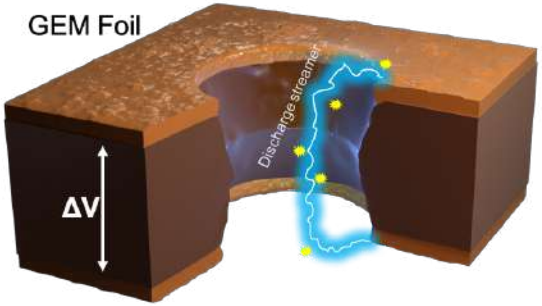
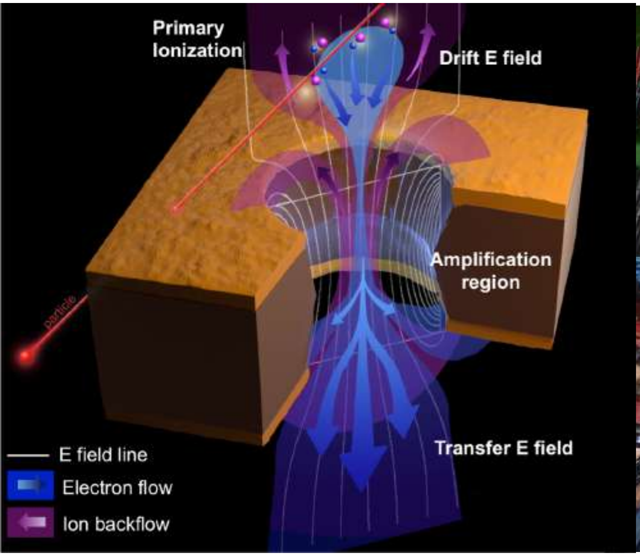
Study and Mitigation of Discharges in CMS Triple-GEM Detectors

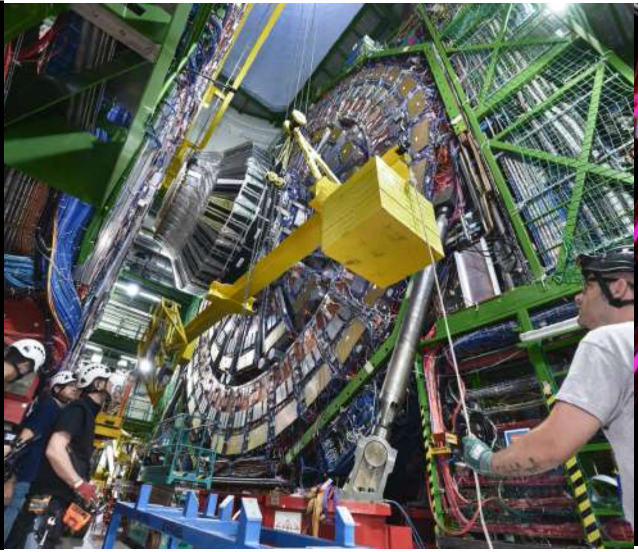
Jeremie MERLIN on behalf of the CMS Muon group

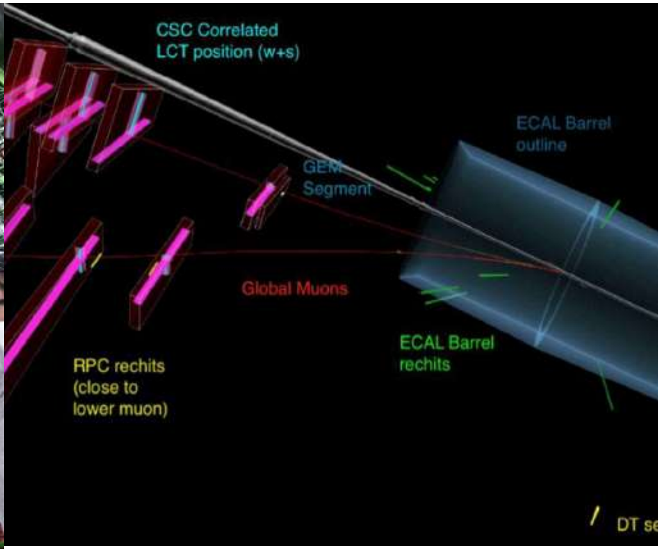
3rd International Conference on Detector Stability and Aging Phenomena in Gaseous Detectors

November 2023









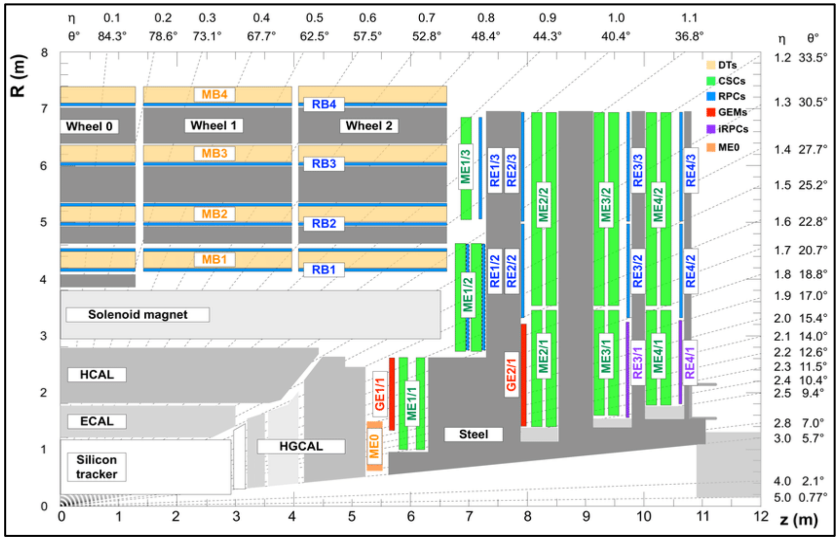
Introduction

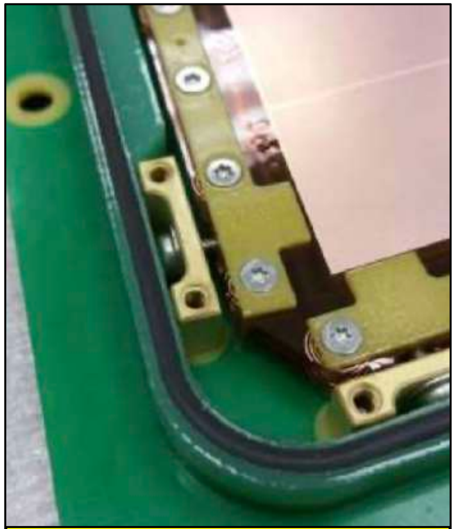
GEM upgrade projects for CMS:

- 3 detector projects in the forward muon endcap
- All based on same triple-GEM technology and same material
- GEM configuration 3(drift)/1/2/1 mm
- Baseline gas: Ar/CO_2 (70/30%)
- Max. background rates from a few kHz/cm^2 (GE2/1) to 150 kHz/cm^2 (ME0)

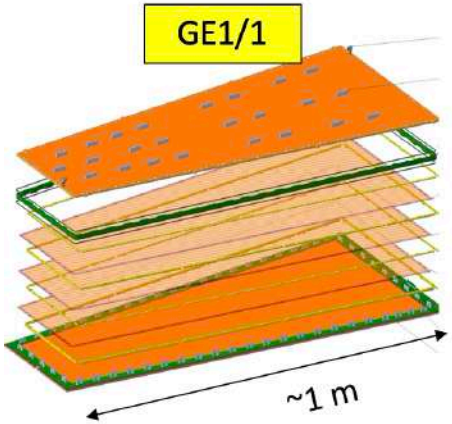
→ About 600 m^2 of GEM foils for about 1.5 M of RO channels

CMS Quadrant

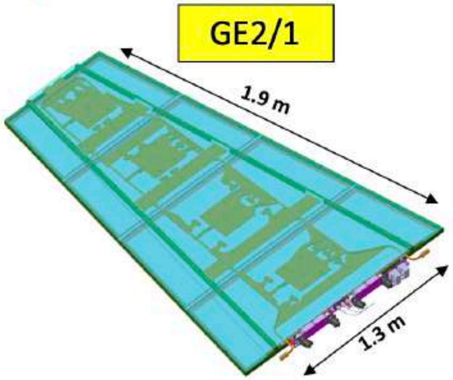




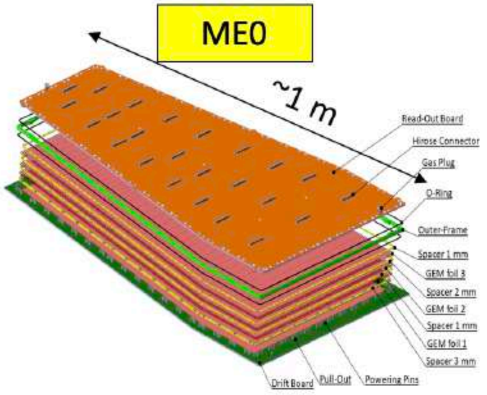
Mechanical stretching



GE1/1:
144 detectors



GE2/1:
288 detectors

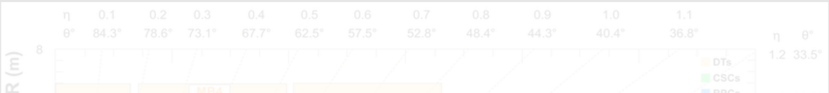


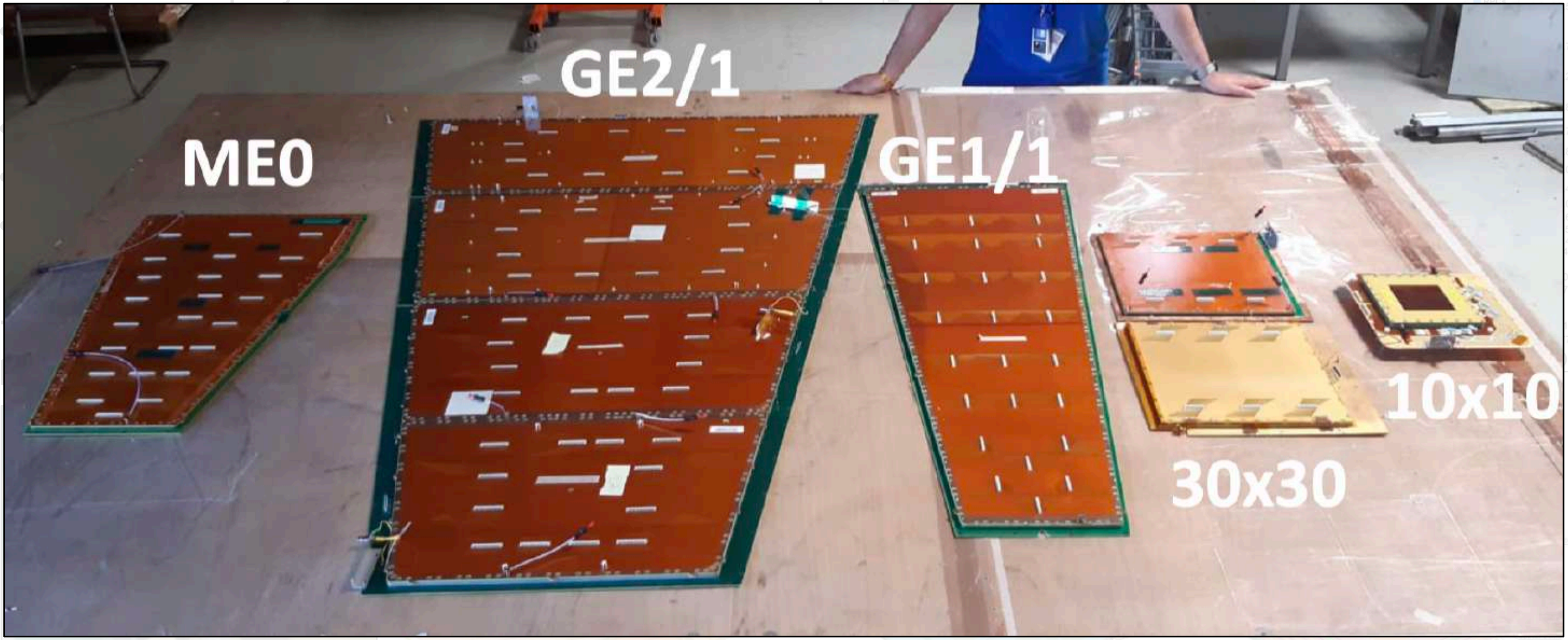
ME0:
216 detectors

Introduction

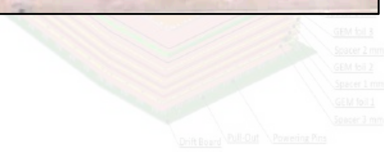
GEM upgrade projects for CMS:

- 3 detector projects in the forward muon endcap





Self-stretching mechanism



GE1/1:
144 detectors

GE2/1:
288 detectors

ME0:
216 detectors

Discharge Probability

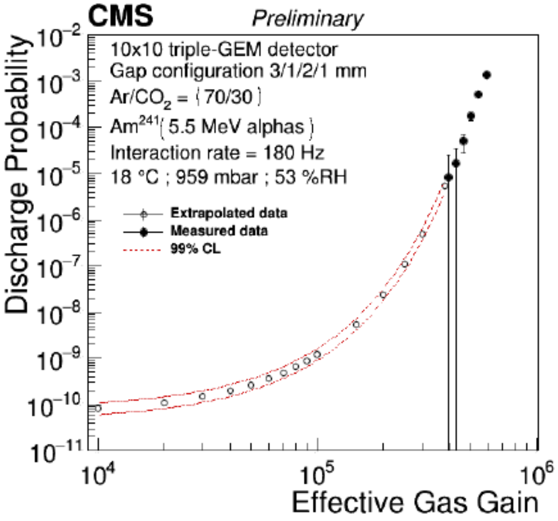
Measuring the probability of discharges:

- Tests in laboratory (alpha particles) with both small and large detectors
- Tests in neutron facilities with CMS-like particle background

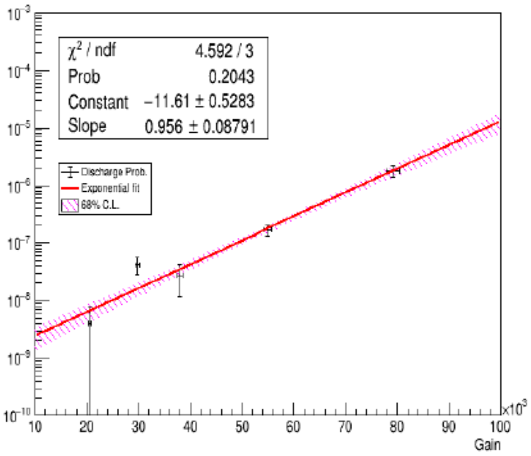
Discharge probability at G=3.5x10^4 (HIP)

- 10x10@GDD Lab: **1.5x10^{-10}**
- GE1/1(KR)@904 GEM Lab: **1.7x10^{-8}**
- 10x10@CHARM: **2.85x10^{-9}**

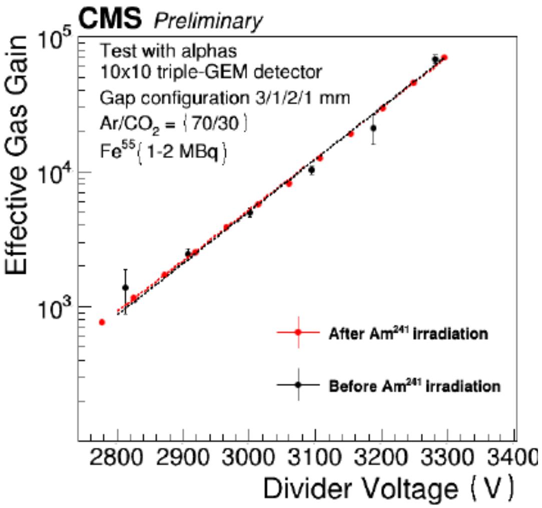
- No temporary or permanent degradation of the detector performance could be measured after alpha irradiation, nor in neutron environment (up to 500 discharges/cm^2)



