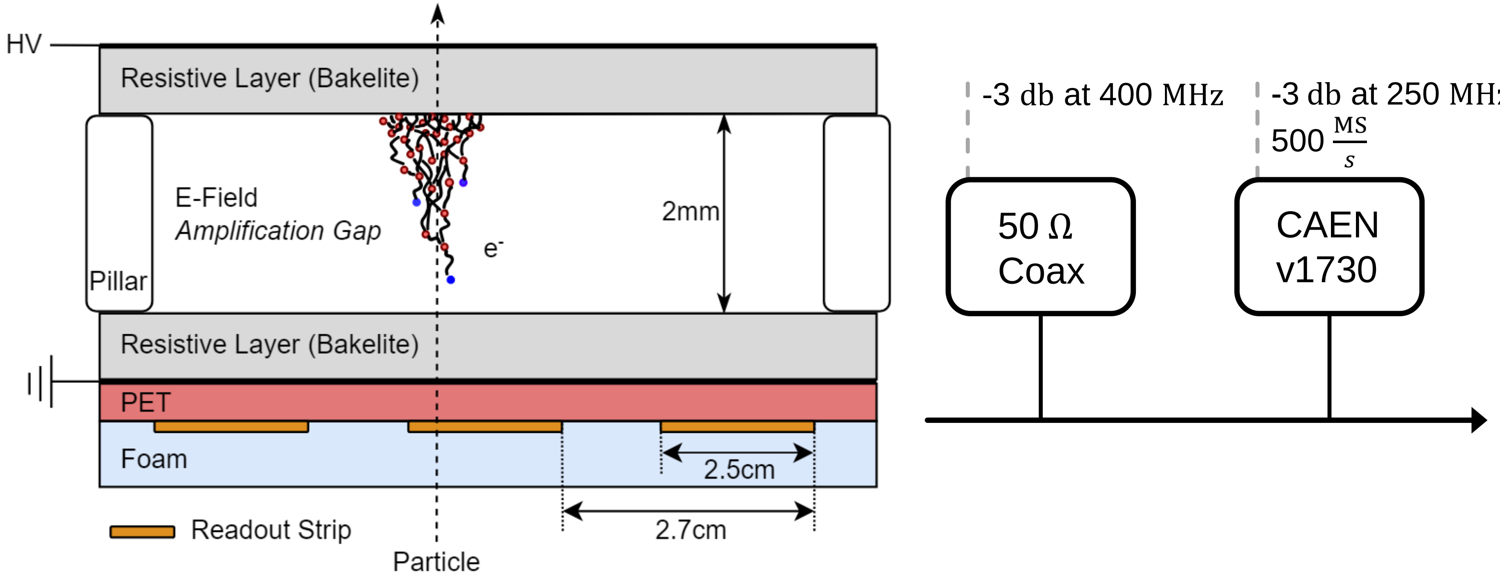

Figure A: Illustration of the three-layer single gap HPL-RPC with 1d read-out strip system and graphite-coated HV electrodes.

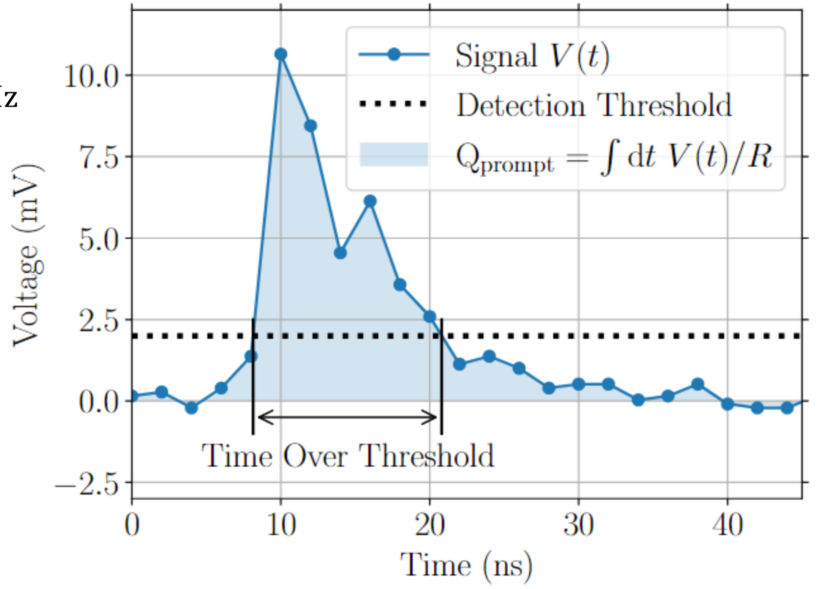

Figure B: Example signal from measurements illustrating detection-, large signal-, and time over threshold.

GIF++ muon beam: 100 GeV with irradiated area: ≈10 cm^2

Threshold values:

- 2 mV signal threshold
- 16 pC streamer threshold

A few details on the simulation pipeline

Primary ionization → **Electron transport** →

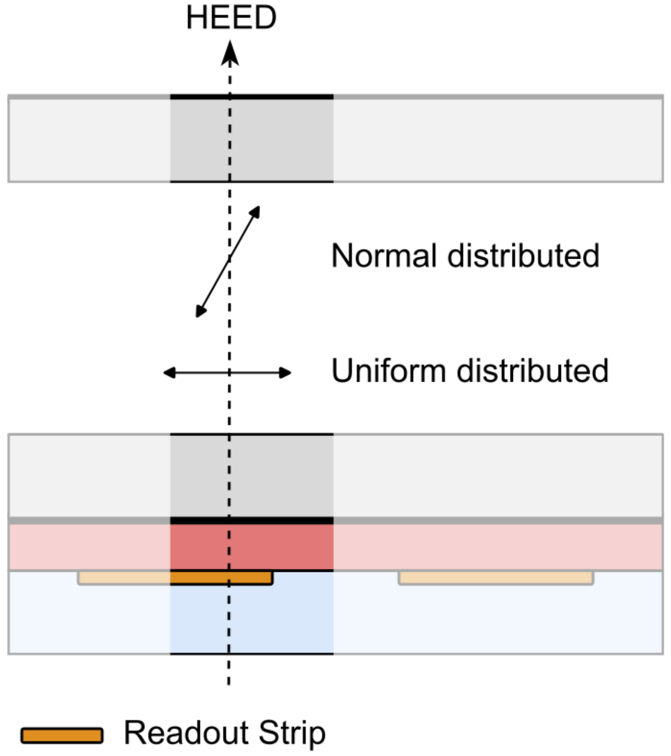

Figure: Generation of primaries with HEED reflecting the GIF++ beam size and shape.

