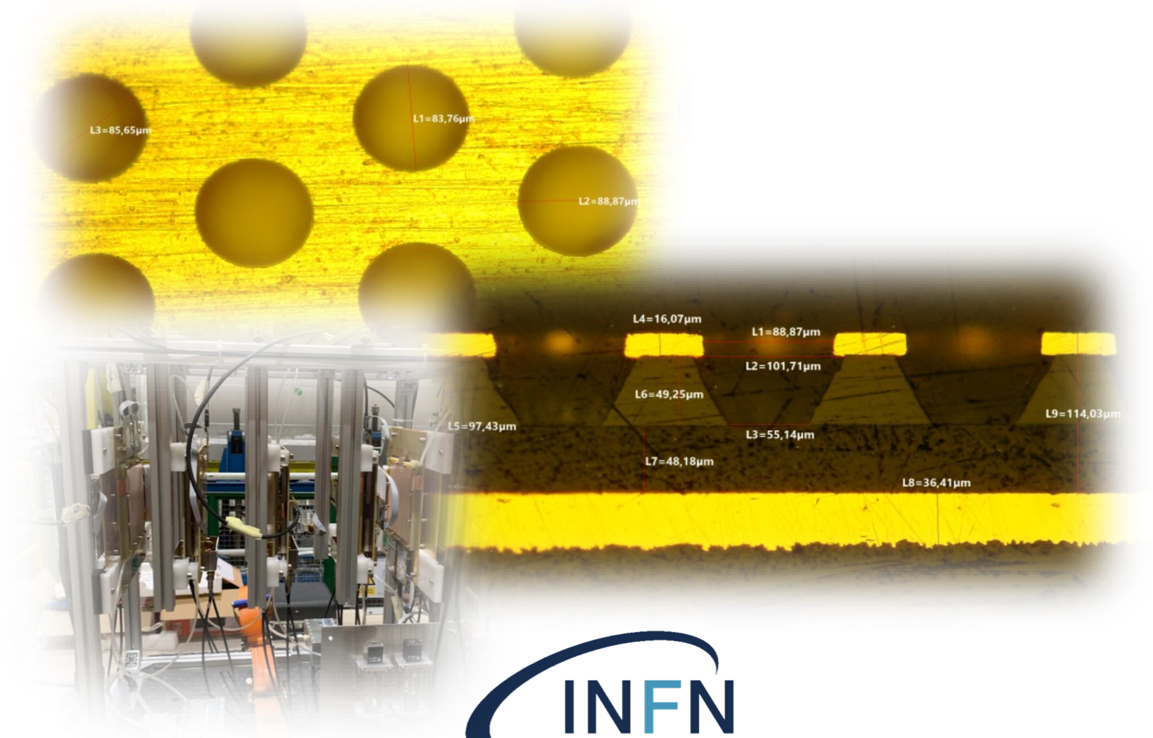
The µ-RWELL technology for the IDEA Muon System



Marco Poli Lener
on behalf of INFN – IDEA group

INFN
LNF - DDG

CepC in pills

- CepC will operate at 4 different center-of-mass energies:
  - Z pole (90 GeV)
  - WW pole(160 GeV)
  - HZ pole (240 GeV)
  - $t\bar{t}$ pair pole (360 GeV)

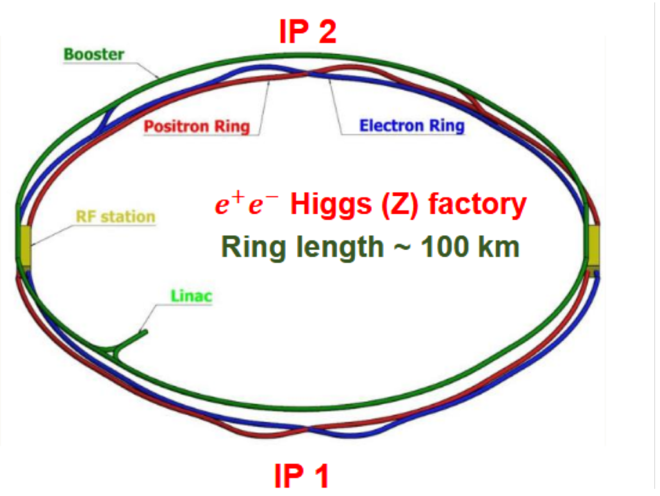
- Higher Luminosity ($\sim$ **$10^{34} \div 10^{36}$ cm^{-2}s^{-1}**) and lower rate environment than HL-LHC

- Maximum **muon momentum roughly 180 GeV/c**

- Detection of isolated muons is similar to that in LEP. Identifying non-isolated muons from hadron decays within jets requires stricter measurements to achieve precision in flavor physics.

- High statistics of inelastic electron-positron collisions enable the production of rare processes involving feebly interacting and slow particles.

Particle	$E_{c.m.}$ (GeV)	Years	SR Power (MW)	Lumi. /IP (10^{34}cm^{-2}s^{-1})	Integrated Lumi. /yr (ab^{-1}, 2 IPs)	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H*	240	10	50	8.3	2.2	21.6	4.3×10^6
			30	5	1.3	13	2.6×10^6
Z	91	2	50	192**	50	100	4.1×10^{12}
			30	115**	30	60	2.5×10^{12}
W	160	1	50	26.7	6.9	6.9	2.1×10^8
			30	16	4.2	4.2	1.3×10^8
$t\bar{t}$	360	5	50	0.8	0.2	1.0	0.6×10^6
			30	0.5	0.13	0.65	0.4×10^6



[1] The Circular Electron-Positron Collider The CEPC Project

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.

Advantageous attributes for flavour physics studies at Belle II ($\Upsilon(4S)$), 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	✓		(✓)

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

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

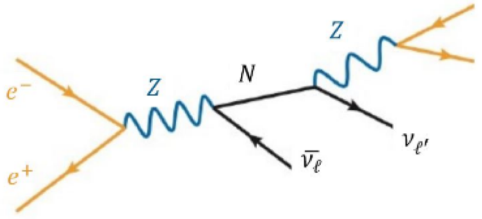
B^0s → $\mu^+ \mu^-$ (5366 MeV/c2)

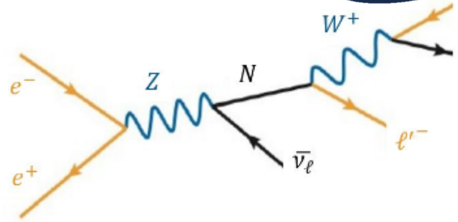
B^0 → $\mu^+ \mu^-$(5279 MeV/c2)

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

Muon physics



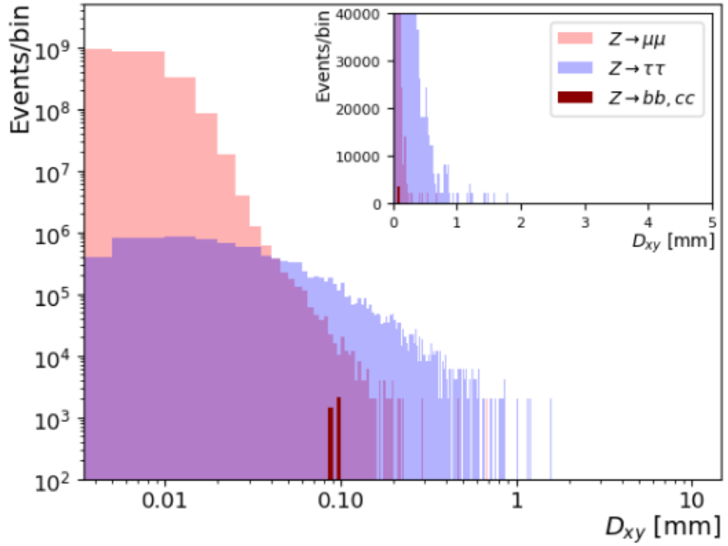


Heavy Neutral Lepton searches

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 $\mu\ \mu\ \nu_\mu$
  - **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]

Muon detector challenges

INFN LNF - DDG

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 t**ail-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. O(100 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

The IDEA detector

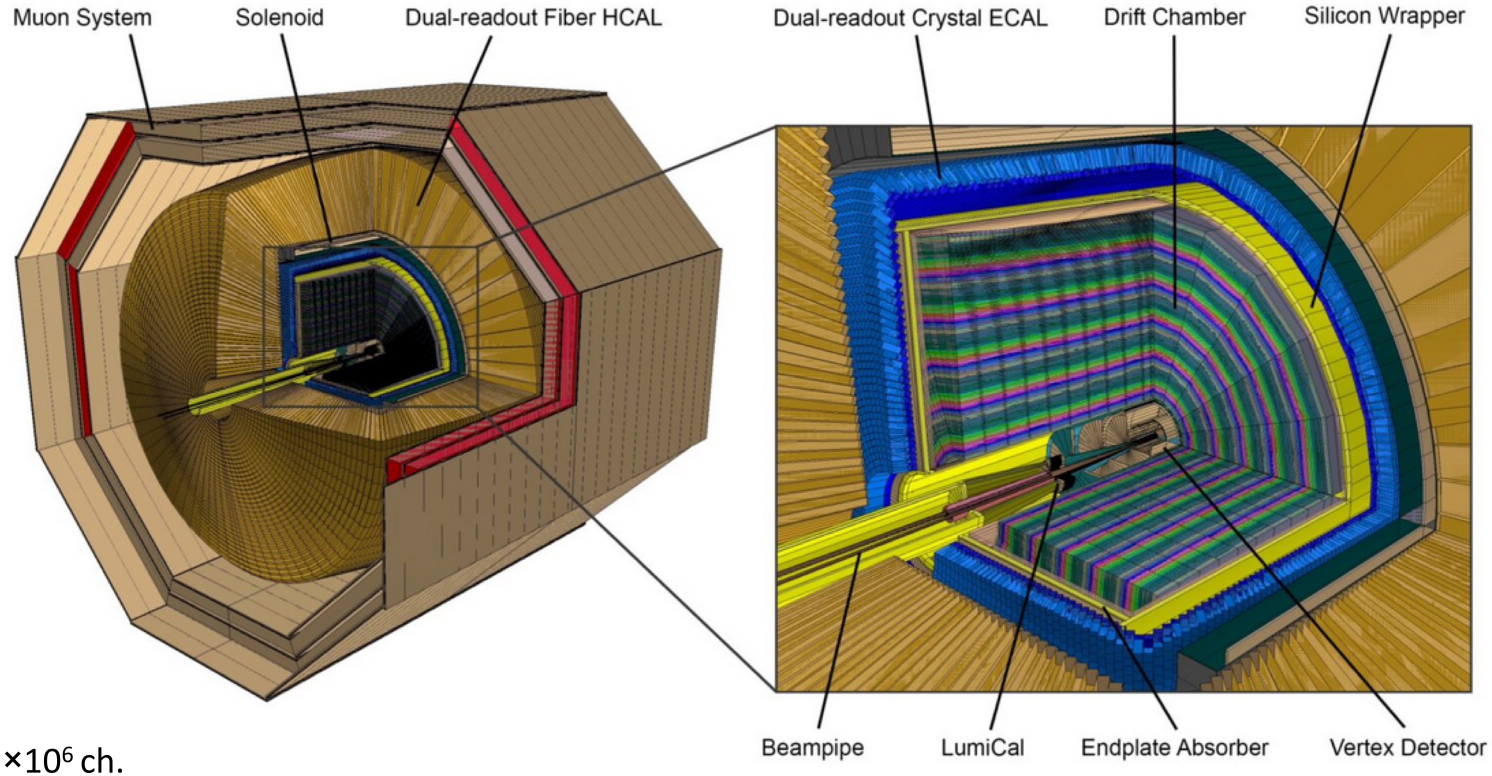
The Innovative Detector for e+e- Accelerator (IDEA) was originally proposed by a **few Italian groups**