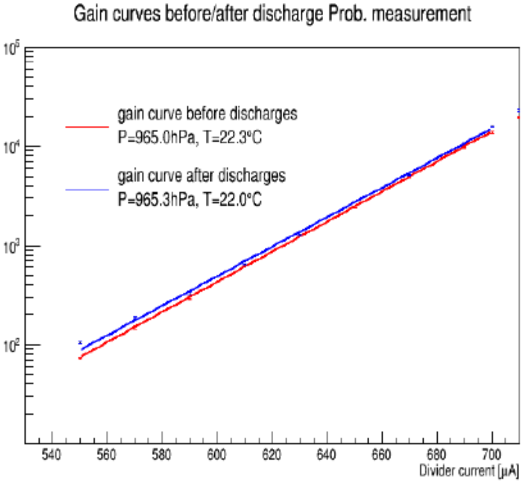
J. Merlin, CMS-TDR-016, 2017



I. Yoon, LHC KCMS Workshop, 09/01/2019



J. Merlin, CMS-TDR-016, 2017

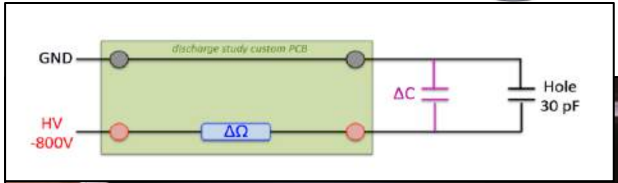


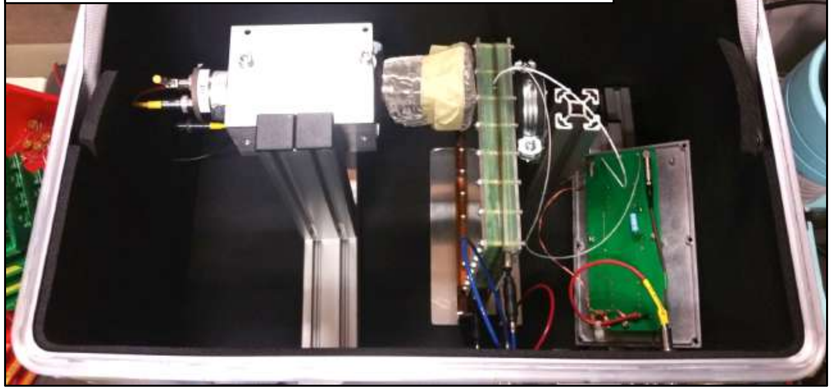
I. Yoon, LHC KCMS Workshop, 09/01/2019

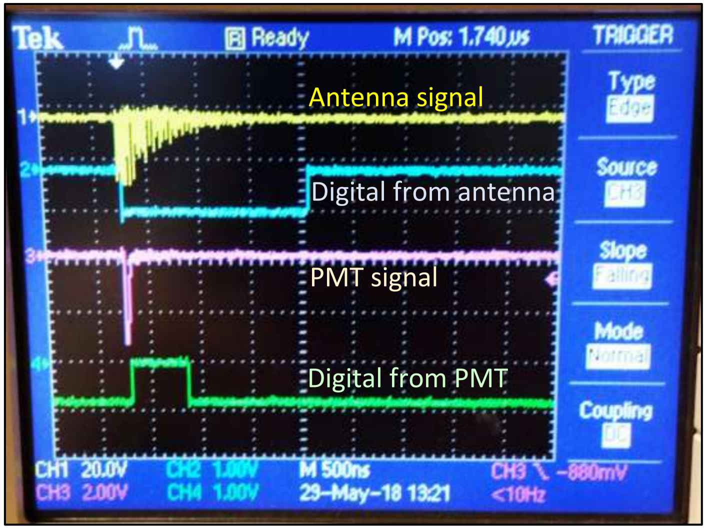
Discharge Effects

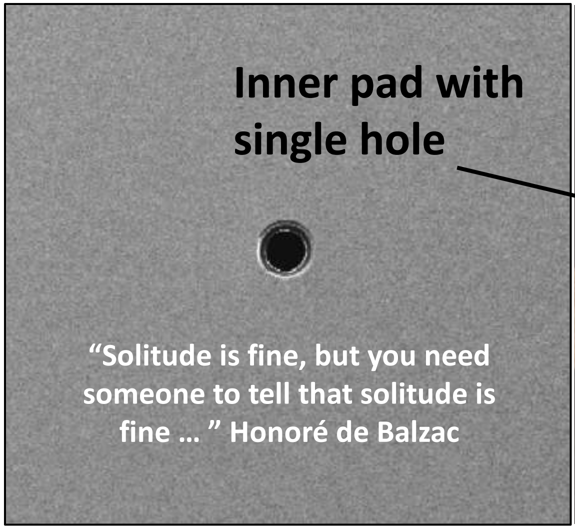
Specific study on single GEM hole systems:

- Special GEM foil design with single hole to control the conditions of discharges and isolate the elements that play a role
  - → 30 pF base capacitance
  - → Possibility to operate up to 800 V (stable)
- Discharges triggered with a Cd109 source
- Discharge identification made by cross-comparing PMT signals (light) and antenna signals (EM)

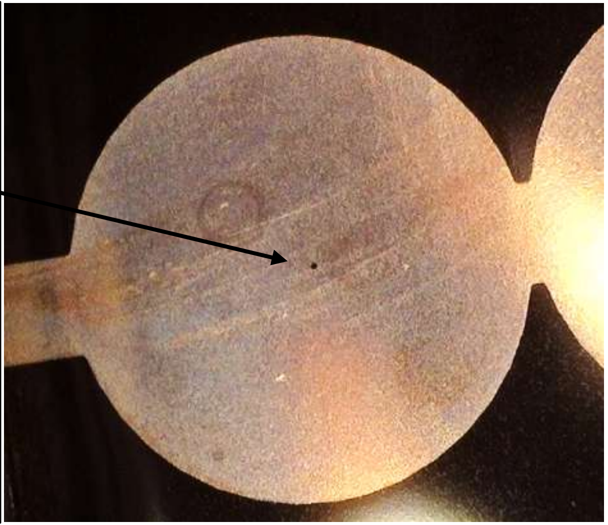








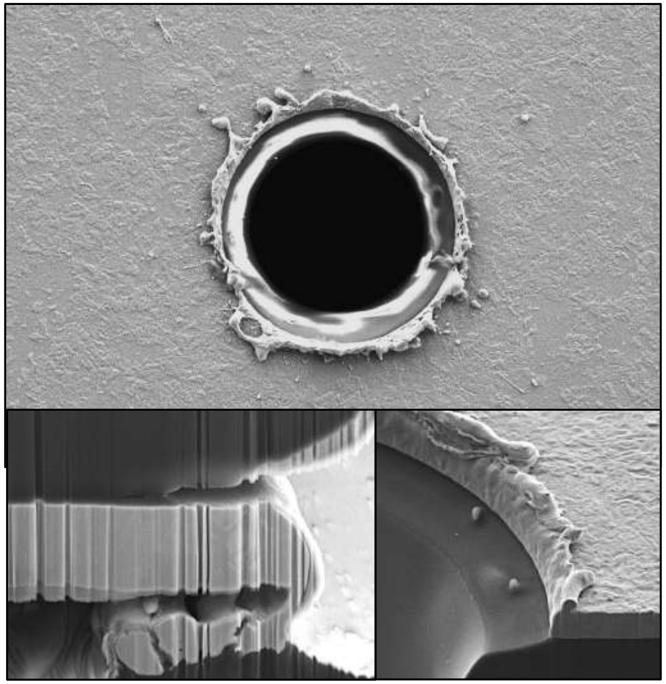
“Solitude is fine, but you need someone to tell that solitude is fine … ” Honoré de Balzac

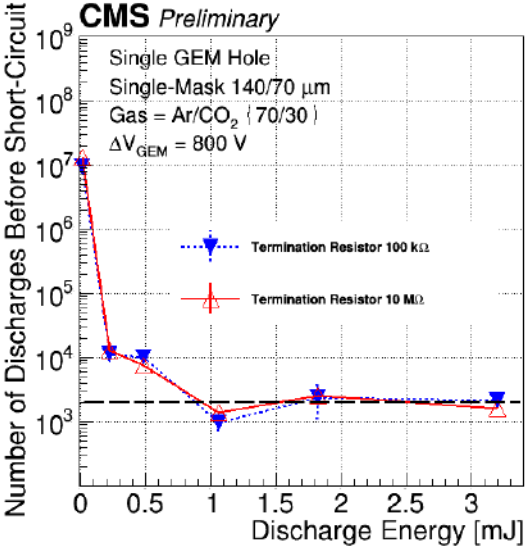


Inner pad with single hole

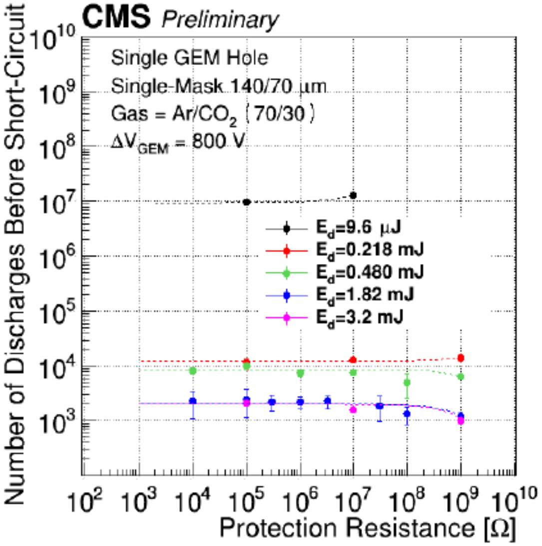
Discharge Effects

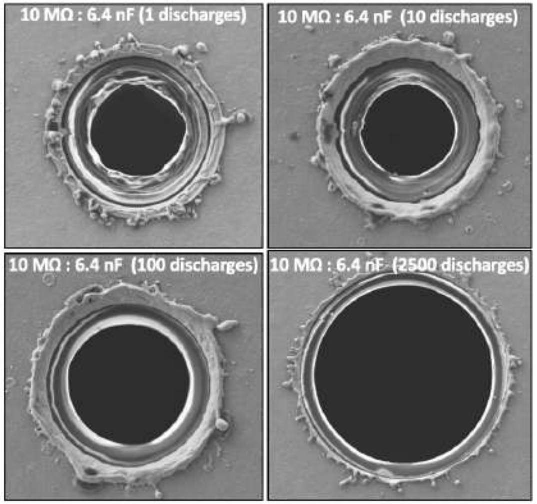
- **Test results:**
  - Measurements reveal high resistance to discharges, even at high energy (>10^3)
  - Increase of the hole diameter after 10-20 accumulated discharges





J. Merlin, IEEE-NSS, Sydney, 2018





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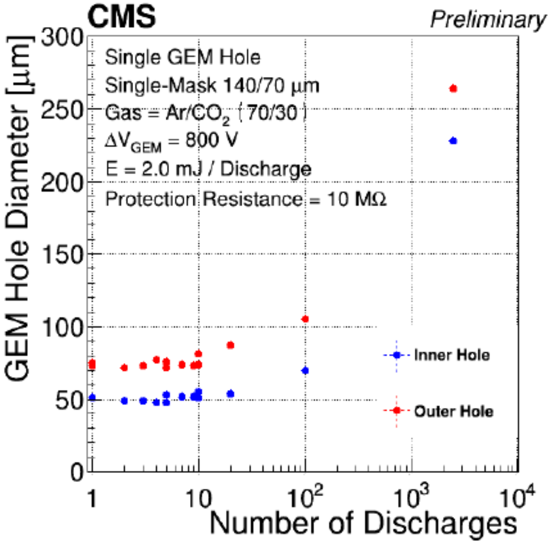


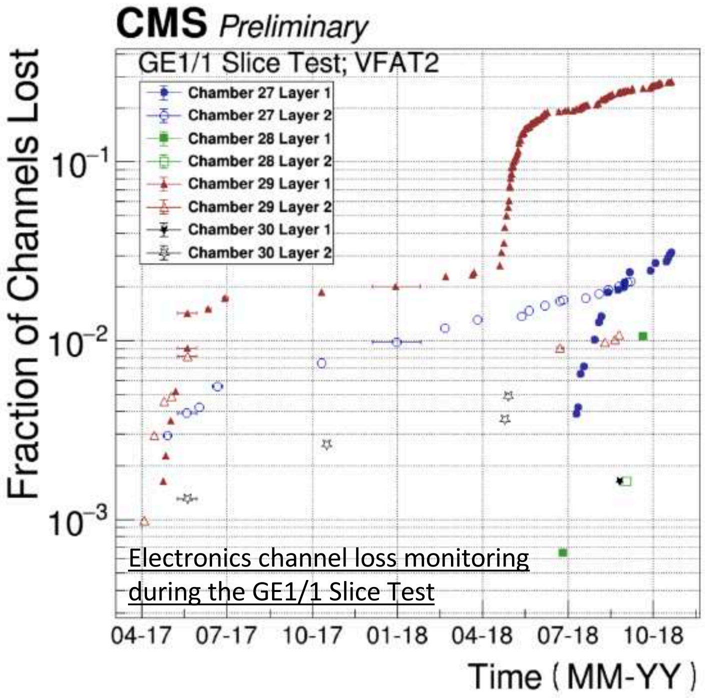
J. Merlin, IEEE-NSS, Sydney, 2018

Initial Observations

GE1/1 Slice test (2017-2018)

- First operational experience in the real CMS environment
- First observation of discharge propagation
- Experienced VFAT3 channel loss

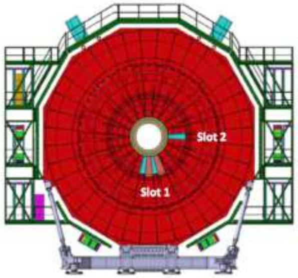
Start of a new discharge R&D campaign to cope with discharge propagation
(+ define new setups and protocols to reproduce the problem in the lab)



Electronics channel loss monitoring during the GE1/1 Slice Test

Channel loss :

- GEM discharges are normally confined within the GEM holes
- Discharges can propagate toward the readout board
- Possible damage of the electronics



Channel loss ∝ Discharge probability x Propagation probability x Damage probability

The most effective mitigation consists of reducing the probability of **discharge propagation**

Discharge Propagation

Propagation process:

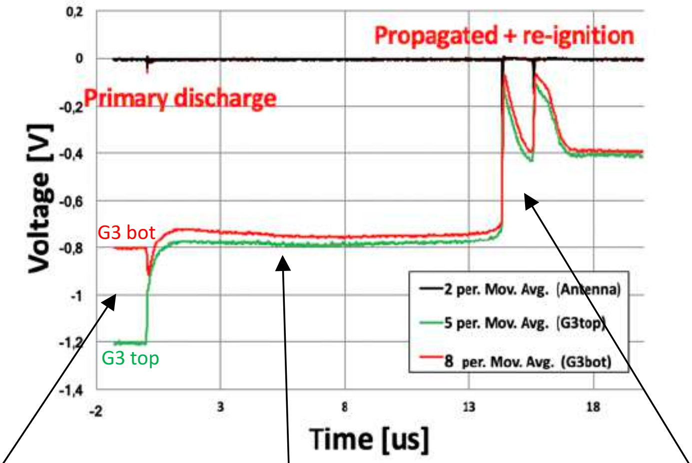
Step1: the **primary discharge** develops inside the GEM holes (temporary short circuit)

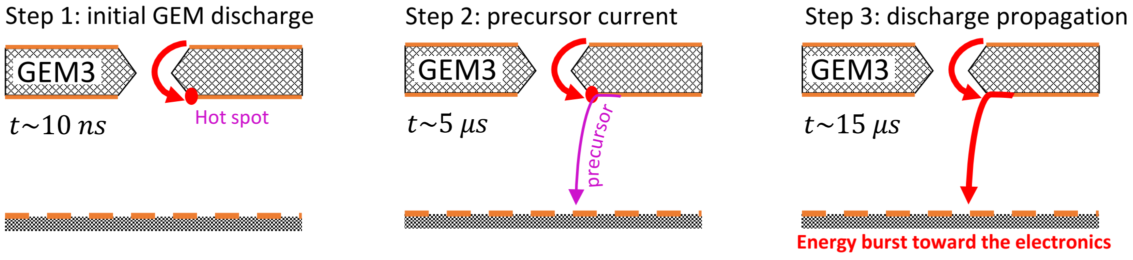
Step2: a **precursor current** arises from the hot spot created by the primary discharge (thermionic emission enhanced by the Schottky effect)

Step 3: the precursor current grows from the energy available in the foil to become a streamer

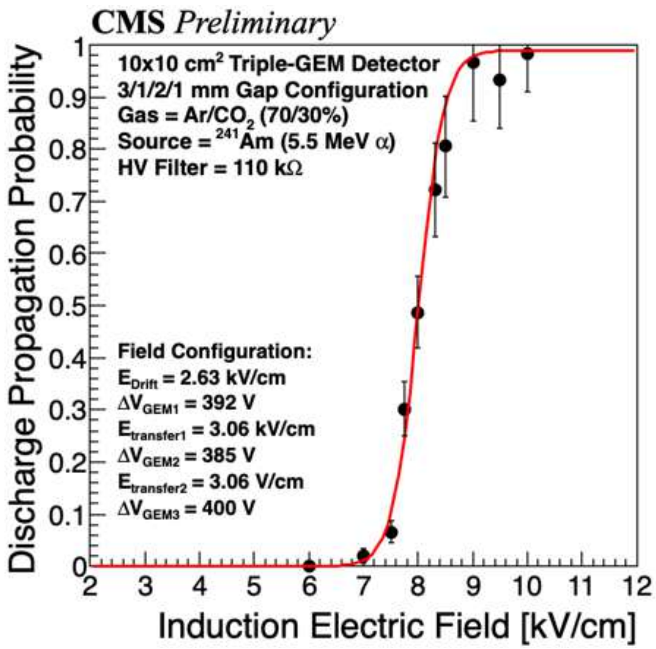
→ **secondary discharge** between the GEM and the RO

Oscilloscope capture of a propagating discharge



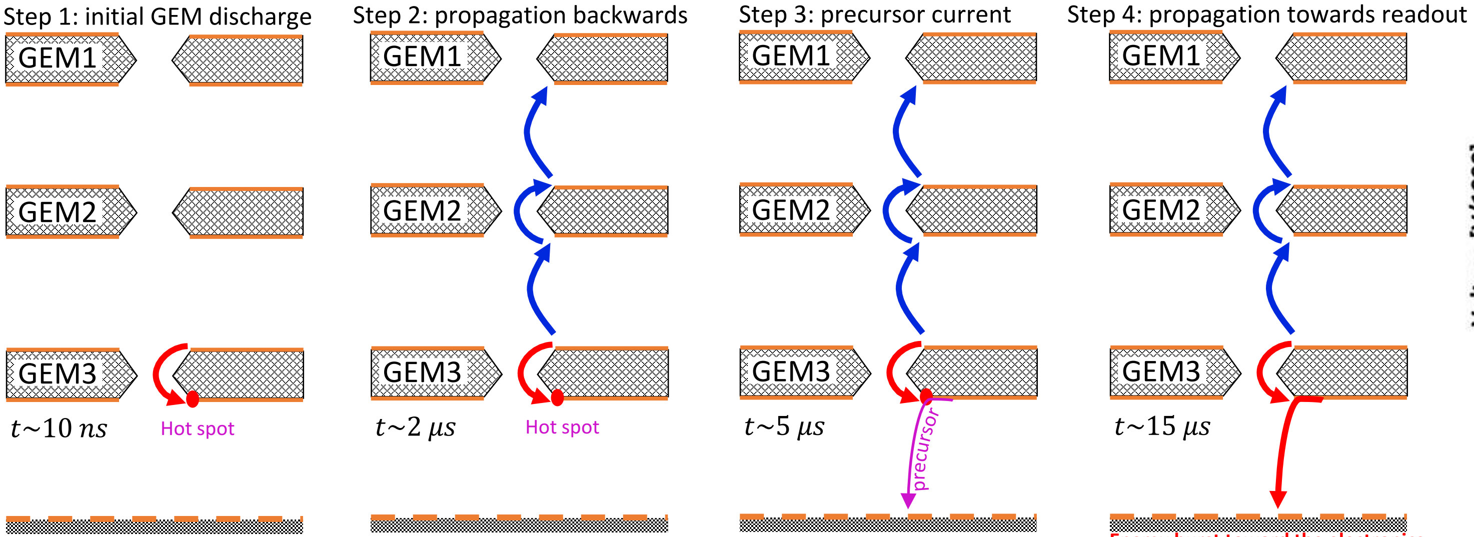


Schematic view of the discharge propagation process



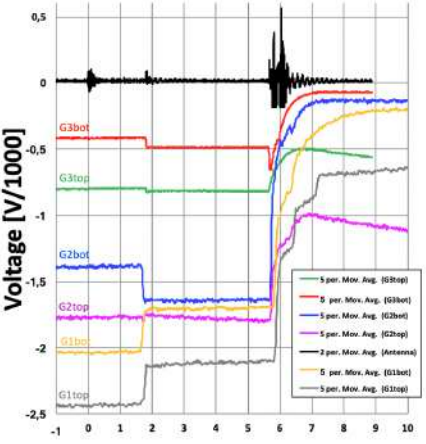
The probability to observe a discharge propagation in small detectors is **insignificant** below inductions fields of **7 kV/cm**:
→ CMS GEM typical induction field = **4.1 - 4.5 kV/cm**

