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Istituto Nazionale di Fisica Nucleare

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A Muon detector based on the μ-RWELL technology

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EuroCirCol EASITrain ARIES IEEE CSC UNIVERSITY OF TWENTE. Nikhef

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For evident reasons of price, gas detectors are the obvious choice for equipping these extremely large surfaces.

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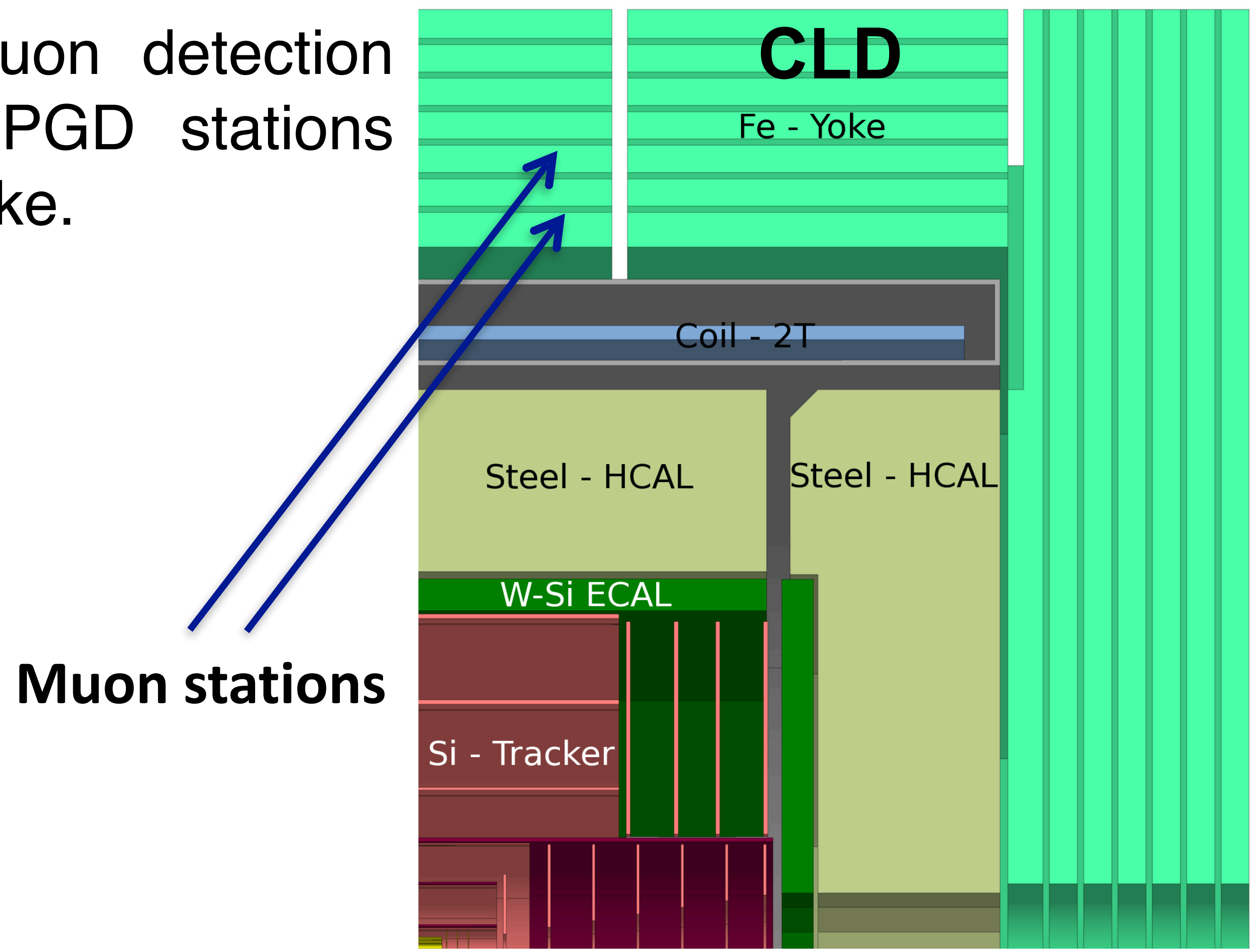

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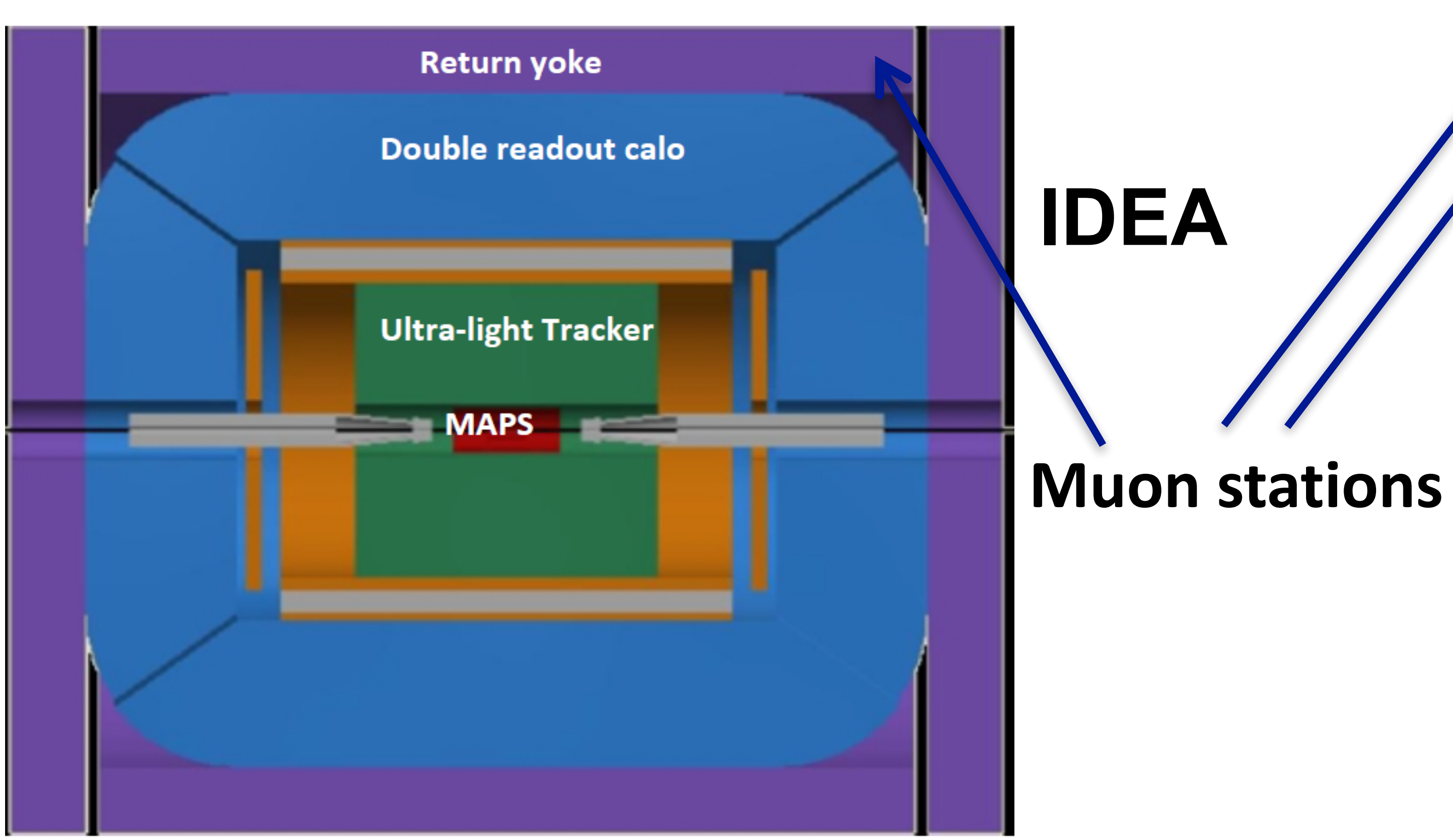

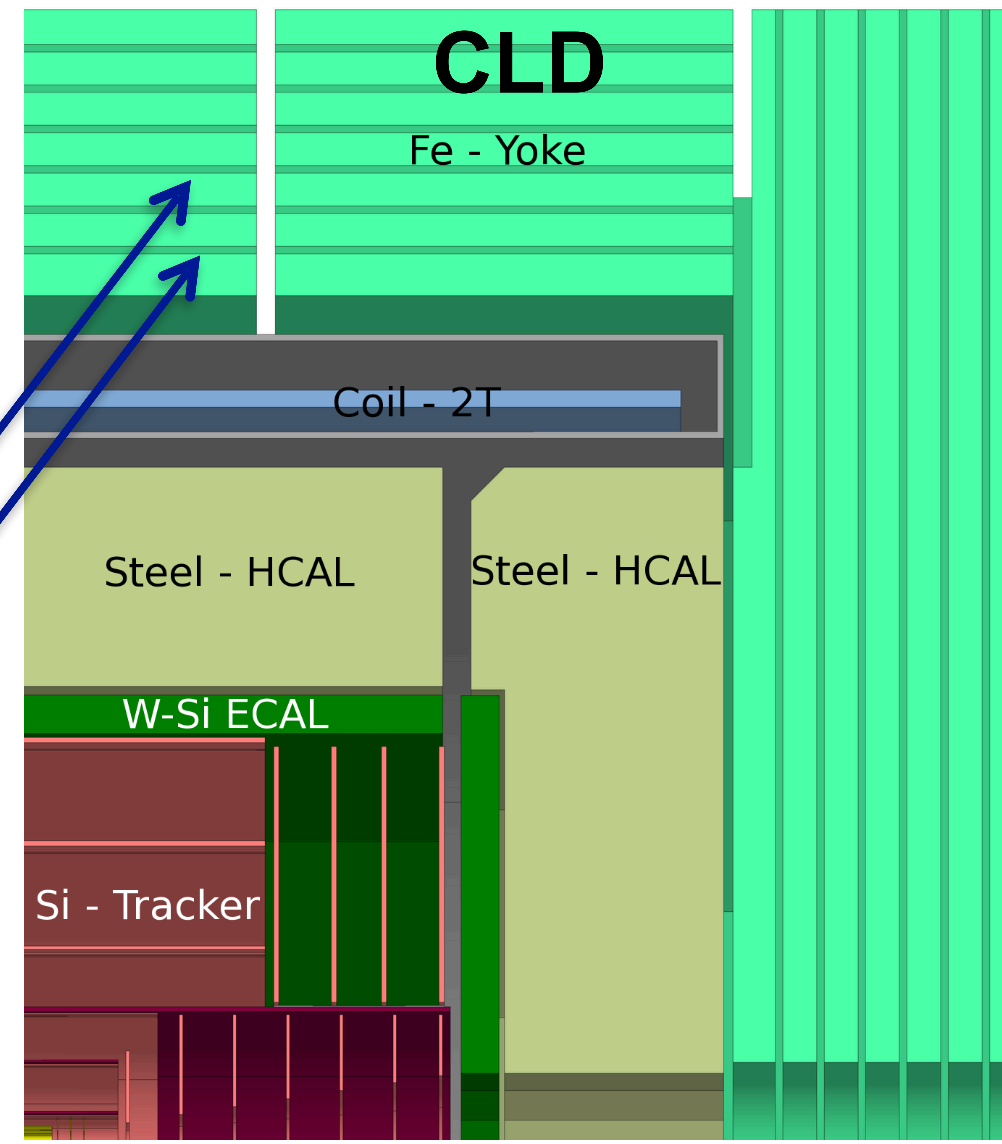

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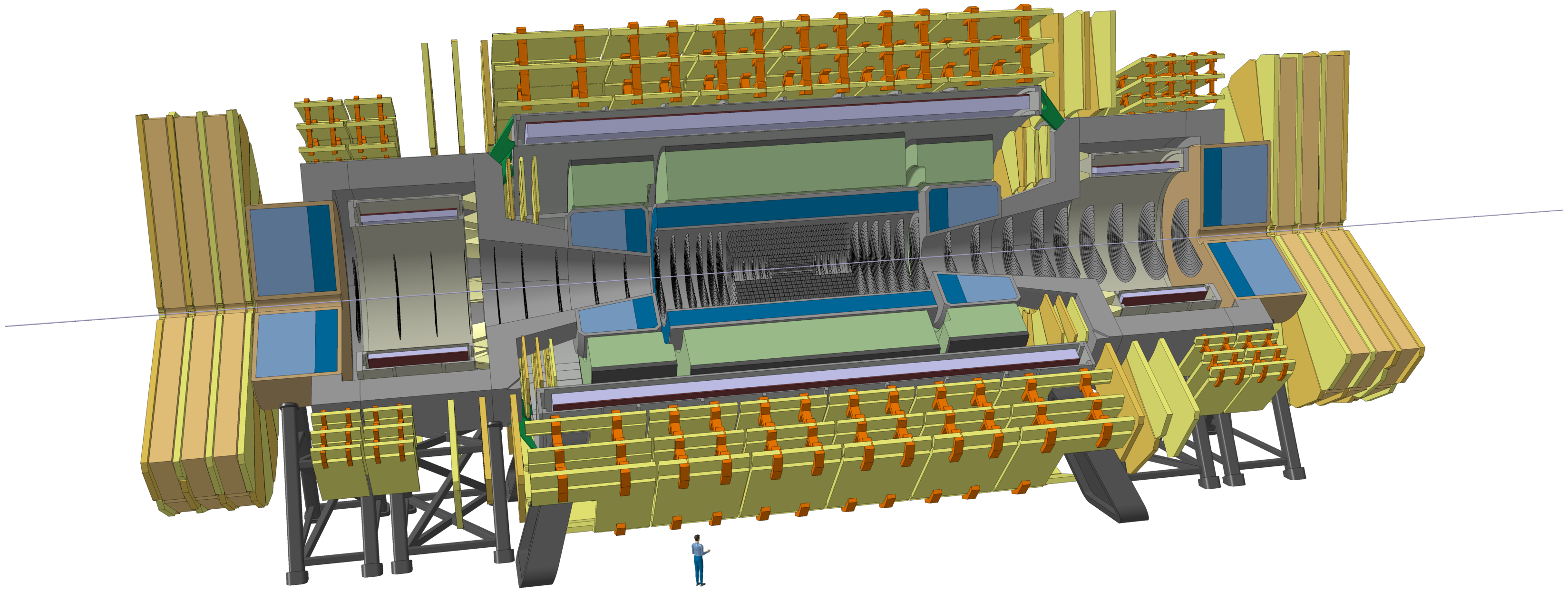

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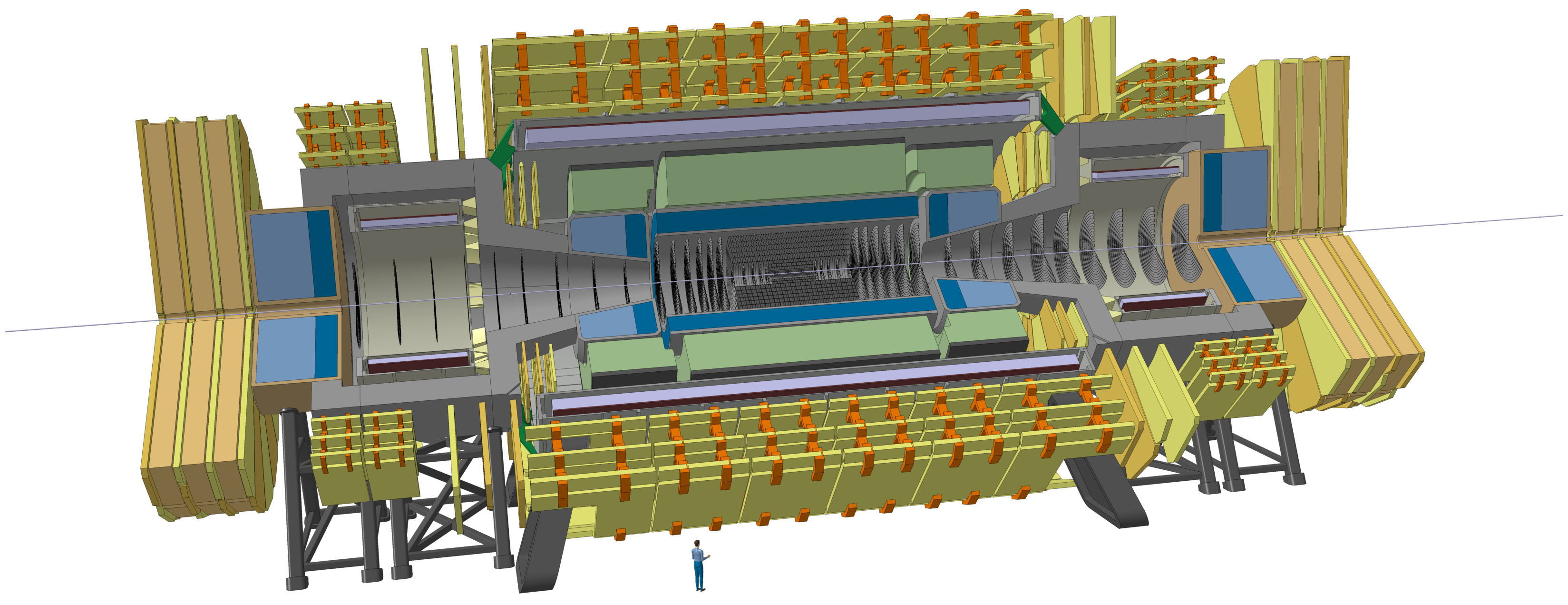

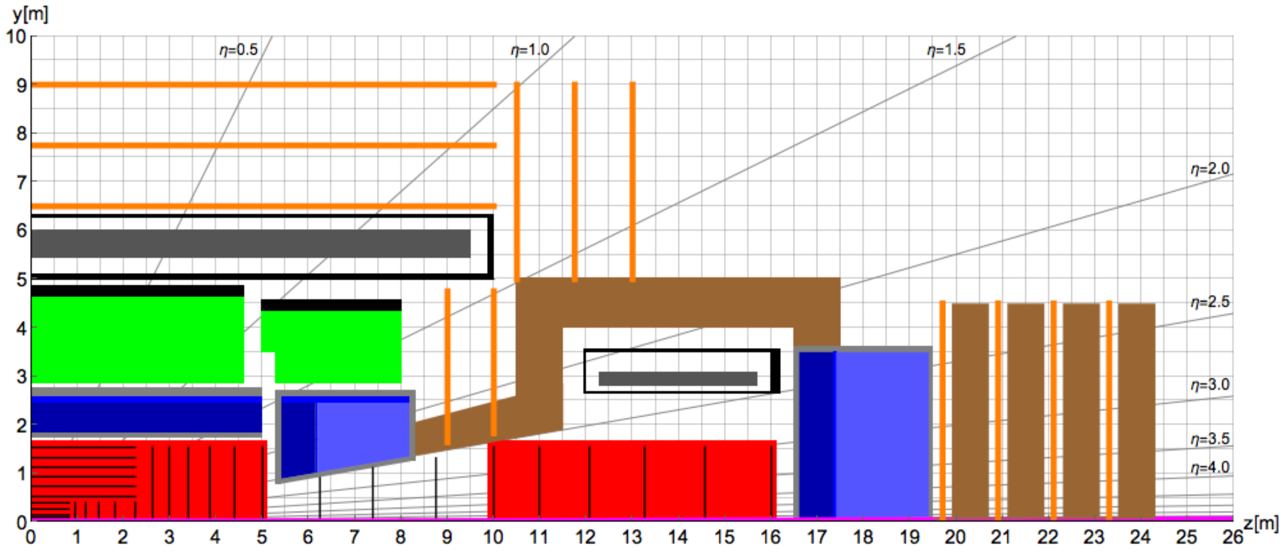

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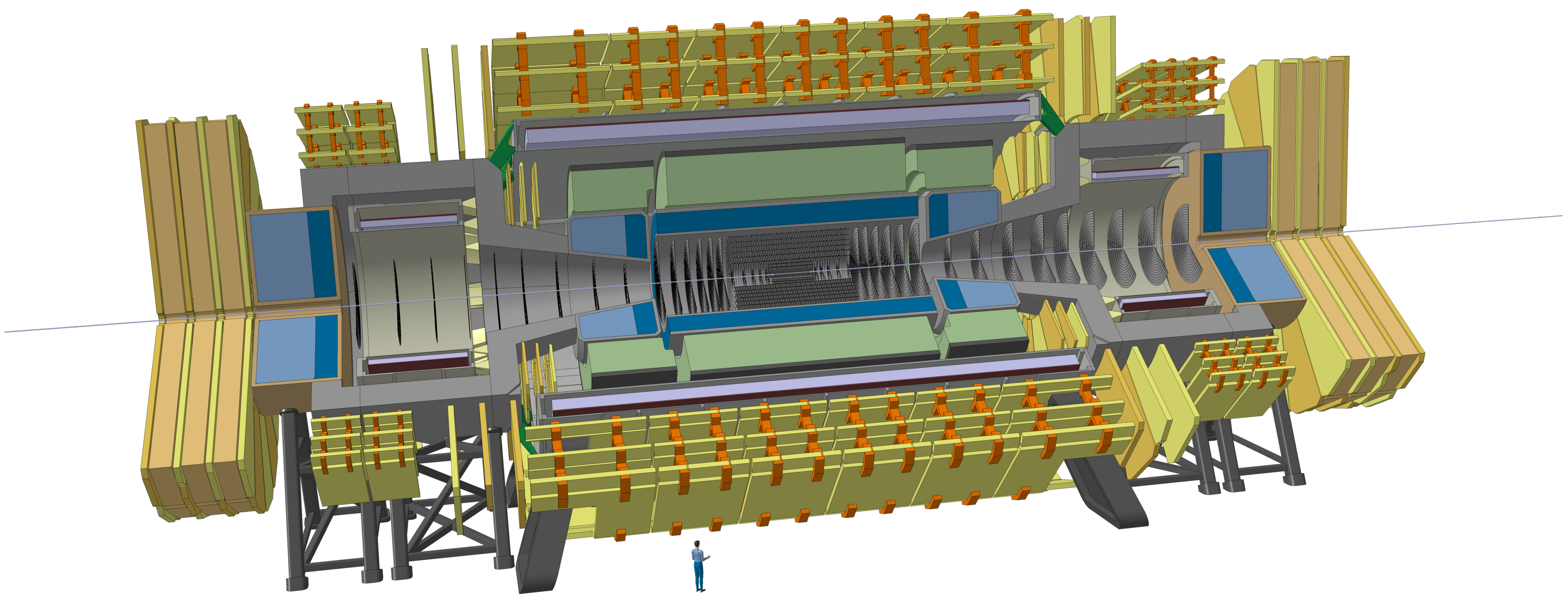

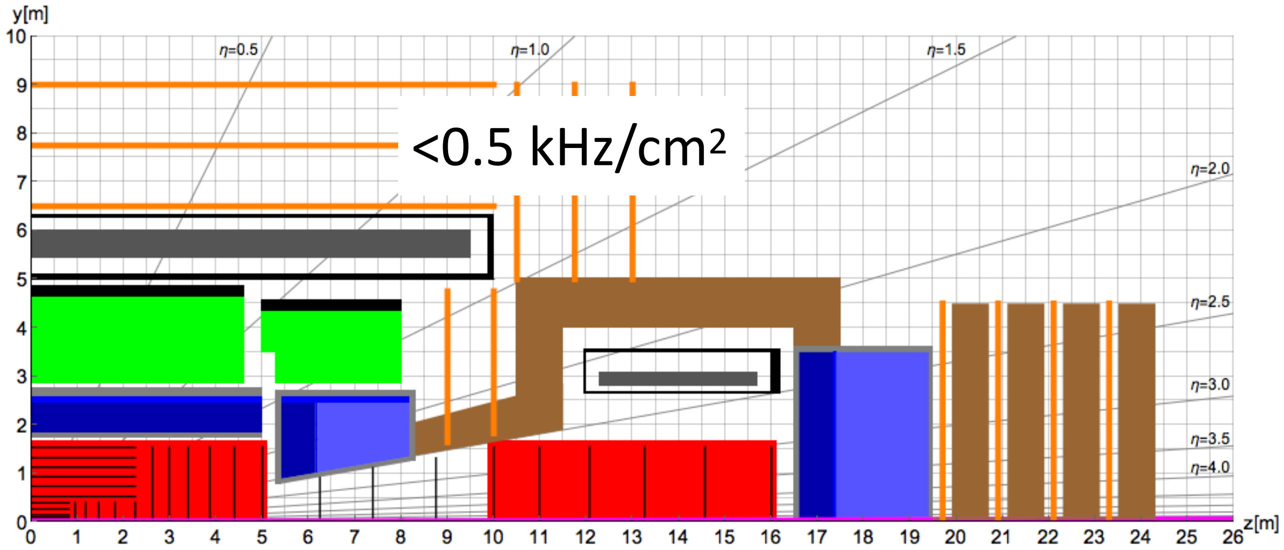

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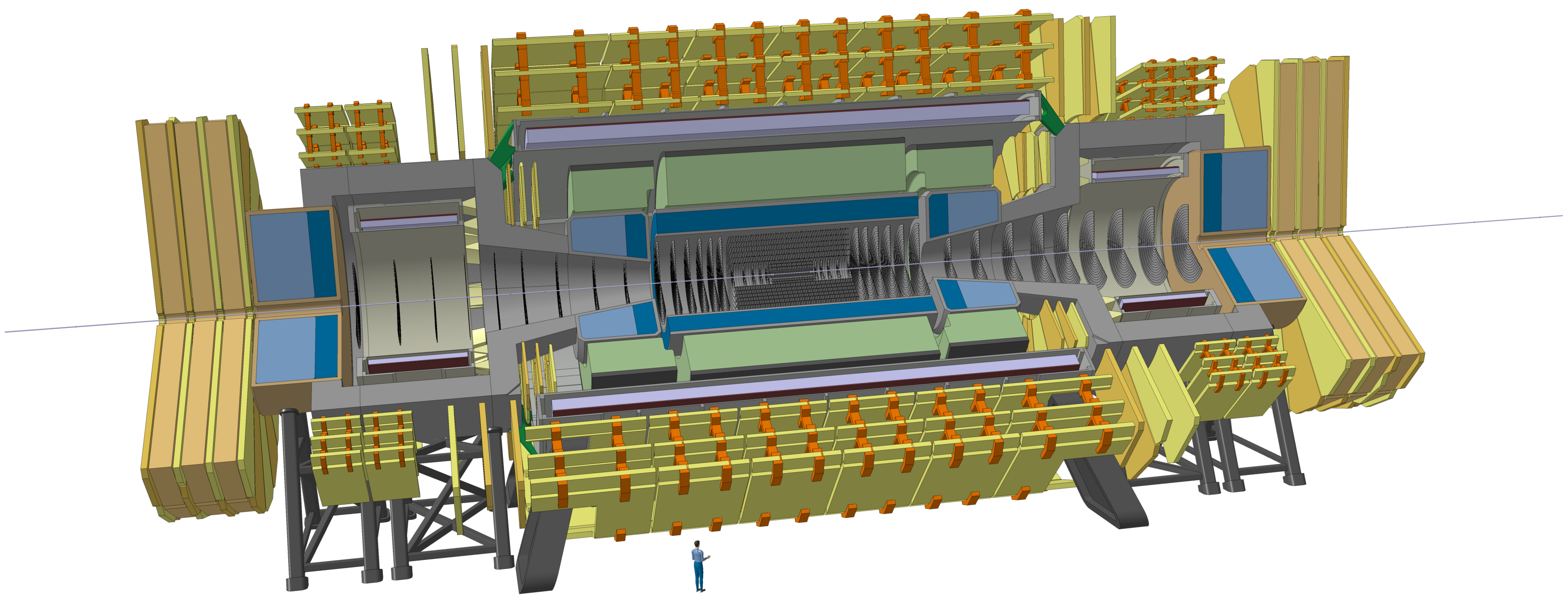