- C. Lippmann 2d space-charge routine [12]
  - Symmetrization of: primaries or primaries + AVALANCHEMICROSCOPIC
  - Streamer probabilities: *flag critical events*
  - ➢ refactored into GARFIELD++ *(available this month)*
- Two mirror charges to reflect the geometry
- Swarm parameters generated with MAGBOLTZ v11.19
  - TOF parameters instead of SST parameters [13]

Displacement Currents

to python post-processing

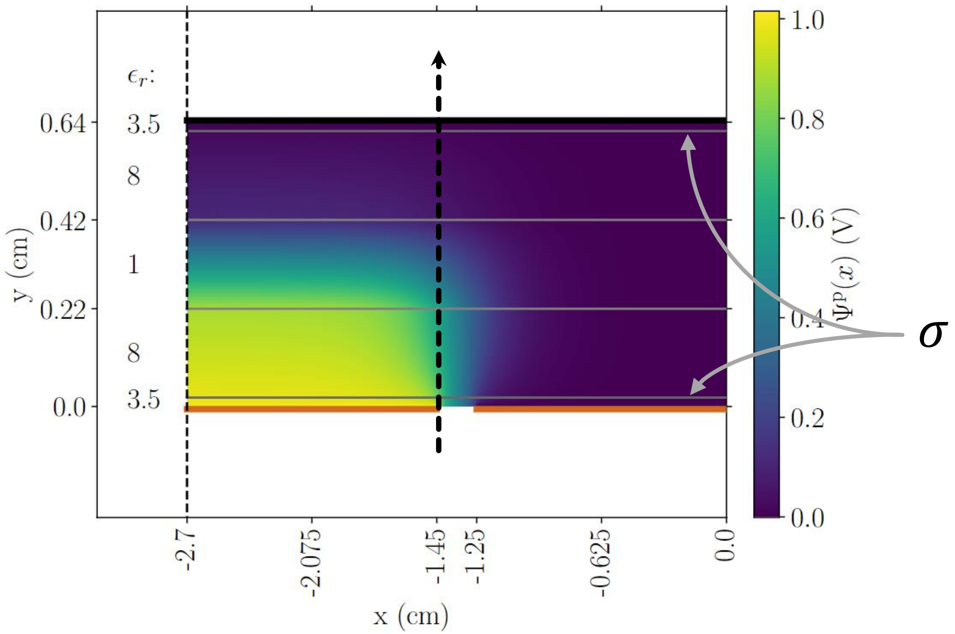

Figure A: Prompt weighting potential calculated with FEM.

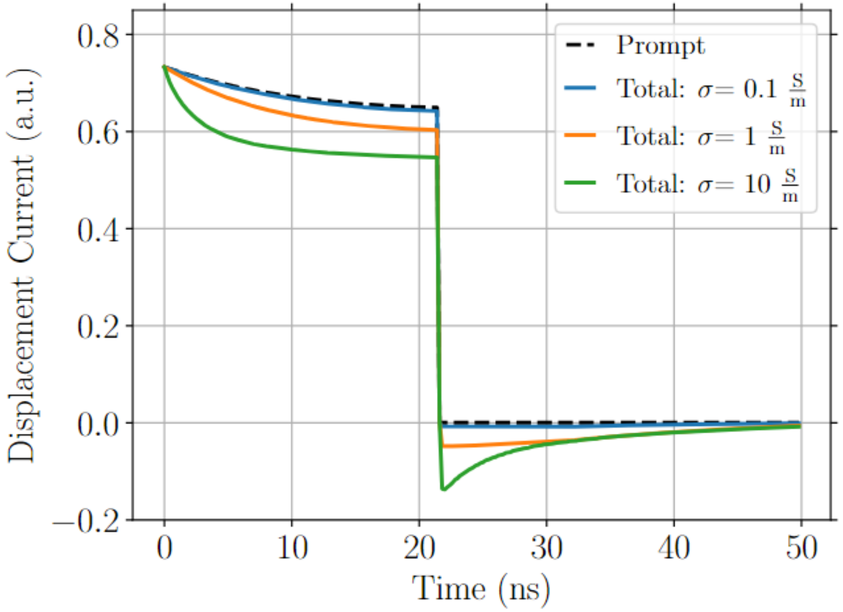

Figure B: Displacement currents for different bulk resistivities for constant velocity trajectory as shown in Figure A.

- Conductive materials *shield/delay* displacement currents [9, 10]
- Expect conductivity of around 0.1 S/m for graphite layer [11]

⇒ **Shielding is negligible**

from Garfield++

Multiconductor transmission line

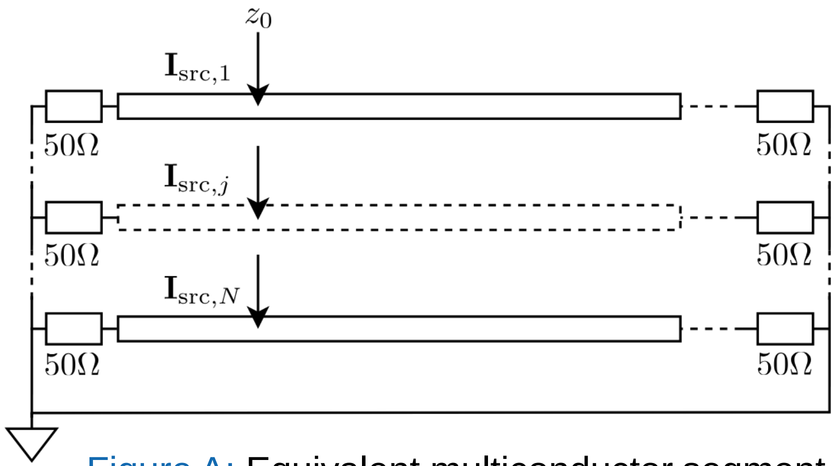

Figure A: Equivalent multiconductor segment terminated on both sides with 50Ω resistors.

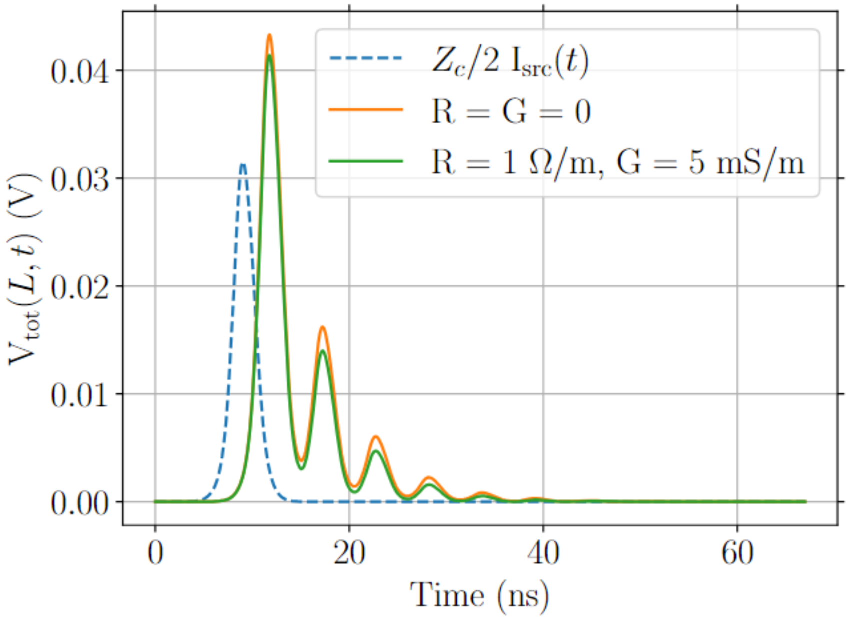

Figure B: Transmitted signal at segment end comparing the worst-loss case to the loss-less line.

