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High-rate capability studies of triple-GEM detectors for the ME0 upgrade of the CMS muon spectrometer

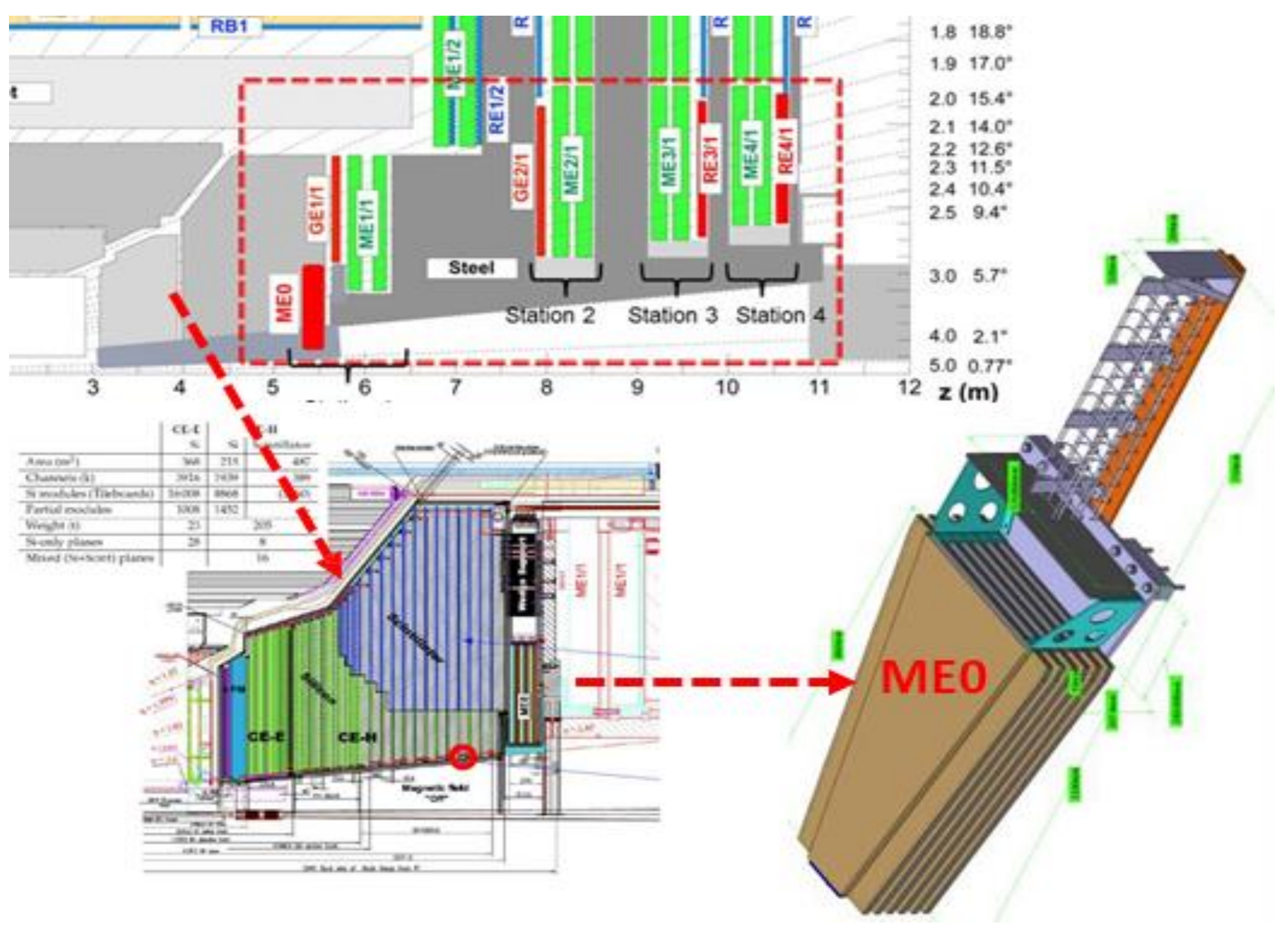
M. Bianco[1], F. Fallavollita[1], D. Fiorina[2], M. Maggi[3], A. Pellecchia[3],
L. F. Ramirez[4], N. Rosi[2] & P. Verwilligen[3]

on behalf of the CMS Muon Group

[1] CERN - Geneva, Switzerland, [2] Università degli Studi di Pavia & INFN sezione di Pavia
[3] Università degli Studi di Bari & INFN sezione di Bari, [4] Universidad de Antioquia

francesco.fallavollita@cern.ch

1. CMS GEM ME0 Project: challenges



6-Layer Triple-GEM stack installed behind HGCAL (**complex environment**)

$2 \times 18\ stacks\ (20°)\ covering\ 2.0 < \eta < 2.8$

Requirements [1]*:

- 97% *module efficiency*
- $< 500\ \mu rad$ *resolution*
- 8 - $10\ ns$ *time resolution*
- $\leq 15\%$ *gain uniformity*
- *Work in high-rate environment:* $\mathbf{150\ kHz/cm^2}$ *
- *Survive harsh radiation environment:* $\mathbf{7.9\ C/cm^2}$ *
- *Discharge rate that does not impede performance or operation*

