The 8th International Conference on Micro-Pattern Gaseous Detectors
Oct.14th - Oct.18th 2024 USTC·Hefei, China

μ-RWELL muon system and pre-shower for FCC-ee

R. Farinelli, on behalf of INFN Bologna/Ferrara/Frascati/Torino

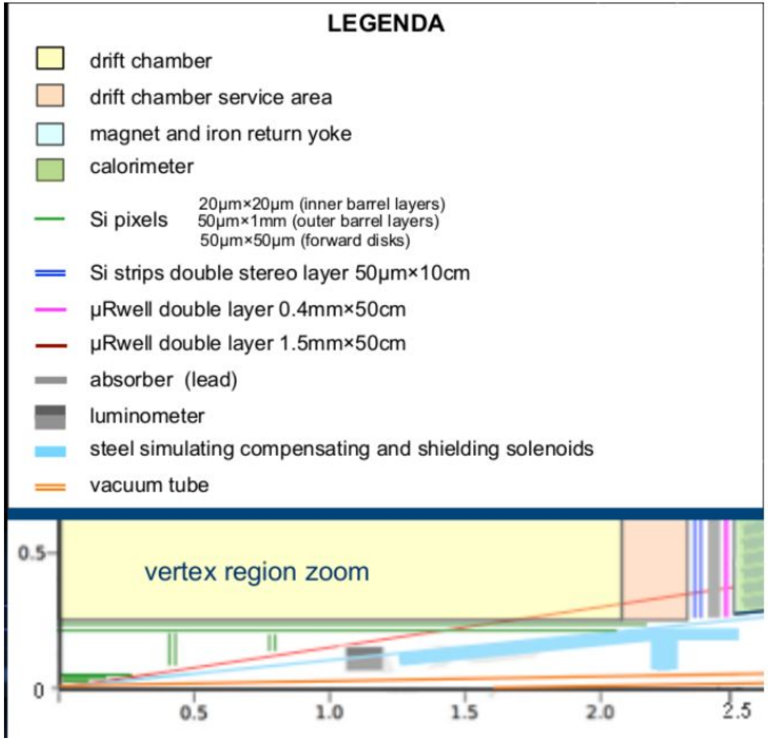
Outline

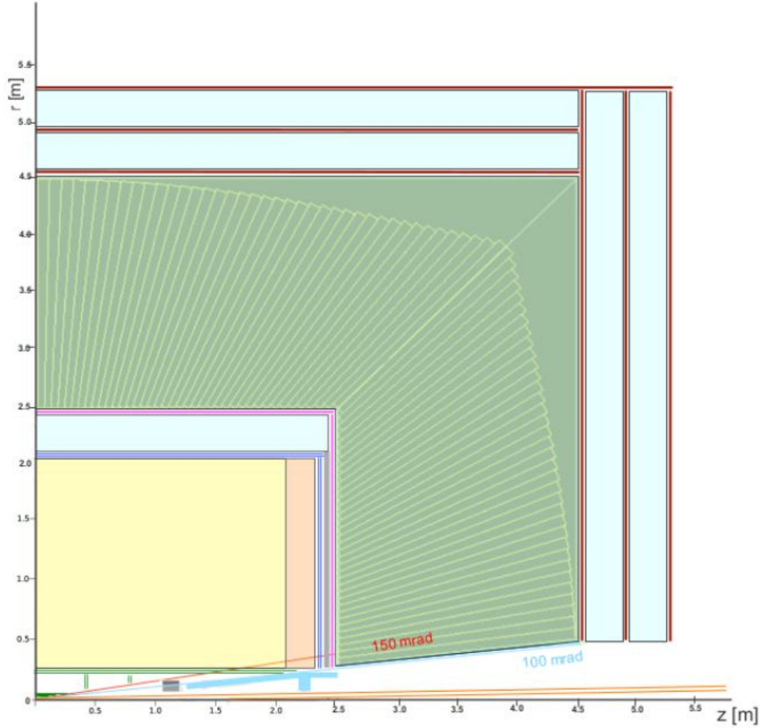
- IDEA detector and μRWELL pre-shower and muon systems
- μRWELL technology
- Layout optimization 1D
- Layout optimization 2D
- TIGER + μRWELL testbeam preliminary results
- Simulation plans

IDEA detector

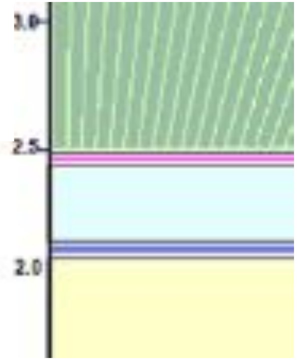
IDEA baseline detector concept

Here is shown the original concept but some update/upgrade are under study (i.e. EM calorimeter)





The IDEA pre-shower



High resolution after the magnet to maximize the energy resolution of the dual readout calorimeter and tag π0 and γ

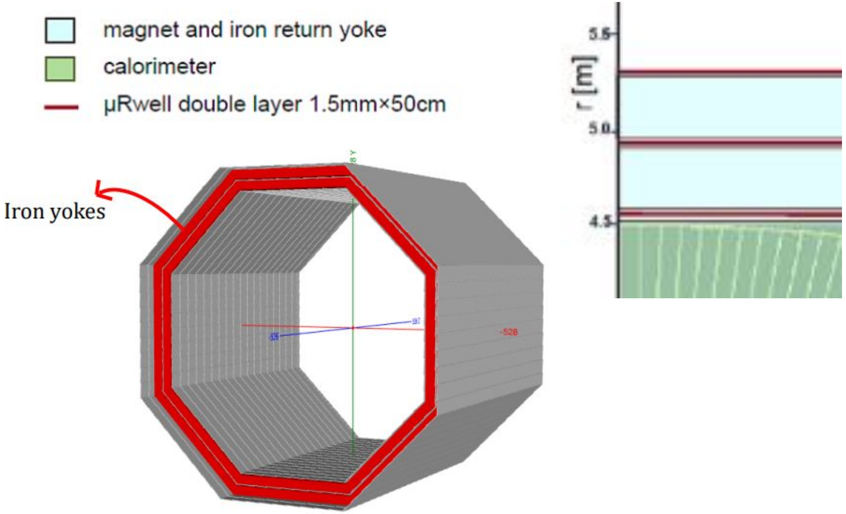
Efficiency > 98%
Space Resolution < 100 μm
Mass production
Optimization of FEE channels/cost

50x50 cm^2 2D tiles
to cover about **130 m^2**

pitch = 0.4 mm
FEE capacitance = 70 pF
1.3 million channels

The IDEA muon detector

Reconstruct and tag the muon with three layers in between the iron return yoke and reconstruct LLP



Efficiency > 98%
Space Resolution < **400 μm**
Mass production
Optimization of FEE channels/cost

50x50 cm^2 2D tiles
to cover about **1525 m^2**

pitch = 1.5 mm
FEE capacitance = 270 pF
5 million channels

μRWELL
technology and R&D activities

μ-RWELL technology

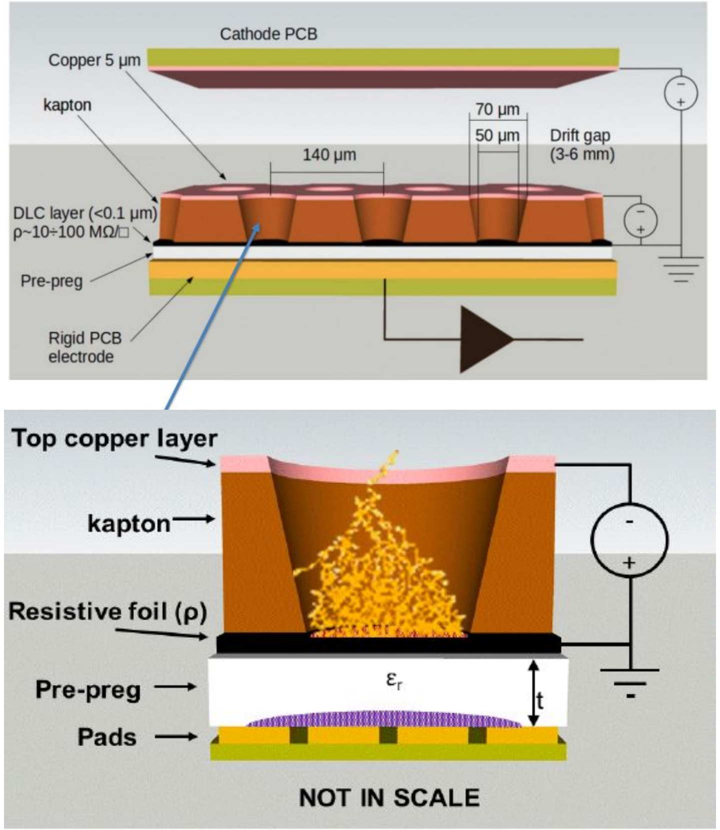
G. Bencivenni et al., 2015 JINST 10 P02008

The μ-RWELL is composed of only **two elements**:

- **μ-RWELL_PCB** = amplification-stage ⊕ resistive stage ⊕ readout PCB
- **cathode** defining the gas gap

μ-RWELL **operation**:

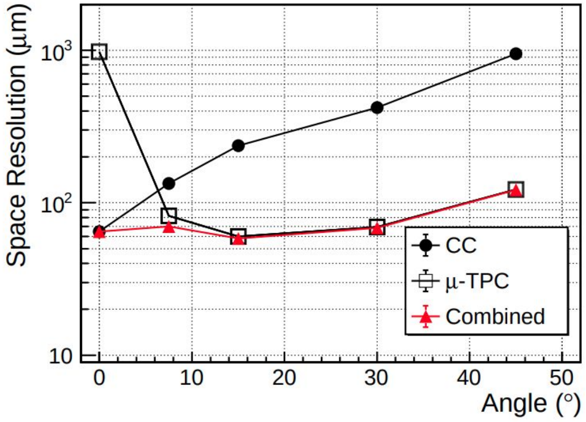
1. A charged particle **ionizes** the gas between the two detector elements
2. Primary electrons **drift** towards the μ -RWELL_PCB (anode) where they are **multiplied**, while ions drift to the cathode or to the PCB TOP
3. The signal is **induced** capacitively, through the DLC layer, to the readout PCB
4. only two HV for the drift region (cathode-drift wrt PCB TOP) and the amplification region (PCB TOP wrt resistive stage)



μ-RWELL technology

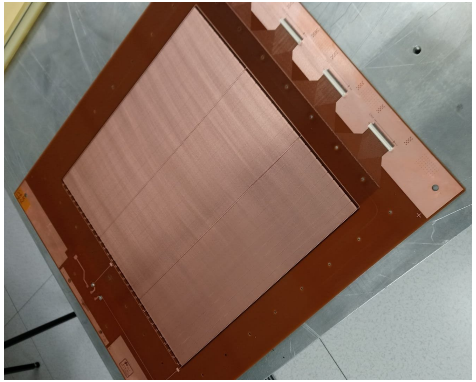
G. Bencivenni et al., JINST 16 (2021) 08, P08036

Well **known performance** on prototypes 10x10 cm^2 active area:



efficiency > 98%
spatial resolution < 100μm
rate capability ~ 1-10 MHz/cm^2

The detector is build up by two “pieces” only.
This simplifies the construction, the assembly and the HV operation wrt MicroMegas and triple-GEM



The μRWELL technology fully compatible with standard PCB building procedures **allows an easy Technological Transfer** to industry, opening the way towards industrial **mass production**.