Discharge Propagation



Energy burst toward the electronics

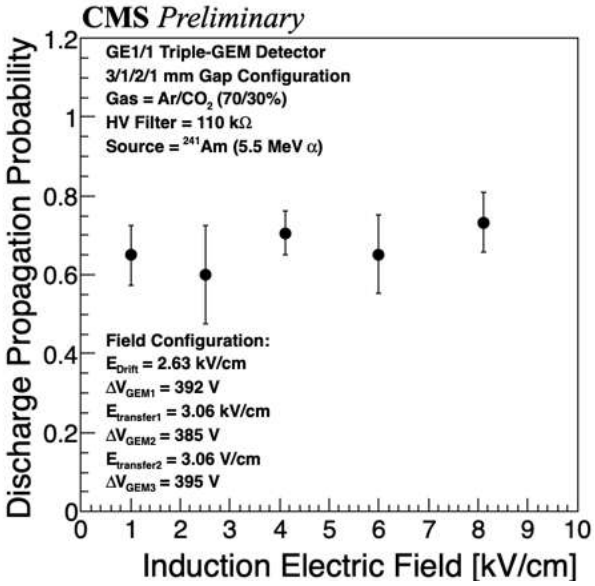
Schematic view of the discharge propagation process in large detectors



Oscilloscope capture of a propagating discharge

More complex propagation in large detectors:

- The primary discharge is systematically followed with a propagation backward **GEM2** and **GEM1**
- The backward propagation "gives" the primary discharge the strength to propagate **toward the readout** even at **low induction fields**
- After a full propagation, the electronics is connected (via short circuits in the gas) to all the GEM electrodes

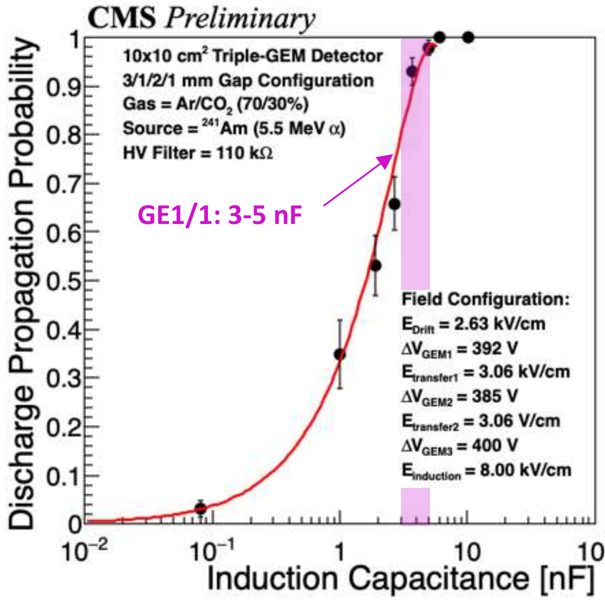


The probability to observe a discharge propagation in large detectors is **significant** even at **low inductions fields**

Discharge Propagation

Large reservoir of energy:

- The probability for a discharge to propagate depends on the **gap capacitance**
- A large gap capacitance means more energy to **feed the precursor current** and trigger the streamer development
- GE1/1 foils typically have enough **energy stored** in the gap to trigger the propagation, even at low induction field

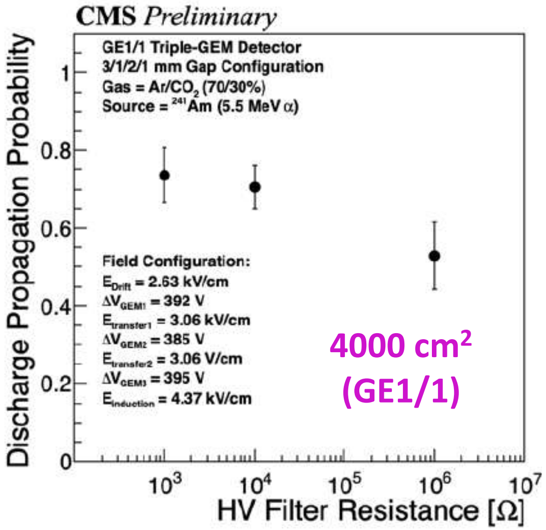


GE1/1: 3-5 nF

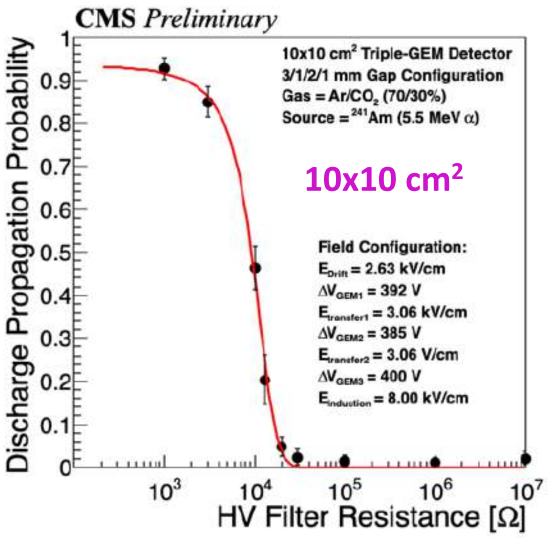
Influence from outside:

- The energy stored "outside" the GEM foil can participate to the discharge propagation
- The **filter resistance** helps to prevent energy transfer to the foil

GE1/1-size foils contain enough energy to maintain an almost-systematic discharge propagation without the help of external energy



4000 cm² (GE1/1)



10x10 cm²

Discharge Mitigations

Channel loss ∝ Discharge probability x Propagation probability x Damage probability

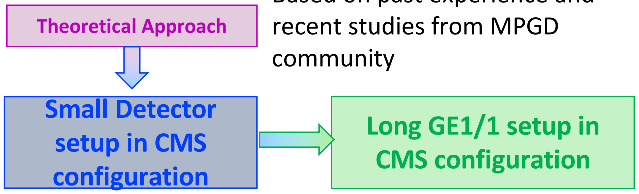
Discharge Probability

Intrinsic to gaseous technologies
Low probability with triple-GEM (~10^{-9})

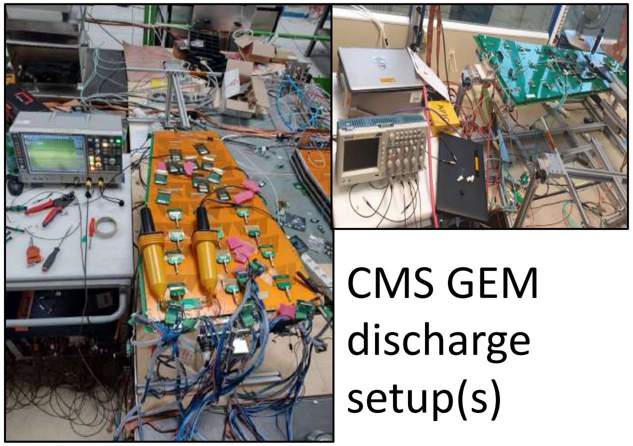
It is a “no pain no gain” parameter

Propagation Probability

Complex process depending on:
- **De-coupling circuits**
- **Gap Capacitance**
- **Electric Fields**


Theoretical Approach
Small Detector setup in CMS configuration
Long GE1/1 setup in CMS configuration

Based on past experience and recent studies from MPGD community


CMS GEM discharge setup(s)

- Full size prototypes
- Modified PCBs to allow for alpha irradiation
- Antenna + HF-HV probes for discharge monitoring
- Increased HV on GEM3 to trigger discharges at interesting rate (few Hz)

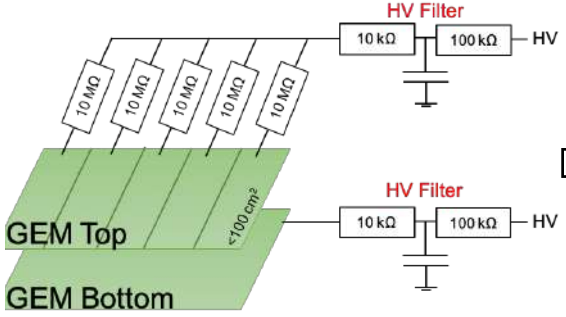
→ Became a standard setup for discharge investigations

Discharge Mitigations

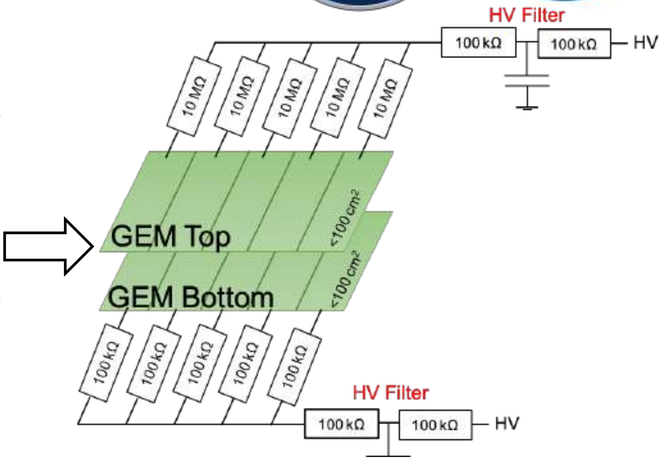
GEM Double-Segmentation:

Basic principle:

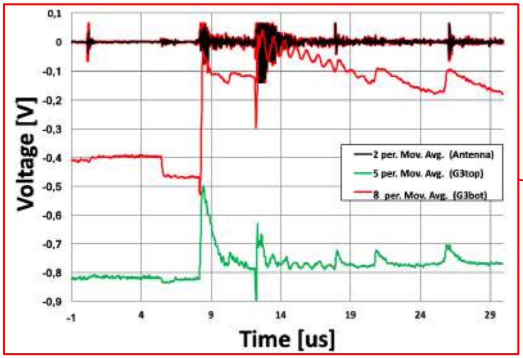
- **Top segmentation** : GEM protection against regular discharges
- **Bottom segmentation**: protection against discharge propagation



"Single-segmented" GEM foil concept

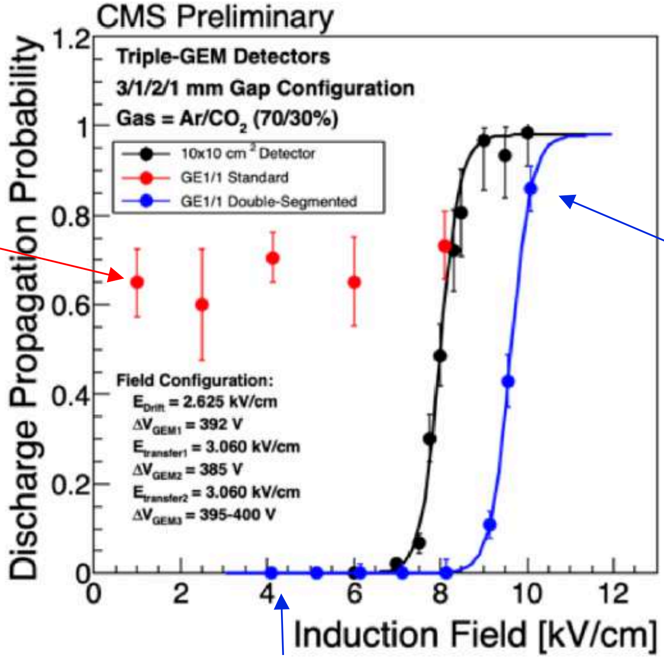


"Double-segmented" GEM foil concept

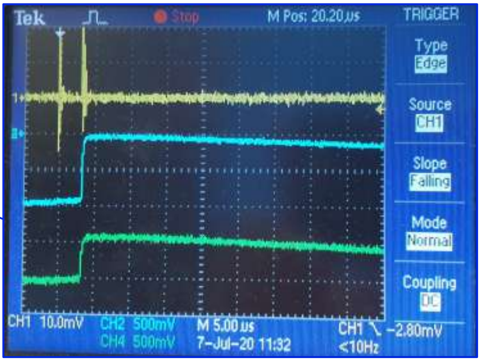


Single-segmented large setup:

→ Complex multi-stage propagation process even at low HV



Upper limit at 4.12 kV/cm: $Pd_{propa} < 3\times10^{-4}$



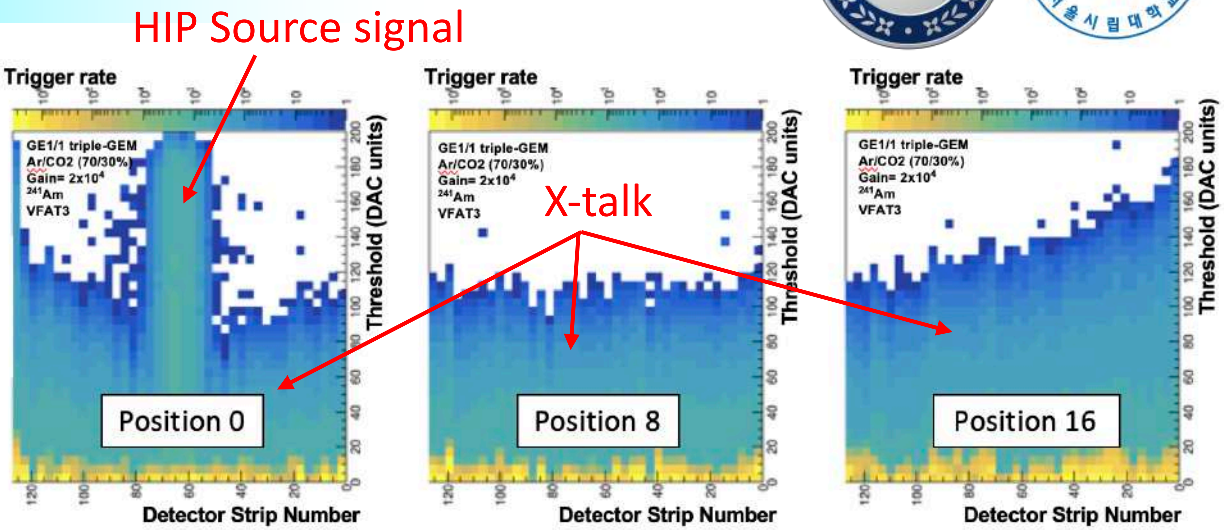
Double-segmented large setup:

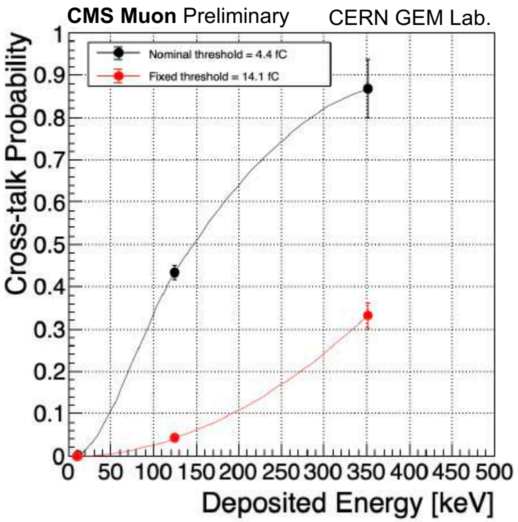
- → Simple propagation process only at high HV
- → Similar profile as 10x10 propagations

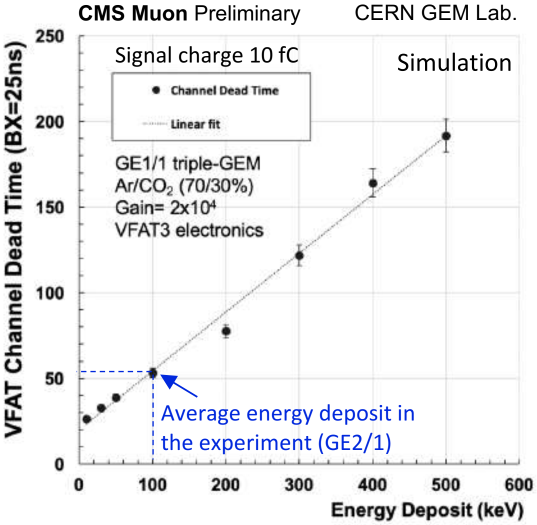
Discharge Mitigations

Side effect:

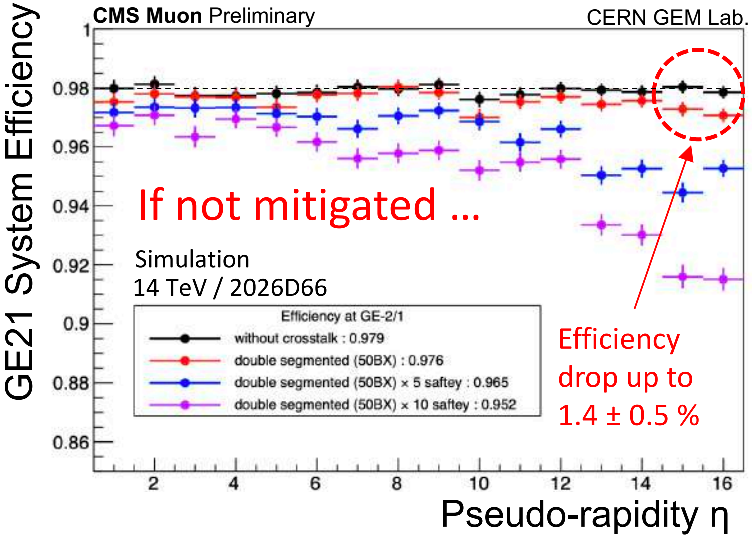
- The use of double-segmented foil in front of the RO board creates a strong cross-talk effect with HIPs
- The resulting parasitic signals induce a deadtime in the electronics
- With no mitigations, cross-talk could affect the detector efficiency by a few % at highest eta regions







