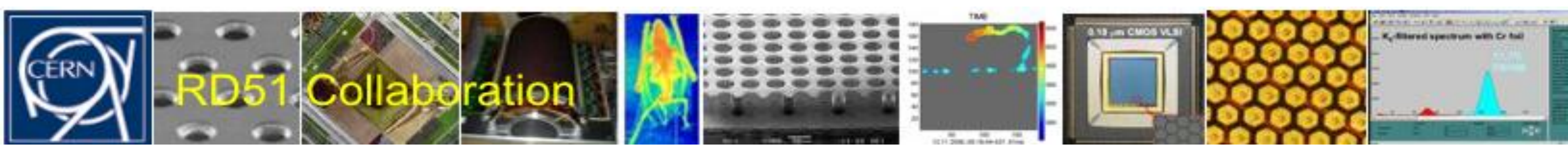
The micro-RWELL

M. Poli Lener[1]

G. Bencivenni[1] , R. De Oliveira[2], G. Felici[1] , M. Gatta[1],
M. Giovanetti[1], G. Morello[1], A. Ochi[3]

1. Laboratori Nazionali di Frascati - INFN
2. CERN
3. Kobe University



Muon Detectors for future colliders

- The future colliders (CepC, SppC and FCC – hh) requires for extremely large muon detectors :
  - ~10000 m^2 in the barrel
  - 3-5000 m^2 in the endcap
  - 300 m^2 in the very forward region

- The detectors have to be operated in high background (very large uncertainties depending on shielding, actual structure,etc.):
  - **O(1 – 10 kHz/cm²)** in the barrel
  - **O(10 – 100 kHz/cm²)** in the end-cap
  - **O(1 MHz/cm²)** in the forward region

- Taking into account the **surface** and the **expected rates** gaseous detectors and in particular **MPGDs is the natural solution** (straight-forward for CepC, requiring an R&D for the harsher conditions of SppC & FCC-hh)

- **R&D for HL-LHC** (LHCb phase-2 muon upgrade) is clearly a good starting point

- Last but not least, cylindrical or planar MPDG, could be adopted to equip tracking devices

The μ-RWELL

The R&D on μ-RWELL is mainly motivated by the wish of improving the

- **stability under heavy irradiation (discharge suppression)**
- **construction technology (simplifying the assembly)**
- **Technology Transfer to industry (mass production)**

a MUST for **very large scale applications** in fundamental research at the future colliders as well as for technology dissemination beyond HEP

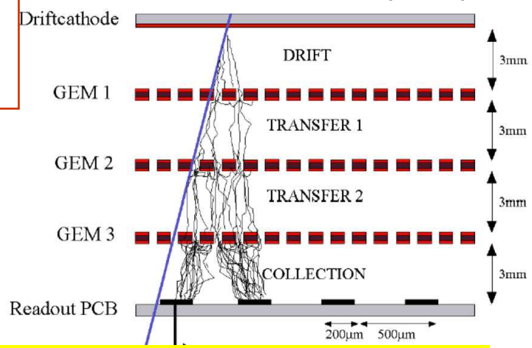
The original idea was conceived in 2009 @ LNF during the construction of the CGEM, to try to find a way to simplifying as much as possible the construction of the CGEM and its toolings. Only in the 2014 we really started a systematic study of this new technology in collaboration with Rui de Oliveira

MPGDs: stability

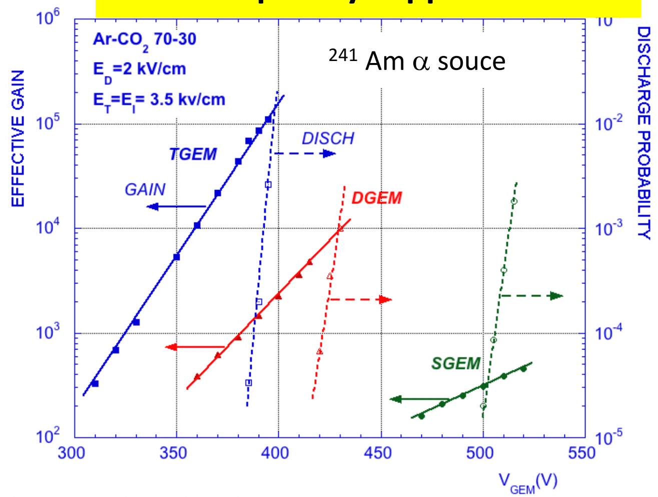
The **biggest "enemy"** of MPGDs are the **discharges.**
Due to the **fine structure** and the **typical micrometric distance of their electrodes**, MPGDs generally suffer from **spark occurrence** that can eventually **damage the detector and the related FEE.**

GEM

F. Sauli, NIM A 386 (1997) 531



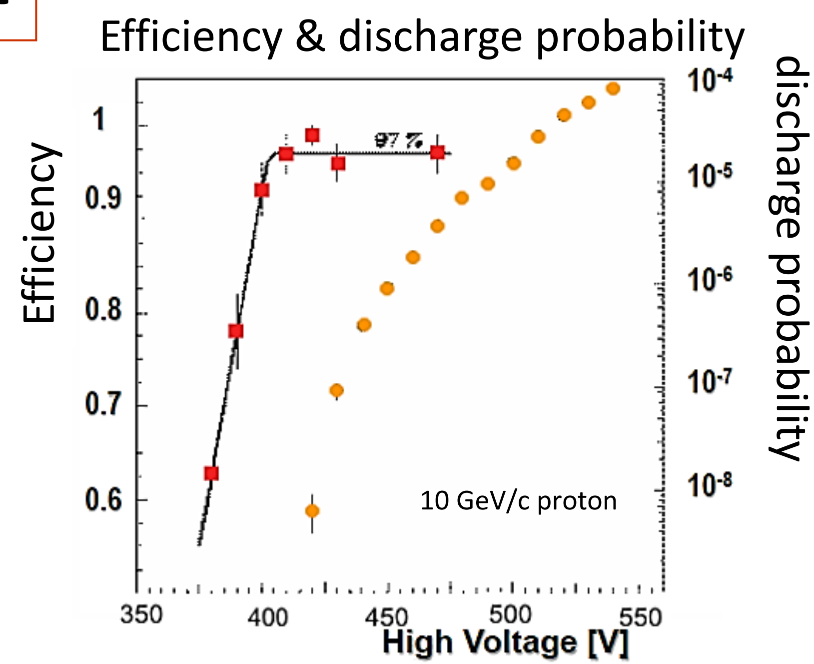
Strongly reduced but not completely suppressed



S. Bachmann et al., NIM A 479(2002) 294

MM

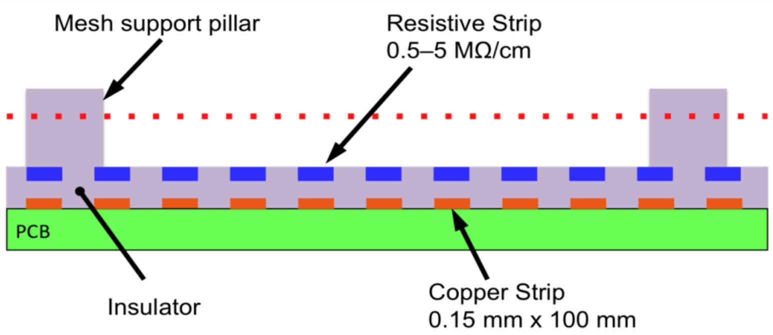
I. Giomataris , NIM A 376 (1996) 29



A. Bay et al., NIM A 488 (2002) 162

Technology improvements
for MicroMegas

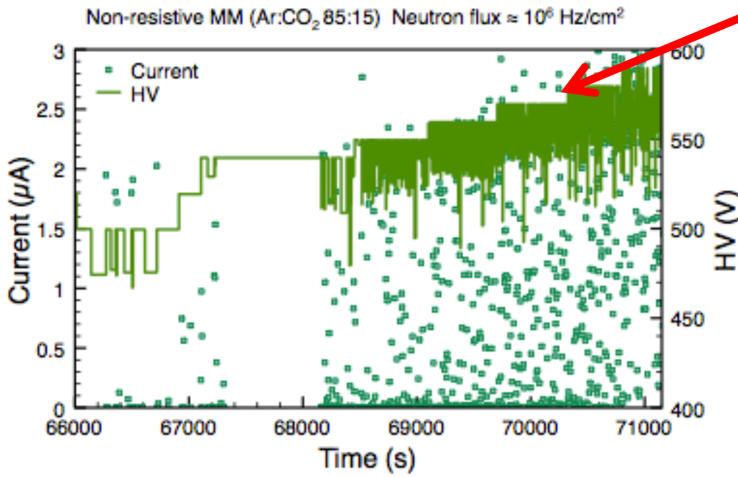
For **MM**, the spark occurrence between **the metallic mesh and the readout PCB** has been **overcome** with the **implementation of a "resistive layer"** on top of the readout. The principle is the same as the **resistive electrode used in the RPCs**: the **transition from streamer to spark is strongly suppressed by a local voltage drop.**

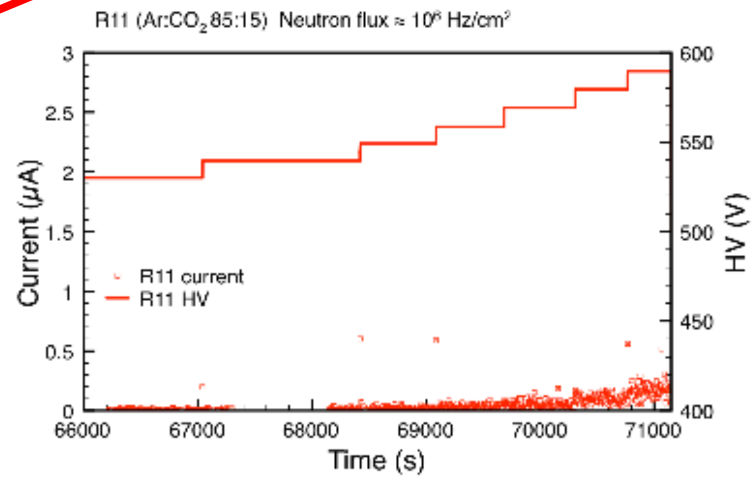


by R.de Oliveira TE MPE CERN Workshop

The resistive layer is realized as resistive strips capacitive coupled with the copper readout strips.

voltage drop due to sparking



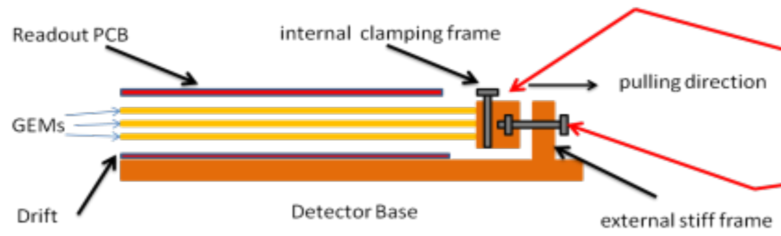


MPGDs: construction issues (I)

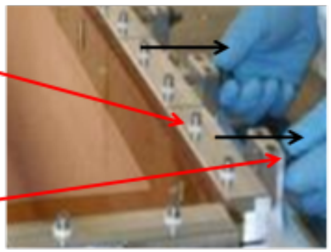
An **important limitation of such MPGDs** is correlated with the **complexity of their assembly procedure**, particularly evident in case of **large area devices.**

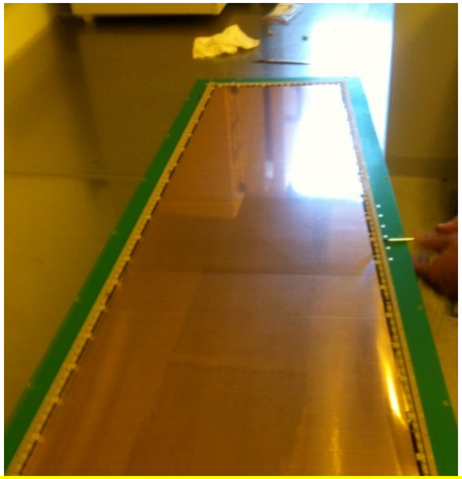
- The construction of a **GEM chamber requires time-consuming assembly steps such as the stretching** (with quite large mechanical tension to cope with – 1 kg/cm) and the **gluing** of the **GEM foil on frames**

New GEM detector assembly scheme

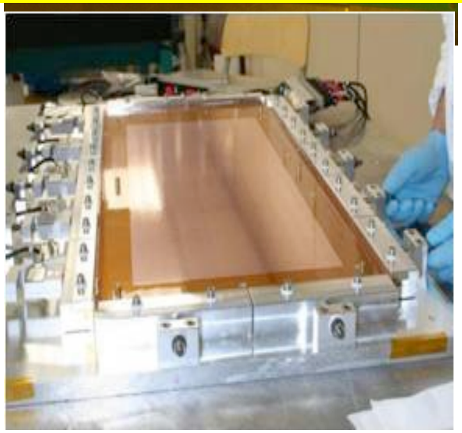


GEM foil Stretching tool operation





NS2(CERN – R. de Oliveira): no gluing, but still stretching



- A **2 m long** detector requires a ~**200 kg mechanical tension** that must be sustained by **stiff mechanical structures (large frames, rigid panels** ...). While the max width of the raw material is about 60 cm.
- The **splicing/joining of smaller detectors** in order to realize large surfaces (as used for silicon detectors) is difficult **unless introducing not negligible dead zones .**

MPGDs: construction issues (II)

Similar considerations hold for MM:

- the **splicing/joining of smaller PCBs is possible**, opening the way towards the **large area detection covering**

- the **fine metallic mesh**, that defines the amplification gap, is a ***"floating component"***, because it is stretched on the cathode (@ 1 kg/cm) and electrostatically attracted toward the PCB ($P = \epsilon_0 \times (^{\Delta V}/_{d})^2$).