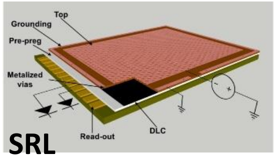
See M. Giovannetti talk.

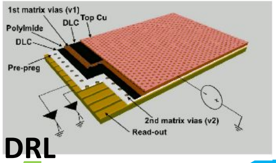
μ-RWELL R&D history

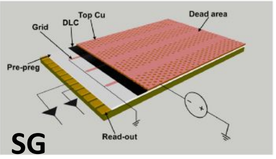
R&D on low-rate layout

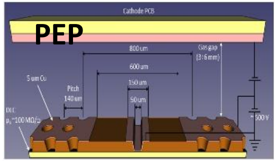
R&D on high-rate layout

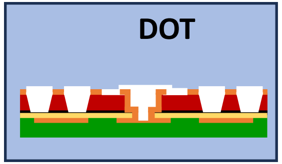
New μ-RWELL ideas (in collaboration with RD51)







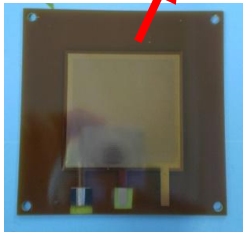




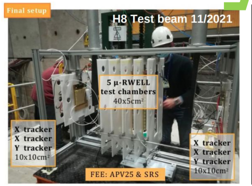
R&D start

TT @ ELTOS

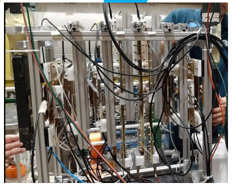
2009 — 2014 — 2015 — 2016 — 2017 — 2018 — 2019 — 2020 — 2021 — 2022 — 2023 — 2024



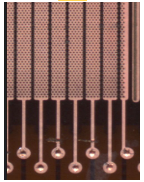
IDEA slice test: DC+ preshower+ dual_calo+ muon



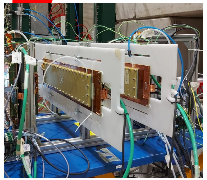
DLC Resistivity



Readout segmentation + 2D readout



2D readout



TIGER FEE

R&D on large area and 2D readout

Layout optimization 1D

the following results are evaluated using **APV25** electronics and **Ar:CO2:CF4** gas mixture (45:15:40)

Resistivity Optimization

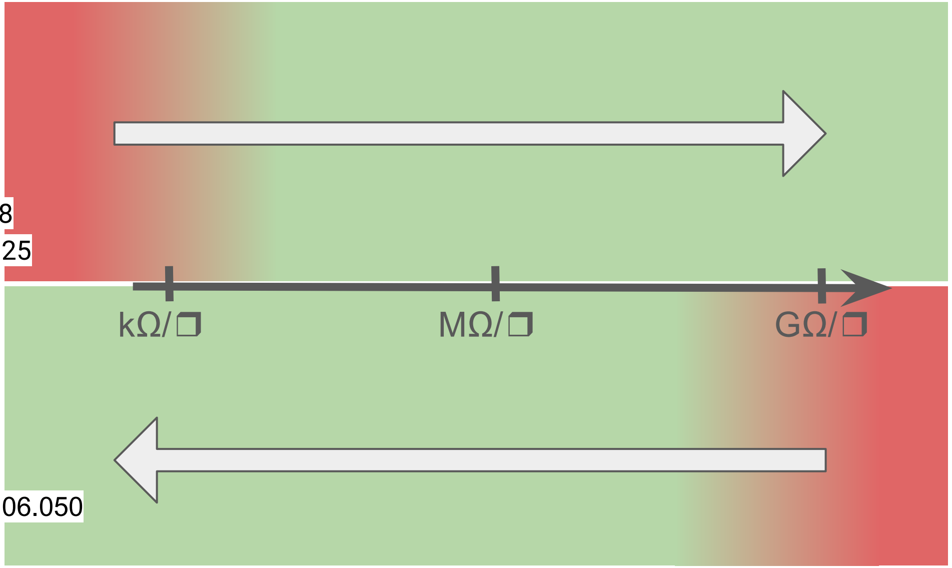
Resistivity

Stability operation

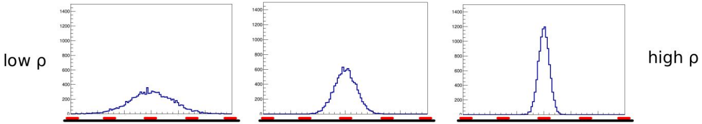
G. Bencivenni et al., 2015 JINST 10 P02008
T. Alexopoulos et al., 2011 NIMA 2011.03.025

Charge dispersion

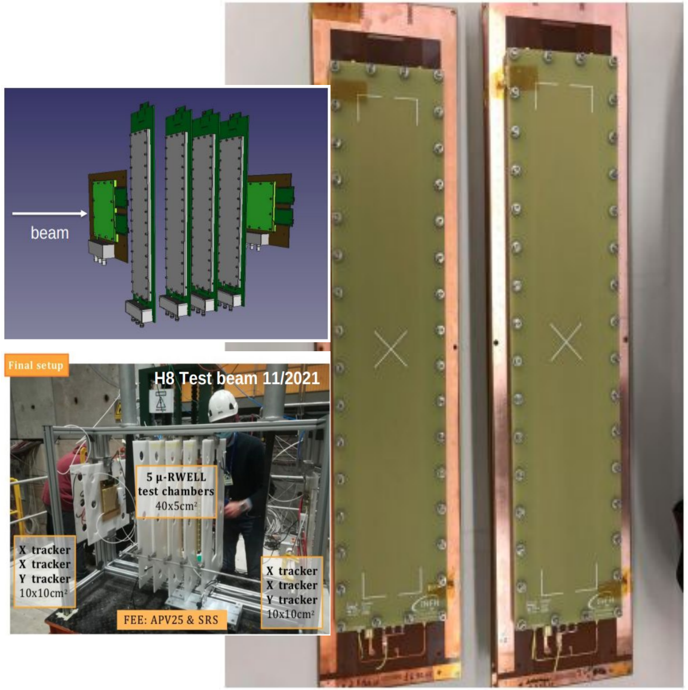
M.S. Dixit et al., 2004 NIMA 2003.09.051
M.S. Dixit and A. Rankin, 2006 NIMA 2006.06.050



Charge distribution example



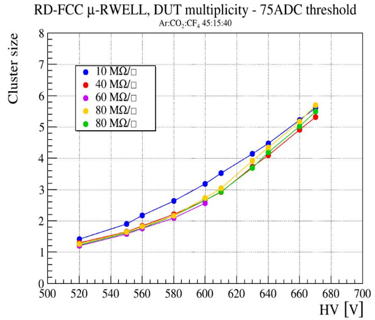
Resistivity Optimization

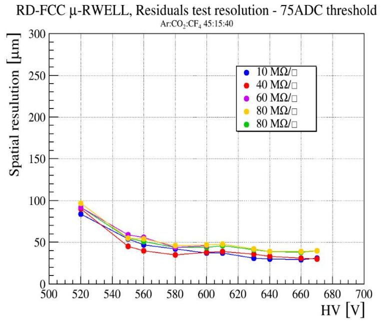


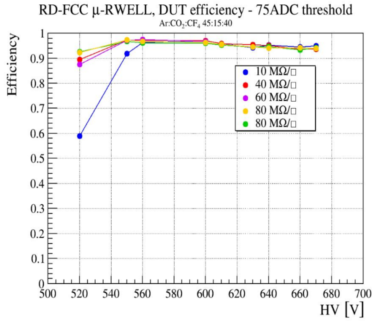
Active area = 400 x 50 mm2
Pre-preg thickness = 50 μm
Resistivity = 10-80 MΩ/❑
Strip pitch = 0.4 mm
Strip width = 0.15 mm
Ratio p/w = 2.66

An **HV scan** shows a large range of operability with a cluster size range [1-5]. The core spatial resolution is better than 50 μm with a strip pitch of 400 μm and center of gravity algorithm.

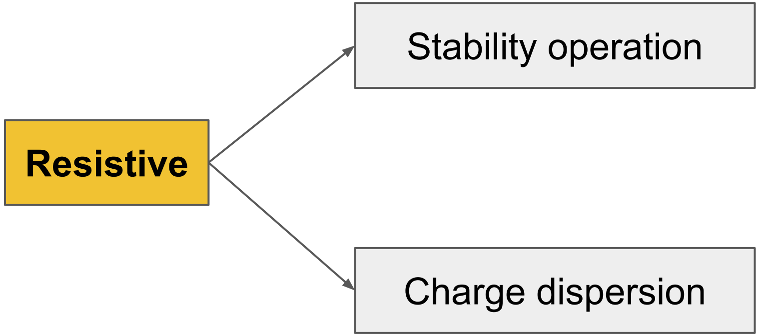
The **dependence** on the DLC **resistivity** is smaller in the range 40-80 MΩ/□ for cluster charge and cluster size, while the major dependency are observed in the efficiency.

