μ-RWELL technology for the muon apparatus in the detector concept of the IDEA experiment

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Outline

- IDEA detector and μRWELL muon systems
- μRWELL technology
- Layout optimization 1D
- Layout optimization 2D
- TIGER + μRWELL testbeam preliminary results
- Detector simulation
- Muon apparatus simulation
- Possible synergies

IDEA detector

IDEA baseline detector concept

Beam pipe: R~1.0 cm

Vertex:
5 MAPS layers
R = 1.37-31.5 cm

Drift Chamber: 112 layers
4 m long, R = 35-200 cm

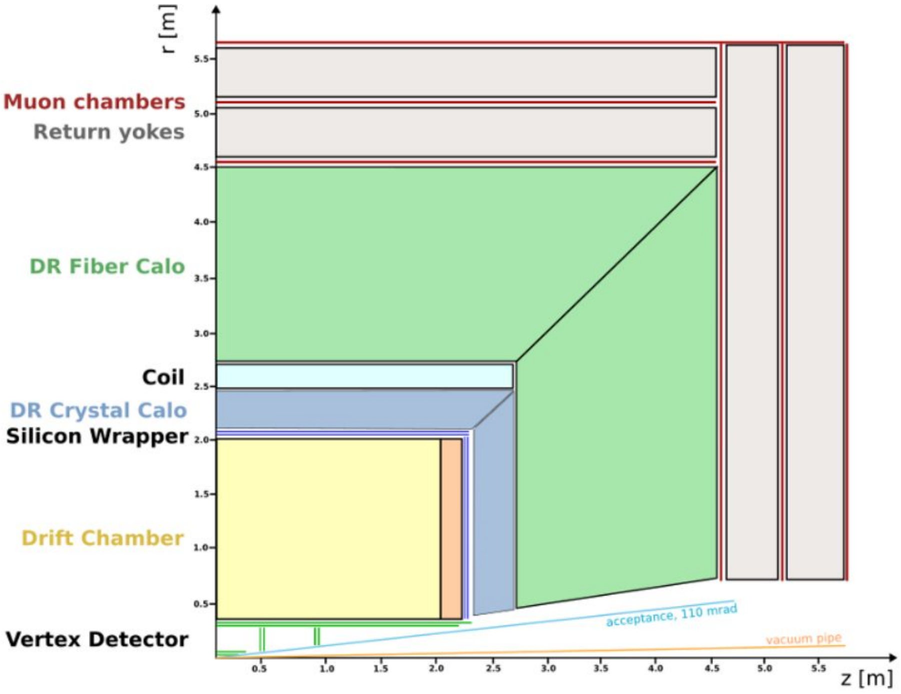
Outer Silicon wrapper:
R = 200-215 cm

DR crystal ecal: ~ 22 X_0
R = 215-250 cm

Superconducting solenoid coil:
3 T, R ~ 2.5-2.8 m

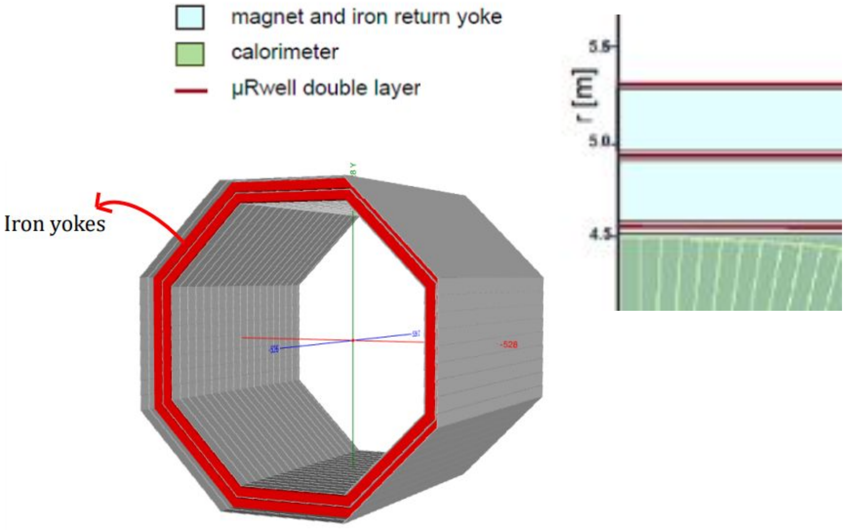
Dual-Readout Calorimeter:
R = 280-460 cm

Yoke + Muon chambers
R = 460-570 cm



The IDEA muon detector

1. **Reconstruct and tag the muon with three layers in between the iron return yoke**
2. **Reconstruct the displaced vertex i.e. LLP decays**



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 = 1.2 mm
FEE capacitance = 270 pF
5 million channels

μRWELL
technology and R&D activities

μ-RWELL technology

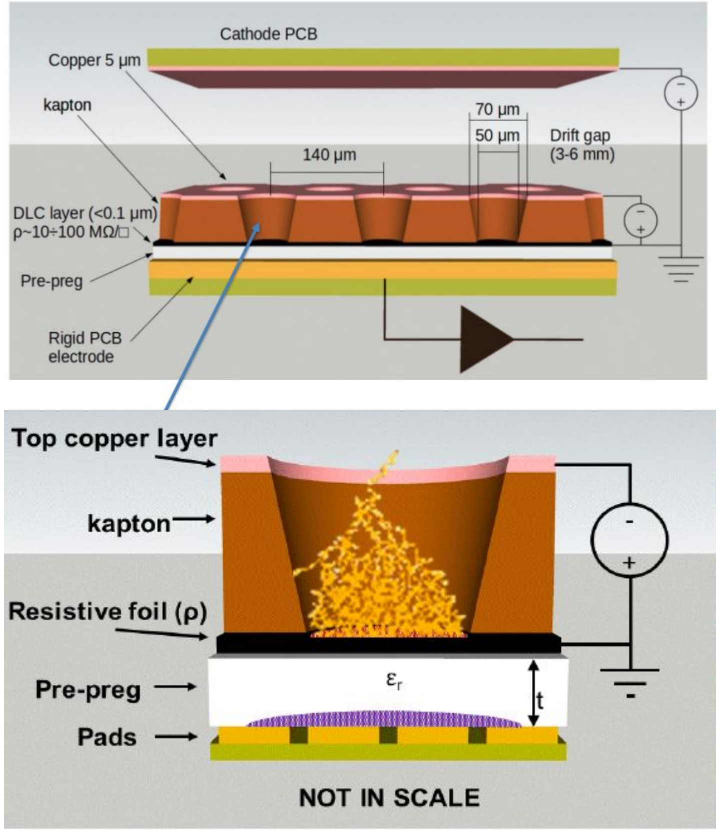
G. Bencivenni et al., 2015 JINST 10 P02008

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)

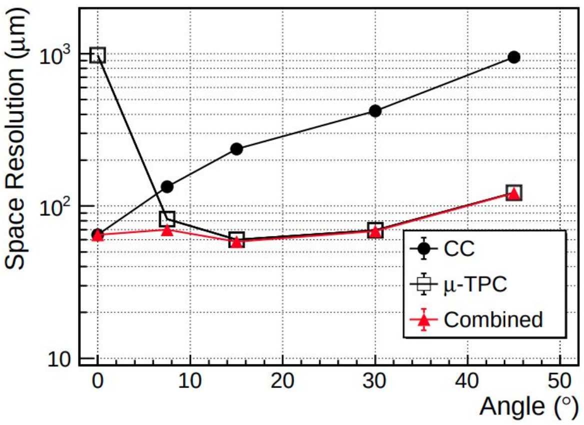


μ-RWELL technology

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

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

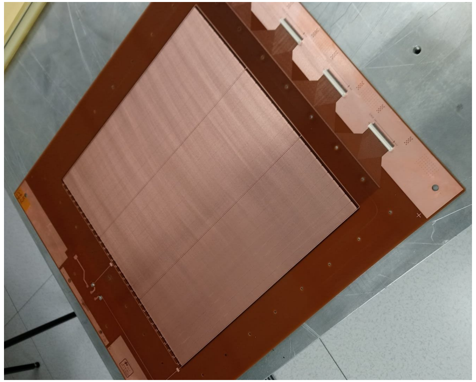
efficiency > 98%
spatial resolution < 100μm
rate capability ~ 1-10 MHz/cm^2



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.