* *updated w.r.t. TP & TDR*

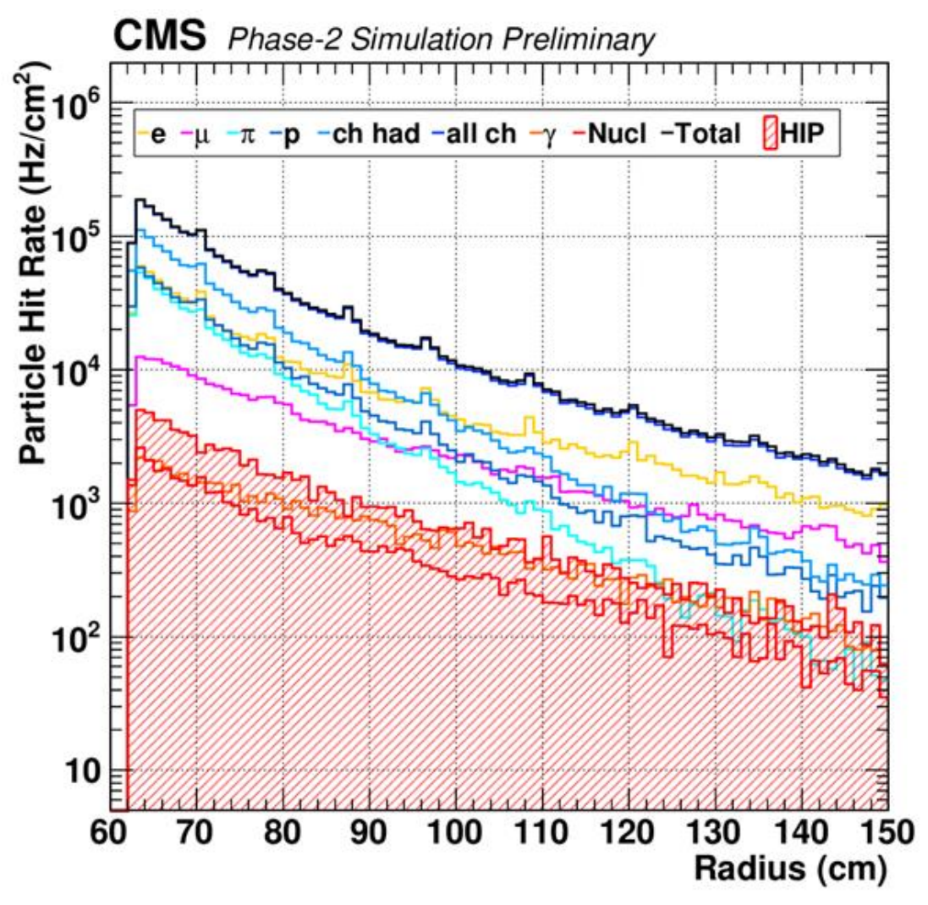
2. ME0 Background Particle Environment

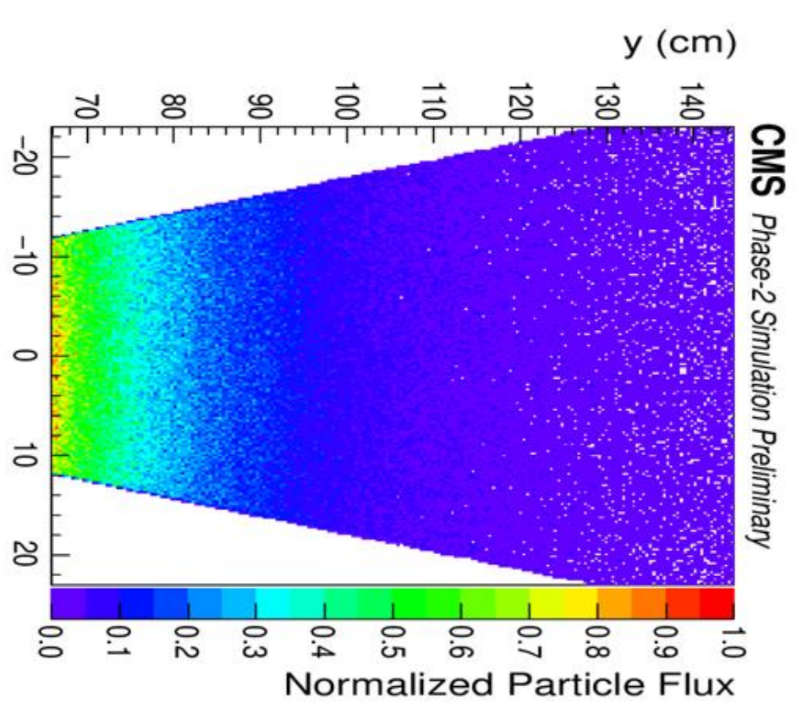
- Rate estimation from radiation bkg. essential to choose detector technologies and design detectors and electronics
- *FLUKA* used to simulate pp primary interactions and particle transport and to estimate the expected fluxes. Hit rates estimated normalizing the fluxes by the detector sensitivities determined with *GEANT4*
- ME0 background dominated by (prompt) charged hadrons (contributing 60%), photons and neutrons (contributing 40%) - radiation shielding effective only against γ and n
- Photon and neutron rate have gone up (factor 1.5 - 2) due to increased technical details inside HGCAL since muon TDR
- Implementation of HGCAL TDR in Fluka Geometry has led to increase in ME0 background hit rate
- Hit rate in highest pseudorapidity region: $\sim \mathbf{150\ kHz/cm^2}$ (factor 3 w.r.t. last Muon TDR); average hit rate (detector active area $\sim 2900\ cm^2$): $\sim \mathbf{24\ kHz/cm^2}$. On average, each of this particle produces about $\mathbf{300\ electron\text{-}ion\ pairs}$

