# Advanced GEM detectors for future collider experiments

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Snowmass 2021 - IF05 Micro Pattern Gas Detectors Meeting
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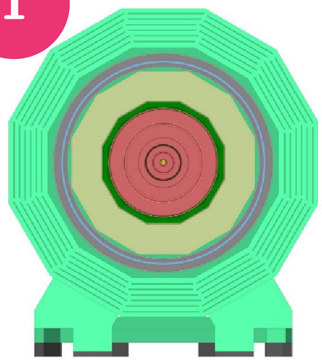
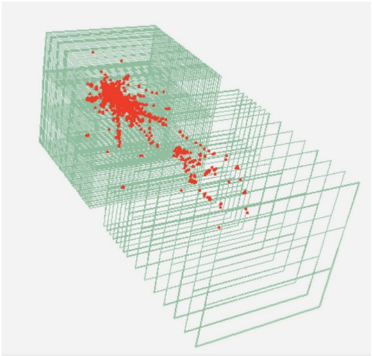
# Content overview

1





Variety of applications for **MPGDs at future colliders**

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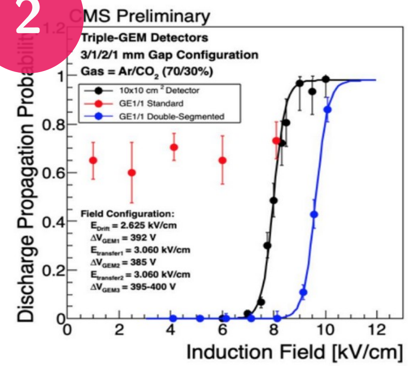
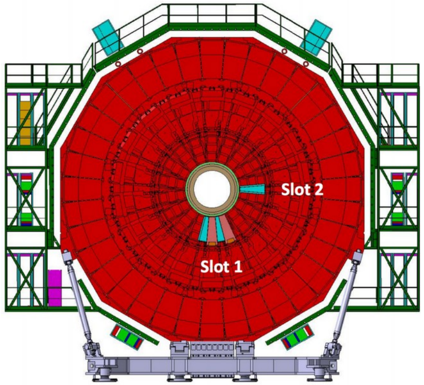
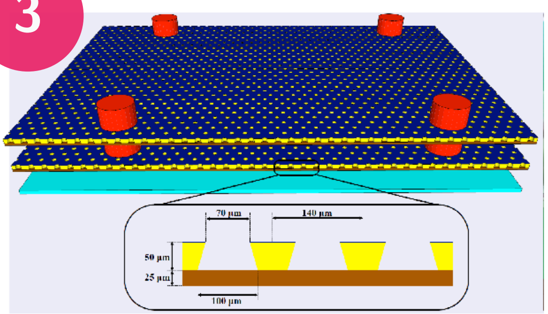
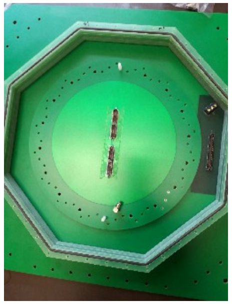



Past and present GEM technology development: active and **growing community**

3





Challenges and points of **improvement for future applications**

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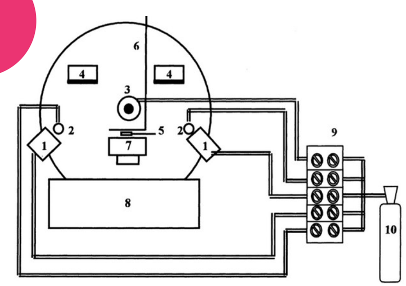
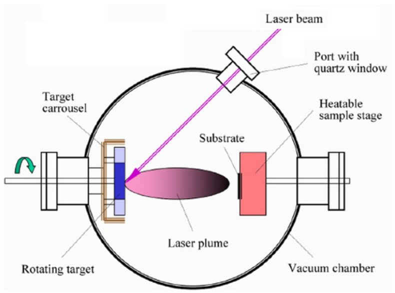


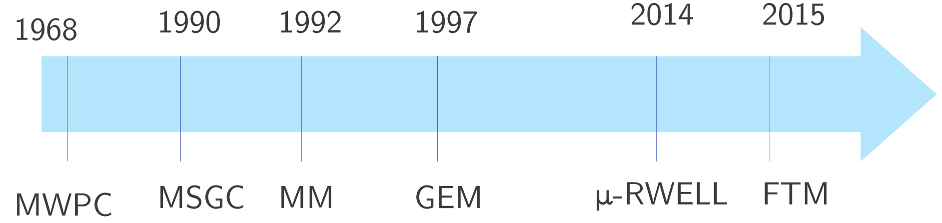



Ongoing and **foreseen advancement** on new detectors

# Micro-pattern gaseous detectors

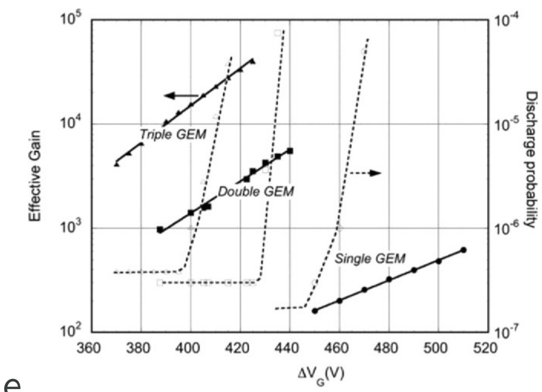
MPGDs are **gaseous detectors** with **micrometric** amplification layers

- ✓ High **rate capability** O(MHz/cm$^2$)
  Measured in laboratory and achieved at COMPASS
- ✓ High **space resolution** (50-100 µm)
- ✓ Good **time resolution** (5-10 ns)
- ✓ Cheaper than solid state detectors at equal **covered areas**

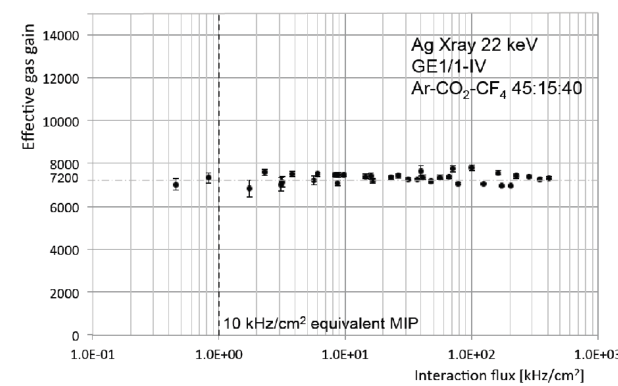



The **gas electron multiplier** (GEM) is one of the most consolidated MPGD technology

