# First FCC-Italy Workshop

Roma

21-22 marzo 2022

# R&D on tracking detectors of IDEA

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https://agenda.infn.it/event/29752/

FUTURE CIRCULAR COLLIDER

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# Introduction

- A lot of tracking R&D activities are on-going
  - I have selected a few specific R&D activities relevant to the IDEA detector concept
  - Italian colleagues are heavily involved in all of these activities
- Profiting from different funding sources
  - **National funding**
    - ARCADIA, INFN's CSN1 and CSN5
  - **EU funding** (INFN is playing a leading role in several of them)
    - AIDAinnova
    - EURO-LABS (coming shortly...)
    - Cremlin2 (now halted), FEST (suspended for Covid, hope to restart in 2022)
- Sinergies with other developments
  - CEPC
  - LHCb upgrade, MEG2, STCF

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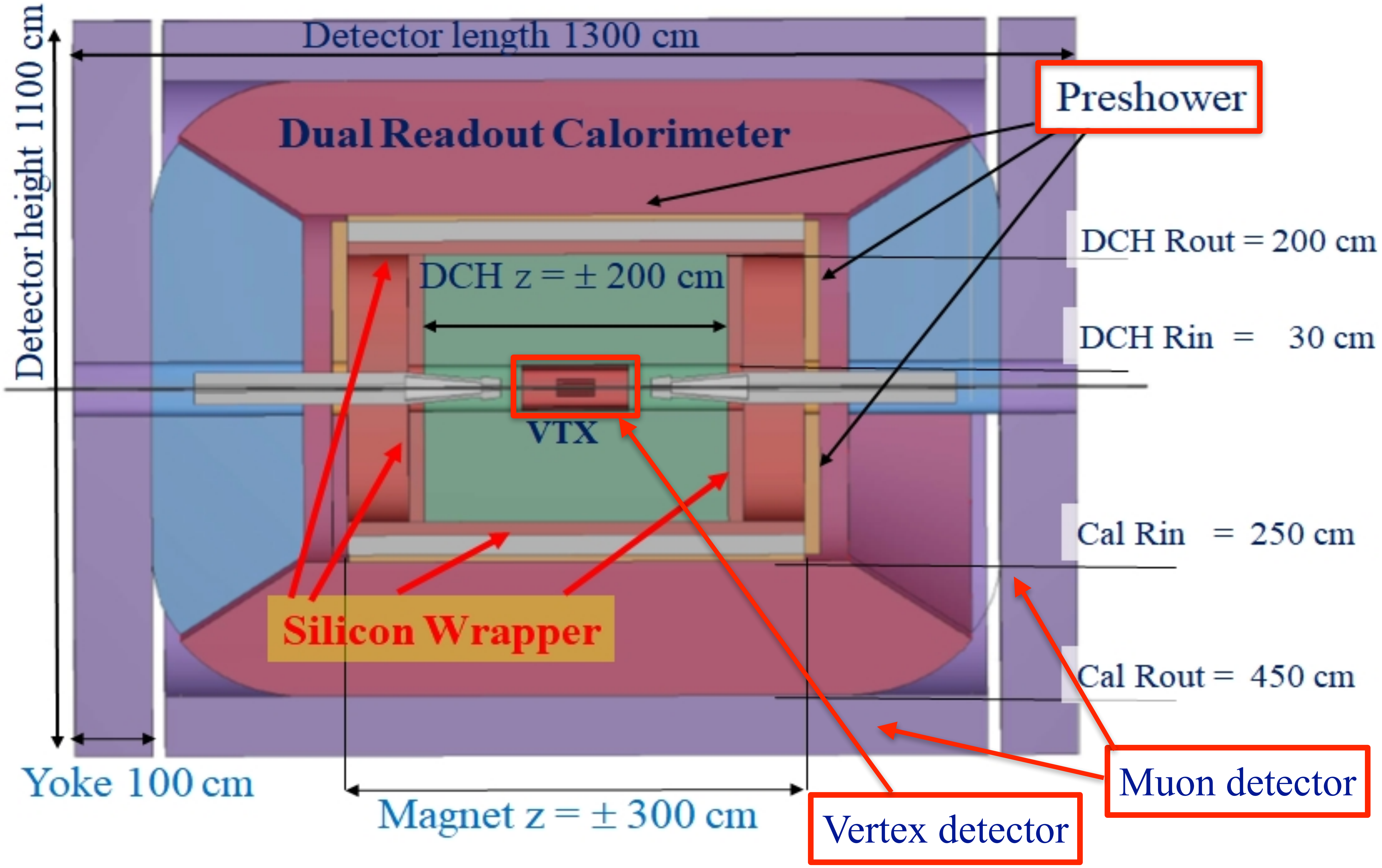
BARI
BOLOGNA
FERRARA
LECCE
LNF
MILANO
PISA
TORINO

**Acknowledgments**

I need to thank many colleagues, in particular:
A. Andreazza, F. Bedeschi, F. Grancagnolo,
M. Rolo and R. Santoro

# IDEA detector layout




**Detector for circular lepton collider**

- New, innovative, cost-effective concept
  - Silicon vertex detector
  - Short-drift, ultra-light wire chamber
  - Si wrapper
  - Preshower
  - Dual-readout calorimeter
  - Thin solenoid coil *inside* calorimeter system
  - Muon system, 3 layers of μ-RWELL detectors in the return yoke

https://pos.sissa.it/390/

# $e^+e^-$ detector requirements

| Physics process | Measur[illegible] | [illegible] | Performance requirement |
|---|---|---|---|
| $ZH, Z \to e^+e^-, \mu^+\mu^-$ <br> $H \to \mu^+\mu^-$ | $m_H, \sigma(ZH)$ <br> $\mathrm{BR}(H \to \mu^+\mu^-)$ | Tracker | $\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$ |
| $H \to b\bar{b}/c\bar{c}/gg$ | $\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$ | Vertex | $\sigma_{r\phi} = 5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$ |
| $H \to q\bar{q}, WW^*, ZZ^*$ | $\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$ | ECAL <br> HC[illegible] | $\sigma_E^{\mathrm{jet}}/E = 3 \sim 4\%$ at 100 GeV |
| $H \to \gamma\gamma$ | BR($H$ [illegible] | [illegible] | $\Delta E/E = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$ |

High precision measurement at end of tracking volume

Challenging requirements on detector material

Finely segmented vertex detector

- Similar approaches for ILC, CLIC, FCCee, CepC:
  - High resolution **pixel vertex detector** O(few $m^2$)
  - Either **full silicon tracker** or **central gas chamber + Si wrapper** O(100 $m^2$)
  - Light detectors, as little material as possible for best possible momentum measurement

# Vertex detector

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## ***Requirements***

Fast readout (***one full frame read-out in less than ~ 85 µsec***), low power consumption (***< 20 mW/cm$^2$***), low material budget (***0.15% $X_0$***), single point resolution of: ***~ 3 µm***

**Today: ALICE ITS*** (**5 µm** spatial resolution, **> 100 kHz** readout, **0.3-1% $X_0$**, **41-27 mW/cm$^2$**)

**Tomorrow:** Exploit what is being done (e.g. **ARCADIA** - INFN project).

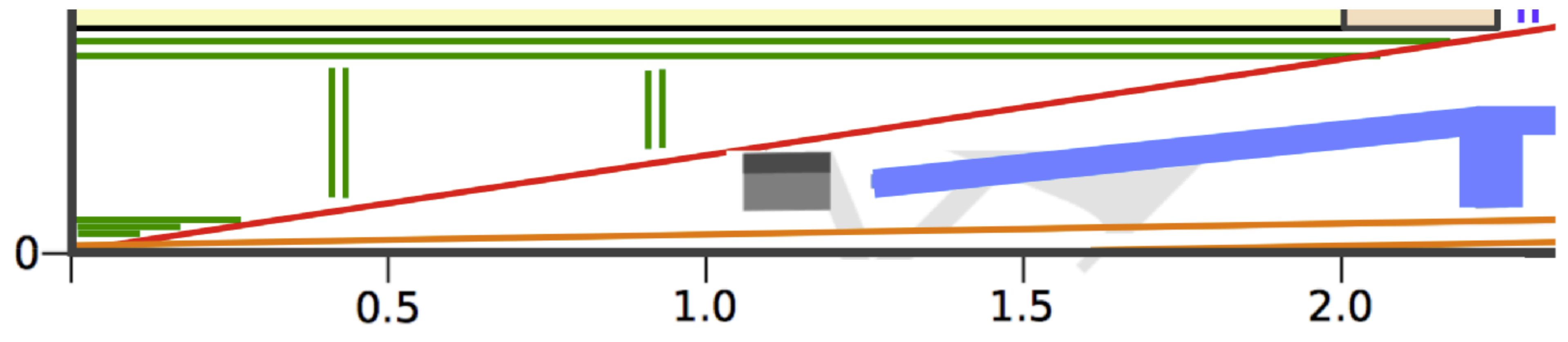
***5 MAPS*** layers:

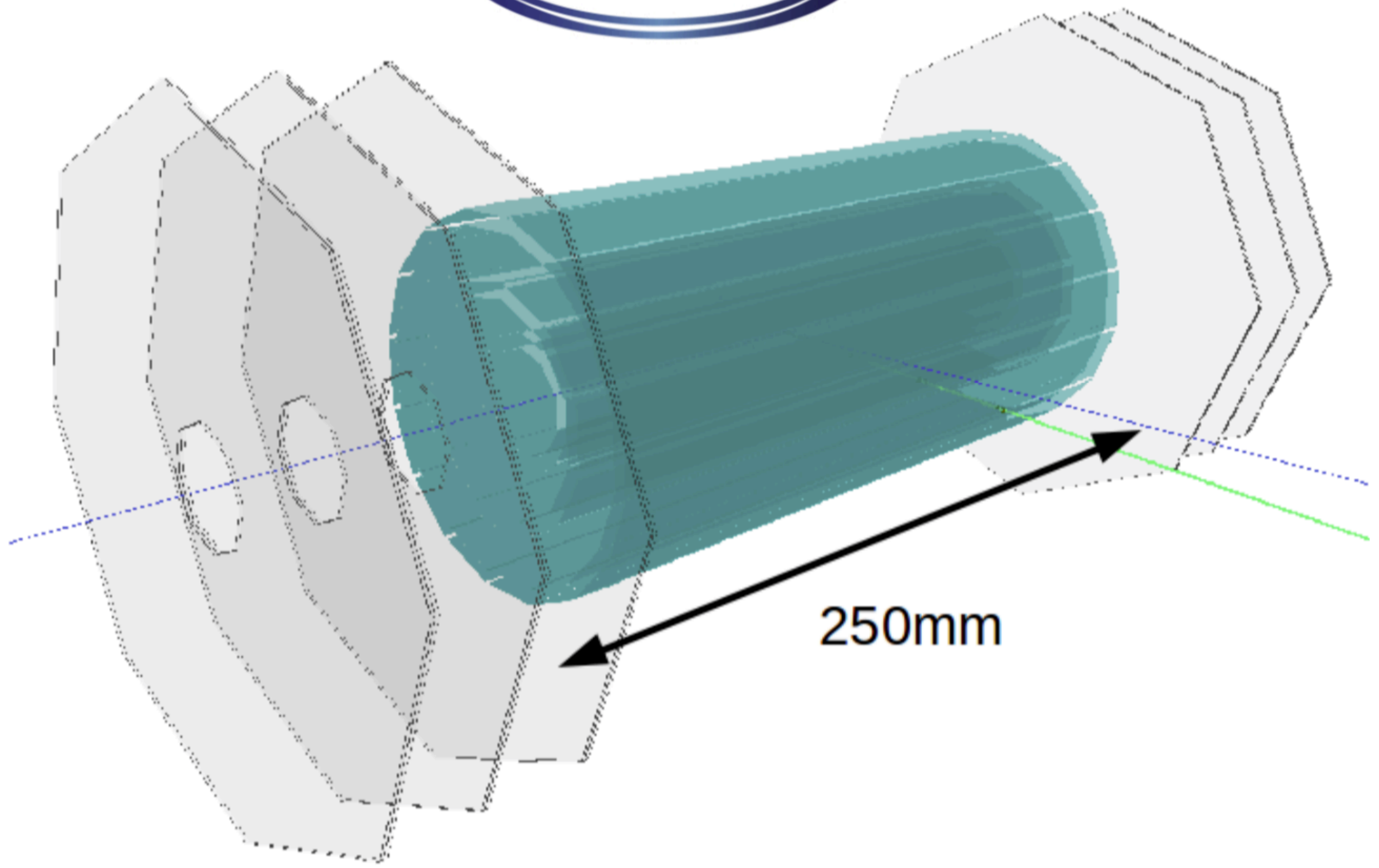
R = 1.7 - 2.3 - 3.1 cm

Pixel size: 20 x 20 µm$^2$

R = 32 - 34 cm

Pixel size: 50 x 100 µm$^2$



# ARCADIA project

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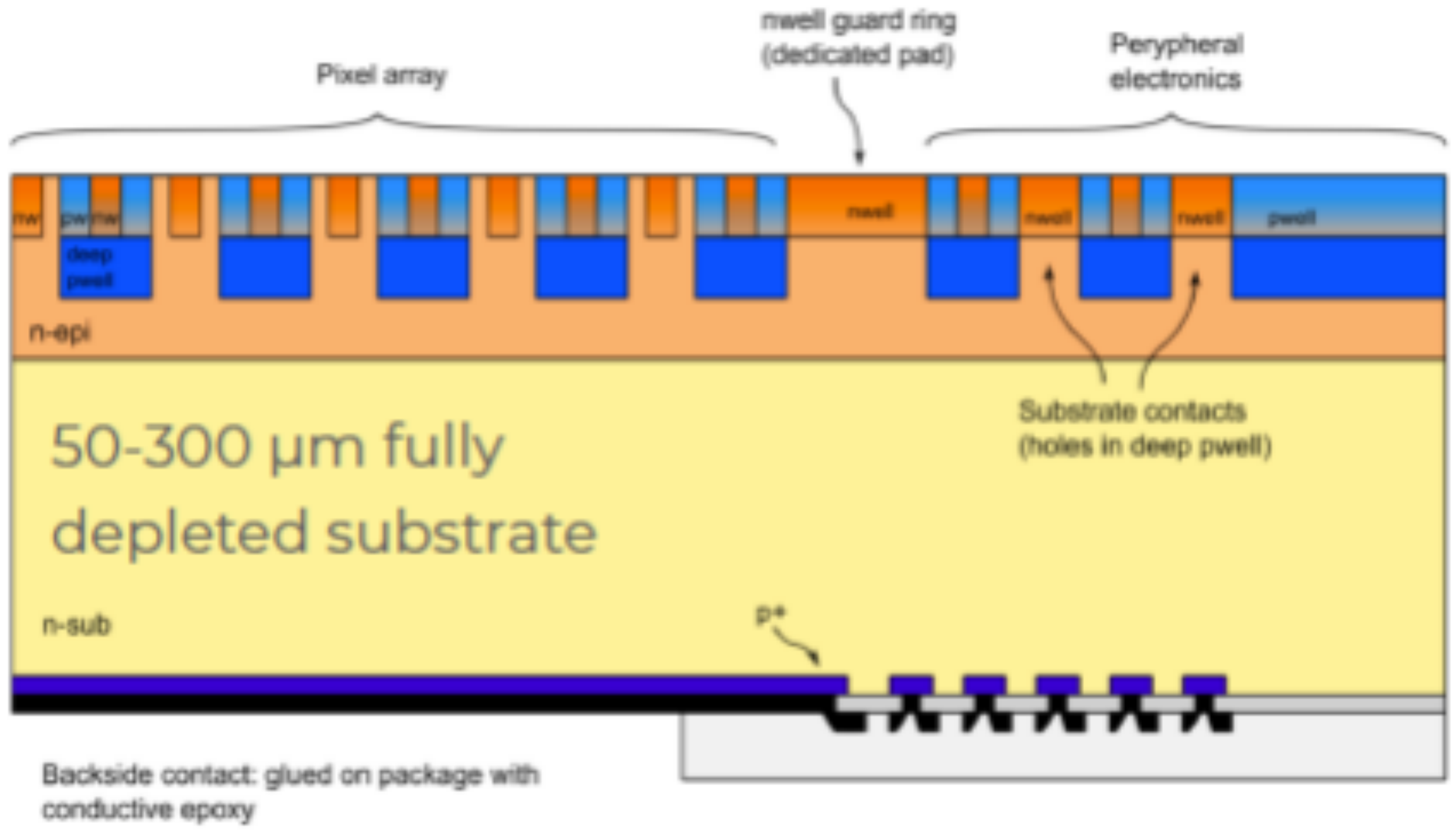
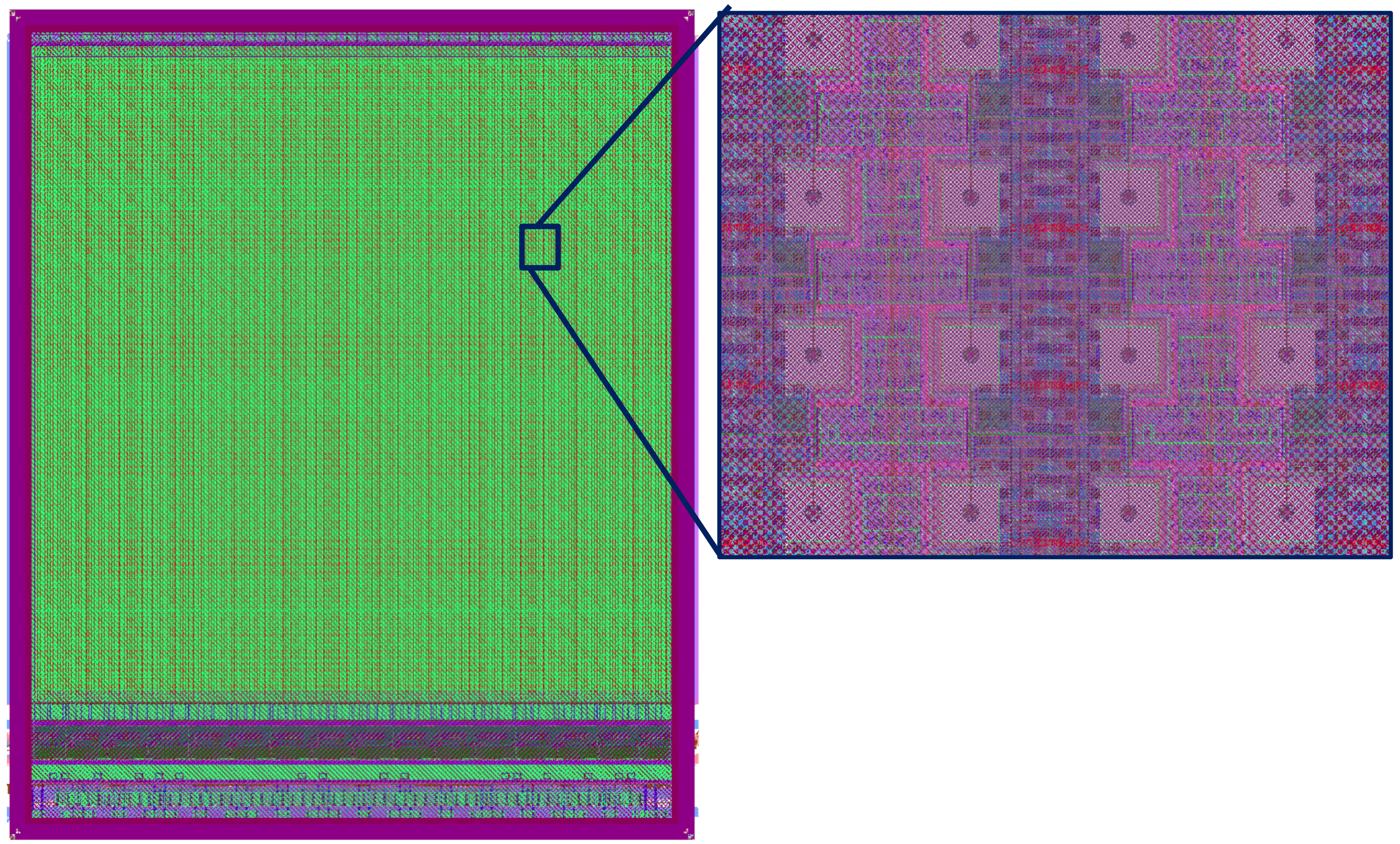
- CMOS DMAPs Platform
  - Started as INFN project,
    collaborations with Switzerland and China
  - Project within AIDAInnova WP5
- Fully depleted monolithic sensor
- LFoundry 110 nm CMOS process
- Pixels:
  - sensor and back-side processing already tested
    on silicon
  - $25 \times 25\ \mu m^2$ size
  - pixel area 50% analog – 50% digital
  - small collection electrode (20% of pixel area)
  - versions with ALPIDE and BULKDRIVEN front-ends
  - characterization of the readout architecture ongoing




