

Muon upgrades: LS2 and beyond

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for the Muon group

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The muon system at 2×10^{33} and beyond

The muon system has performed exceptionally well in Run 1 and Run 2

- Tracking inefficiencies from deadtime 1% in Run 1, ~2.6% in Run 2

Increase in luminosity in Phase 1 and Phase 2 has consequences

- Large increase in dead time induced inefficiencies
(reminder: in most regions of the detector the reconstructed hits are obtained by crossing large area X and Y strips)
- Increased rate of ghost hits from accidental crossings of X-Y channels.
- Increased pion misidentification

I will review the steps in order to ensure best performances of the muon detector in the future

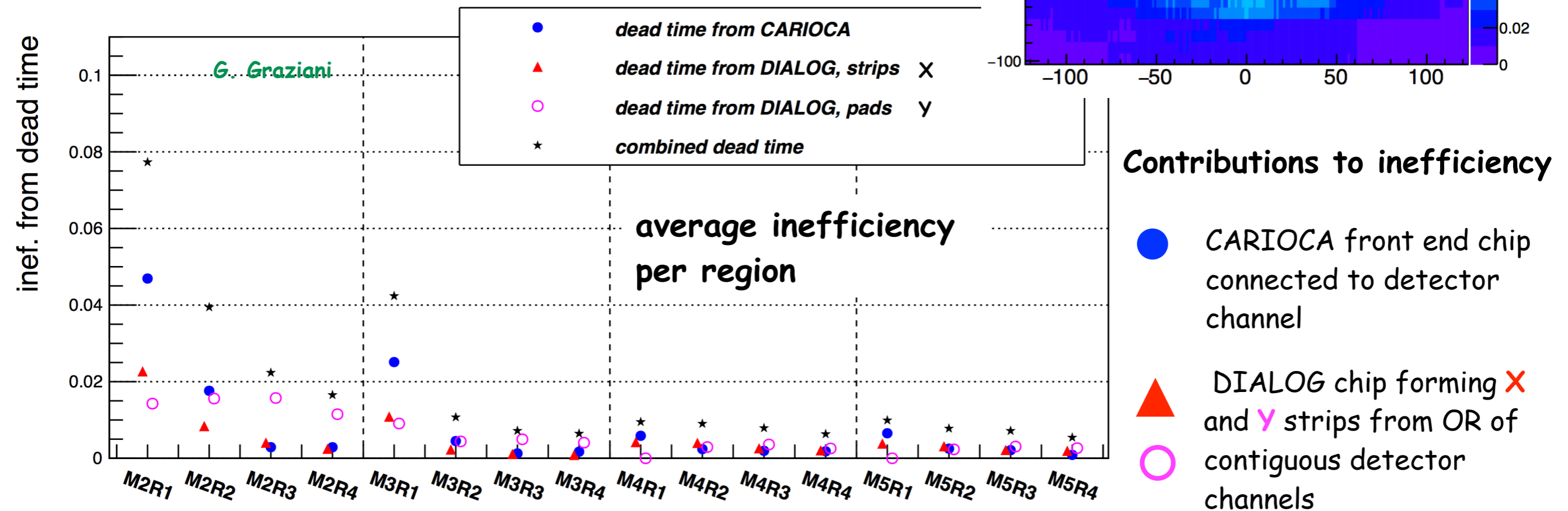
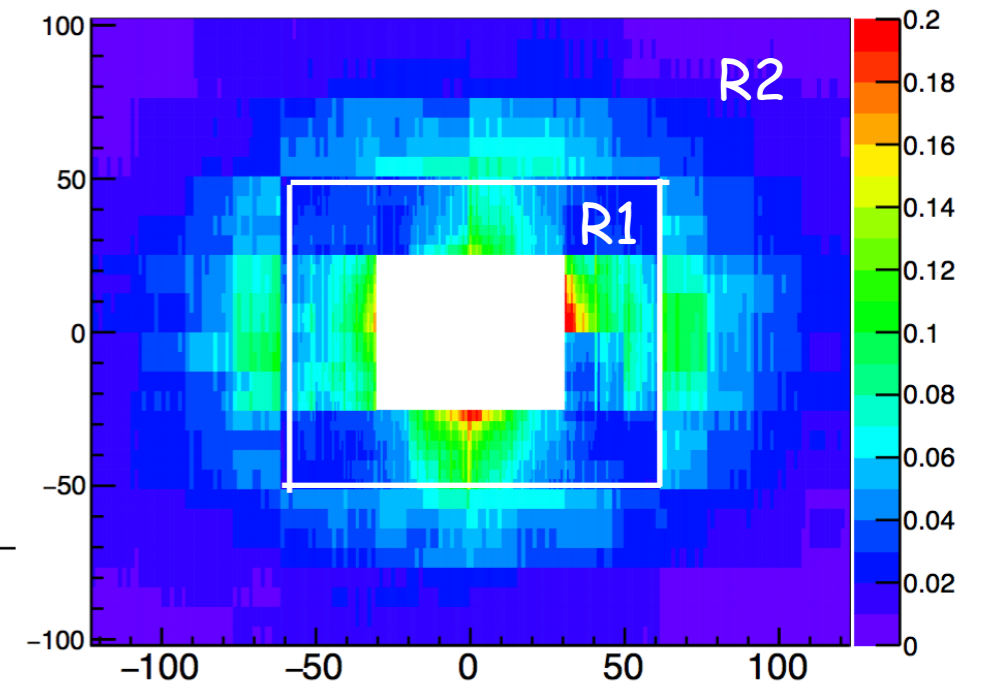
- What has been planned for LS2
- What we're planning before or at LS3 to consolidate our detector
- Ideas and ongoing R&D for the phase 2 upgrade (LS4)

Dead time induced inefficiency at 2×10^{33}

Distribution of the expected inefficiency is highly non uniform and concentrated in the inner regions;
Particularly important in M2, where the inefficiency can be as high as 25%

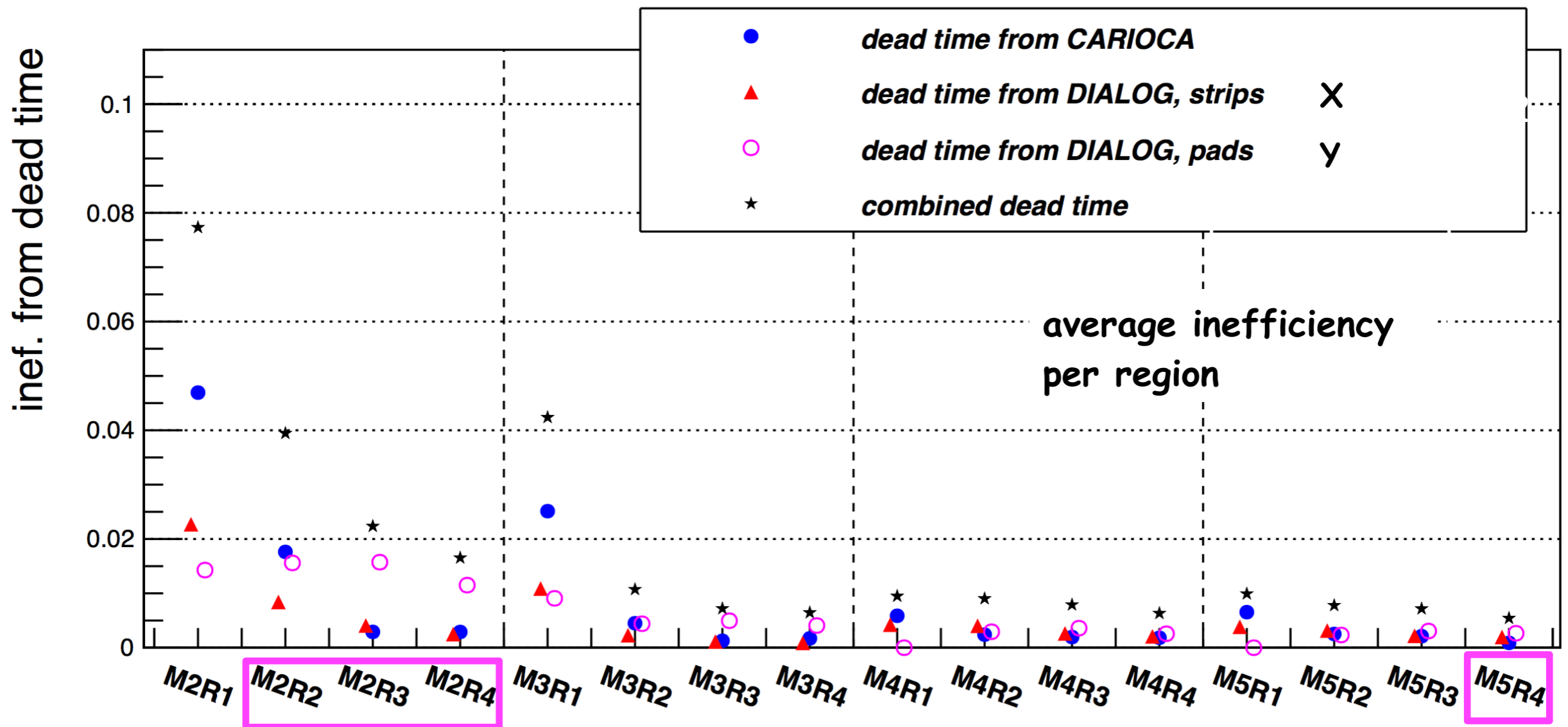
These projections include the mitigation effect from an improved shielding of beam pipe in front of M2: expect 50% rate reduction (only 30% assumed)

M2 inner regions



The expected loss on dimuon events is about 10%

Mitigation strategy at LS2



G. Graziani

At LS2: beside the aforementioned improved beam pipe shielding, we plan to increase the granularity of X and Y strips by removing the OR of contiguous channels (IB boards) in M2R2 (*dialog ineff /2*), in M2R3 (*/24*), and in M2R4 (*/24*), and in M5R4 (*/6*)

The expected loss on dimuon events becomes 8%

Further mitigation strategy for Run3

At LS2 or immediately after: install PAD chambers in M2R1, M2R2 and M3R1, to increase readout granularity and reduce CARIOCA induced dead time

20A3	20A1		20A1	20A3
19A3	19A1		19A1	19A3
18A3	18A2	18A1	18A1	18A2
17A3	17A2			17A2
16A3	16A2			16A2
15A3	15A2	15A1	15A1	15A2
14A3	14A1		14A1	14A3
13A3	13A1		13A1	13A3