↓

increase in particle background = change in detector requirements

Verify rate capability of the detector up to $150\ kHz/cm^2$



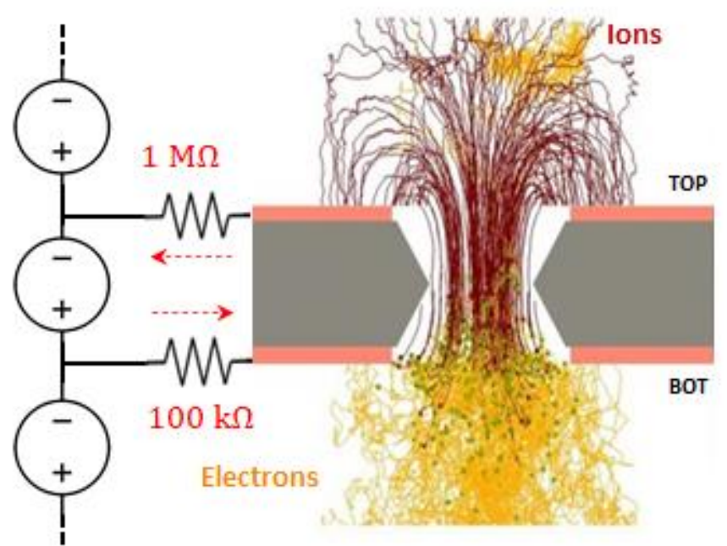


3. High-Rate Capability Studies

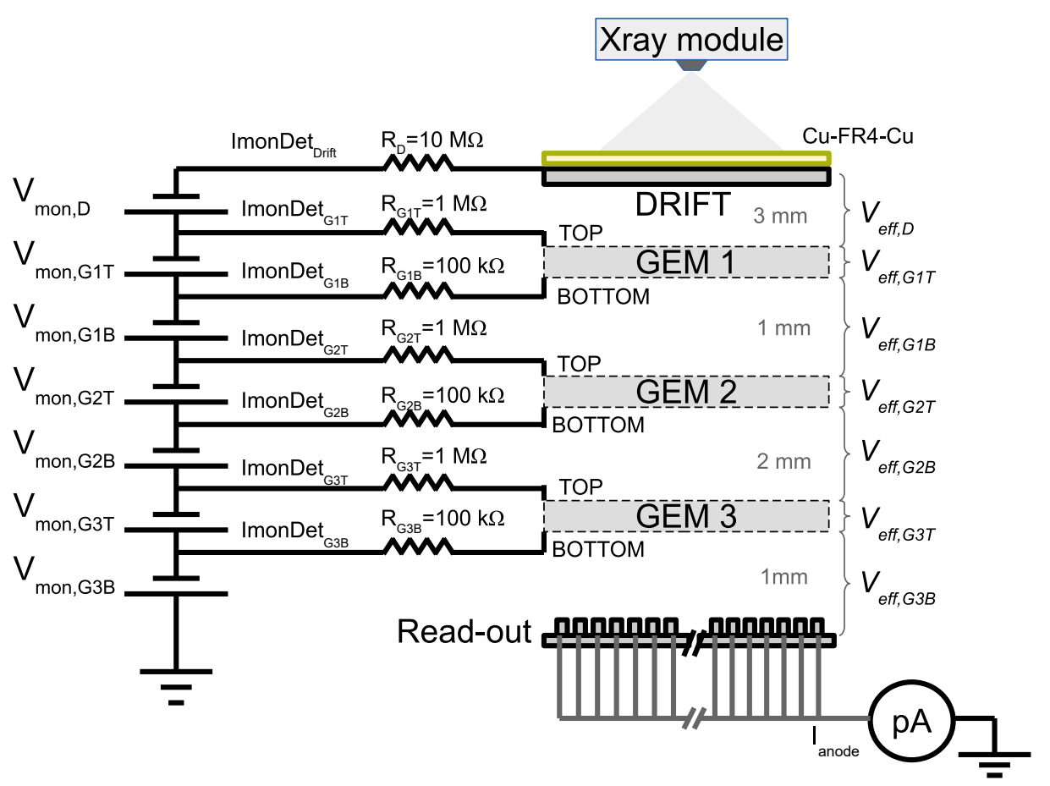
State of the art of the rate capability studies

Two main phenomena could affect the rate capability of a GEM-based detector:

1. the ***space charge***, which could modify the electric fields, resulting in a reduction of the gas gain above a certain value of radiation flux
   - → the ***slowly moving ions*** are ***quickly evacuated*** minimizing the space charge effect and improving the rate capability by several orders of magnitude w.r.t. the MWPCs
2. the ***electron / ion-induced current***, which could flow through the protection resistors and induce a voltage drop across the GEM-foil, resulting in a decrease of the gas gain
   - → this current is due to the ***high number of ions*** collected on the top electrode of the GEM-foils during the high-flux irradiation
   - → the ***voltage drop*** strongly depends on the value of the ***protection resistors*** and percentage of the ***irradiated area***, as well as the ***radiation flux***



Experimental Setup for High-Rate Studies



Detector:

- $10 \times 10\ \mathrm{cm}^2$ triple-GEM detector
- $\mathrm{Ar/CO_2}$ gas mixture
- $3/1/2/1\ \mathrm{mm}$ gap configuration
- $\mathrm{Cu(35\mu m)\text{-}FR_4(3mm)\text{-}Cu(35\mu m)}$: ME0 material budget included
- Protection resistors:

$10\ \mathrm{M\Omega}$ resistor on Drift board

$1\ \mathrm{M\Omega}$ resistor on top (for each foil)

$100\ \mathrm{k\Omega}$ resistor on bottom (for each foil)

Irradiation Source:

- 2 Amptek Mini-X2 X-Ray tubes (*Silver target*)
- Operating voltage: $40\ \mathrm{kV}$
- Operating current: from $5\ \mu\mathrm{A}$ to $100\ \mu\mathrm{A}$
- Number of primary gas ionization electrons per incident X-ray photon: 418 ± 9
- Irradiation distances 0 to $110\mathrm{cm}$

High Voltage Power Supply:

- CAEN A1515TG multichannel
- Current resolution $100\ \mathrm{pA}$

Data Analysis (I): Extrapolated Interaction Flux

The ***rate measurement*** is fully performed in ***current mode*** using a *Keithley 6487* pico-ammeter:

1. for a ***low particle flux*** (i.e., low X-ray powering current), the anode current increase linearly with the increasing count rates
2. for a ***high particle flux*** (i.e., high X-ray powering current), the anode current fairly saturates with the increasing count rates

→ ***the saturation is exclusively due to gas gain drop!***

→ a ***curve fitting*** is used for parameterizing the experimental data and allows to extrapolate the ***expected (real) anode current***:

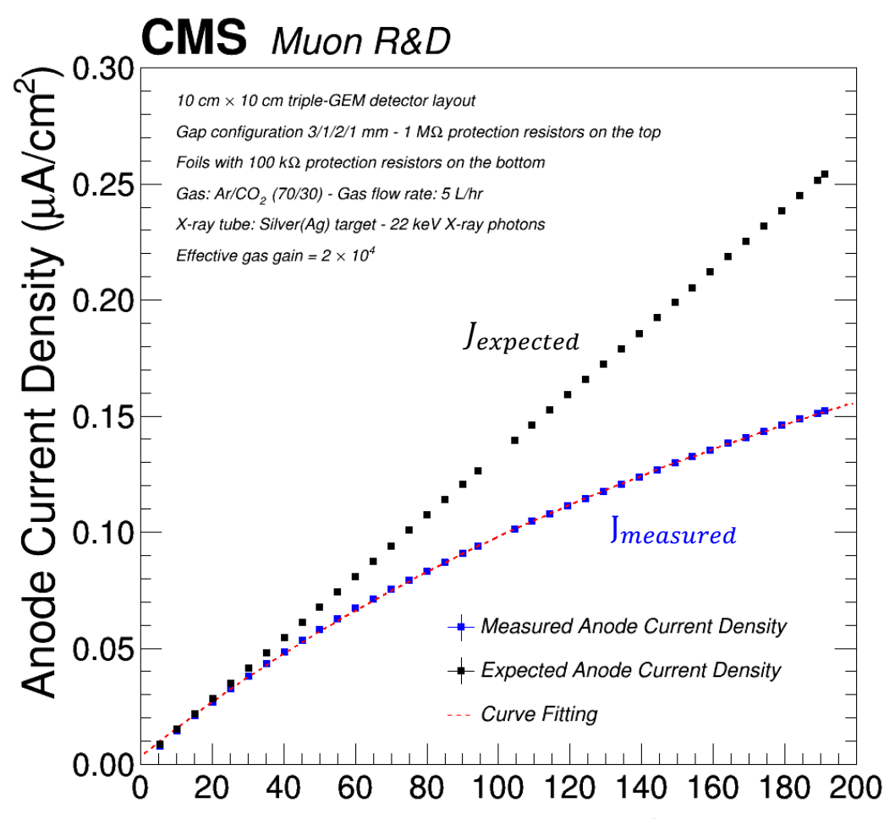
$$J_{measured} = \frac{J_{expected}}{1+k\,J_{expected}} \quad \text{with} \quad J_{expected} = A\,I_{xray} + B$$

