

ICFDT8

8th International Conference on Frontiers in Diagnostics Technologies

Towards four-dimensional particle detection: spatial and temporal precision with gas detectors and emerging MPGD technologies

G. Bencivenni¹, G. Felici¹, M. Gatta¹, M. Giovannetti¹, G. Morello¹, M. Poli Lener¹, L. Torlai²,
G. Zunica¹

1. INFN – Laboratori Nazionali di Frascati
2. Università Roma Tor Vergata – INFN Sezione di Roma Tor Vergata

Frascati, October 20th, 2026



Istituto Nazionale di Fisica Nucleare
SEZIONE DI ROMA TOR VERGATA



TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA

Gaseous detectors in HEP

An experimental apparatus, especially in HEP, consists of several subsystems of detectors chosen according to their best performance. The main goal is to measure the characteristics of the particles produced in collisions by answering to the following points:

- Vertex reconstruction
- Charged-particle momenta measurement
- Particle energy determination
- Particle identification

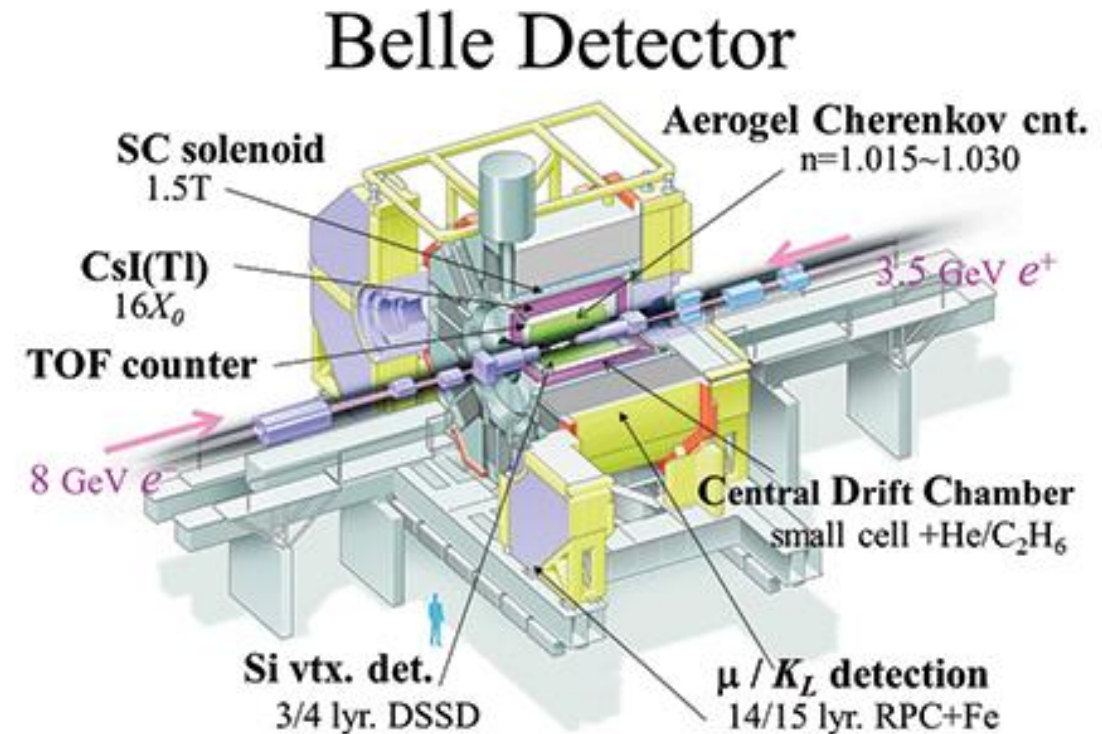
Gruppen & Schwartz, Particle Detectors, CAMBRIDGE

Each of the above points demands for the "best" characteristic of the detector:

- Spatial resolution
- Energy resolution
- Time resolution
- Rate capability

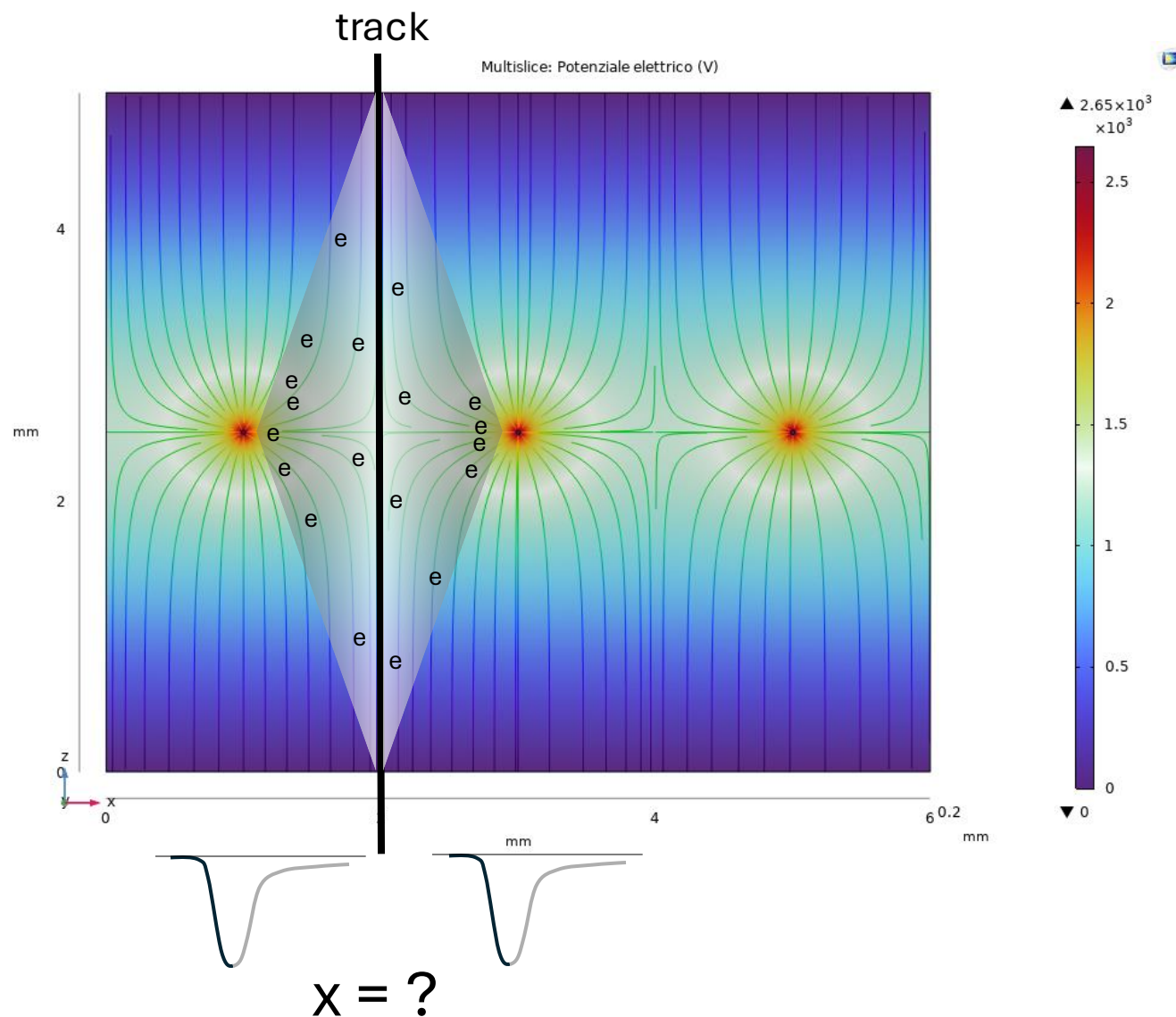
...

Let's start this talk by the first gaseous detectors providing good spatial resolution: Multi-Wire Projection Chambers (**G. Charpak et al., NIM 62 (1968)**)



<https://ihepa.phys.ufl.edu/the-belle-and-belle-ii-experiments-at-kekb/>

Spatial resolution in MWPC



$$\sigma_x^2 = \frac{\int (x - \langle x \rangle)^2 D(x) dx}{\int D(x) dx}$$

In the case of Multi-Wire Proportional Chambers

$$D(x) = \Theta(x - pitch/2)$$

$$\sigma_x = \frac{pitch}{\sqrt{12}}$$

With a typical pitch of the sense wires of 2 mm, we have a spatial resolution around 600 μm

Another way to operate MWPC is to segment the planar electrodes (usually cathodes) in strips/pads with lower pitch, leading to a better spatial resolution

Time resolution

By statistical considerations*, the space distribution of the cluster j ($1 \leq j \leq k$), given the average number per unit length (n), along a normalized z ($0 < z < 1$) coordinate is

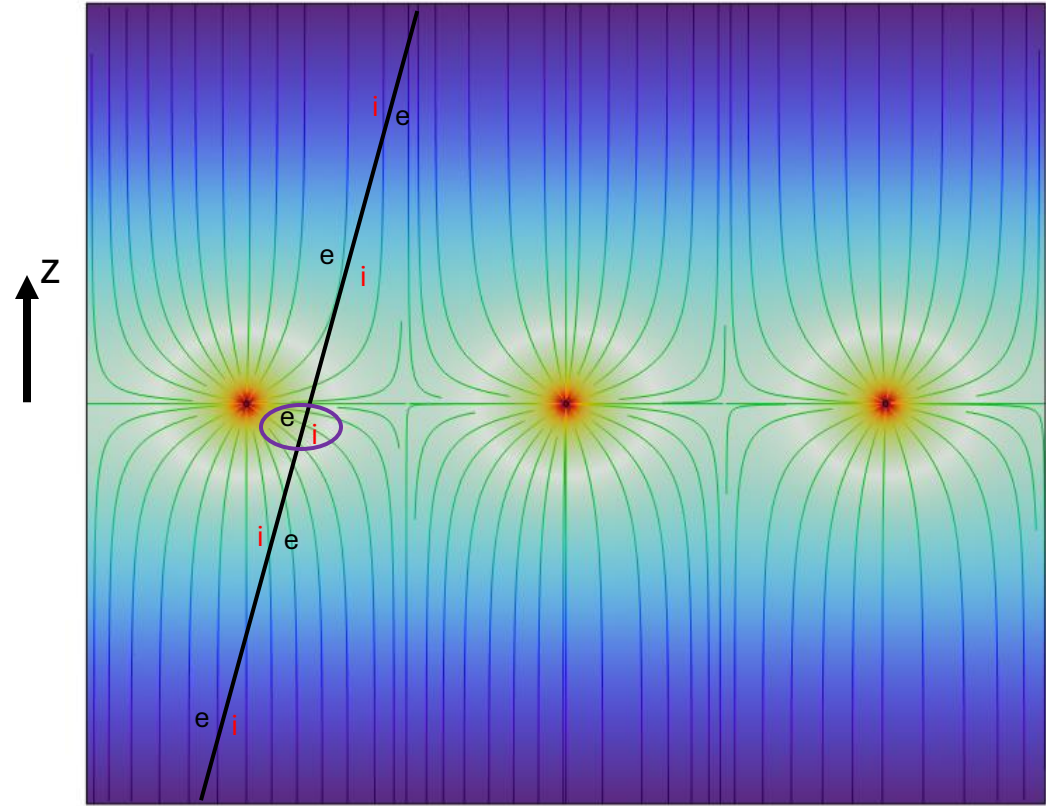
$$A_j^n(z) = \frac{z^{j-1}}{(j-1)!} n^j e^{-nz}$$