It has **evolved** into one of the **most advanced detector concepts**, specifically designed for a large circular e+e⁻ collider.

Many **International collaborators** (CERN, USA, UK, South Korea, Switzerland, France, Slovenia, etc.) have joined the R&D work

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**

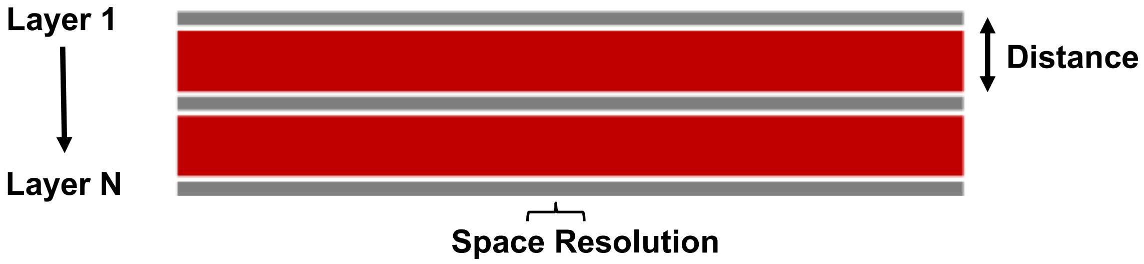
[11] "The IDEA detector concept for FCC-ee", arXiv:2502.21223 [physics.ins-det]

The IDEA Muon System: Simulation

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 level-arm distance (30 cm to 50 cm)
- Varying the space resolution of the detector (400 μm to 200 μm)



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

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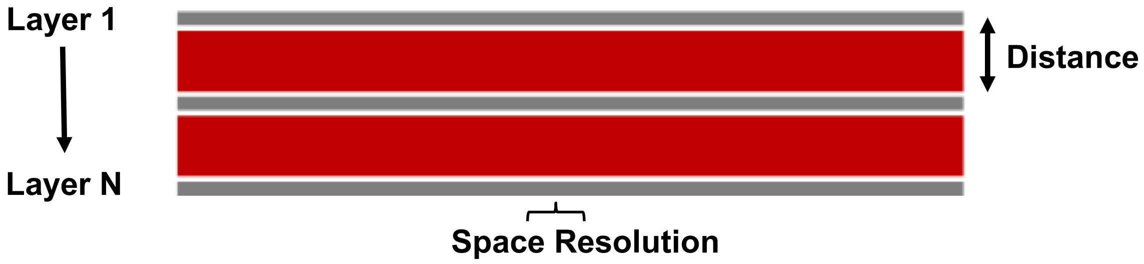

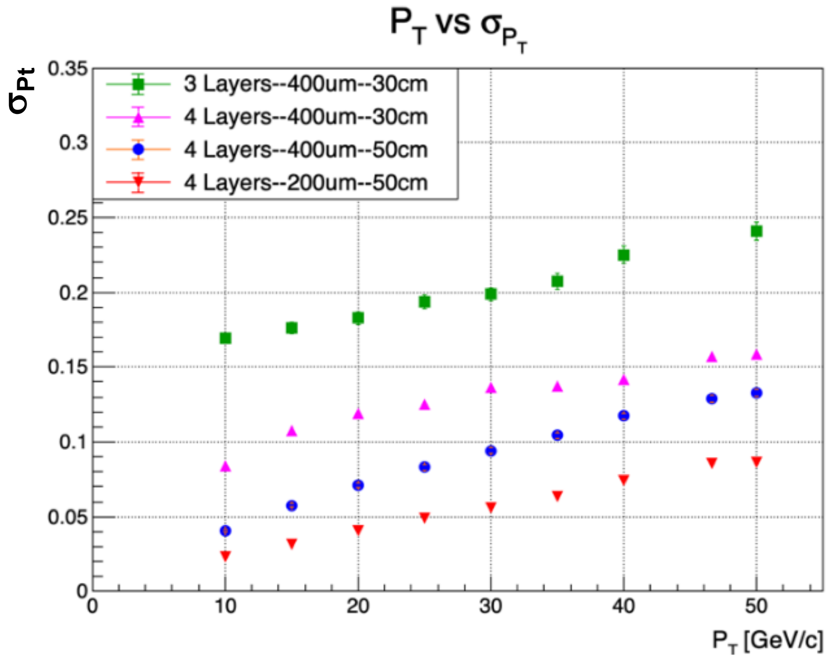

[12] "Full simulation of the muon system of IDEA detector concept for future circular lepton colliders ", Master's Thesis

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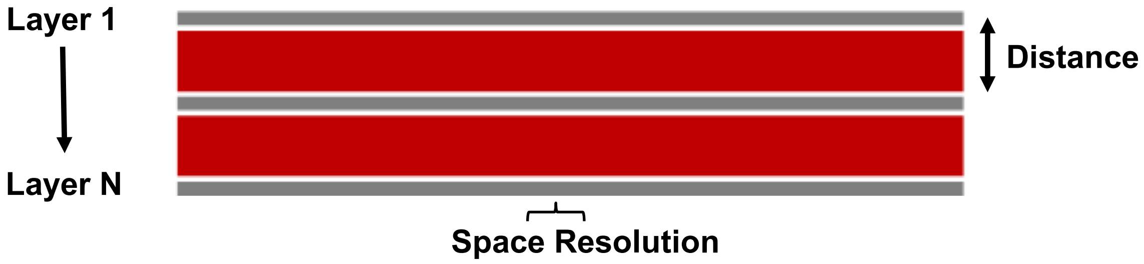
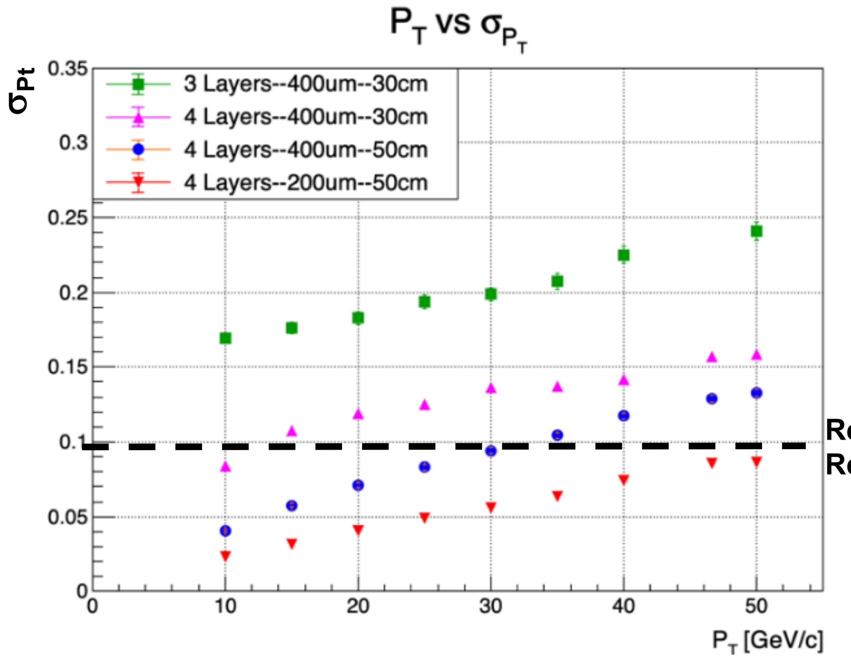
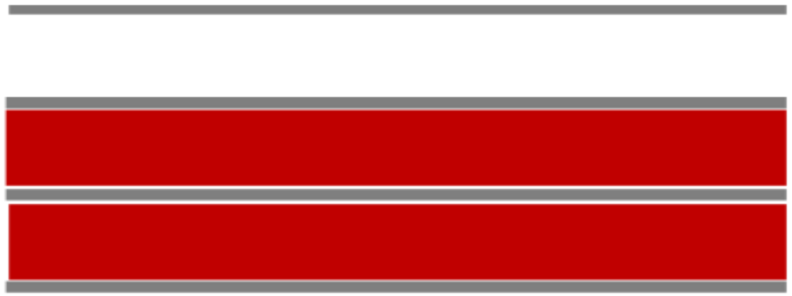