Measured matrices per unit length **L, C, R, G**

- Off-diagonal elements (*cross-talk*)
- Impedance mismatch (*voltage build-up, reflections*)
- Losses (negligible, see Figure B)

Coaxial cable → **Digitizer**

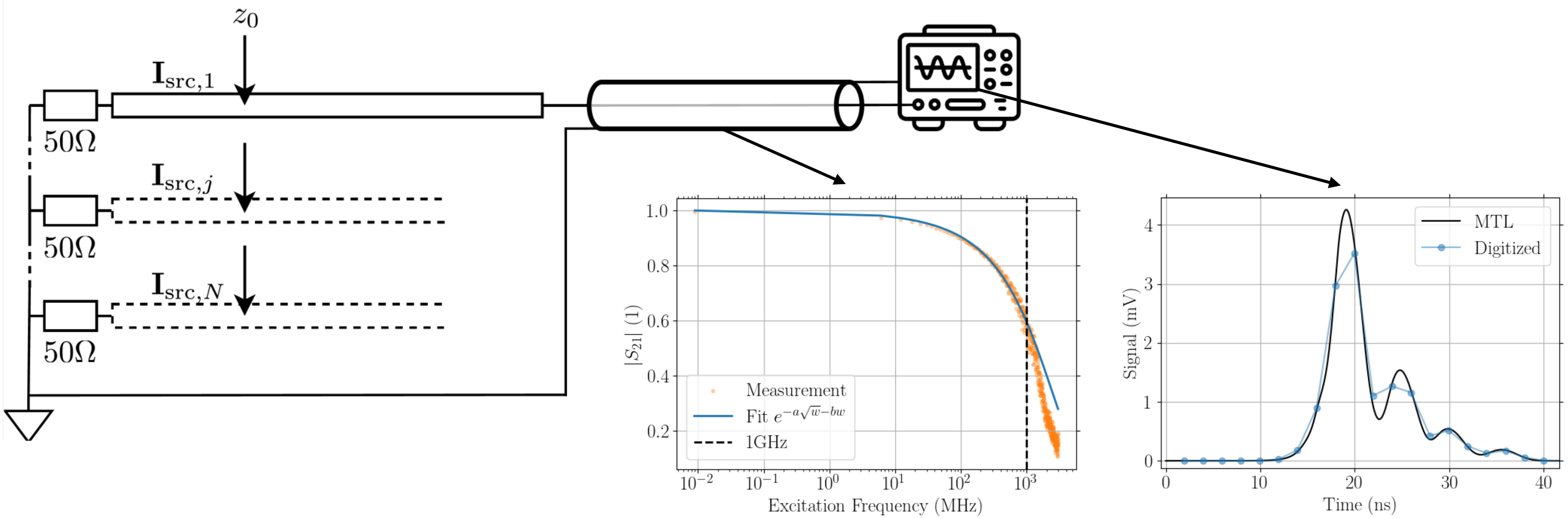

Figure: MTL junction to the single transmission line and digitizer.

- Frequency- and cable length-dependent attenuation
- Input bandwidth & signal digitization
  - ➢ 2ns mask with random start point

Validation: Trigger RPC Standard Mixture

95.2% R134a, 4.5% isobutane, and 0.3% SF_6

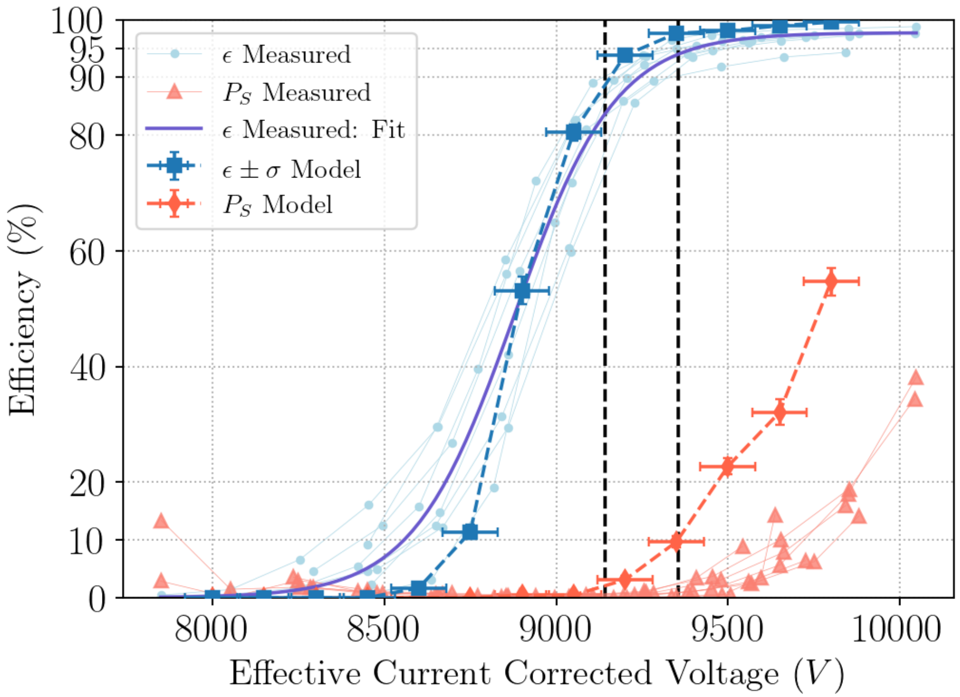

Figure: Measured and simulated efficiency and streamer probabilities. Measurements include various RPCs from different runs. The dashed horizontal lines indicate the avalanche-streamer separation: *k*=0.95.

