



Rate capability of large-area triple-GEM detectors and new foil design for the innermost station, ME0, of the CMS endcap muon system



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on behalf of the CMS Muon Group

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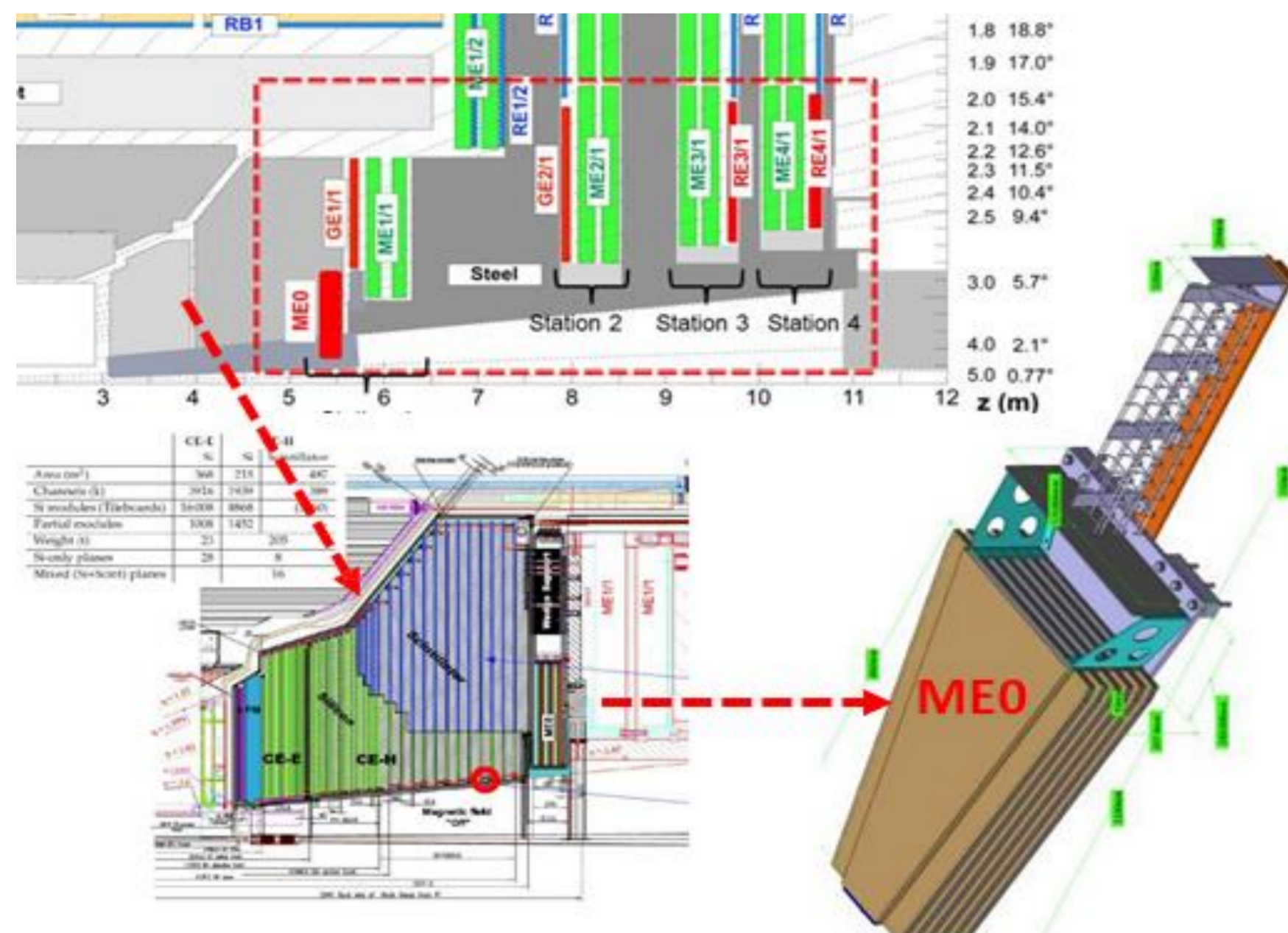
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1. CMS GEM ME0 Project: challenges



Requirements [1]*:

- 97% module efficiency
- < 500 μrad resolution
- 8 - 10 ns time resolution
- $\leq 15\%$ gain uniformity
- Work in high-rate environment: **150 kHz/cm²***
- Survive harsh radiation environment: **7.9 C/cm²***
- Discharge rate that does not impede performance or operation