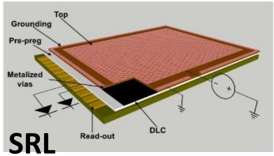


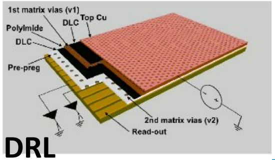
μ-RWELL R&D history

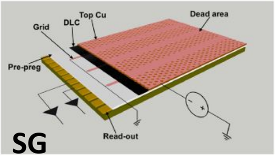
R&D on low-rate layout

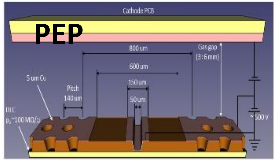
R&D on high-rate layout

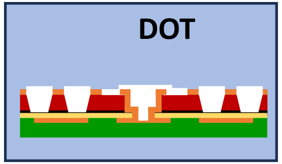
New μ-RWELL ideas (in collaboration with RD51)







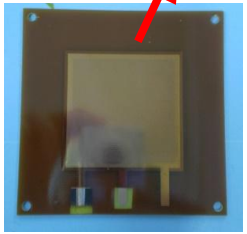




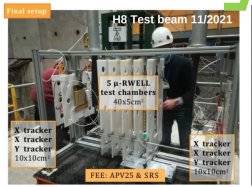
R&D start

TT @ ELTOS

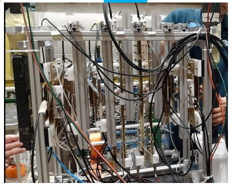
2009 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024



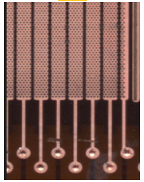
IDEA slice test: DC+ preshower+ dual_calo+ muon



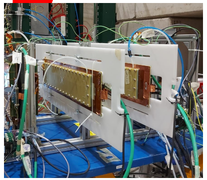
DLC Resistivity



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

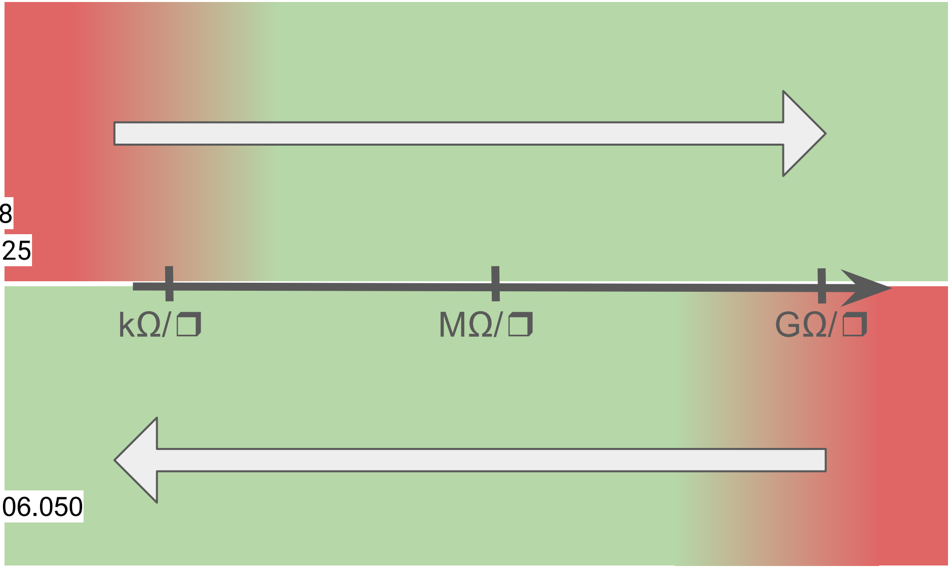
Resistivity

Stability operation

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

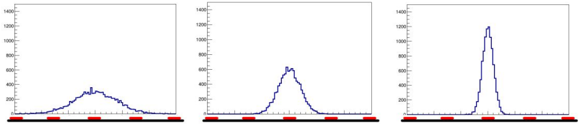
Charge dispersion

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



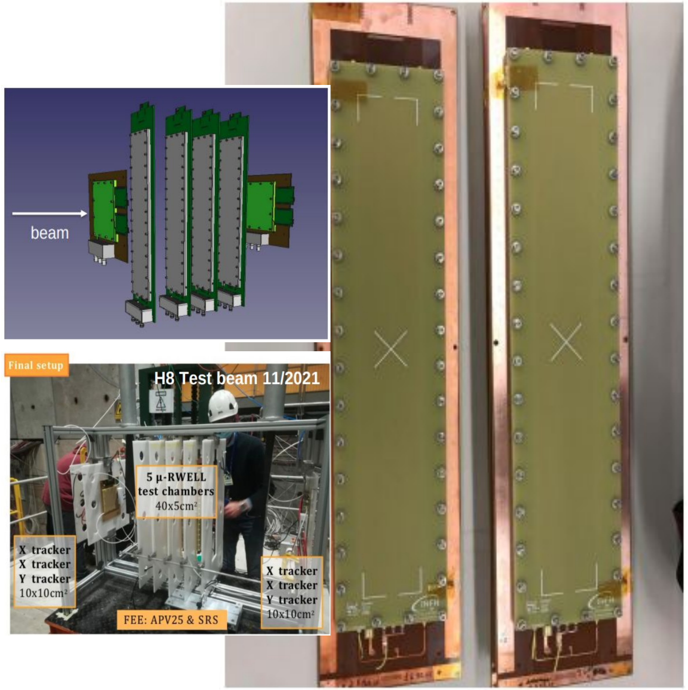
Charge distribution example

low ρ



high ρ

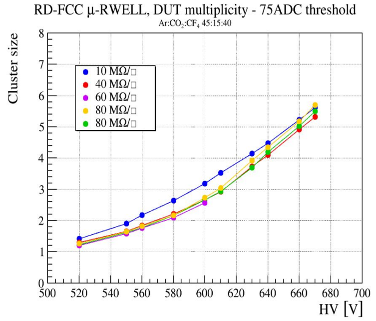
Resistivity Optimization

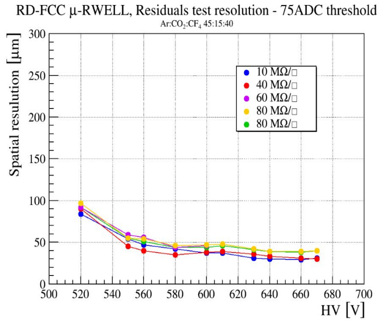


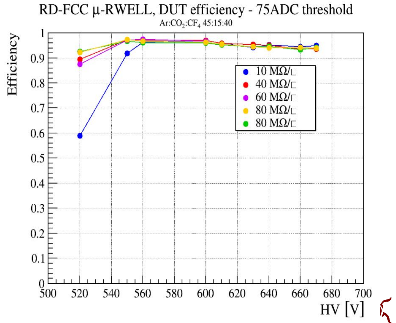
Active area = 400 x 50 mm2
Pre-preg thickness = 50 µm
Resistivity = 10-80 MΩ/❑
Strip pitch = 0.4 mm
Strip width = 0.15 mm
Ratio p/w = 2.66

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.

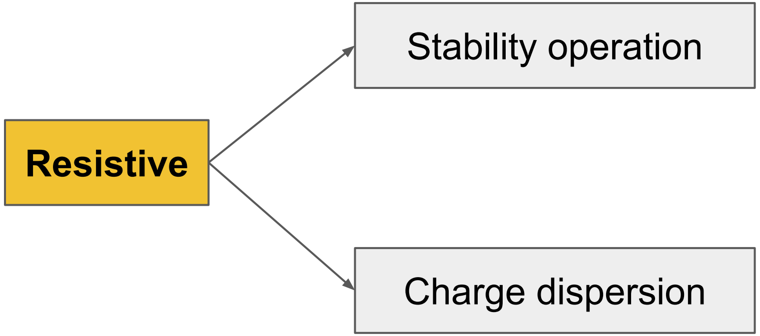
The **dependence** on the DLC **resistivity** is smaller in the range 40-80 MΩ/□ for cluster charge and cluster size, while the major dependency are observed in the efficiency.

