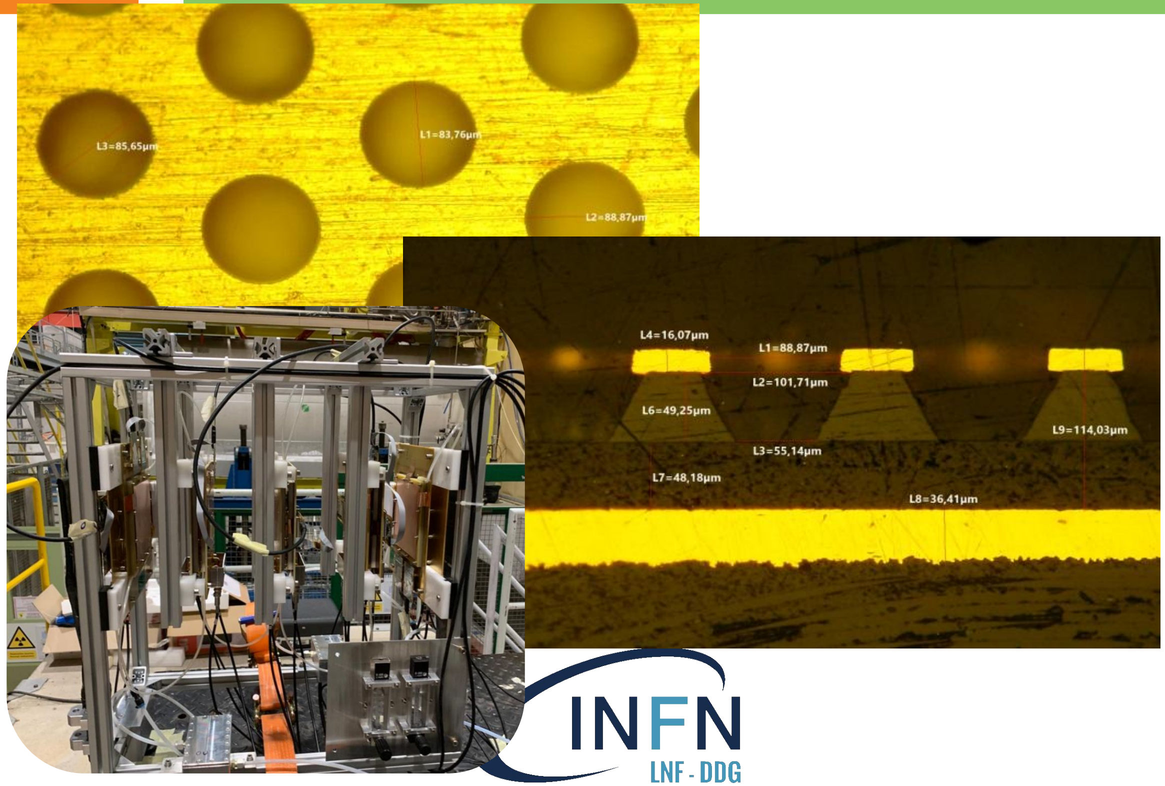
The µ-RWELL technology for the IDEA Muon System



INFN
LNF - DDG

Marco Poli Lener
presented by **Riccardo Farinelli**
on behalf of INFN – IDEA group

Muon physics

Flavour and rare decays

The abundant production of **beauty and charm hadrons** at Z^0 pole offers outstanding opportunities in flavour physics that in general exceed those available at Belle II and are complementary or more sensitive to the heavy-flavour programme of the LHC.

Rare flavour-changing neutral currents sensitive to **new physics**

Mass resolution and **muon identification** → crucial for separating close-in-mass states like

B^0s → **$\mu^+ \mu^-$** (5366 MeV/c2)

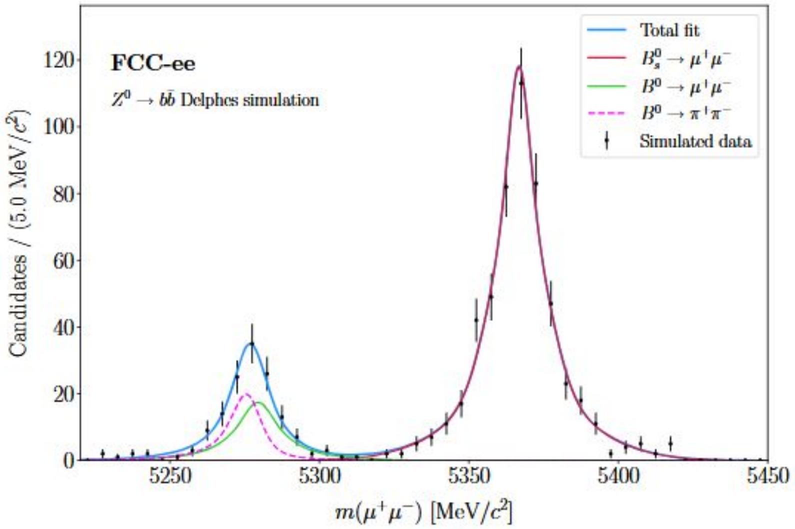
B^0 → **$\mu^+ \mu^-$**(5279 MeV/c2)

with their branching fractions → powerful test of minimal flavour violation

[2] LHCb collaboration, Phys. Rev. Lett. 118, 191801 (2017) [1703.05747]
[3] ATLAS collaboration, JHEP 04, 098 (2019) [1812.03017]
[4] CMS collaboration, JHEP 04, 188 (2020) [1910.12127]
[5] M. Beneke, C. Bobeth, R. Szafron, JHEP 10, 232 (2019)
[6] S. Monteil and G. Wilkinson, Eur. Phys. J. Plus (2021) 136:837

Advantageous attributes for flavour physics studies at Belle II (ϒ(4S)), the LHC (pp) and at Z^0 pole

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

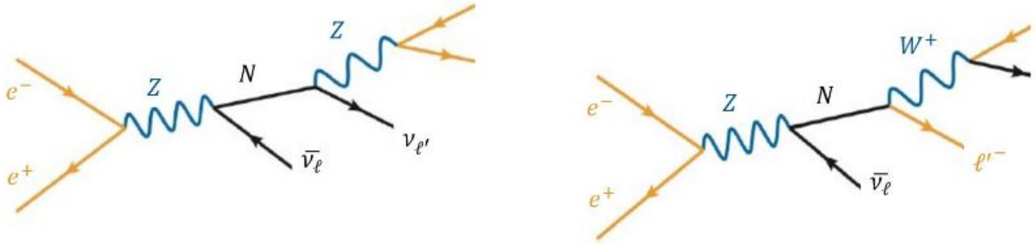


Muon physics

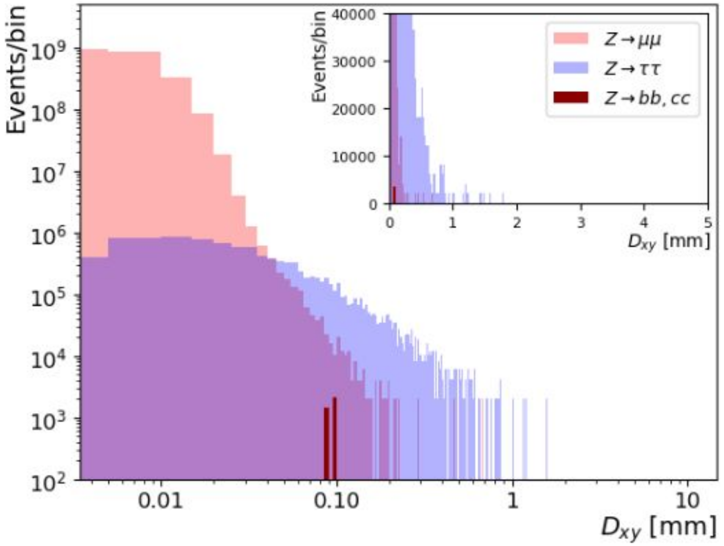
Heavy Neutral Lepton searches

Detecting HNLs

- **LLP signature** discrimination due a **clean background**
- **Reconstruction displaced** decays with **precise tracking/ vertixing**
- Sensitive to **low-mass HNLs** (5 ÷ 85 GeV) via rare Z or W decays
  - **Fully leptonic** decay **μ μ v_μ**
  - **Semi-leptonic** decay into **μj j'** where j and j' are jets from q q′ pairs coming from the charged vector boson coupling with HNL and muon



Reconstructed transverse distance Dxy between the displaced vertex and the interaction point.



Background from heavy-quark **production is strongly suppressed** by the exclusive requirement of **two final-state muons**, while **the τ -induced background** exhibits a tail extending up to **a few millimeters**

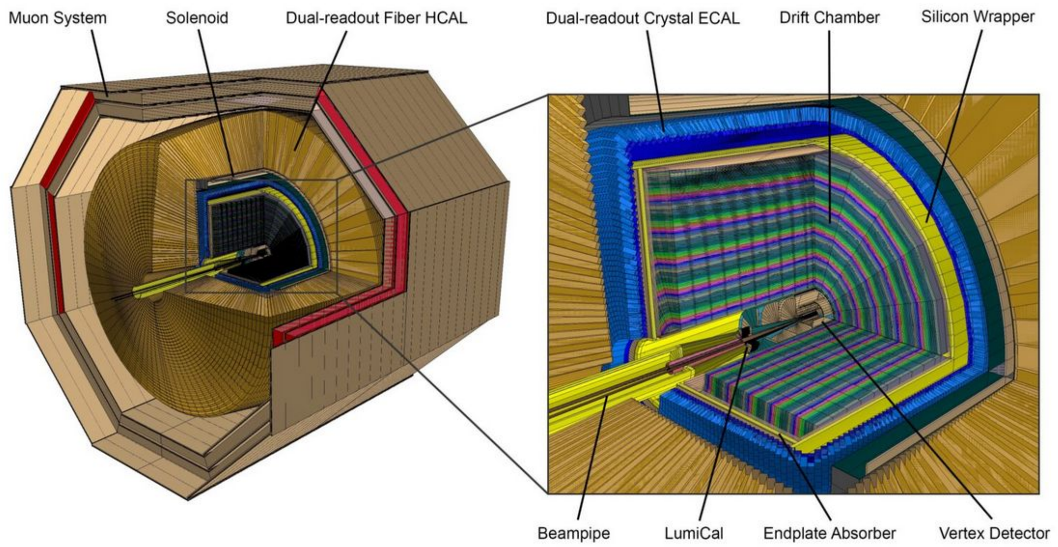
[7] L. Bellagamba et al., arXiv:2503.19464 [hep-ex]

The IDEA detector

Gaseous detectors have historically been favoured for muon detection at colliders like LEP and LHC due to their **cost-effectiveness** for **large areas**, **high time and position resolution and robustness** (RPC, drift-tube, etc).

Decades have passed since the last muon apparatus were built, during which significant advancements have been made in detector technologies, particularly in **Micro-Pattern Gaseous Detectors (MPGDs):**

- **Micro-Megas** and **GEM** are used for **ATLAS and CMS** muon detector upgrade in the endcap region to handle the LHC rate
- **μ-RWELL**, an innovative type of gaseous detector, expected to have significantly improved capabilities in high-rate intensity environments such as in **LHCb Phase II**.