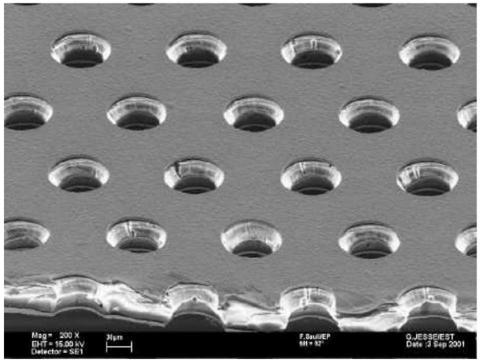
**Novel GEM-based** detectors are the **main focus** of this presentation

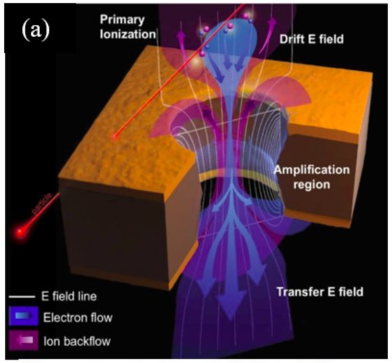


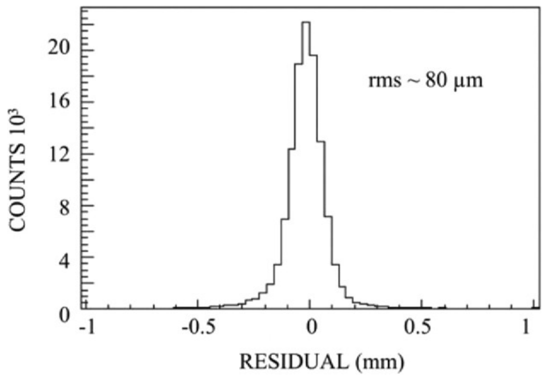

Effective gas gain of single and multi-GEM detector[12]

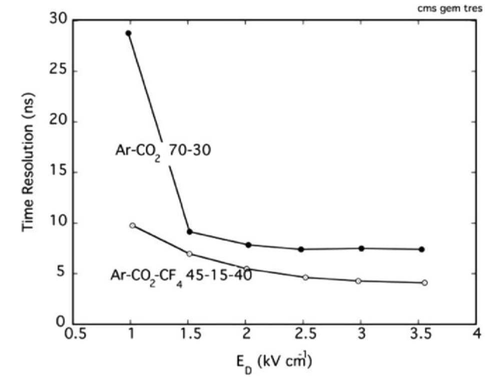



No gain drop observed in bare GEM detectors at high particle rates[13]





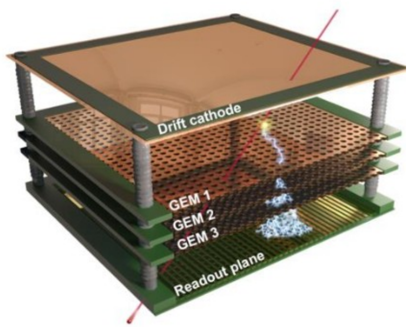



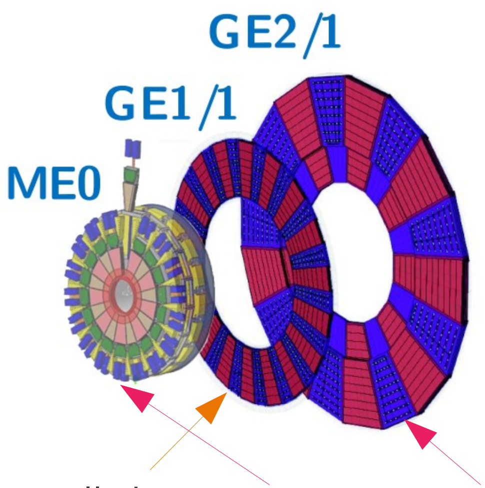

Typical space and time resolution of GEM detectors[12]

# GEM detectors at the LHC

State-of-the-art GEM technology are the **triple GEM chambers** at the LHC experiments




**CMS Phase 2 upgrade: three GEM stations** for each muon endcap

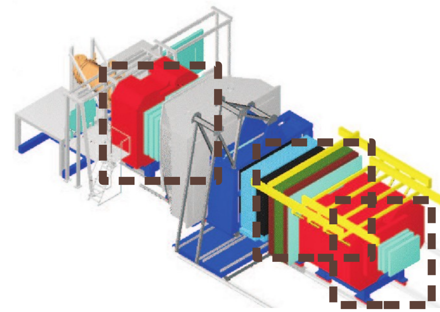



Already installed

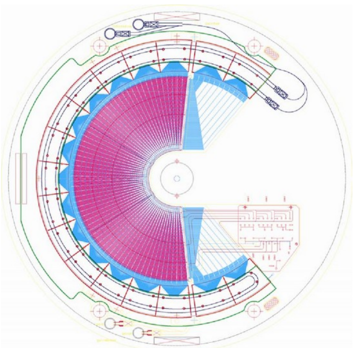
Installation by LS3

Total 1000 $m^2$ instrumented surface

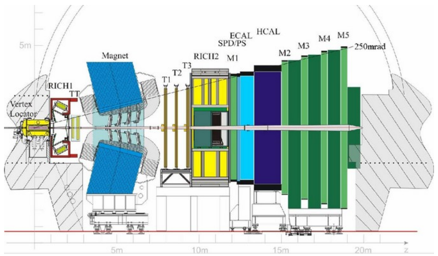
## In ongoing experiments



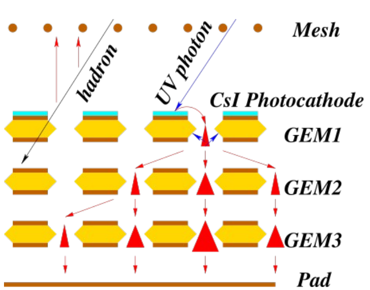
**COMPASS**, first experiment to use GEMs in a physics run[14]