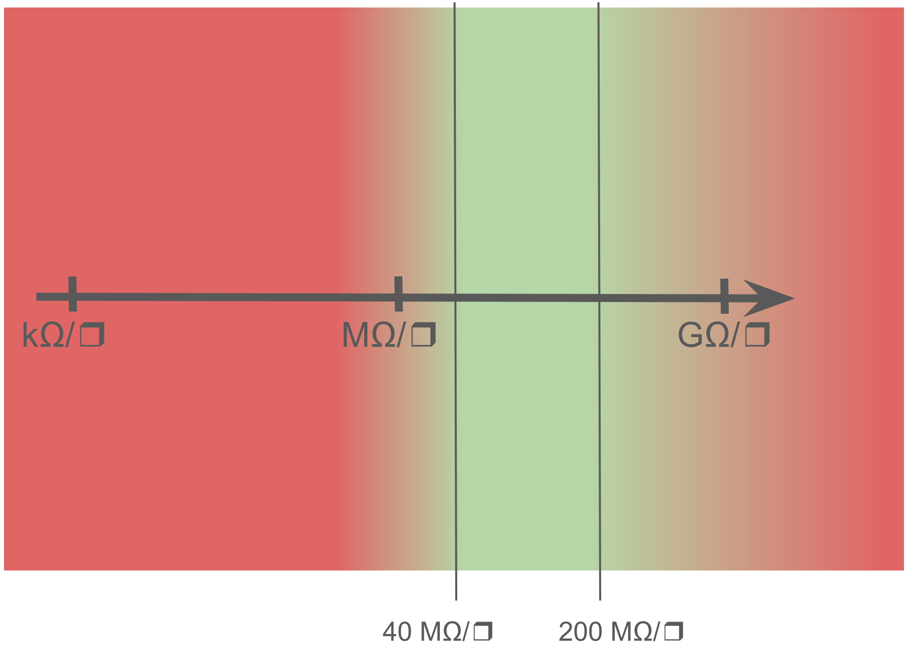




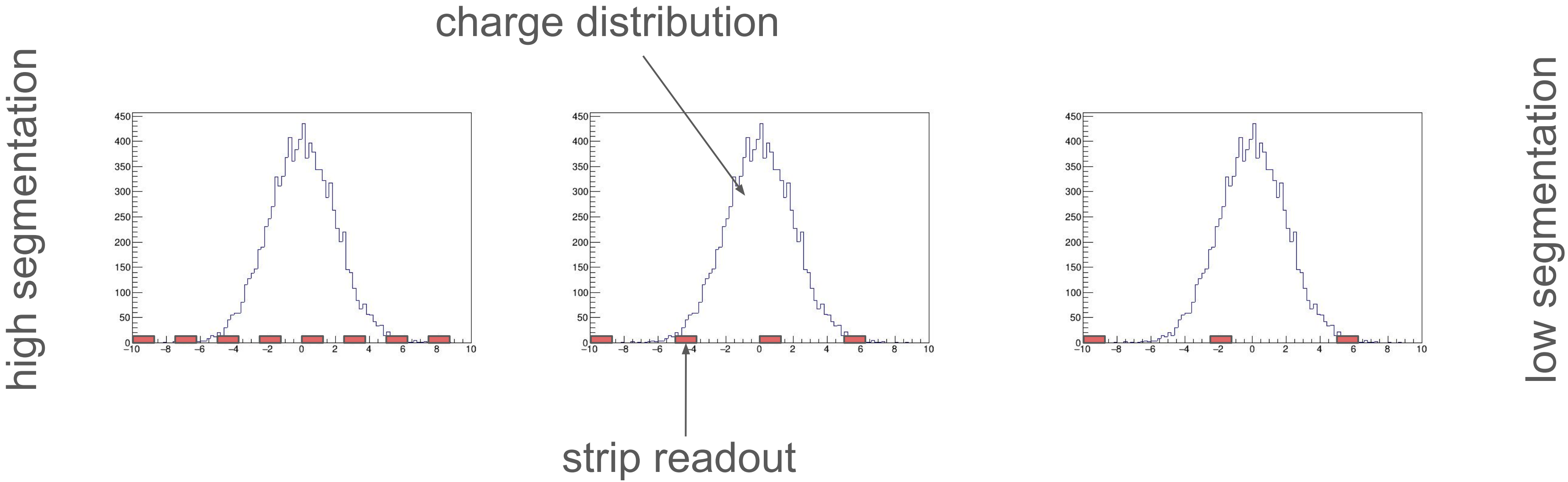


Resistivity Optimization





Pitch scan


high segmentation
charge distribution
strip readout
low segmentation

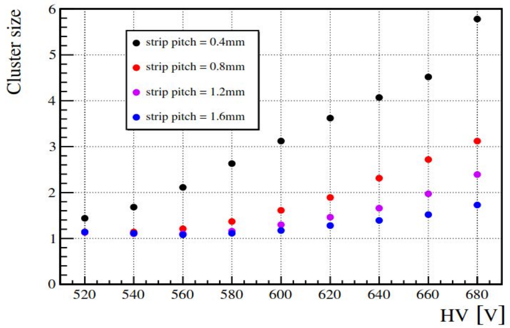
Pitch scan

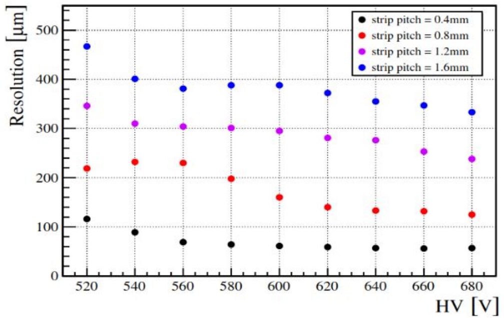
Active area = 400 x 50 mm2
Pre-preg thickness = 50 μm
Resistivity = 80 MΩ/❑
Strip pitch = 0.4/0.8/1.2/1.6 mm
Strip width = 0.15 mm
Ratio p/w = 2.66/5.33/8.0/10.66

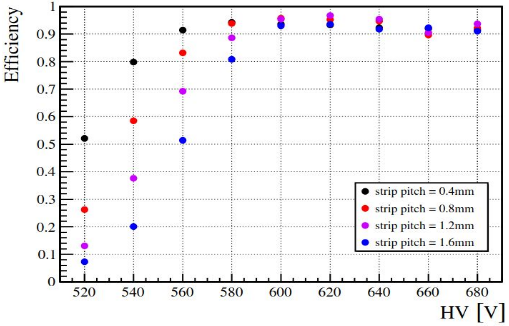
An **HV scan** shows a cluster size scaling with the pitch plus threshold effects.

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



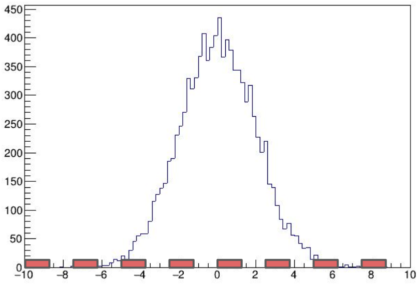




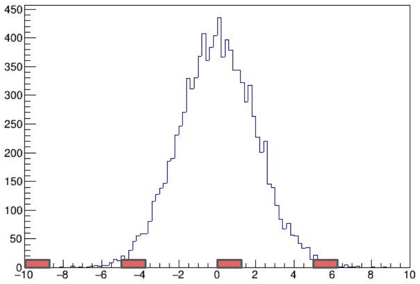
INFN

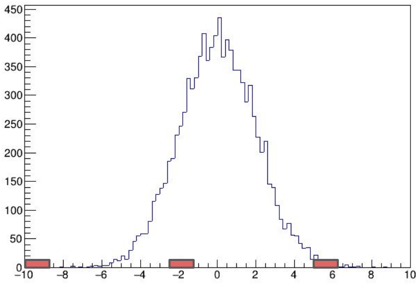
Pitch scan

high segmentation



pitch = 0.4 mm





pitch = 1.6 mm

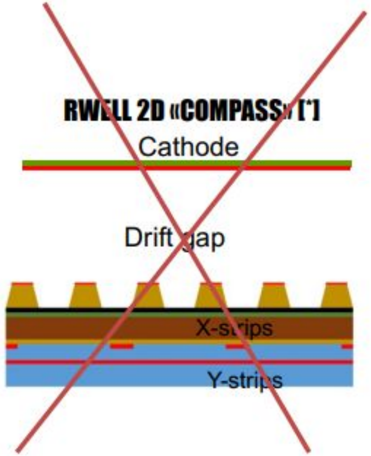
low segmentation

σ_x < 100 µm → pitch = 1.2 mm ← σ_x < 400 µm but larger gain needed

Layout optimization 2D

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

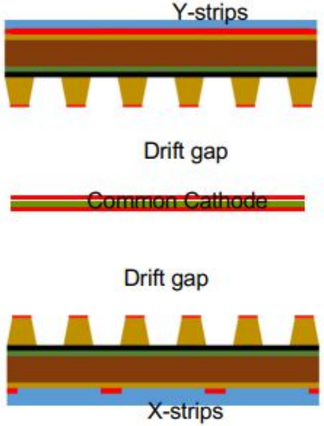
Possible 2D R/out layout



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

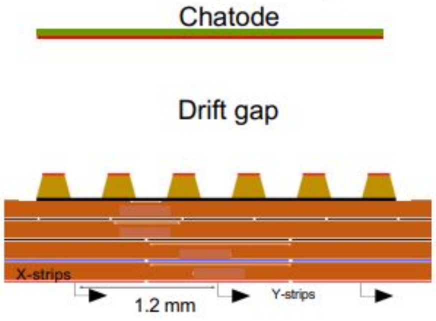
(*) Y. Zhou et al. NIMA 927 (2019) 31

N.2 u-RWELLs 1D (2x1D)



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

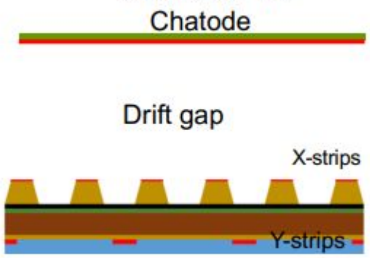
u-RWELL - Charge Sharing r/o (*)