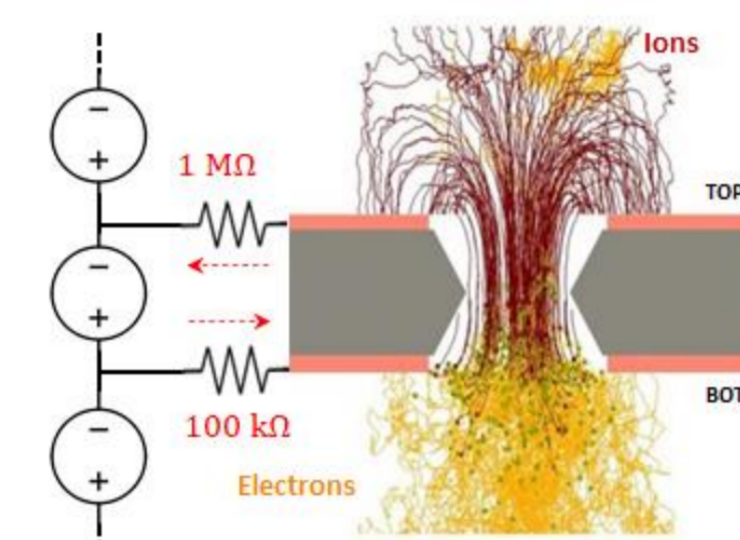
6-Layer Triple-GEM stack installed behind HGCAL (complex environment)
2 x 18 stacks (20°) covering 2.0 < η < 2.8

3. High-Rate Capability Studies

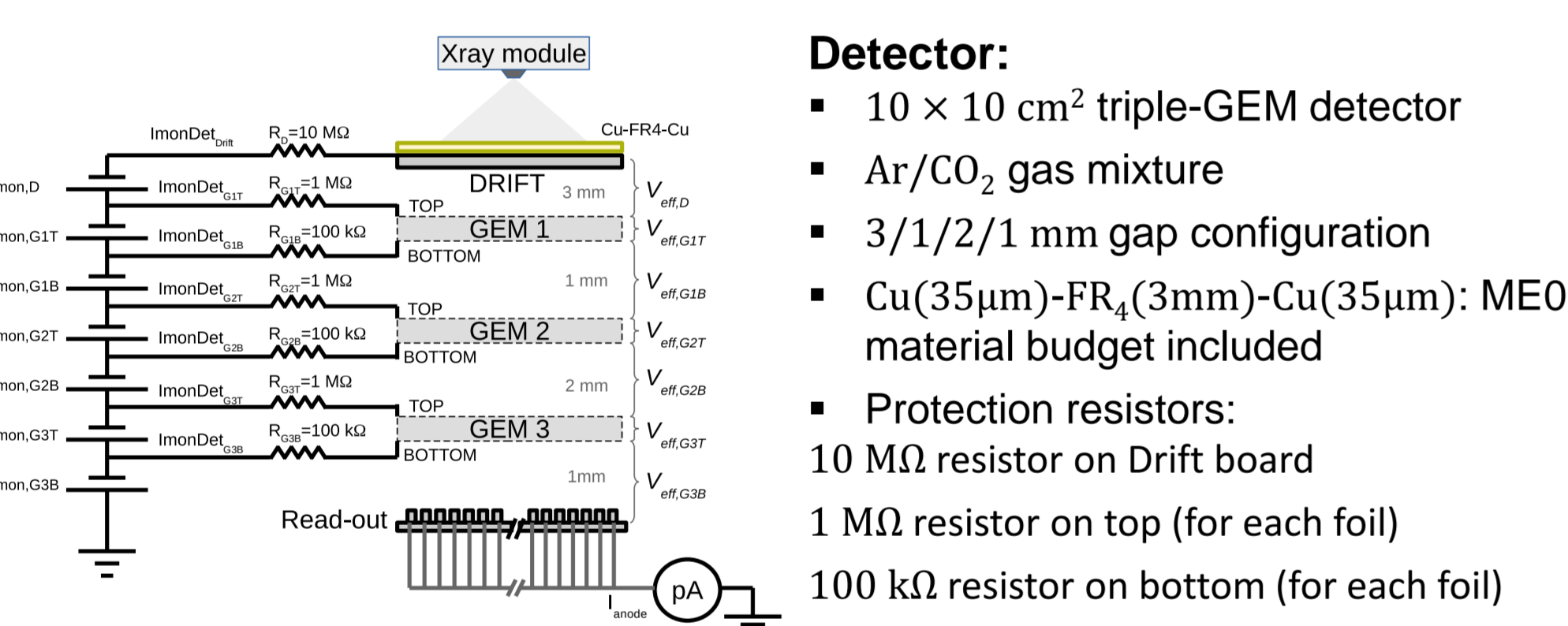
State of the art of the rate capability studies

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

- 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
- 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 x 10 cm² triple-GEM detector
- Ar/CO₂ gas mixture
- 3/1/2/1 mm gap configuration
- Cu(35 μm)-FR₄(3mm)-Cu(35 μm): ME0 material budget included
- Protection resistors: 10 M Ω resistor on Drift board
- 1 M Ω resistor on top (for each foil)
- 100 k Ω resistor on bottom (for each foil)

Irradiation Source:

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

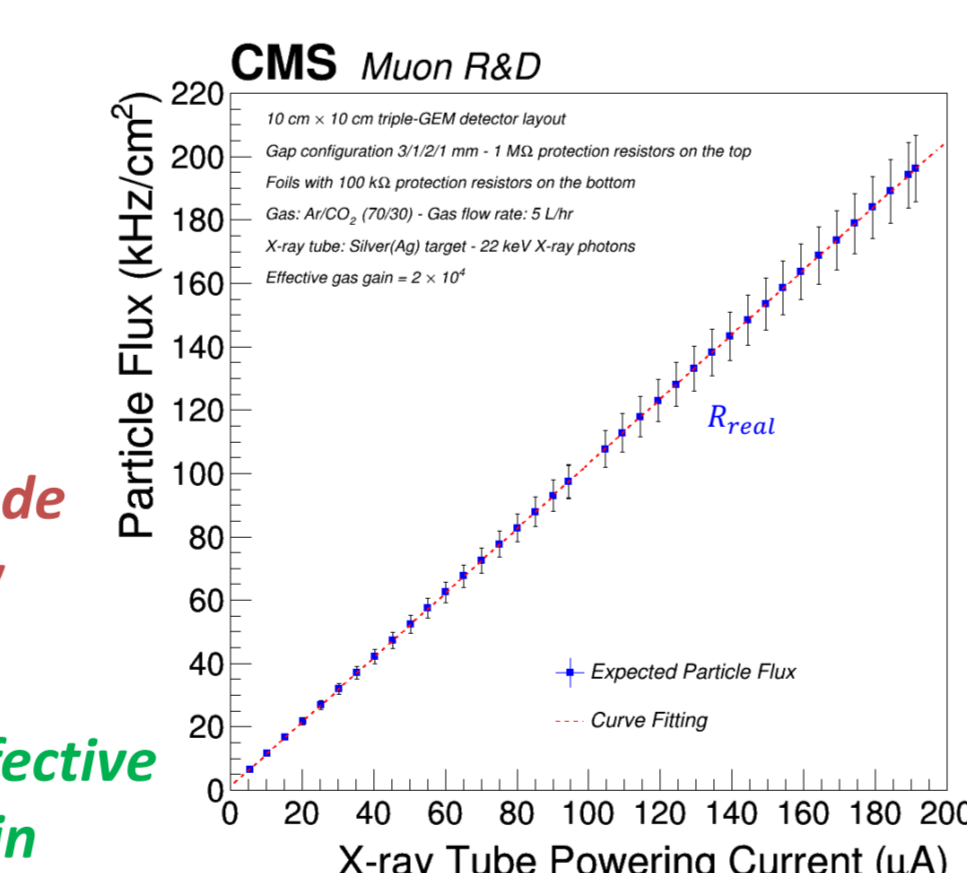
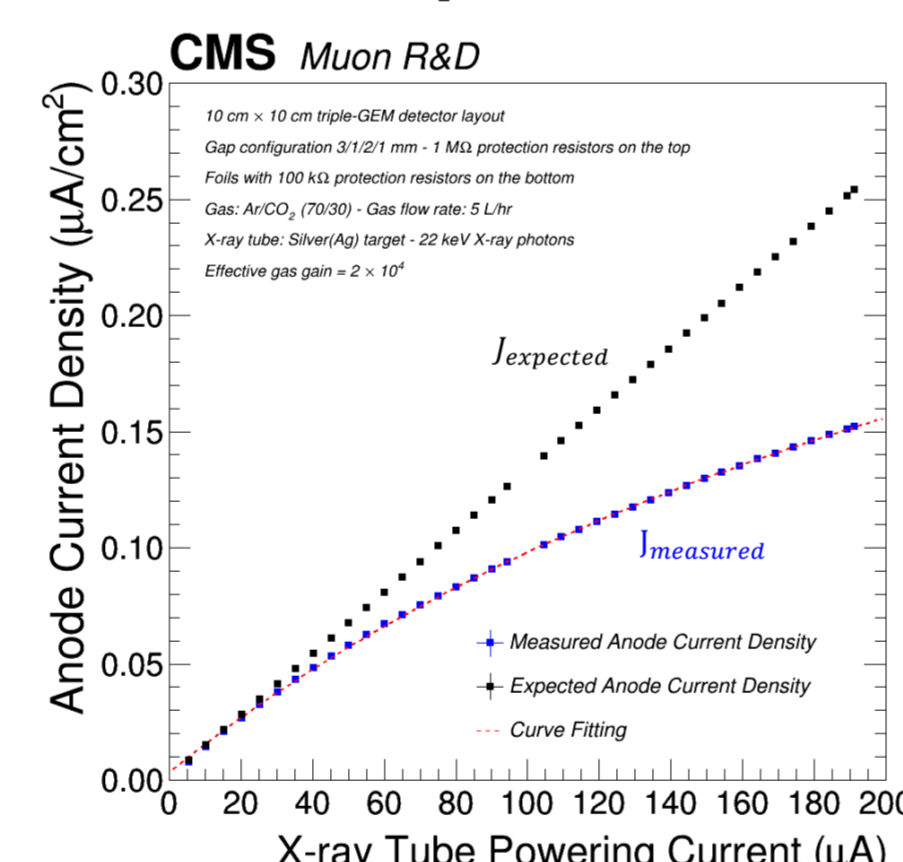
High Voltage Power Supply:

- CAEN A1515TG multichannel
- Current resolution 100 pA

Data Analysis (I): Extrapolated Interaction Flux

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

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



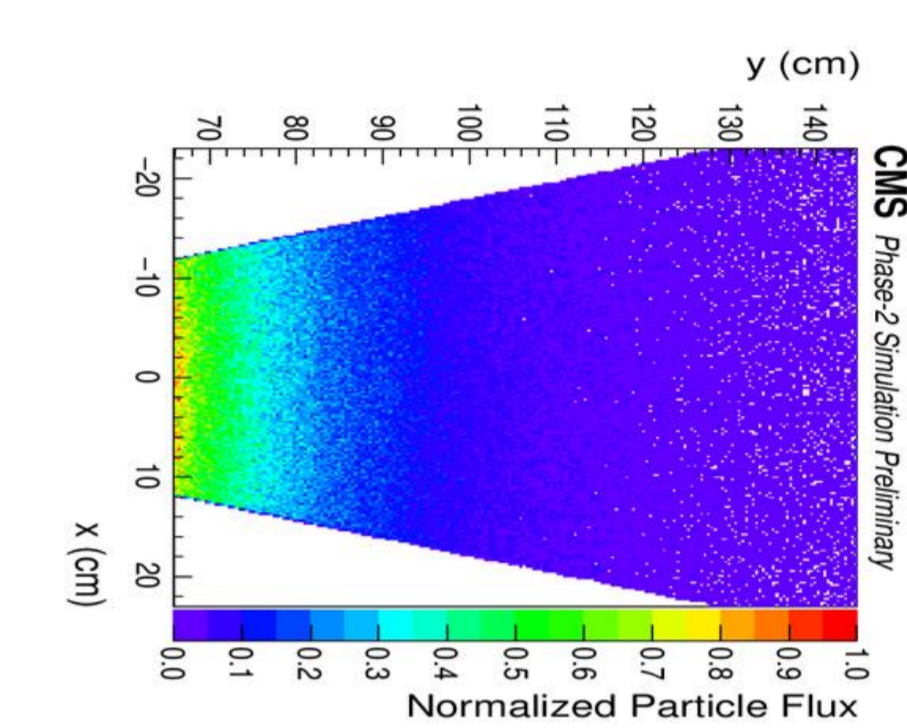
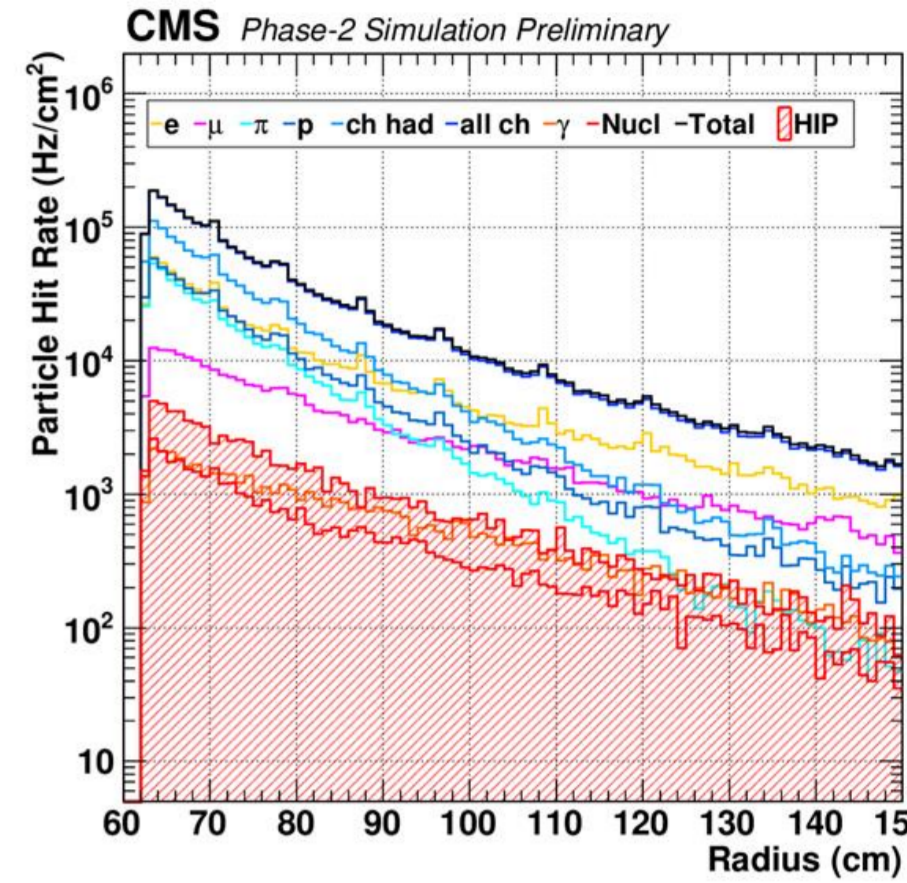
$$J_{\text{measured}} = \frac{J_{\text{expected}}}{1+k} \text{ with } J_{\text{expected}} = A I_{\text{xray}} + B$$

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

$$R_{\text{real}} = \frac{J_{\text{expected}}}{n_p \times q_e \times \langle G \rangle}$$

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: **$\sim 150 \text{ kHz/cm}^2$** (factor 3 w.r.t. last Muon TDR); average hit rate (detector active area $\sim 2900 \text{ cm}^2$): **$\sim 24 \text{ kHz/cm}^2$** . On average, each of this particle produces about **300 electron-ion pairs**