M2R1 and M3R1: 12+12 PAD chambers

half M2R2: 12 PAD chambers

- A total of 360 additional FEBs, 12 additional nODEs, 6 additional TELL40 are needed: all available within the planned LS2 resources

The expected loss on dimuon events becomes 4.5%

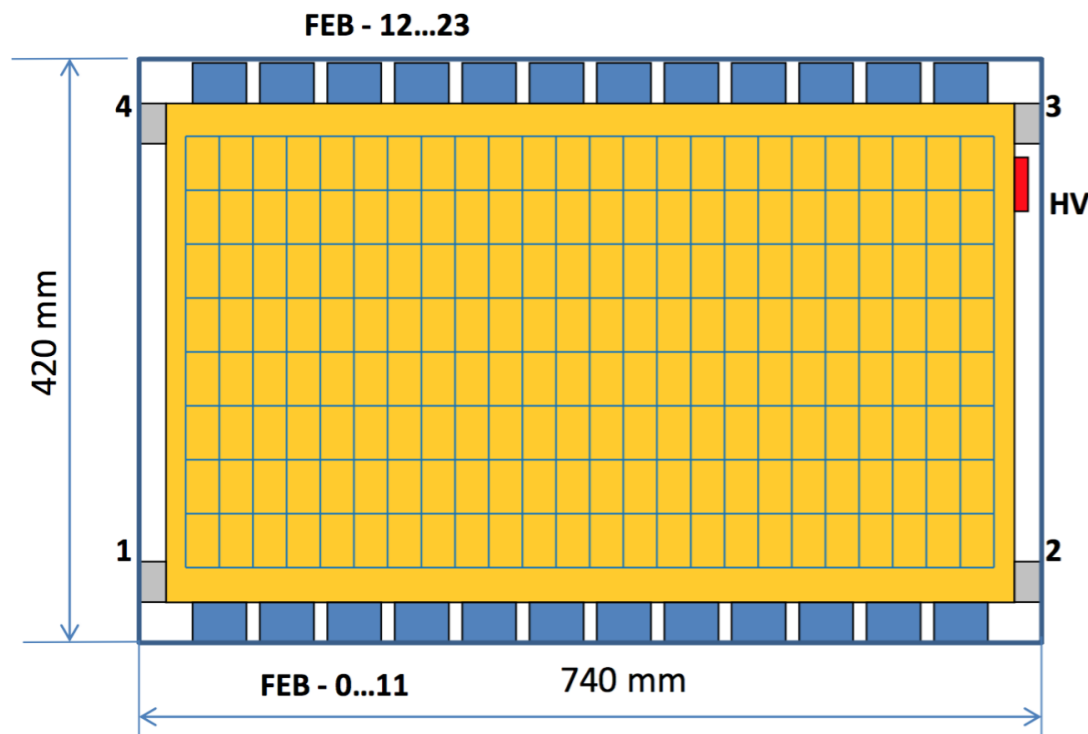
- Even more remarkable than the improvement on the average efficiency is the strong reduction of the localised inefficiency spots up to a factor ~ 7 , with great advantages in all analyses with muons in the final state
- Last but not least, the absence of ghost crossings will reduce the number of reco hits (and of combinatorial bkg) up to a factor of ~ 2

Status of the PAD chambers

The proposed chambers will have the same mechanical structure (with 4 gaps) and same active area, and will use the same front-end boards

The PNPI team is ready to build such pad chambers: a prototype for M2R2 has been already tested successfully more than on year ago, it is now at CERN; a prototype for M2R1 is in preparation

N.Bondar, B.Bochin, et al.



We're targeting an early installation: additional cables on the M2/M3 walls at LS2; the single regions of PAD chambers when ready, at LS2 or during the following winter shutdown; this scenario would allow to profit of the improved performances already during RUN3.

Production plan approved by last TB, installation plan to be further discussed

Towards phase 2 upgrade

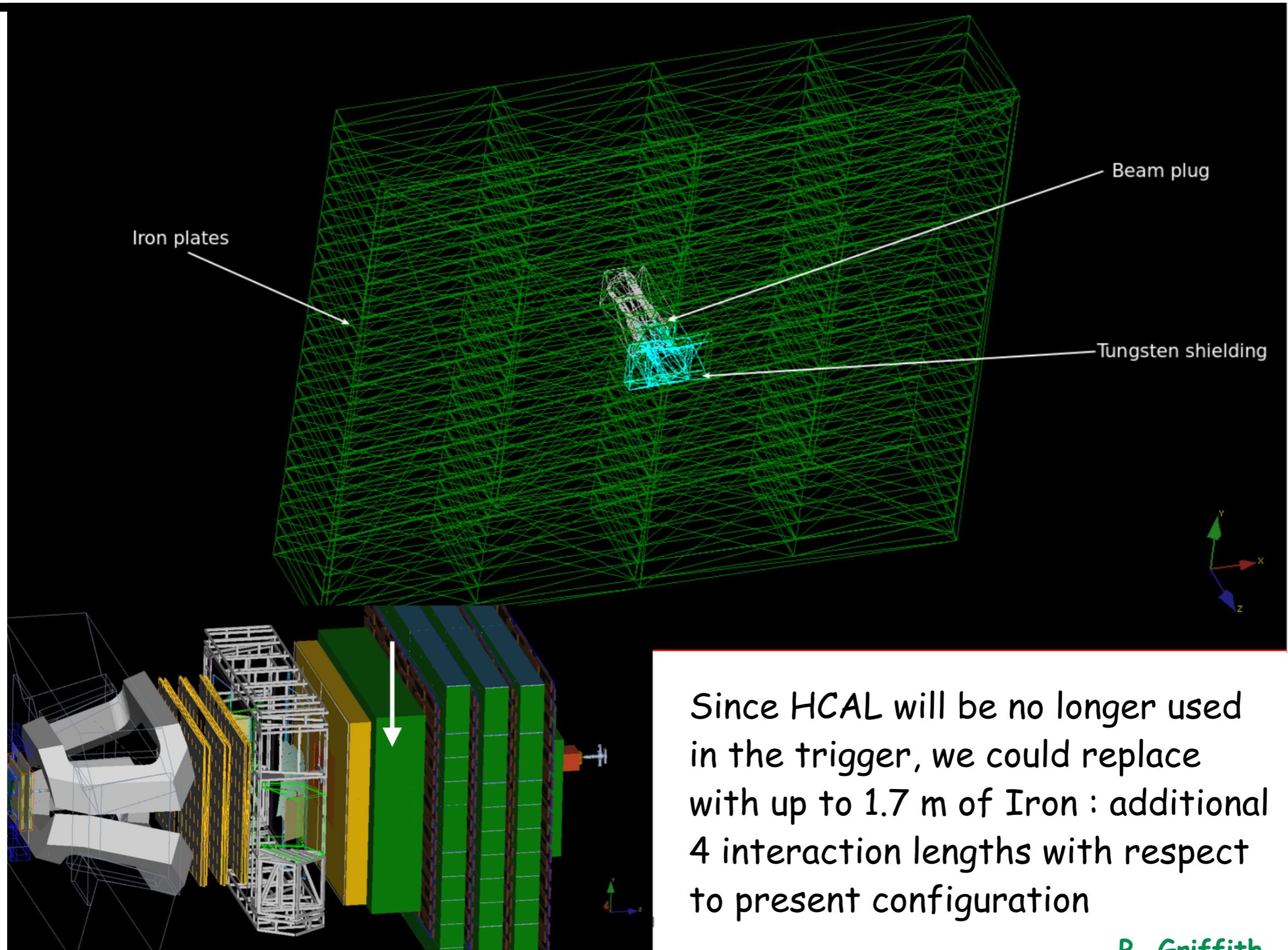
The installation of the above mentioned PAD chambers, together with the other planned interventions, is motivated by ensuring best performances of the muon detector during Run 3 and Run 4, but does not represent a phase 2 upgrade

At 10^{34} a maximum rate exceeding 5 MHz/cm² is expected in M2R1: we need some additional shielding in from of M2!

New detectors, more tolerant to radiation and with an order of magnitude higher readout granularity are also needed for the inner regions

A new electronics for all of the other chambers will be needed, since the presently installed one will be 25 years old at the beginning of phase 2; the replacement of most of the chambers in the detector due to ageing is to be carefully considered

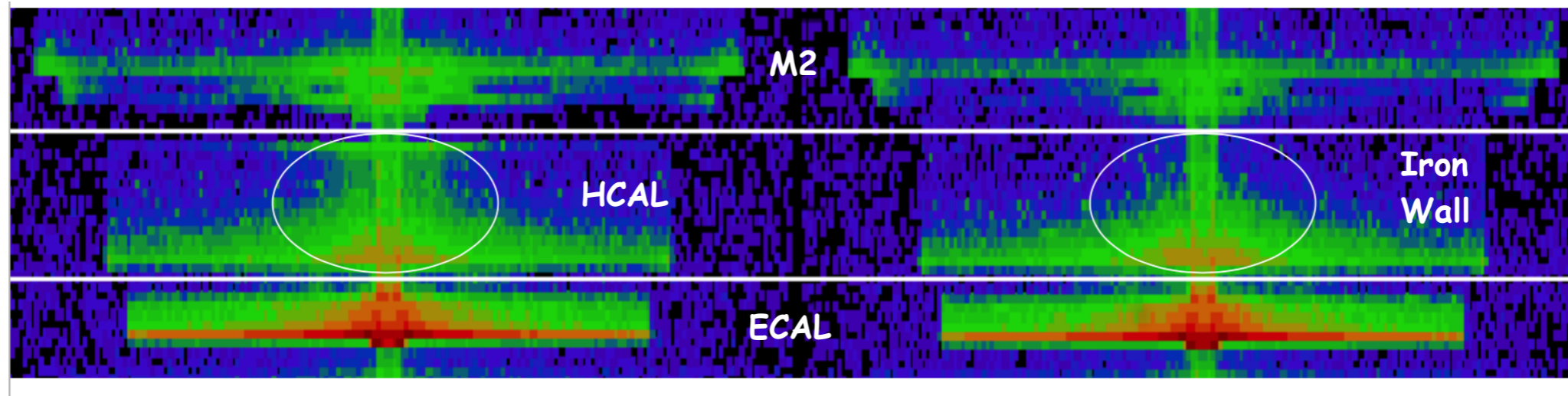
Rate reduction: additional iron wall



Since HCAL will be no longer used in the trigger, we could replace with up to 1.7 m of Iron : additional 4 interaction lengths with respect to present configuration