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

u-RWELL TOP r/o

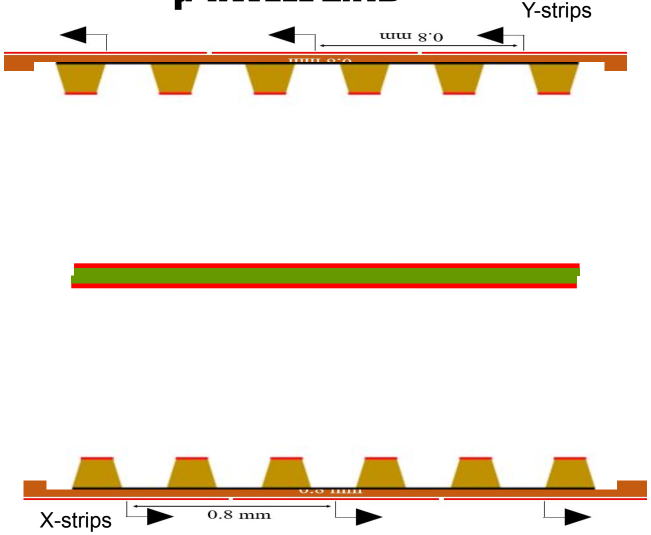


The **TOP layout** centainly allows to work at **lower gas gain** wrt the «COMPASS» r/out (X-Y r/out are decoupled)

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

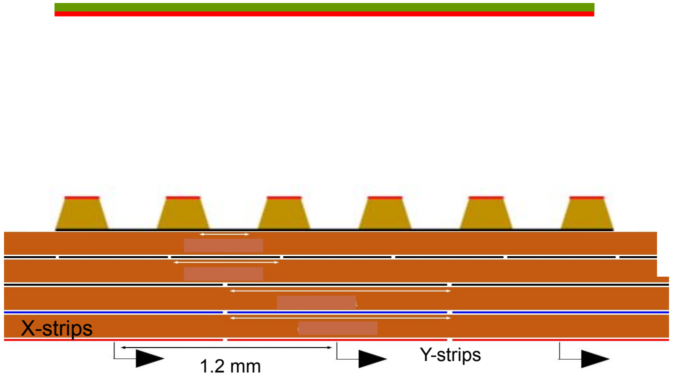
Experimental measurements - 2D readout

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

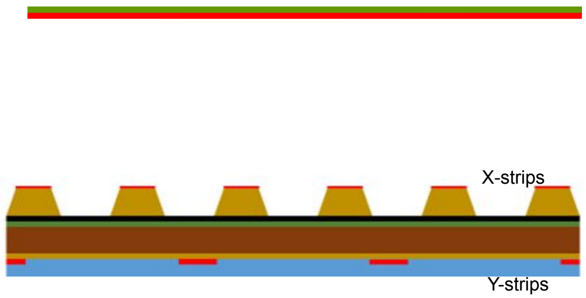
µ-RWELL 2D (Charge Sharing r/o)



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

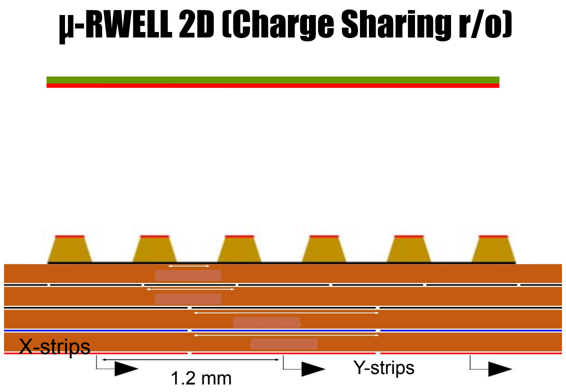
µ-RWELL 2D (TOP r/o)

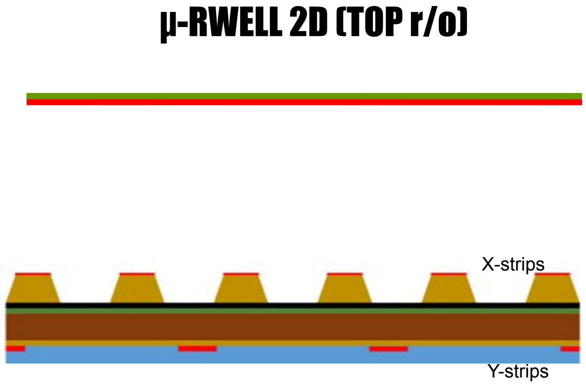


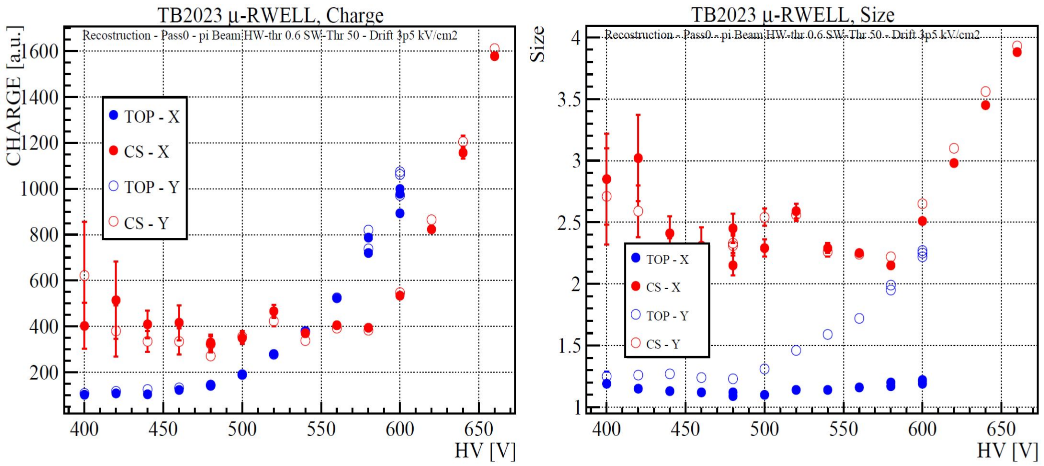
X coordinate on the TOP of the amplification stage

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



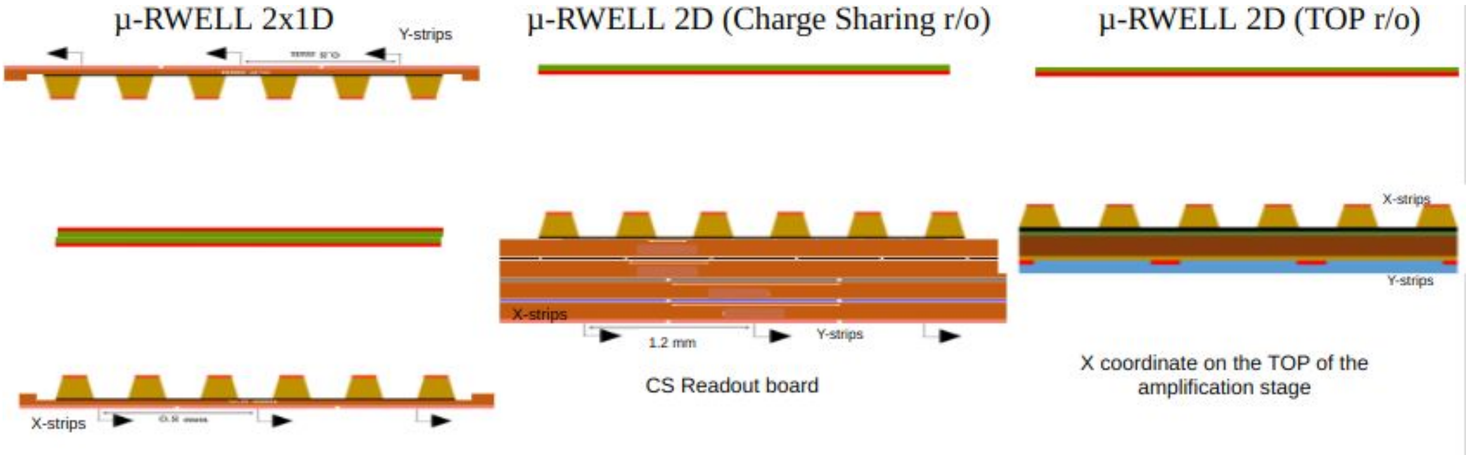




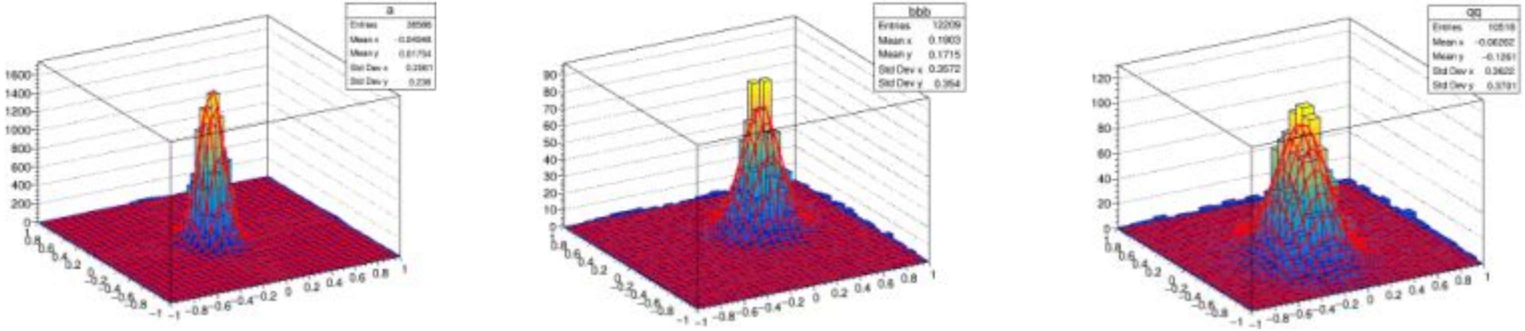
TOP r/o does not share the signal charge between X and Y. On the X (TOP) its cluster size is fixed and the spatial resolution is digital; while on the Y it has a standard behavior.