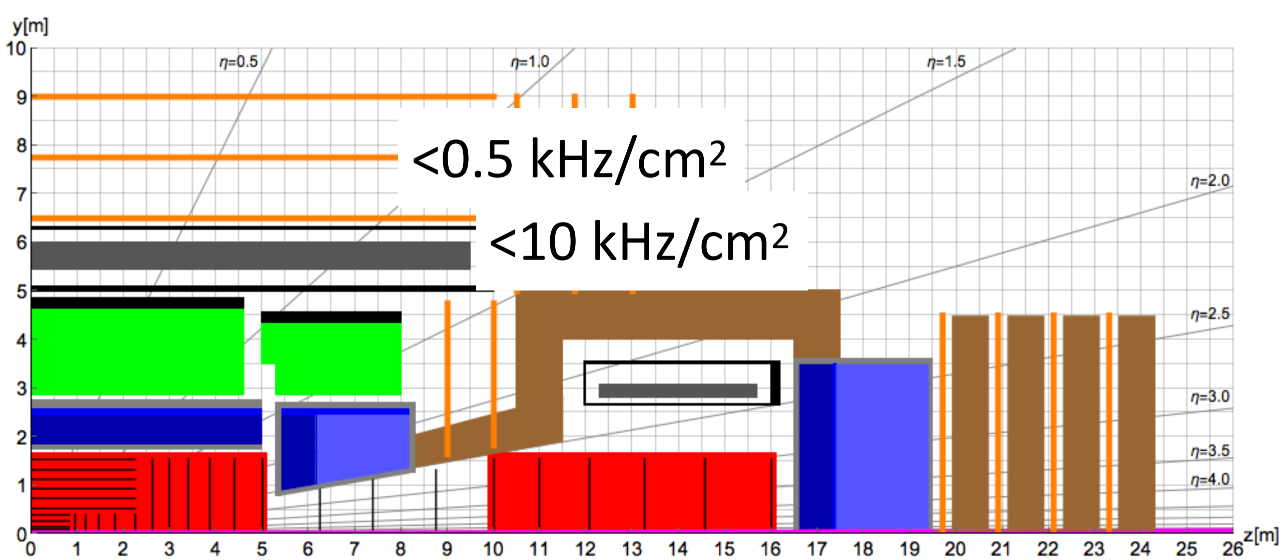

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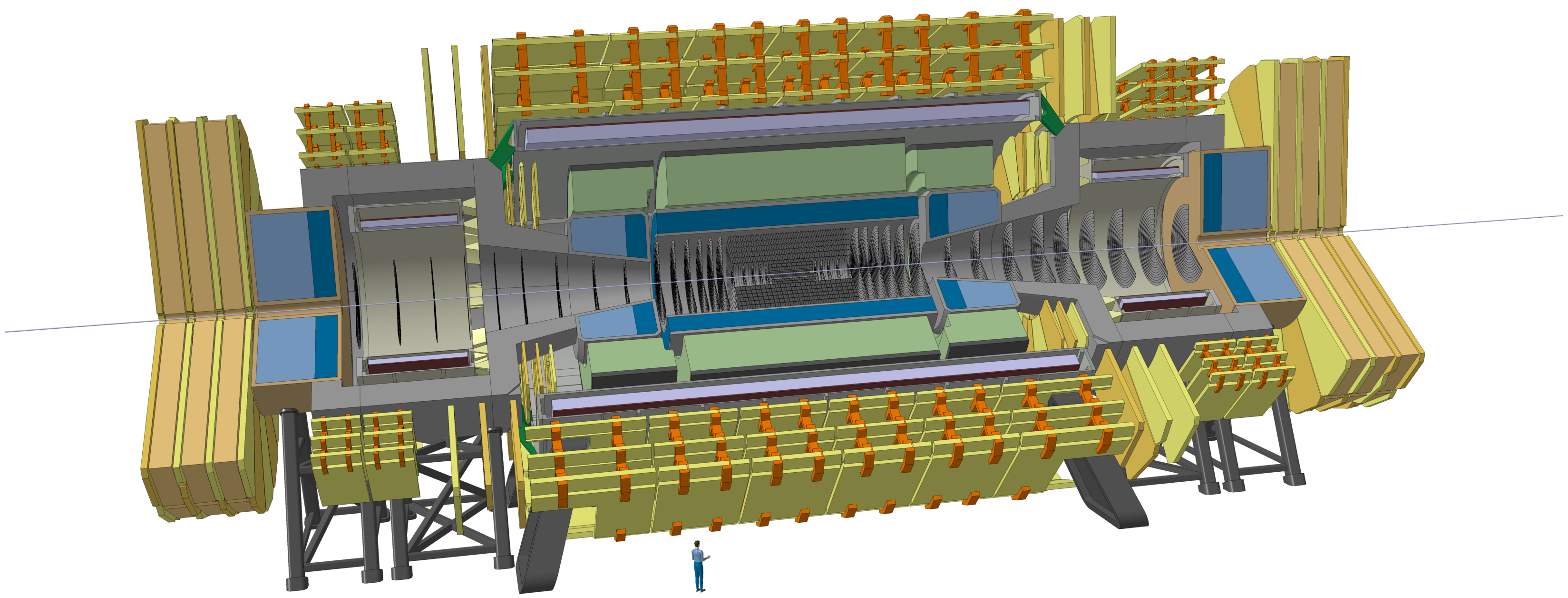

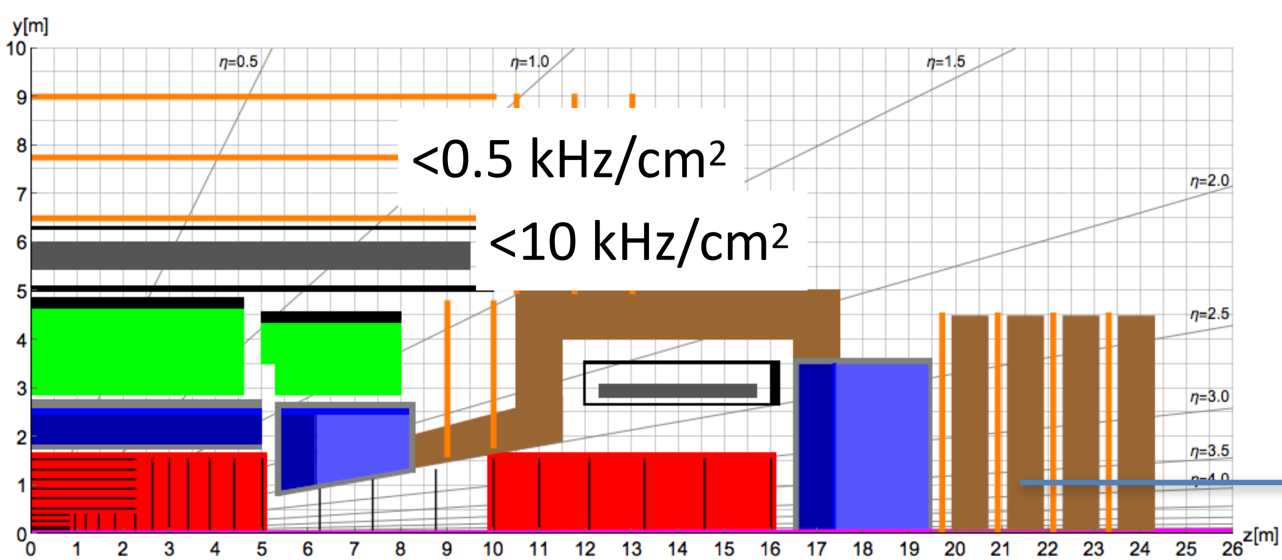

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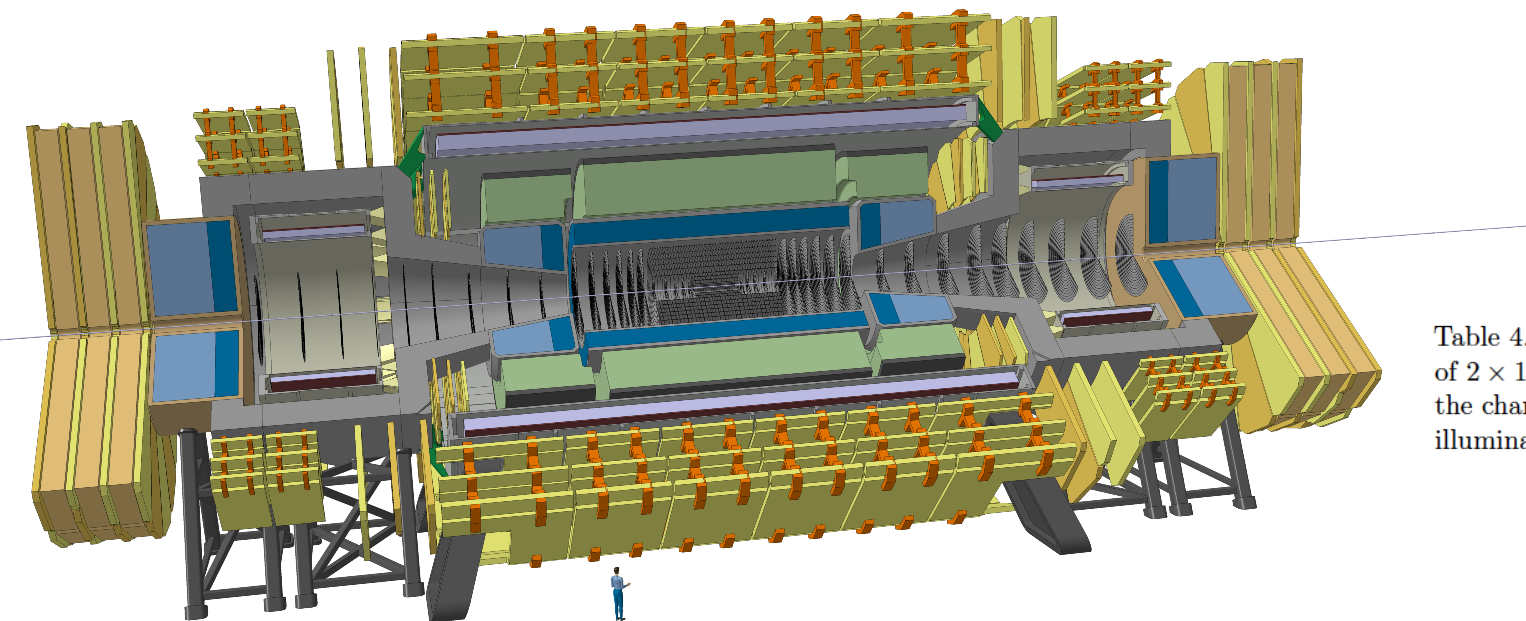

ATLAS muon system HL-LHC rates (kHz/cm^2):

MDTs barrel:	0.28
MDTs endcap:	0.42
RPCs:	0.35
TGCs:	2
Micromegas and sTGCs:	9-10

Table 4.5: Expected rates on the muon detector when operating at an instantaneous luminosity of 2×10^{33} cm^{-2}s^{-1} at a collision energy of 14 TeV. The values are averages, in kHz/cm^2, over the chamber with the minimum illumination, the whole region and the chamber with maximum illumination. The values are extrapolated from measured rates at 8 TeV.

LHCb

Region	Minimum	Average	Maximum
M2R1	162 ± 28	327 ± 60	590 ± 110
M2R2	15.0 ± 2.6	52 ± 8	97 ± 15
M2R3	0.90 ± 0.17	5.4 ± 0.9	13.4 ± 2.0
M2R4	0.12 ± 0.02	0.63 ± 0.10	2.6 ± 0.4
M3R1	39 ± 6	123 ± 18	216 ± 32
M3R2	3.3 ± 0.5	11.9 ± 1.7	29 ± 4
M3R3	0.17 ± 0.02	1.12 ± 0.16	2.9 ± 0.4
M3R4	0.017 ± 0.002	0.12 ± 0.02	0.63 ± 0.09
M4R1	17.5 ± 2.5	52 ± 8	86 ± 13
M4R2	1.58 ± 0.23	5.5 ± 0.8	12.6 ± 1.8
M4R3	0.096 ± 0.014	0.54 ± 0.08	1.37 ± 0.20
M4R4	0.007 ± 0.001	0.056 ± 0.008	0.31 ± 0.04
M5R1	19.7 ± 2.9	54 ± 8	91 ± 13
M5R2	1.58 ± 0.23	4.8 ± 0.7	10.8 ± 1.6
M5R3	0.29 ± 0.04	0.79 ± 0.11	1.69 ± 0.25
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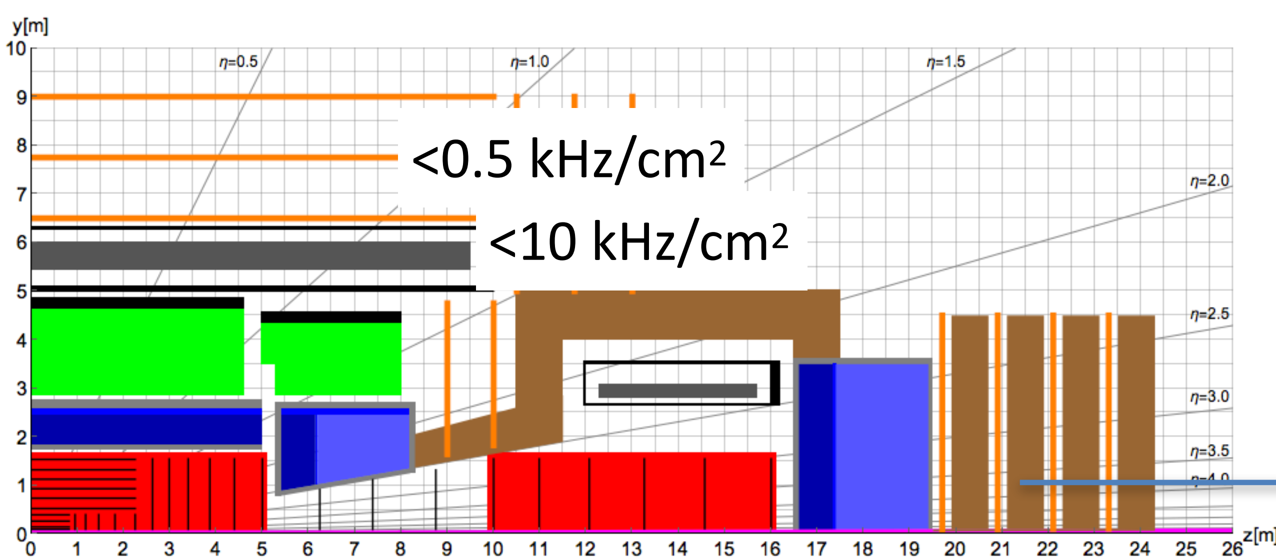

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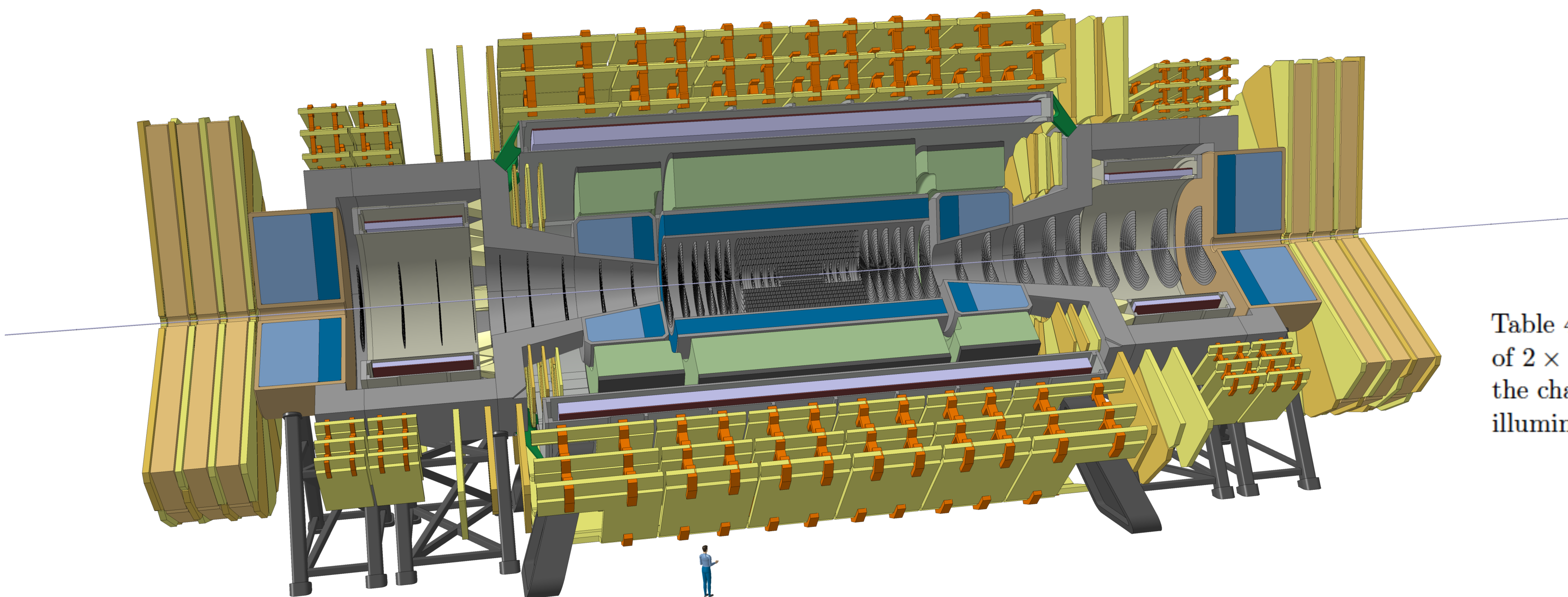

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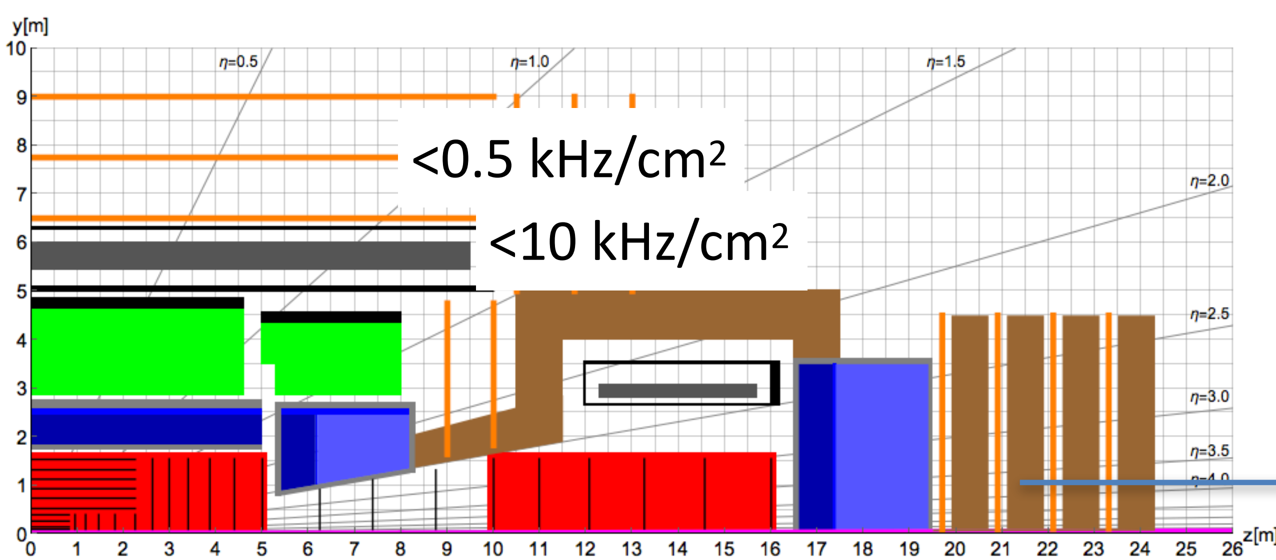

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HL-LHC muon system gas detector technologies, and especially MPGDs, would work for most of the FCC-hh detector area.

Muon detectors for CepC

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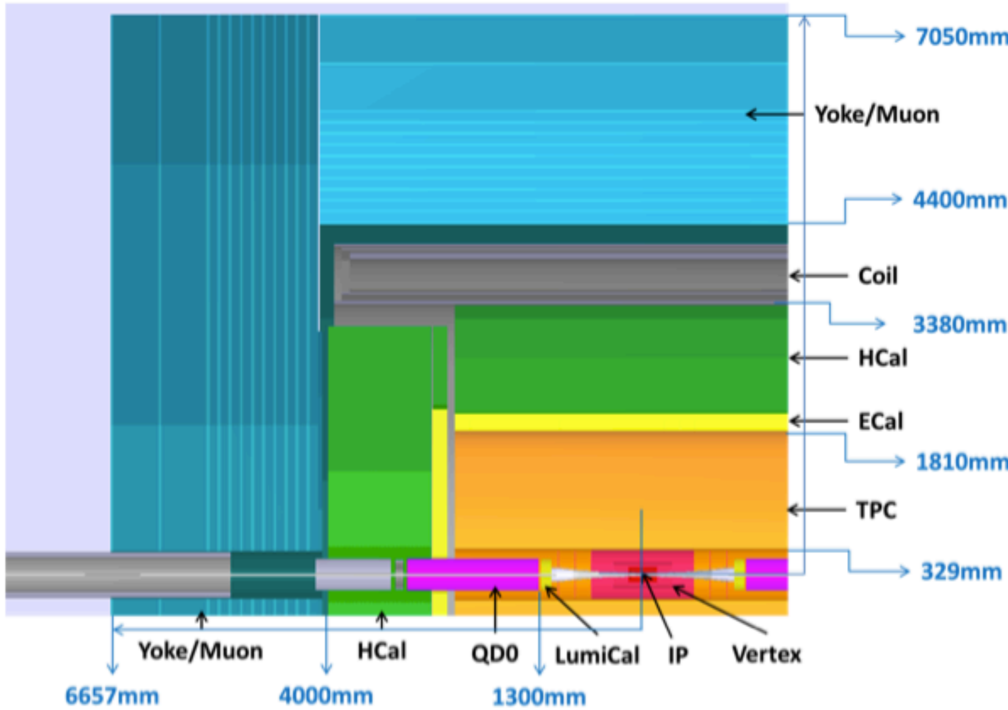
In the baseline option, inspired from ILD, the muon detection system is composed of two layers of RPC stations.

An upgrade of the muon detector by using MPGDs could provide a much finer space resolution with a similar time resolution at a relatively modest increase in price.

The fine space resolution of the detectors could allow to obtain a standalone muon momentum measurement and to trace back the muon stabs to the tracker tracks.



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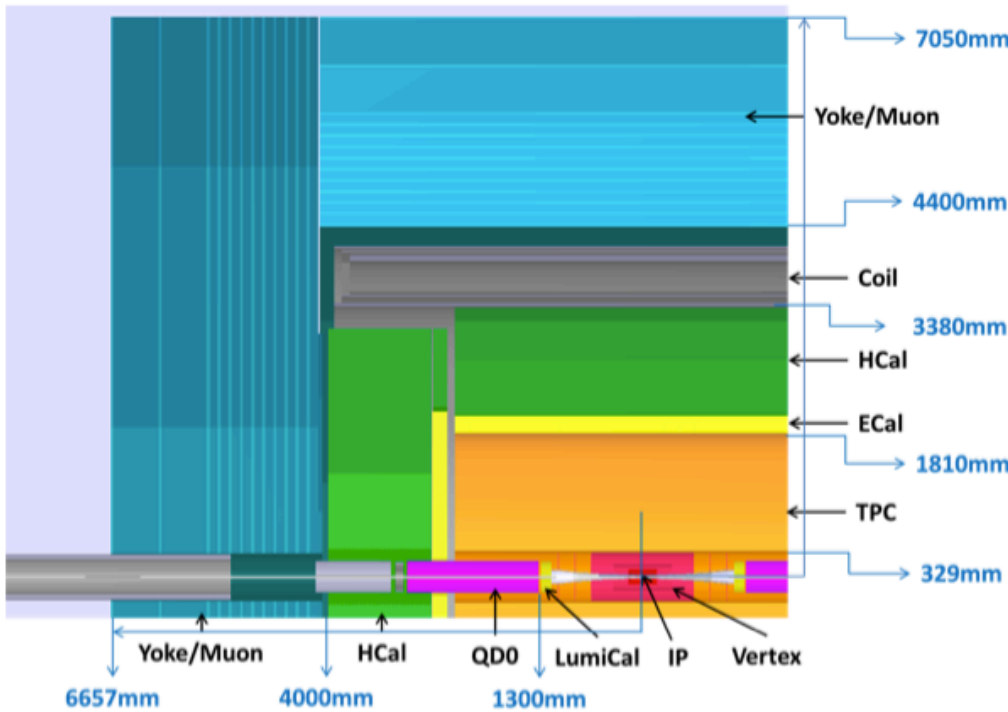

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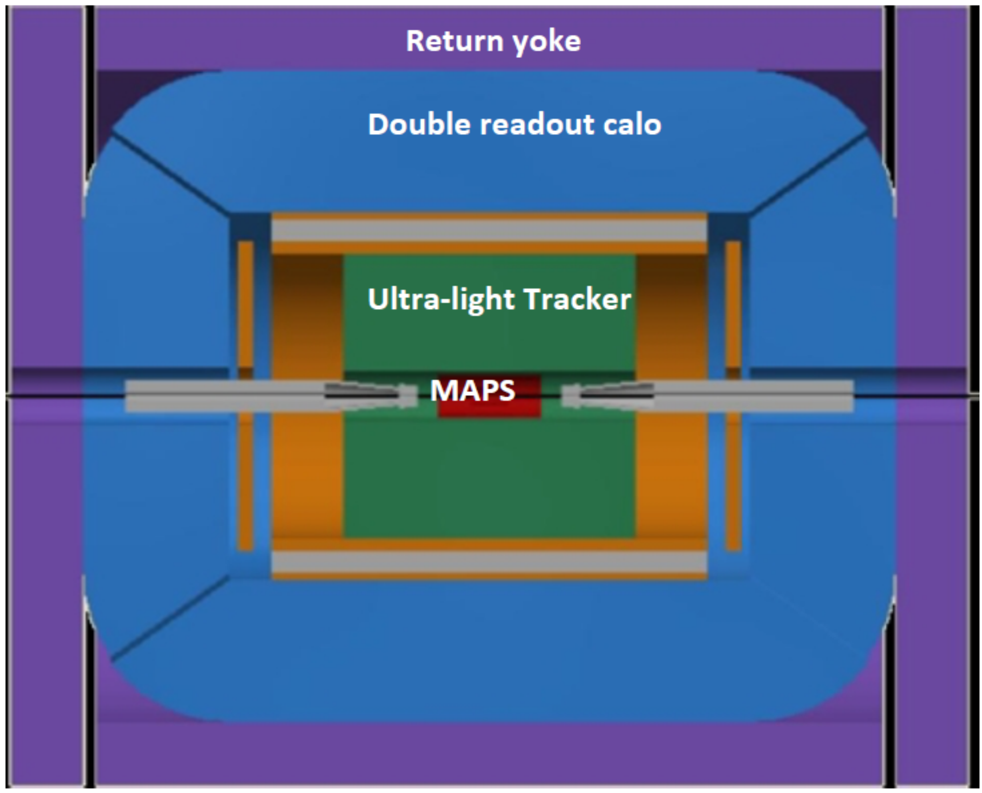

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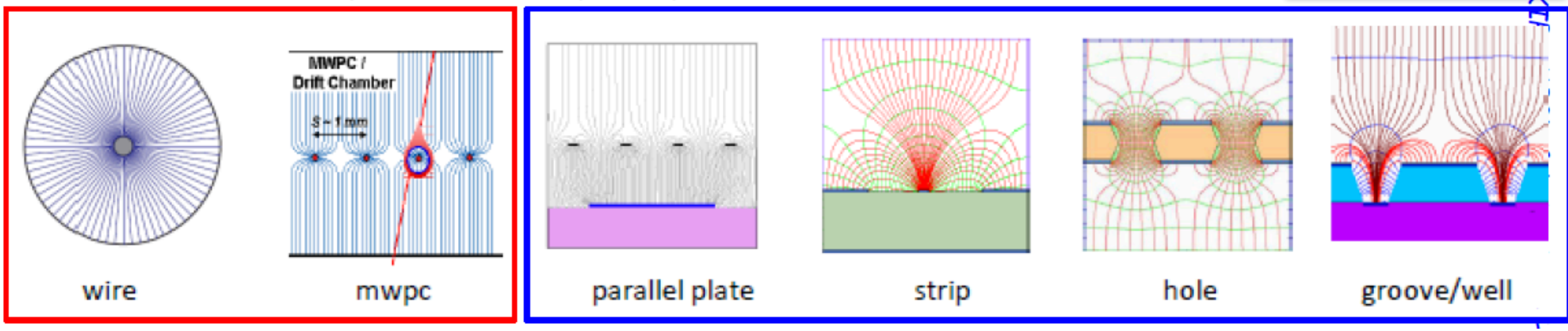
First MPGD: Micro Strip Gas Chamber (MSGC) OED, 1988



Istituto Nazionale di Fisica Nucleare

Principle of operation of MPGDs

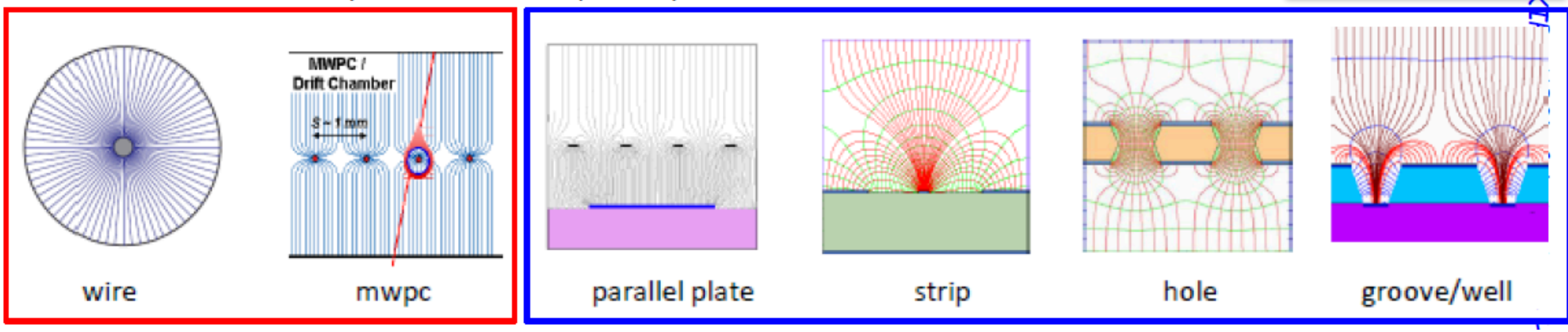
Improve gas detectors

Slow ion motion
Limited multi-track separation

Reduce multiplication region size
Faster ion evacuation
Higher spatial resolution

S. Franchino, 2016

First MPGD: Micro Strip Gas Chamber (MSGC) OED, 1988



Reduce the size of the detecting cell (~100 μm) using chemical etching techniques

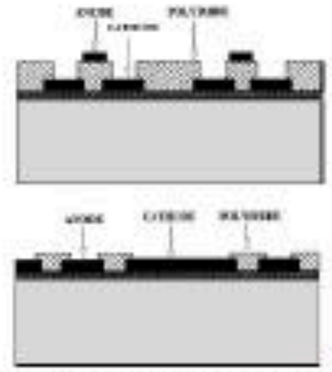
Use PCB technology to obtain very fine electrodes O(10 μm)

Same working principle as proportional wire chambers

- Conversion region (low E field)
- High E field in well localised regions where multiplication happens

Evolution of MPGDs

Micro Gap Chambers



Angelini F, et al. Nucl. Instrum. Methods A335:69 (1993)

Micro Gap Wire Chamber

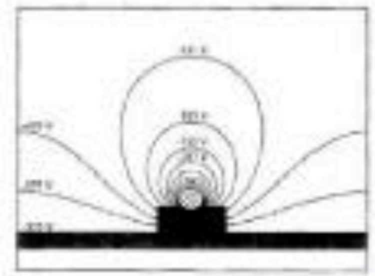
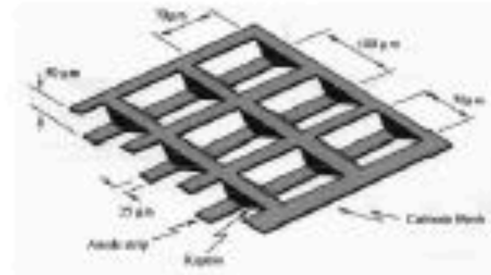


Figure 2.27 Scheme of a MGWC with equipotential and field lines. The circle filled with lines is the section of an anode wire [CHRISTOPHEL1997]

E. Christophel et al, Nucl. Instr. and Meth, vol 398 (1997) 195

Micro Wire Chamber



B. Adeva et al., Nucl. Instr. And Meth. A435 (1999) 402

MicroDot

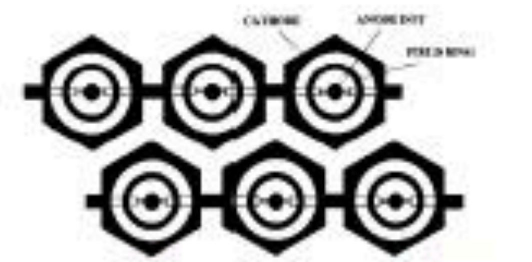
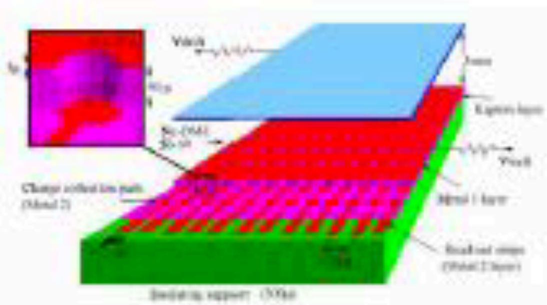


Figure 26 Schematics of the microdot chamber. A pattern of metallic anode dots surrounded by field and cathode electrodes is implemented on an insulating substrate, using microelectronics technology. Anodes are interconnected for readout.

