Detector Physics-Driven Concepts for Future RPC systems

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RPC technology beyond the LHC era

Versatile and successful across the LHC era

RPC technology has demonstrated reliable performance in demanding large-scale experiments.

WHY RPCs WORK	Simple
CONSTRUCTION	Robust
OPERATION	Low per unit area
COST	High efficiency and very good timing
PERFORMANCE	

POST-LHC EXPERIMENTAL HORIZON

New experiments are being studied in three main areas:

01 **Later stages of the HL-LHC**
Extensions of the current experiments, including searches for long-lived particles.

02 **Future colliders**
New detector concepts for FCC-ee and FCC-hh.

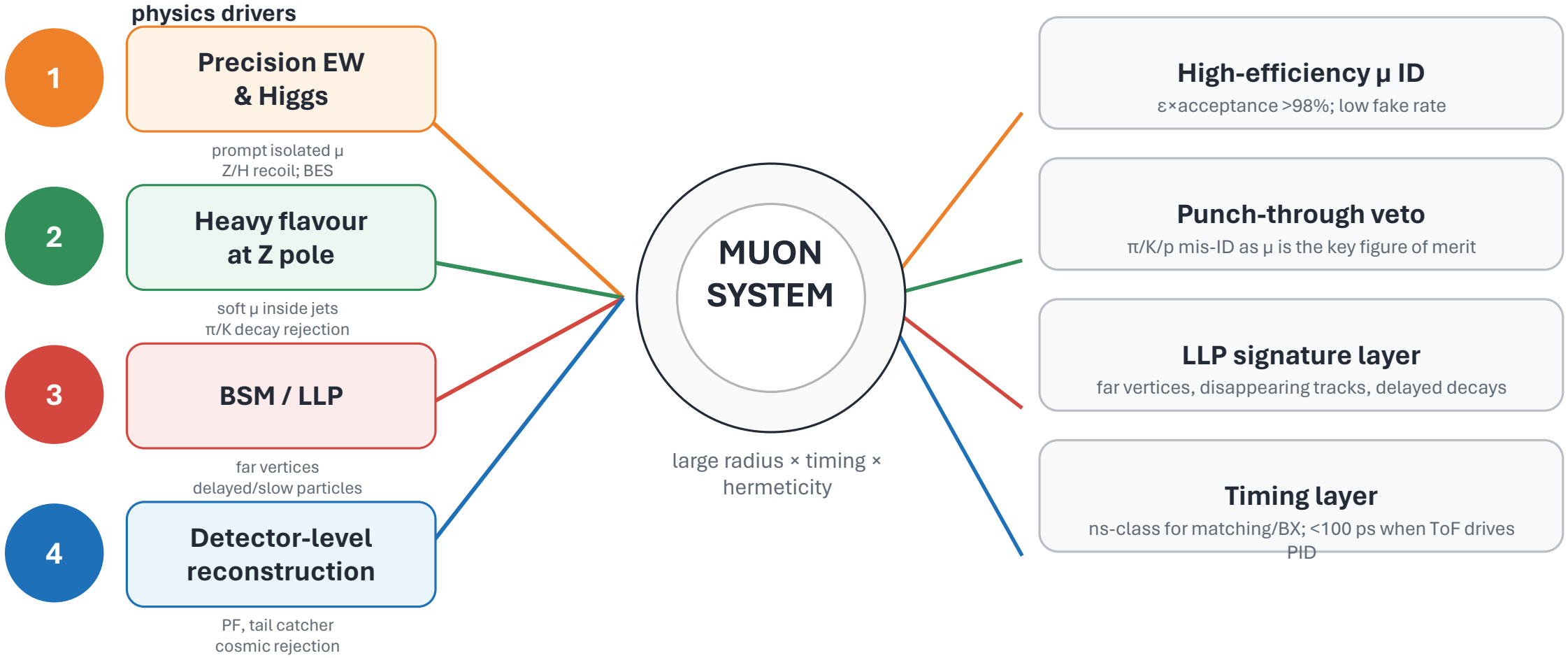
03 **Space-based experiments**
A new application domain for gaseous detectors.

THE NEXT CHALLENGE

Gaseous detectors, and RPCs in particular, must meet new requirements. For the first time, they will also compete directly with solid-state technologies already prominent in FCC proposals.

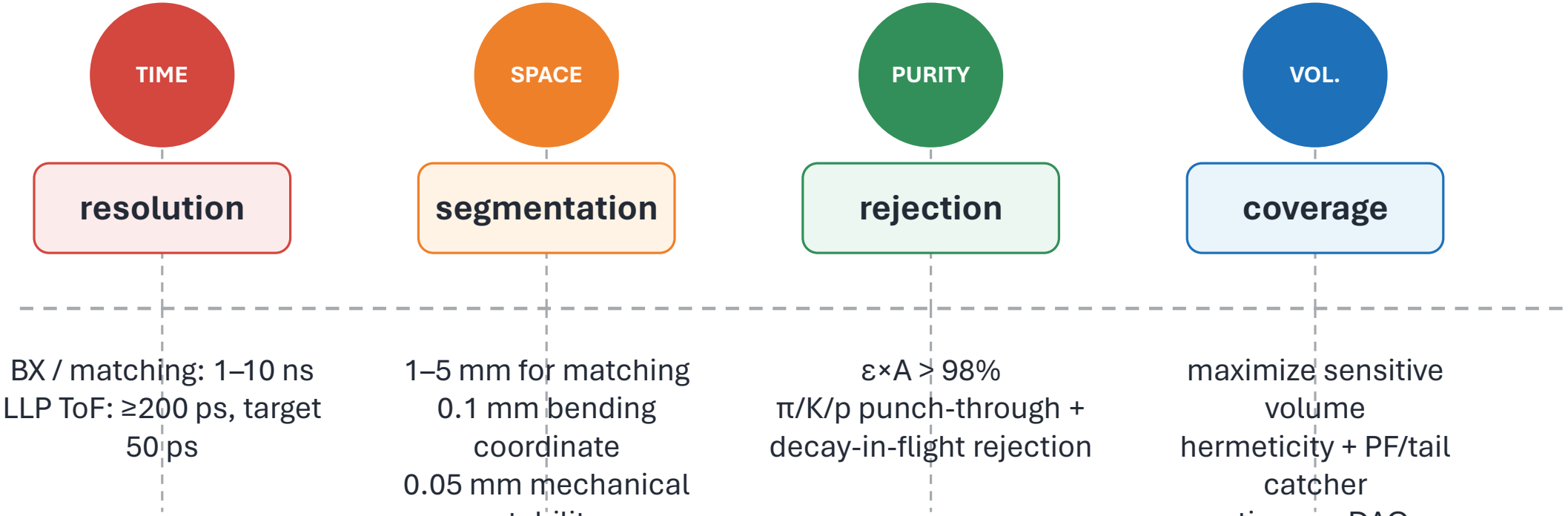
Muon-system features (1): physics → functions

Narrative: FCC-ee is primarily tracker-driven; outer-radius information becomes PID, background rejection and exotic-signature acceptance.



Consequence: low occupancy relaxes rate constraints, but rare signatures make efficiency, fake rejection, timing and volume the real optimization axes.

Muon-system features (2): detector-design consequences



Boundary conditions from FCC-ee running

triggerless / software event selection under study

rates are modest: chamber design driven more by physics than rate capability

integration matters: HCAL granularity, magnetic field, material budget, mechanics

Design question: choose the detector mix that preserves standard μ identification while adding timing and volume for LLP/exotic signatures.

RPC design

RPC-specific design challenges

Efficiency

TARGET Maximize single-detector efficiency while exploiting the sensor and optimizing readout cost.

LEVERS Gaseous target · electron-avalanche physics · front-end electronics sensitivity.

COMPETING REQUIREMENTS Gas-mixture constraints · rate capability · longevity · time resolution.

Gas mixture

TARGET Minimize cost, environmental, and detector impact while maintaining high performance.

LEVERS Electron-avalanche physics · front-end electronics sensitivity.

COMPETING REQUIREMENTS Efficiency · longevity.

Time resolution

TARGET Sub-nanosecond timing, down to <100 ps.

LEVERS Gaseous-target segmentation · faster mixture · front-end electronics sensitivity.

COMPETING REQUIREMENTS Single-gap efficiency · simplicity · robustness · low cost.

Low cost per unit area

TARGET Build simple, low-cost modules larger than 1 m^2 while retaining the current advantage over competing technologies.

LEVERS Efficient design · gas mixture · front-end electronics sensitivity.

COMPETING REQUIREMENTS High time resolution and spatial resolution.

The gas-mixture challenge

1 **Initial motivation — control ageing**

Adding CO_2 to the RPC gas mixture was first studied to moderate the ageing effects of HFO-based replacements for R134a.

2 **Since 2022 — a pragmatic ATLAS programme [*]**

ATLAS launched a long-term study to partially replace R134a with CO_2 and enable an immediate, practical transition.

3 **2024–2026 — replacement of the standard mixture**

64.5% R134a · 30% CO_2 · 5% i-C_4H_{10} · 0.5% SF_6

Outcome versus the standard mixture

The CO_2-rich mixture outperformed the standard mixture across the evaluated criteria:

- Strong reduction in ageing
- 25% improvement in time resolution
- Lower global-warming potential and operating cost
- Same efficiency
- Lower operating voltage

WHY NOT FROM THE START?