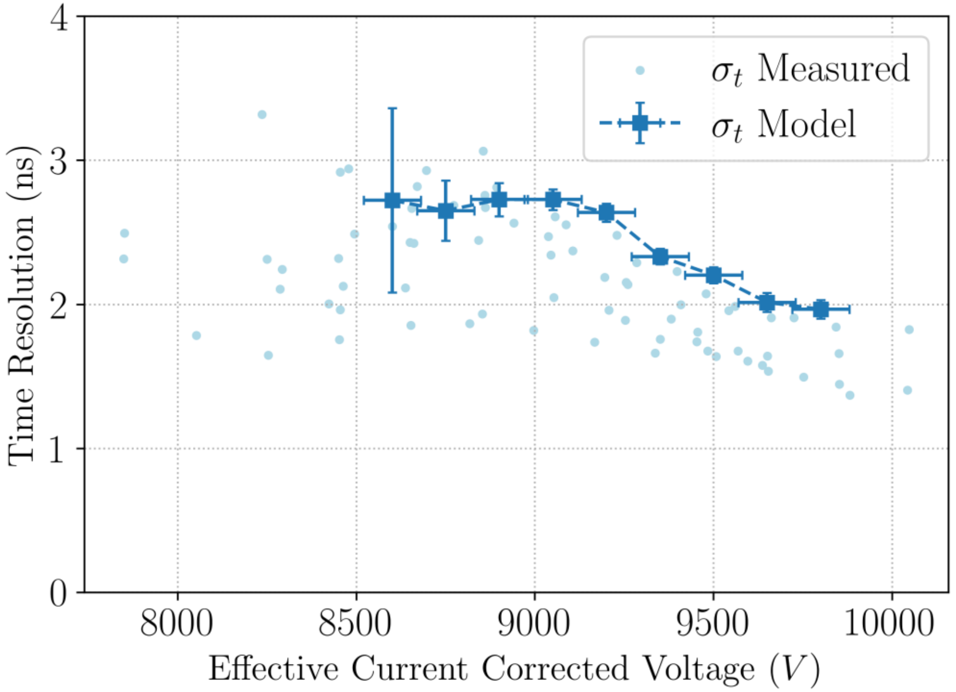

Figure: Measured and simulated time resolution. Measurements include various RPCs from different runs.

Results: CO_2-based Standard Mixture

Avalanche-Streamer Separation

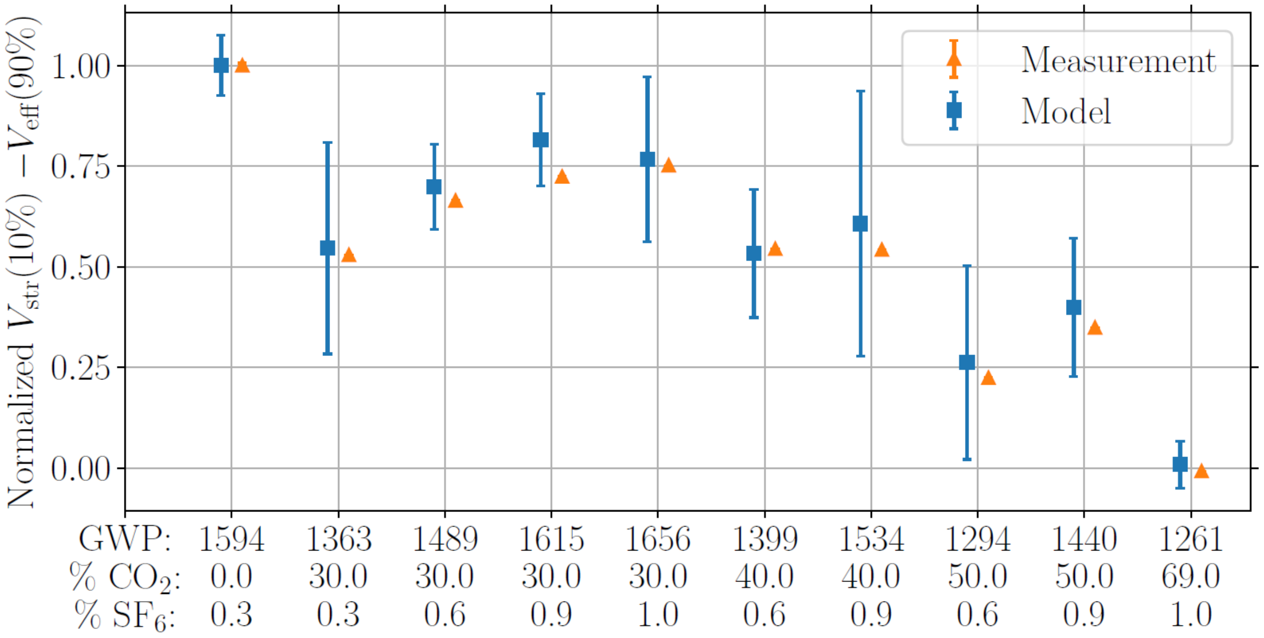

Figure: Avalanche-streamer separation for various CO2-based standard mixtures, normalized to the standard mixture: *k*=0.95.

Measurements from the same RPC

Simulation facts:

- Between 400 and 900 events per HV
- Event simulation in average 30 minutes

➢ Uncertainties on simulated values conservative

➢ Excellent agreement

Conclusion & Outlook

Conclusion:

a. Detailed simulation pipeline
   - Refactored 2d model by Lippmann into Garfield++
   - Signal generation and transmission
   - No fine-tuning

b. Improved criterion to predict streamer inception
   - Avalanche-streamer separation prediction exceptionally well
   - Absolute value prediction vague: free parameter *k*

Outlook:

➢ Model validation of avalanche-streamer separation for HFO1234ze(E) based mixtures

➢ Optimization based on the avalanche-streamer separation and data-driven techniques
   - Find the optimal *fine-tuned* percentage of each constituent in the mixture