Requiring a momenutm Resolution < 10%



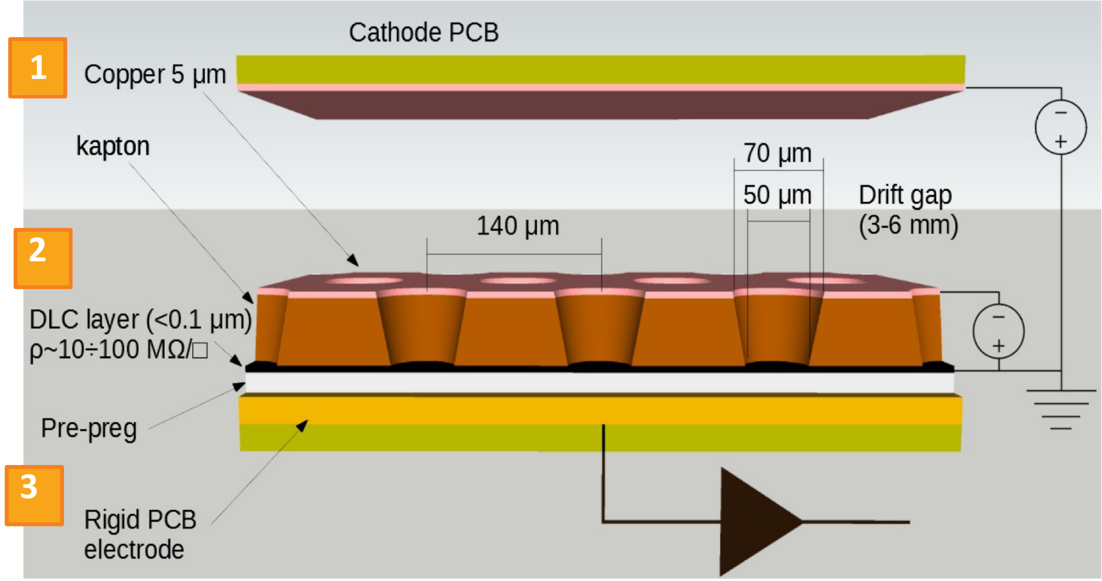
4 Layers with level-arm = 50 cm, only two yokes and 200 μm space resolution

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

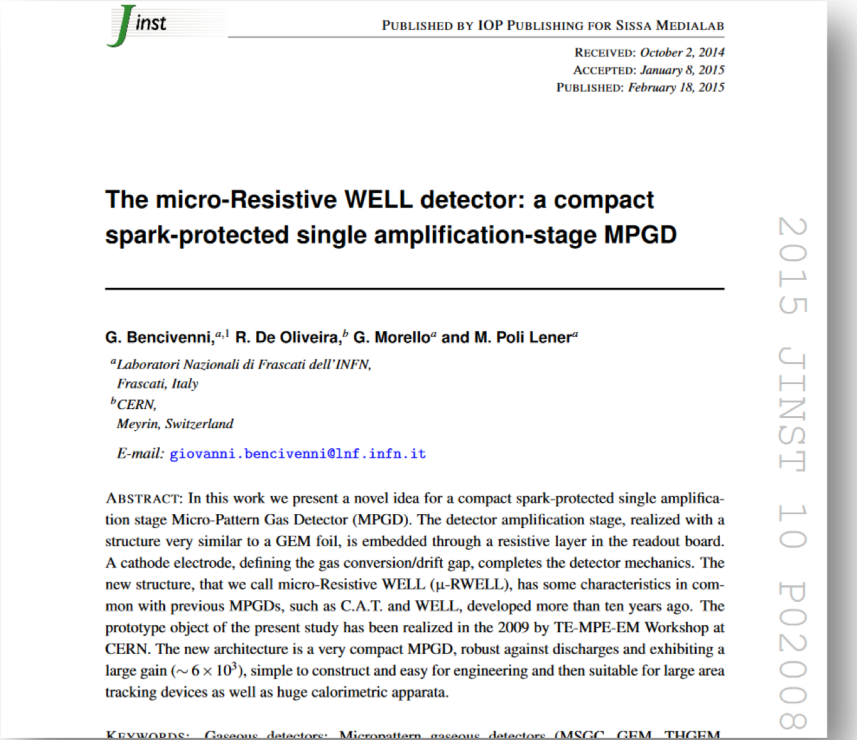
The IDEA Muon System:
Detector & Transfer to Industry

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:



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



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

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[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 (~ 6×10^3), simple to construct and easy for engineering and then suitable for large area tracking devices as well as huge calorimetric apparata.

2015 JINST 10 P02008

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

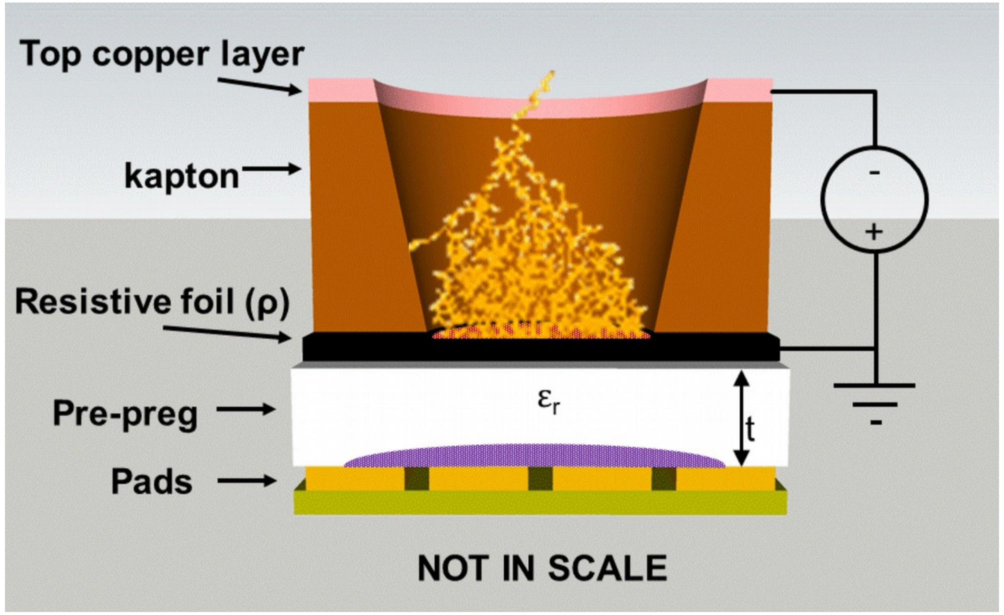
[13] G. Bencivenni et al. JINST 2015 10 P02008

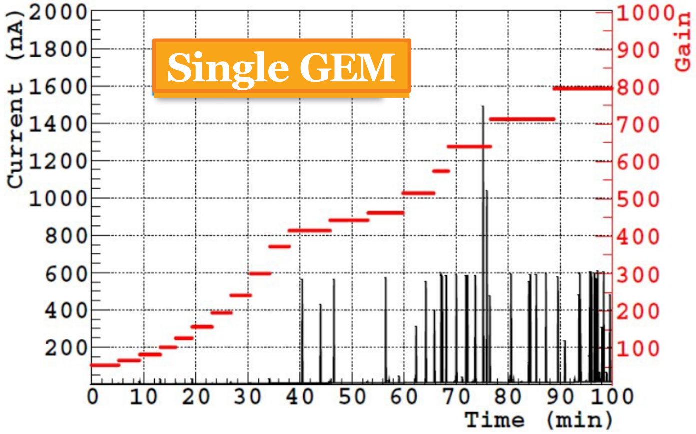
The μ-RWELL: principle of operation

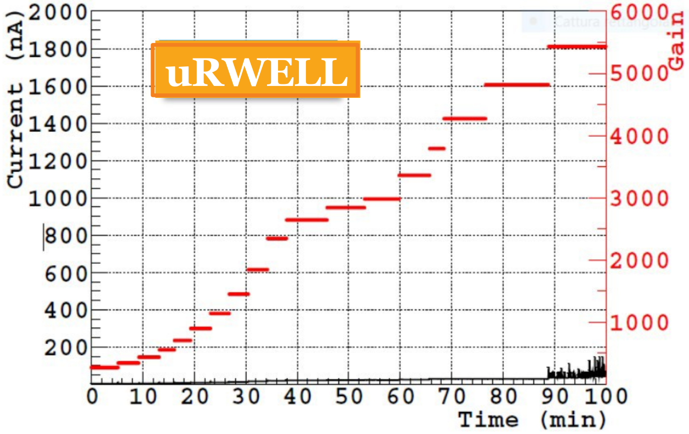
Applying a suitable voltage between the **top Cu-layer and the DLC** the WELL acts as a **multiplication channell for the ionization** produced in the conversion/drift gas gap.

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 layer solves this problem





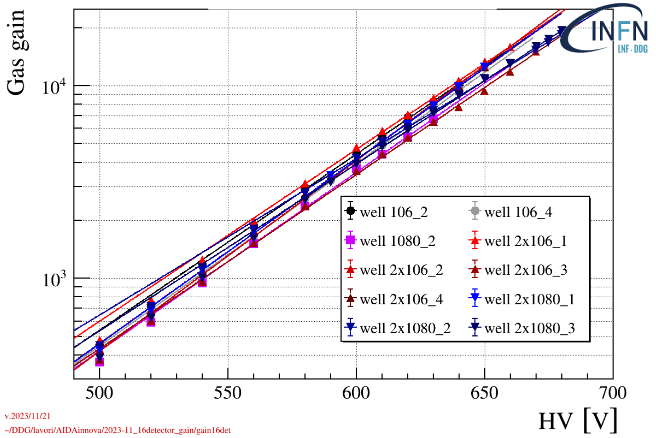


Comparison between the **current** drawn by a single GEM and a μ-RWELL at various **gas gain**.