ARCADIA-MD1: Integration



# ARCADIA-MD2

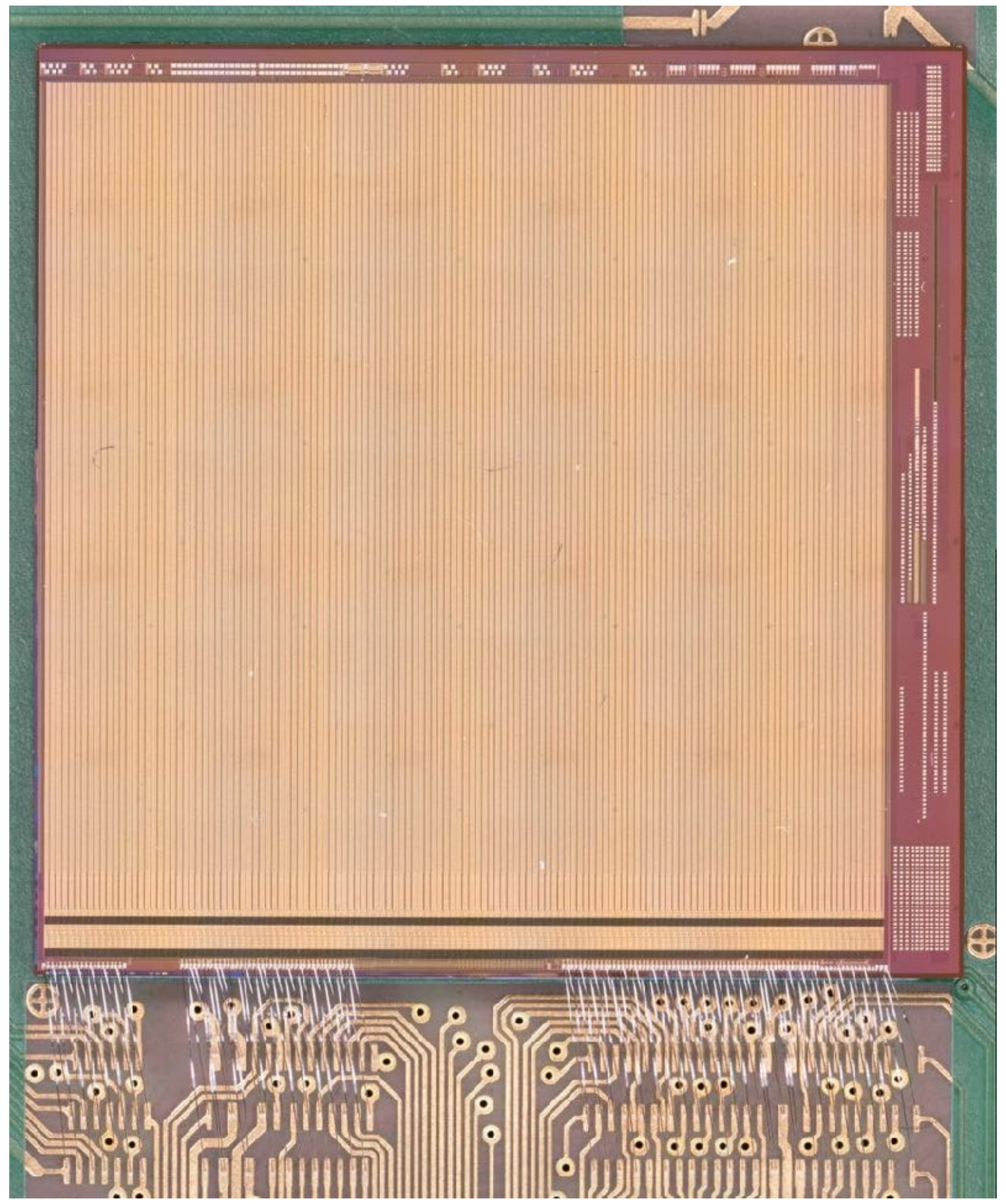
A second main demonstrator (codename ARCADIA-MD2) has been submitted in Summer 2021, featuring design and architecture improvements targeting power reduction, scalability.

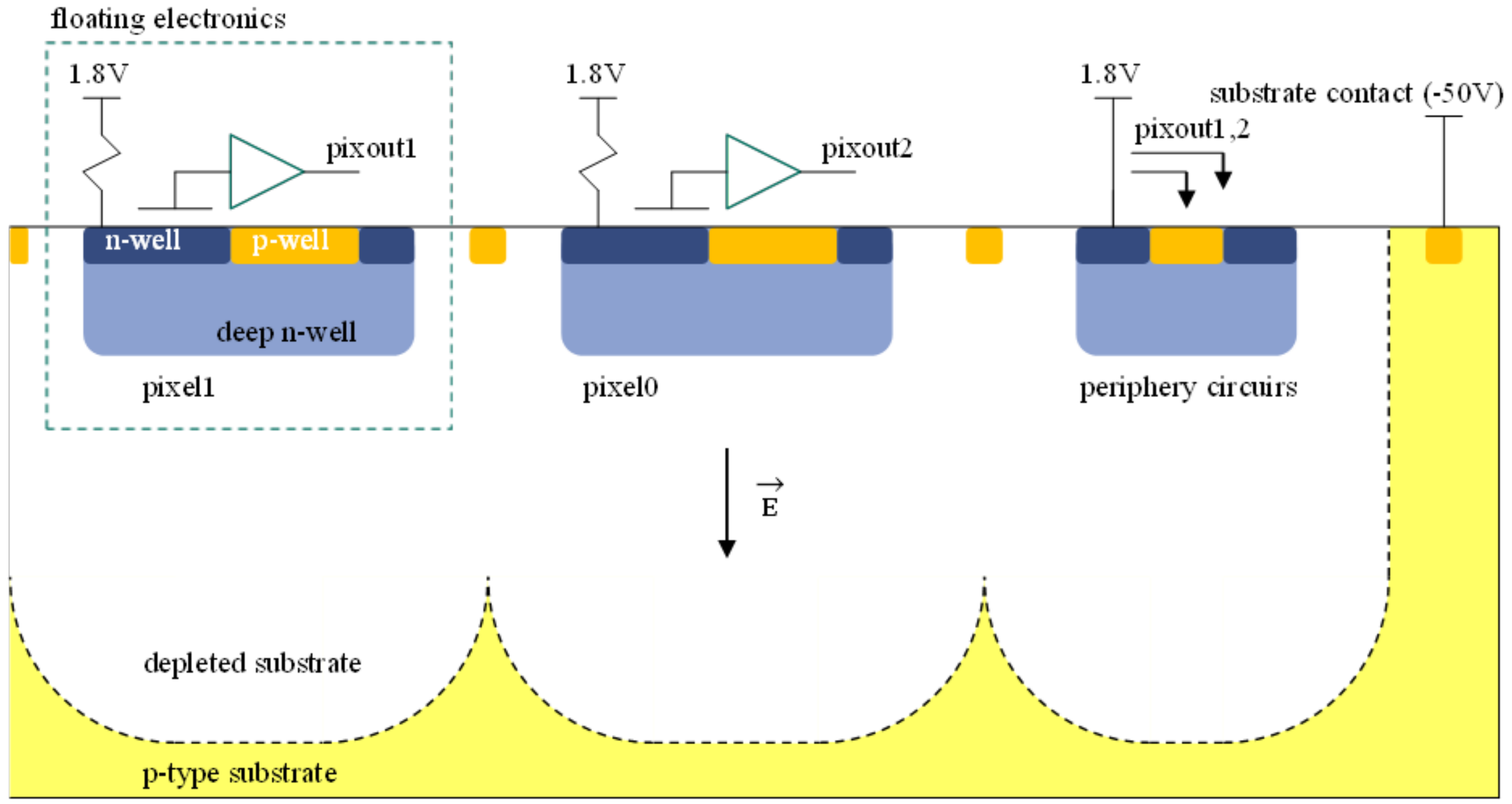
- 16x2 pixel Cores, 8 Cores in the Matrix
- Logic and buffering optimisation -> Acknowledge signal propagates 7 times faster!
  - Simulations validated matrices up to 8192 pixels high
- Power optimisation in the periphery
- 1 GHz DDR serialiser -> 2Gbps bandwidth!
- design fixes (excess digital current and bug on periphery)
- First wafers just received, smoke tests ongoing on MD2

- **ARCADIA Status and Schedule for 2022**
  - ARCADIA-MD1 submitted in October 2020, first dies in June 2021
  - 1st SPW run included 800 mm2 of innovative DMAPS, sensor and CMOS technology
  - 2nd run mid-2021: silicon just received and first tests ongoing
  - 3rd run scheduled for mid-2022

# DMAPS (example ATLASPIX3)

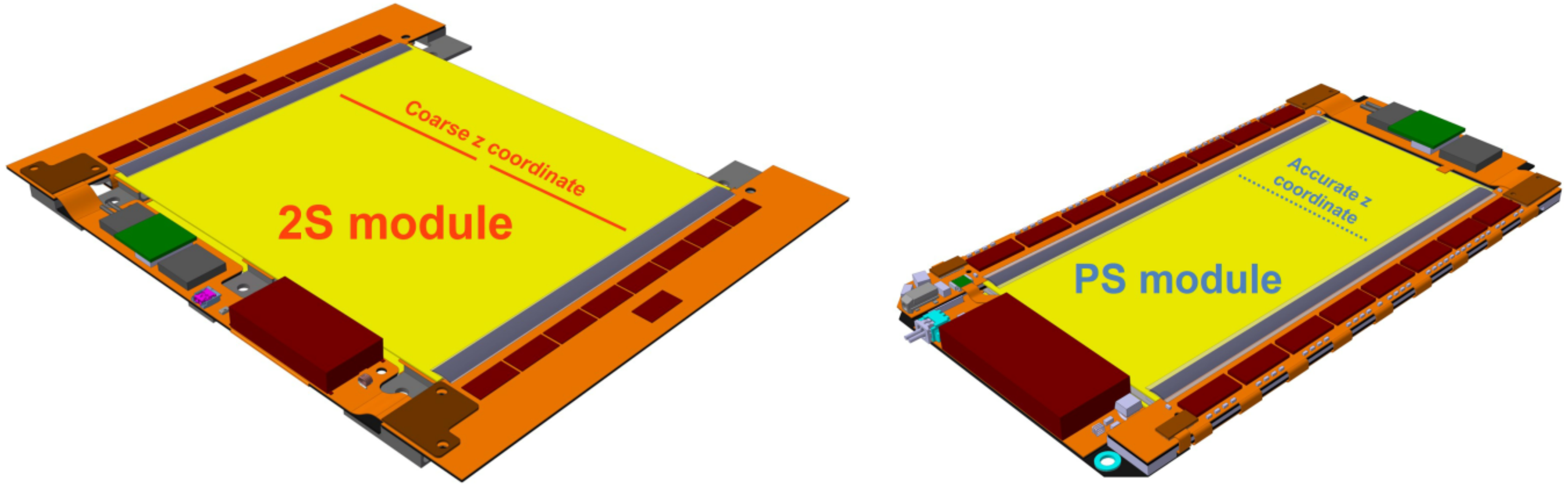
- **Depleted Monolithic Active Pixels Sensors**
  - CMOS process allows to produce **large areas**, **fast** and **cheap**
  - **no hybridization** (bump-bonding) needed
  - **single detection layer**, can be **thinned** keeping high signal
    efficiency and low noise rate
- **ATLASPIX3 features**
  - pixel size 50×150 μm² (25×165 μm² feasible)
  - up to 1.28 Gbps downlink
  - reticle size 20×21 mm²
  - TSI 180 nm process on 200 Ωcm substrate
  - 132 columns of 372 pixels
  - digital part of the matrix located on periphery
  - both **triggerless** and **triggered** readout possible:
    - two End of Column buffers
    - 372 hit buffers for triggerless readout
    - 80 trigger buffers for triggered readout





# Si wrapper: why DMAPS?

| 2S module | PS module |
|---|---|
| $\sim 2 \times 90\ \text{cm}^2$ active area | $\sim 2 \times 45\ \text{cm}^2$ active area |
| $2 \times 1016$ strips: $\sim 5\ \text{cm} \times 90\ \mu\text{m}$<br>$2 \times 1016$ strips: $\sim 5\ \text{cm} \times 90\ \mu\text{m}$ | $2 \times 960$ strips: $\sim 2.4\ \text{cm} \times 100\ \mu\text{m}$<br>$32 \times 960$ macro-pixels: $\sim 1.5\ \text{mm} \times 100\ \mu\text{m}$ |
| Front-end power $\sim 5$ W<br>Sensor power ($-20\,^\circ$C) $\sim 1.0$ W | Front-end power $\sim 8$ W<br>Sensor power ($-20\,^\circ$C) $\sim 1.4$ W |

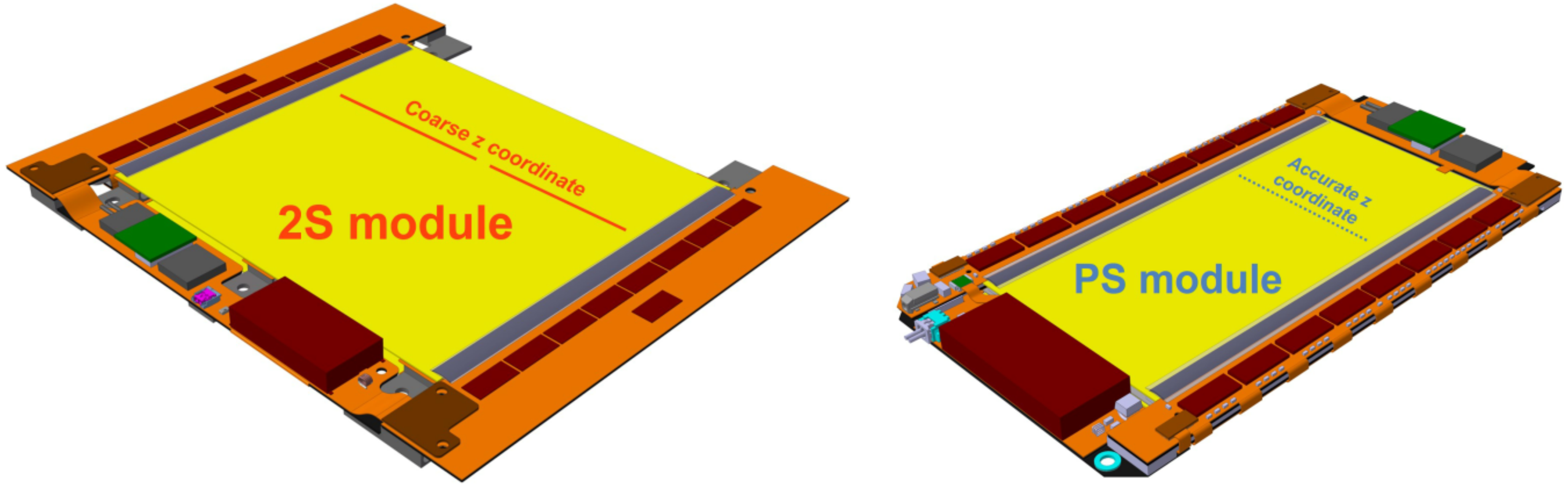



- Tracker area is similar to LHC trackers
- Area size within production capabilities of CMOS foundries
- One thin silicon layer instead of strip doublets
- The target power density of next generation DMAPS detector is comparable with HL-LHC strips
- Cost is not so different, if one considers half silicon area is needed

| | 2S | PS | Pixels | ATLASPIX3 |
|---|---|---|---|---|
| Area | 192 $m^2$ | 25 $m^2$ | 4.9 $m^2$ | (estimation at ATLAS TDR) |
| Power density | 27 $mW/cm^2$ | 89 $mW/cm^2$ | 700 $mW/cm^2$ | 150 $mW/cm^2$ |
| Module cost (TDR) | 26990 kCHF | 20780 kCHF | 11691 kCHF | |
| | 140 $kCHF/m^2$ | 830 $kCHF/m^2$ | 2400 $kCHF/m^2$ | 400-500 $kCHF/m^2$ |

# Si wrapper: why DMAPS?

Precision θ measurements also improving systematics and accurate measurements on the Z pole
See A. Andreazza *From vertex to wrapper: the IDEA tracking system for FCC-ee* FCC Workshop June 2021

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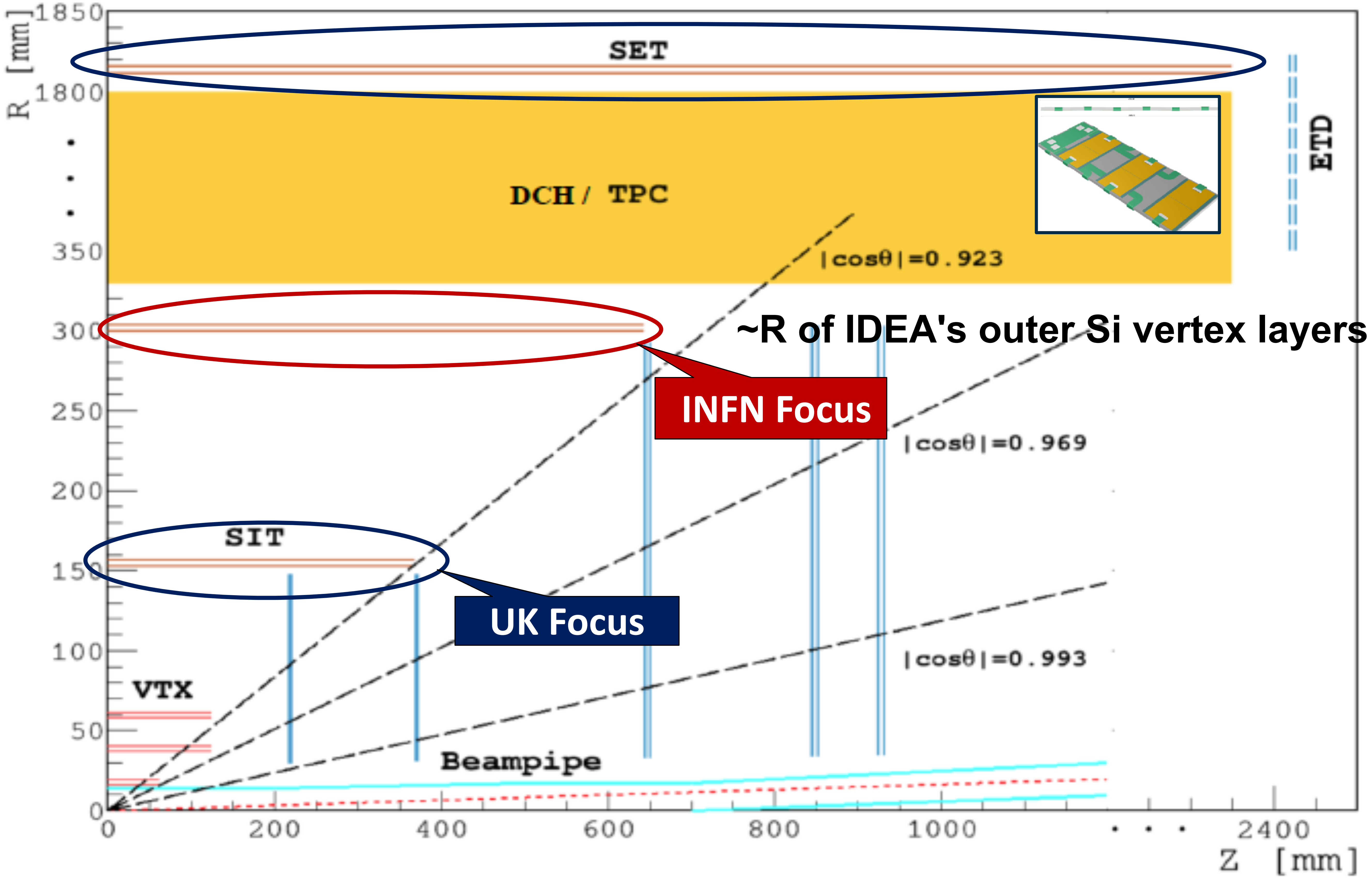
# CEPC baseline layout

Baseline tracker design: TPC

and 3 layers / 5 disks of silicon sensors,

50 m² (33 w/o ETD) if built in CMOS pixels (strips default)