The standard mixture was performing well, so there was no immediate pressure to change.

OPEN QUESTION

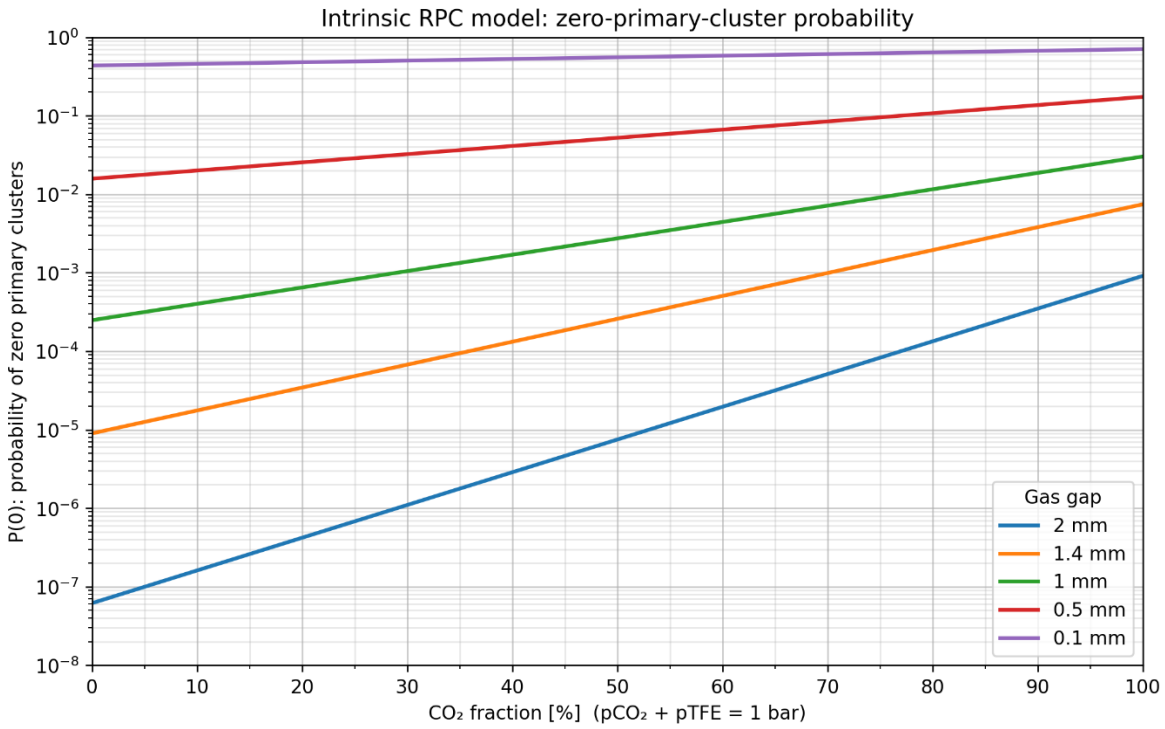
How far can this substitution path go?

[*] See on Sinem's slides in this conference

Primary Poisson probability and the useful gas gap

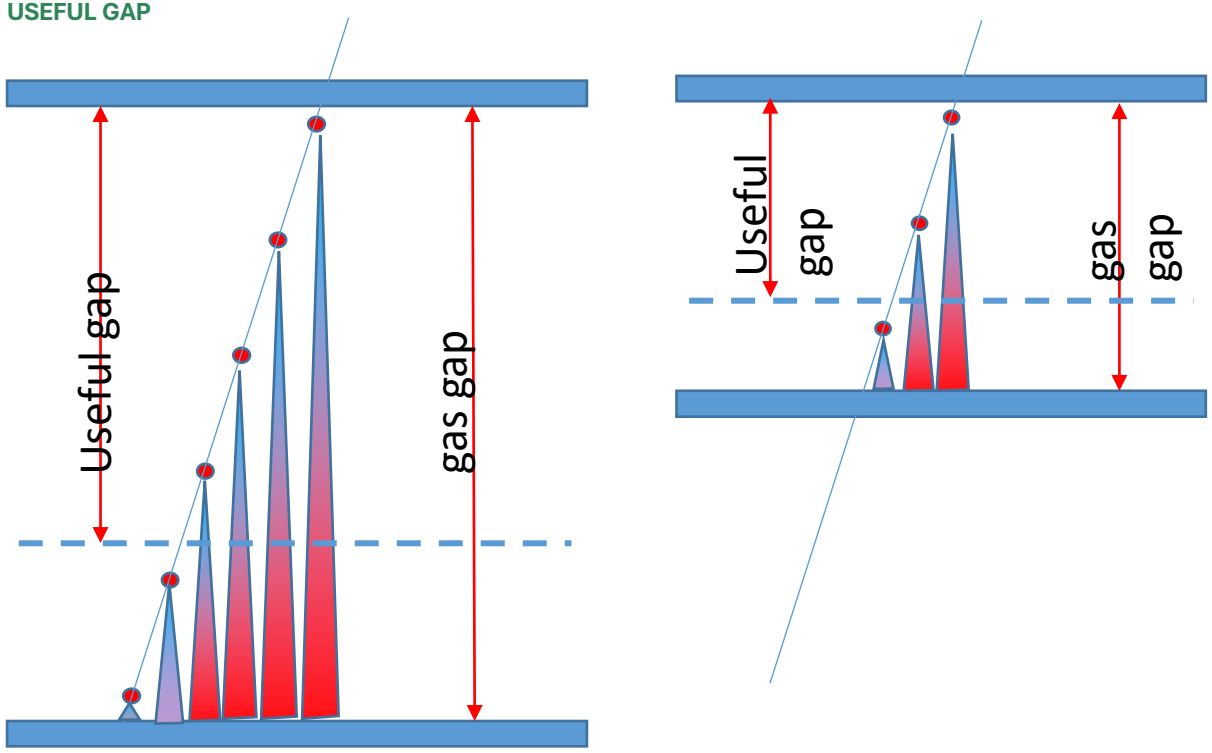
The total gaseous target sets P(0); only ionizations inside the useful region can generate a detectable avalanche.

PRIMARY-CLUSTER POISSON LIMIT



P(0) depends mainly on the total gaseous target: the gap thickness and the mixture density.

USEFUL GAP



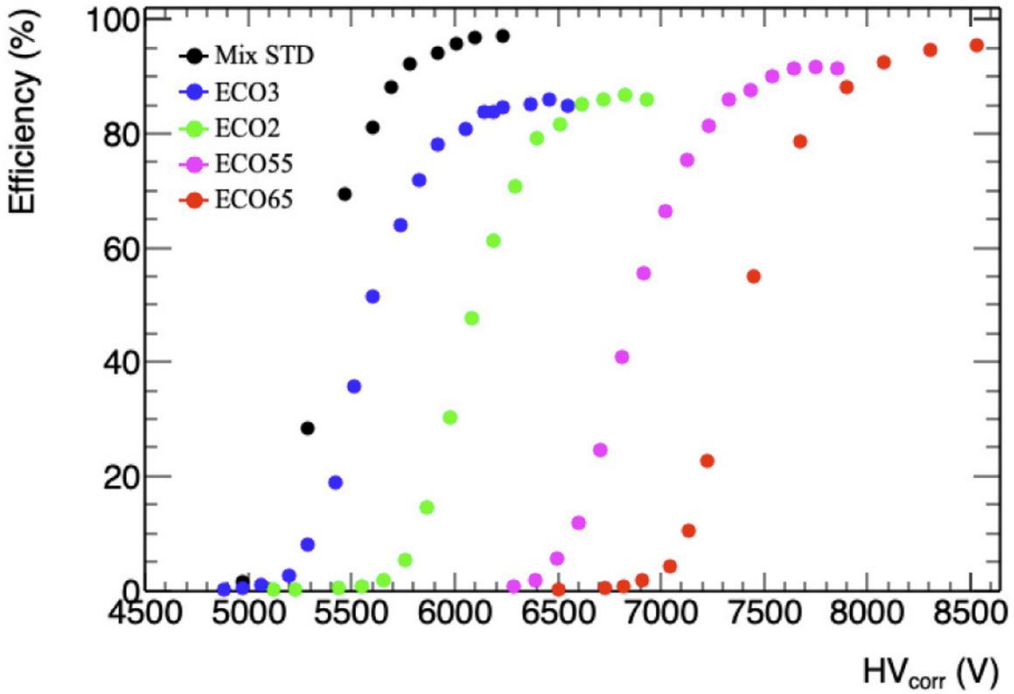
The useful gap is empirical: it is the region where an ionization can develop into an avalanche large enough to be detected.

Consequence: Poisson P(0) is smaller than the observed inefficiency because not every primary ionization lies inside the useful gap.

