Update on FORMOSA

24.02.29

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Juan Salvador Tafoya Vargas

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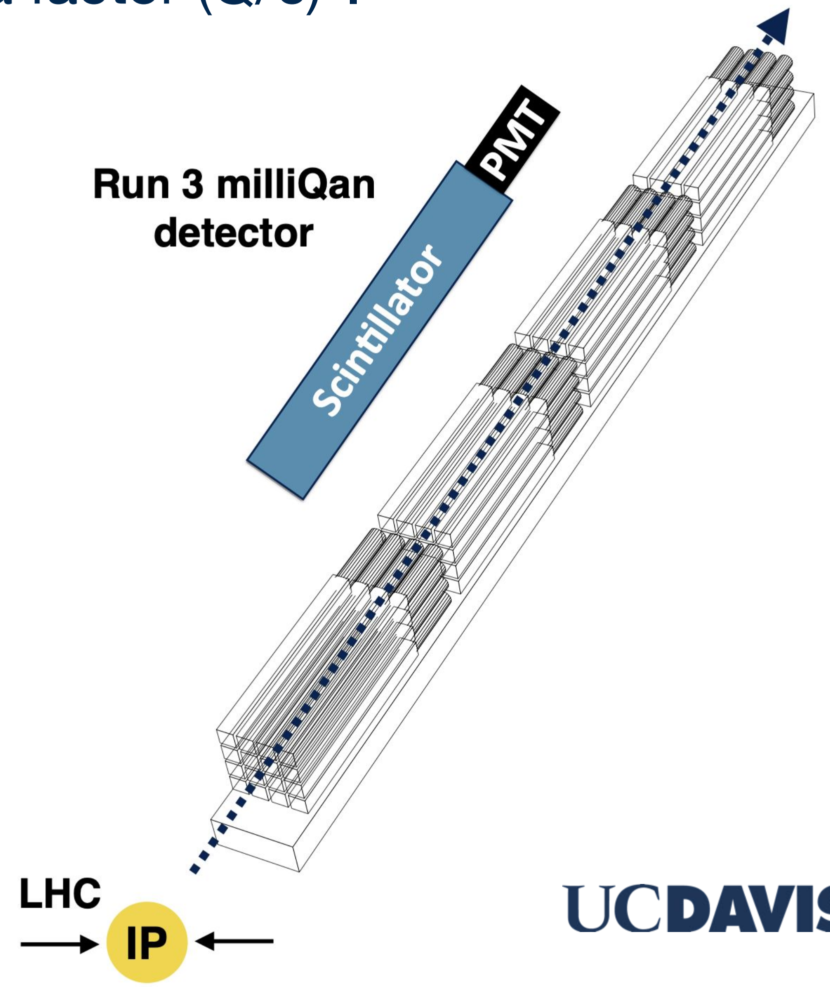
Direct millicharged particle searches at the LHC

Millicharged particles (**MCPs**) are well motivated in dark sector theories, but difficult to detect because the interaction strength is reduced by a factor $(Q/e)^2$.

Core concept: Use array of efficient scintillator bars + PMTs to detect ionisation from MCPs.

Challenges:

- Expect few scintillation photons to be produced → must be able to detect single photons
- Well controlled backgrounds → “point” towards the interaction point, triggering on sets of signals within small time windows