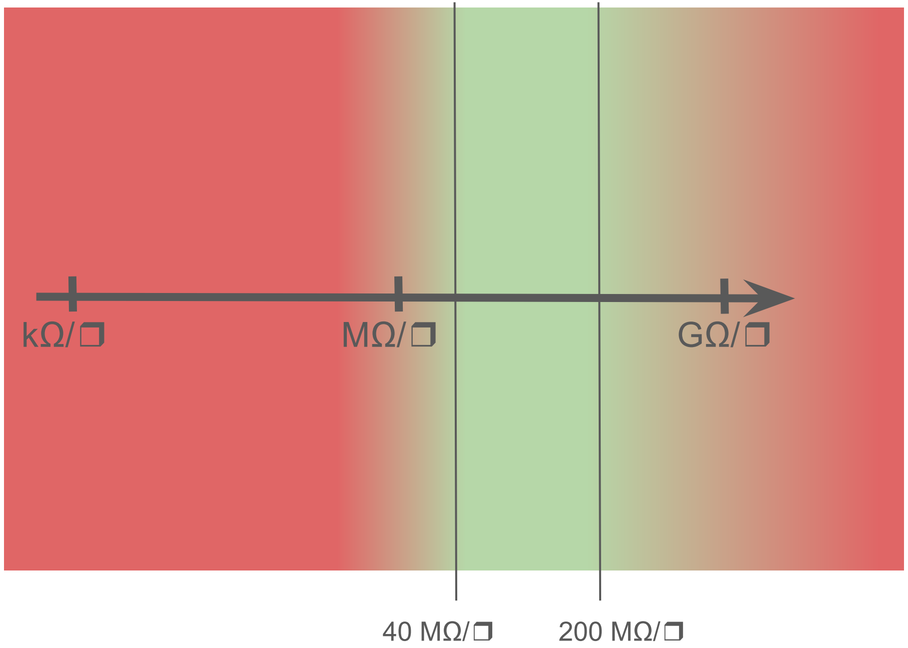




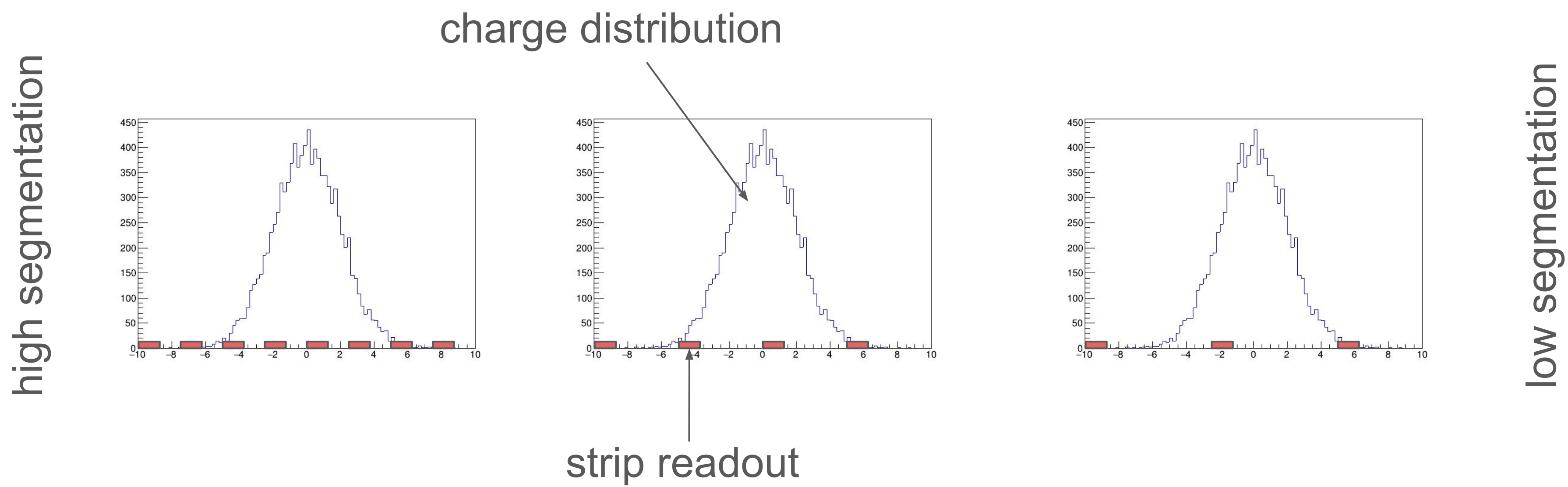


Resistivity Optimization





Pitch scan


charge distribution
high segmentation
low segmentation
strip readout

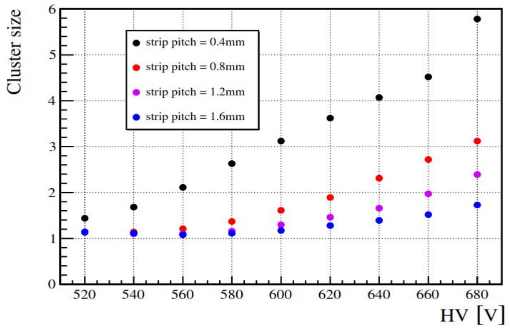
Pitch scan

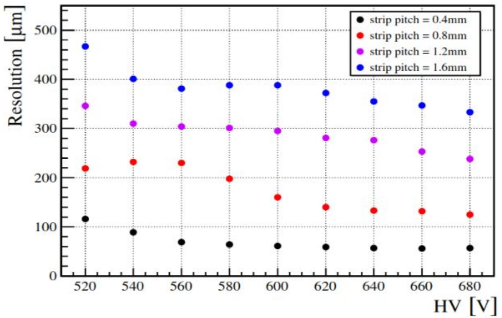
Active area = 400 x 50 mm2
Pre-preg thickness = 50 μm
Resistivity = 80 MΩ/❑
Strip pitch = 0.4/0.8/1.2/1.6 mm
Strip width = 0.15 mm
Ratio p/w = 2.66/5.33/8.0/10.66

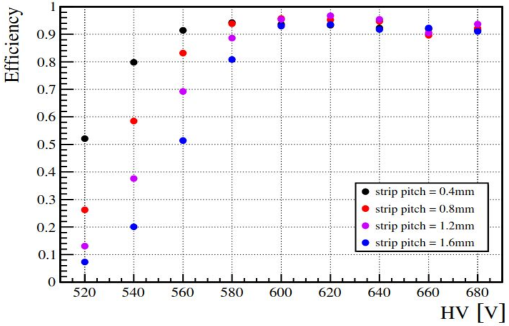
An **HV scan** shows a cluster size scaling with the pitch plus threshold effects.

The smaller is the pitch the better is the resolution. If a cluster size of 2 is not reached then resolution of pitch/sqrt(12) is expected.

A larger gain is needed to achieve the efficiency plateau. A shift of 40V is observed between 0.4 mm and 1.6 mm

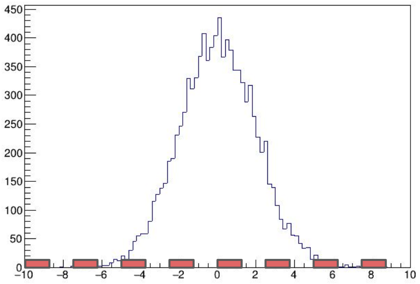


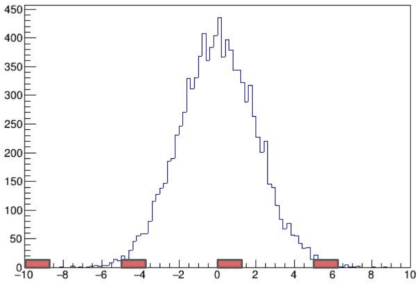


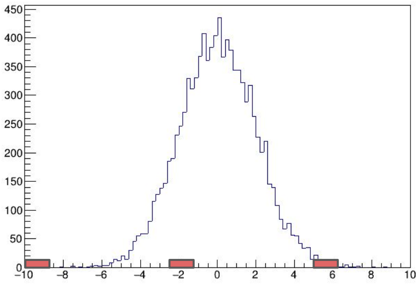


Pitch scan

high segmentation







low segmentation

pitch = 0.4 mm

↓

σ_x < 100 μm

pitch = 1.6 mm

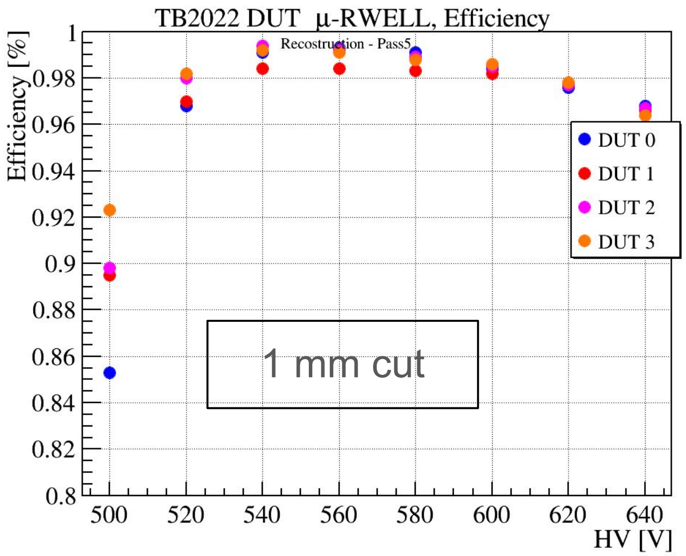
↓

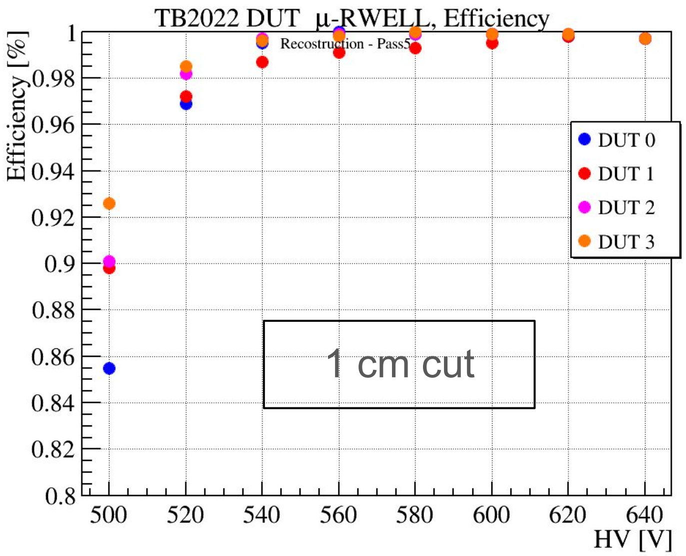
σ_x < 400 μm
but
larger gain needed

Focus on efficiency at high gain

Looking at the efficiency at high gain, a drop is observed if the “efficient” event are selected within 1mm (10 sigma) or 1cm (100sigma).

Clusters are there but a small faction has a larger residual value.