Maximum efficiency measurements

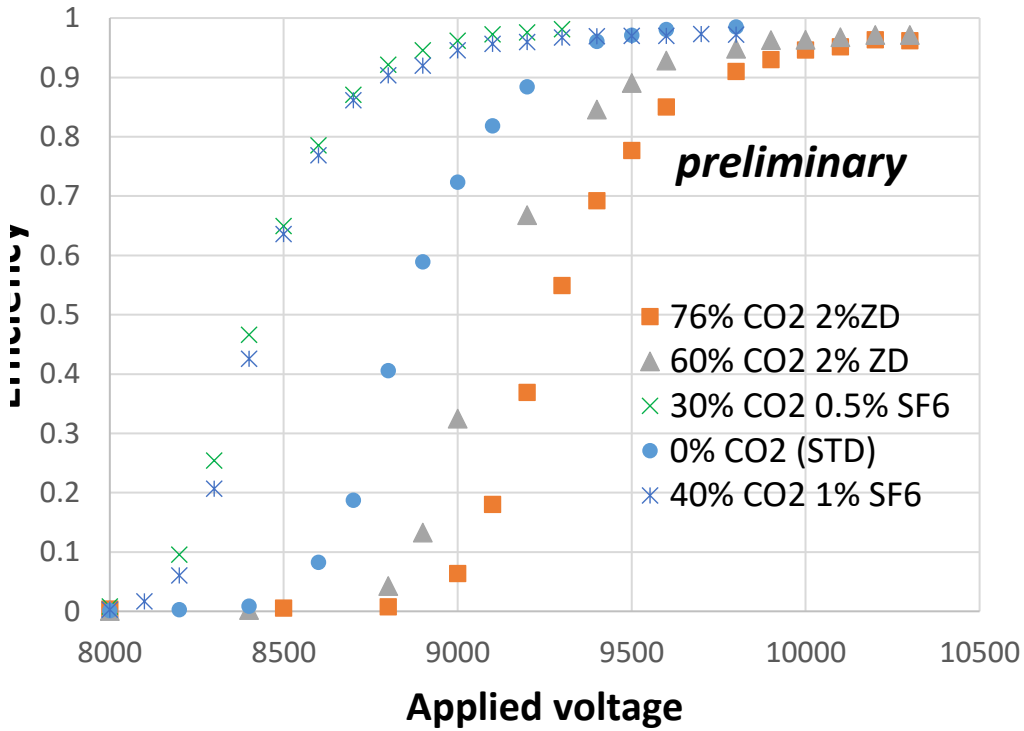
1 mm gas gap (BIS7 test 2021)

Nuclear Inst. and Methods in Physics Research, A 1066 (2024) 169580

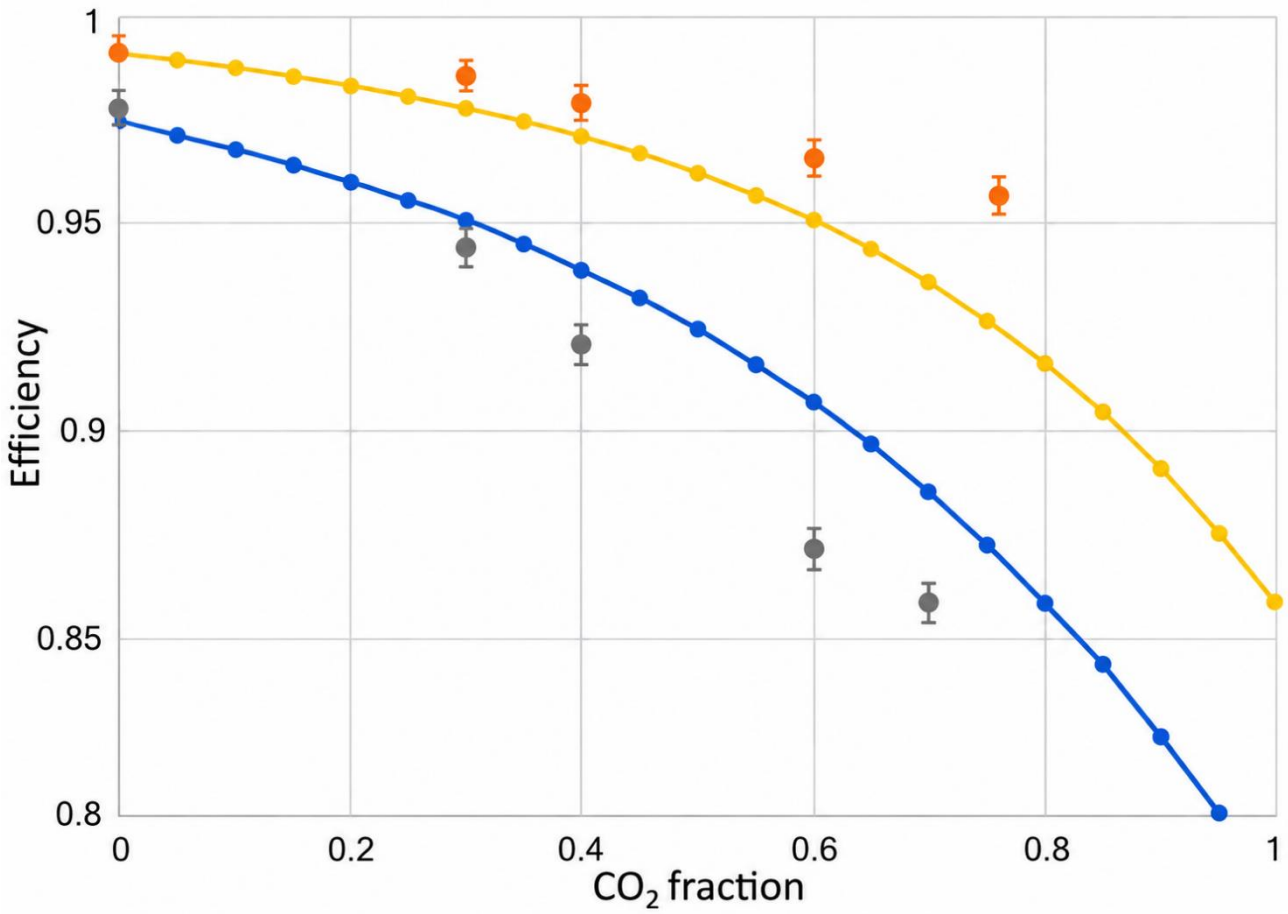


2 mm gas gap (test 2025-26)

DOI:10.5281/zenodo.22809853



Effective maximum efficiency and constrained Poisson



1. Effective maximum efficiency

An empirical working value rather than a rigorous limit. Efficiency may still increase with HV, but at increasing operating cost.

2. Constrained Poisson prediction

The Poisson maximum from primary-cluster statistics versus gas composition, normalized to the Standard-mixture measured efficiency and assuming 100% acceptance.

3. Direct comparison

The Poisson curve follows the decrease approximately, but shows a growing quantitative difference and a different functional shape.

Equation placeholder: constrained Poisson normalization

Takeaway: the primary Poisson constraint is a baseline; detector-dependent response is required to describe the measured effective plateau.

Model structure used

Primary clusters → nclus before extinction

Cluster mortality → lineage extinction

Surviving clusters → effective nclus

Effective response → logistic closure

$$\mu_P(f) = N_{\mathrm{TFE}}(1-f) + N_{\mathrm{CO_2}} f$$

$$\epsilon_P(f) = 1 - \exp[-\mu_P(f)]$$

$$M_{\mathrm{cl}} = \Sigma_m p_m q_1^m$$

$$n_{\mathrm{eff}} = n_{\mathrm{cl}}(1 - M_{\mathrm{cl}})$$

Degrad → p_m

Magboltz → $\alpha, \eta \rightarrow q_1$

$$G(f) = 1 + K \ln[1 + \exp\{\alpha(f - \rho_0)\}]$$

$$\mu_{\mathrm{full}}(f) = C_M(f)\left[N_{\mathrm{TFE}}(1-f) + N_{\mathrm{CO_2}} f\, G(f)\right]$$