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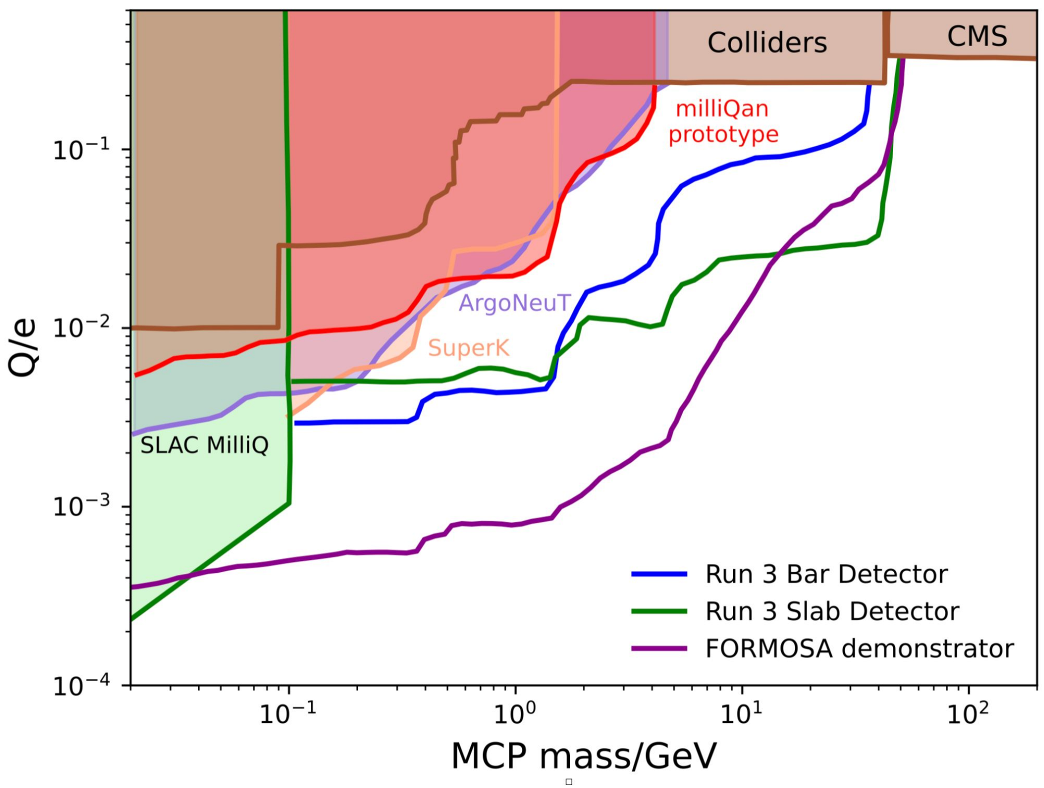
The milliQan experiment

Located in P5, looking at the central region of the CMS interaction point.

First search for MCPs at a hadron collider with new sensitivity carried out with the milliQan demonstrator.