Iron wall: simulation results

Started with something simple: HCAL replaced in LHCb simulation (current upgrade configuration) with iron wall, with the same outer dimensions



Average rate reduction
for inner regions

M2R1	M2R2	M3R1	M3R2
46%	77%	6%	20%

Muon losses

$3 < p < 6 \text{ GeV}$	$6 < p < 10 \text{ GeV}$	$p > 10 \text{ GeV}$
17%	2,7%	0,6%

2-3% on $B_s \rightarrow \mu^+ \mu^-$, $B_s \rightarrow J/\Psi \phi$, $D^0 \rightarrow \mu^+ \mu^-$
11% on $K_s \rightarrow \mu^+ \mu^-$, $\tau \rightarrow 3\mu$

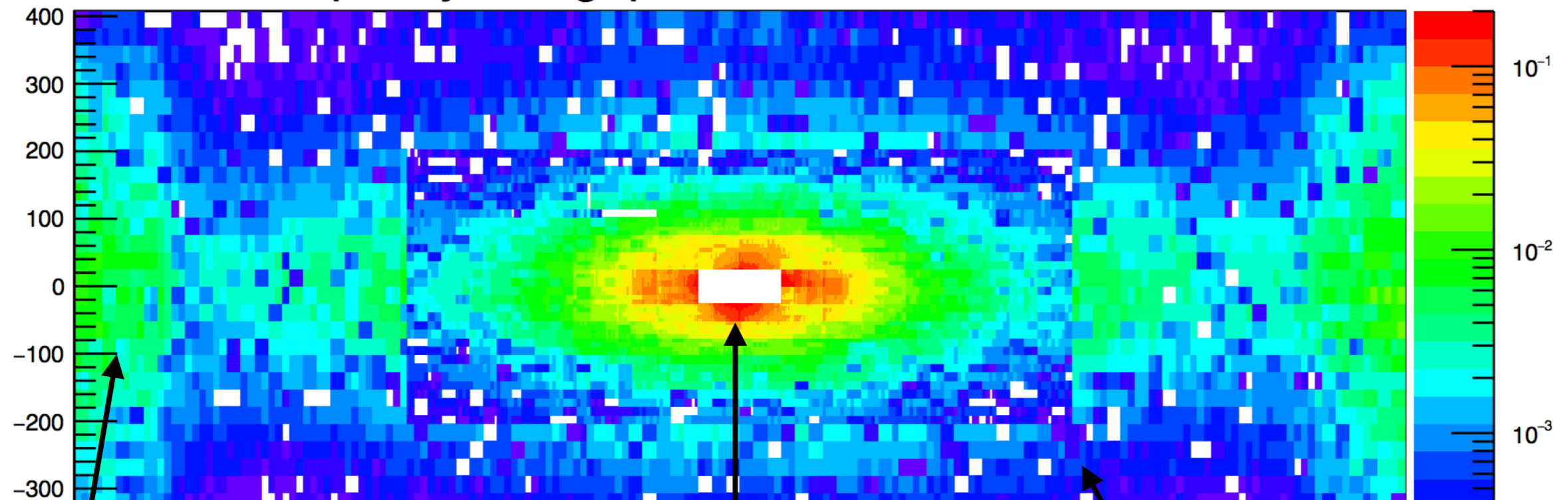
Large room for optimizing the shape of the iron wall

- On the middle plane increase at large X to filter out particles escaping the calorimeter volume
- Away from the middle plane, try to reduce the iron thickness in order to minimise muon losses at low P

M2 occupancy from data extrapolations

Phase 1 conditions

Occupancy of log. pads M2



we need to
extend the iron
filter here

maximum
possible
thickness

we should
reduce the iron
thickness here

Simulation validation

Comparison on the occupancies between data noBias 2017 and MC 2016, produced with very low thresholds for muon bkg

1) data vs MC agreement better than 10% on M23_R12: this means that the rate reduction on internal regions is reliably estimated

2) Quite some disagreement in the external regions: missing material? missing infrastructures?

average occupancy per region (nPV=1)

	DATA	MC low_thr
M2 R1	29.18+- 0.02	24.5 +- 0.2
M2 R2	17.54 +- 0.02	17.3 +- 0.1
M2 R3	5.916 +- 0.009	9.2 +- 0.1
M2 R4	2.740 +- 0.006	5.27 +- 0.07
M3 R1	9.66 +- 0.01	9.4 +- 0.1
M3 R2	3.999 +- 0.008	4.24 +- 0.07
M3 R3	1.125 +- 0.004	2.01 +- 0.05
M3 R4	0.490 +- 0.003	0.86 +- 0.03
M4 R1	3.414 +- 0.007	2.55 +- 0.05
M4 R2	1.570 +- 0.005	1.41 +- 0.04
M4 R3	0.600 +- 0.003	0.83 +- 0.03
M4 R4	0.234 +- 0.002	0.43 +- 0.02
M5 R1	3.450 +- 0.007	2.31 +- 0.05
M5R2	1.453 +- 0.005	1.30 +- 0.04
M5 R3	0.871 +- 0.004	1.42+- 0.04
M5 R4	1.114 +- 0.004	2.54 +- 0.05

Work is ongoing to improve the simulation, which is relevant to optimise the iron wall shape, especially on the outer regions

Prospects for iron wall installation

Possibility to reuse iron from Opera spectrometer

336 slabs $125 \times 50 \times 820 \text{ cm}^3$, 4 tons each

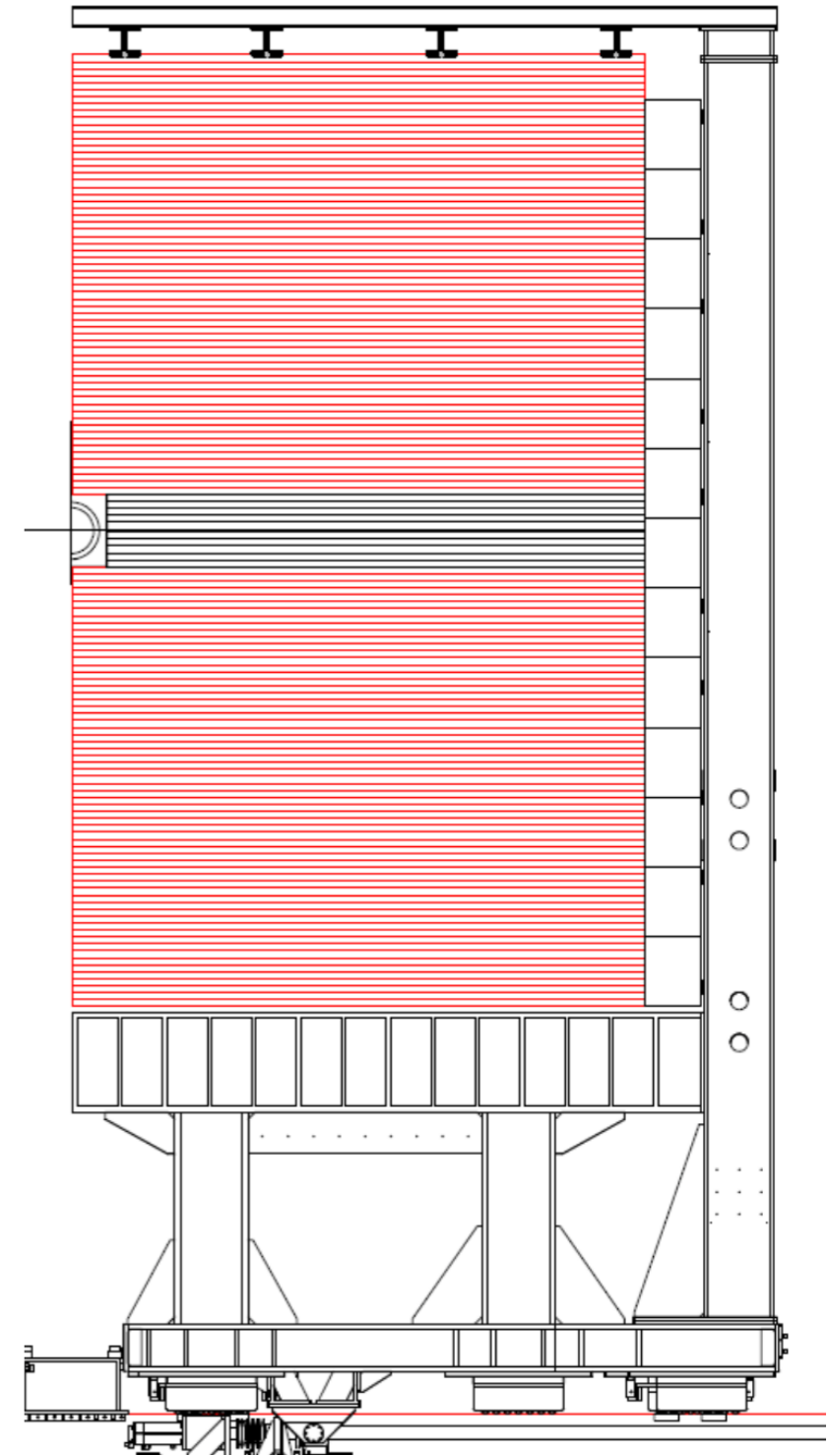
Several drawings have been already prepared, with different balance btw machining, reuse of HCAL mechanical structure, amount of iron

Before going on, we need to finalise iron wall design from MC studies: the overall dimensions could be indeed reduced

An manifestation of interest was sent by Guy to INFN one year ago; there's also interest from SHIP

Iron is presently stored at LNGS, less pressure for a quick decision than one year ago, but we must finalise soon our design to be ready for it

If there's a clear path to phase 2 upgrade, then it would be nice to profit of LS3 to install the iron wall



A. Cardini, S. Saputi

Rates at 2×10^{34}

The following max rates for phase 2 are obtained by scaling the phase 1 extrapolations

	kHz/cm ²		kHz/cm ²		kHz/cm ²		kHz/cm ²
M2R1	2800	M3R1	1900	M4R1	650	M5R1	550
M2R2	425	M3R2	220	M4R2	85	M5R2	55
M2R3	45	M3R3	19	M4R3	9	M5R3	7
M2R4	20	M3R4	5	M4R4	3	M5R4	4