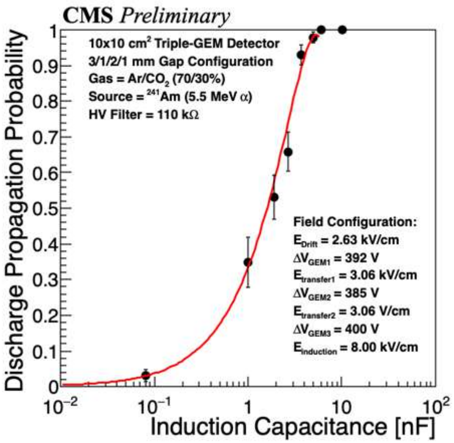
Average energy deposit in the experiment (GE2/1)

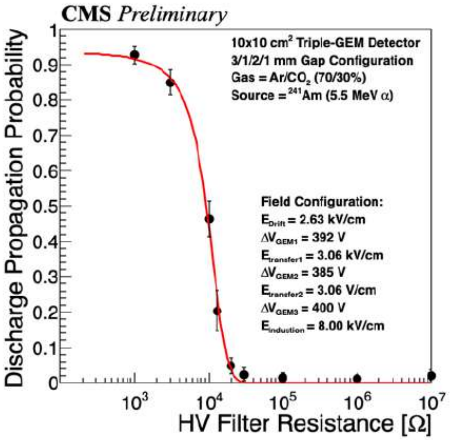


If not mitigated …

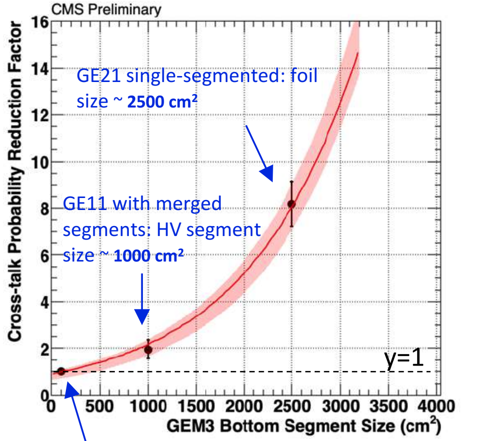
Efficiency drop up to 1.4 ± 0.5 %

Discharge Mitigations





Side effect
X-talk



GE21 single-segmented: foil size ~ **2500 cm²**

GE11 with merged segments: HV segment size ~ **1000 cm²**

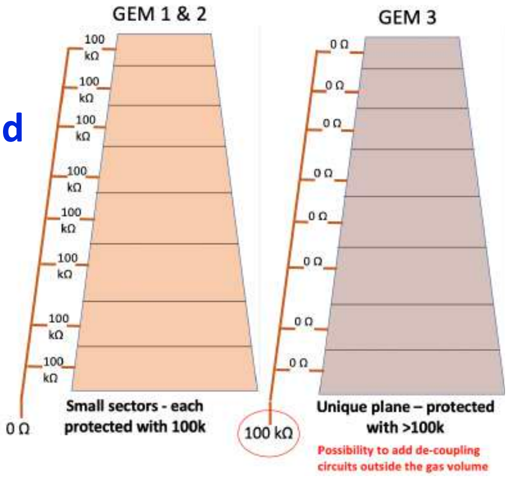
GE11 double-segmented: HV segment size ~ **100 cm²** (reference for this plot)

Mitigate discharge Propag.

Mitigate X-talk

→ **Introducing the final configuration based on the “mixed” design:**

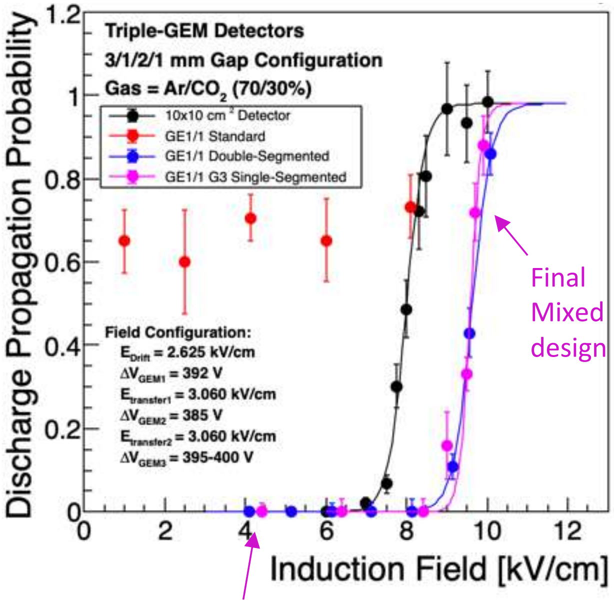
- GEM1 and GEM2 are **double-segmented** to prevent the **discharge propagation**
- GEM3 is **single-segmented** to minimize the **crosstalk**
  - → The foil is actually double-segmented but the bottom segments are merged together using **0 Ω jumpers**



Small sectors - each protected with 100k

Unique plane – protected with >100k

Possibility to add de-coupling circuits outside the gas volume



Final Mixed design

Upper limit at 4.12 kV/cm: $Pd_{propa} < 3\times10^{-4}$

Discharge Mitigations

Discharge Probability

Intrinsic to gaseous technologies
Low probability with triple-GEM (~10^{-9}-10^{-10})

It is a “no pain no gain” parameter

Propagation Probability

Understood the process od propagation in large detectors
→ Mainly driven by the large induction capacitance

Found 2 ways to mitigate discharge propagation:
→ Reduce foil capacitance (segmentation)
→ Increase filter resistance (resistive de-coupling)

Damage Probability

Depends mainly on:
- Energy of the propagating discharges
- Electronics input protection

Theoretical Approach

Based on past experience and recent studies from MPGD community

Small Detector setup in CMS configuration

Long GE1/1 setup in CMS configuration

Discharge Mitigations

Front-End protection:

→ VFAT3 + custom plugin cards (HV3b)

→ 3 variants developed for GE1/1

- Baseline V2 (no external protection)
- V3 with External 300-400 Ω
- V4 with external diodes to GND

→ Further optimization implemented for GE2/1 and later ME0 (new hybrid design)

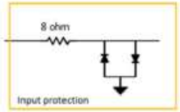
→ All variants thoroughly tested in laboratory + test beams

HV3b_V2

Initial baseline

Internal input protection only (diode)

Channels burnt with E>28uJ/disc



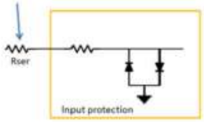
HV3b_V3

Ext. input protection (R=330 Ω)

OK after 500 ESD 470uJ/disc

X-talk +15%; Noise +20%

No radiation issues expected



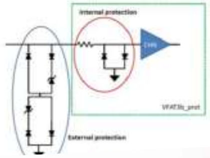
HV3b_V4

Ext. input protection (diodes)

OK after 540 ESD 470uJ/disc

No increase of noise observed

Rad Hard studies OK (10Mrad)

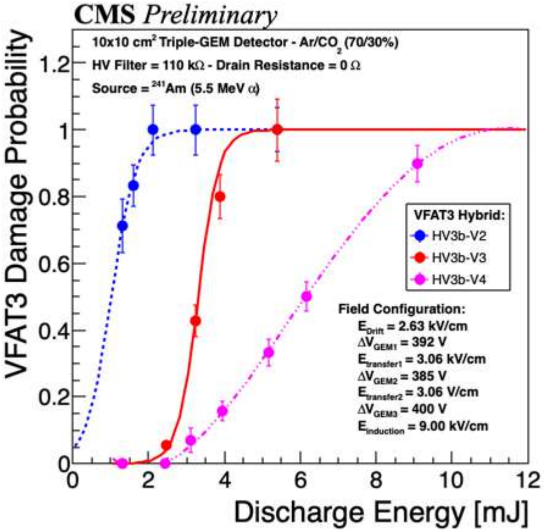


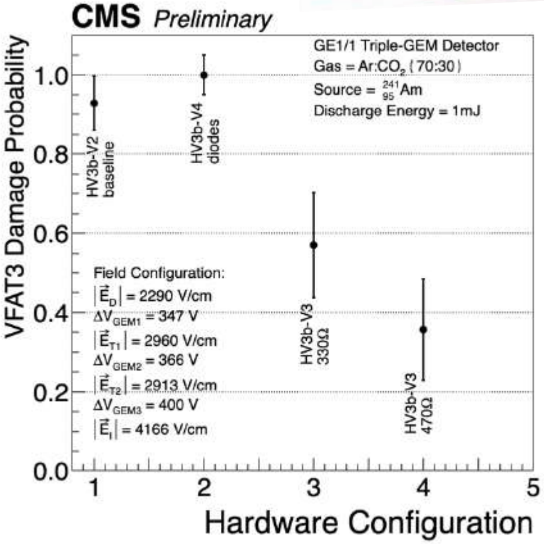
Early Conclusions (2019):

→ working as expected in 10x10 detector with controlled discharge energy

→ Different situation when operating with large detectors

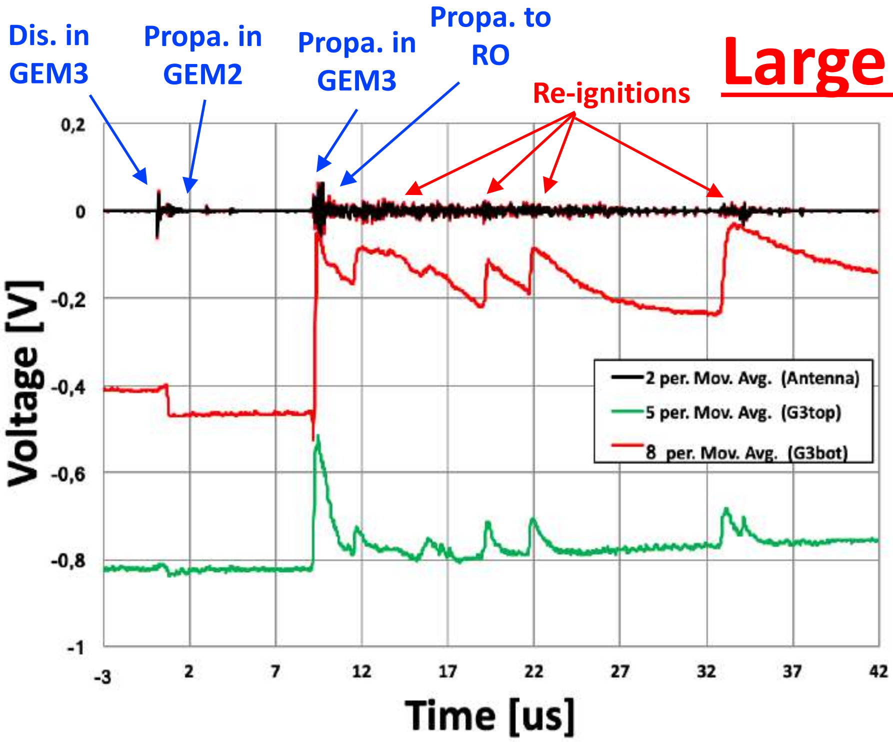
- Increased propagation energy
- Parasitic effects from the other electronics components

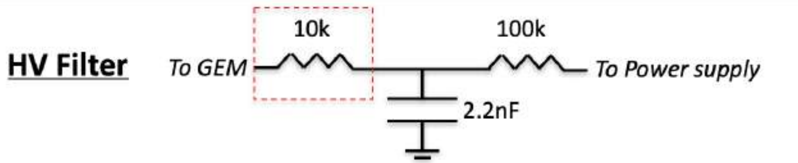


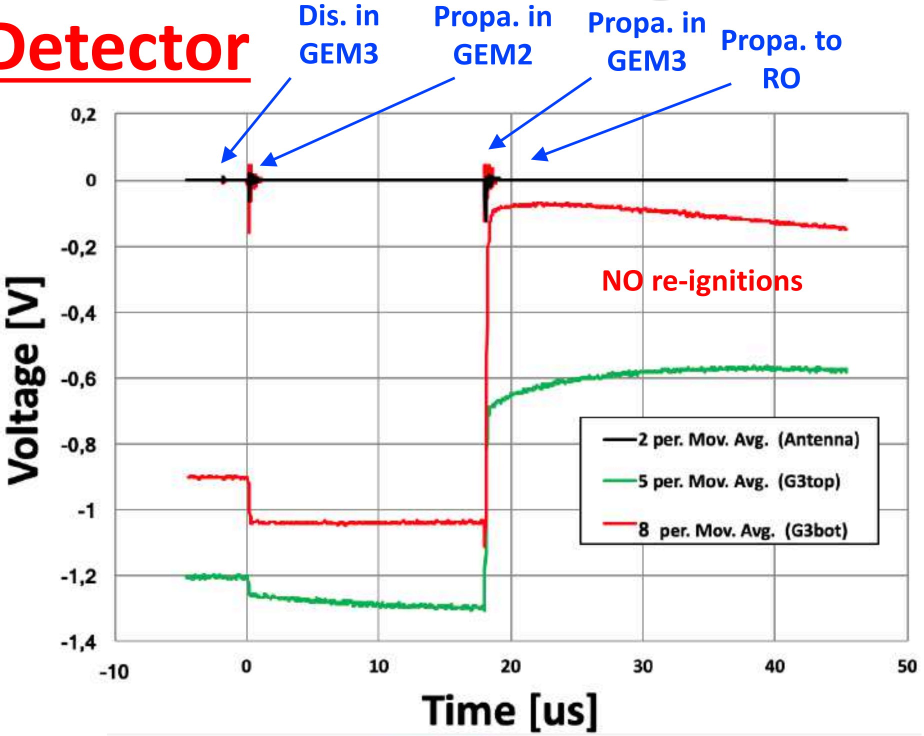


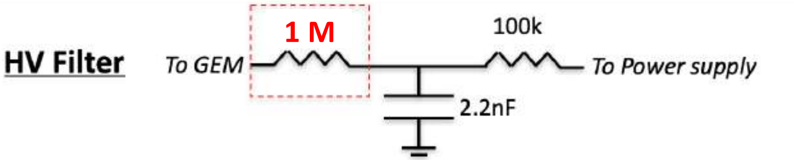
Discharge Mitigations

Large Detector





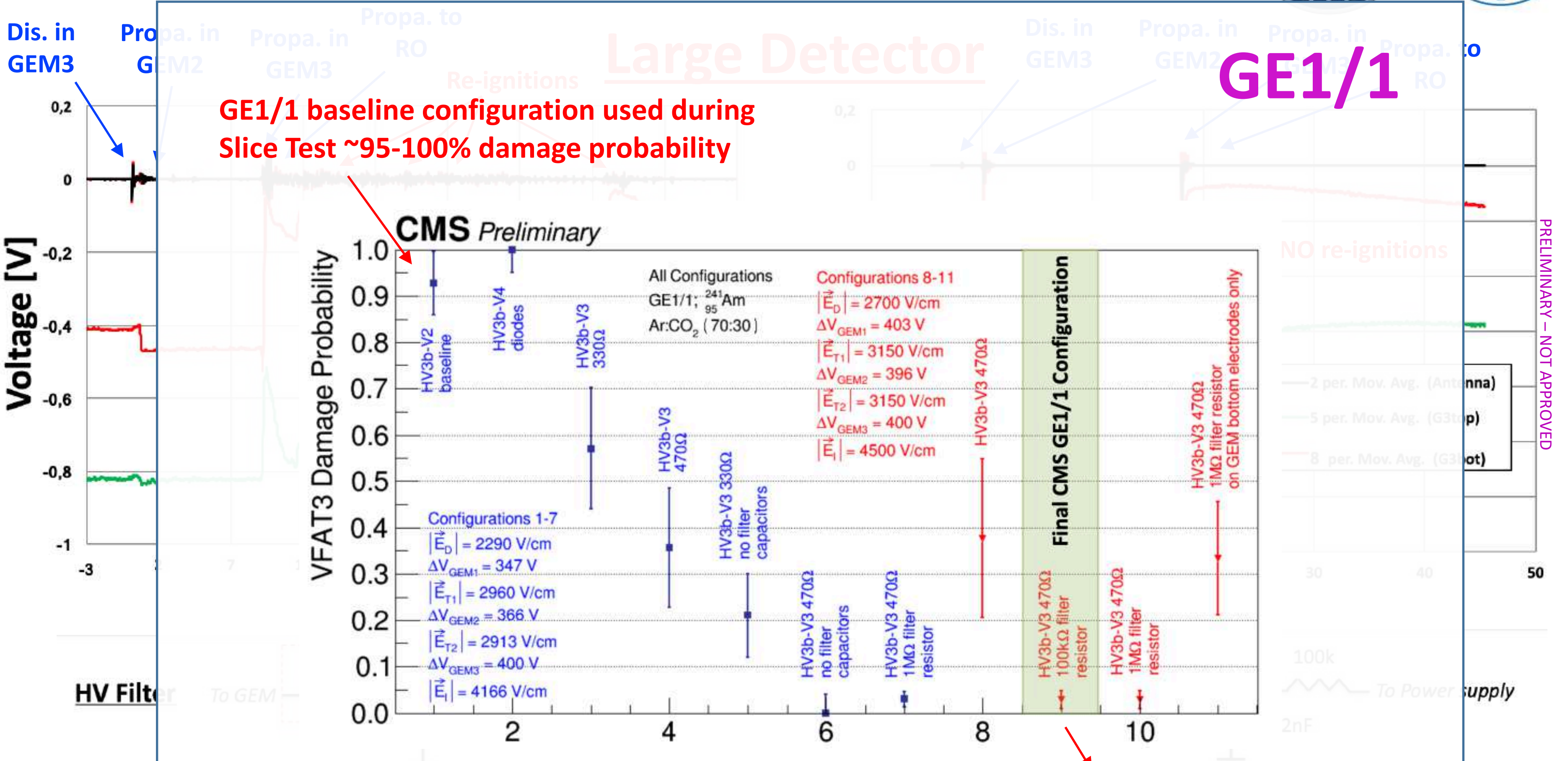




In-depth investigations with large detectors:

- Additional studies indicated that the damage probability in large detectors is mainly due to propagation re-ignitions
- Re-ignitions are fed by the energy stored in the filter capacitance → can be mitigated by tuning the filter resistance → can reduce by a factor 5 the damage probability

Discharge Mitigations



GE1/1 baseline configuration used during Slice Test ~95-100% damage probability

Improved GE1/1 configuration = 3% damage probability
→Improved VFAT input protection (R=470)
→Suppressed re-ignition (HV resistor >100 k)

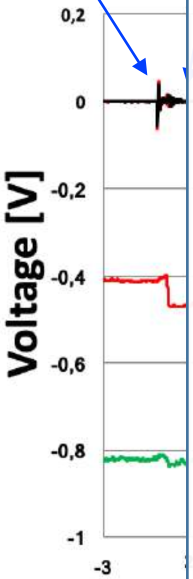
In-depth investigations with large detectors:

- Additional studies indicated that the damage probability in large detectors is mainly due to propagation re-ignitions
- Re-ignitions are fed by the energy stored in the filter capacitance → can be mitigated by tuning the filter resistance → can reduce by a factor 10 the damage probability

Discharge Mitigations

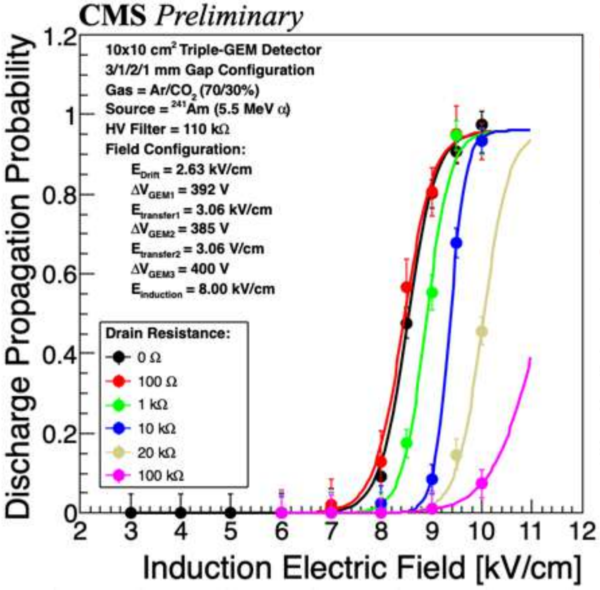
Dis. in GEM3

Pro GE



HV Filt

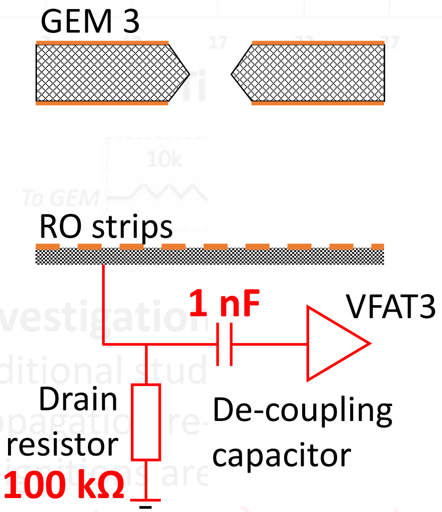
GE2/1 & ME0



An additional layer of discharge protection on the readout side:

→ The discharge propagation can be stopped at the input of the RO strips using a drain resistor:

- the **precursor current** induced before the discharge propagation runs through the drain resistor
- the **voltage drop** across the drain resistor temporarily suppresses the **induction field**
- the precursor current is quenched and the discharge propagation **is stopped before reaching the RO strips**



GE21 plugin card

→ with drain resistors as low as 100 kΩ, the propagation probability is reduced by a **factor > 10²**

In-depth

- A
- p
- R

ning the

filter resistance → can reduce by a factor 10 the damage probability

Mitigations Issues

However: some problems appeared when implementing the mitigations on full size detectors

Problem 1: the addition of the GEB increases the propagation probability by a factor ~5

GEM Electronics Board

Problem 2: the use of the de-coupling circuit on the VFAT plug-in card does **not** reduce the propagation probability as expected

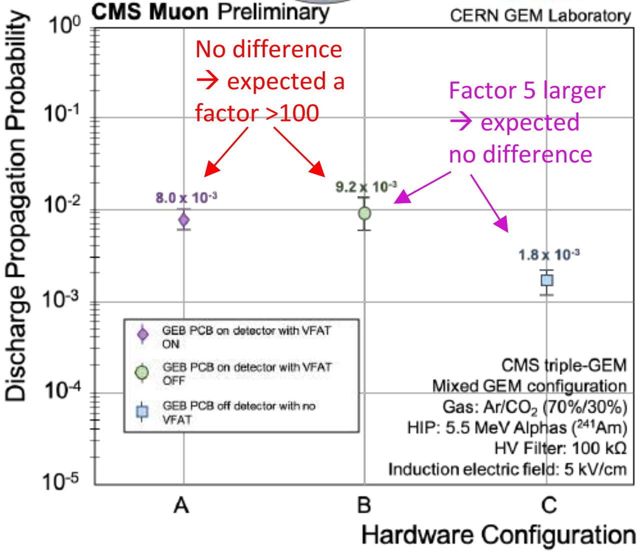
Problem 3: the final prototypes of GE2/1 plug-in cards still suffered dead channels, not only during operation but also during the production process when performing HV curing of GEM3 (a.k.a Megger test)

In summary:

→ Increased propagation probability when connecting the final front-end electronics

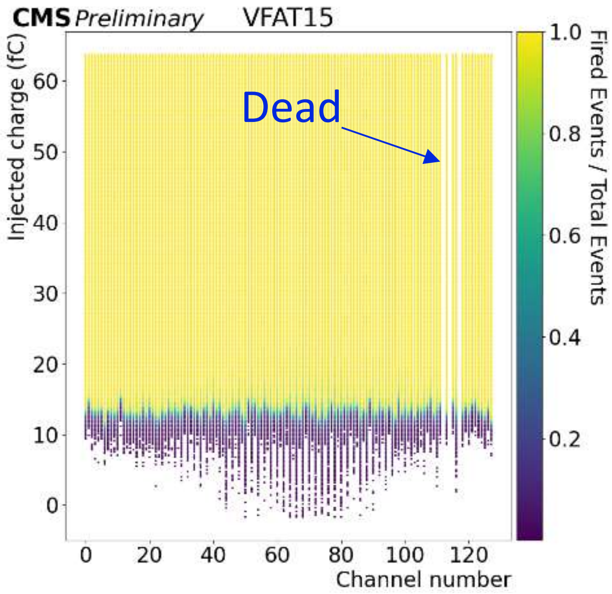
→ No reduction of the propagation probability when using the new plug-in card

→ Increased susceptibility to discharges



No difference → expected a factor >100

Factor 5 larger → expected no difference

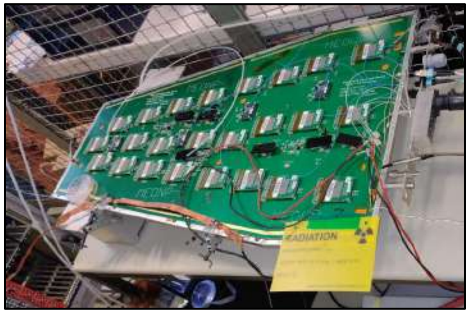


Dead

Mitigations Issues

PROBLEM 1

Adding GEB electronics

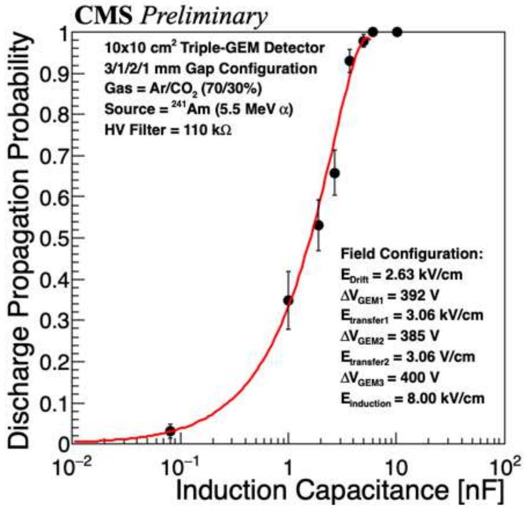


Without on-detector electronics

			Calculated			
		area cm2	Capa nF	Measured Capa nF	Voltage V	Energy mJ
induction	GE1/1-L	4090	2.84	2.88	420	0.25
	10x10	115	0.08	0.08043859	420	0.01
foil	GE1/1	100	4.7	-	400	0.38
	10x10	115	5.47	5.6	400	0.44

With on-detector electronics

			Calculated	with electronics/cooling/chimney		
		area cm2	Capa nF	Measured Capa nF	Voltage V	Energy mJ
induction	GE1/1-L	4090	2.84	8.57	420	0.76
	10x10	115	0.08	3.2	420	0.28
foil	GE1/1	100	4.7	-	400	0.38
	10x10	115	5.47	5.6	400	0.44



GEB capacitance effects

- Past measurement indicated that GEB (GEM Electronics Board) and electronics can add parasitic capacitance to the induction gap
  - → **With an increase of 5-6 nF the propagation probability can be multiplied by a large factor (based on 10x10 measurements)**
- Not possible to mitigate without a significant re-design of the electronics and PCBs
  - → But not a real problem if the detector is in the mixed-design configuration

Mitigations Issues

PROBLEM 2 & 3

Drain resistor solution:

- Use of a drain resistor on the RO strips is a powerful mitigation solution
- Measured clear improvement with 10x10 detectors when connecting all RO strips to a single resistive output

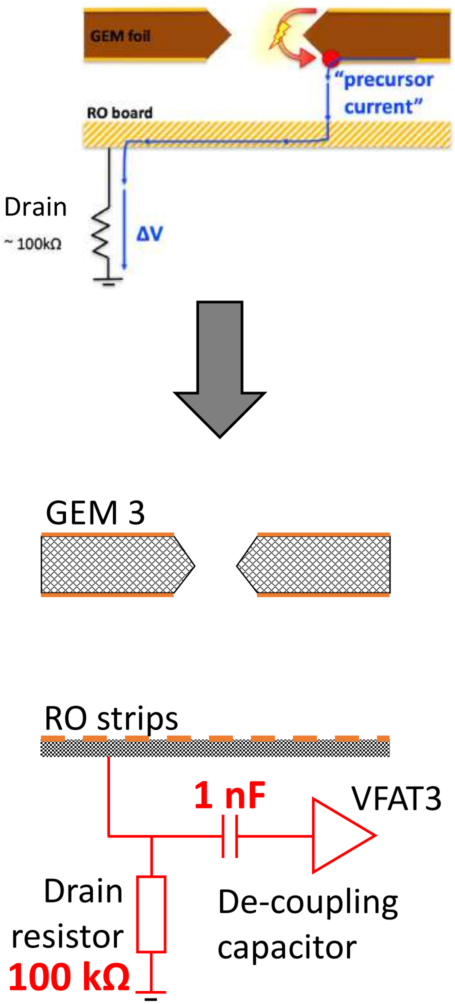
Large scale mitigation

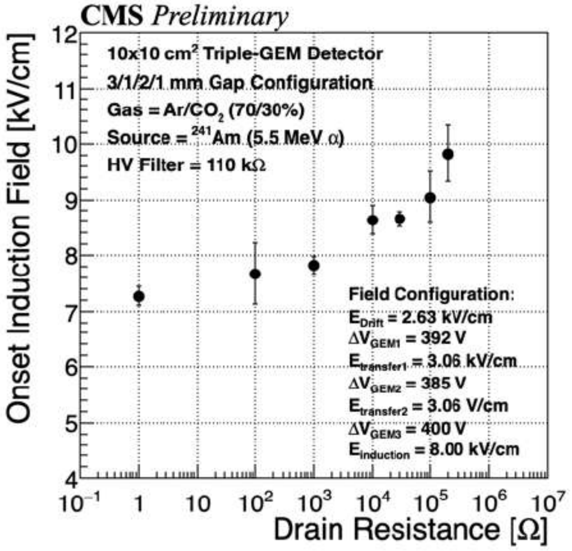
- Need to implement an AC-coupling circuit with 1nF capacitor (and drain resistor) at the input of the electronics
- Parallel use of 1500-3000 input circuits significantly increase the capacitance of the induction gap

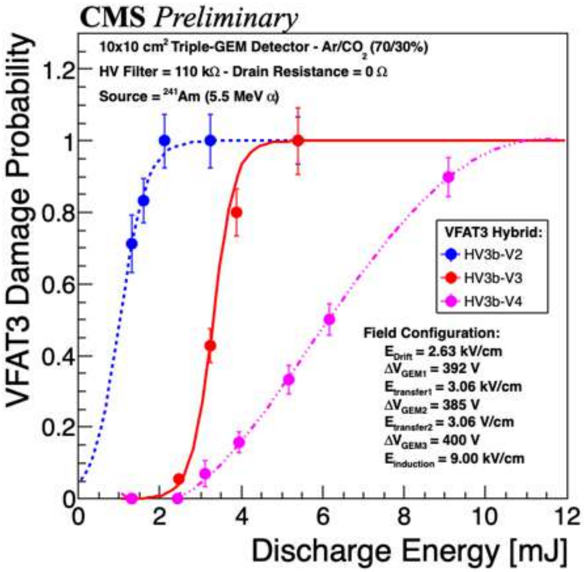
→ Increased propagation probability

→ Increase propagation energy

→ Rollback to previous GE1/1 protection

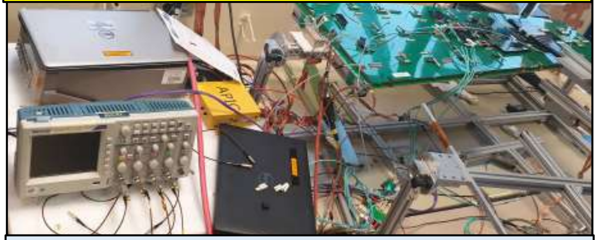






Final Measurements

Early 2022

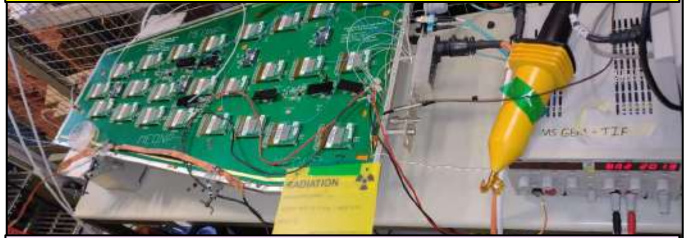


GE11 detector with GE21 foil config.

Late 2022

Early ME0 prototype

2023



Final ME0 prototype

Discharge propagation probability:

In total:

- More than 5000 discharges provoked on GEM3 with HIP

→ **Propagation probability : 2.28x10^{-3}** (at nominal gain 2x10^{4} in Ar/CO2)

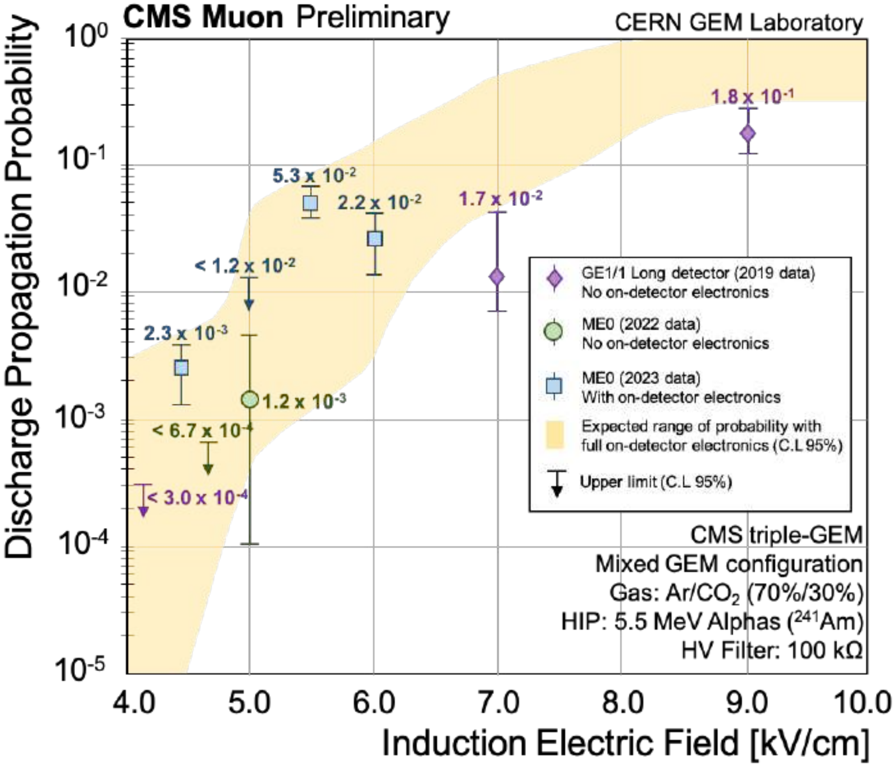
VFAT Damage probability:

In total:

- > 120 confirmed propagations
- No channel damage observed

→ **Damage probability upper limit: 2.4x10^{-2}**

(expecting same or better than 3.0x10^{-2} from GE1/1)



Mitigations Overview

HIP with $E_{deposited}$ > 30keV

$P_d=1.24\times10^{-9} \pm 1.16\times10^{-9}$
(average of the two sets of tests we performed)
Measured with $E_{deposited}$ ~ 350 keV