Run 3 milliQan experiment ongoing

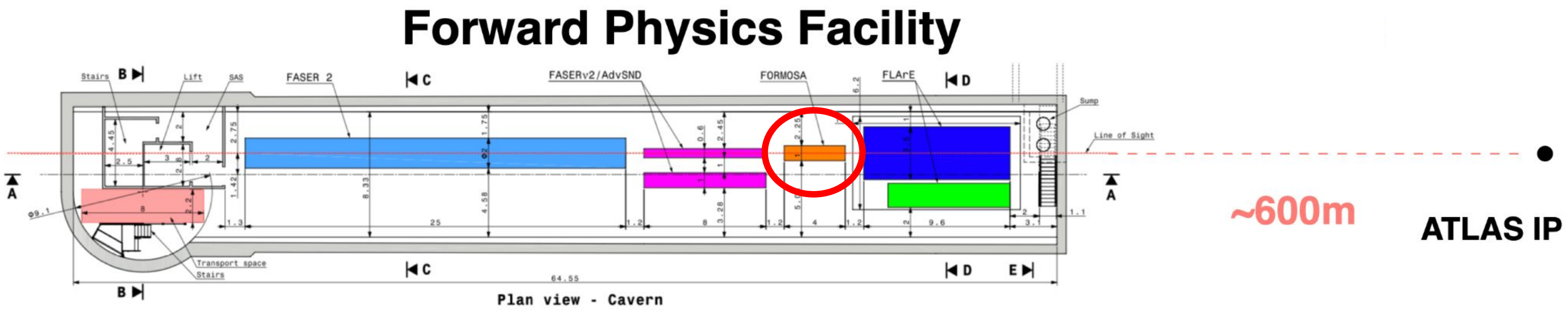


Overall, this means that **FORMOSA is not starting from zero!**

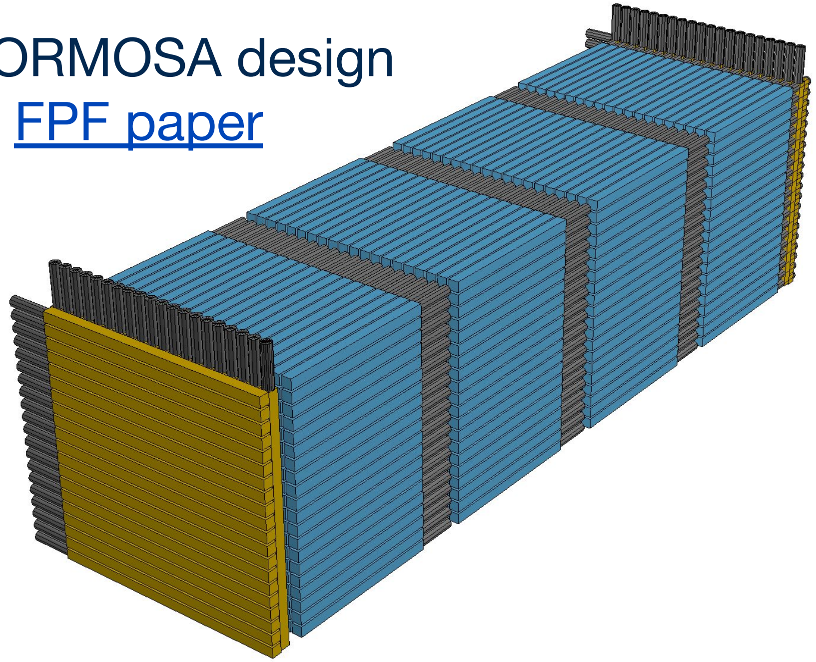
Tons of expertise acquired on the milliQan experiment: R&D, manufacturing, installation, calibration, commissioning, backgrounds, operation, analysis

→ FORMOSA is the natural next step

FORMOSA



FORMOSA design
in FPF paper



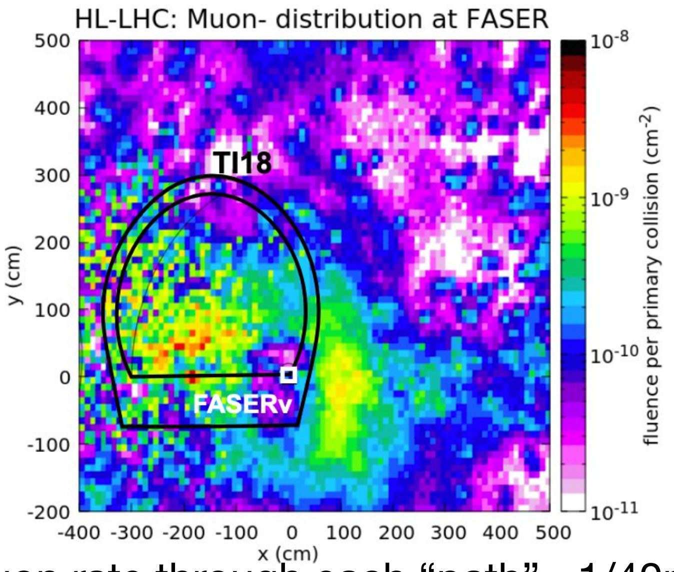
Expect to see **~250x rate** of millicharged particle detection in the forward region compared to the central one (milliQan)