(the estimated mitigation from iron wall is assumed for M2R1 and M2R2)

Detector requirements

- Rate capability up to 3 MHz/cm²
- Efficiency for single gap $\geq 95\%$ within 25 ns
- Operation stability up to 6C/cm² accumulated charge in 10 years
- Pad cluster size <1.2

μ -RWELL detector seems to be a good candidate for both the low and high rate regions of the upgraded muon detector

The μ -RWELL detector

The μ -RWELL is composed of only two elements: the μ -RWELL_PCB and the a cathode PCB defining the drift gap

The μ -RWELL_PCB is realized by coupling:

1) a suitably patterned kapton foil as amplification stage

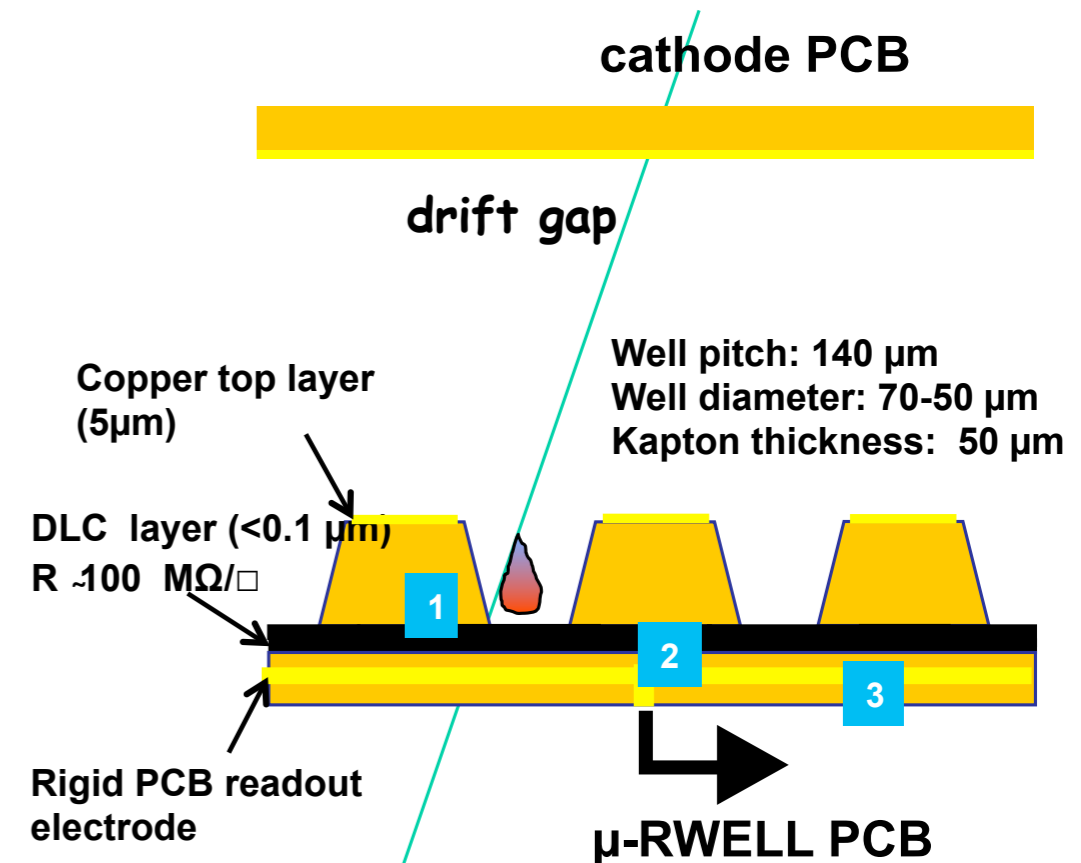
2) a resistive layer for discharge suppression and current evacuation:

"Single resistive layer" (Low Rate, LR) $< 100 \text{ kHz/cm}^2$: single resistive layer with surface resistivity $\sim 100 \text{ M}\Omega/\square$

"Double resistive layer" (High Rate, HR) $> 1 \text{ MHz/cm}^2$: more sophisticated resistive scheme must be implemented

3) a standard readout PCB

G. Bencivenni et al., 2015_JINST_10_P02008



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

The main effect of the introduction of the resistive stage is the suppression of sparks, but this needs a careful design in order to keep a high rate capability

Other advantages of μ -RWELL: simple assembly procedure, easy to operate

A crucial point is to achieve, in cooperation with printed circuit industry, an effective process for the production of the μ -RWELL_PCB

Status of the R&D for the μ -RWELL

An intense R&D is ongoing in Frascati, in cooperation with the CERN PCB workshop, with ELTOS (Italy) and Techtra (Poland) as industrial partners

Low Rate

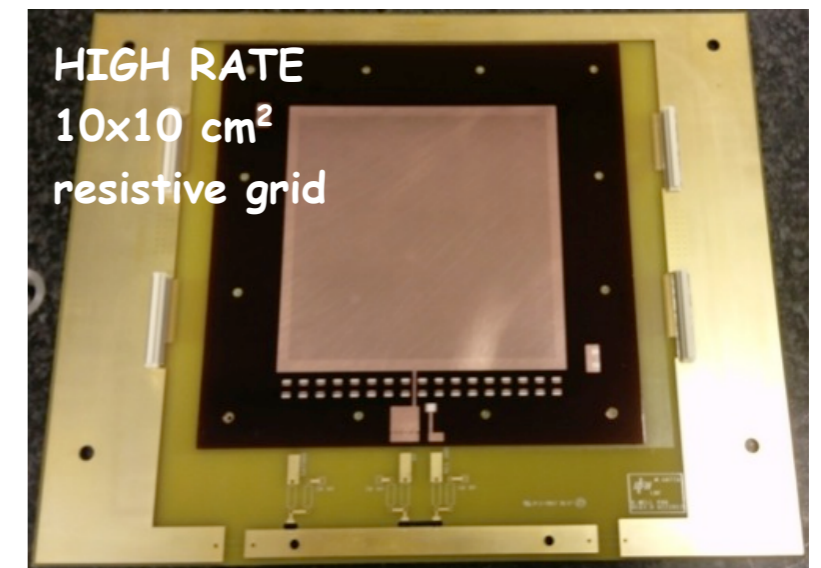
Large size prototypes ($1.2 \times 0.5 \text{ m}^2$) have been realised, and tested up to 40 kHz/cm^2 MIP rate, without loss of gain

Industrialization process is mature, PCB is produced at ELTOS and sent to CERN for final etching

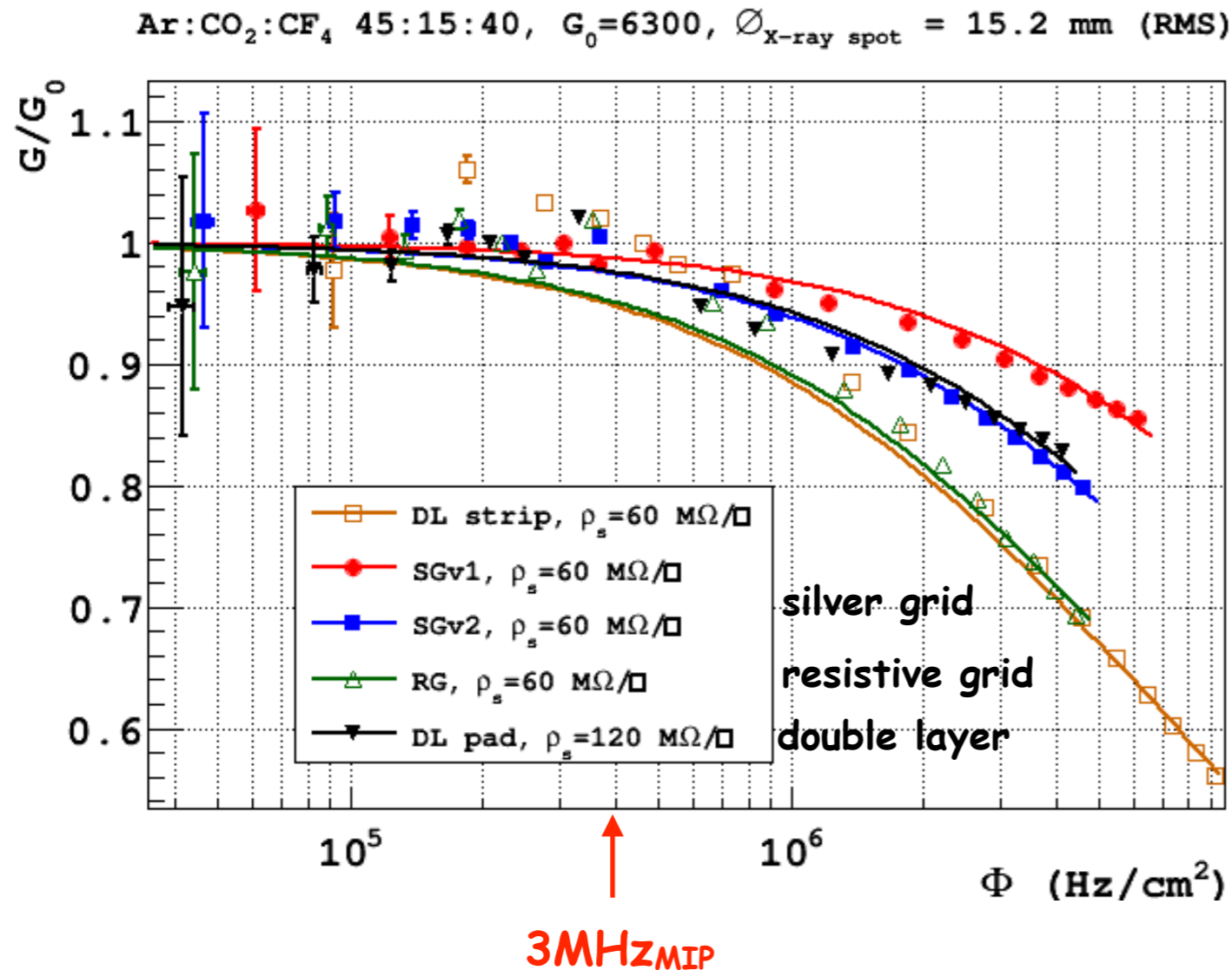
High Rate

Double resistive layer with conductive vias designed to evacuate the charge is very effective, but is not suited for industrial production

new Other simpler layouts have been developed, with silver or resistive grids printed on the bottom of the amplification stage: the constructive parameters are still to be optimized, but these seem viable solutions (can be implemented by industry)