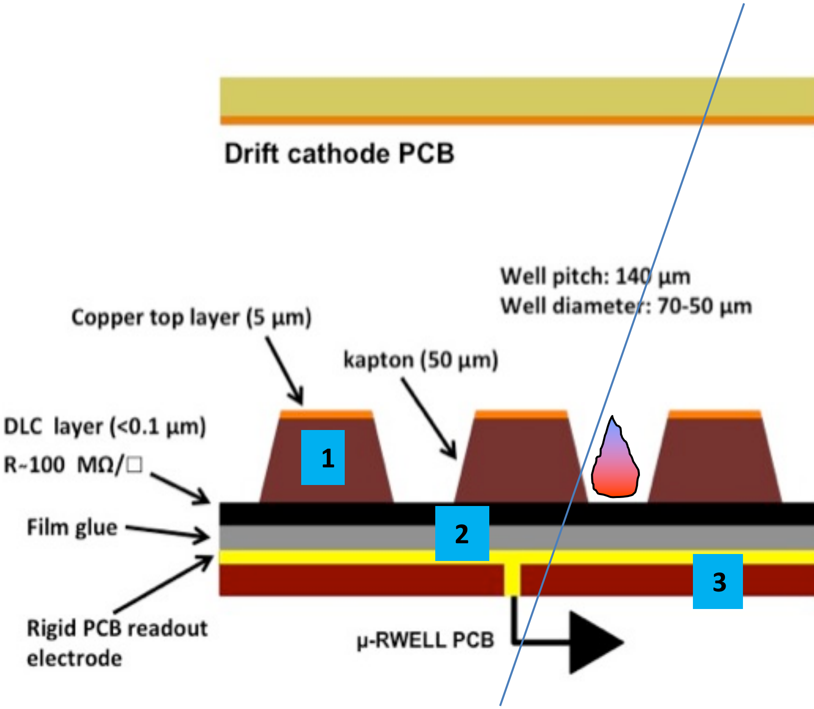
- this could be a **source of instability because a "not well defined" amplifying gap could generate gain non-uniformity.**
- In addition: **handling of large meshes is clearly "not trivial" (of course for large area)**
  cleaning of the amplification stage could be an issue

The μ-RWELL: the detector architecture

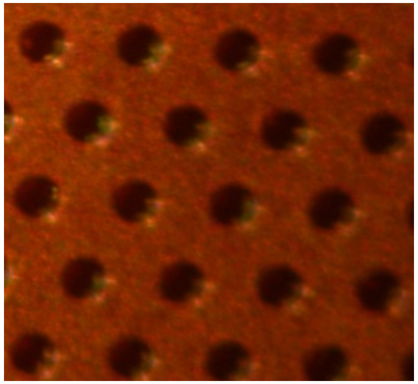
The **μ-RWELL is composed of** only **two elements**:
the **μ-RWELL_PCB** and the **cathode**

The **μ-RWELL_PCB, the core of the detector,** is realized by **coupling:**

1. a **WELL patterned kapton foil** as **amplification stage**
2. a **resistive layer**(*) for discharge suppression:
    i. **Single resistive layer (SRL) <100 kHz/cm²:** single resistive layer → surface resistivity ~100 MΩ/☐ (SHiP; CepC, Novosisbirsk, EIC, HIEPA)
    ii. **Double resistive layer (DRL) >1 MHz/cm²**: for LHCb-Muon upgrade
3. a **standard readout PCB**



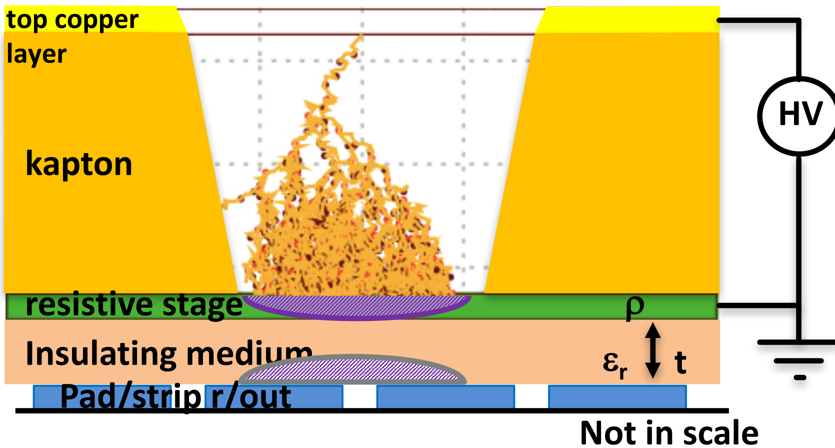
G. Bencivenni et al., 2015_JINST_10_P02008



(*) DLC = Diamond Like Carbon
highly mechanical & chemical resistant

Principle of operation

Applying a suitable voltage between **top copper layer and DLC** the "**WELL**" **acts as multiplication channel for the ionization.**



The charge induced on the resistive foil is dispersed with a ***time constant, τ = ρC ,*** determined by

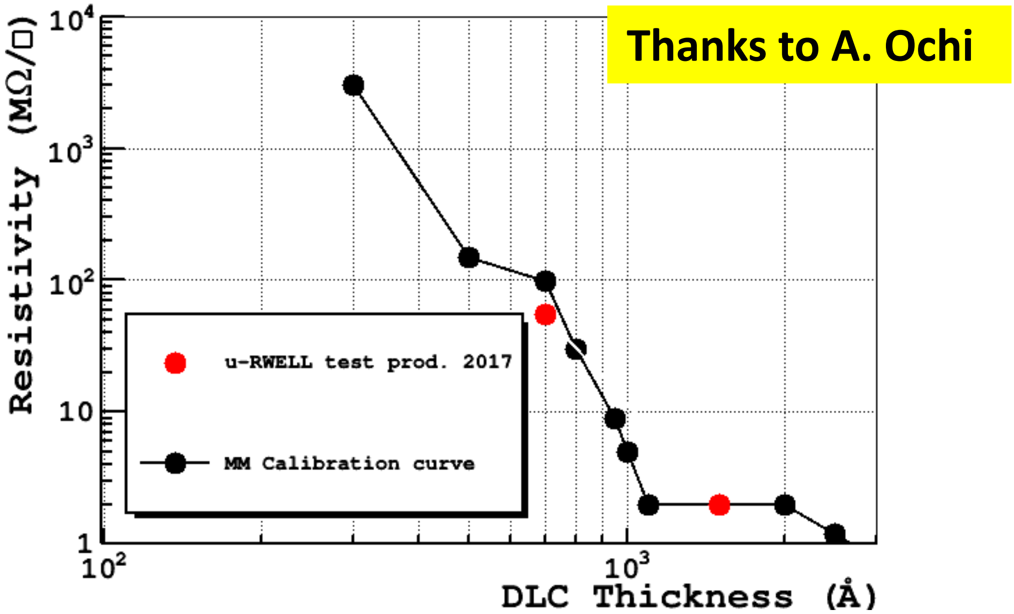
- the ***surface resistivity, ρ***
- the ***capacitance per unit area,*** which depends on the **distance between the resistive foil and the pad/strip readout plane,** ***t***
- the ***dielectric constant*** of the insulating medium, ε_r ***[M.S. Dixit et al., NIMA 566 (2006) 281]***

- **The main effect of the introduction of the resistive stage is the suppression of the transition from streamer to spark**
- As a drawback, the **capability to stand high particle fluxes is reduced**, ***but an appropriate grounding of the resistive layer with a suitable pitch solves this problem (see High Rate scheme)***

The resistive layer: DLC sputtering

The **kapton foils (copper etched on one side)** are at moment sputtered with DLC, provided by Be-Sputter Co., Ltd. in Japan. They are able to sputter 6 foils (1.2x0.6 m^2) per production batch.

The resistivity depends on several manufacturing conditions, but can be parametrized as function of the DLC thickness. The resistivity uniformity is at level of 10-20%



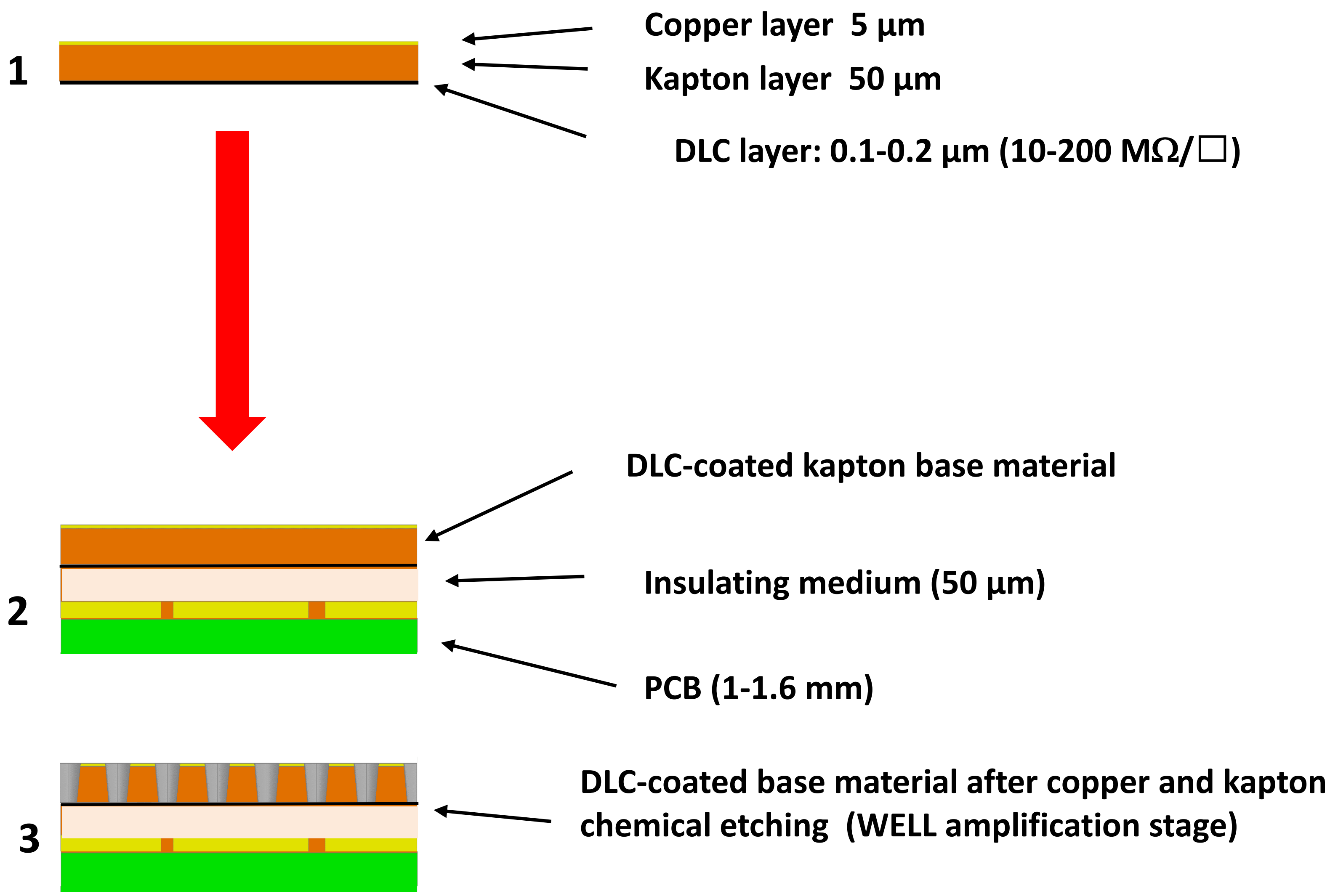
Recently we are starting a profitable collaboration with Zhou Yi and Jianbei Liu from USTC – Hefei for the manufacturing of improved DLC foil

Main detector features

The **µ-RWELL** is a **single-amplification stage**, intrinsically **spark protected** MPGD characterized by:

- ***simple assembly procedure***:
  - ***only two components → µ-RWELL_PCB + cathode***
  - no critical & time consuming **assembly** steps:
    - ***no gluing***
    - ***no stretching*** **(→** no stiff & large frames needed)
    - ***easy handling***
  - ***suitable for large area with PCB splicing technique w/small dead zone***
- ***cost effective:***
  - 1 PCB r/o, 1 µ-RWELL foil, 1 DLC, 1 cathode and **very low man-power**
- ***easy to operate:***
  - very simple HV supply → only ***2 independent HV channels*** or a trivial ***passive divider*** (while 3GEM detector → 7 HV floating/channels)

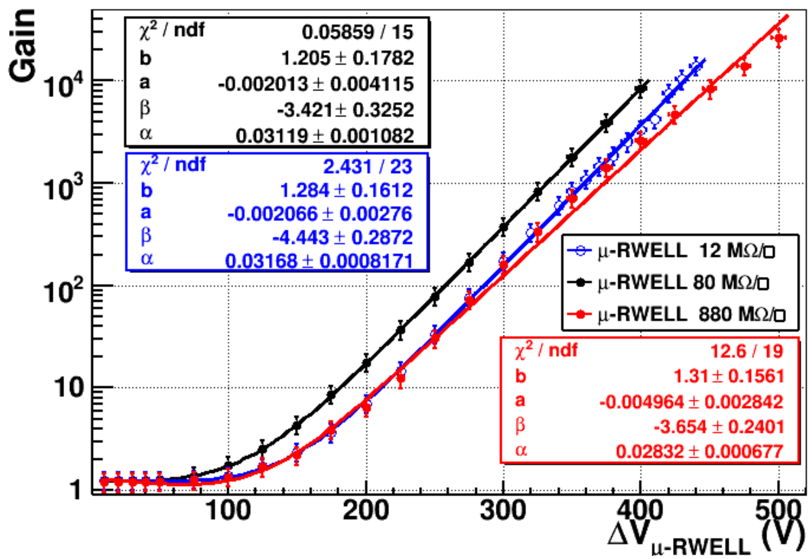
The Low Rate scheme



Single Resistive μ-RWELL performance

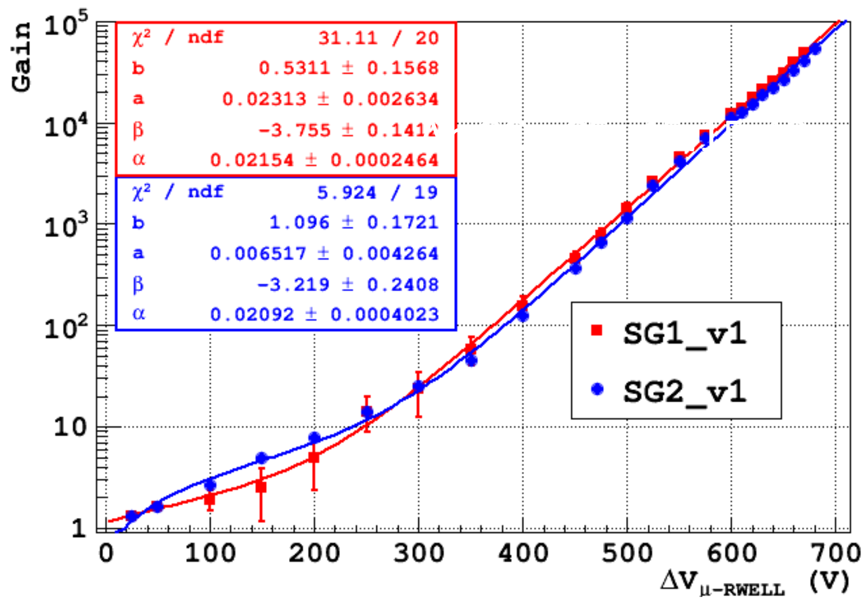
Detector Gain

Ar/iC_4H_{10}= 90/10



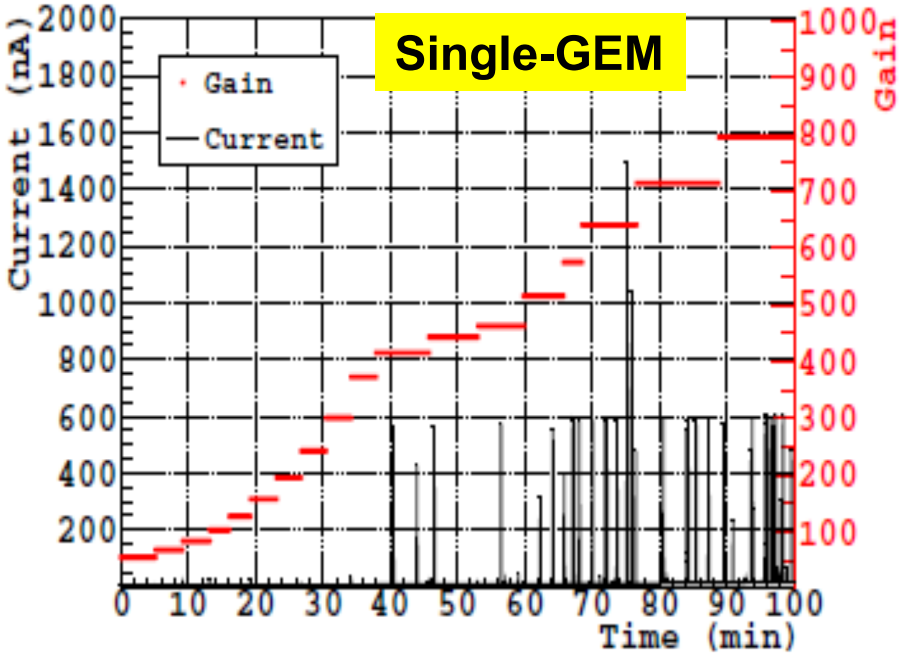
Prototypes with different resistivity have been tested with **X-Rays** (5.9 keV), with **Ar/iC_4H_{10}= 90/10** gas mixture, and characterized by measuring the **gas gain** in **current mode**.