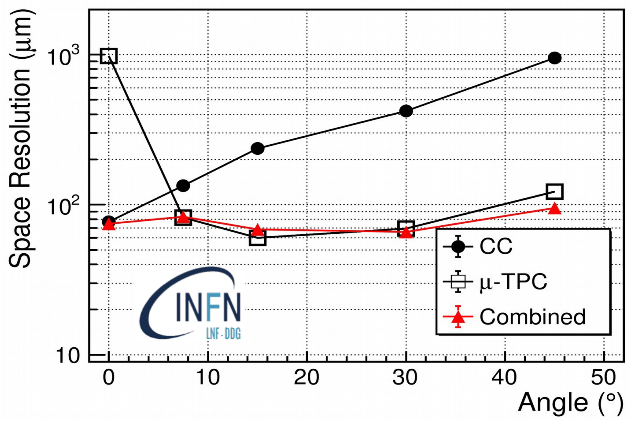
The black spikes are the sparks in the detectors, clearly dumped in the μ- RWELL for higher gains

μ-RWELL performance overview

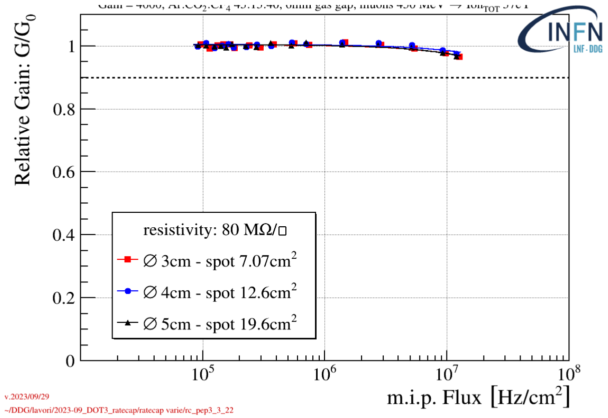
Gain up to 10^4

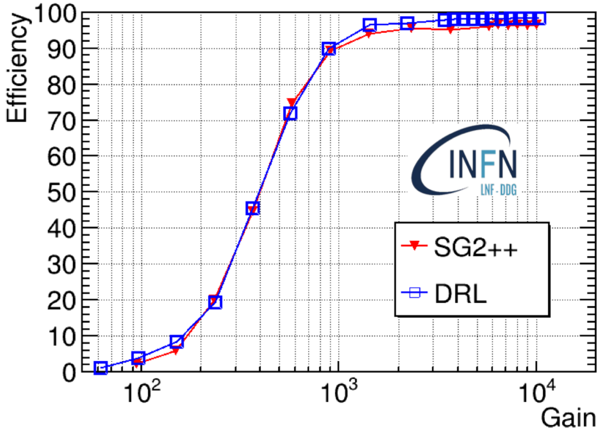


Space resolution ~ 100 μm

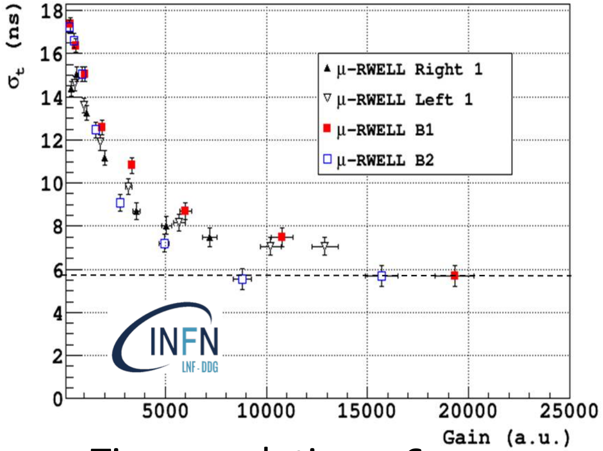


Rate Capability ~ 5-10 MHz/cm^2

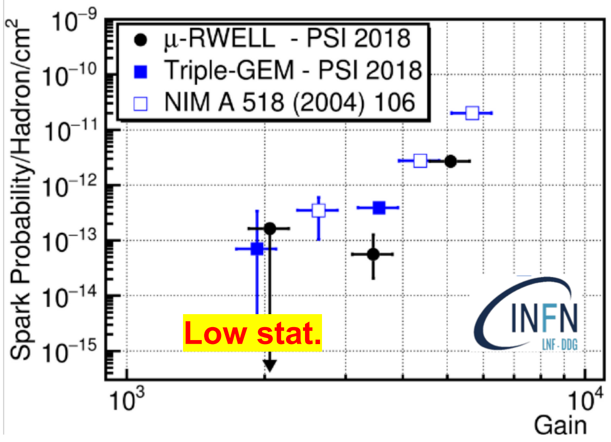




Efficiency ~ 98%



Time resolution < 6 ns

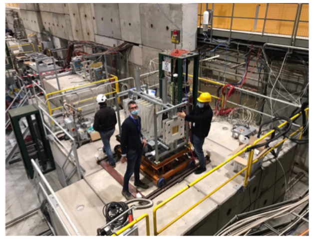


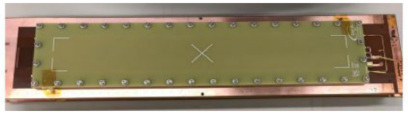
Discharge probability ~ 10^{-13} @ 4000

[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

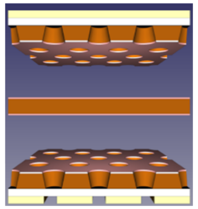
u-RWELL R&D History

1D Layout optimization



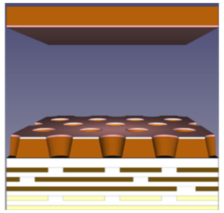


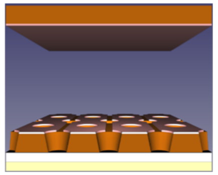
2D layouts optimization



2x1D layout

Capacitive Sharing layout



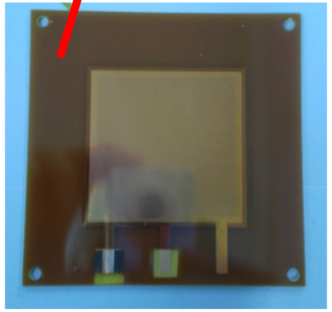


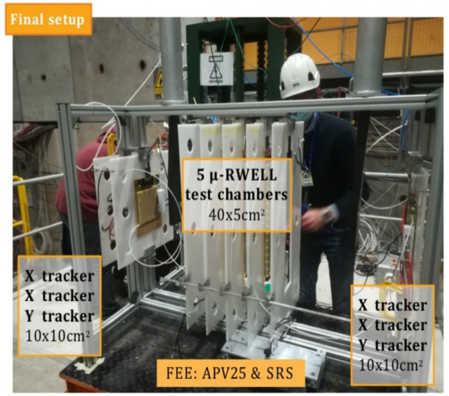
TOP layout

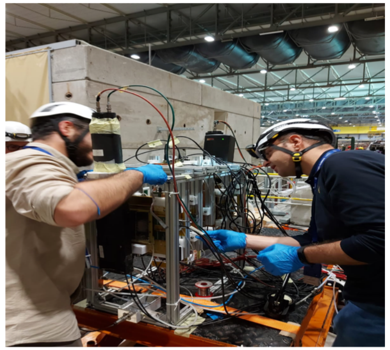
New u-RWELL ideas
(in collaboration
with RD51)

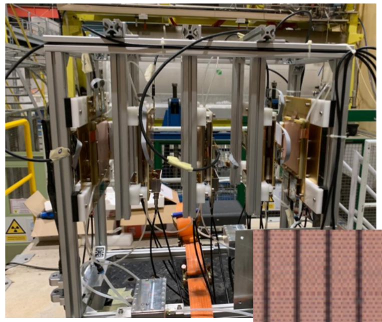
R&D for FCC start

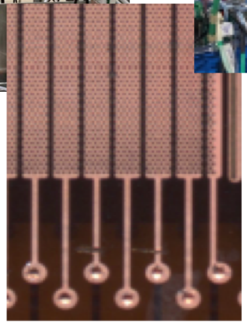
2009 · 2020 · 2021 · 2022 · 2023 · 2024

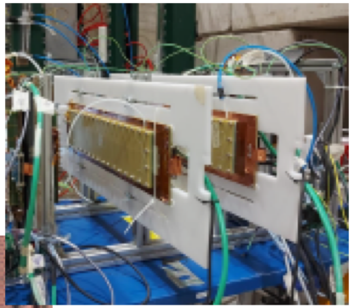










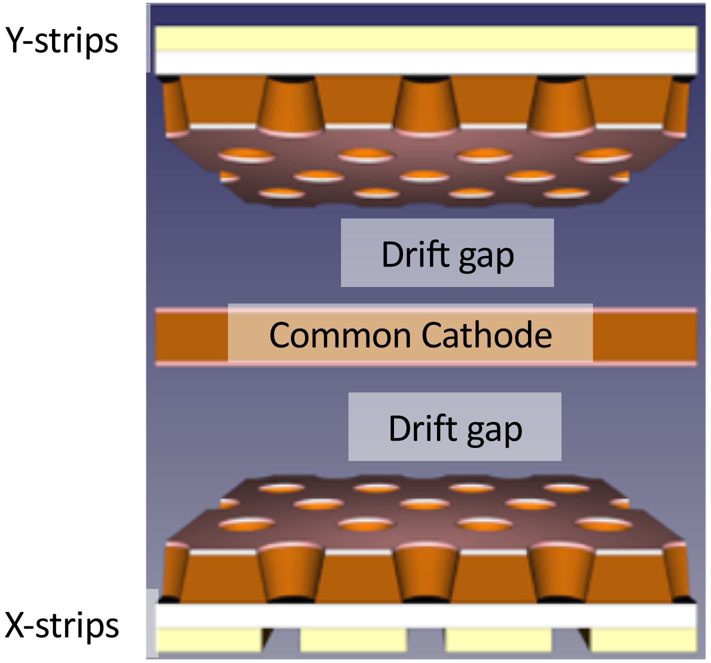


IDEA slice test:
DC + pre-shower +
dual_calo + muon

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

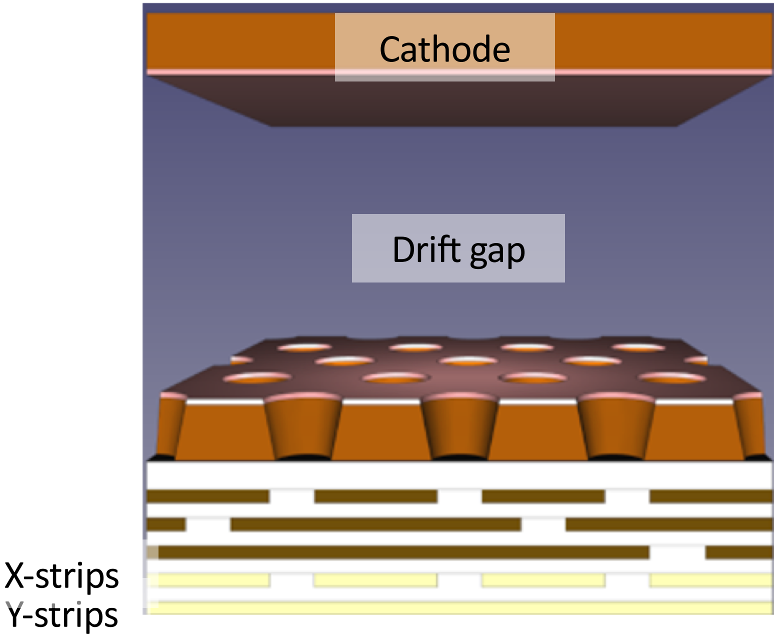
INFN LNF - DDG

n.2 µ-RWELL 1D [2×1D]