20rows x 20cols x 4layers of bars for detection

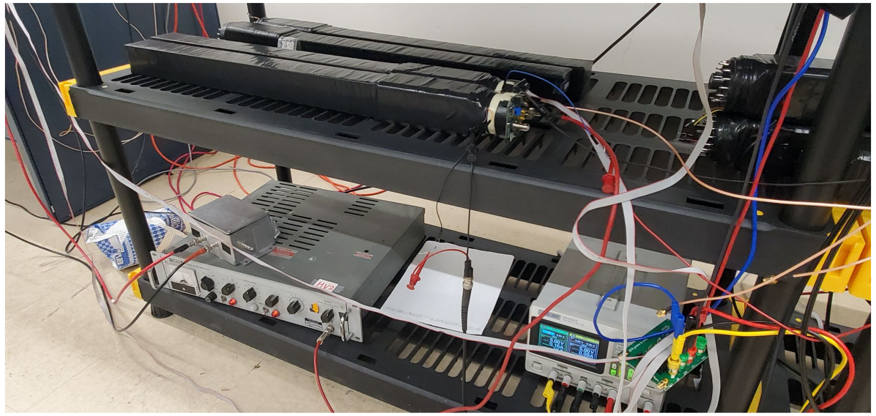
Main background: beam muons → veto panels

Why do we need the demonstrator?

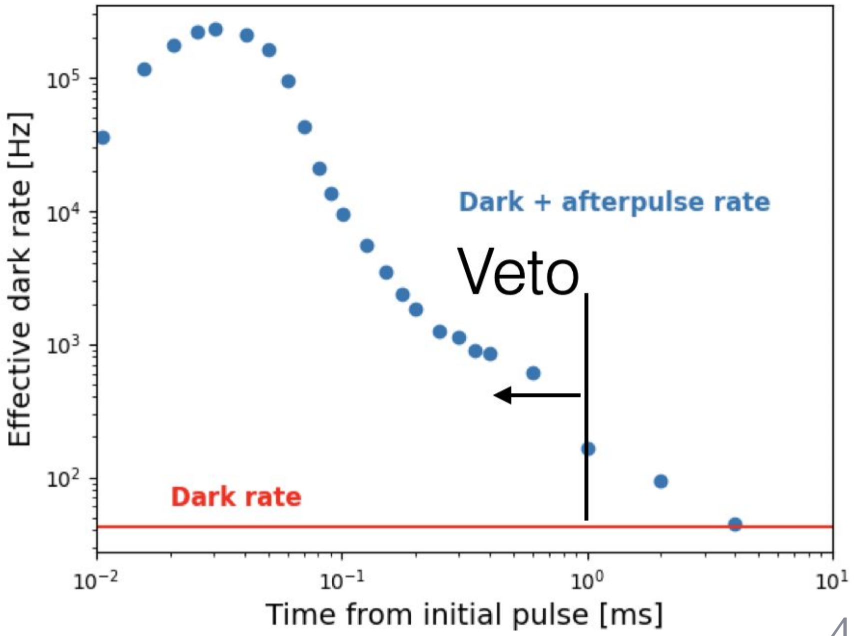
Dominant background in the forward region: afterpulses initiated by through-going muons