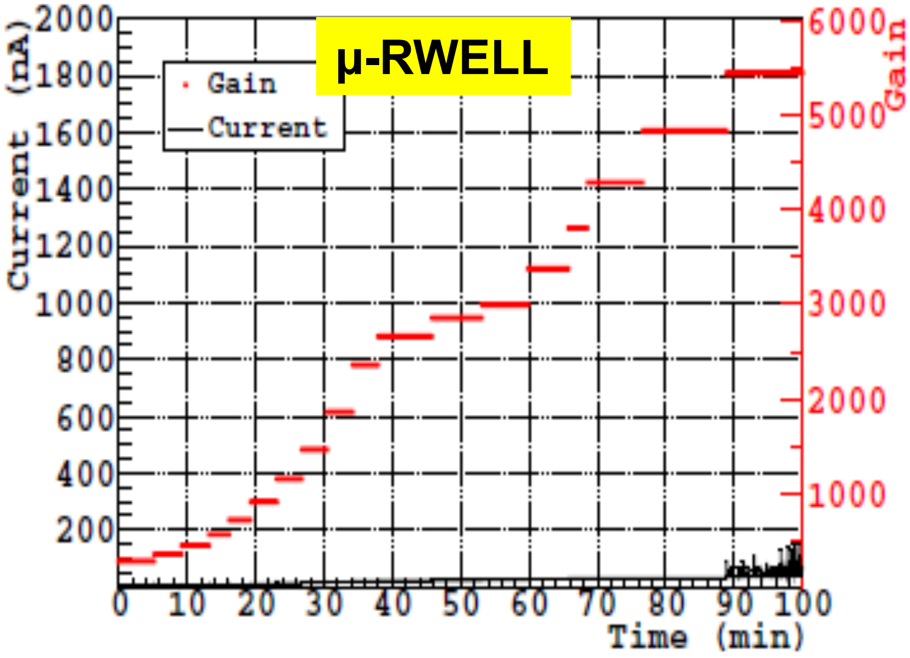
$Ar/CO_2/CF_4$= 45/15/40



Some recent prototypes achieved a Gain ~10^5 in $Ar/CO_2/CF_4$= 45/15/40

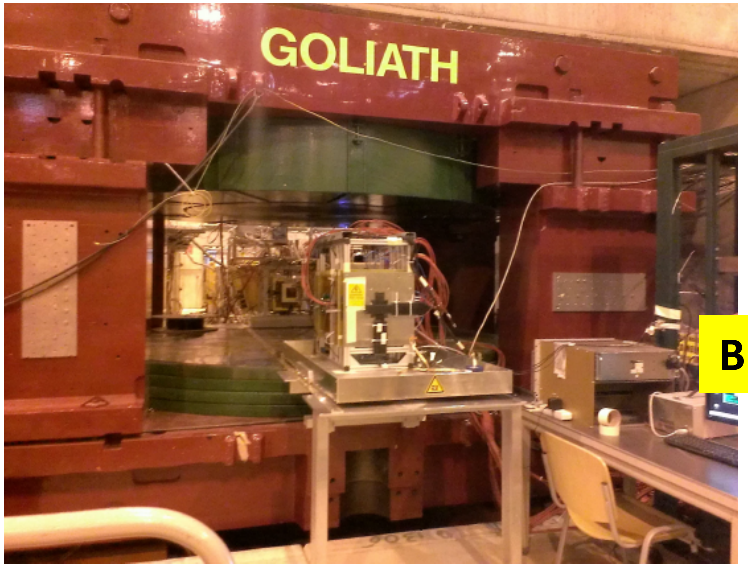
Discharge study: µ-RWELL vs GEM





- discharges for <u>µ-RWELL</u> of the order of <u>few tens of nA</u> (<100 nA @ high gain)
- for <u>GEM</u> discharges the order of <u>1µA</u> are observed at high gas gain

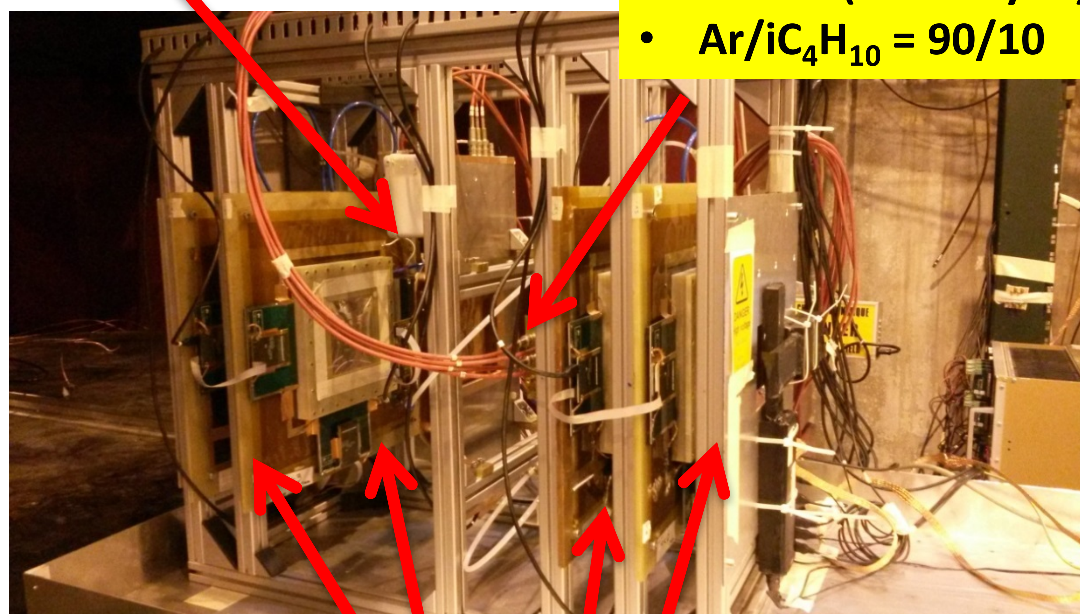
Beam Tests results



H4 Beam Area (RD51)
Muon beam momentum: 150 GeV/c
Goliath: B up to 1.4 T

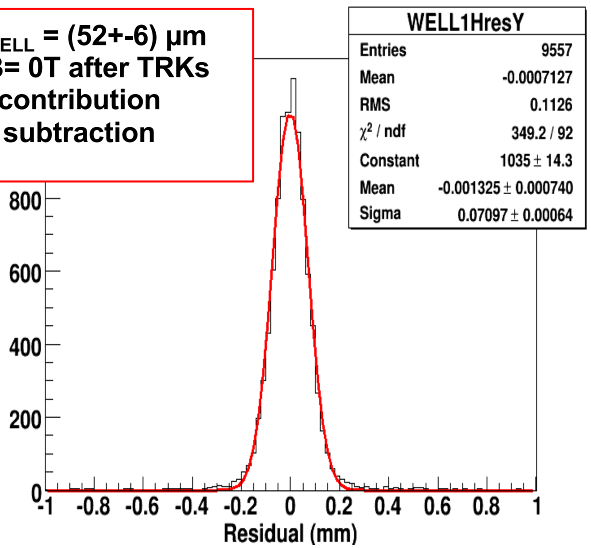
μ-RWELL prototype:
- **12-80-880 MΩ /□**
- **400 μm pitch strips**
- **APV25 (CC analysis)**
- **Ar/iC_4H_{10} = 90/10**

BES III-GEM chambers



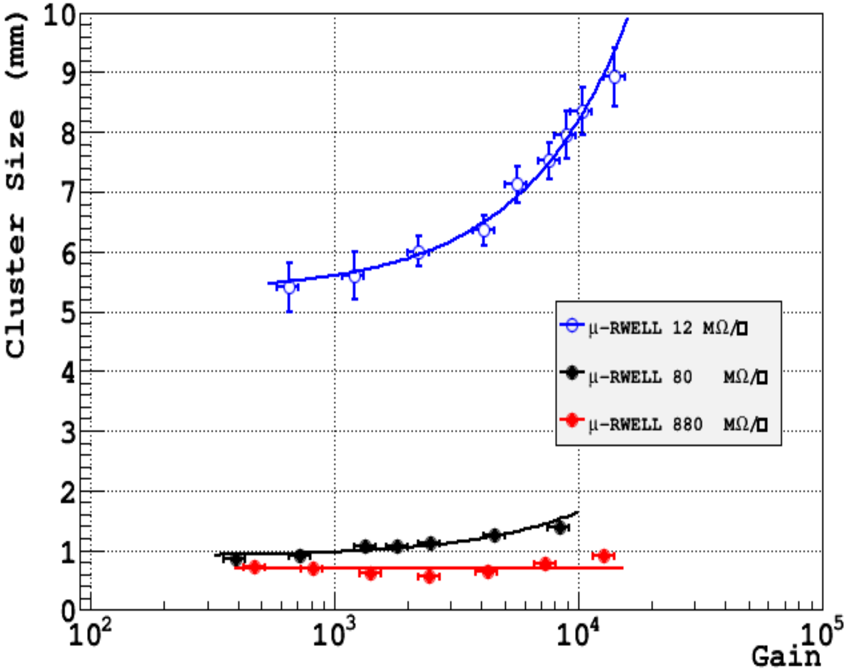
GEMs Trackers

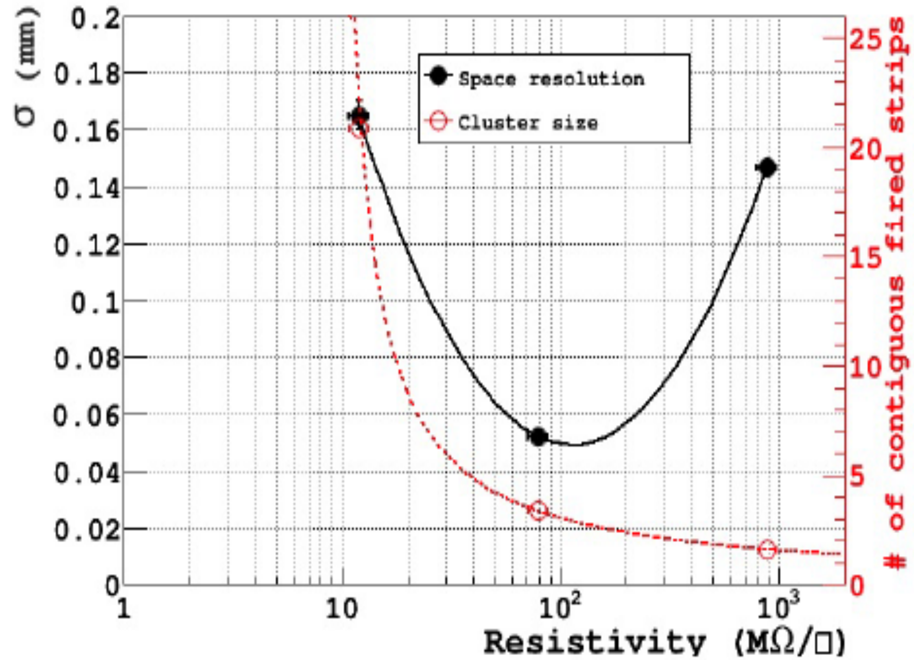
σ_{RWELL} = (52+-6) μm @ B= 0T after TRKs contribution subtraction



Space resolution *vs* resistivity

Charge Centroid analysis
Strip readout





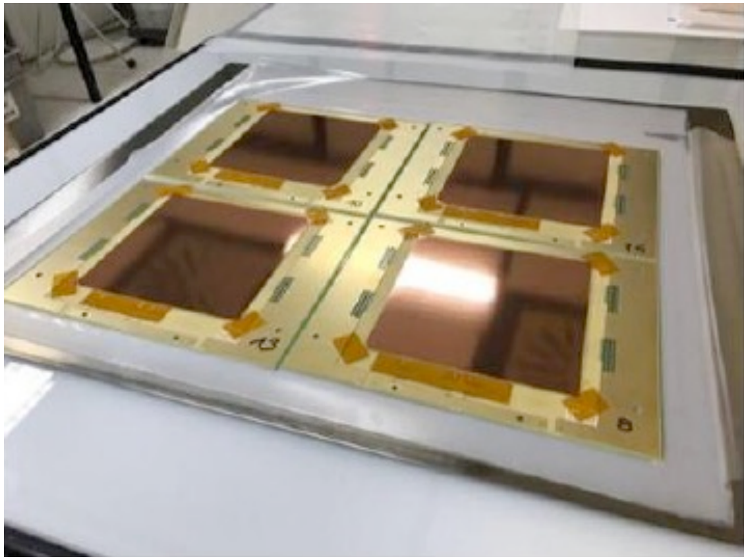
The **space resolution** exhibits a **minimum around 100MΩ/□**

→ at **low resistivity** the **charge spread increases** and then **σ is worsening**

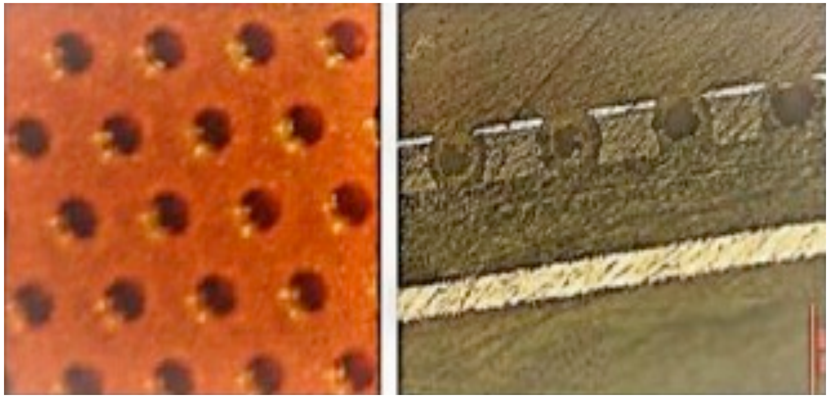
→ at **high resistivity** the **charge spread is too small (Cl_size → 1 fired strip)** then the Charge Centroid method becomes no more effective **(σ → pitch/√12)**

Technology Transfer to Industry (I)

The engineering and industrialization of the μ-RWELL technology is one of the main goal of the project. Transferring the manufacturing process to industry will allow a cost-effective mass production: a must for the construction of muon systems at future HEP Colliders



Manufacturing process of the single resistive layer has been already tested at the ELTOS SpA (http://www.eltos.it)



Production @ ELTOS:
- 8 PCB – uRWELL (PAD r/o)
- 16 PCB – uRWELL (strip r/o)

coupled with kapton/DLC foils.