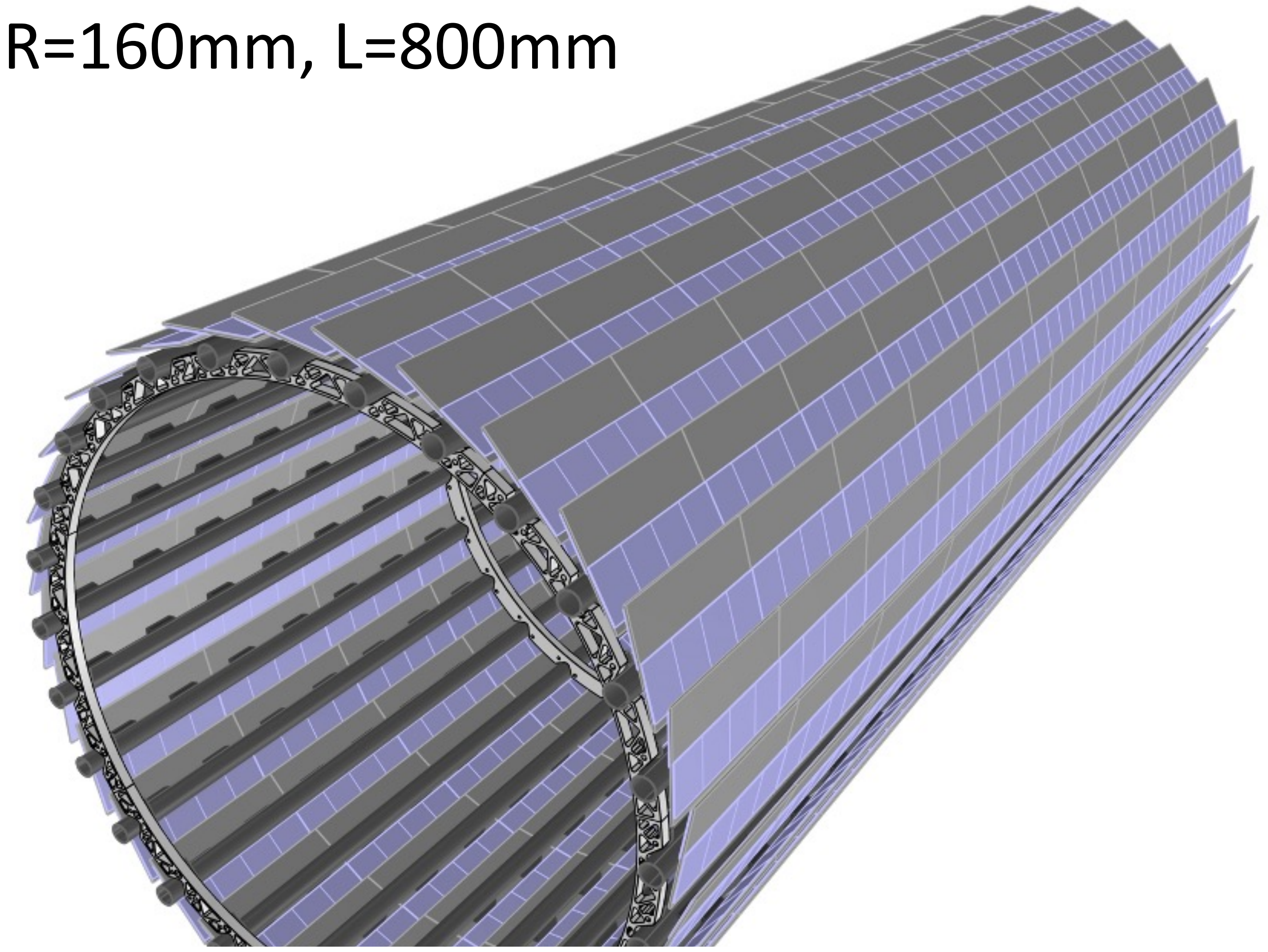

| Detector | | Radius $R$ [mm] | | $\pm z$ [mm] | Material budget [$X_0$] |
|---|---|---|---|---|---|
| SIT | Layer 1 | 153 | | 371.3 | 0.65% |
| | Layer 2 | 300 | | 664.9 | 0.65% |
| SET | Layer 3 | 1811 | | 2350 | 0.65% |
| | | $R_{in}$ | $R_{out}$ | | |
| FTD | Disk 1 | 39 | 151.9 | 220 | 0.50% |
| | Disk 2 | 49.6 | 151.9 | 371.3 | 0.50% |
| | Disk 3 | 70.1 | 298.9 | 644.9 | 0.65% |
| | Disk 4 | 79.3 | 309 | 846 | 0.65% |
| | Disk 5 | 92.7 | 309 | 1057.5 | 0.65% |
| ETD | Disk | 419.3 | 1822.7 | 2420 | 0.65% |

| Physics process | Measurands | Detector subsystem | Performance requirement |
|---|---|---|---|
| $ZH, Z \to e^+e^-, \mu^+\mu^-$<br>$H \to \mu^+\mu^-$ | $m_H, \sigma(ZH)$<br>$\mathrm{BR}(H \to \mu^+\mu^-)$ | Tracker | $\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$ |

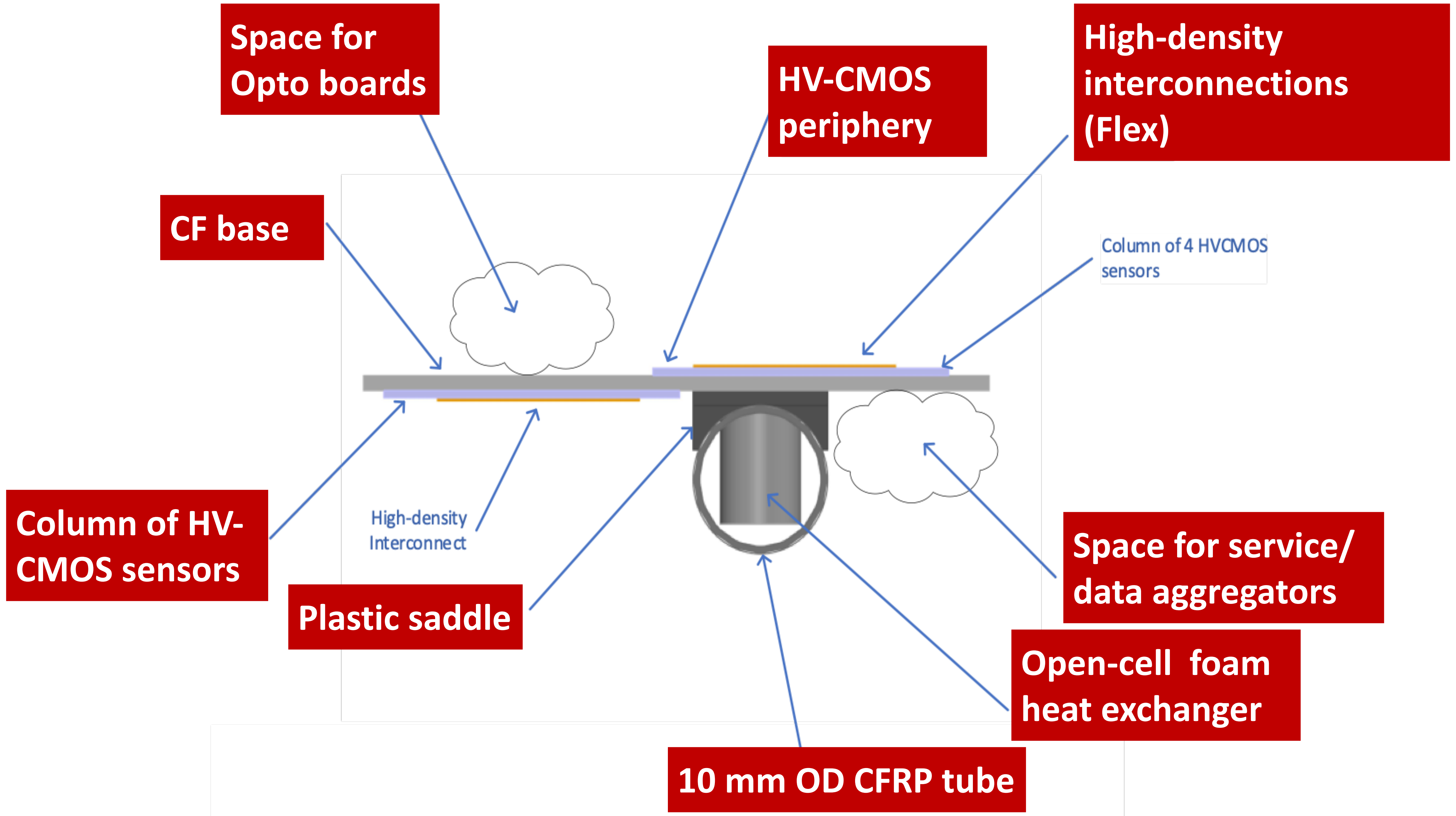
$\sigma_{r\phi} \approx 7\mu m$

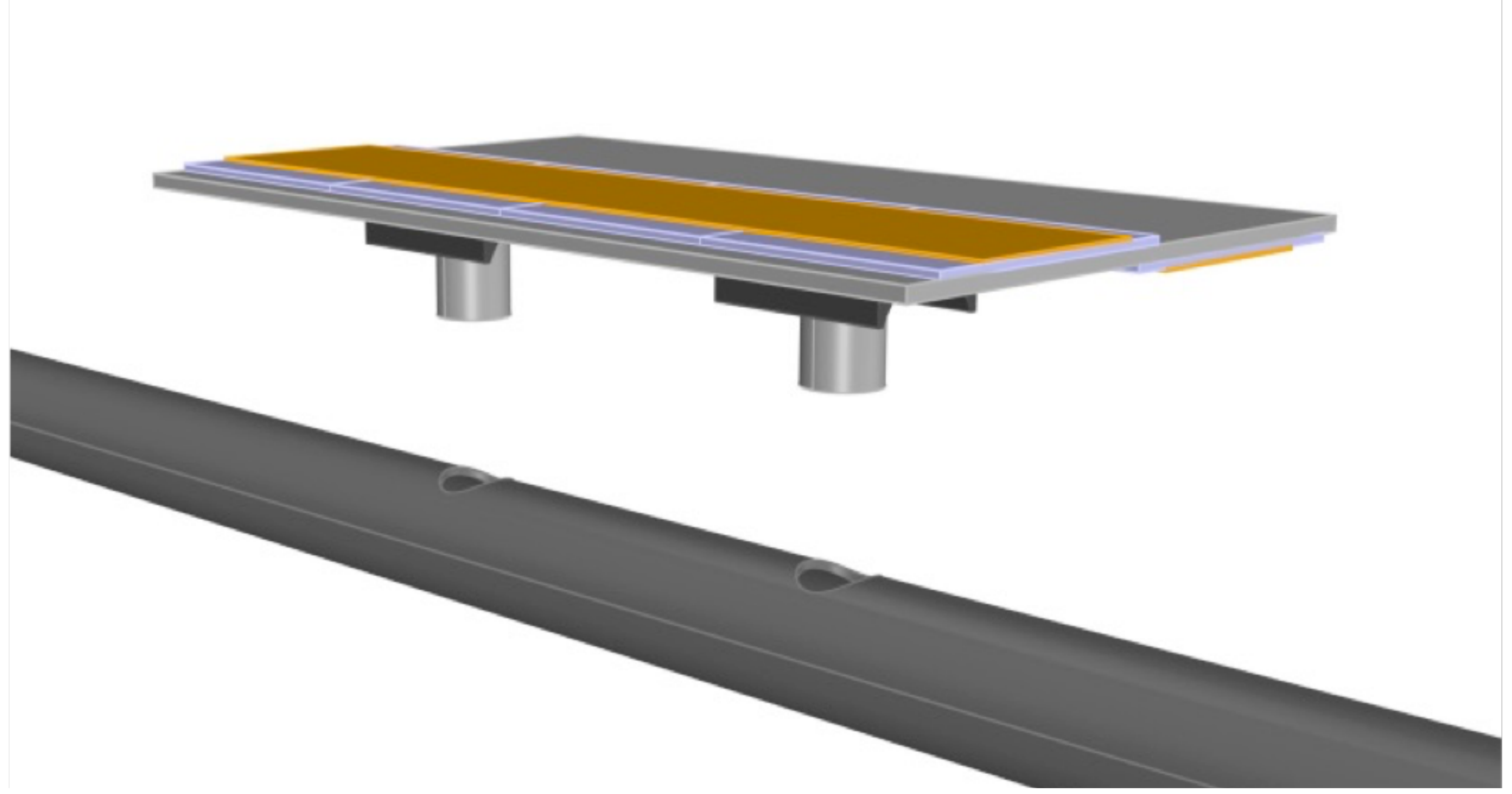
# Low radius structures

R=160mm, L=800mm



- Functional 8-chip unit glued on carbon support
- Asymmetric arrangement:
  - hermeticity along φ
  - space for data and power connection
- Carbon tube support
- Saddles provide mechanical and thermal connection to support by foam heat exchanger

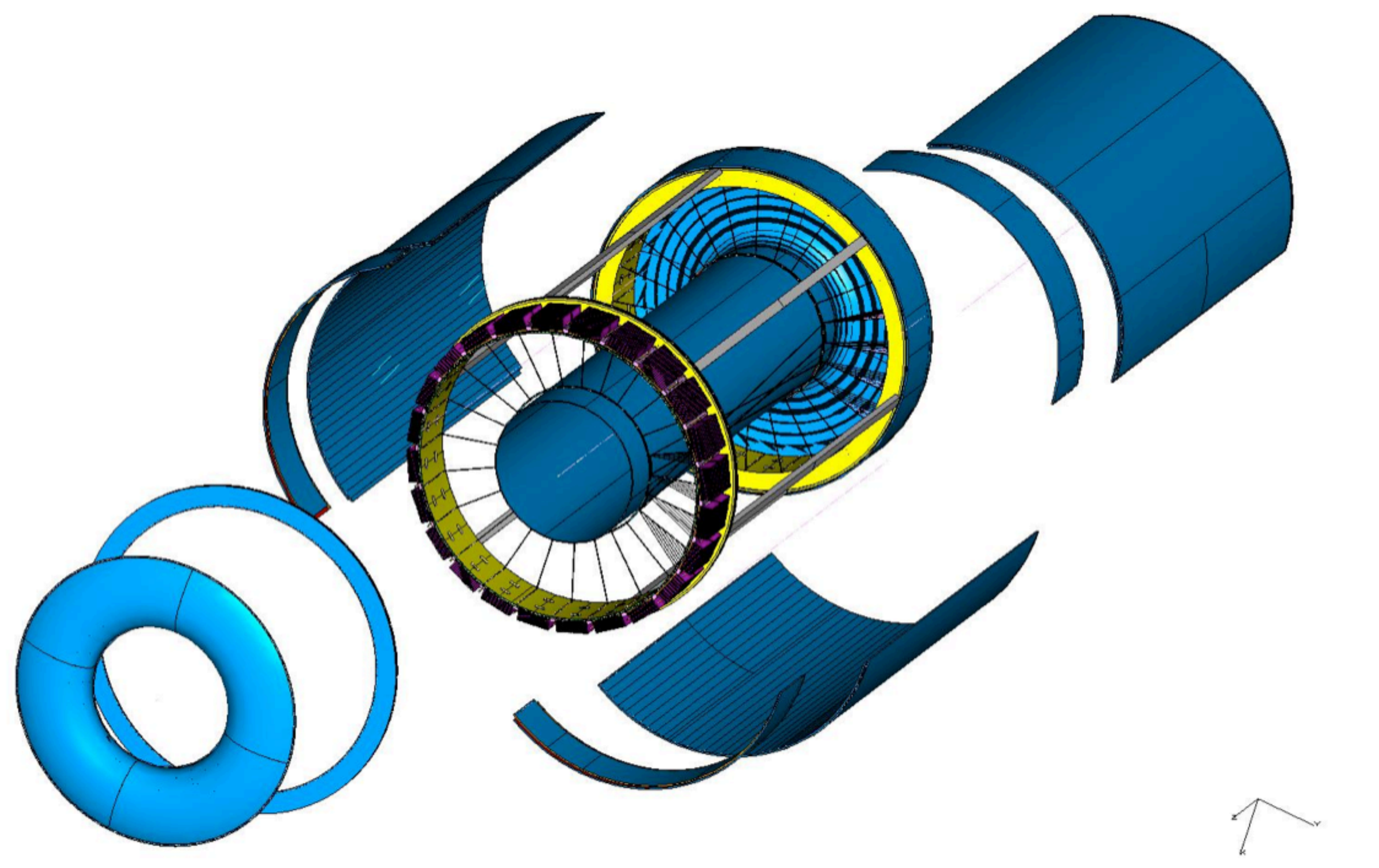


Liverpool

# Wire chamber

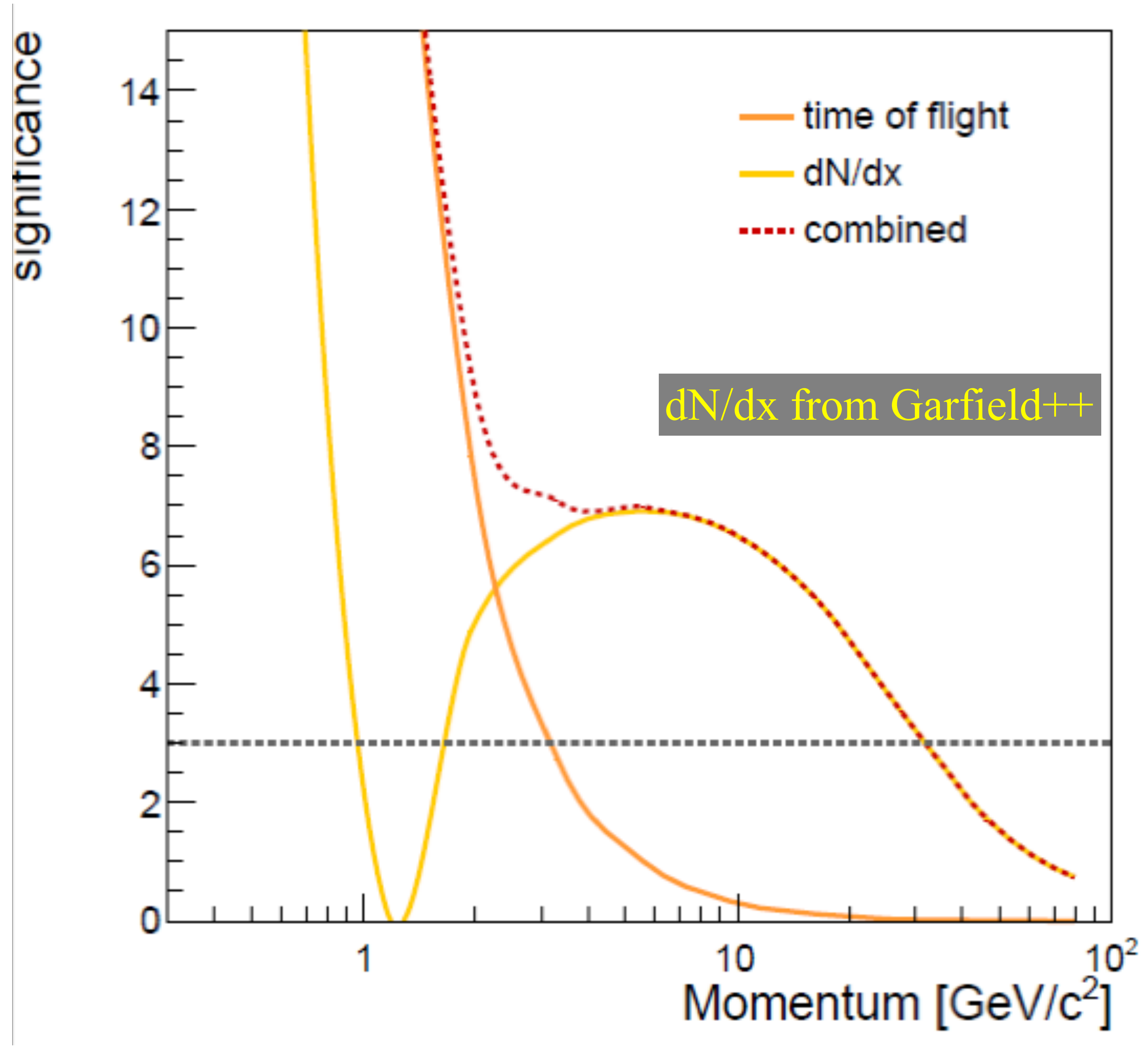
# Wire chamber



The IDEA drift chamber by numbers:

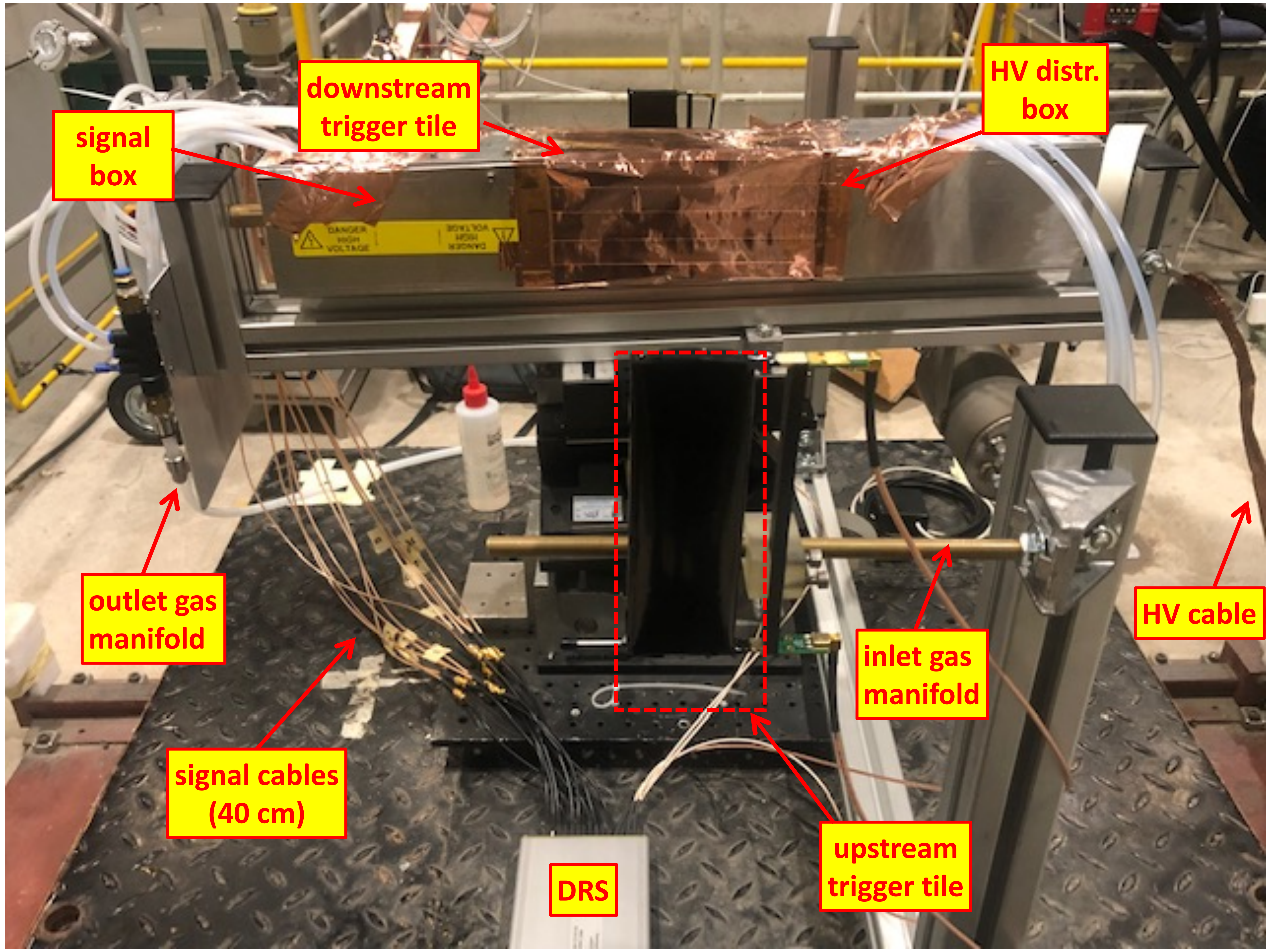
- L = 400 cm
- $R_{in}$ = 35 cm
- $R_{out}$ = 200 cm
- 112 layers for each 15° azimuthal sector
- 56 448 squared drift cells of about 12-13.5 mm edge
- max drift time: 350 ns in 90%He-10%$iC_4H_{10}$