Assuming a HL-LHC duty cycle = 0.33

Factor based on the GEM foil design

Factor based on the RO coupling circuit

Factor based on the electronics protection circuit

Factor based on the optimization of the internal electric fields

Work in progress

System	HIP rate R_{HIP}^{max}	Disch. probability P_d	Discharge rate R_d^{max}	Number of disch. per year (per module)	Transfer propagation probability	Induction propagation probability	Damage probability	Improvement factor (E_field optimization)	Number of damaged RO channels per 10 year	Fraction of damaged RO channels per 10 year
(Unit)	Hz/sector	-	Hz/sector	y^{-1}/sector	-	-	-	-	$(10y)^{-1}$	$(10y)^{-1}$ (%)
Slice test*	3.15×10^{3}	1.24×10^{-9}	3.90×10^{-6}	39	0.5	1	0.95	1	185 per VFAT(128 ch)	**100 %**
GE11	3.15×10^{3}	1.24×10^{-9}	3.90×10^{-6}	987	0.5	1	0.03	1	148 per module	**4.82 %**
GE21	1.92×10^{3}	1.24×10^{-9}	2.38×10^{-6}	405	2.3×10^{-3}	1	2.4×10^{-2}	1	0.2 per module	**~ 0.01 %**
ME0	2.36×10^{5}	1.24×10^{-9}	2.93×10^{-4}	25080	2.3×10^{-3}	1	2.4×10^{-2}	1	13 per module	**~ 0.45 %**

*** Obsolete design – for comparison purpose**

Improved by the double-segmentation on GEM1 and GEM2

De-coupling capacitor + drain resistor is not optimal

Improved by VFAT protection resistor and optimized HV filter

Studies are on-going: the improvement is not yet quantified

Note on the discharge rate:

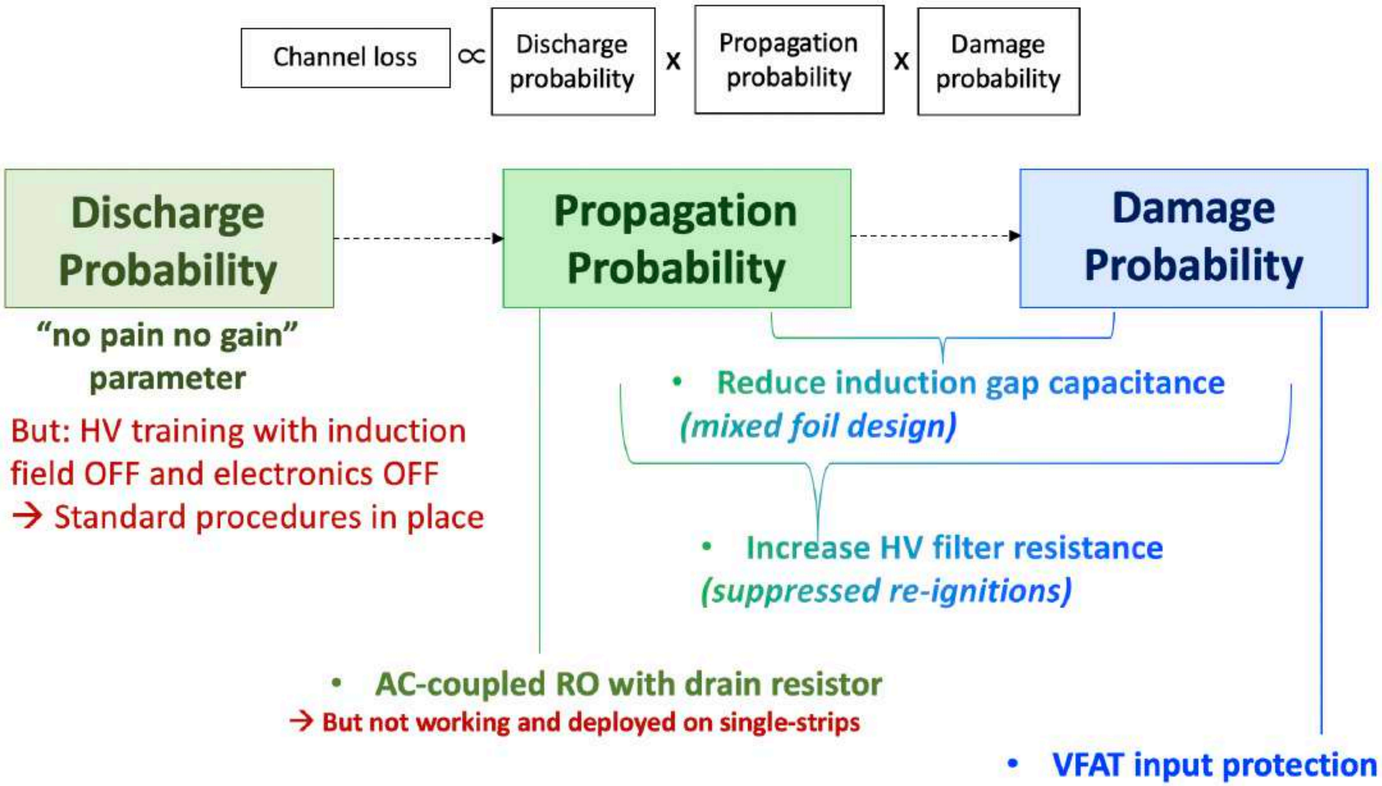
- the table only takes into account discharges caused by incoming BKG particles
- Spontaneous discharges may occur at the beginning of the detector life due to the presence of dust and contaminants after the chamber movement/installation
  - A" **training procedure**" is in place to eliminate the dust and clean the foils in safe conditions

Conclusions

→ **Discharges studies in the CMS GEM group**

- Long experience → almost continuous studies in place since 2015-2016
- Developed/improved/standardized setups for discharge investigations (with the help of CERN GDD and other RD51 groups)

→ **Mitigation Strategy**



Channel loss ∝ Discharge probability x Propagation probability x Damage probability

Discharge Probability

"no pain no gain" parameter

But: HV training with induction field OFF and electronics OFF
→ Standard procedures in place

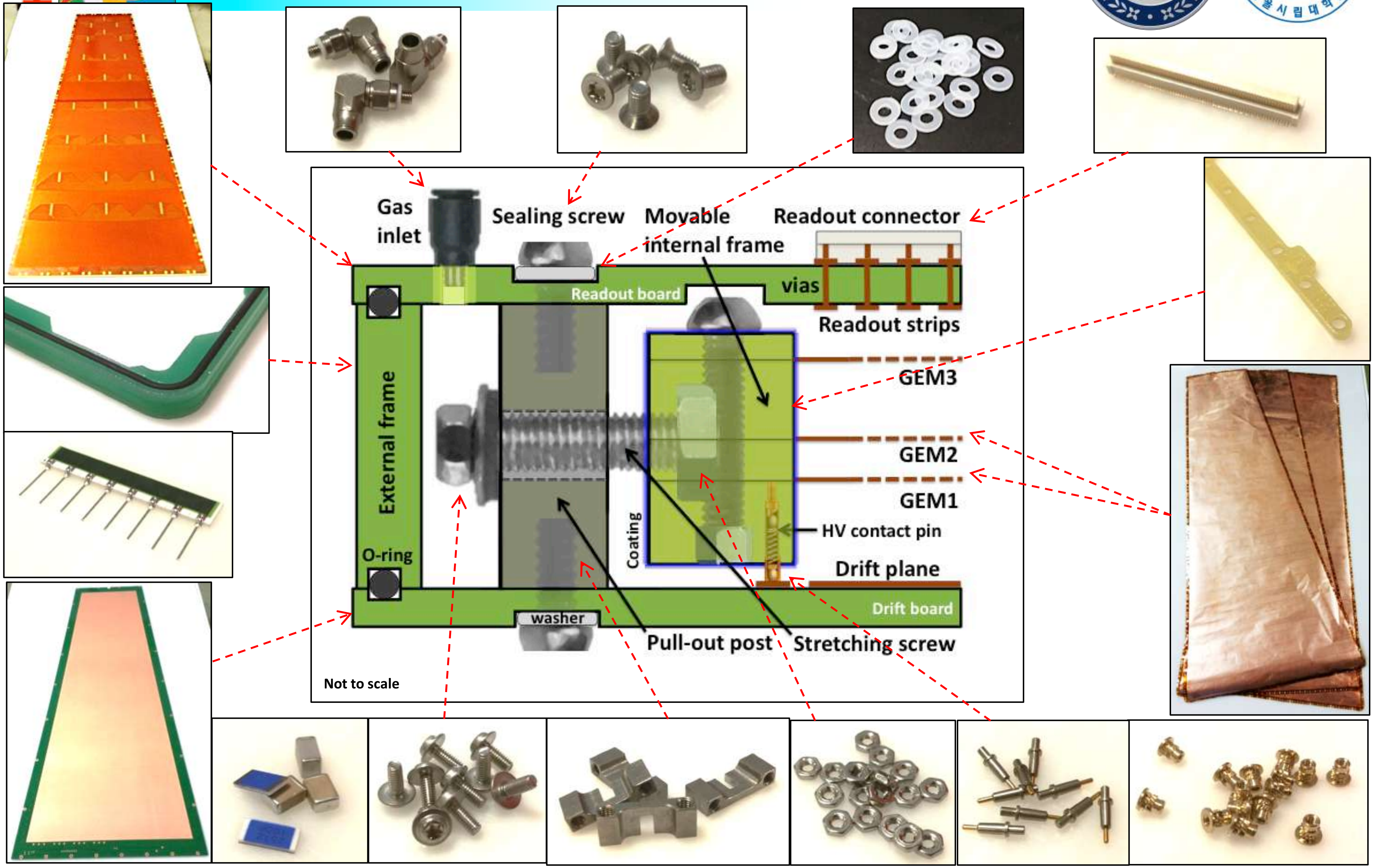
Propagation Probability

Damage Probability

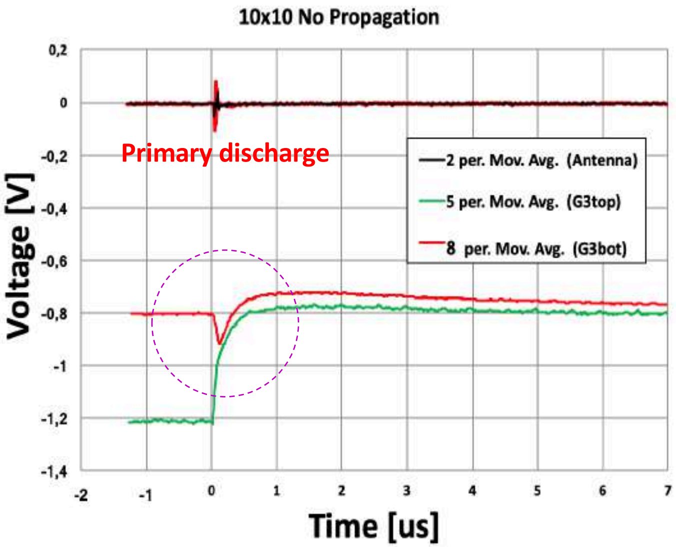
- **Reduce induction gap capacitance** *(mixed foil design)*
- **Increase HV filter resistance** *(suppressed re-ignitions)*
- **AC-coupled RO with drain resistor**
  → **But not working and deployed on single-strips**
- **VFAT input protection**