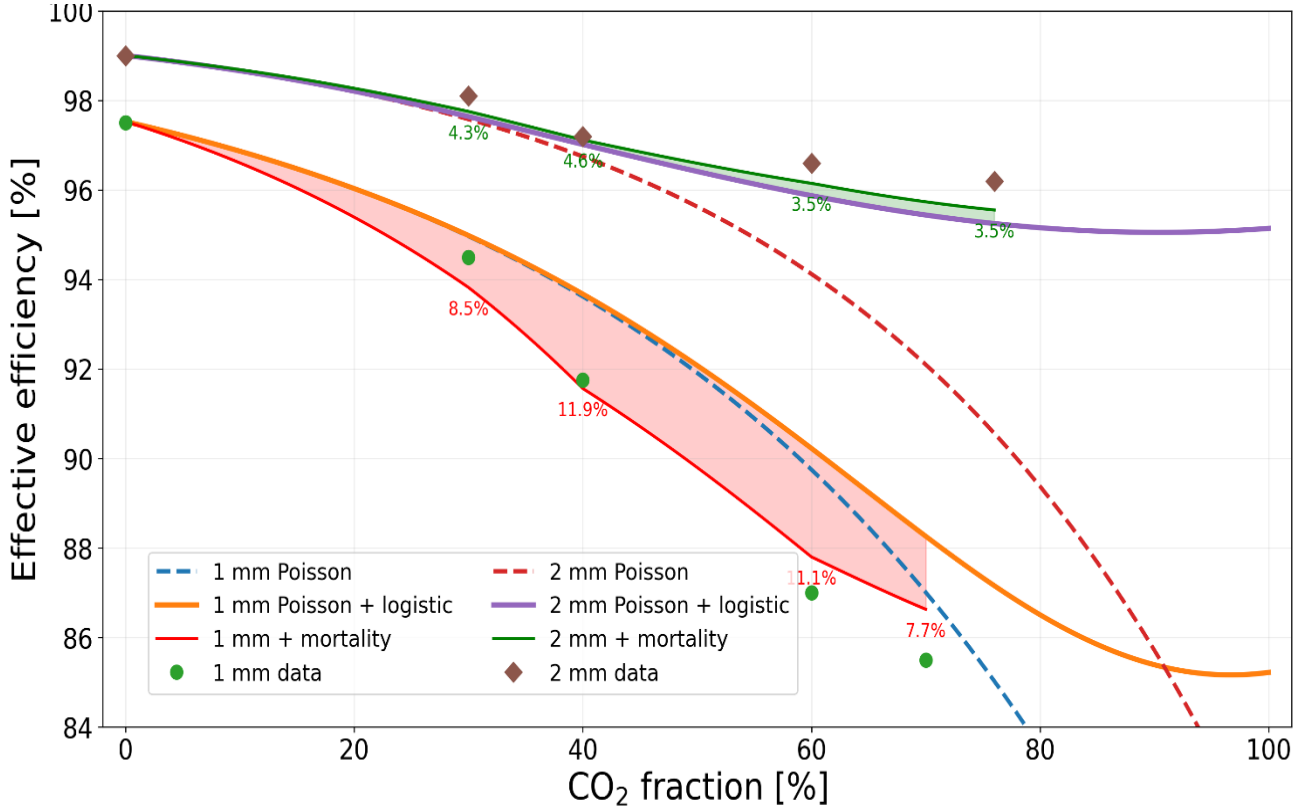
Interpretive rule

Attachment-induced complete cluster extinction is kept separate from the detector-dependent effective useful response.

Current simplification

Thinning / RQ constrains charge cost and working point; it is not used as a direct plateau-loss term in this closure.

Realistic efficiency model



Colored bands are shown only over the CO_2 ranges where mortality inputs are available; Poisson and Poisson+logistic are extrapolated to 100% CO_2.

1. Common ionization constraint

nclus for TFE is imposed for the STD mixture, we dont have a strong constraint for the CO2 nclus.
he same CO_2/TFE primary-ionization ratio as the 2 mm case.

2. Mortality fills most of the gap

Relative to the STD point, the HFO/SF_6 mixtures have much larger cluster extinction: Mcl rises from about 1.7% to roughly 8.5–12%.

3. Logistic term is residual

After mortality is applied to nclus, the calibrated logistic response only absorbs the remaining effective-response evolution.

$$G(f) = 1 + K\ln[1 + \exp\{\alpha(f - \rho_0)\}]$$

$$\mu_{\text{full}}(f) = C_M(f)\left[N_{\text{TFE}}(1 - f) + N_{\text{CO}_2} f\, G(f)\right]$$

The cluster mortality plays an important role, especially for the 1mm gas gap and for very electronegative gases such as HFO

No error bars shown for 1 mm points, as requested. Logistic fit is regularized to avoid an artificial elbow.

Front-end electronics sensitivity test

TEST CONFIGURATION

- **Chamber:** ATLAS-like layout [*]
- **Geometry:** 2 mm gas-gap doublet with one test chamber and one monitoring chamber
- **Test readout:** vertical strips equipped with ATLAS electronics
- **Reference readout:** horizontal strips equipped with a high-sensitivity analog preamplifier, the baseline for the Phase-1 and Phase-2 upgrades

GIF++ EXPOSURE AND MEASUREMENTS

- **Beam and source exposure**
- Efficiency under irradiation
- V–A curve

EXAMPLE GAS MIXTURE

0% R134a 88% CO_2 10% i-C_4H_{10} 2% R1233zd

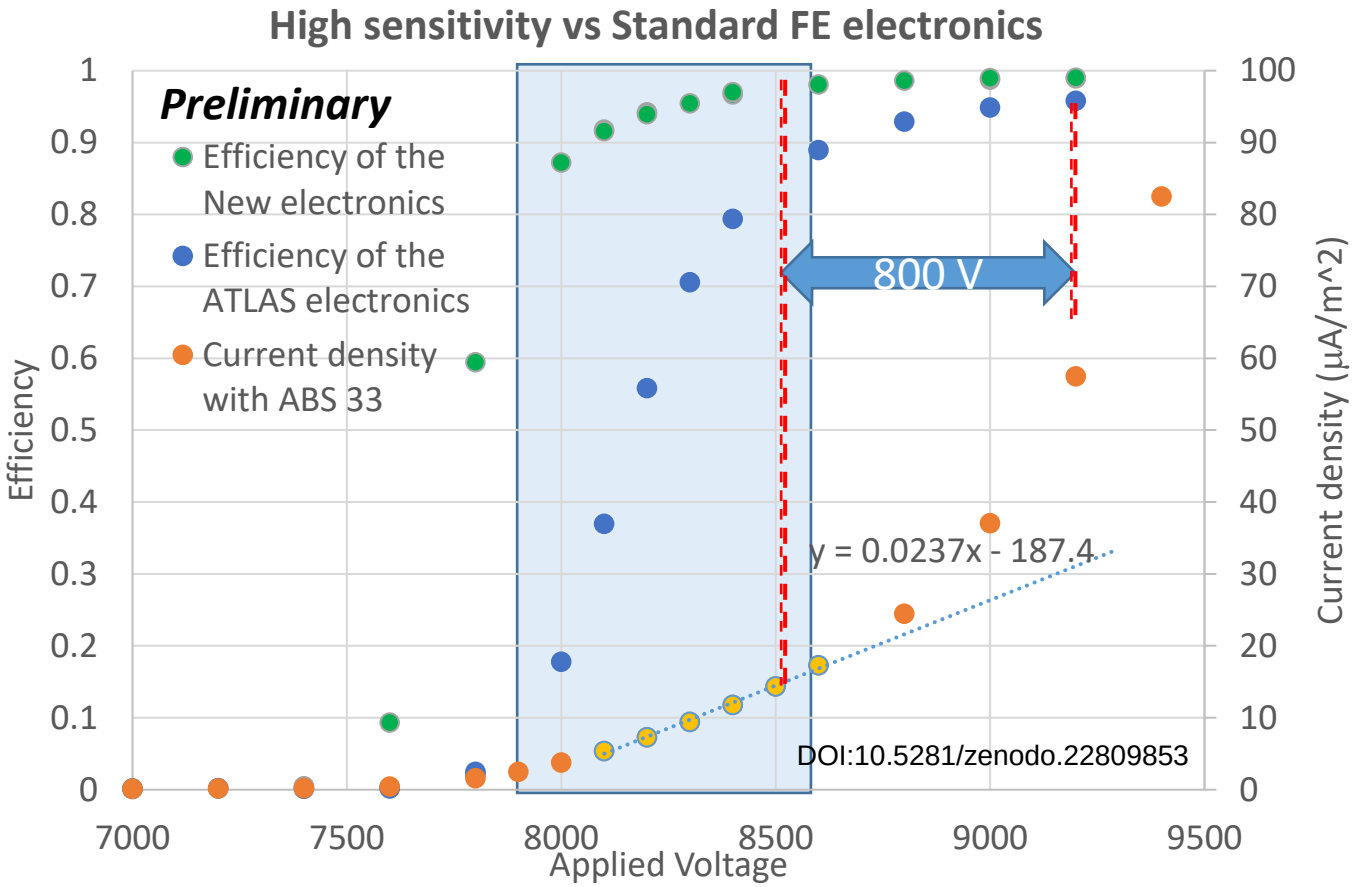
Flammable and freon-free. Example only, not (yet) an official proposal.

OBJECTIVE **Compare the two amplifiers event by event on the same avalanche signal.**

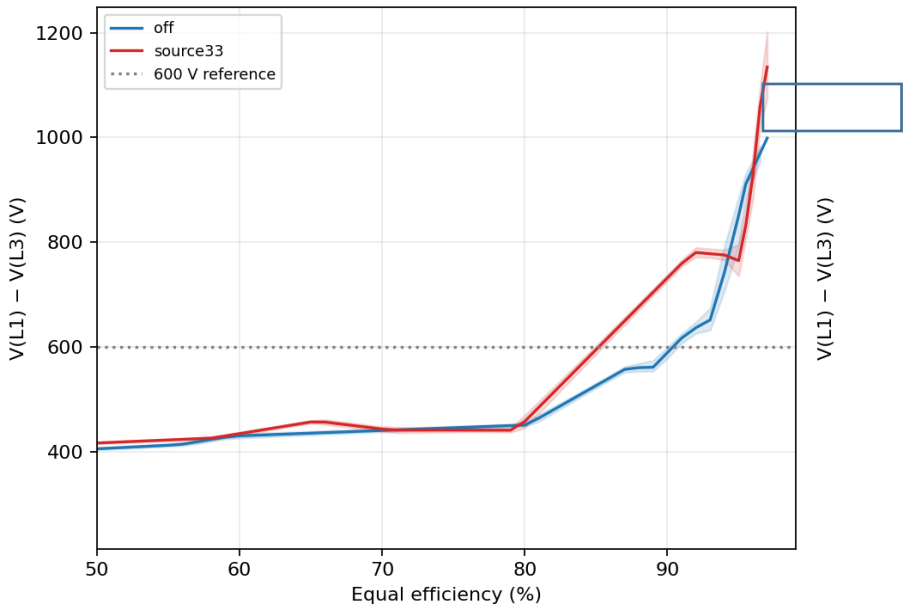
Both electronics record each avalanche simultaneously.