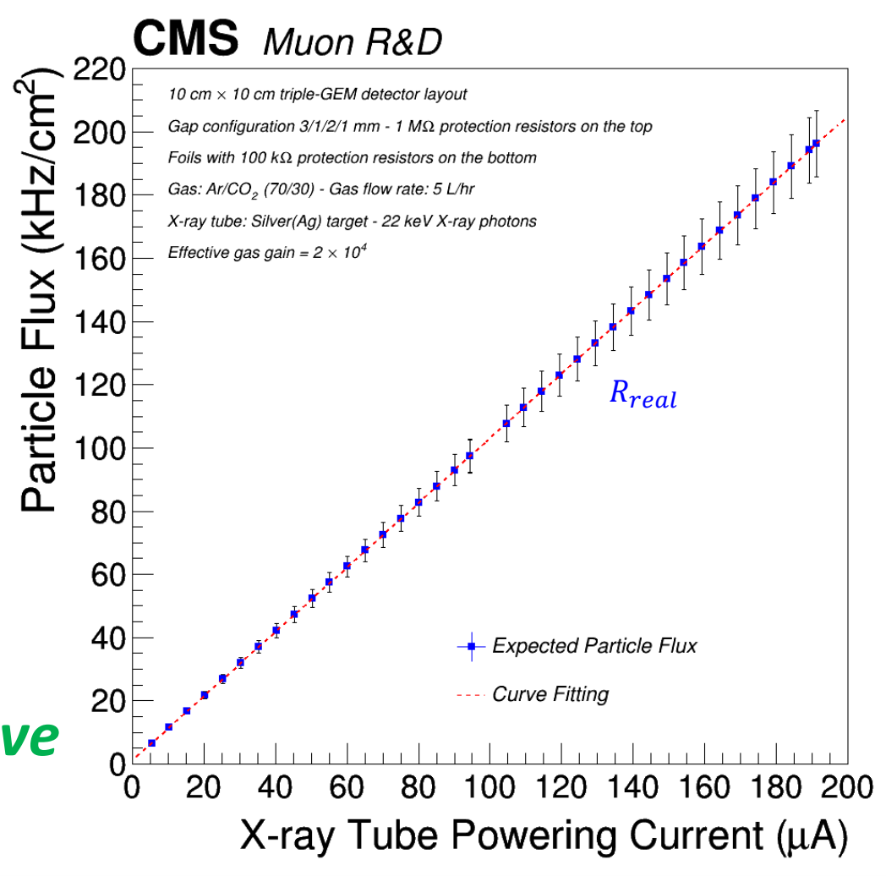
3. at fixed X-ray powering current, the ***extrapolated interaction X-ray photon flux*** is given by inverting the gas gain formula:

extrapolated anode current density

$$\underset{\text{extrapolated interaction photons flux}}{R_{real}} = \frac{J_{expected}}{n_p \times q_e \times \langle G \rangle}$$

detector effective gas gain





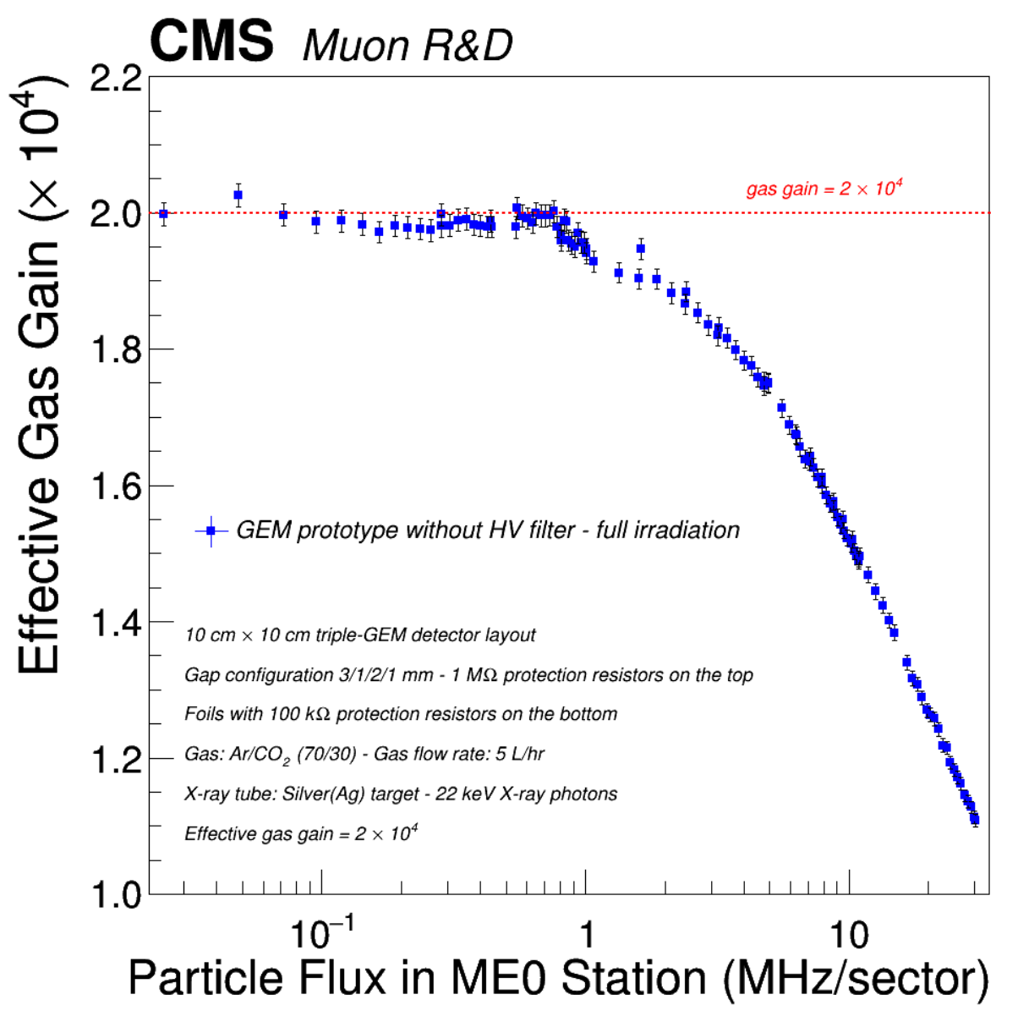
Data Analysis (II): Effective Gas Gain Drop