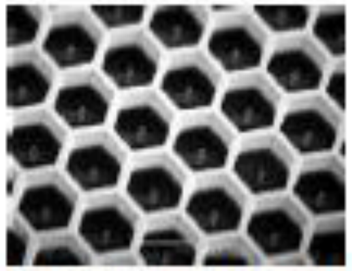
Biagi SF, Jones TJ. Nucl. Instrum. Methods A361:72 (1995)

MicroWELL



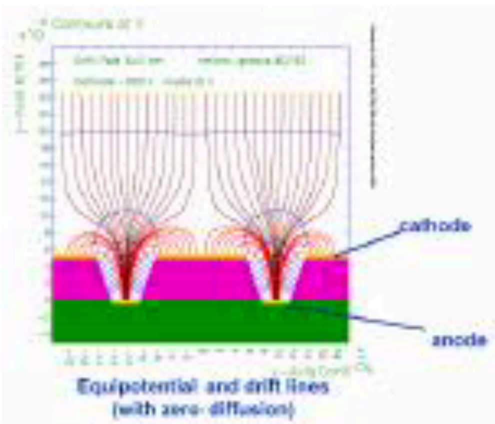
R. Bellazziniet al Nucl. Instr. and Meth. A423(1999)125

MicroPin



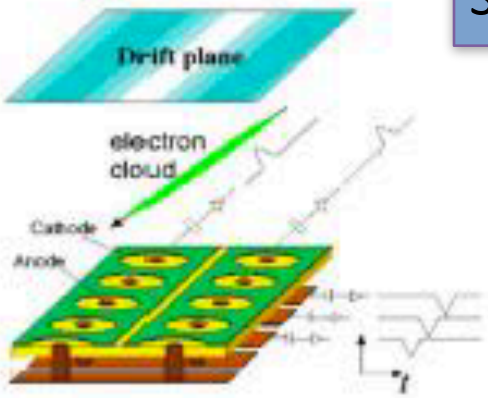
P. Rehak et al., IEEE Nucl. Sci. Symposium seattle 1999

MicroGroove



R. Bellazzini et al Nucl. Instr. and Meth. A424(1999)444

µPIC



Ochi et al NIMA471(2001)264

S. Franchino, 2016

3rd July 2014 DT Training Seminar 15

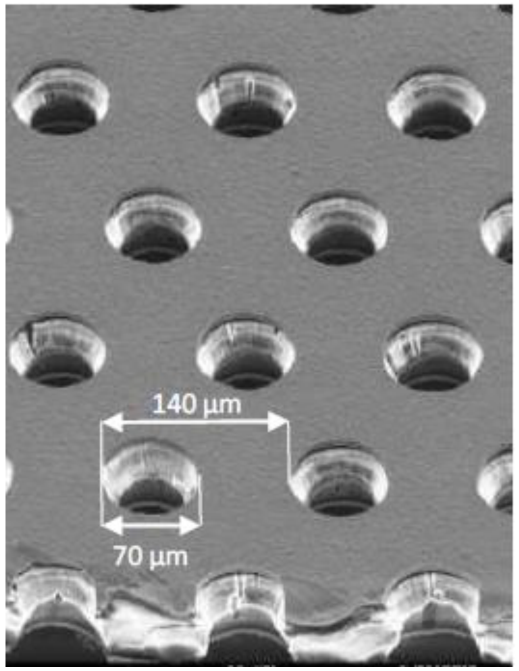
More recent MPGDs

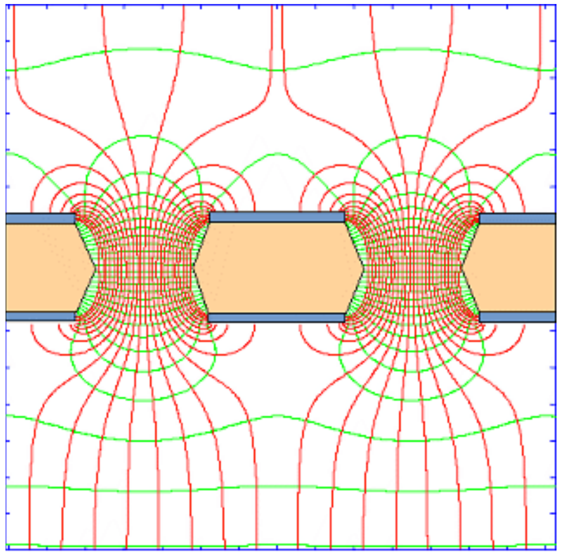
S. Franchino, 2016

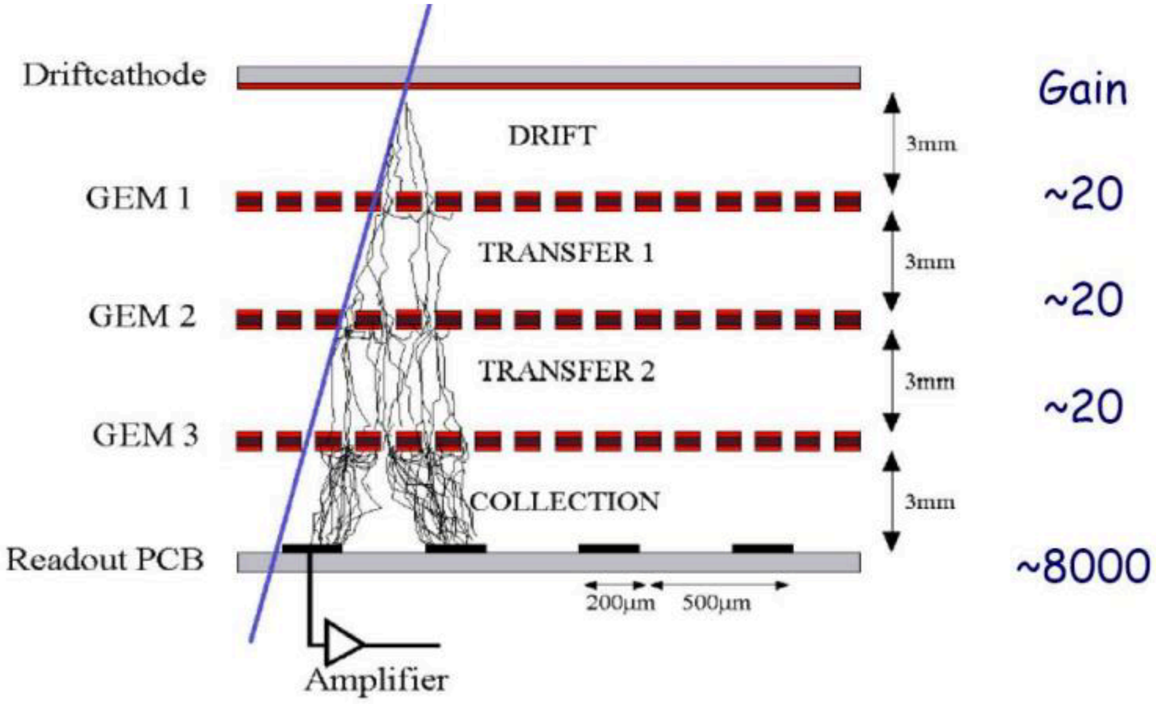
More recent MPGDs

F. Sauli, NIM. A386(1997)531

GEM (std, Thick, glass, …)







S. Franchino, 2016

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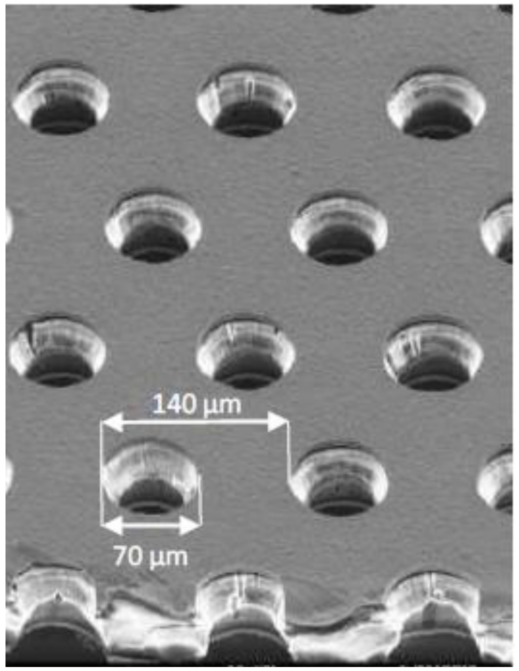
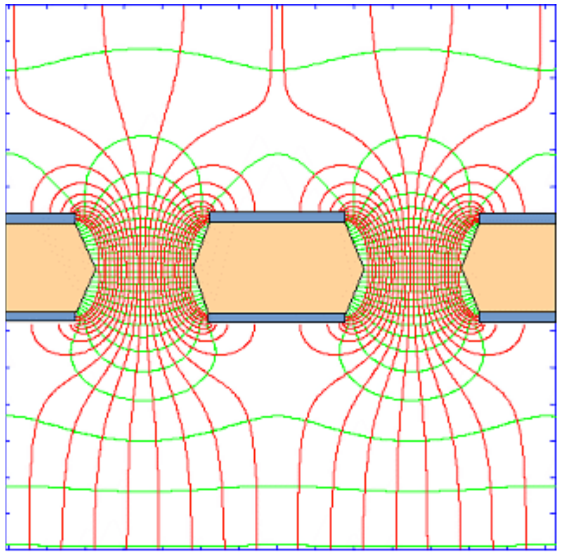
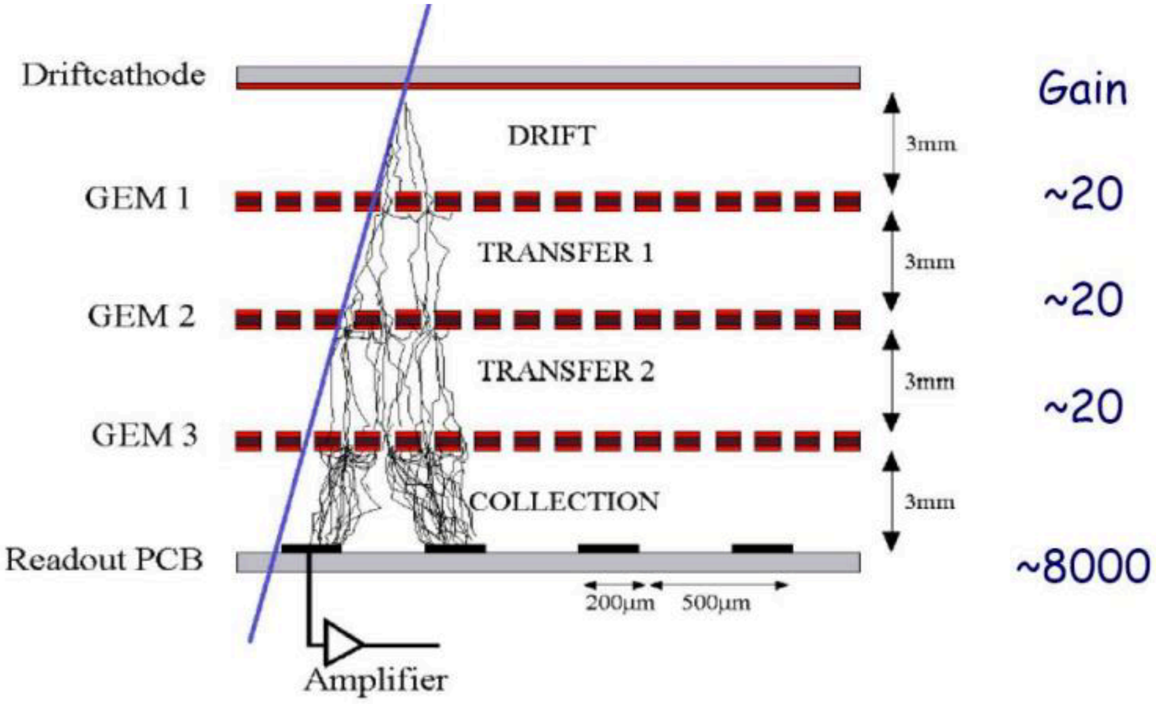
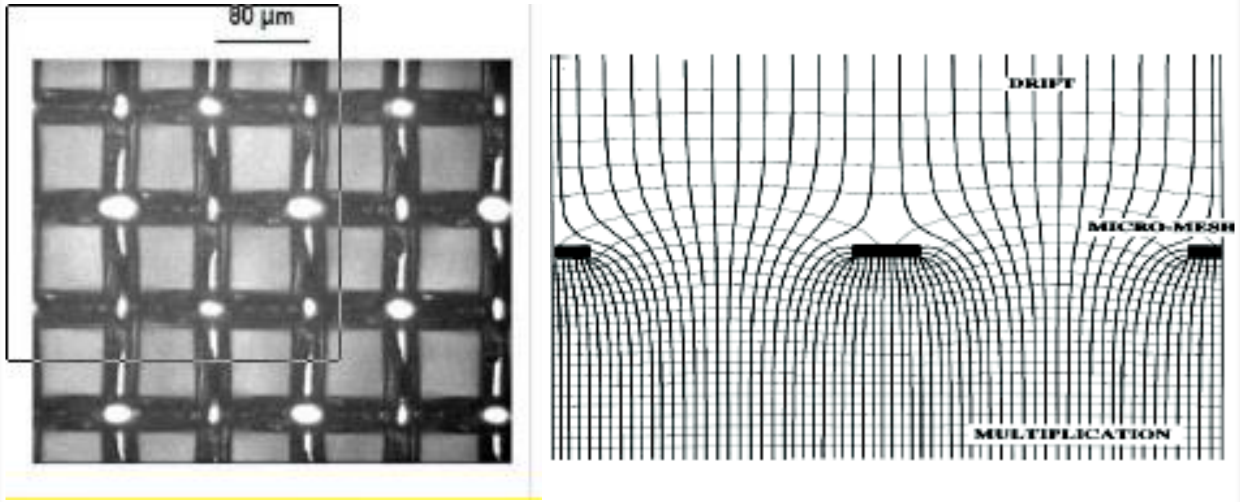


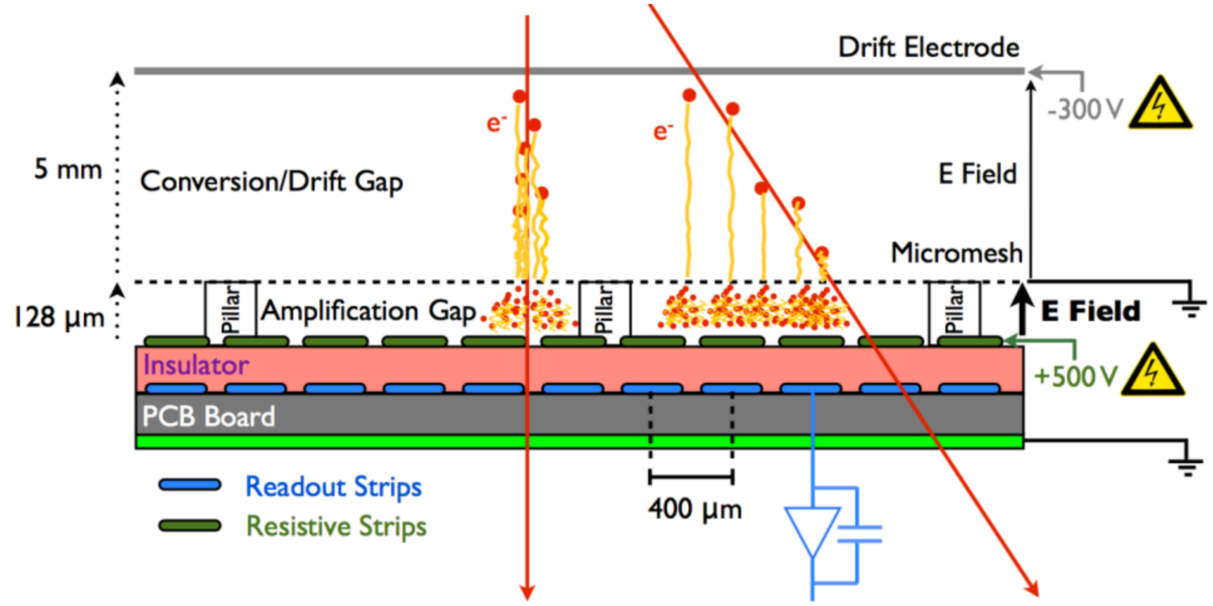




I. Giomataris et al., NIM A 376 (1996)

Micromegas (bulk, micro bulk, resistive, ..)





S. Franchino, 2016

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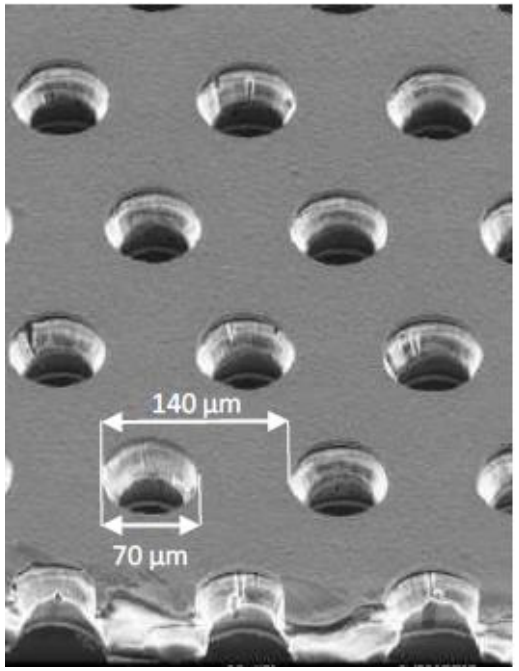

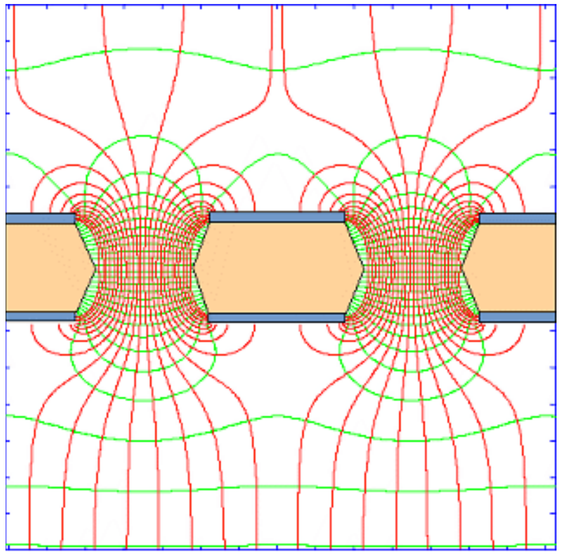

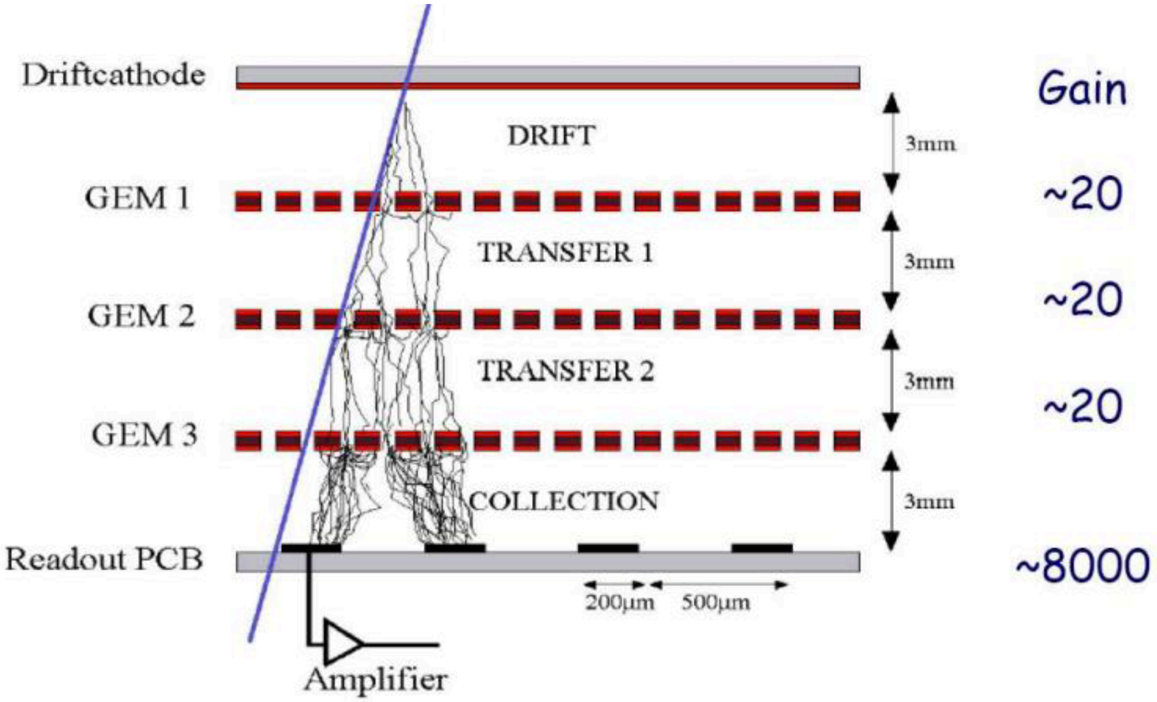

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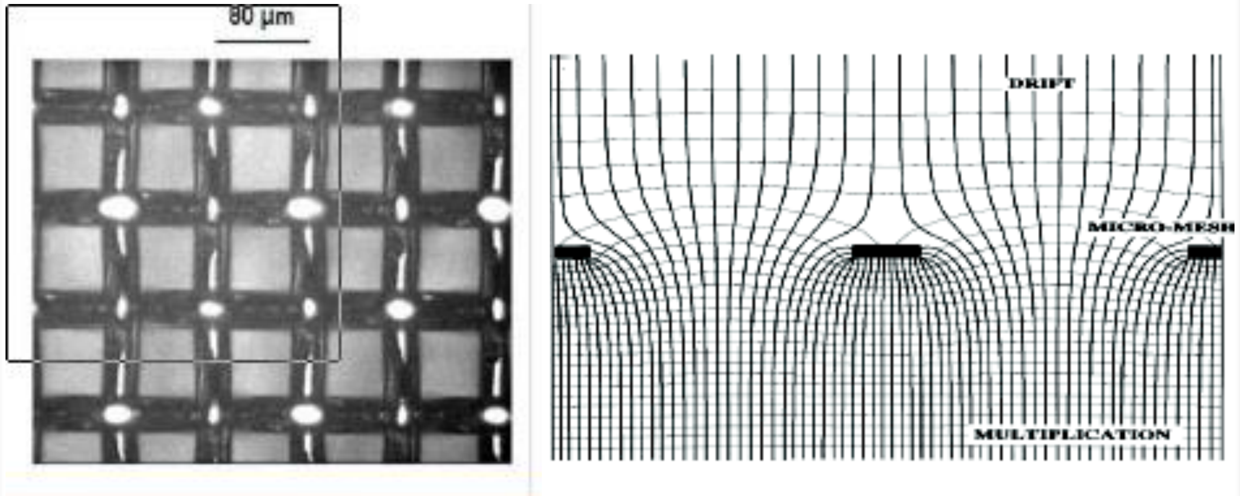

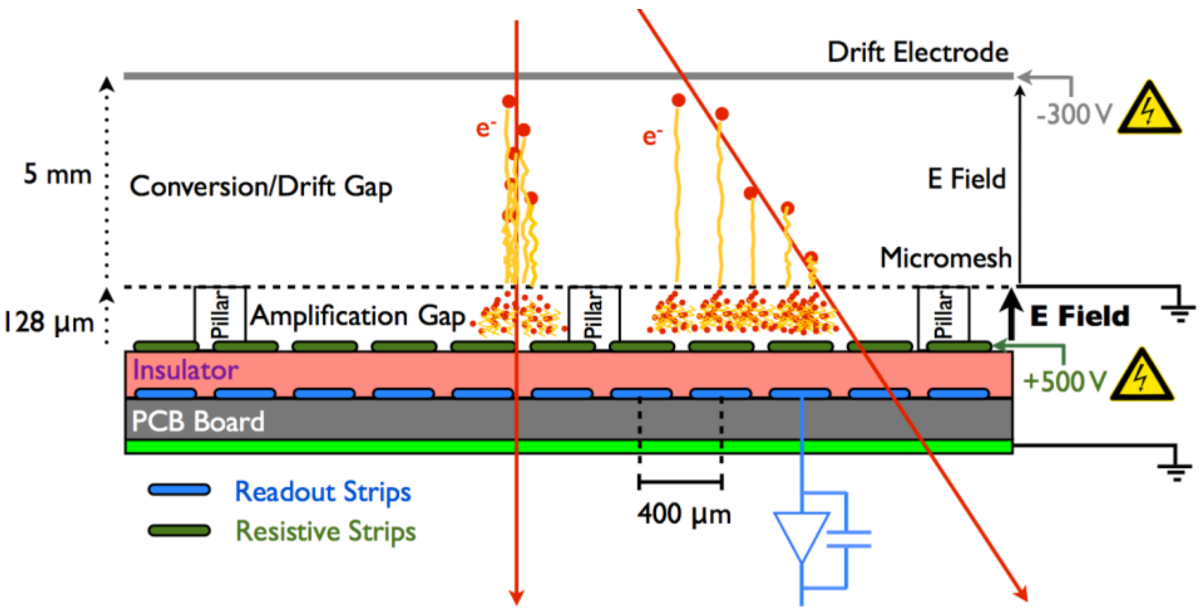

S. Franchino, 2016

Ageing: OK (no thin wires)

Spark protection: multiple amplification stages, resistive electrodes

Properties of MPGDs

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- Gas multiplication and/or readout are performed by “micro patterns” instead of conventional wire chambers

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  - Use components that can be mass produced by industry