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 .

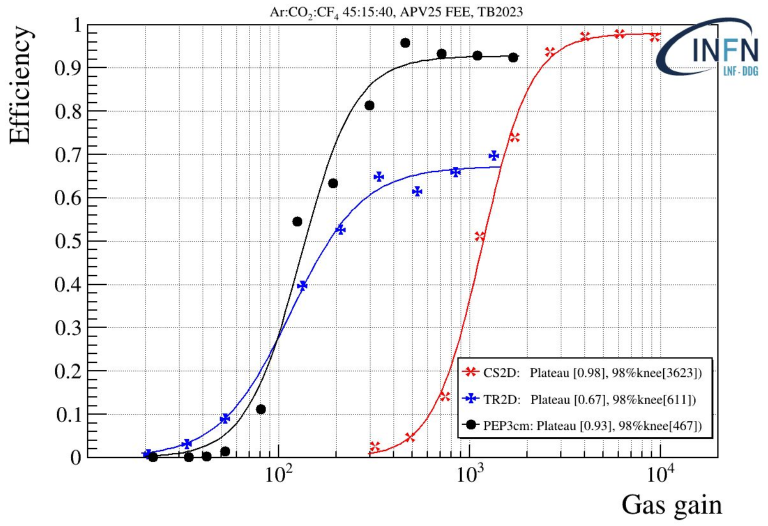
Experimental measurements - 2D readout

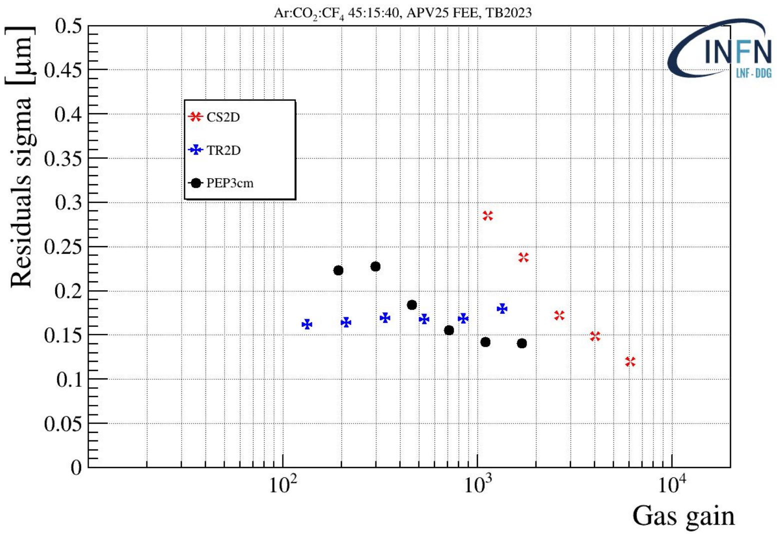


Fit Gauss2D on 2D residual distribution



Spatial resolution and 2D efficiency





2x1D is the first to reach the plateau and a spatial resolution of about 150 μm 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 shifted w.r.t. the 2x1D but it can provide a resolution better than 150 μm using a pitch of 1200 μm

µRWELL + TIGER asic

TIGER electronics

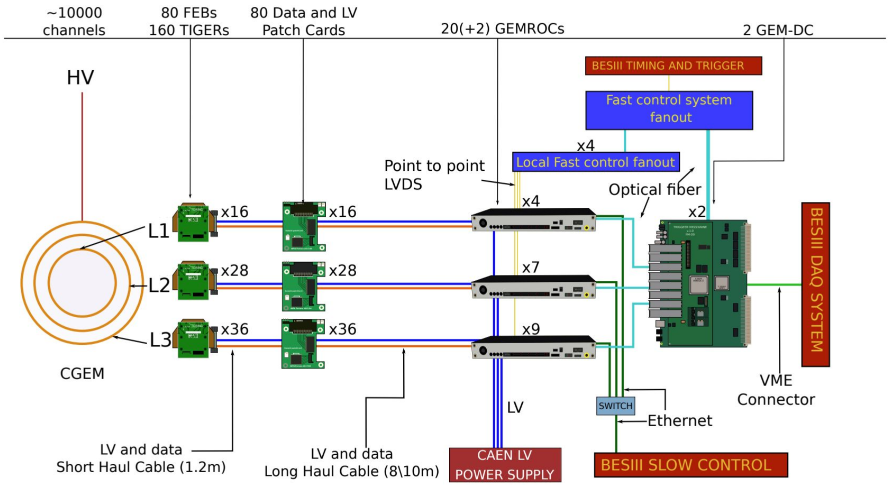
TIGER chip features:

- 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

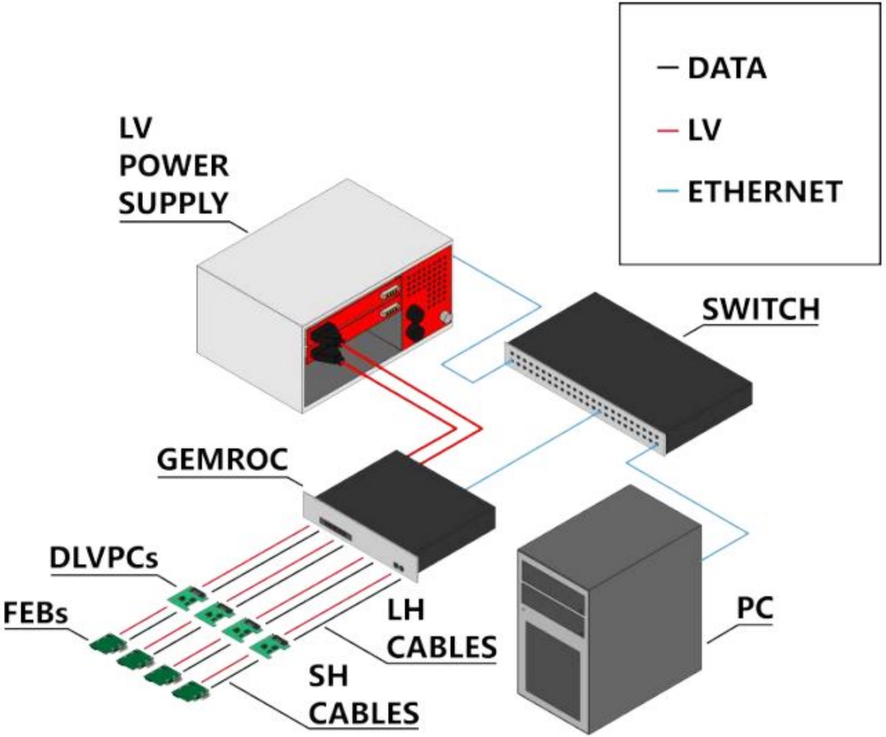
Readout chain:

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

Readout chain



TIGER electronics



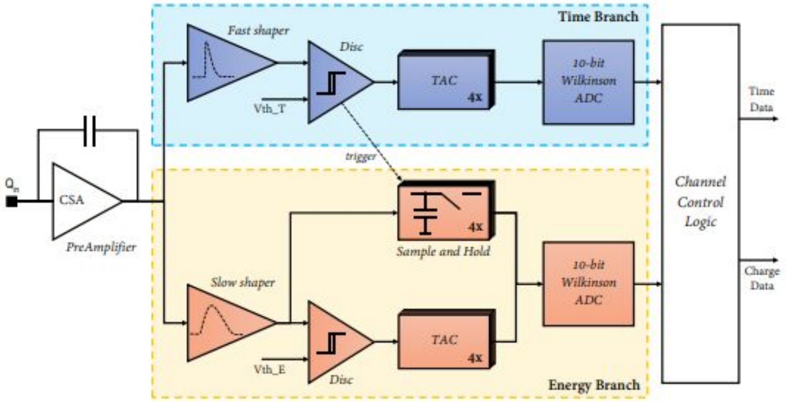
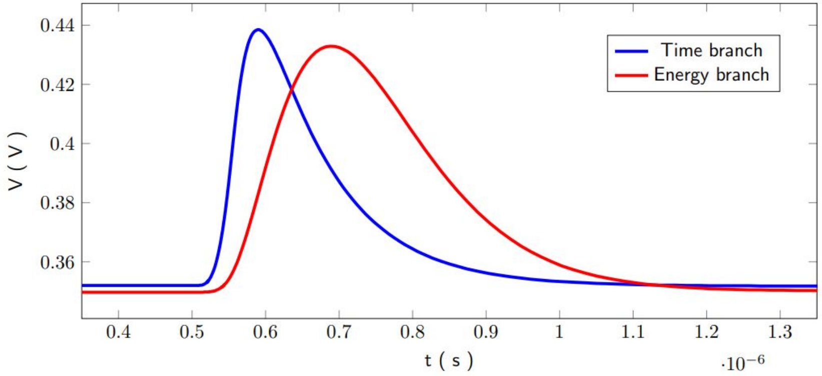
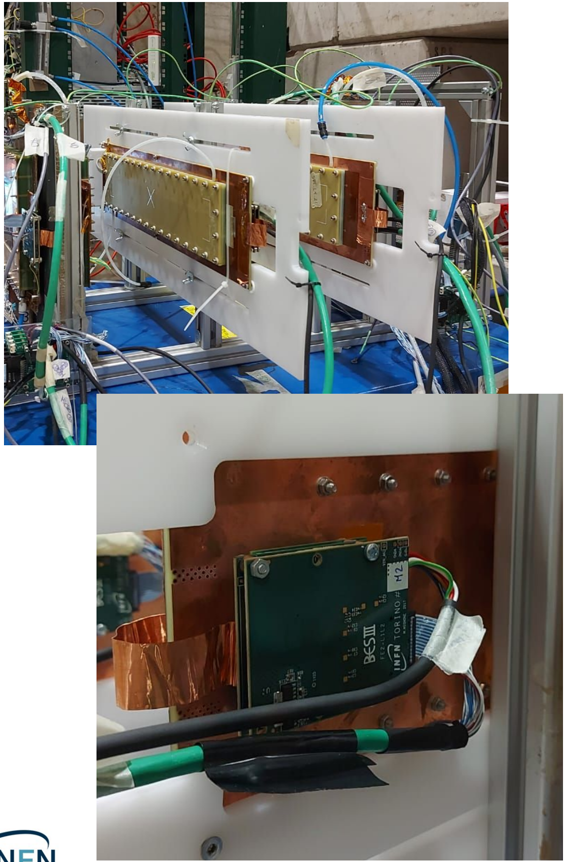


Figure 3.1: TIGER channel architecture scheme.



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)

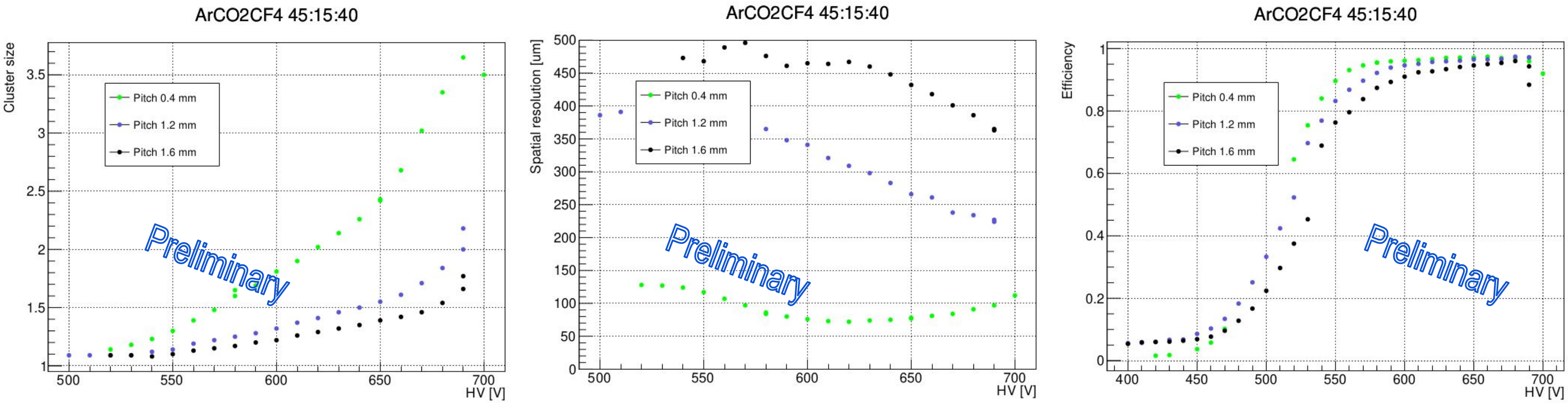
Goals of the testbeam:
- Define the state of art of μRWELL+TIGER for IDEA Muon system optimization studies
- Compare the APV-25 performance studies with TIGER
- Performance in Ar:CO2 and Ar:CO2:CF4 comparison
- Collect data to compare experimental measurement and simulation

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).

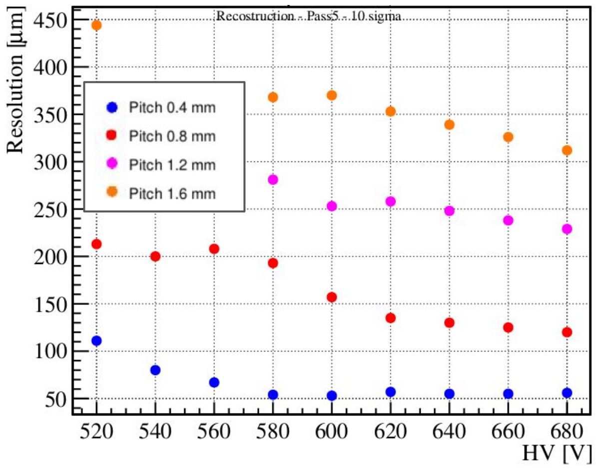
A spatial resolution of 100 μm is achieved with 400 μm pitch and a shift between the efficiency plateau of 0.4 mm and 0.8 mm pitch is observed, as expected.



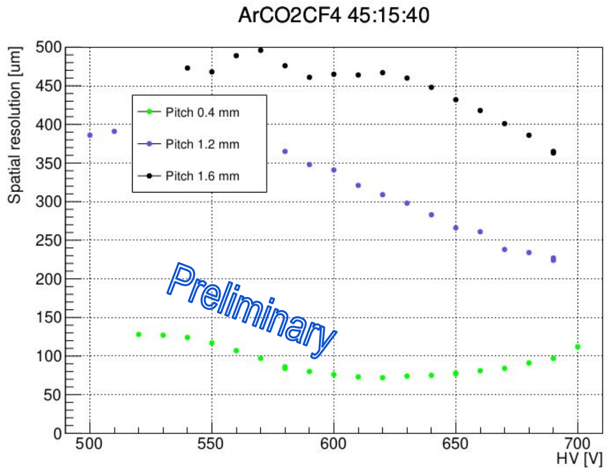
Pitch scan comparison TIGER - APV

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).

APV



TIGER

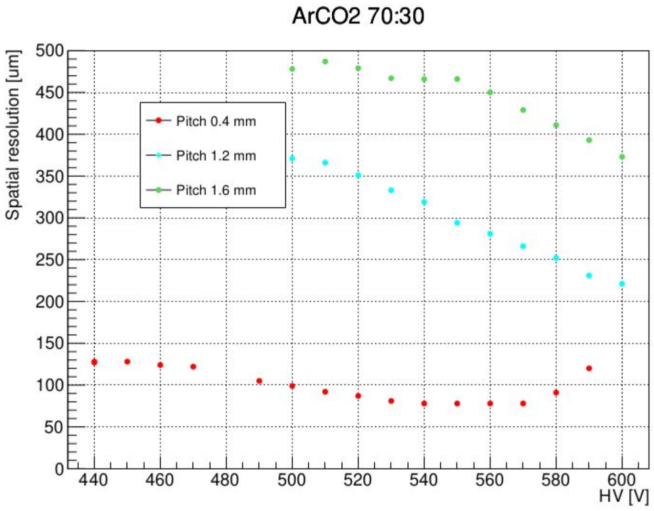


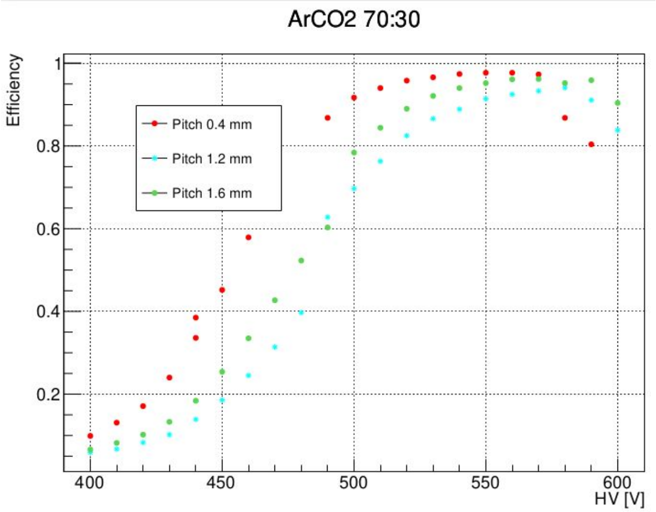
Results without CF4 gas

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.