Muon requirements:

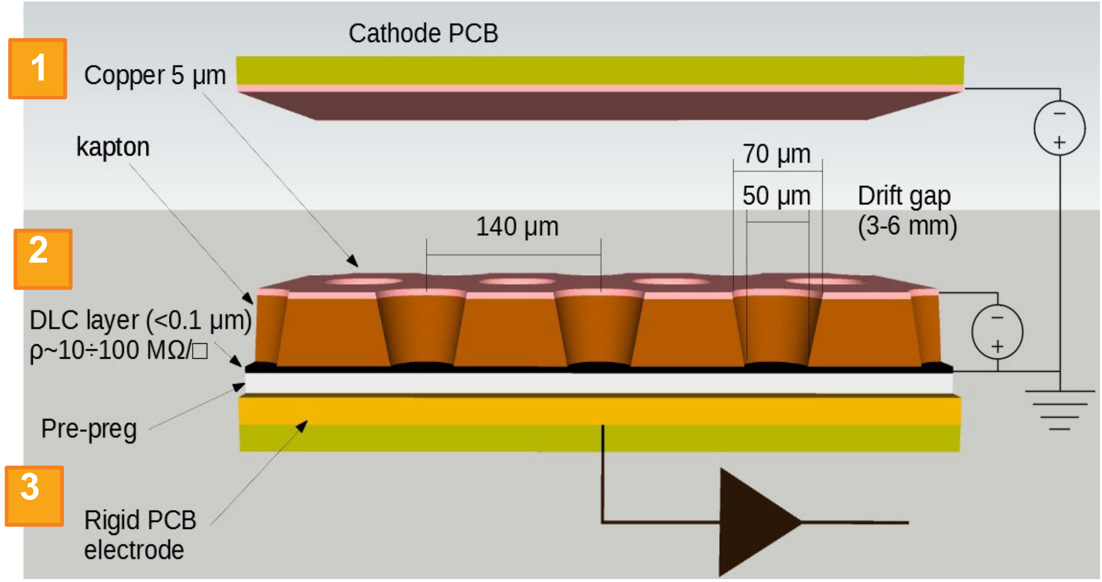
- Tiles: 50x50 cm^2 with X-Y readout
- Efficiency ≥ 98%
- Space resolution ≤ 200 μm
- Particle Flux < $1kHz/cm^2$
- Instrumented Surface/FEE: 1500 m^2 (6000 det.), ~5×10^6 ch.
- Mass production ⟶ Technology Transfer to Industry
- FEE Cost reduction ⟶ custom made ASIC (based on TIGER or the new TORA CHIP)

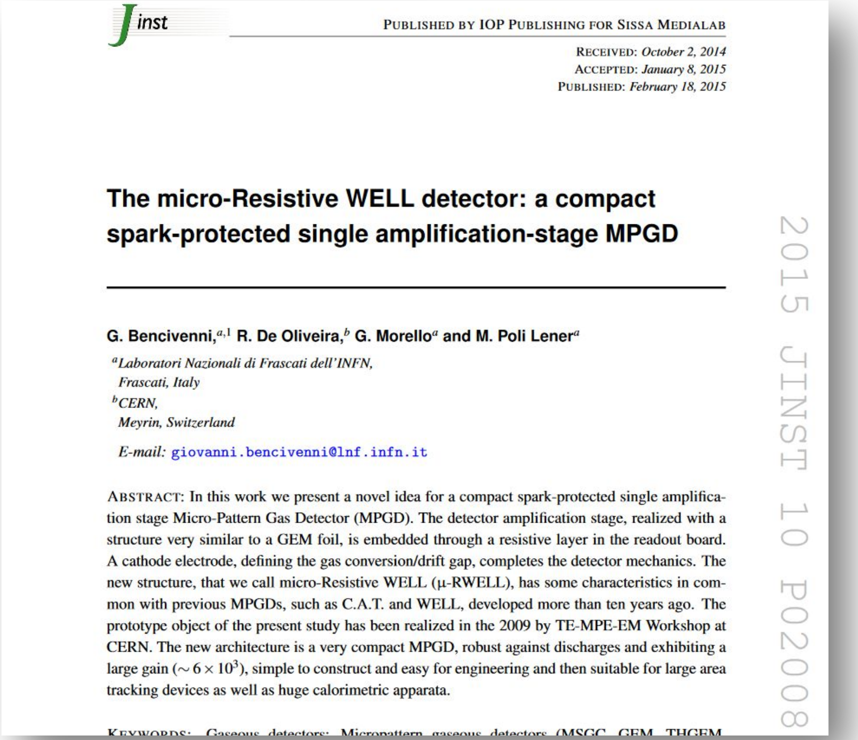
Muon system are designed to be instrumented with **μ-RWELL technology**

[8] "ATLAS New Small Wheel TDR", CERN-LHCC-2013-006; ATLAS TDR-020
[9] "CMS Technical Design Report for the Muon Endcap GEM Upgrade", CERN-LHCC-2015-012 ; CMS-TDR-013
[10] "LHCb Upgrade II Scoping Document", CERN-LHCC-2024-010 ; LHCB-TDR-026
[11] "The IDEA detector concept for FCC-ee", arXiv:2502.21223 [physics.ins-det]

The μ-RWELL: detector scheme

The μ-RWELL is a Micro Pattern Gaseous Detector (MPGD) composed of only two elements: the μ-RWELL_PCB and the cathode. **The core is the μRWELL_PCB** realized by coupling three different elements:





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The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD

2015 JINST 10 P02008

G. Bencivenni,[a,1] R. De Oliveira,[b] G. Morello[a] and M. Poli Lener[a]

[a] *Laboratori Nazionali di Frascati dell'INFN, Frascati, Italy*
[b] *CERN, Meyrin, Switzerland*

E-mail: giovanni.bencivenni@lnf.infn.it

ABSTRACT: In this work we present a novel idea for a compact spark-protected single amplification stage Micro-Pattern Gas Detector (MPGD). The detector amplification stage, realized with a structure very similar to a GEM foil, is embedded through a resistive layer in the readout board. A cathode electrode, defining the gas conversion/drift gap, completes the detector mechanics. The new structure, that we call micro-Resistive WELL (μ-RWELL), has some characteristics in common with previous MPGDs, such as C.A.T. and WELL, developed more than ten years ago. The prototype object of the present study has been realized in the 2009 by TE-MPE-EM Workshop at CERN. The new architecture is a very compact MPGD, robust against discharges and exhibiting a large gain ($\sim 6 \times 10^3$), simple to construct and easy for engineering and then suitable for large area tracking devices as well as huge calorimetric apparata.

1. a **WELL** patterned kapton foil acting as **amplification stage** (GEM-like)
2. a **resistive DLC** layer(*) (Diamond Like Carbon) for discharge suppression w/ surface resistivity ~ 50÷100 MΩ/□
3. a standard readout PCB

(*) The DLC foils are currently provided by CID DLC machine @ CERN

[12] G. Bencivenni et al. JINST 2015 10 P02008

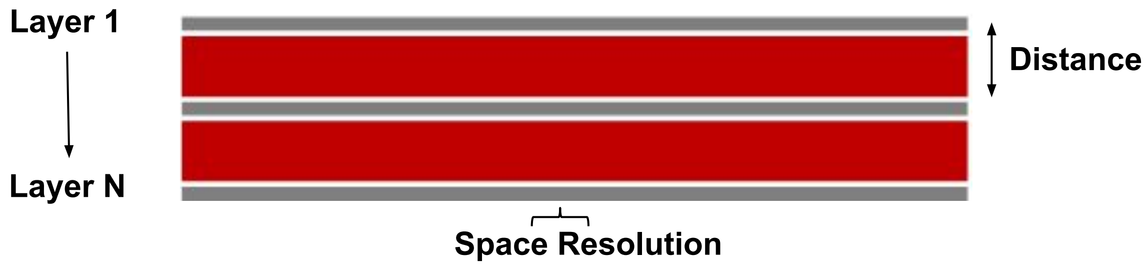
Activities 2025

- Muon System Simulation in IDEA
- New Layout & Characterization
- Test Beam with TIGER
- Parametric Simulation of TIGER

Standalone Muon-system reconstruction

Simulation studies has been started in order to investigate different Muon configuration to define the best performance for standalone reconstruction by:

- Varying the number of layers (3 vs 4 layers).
- Varying the lever-arm distance (30 cm to 50 cm)
- Varying the space resolution of the detector (400 μm to 200 μm)



[13] “Full simulation of the muon system of IDEA detector concept for future circular lepton colliders ”, Master's Thesis

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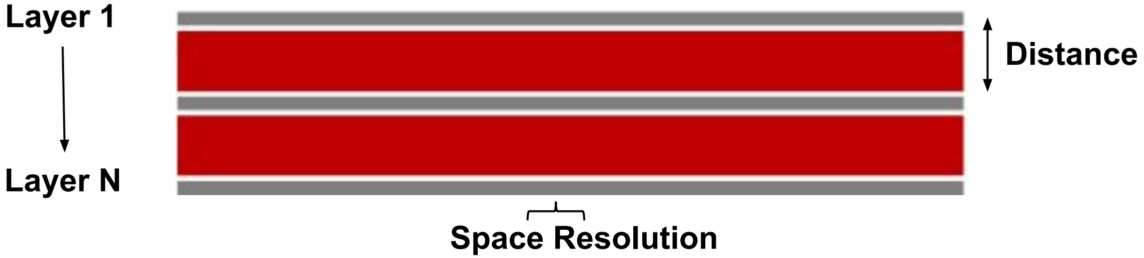