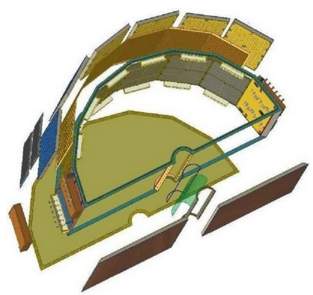


**TOTEM** T2 telescope for tracking and triggering[15]



**LHCb** M1R1 muon station

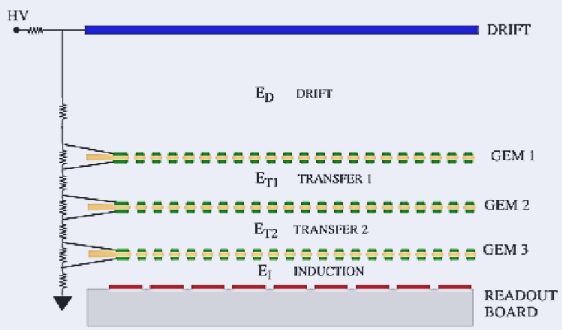


Hadron-Blind Detector at **PHENIX**, conceptually unique application for combinatorial background rejection[16,17]

# Improvements on GEM technology at LHC experiments

Triple GEM detectors have come a **long way since early applications**




"Standard" COMPASS triple GEM schematic

**At LHCb (2000→)**

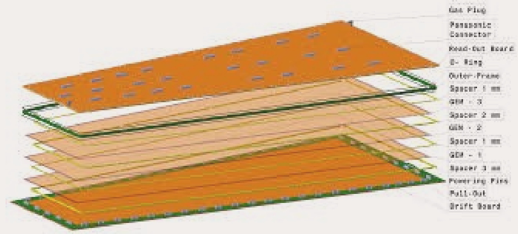
**For time resolution**

**Optimization** of gap sizes, gas mixture, operation voltage

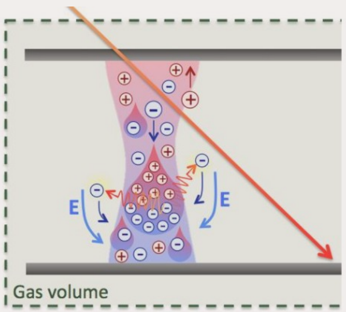
**CMS R&D (2015→)**

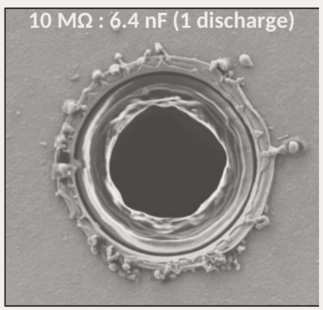
**For large areas**

New scope of operation, with focus on **discharge mitigation**



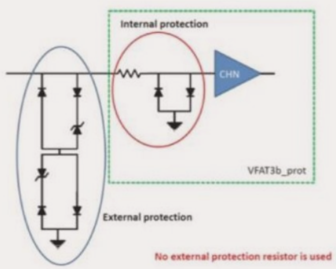
Interest sparked also in the **RD51 community**

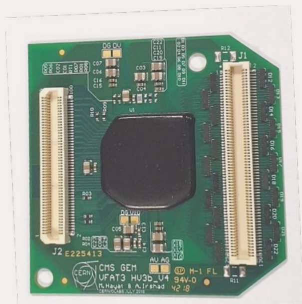



Streamer development in gas gap and discharge effect on GEM hole

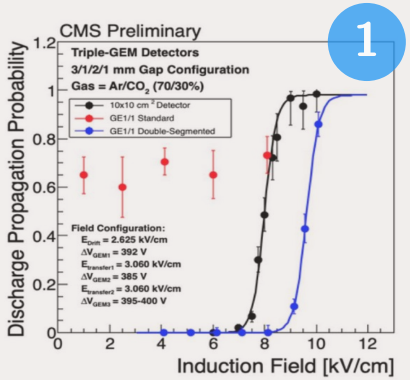
**Short-term solution (GE1/1)** → R/O chips (VFAT) protection circuits

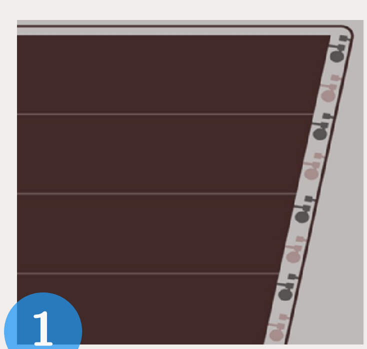


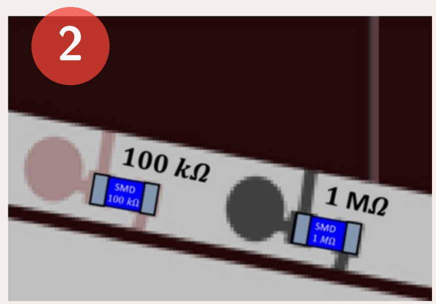



**Long-term solutions (GE2/1, ME0)**

1. GEM **foil segmentation** to reduce gap capacitance
2. HV **protection resistors**



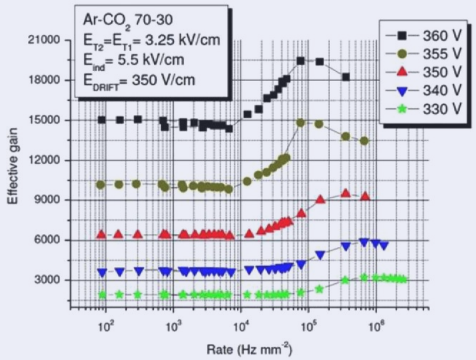



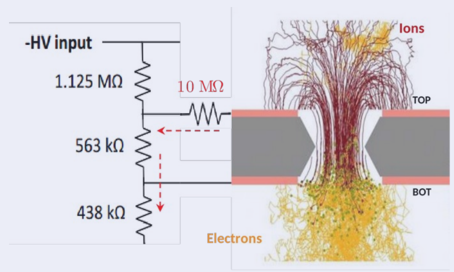
# Ongoing progress on GEM detectors optimization

**Development of GEM technology** is far from being over

Examples of **present challenges** in che CMS Phase 2 upgrade

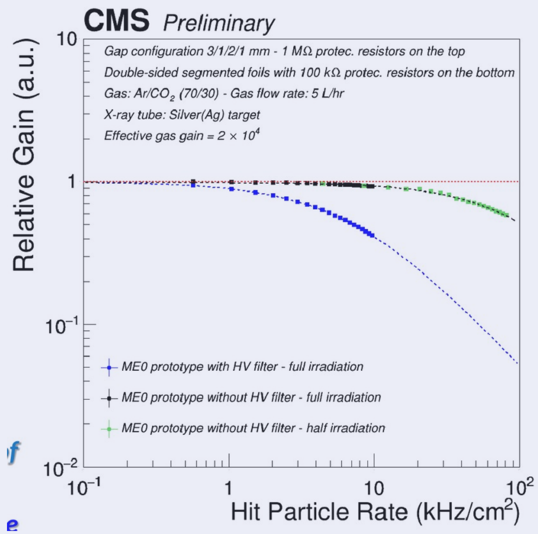
GEM detectors were born for high rate capability...