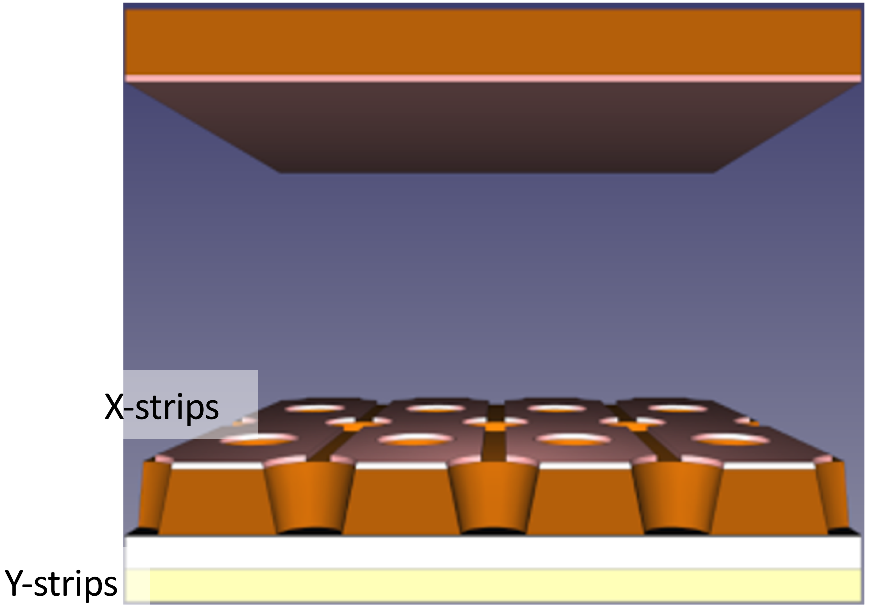
- Lower gas gain w.r.t. the "COMPASS R/O" (X / Y are not sharing any charge)
- Tested @ TB2022

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

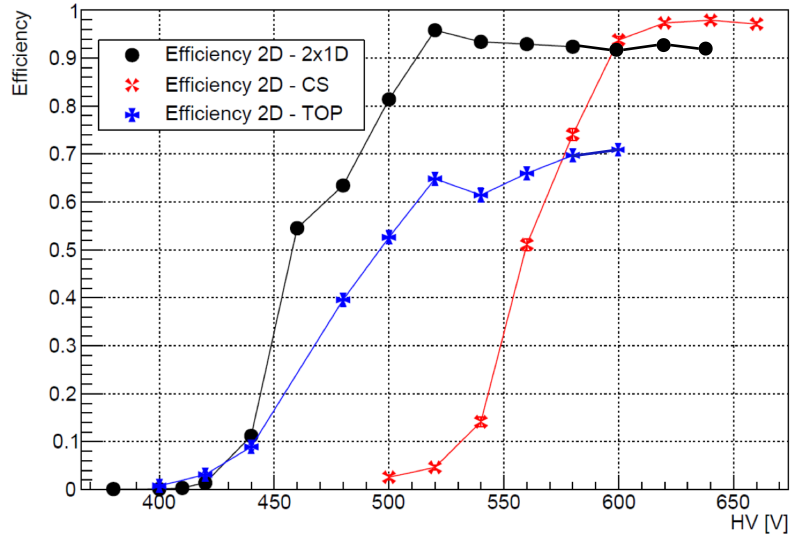
[18] K. Gnanvo et al., NIM A 1047 (2023) 167782

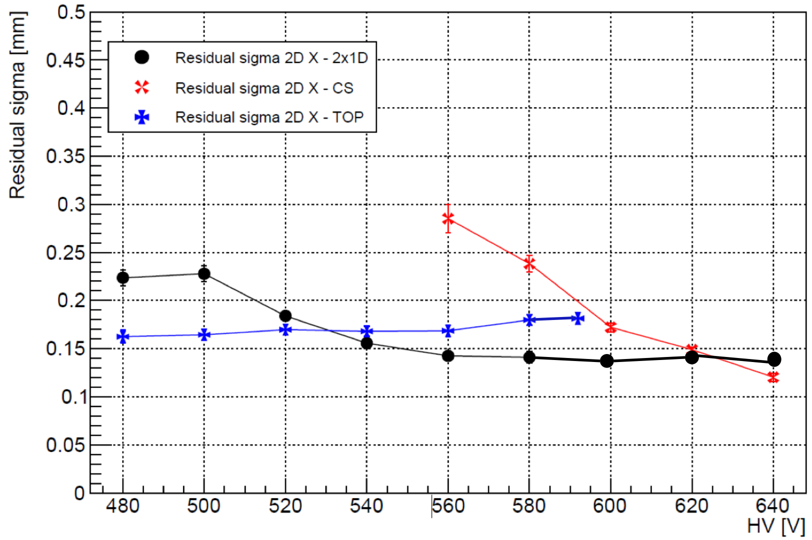
2D layouts performance

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)





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

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

New layouts under study for Muon systems:

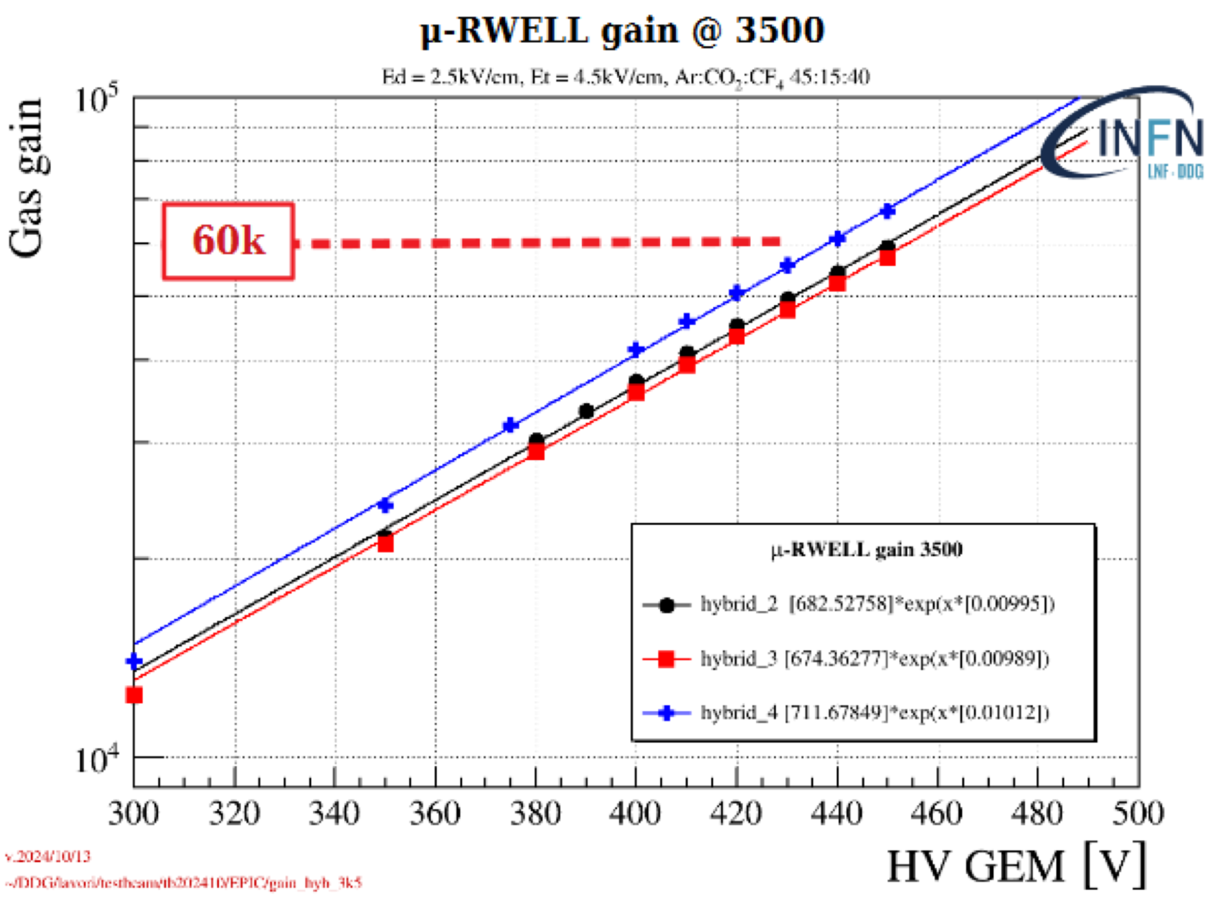
WIDE STRIP PITCH

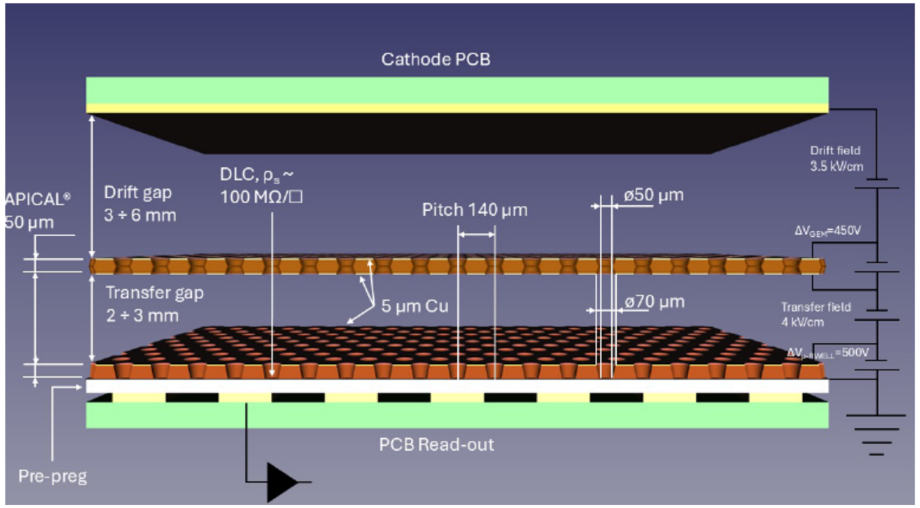
1. **GEM + CS µ-RWELL 10x10 CM2**→ GEM pre-amplification stage, to lower the operating point, greatly improving the RWELL stability and maintaining high spatial performance with millimetric pitches.