Muon rate through each "path" ~1/40ms

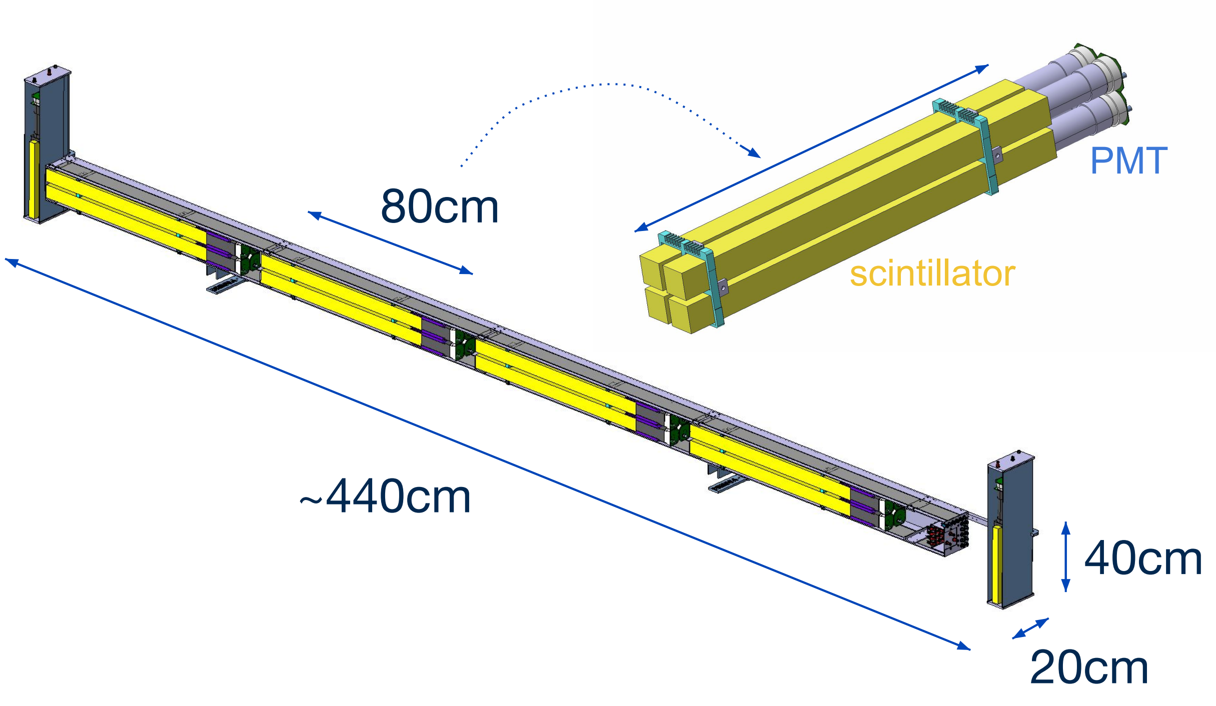


Measure afterpulsing induced by LED pulses



- This is a new background w.r.t. milliQan
- Bench studies suggest veto possible with ~ few % deadtime
- The demonstrator will **provide critical insights into backgrounds/operation in forward environment**

The FORMOSA demonstrator

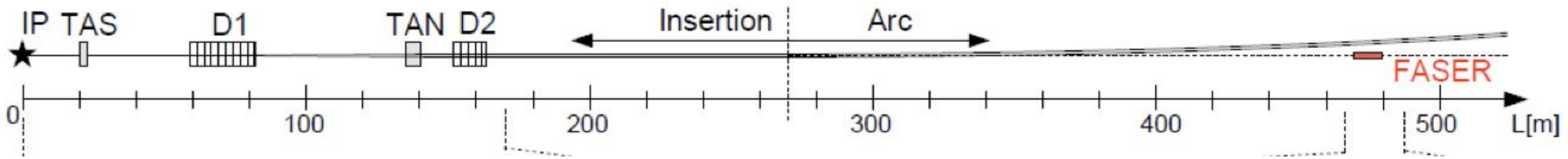


Lower scale version of the detector:
- 2 rows x 2 cols x 4 layers of bar+PMT
- 2 veto panels + PMT

Bars: 5cmx5cmx80cm
Panels: 20cmx40cmx2.5cm

PMTs: Hamamatsu R7725 and R878 with -HV

DAQ: CAEN V1743 digitisers + dedicated trigger board



Installed in the UJ12 cavern (behind FASER)

Huge thanks to FASER for all their help!