Electron- and ion- induced currents flowing through protection resistors

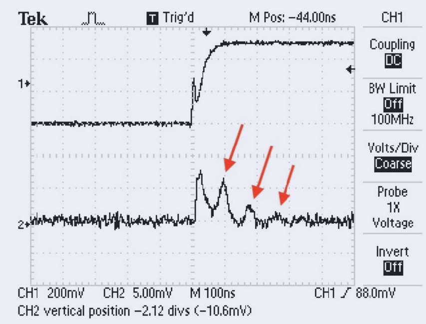
However, gain drop observed on **CMS ME0 prototypes** with **HV protection circuits**




**Ongoing** measurements and simulations to attain ***gain drop compensation*** in the **ME0 background** environment

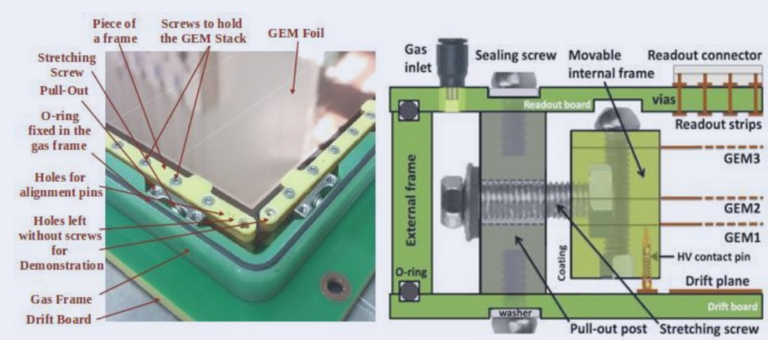
*Bare* triple GEM chambers maintain high rate capability, but external protection circuits lower it!

Researching on signals **cross-talk** due to **double foil segmentation**...




Inducing **dead time in the read-out** electronics

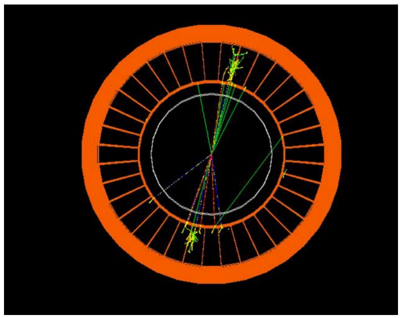
Continuous progress also focused on **detector mechanics**




GEM foils held by stretching screws

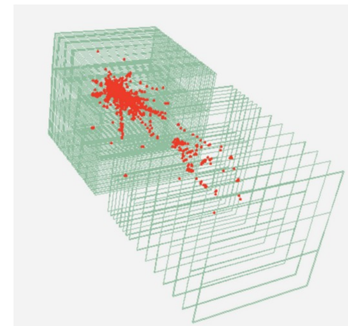
# MPGD applications at future colliders

Foreseen development of MPGDs **at future colliders** (FCC-ee, FCC-hh, Muon Collider)



### Preshower detector

Before the barrel and endcap calorimeters of the IDEA experiment at the FCC-ee[1]



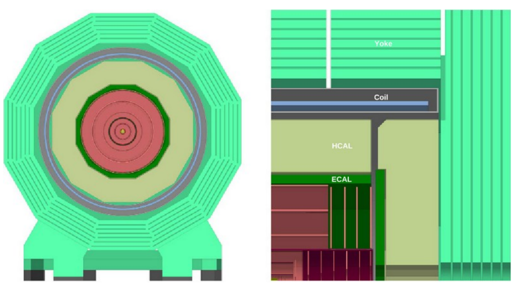
### Calorimeter readout

For digital readout of hadron calorimeter, as higher-rate alternative to RPCs[2]

**Longevity**
*no access after installation*

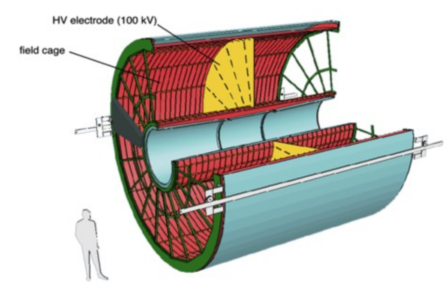
**High rates**

Applications **beyond muons**




### Muon tracker

High-rate muon systems, e.g. IDEA (FCC-ee) or muon collider experiments



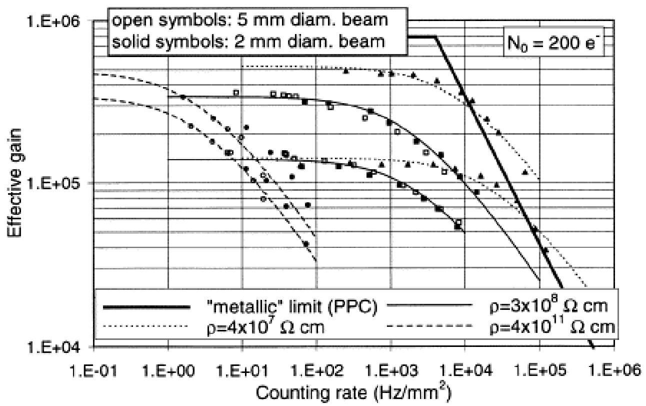

### Time projection chamber readout

Following the example of ALICE 4-GEM TPC upgrade

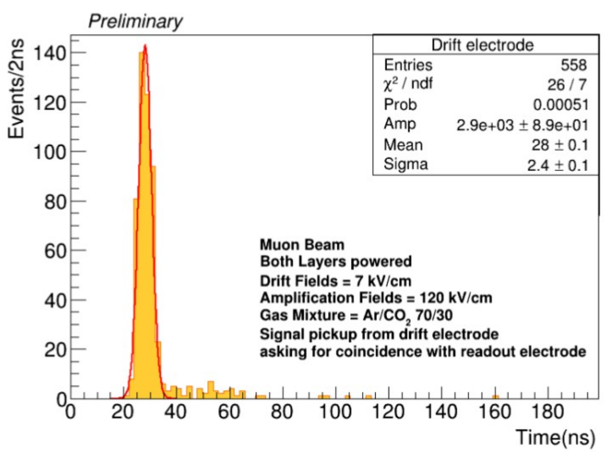
# Requirements for future MPGDs

Constraints at future HEP experiments will require R&D on current MPGD technologies to improve