- cluster counting for improved particle identification: it is essentially based on the well known method of measuring the [truncated] mean dE/dX but it replaces the measurement of an ANALOG information with a DIGITAL one, namely the number of ionisation clusters per unit length:



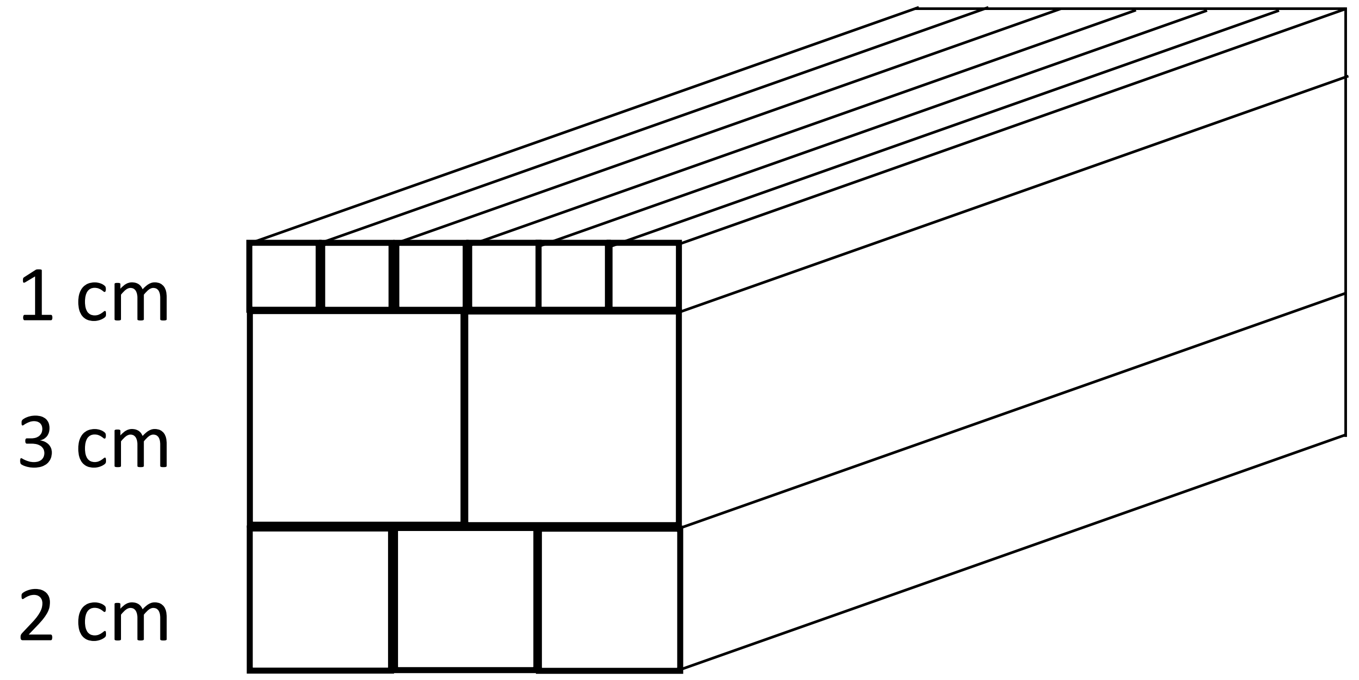

>3σ K/π separation up to ~35 GeV

# Cern H8 test beam 11-2021

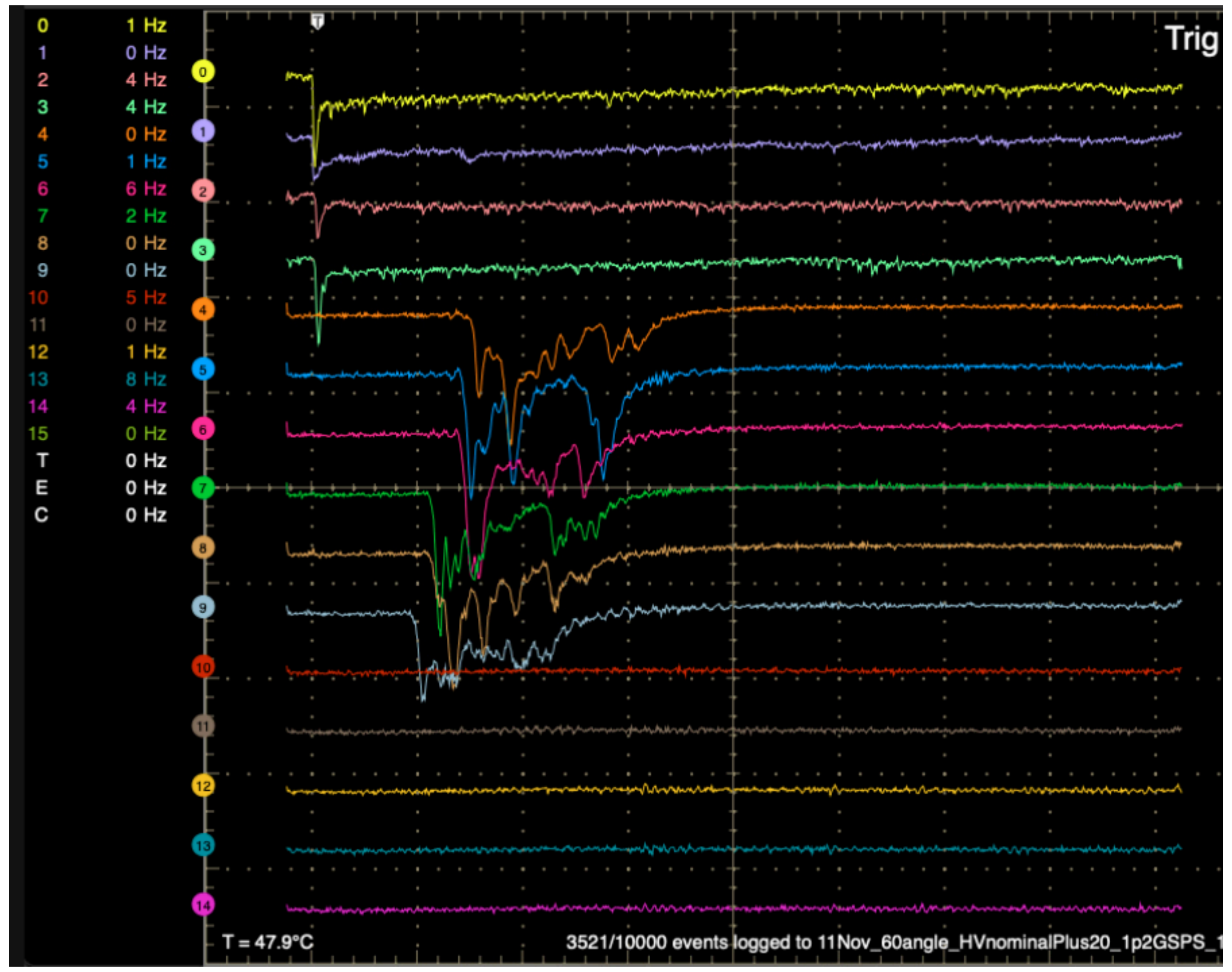



The experimental setup
at CERN H8 beam
November 2021

Drift tubes pack

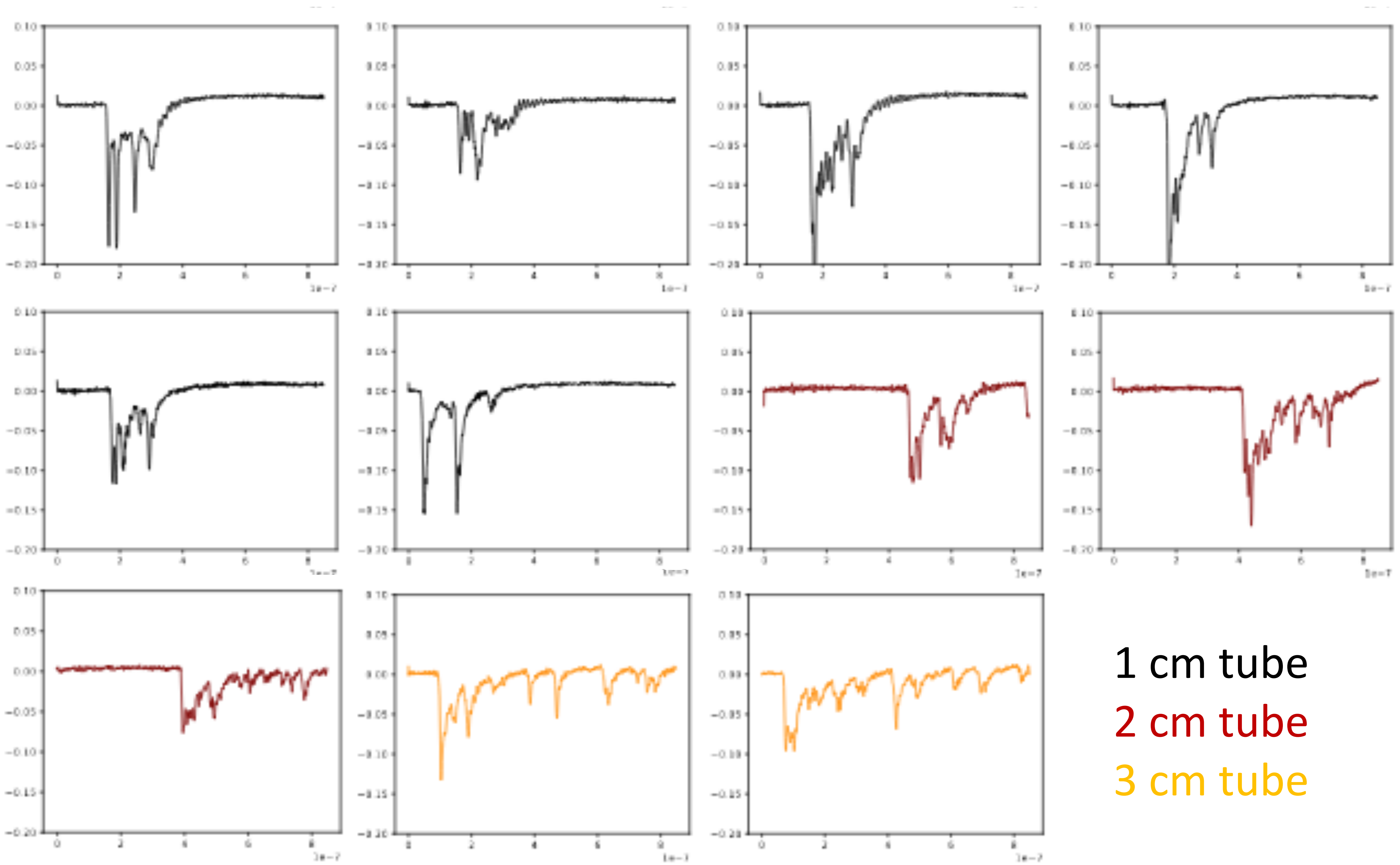



Event display



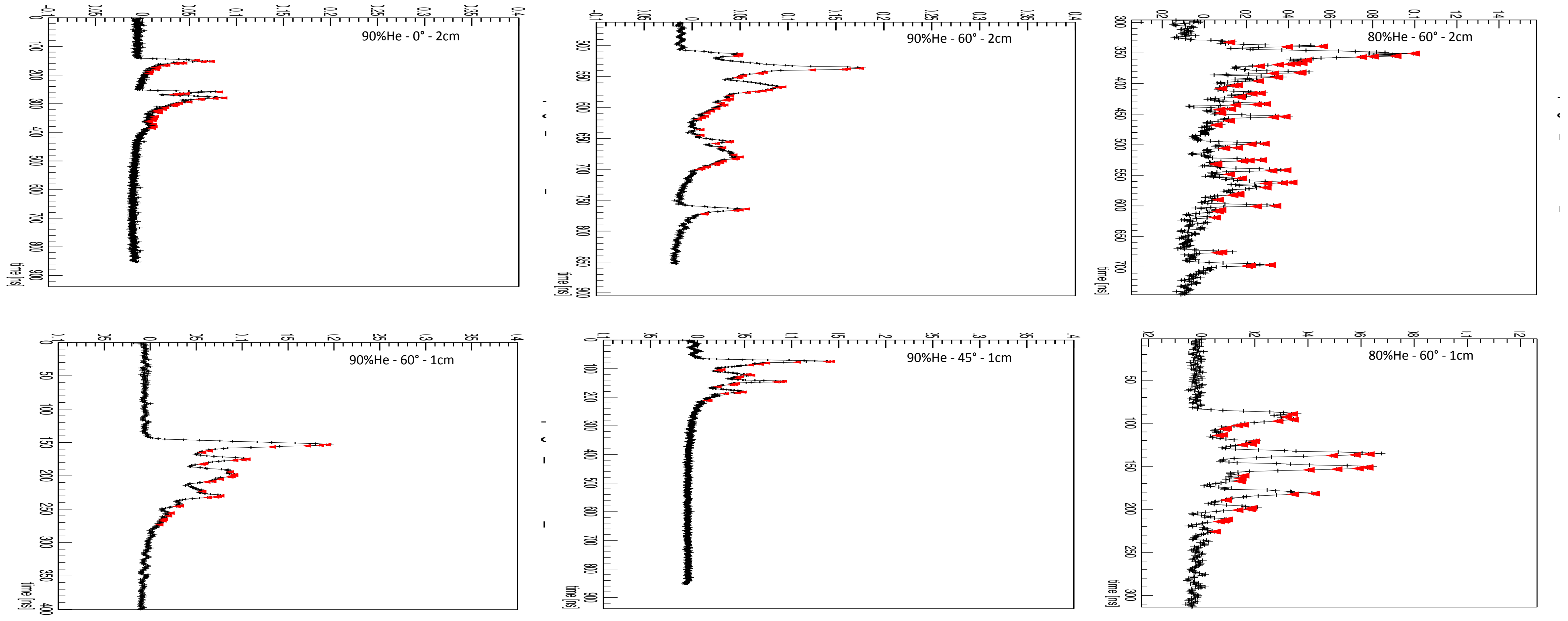
# Wire chamber

## Typical pulse spectra

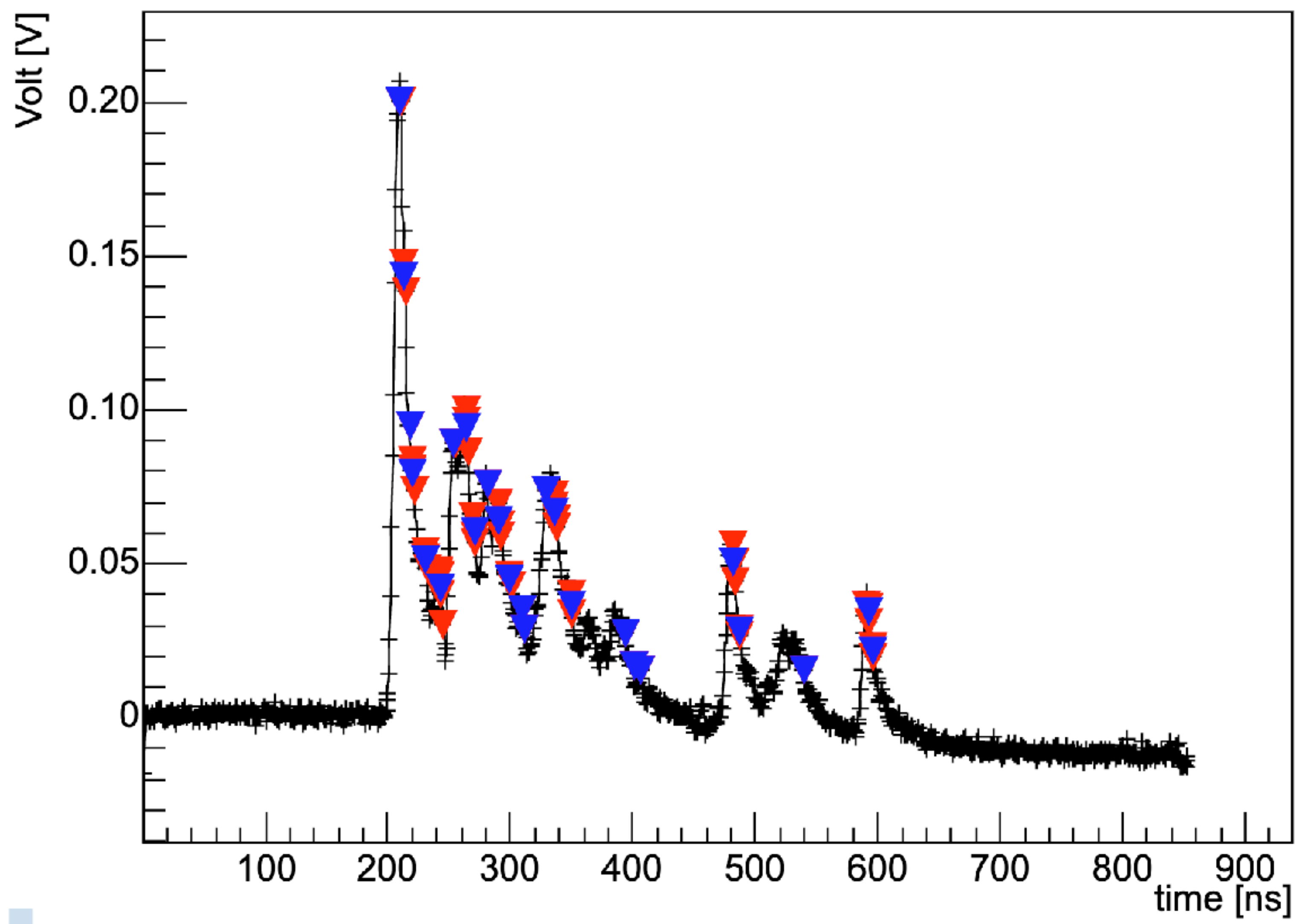


1 cm tube
2 cm tube
3 cm tube

## Electron peak finding




Ionization clusters (▼) and single electron pulses (▼)