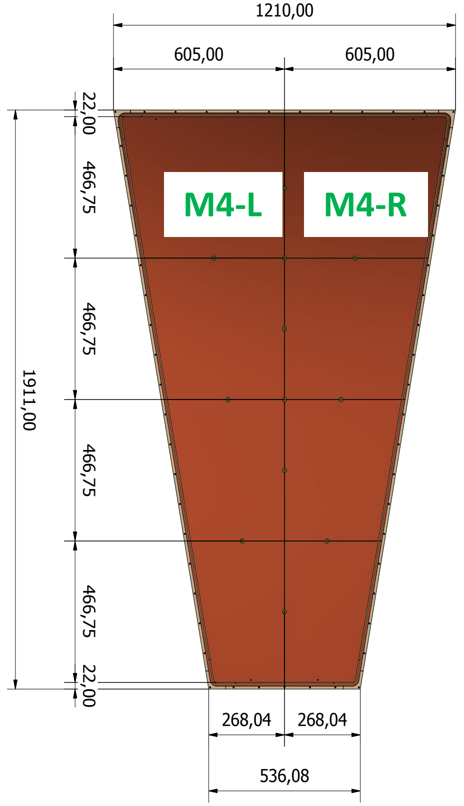
The etching of the kapton done by Rui

Technology Transfer to Industry (II)

In the framework of the **CMS-phase2 muon upgrade** different prototypes of **large size single-resisitive layer μ-RWELLs** has been built at ELTOS:

- **1.2x0.5m² μ-RWELL**
- **1.9x1.2m² μ-RWELL**

1.2x0.5m² (GE1/1) μ-RWELL



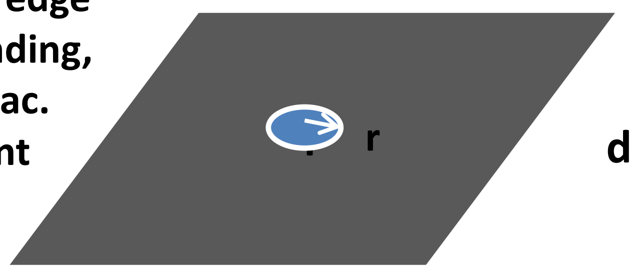
1.9x1.2m² (GE2/1) μ-RWELL

In collaboration with CMS-Muon:
L. Benussi, L. Borgonovi, P. Giacomelli, A. Ranieri, M. Ressegotti, I. Vai, V. Valentino

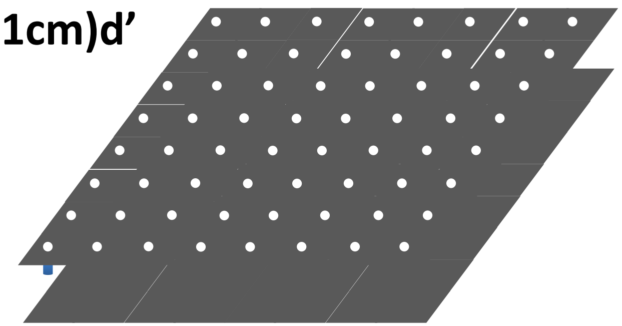
From Low Rate μ-RWELL to High Rate version

Towards the High Rate

single resistive layer, edge grounding, 2D evac. current



double resistive layer, 3D grounding



(*) point-like irradiation, r << d
Ω is the resistance seen by the current generated by a radiation incident the center of the detector cell

$$\Omega \sim \rho_s \text{ x } d/2\pi r \qquad \Omega' \sim \rho_s' \text{ x } 3d'/2\pi r$$

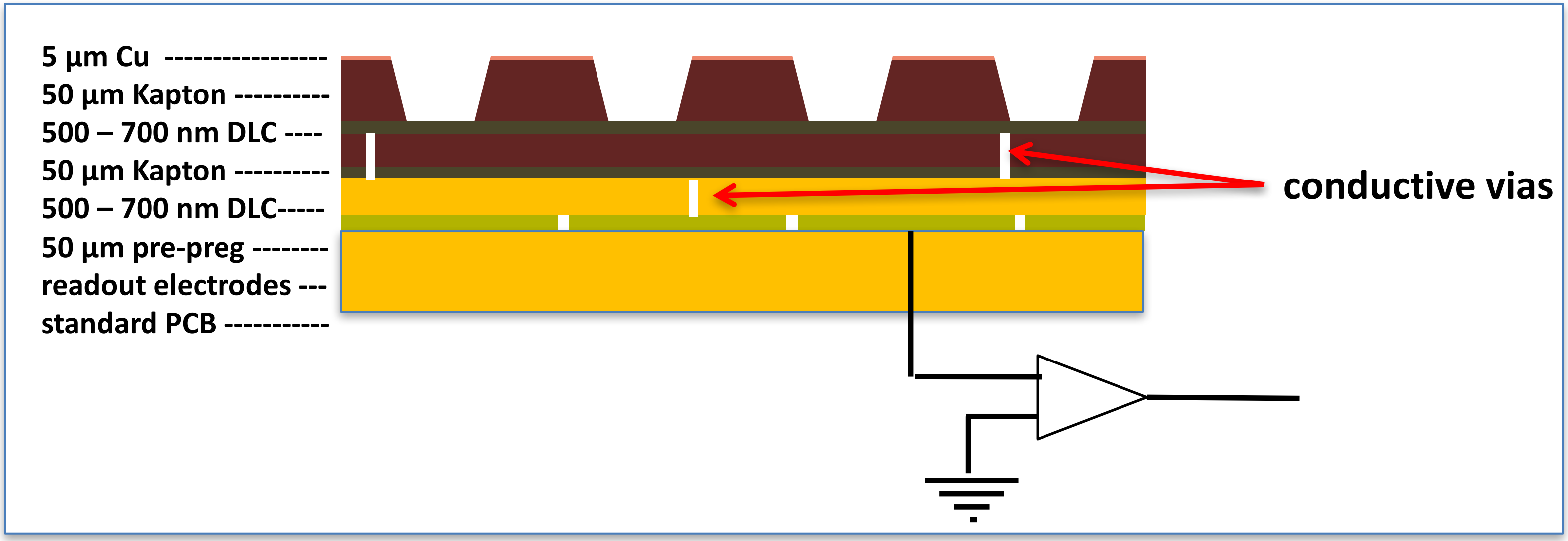
$$\Omega/\Omega' \sim (\rho_s/\rho_s') \text{ x } d/3d'$$

$$\text{If } \rho_s = \rho_s' \rightarrow \Omega/\Omega' \sim \rho_s/\rho'_s * d/3d' = 50/3 = 16.7$$

(*) Morello's model: appendix A-B (G. Bencivenni et al., 2015_JINST_10_P02008)

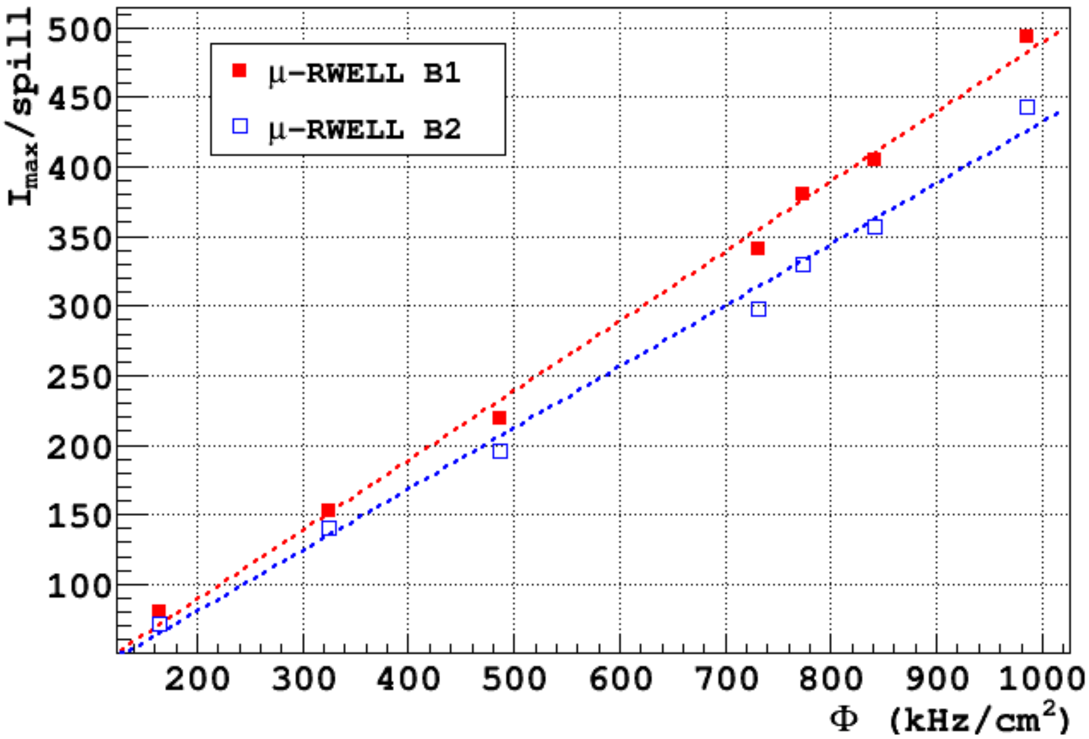
1st High rate layout: the double-resistive layer

The **idea is to reduce the path of the current on the DLC,** a **matrix of conductive vias** connecting the **two resistive layers is introduced**. Another **matrix of vias** connects the **second resistive layer to ground** through the readout



Double-resistive layer: the performance

Rate capability as a function of the pion beam (H4-SpS CERN) intensity

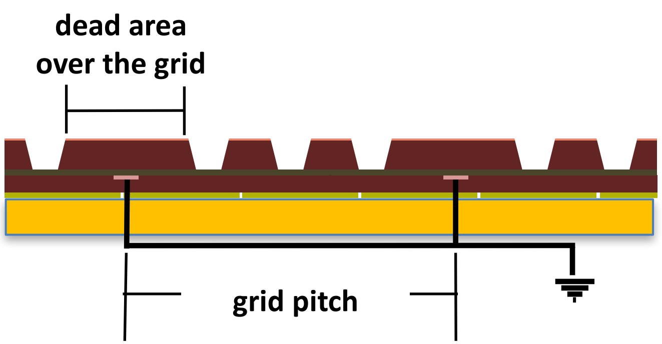


Detectors operated at a gain of 10^4.
Beam spot ~2 cm^2 (RMS)

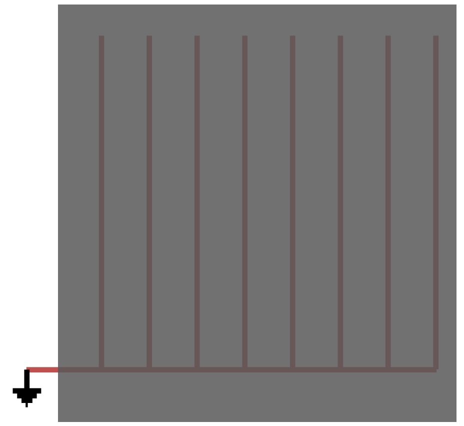
WARNING: The **engineering/industrialization of the double-resistive** layer is **difficult** due to the **manufacturing of the conductive vias**

New ideas for the HR version

The aim is **to maintain a very short path for current moving on the resistive layer,** while **simplifying the construction process.**
Two ideas are now under development: **silver grid and resistive grid on the bottom of the DLC**



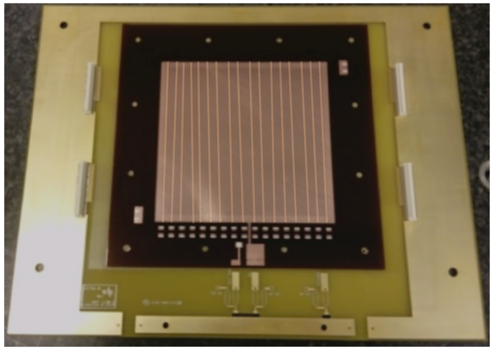
High Rate scheme	Resistivity [MΩ/]	Dead Area over grid	Grid Pitch	Geometrical efficiency [%]	Type
Silver Grid 1 (SG1)	60-70	2 mm	6 mm	66	conductive grid
Silver Grid 2 (SG2)	60-70	1,2 mm	12 mm	90	conductive grid
Resistive Grid (RG)	60-70	-	6 mm	Full	resistive grid

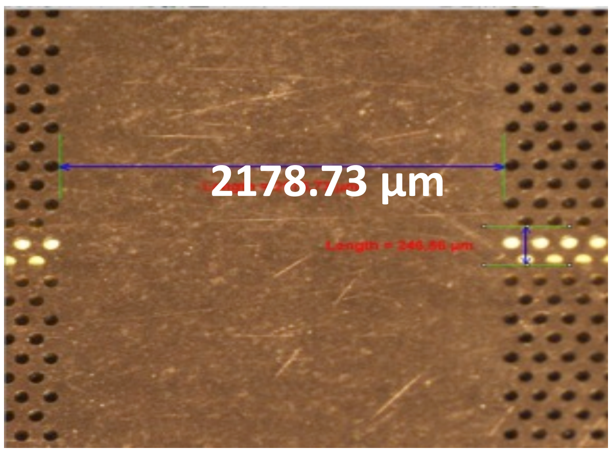


The **conductive grid** on the bottom of the amplification stage **can induce instabilities due to discharges over the DLC surface, requiring for the introduction of a dead zone on the amplification stage. This is not the case for the resistive grid scheme.**