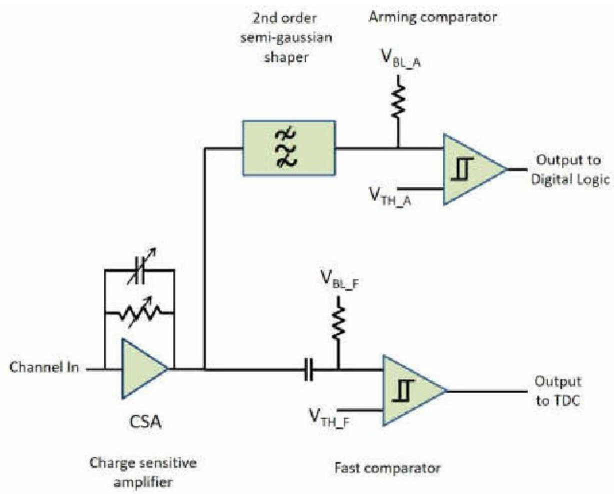
- **Rate capability** ($\geq$ 100 Mhz/cm$^2$)
  *Alternative to solid-state detectors*
- **Radiation-hardness** (up to 10 C/cm$^2$)
  *No maintenance during experiment lifetime*
- Improved **time resolution** (< 1 ns)
  *To sustain higher pileup*
- Fast, high-gain readout **electronics**
- Maintaining fast manufacturing



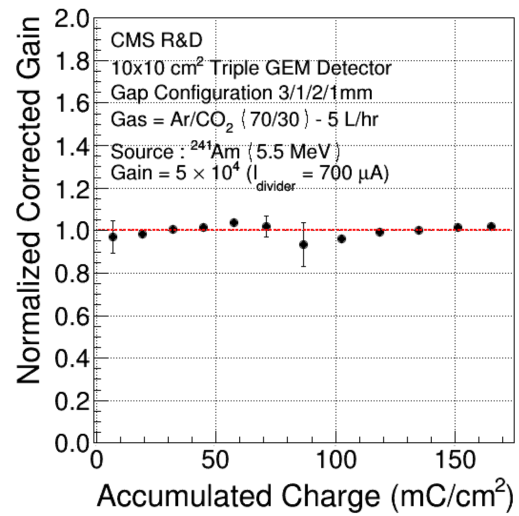

Resistive electrodes **reduce rate capability** w.r.t. to traditional MPGDs[24], but there are high-rate solutions e.g. G. Bencivenni et al 2019 JINST 14 P05014




Time resolution of the first FTM prototype




Architecture of the FATIC developed for the FTM[6]

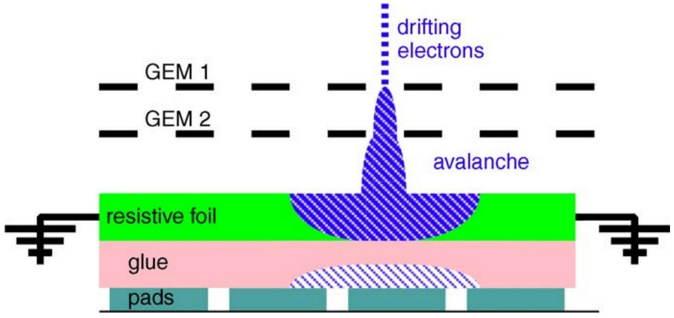



CMS triple-GEM aging effects

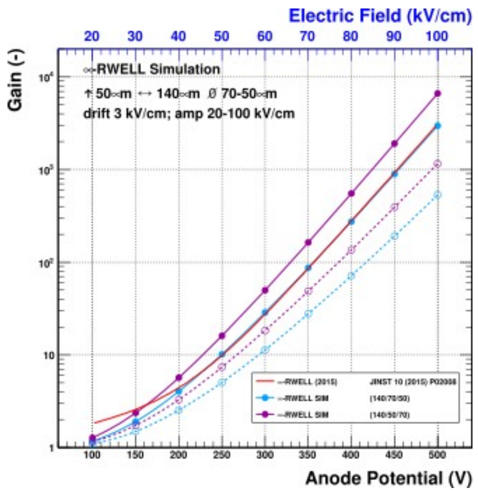
# Resistive MPGDs based on GEM technology

Introduction of **resistive electrodes** in GEM chambers will improve

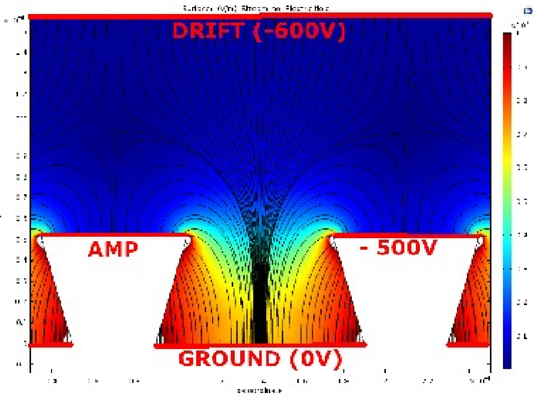
- Intrinsic **spark protection**
  *No external discharge mitigation circuits*
- **Simpler detector** structure
  *Multi-GEM stack not needed*
- **Space resolution**
  *Due to smaller drift fluctuations*
  *And charge weighting over larger avalanche*
- **Higher gain** at lower voltages
  *Up to $10^4$ with single layer*



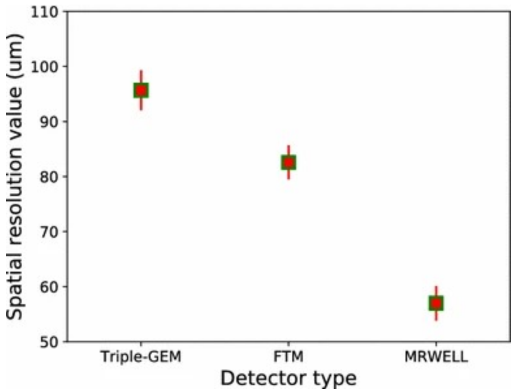

Charge spreading in a resistive ground detector[23]




Simulated gain curves of RWELL detectors for different hole geometries

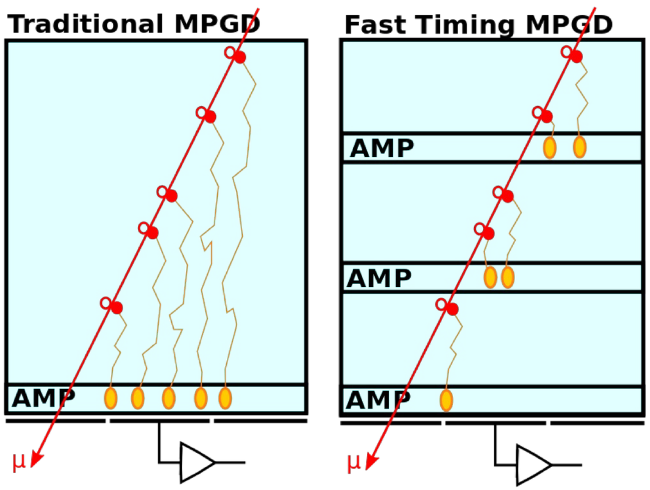



Geometry and electric field simulated in a WELL detector made of a single drift+amplification layer