High rate performances with X-rays



The gain drop is only due to Ohmic effect on the resistive layer (order 10 M Ω), and depends on the details of the evacuation scheme

to be noted: equivalent
MIP rate = X-ray rate x7

Rate capability already well above 1MHz for all evacuation schemes

To be confirmed at PSI with high intensity hadron beam up to 20MHz/cm²

Large room for optimizing the resistive grid, very promising

Readout electronics

Chambers will have the same active area as present ones, 2 gaps/chamber

example of
readout
granularity
for the inner
regions

Sta/Reg	max rate kHz/cm ²	active area cm ²	PAD area cm ²	C pF	rate/ PAD kHz	Nch/gap	Nch/ chamber	Nch/ region
M2R1	2800	30x25	0.63x0.78	3.9	1400	1536	3072	36864
M2R2	425	60x25	1.25x1.56	15.6	830	768	1536	36864
M3R1	1900	32x27	0.67x0.84	4.5	1070	1536	3072	36864
M3R2	220	65x27	1.35x1.69	18.3	500	768	1536	36864

- **Max rate is challenging**, we're evaluating the possibility to use one among VFAT3 (CMS), VMM3 (ATLAS) and TIGER (BES) ASICs developed for the next generation of MPGDs
- Number of channels seems affordable: e.g. VFAT3 has 128 ch.
- **Important**: the new readout electronics need to integrate the functionality of the nODE too, and will be interfaced directly with future low-power versions of GBT-X, in order to transmit via optical fibers serialized data without an off-detector electronics stage

Scenarios for an upgraded detector

0) Install an additional iron shielding in front of M2

1) High rate, R1 and R2 all stations + M2R3: 192 chambers, 37 m² total area

→ replace with μ -RWELL

disclaimer: other detector options are in principle possible, not discussed today: GEMs, scintillator pads

2) Low rate: R3 and R4 all stations (but M2R3): 912 chambers, 350 m² total area

→ replace with μ -RWELL

simpler assembly procedure than MWPC, increasingly competitive in terms of price following the recent R&D

→ replace with new MWPC

very challenging to afford a new large production in the next years, need also new front-end electronics

→ keep a large fraction of old MWPC

need to replace the front-end electronics at least, large reduction of costs

The possibility to keep our old MWPCs in operation beyond Run 4 poses serious questions, but since building a completely new muon detector is a big enterprise, this is a legitimate point to be addressed in the next future

Considerations about MWPC ageing

Estimated average deposited charge (C/cm of wire) after 50/fb, in the most irradiated chamber of each station/region.

LHCb-TDR-014

	R1	R2	R3	R4
M2	0.67	0.42	0.10	0.02
M3	0.17	0.08	0.02	0.01
M4	0.22	0.06	0.01	0.004
M5	0.15	0.03	0.01	0.003

MWPCs were tested up to 0.45 C/cm without visible effect

LHCb-2004-029

More interestingly, most irradiated chambers in M1R2 already reached 0.7 C/cm, i.e. what foreseen in M2R1 at the end of phase 1 upgrade, again w/o visible effect; in addition, the fraction of gaps affected by Malter is stable at the moment

O.Maev, LHCb-INT-2017-029

Phase 1 Given the above, we're optimistic for what concern the chamber ageing up to Run 4; the planned installation of new PAD chambers on M2R1 and M2R2 will be of course beneficial

Phase 2 Targeting 500/fb seems possible for R3 and R4 of all stations, provided the projections above are confirmed by the first years of operation in Run 3;

IMPORTANT CAVEAT: the maximum possible readout granularity achievable with these chambers may be not sufficient to avoid inefficiency problems → appropriate studies are needed

Conclusions

Phase 1: great attention in maximising the detector performances for Run 3 and Run 4

- granularity increase via removal of logical OR of contiguous channels already planned where possible
- new MWPC with PAD readout proposed for M2R1, M2R2 and M3R1, to be installed at the beginning of Run 3

Phase 2 preparation: install new iron shielding wall in front of M2 to reduce the rate

- the wall shape need to be finalised: expand in the horizontal plane, reduce thickness elsewhere (if possible)
- opportunity to reuse the iron from Opera spectrometer, LS3 could be a good time window for installation

Phase 2: install new detectors

- inner regions: intense R&D ongoing on μ -RWELL, which appear as a promising solution (to be compared with others)
- outer regions: new front-end electronics needed for all chambers, a careful consideration is needed on the possible replacement of all of the chambers: MWPC or again μ -RWELL are good candidates

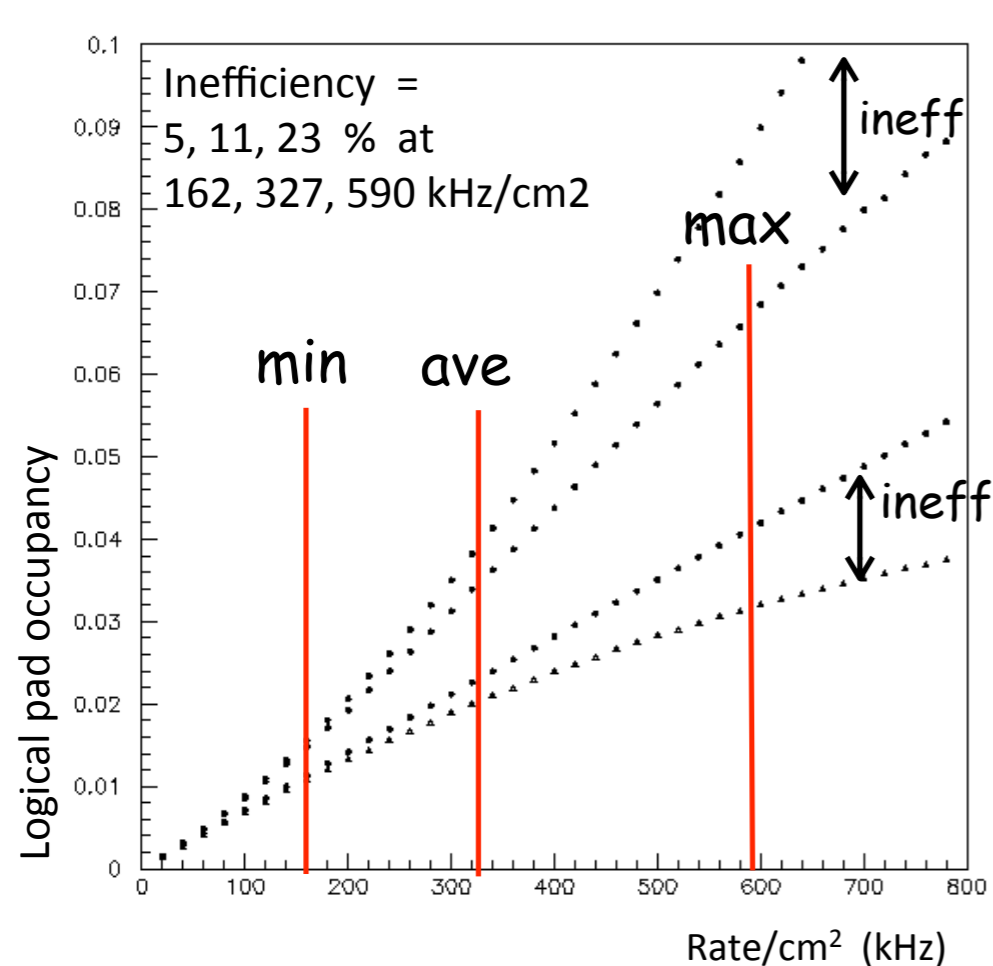


SPARES

The image features a minimalist design with several horizontal black lines of varying lengths. A light blue wedge shape points from the right towards the center. The word "SPARES" is written in a bold, blue, sans-serif font. A thick black L-shaped line is positioned on the left side of the composition.

Strips vs pad readout: simulation results on M2R1

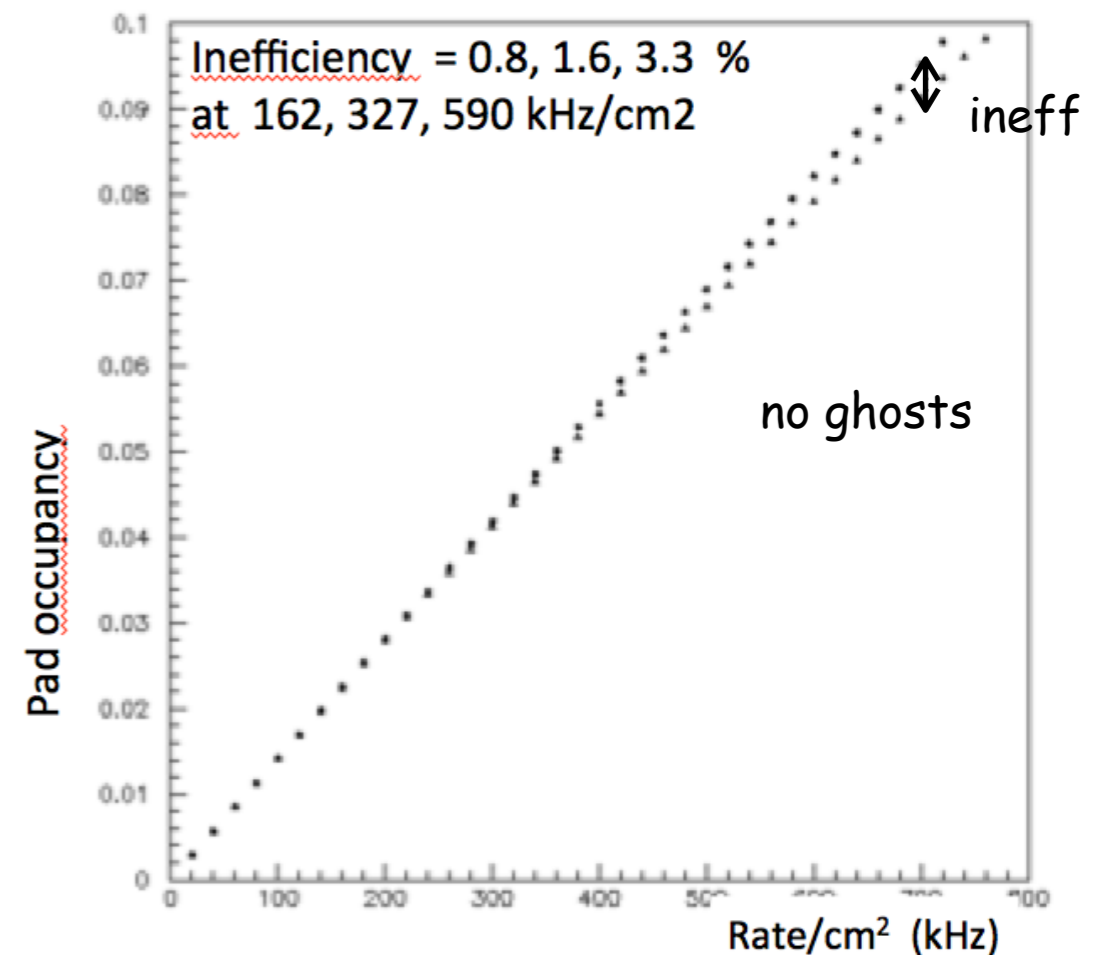
M2R1 present detector (X and Y strips):
48x8 = 384 crossings per chamber,
logical PAD area $0.6 \times 3.2 \sim 2 \text{ cm}^2$