Posing $j=1$, considering then the cluster closest to the amplification volume

$$A_1^n(z) = n e^{-nz}$$

Substituting $z = v_d t$

$$A_1^n(z) = n e^{-nv_d t} \Rightarrow \sigma_t(t_d) = \frac{1}{nv_d}$$

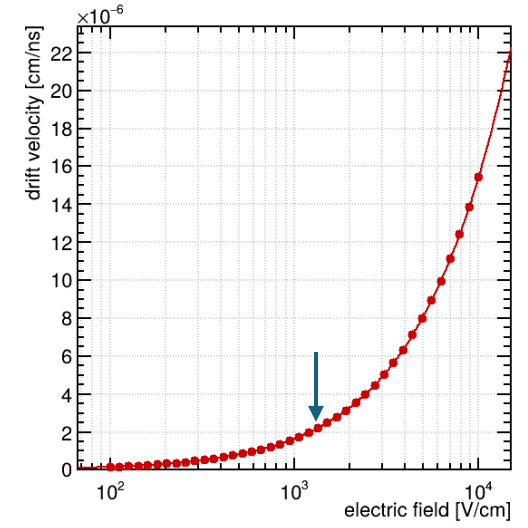
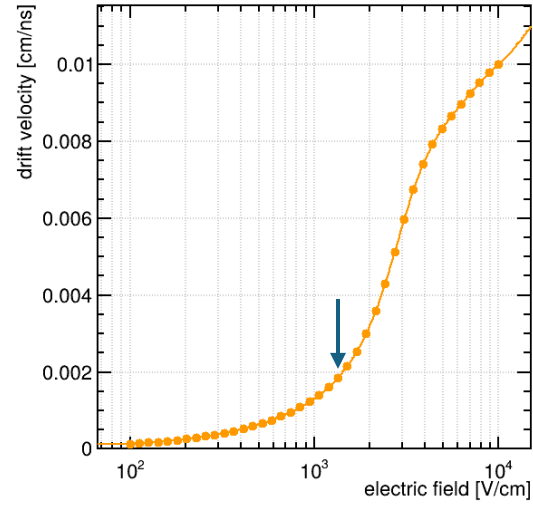


The intrinsic time resolution of a proportional gas, deeply dependent on the capability to detect «the cluster $j=1$ », depends then on the electron drift velocity ($\rightarrow$ drift field) and on the density of cluster ($\rightarrow$ gas mixture).

The intrinsic time resolution represents the maximum limit of the detector time performance. The real time resolution is actually larger.

*F. Sauli, Principles of operation of multiwire proportional chambers, CERN 77-09

Occupancy



MAGBOLTZ 12

- Gas mixture: Ar/CO₂/CF₄ 40/55/5
- $|\vec{E}_{drift}| = 1325 \text{ V/cm}$
- Electron $v_{drift} = 18.4 \text{ } \mu\text{m/ns}$
- Ion $v_{drift} = 0.022 \text{ } \mu\text{m/ns}$
- Ion evacuation time $\sim 2 \text{ mm}/(0.022 \text{ } \mu\text{m/ns}) = 90 \text{ } \mu\text{s} !$

MWPC maximum rate capability: 100 kHz/cm²

Micro-Pattern Gaseous Detectors

The drift field in MWPC is quite constant, excluded a volume of small radius coaxial to the wires
If we cannot play on speed, the only way to reduce the dead time is to act on DRIFT PATH (→ micrometric amplification volume)

MICRO-MESh-GASEous Structure

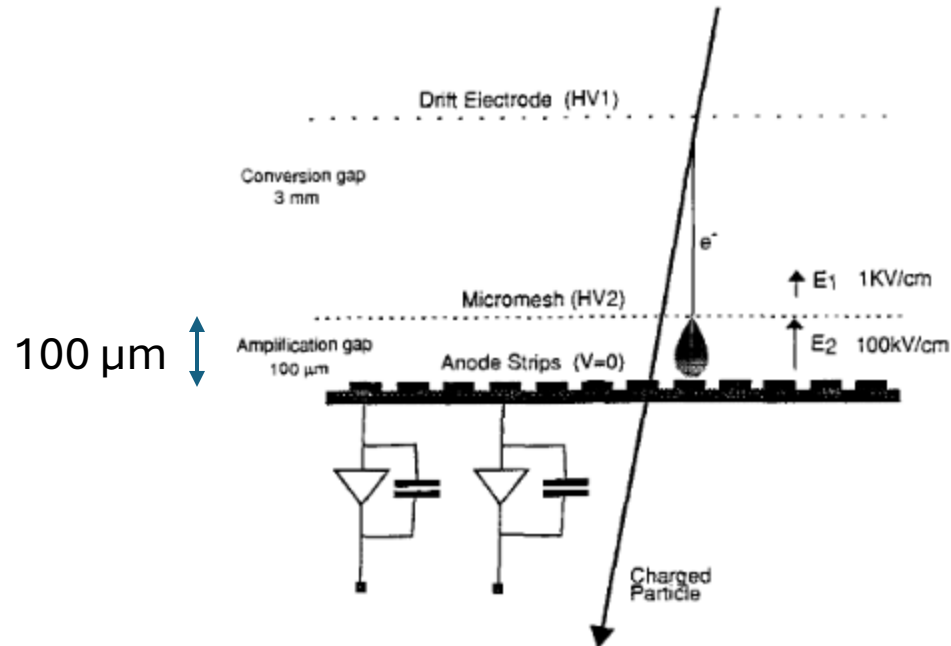


Fig. 1. A schematic view of MICROMEAS: the 3 mm conversion gap and the amplification gap separated by the micromesh and the anode strip electrode.

Y. Giomataris et al., NIM A 376 (1996)

Gas Electron Multiplier

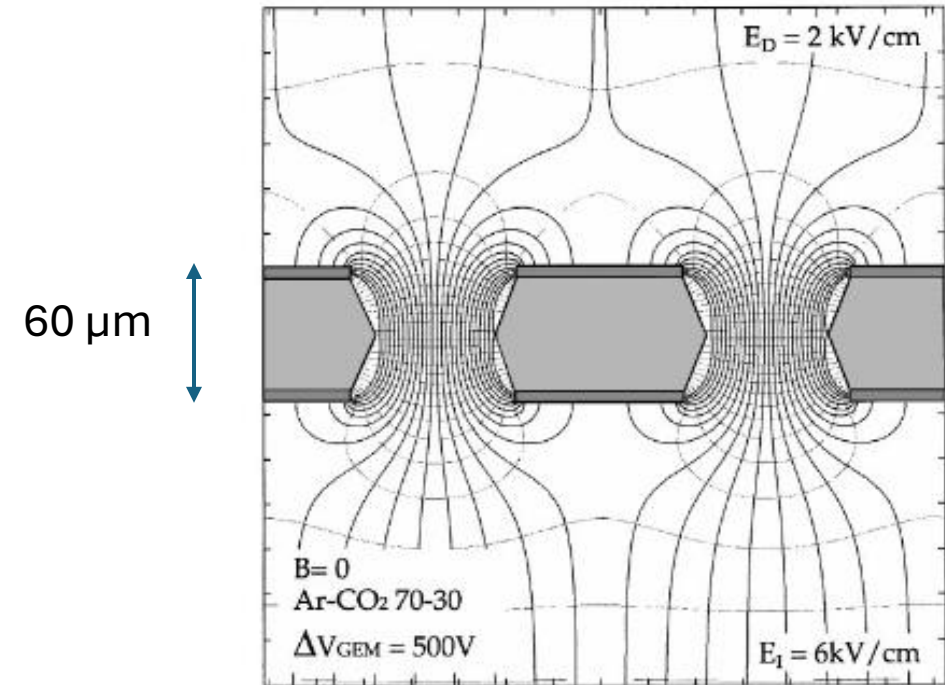


Fig. 6. Electric field map in a typical operating condition.