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Literature

[1] G. Rigoletti *et al* (2023), 10.1016/j.nima.2023.168088

[2] F. Paschen (1889), 10.1002/andp.18892730505

[3] C. Lu (2009), 10.1016/j.nima.2008.12.225

[4] B.A. Lombos *et al* (1967), 10.1016/0009-2614(67)85056-5

[5] H. Raether (1940), 10.1007/BF01475193

[6] J. M. Meek (1940), 10.1103/PhysRev.57.722

[7] R. Färber and C. M. Franck (2021), 10.1088/1361-6463/ac1888

[8] C. Lippmann and W. Riegler (2003), 10.1109/TNS.2003.814536

[9] W. Riegler (2004), 10.1016/j.nima.2004.07.129

[10] D. Janssens (2023), *Dissertation*

[11] A. Sen *et al* (2022), 10.1016/j.nima.2021.166095

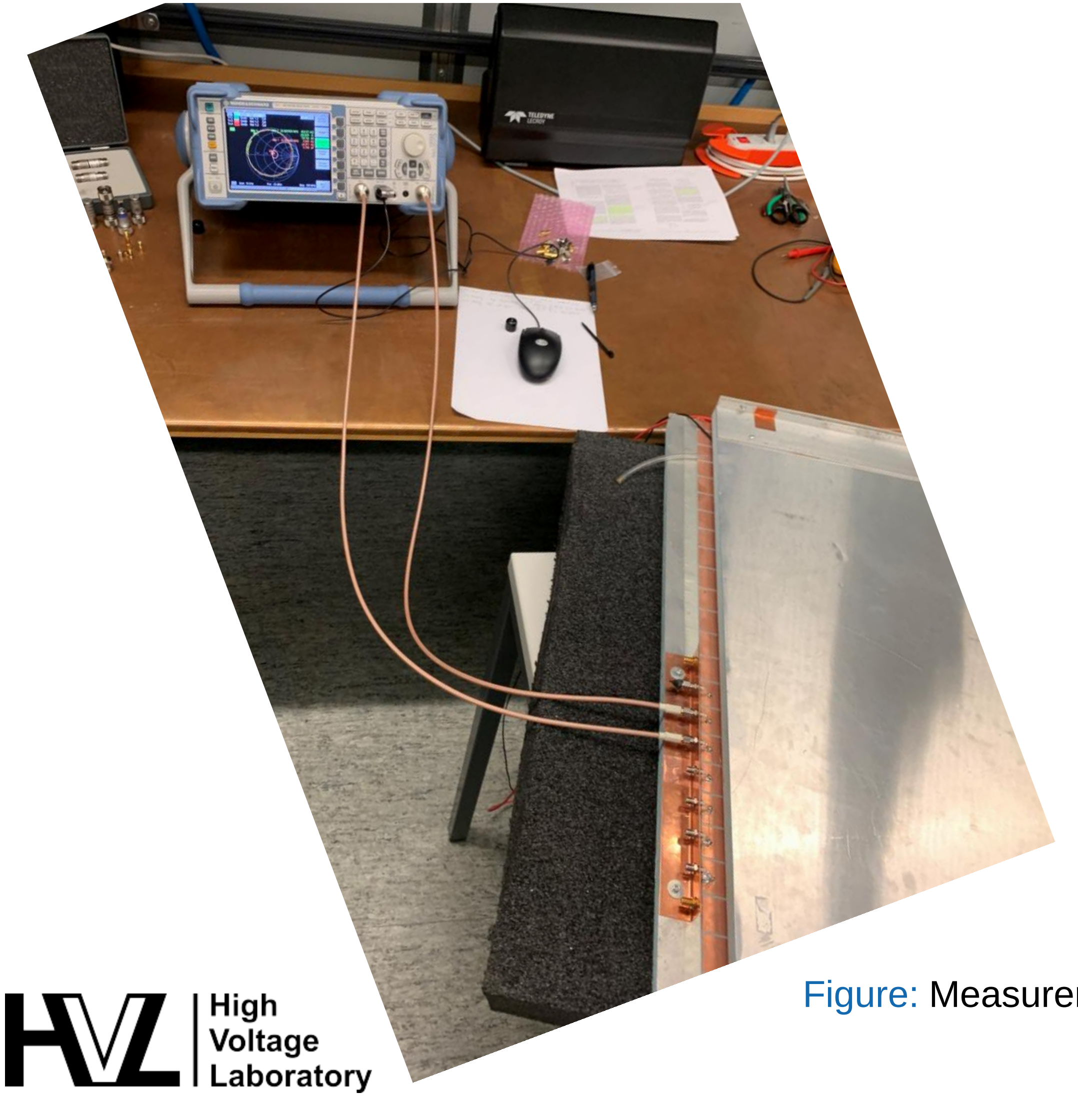
[12] C. Lippmann (2004), *Dissertation*

[13] M. J. E. Casey *et al* (2021), 10.1088/1361-6595/abe729

Additional Slides

[A] J. van der Merwe et al., *IEEE Transactions on Electromagnetic Compatibility*, vol. 40, no. 3, pp. 249-256, Aug. 1998, doi: 10.1109/15.709423

Measurement of Characteristic Matrices



- Measure S-matrix for **open** and **short-circuited** far-end using Vector Network Analyzer:

$$S_{ij} = \frac{A_i}{A_j} e^{i\phi_{ij}}$$

- MTL theory connects far-end impedance with near-end impedance, which is determined via the S-matrix [A]
  - ➢ Able to determine per unit length matrices up to wavelengths $\lambda(f) \sim \frac{L}{4}$

Figure: Measurement Setup with custom SMA adapter.

Per unit length matrices

Measurements

$$\mathbf{L} = \begin{pmatrix} 125.6 \pm 3.5 & 6.62 \pm 0.39 & 1.82 \pm 0.17 \\ 6.59 \pm 0.39 & 126.3 \pm 2.4 & 6.26 \pm 0.43 \\ 1.81 \pm 0.16 & 6.23 \pm 0.42 & 126.3 \pm 3.7 \end{pmatrix} \frac{\text{nH}}{\text{m}}$$

$$\mathbf{R} = \begin{pmatrix} 0.31 & 0.05 & 0.05 \\ 0.04 & 0.27 & 0.05 \\ 0.05 & 0.05 & 0.24 \end{pmatrix} \frac{\Omega}{\text{m}} \pm 100\%$$

$$\mathbf{C} = \begin{pmatrix} 239.8 \pm 4.5 & -26.0 \pm 1.6 & -1.89 \pm 0.08 \\ -25.9 \pm 1.7 & 236.9 \pm 4.0 & -23.9 \pm 1.6 \\ -1.86 \pm 0.08 & -23.9 \pm 1.6 & 232.0 \pm 4.6 \end{pmatrix} \frac{\text{pF}}{\text{m}}$$

$$\mathbf{G} = \begin{pmatrix} 2.22 \pm 0.37 & -0.97 \pm 0.06 & -0.087 \pm 0.047 \\ -0.96 \pm 0.09 & 2.18 \pm 0.30 & -0.81 \pm 0.08 \\ -0.086 \pm 0.045 & -0.80 \pm 0.06 & 1.81 \pm 0.38 \end{pmatrix} \frac{\text{mS}}{\text{m}}$$

Cross-talk between read-out strips

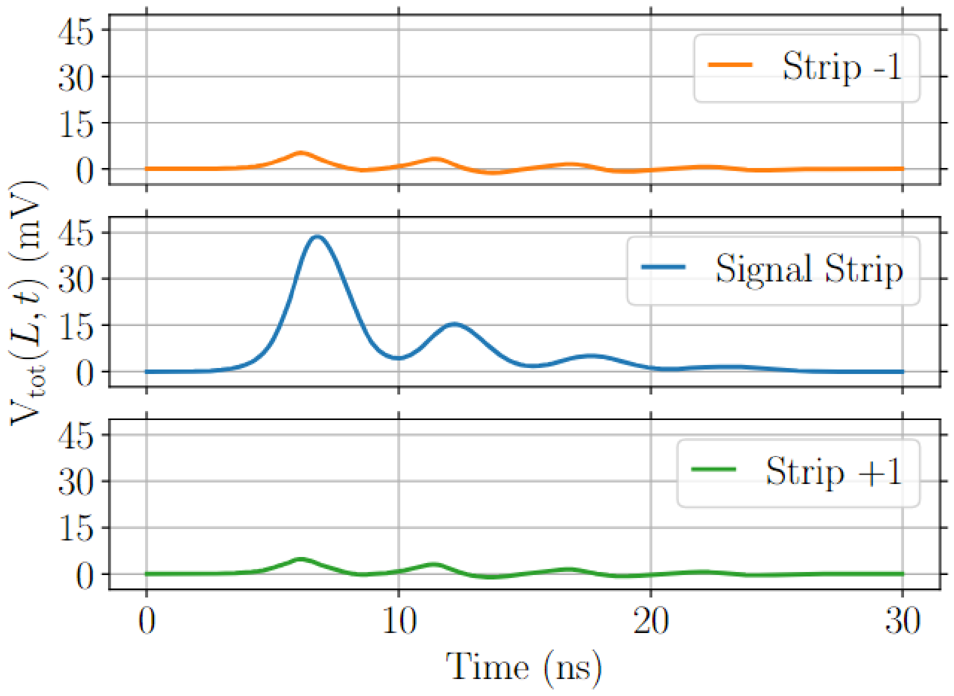


Figure: Cross-talk between neighbored strips from an example signal.