Simulated space resolution of a triple-GEM detector compared with resistive MPGDs[7]

# Resistive MPGD for fast timing



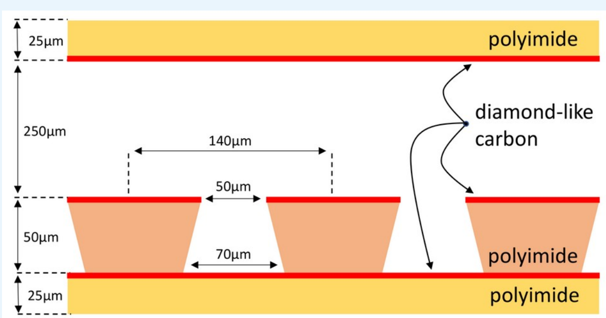

Purpose of the **fast timing MPGD (FTM):**
Improving on the **time resolution** of traditional MPGDs

**Working principle**[8] Competition of arrival time of **independent signals** generated by **fully decoupled** drift+amplification layers

$$\sigma_{\mathrm{FTM}} = \frac{\sigma_{\mathrm{layer}}}{N_{\mathrm{layers}}}$$

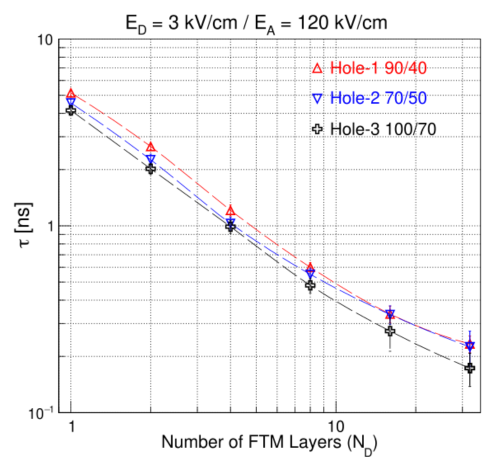
$N_{\mathrm{layers}}$ up to 12 → σ down to **400 ps**

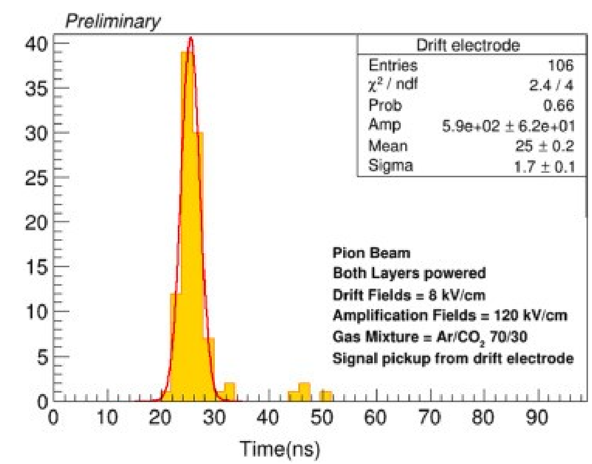
Signal pick-up by **external R/O electrodes**
→ **fully resistive** detector structure




Structure of a single FTM layer

Prototypes undergoing tests in
Bari, Pavia (Italy), Ghent (Belgium)



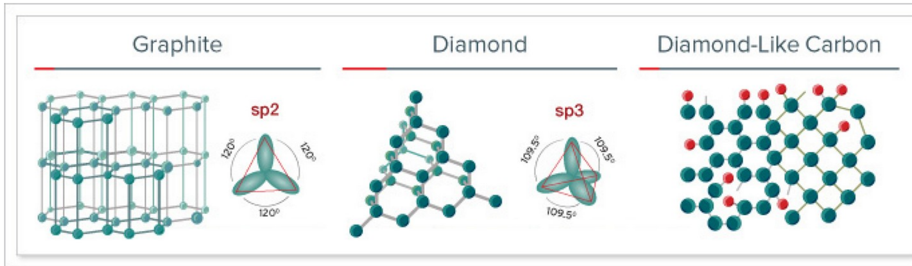




Simulated **FTM time resolution** for different n. of layers[9] and measured **two-layer time resolution** at test beam[10]

# DLC coating for the FTM

Large scale production of **resistive electrodes** requires up-to-date **deposition techniques**

- uniform coating of large areas
  *> 1000 $m^2$ to be covered*
- precise control over electrode resistivity
  *>200 kΩ/sq. required for foil transparency*
- stable adhesion over long time



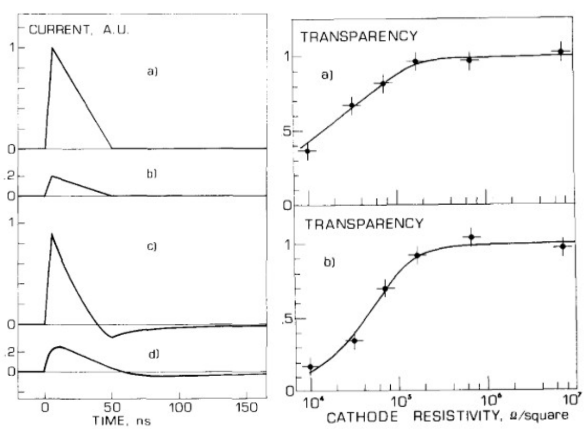

Resistive materials of choice

- → **Diamond-like carbon** ← ongoing R&D
- → **Graphene** ← future developments

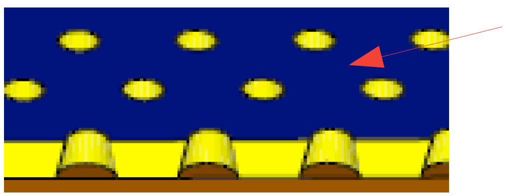
RESISTIVE CATHODE TRANSPARENCY

G. BATTISTONI, P. CAMPANA, V. CHIARELLA, U. DENNI, E. IAROCCI and G. NICOLETTI
*INFN – Laboratori Nazionali di Frascati, Frascati, Italy*