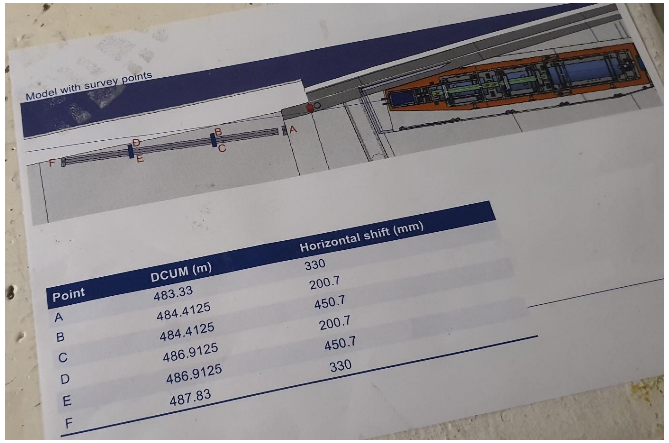
Undergrads: A.Gilotra, M. Legeard, L. Baillloeul, K. Sun, S. Arias-Obando, J. Zhu

Preliminary preparations

August:
Cabling installed by cern

REU student: N. Gonzalez
(Holding a scintillator bar and PMT)

Grad students: J. Steenis, S. Kelly



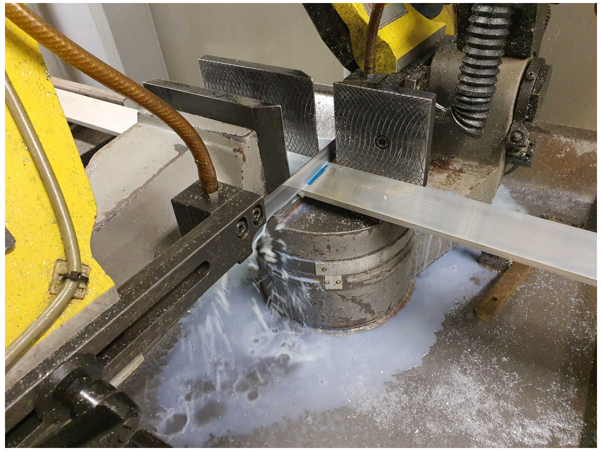
Model with survey points

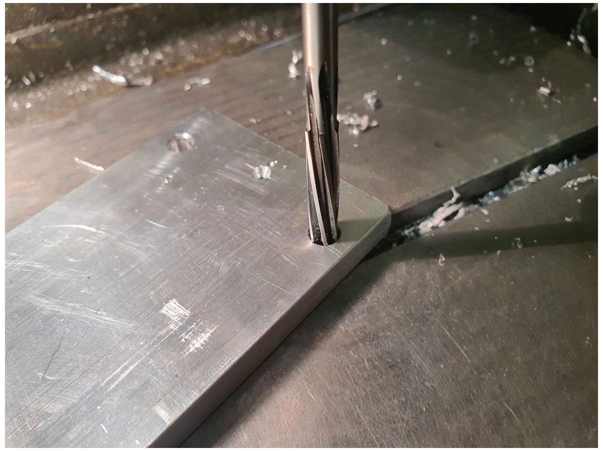
Point	DCUM (m)	Horizontal shift (mm)
A	483.33	330
B	484.4125	200.7
C	484.4125	450.7
D	486.9125	200.7
E	486.9125	450.7
F	487.83	330