- Three-strip line with the measured 3x3 matrices per unit length.

Standard Mixture Validation
Voltage Peak Spectrum

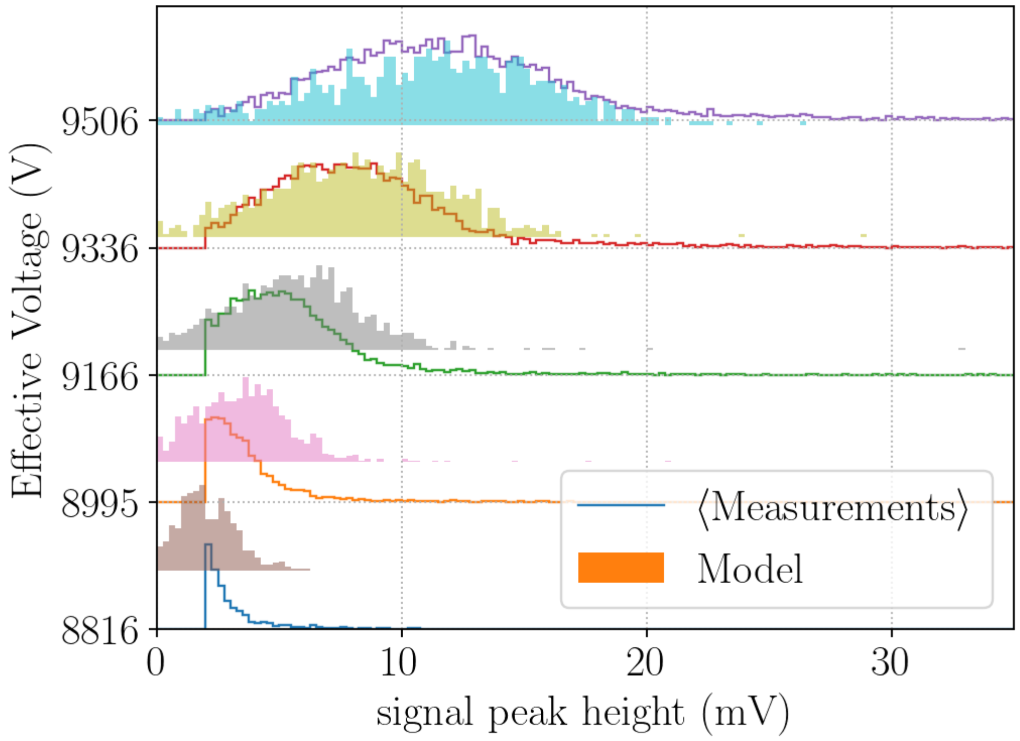


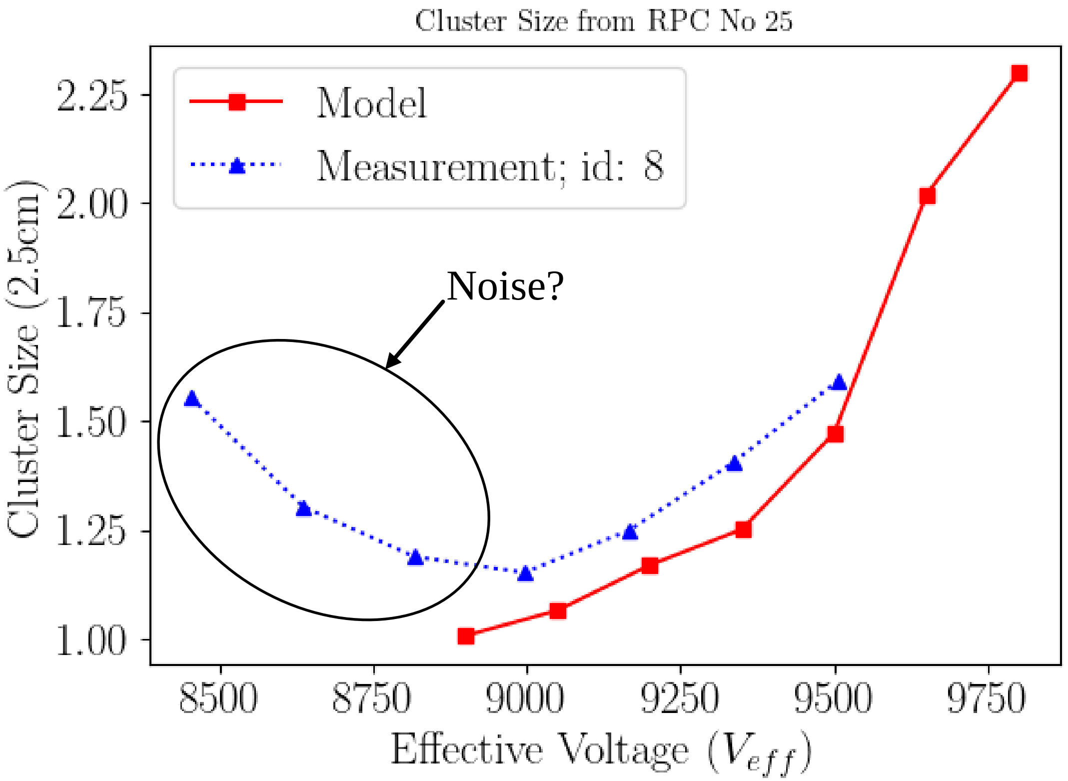
Figure: Simulated signal peak height of the standard mixture compared to measurements.

- Current corrected voltage

➢ Excellent agreement, indicating good post-processing with network-pipeline

Standard Mixture Validation

Cluster Size



- Current corrected voltage
- Extension to 5-strip MTL (5x5 matrices)

Figure: Cluster size of standard mixture compared to measurements.