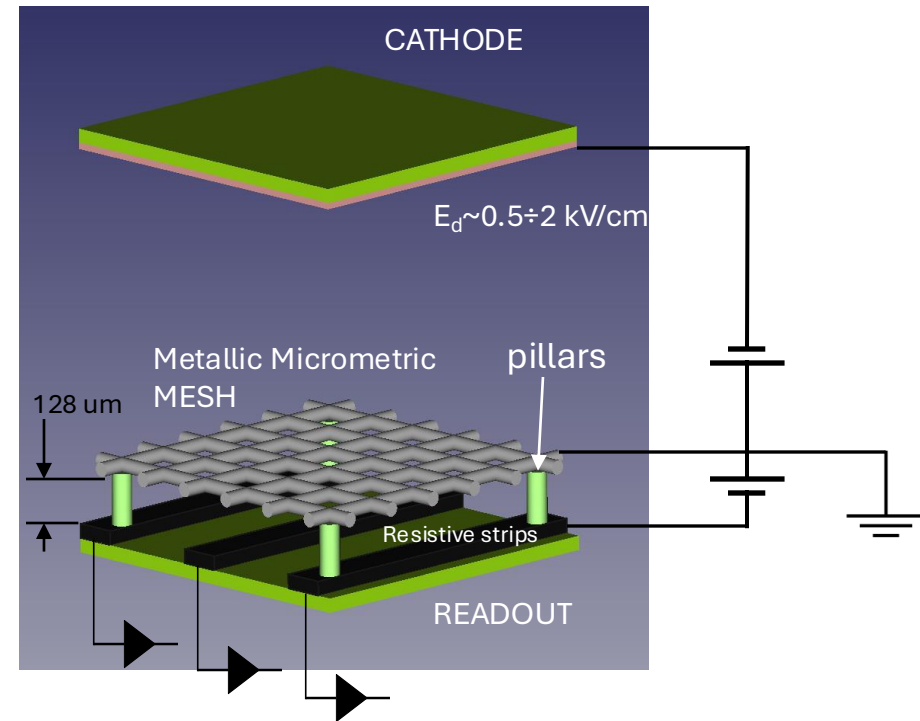
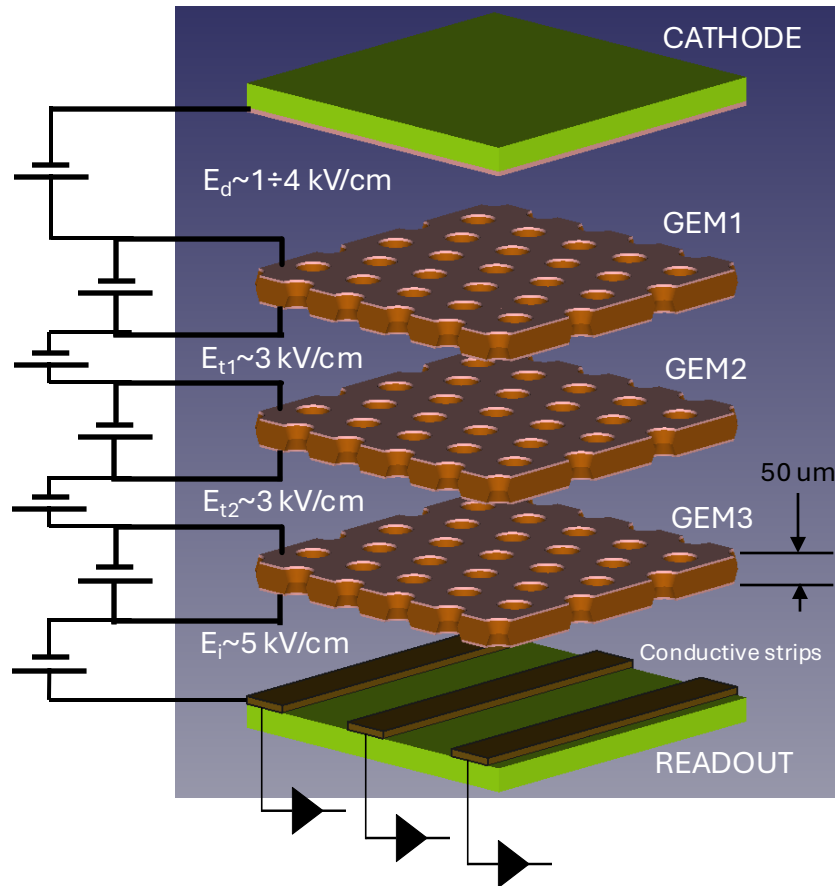
S. Bachmann, F. Sauli et al., NIM A 438 (1999)

Keeping electrodes so close, the discharge probability increases (→ det. stability decreases)

Micro-Pattern Gaseous Detectors

MicroMegas and GEM have been for long time the main detectors belonging to the class of MPGD

MicroMegas improved the robustness to discharges thanks to the introduction of a resistive layer, while GEMs, with a stack of amplification stages allowing to operate each stage at lower potential, reduced the discharge probability **for a single foil**



How to merge and improve the most important features of the two detectors (rate capability, compactness and spark robustness with no need to stretch any electrode)?

Micro-Resistive WELL technology at a glance

Developed in collaboration with CERN-EP-DT-MPT workshop.

- **Spark suppression:** presence of a resistive layer (Diamond-like Carbon) to quench sparks amplitude (like MM)
- **Compactness:** amplification stage (geometry like WELL and GEM) embedded in the PCB readout → multi-layer PCB std. industrial technology → mass production

- **Rate capability** of the order of 1 MHz/cm²
- But the resistive layer introduces a local gain drop as the rate increases

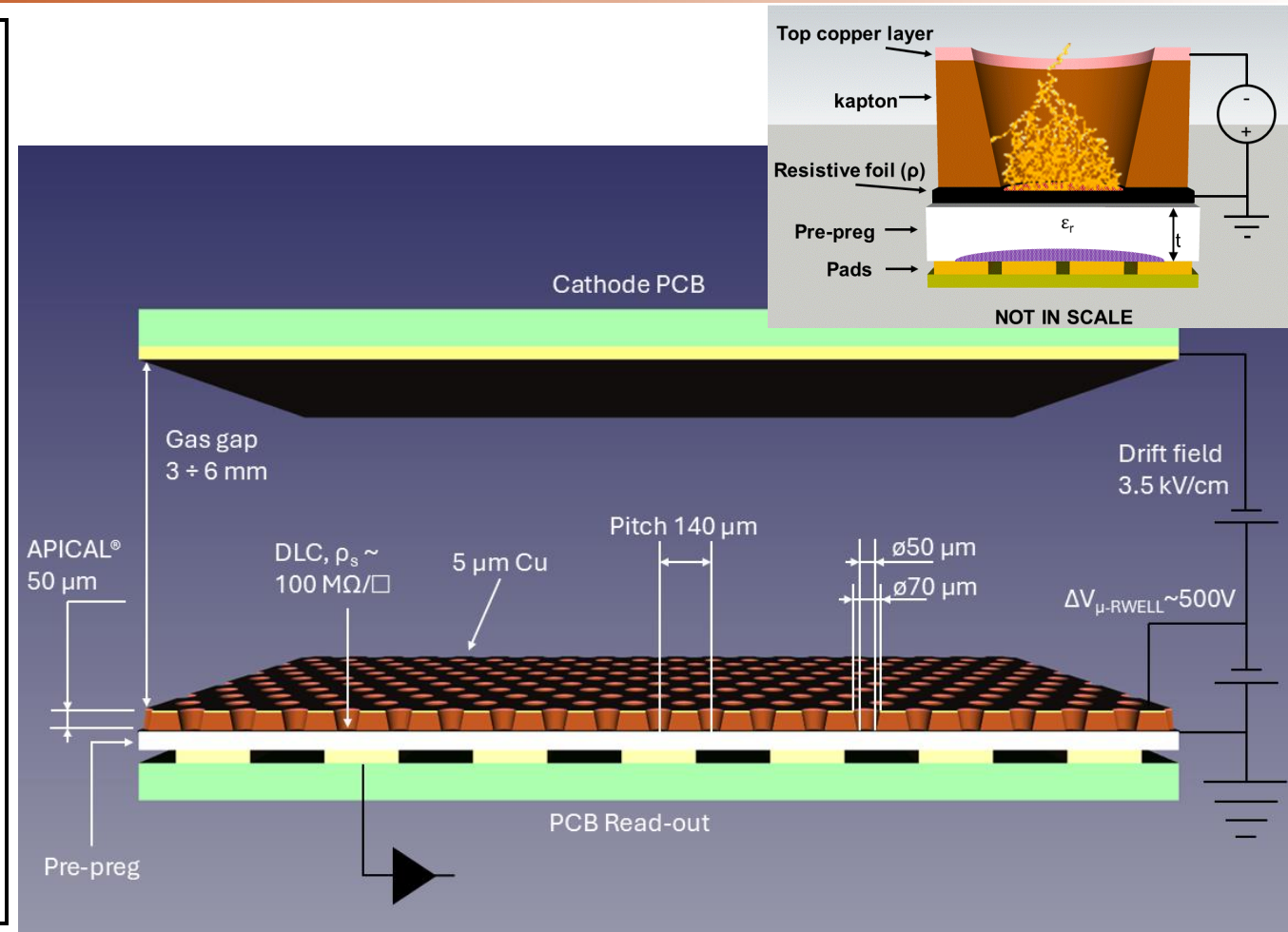
$$\frac{G}{G_0} = \frac{-1 \pm \sqrt{1 + 4p_0\phi}}{2p_0\phi}$$

G. Bencivenni et al., 2015 *JINST* **10** P02008

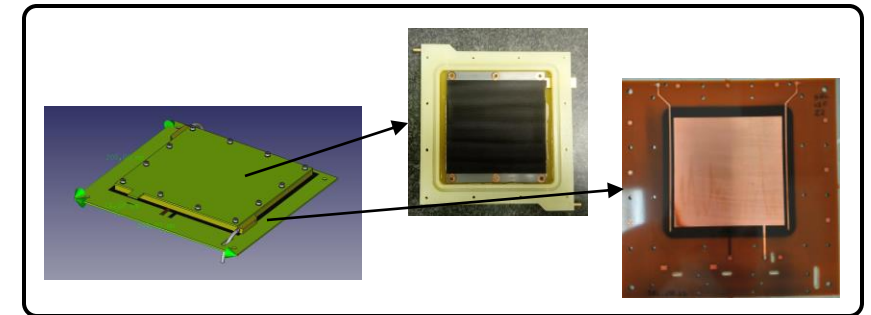
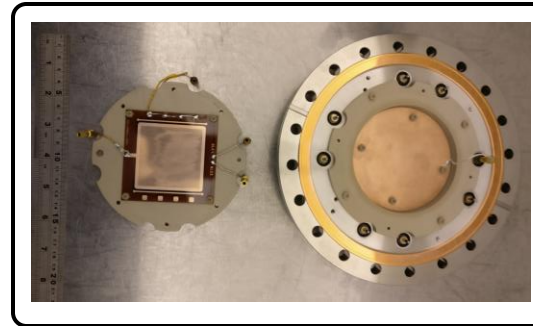
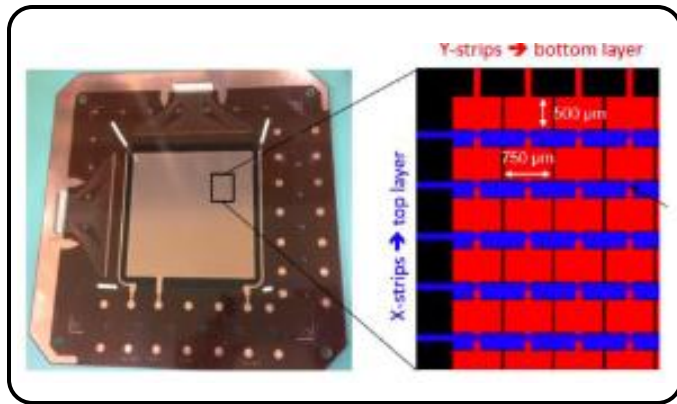
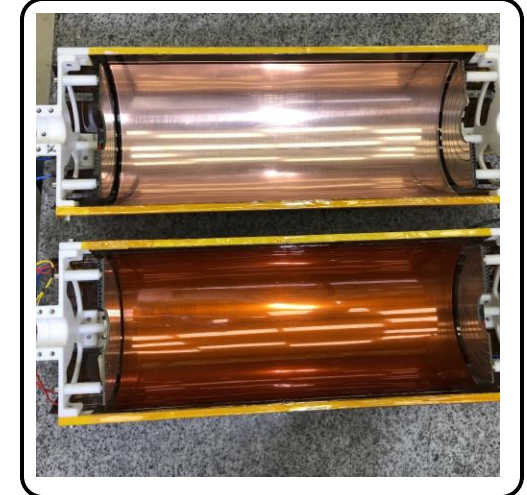
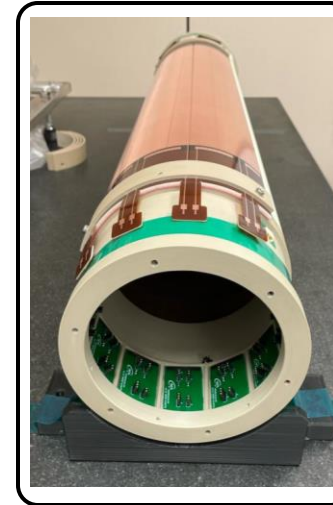
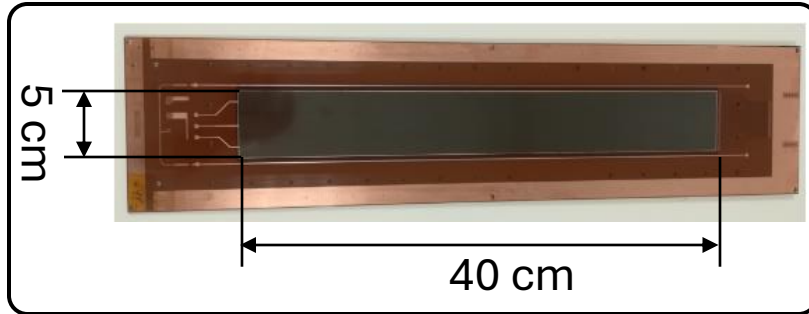
Naïf model for the **average resistance** Ω between the charge point collection and the perimetrical grounding line