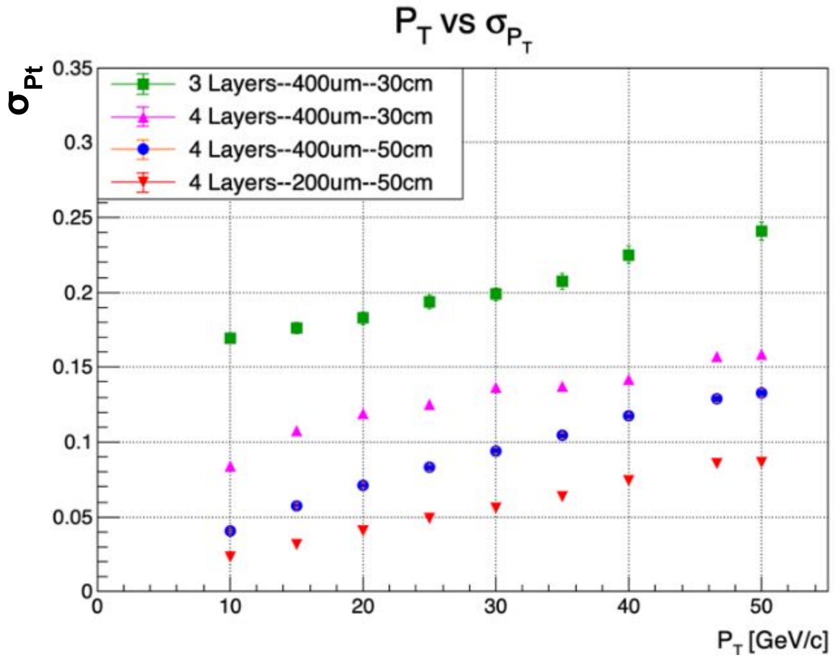

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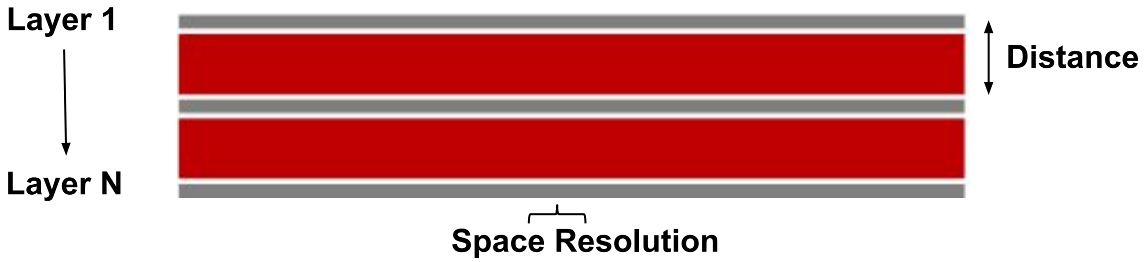
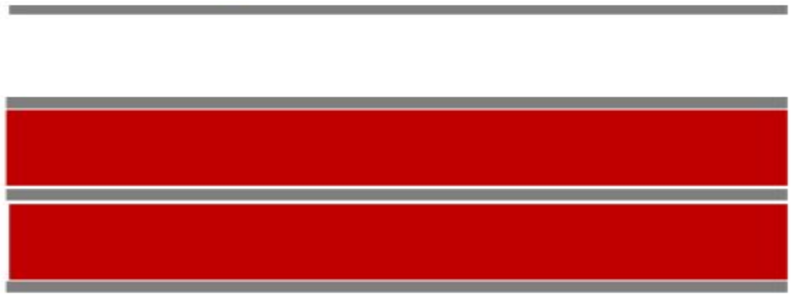
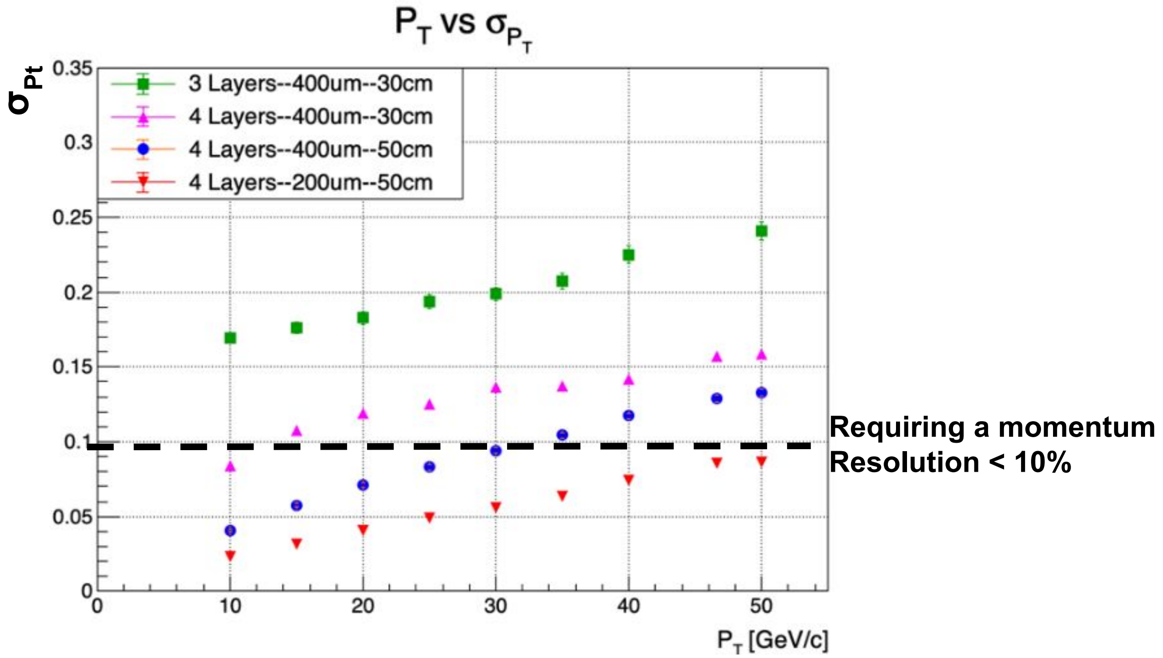




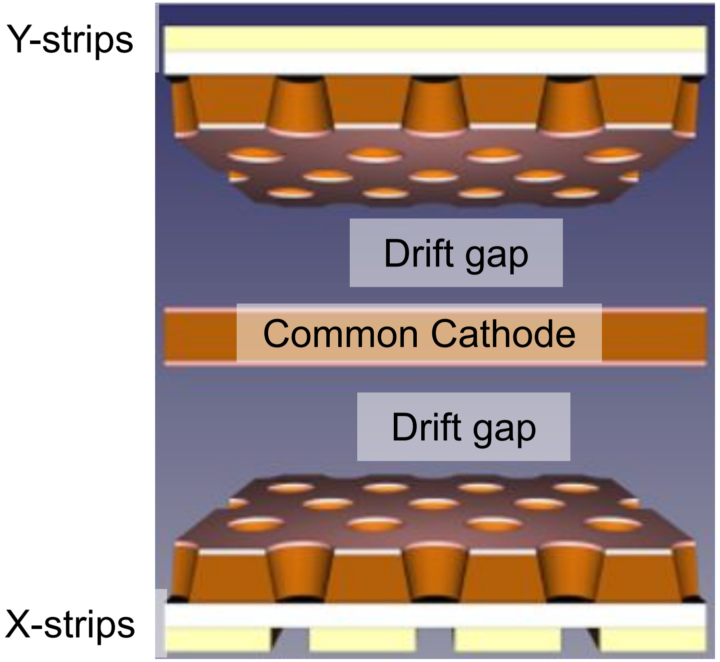
4 Layers with level-arm = 50 cm, only two yokes and 200 μm space resolution



[13] "Full simulation of the muon system of IDEA detector concept for future circular lepton colliders ", Master's Thesis

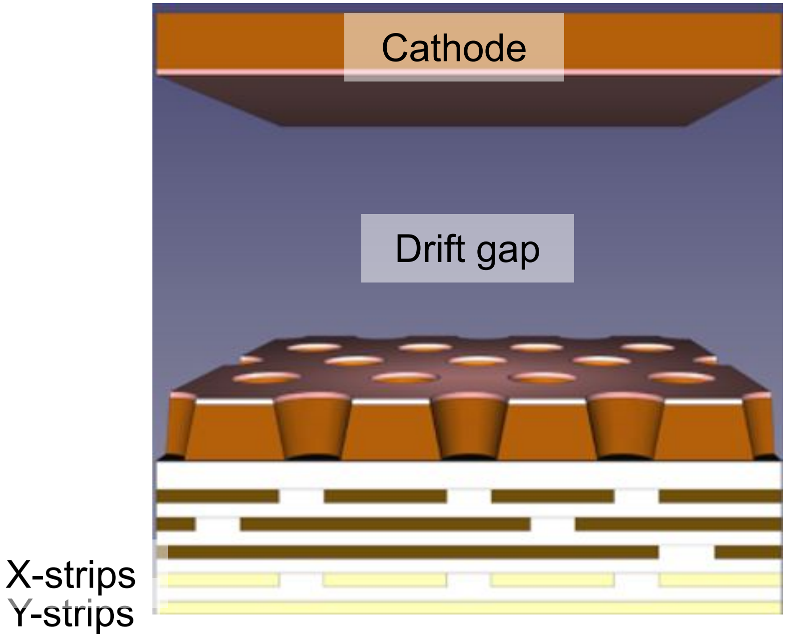
TB Analysis finalization -2D layouts – 10x10 cm^2

n.2 μ-RWELL 1D [2×1D]



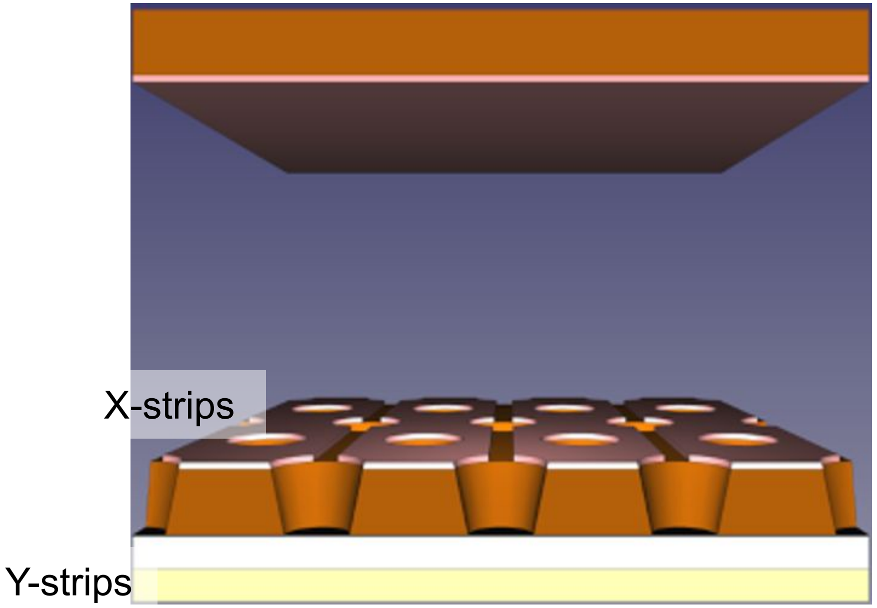
- Lower gas gain w.r.t. the "COMPASS R/O" (X / Y are not sharing any charge)
- Tested @ TB2022

Capacitive Sharing [*]



- Stack of layers of pad
- Reduce the FEE channels
- The charge is divided between X and Y → Higher gas gain required w.r.t. 1D
- Tested @ TB2023

Top R/O



- Lower gas gain w.r.t. the "COMPASS R/O" (X / Y are not sharing any charge)
- The "Top" coordinate introduces dead zone in the active area
- Tested @ TB 2023

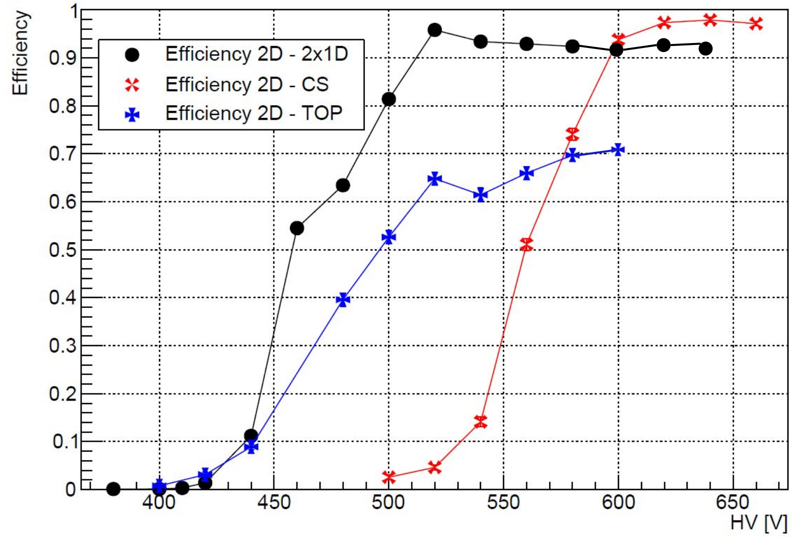
[14] K. Gnanvo et al., NIM A 1047 (2023) 167782

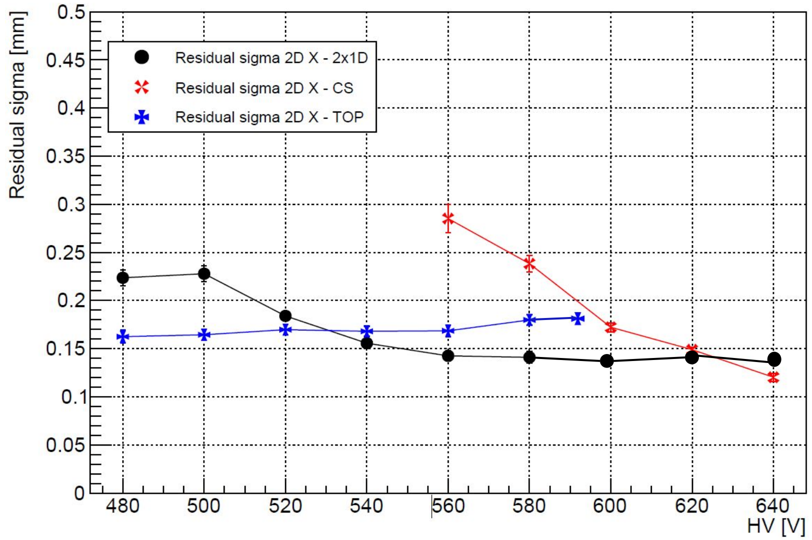
2D layouts performance with APV25

2x1D layout:
spatial resolution < 200um (pitch 0.8 mm),
low gain operating point 700 (HV~520V),
efficiency ≥98% (large eff. plateau)

CS layout:
spatial resolution <200um (with pitch 1.2 mm),
high gain operating point 4000 (HV≥ 600V),
efficiency ≥98%

Top layout:
spatial resolution < 200um (pitch 0.8 mm),
low voltage operating point ~520V,
efficiency ~ 70% (dead-zone)





2D layouts performance with APV25

2x1D layout:
spatial resolution < 200um (pitch 0.8 mm),
low gain operating point 700 (HV~520V),
efficiency ≥98% (large eff. plateau)