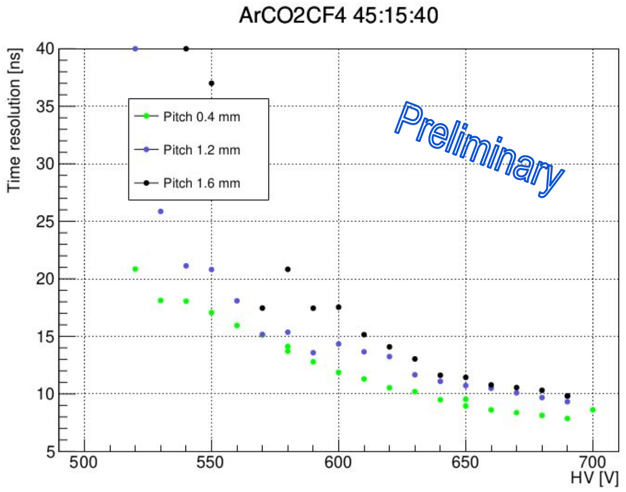


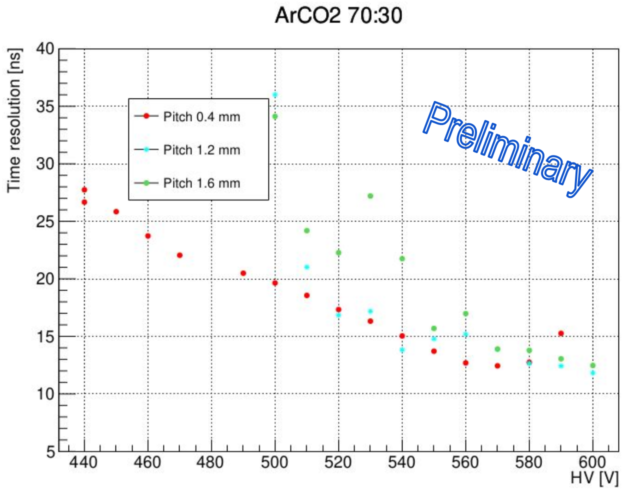
Results without CF4 gas

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





Detector simulation

Parametrization of a μ-RWELL

Ionization

Electron Drift

Amplification

Resistive ← [Dixit et al.](#)

Induction

Readout

Reco

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 $\sigma_{xy} = \sqrt{2th + w^2}$.

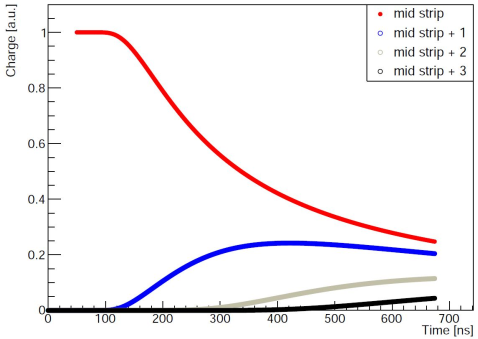
and it can be extended to the strip layout:

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

Parametrization of a μ-RWELL

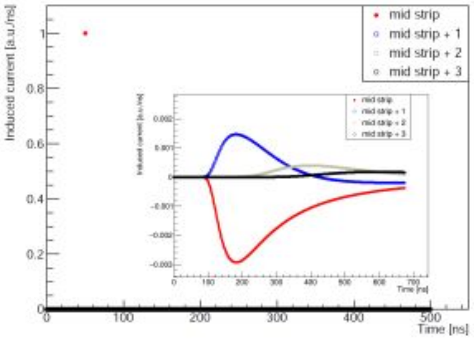
A charge q=1 is injected at t=50ns, using a tau=10ns and sigma0=10μm (see prev. formula).
See the full presentation on μRWELL on my contribution here

CHARGE



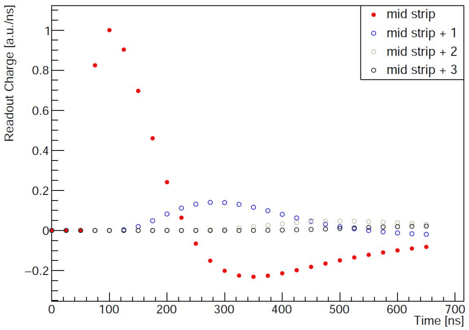
At t=50ns the charge is collected on the middle strip and then the charge is moved from the mid strip to the neighbors

CURRENT



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

ELECTRONICS



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

Simulation results

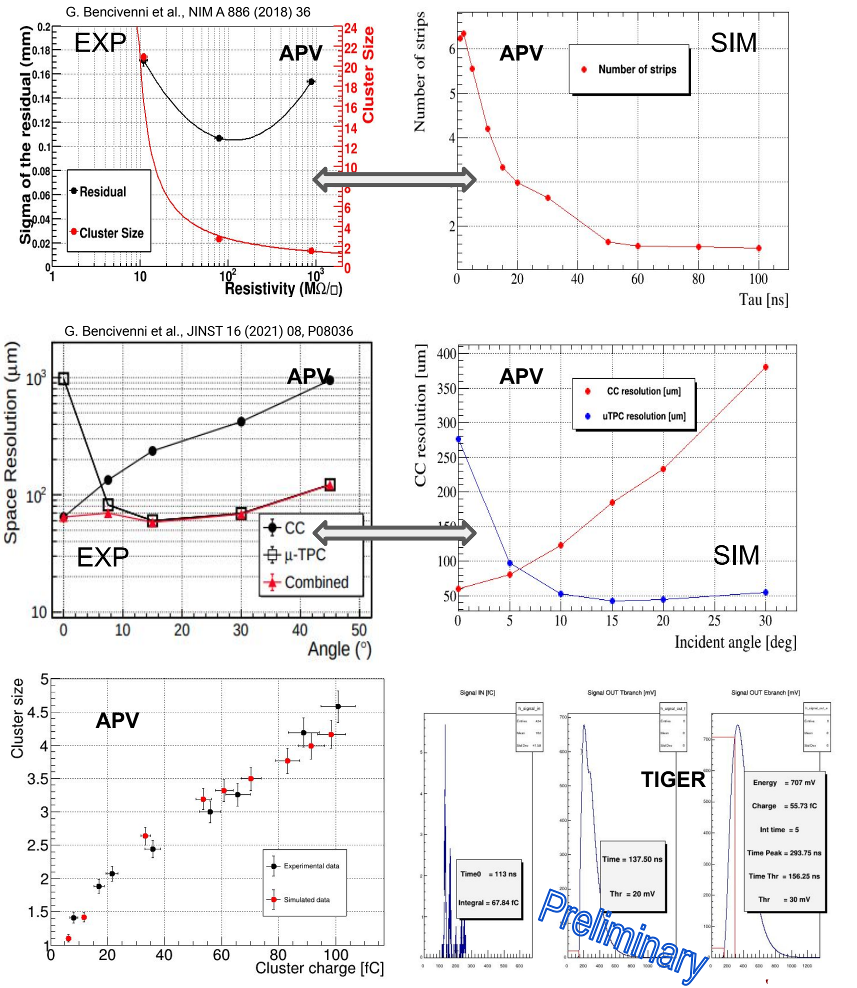
Thanks to a detector parametrization,
it is possible to reproduce the **µ-RWELL signal**.