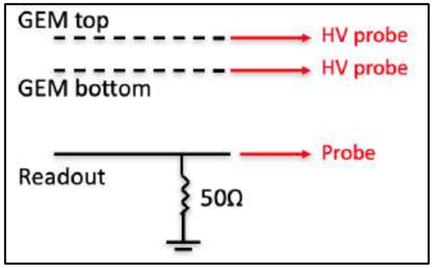
Thank you

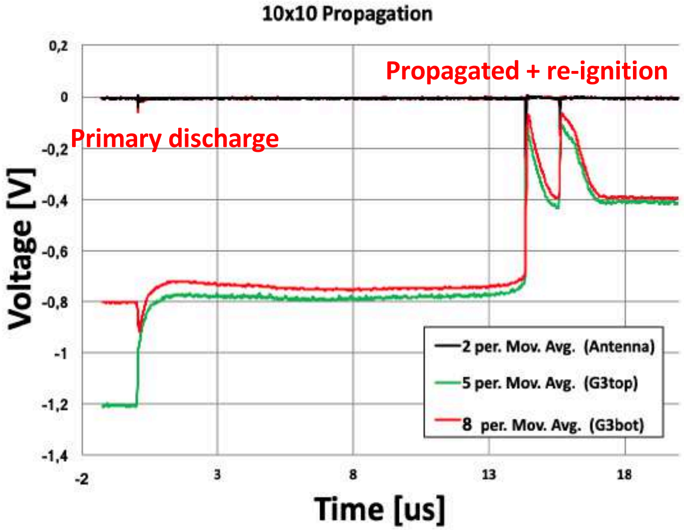
Detector Components

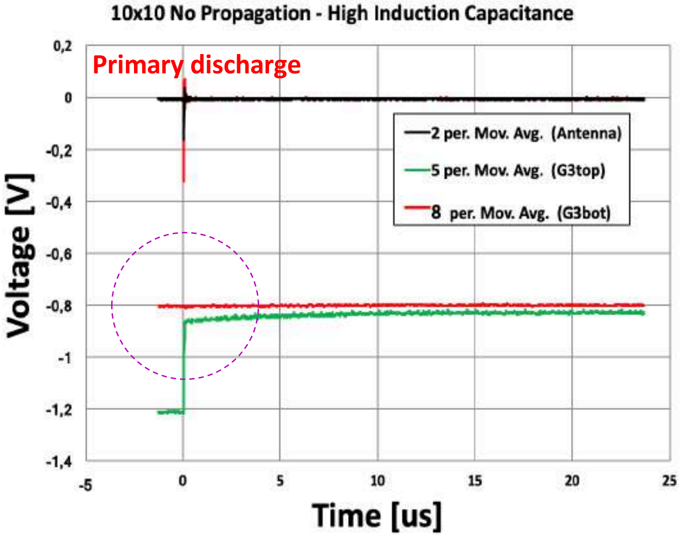


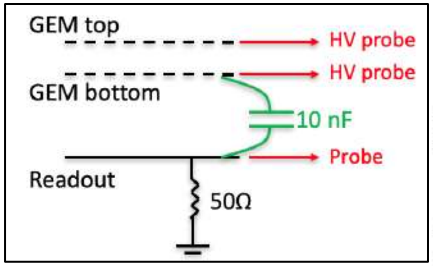
Discharge Propagation



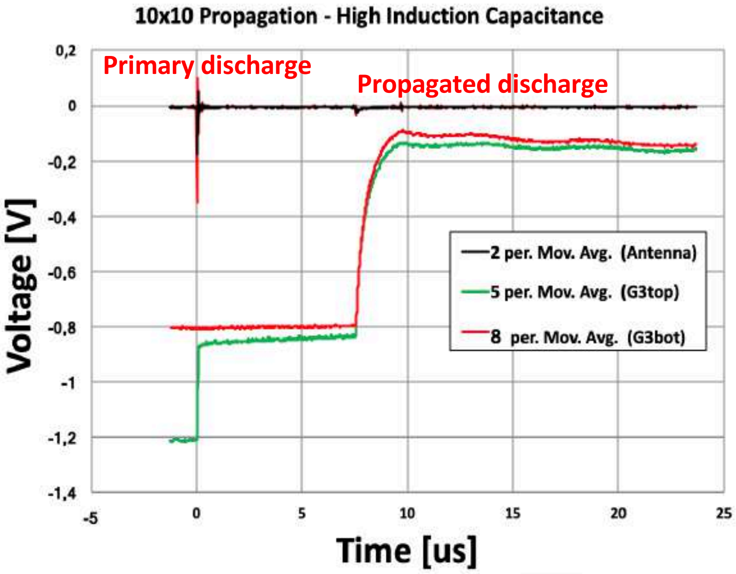






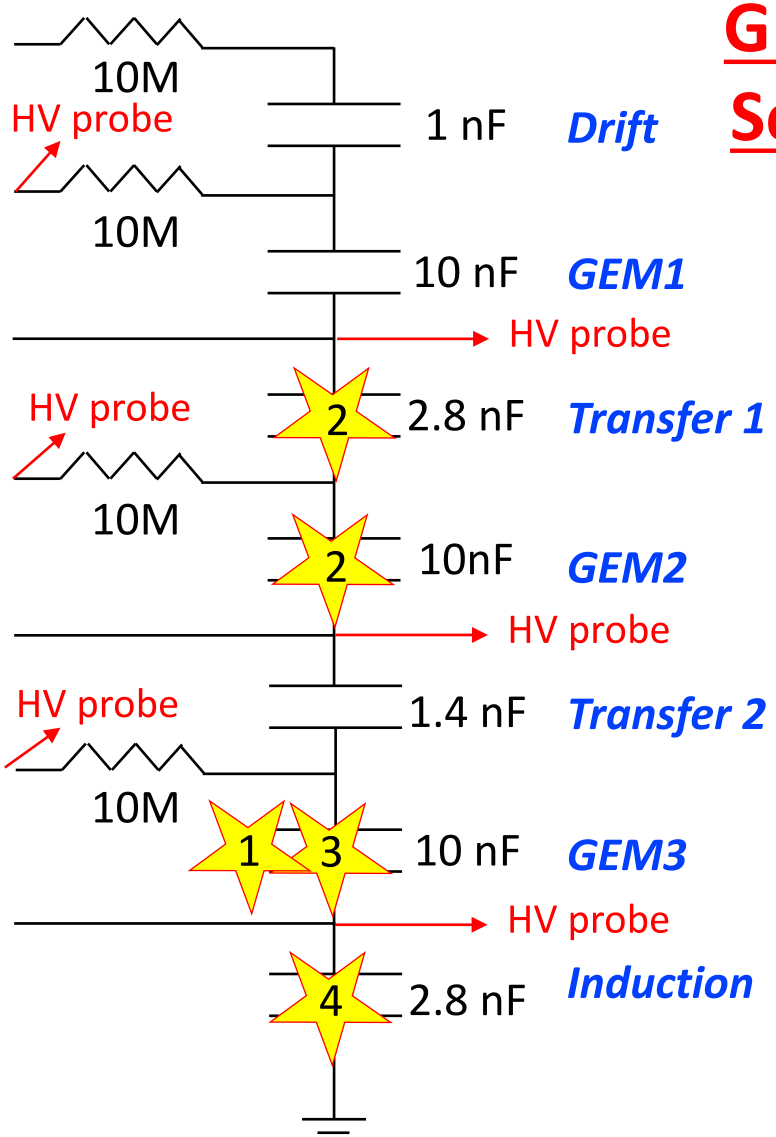


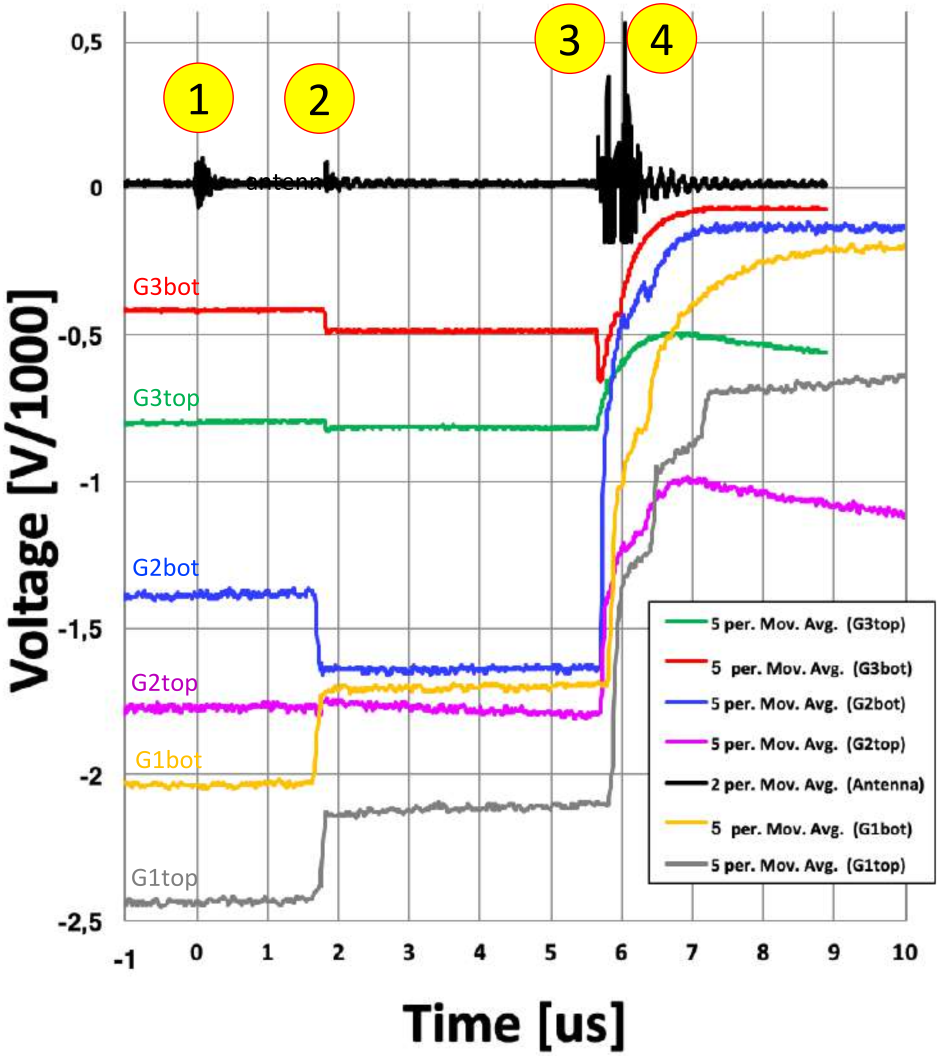
No voltage jump on G3bottom during the discharge



Discharge Propagation

GE1/1 Setup

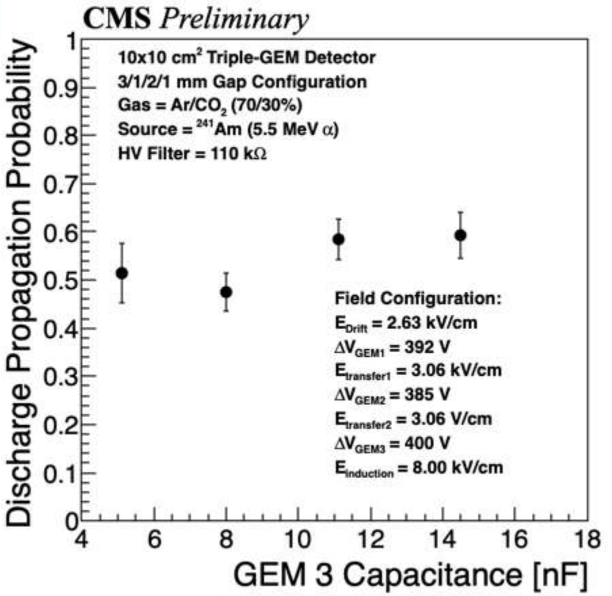


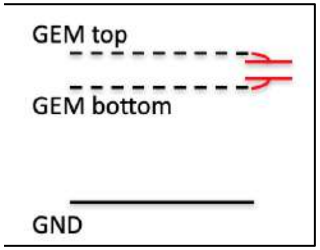


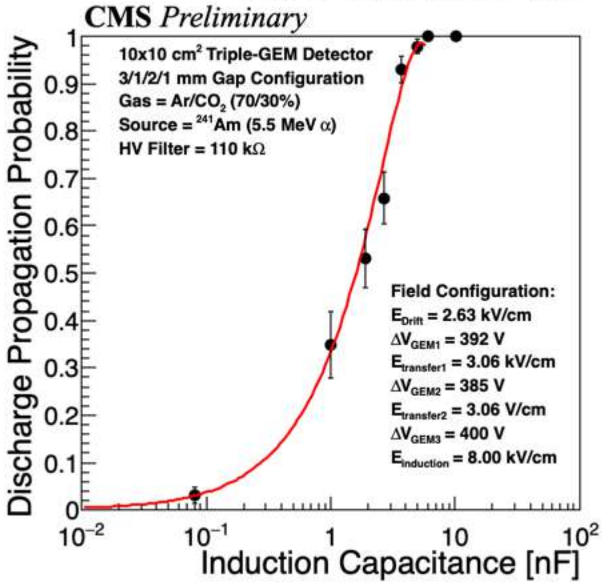
Propagation studies (2019-2021)

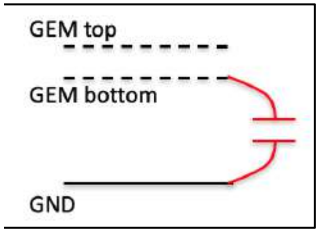
- **Further studies to understand differences between small and large chambers:**
  - No dependency with the GEM foil capacitance → no influence of the primary discharge energy
  - Clear increase of the propagation probability with the induction capacitance → i.e. sufficient amount of energy on the foil to feed the precursor current and trigger discharge propagation

  - All measurements indicate that the discharge propagation is more likely to happen in large foils due to the availability of energy directly stored in the foil

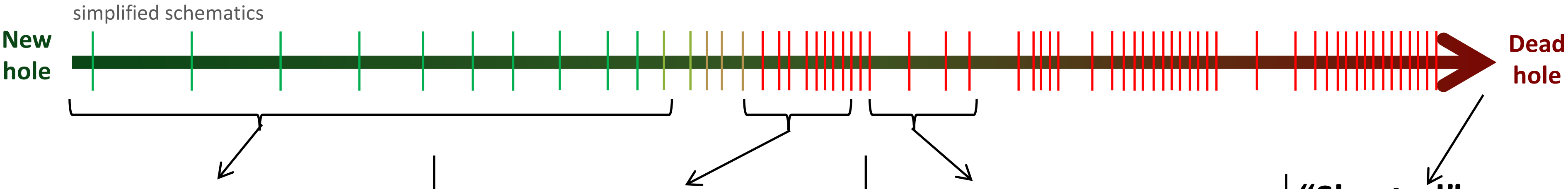








Discharge Effects



“Stable” Phase:

- Progressive and uniform surface etching
- Clean internal surface

“Weak State” :

- Presence of cavities and defects on the internal surface of the PI

→ Self-discharging

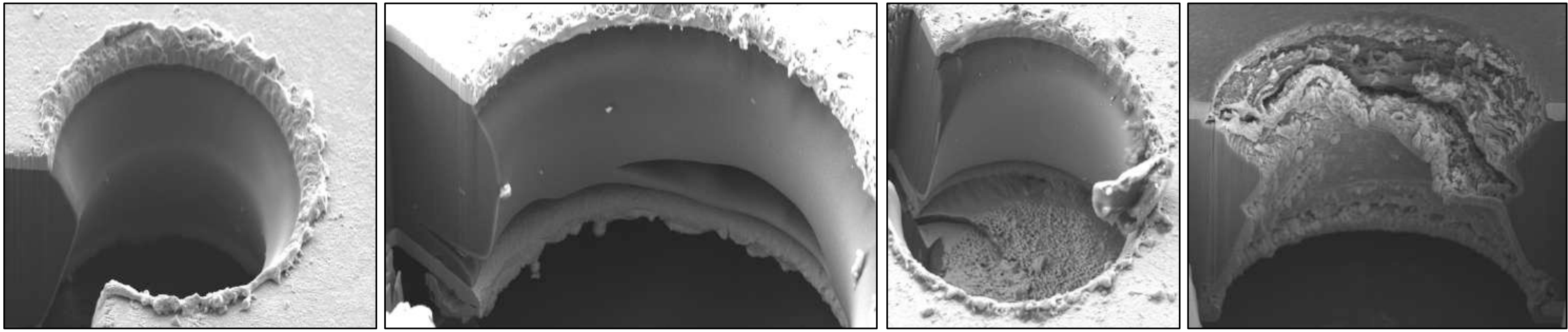
“Strong State:

- Attenuation of cavities and defect due to uniform surface etching

→ Curing effect

“Shorted”:

- Strong irregularities and defects



Crosstalk – General Description

Side effect of using double-segmented design on GEM3:

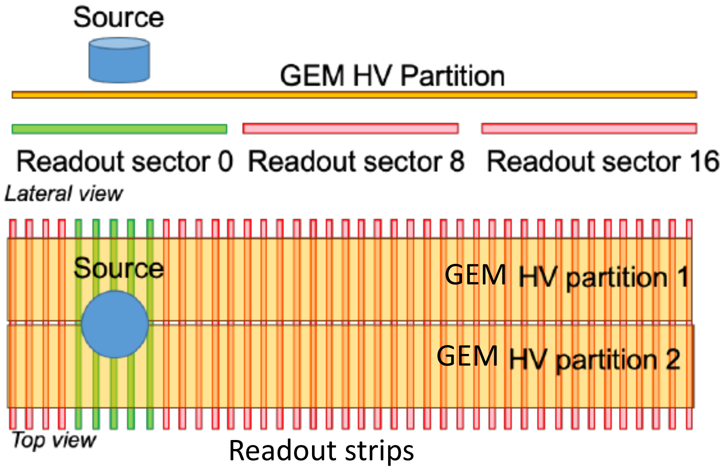
- Reducing the size of the HV segments on the last GEM increases the HF impedance to ground:

→ Induces **cross-talk**

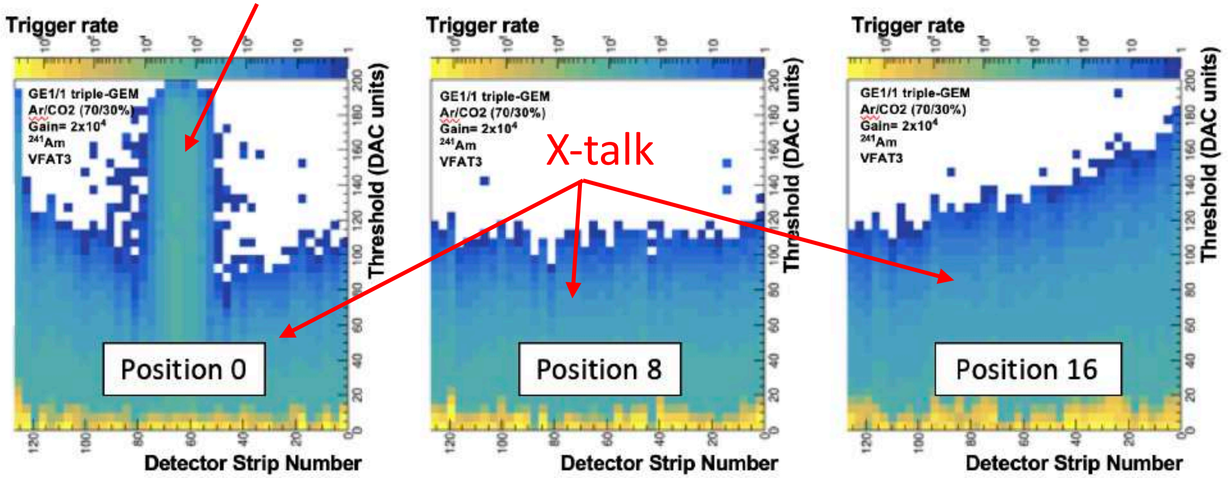
→ All strips facing the **same HV partition** can suffer crosstalk

→ In case of **large signals (HIP)**, the corresponding crosstalk signals can trigger the electronics and make the channels unusable for several BX

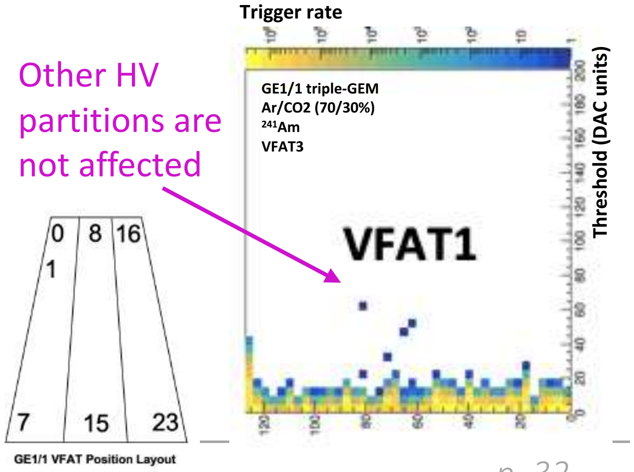
⇨ Start of a R&D campaign to cope with the crosstalk issue



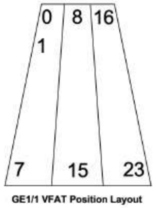
Source signal



Other HV partitions are not affected

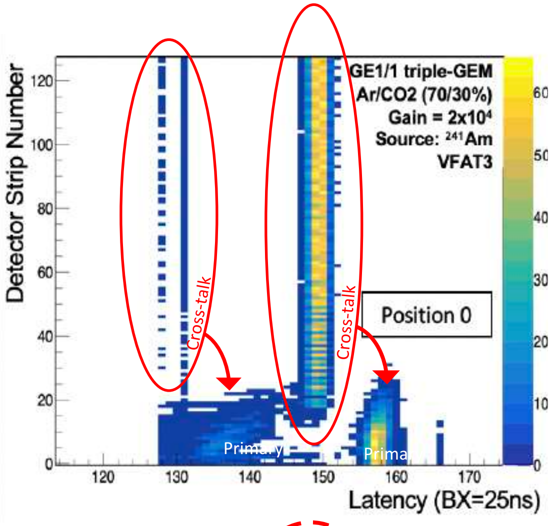


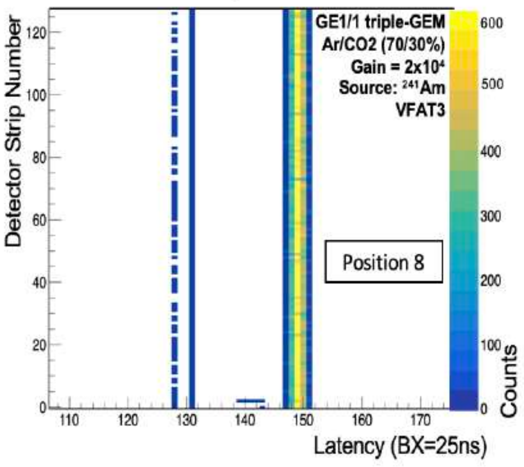
Crosstalk - Signature



Timing characteristics:

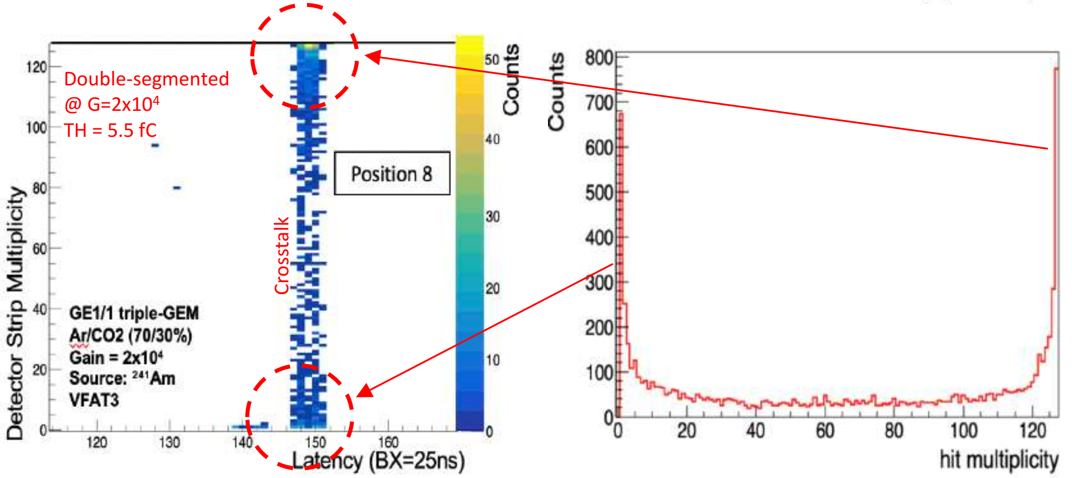
- Each primary signal structure has its own cross-talk structure coming after **10 BX** (250 ns)
- Probability of cross-talk depends on the amplitude of the primary signal (expected)





Range and probability:

- Eventually, all channels sharing the same HV partition are affected by the cross-talk
- On average, **61%** of the channels are seeing the same crosstalk signal for a given event