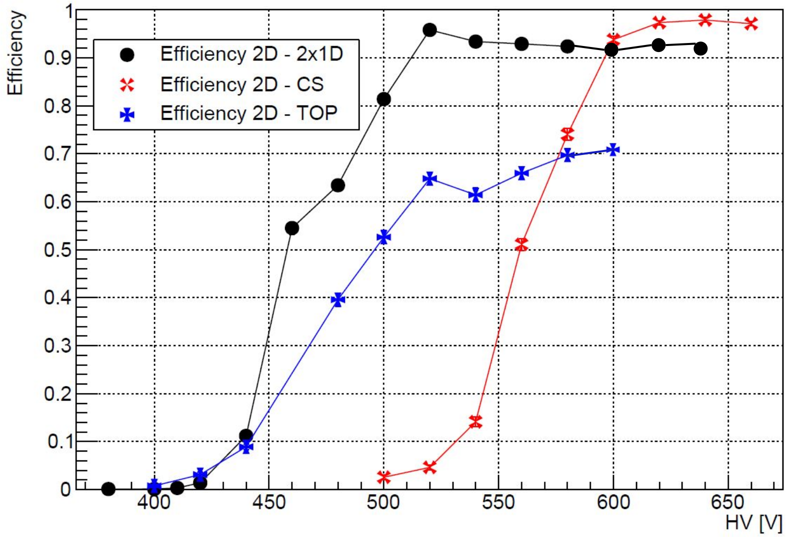
Economic Impact: Higher Cost

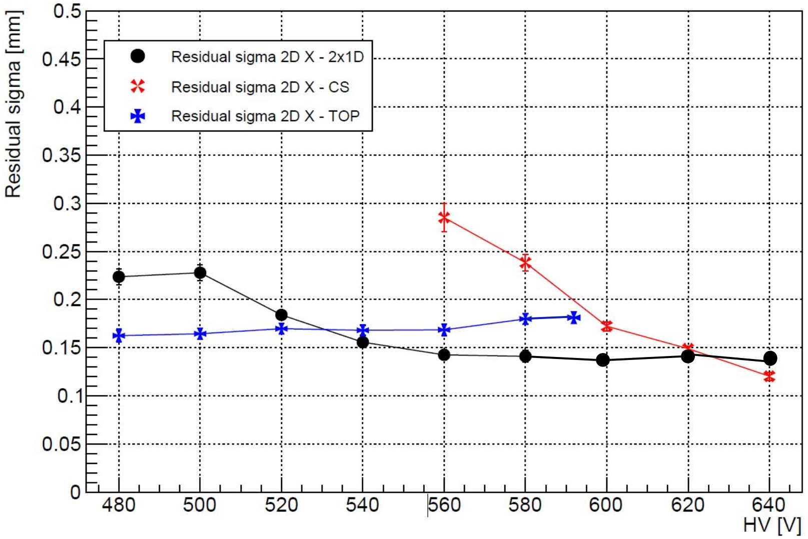
CS layout:
spatial resolution <200um (with pitch 1.2 mm),
high gain operating point 4000 (HV≥ 600V),
efficiency ≥98%

Drawback: Operation Close to Stability Limit

Top layout:
spatial resolution < 200um (pitch 0.8 mm),
low voltage operating point ~520V,
efficiency ~ 70% (dead-zone)

Limitation: Reduced Efficiency





The **results are promising**, but the layouts require **same optimization** as their performance is **not yet ideal for the IDEA Muon system**.

Layout under study (financed in the past)

Solution under study to increase detector stability:

1. **μ-RWELL "well optimization"** → This study was done with GEM detectors but never with uRWELL → well pitch from 140 μm to 90 μm with an increase in gain of about a factor of 2. **Protos cleaned@CERN, ready to be tested with X-ray**

CS Evolution

Increased Operational Stability

New layouts under study for Muon systems:

1. **GEM + CS μ-RWELL 10x10 CM2**→ GEM pre-amplification stage, to lower the operating point, greatly improving the RWELL stability and maintaining high spatial performance with millimetric pitches. **GEMs just arrived @ LNF.**

2. **GEM + CS μ-RWELL 50X50 CM2** → first large μ-RWELL for IDEA**. Detectors repaired (vias metallization). GEMs will arrive in Sept.**

New layout

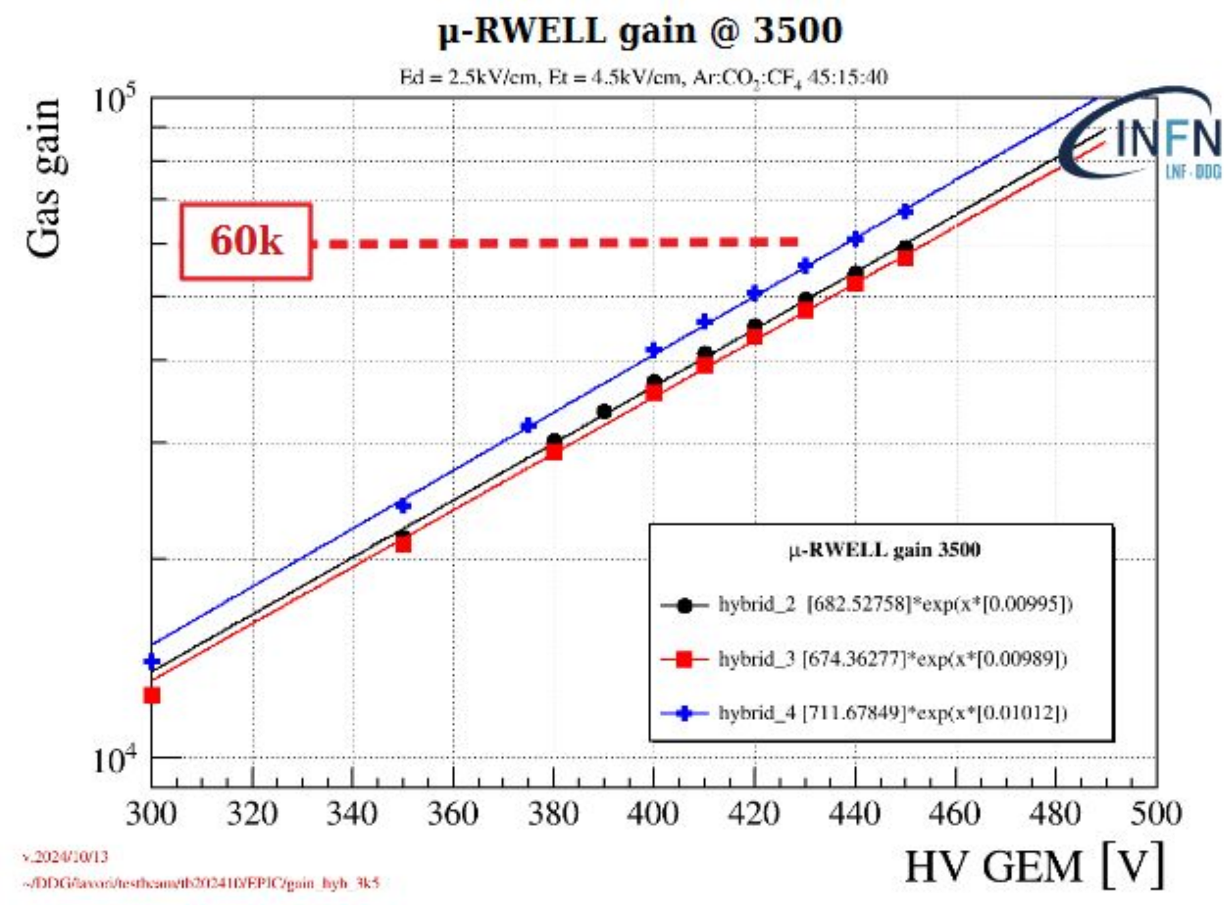
3. **Dual DLC μ-RWELL 10x10 CM2** → new idea of layout with two DLC foils, the first will be used as standard resistive layer (100 MΩ/□), while the second one (1 MΩ/□) to spread the charge on the readout. **Protos will be arrive in Oct.**

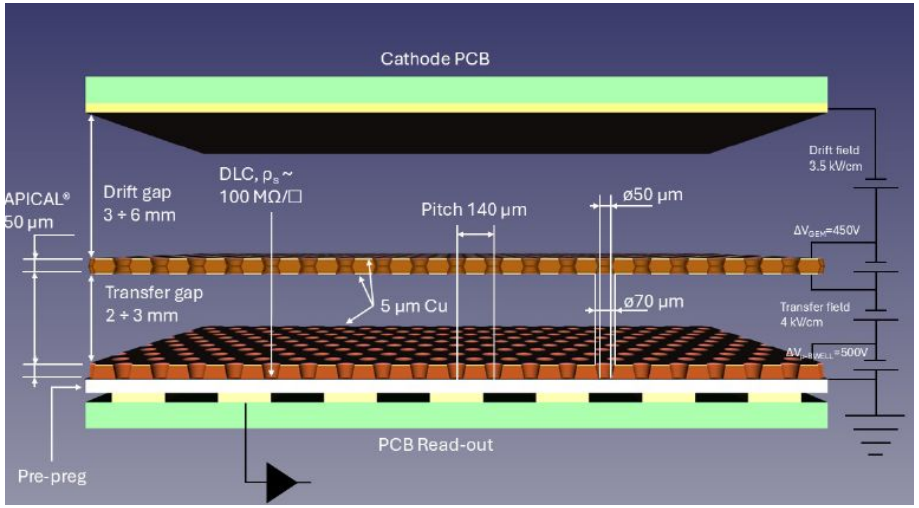
Top Evolu tion

4. **μ-RGROOVE 10x10 CM2** → new layout, where the amplification stage is not based on the **«wells» but on the «grooves».** This facilitates the realization of the strip readout on the top, without introducing dead-zones. **Protos cleaned@CERN, ready to be tested with X-ray**

Hybrid u-RWELL

GEM+ μ-RWELL hybrid (G-RWELL) uses a GEM as pre-amplifier





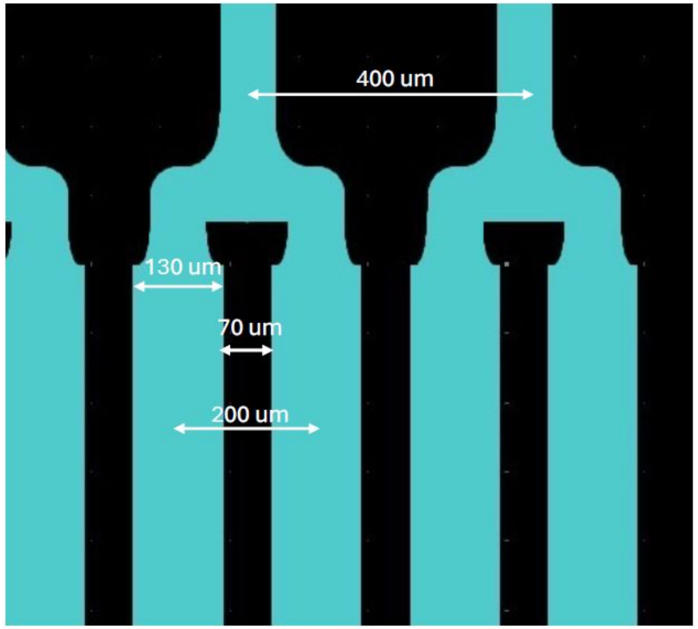
The operating principle has been tested within the framework of the LHCb experiment (pad readout). As expected, the detector achieves higher gain »10^4 compared to a single-stage configuration, without exhibiting any instability.