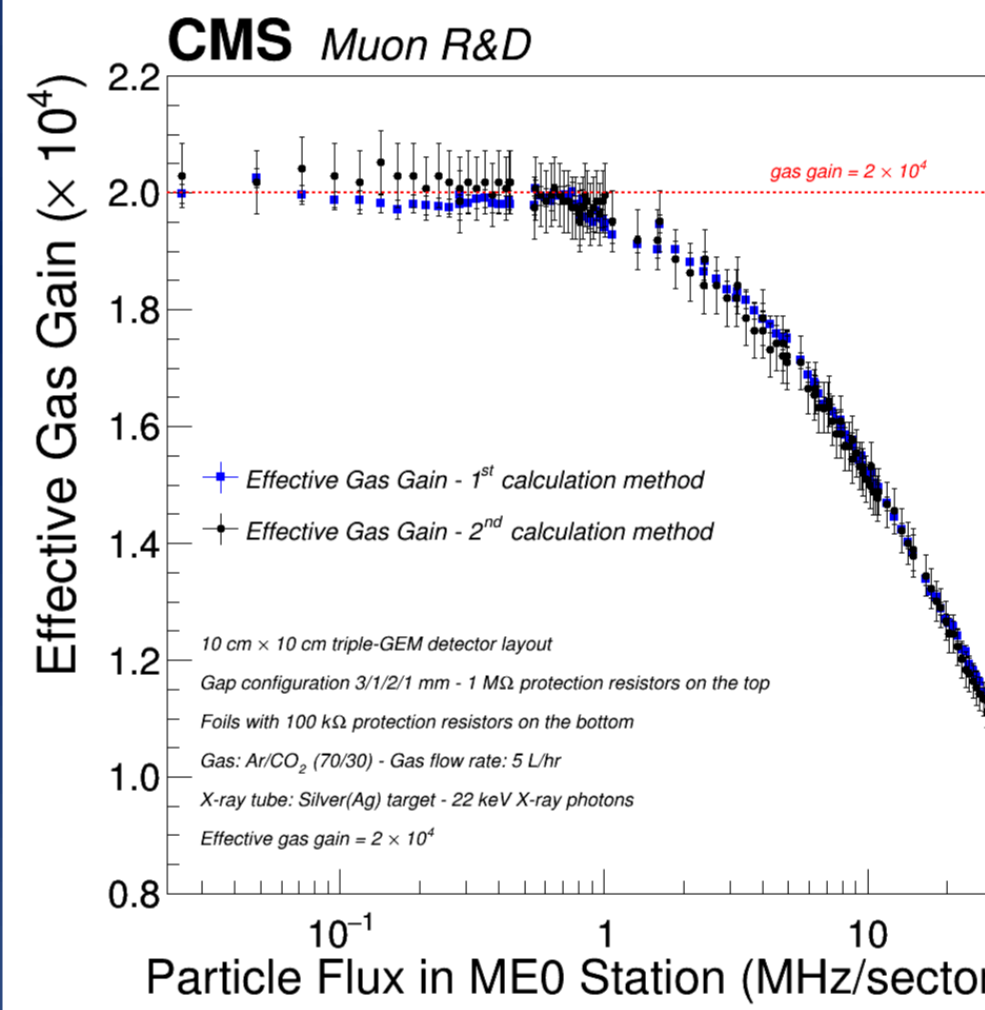


increase in particle background = change in detector requirements
Verify rate capability of the detector up to 150 kHz/cm²

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:

$$\langle G \rangle = \frac{J_{\text{measured}}}{n_p \times q_e \times R_{\text{real}}}$$

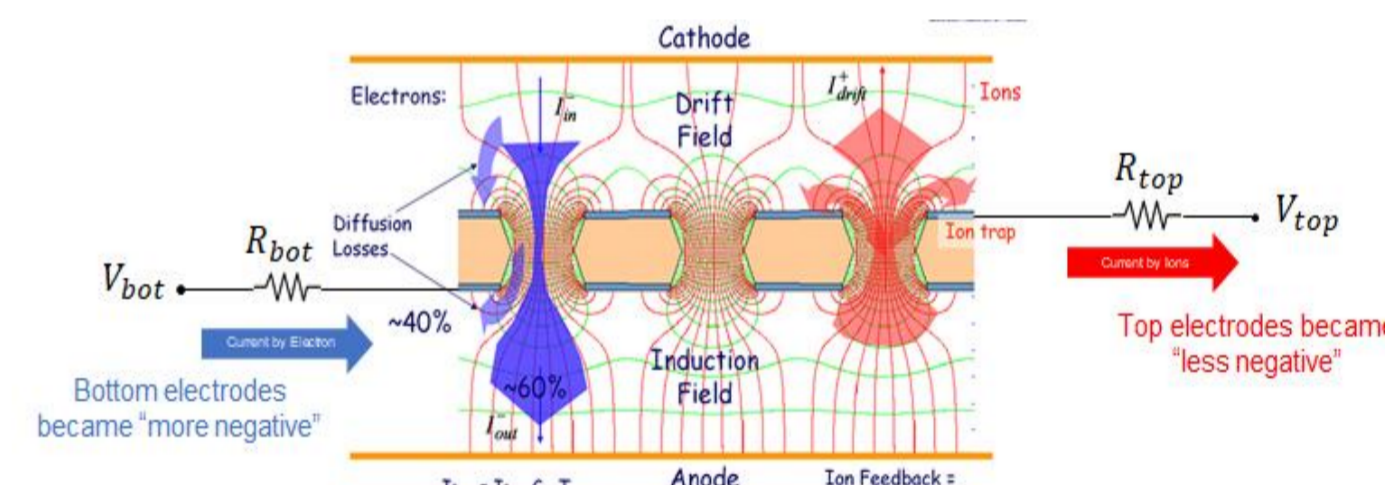


The **gas gain drop** is also estimated by measuring the **voltage drop** across the three GEM-foils during the high-flux irradiation