New ideas for the HR version

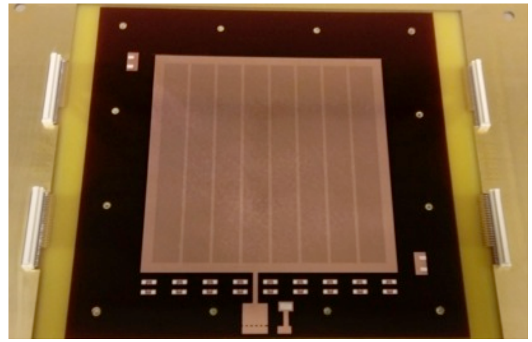
Silver Grid v1

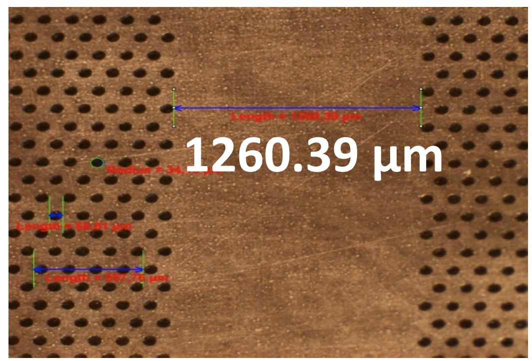




grid-pitch 6 mm
dead area 2 mm
→ Geometrical effi.: 66%

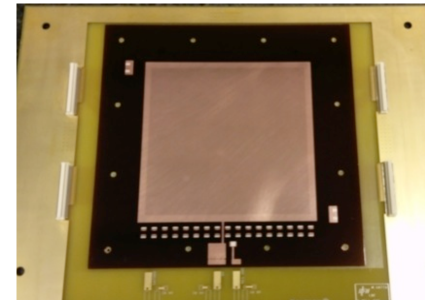
Silver Grid v2

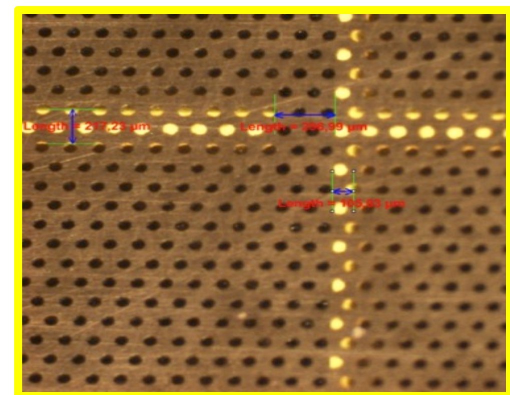




grid-pitch 12 mm
dead area 1 mm
→ Geometrical effi.: 90%

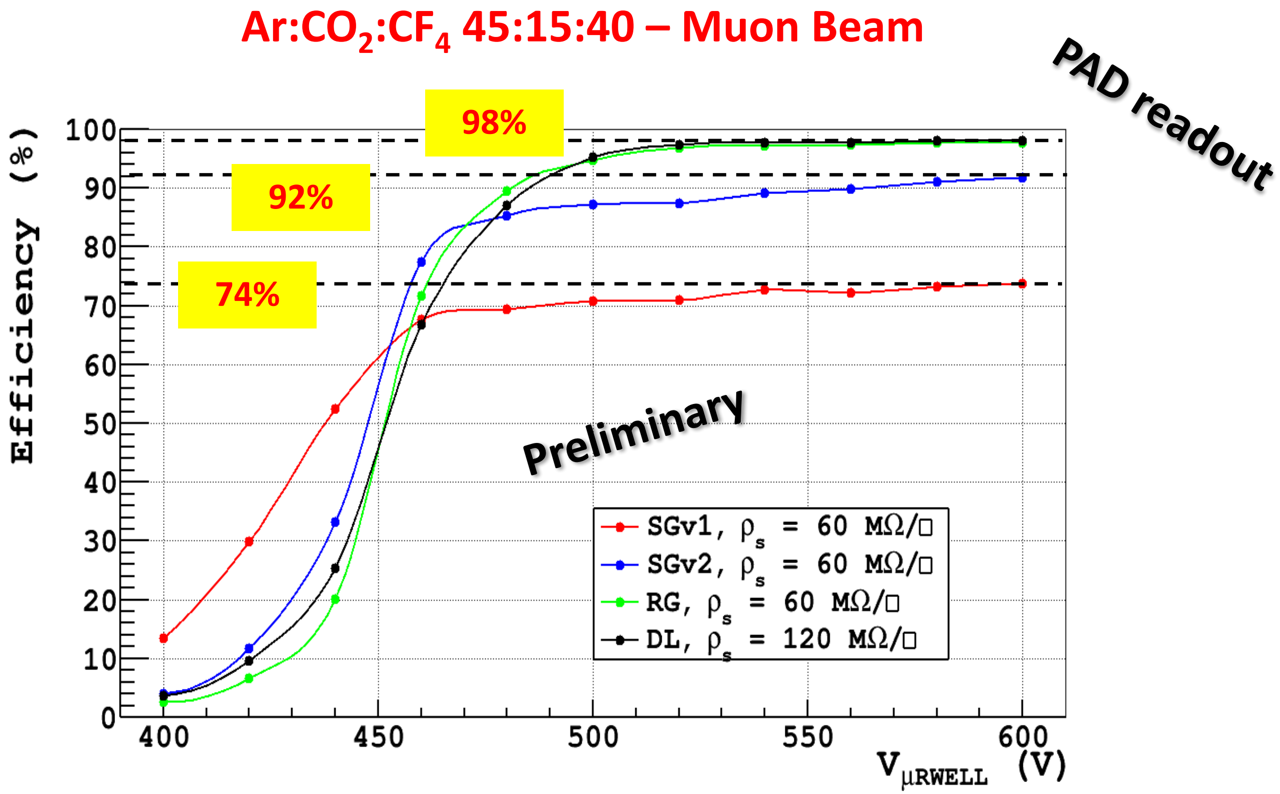
Resistive Grid





grid-pitch 6 mm
NO dead area
→ Geometrical effi.: full

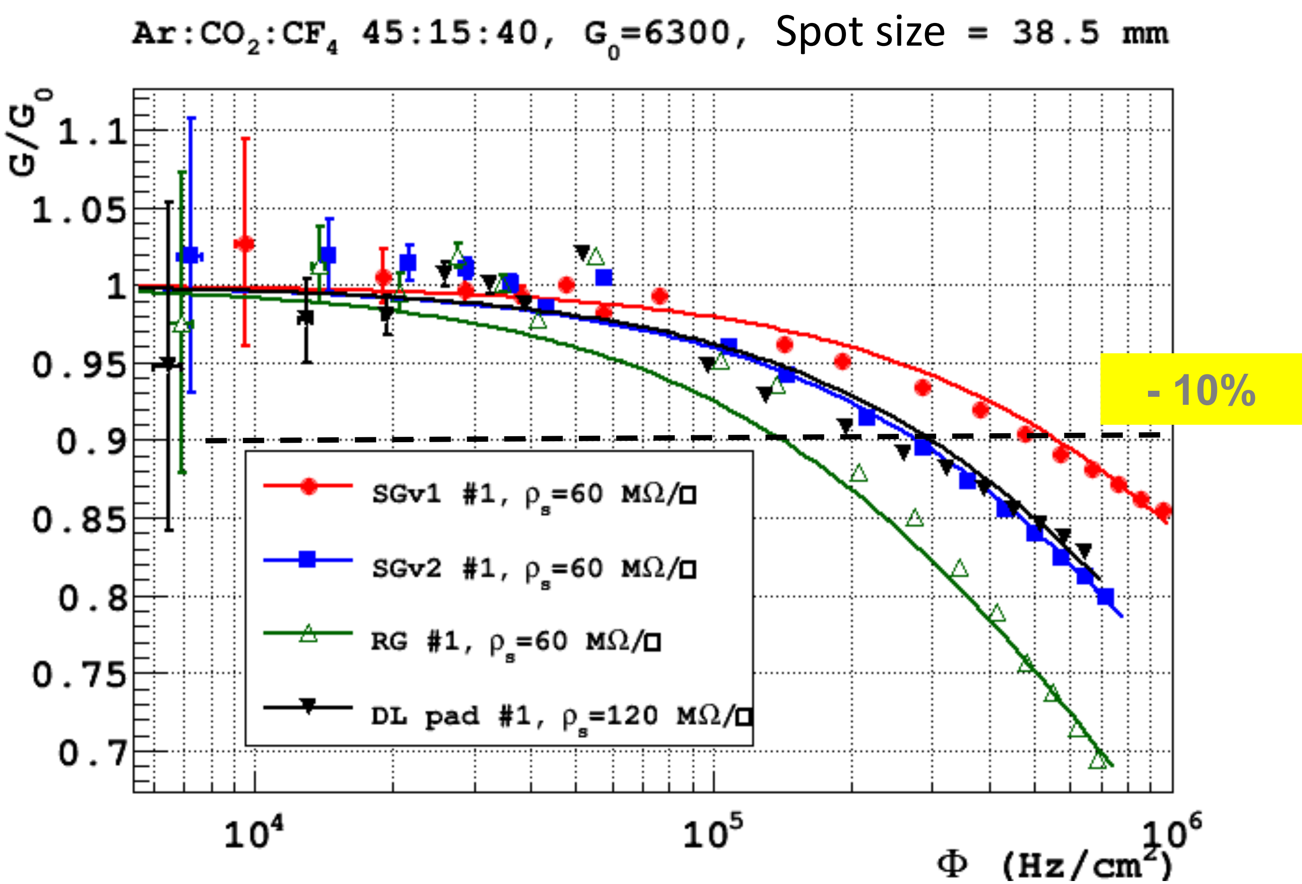
HR layouts performance: efficiency



As expected, the **RG & DL prototypes** reach full tracking efficiency ~ **98%** (NO DEAD AREA in the amplification stage is present).

The **SG1 & SG2** show lower efficiency (**74% - 92%**) BUT higher than their geometrical acceptance (**66% and 90% respectively**), thanks to the **efficient electron collection mechanism** of the combined drift/amplification electric field, **reducing the effective dead zone**.

Gain drop measurement w/5.9 X-ray



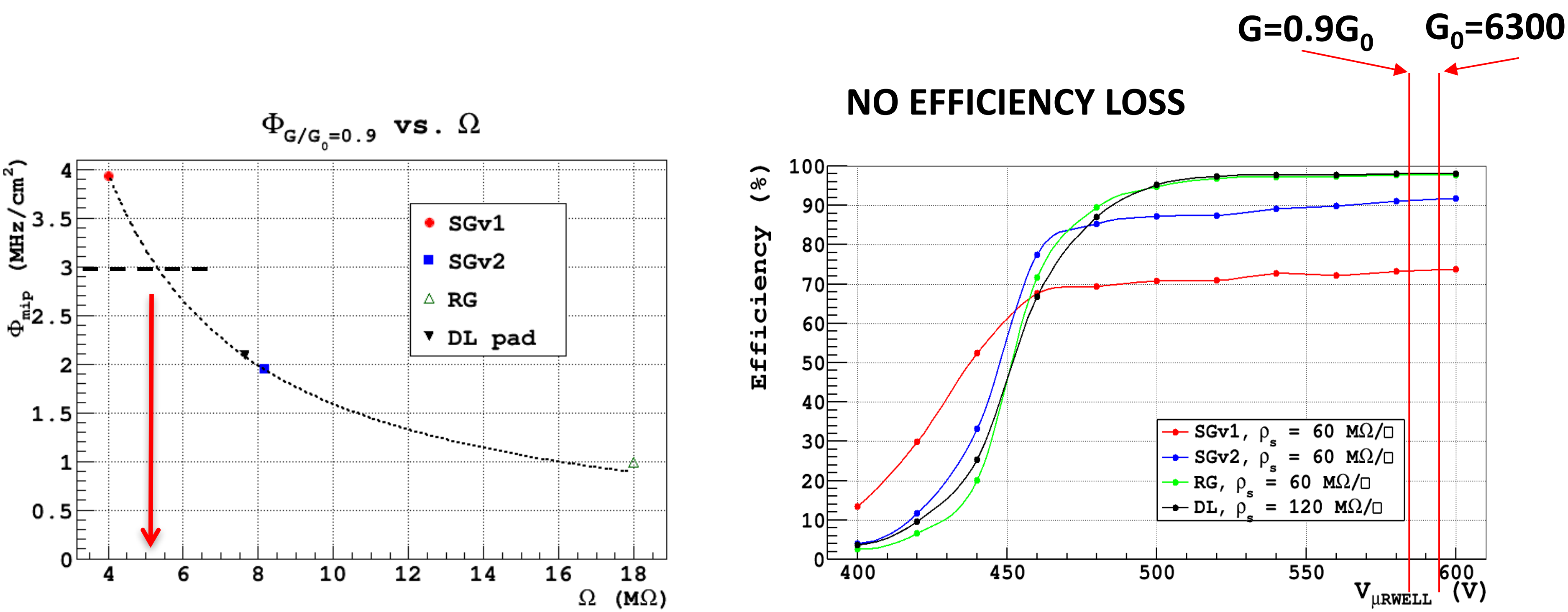
The **gain drop** is due to the **Ohmic effect** on the resistive layer: **charges collected on the DLC drift** towards the **ground** facing an **effective resistance Ω**, depending on the **evacuation scheme geometry and DLC surface resistivity.**

Ω is computed by the **parameter p_0** coming from the **fit of the Gain curve.**

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

where $\mathbf{p_0 \propto \Omega}$ **(effective resistance)**

Gain drop vs efficiency



The **primary ionization of 5.9 keV is ~7 times larger than the one created by a m.i.p.** In order to stand a **3 MHz/cm² m.i.p. fluence, accepting a 10% gain drop,** the **effective resistance Ω must be <3 MΩ.**

It must be stressed that **10% drop of G_0=6300** allows **still to operate the detector at full efficiency**.