2. **GEM + CS µ-RWELL 50X50 CM2 → first large µ-RWELL for IDEA**

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.

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

Layout under study

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

New layouts under study for Muon systems:

WIDE STRIP PITCH

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.
2. **GEM + CS μ-RWELL 50X50 CM2** → **first large μ-RWELL for IDEA**

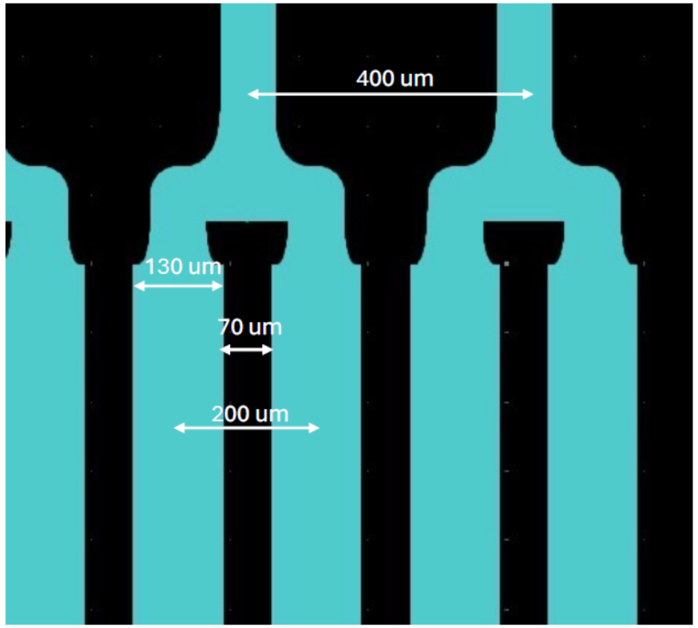
NARROW STRIP PITCH

3. **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.

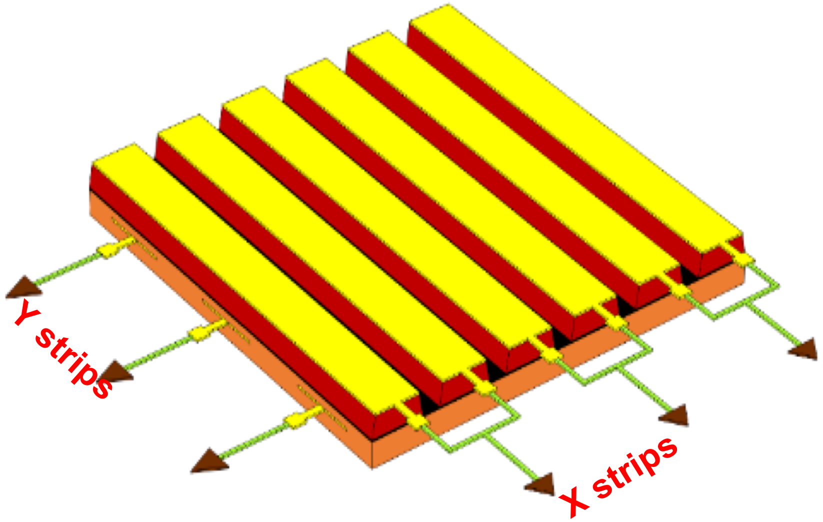
u-RGroove

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

TOP STRIP readout

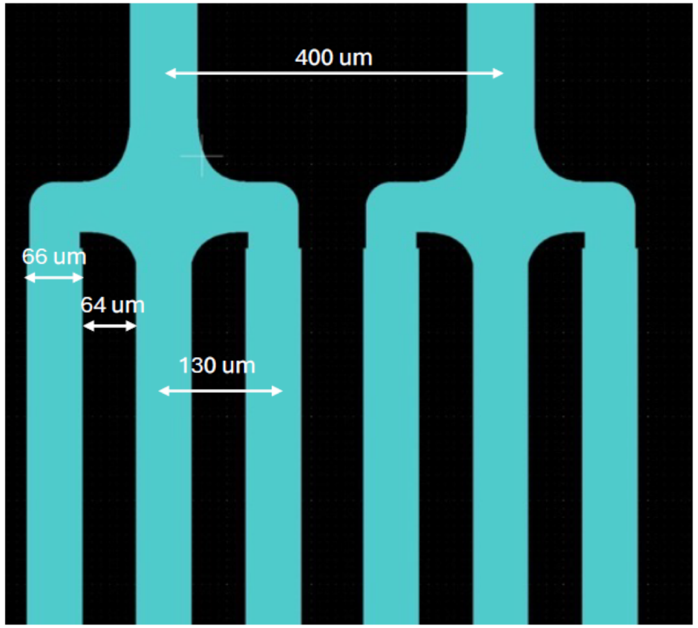


Layout with 2 strip OR-ed:
FEE Strip pitch 400 µm
Pitch strip 200 µm



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

TOP STRIP readout



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

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

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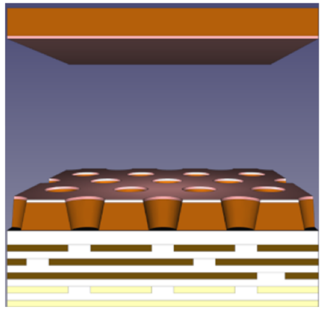
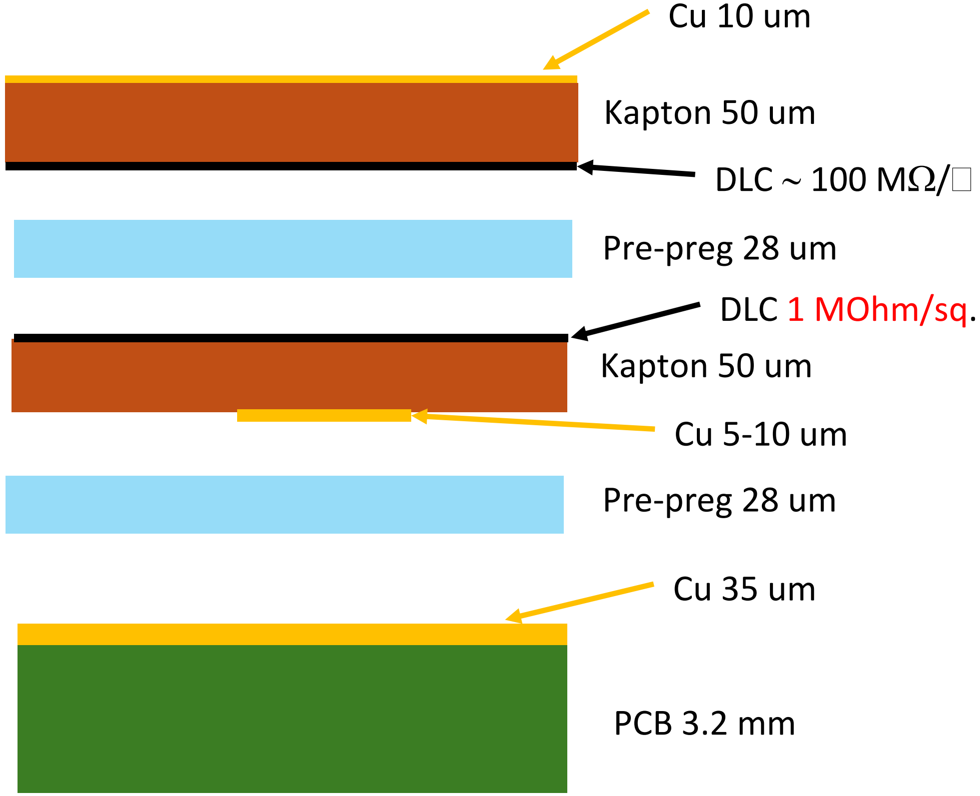
4. **DOUBLE DLC FOIL μ-RWELL 10x10 CM2** → new idea of layout, where the first DLC foil will be used as standard resistive layer (100 MΩ/□), while the second one (1 MΩ/□) to spread the charge on the readout.

Double-DLC u-RWELL

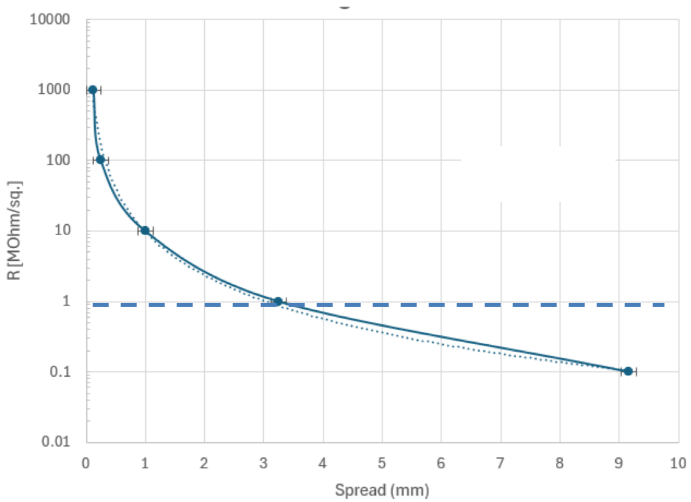
Double DLC μ-RWELL, as we envision it, should represent the evolution of the CS layout by eliminating capacitive coupling to conductive elements in the CS, replacing them with a single resistive element