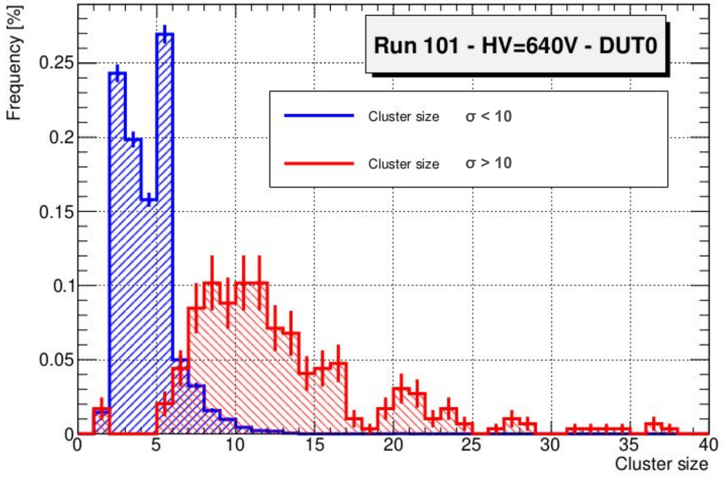


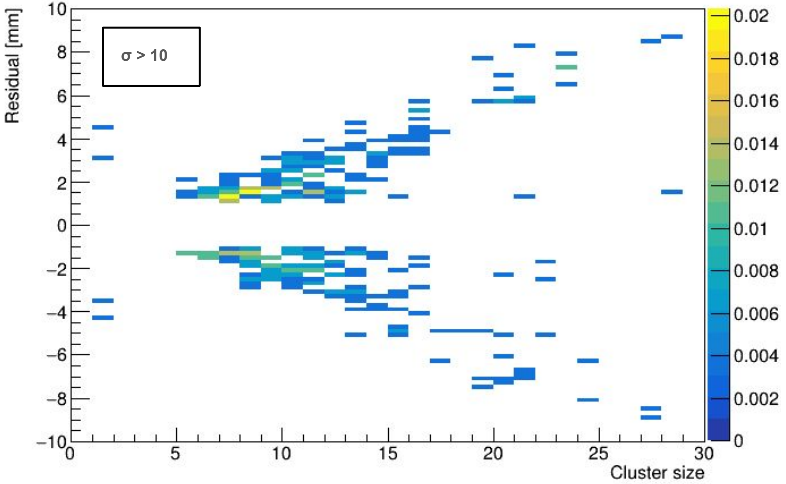


Focus on the cluster topology at high gain: size

A topological study on the “cluster shape” is performed considering two groups of clusters with a selection on the residual distribution: **within 10 sigma and outside**.

The cluster size outside 10 sigma is about the double of the good ones and seems that the average residual is linear with the cluster size.



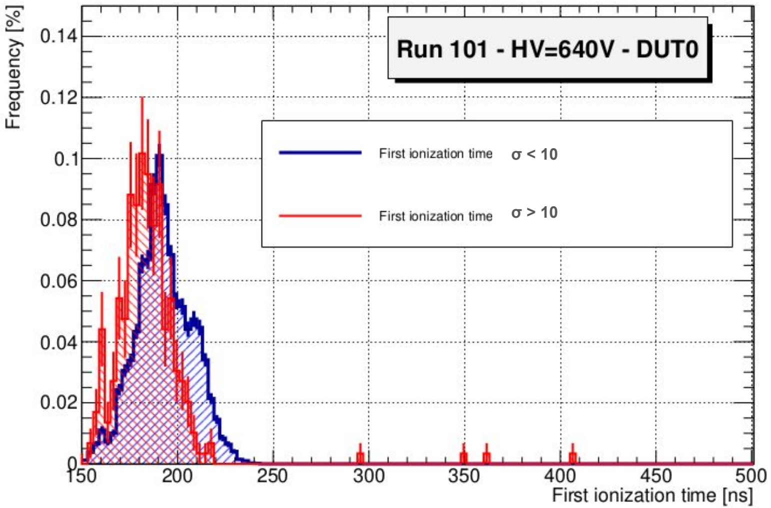


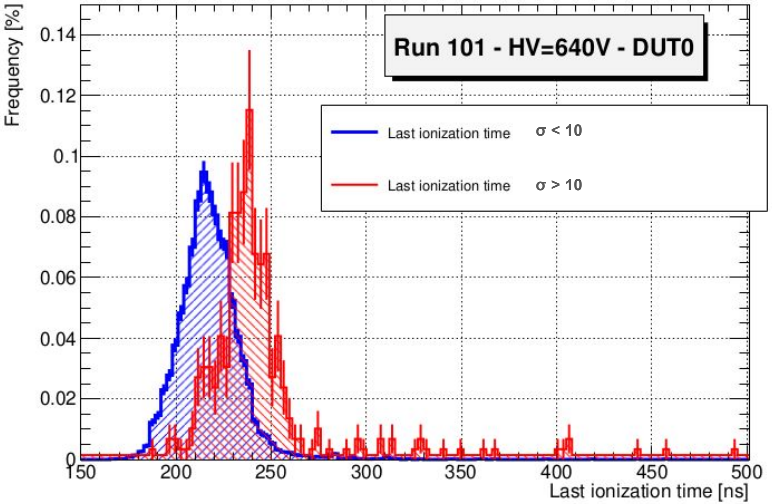
Focus on the cluster topology at high gain: time

A shift is also observed the first and the last ionization time.

The faster time in the cluster for good and bad event is shifted of - **10~20 ns**

The slowest time in the cluster for good and bad event is shifted of **+ 30~40 ns**

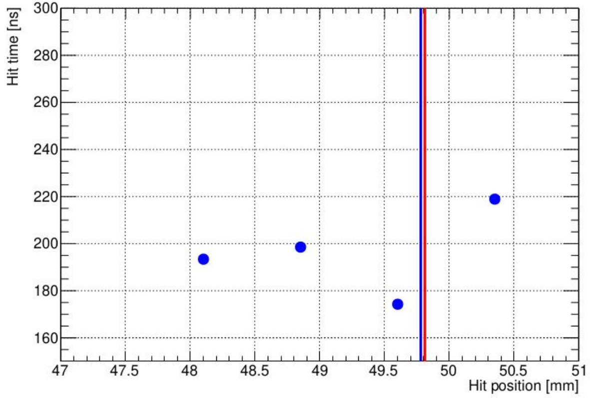


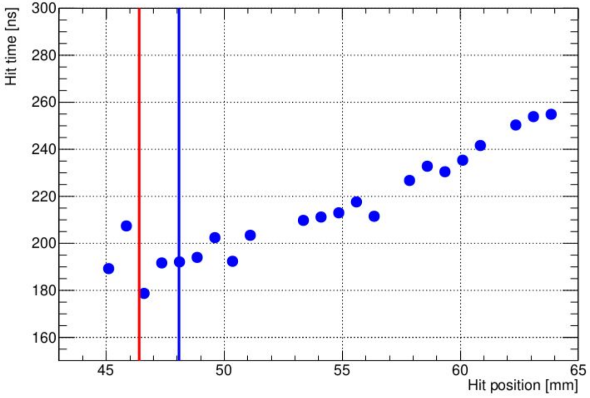


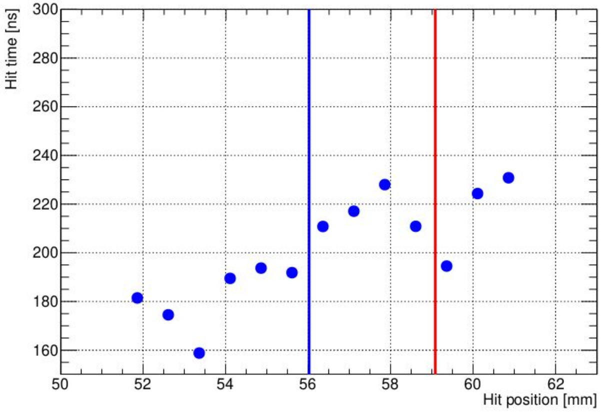
Focus on the cluster topology at high gain: events

A good event example (left), shows the agreement between test chamber (blue line) and tracking system (red line). Charge centroid is used to evaluated the position in the test chamber.

Bad event examples (mid and right), show the directional displacement of the hits from the expected position (red). Mid (right) example has extra hits for larger (smaller) time values.







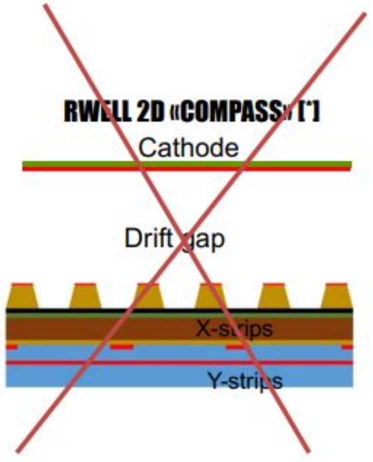
● = strip position vs time measurement

INFN

Layout optimization 2D

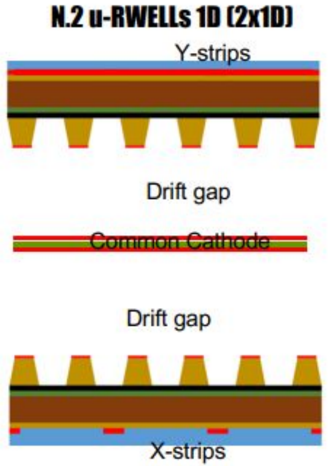
the following results are evaluated
using **APV25** electronics and
Ar:CO2:CF4 gas mixture (45:15:40)

Possible 2D R/out layout

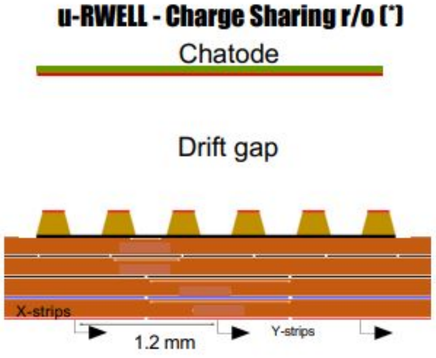


The «COMPASS» R/out requires higher gas gain due to the coupling of the X and Y R/out strips
Good perfomance
No easy optimization of the charge sharing on X-Y views