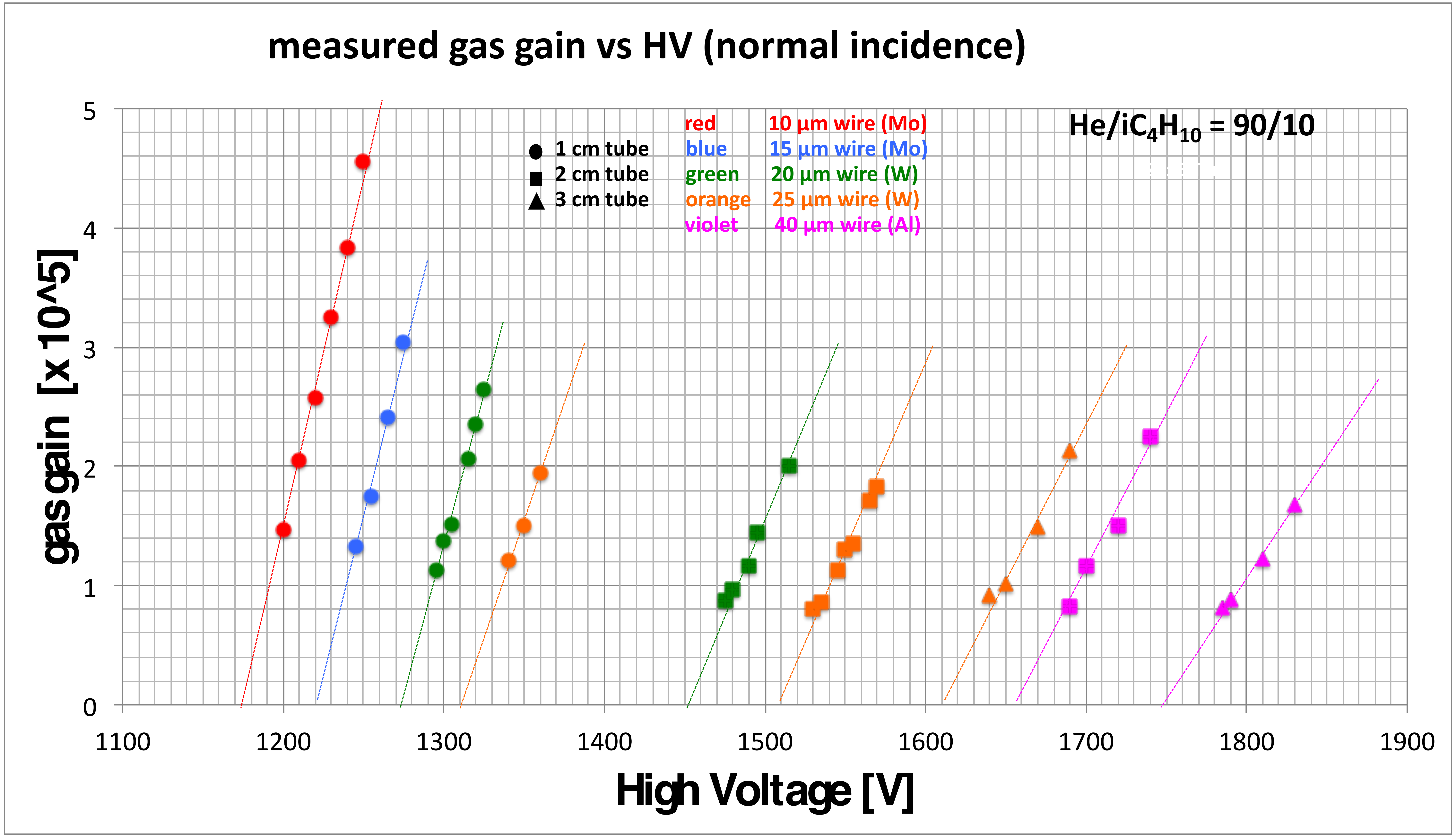


# Current activities

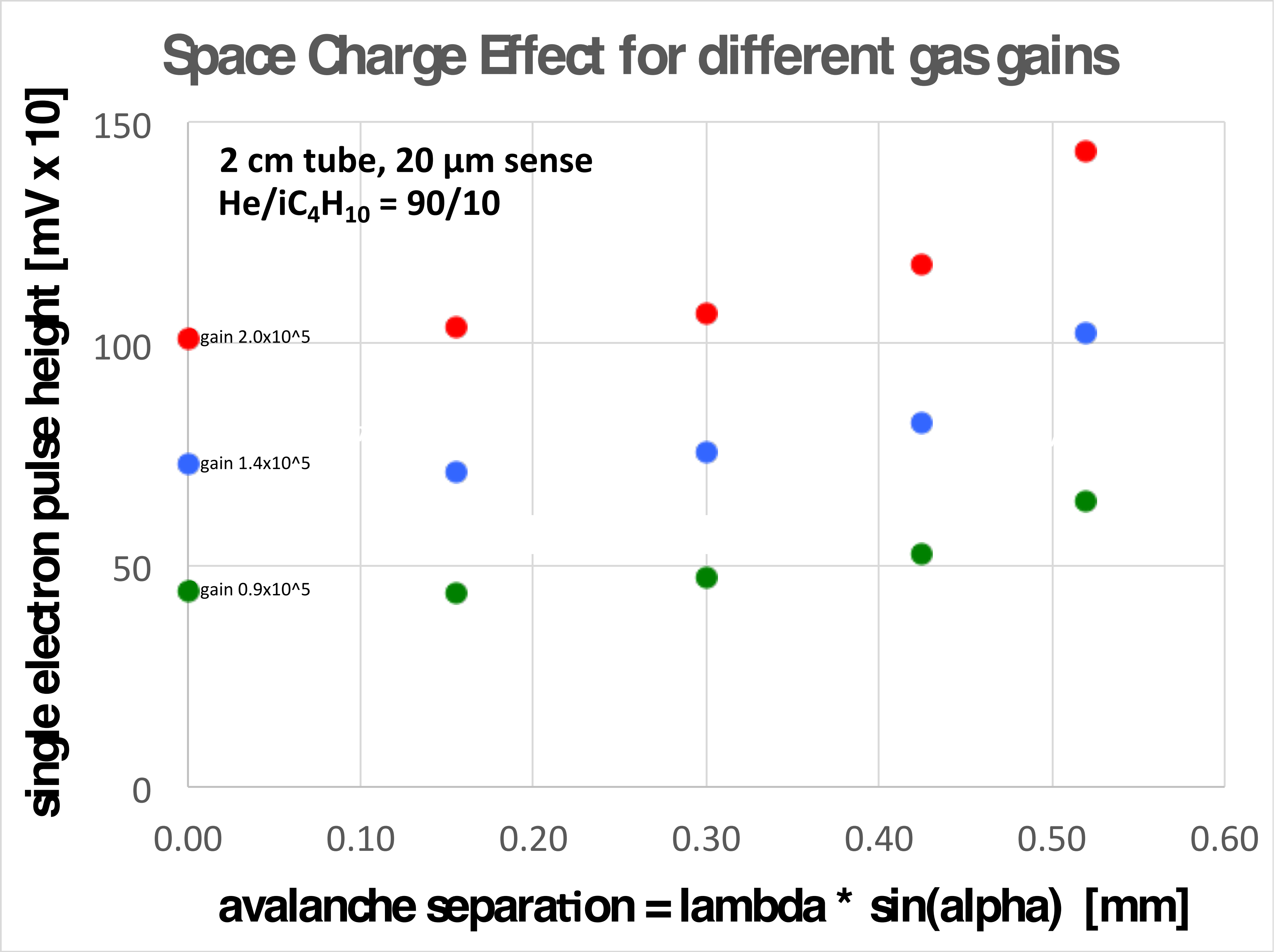
- Analysis of beam test data for different cell size, sense wire diameter, ionization length (angle between beam direction and sense wire), gas gains, gas composition, aimed at:
  - Gas gain curves vs. reduced electric field ✓
  - Avalanche size and space charge effects ✓
  - Optimization of electron peak finding algorithms based on first and second derivatives (in progress)
  - New counting algorithms based on running pulse template (preliminary)
  - Ionization clustering algorithms ✓
  - Cluster population distribution (in progress)

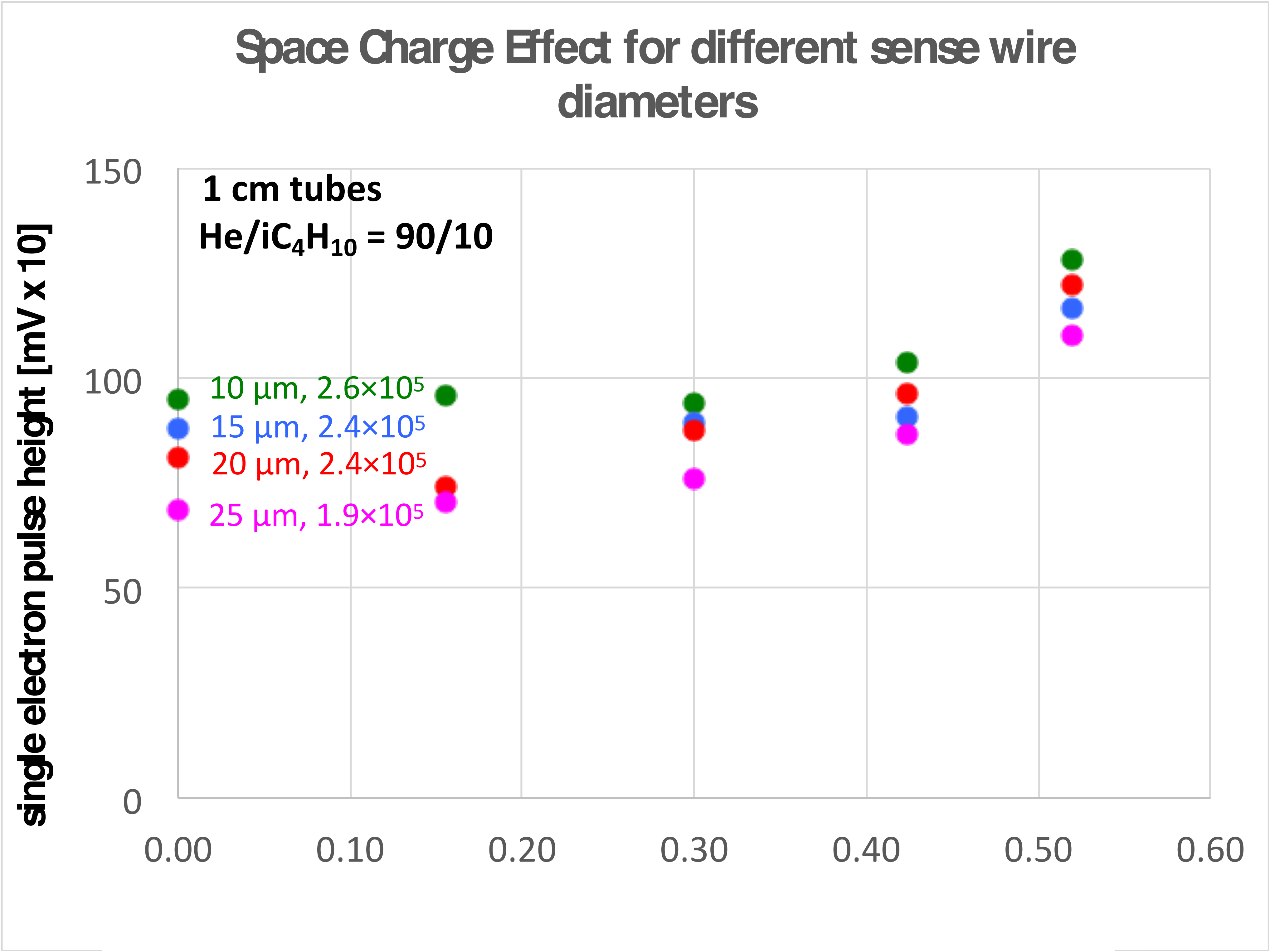
Lot of software and hardware work to demonstrate the cluster counting performances

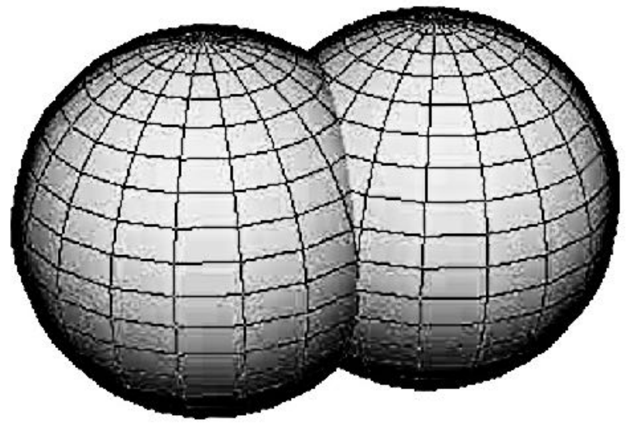
# Gas gain vs HV



# Space charge effect



A naive model based on spherical avalanche gives, for this particular configuration, an **avalanche radius** of

$r_V \approx 450\mu m$.

assuming $\lambda \geq r_V$ , on the Fermi plateau

$N \leq 22$/cm or $N_{max} = 15$/cm for m.i.p.

Space charge effects, in this range of gas gain do not seem to depend on gas gain or, surprisingly enough, on sense wire diameter. The maximum **avalanche suppression**, for this gas mixture, amounts to

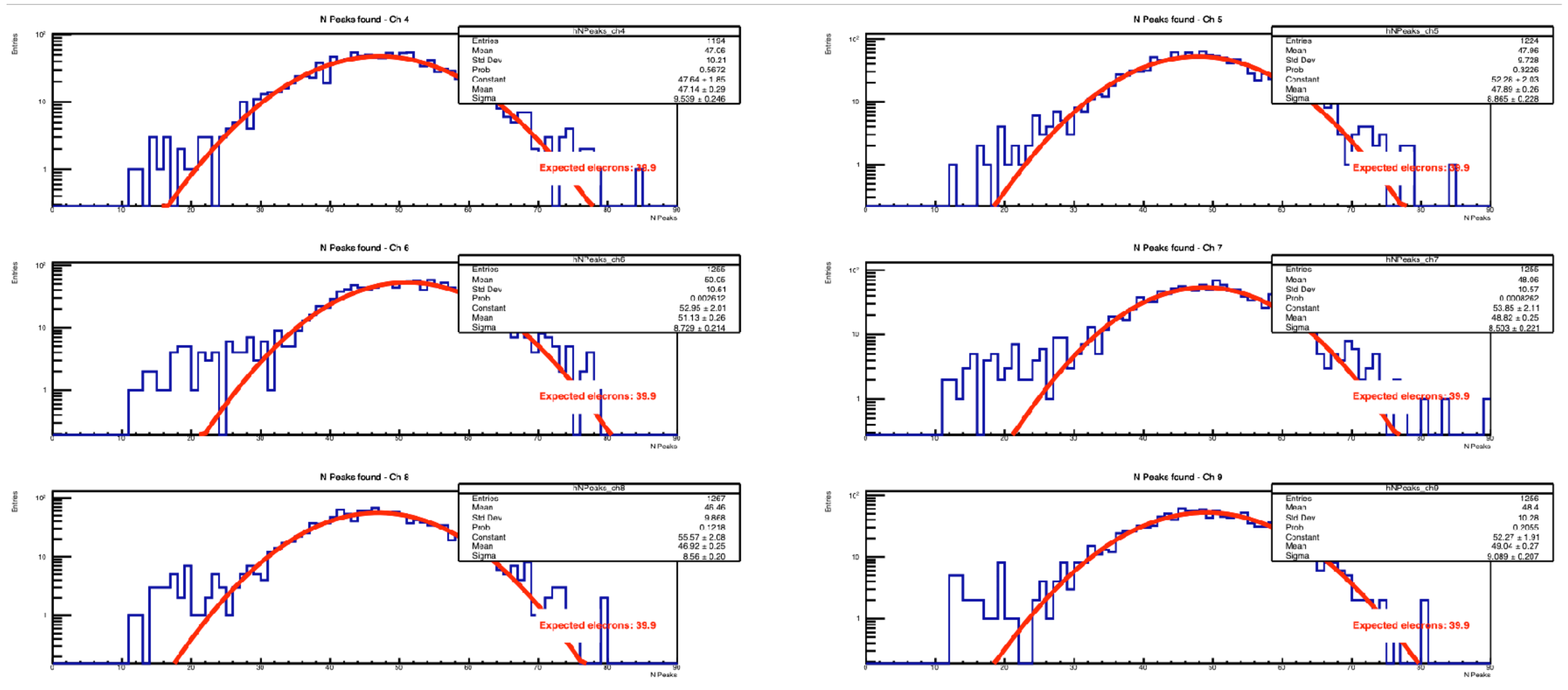
≈ 70%, at 0°.

N = 15/cm for m.i.p. → $He/iC_4H_{10}$ = 85/15

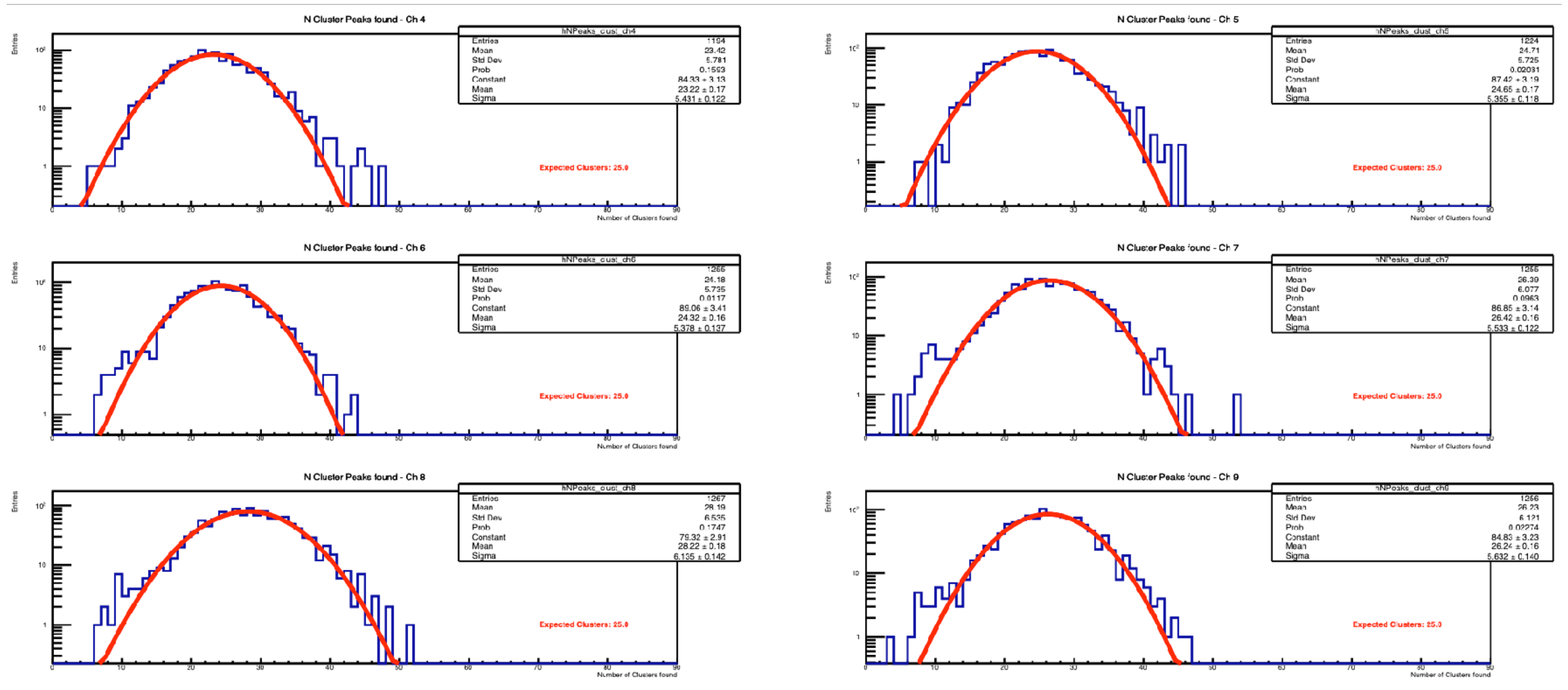
(N = 12/cm for $He/iC_4H_{10}$ = 90/10)

# Wire chamber

## Number of electron peaks



## Number of clusters



165 GeV/c muons   60° angle   90% He – 10% $iC_4H_{10}$   1 cm drift tubes   2x$10^5$ gas gain   x10 amplifier

**Expected clusters**: 12 clusters/cm (for m.i.p.) x 1.3 (presumed relativistic rise) x 0.8 cm/cos(60 °) ionization length = **25**

**Expected electrons**: 25 (expected clusters) x 1.6 electrons/cluster (average value from literature) = **40**

Measured sigma/√mean = 5.58/ √ 25.51 = 1.10

# Future activities

- Beam test scheduled for next June at CERN H8 aimed at:
  - measuring the cluster density as a function of $\beta\gamma$ at different muon beam momenta
  - defining the relativistic rise and the Fermi plateau of dE/dx and dN/dx in He based gas mixtures (lack of experimental data and discrepancies among different simulation models)
- Checking the particle identification performance with cluster counting and with dE/dx using as a benchmark the CP violating process:

$$B_s \rightarrow D_s K$$

Plenty of scope for new collaborators!