$$\begin{aligned}\Omega(r) &= \frac{p_0(r)}{\alpha e N_0 G \pi r^2} \\ &= \rho_s \frac{d - \frac{r}{2}}{\pi r}\end{aligned}$$

α from the fit to the gain vs. applied ΔV
 N_0 from GARFIELD++ simulation
 r radius of the X-rays spot
 d average distance to the ground



Micro-Resistive WELL technology



The technology can be adapted to many geometries, even cylindrical by realizing the μ -RWELL_PCB on flexible substrate

APPLICATIONS FOR HEP AND BEYOND

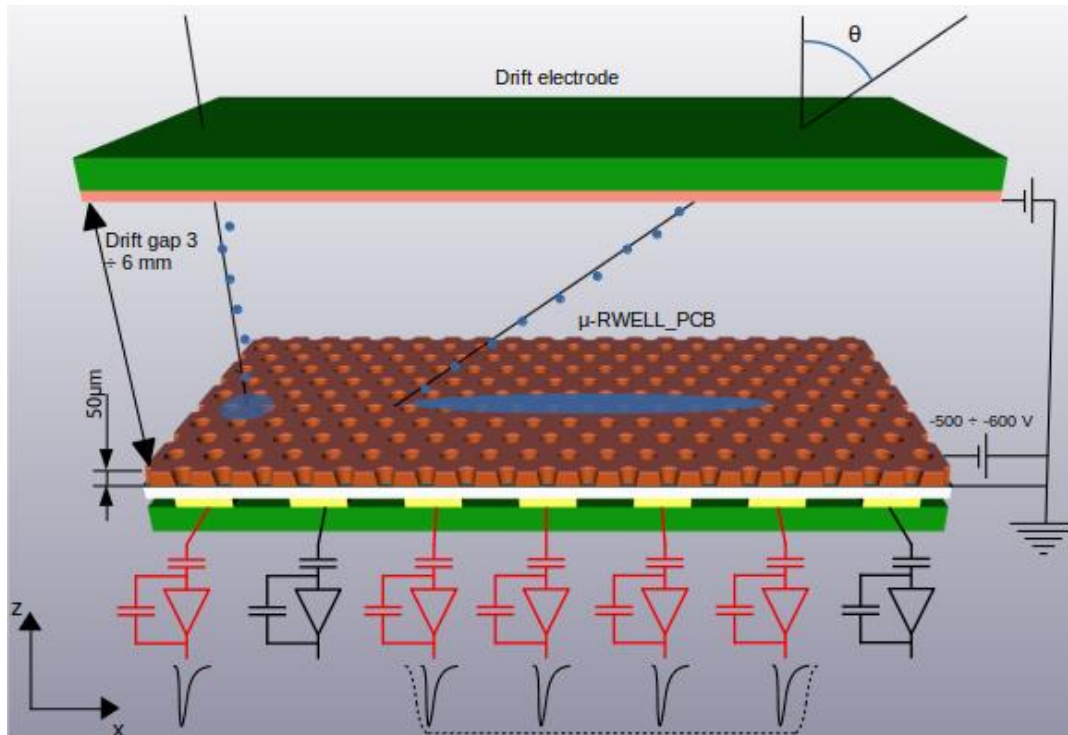
Application in HEP: tracking

The availability to produce large area detector makes this technology suitable for HEP experiments (several m² to be covered), in particular for the subsystems dedicated to particle tracking (→ momentum measurement in magnetic field)

Gluckstern formula:
$$\frac{\sigma(p_T)}{p_t} \approx \frac{\sigma(x)p_T}{0.3 B L^2} \sqrt{\frac{720}{N+4}}$$

↓

Geometrical parameters of the apparatus + detector resolution



The most classical way to translate a collection of signals into a coordinate is through the Charge Centroid (CC) method:

$$x = \frac{\sum x_i q_i}{\sum q_i}$$

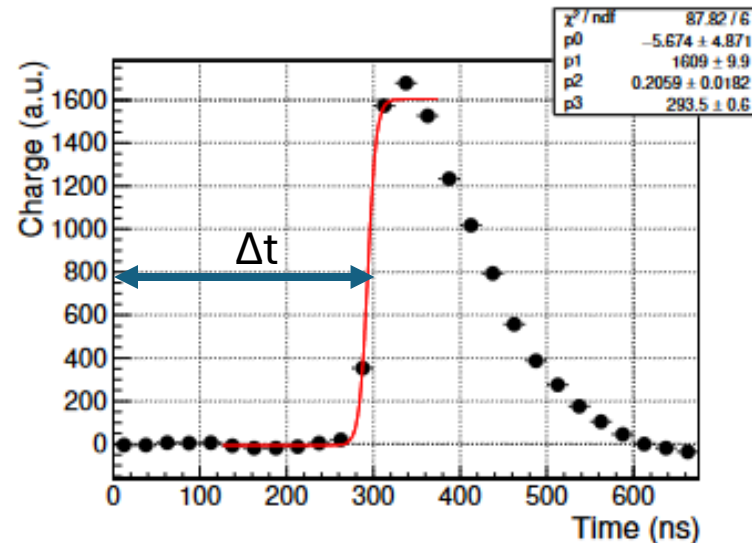
This is possible only by analog front-end electronics (FEE)
The spatial resolution is obviously dependent on how the readout plane is segmented (strips/pads)

Application in HEP: tracking

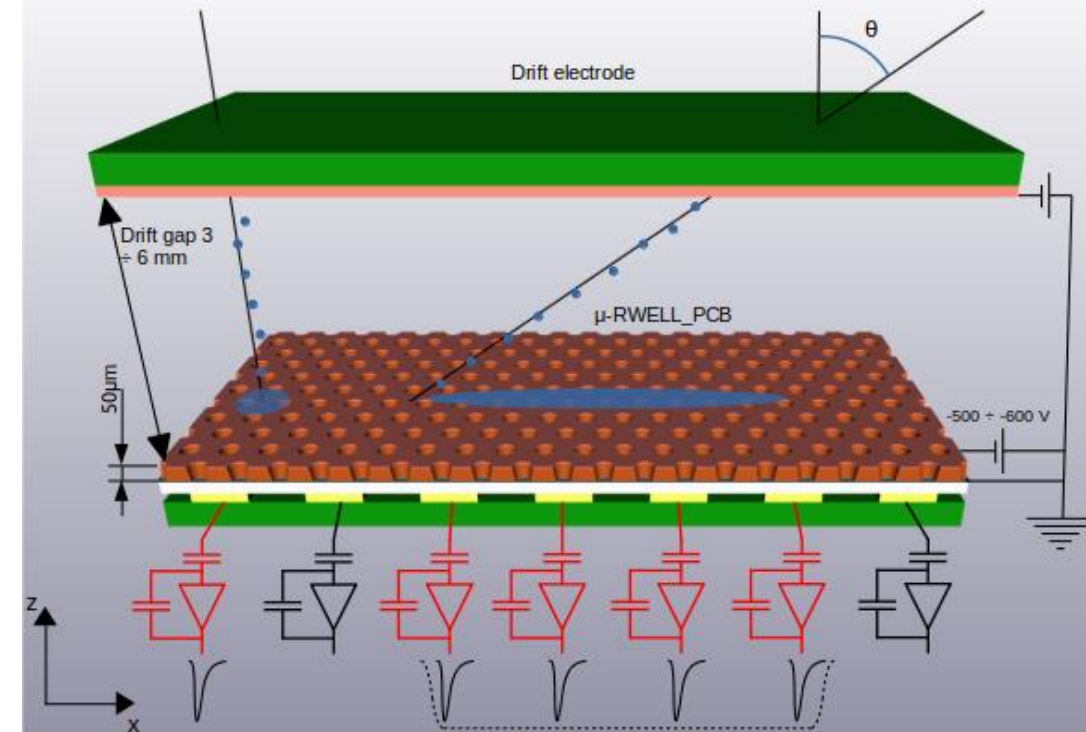
For inclined tracks and/or in presence of high B field, **the charge centroid method doesn't provide an accurate coordinate** on the anode-strip plane.