(*) Y. Zhou et al. NIMA 927 (2019) 31

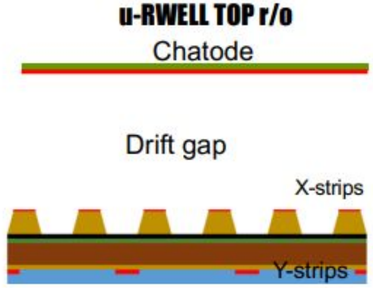


This option centainly allows to work at **lower gas gain** wrt the «COMPASS» R/out (X-Y r/out are decoupled)
→ **TB2022 results:**
- **IDEA pre-shower:** Efficiency knee @ 550 V, σ_x < 100 um with 0.4 mm strip pitch for the
- **IDEA Muon:** Efficiency knee @ 600 V & σ_x < 400 um for a strip pitch = 1.6 mm



The charge sharing structures: the **charge transfer** and **charge sharing** using **capacitive coupling between a stack of layers** of pads and **the r/out board.**
This technique offers the possibility **to reduce the FEE channels**, but the **total charge is divided between the X & Y r/out** (similar to the «COMPASS» R/out)

(*) K. Gnanvo et al. NIMA 1047 (2023) 167782

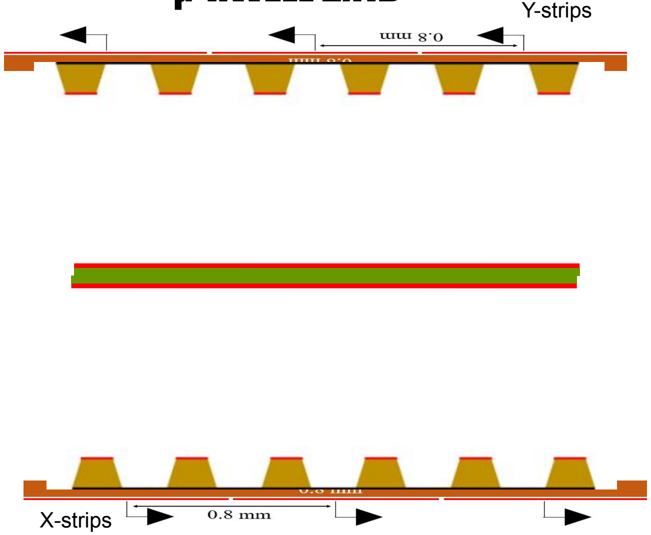


The **TOP layout** centainly allows to work at **lower gas gain** wrt the «COMPASS» r/out (X-Y r/out are decoupled)

→ X coordinate on the TOP of the amplification stage introduces same **dead zone in the active area**

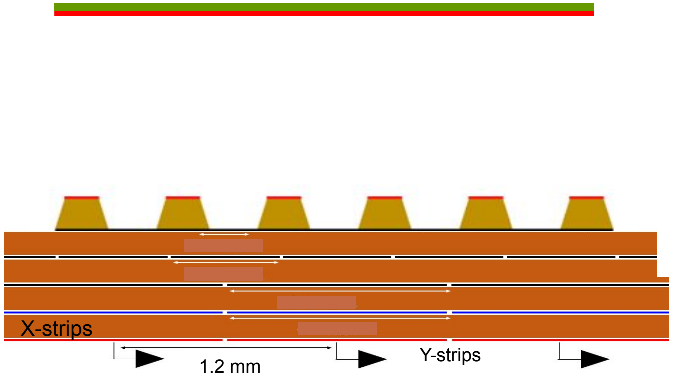
Experimental measurements - 2D readout

µ-RWELL 2x1D



Active area = 100 x 100 mm2
Pre-preg thickness = 20 µm
Resistivity = 50 MΩ/❑
Strip pitch = 0.76 mm
Strip width = 0.30 mm
Ratio p/w = 2.53

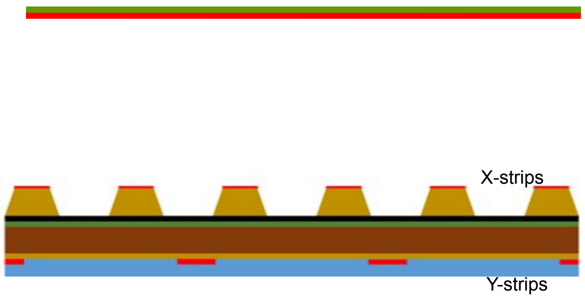
µ-RWELL 2D (Charge Sharing r/o)



CS Readout board

Active area = 100 x 100 mm2
Pre-preg thickness = 4 x 50 µm
Resistivity = 50 MΩ/❑
Strip pitch = 1.2 mm
Strip width = 1.10 mm
Ratio p/w = 1.09

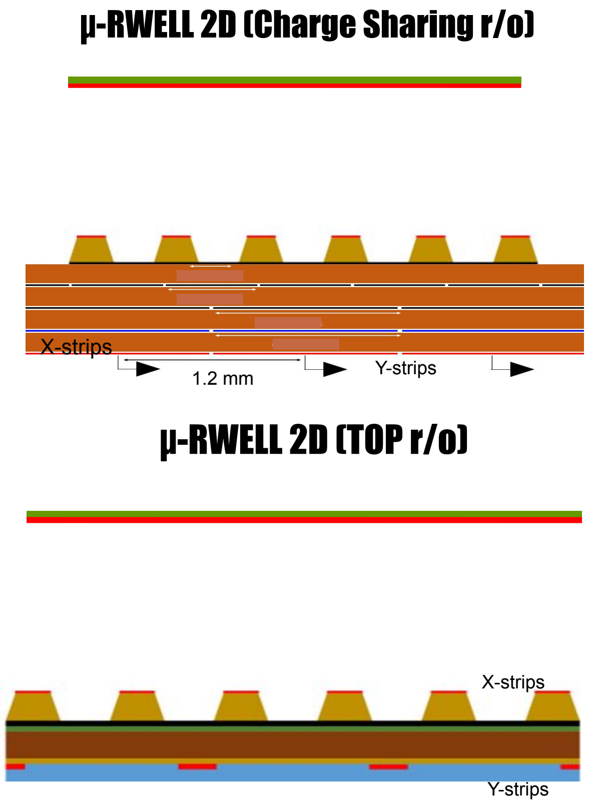
µ-RWELL 2D (TOP r/o)

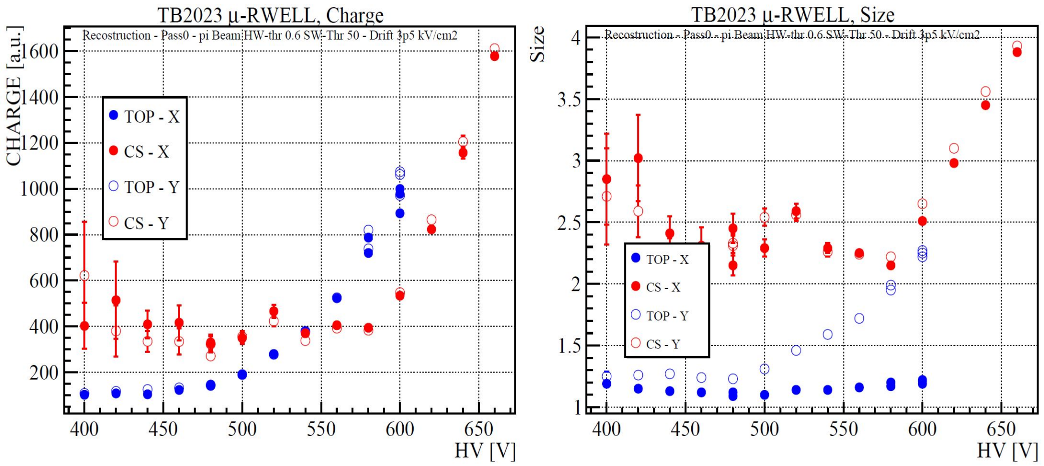


X coordinate on the TOP of the amplification stage

Active area = 100 x 100 mm2
Pre-preg thickness = 70 µm
Resistivity = 50 MΩ/❑
Strip pitch = 0.8 mm
Strip width = 0.7 mm
Ratio p/w = 1.14

Charge Sharing and TOP r/o results

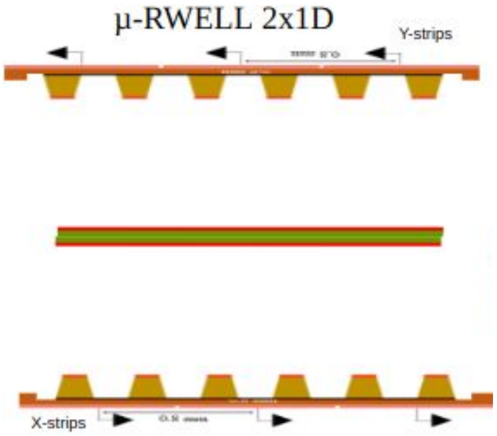


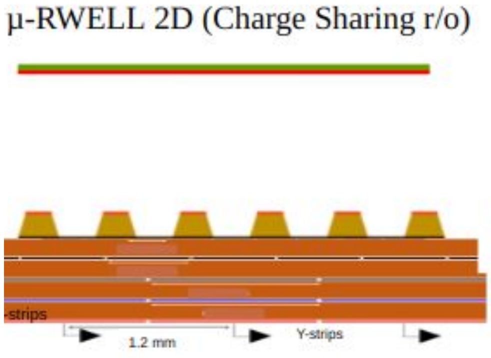


TOP r/o does not share the signal charge between X and Y. On the X (TOP) its cluster size is fixed and the spatial resolution is digital; while on the Y it has a standard behavior.

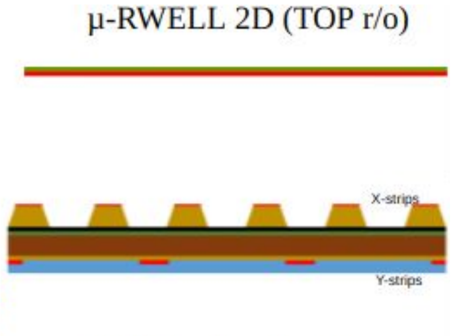
CS r/o shares the signal charge between X and Y. The charge sharing mechanics works properly and it increases the cluster size up o 4; this improves the spatial resolution .