# μ-RWELL based detectors

# μ-RWELL technology

The μ-RWELL is composed of only two elements:

- μ-RWELL_PCB
- drift/cathode PCB defining the gas gap

μ-RWELL_PCB = amplification-stage ⊕ resistive stage ⊕ readout PCB

μ-RWELL operation:

- A charged particle ionises the gas between the two detector elements
- Primary electrons drift towards the μ-RWELL_PCB (anode) where they are multiplied, while ions drift to the cathode
- The signal is induced capacitively, through the DLC layer, to the readout PCB
- HV is applied between the Anode and Cathode PCB electrodes
- HV is also applied to the copper layer on the top of the kapton foil, providing the amplification field

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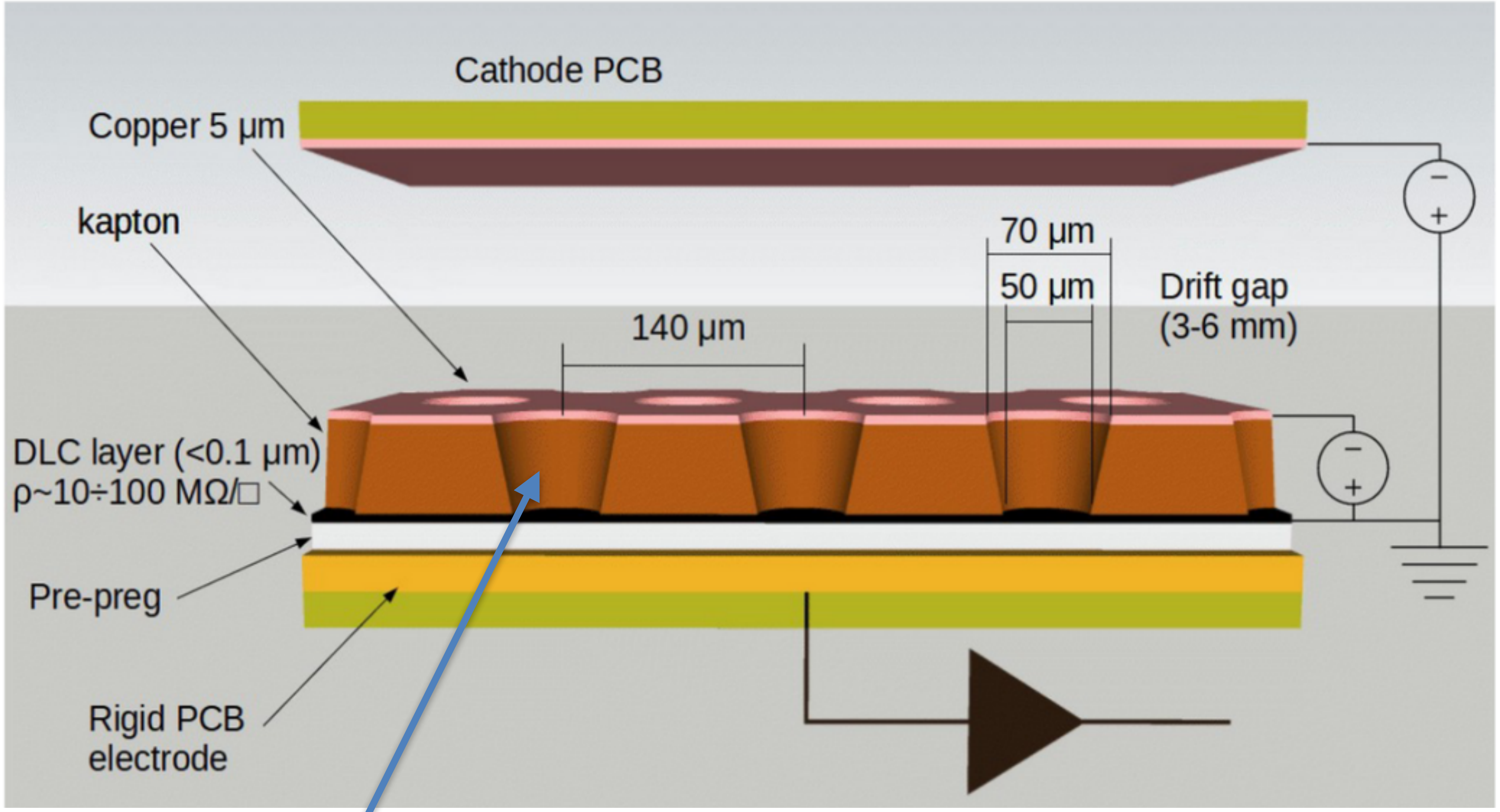
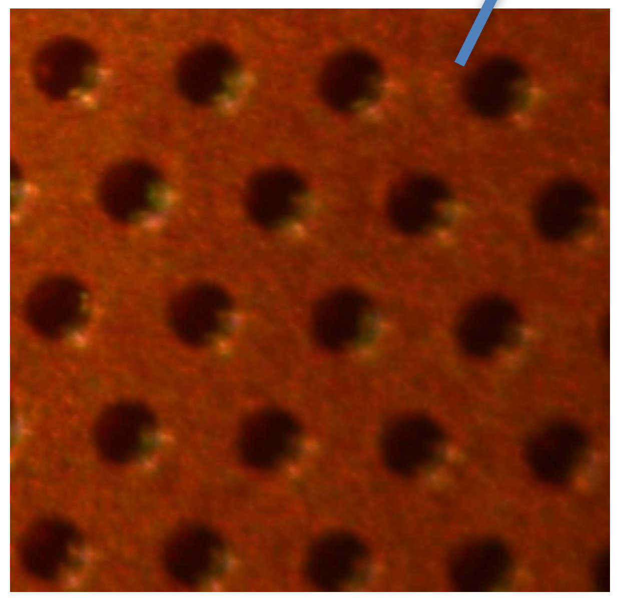
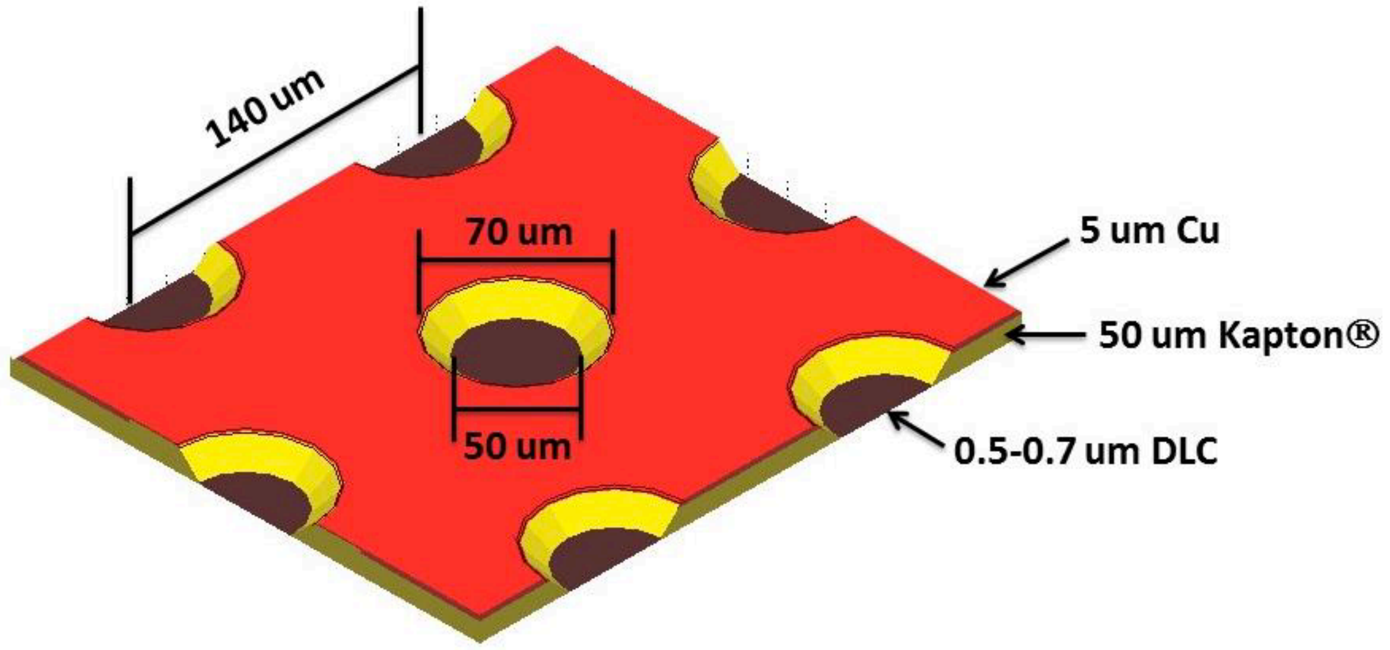





(*) G. Bencivenni et al., “The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD”, 2015_JINST_10_P02008)

# IDEA's preshower and muon detector

## Preshower Detector

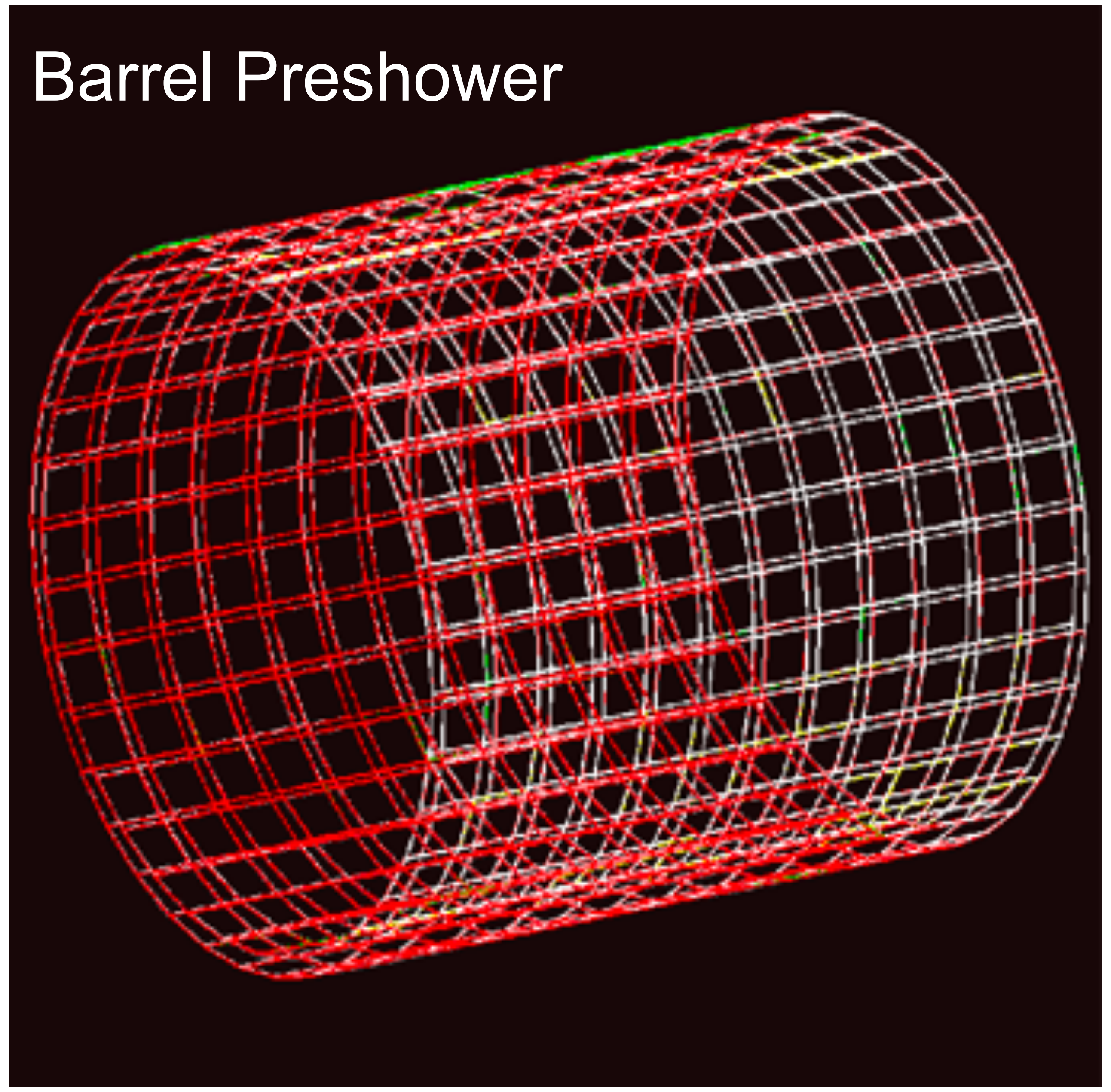
High resolution before the magnet
to improve cluster reconstruction

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

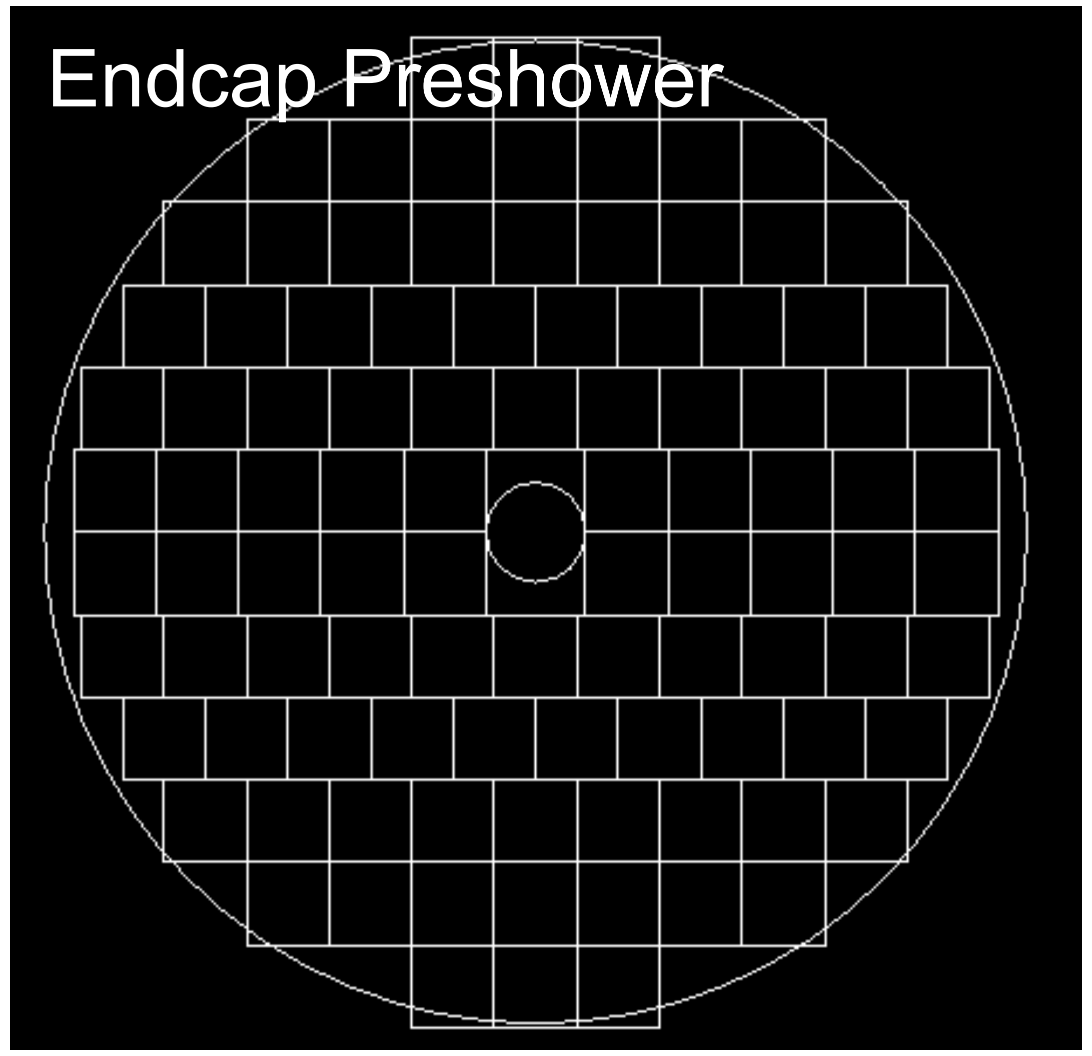
## Muon Detector

Identify muons and search for LLPs

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




Similar design for
the Muon detector




Similar design for
the Muon detector

50x50 cm² 2D tiles to
cover more than 4330 m²

**Preshower**
pitch = 0.4 mm
FEE capacitance = 70 pF
1.5 million channels

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

# Resistivity validation

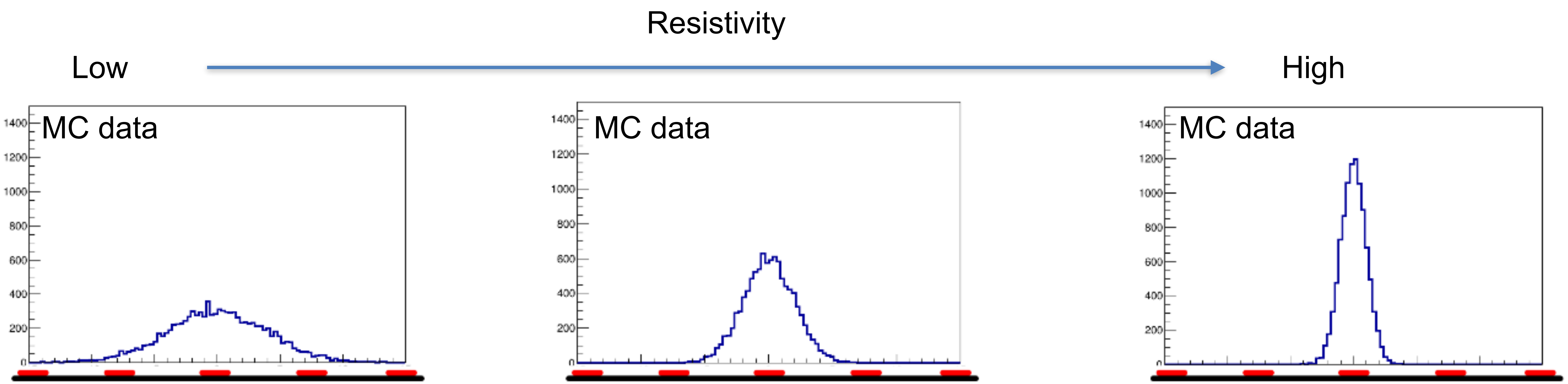
strips

R&D to identify optimal DLC resistivity by studying spatial performance

**Preshower**: 10, 30, 50, 70, > 100-200 MOhm/square

**Muon**:15, 35 MOhm/square

## Effect of resistivity on charge spread

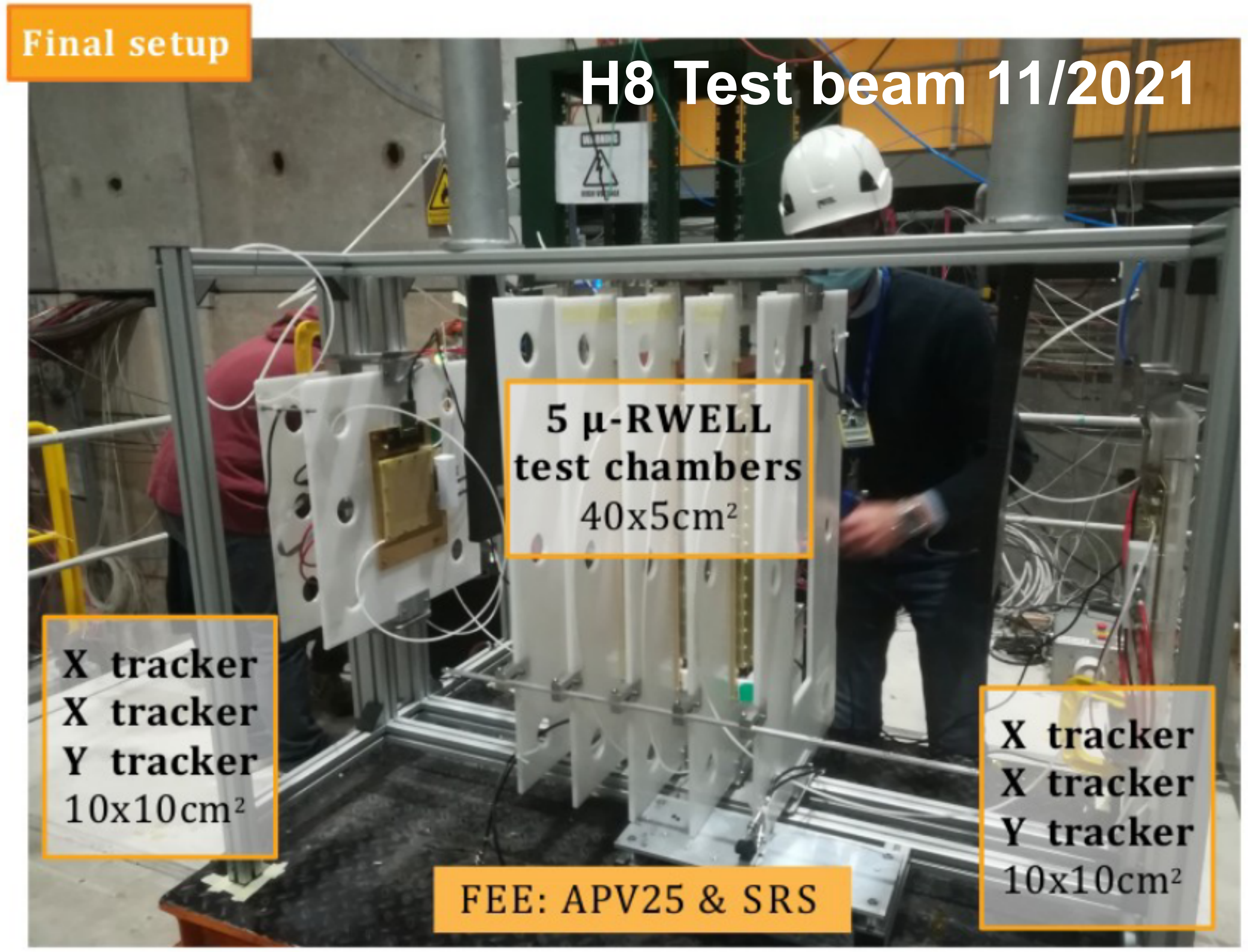



Test beam performed in October 2021 at SPS-H8 CERN line

Instrumented 5x40 $cm^2$ 1D μ-RWELL modules with SRS DAQ and APV readout to have a comparison with previous results

G.Bencivenni et al., “Performance of μ-RWELL detector vs resistivity of the resistive stage”, NIM A 886 (2018) 36

# Test beam 2021




140-180 GeV/c muon and pion beam
Operated in $Ar/CO_2/CF_4$ (45/15/40)