[15] G. Bencivenni et al. NIM A 1080 (2025) 170623

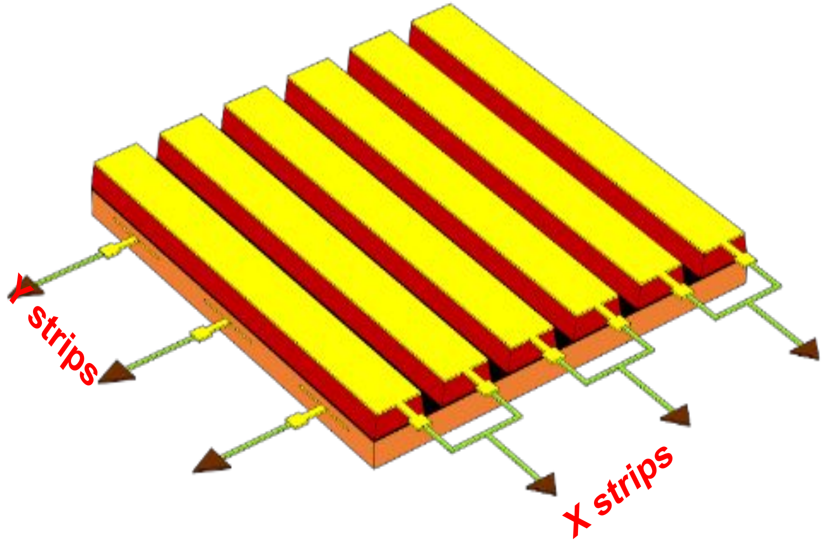
u-RGroove

μ-RGroove is the development of the “TOP” layout without dead-zone and no sharing between X/Y strips

TOP STRIP readout



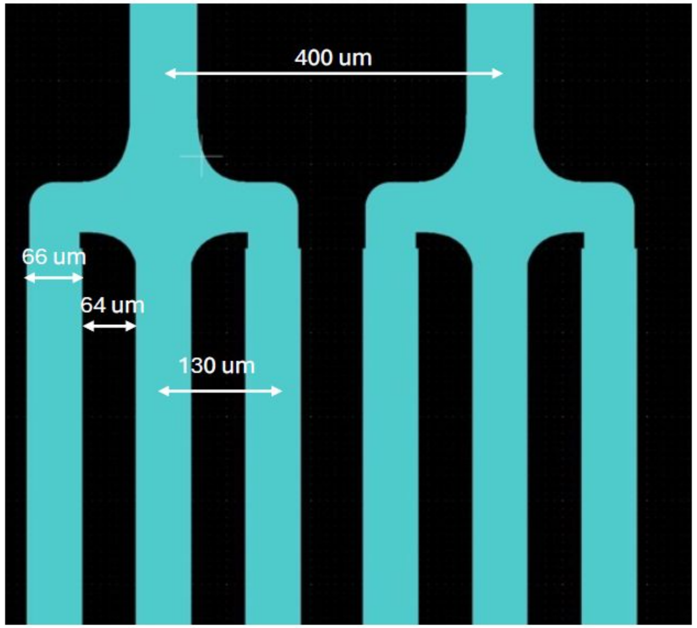
Layout with 2 strip OR-ed:
FEE Strip pitch 400 μm
Pitch strip 200 μm



Bottom STRIP (Y):
Strip pitch 400 μm
Strip width 300 μm

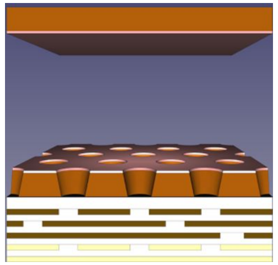
[16] Xiangqi Tian *et al* 2024 *JINST* **19** P07031

TOP STRIP readout

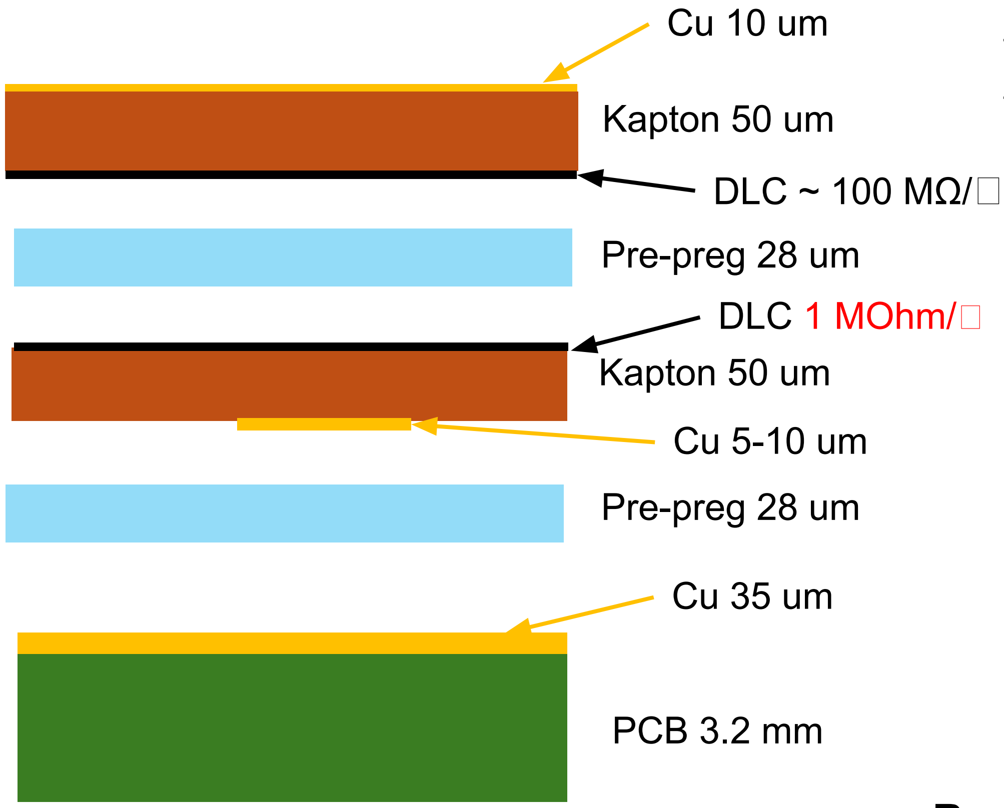


Layout with 3 strip OR-ed:
FEE Strip pitch 400 μm
Pitch strip 130 μm

Dual-DLC µ-RWELL

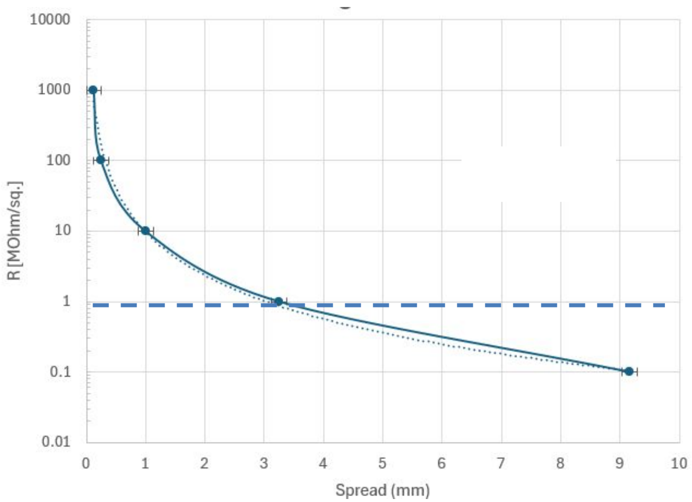


Dual DLC μ-RWELL, as we envision it, should represent the evolution of the CS layout by eliminating capacitive coupling to conductive elements in the CS, replacing them with a single resistive element



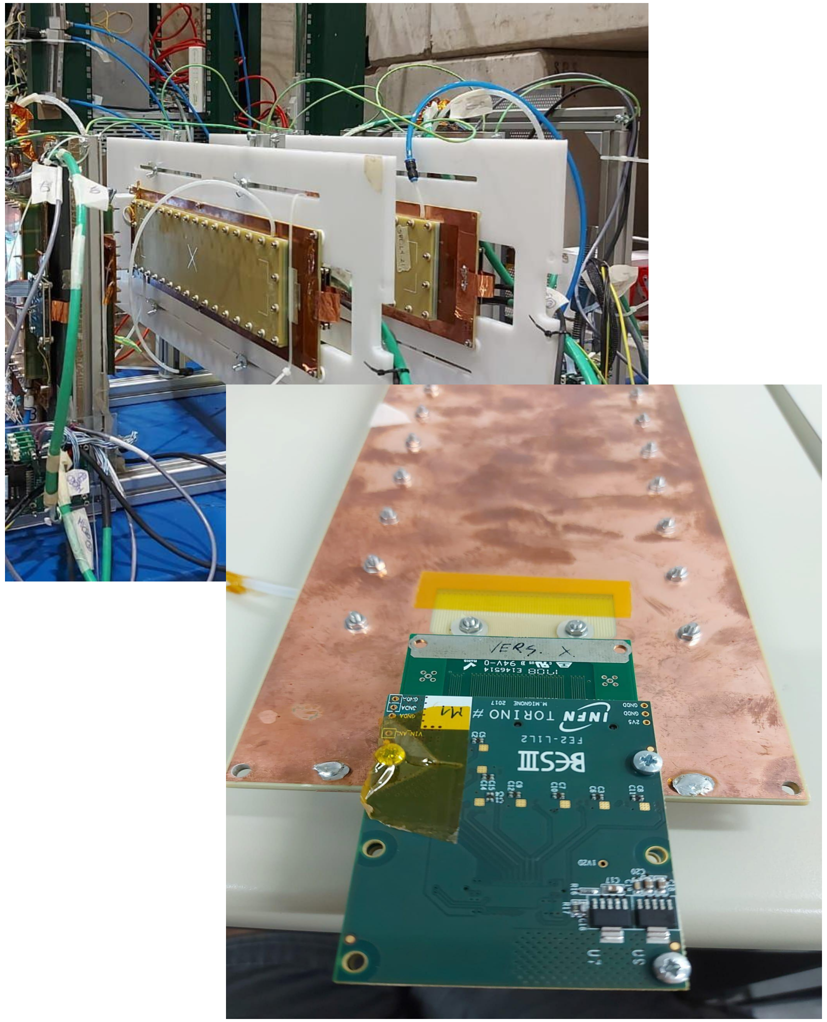
→ **First DLC layer** with high resistivity for **local HV drop**

→ **Second DLC layer** with low resistivity for **charge dispersion**



Resistivity below 1 MΩ/sq results in 4-5 fired strips with a 1.6 mm pitch

Test Beam with TIGER electronics



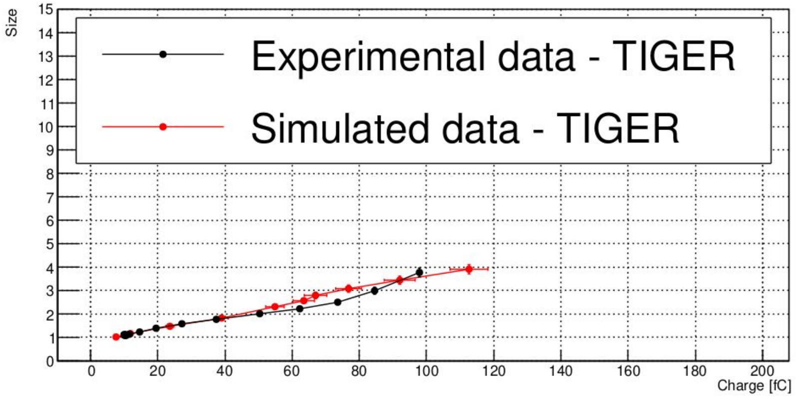
With 2025 funding, a new support system for the test beam was designed, and new patch cards were developed to **reduce noise** on the TIGER electronics. Additional studies were carried out to further decrease electronic noise and a new setup will be **tested on Beam** in November 2025.

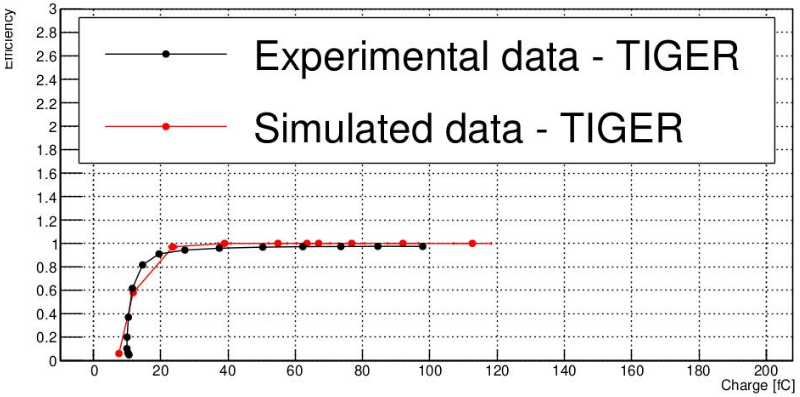
Activities involving the TIGER electronics will not continue beyond the current year due to the project's decommissioning and lack of support for further R&D. For this reason, a series of meetings has started with the Torino group to establish a synergy for the development of the **TORA** chip and its readout chain.