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

$$V_{\text{eff}}^{\text{electrode}} = V_{\text{electrode}}^{\text{nominal}} - I_{\text{electrode}} \times R_{\text{electrode}}$$

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



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!

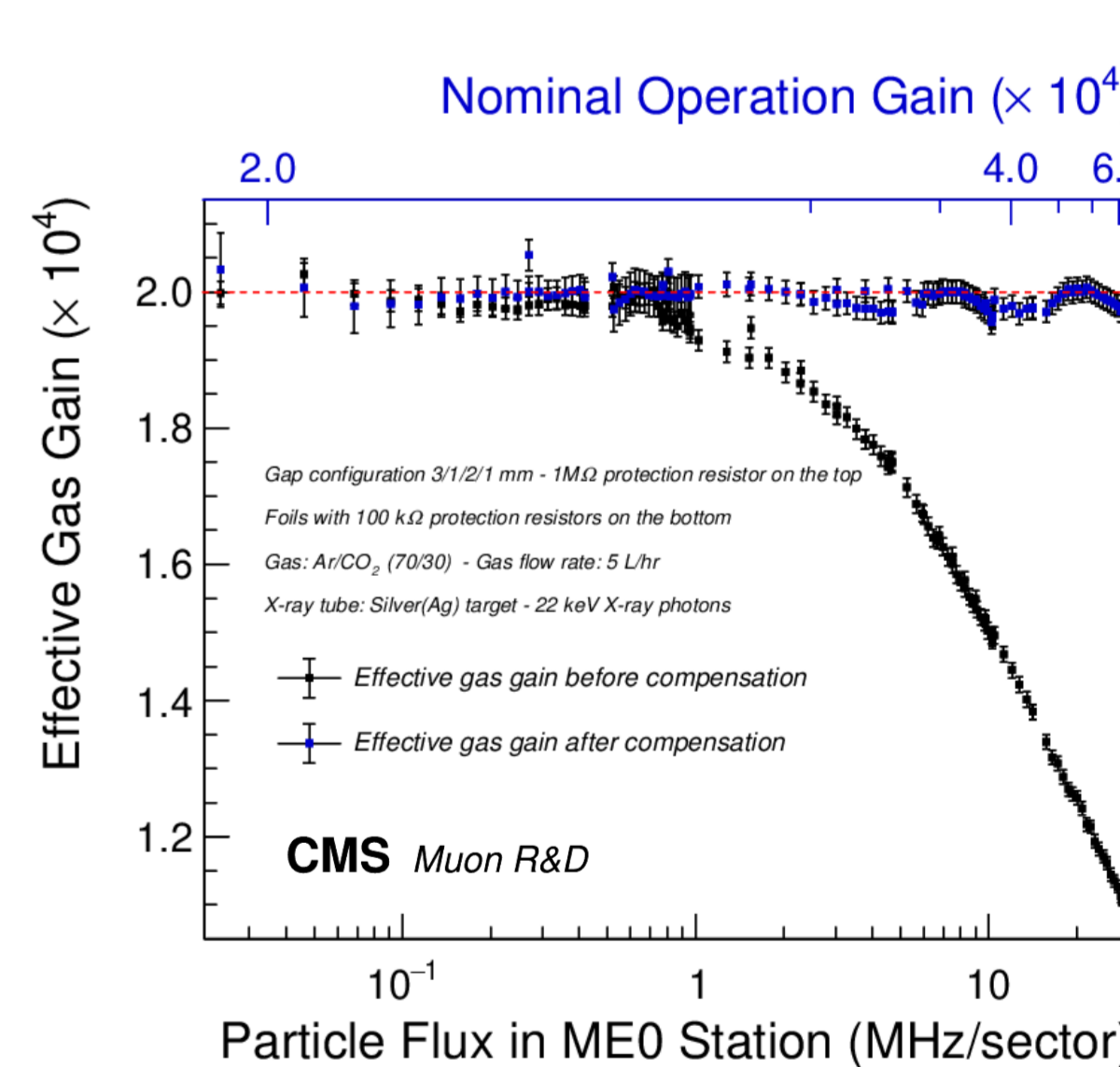
Data Analysis (III): Effective Gas Gain Compensation

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

- to recover the original **nominal gas gain** of 2×10^4
- 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:

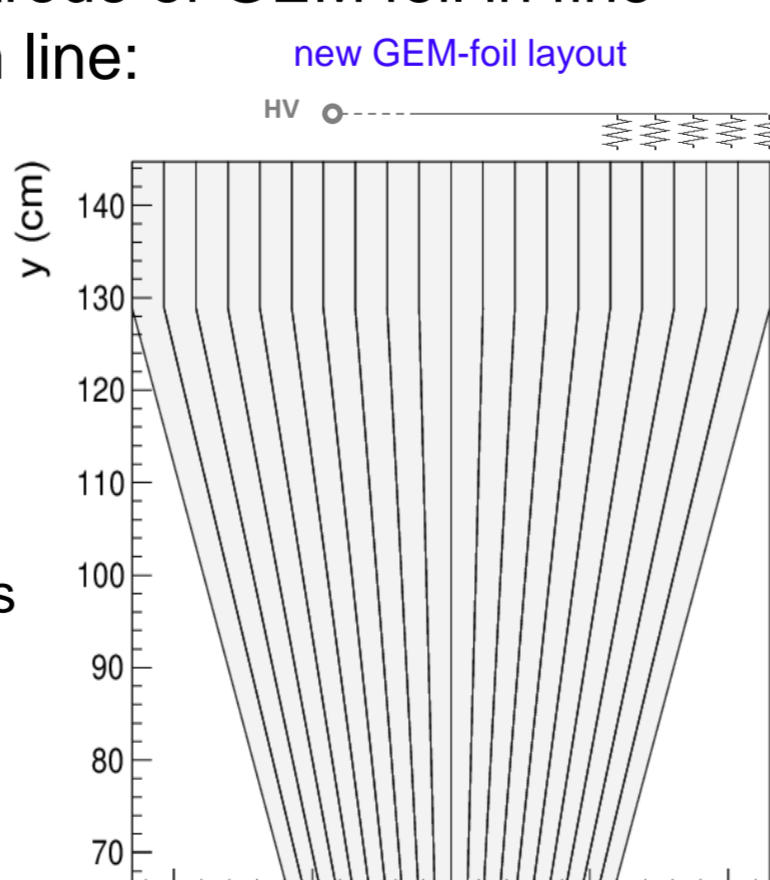
- measure the $V_{\text{eff}}^{\text{electrode}}$ and the $V_{\text{electrode}}$ on each electrodes to calculate the effective voltage on the electrode during the high-flux irradiation:
- $$V_{\text{eff}}^{\text{electrode}} = V_{\text{electrode}}^{\text{nominal}} - I_{\text{electrode}} \times R_{\text{electrode}}$$
- II. calculate the discrepancy with respect to the electrode voltage ($V_{\text{eff}}^{\text{electrode}}$) at the nominal effective gas gain of 2×10^4 :
- $$V_{\text{err}}^{\text{electrode}} = V_{\text{electrode}}^{\text{nominal}} - V_{\text{eff}}^{\text{electrode}}$$
- III. increase iteratively each electrode voltage by $V_{\text{err}}^{\text{electrode}}$ until:
- $$V_{\text{eff}}^{\text{electrode}} = V_{\text{electrode}}^{\text{nominal}}$$