An improvement of the position reconstruction is given by the μ TPC algorithm (*T. Alexopoulos et al., NIM A 617 (2010) 161*):

the three-dimensional reconstruction of the particle track inside the detector drift gap is performed using the arrival time of the induced signals on the readout

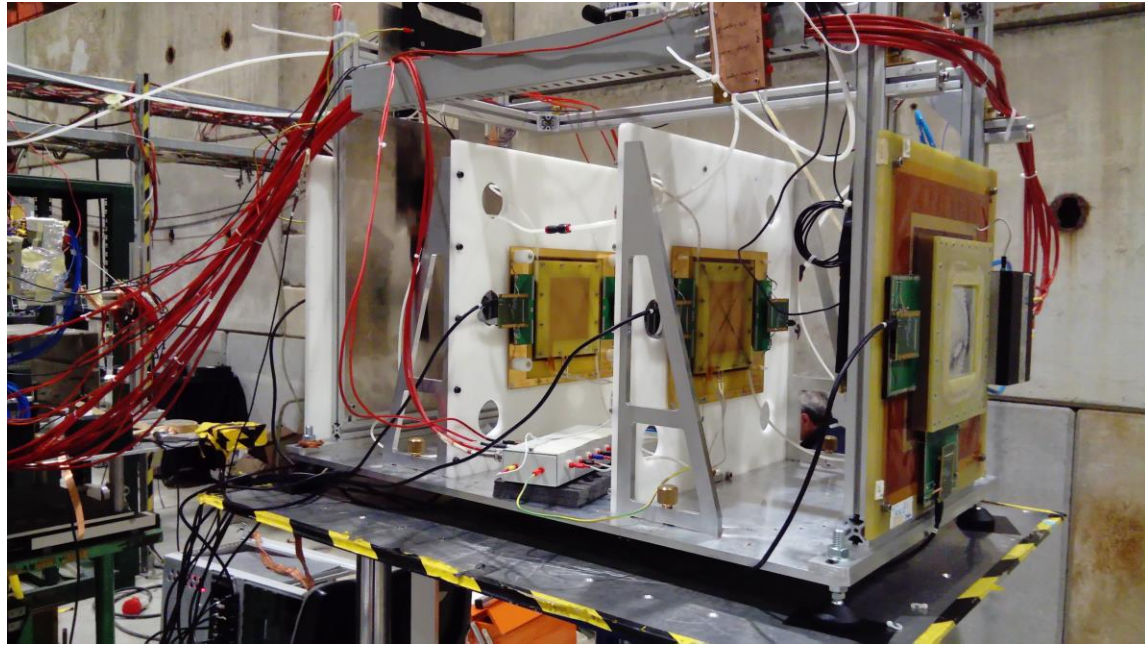


$$z_i = \Delta t_i \cdot v_{\text{drift}}(|\vec{E}|)$$



The track segment is the fit to the (x_i, z_i) coordinates: the associated reconstructed point is then $x @ z = \text{gap}/2$

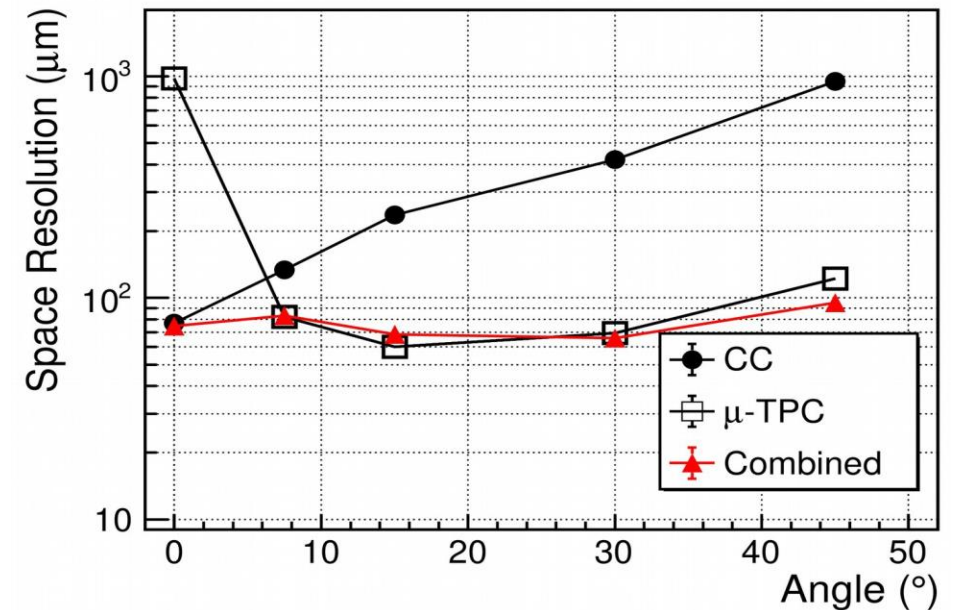
Application in HEP: tracking



- SPS North Area CERN
- Muon beam, $p=150$ GeV/c
- External tracking system based on triple-GEM detectors
- Micro-RWELL detectors installed on rotating plates
- Ar:CO₂:CF₄ 45:15:40
- Studies on spatial resolution with the two methods

The combination of the two methods is a sort of weighted average; the residuals distributions are built with both algorithms and each average and st. dev. (at a given track angles) are then used:

$$x_{\text{comb}} = \frac{x_{\text{CC}}/\sigma_{\text{CC}}^2 + x_{\text{TPC}}/\sigma_{\text{TPC}}^2}{1/\sigma_{\text{CC}}^2 + 1/\sigma_{\text{TPC}}^2}$$



$\sigma_x < 100 \mu\text{m}$ for a wide range of angles

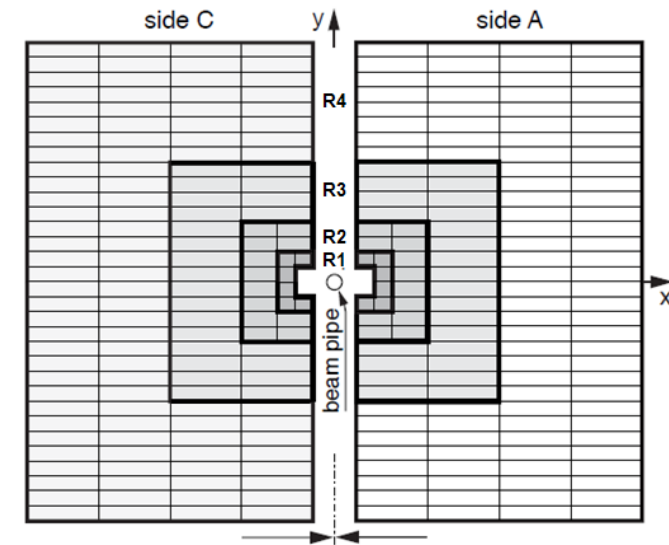
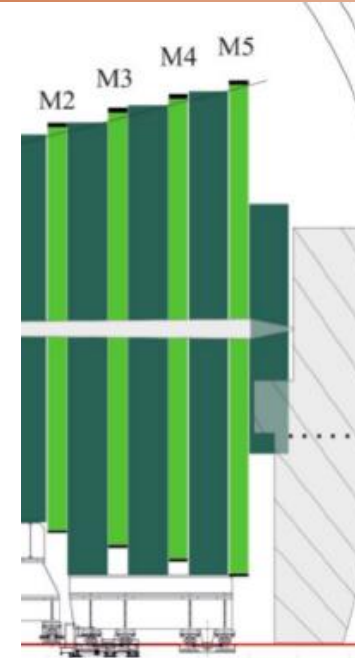
G. Bencivenni et al., 2021 *JINST* **16** P08036

Application in HEP: timing. The LHCb muon case

The muon station of LHCb must provide a high muon detection efficiency in the 25 ns of the LHC bunch-crossing. With the increased luminosity scheduled of LHC (HL-LHC) the present MWPC cannot guarantee this efficiency. The collaboration then looked at MPGD technologies for the innermost region (R1) of the walls.

Requirements for Run 5-6:

- Rate up to 1 MHz/cm^2 per single detector gap; 600 kHz per pad
- Efficiency (station) $> 99\%$ within a BX (25 ns)
- **Stability for 6 y of operation (up to 3 C/cm^2)**

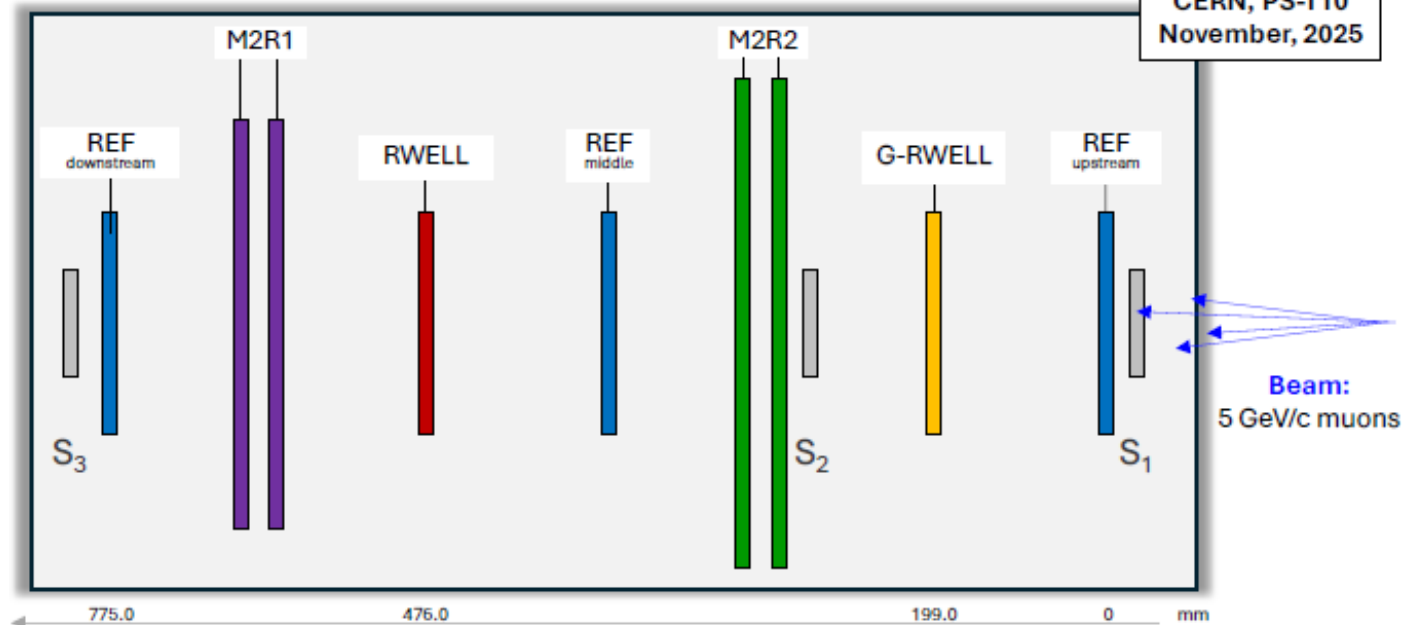


Micro-RWELL technology chosen!