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

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

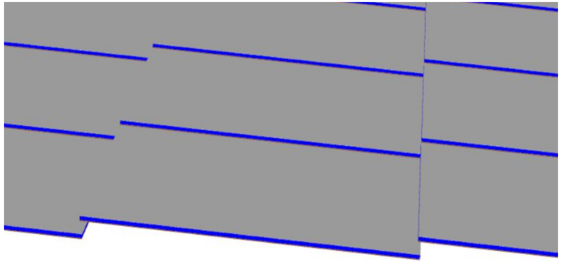
- Cluster Size and Cluster Charge
- Charge Centroid and µTPC spatial resolution
- Charge Dispersion of the DLC

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

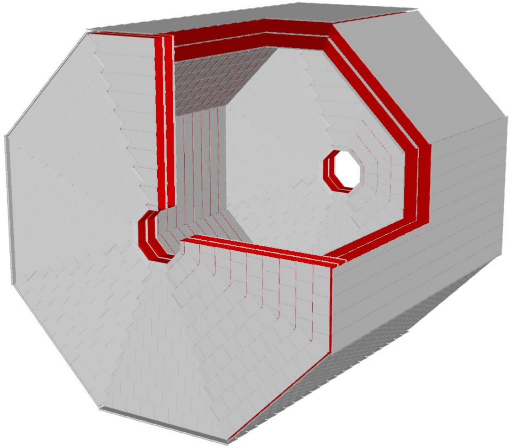


Muon apparatus simulation

μRWELL description in DD4hep



- Detector description implemented in DD4hep using 50x50cm2 tiles and the μRWELL materials
- μRWELL chambers arranged to cover the surface with minimal dead areas through overlapping
- The IDEA Muon-system is composed by three sensitive layers and two return-yokes layers. It is an octagon shape
- Digitization is implemented with a smearing of 400 μm



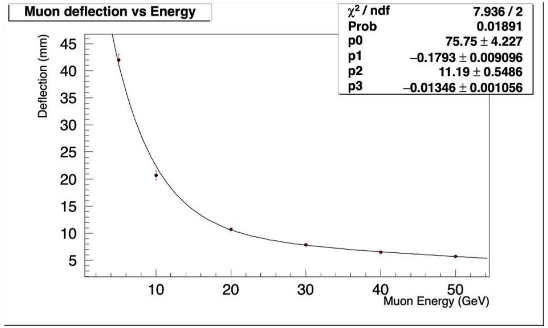
Multiple scattering measurement

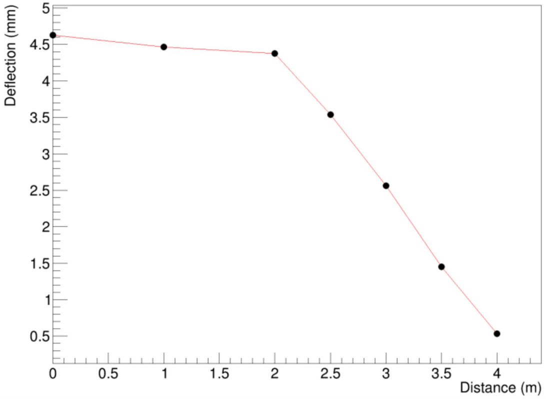
Special thanks to Ali Mahmoud

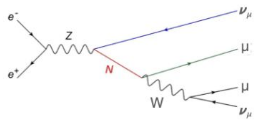
- A muon with different momentum and initial position is simulated to measure the smearing due to the multiple scattering.

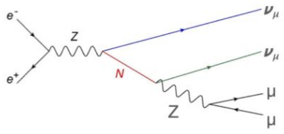
- If the muon starts from the IP then
  the MS contribution changes from 5 mm to 40 mm
  i.e. $Z \rightarrow \mu^+ \mu^-$

- If the muon starts in the range [0, 4] m then
  the MS contribution changes from 0.5 mm to 4.5 mm
  i.e. $Z \rightarrow \mu^+ \mu^- \nu_\mu \nu_\mu$ (Delphes)









Special thanks to
Ali Mahmoud

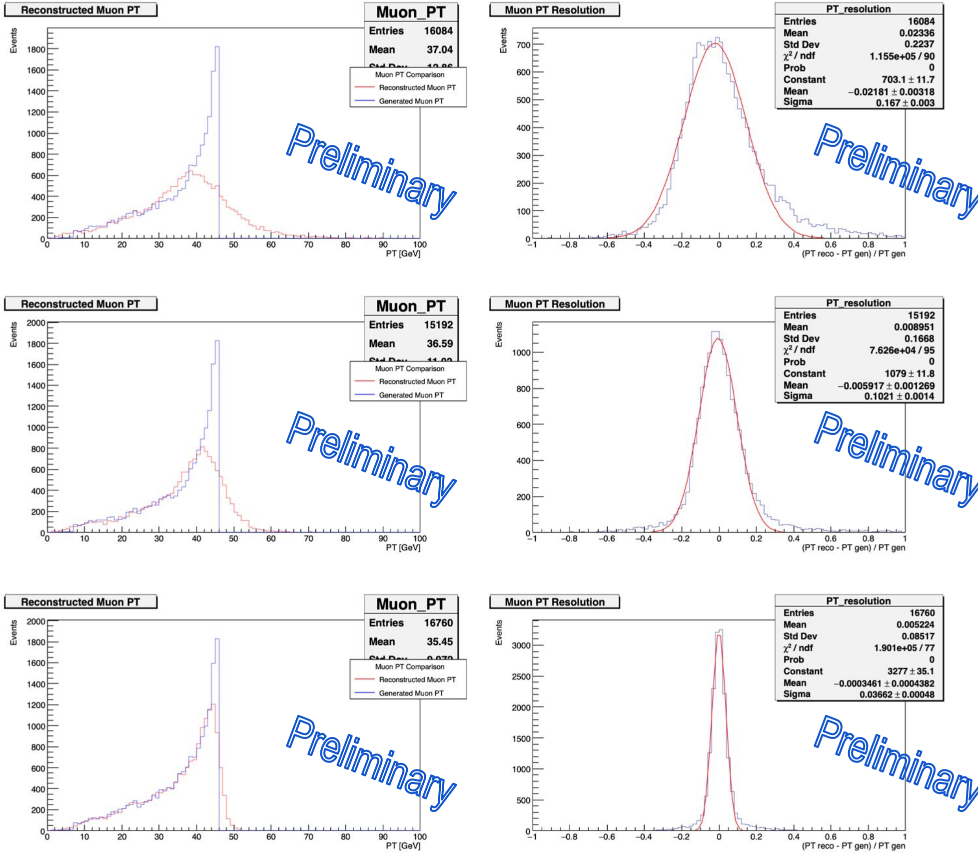
Momentum measurements

The channel: LLP → μ+ μ-
is simulated in Delphes.
The decay vertex is outside the magnet.

A first evaluation of the reconstructed muon momentum is reported and further optimization is needed to achieve fulfil this application of the muon apparatus.

Three layout are simulated:

- ➢ 3 muon layers with 30 cm distance each
- ➢ 3 muon layers with 60 cm distance each
- ➢ 6 muon layers with 30 cm distance each



Future plans

Ongoing activities and 2025 plans

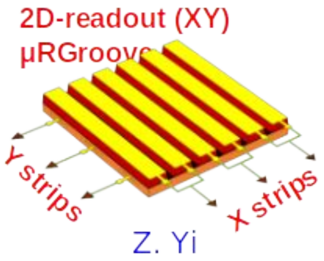
Solution under study to increase detector stability:

- 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.

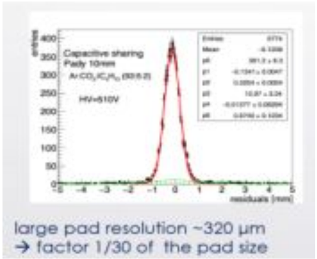
- μ-RGroove layout new layout, where the amplification stage is not based on the «wells» but on the «grooves». This facilitates the realization of the strip readout on the top, without introducing dead-zones (introduced by Z. Yi in RD51).

- " μ-RWELL CS" layout with pad readout new layout, where the readout PCB is not segmented in strips but with pad. This choice allows to collect all the charge on a single readout electrode with a small increase of FFE channels (30%). With pad of few cm2 a spatial resolution of 300 um has been achieved (introduced by M. Iodice in RD51).

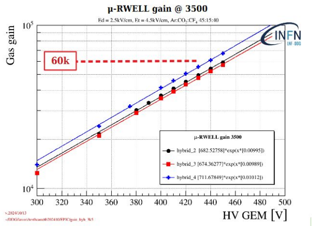
- "GEM + μ-RWELL CS" (strip/pad readout) GEM pre-amplification stage, to lower the operating point, greatly improving the RWELL stability and maintaining high spatial performance with millimetric pitches.



Z. Yi



M. Iodice



Possible synergy

The R&D for a future muon apparatus is still long and many aspect needs to be studied to define the detector requirement and optimize the performance. Here a list of some common studied that the full community can profit:

- simulation of the expected rate at the muon apparatus (given the latest IDEA proposal)
  - -> preliminary result report a rate of O(1Hz/cm2) on average
  - -> what is the expected rate in the high eta region ?
- simulation of LLP decay channel to evaluate the needs of a tracking muon system
  - -> if the MS has a large contribution, how can we profit of the good performance of sub-mm resolution?
- optimization of the electronics to reduce the noise and the number of channels
  - -> how the signal/noise can be improved?
  - -> pad or strip ? how to manage 5M channels?

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						

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.

Simulation studies of the electronics are ongoing to define a new ASIC design.

Simulation of the muon apparatus are started to improve the requirement evaluation.

Thanks