The μ-RWELL technology

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The μ-RWELL detector is composed of two elements:
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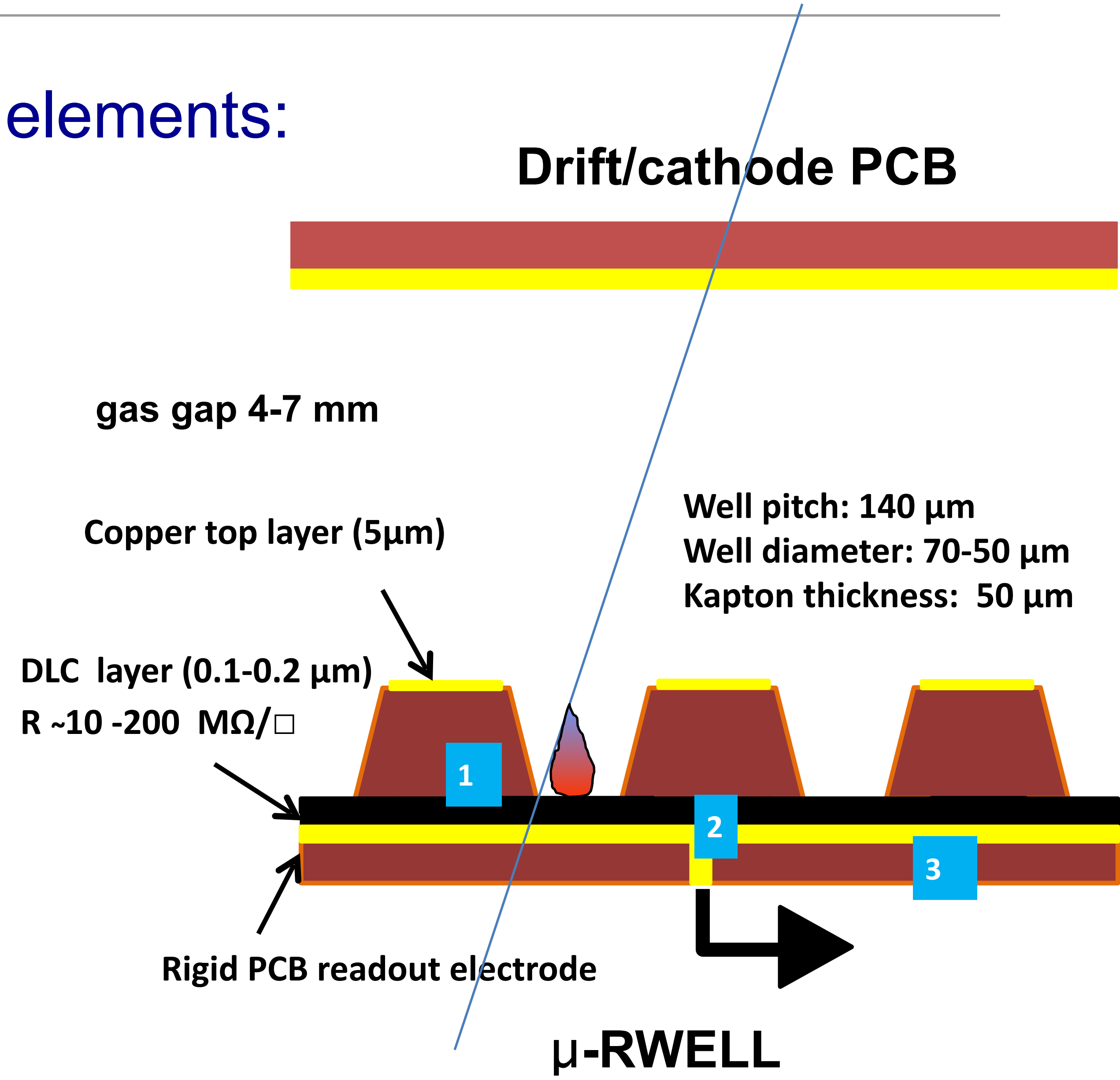

G. Bencivenni et al., 2015_JINST_10_P02008

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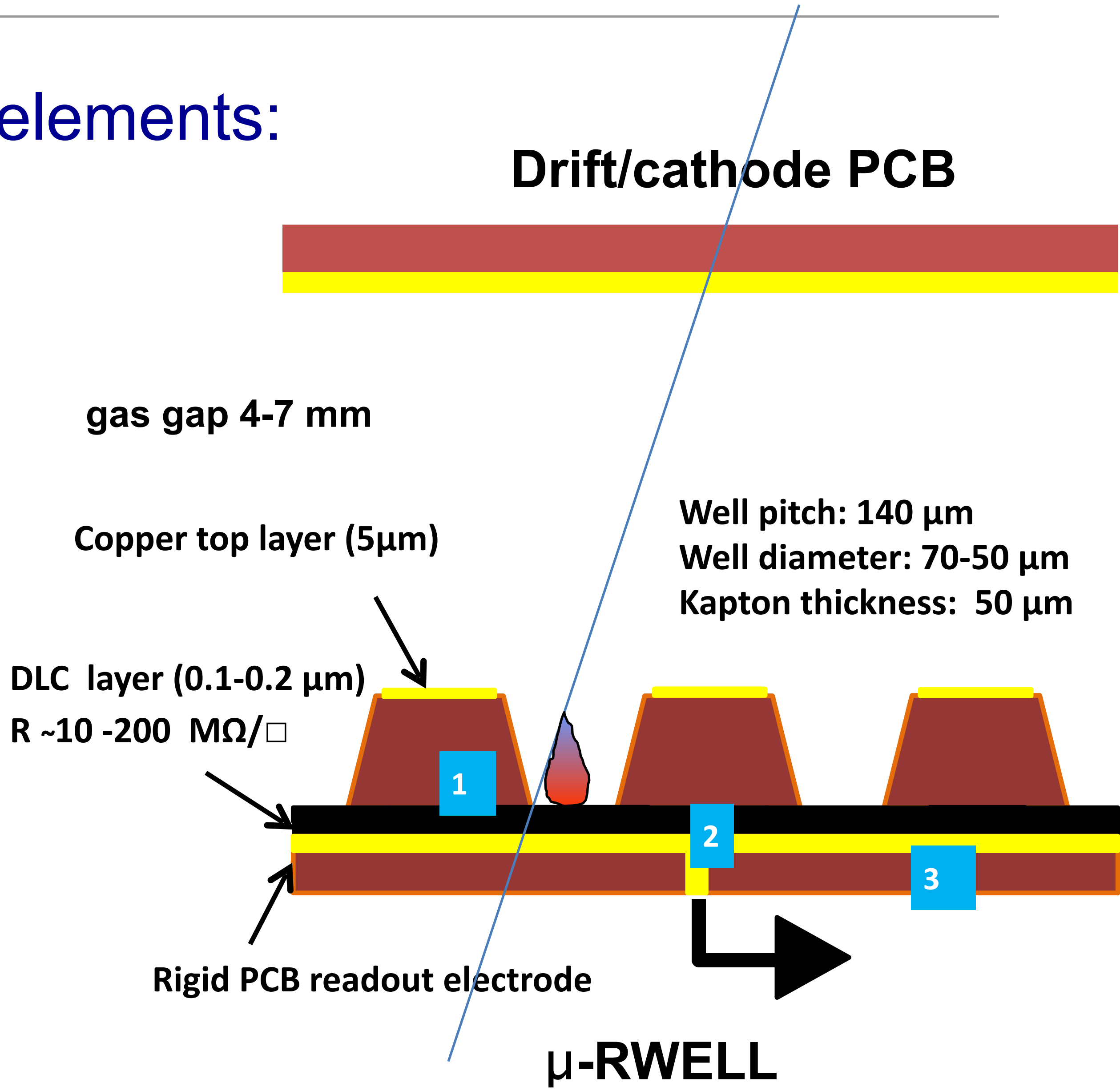

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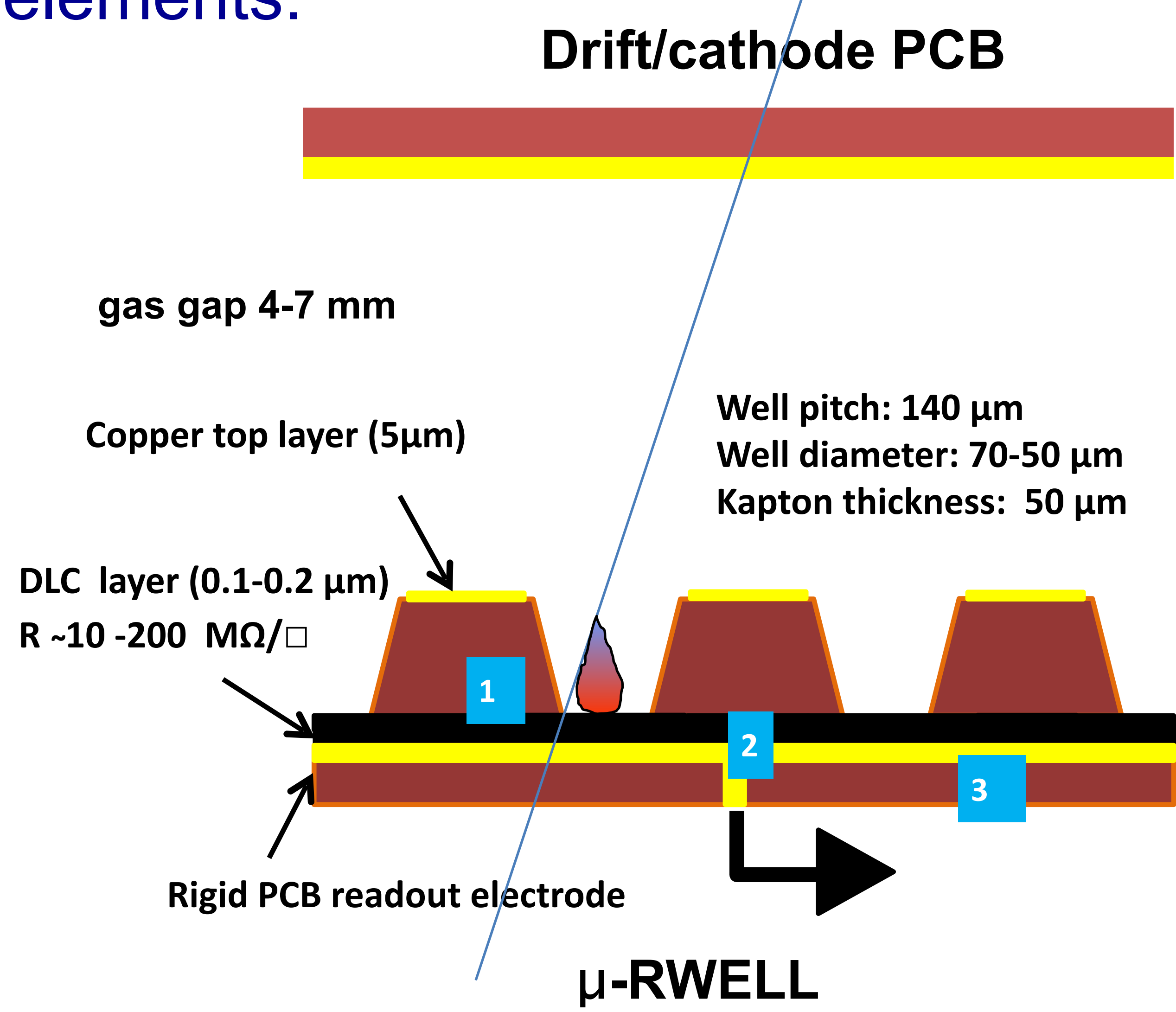

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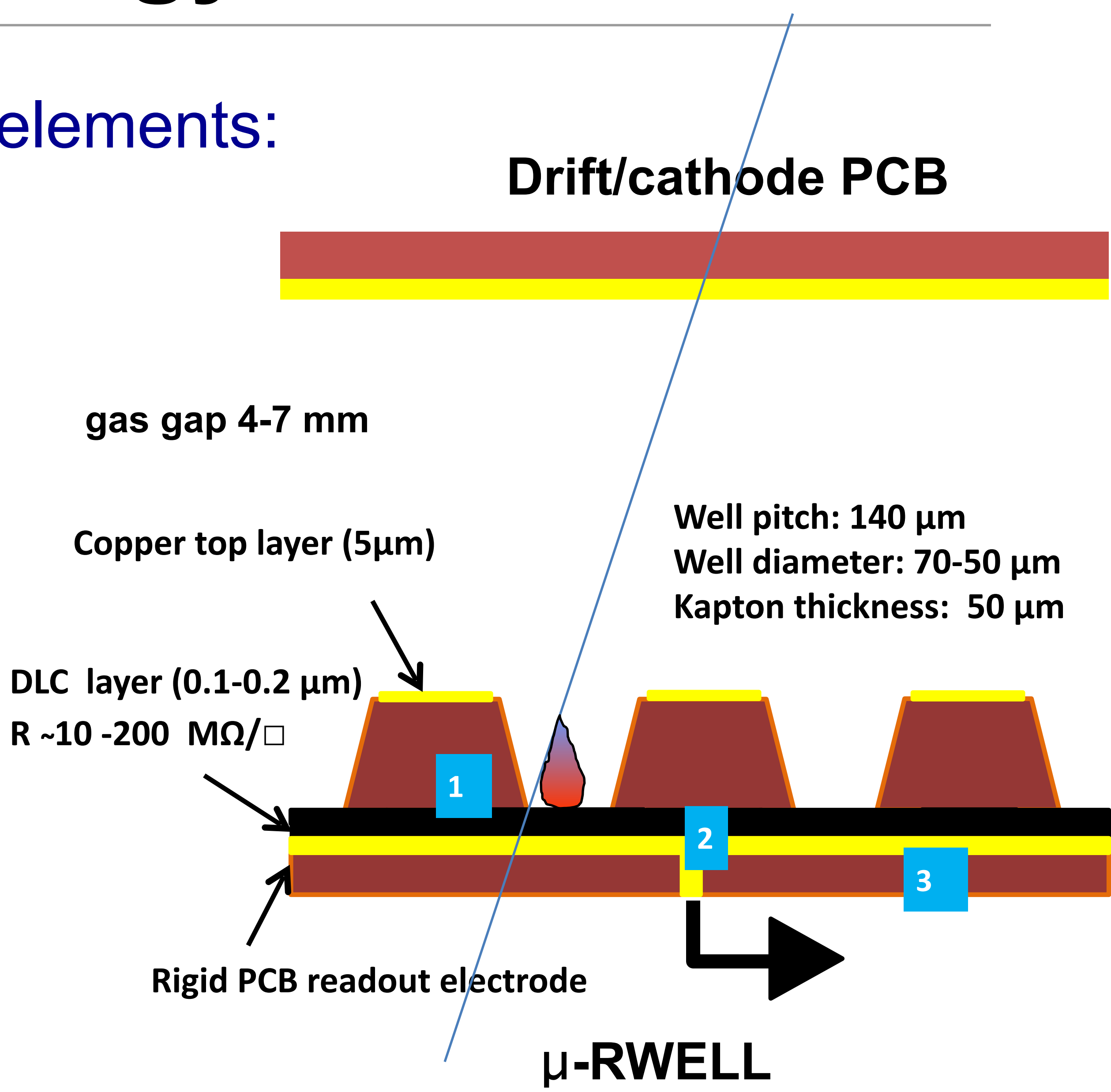

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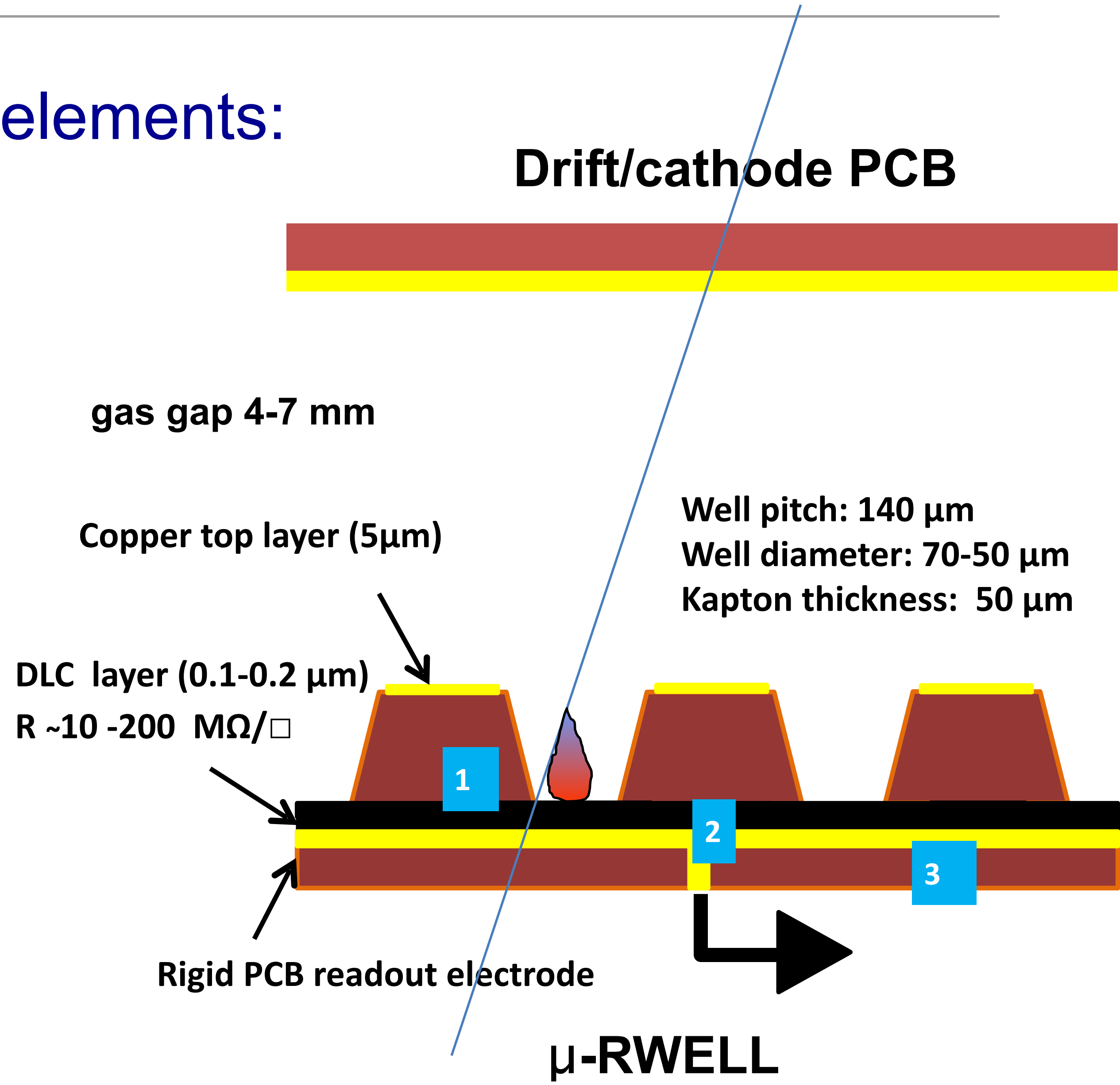

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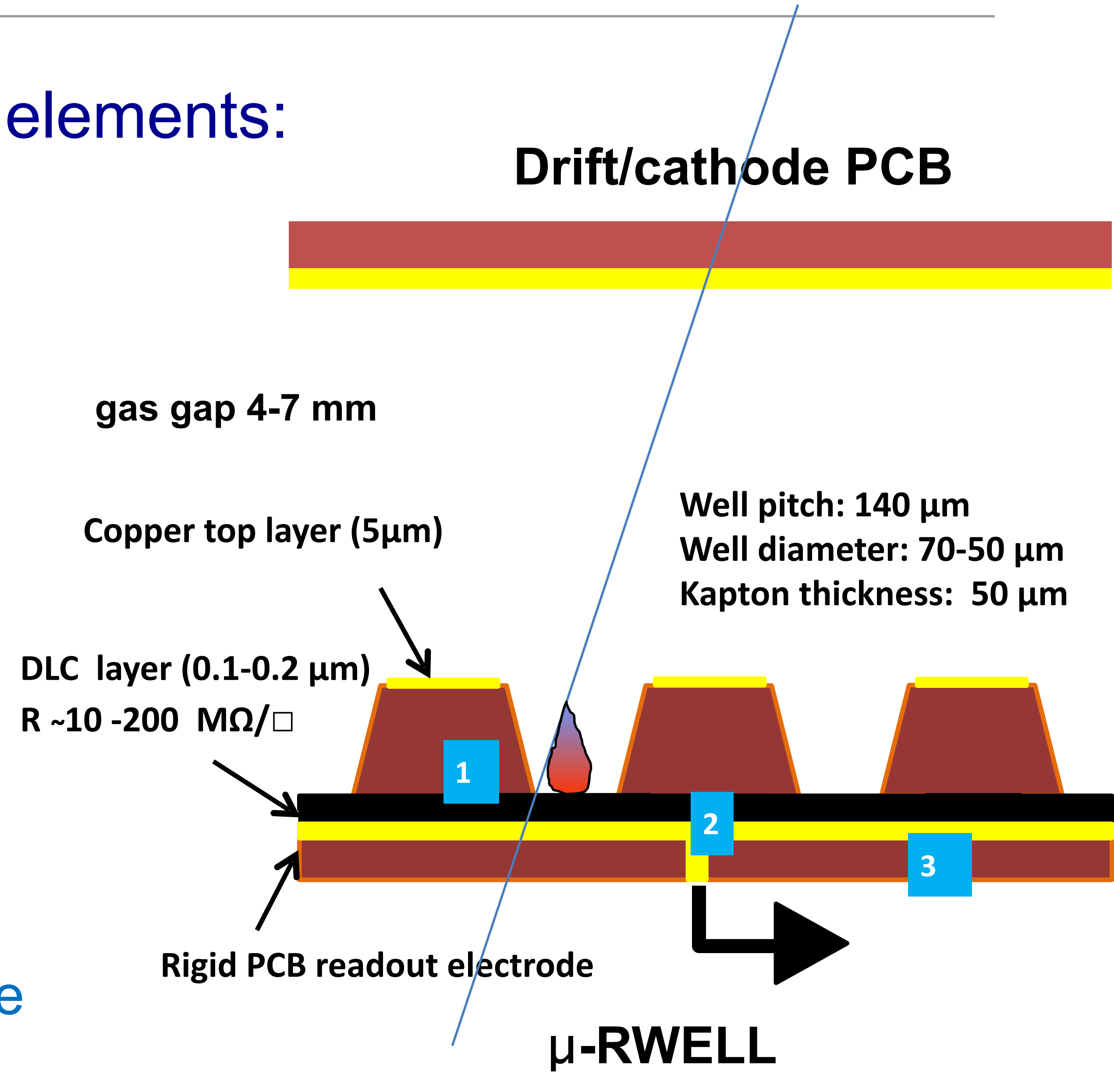

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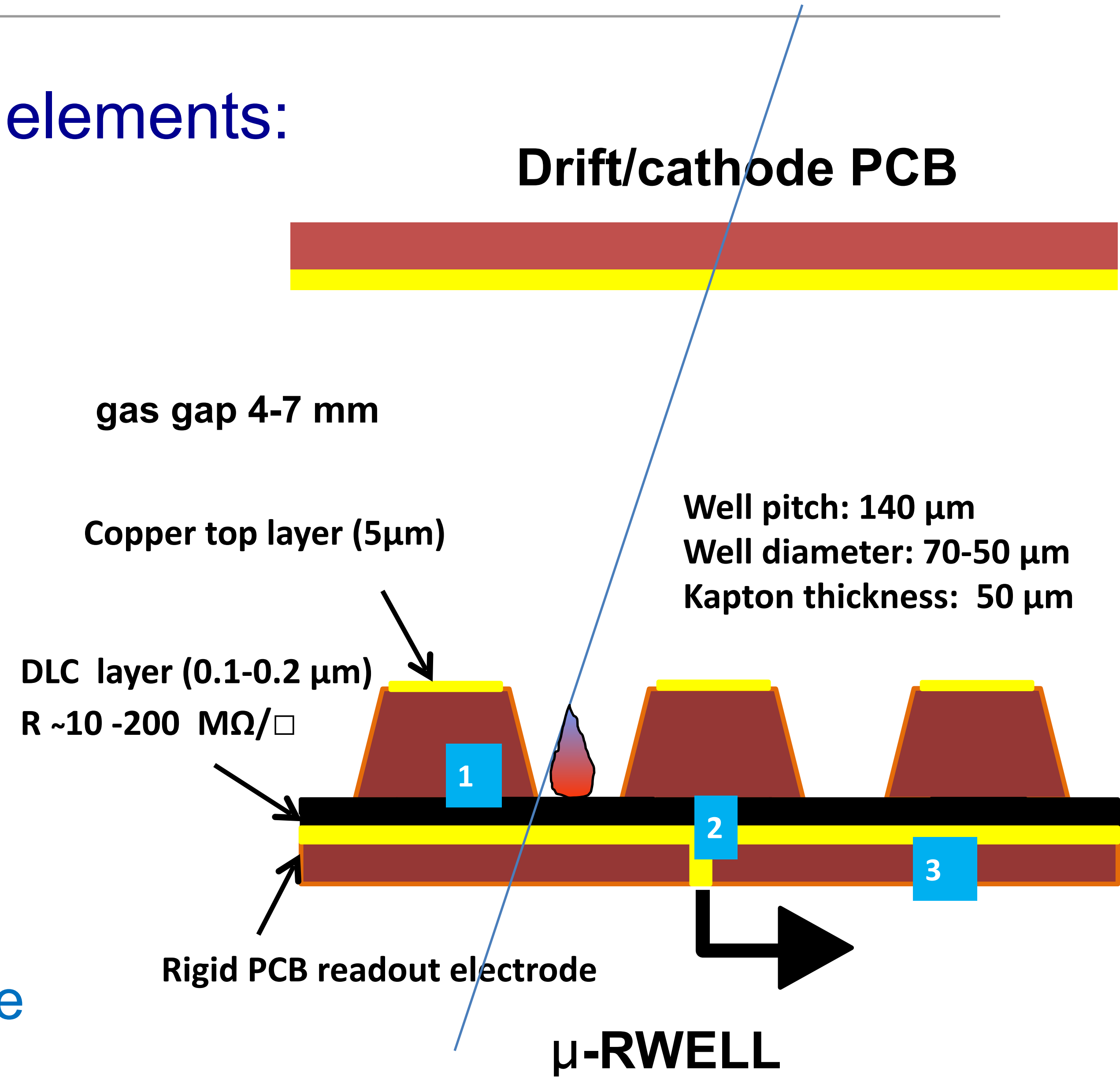

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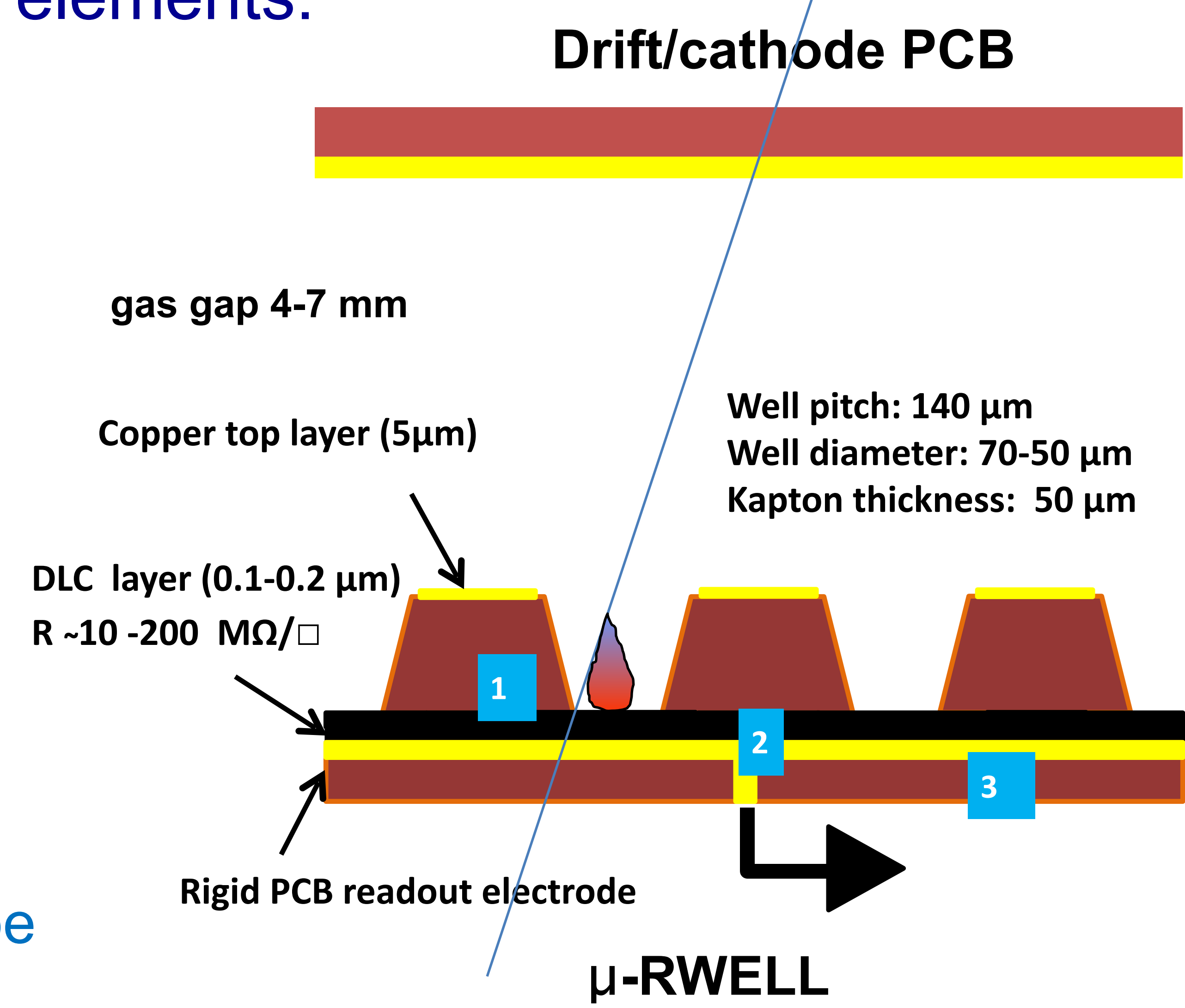

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Collaboration of INFN, CERN, Eltos