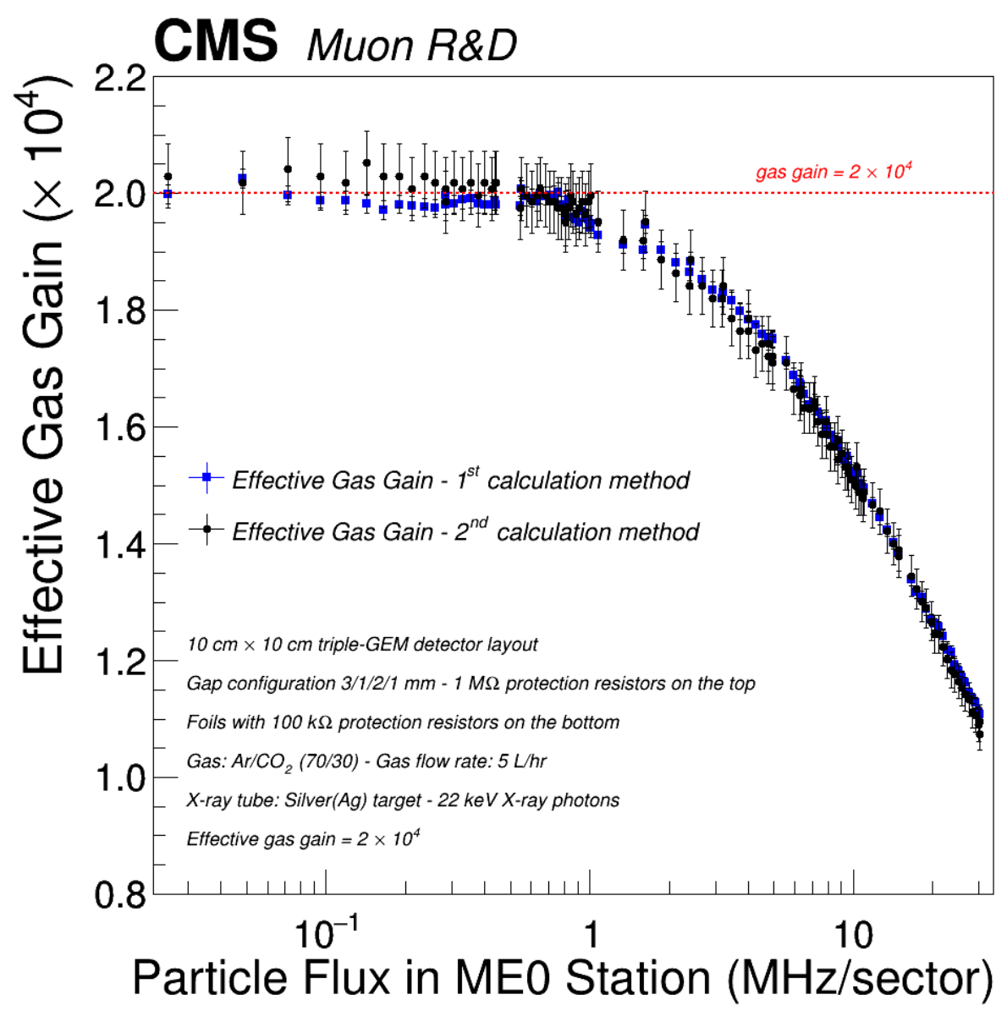
The ***gas gain drop*** is estimated with the usual formula by measuring the ***anode current density*** and extrapolating the ***interaction photons flux*** during the high-flux irradiation:

measured anode current density

$$\underset{\text{detector effective gas gain}}{\langle G \rangle} = \frac{J_{measured}}{n_p \times q_e \times R_{real}}$$

extrapolated interaction photons flux





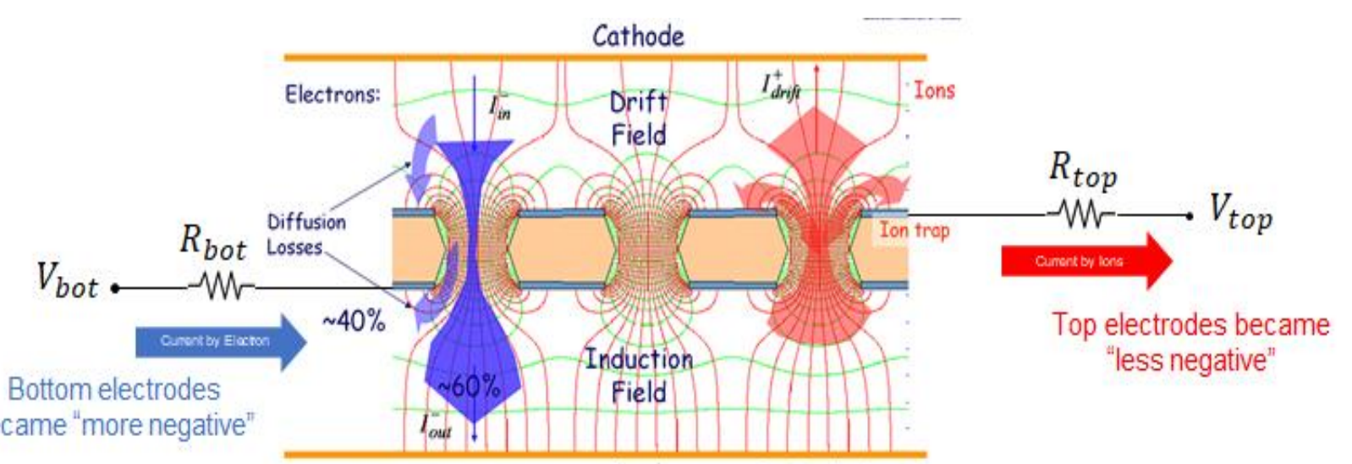
The ***gas gain drop*** is also estimated by measuring the ***voltage drop*** across the three GEM-foils during the high-flux irradiation