Experimental measurements - 2D readout



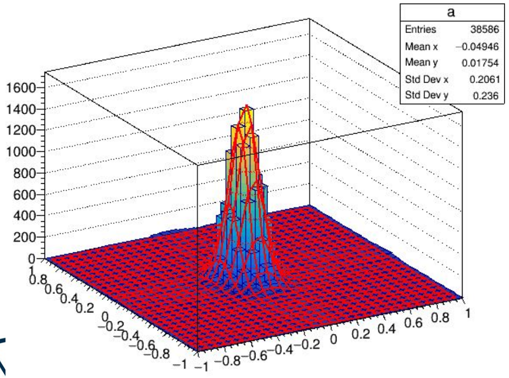


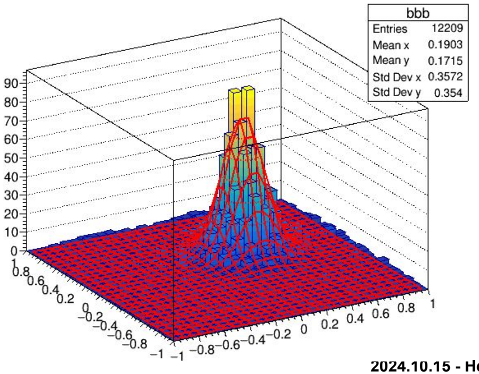
CS Readout board

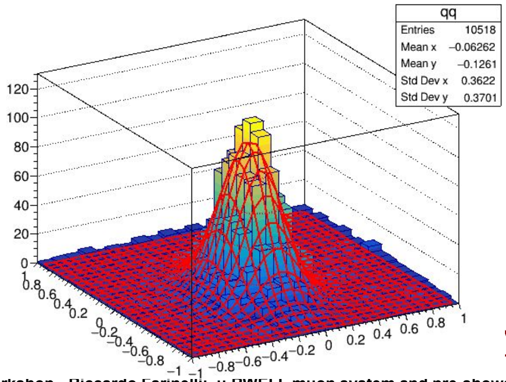


X coordinate on the TOP of the amplification stage

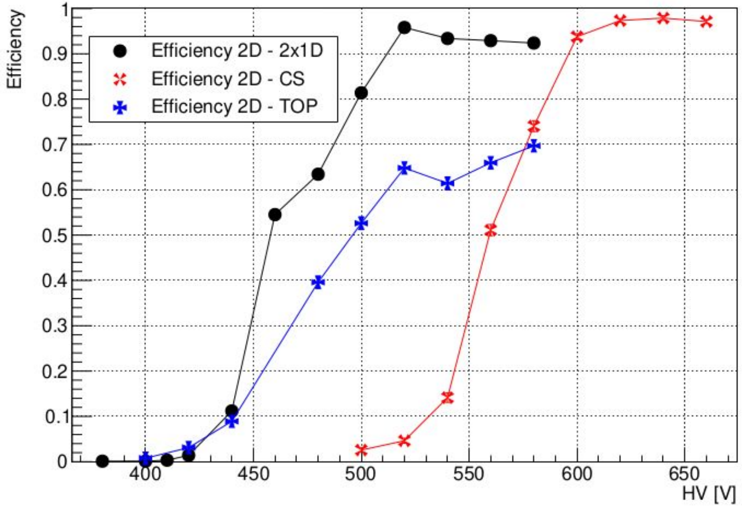
Fit Gaus2D on 2D residual distribution

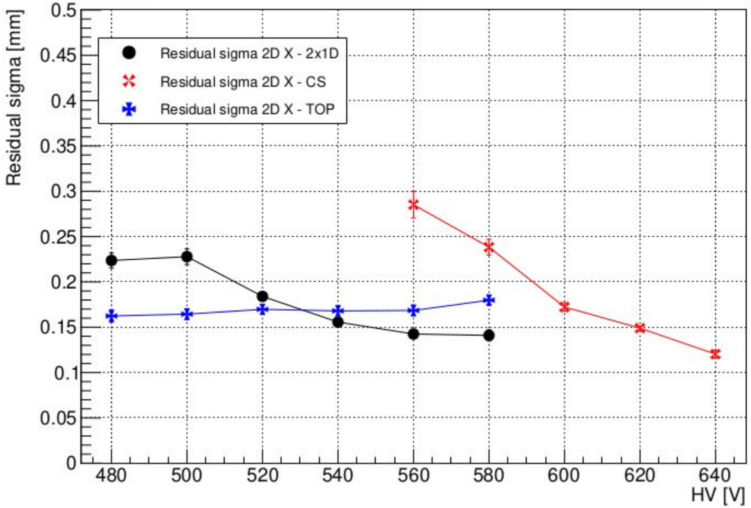






Spatial resolution and 2D efficiency





2x1D is the first to reach the plateau and a spatial resolution of about 150μm with a pitch of 760 μm

TOP r/o best efficiency is 70% due to the dead area on the amplification stage and it shows similar performance of the 2x1D

CS r/o has a plateau 100V after the 2x1D but it can provide a resolution better than 150 μm using a pitch of 1200 μm

µRWELL + TIGER asic

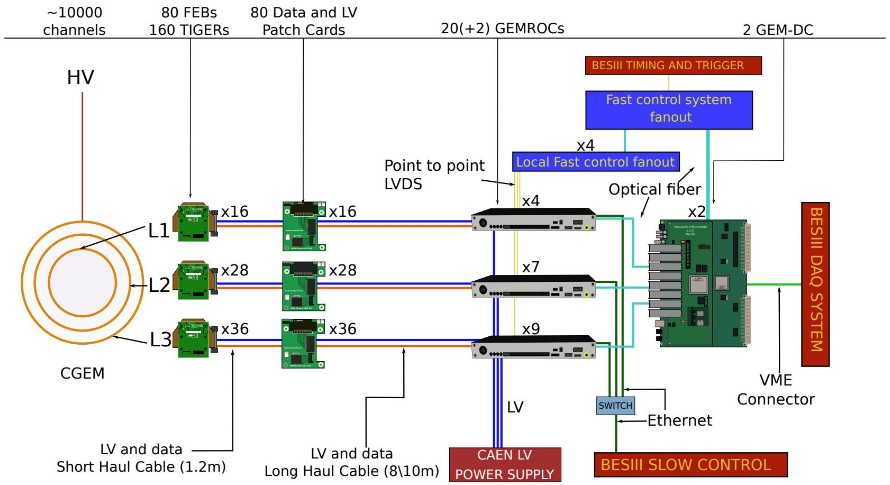
TIGER electronics

TIGER chip features:

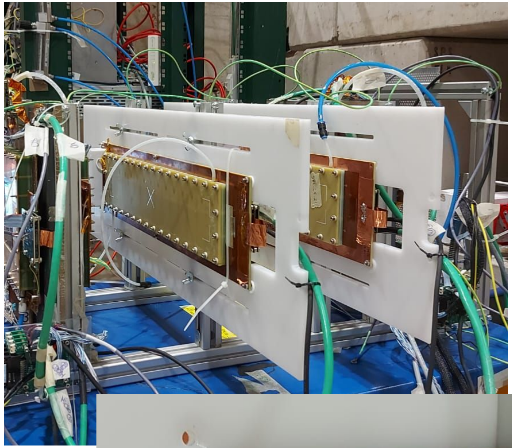
- 64 channels
- Event rate 100 kHz/channel
- Input dynamic range up to 50 fC
- Time resolution < 5 ns
- ENC < 2000 e^- rms with 100 pF input capacitance

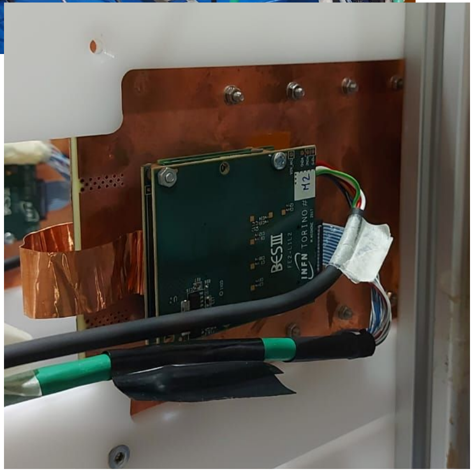
Readout chain:

The full readout chain proposed is well known. A complete setup is under deployment in Beijing for the BESIII CGEM-IT where a cosmic ray data taking is ongoing since Dec. 2019



µRWELL and TIGER electronics





Detector under test:
- 4 µRWELL w/ 40 cm strip length
  1D strip pitch of 0.4/0.8/1.2/1.6 mm

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

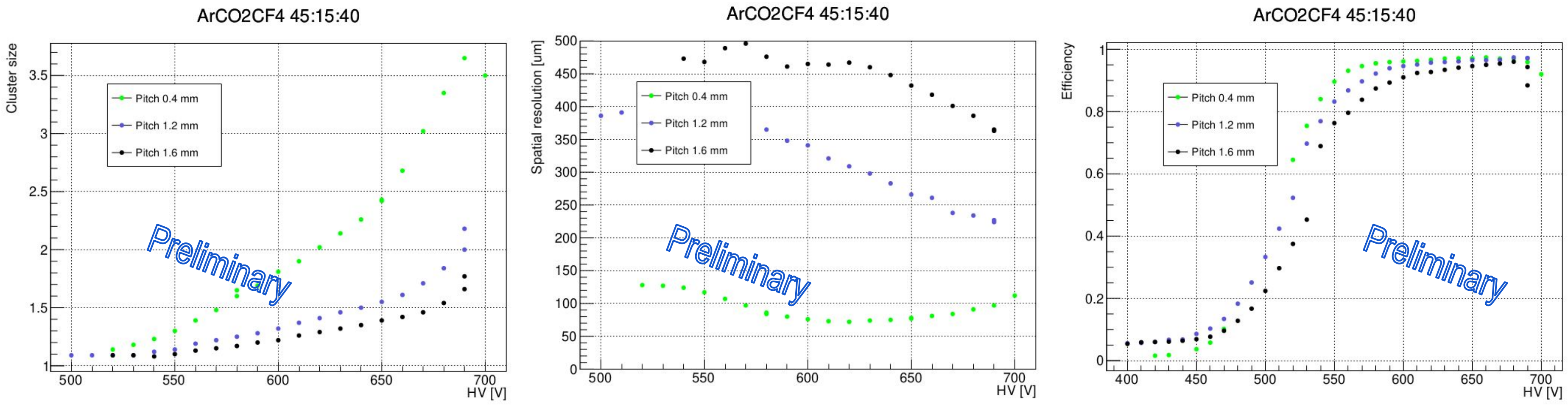
Goals of the testbeam:
- **Define the state of art of µRWELL+TIGER** for IDEA Muon system optimization studies
- Compare the APV-25 performance studies with TIGER
- Performance in **Ar:CO2 and Ar:CO2:CF4** comparison
- Collect data to **compare experimental measurement and simulation**

Measurements:
- Gain scan to evaluate the amplification/saturation/performance
- Drift scan to evaluate the signal collection
- Threshold scan to optimize S/N

Pitch scan w/ TIGER

Similar results are obtained with TIGER electronics and APV as shown in previous slides, even if some differences are present in the two setup (noise, threshold): 1-2 fC w/ APV and 2-4 fC w/ TIGER. Grounding scheme will be improved in future setup.