Time performance

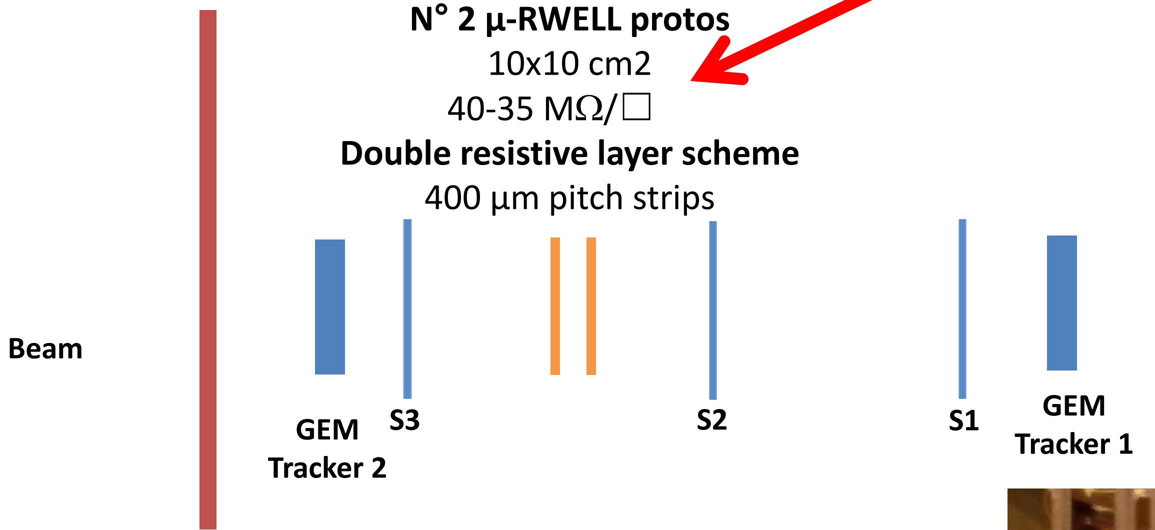
H8 Beam Area (18th Oct. – 9th Nov 2016)

Muon/Pion beam: 150 GeV/c

3 μ-RWELL prototypes:

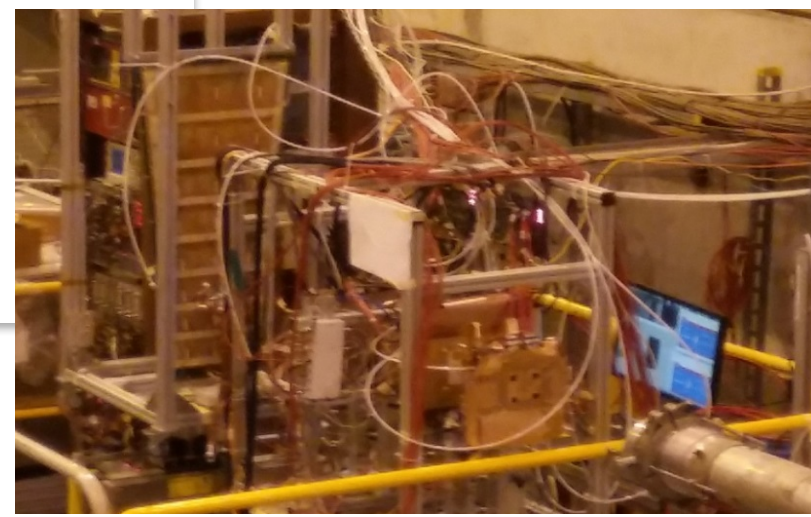
- **40-35-70 MΩ /□**
- **VFAT (digital FEE)**
- **$Ar/CO_2/CF_4 = 45/15/40$**

N° 2 μ-RWELL protos
10x10 cm2
40-35 MΩ/□
Double resistive layer scheme
400 μm pitch strips



Trigger=S1+S2+S3

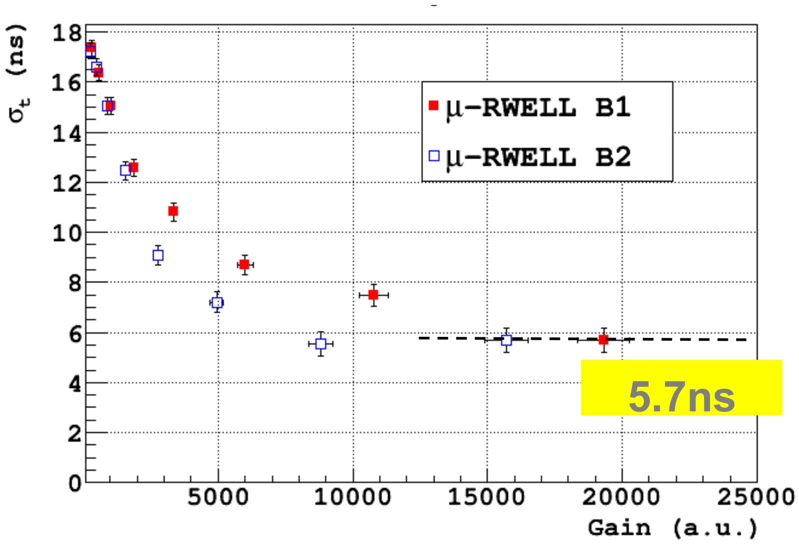
N° 1 μ-RWELL proto
100x50 cm2
70 MΩ/□
Single resistive layer scheme
800 μm pitch strips

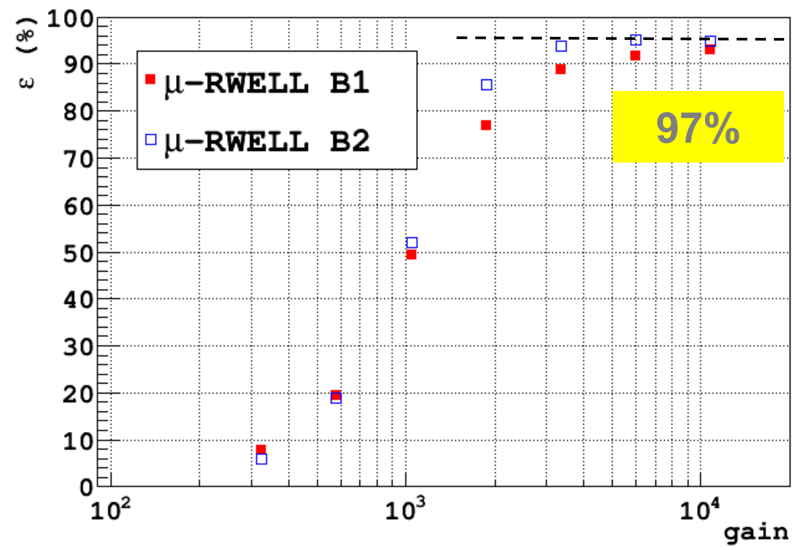


GOAL: time resolution measurement (never done before)

Time Performance

Ar:CO_2:CF_4 45:15:40 – Strip readout





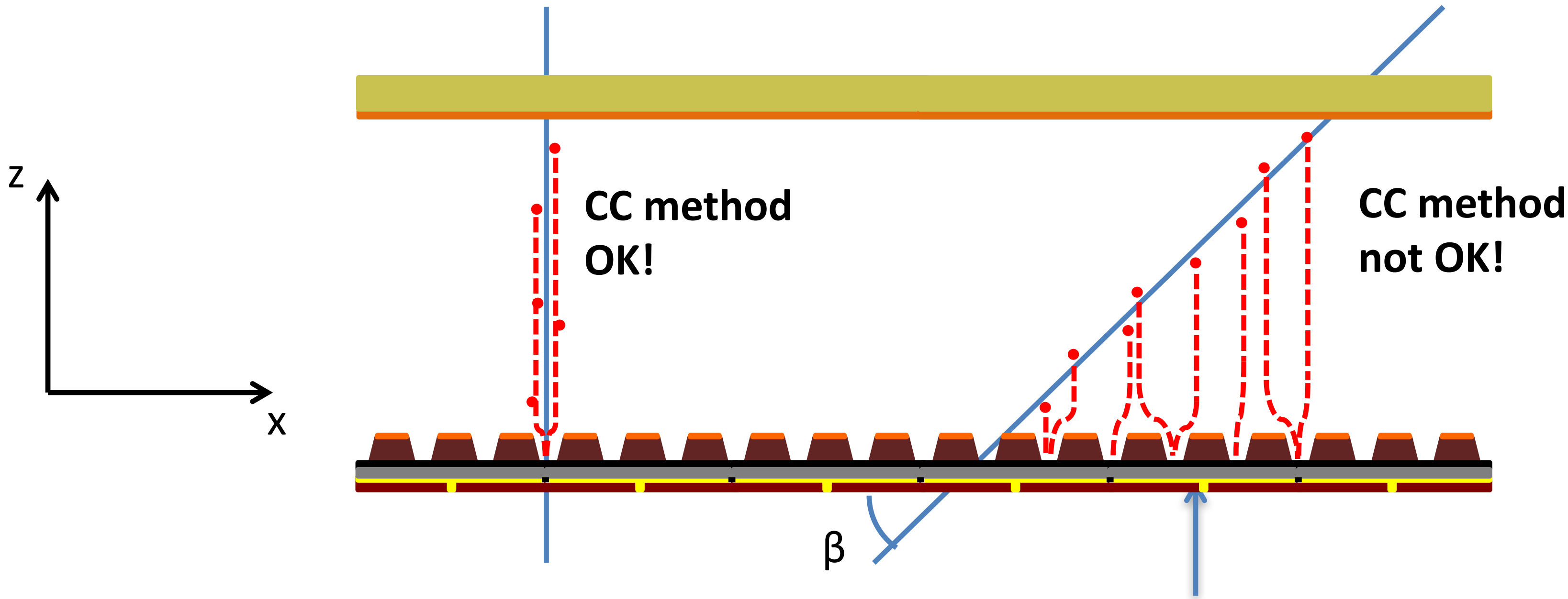
A time resolution of 5.7 ns has been measured with VFAT2. The saturation at 5.7 ns is dominated by the FEE. To be compared with past measurements done by our LHCb with GEM: σ_t = 4.5 ns with VTX chip and CF discriminator

[G. Bencivenni et al., NIM A 494 (2002) 156]

Improving space resolution: the µ-TCP mode

Thanks to the collaboration of R.Farinelli, L.Lavezzi (BESIII-CGEM)

The use of an **analogic front-end** allows to associate a hit to a track using the charge centroid (CC) method. The uncertainty associated to the hit with this algorithm is dependent on the track angle: minimum for orthogonal tracks and larger as the angle increases

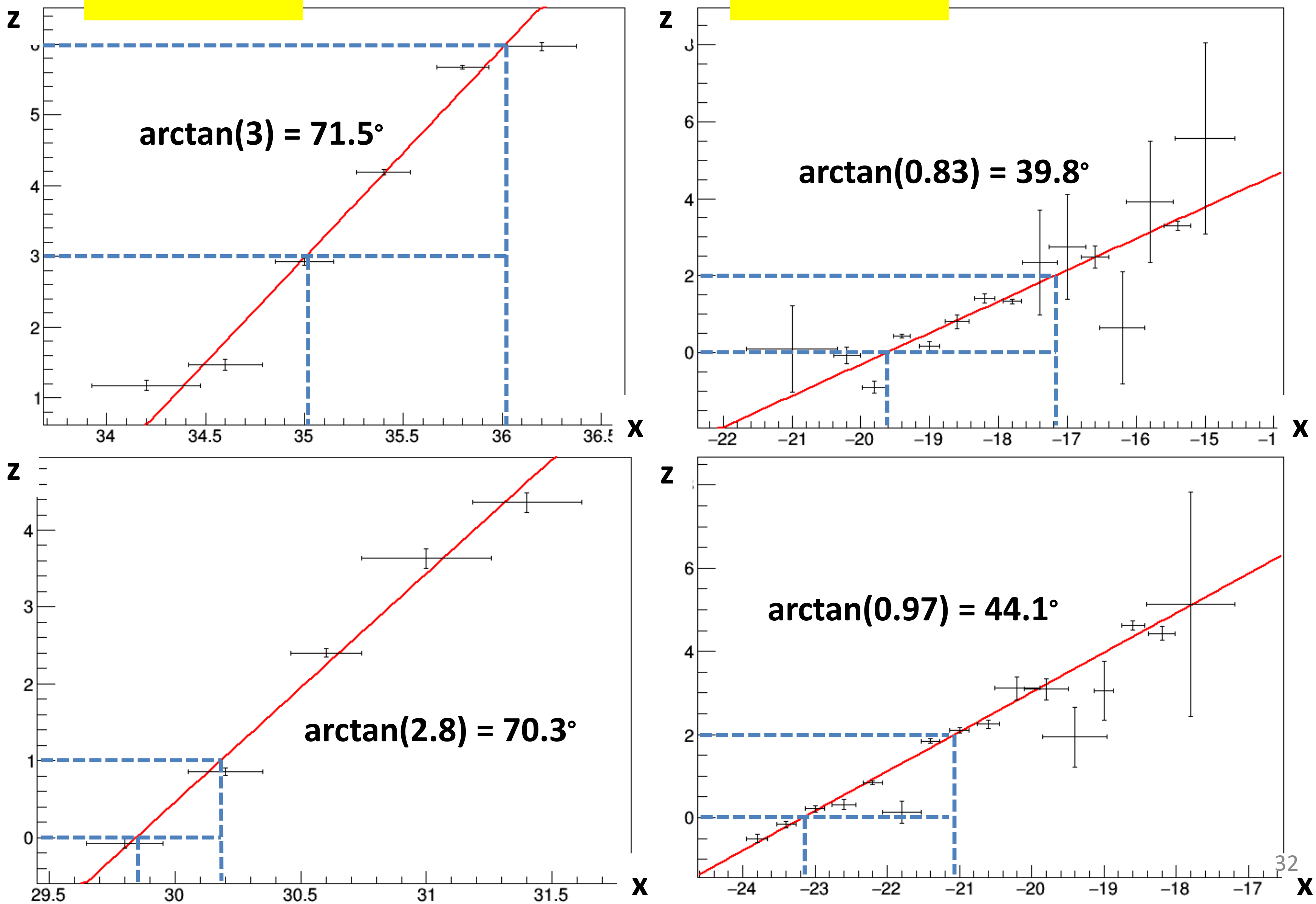


To improve the space resolution the **u-TPC algorithm** combined with the CC method has been implemented

Example of μ-TPC reconstruction

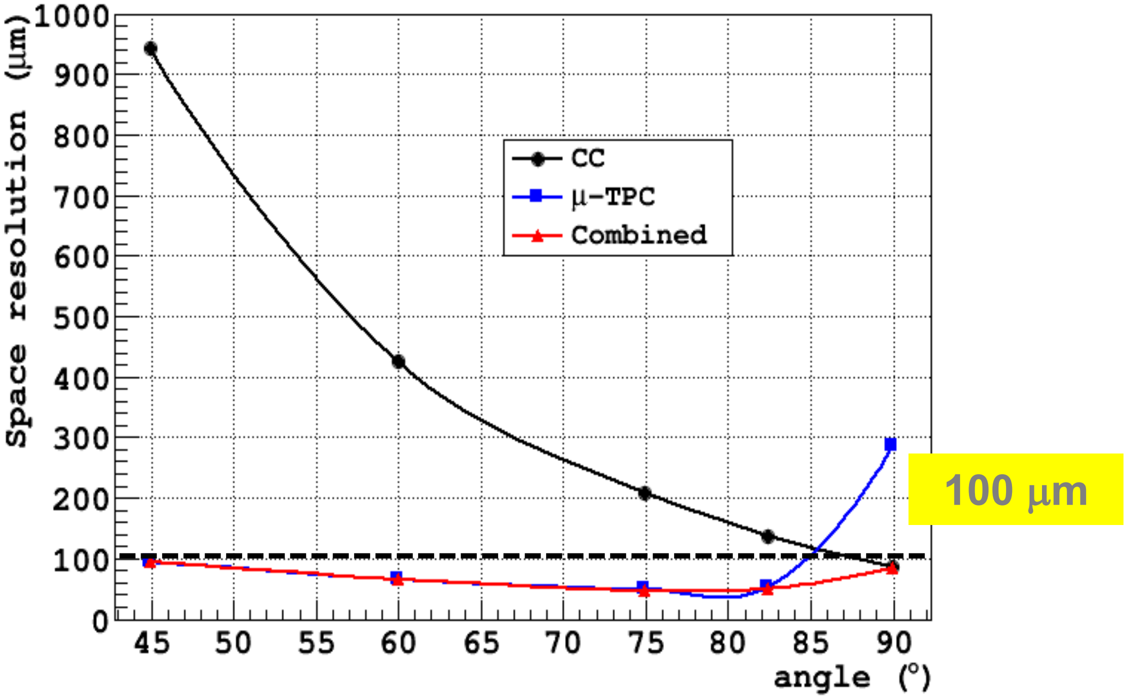
Some examples where the tracks have an angle w.r.t. the readout plane