4. Radial Segmentation of the GEM-foils

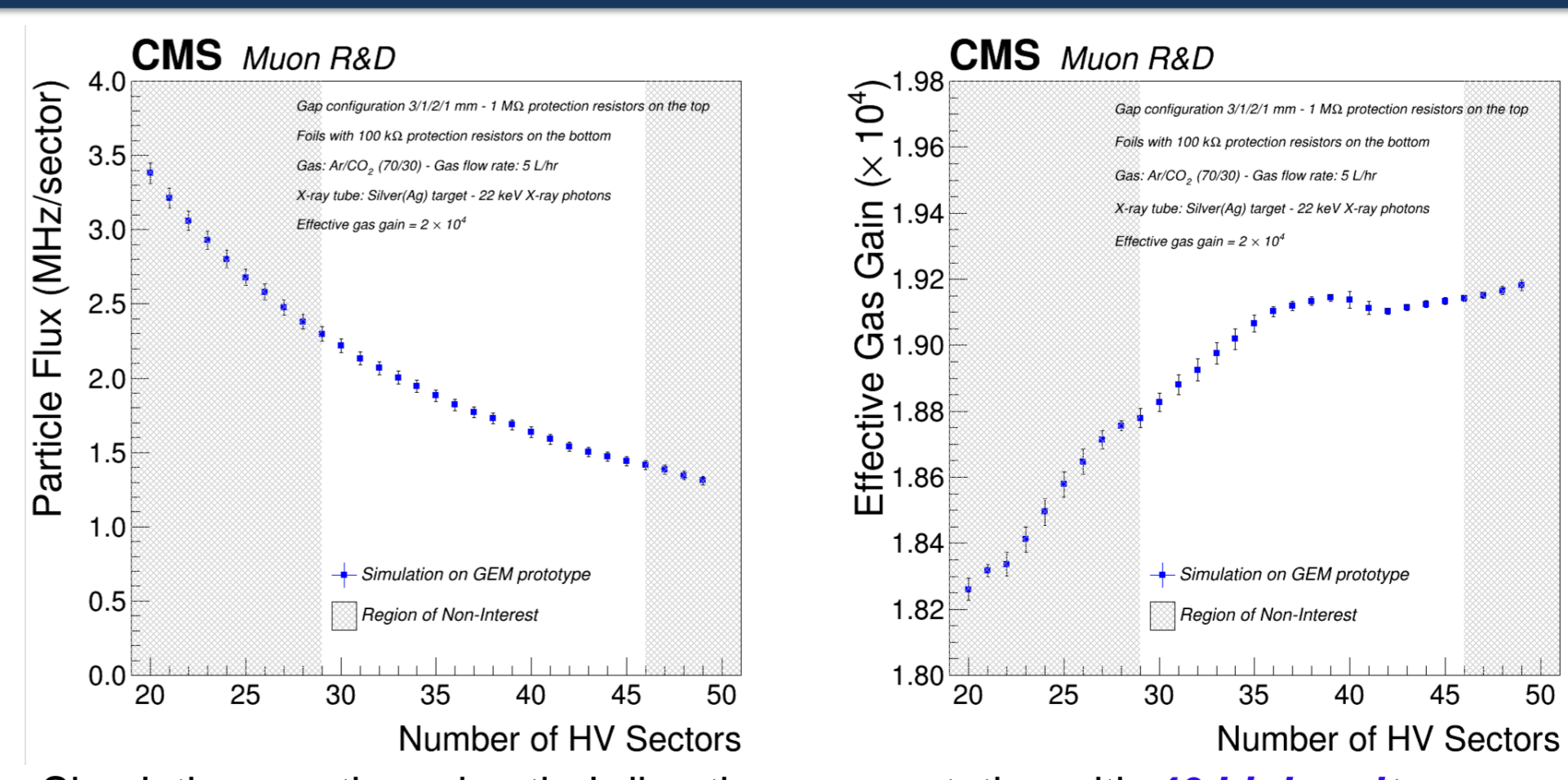
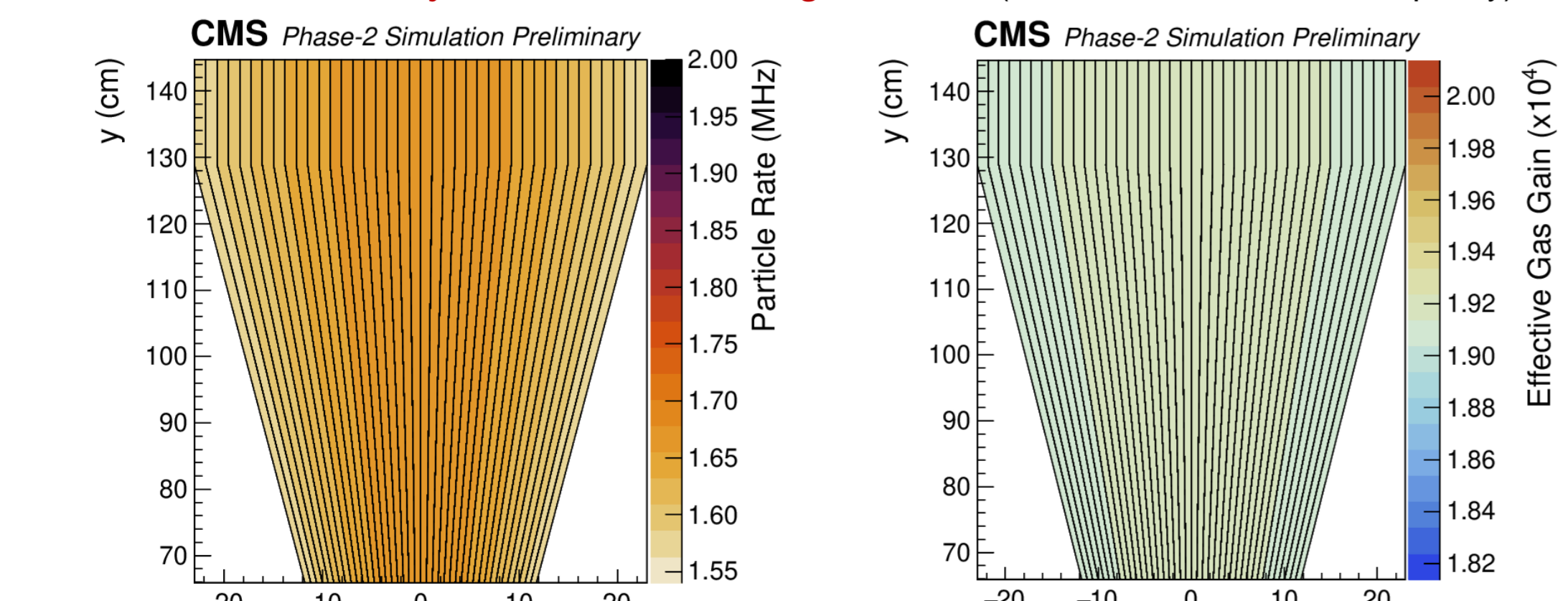
The solution adopted to minimize the gas gain drop consists of dividing each electrode of GEM foil in fine high-voltage sectors along the **azimuthal-direction** with respect to the LHC beam line:

- 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 $\sim 100 \text{ cm}^2$ 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])



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 **1.5 MHz/sector**, while the **gas gain drop** can be minimized to about **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.