Beam tests: TB-2025 setup



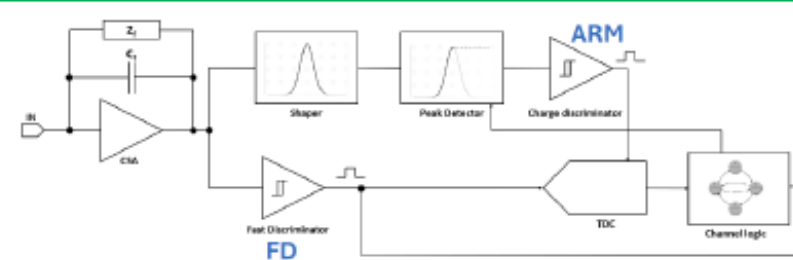
TB area:
CERN, PS-T10
November, 2025



The trigger provided by the coincidence of the three scintillators S₁, S₂, and S₃.

FEBs based on FATIC electronics with dual-threshold (FD-ARM) discrimination, providing independent timing and charge measurements *.

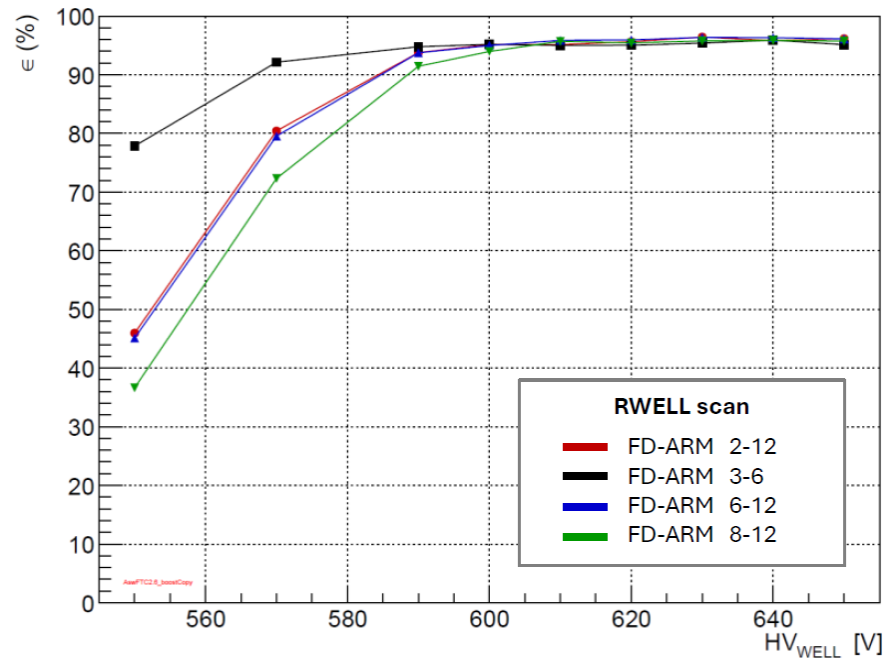
Tracker: μRWELL 10x10 cm ² Pad R/O, 9x9 mm ² Drift: 6 mm TB2024: 1.2 mm pitch-strip	M2R1: G-RWELL 60x25 cm ² instrum. 12.6x15.3 cm ² Pad R/O, 9x9 mm ² Drift-Tran: 6-2 mm	RWELL: μRWELL 10x10 cm ² Pad R/O, 9x9 mm ² Drift: 6 mm	Tracker: μRWELL 10x10 cm ² Pad R/O, 9x9 mm ² Drift: 6 mm	M2R2: G-RWELL 30x25 cm ² Instrum. 14.4x14.4 cm ² Pad R/O, 9x9 mm ² Drift-Tran: 6-2 mm	G-RWELL: G-RWELL 10x10 cm ² Pad R/O, 9x9 mm ² Drift-Tran: 6-3 mm	Tracker: μRWELL 10x10 cm ² Pad R/O, 9x9 mm ² Drift: 6 mm TB2024: 1.2 mm pitch-strip
--	---	--	--	---	--	--



F. De Bernardis, MPGD26, Prague

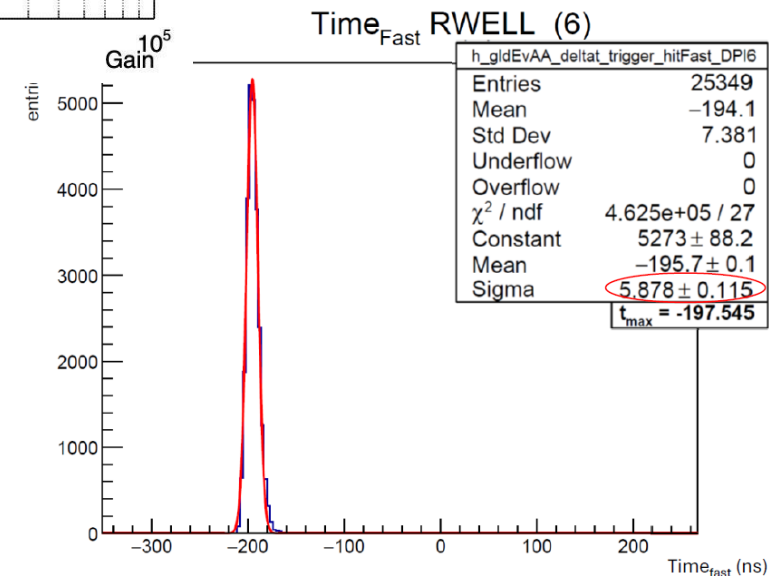
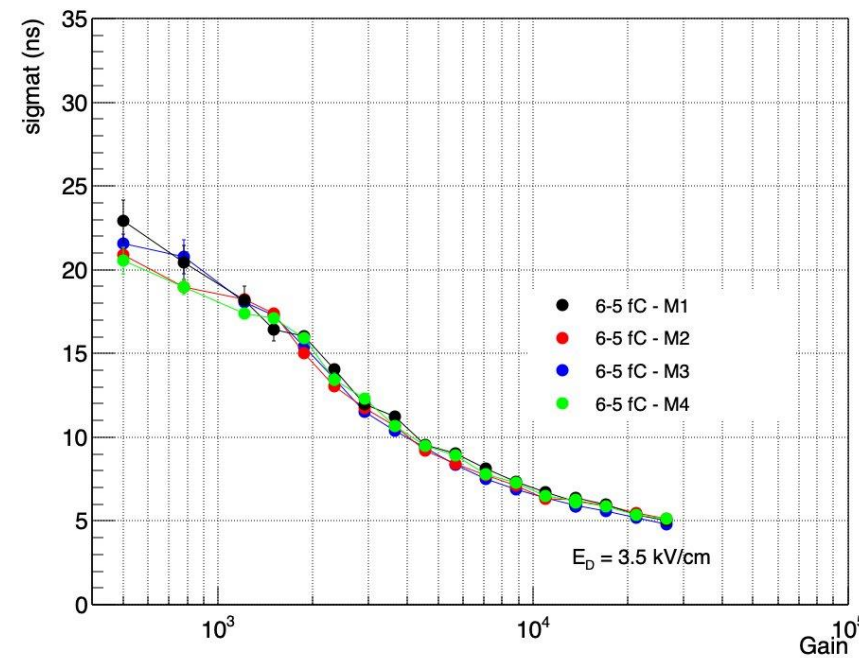
Application in HEP: timing

μ RWELL Raw Efficiency



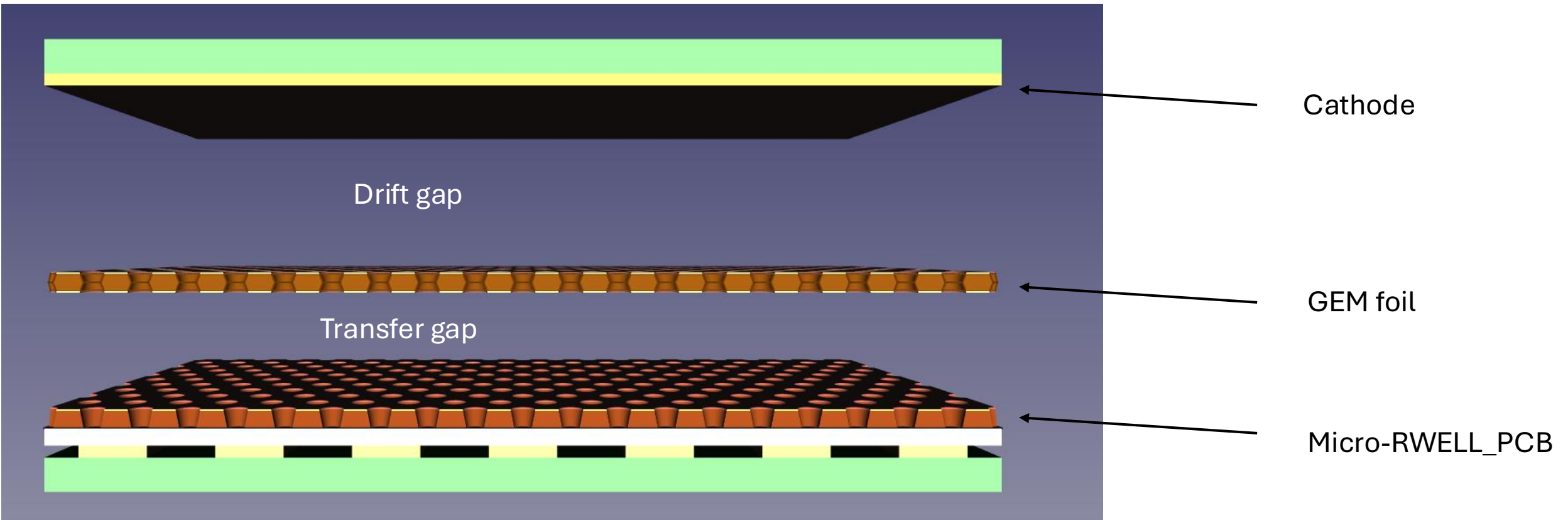
Fraction of event recorded in a Field of Interest around the expected track position

Efficiencies scans for different amplification value ($\rightarrow$ detector gain)
Gas mixture: Ar/CO₂/CF₄ 45/15/40