75° tracks | **45° tracks**



Improving space resolution: the μ-TPC mode

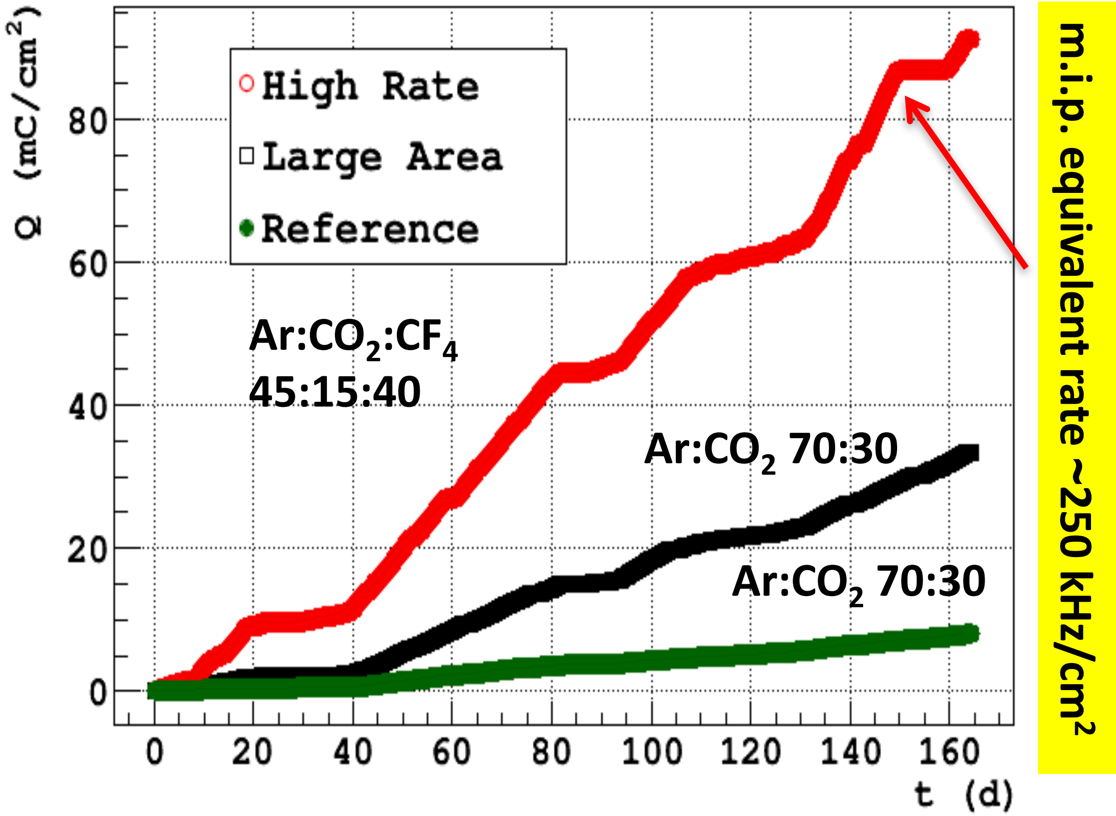
Ar:CO_2:CF_4 45:15:40 – Strip readout



The **combination of the CC and the μ-TPC mode** with E_d= 1 kV/cm
The **spatial resolution is flattened for a wide range of angles**.

$$x_{merge} = \frac{x_{cc} \cdot w_{cc} + x_{tpc} \cdot w_{tpc}}{w_{cc} + w_{tpc}} \qquad w_{cc} \propto (clsize)^{-2} \quad w_{\mu-TPC} \propto (clsize)^{2}$$

Ageing test at GIF^{++} (CERN)



The ageing effects on DLC is under study at the GIF++ by irradiating different µ-RWELL prototypes operated at a gain of 4000 .

Up to now on the most irradiated detector (~250 kHz/cm^2 m.ip. equivalent) a charge of about 90 mC/cm^2 has been integrated

In collaboration with CMS-Muon:
L. Borgonovi, P. Giacomelli, A. Ranieri

Summary

Recent R&D on a novel MPGD architectures lead to the introduction of the μ-RWELL in the MPGDs world.

The μ-RWELL is a very promising technology showing important advantages for large area applications in harsh environment: the detector is compact, simple to assemble and intrinsically spark-protected

- **gas gain > 10^4**
- **rate capability > 1 MHz/cm^2 (HR version)**
- **space resolution < 100μm (over a large incidence angle of tracks)**
- **time resolution ~ 5.7 ns**

R&D/engineering in progress:

- **Low rate (<100kHz/cm^2) :**
  - **small and large area prototypes built and extensively tested**
  - **<u>Technological Transfer to industry is ongoing with good achievements</u>**
- **High rate (>1 MHz/cm^2):**
  - **R&D well advanced, completed by end of 2018**
  - **prototypes show very good performance**

Thanks for your attention

Reference for the μ-RWELL detector:

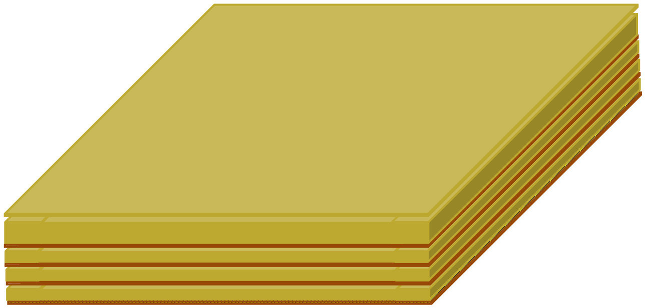
Low rate version:

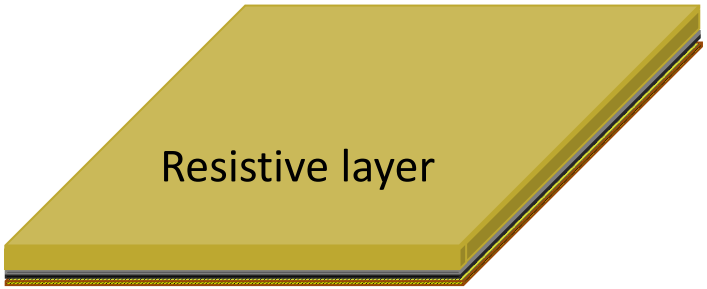
- G. Bencivenni et al., "The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD", 2015_JINST_10_P02008
- G.Bencivenni et al., "The Resistive-WELL detector: a compact spark-protected single", PoS (BORMIO2015) 024
- G. Bencivenni et al., "The μ-RWELL: a compact, spark protected, single amplification-stage MPGD", NIM A 824 (2016) 565
- G.Bencivenni et al., "Advances on micro-RWELL gaseous detector", PoS (BORMIO2017) 002
- G.Bencivenni et al., "The μ-RWELL detector", 2017_JINST_114P_0517
- G.Bencivenni et al., "Performance of u-RWELL detector *vs* resistivity of the resistive stage", NIM A 886 (2018) 36

High rate version:

- G.Bencivenni et al., "Recent results of u-RWELL detector", PoS(MPGD2017)019
- G.Bencivenni et al., "The u-RWELL technology: status and perspective", to be submitted to Pos

backup





GEM μ-RWELL MicroMegas

The μ-RWELL *vs* single-GEM

μ-RWELL is expected to exhibit a gas gain larger than a single-GEM

Single-GEM

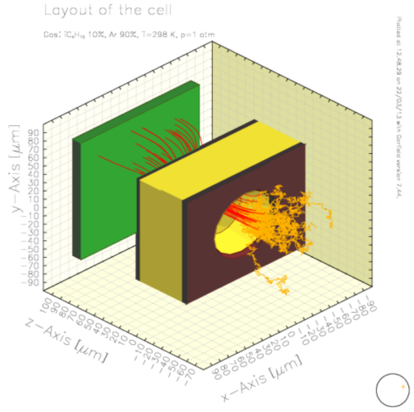
- **~50% of the electron charge** produced into the hole **contributes to the signal,** the rest of the electron charge is collected by the **bottom side of the GEM foil**
- the signal is **mainly due to the electron motion,** the **ion component is largely shielded by the GEM foil itself**

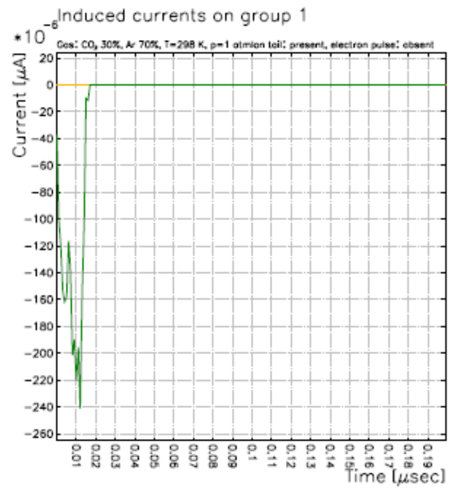
μ-RWELL

- **100% electron charge produced into the amplification channel is promptly collected on the resistive layer**
- the **ionic component, apart ballistic effects, contributes to the formation of the signal**
- further **increase of the gain achieved thanks to the resistive electrode which, quenching the discharges, allows to reach higher amplification field** inside the channel

The µ-RWELL vs GEM *(Garfield)*

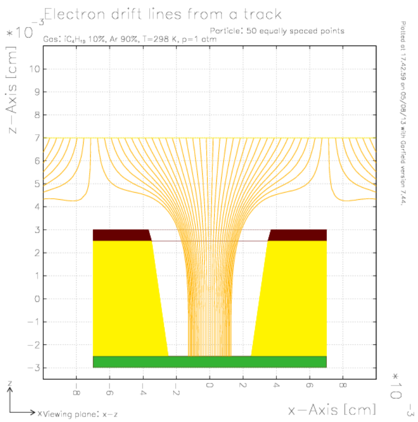
GEM – Ar:CO2 70:30 gas mixture

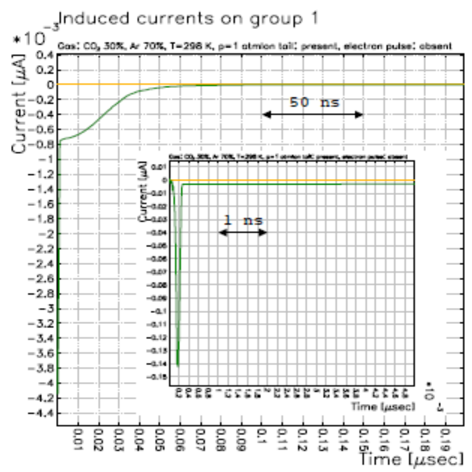




Signal from a single ionization electron in a GEM.

The **duration of the signal, about 20 ns**, depends on the **induction gap thickness, drift velocity and electric field in the gap.**





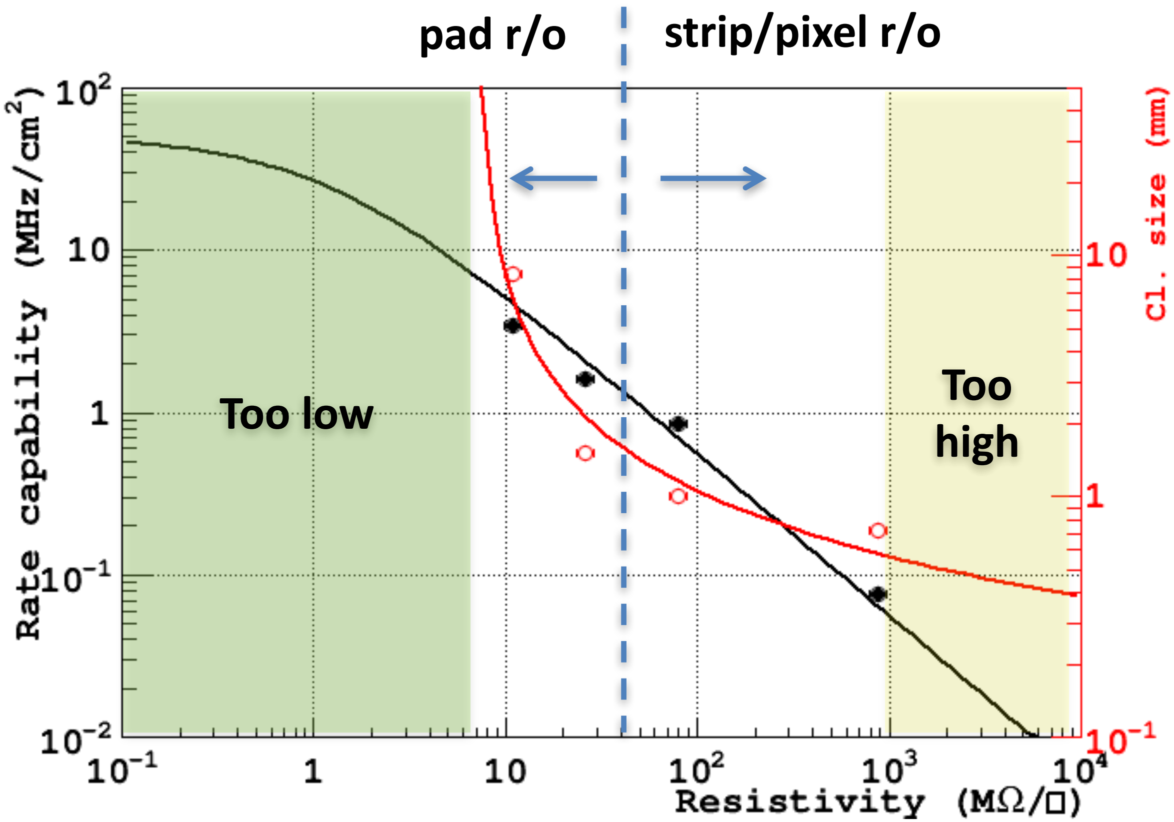
µ-RWELL – Ar:CO2 70:30 gas mixture

Signal from a single ionization electron in a µ-RWELL.

The absence of the induction gap is responsible for the **fast initial spike, about 200 ps**, induced by the **motion and fast collection of the electrons** then **followed by a ~50 ns ion tail.**

More similar to a MM !!!