A spatial resolution of 100 µm is achieved with 400 µm pitch.
An HV shift between the efficiency plateau of 0.4 mm and larger pitch is observed, as expected.

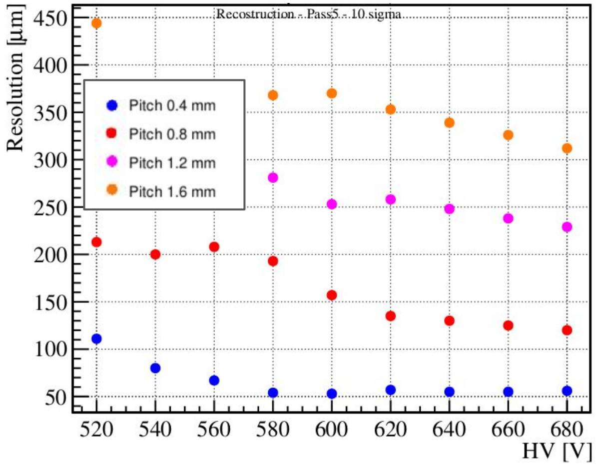


Pitch scan comparison TIGER - APV

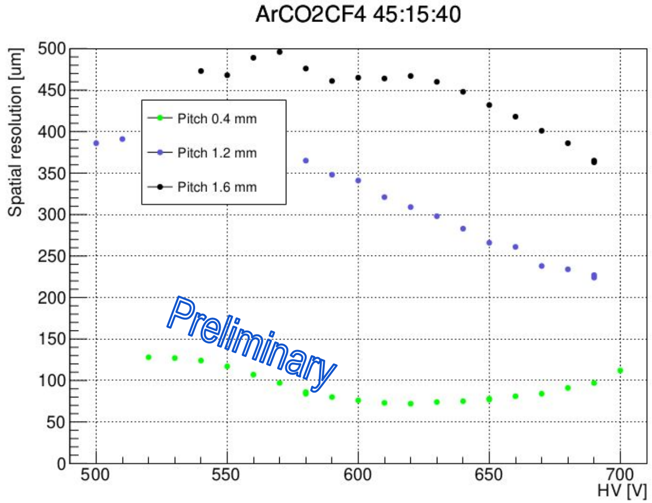
Similar results are obtained with TIGER electronics and APV as shown in previous slides, even if some differences are present in the two setup (noise, threshold).

A spatial resolution of 100 μm is achieved with 400 μm pitch and a shift between the efficiency plateau of 0.4 mm and 0.8 mm pitch is observed, as expected.

APV



TIGER



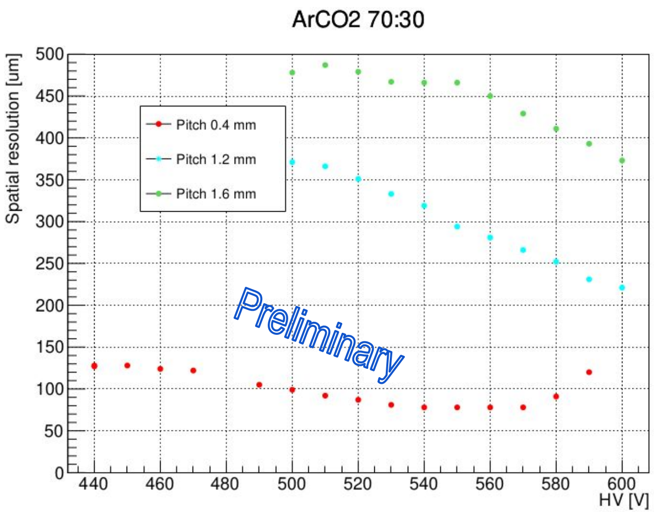
Results without CF4 gas

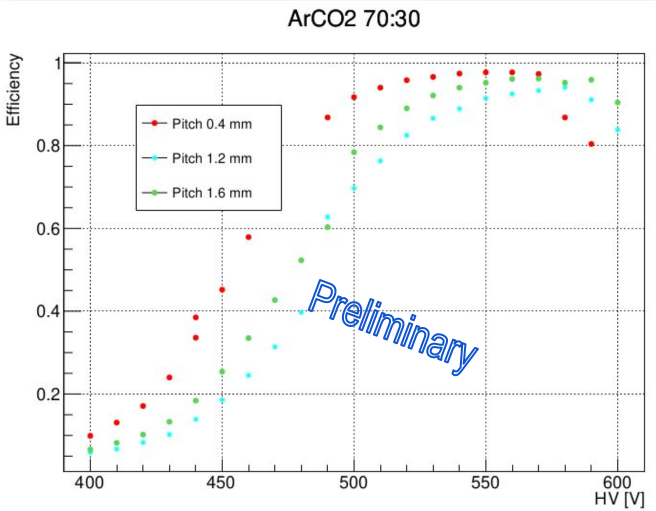
The gas mixtures based on CF4 are suitable for a fast electron diffusion but they are not classified as eco-gases.

Alternative to CF4 are needed. Here the performance of a µRWELL with Ar:CO2 (70/30) is compared with Ar:CO2:CF4 (45:15:40)

A shift in the working point of about 50-100V is observed due to different ratio of Argon but similar results are achieved.

The efficiency plateau is only 50V long, while in ArCO2CF4 it is about 150V.



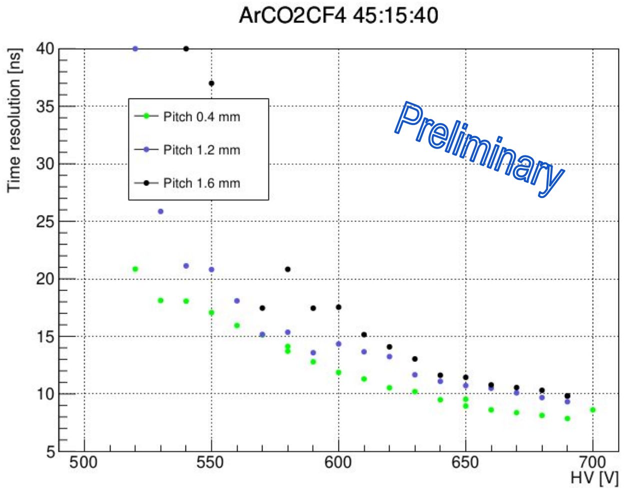


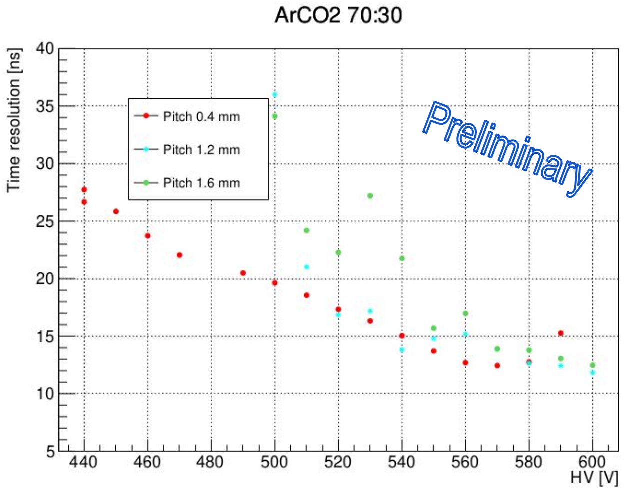
Results without CF4 gas

An important comparison between these two gas mixtures is given by the time resolution:

12 ns is reached with ArCO2
7.8 ns is reached with ArCO2CF4

The contribution of the electronics (2ns) and the time-walk are included





Simulation

Parametrization of a μ-RWELL

Ionization

Electron Drift

Amplification

Resistive

Induction

Readout

Reco

Dixit et al.

Reading from the webpage https://garfieldpp.web.cern.ch

is a toolkit for the **detailed simulation of detectors which use gases** or semi-conductors as sensitive medium.

the main area of application is currently in **micropattern gaseous detectors.**

Ionisation → Heed generates ionisation patterns of fast charged particles

Electric fields → interfaces with the finite element programs (Ansys, Elmer, Comsol and CST) which can compute approximate fields in nearly arbitrary 3D configurations with dielectrics and conductors

Transport of electrons → Magboltz is used for computing electron transport and avalanches in nearly arbitrary gas mixtures

GARFIELD++ capabilities

+

More speed

Parametrization!

Parametrization of a μ-RWELL

The charge density evolution inside the resistive is described by Dixit et al.

The charge on a pad can be found by integrating the charge density function over the pad area:

$$Q_{pad}(t) = \frac{Nq_e}{4}\left[erf\left(\frac{x_{high}}{\sqrt{2}\sigma_{xy}}\right) - erf\left(\frac{x_{low}}{\sqrt{2}\sigma_{xy}}\right)\right]\left[erf\left(\frac{y_{high}}{\sqrt{2}\sigma_{xy}}\right) - erf\left(\frac{y_{low}}{\sqrt{2}\sigma_{xy}}\right)\right]. \quad (4)$$

where x_{low}, x_{high}, y_{low}, y_{high} define the pad boundaries, and $\sigma_{xy} = \sqrt{2th + w^2}$.