1. the ***current*** flowing through the ***protect. resistors*** changes the voltage on each electode by applying the ***Kirchhoff's second law***, the effective voltage on the electrode will be:

$$V_{eff}^{electrode} = V_{bias}^{electrode} - I^{electrode} \times R^{electrode}$$

2. the ***effective gas gain*** is measured by powering the detector with the ***effective voltages*** ($V_{eff}^{electrode}$) and irradiating with low X-ray photon flux ($\sim 100\ \mathrm{Hz/cm^2}$)

The gas gain curve taken by ***"emulating"*** the voltages under irradiation is ***consistent*** to the one ***measured under irradiation***: gas gain drop is only due to the voltage drop across the resistance!



Data Analysis (III): Effective Gas Gain Compensation

A ***compensation measurement*** is performed to determine the ***new bias voltage*** at which the detector should be powered during the high-flux irradiation:

1. to recover the original ***nominal gas gain*** of 2×10^4
2. to maintain the ***nominal electric fields*** between the foils and gaps

A ***compensation algorithm*** has been developed to restore the gas gain stability in a harsh background environment:

I. measure the $V_{bias}^{electrode}$ and the $I^{electrode}$ on each electrodes to calculate the effective voltage on the electrode during the high-flux irradiation:

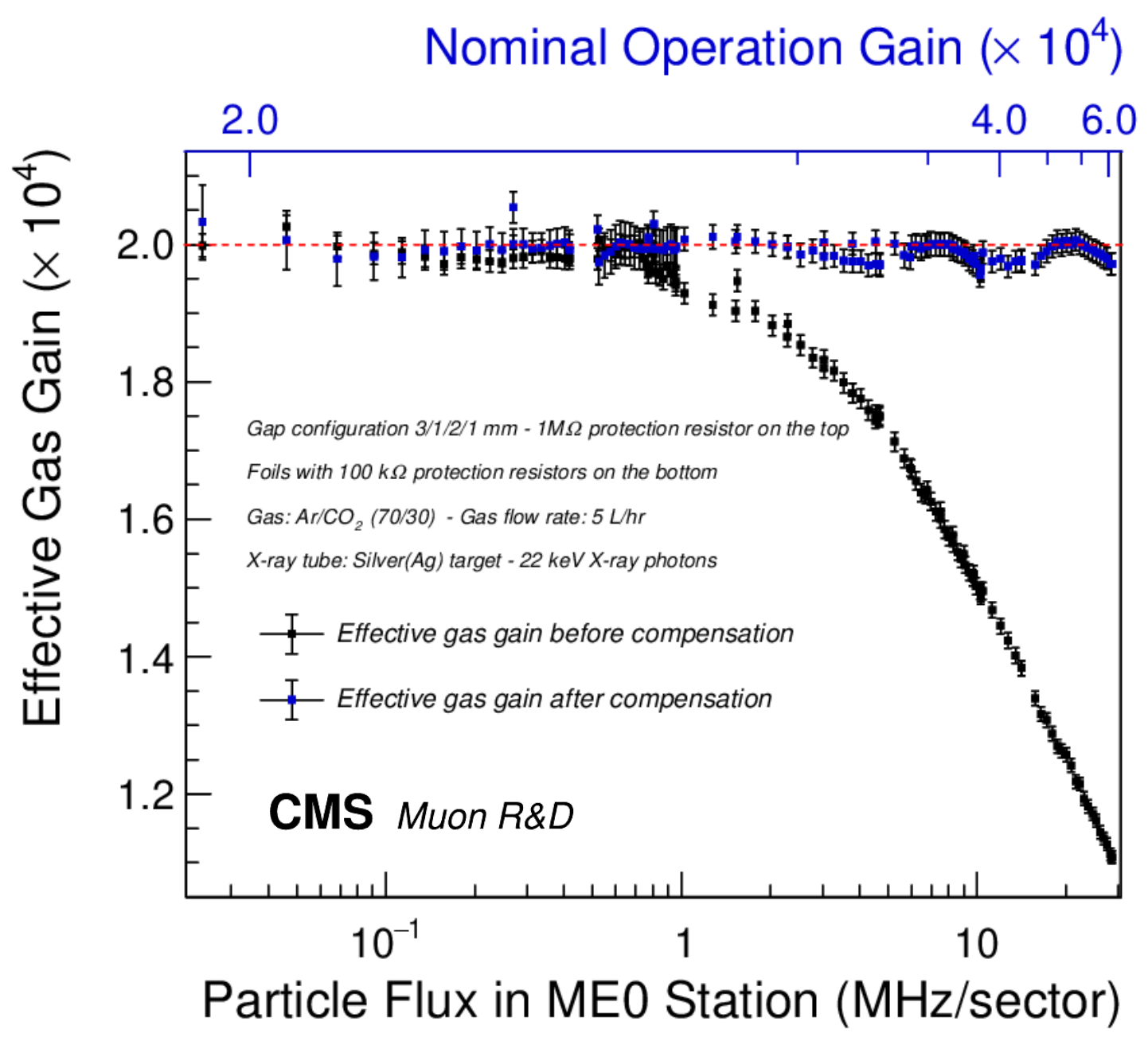
$$V_{eff}^{electrode} = \underbrace{V_{bias}^{electrode}}_{\text{bias voltage}} - \underbrace{\underbrace{I^{electrode}}_{\text{current collected on the electrode}} \times R^{electrode}}_{\text{voltage drop on the resistor}}$$