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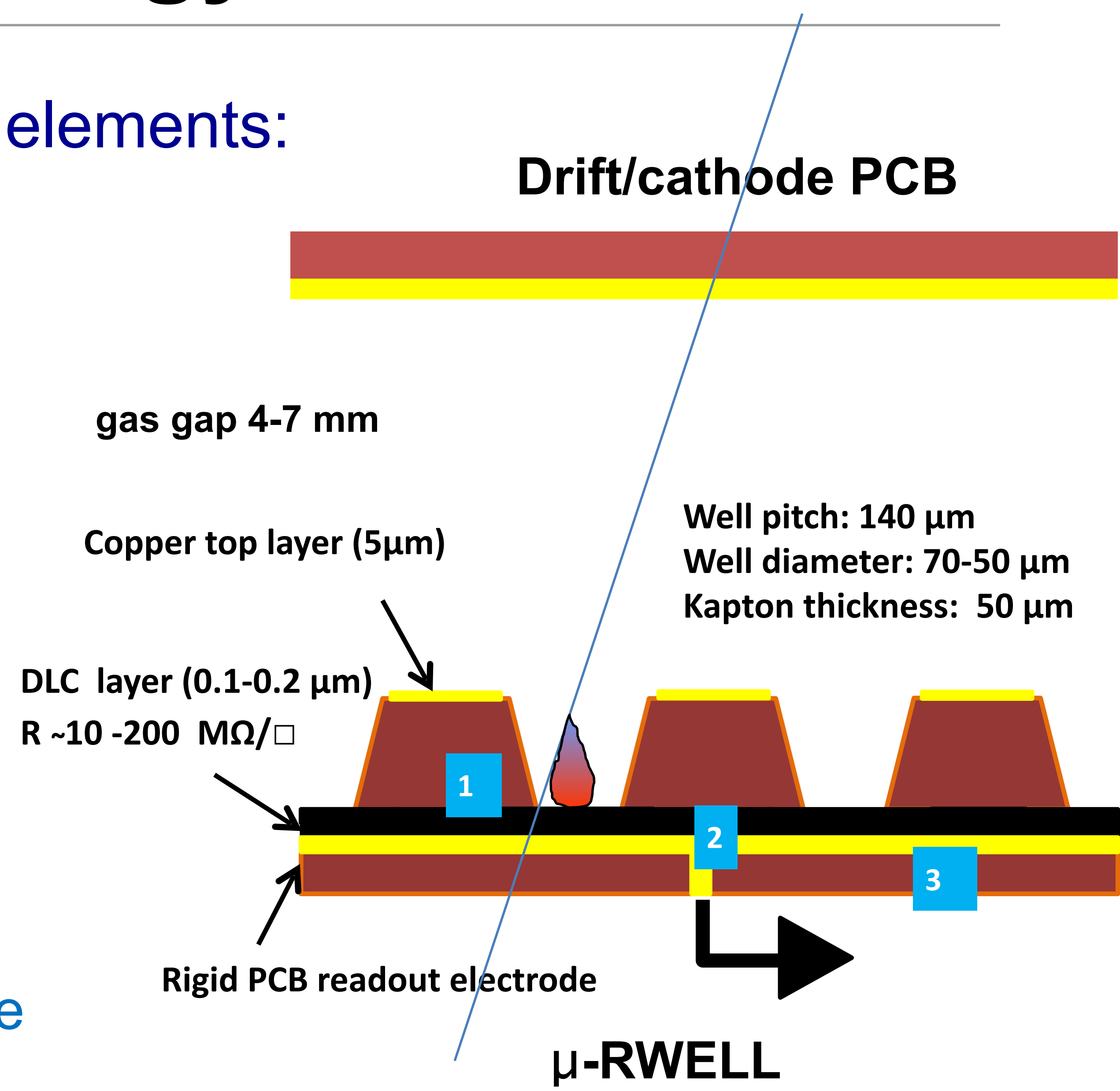

G. Bencivenni et al., 2015_JINST_10_P02008

Major **advantages** wrt. GEM

- 1 kapton foil instead of 3
- No stretching
- Spark safe

μ-RWELL References

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 μ-RWELL detector *vs* resistivity of the resistive stage", NIMA 886 (2018) 36**

High rate version:

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

For more informations on the μ-RWELL technology please follow M. Poli Lener's poster "The Micro-Resistive-WELL (μ-RWELL) detector for large area Muon systems at future circular colliders"

μ-RWELL features

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- μ-RWELL guiding principles
  - Retain the same excellent performances of GEM and MM
  - Improve the resistance to sparks
  - Simplify the components construction and final assembly

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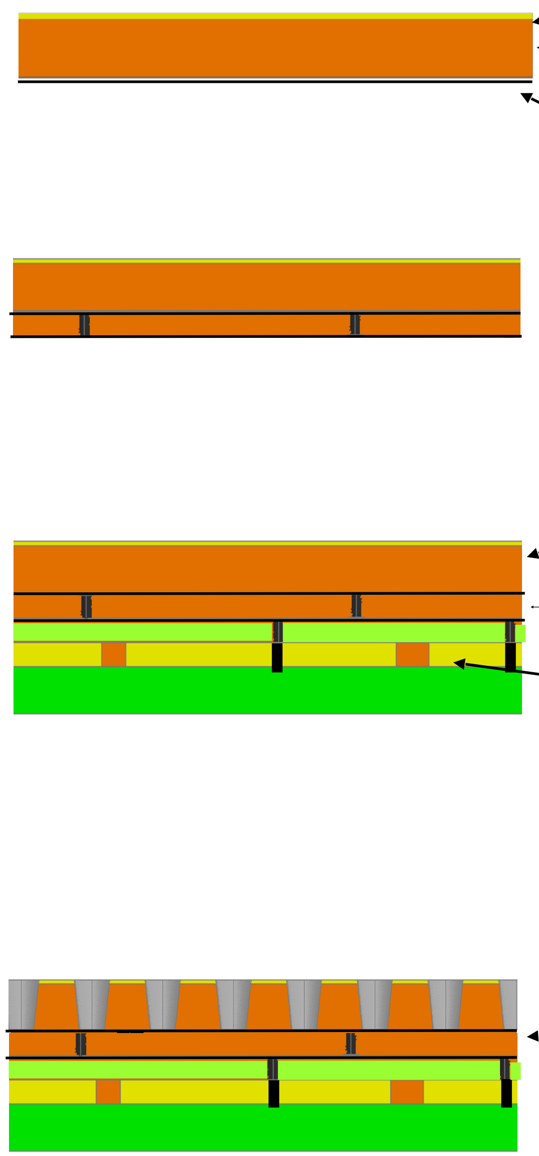
  - Kapton foil glued to PCB: no stretching needed

- Less components, simpler construction → significant cost reduction

μ-RWELL High Rate version

The High Rate scheme (LHCb)

- **G.Bencivenni et al., PoS(MPGD2017)019**
- **G.Bencivenni et al., to be submitted to Pos**



1
Copper layer 5 μm
Kapton layer 50 μm
DLC layer: 0.1 – 0.2 μm (10-200 MΩ/□)

2
2nd resistive kapton layer with ~ 1/cm² "*through vias*" density

3
DLC-coated kapton base material
2nd resistive kapton layer
pad/strips readout on standard PCB

4
DLC-coated base material after copper and kapton chemical etching (WELL amplification stage)

This resistive scheme allows to reach a detector rate capability > 1 MHz/cm² with a negligible gain drop (see M. Poli Lener's poster: «The micro-Resistive-WELL (μ-RWELL) detector for large area Muon system at Future Circular Colliders»

CMS GE1/1 μ-RWELL prototype at H8 test beam

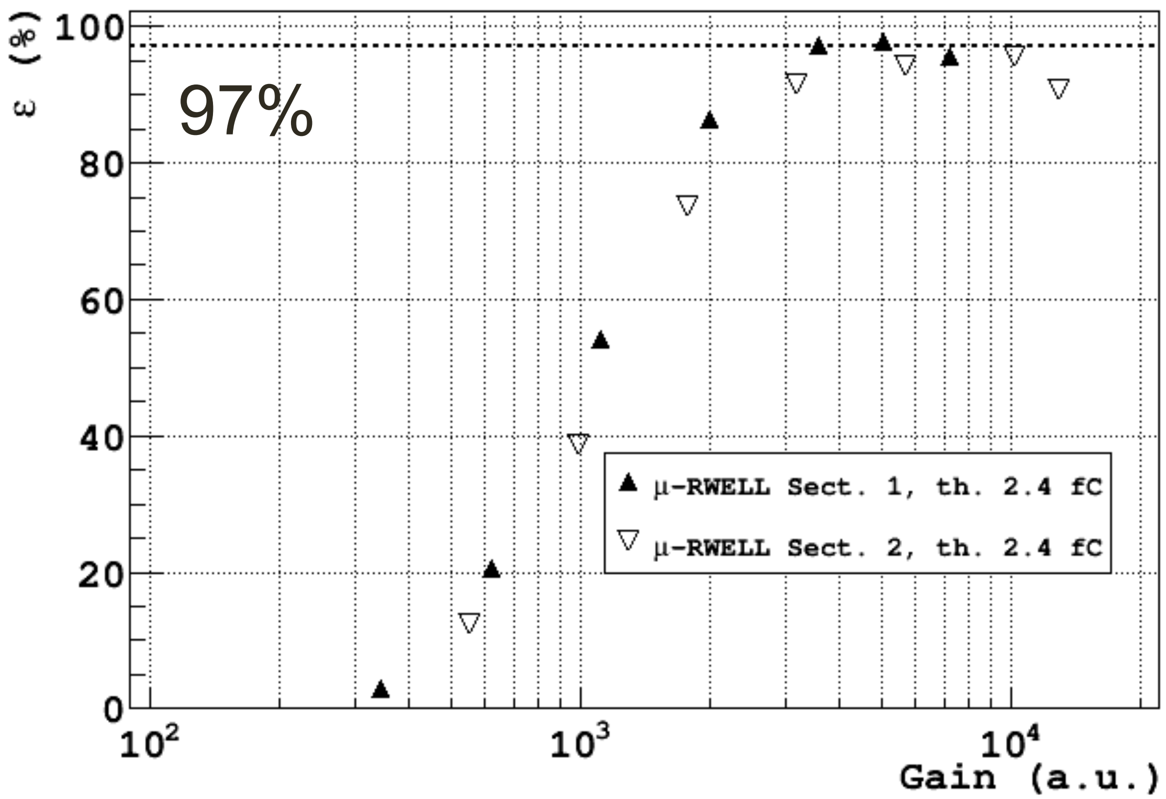
CMS GE1/1 μ-RWELL prototype at H8 test beam

Ar/CO_2/CF_4 45/15/40

VFAT FEE

CMS GE1/1 μ-RWELL prototype at H8 test beam

Efficiency



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

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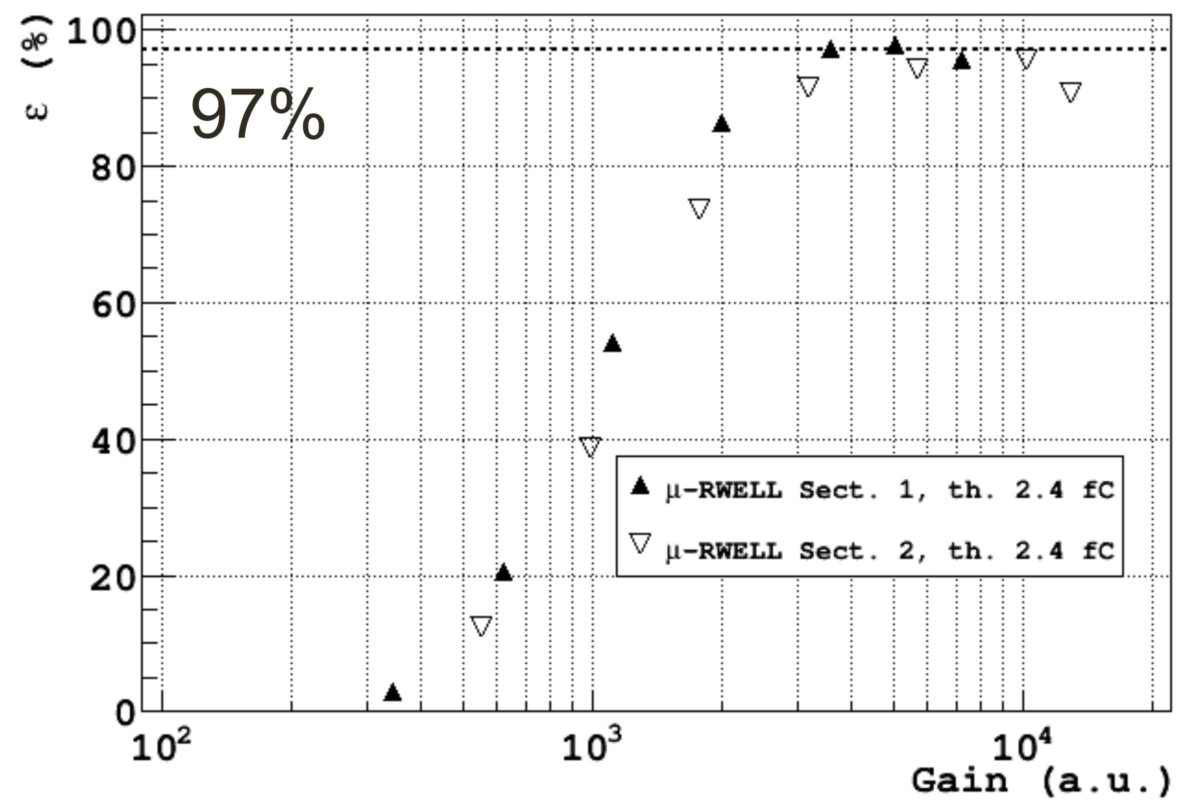
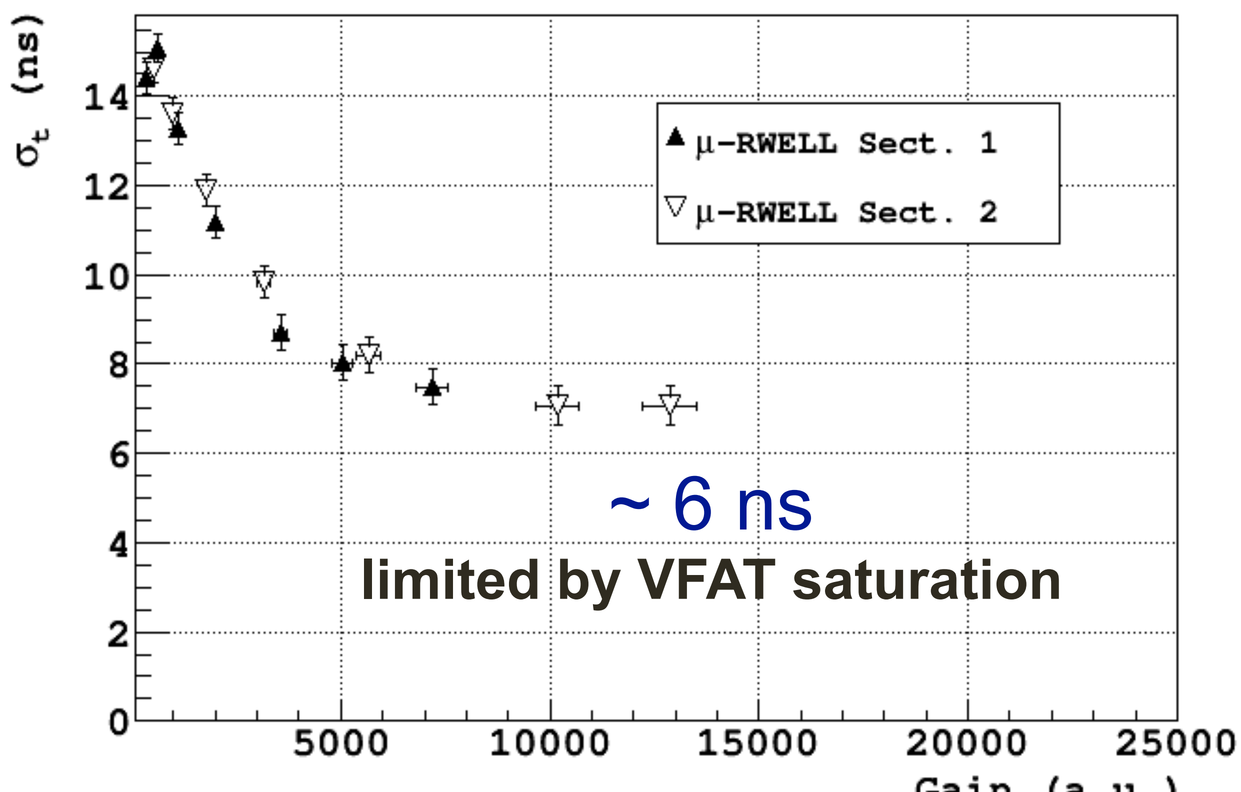


Time resolution



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CMS GE1/1 μ-RWELL: GIF++ ageing test

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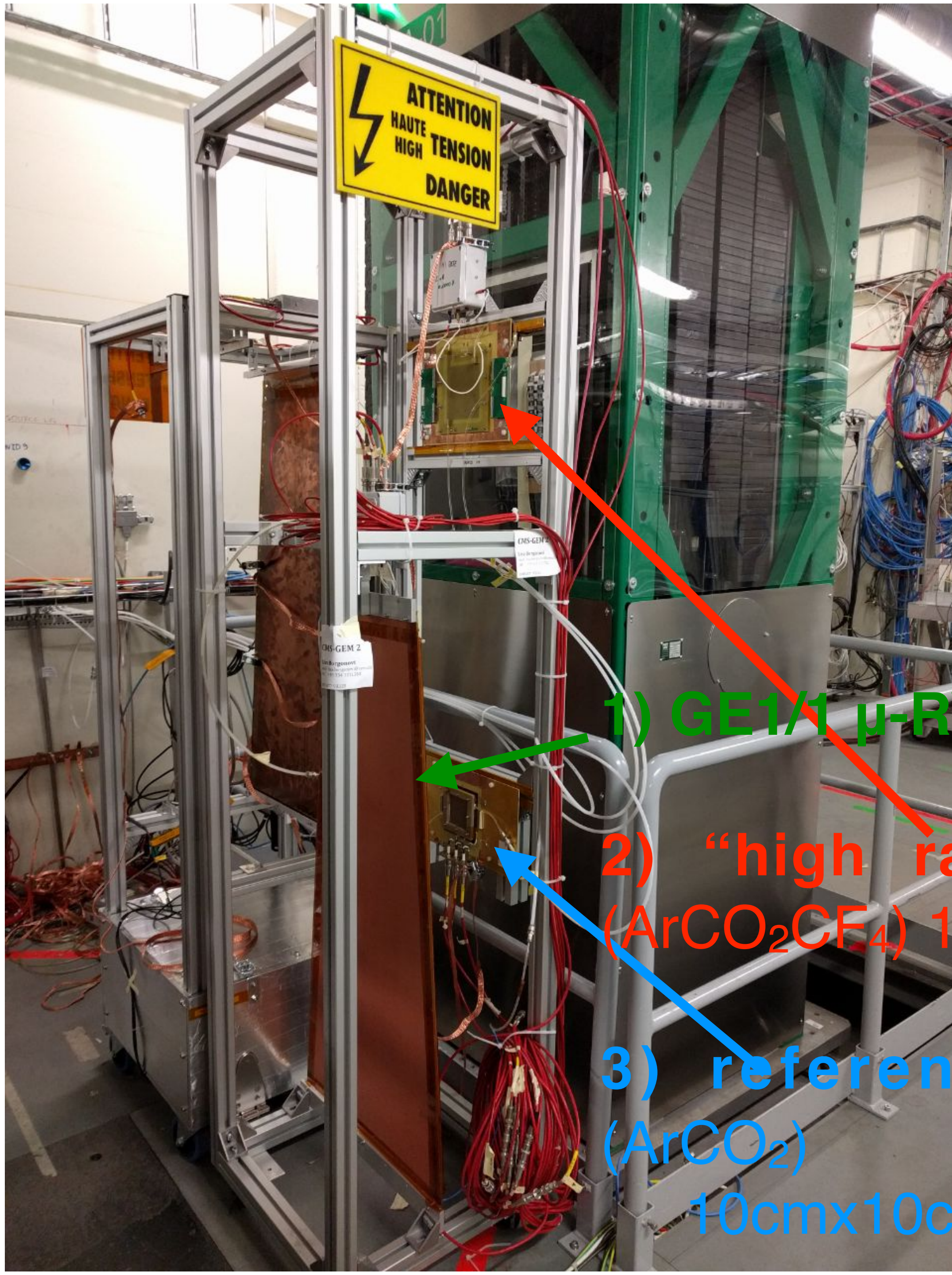


1) GE1/1 μ-RWELL ($ArCO_2$)

2) "high rate" μ-RWELL ($ArCO_2CF_4$) 10cmx10cm

3) reference μ-RWELL ($ArCO_2$) 10cmx10cm

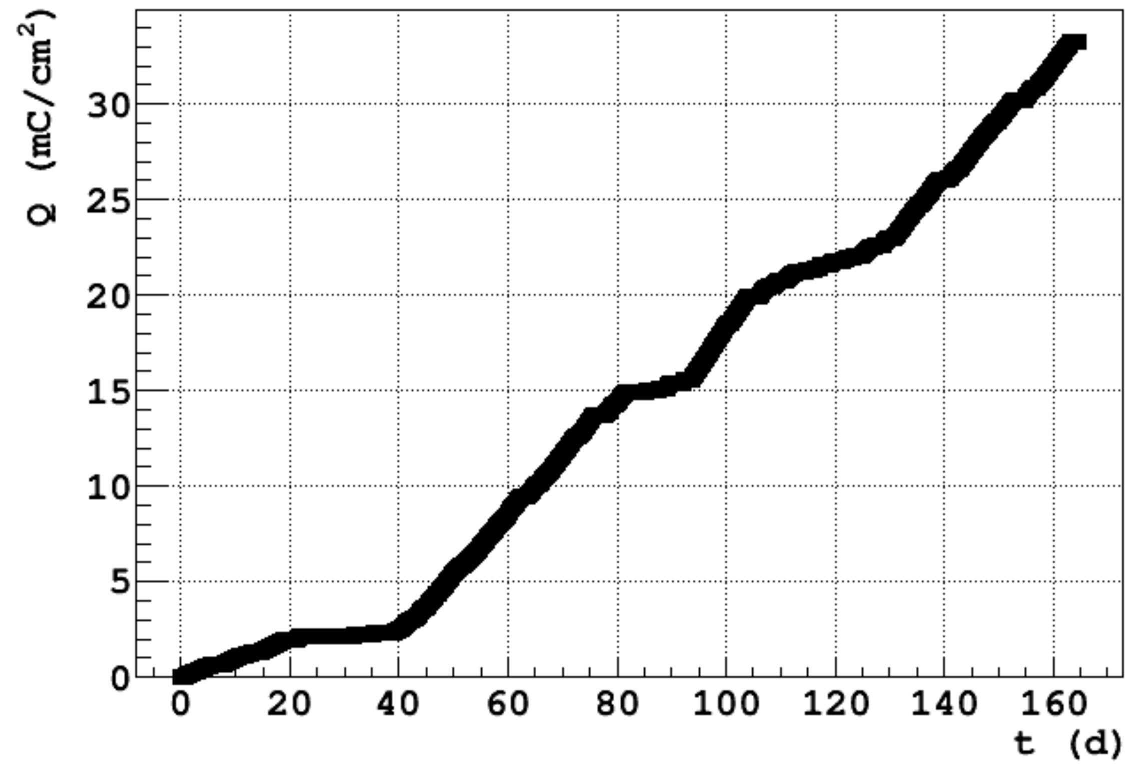
μRWELL prototypes exposed inside the GIF++

CMS GE1/1 μ-RWELL: GIF++ ageing test

1) **GE1/1 μ-RWELL** ($ArCO_2$)

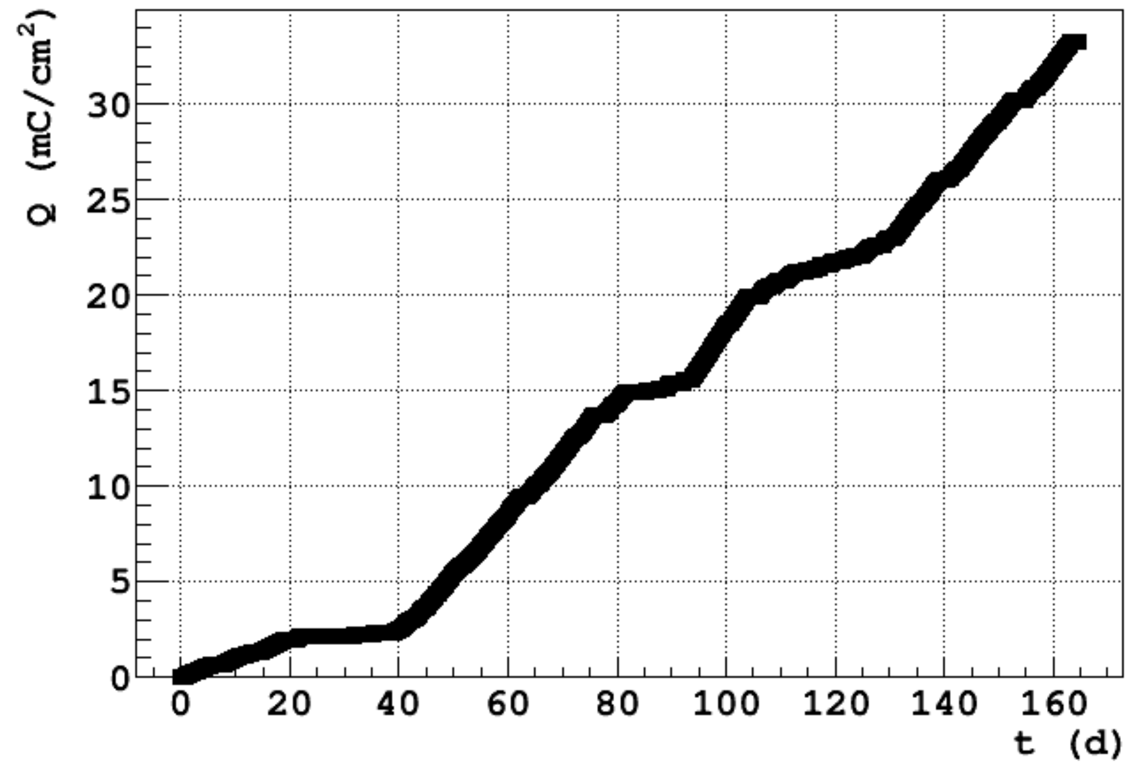
2) **“high rate” μ-RWELL** ($ArCO_2CF_4$) 10cmx10cm

3) **reference μ-RWELL** ($ArCO_2$) 10cmx10cm



μRWELL prototypes exposed inside the GIF++

CMS GE1/1 μ-RWELL: GIF++ ageing test

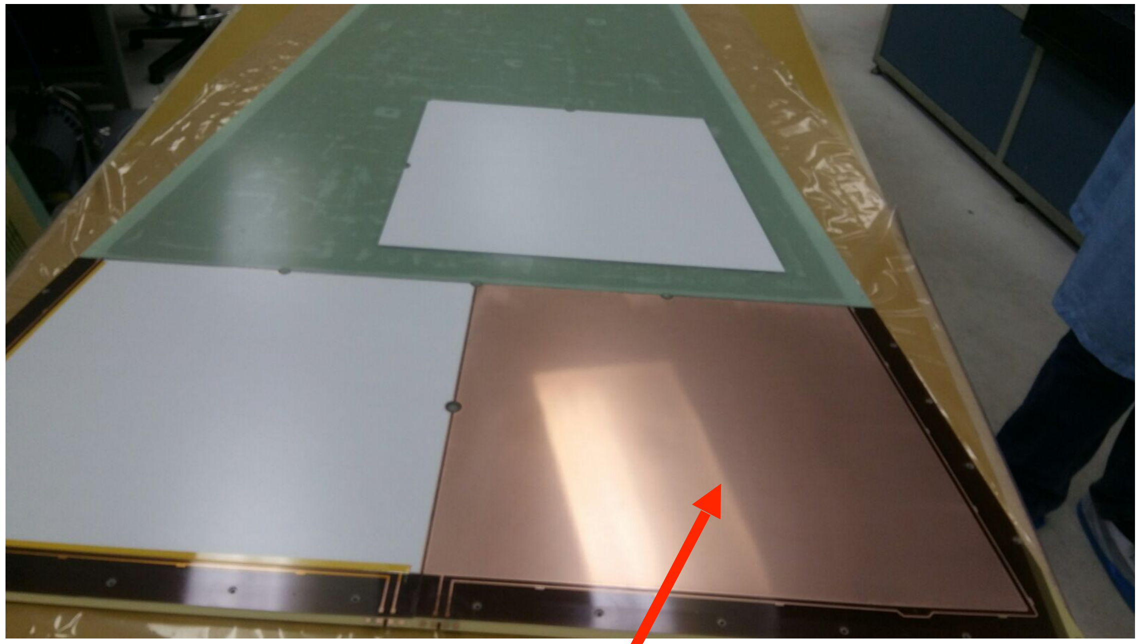


GE1/1 has accumulated a dose of ~32 mC/cm^2 (more than 10 times the dose after 10 years of HL-LHC)

μRWELL prototypes exposed inside the GIF++

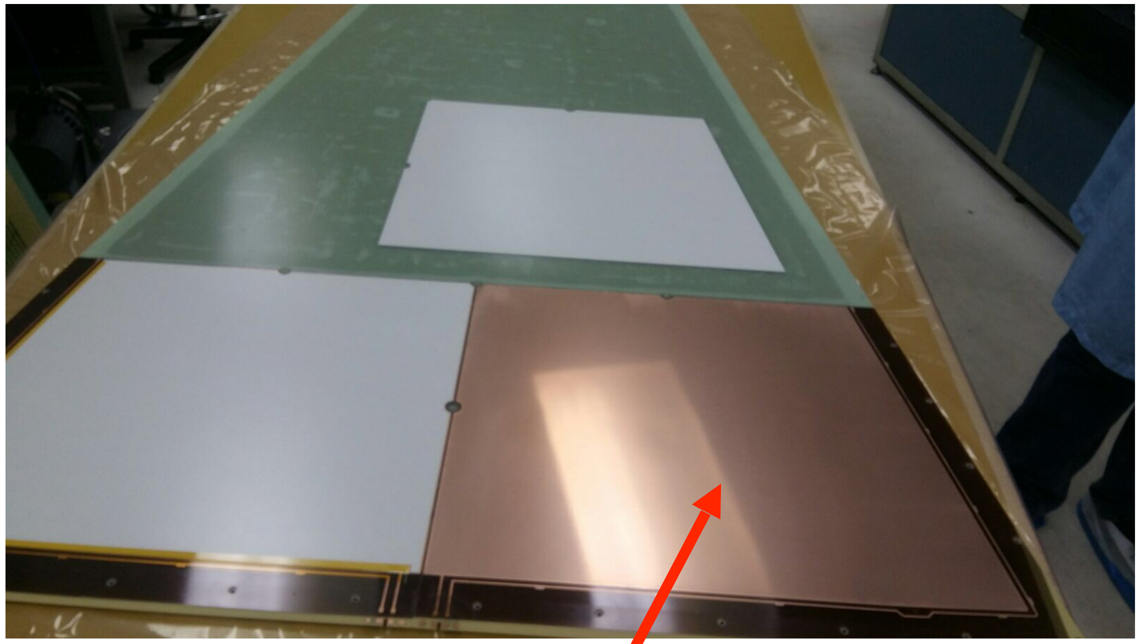
CMS GE2/1 sector μ-RWELL prototype

CMS GE2/1 sector μ-RWELL prototype



M4 μ-RWELL

CMS GE2/1 sector μ-RWELL prototype



M4 μ-RWELL prototype is a trapezoid of ~55-60x50 cm^2

Largest μ-RWELL ever built and operated!