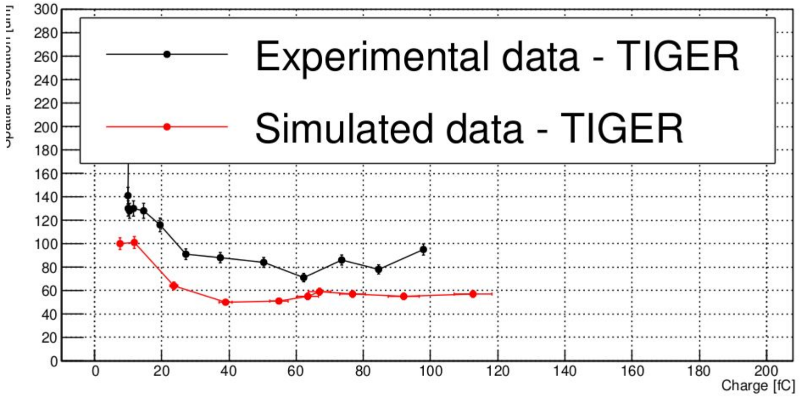
[17] A. Amoroso et al., 2021 JINST 16 P08065

Parametric Simulation of TIGER

- Finalization of the μRWELL+TIGER simulation for instrument validation
- Analysis of chip limitations impacting μRWELL performance
- Optimization of alternative design options
- Study of expected performance with the new TORA chip (v1)







Planned Activity Plan 2026–2028

2026

- **Parametric Simulation:** Analysis of the expected performance of the µRWELL technology combined with the TORA v1 chip (chip delivery expected in May 2026), using internally developed simulation tools.
  - ➢Objective: provide input for the design of TORA v2, with delivery planned for 2026.
- **Readout development:** Assembly of a readout chain (FEB_TORA, FireFly cables, Breakout Board, FPGA, PLL board). Initial development of firmware and software for TORA chip configuration and data readout.
- **Procurement:** Joint purchase of TORA v2 chips with the Torino group for use in AMBER (collaborative effort).
- **Test Beam:** Study of performance using prototypes with APV chips, as previously described.

2027

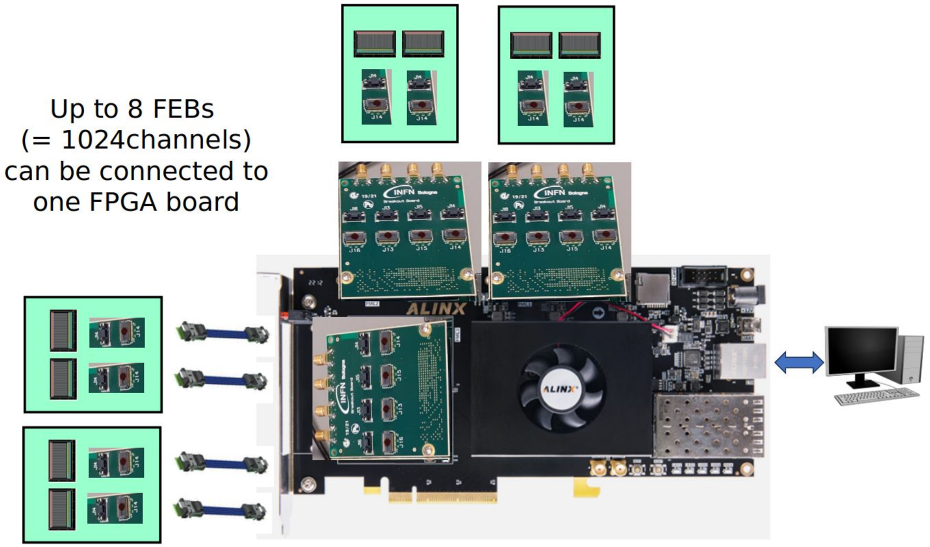
- **Test TORA v2:** Bench test with the complete readout chain
- **Procurement:** Addition of 3 readout chains to enable the readout of one tracking system and 6 test chambers
- **Cosmic ray test:** TORA v2 validation with readout chains and µRWELLs

2028

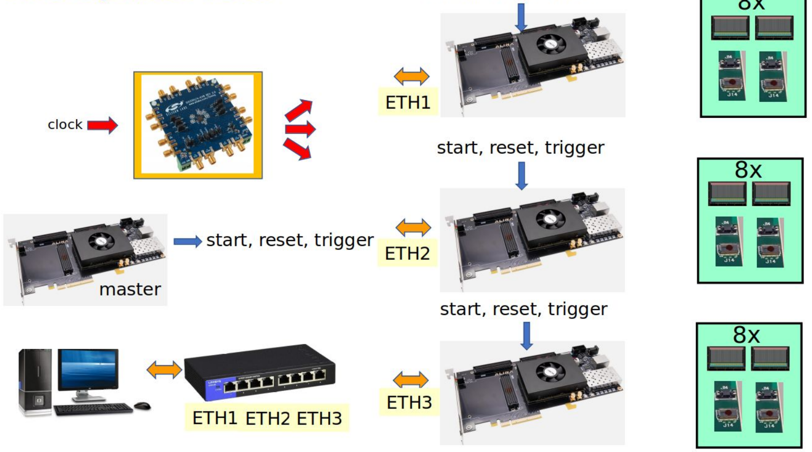
- **Test Beam:** Performance study of TORA v2 with readout chains at PS or DESY

2026 Funding Requests

Readout: design of a new readout chain. Firmware development for one chain (1 chip + FPGA + ...) = 8x64 channels electronics



Telescope/test beam



2026 Funding Requests:

- N. 1 Complete Chain -> 5 keuro (Bologna)
- N. 20 FEB -> 12 keuro(SJ) (Bologna)
- N. 50 TORA v2 -> 10 keuro (Torino)
  [Estimated cost pending quotation]
  [Not entered into the database due to oversight]
- Premixed bottles gas: 6k€
  2k€/section (Bologna, Ferrara e LNF)
- Missioni per TB: 15 k€ (SJ),
  5k€/section (Bologna, Ferrara e LNF)

2027 Expected Funding Requests:

- N. 3 complete chains -> 15 keuro

Summary

Future Muon systems pose new challenges compared to LEP, requiring the identification of both isolated muons and those embedded within hadronic jets. This ability is essential for precise flavor physics studies and rare process searches. Achieving good momentum resolution will be decisive for the detection of LLP particles.

Summary

Future Muon systems pose new challenges compared to LEP, requiring the identification of both isolated muons and those embedded within hadronic jets. This ability is essential for precise flavor physics studies and rare process searches. Achieving good momentum resolution will be decisive for the detection of LLP particles.

The pillars

μ-RWELL

- R&D is ongoing to optimize a **high-precision, robust, and cost-effective detector**, with INFN-LNF leading the effort.
- Ongoing R&D efforts focus on performance (efficiency, resolution, timing) preparing for potential large-scale industrial production. Collaborative efforts are strongly encouraged

Front-end Electronics & Off-detector

- New chip/Off-detector are needed for this technology INFN-Torino is responsible for the chip, while INFN-Bologna/Ferrara are in charge of the off-detector systems. Contributions from partners are appreciated.

Software

- Simulation, reconstruction, and software development are essential. INFN-Bologna is in charge of this effort. External support is welcome.

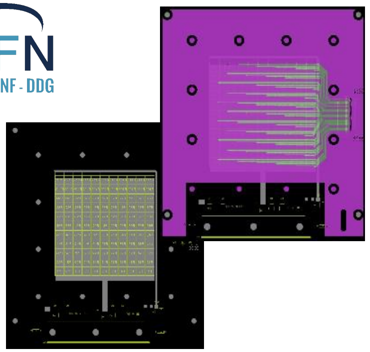
There are multiple options to contribute, with the possibility of leading contributions in many areas.

Thanks for your attention

Back UP

Technology Transfer

LAYOUT design



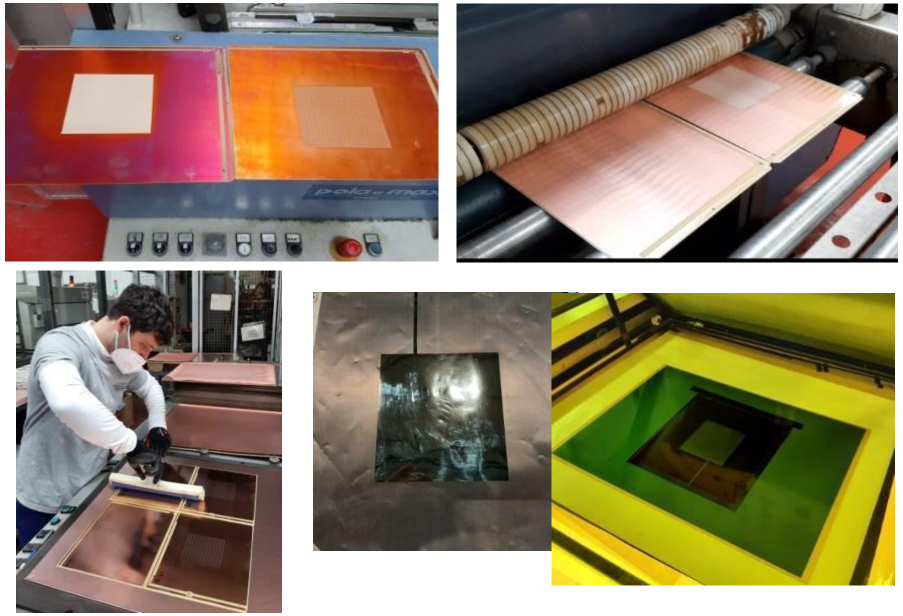
Feedback from tests

DLC foil production[*]

[*] DLC Magnetron Sputtering machine co-funded by INFN-CSN1

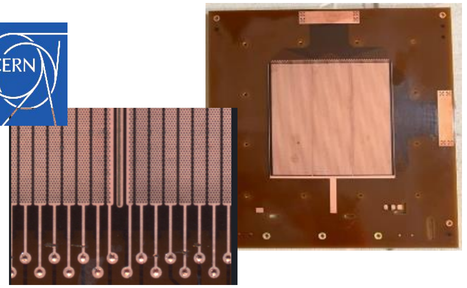
PCB production

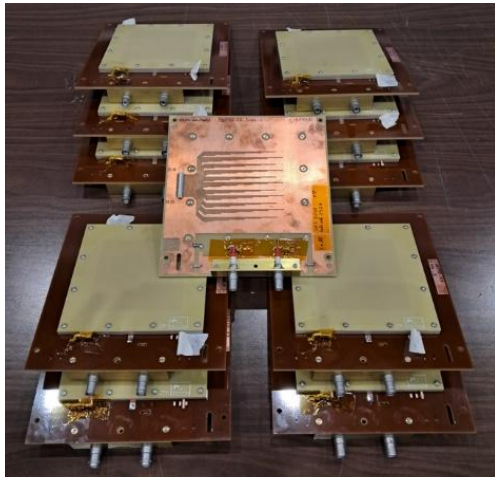
ELTOS INFN LNF - DDG



[22] G. Bencivenni et al., "Milestone Report WP7.3.2", AIDAinnova- MS27

Final detector manufacturing





IDEA→ μ-RWELL for muon apparatus

The **IDEA detector** is a general purpose detector designed for experiments at future e^+e^- colliders.
The Muon system are designed to be instrumented with μ-RWELL technology.

Muon requirements:

Tiles: 50x50 cm^2 with X-Y readout

Efficiency ≥ 98%

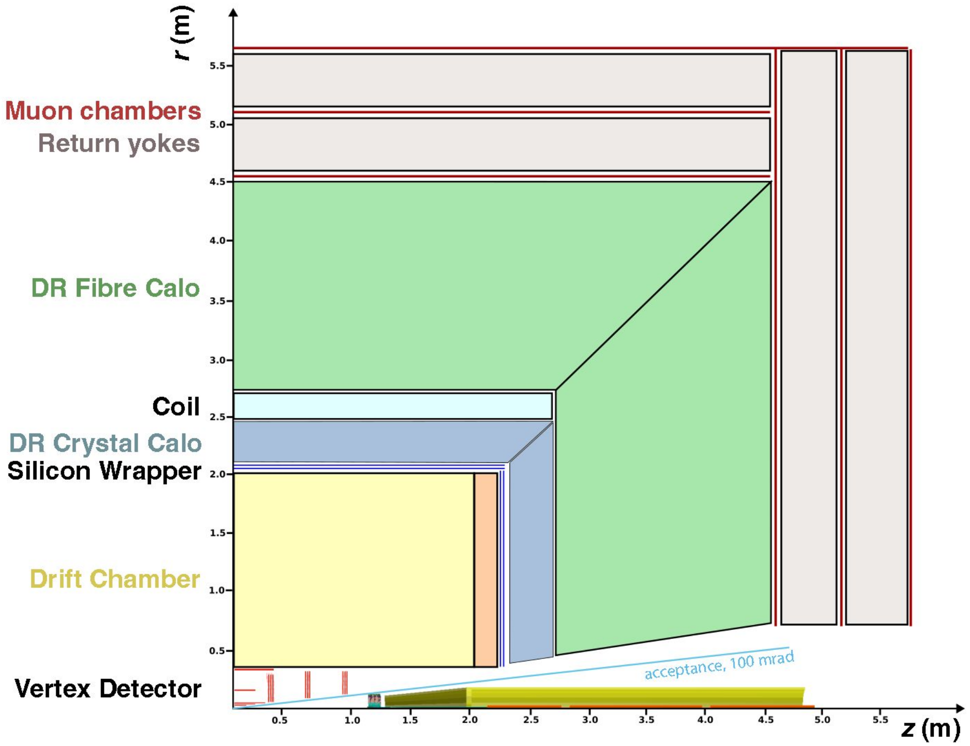
Space resolution ≤ 200 μm

Particle Flux < 1kHz/cm^2

Instrumented Surface/FEE: 1500 m^2, 6000 det., ~5×10^6 ch.