Standard Mixture Validation

Time over threshold

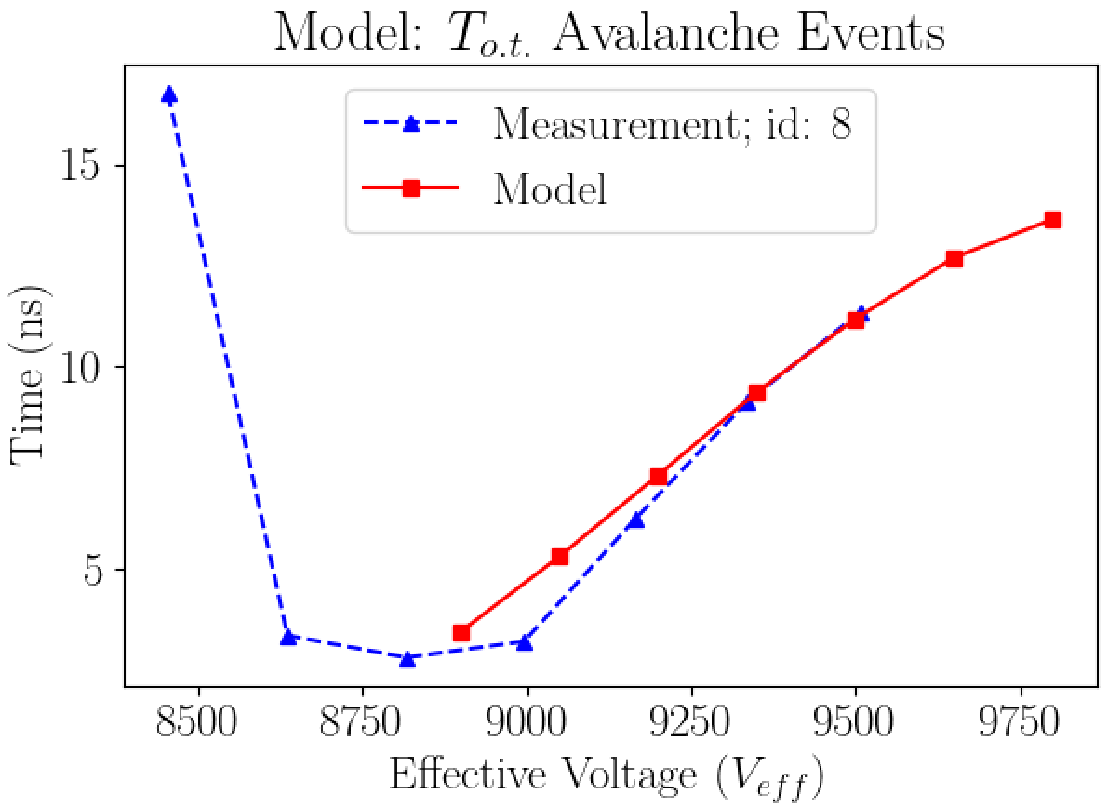
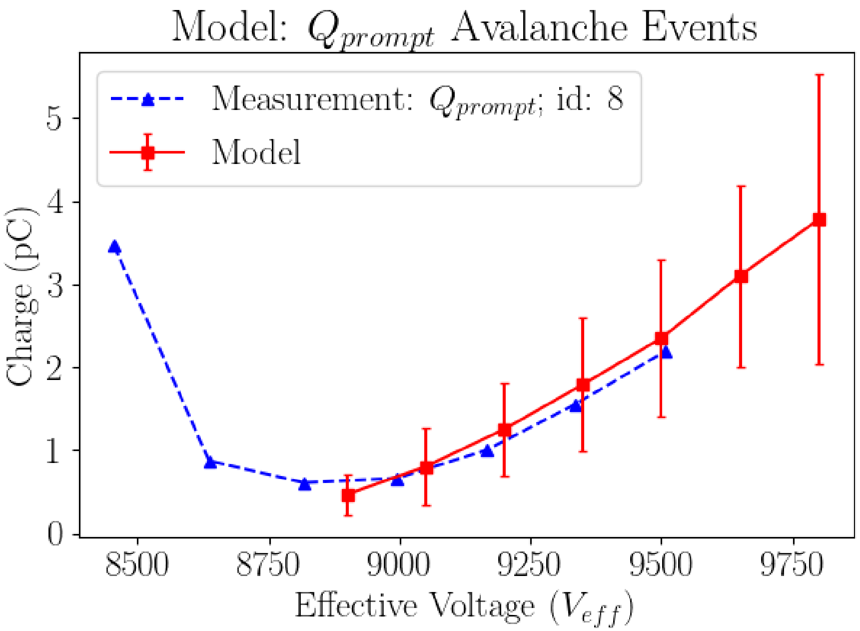


Figure: Time over threshold of standard mixture compared to measurements.

- Current corrected voltage
- 3-strip MTL

Standard Mixture Validation

Prompt charge



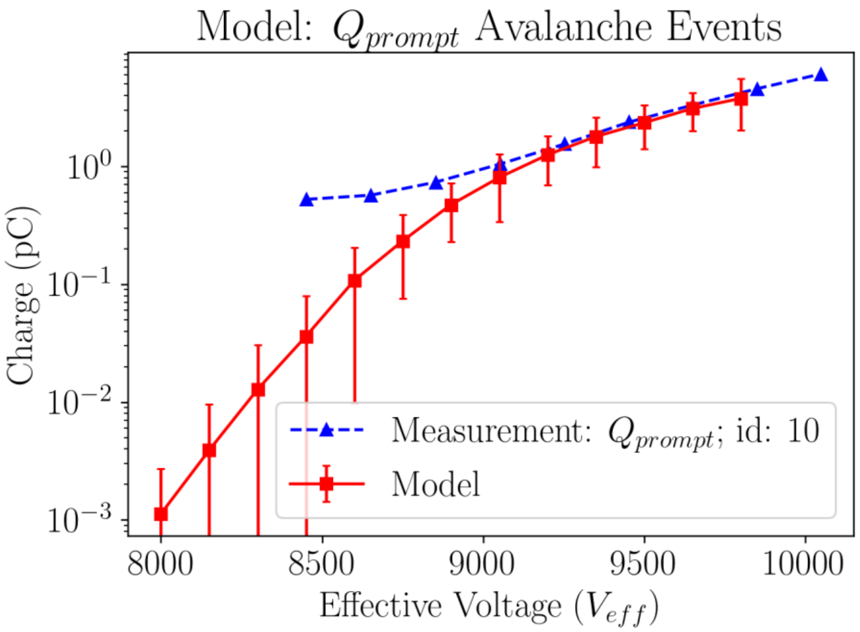


Figure: Prompt charge of standard mixture compared to measurements with two different RPCs and runs.