reco hits
(including
ghosts)

real
particles

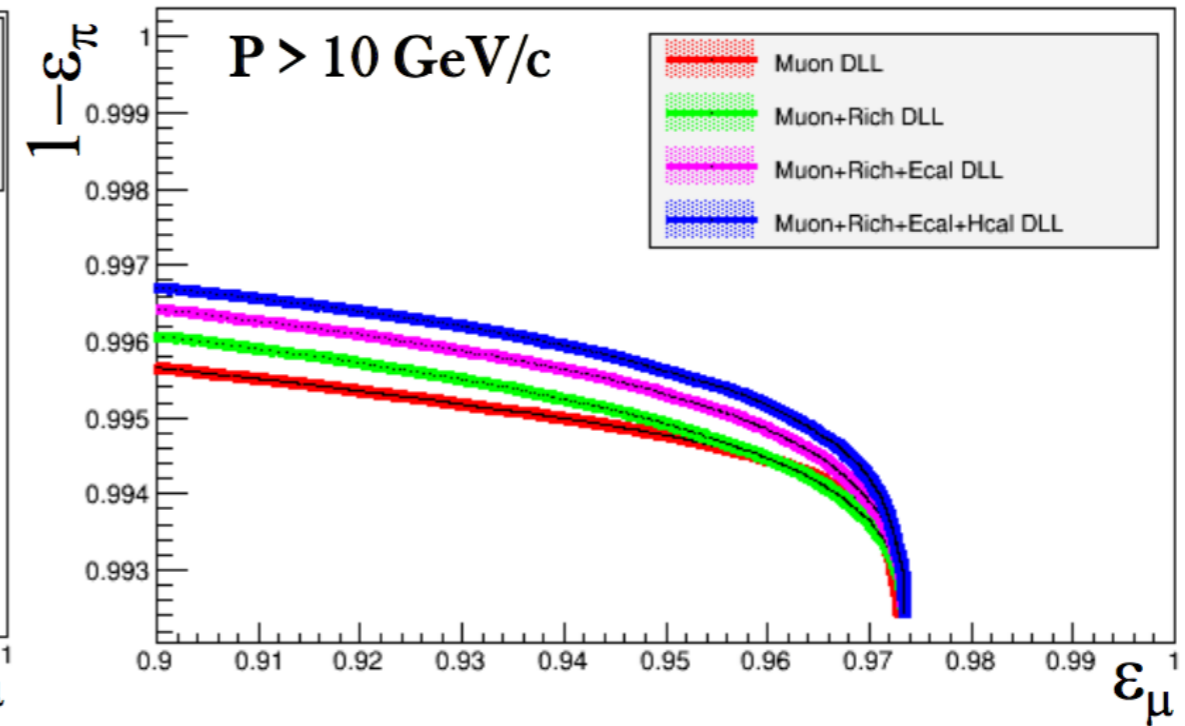
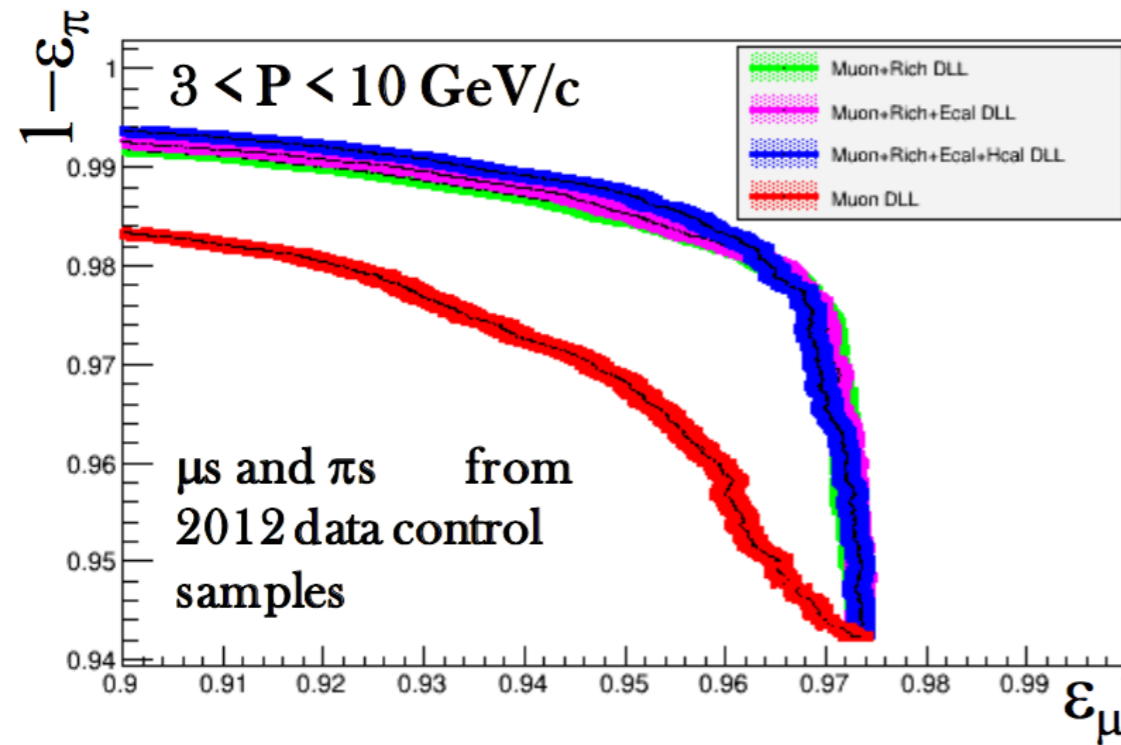
M2R1 proposed PAD detector:
192 pads per chamber,
PAD area $1.2 \times 3.2 \sim 4 \text{ cm}^2$



- **Strip readout:** large inefficiency due to the size of the physical X and Y channels, and up to 50% of ghost fraction, which increase the comb. bkg
- **Pad readout:** inefficiency reduced by a factor of $\sim 6-7$; no more ghost crossings