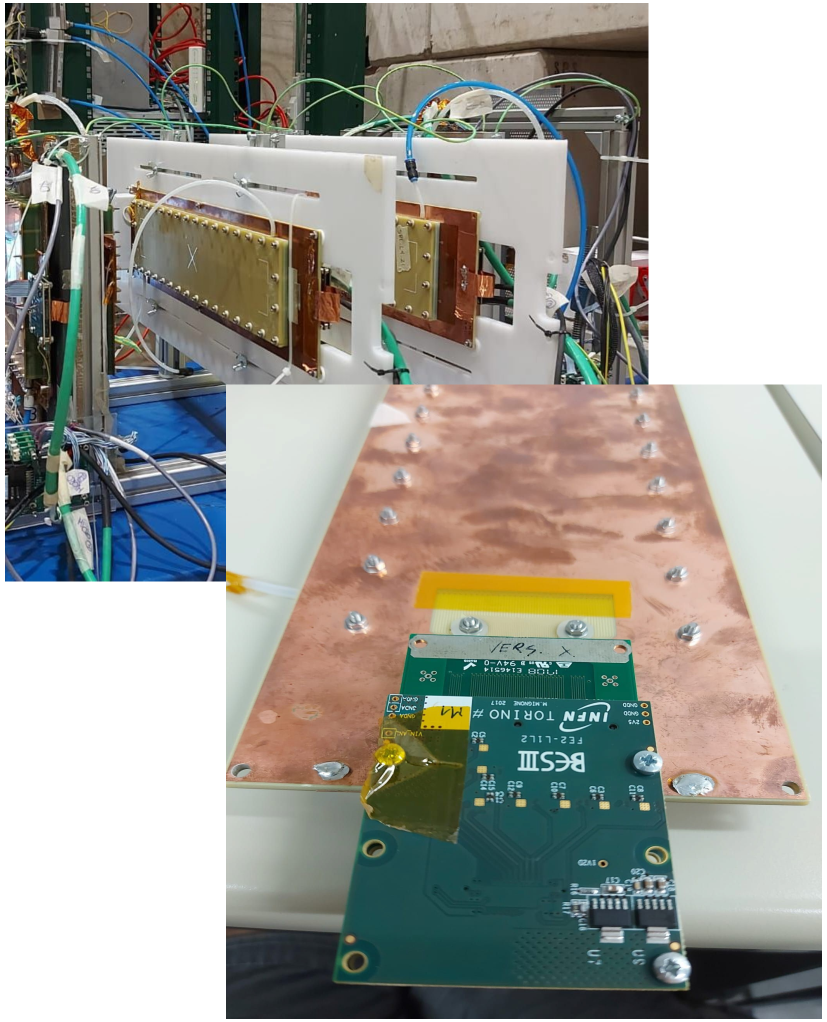
→**First DLC layer** with high resistivity for **local HV drop**

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



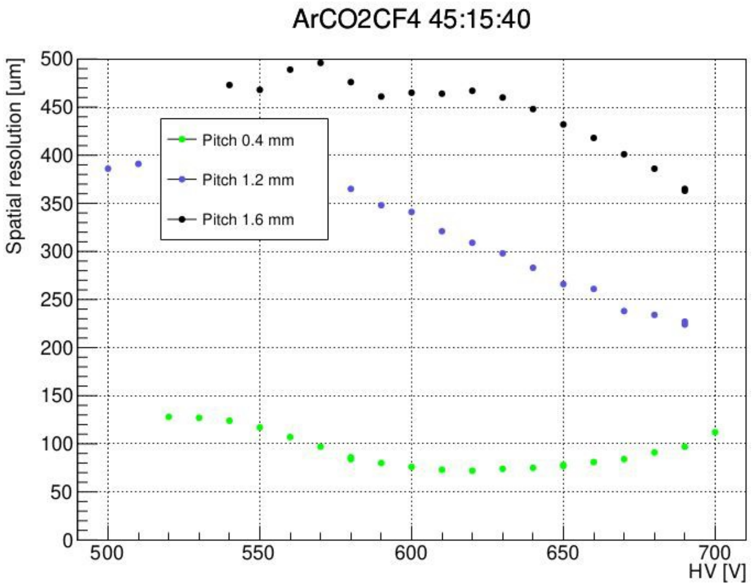
Resistivity below 1 MΩ/sq results in 4-5 fired strips with a 1.6 mm pitch

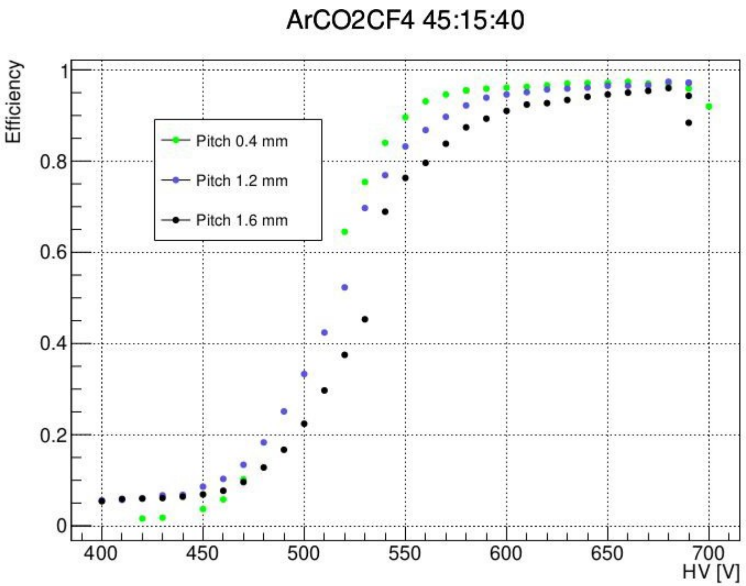
Performance with TIGER electronics



Test beam performed in 2024 to:
- Define the state of art of µRWELL+TIGER for IDEA Muon system optimization studies
- Compare the APV-25 performance studies with TIGER

Readout under test:
- TIGER FEE (INFN-TO)
- GEMROC FPGA (INFN-FE)





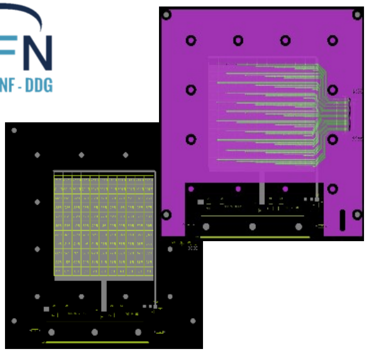
[21] A. Amoroso et al., 2021 JINST 16 P08065

Performance confirmed the ones evaluated with APV 25

Technology Transfer

Feedback from tests

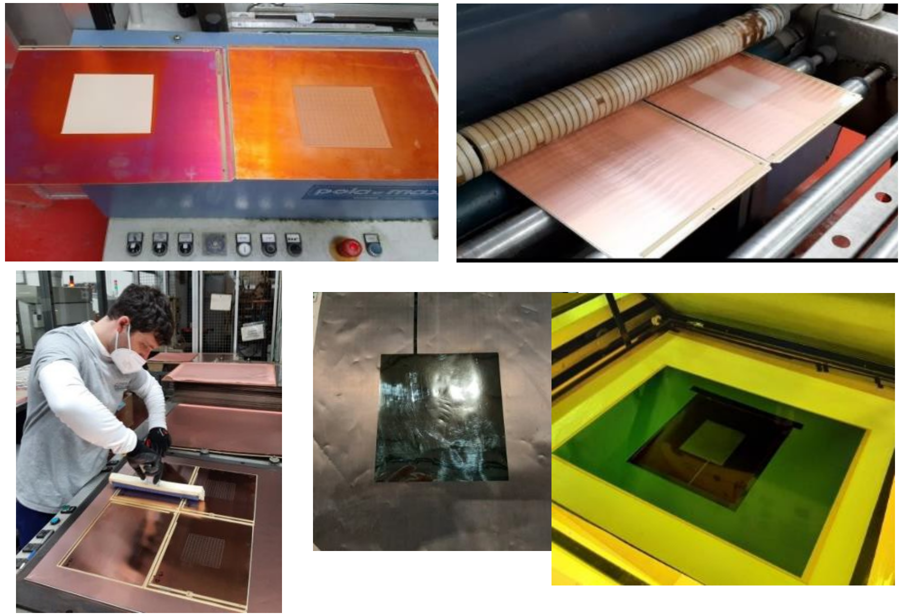
LAYOUT design



DLC foil production[*]

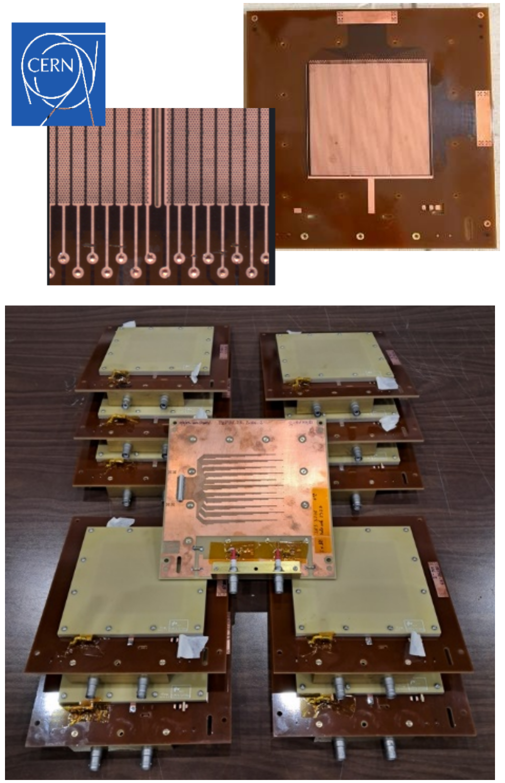
[*] DLC Magnetron Sputtering machine co-funded by INFN- CSN1

PCB production



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

Final detector manufacturing



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.

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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 NFN-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.