M4 μ-RWELL

CMS GE2/1 sector μ-RWELL prototype

GE2/1 20^0 sector with 2 M4 μRWells
(2 m height, 1.2 m base)

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M4 μ-RWELL

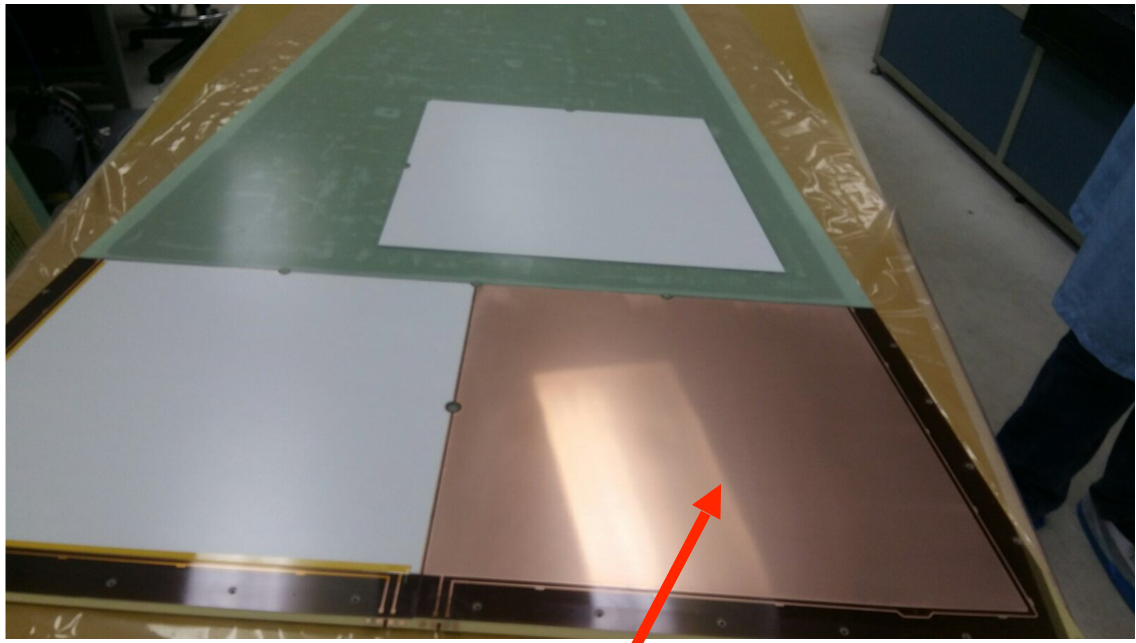
CMS GE2/1 sector μ-RWELL prototype

<u>H4 test beam with 150 GeV muons:</u>

- Voltage scan (amplification scan)
- Uniformity scan across the surface of the detector at 530 V (~12000 gain, still to be conditioned)

The excellent results obtained demonstrate the great collaboration between INFN-Eltos and Rui de Oliveira's lab

GE2/1 20^0 sector with 2 M4 μRWells
(2 m height, 1.2 m base)



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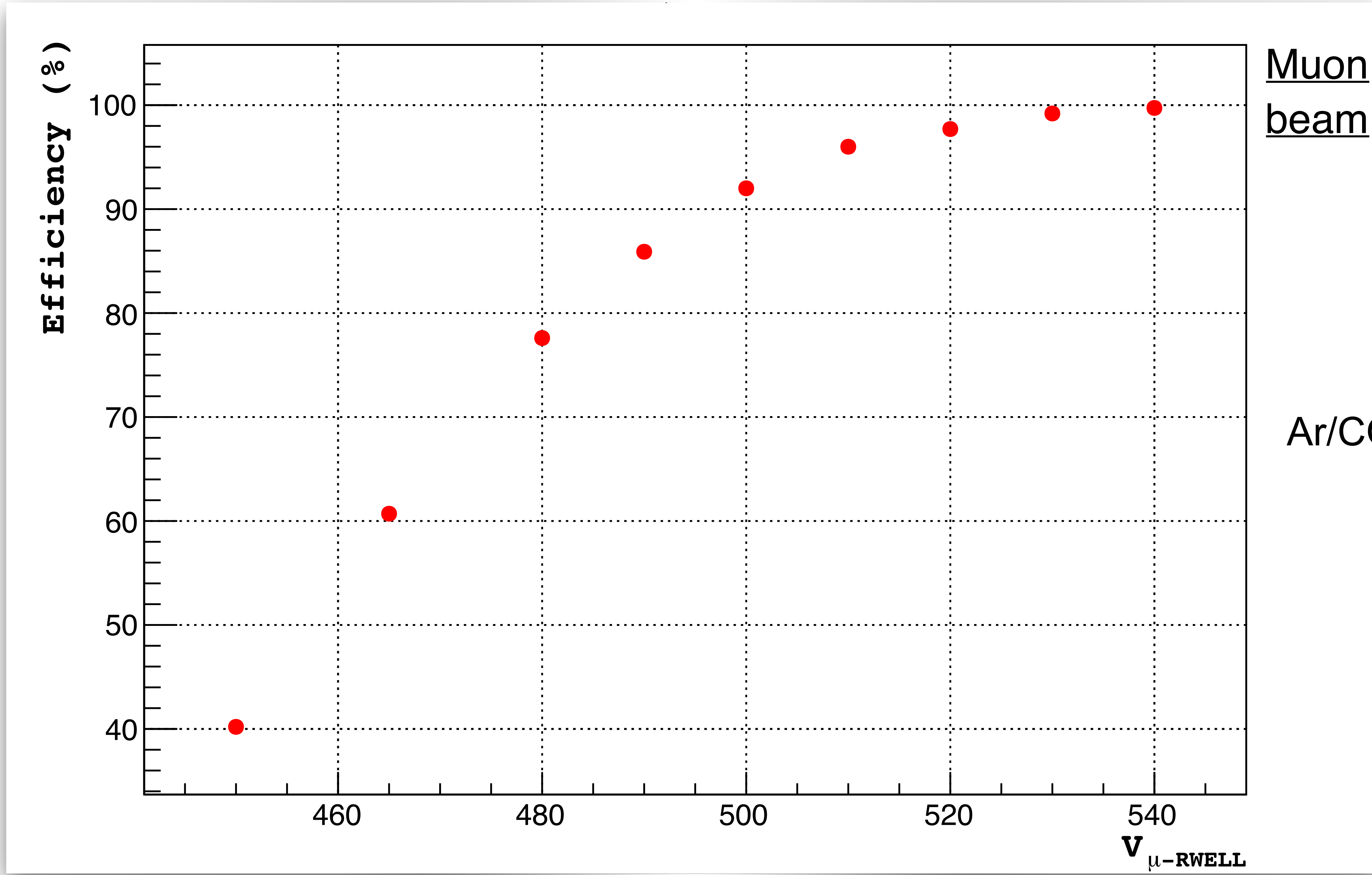
M4 μ-RWELL

CMS GE2/1 sector μ-RWELL: HV scan

M4 right side:

- Drift Field = 3.0 kV/cm
- $V_{\mu\text{-RWELL}}$ = scan

Efficiency = # hits (Tracker 1 & Tracker 2 & M4 right) / # hits (Tracker 1 & Tracker 2)



Muon beam

Ar/CO_2 70/30

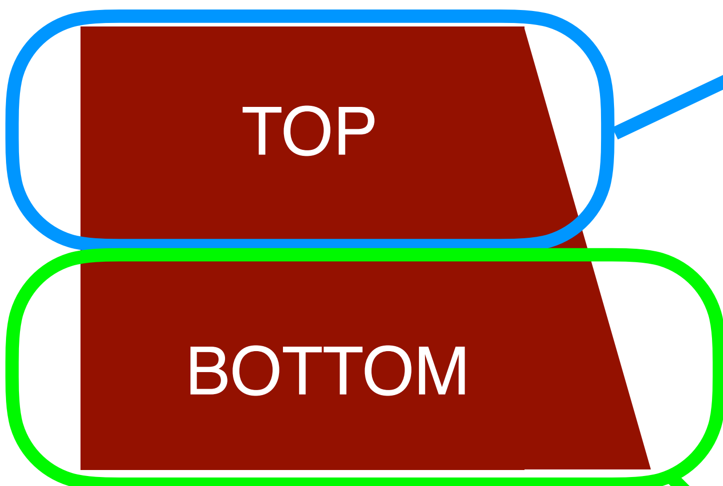
CMS M4 μ-RWELL: homogeneity

Efficiency = # hits (Tracker 1 & Tracker 2 & M4 right) / # hits (Tracker 1 & Tracker 2)

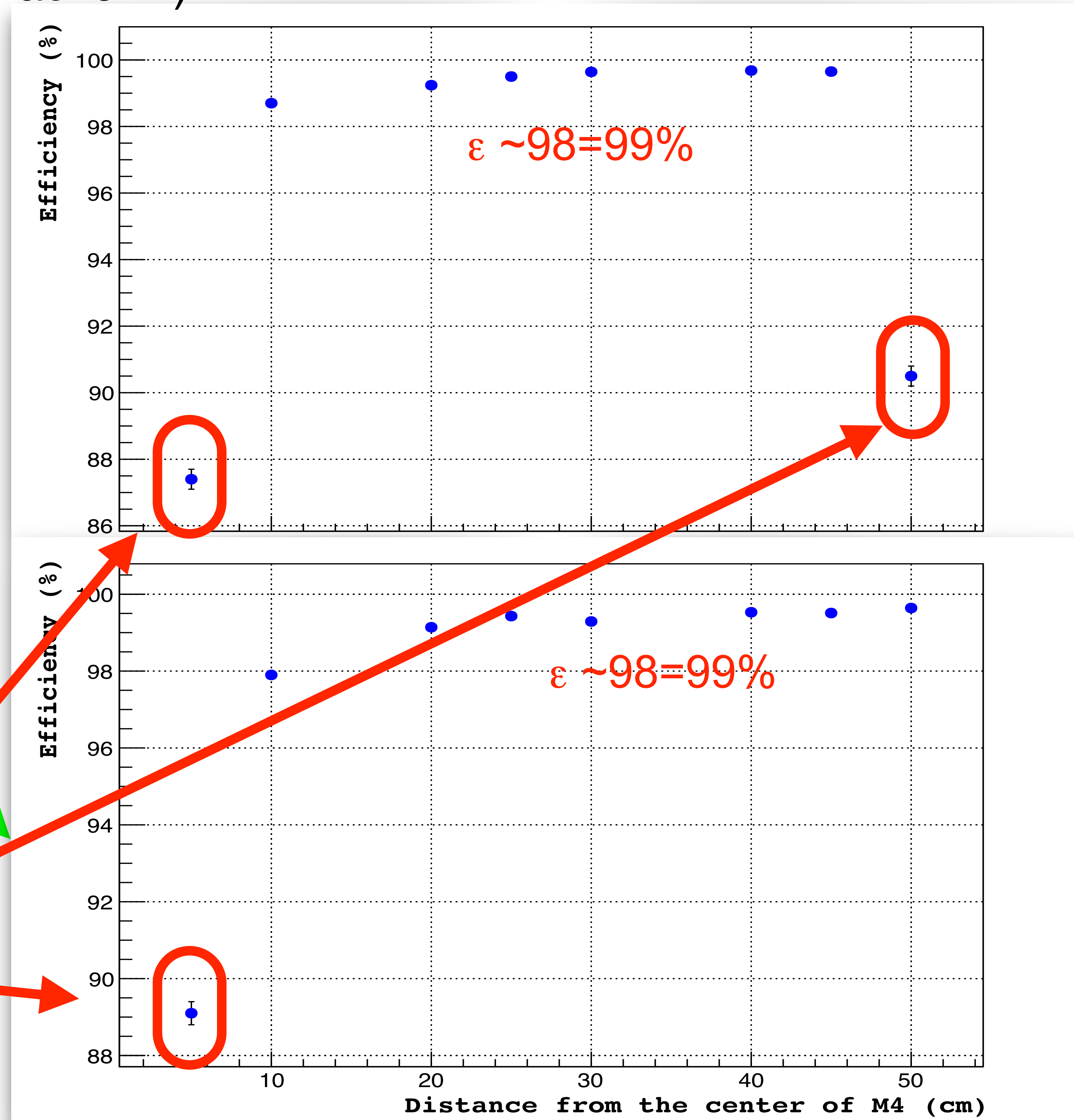
Muon beam

M4 right side:

- Drift Field = 3.0 kV/cm
- $V_{\mu\text{-RWELL}}$ = 530 V



M4 right scheme



Beam on the edge of the detector
NOT inefficiency!!

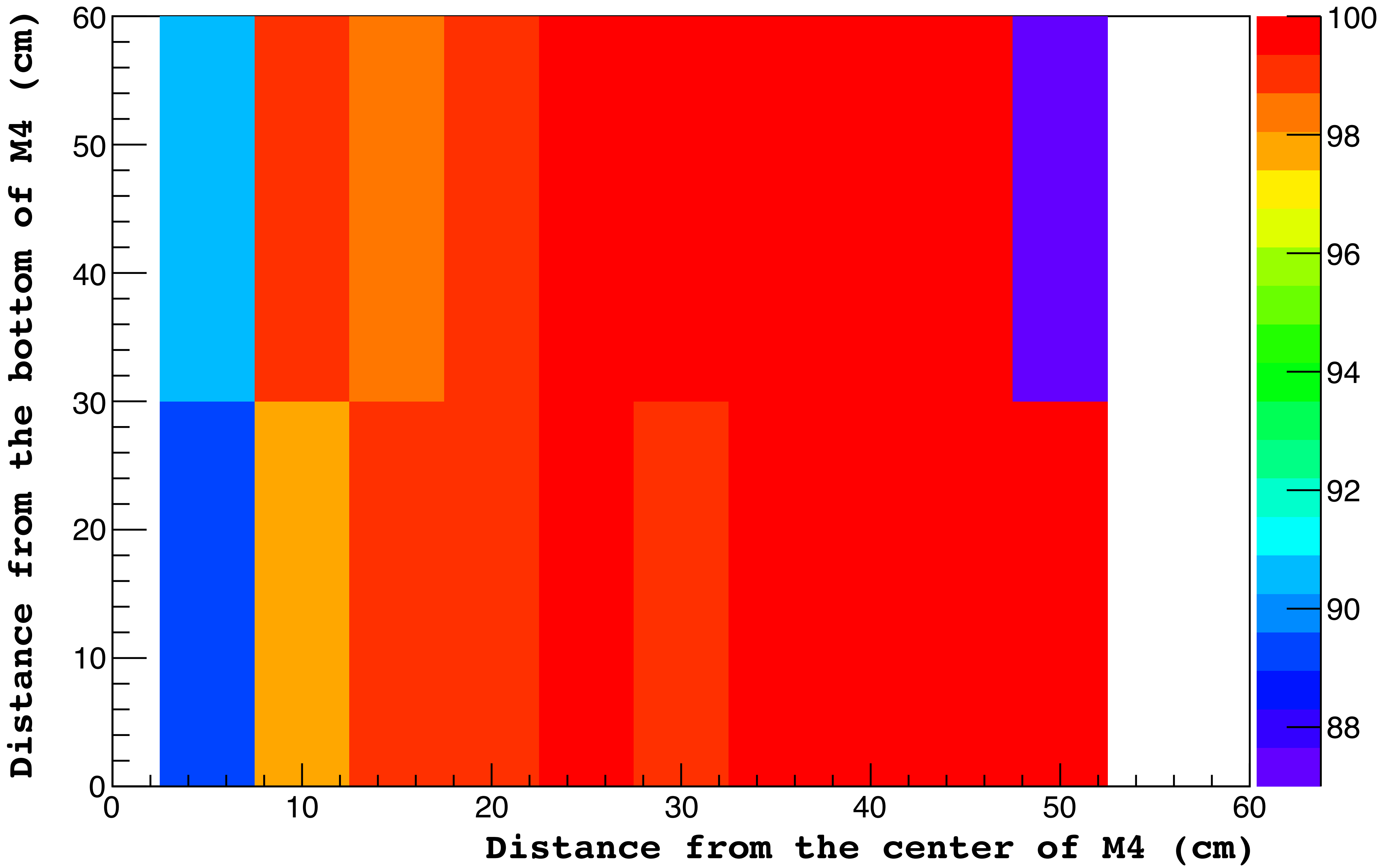
CMS GE2/1 sector μ-RWELL prototype

M4 right side:

- Drift Field = 3.0 kV/cm
- $V_{\mu\text{-RWELL}}$ = 530 V

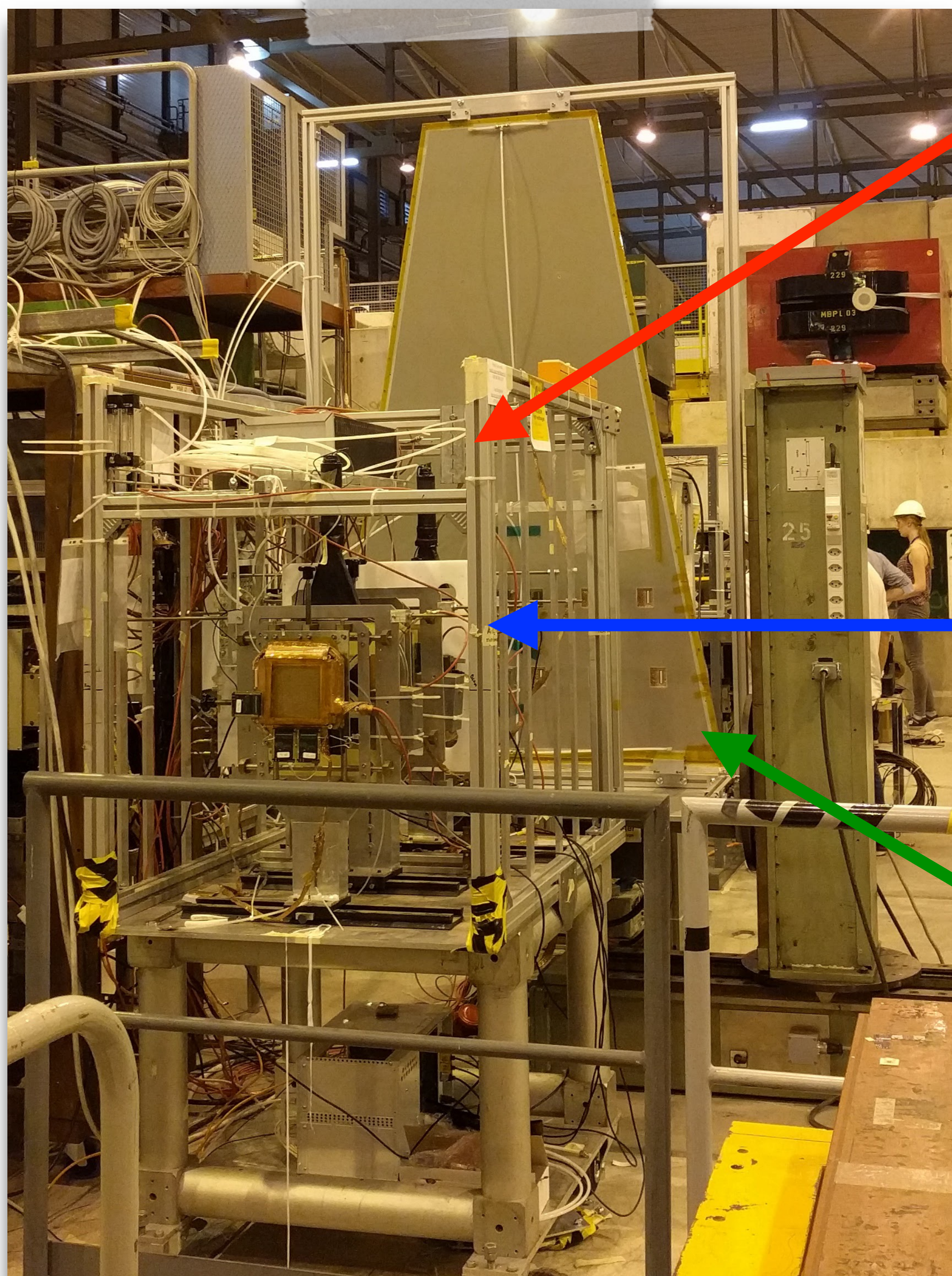
$$\text{Efficiency} = \frac{\text{\# hits (Tracker 1 \& Tracker 2 \& M4 right)}}{\text{\# hits (Tracker 1 \& Tracker 2)}}$$

Muon beam



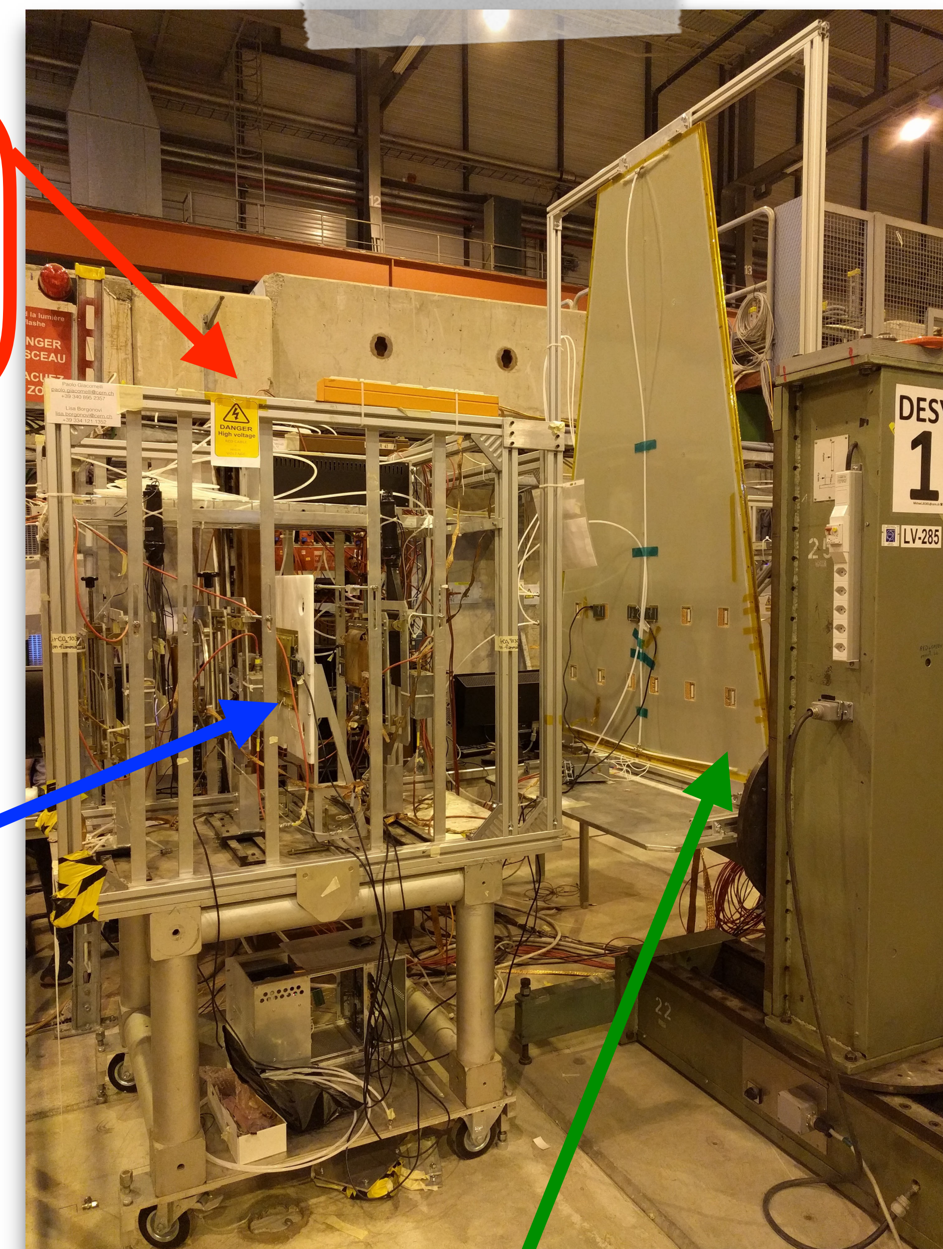
μ-RWELL High Rate version

When: 5 - 19 July 2017



2 GEM Trackers
(10x10 cm²)
RD51 setup

2 μ-RWELLs
(10x10 cm²)
HR scheme



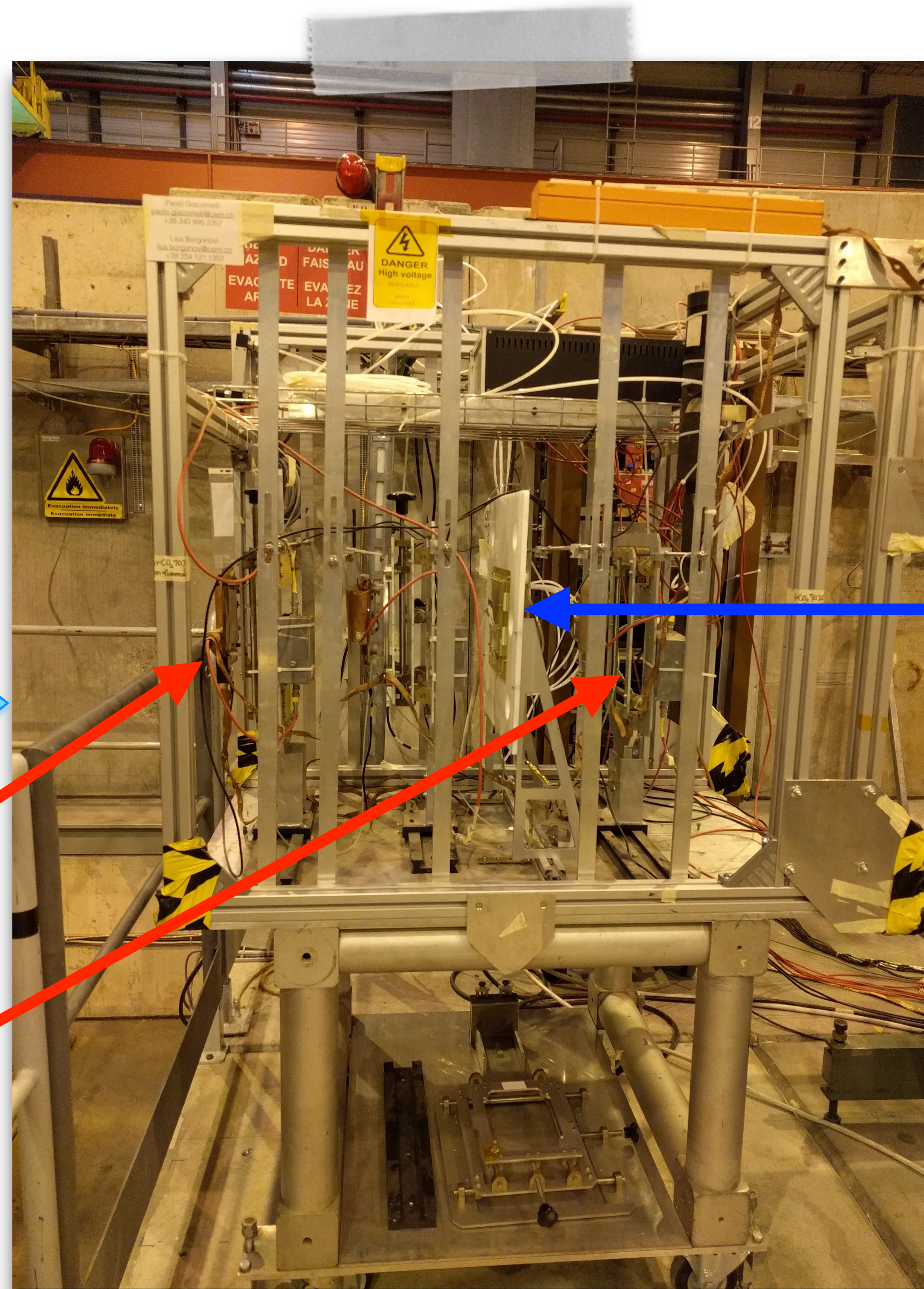
1 μ-RWELL
(CMS-GE2/1 M4 shape)
LR scheme