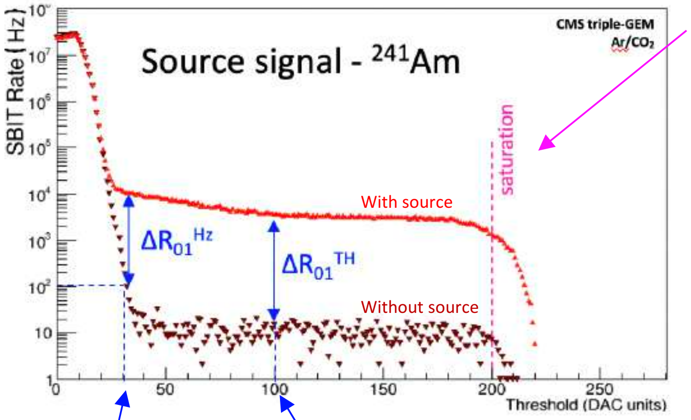


Crosstalk signals are typically affecting **61% of the channels** sharing the **same HV segment**, with a **delay of 250 ns** with respect to the original signal

Crosstalk - Probability

Probability measurement:

- At fixed threshold to estimate the rate for the highest amplitude signals
- At nominal threshold (= 100Hz of noise)



ARMDAC 100 = 14.1 ± 2.1 fC
(may vary a bit from one VFAT to another)

ARMDAC 30 = 4.4 ± 0.6 fC
(may vary a bit from one VFAT to another)

Saturation:

→ Not possible to **quantify the max amplitude** of a signal if the SBIT rate drops around 200 DAC units

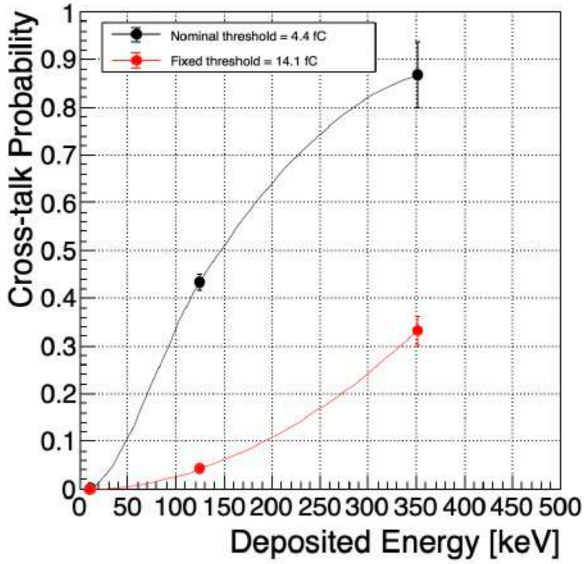
→ A "plateau like" rate profile indicates that the signal is above the VFAT range

Crosstalk probability:

$P_{XT}^{TH} = \Delta R_{neighbourg}^{TH} / \Delta R_{source}^{TH}$ → at fixed threshold 100 DAC units

$P_{XT}^{Hz} = \Delta R_{neighbourg}^{Hz} / \Delta R_{source}^{Hz}$ → at nominal threshold 100 Hz noise

Crosstalk probability in double-segmented foils becomes problematic for energy deposits above **30 keV**. X-rays and lower ionization particles **do not trigger** crosstalk



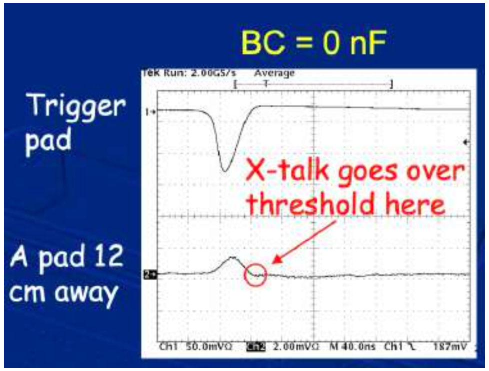
Crosstalk Mitigation in Other Experiments

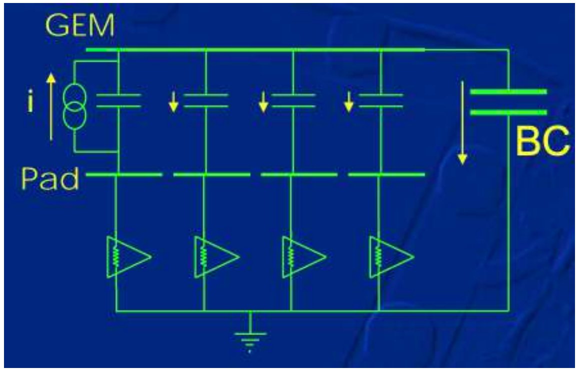
LHCb Experience:

- Triple-GEM ~ 480 cm^2
- 3/1/2/1 configuration
- HV segments top ~ 80 cm^2
- HV segments bottom ~ none
- Induction Capa ~ 0.2 nF

A. Cardini for the LHCb Collaboration (2006)

https://indico.cern.ch/event/473/contributions/1983755/attachments/954021/1353774/Cardini.pdf



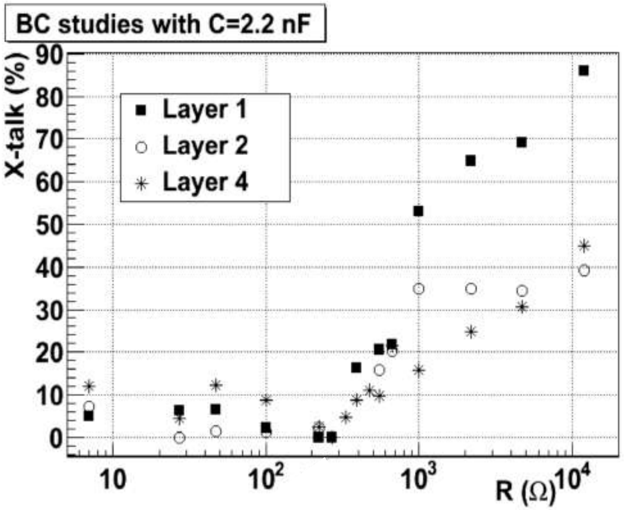


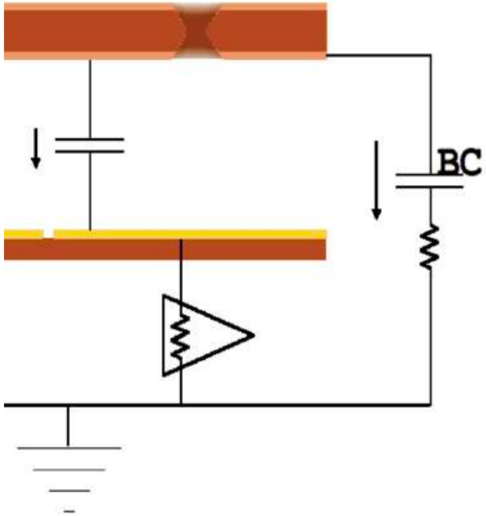
KLOE-2 Experience:

- Triple-GEM ~ 2450 cm^2 (cylindrical)
- 3/2/2/2 configuration
- HV segments top~ 105 cm^2
- HV segments bottom ~ 615 cm^2
- Induction Capa ~ 0.8 nF

G. Morello for the KLOE-2 IT group(2013)

https://https://indico.cern.ch/event/258852/contributions/1589820/attachments/456014/632021/MPGD2013_morello.pdf





Crosstalk mitigation:

- Use of a **blocking capacitor** between G3 bottom and GND to bypass the induction gap:
  LHCb: C_b = 0.7 nF
  KLOE-2: C_b = 2.2 nF

Crosstalk Mitigation in Other Experiments

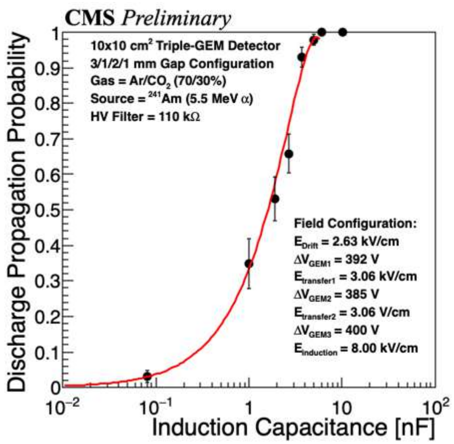
Technical limitations:

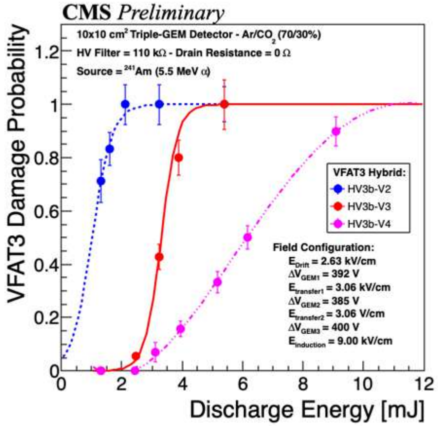
- GE2/1: 40 to 80 HV segments per foil → the blocking circuit must be inside the gas volume
- Significant re-design of the foils (add space for the RC components, bring GND line on the foil)
- Significant re-design of other detector components (DRIFT board, Mechanics etc …), possible reduction of the active area
- Introduce new weaknesses (e.g. long term failure of the capacitor)
- **Hard to find nF capacitors which can fit in a 1mm gap (including safe distance with other electrodes)**

Conceptual limitations:

- Adding the blocking capacitor means increasing the gap capacitance by a factor 3:
  - → **Increase of the discharge propagation probability (defeats the primary purpose of the double-segmented design)**
  - → **Increase of the discharge energy, i.e. the probability to damage the electronics in case of propagation**

	Induction C_i (nF)	**Blocking C_b (nF)**
LHCb	~ 0.2 nF	0.7
KLOE-2	~ 0.8 nF	2.2
GE2/1	**~ 2 - 3 nF**	**> 6 – 9 nF**





Investigating the HV sector size

3 configurations are compared:

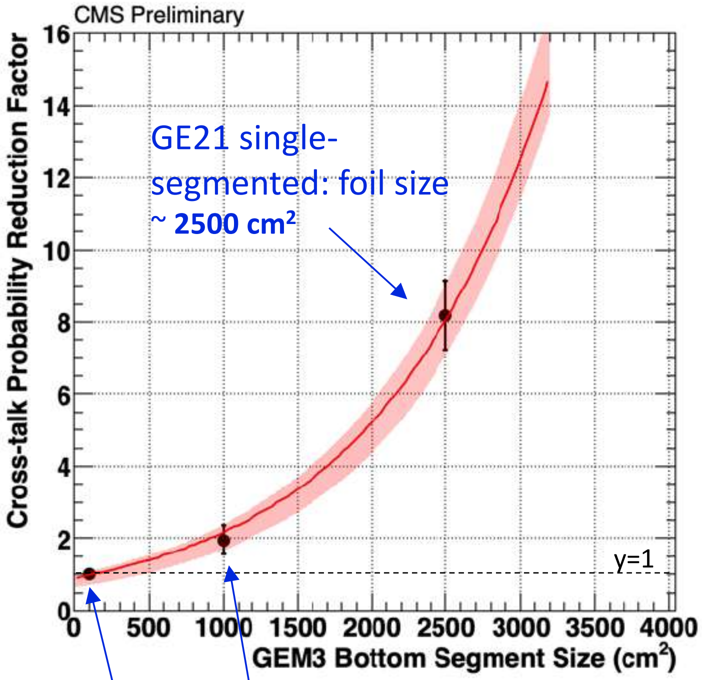
- GE11 double segmented; segment size ~ **100 cm²**
- GE11 with merged segments; segment size ~ **1000 cm²**
- GE21 single segmented; "segment" size ~ **2500 cm²**

Improvements:

- Increasing the HV segments size helps to evacuate the crosstalk current and "dilute" the crosstalk effect over a larger surface
- Maximum segment size: ~ 1200 cm^2 (i.e. 2 segments per foil)
  - → Crosstalk probability reduced by a factor ~ 2.5
  - → Crosstalk amplitude reduced to less than ~ 20-25 fC

But the improvement is much less compared to a regular single segmented foil:

- Unnecessary complication of the design
- Both options would give **poor discharge mitigation**



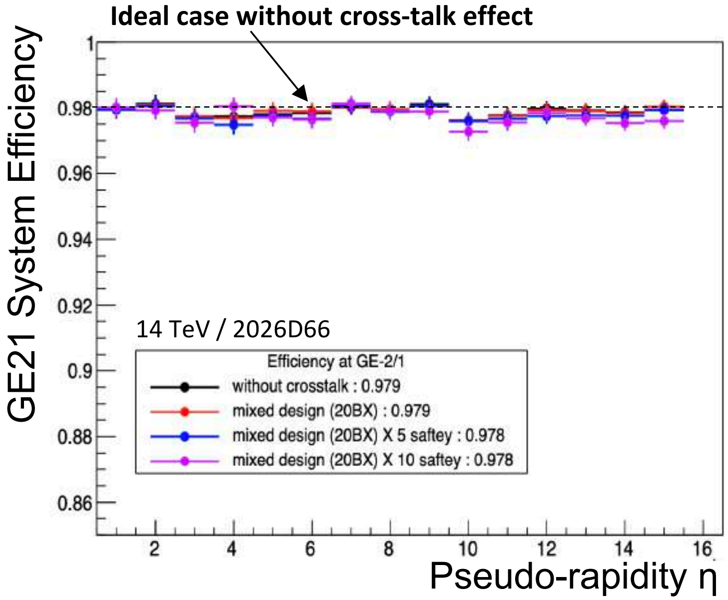
GE21 single-segmented: foil size **~ 2500 cm²**

GE11 with merged segments: HV segment size ~ **1000 cm²**

GE11 double-segmented: HV segment size ~ **100 cm²** (reference for this plot)

The improvement of the crosstalk is **not sufficient** to justify the increasing of the HV segment size
→ better results are obtained by completely removing the bottom segmentation
→ **The real choice is between single-segmented or double-segmented with fine segments**

GE21 Final Design Validation


Ideal case without cross-talk effect

Simulation parameters:

- Event samples for Z → Mumu @ 14 TeV
- The **HIP rate** is estimated from the BKG simulation, convoluted with the crosstalk probability vs. **deposited energy** (> 83 keV).
- Each strip can possibly see the crosstalk from **the entire module**
- **Inoperative time** of **20 BX** based on the electronics simulation

First order approximation given by:

Probability of inactive RO per event : $P_{DT} = \frac{HIP_{rate}}{BX} \times Prob_{XT} \times InoperativeTime$

Rate Normalized to 1 BX

Then the real chamber efficiency is : $Eff_{real} = Eff_{ideal} \times (1 - P_{DT})$

The maximum **efficiency drop** due to the crosstalk effect is of the order of **0.04 %** at the highest eta (without safety factor)

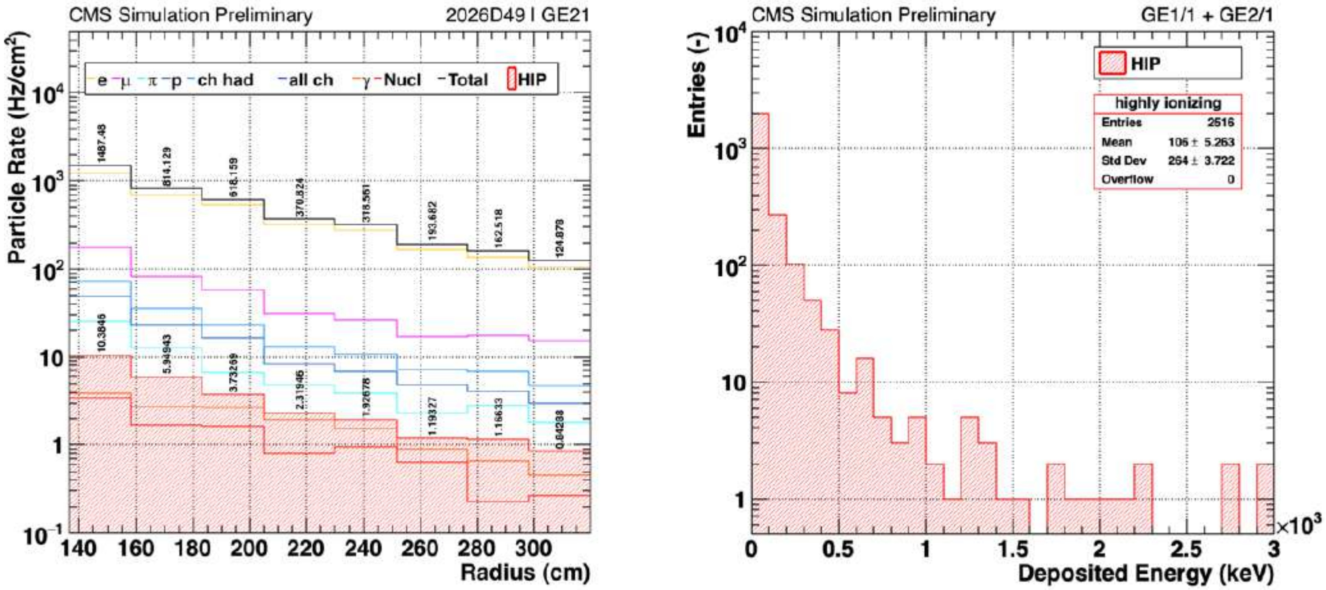
→ **Successful mitigation**

Crosstalk – Rate Estimations

Evaluation of the Crosstalk rate in CMS:

- Prediction of the total particle rate per eta partition of a single GE2/1 chamber
- Simulation including neutron background hits has been performed with GEANT
  - Total hit rate of Highly Ionizing Particles (HIPs) (mostly protons and nuclei) depositing 30 keV or more
- The HIP rate can be convoluted with the energy-deposit dependent probability to create a cross talk signal to obtain the prediction of the cross talk signal rate

BKG population susceptible to **trigger crosstalk** is derived from the 30 keV energy cut: up to **10.4 Hz/cm^2** in the hottest GE21 region. The average energy deposit for this population is **107 keV**



GEANT4 based simulation model including the latest CMS configuration (with all subdetectors upgrades)
CMSSW 11_0_0_pre13 Min Bias collisions with hit time 100ms