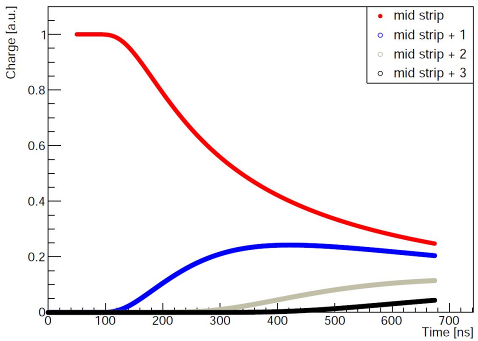
and it can be extended to the strip layout:

$$\frac{q}{2}\left[\mathrm{erf}\left(\frac{x_2 - x_0}{\sqrt{2}\sigma_0\left(1 + \frac{t-t_0}{\tau}\right)}\right) - \mathrm{erf}\left(\frac{x_1 - x_0}{\sqrt{2}\sigma_0\left(1 + \frac{t-t_0}{\tau}\right)}\right)\right]\Theta(t - t_0)$$

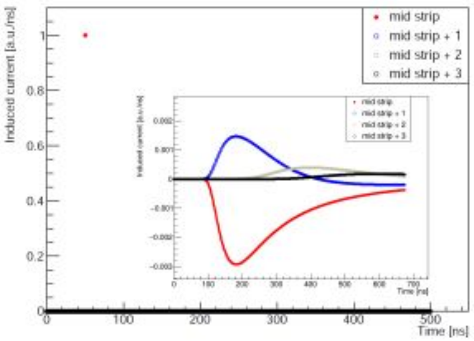
Parametrization of a μ-RWELL

A charge q=1 is injected at t=50ns, using a tau=10ns and sigma0=10μm (see prev. formula).
See the full presentation on μRWELL on my contribution [here]

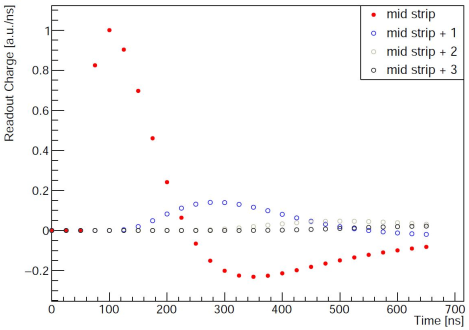
CHARGE



CURRENT



ELECTRONICS



At t=50ns the charge is collected on the middle strip and then the charge is moved from the mid strip to the neighbors

At t=50ns the current has a delta to 1 and then a small current value flows from the mid strip to the neighbors. There the total current is conserved

The induced current is readout by the electronics and it is simulated by means of a shaper (50ns) and an integrator

Simulation results

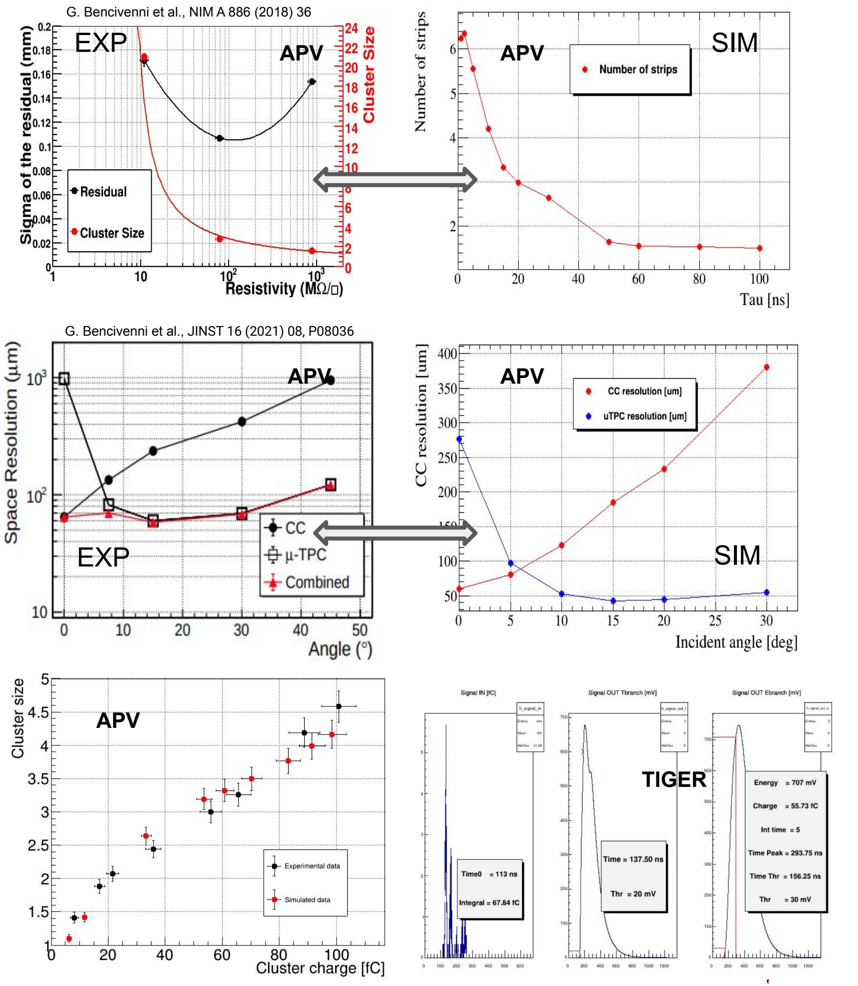
Thanks to a detector parametrization,
it is possible to reproduce the **μ-RWELL signal**.

Different **configuration** (resistivity, angle, etc…)
can be tested

Results shows a good agreement with the experimental data w/ APV electronics

- Cluster Size and Cluster Charge
- Charge Centroid and μTPC spatial resolution
- Charge Dispersion of the DLC

Next activities will implement the TIGER electronics in the simulation and a tuning with the experimental data will be performed.



Conclusion

Ongoing R&D on µRWELL technologies is focused on developing large-area detectors (50x50 cm tiles) for the pre-shower and muon systems in the IDEA detector. These efforts aim to optimize performance together the segmentation of the readout.

Key studies on DLC resistivity, strip pitch, and various 2D readout configurations have provided valuable information for defining the preliminary layout of the tiles. Further studies are planned to finalize the design, including the characterization of 2D readouts with final dimensions.

An electronics design campaign has also begun. A test beam using TIGER electronics has been performed, and simulations will be used to optimize the integration between the detector and electronics.

Thanks

IDEA R&D and DRD1

The ECFA DRD themes define the key R&D areas of interest within the Detector Roadmap, and the µRWELL R&D for IDEA aligns with these priorities.

The µRWELL activities focus on detector technology (e.g., new resistive MPGD structures), front-end electronics and readout systems, eco-friendly gases, manufacturing, and longevity.

The DRD1 proposal outlines several Working Packages (WP) to group strategic R&D efforts from various institutes.

A significant overlap between the ongoing and future tasks of µRWELL and DRD1-WP1 is present.

#	Task	Performance Goal	DRD1 WGs	ECFA DRDT	Milestones/Deliverable 12M	Milestones/Deliverable 24M	Milestones/Deliverable 36M	Institutes
T1	New RPC structures	- Develop low-cost resistive layers - Increase rate capability from 10 kHz to 1 MHz per cm^2 - Improve timing resolution from sub-ns to ps levels	WG1, WG2, WG3, WG4, WG5, WG6, WG7, WG8	1.1, 1.3	**M1.1** **Review of Detector Prototypes:** examining the current status and future prospects of innovative resistive materials, novel structures, and challenges in hybridizing Resistive Plate Chambers (RPC) and Micro-Pattern Gas Detectors (MPGD). This evaluation includes compiling of a comprehensive report highlighting comparative performance, along with the respective advantages and disadvantages of available technologies. **[T1, T2, T5, T6, T7, T8]** **M1.2** **Review of the status of the art of ASICs and DAQ systems**, and definition of the requirements for next-generation large area muon systems. **[T3, T4]**	**M2.1** **Detector Prototypes Enhancement:** building upon the insights from M1.1. Proof of rate capability above 100 kHz/cm^2, assessing the status and potential improvements of RPC and MPGD detectors, informed by feedback from the previous phase. **[T1, T2, T5, T6, T7, T8]** **M2.2** **Design and Simulation studies of new ASIC**: Building blocks for MPGD and RPC and technical note(s) about the chips expected performance. **[T3]** **M2.3** **Design of a novel readout system for Gaseous Detectors**: assessment of performance achievements based on DAQ modelling. **[T4]**	**D1** **Large area RPC and MPGD prototypes:** design, construction, and test of RPC and MPGD-based prototypes **[T1, T2]** with advanced solutions for extensive surface coverage **[T6]**, optimized for medium-high flow rates (range tens kHz/cm^2 – few MHz/cm^2), precise tracking (100 µm) and timing (ns and sub-ns time resolution). This includes considerations for the compatibility of eco-friendly gases. **[T5, T7]** **D2** **New frontend and DAQ systems:** completion of the innovative ASICs' final design; compilation of comprehensive production documentation; if applicable, initiation of the engineering run for the first chip, should it be in an advanced stage **[T3]**. DAQ system prototyping for gaseous detectors, aiming to push the boundaries in terms of timing, radiation resistance, multi-channel high rate acquisition and performance, for large systems **[T4]**.	INFN-BA, UniBA, PoliBA, INFN-LNF, INFN-RM2, UniRomaTOV, INFN-BO, INFN-FE, INFN-NA, INFN-RM3, INFN-TO, IRFU/CEA, IFIN-HH, Istinye U, CERN, CIEMAT, LMU, WIS, Wigner, U Kobe, U Cambridge, USTC, U Oviedo, UNSTPB, UTransilvania, VUB and UGent, U Genève, U Hong Kong, MPP, BNL, FIT, JLab, MSU, Tufts, UC Irvine, U Florida, U Massachusetts, Amherst, U Michigan, UW–Madison, IGPC
T2	New Resistive MPGD Structures	- Stable up to gains of $\mathcal{O}(10^6)$ - High gain in a single multiplication stage - High rate capability (1 MHz/cm^2 and beyond) - High tracking performance (100 µm) - Development of low-granularity 2D-readout with high-tracking performance						
T3	New Front-end electronics	- New front-end - 1 fC threshold - High-sensitivity electronics to help achieve stable and efficient operation up to ≈MHz/cm^2 - High granularity detector capability						
T4	Optimization of scalable multichannel readout systems	- Front-end link concentrator to a powerful FPGA with possibilities of triggering and ≈20 GBit/s to DAQ for high-rate experiment -Develop robust, compact, and low power DAQ for low-rate experiment						
T5	Eco-friendly gases	- Guarantee long-term operation - Explore compatibility and optimized operation with low-GWP gases						
T6	Manufacturing	- Technological transfer for cost-effective production of high-quality, high-performance large area resistive MPGD. - Reliable production of homogeneous resistive large DLC foils with the CERN-INFN sputtering machine						
T7	Longevity on large detector areas	- Study discharge rate and the impact of irradiation and transported charge (up to C/cm^2) - Study the impact of low-GWP gases and new materials on high radiation hardness environment						
T8	New Hybrid-multi-technologies Structures	- Development of new ideas of detector structures and hybridization						

INFN

TIGER pitch scan

Threshold on DUT w/ pitch 0.4/1.2/1.6 mm is 4 fC while DUT w/ pitch 0.8 mm is 8 fC, then the HV dependence of the performance is shifted to higher HV values