[*] INSPIRE-HEP 2955768

Voltage separation new vs. standard FE



DOI:10.5281/zenodo.22809853

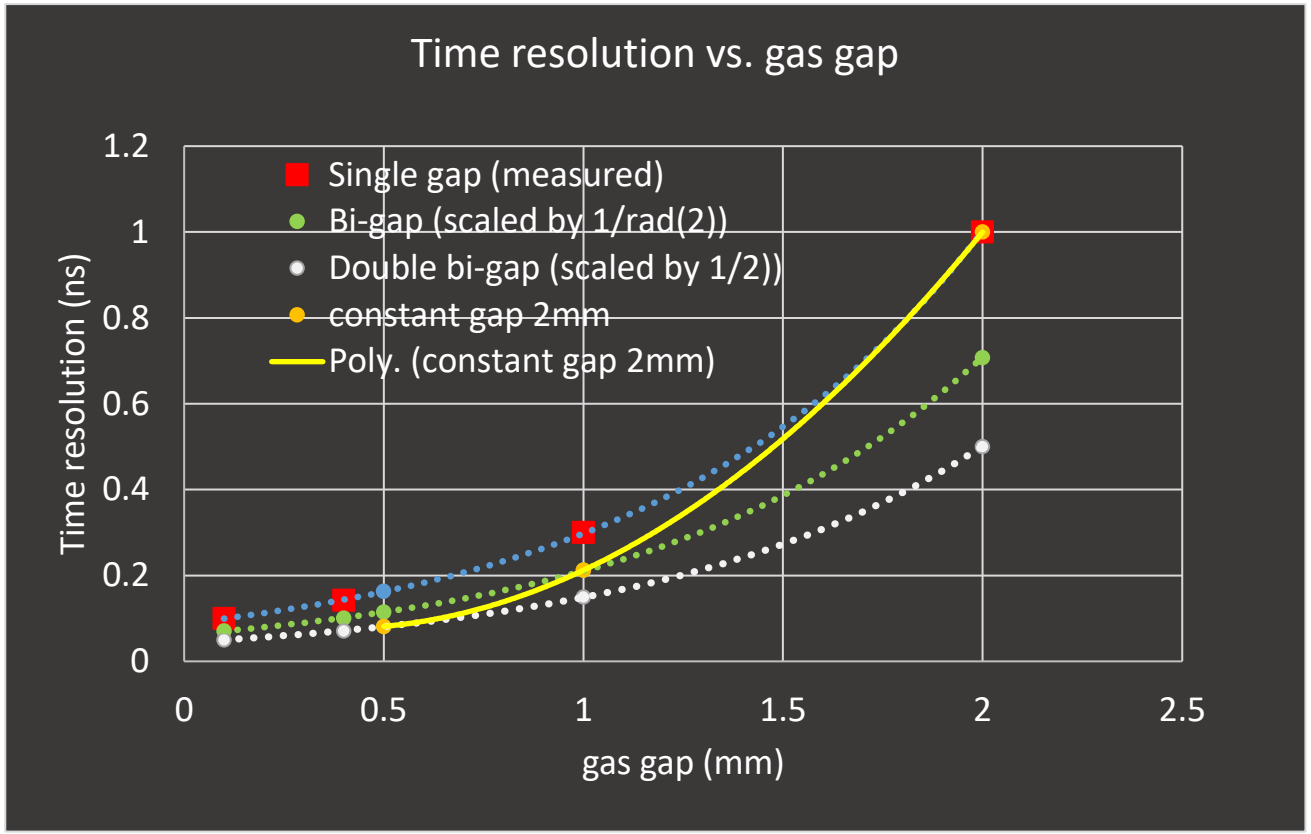


We observe that

- this freon free mixture, is unsuitable for a standard ATLAS chamber working at Efficiency > 90%
- The sensitivity of the new electronics allows to catch very small signals lowering by more of 600V the working point → the mixture becomes fully workable in saturated avalanche regime

RPC design – time resolution

- Time resolution taken for single gas gap and scaled for the number of gas gaps
- The yellow line il for total gas gap = 2 mm



- Time resolution Depends mainly on:
  - Gas gap thickness → resolution scales regularly with gas gap thickness
  - Number of gas gaps (suppressing fluctuations as $1/\sqrt{n}$)
  - The gas drift velocity
- Dependence on electronics
  - To make the electronic noise contribution negligible for the time resolution it should be << intrinsic signal fluctuations

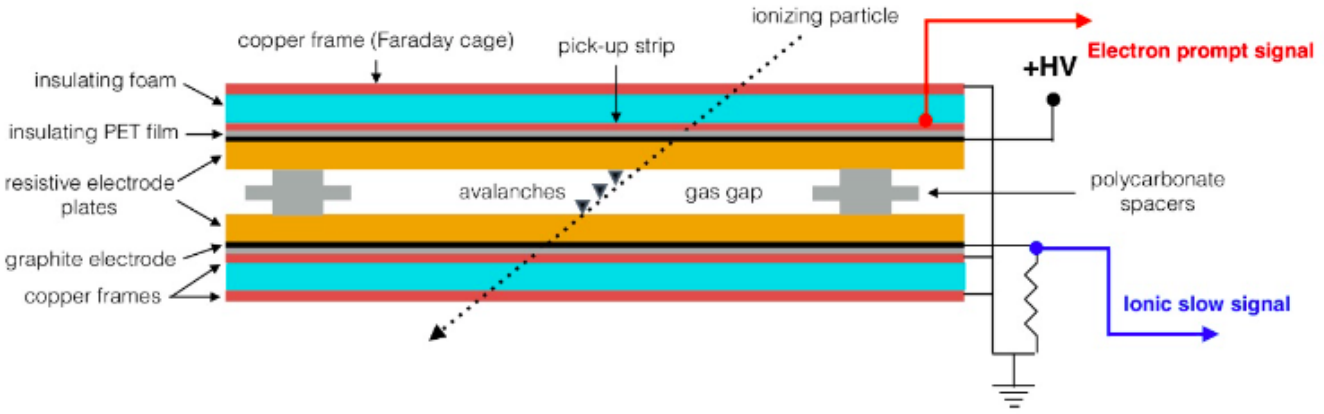
Detector design from performance targets

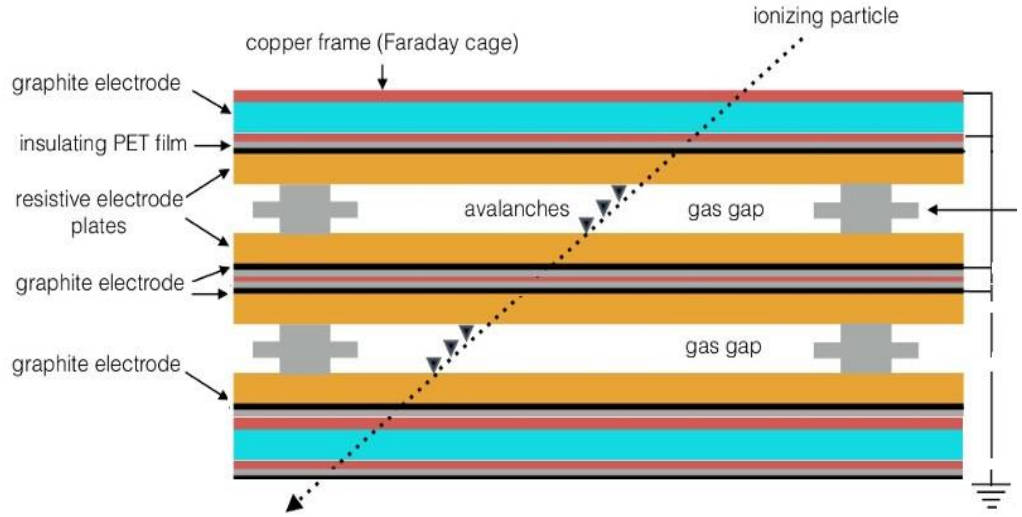
FIXED DESIGN TARGETS

1. Target efficiency — **99%**
2. CO_2 fraction — **> 90%**
3. Gas thickness required per efficient unit — **2 mm**

TIME RESOLUTION SETS THE GAP ARCHITECTURE

TARGET	GAP LAYOUT	ASSESSMENT
1 ns	Single 2 mm gap	Simple, robust and low cost
400 ps	1.4 + 1.4 mm bi-gap	CMS Phase-2 geometry Resolution to be verified
200 ps	1 + 1 mm bi-gap	ATLAS Phase-2 geometry Resolution to be verified
80 ps	2 × (0.5 + 0.5 mm) bi-gaps	**Critical** **Dedicated R&D required** **Scaling to be verified**