μ-RWELL High Rate version

Tracker GEMs
gas mixture:
Ar/CO_2 70/30

HR μ-RWELLs
gas mixture:
$Ar/CO_2/CF_4$ 45/15/40

BEAM



HR μ-RWELL prototypes
- 10x10 cm^2
- 6x8 mm^2 pad readout

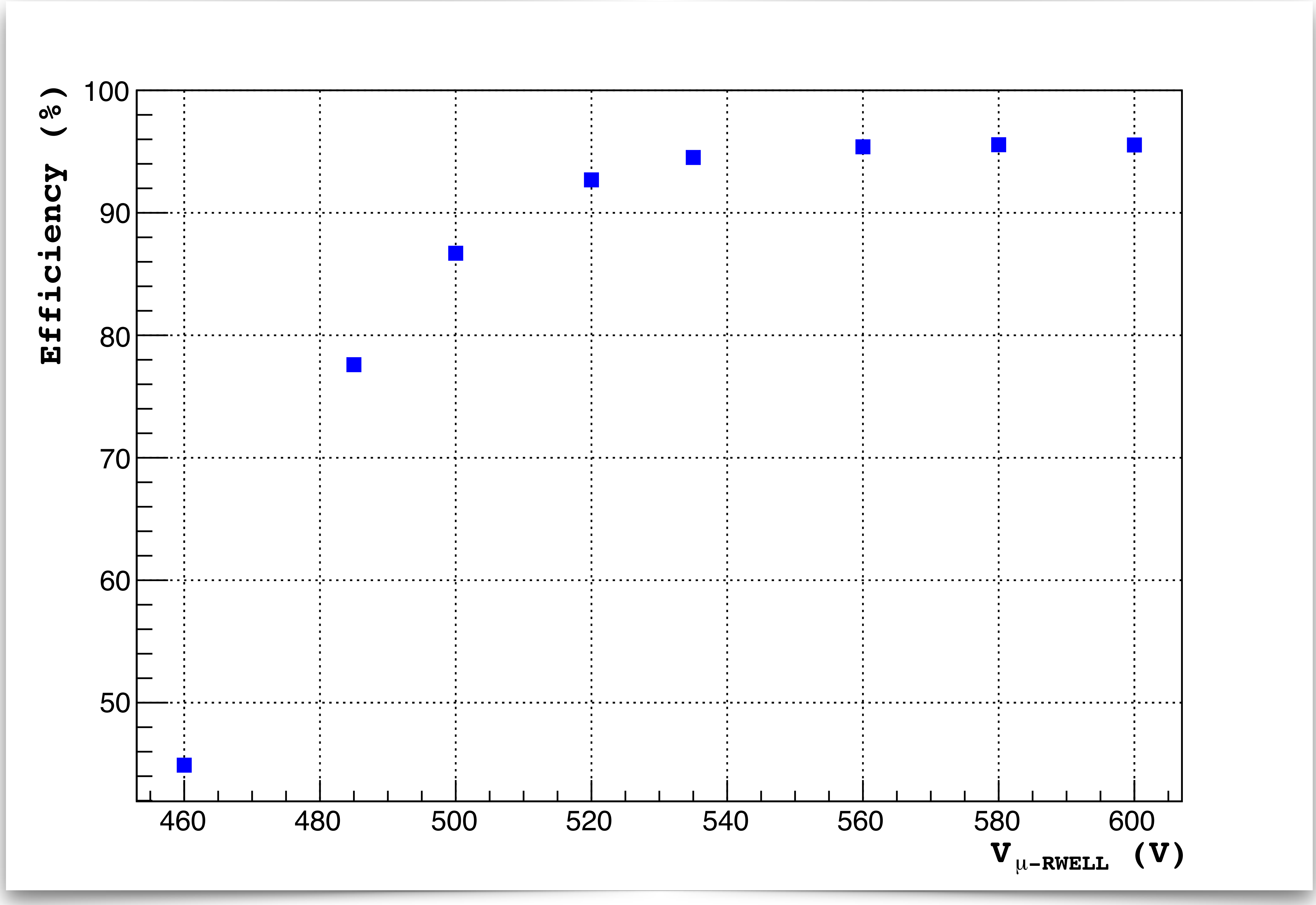
2 GEM Trackers
- 10x10 cm^2
- 400 μm strip-pitch
- X-Y strip readout

All detectors readout:
APV 25
(Charge Centroid analysis)

μ-RWELL High Rate version

- Drift Field = 2.5 kV/cm
- $V_{\mu\text{-RWELL}}$ = scan

$$\text{Efficiency} = \frac{\text{\# hits (Tracker 1 \& Tracker 2 \& HR proto)}}{\text{\# hits (Tracker 1 \& Tracker 2)}}$$

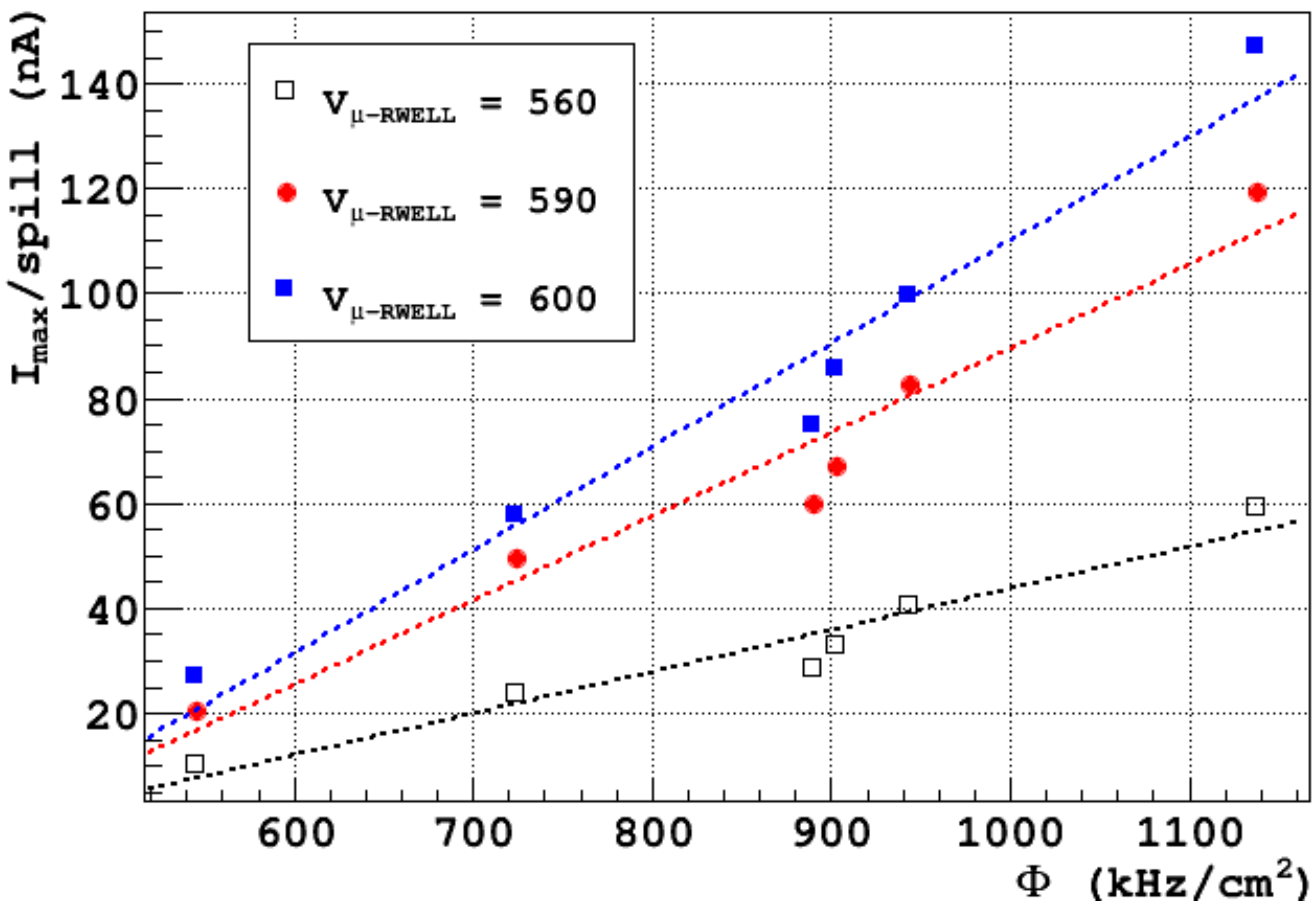


$Ar/CO_2/CF_4$
45/15/40

Courtesy of LNF-DDG

μ-RWELL High Rate: rate capability

Pion beam



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

Courtesy of LNF-DDG

Rate = beam scint. counts/4.2 s/($\sigma_x\sigma_y$*2.53^2)

Beam profile: GEM trackers

Summary of results with μ-RWELLs

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- GE1/1 prototype at H8 test beam in 2016
  - Very good time resolution, σ_t <6 ns (about 4.5 ns obtained)
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  - Excellent uniformity! Efficiency between 98-99% over the whole surface.

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  - Stadalone muon reconstruction
  - Trace back the muon stubs to the tracker tracks
  - Provide excellent momentum resolution and a robust muon trigger
- μ-RWELL technology is also suitable for the muon systems of detectors at future hadron colliders, like FCC-hh

Backup

Muon detectors for FCC-ee

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There are two detector concepts for FCC-ee: the CLD (CLIC-inspired detector) model and the IDEA concept.

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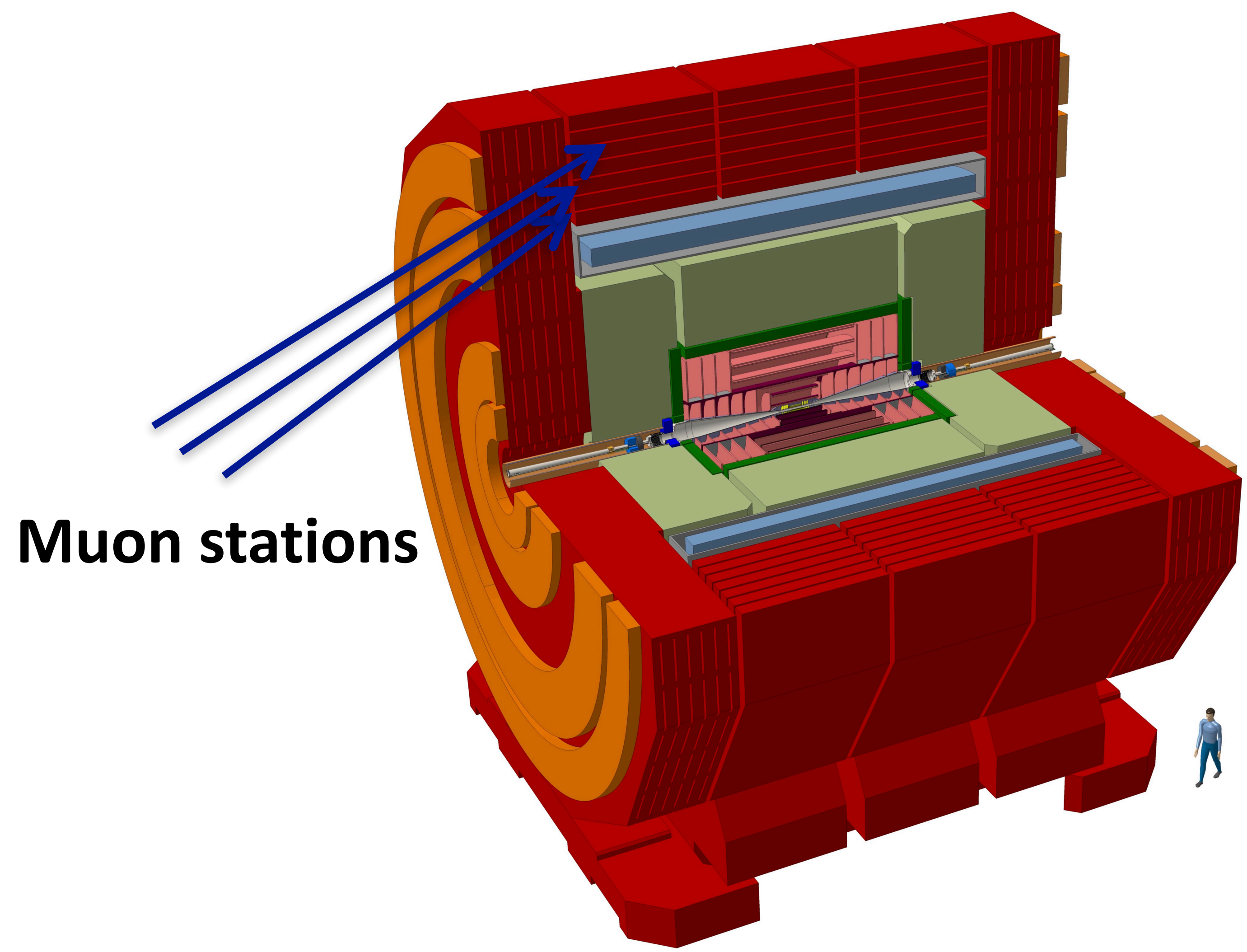

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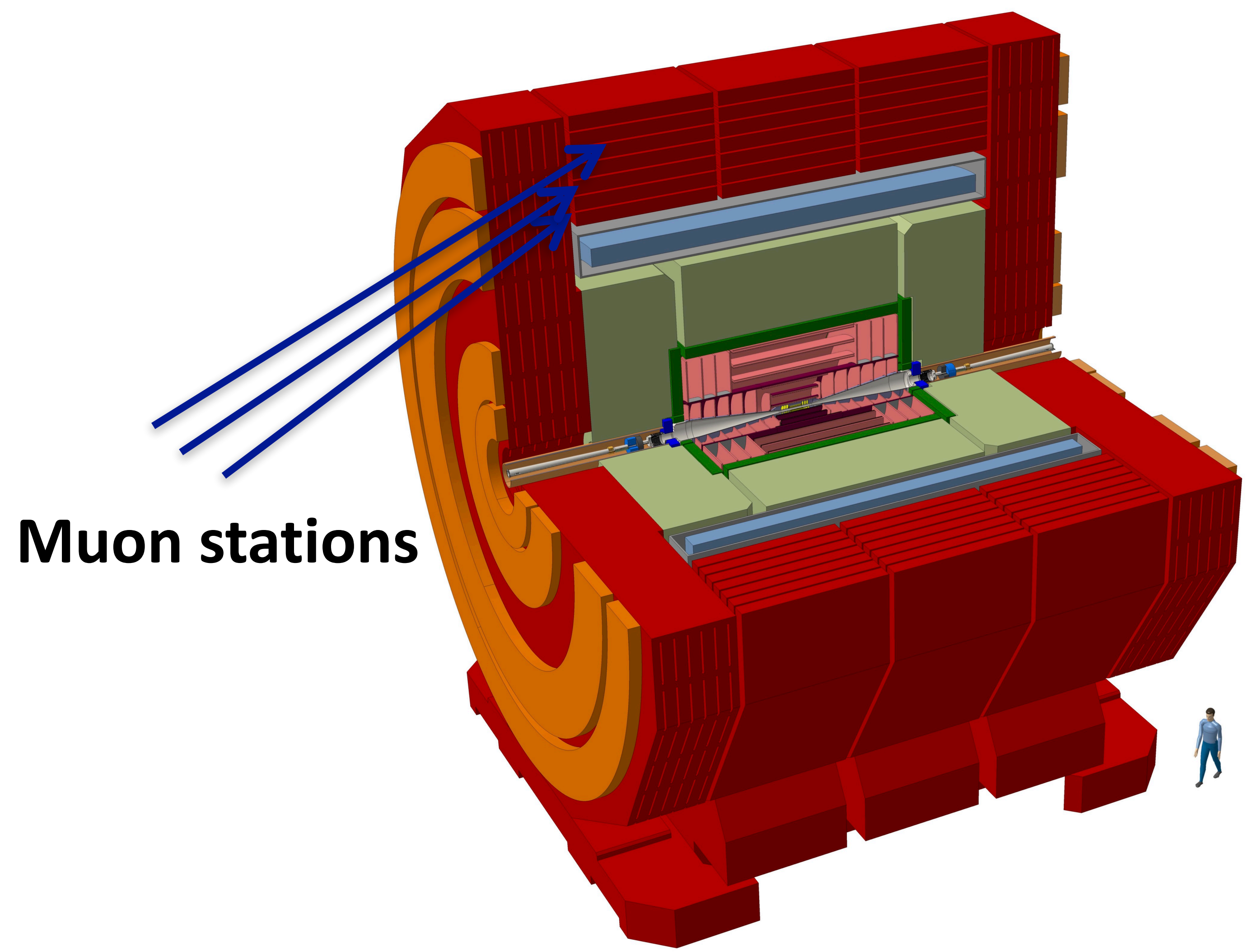
Also this muon detector could be improved by adopting finer space resolution MPGDs.



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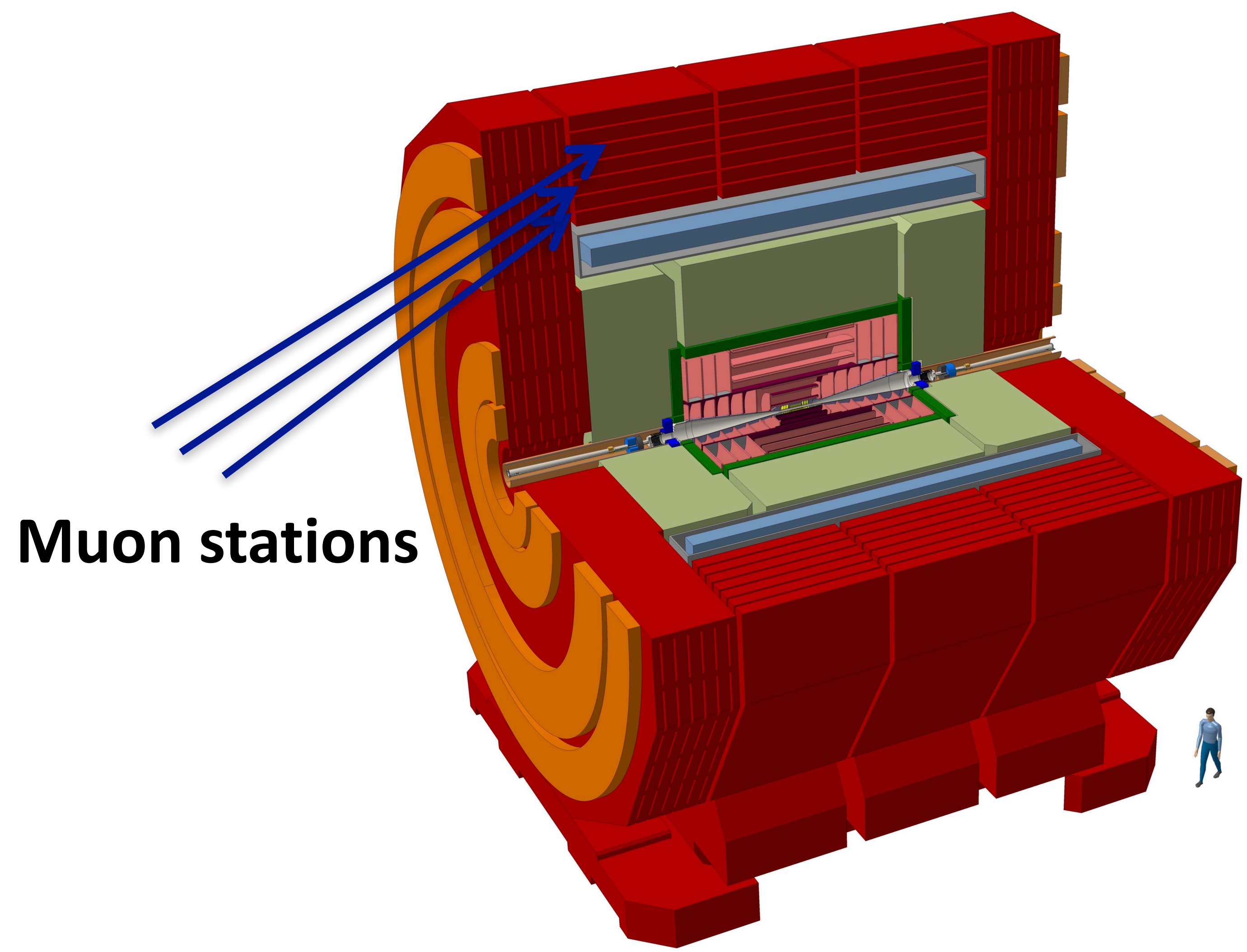
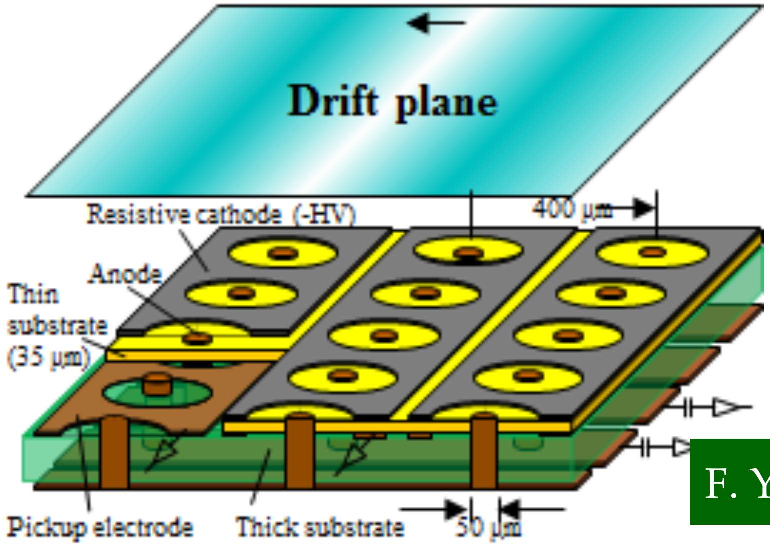


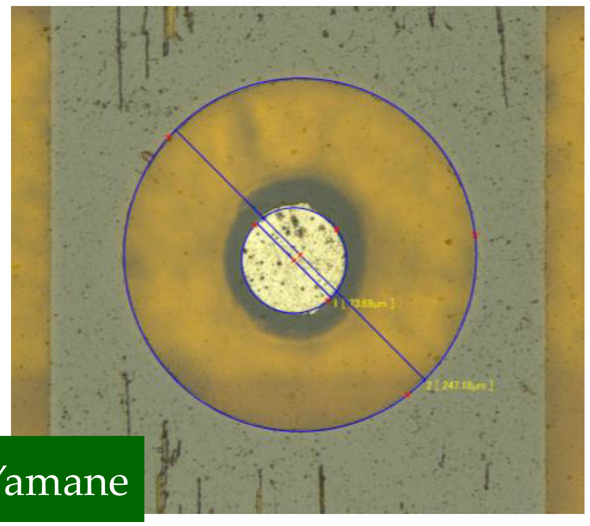
There is also the IDEA concept, discussed in the previous slide.

μPIC / μ-RWELL for ATLAS Large-η Tagger Phase II Upgrade

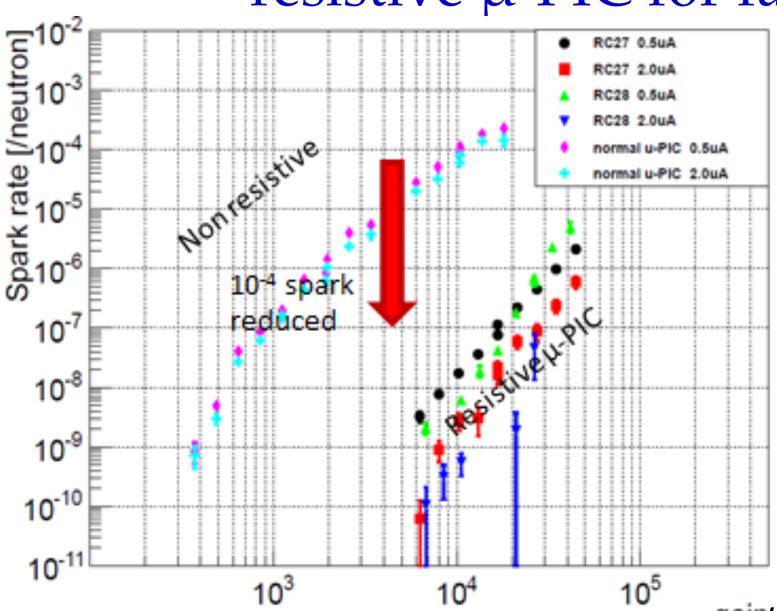
- ➢ Proposed for Phase II upgrade (~2023)
- ➢ Need high granularity ~ 0.1mm
- ➢ BG rate > 100kHz/cm² (HIP, gamma)
- ➢ Rate tolerant, Pixel type detector needed

μ-PIC with resistive Diamond-LC electrodes:

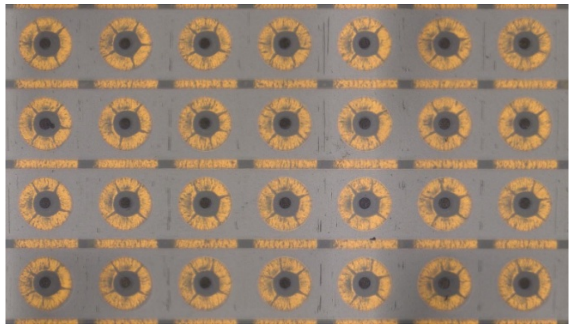




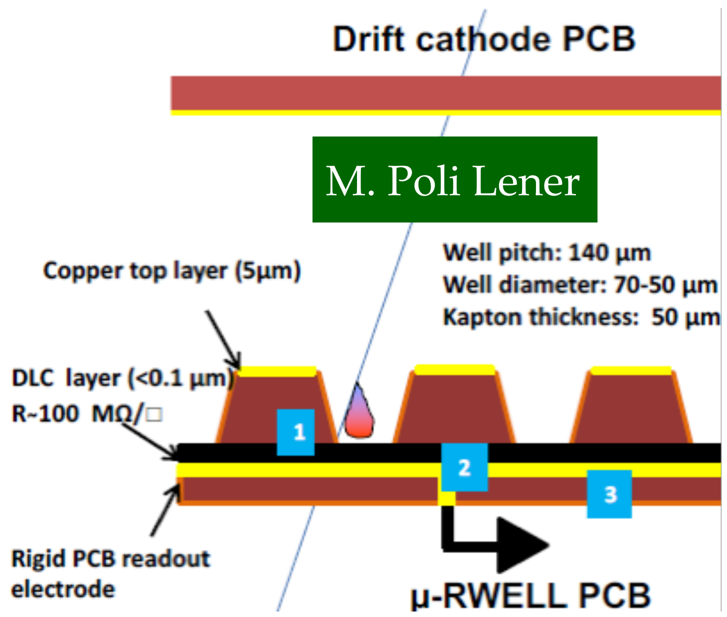
Spark rate reduction using resistive μ-PIC for fast neutron

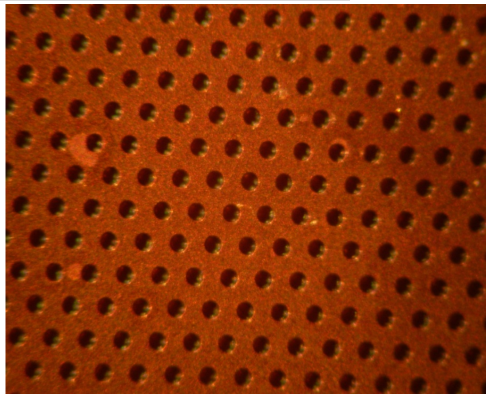


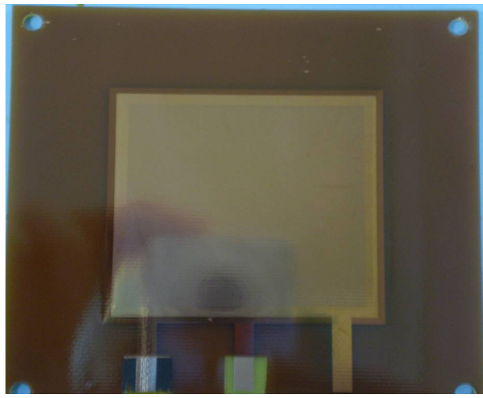
Resistive μ-PIC using sputtered C:



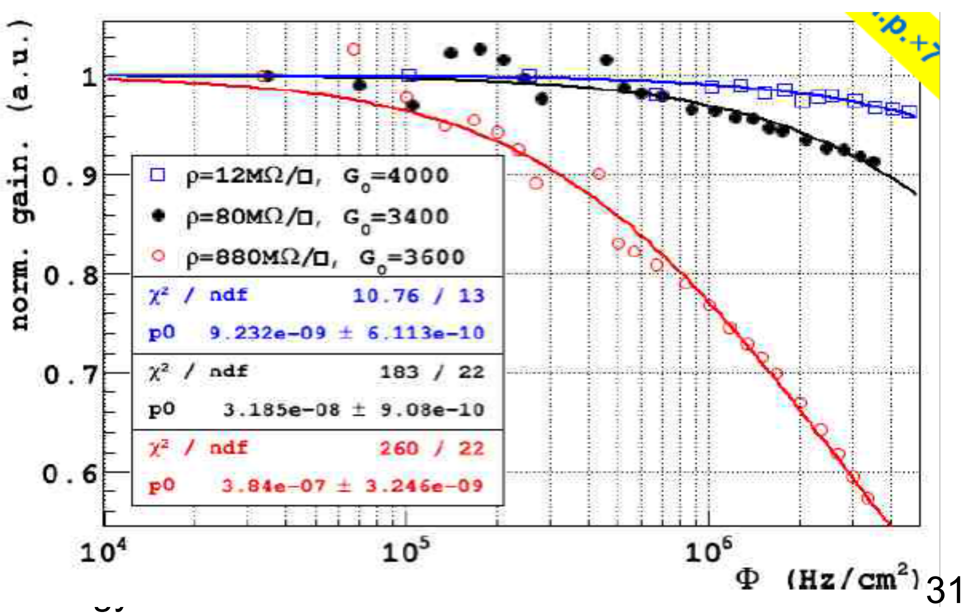
μ-RWELL Detector:







- Very reliable
- Almost completely *discharge-free*
- adequate for high particle rates O(1MHz/cm²) thanks to the *segmented-resistive-layer*
- suitable for large area applications (1.8 x 1.2 m² proto was tested in 2017)

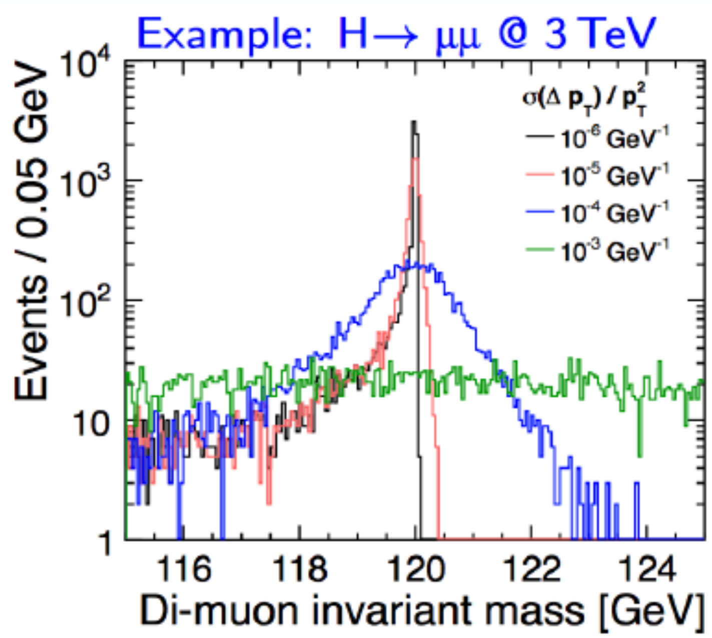


Muon detector for FCC-ee

CLIC Detector requirements from physics

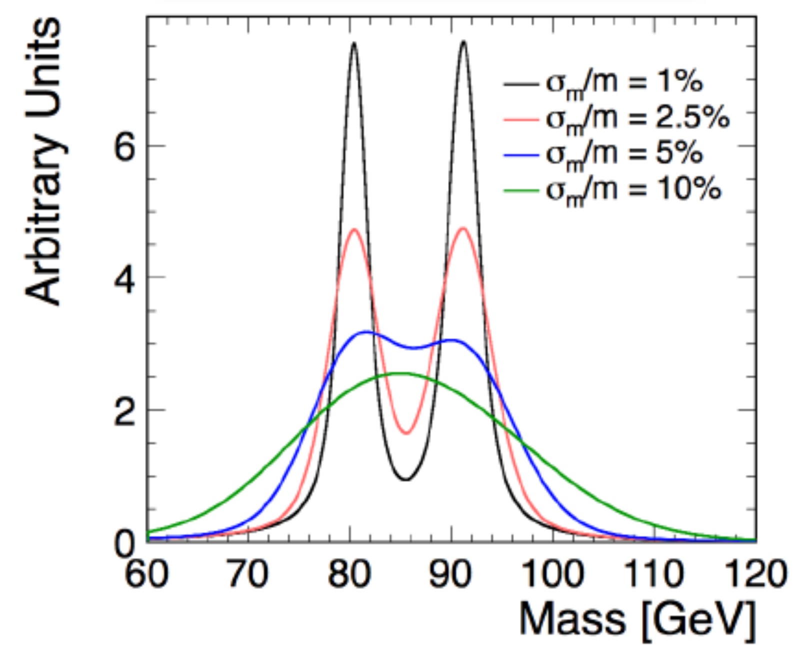
- momentum resolution
  - Higgs recoil mass, Higgs coupling to muons, BSM (smuon and neutralino masses)
  - for high p_T tracks

$$\sigma_{p_T}/p_T^2 \simeq 2\times10^{-5} GeV^{-1}$$



- jet energy resolution
  - W/Z di-jet mass separation
  - jet energy up to 1 TeV

$$\sigma_E/E \simeq 3.5\%$$



- impact parameter resolution
  - c/b tagging, Higgs BR

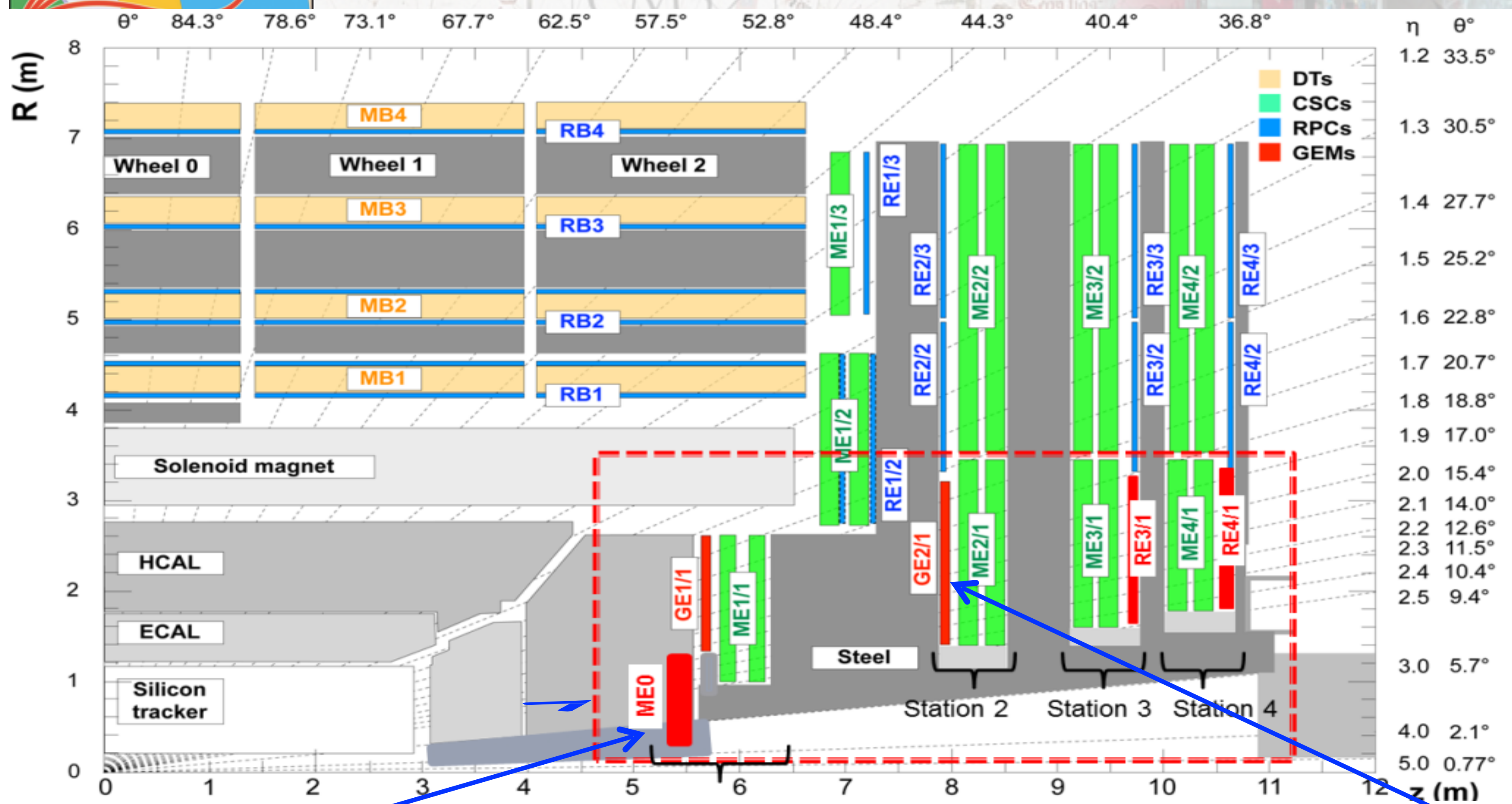
$$\sigma_{d_0}^2 = a^2 + \frac{b^2}{p^2 \sin^3\theta}$$

$$a \lesssim 5\mu m \quad b \lesssim 15\mu m GeV$$

- lepton ID efficiency > 95 %
  - over full energy range

- forward coverage
  - electron and photon tagging (e.g. dark matter studies)

GEM Phase 2 Forward muon system



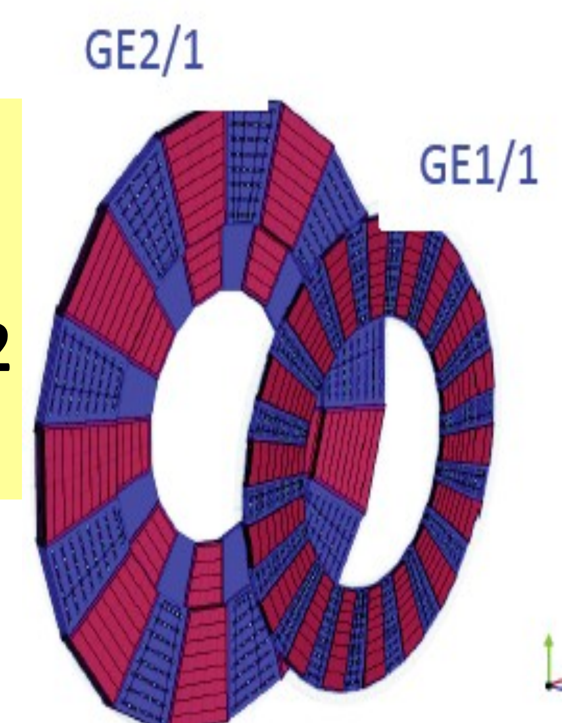
GE21 L1 trigger rate reduction, enhance via redundancy, reconstruction
ME0 detector extends coverage and performance of muon Id and trigger beyond $\eta=2.4$ up to $\eta<2.8$

ME0:

- **Muon tagger** at highest η ($\eta < 2.8$)
- 36 20° super-module wedge each consists 6 layers of chambers.
- **Numb. of chambers: 216**
- **Installation: July 2024**

GE2/1:

- $1.6 < |\eta| < 2.4$
- 36 20° super-chambers
- **Total number of chambers:72**
- **Installation: YETS 2022**



GEM Phase 2 : Trigger and reconstruction

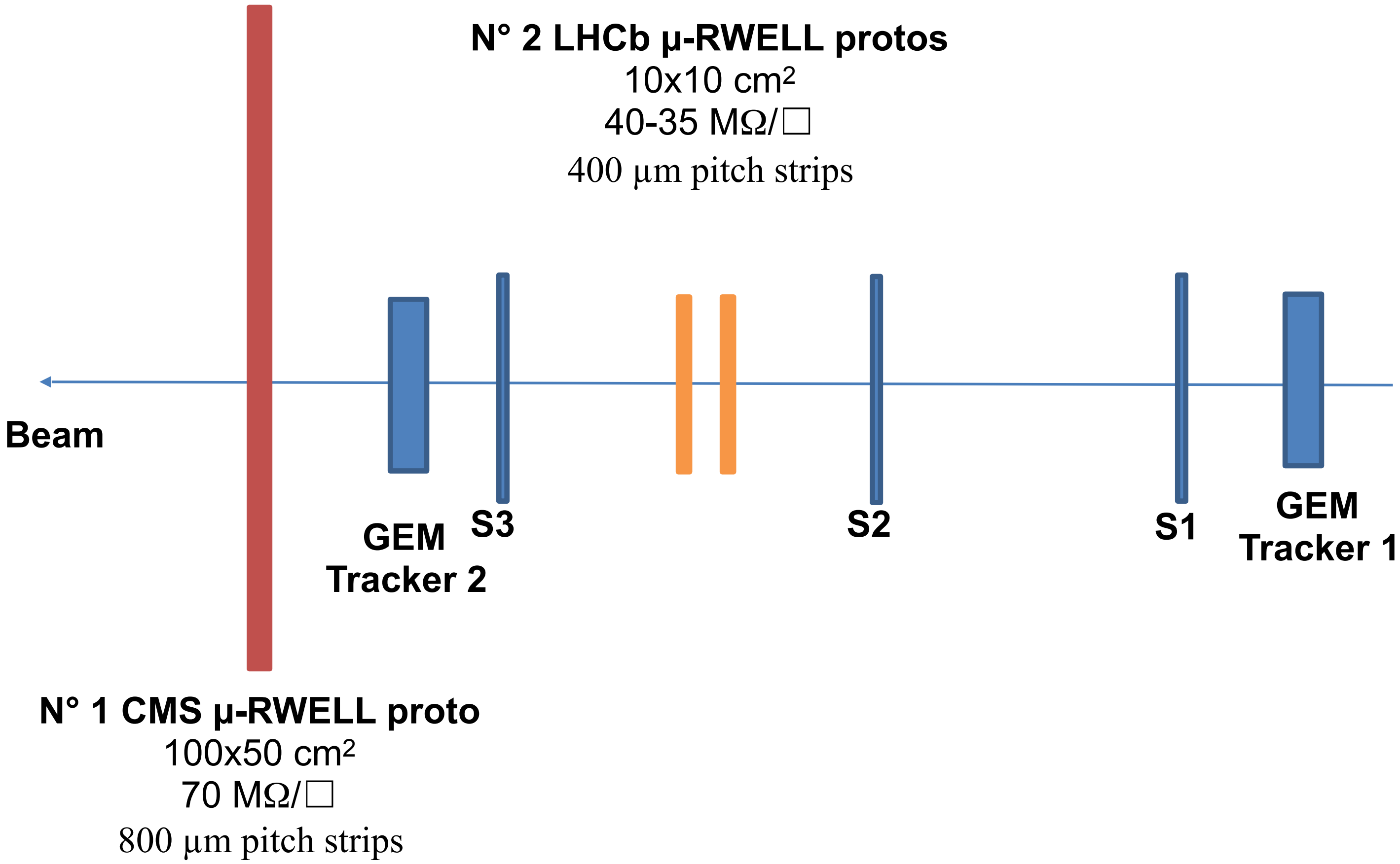
GE1/1 μ−RWELL: test at H8 (nov. 2016)

1. Construction & test of the first **1.2x0.5m² (GE1/1) μ-RWELL** **2016**
2. Mechanical study and mock-up of 1.8x1.2 m² (GE2/1) μ-RWELL **2016-2017**
3. Construction of the first **1.8x1.2m² (GE2/1) μ-RWELL (only M4 active)** **01-09/2017**

GE1/1 μ−RWELL prototype

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

Muon/Pion beam: 150 GeV/c



GE2/1 μ-RWELL: GIF++ ageing test

Context:
CMS Muon System, R&D Phase II Upgrade with MPGD: μ-RWELL

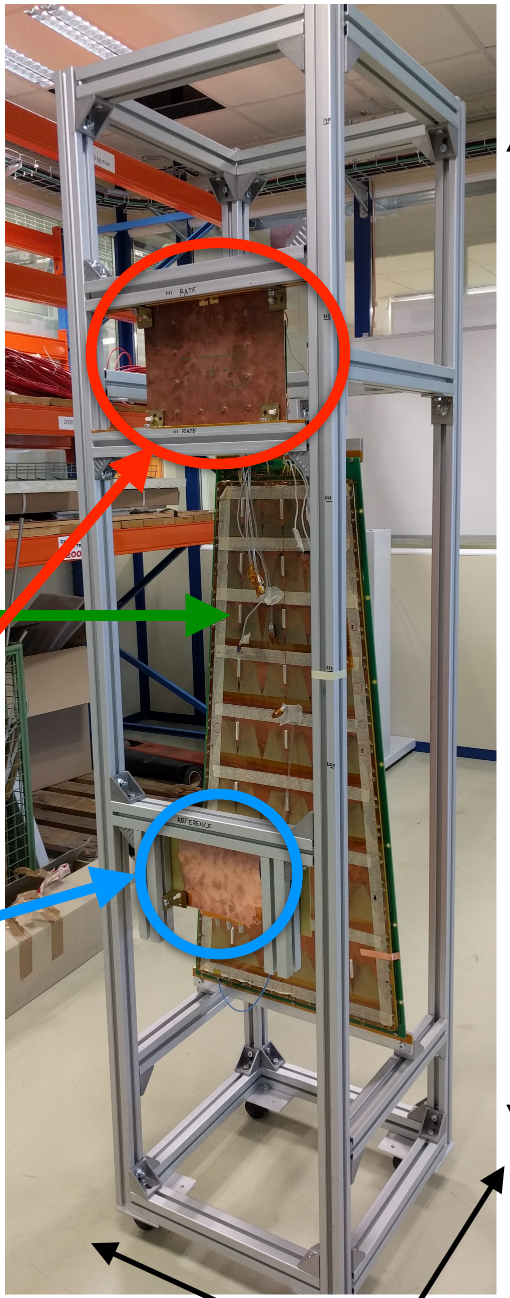
Motivations:
Need to qualify the behaviour and performance of μ-RWELL detectors in a harsh radiation environment.

Duration of the test:
will stay at least 6 months. GE2/1 HL-LHC dose achievable in a short time (few weeks)

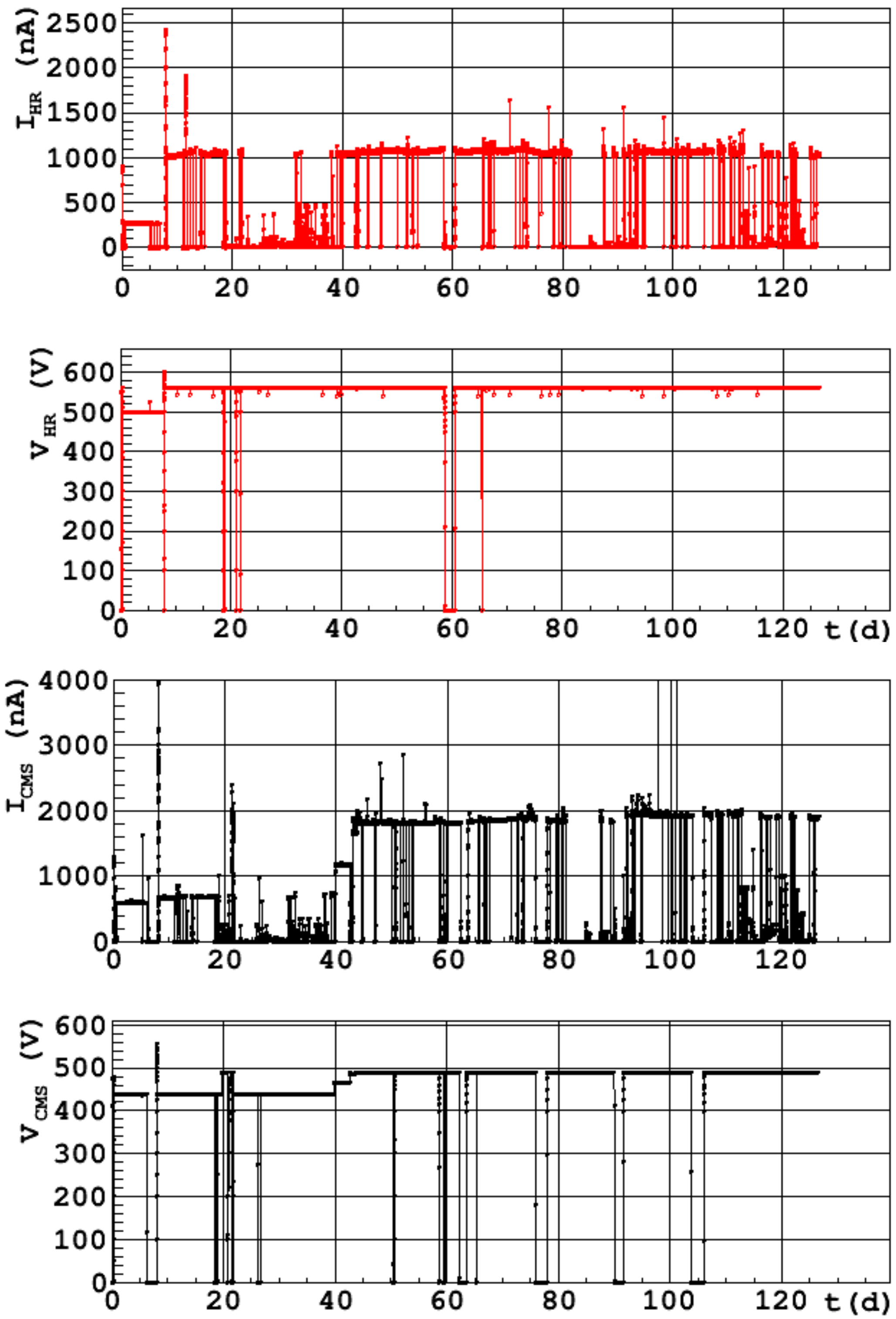
1) **GE1/1 μ-RWELL** ($ArCO_2$)

2) **“high rate” μ-RWELL** ($ArCO_2CF_4$)
10cmx10cm

3) **reference μ-RWELL** ($ArCO_2$)
5cmx5cm



GE2/1 μ-RWELL: GIF++ ageing test

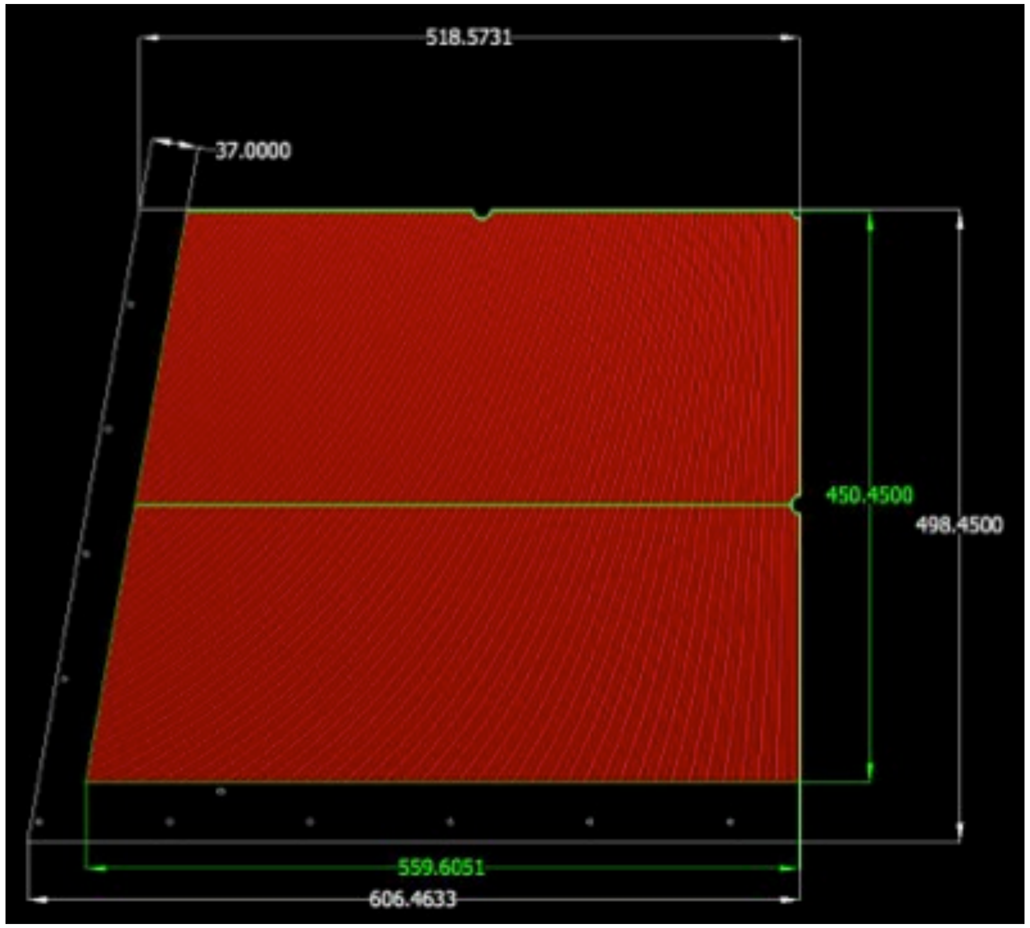


Highest spikes are of the order of 1-2 μA. This further demonstrates the intrinsic robustness of μ-RWELL.

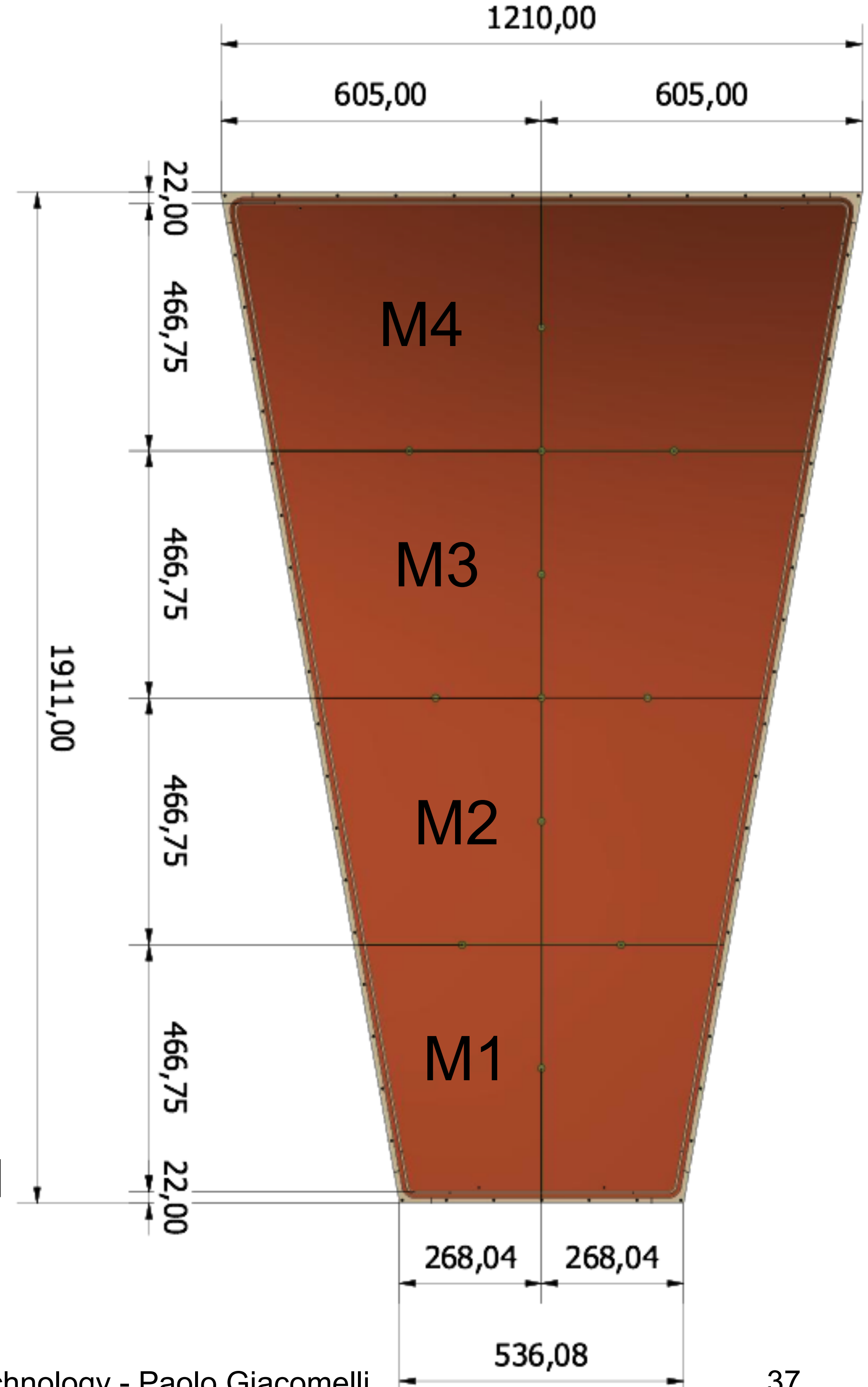
GE2/1 alternative option: μRWELL

We have built a full scale GE2/1 sector with 2 M4 μ-RWELL operating detectors.

1) M4 left and right are mirrored.
2) Size: 606.5 x 498.5 x 1 mm
3) Strip layout inspired to the GE2/1 GEM option
4) Final drawing finished (Gatta-LNF)
5) DLCed foils ready (Ochi-Kobe)
6) Preliminary tests at ELTOS done
7) PCB production at Eltos done, then glueing with kapton foil



Modules fit within 74 mm splicing → dead space less than 0.01%



INFN Istituto Nazionale di Fisica Nucleare

GE2/1 sector equipped with two active M4 μRWELL

M4 μRWell

M4 μRWELL detectors

Brought to H4 test beam on July 12th