HCAL contribution to the combined PID

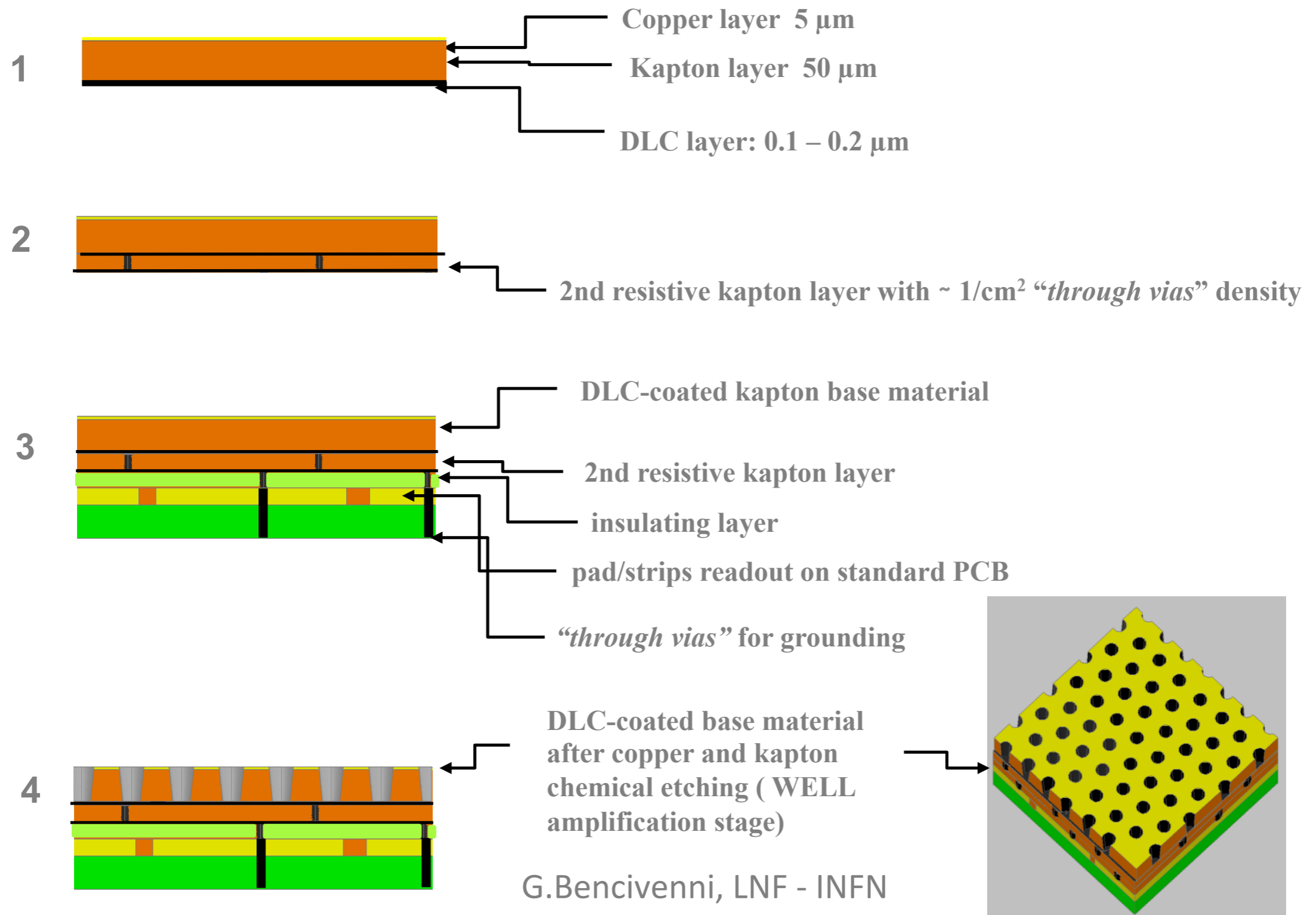
presented at TTFU 19/09/2016



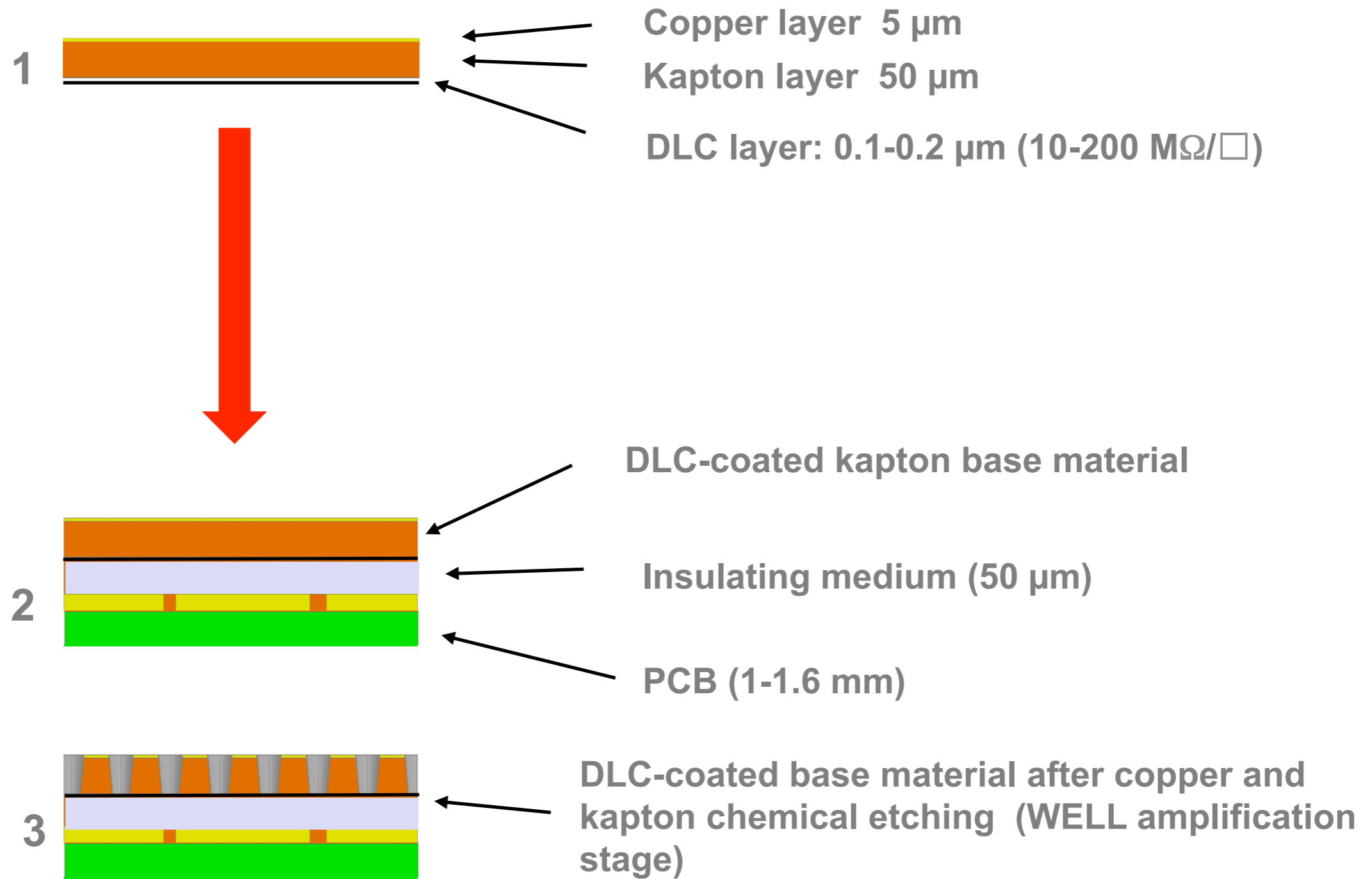
$\pi_{\text{MisID}} \epsilon_\pi$ evaluated at $\epsilon_\mu = 90\%$

	$3 < P < 10 \text{ GeV/c}$	$P > 10 \text{ GeV/c}$
ϵ_π MUON	17.2×10^{-3}	4.4×10^{-3}
ϵ_π MUON+RICH	8.2×10^{-3}	4.0×10^{-3}
ϵ_π MUON+RICH+ECAL	7.4×10^{-3}	3.6×10^{-3}
ϵ_π MUON+RICH+ECAL+HCAL	6.4×10^{-3}	3.3×10^{-3}

The μ -RWELL_PCB for High Rate (LHCb)



The Low Rate scheme (CMS/SHiP)