Multiple-gap detector layout options

OPTION 1

Four individual gaps in two double-gaps

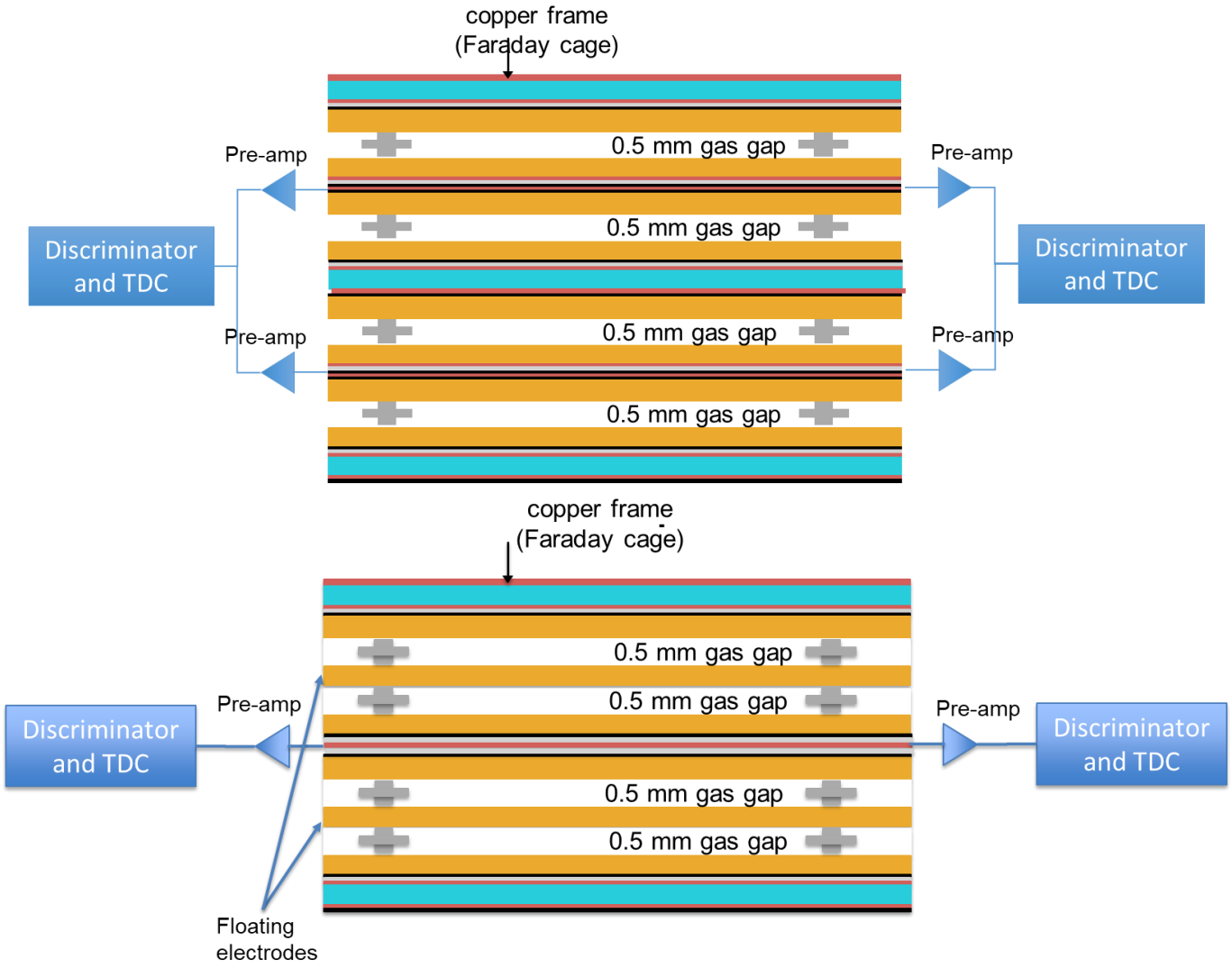
- **Readout:** at the center of each double-gap
- **Signal chain:** preamplifiers at both strip ends. A wired-OR combines the two double-gaps before the discriminator and TDC
- **Advantage:** simpler chamber construction with no floating electrodes
- **Trade-off:** greater complexity in the front-end electronics

OPTION 2

Two bi-gaps in a double-gap configuration

- **Readout:** at the center of the double-gap
- **Signal chain:** preamplifier and digital stage integrated at both ends of each readout strip
- **Advantage:** simpler interface to the front-end electronics
- **Trade-off:** more delicate chamber construction with floating electrodes

In both cases the second coordinate is obtained from time difference



If this is not enough...

innovative proposals: SHARP and RCC

SHARP: A Schottky-enhanced Hybrid Avalanche Resistive Photodetector for ps timing and high-rate large-area detection

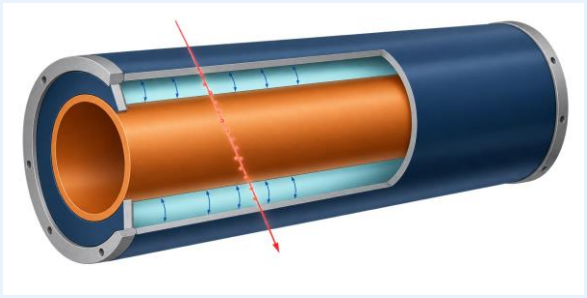
RCC: Resistive cylindrical chamber

RCC and SHARP as alternatives to complex RPCs

For FCC, both concepts become relevant when timing, rate or integration requirements make the RPC architecture too elaborate.

WHY CONSIDER THEM **Preserve gaseous-detector scalability while changing one fundamental lever: RCC reshapes the field geometry, SHARP separates signal creation from charge amplification.**

RCC Resistive Cylindrical Chamber



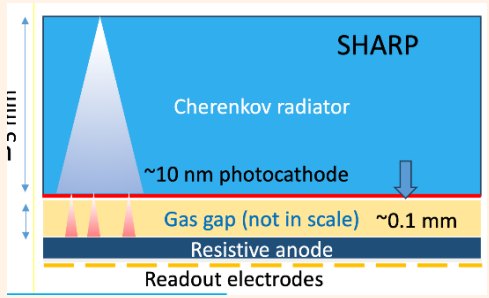
Coaxial resistive electrodes with a thin radial gas gap

FEATURES Coaxial resistive electrodes, thin annular gap, radial nonuniform field. Can be pressurized

PROS
- New freedom for field shaping
- Compact cylindrical integration with resistive discharge protection
- Ideal for space applications
- Can work without fluorinated gases

CONS
- Polarity-dependent response and nonuniform field
- Readout, mechanics and scalability remain open

SHARP Schottky-enhanced Hybrid Avalanche Resistive Photodetector



Photocathode conversion followed by RPC-like microgap gain

FEATURES Cherenkov radiator, nanometric photocathode, about 0.1 mm gas gap, resistive anode.

PROS
- Targets <50 ps timing and high rate over large areas
- May avoid multigap stacks and reduce charge fluctuations
- Intrinsically fluorinated gas free

CONS
- Photocathode lifetime and uniformity are critical
- Surface control and very low noise electronics are demanding

SELECTION LOGIC **RCC changes the field geometry. SHARP changes how the first electron is produced. Both are justified when a conventional RPC loses its main advantage: simplicity.**

Conclusion and EOI proposal

- Basing on the analysis above we are convinced that RPC can play a crucial role in the far future
- It would be appropriate to propose in any of the FCC muon systems such a modular detector based on these elements
- CMS proposal based on 0.5 mm bi-gaps foresees to use floating glass electrodes our proposal is based on referenced HPL electrodes. But this is a technical detail so our EOI can reinforce and generalize CMS one.
- The R&D has as a target to demonstrate the system scalability:
  - Studying the gas gap configurations
  - Defining the gas candidates
  - Electronics and faraday cage integration
- RPC based proposals are very few at the moment and this should change

backup

State of the art R&D and EOI

State of the art

- This concept has been applied in PICOSEC based on a MMGAS
- The concept is good but MMGAS have a strong constraint of Gain
- The proof of principle is achieved by the PICOSEC studies
- RPCs have a free gain and this concept can work much better on the same proof of principle

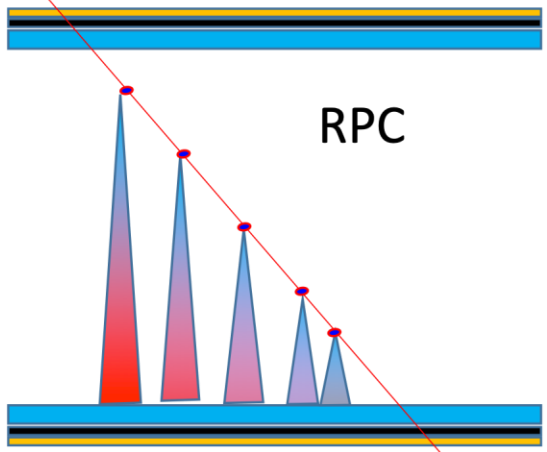
R&D proposal

- Basing on the Proof of principle studies we can aim directly at a reduced number of prototypes:
  - DLC cathode
  - Zr cathode
- Scope: demonstrate the scalability of the principle, substantially impossible with PICOSEC but possible with SHARP
- Request 5000 Euro for a reduced set of prototypes 10x10 cm 5mm quartz plates finished with a nanometric coating of photocathode. The anode can be glas or HPL as for a normal RPC

- EOI
  - This detector, if prooven can feature 20 ps, 100 kHz/cm^2 and since it is based on a rigid quarts plate it han reach a very good mechanical precision, providing the bending coordinate at 0.1 mm level amd becoming a stand alone self triggering muon technology
  - Given its features it can support particle flow calorimetry and provide excellent ToF features in the calorimeter too, providing the function of timing wrap as well.