Mass production Technology Transfer to Industry

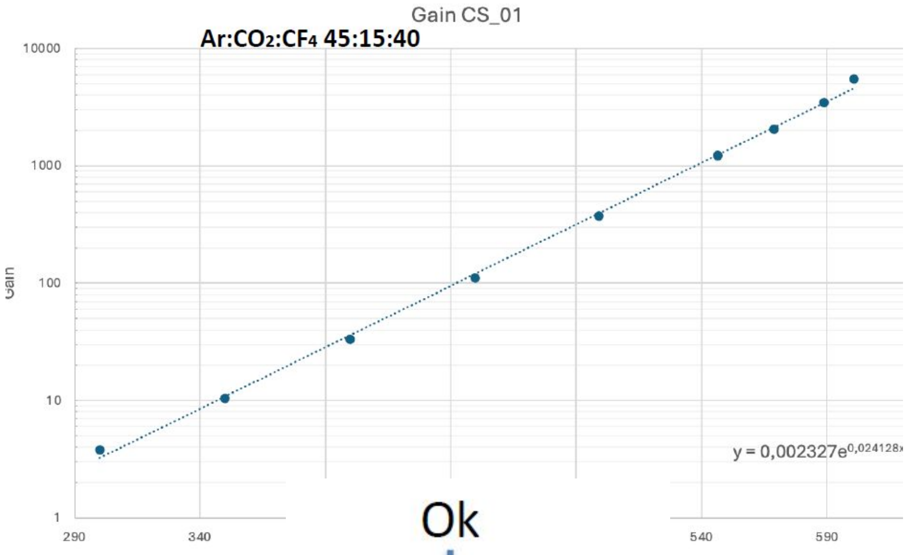
FEE Cost reduction custom made ASIC (based on TIGER or the new T(

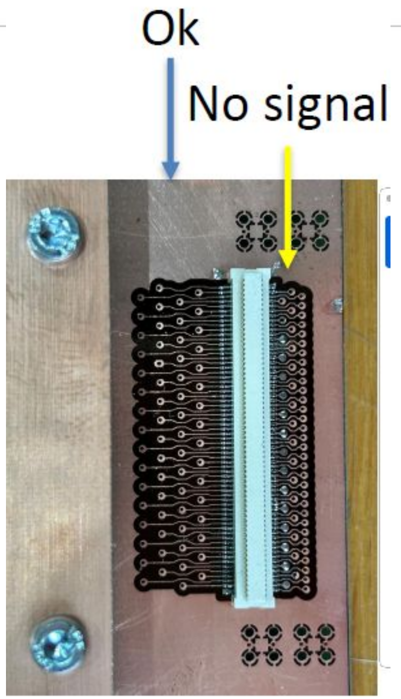


Italian Institutes involved: LNF, Bologna, Ferrara, Torino.
There are opportunities to contribute in multiple areas and leading roles in many fields (software, electronics, detector)

CS u-RWELL layout - 50x50 cm2

Detector delivered at the end of 2024
Gas gain measured using the X-ray





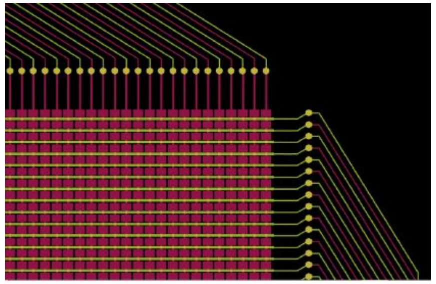
The detector has been instrumented with APV-25 and irradiated with X-ray, revealing that only half of the strips were connected to the FEE.

- Investigations with Rui identified an error in the connection vias.

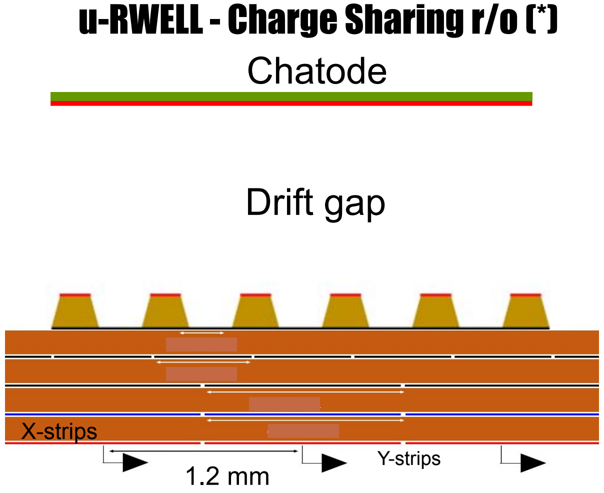
The detector was sent to Rui's workshop for repair and returned last week

- Check gas gain after Rui's hot clean + performance with cosmic stand
- A GEM foil will be added to the 50×50 cm² CS in collaboration with RM2

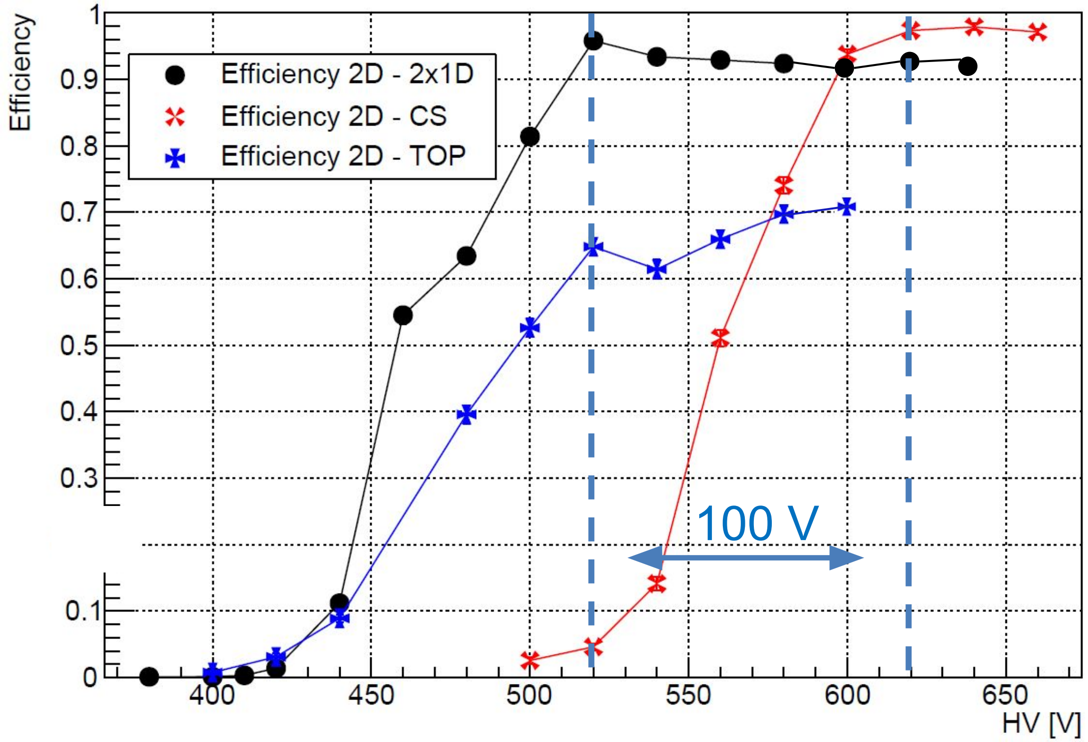
CS layout vs 2x1D



Active area= 100x100 mm2
Resistivity= 50 MΩ/•
Strip pitch= 1.2 mm
Strip width = 1.1 mm
Several layer between DLC and R/out



2D layouts – 10x10 cm^2

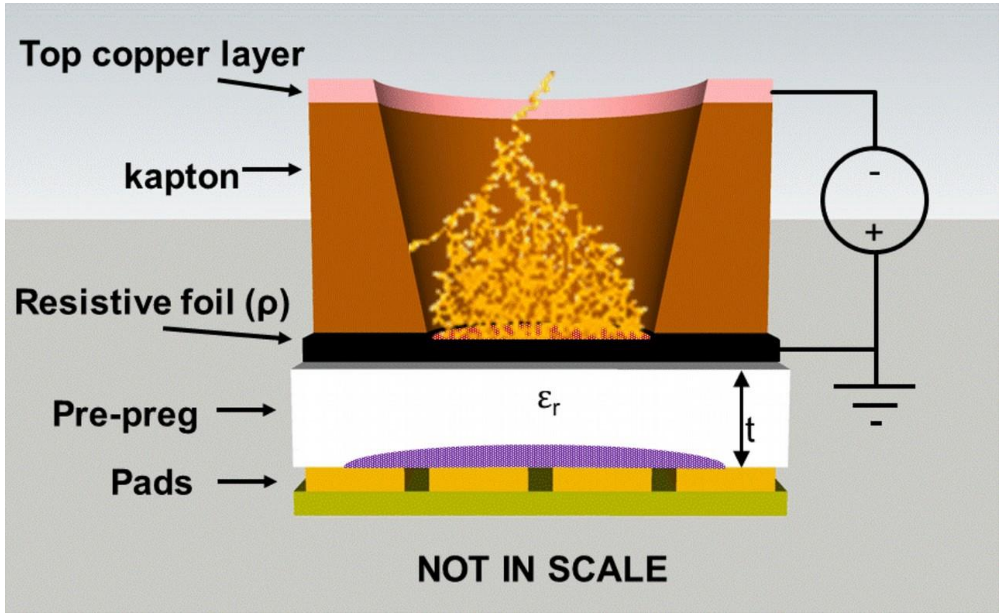


The **CS layout** has demonstrated performance very similar to that of the **2×1D layout**, with increase in gain of a **factor 10**. This gain increase (a factor of 2 attributed to charge sharing between the X-Y views) is not yet fully understood and requires further investigation.

 A new gain test and the addition of a GEM foil to hybridize the detector are planned

The μ-RWELL: principle of operation

Applying a suitable voltage between the **top Cu-layer and the DLC** the WELL acts as a **multiplication channell for the ionization** produced in the conversion/drift gas gap.