Application in HEP: timing

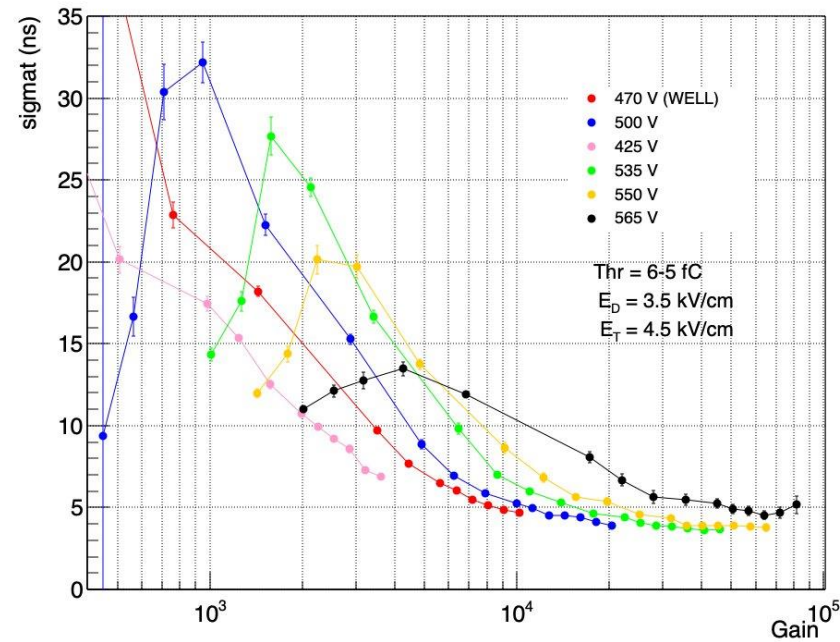
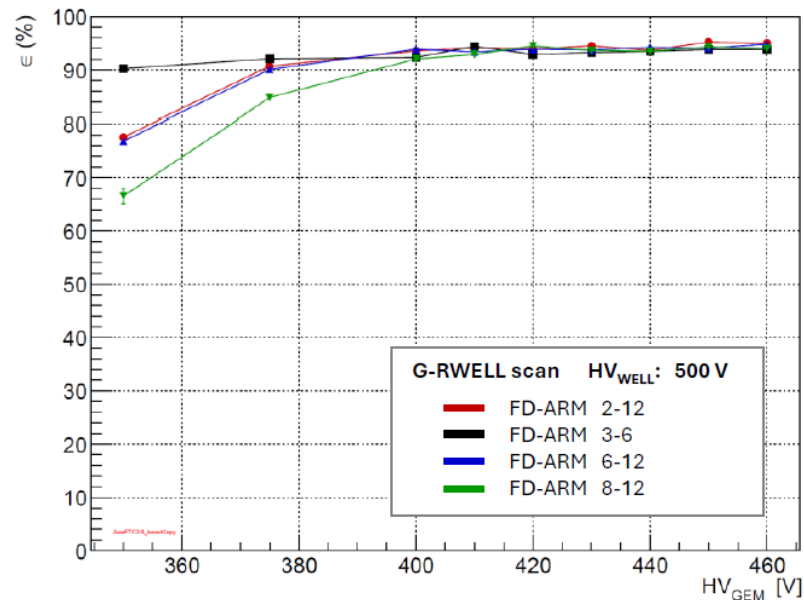
An attempt to improve the time resolution is to insert a pre-amplifications stage, giving birth to the GRWELL



The total gain of the detector strongly increases maintaining the HV of the single stages in «safe operation» (→ reduced instability). On the other side the parameter phase space gets larger

Application in HEP: timing

G-RWELL Raw Efficiency

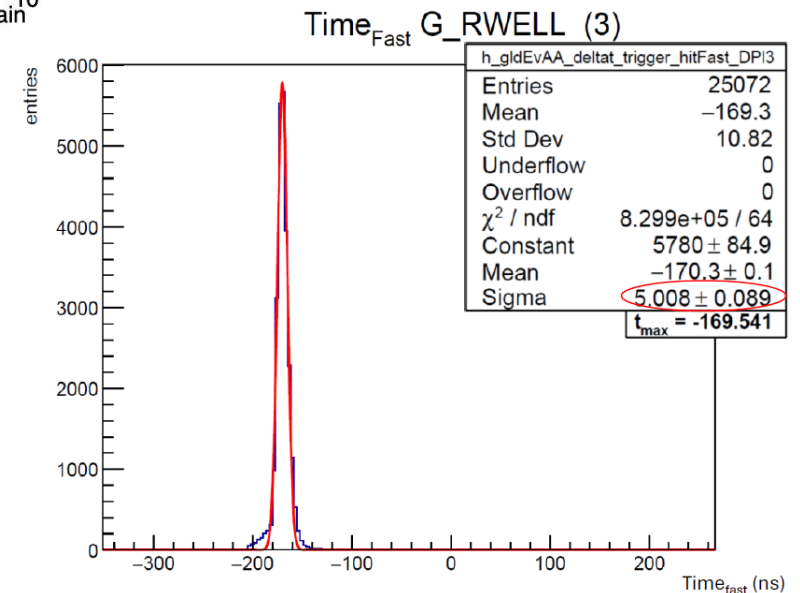


In this case the HV of the μ -RWELL is fixed to 500 V, spanning on the GEM electrodes

The Raw efficiency quickly reaches the plateau thanks to larger signals w.r.t a single amplification stage detector

Gain fluctuations on the μ -RWELL stage produce anticipated signals, consequently worsening the time resolution

Still under investigation solutions to mitigate this effect (thinner transfer gap)



Conclusions

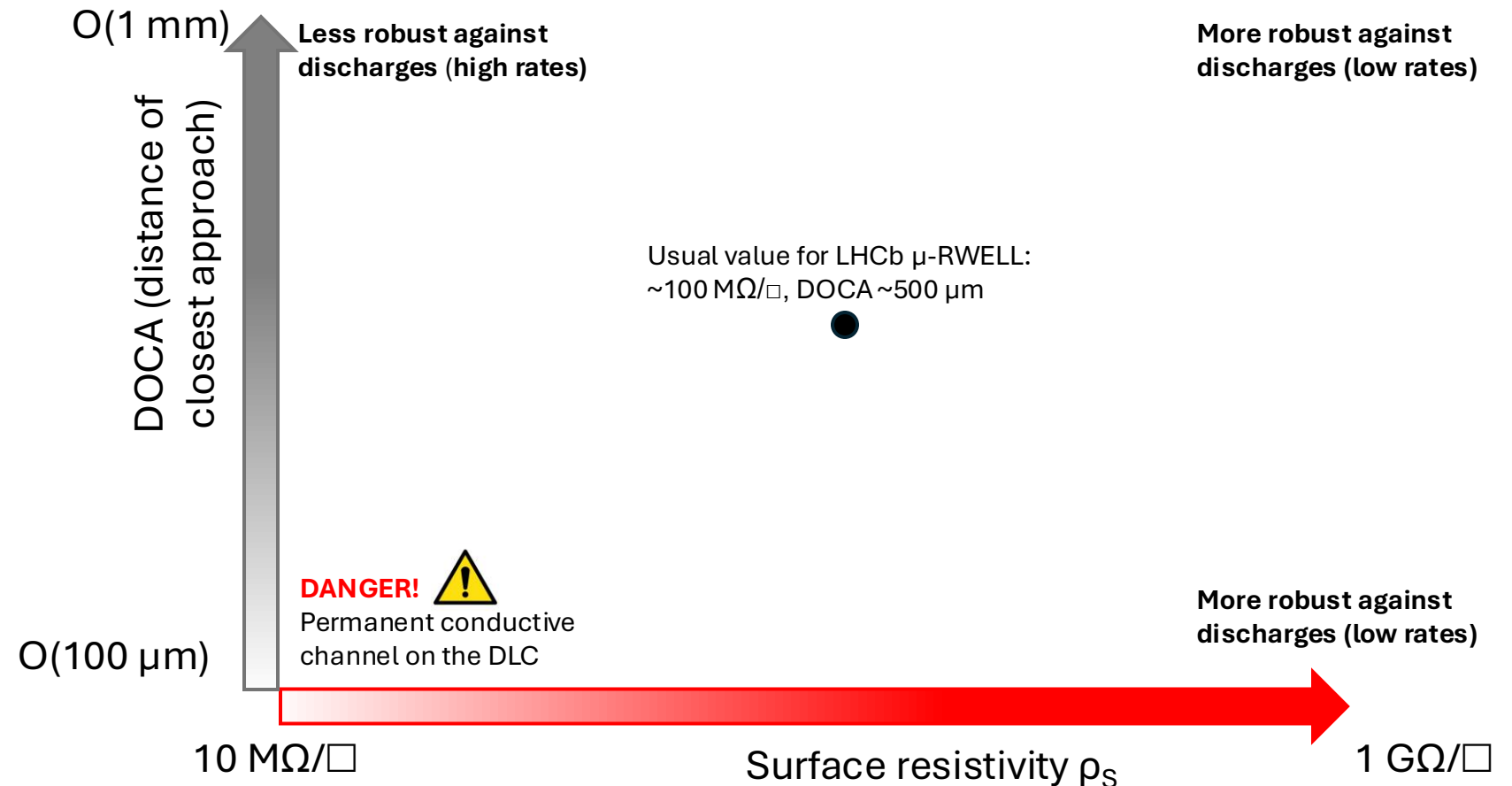
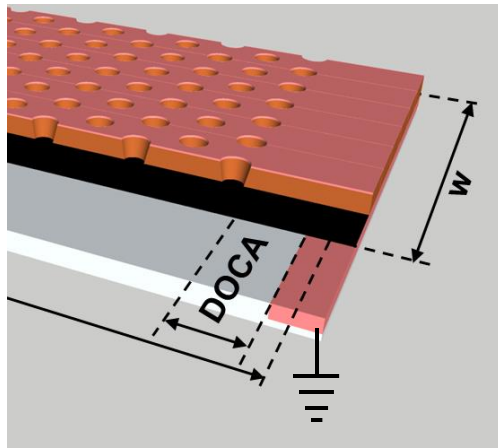
- Gaseous detectors are widely used in HEP and beyond thanks to their versatility
- Good spatial resolution ($>100\text{ }\mu\text{m}$) can be achieved with μ -RWELL
 - a proper segmentation of the readout plane
 - with a suitably performing front-end electronics
 - applying algorithms to adapt the track reconstruction to the geometry of the apparatus
- Good time resolution (around 5 ns) can be reached already with a single amplification stage; the insertion of a pre-amplification region allows to operate the detector at safer working points ($\rightarrow$ stability)
- Rate capability up to 1 MHz/cm^2
- NEXT STEP: combining the two features for a 4-D response!

SPARE

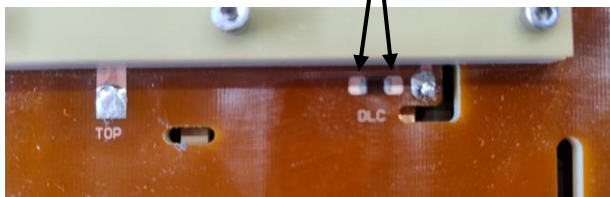
Key points: high-rate or low-rate applications?