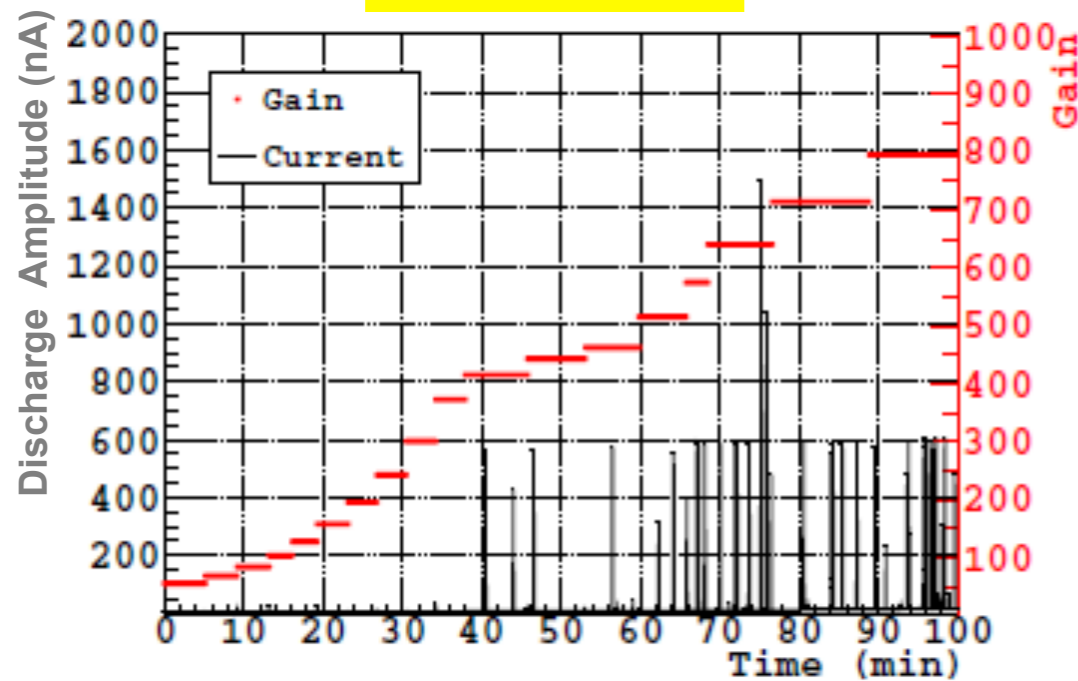


Discharges: μ -RWELL vs GEM

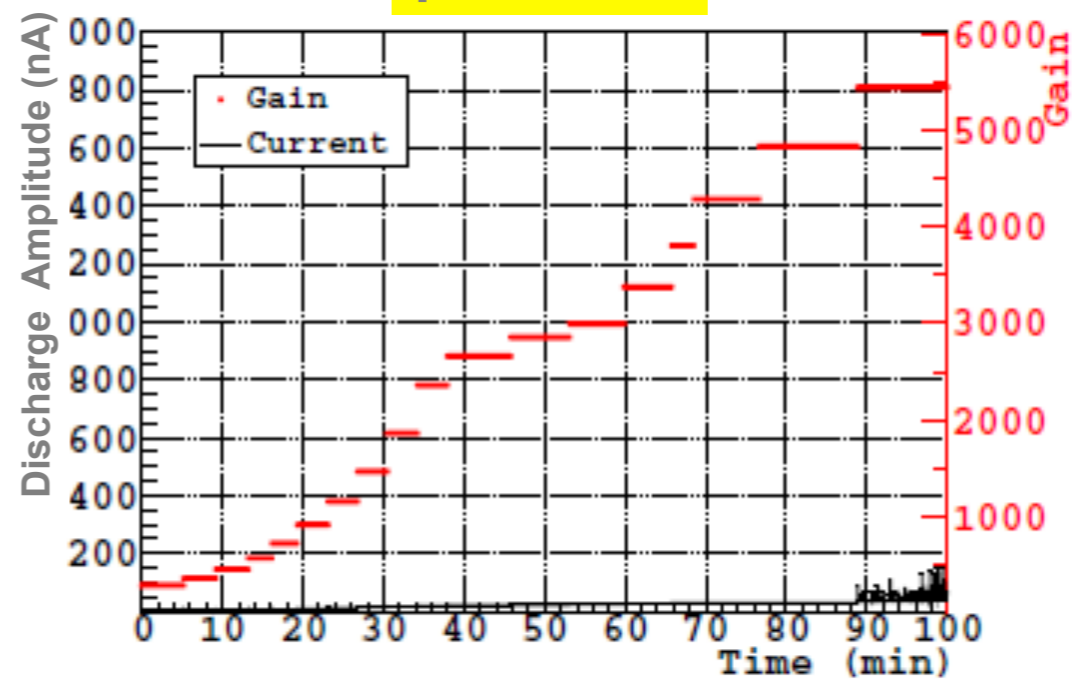
test with X-ray

Ar/CO₂ = 70/30

single-GEM

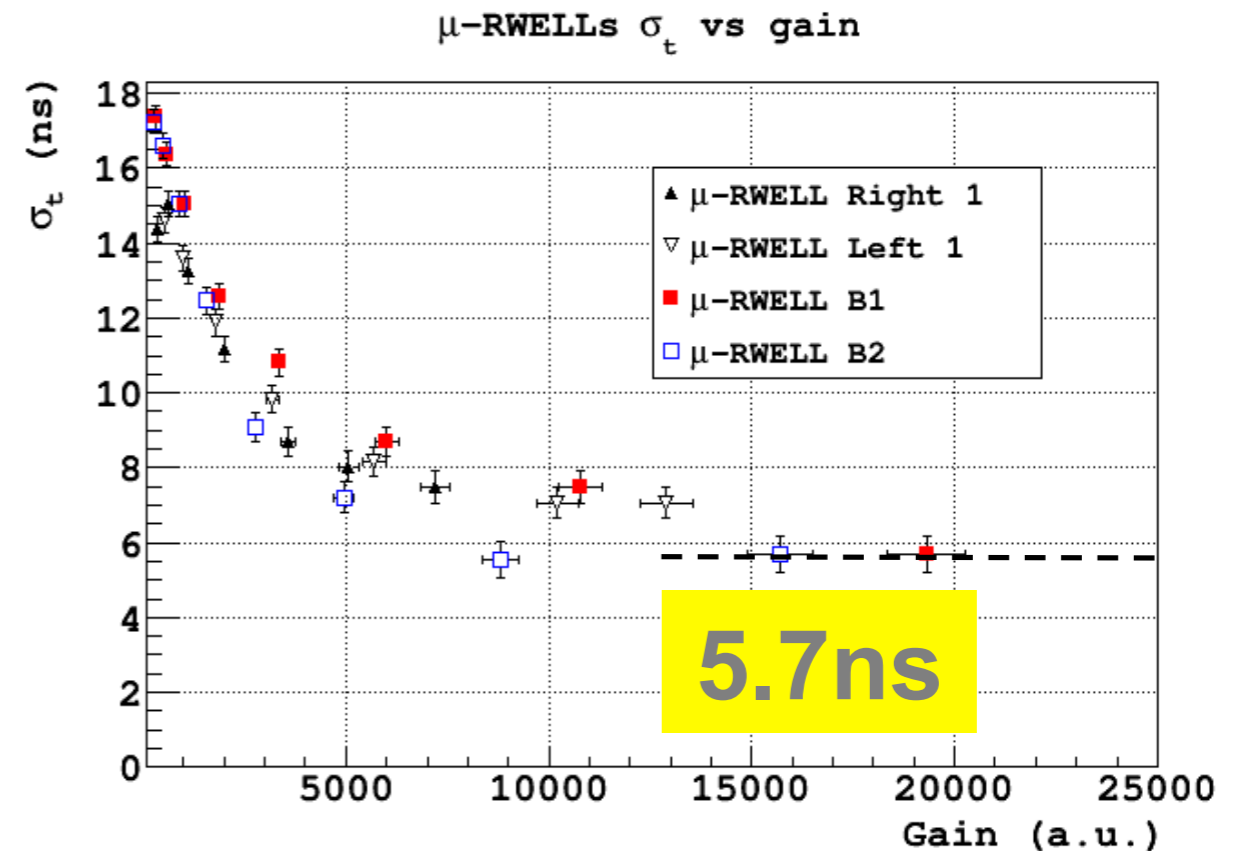
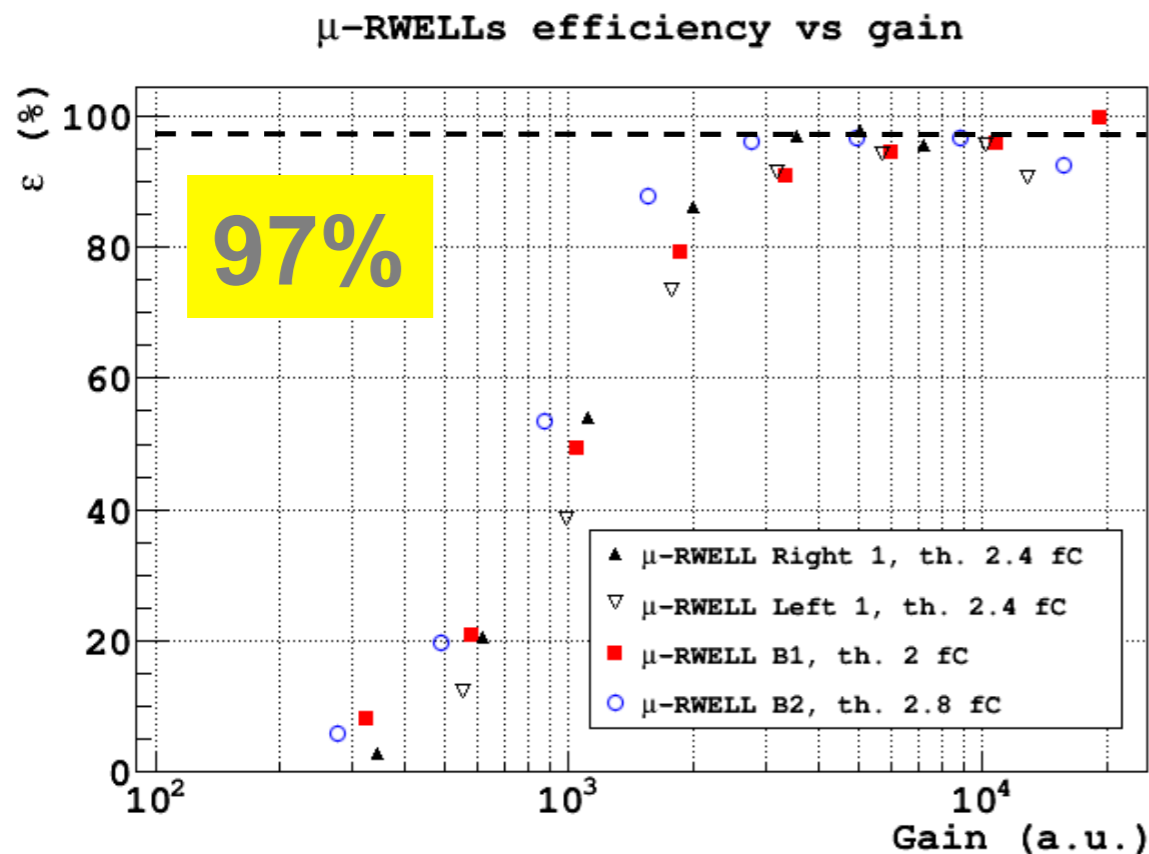


μ -RWELL



- ❑ the μ -RWELL detector reaches discharge amplitudes of **few tens of nA, <100 nA @ max gain**
- ❑ the **single-GEM** detector reaches discharge amplitudes of $\approx 1\mu\text{A}$ (of course the discharge rate is *lower for a triple-GEM detector*)

Time Performance



Different chambers with **different dimensions and resistive schemes** exhibit a very similar behavior although realized in **different sites** (large detector realized @ ELTOS)

The **saturation at 5.7 ns** seems to be dominated by the fee (measurement done with VFAT2).

To be **compared** with a measurement done with **GEM** in **2004 (LHCb)**, giving a $\sigma_t = 4.5$ ns with VTX chip - (*NIM A 494 (2002) 156*).

VFAT3 chip

VFAT3 front-end chip (128 ch. & 130 nm CMOS tech.) is currently under design for the readout of triple-GEM detectors of the CMS phase 1 upgrade

VFAT3 features:

1. selectable peaking time

T_{peak} [ns] **Delay time T_d [ns]**

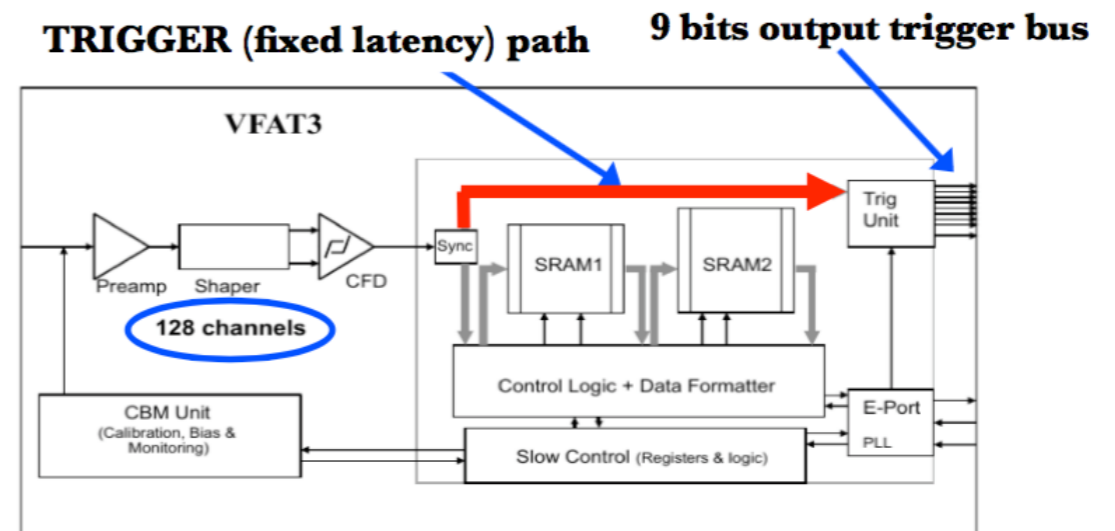
25	15
50	29
75	43.4
100	57.8

2. **rate capability = 1 MHz @ $T_{\text{PEAK}} = 25$ ns**

3. time resolution ~ 6 ns @ $T_{\text{PEAK}} = 25$ ns

4. noise $e_{\text{RMS}} \leq 1500e$ ($\sim 1/4$ fC) @ $T_{\text{PEAK}} = 25$ ns, pad capacitance < 20 pF

5. to transfer 128 channels (bits) in 25 ns \rightarrow 8 bits bus + 640 MHz clock
(40 MHz \times 16)



Cost estimate μ -RWELL

A preliminary cost estimate exercise has been performed

Low Rate = 1300 €/gap

High Rate = 800 € (R1) – 920 € (R2)/gap if the technology transfer to industry is successful

FULL DETECTOR (w/o readout electronics)

single gap region R1 (HR)	→	96 x 800€ =	77 k€
single gap region R2 (HR)	→	192 x 920€ =	177 k€
single gap regions R3 & R4 (LR)	→	1920 x 1300€ =	2,5 M€
			Total = 2,75 M€