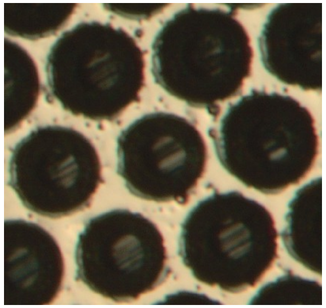
Received 23 February 1982

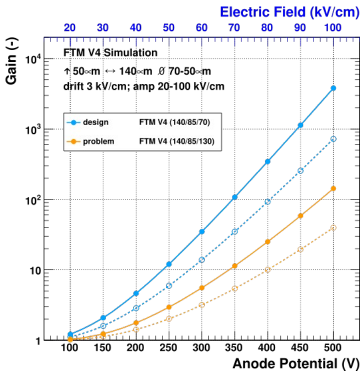



Simulated electrode transparency as a function of resistivity[18]



**Production challenge** for FTM foils: top DLC layer exposed to gas

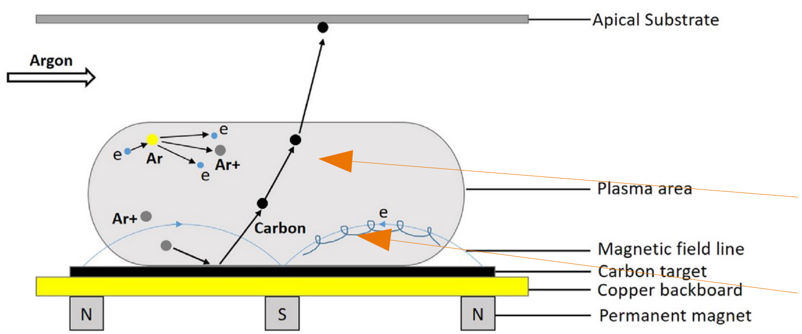





Observed **delaminated DLC** after etching: larger holes, **smaller gain** (simulated)[19]

# Deposition of resistive coating for the FTM

Better understanding of **DLC deposition techniques** is required




Magnetron sputtering apparatus[20]

## Magnetron sputtering

**Most consolidated**, mastered in China (USTC) and Japan (Kobe)

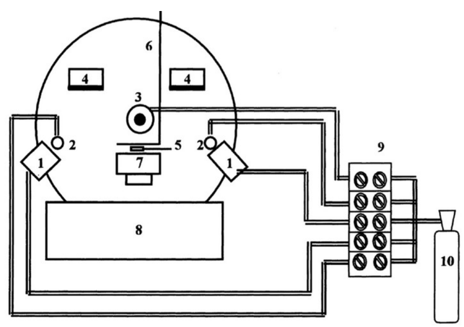
- Ions created in plasma, accelerated by electric field (0.1-10 eV)
- Magnetic field driving secondary electrons channel to increase deposition rate

Optimal **DLC adhesion yet to be reached**

## "Domestic" solutions

### Ion beam sputtering

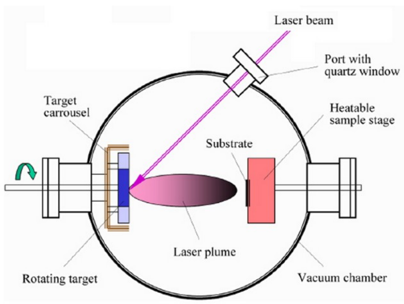
- Assistance ion beam to ensure **better adhesion** to sample
- Possible adoption for **larger production** if suitable partner is found



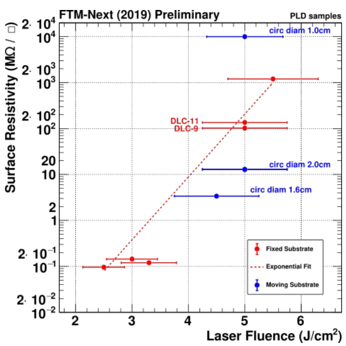

Ion beam sputtering setup at INFN Bari[21]

### Pulsed laser deposition

- Good sample stability
- High **DLC resistivity control** by adjusting source flux
- Suitable for small areas, considered mainly as **R&D tool**



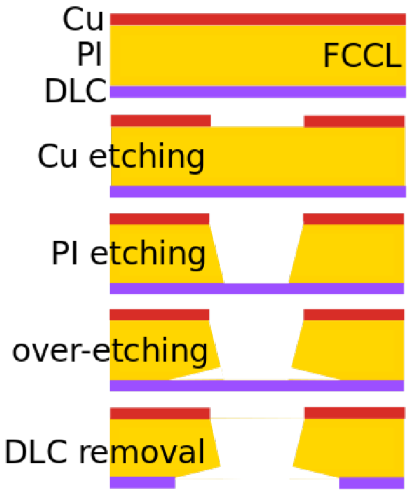

PLD setup[22]




Measured resistivity of DLC sample obtained by pulsed laser deposition at INFN Lecce[11]

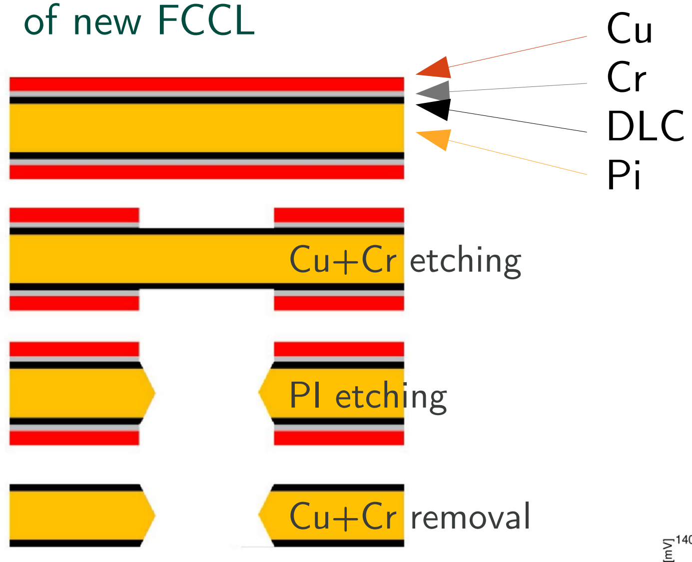
# Foil etching and latest FTM prototype

Single-mask etching "old" FCCL



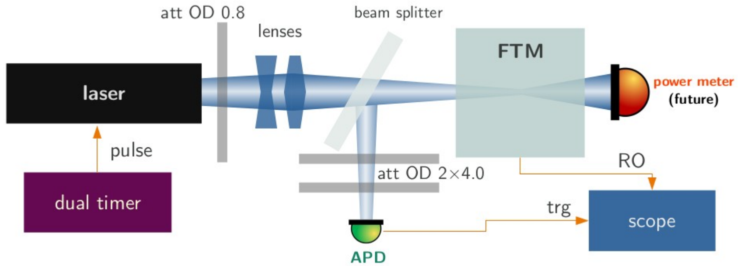

Possible over-etching with resulting biconical hole shape and **too small DLC** electrodes