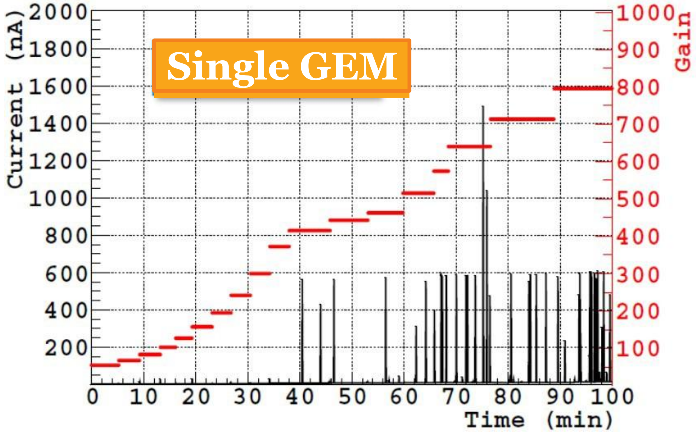
Introduction of the **resistive stage:**

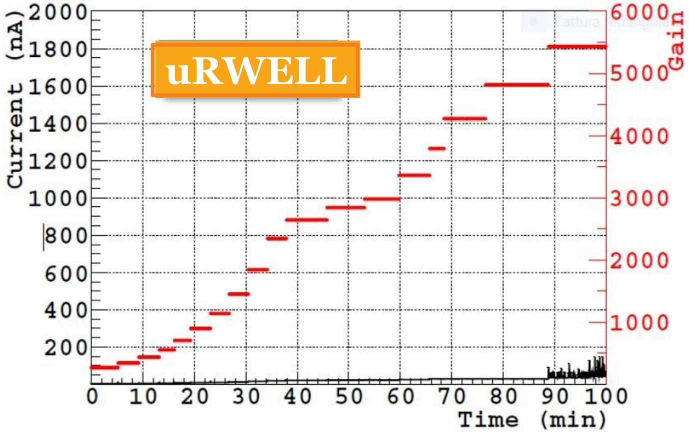
Pros: suppression of the transition from streamer to spark

→ Spark amplitude reduction

Cons: reduction of the capability to stand high particle fluxes.

But an **appropriate grounding schemes** of the resistive



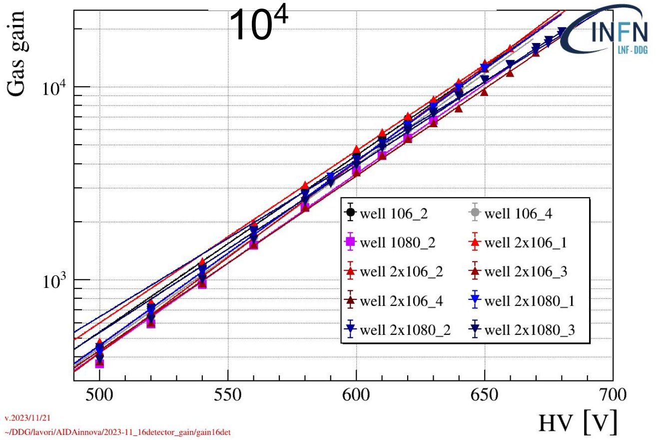


Comparison between the **current** drawn by a single GEM and a μ-RWELL at various **gas gain**.

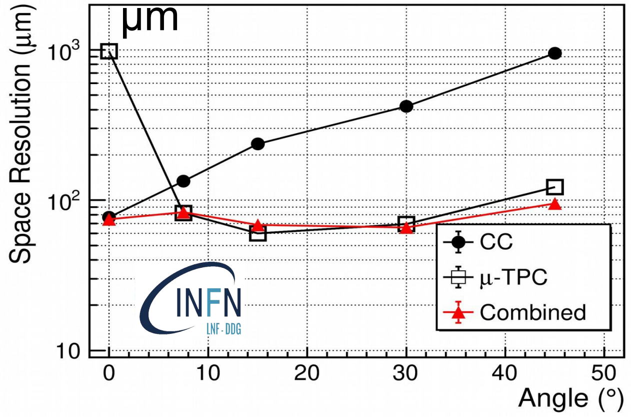
The black spikes are the sparks in the detectors, clearly dumped in the μ- RWELL for higher gains

μ-RWELL performance overview

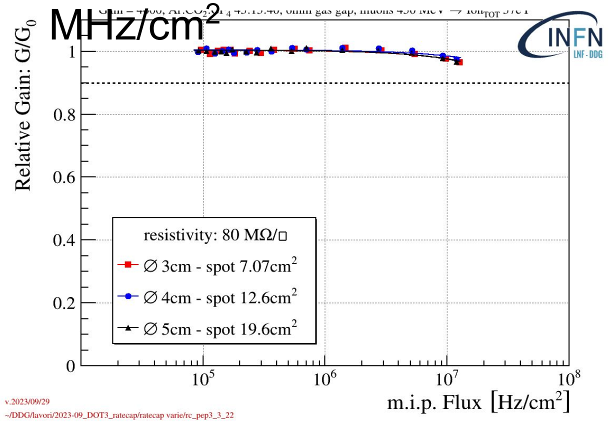
Gain up to 10^4

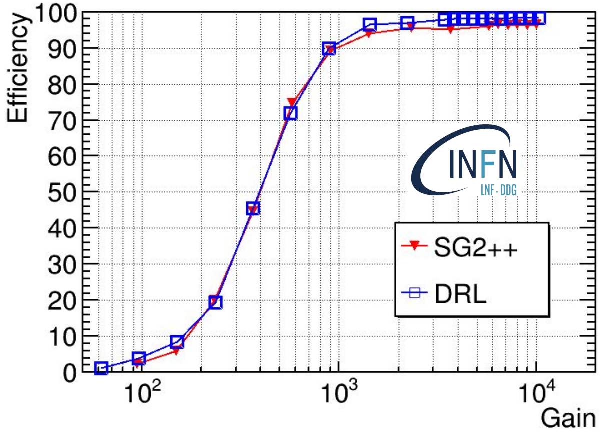


Space resolution ~ 100 μm

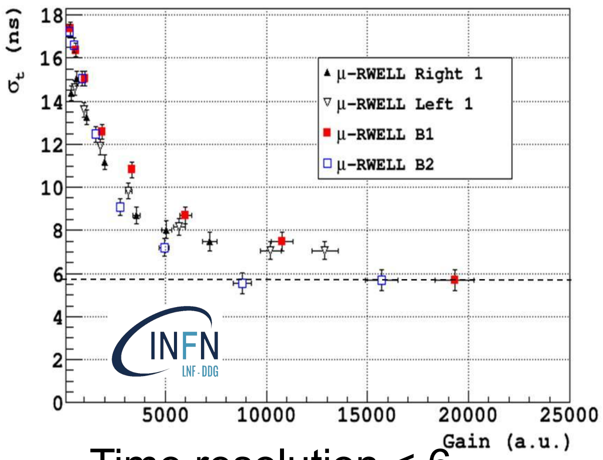


Rate Capability ~ 5-10 MHz/cm^2

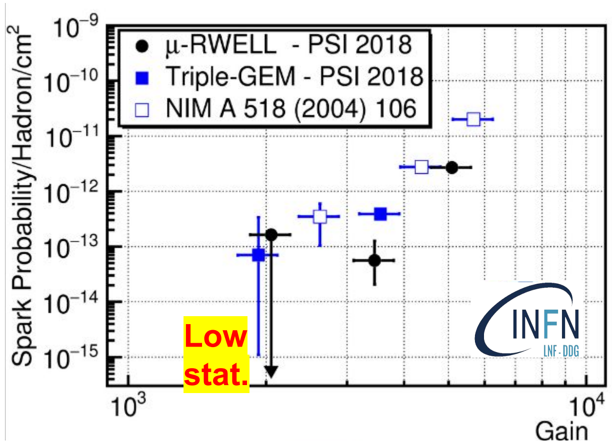




Efficiency ~ 98%



Time resolution < 6 ns



Discharge probability ~ 10^{-13} @ 4000

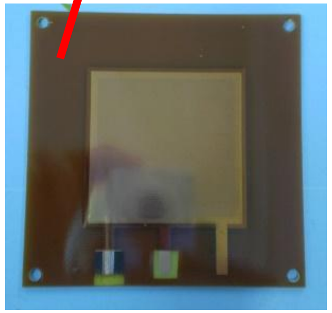
[14] G. Bencivenni et al., 2021 JINST 16 P08036
[15] G. Bencivenni et al., NIM A 886 (2018) 36
[16] G. Bencivenni et al., 2019 JINST 14 P05014
[17] G. Bencivenni et al. 2024 JINST 19 C02057

u-RWELL R&D History

New u-RWELL ideas (in collaboration with RD51)

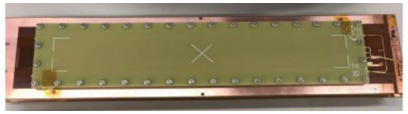
R&D for FCC start

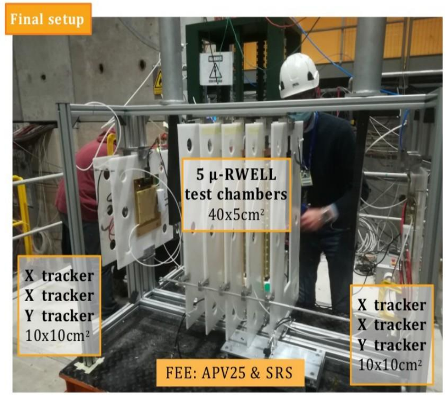
2009 · 2020 · 2021 · 2022 · 2023 · 2024

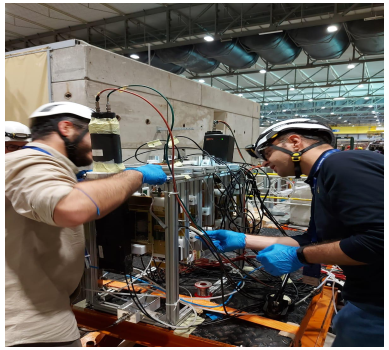


IDEA slice test: DC + pre-shower + dual_calo + muon

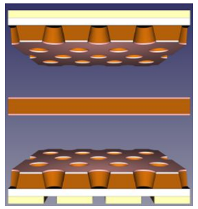
1D Layout optimization





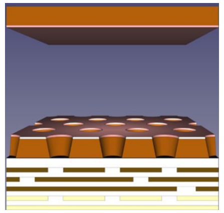


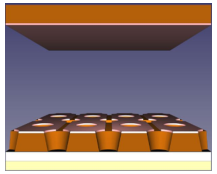
2D layouts optimization



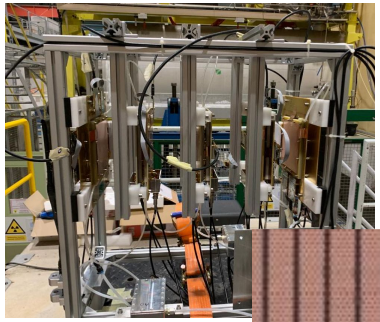
2x1D layout

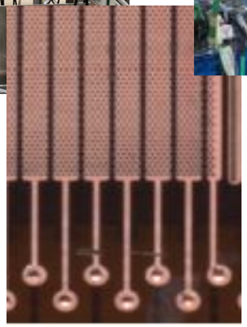
Capacitive Sharing layout

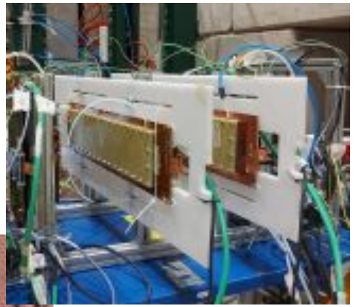




TOP layout







Muon detector challenges

The requirements (still at a preliminary stage) for the muon system include:

- Instrumenting **the return yoke** outside the coil
- **High efficiency** muon identification > 98% (momentum measured by tracking system)
- Serving as **tail-catcher** for the hadron showers not fully contained in the calorimeter (discr./sep. efficiency lower than 1%)
- **Standalone** momentum measurement for long-lived particles (space res. < 200 μm and time better 200 ps)
- Rate capability << 1kHz/cm2
- **Mass production** and **cost effectiveness**

Gaseous detectors have historically been favoured for muon detection at colliders like LEP and LHC due to their **cost-effectiveness** for **large areas**, **high time and position resolution and robustness** (RPC, drift-tube, etc).

Decades have passed since the last muon apparatus were built, during which significant advancements have been made in detector technologies, particularly in **Micro-Pattern Gaseous Detectors (MPGDs):**

- **Micro-Megas** and **GEM** are used for **ATLAS and CMS** muon detector upgrade in the endcap region to handle the LHC rate
- **μ-RWELL**, an innovative type of gaseous detector, expected to have significantly improved capabilities in high-rate intensity environments such as in **LHCb Phase II**.

[8] "ATLAS New Small Wheel TDR", CERN-LHCC-2013-006; ATLAS TDR-020
[9] "CMS Technical Design Report for the Muon Endcap GEM Upgrade", CERN-LHCC-2015-012 ; CMS-TDR-013
[10] "LHCb Upgrade II Scoping Document", CERN-LHCC-2024-010 ; LHCB-TDR-026