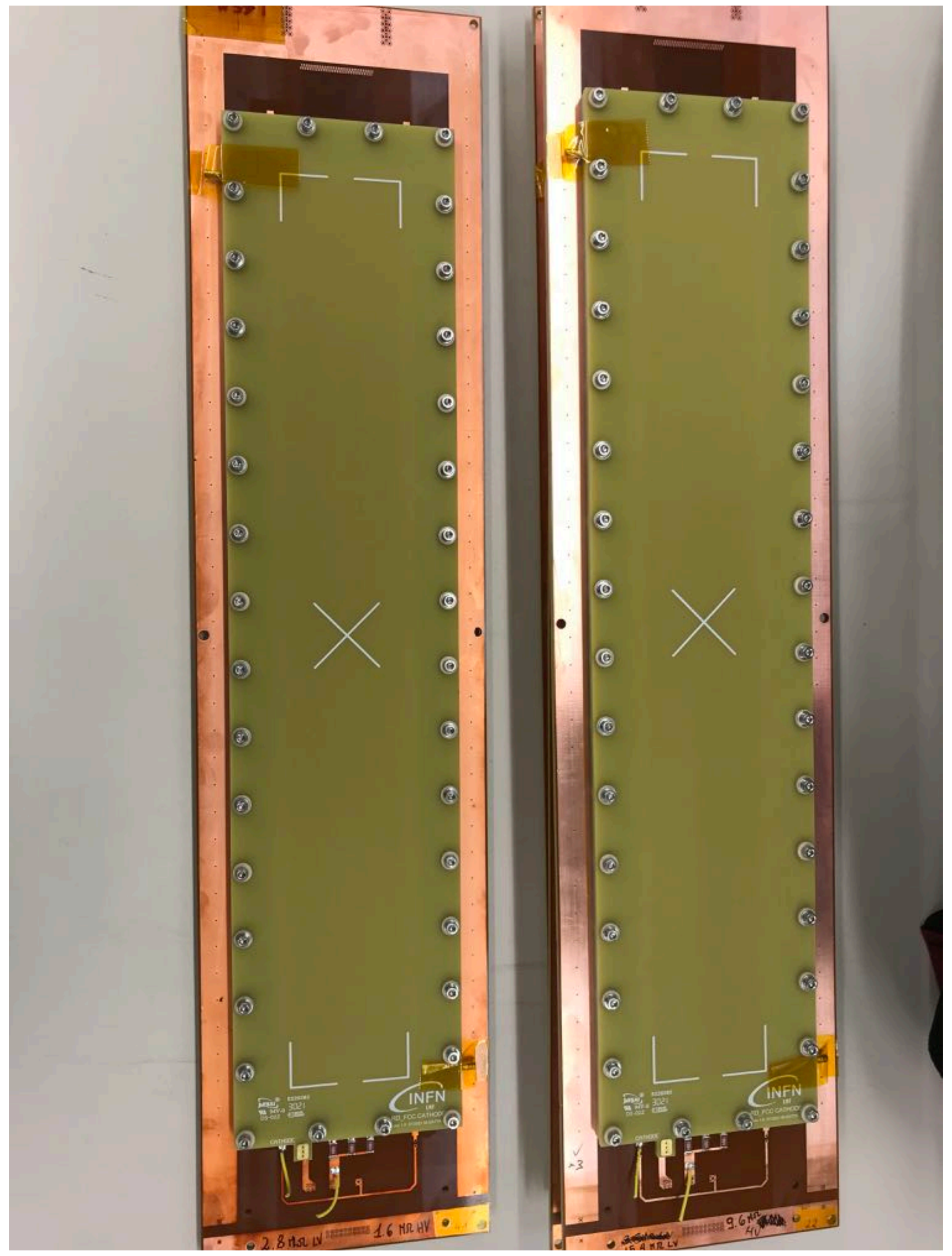
1- Signal shape
(cluster charge, cluster size)
2 - Detector performance
(efficiency, space resolution)

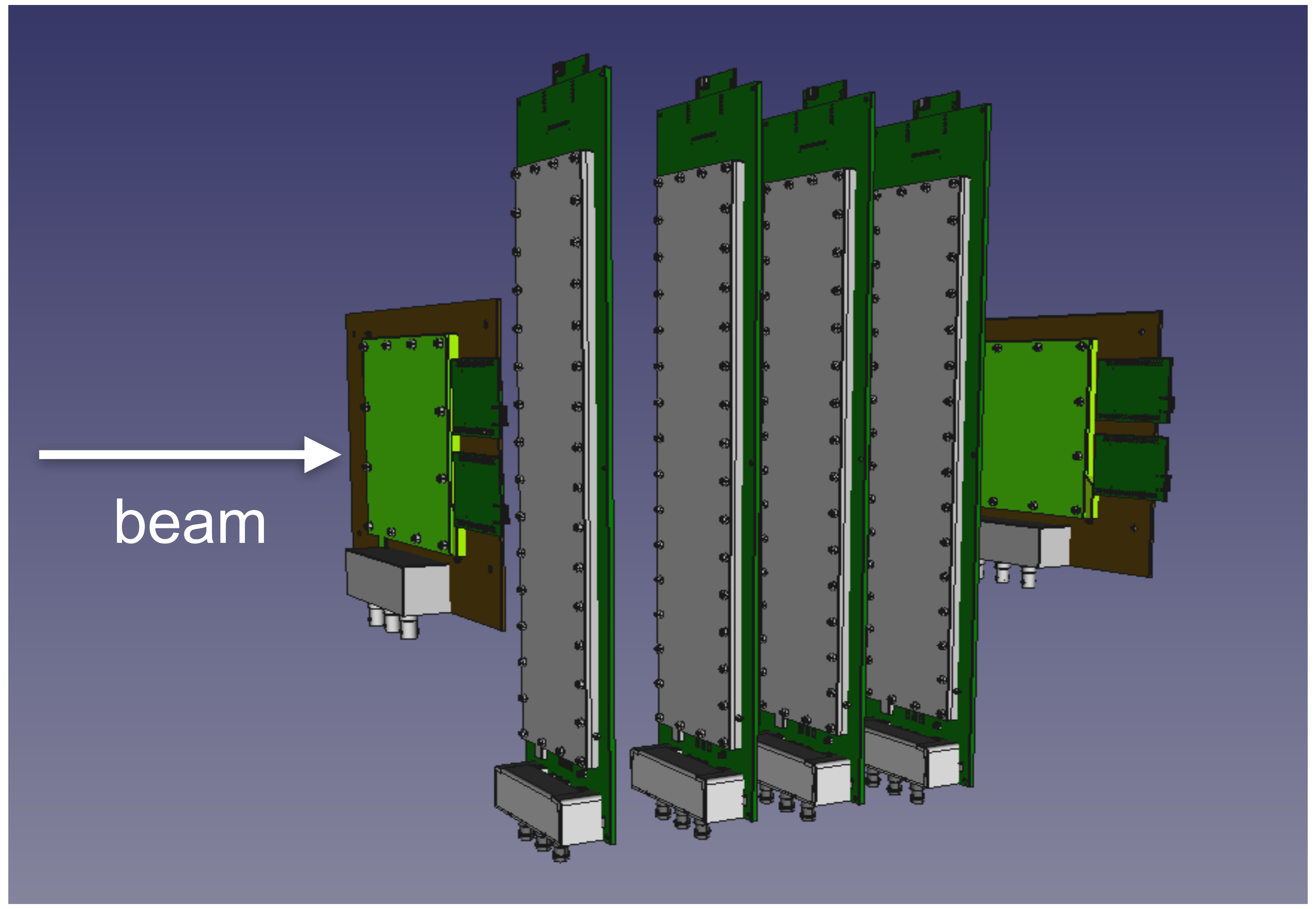
New μ-RWELL prototypes with 40 cm long strips

a) Design optimization:
- different HV filter applied

b) Detector characterization
- HV scan at 0°
- HV scan at different angles and drift field

strips

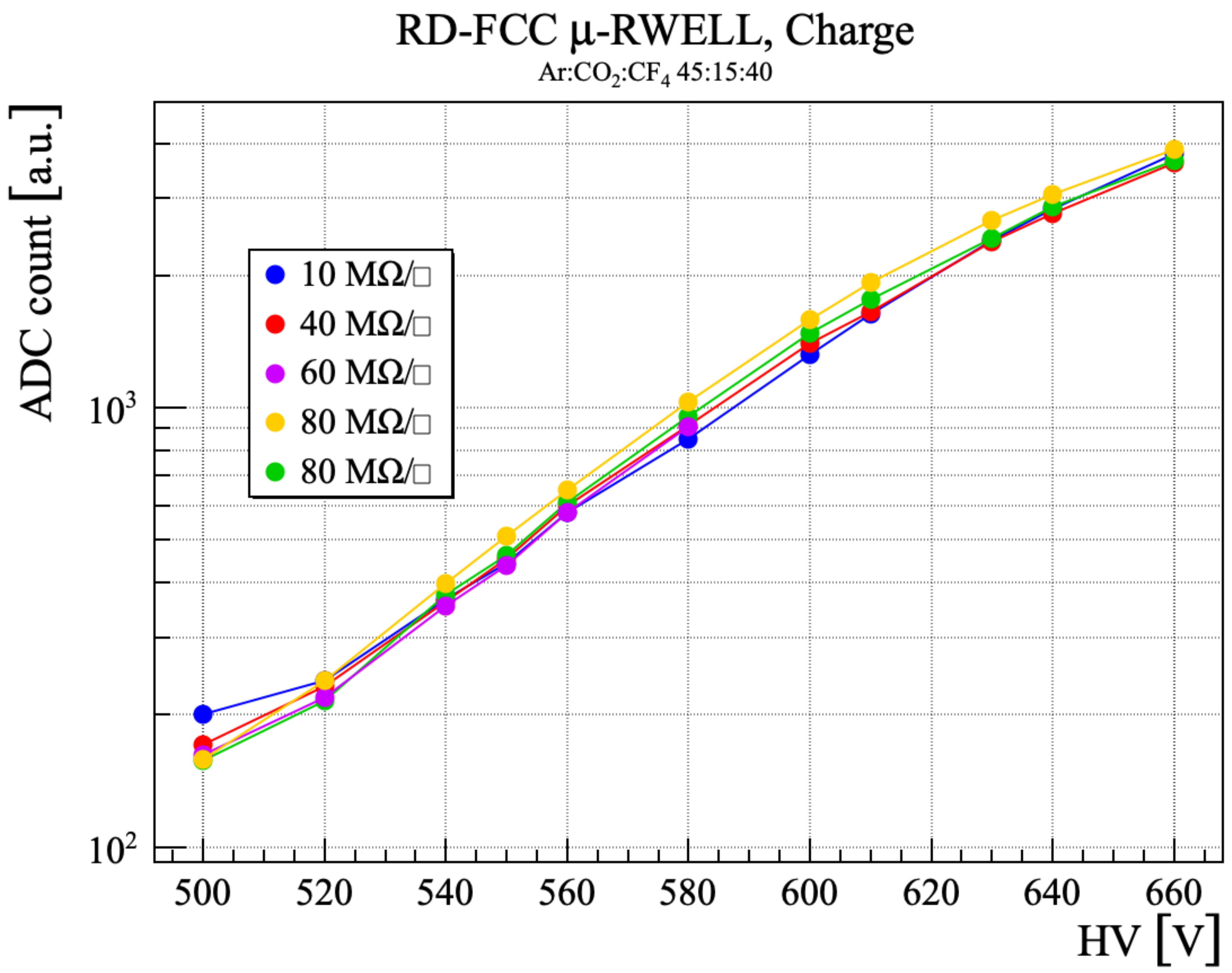


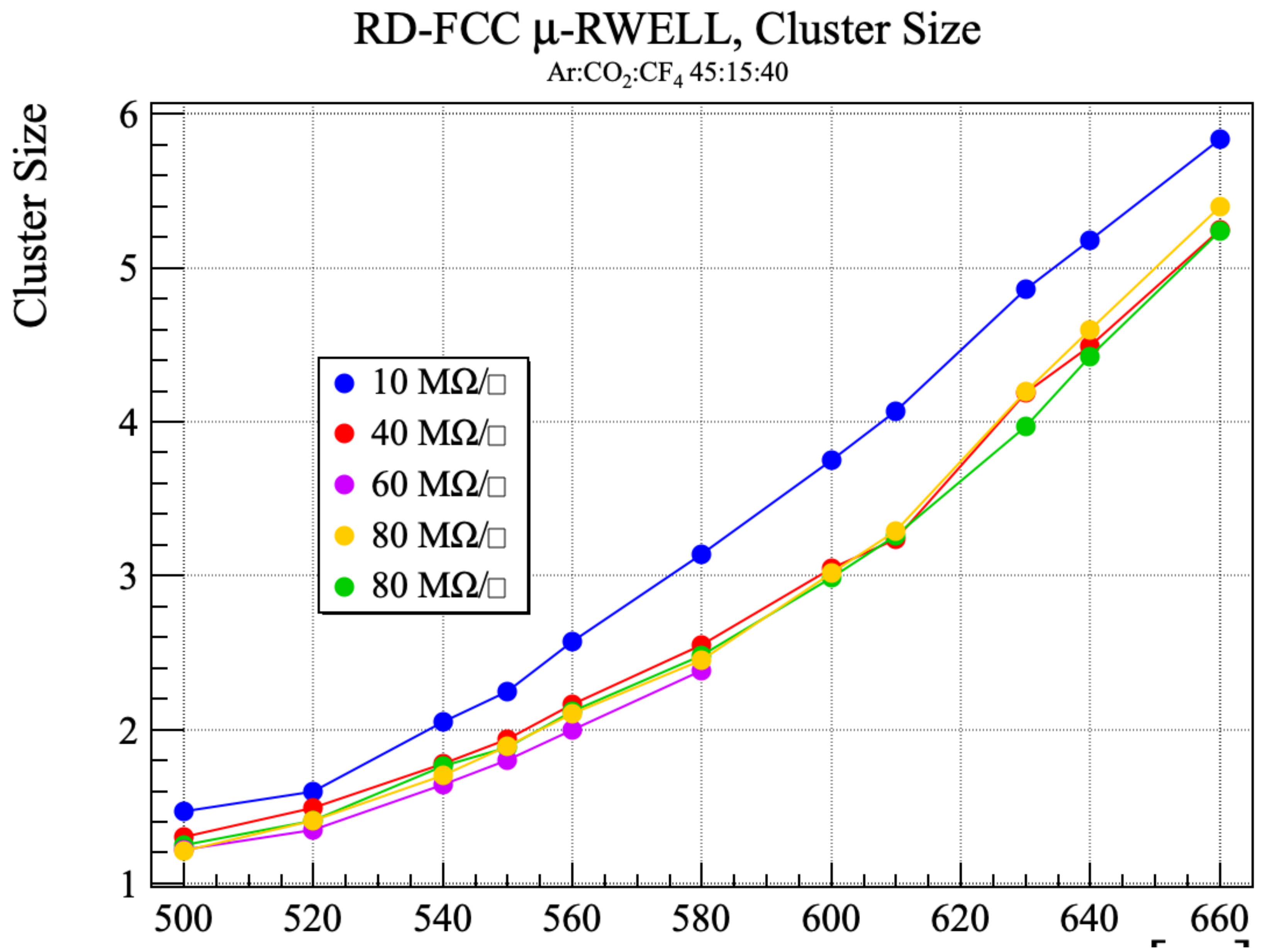


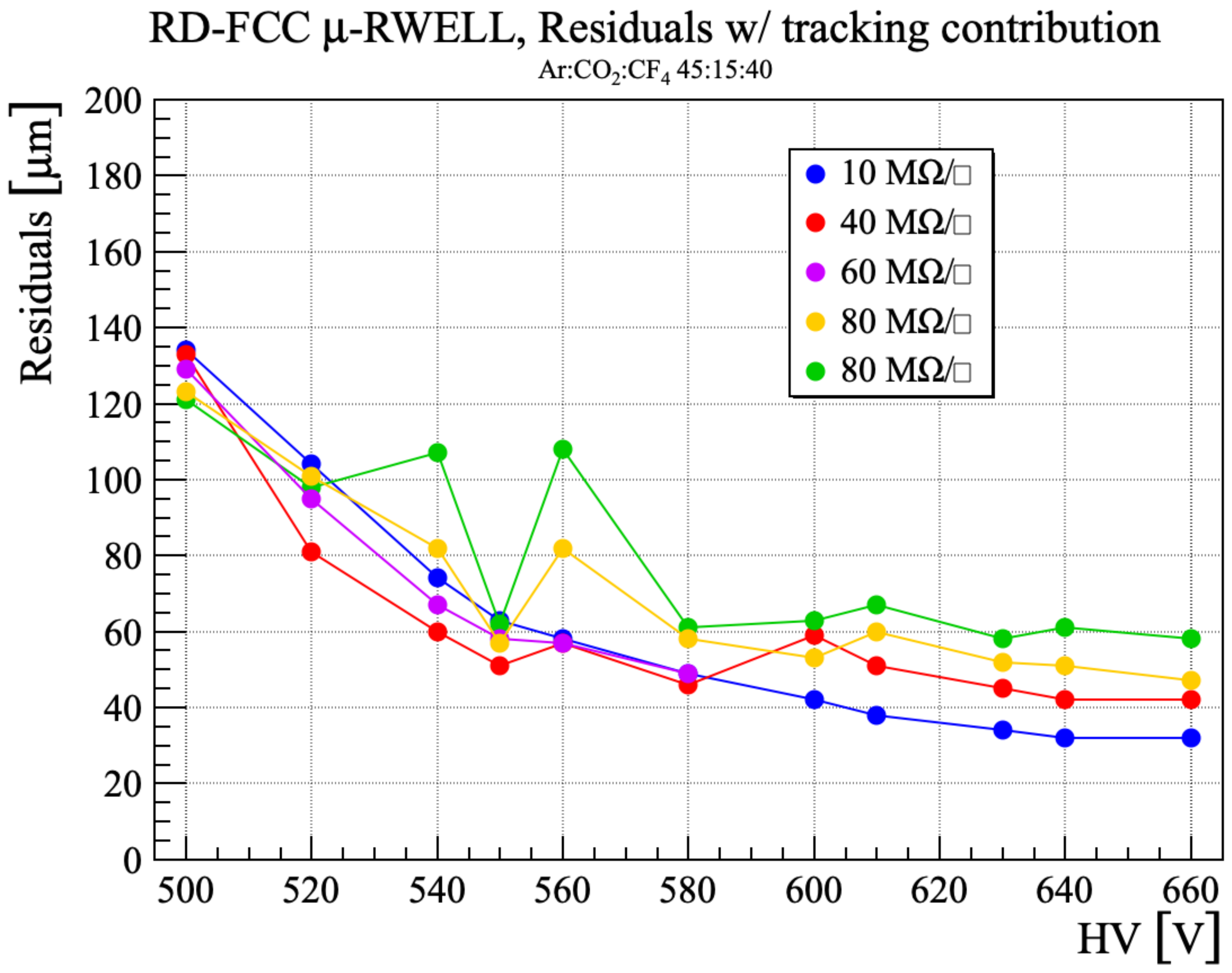

7 μ-RWELL prototypes with resistivity varying between 10 and 80 MOhm/☐ will allow to define best resistivity for final 50x50 $cm^2$ detector