Like any resistive detector, also this technology could suffer high-rate exposition. But the local **charging-up** of the resistive layer can be **mitigated** through proper choices of the parameters.

We can introduce two values:



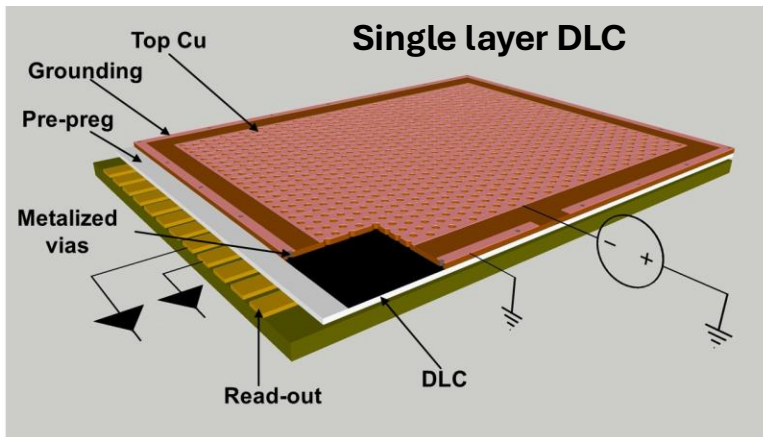
Small pads for local ρ_s meas.



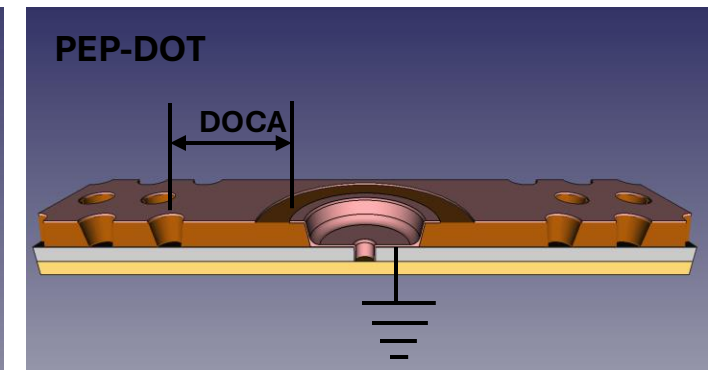
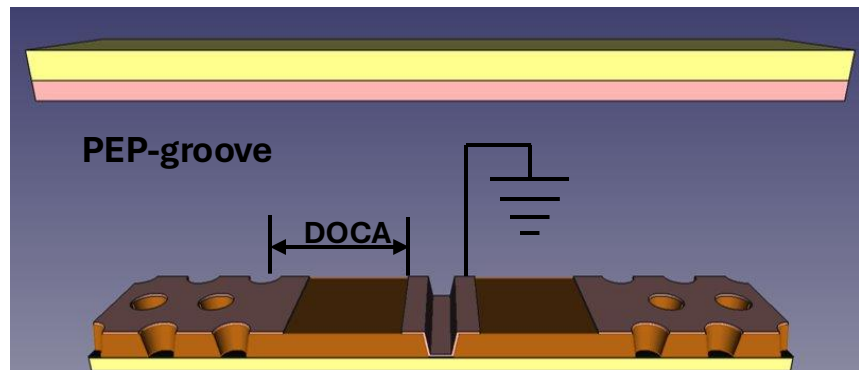
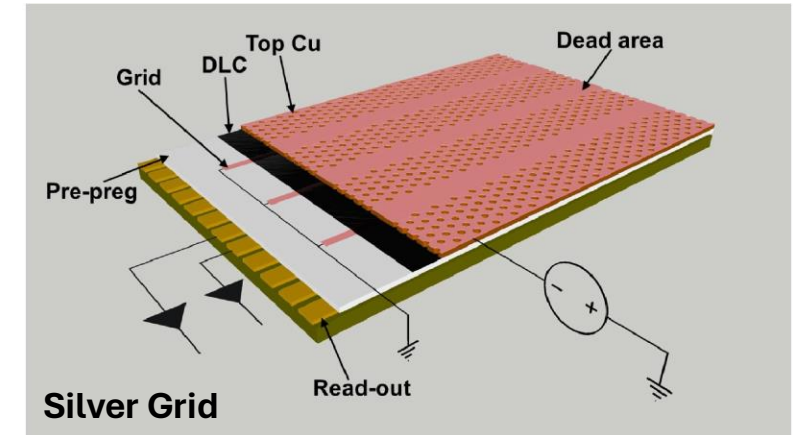
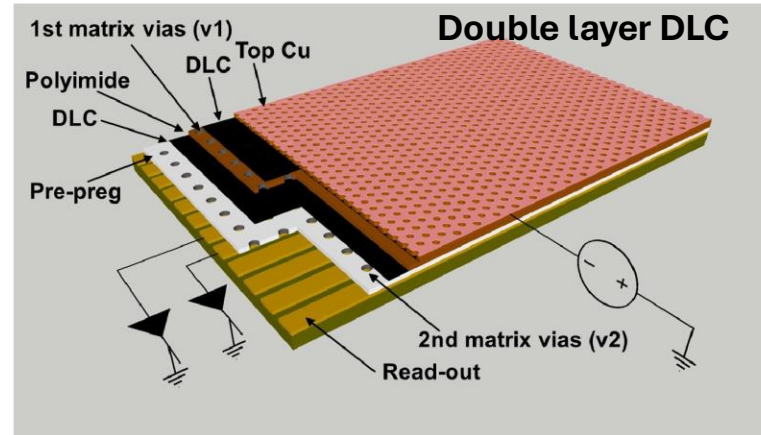
How does the grounding scheme affect the amplification layout?

Key points: DLC grounding, the evolution of the species

Low-rate-oriented DLC grounding scheme



High-rate-oriented DLC grounding schemes

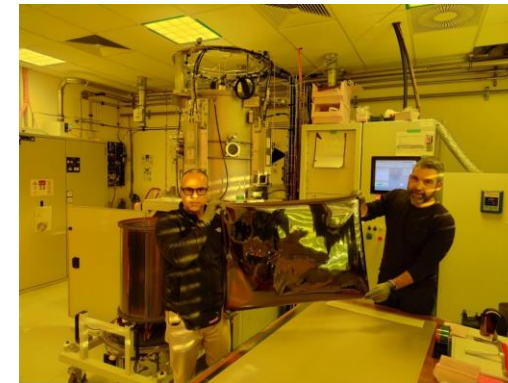
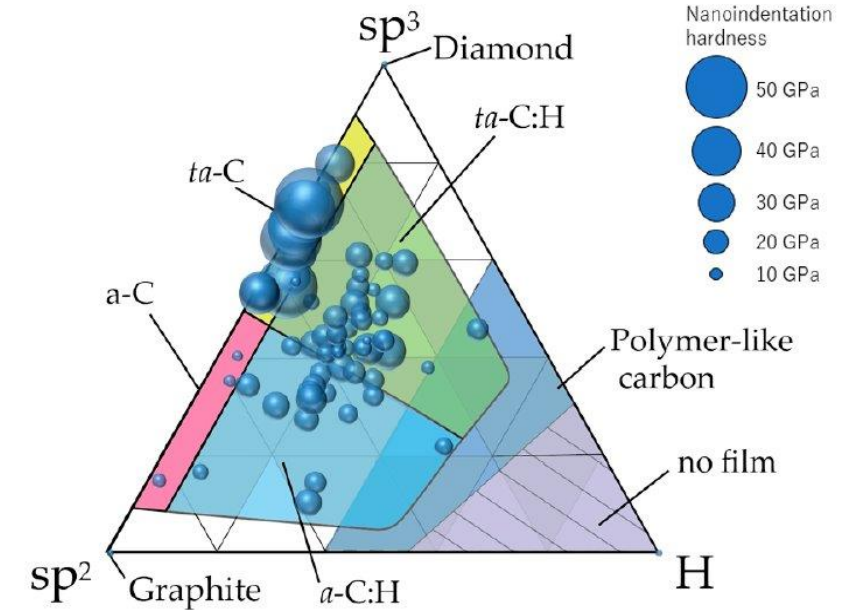
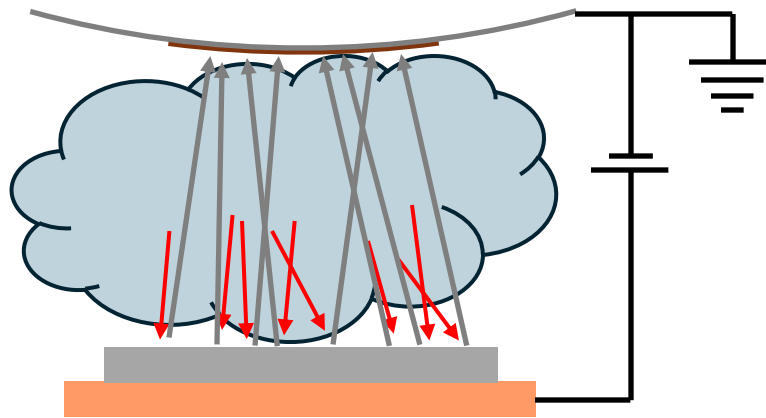


The grounding obviously depends on the destination of the detector; in case of high-rates applications the dead area must be carefully taken into account and of course **it affects the production process (MPT workshop).**

The DLC is connected to the ground of the HV system. The pitch of these connections affects the rate capability.

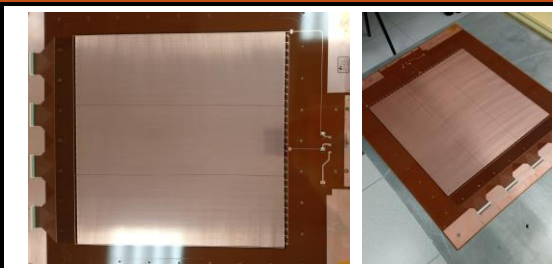
DLC machine

The purpose of this machine is to create another production center for the sputtering of amorphous graphite on rigid/flexible substrates



Thanks to the collaboration with MPT workshop, LNF-DDG is already producing foils for LHCb μ -RWELL ($\sim 100 \text{ M}\Omega/\square$)

Transfer technology



- 576 detectors
- Up to 90 m² to be covered
- **Need for industry!!!**

The three stages are embedded in a single PCB, produced by **standard rigid-flex PCB manufacturing (even involving mixed multi-layer)**.

MEMENTO:
Amplification stage +
Resistive stage +
Readout plane =
 μ -RWELL_PCB