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Thanks for your attention

Back UP

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%

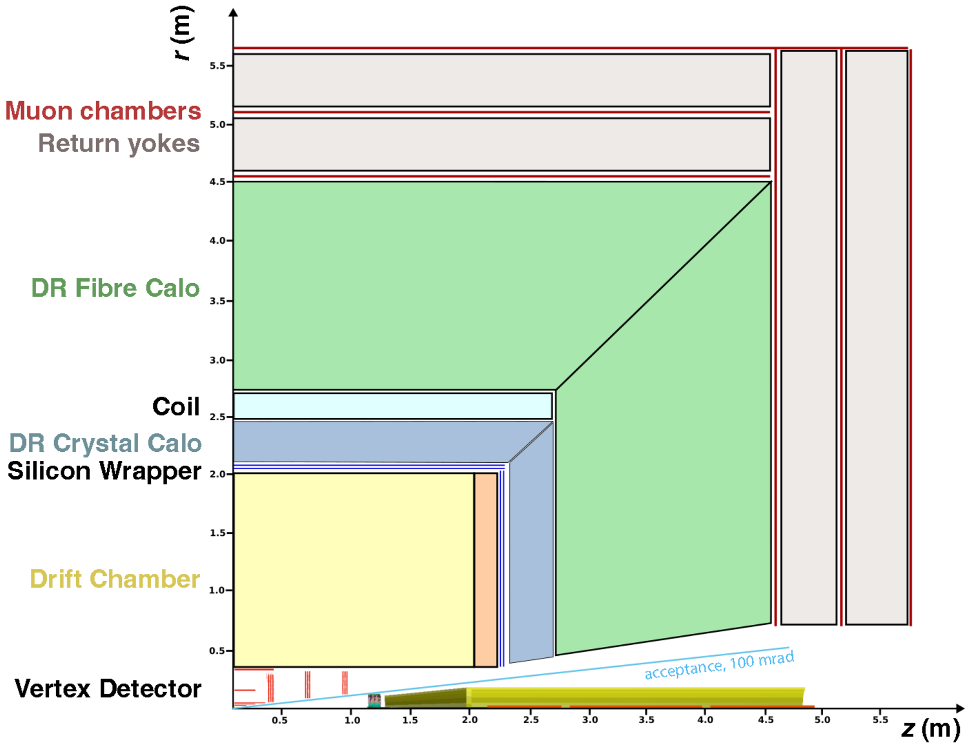
Space resolution ≤ 200 μm

Particle Flux < 1kHz/cm^2

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

Mass production → Technology Transfer to Industry

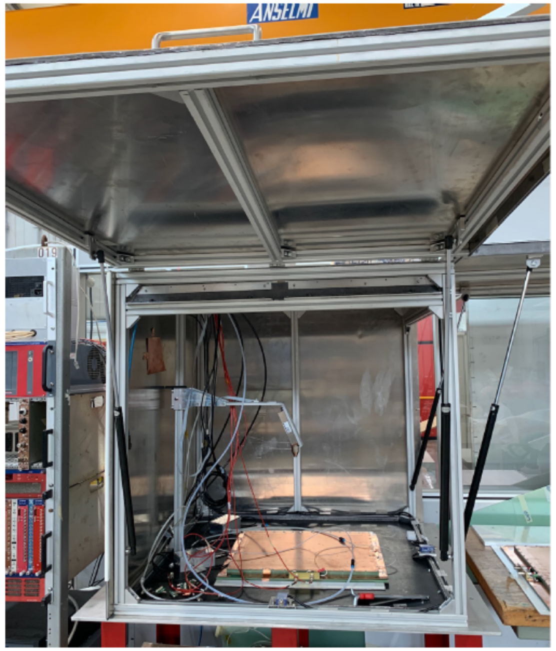
FEE Cost reduction → custom made ASIC (based on TIGER or the new TORA CHIP)

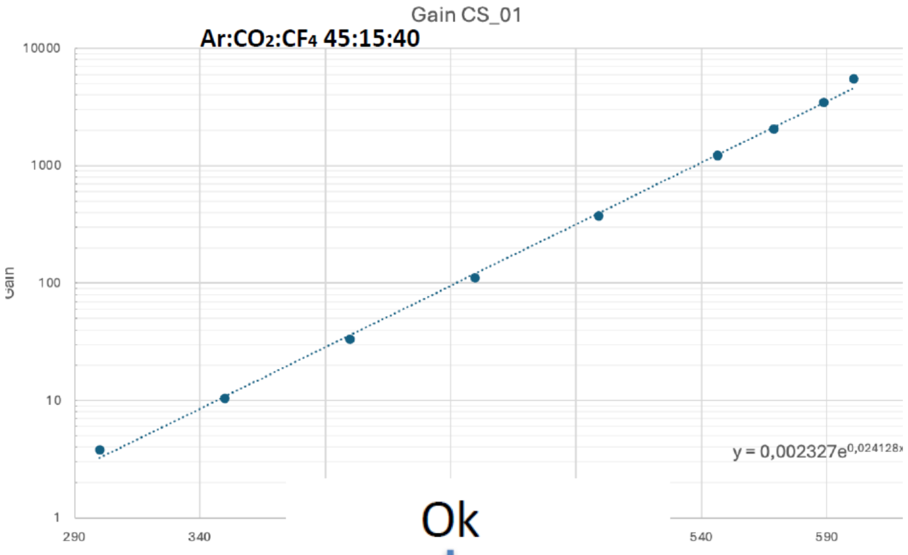


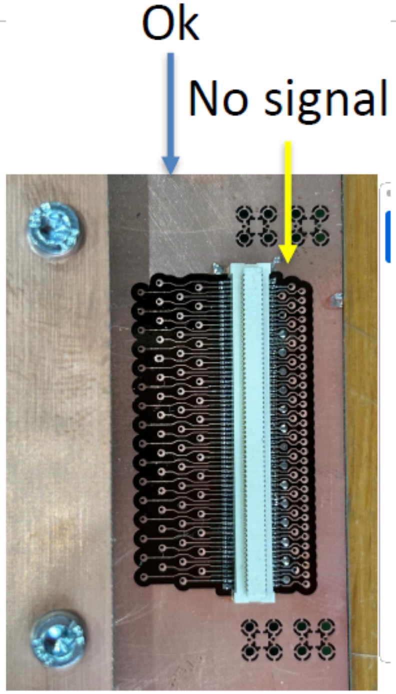
Italian Institutes involved: LNF, Bologna, Ferrara, Torino.
There are opportunities to contribute in multiple areas and leading roles in many fields (software, electronics, detector)

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.

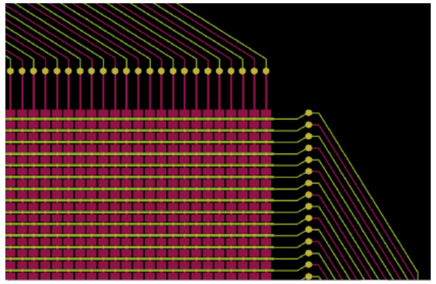
→ Investigations with Rui identified an error in the connection vias.

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

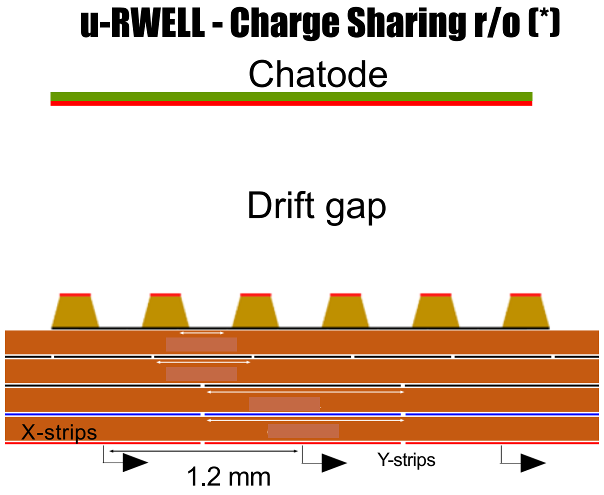
→ Check gas gain after Rui's hot clean + performance with cosmic stand

→ A GEM foil will be added to the 50×50 cm² CS in collaboration with RM2

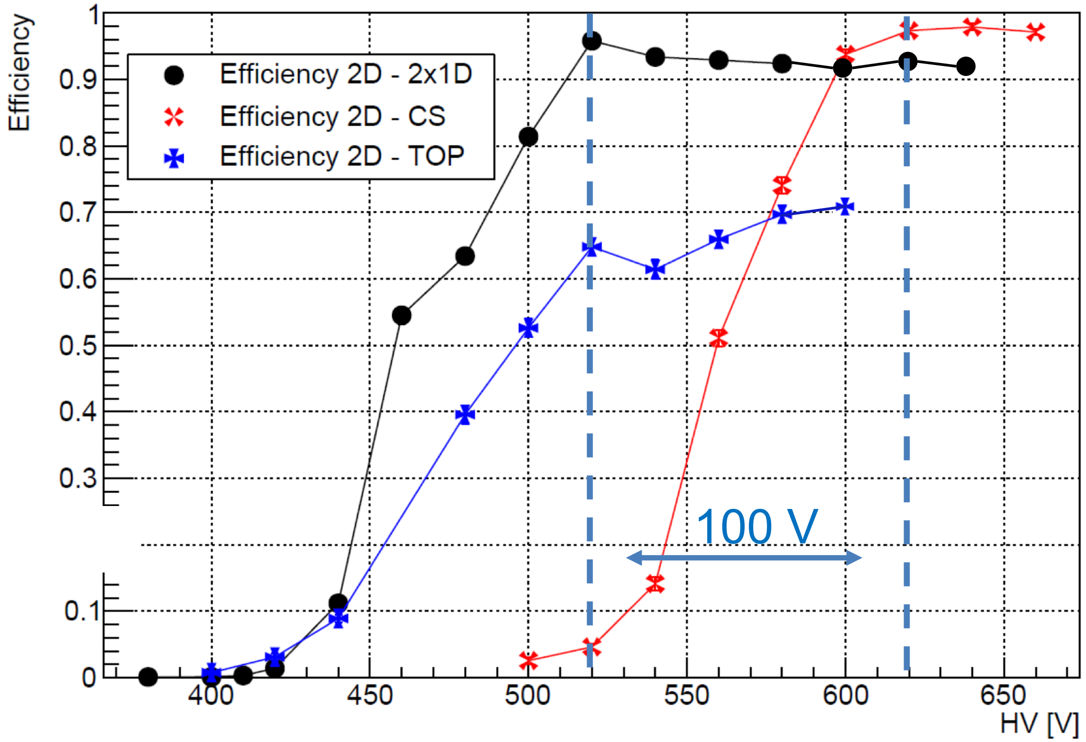
CS layout vs 2x1D



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 cm²



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