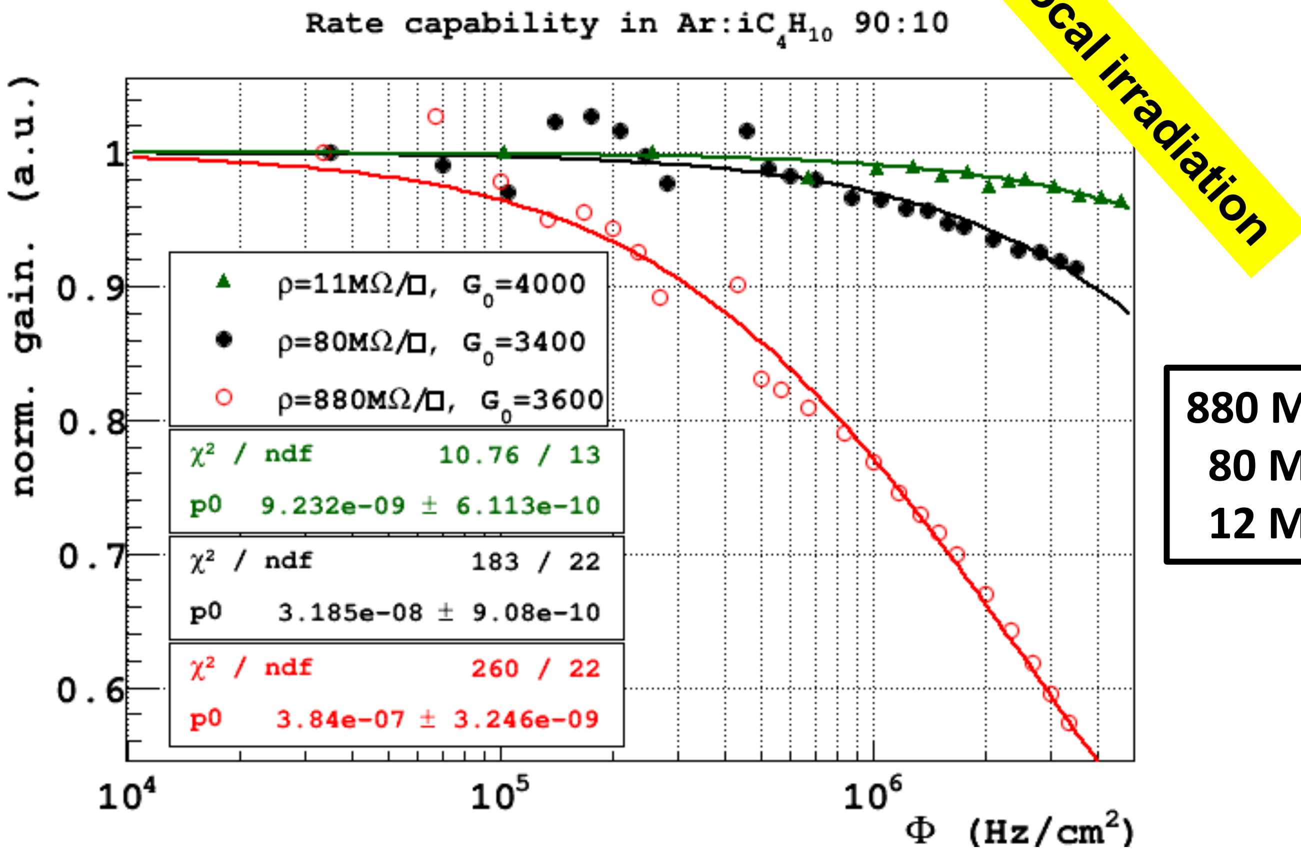
Combining the information



Qualitatively: low resistivity → pad r/out & higher rate

high resistivity → strip/pixel r/out & lower rate

Test with X-rays (single-resistive layer)



The **gain decrease** is correlated with the **voltage drop** due to the **resistive layer: larger the resistivity higher gain drop**

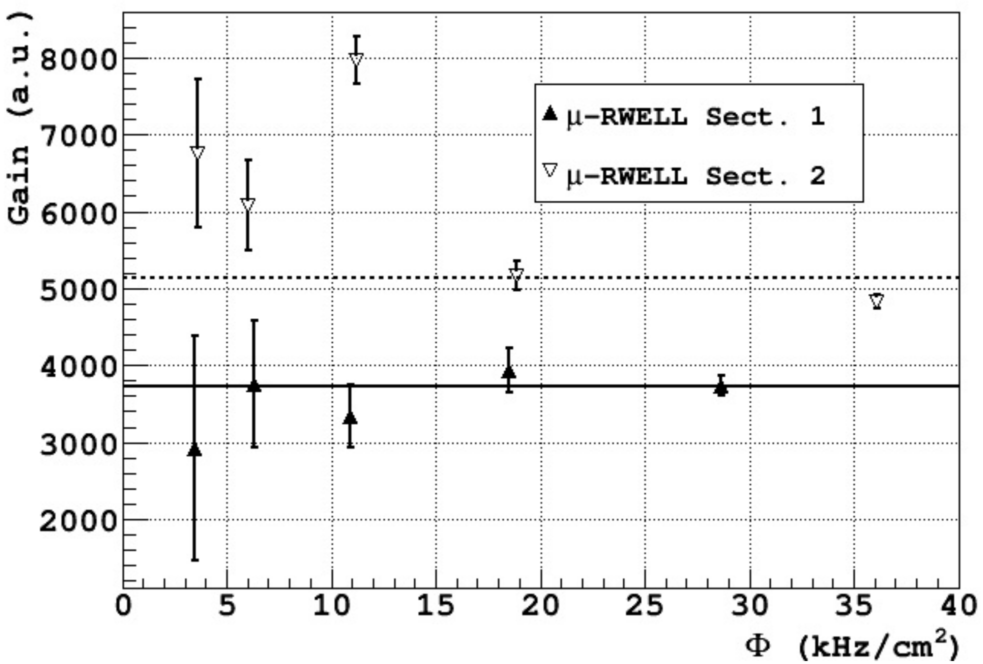
local irradiation ≠ global irradiation ***(to be compared w/slide # 27)***

Rate capability of SRL layout

A **rate capability measurement of a large single-resistive layer detector (1,2x0,5 m^2 – 70 MΩ/□)** has been performed with:

- a local irradiation with a **pion beam @** H8-SPS CERN beam area (**spot area ~3x3 cm^2)**
  → The detector has been **operated up to 35 kHz/cm^2**
- a global irradiation @ GIF++ (see slide …) up to **140 kHz/cm2** without appreciable gain loss (gain ~ 4000)

H8-SPS CERN



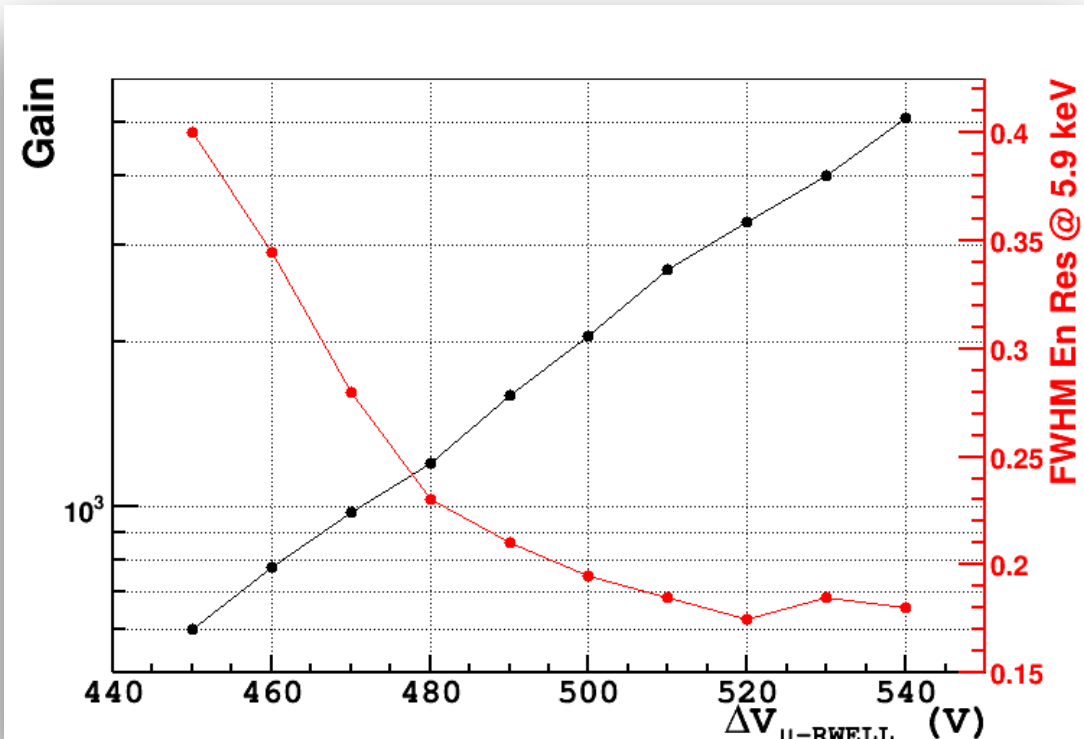
In collaboration with CMS-Muon:

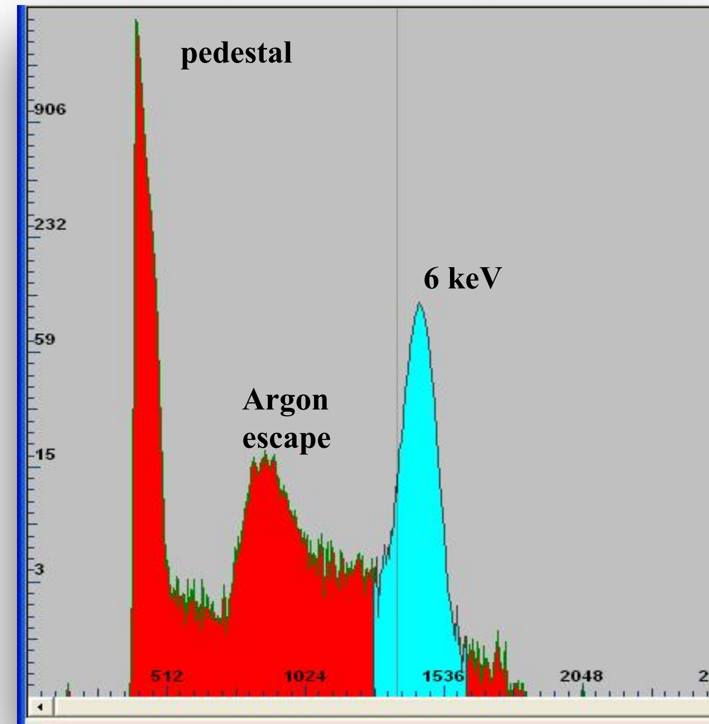
L. Benussi[1], L. Borgonovi[4],
P. Giacomelli[4], L.Borgonovo[4], A. Ranieri[5],
M. Ressegotti[6], I. Vai[6], V. Valentino[5]

1. **LNF- INFN**
2. **INFN Sezione di Bologna**
3. **INFN Sezione di Bari**
4. **INFN Sezione di Pavia**

μ-RWELL: Energy Resolution

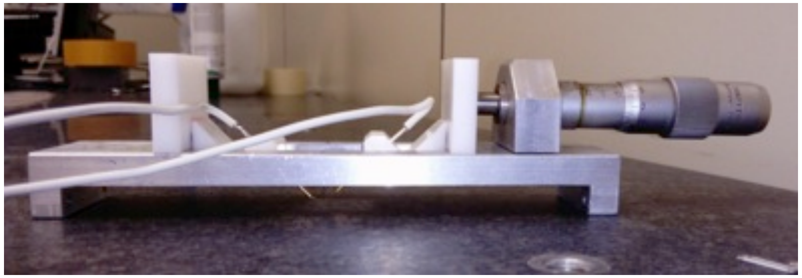
The prototype of μ-RWELL (100 MΩ/□) has been tested with X-rays tube (6keV) (Ar/CO2=70/30) & the signal has been readout vith an ORTEC amplifier

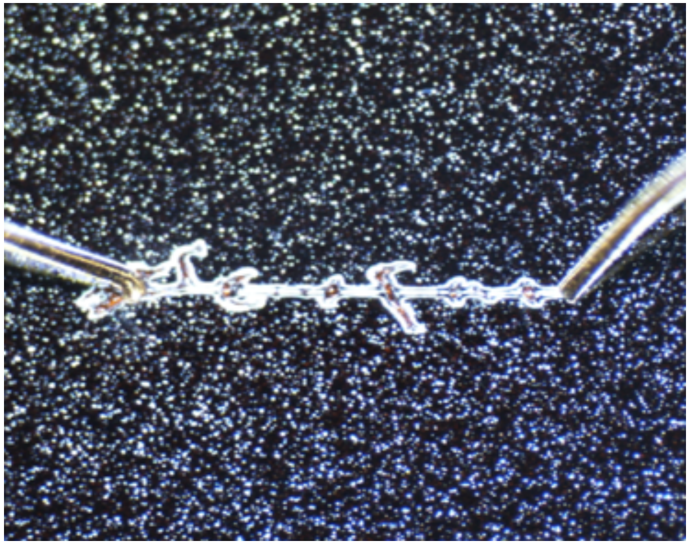


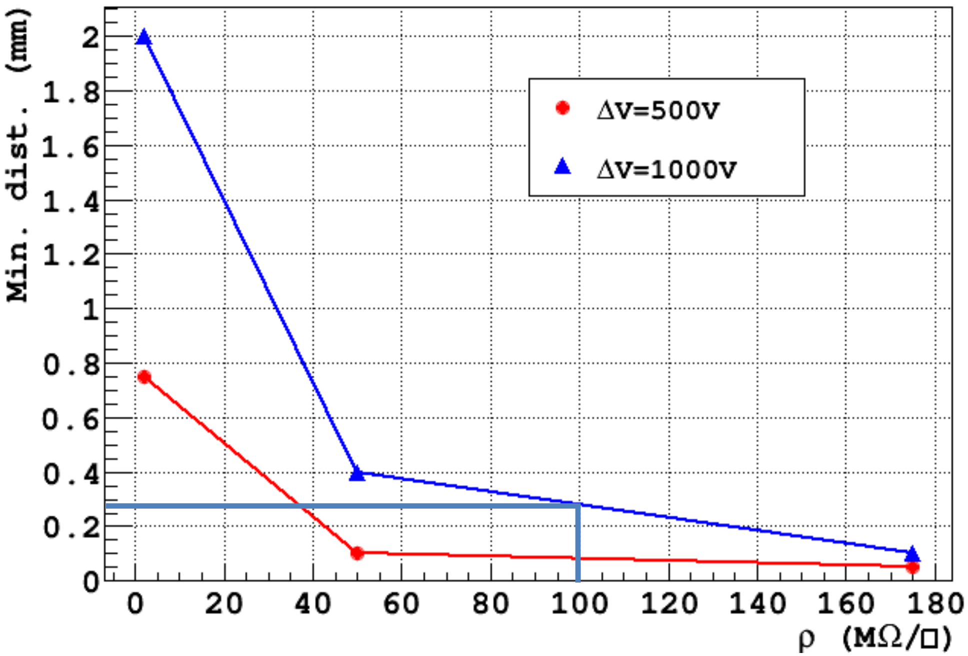


Silver Grid: optimization

In order **to reduce the dead area,** we have studied the **Distance Of Closest Approach** (***without discharges***) between **two tips connected to an HV power supply**. We recorded the **minimum distance before a discharge on the DLC** occurred *vs* the **ΔV supplied** for foils with different surface resistivity.







Improving space resolution: the μ-TCP mode

Introduced for **MicroMegas** by **T. Alexopoulos** et al. [NIM **A 617** (2010) 161] it suggests a way to overcome the **poor position reconstruction of the inclined tracks.**

Each **hit is projected inside the conversion gap**, where the ***x* position is given by each strip and the $z = v_d t$**

The drift velocity is provided by the Magboltz libraries.

The **drift time is obtained with a fit of the charge sampled every 25 ns (APV25)** from each FEE channel associated to the strip.

For each event we obtain a set of projected hits that once fitted provide a track segment