Double-mask etching of new FCCL

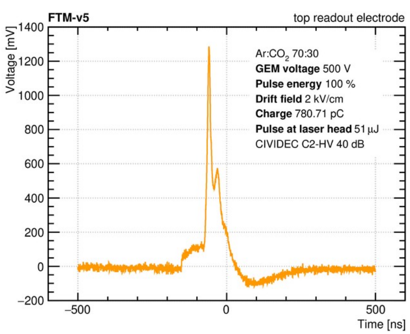



DLC protected by cromium layer
Allows thicker foil for larger gain: essential for **small-gap detectors**

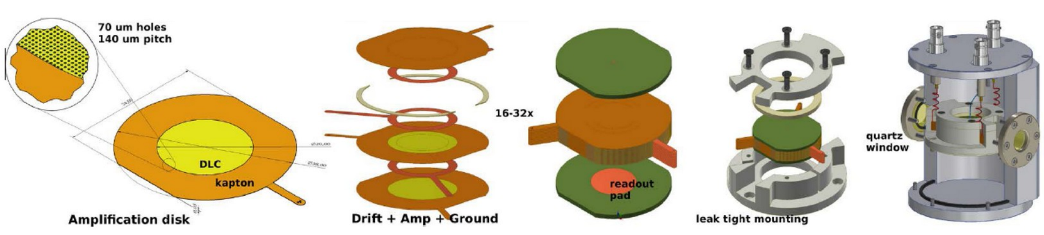
**FTM small-size prototype** in Bari
With new FCCL foils (single mask)



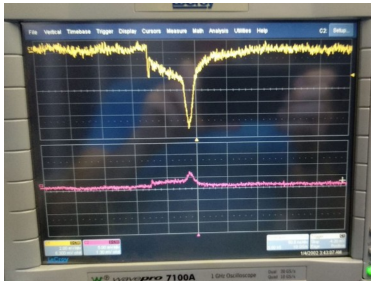

FTM small-size laser test setup




**Example of signal** observed on the prototype with the laser source



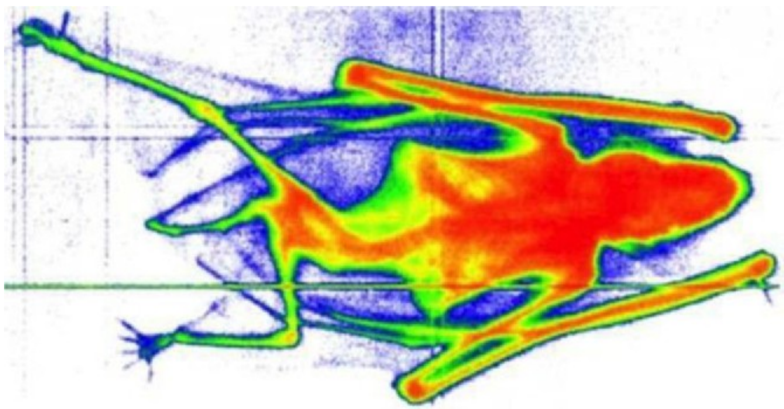

Detailed design of the FTM small-size prototype



**Observed signal transparency** (different scales on the two R/O electrodes)

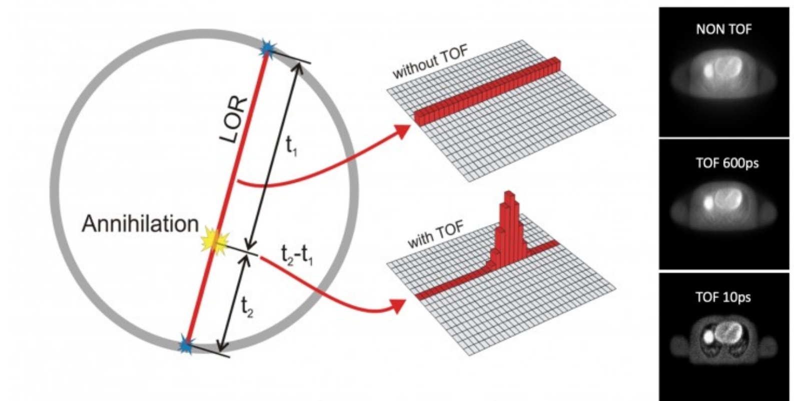
# MPGD applications outside HEP

## X-ray imaging



For security and industrial applications

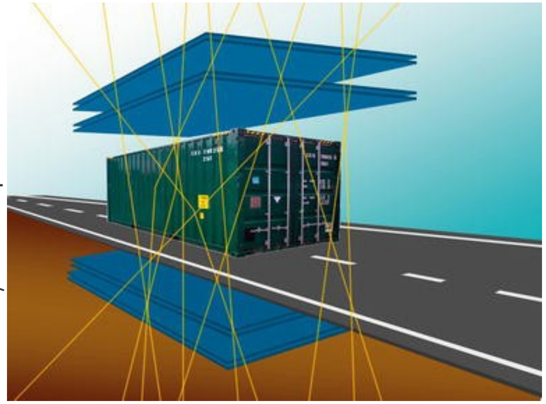
## Medical diagnostics

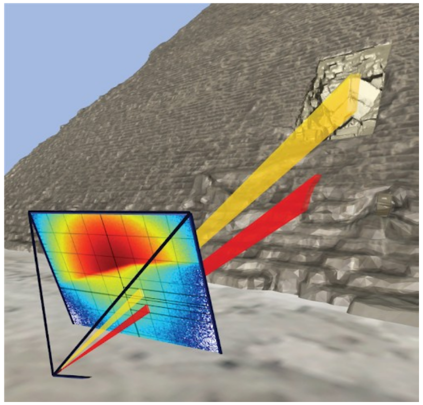



Improved PET with precise time-of-flight over *line of response*

## Muon tomography

10.5772/intechopen.75426





CEA/Irfu

For geology and homeland security

Achieved with micromegas, proposed with GEMs as well

# Conclusions

- Foreseen **roles for micro-pattern gaseous detectors** in HEP experiments at future colliders
  - Muon tracker, calorimeter preshower and readout, TPC readout
- Pivotal role for **resistive MPGDs** in further development from state-of-the-art
  - Higher **space resolution**
  - Intrinsic **spark protection**
  - Multiple layers for **fast timing**
- Ongoing **R&D on resistive materials**

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