II. calculate the discrepancy with respect to the electrode voltage ($V_{nominal}^{electrode}$) at the nominal effective gas gain of 2×10^4:

$$V_{err}^{electrode} = V_{nominal}^{electrode} - V_{eff}^{electrode}$$

III. increase iteratively each electrode voltage by $V_{err}^{electrode}$ until:

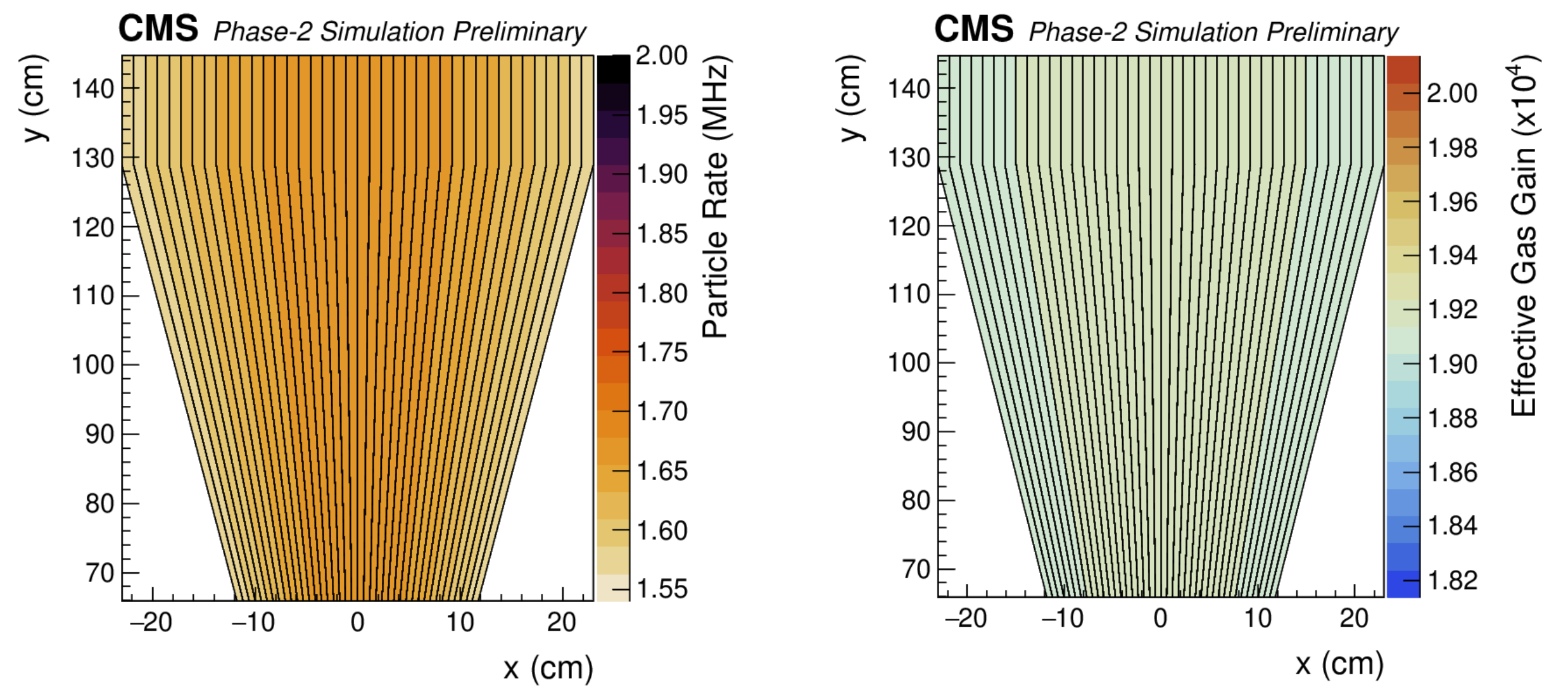
$$V_{eff}^{electrode} = V_{nominal}^{electrode}$$

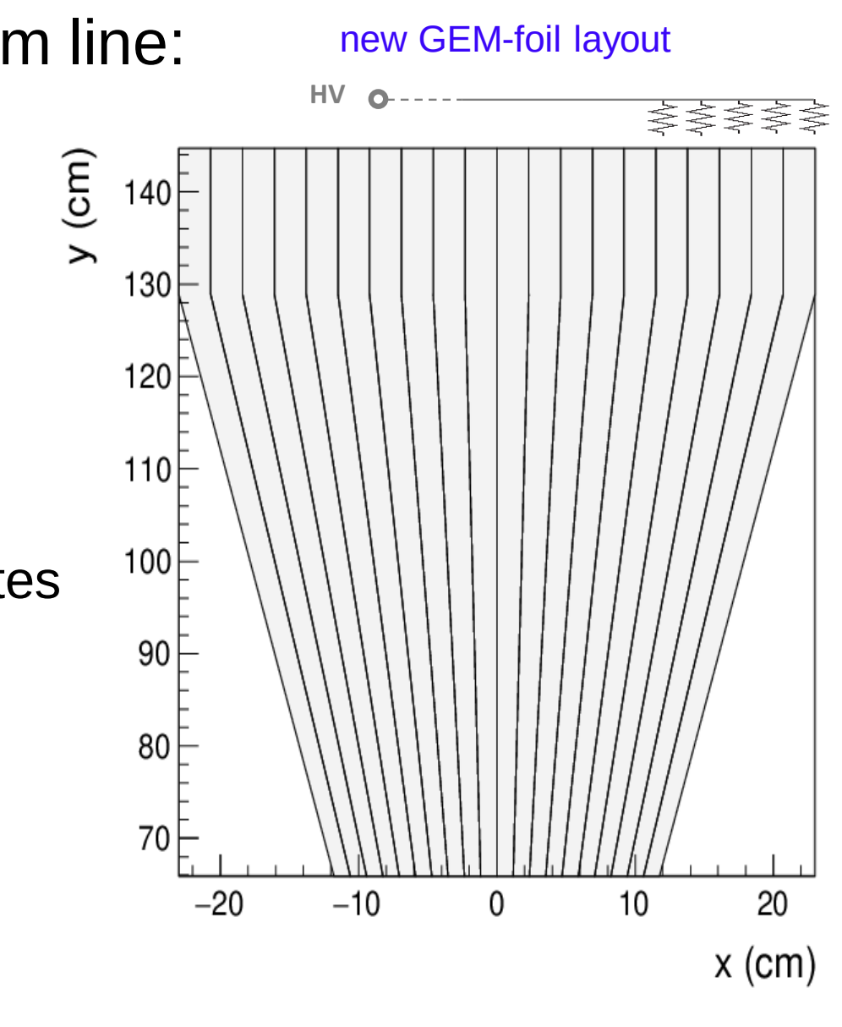


4. Radial Segmentation of the GEM-foils

The solution adopted to minimize the gas gain drop consists of dividing each electrode of GEM foil in fine high-voltage sectors along the ***azimuthal-direction*** with respect to the LHC beam line:

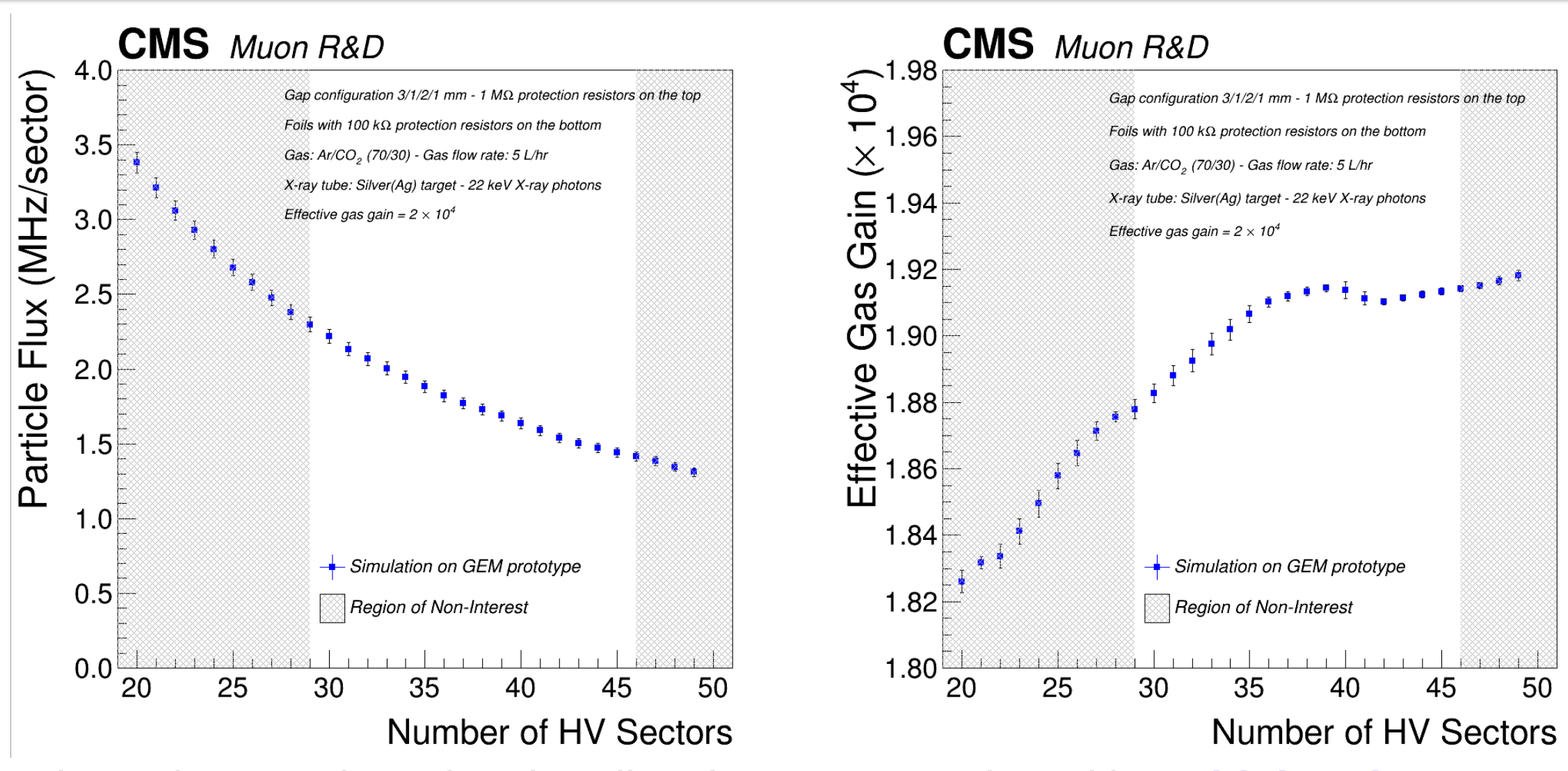
- each high-voltage sector is powered separately and is connected to a protection resistor, in order to limit the total current flowing through each protection resistor
  - → ***equal-area sectors***: maximum safe surface $\sim 100\ cm^2$ to reduce the discharge energy
- the background particle rate is expected to be approximately the same on each sector even though the background flux shape is highly uneven in the radial-direction
  - → ***equal-protection resistors*** to ensure prevention/protection against self-sustained discharges
- the azimuthal-direction segmentation is independent on the background model (i.e., all the rates will move up or down together in parallel with any changes in the radial bkg. radiation profile)
  - → avoid ***uncertainty*** in the ***simulated background flux*** (*GEANT4* vs *FLUKA* discrepancy)





example of azimuthal - segmentation with 40 sectors

- $< 10\%$ non-uniformity in hit rate per high-voltage sector
- $\sim 1\%$ non-uniformity in detector gas gain (lower than the intrinsic detector response uniformity [2])



Azimuthal segmentation constraints:
→ high-voltage sector area: $100\ cm^2$
(to reduce the discharge energy)

→ high-voltage sector side length $> 5\ mm$
(design / manufacturing requirements)

Chosen segmentation for best gas gain drop / sector surface trade-off:

40 high-voltage sectors

Simulations on the azimuthal-direction segmentation with ***40 high-voltage sectors*** shows that the ***hit rate per sector*** in the CMS-ME0 background can be contained to an average of $\mathbf{1.5\ MHz/sector}$, while the ***gas gain drop*** can be minimized to about $\mathbf{10\%}$ of the nominal value of 2×10^4.

5. Conclusion

The studies presented show a new approach on the rate capability problem of triple-GEM detectors, applied to the high-rate environment expected for the innermost muon station of the CMS endcaps for the high-luminosity upgrade:

- The *rate capability* of large-area triple-GEM based detectors has been demonstrated to be *limited by the protection resistors*;
- The measured *gas gain drops can be as high as* 40% of the expected gas gain, which can be recovered by applying overvoltage to the detector electrodes and maintaining the nominal electric fields between the foils and gaps;
- The main mitigation strategy chosen for the CMS-ME0 detectors involves *a radial segmentation of the GEM-foils* with respect to the beam line: such redesign is expected to reduce the *gas gain loss during CMS operations not higher than* 10%.

[1] A. Colaleo et al., *CERN-LHCC-2017-012, CMS-TDR-016*, 12 September 2017.
[2] F. Fallavollita et al., Novel triple-GEM mechanical design for the CMS-ME0 detector and its preliminary performance, JINST 15 (2020) no.08, C08002.