We have until 2028 to provide a clear demonstration of scalable performance

Hybrid RPC: suppress the charge fluctuations

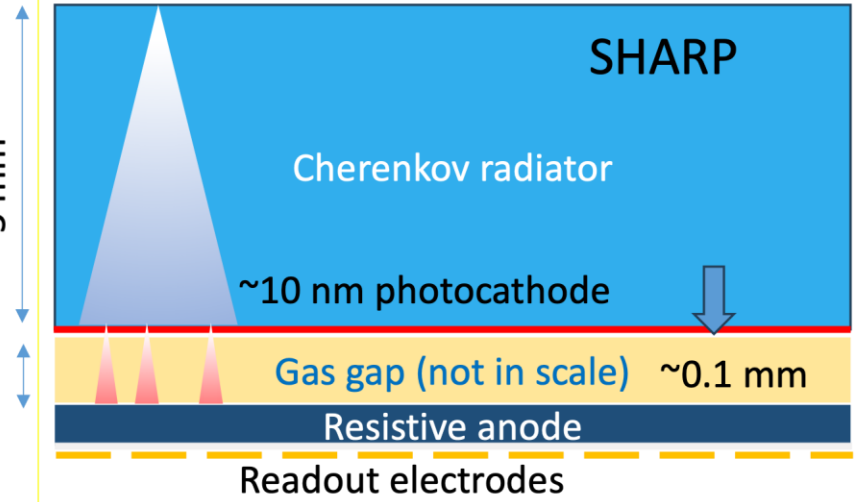


Large charge fluctuations

- Poisson satistics + different cluster depth
- Polya (cluster size)

All electrons start together and CS=1

- Same amplification path
- Minimal fluctuations

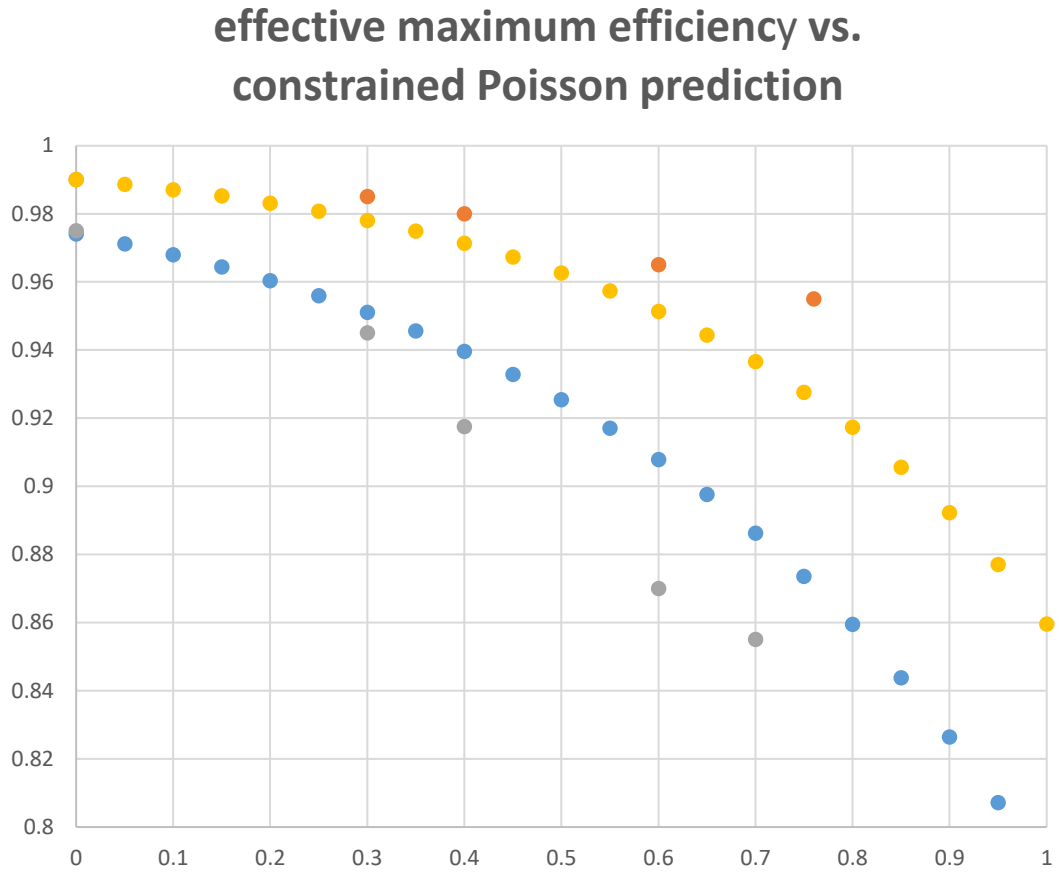


Conventional RPC	Hybrid RPC (SHARP)
• Wide gain spread	• Narrow gain spread
• MRPC for ps timing	• Single micro-gap
• F-gases	• Simple gases
• High charge	• Low charge
• Moderate rate	• High rate

- **RPC simplicity**
- **MPGD like charge and gases**
- **photodetector timing**

Effective maximum efficiency vs. Poisson

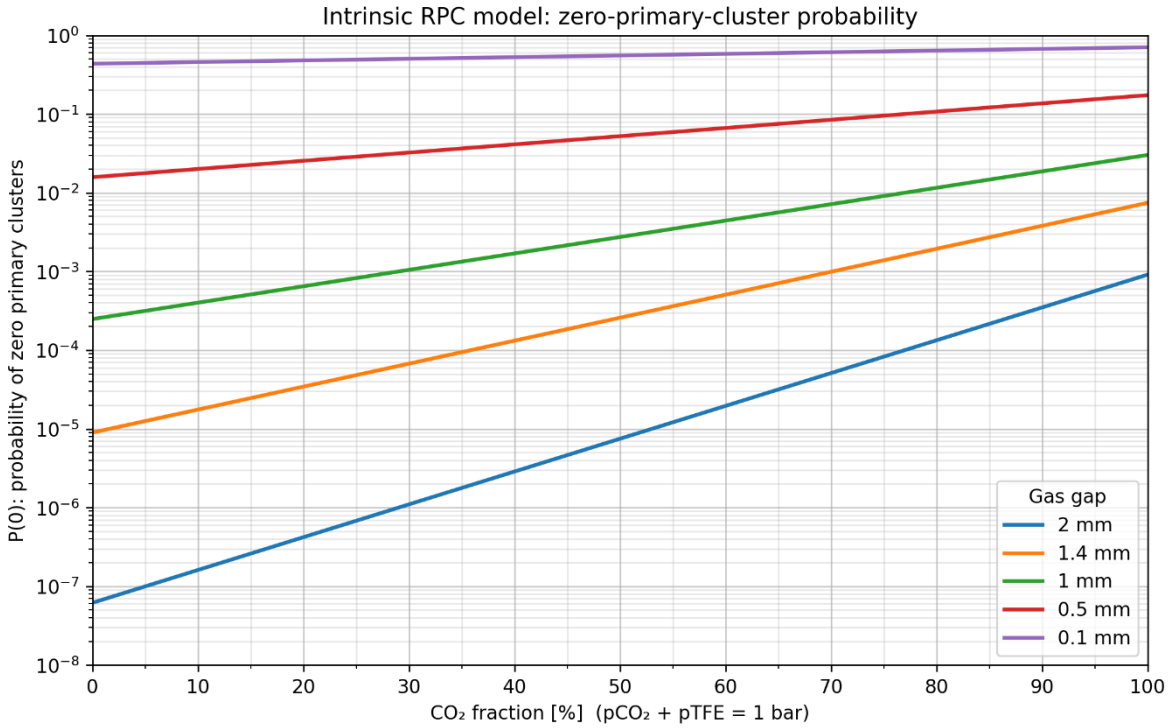
- **effective maximum efficiency** VS. **constrained Poisson prediction**
- **The effective maximum efficiency** is not a rigorous definition since in principle the efficiency still can increase HV, but with increasing cost function which sets an effective value.
- **The constrained Poisson function** is the maximum efficiency predicted by the Poisson primary cluster statistics, as a function of the gas composition, but constraining the effective number of clusters to the Standard mixture measured efficiency, assuming 100% acceptance.
- A direct comparison shows that the Poisson function approximately follows the data for increasing fraction of CO2
  - Quantitatively diverging
  - Different functional shape