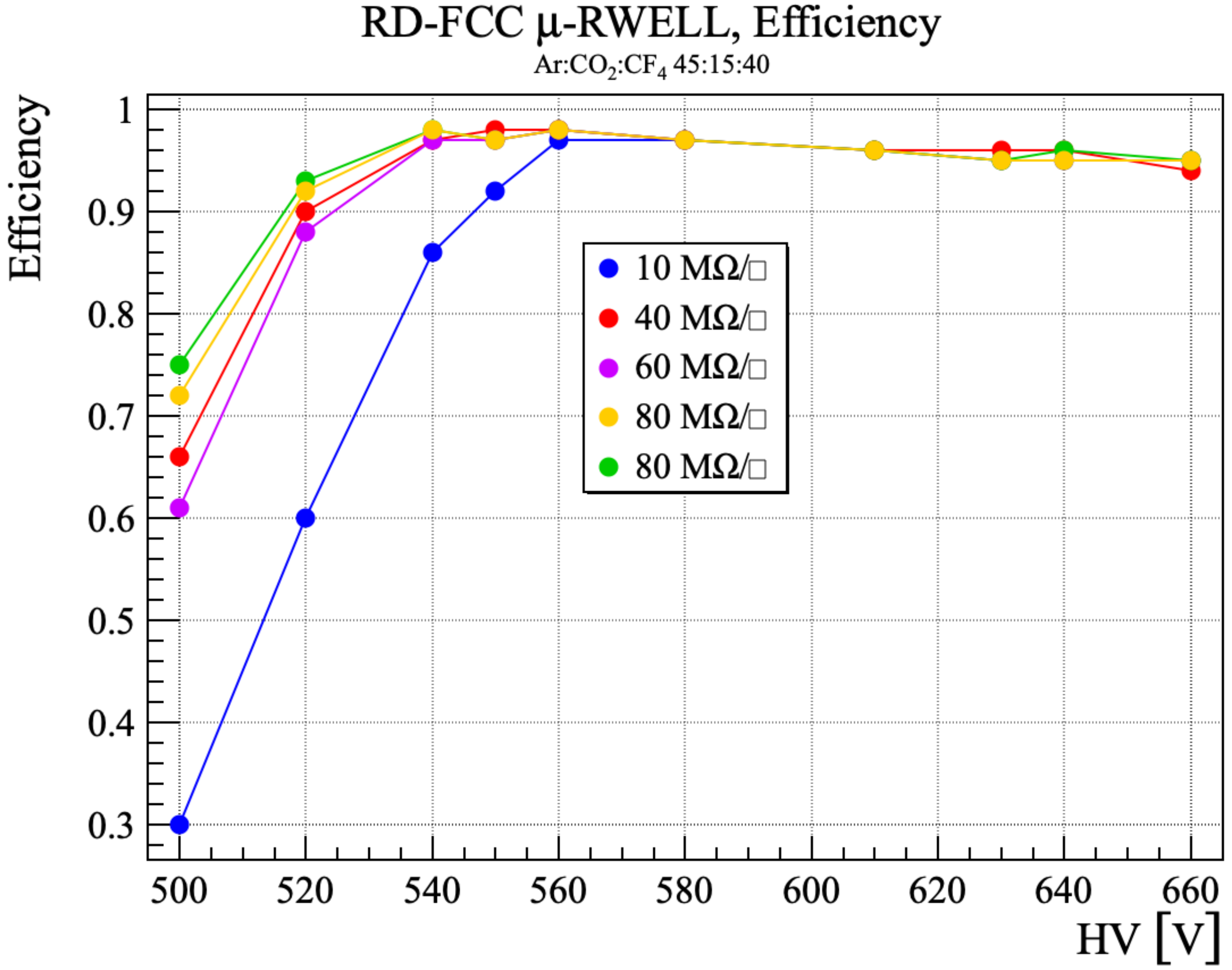
LNF BOLOGNA FERRARA TORINO

# Results from testbeam data



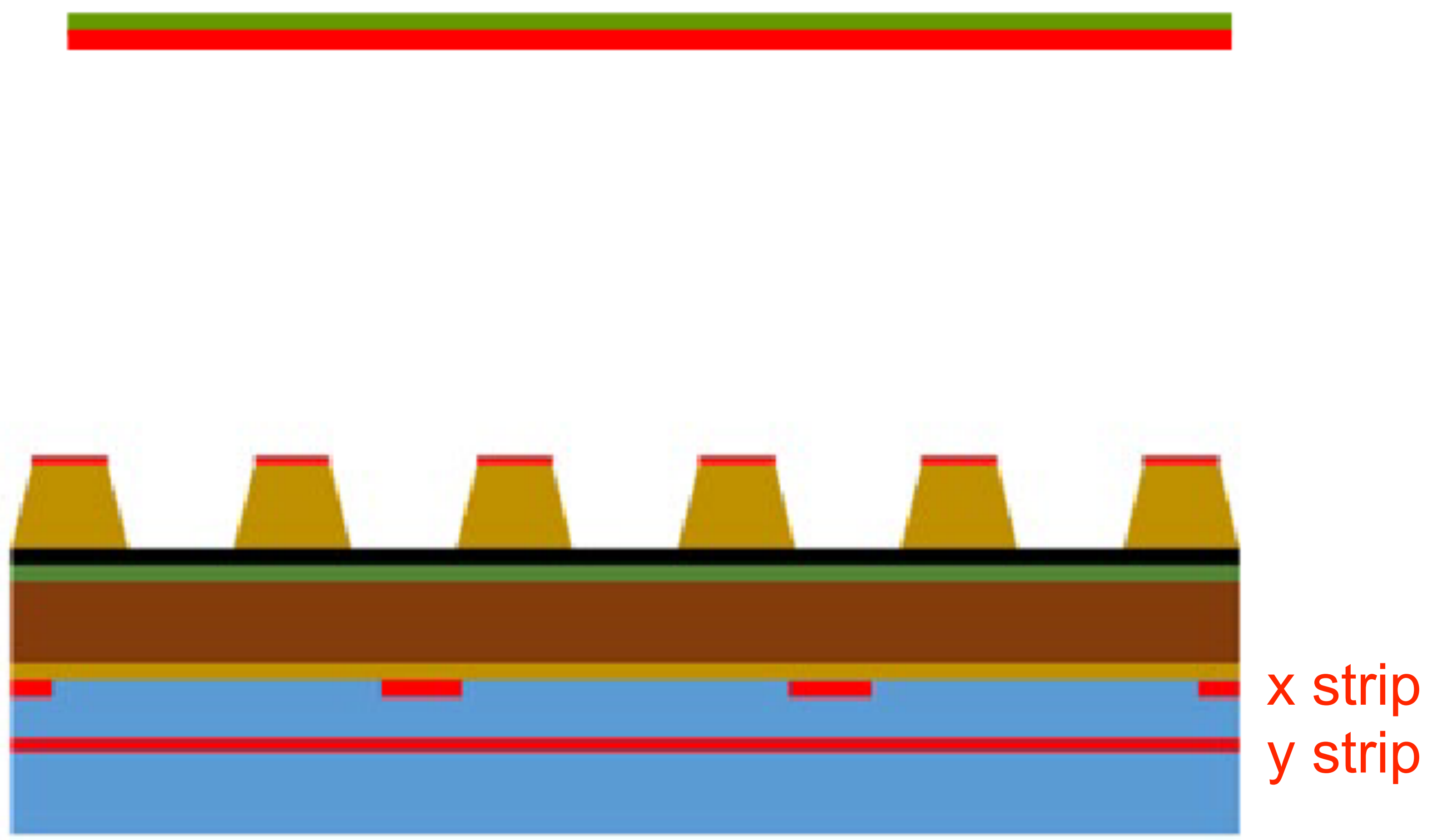



# 2D μ-RWELL ideas

**μ-RWELL with 2D anode readout**

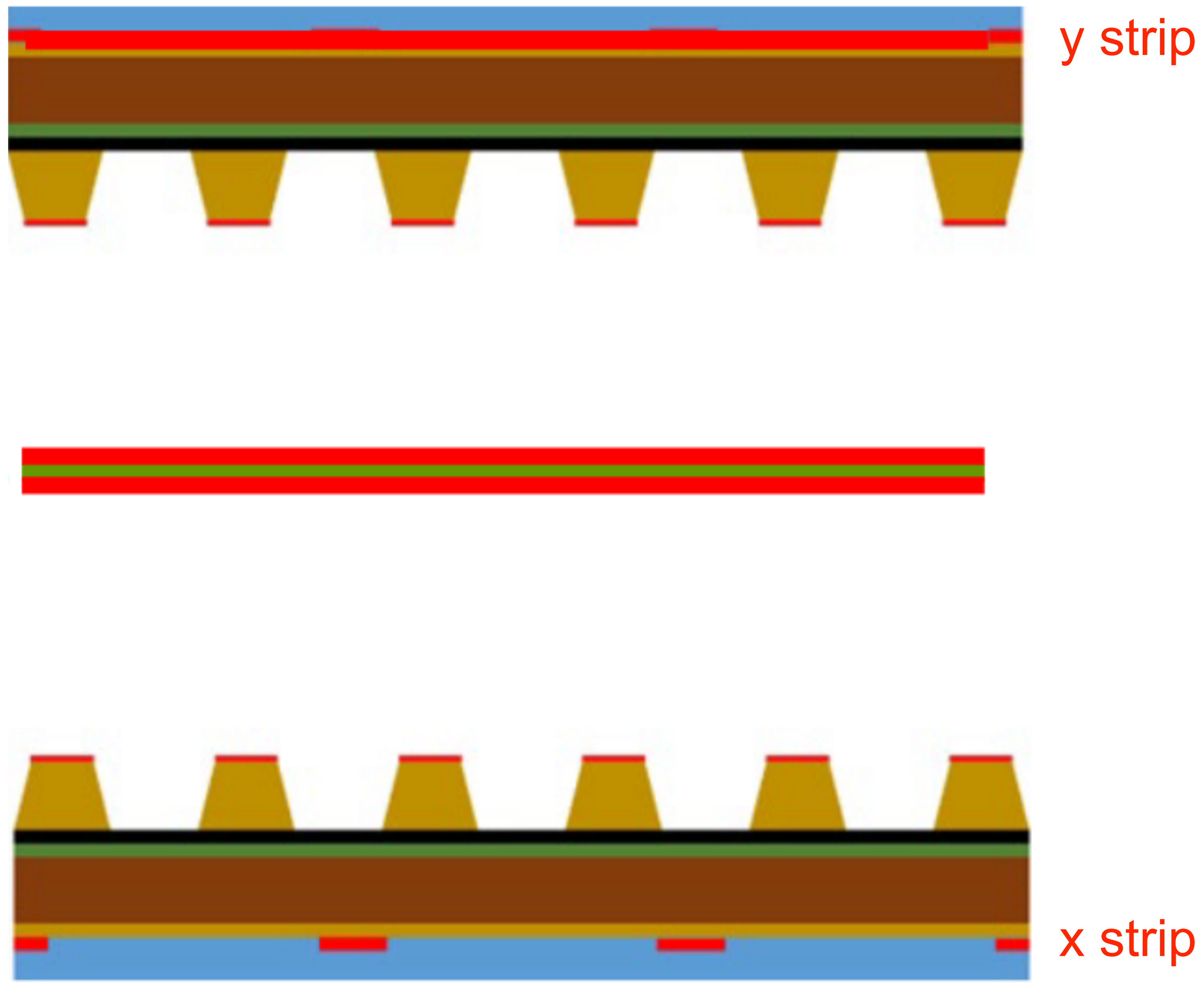
Good performance
but need higher gain wrt. to 1D
μ-RWELL

More complex PCB construction




**2 stacked 1D μ-RWELL**

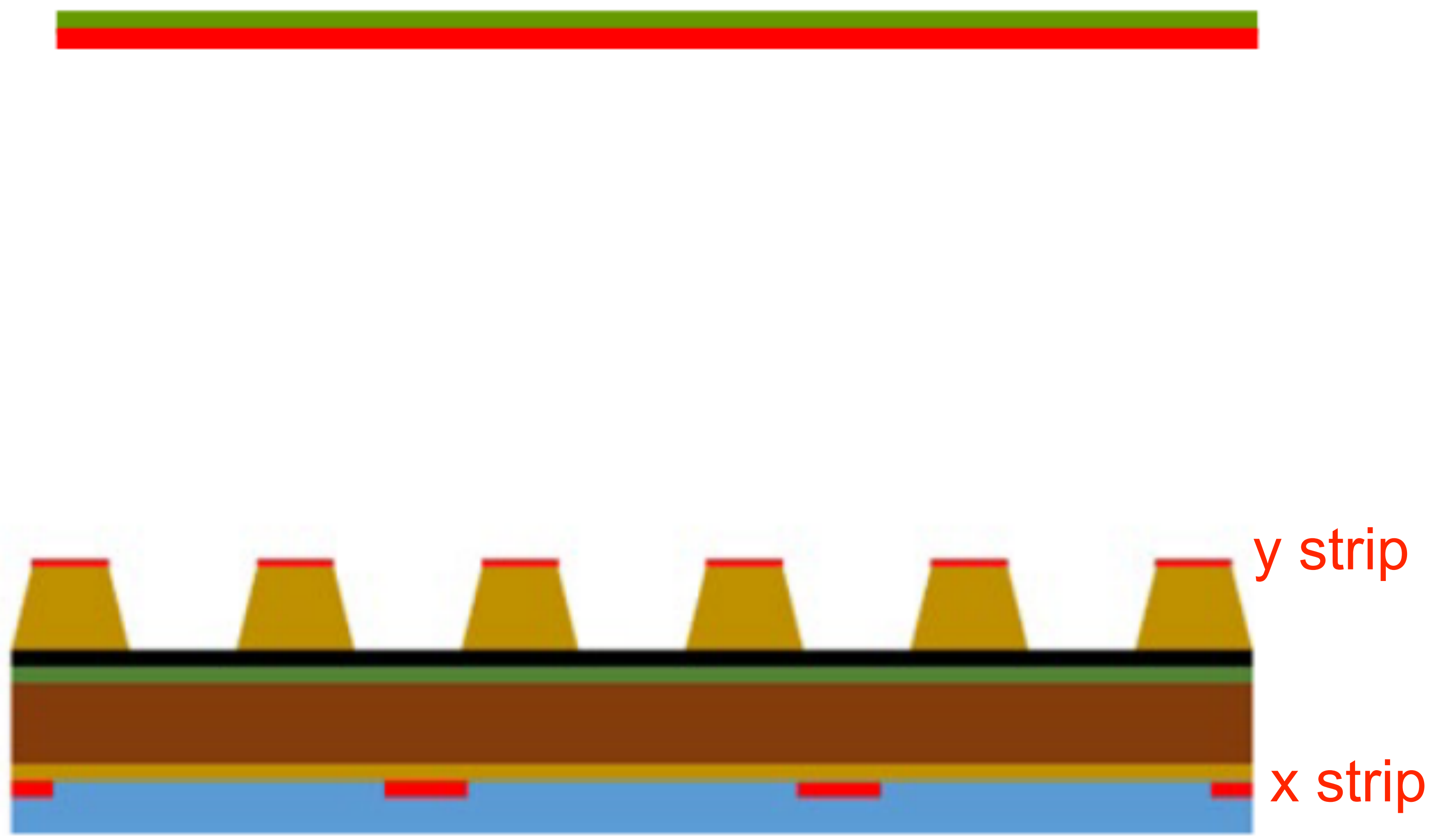
1 view per μ-RWELL
easy PCB construction
2D performance to be
measured




**μ-RWELL with strips on top and anode**

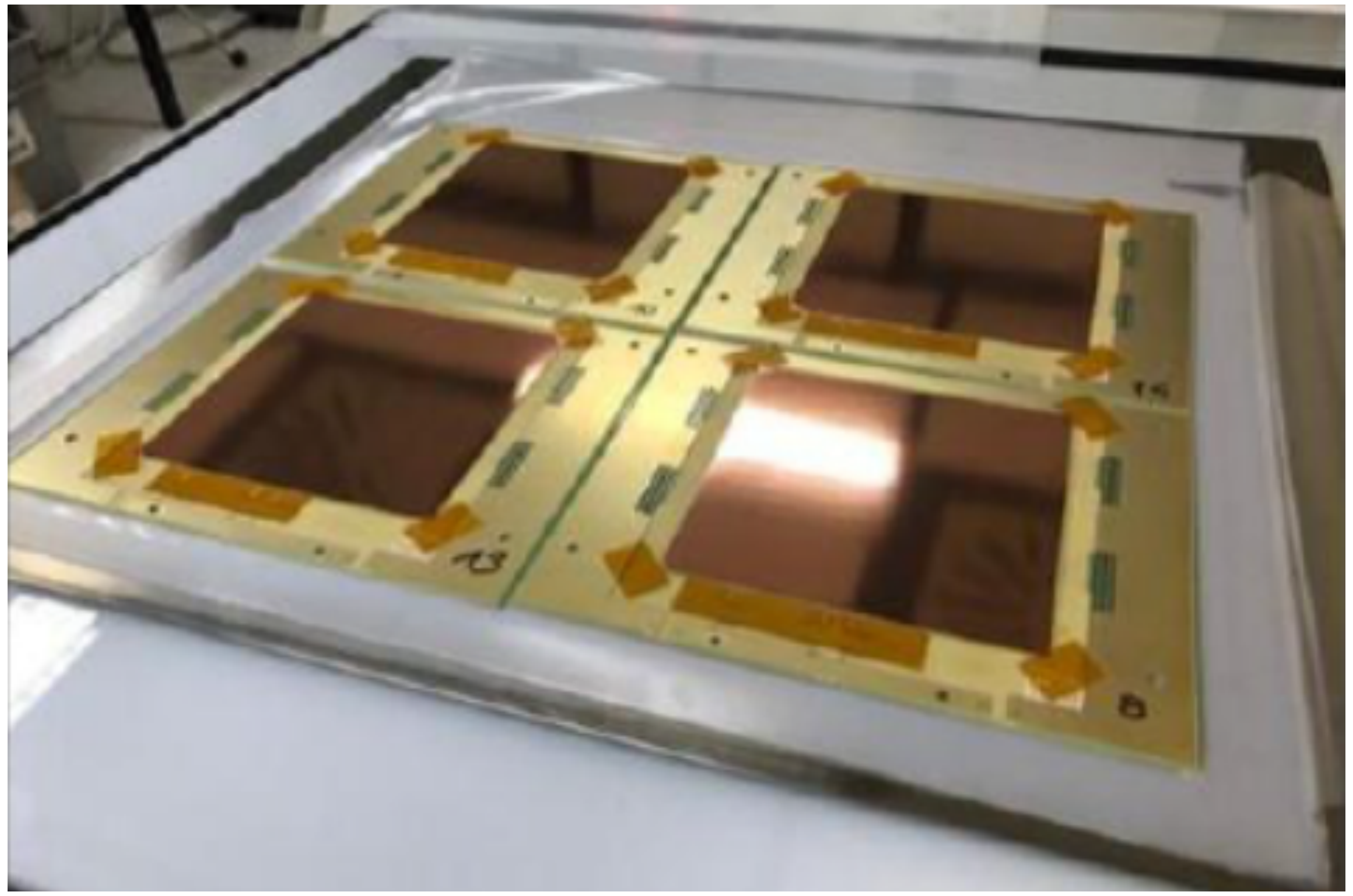
HV on DLC,
TOP to ground

2D performance to be
measured



# Technology transfer with ELTOS

DLC sputtering with new INFN-CERN machine @ CERN



**Step 1**: producing μ-RWELL_PCB

- with top patterned (pad/strip)
- without bottom patterned

**Step 2**: DLC patterning

- in ELTOS with BRUSHING-machine

**Step 3**: DLC foil gluing on PCB

- double 106-prepreg (~2x50 μm thick) (already used in ELTOS)
- pre-smoothing + 106-prepreg (~50 μm thick)
- single 1080-prepreg (~75 μm thick)

**Step 4**: top copper patterning

**Step 5**: Kapton etching on small PCB

**Finalization**

Detector @ CERN for final preparation

# Test with TIGER electronics

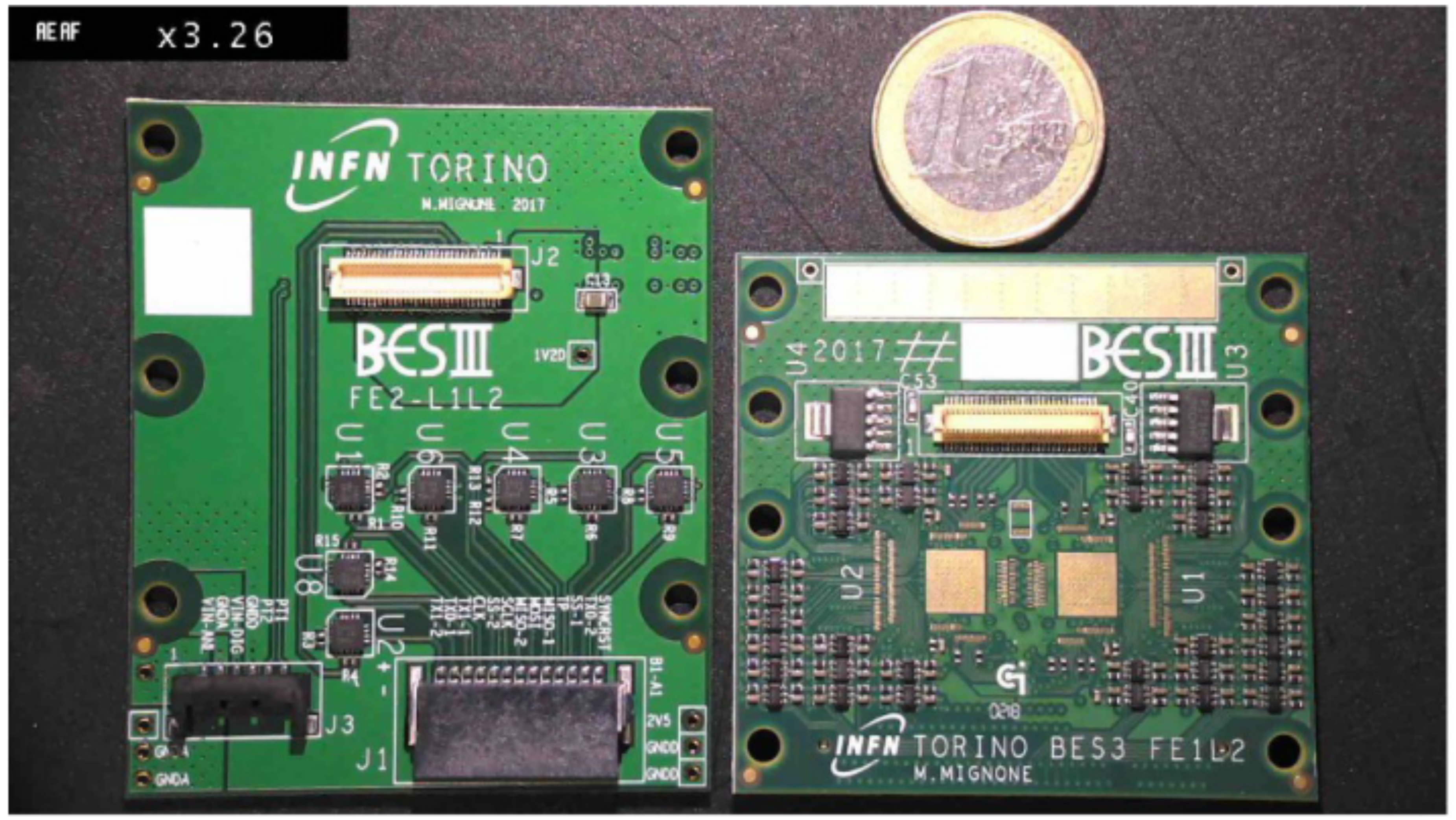



**Table 2**
Measured performance of the TIGER ASIC.

| Parameters | Values |
|---|---|
| Input charge | 5-55 fC |
| TDC resolution | 30 ps RMS |
| Time-walk (5-55 fC range) | 12 ns |
| Average gain | 10.75 mV/fC |
| Nonlinearity (5-55 fC range) | 0.5% |
| RMS gain dispersion | 3.5% |
| Noise floor (ENC) | 1500 $e^-$ |
| Noise slope | 10 $e^-$/pF |
| Maximum power consumption | 12 mW/ch |

## Test with TIGER ASIC

Developed for BESIII CGEM-IT

Prepare new readout card based on System On Modules (SOM)

<u>Aim</u>

Develop dedicated ASIC for μ-RWELL

# Conclusions

- Vertex detector will employ DMAPS
  - Thin detectors in order to have the best possible momentum resolution
  - ARCADIA project for sensors for inner layers
- Silicon wrapper R&D starting from the ATLASPIX3 chips, also for the outer layers of the vertex
- Wire chamber R&D ongoing on many aspects
  - Lot of work, both software and hardware, to demonstrate the cluster counting performances
- Pre-shower and muon detector system will use $\mu$-RWELL technology
  - R&D on DLC resistive, long strips, 2-D sensors, custom ASIC
- Profiting from several national funding schemes, EU projects, etc.
  - INFN was central in all these R&D activities and started many of them
  - Now several international colleagues have joined
- Lots of possibilities for Italian (and International) colleagues to join all these exciting developments!!