- Current corrected voltage and 3-strip MTL
  - ➢ Small HV efficiency discrepancy: finite prompt charge of detected events

CO_2-based Standard Mixture
Overview

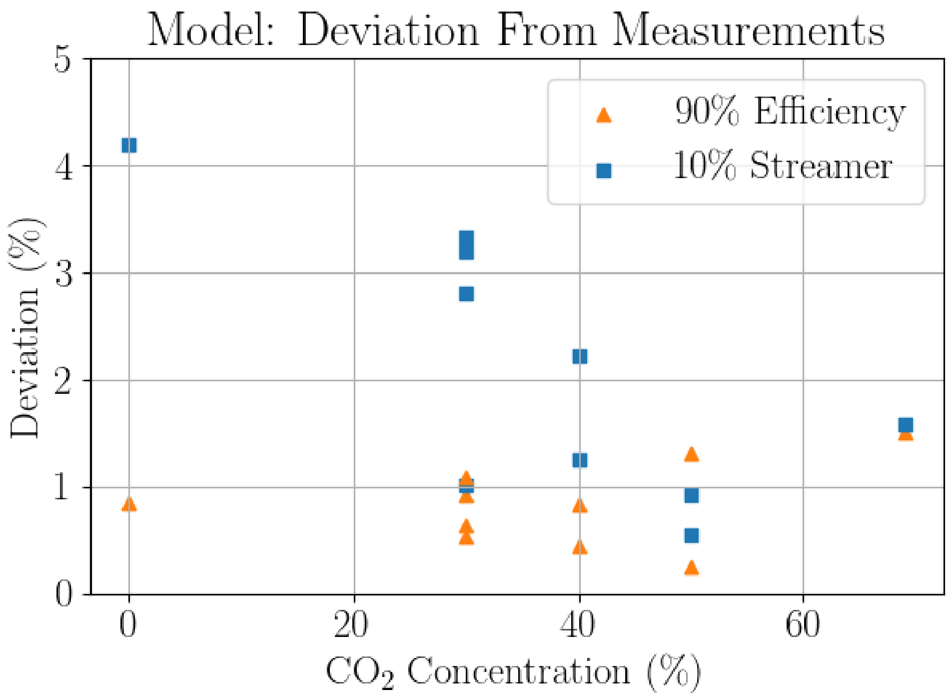


Figure: Deviation of the efficiency and streamer curve between simulation and measurements with respect to the CO2 concentration.

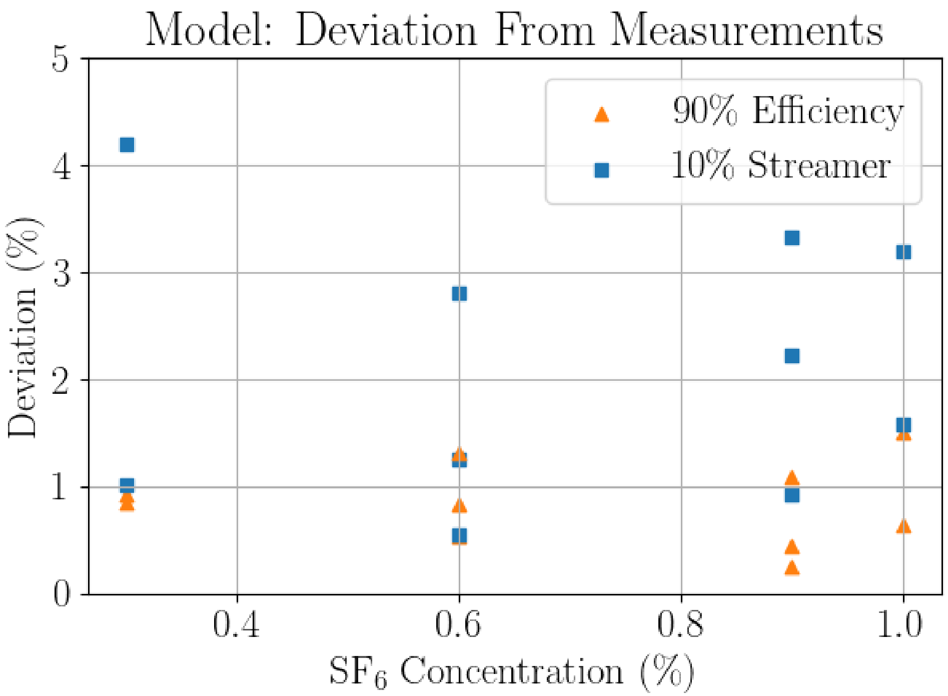


Figure: Deviation of the efficiency and streamer curve between simulation and measurements with respect to the SF6 concentration.

Pulsed Townsend Swarm Parameter Measurements

Magboltz v11.19

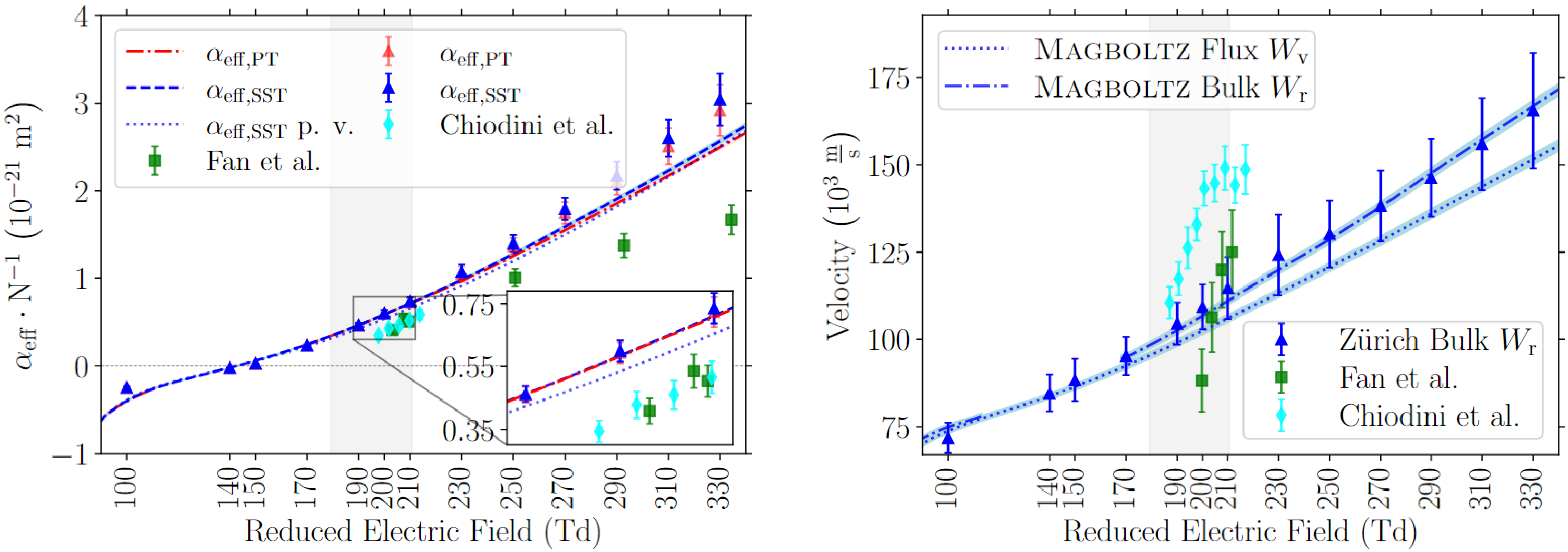


Figure: Trigger RPC standard mixture swarm parameters measured with the Pulsed Townsend Experiment.

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