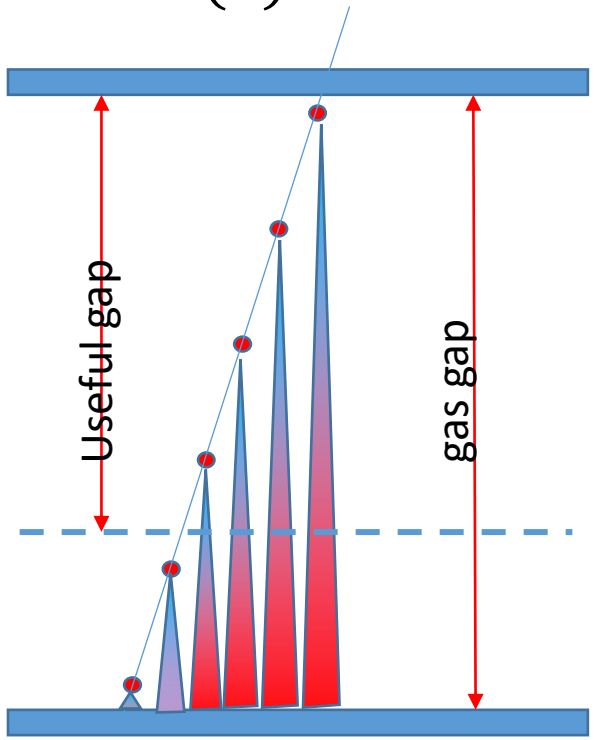


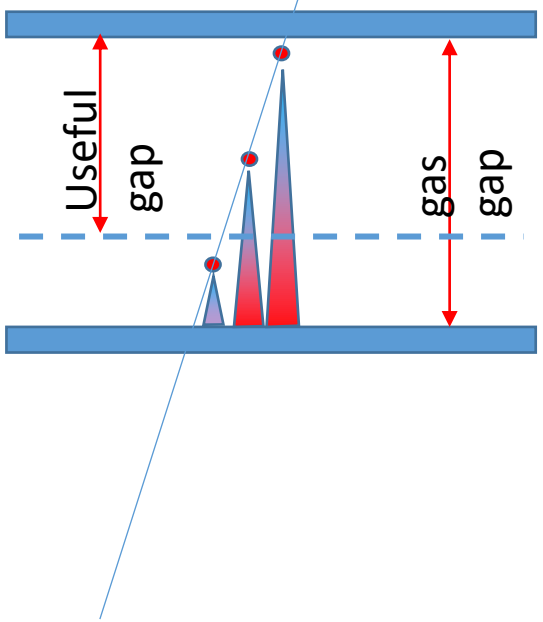
P(0) vs. the useful gap

- Depends primarily on the total gaseous target
  - Total thickness
  - Mixture density
- **Poisson P(0) <** expected inefficiency.

- The useful gas gap g_u is an empirical quantity: the region where, if a ionization occurs, the avalanche can grow to generate a detectable signal
- Given μ as the ionization per unit lenght we have:
- $\varepsilon = 1 - P(0) = e^{-\mu g_u}$

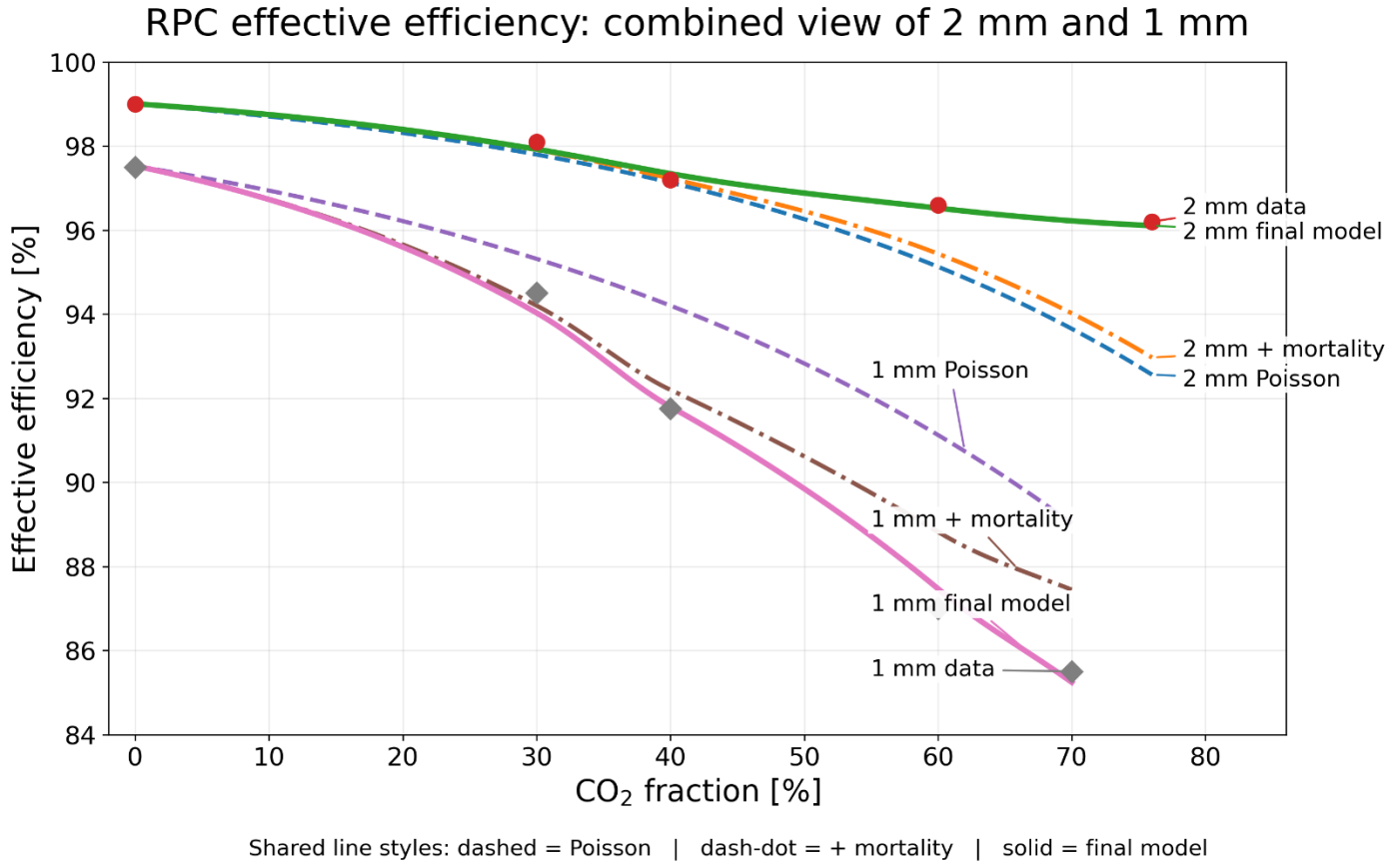






Realistic efficiency

- Real efficiency vs. poisson constrained efficiency
- Effect of the electronic sensitivity → g_u
- Cluster mortality
- Saturation effect on Qtot/Qprompt signal vs. gain



Definition of the RPC specific challenges

- Efficiency
  - Target: Maximum efficiency of the single detector → exploit the sensor and optimize the cost of readout
  - Lever arms: gaseous target, electron avalanche physics, front end electronics sensitivity
  - Competing requirements: gas mixture constraints, rate capability, longevity, time resolution
- Gas mixture
  - Target: Low impact (cost, environmental, detector), high performance
  - Lever arms: electron avalanche physics, front end electronics sensitivity
  - Competing requirements: efficiency, longevity
- Time resolution
  - Target: sub ns, down to < 100 ps+
  - Lever arm: gaseous target segmentation, faster mixture, front end electronics sensitivity
  - Competing requirements: efficiency of a single gap, simplicity robustness and low cost
- Low cost per unit area
  - Target: low cost and simple > m^2 module, holding the present margin with respect to other technologies
  - Lever arm: efficient design, gas mixture, FE electronics sensitivity
  - Competing requirements: high time resolution (and space)

The gas mix challenge

- Adding CO2 to the RPC gas mixture was initially studied to moderate the ageing effects of HFO as R134a replacement → cite ECOGAS
- ATLAS studied a pragmatic strategy to do something immediately and since 2022 performed a long study to partially replace R134a with CO2 → (see Sinem's slides)
- In 2024-2026 ATLAS replaced the standard gas mixture with:
  - 64.5% R134a, 30% CO2, 5% i-C4H10, 0.5% SF6
- The results was that this new mixture outperformed the standard one under any aspect: strong reduction of ageing, increase of time resolution by 30%, reduction of GWP and operation cost, same efficiency and lower operating voltage →link Sinem
- Why this was not done from the beginning? STD was working well, so there was no pressure to change…
- Now it comes spontaneous to wonder: how far one can go on this path…?

The effect of the FE electronics sensitivity

- To test the effect of the FE electronic sensitivity we performed a comparative test
- The chamber is an ATLAS-like layout chamber [*]
- 2mm gas gap doublet one test and one monitoring chamber
  - One side of the test chamber (vertical strips) is equipped with ATLAS electronics
  - The other side (horizontal strips) is equipped with a high sensitivity analog pre-amp (baseline for Phase1 and Phase2 upgrade)
- Each avalanche is seen AT THE SAME TIME by both electronics!

- Exposed to GIF++ beam and source to measure:
  - Efficiency under irradiation
  - V-A curve
- Mixture used:
  - Zero R134a
  - 88% CO2
  - 10% i-C4H10
  - 2% 1233-ZD
- It is flammable but freon free
- It is not meant as an official proposal but as an example

The purpose is to compare event by event the response of the two amplifiers looking exactly at the same signal to compare the performance in an objective way

[*] https://inspirehep.net/literature/2955768