November:
On-site alignment survey by CERN

September - November:
Bars+PMT+mount prepared by under/grad students at UC Davis

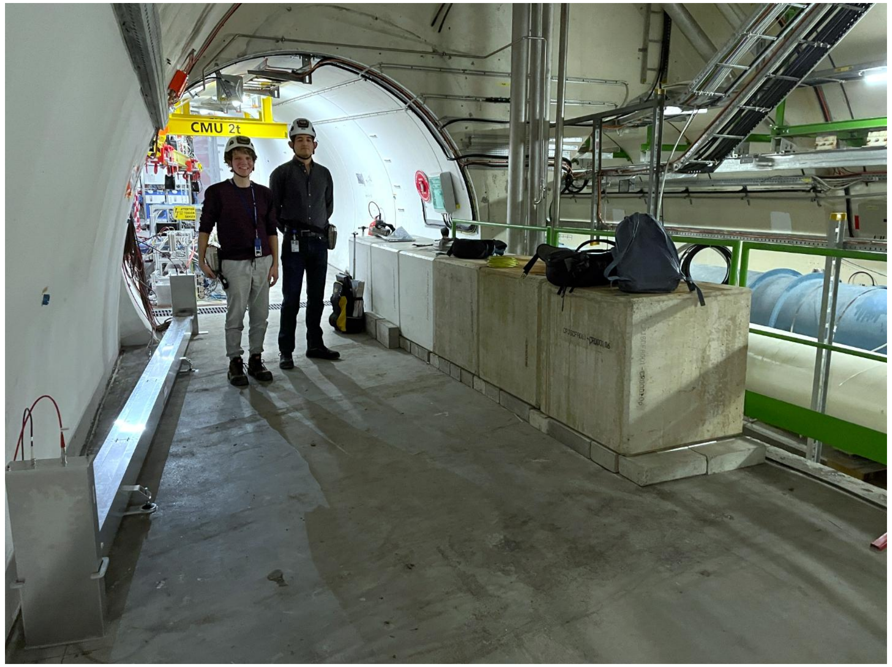
Manufacturing and installation





November - Mid-January:
Machining the structure

Mid-January - Mid-February:
Installation



Grad student: J. Steenis
Postdoc: J.S. Tafoya V.

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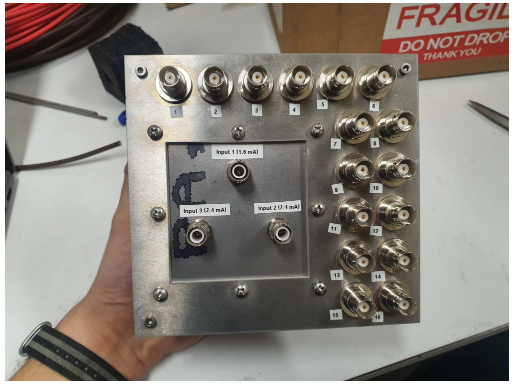
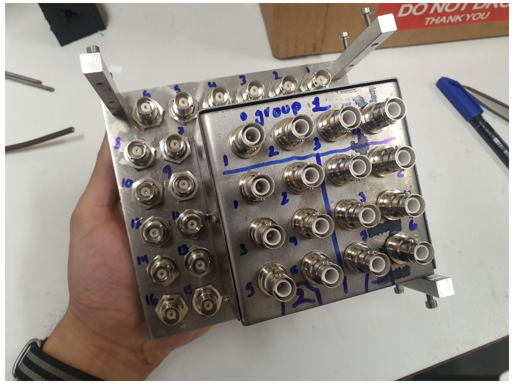
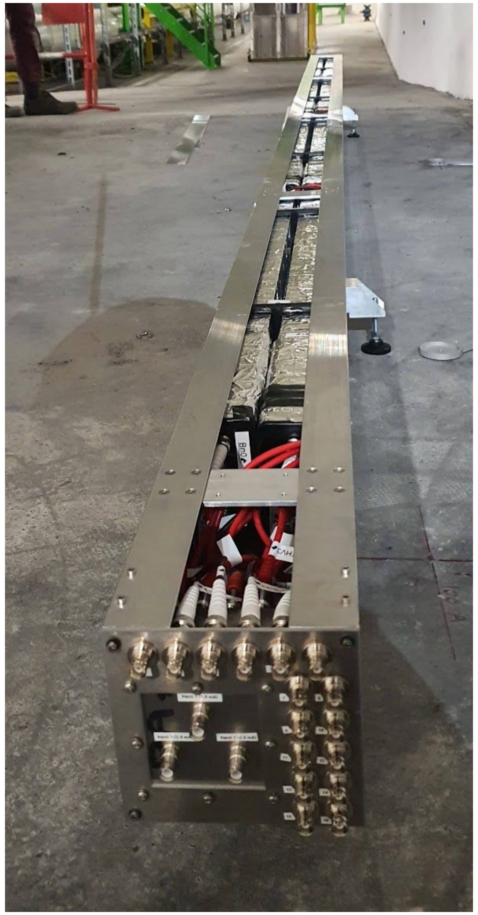
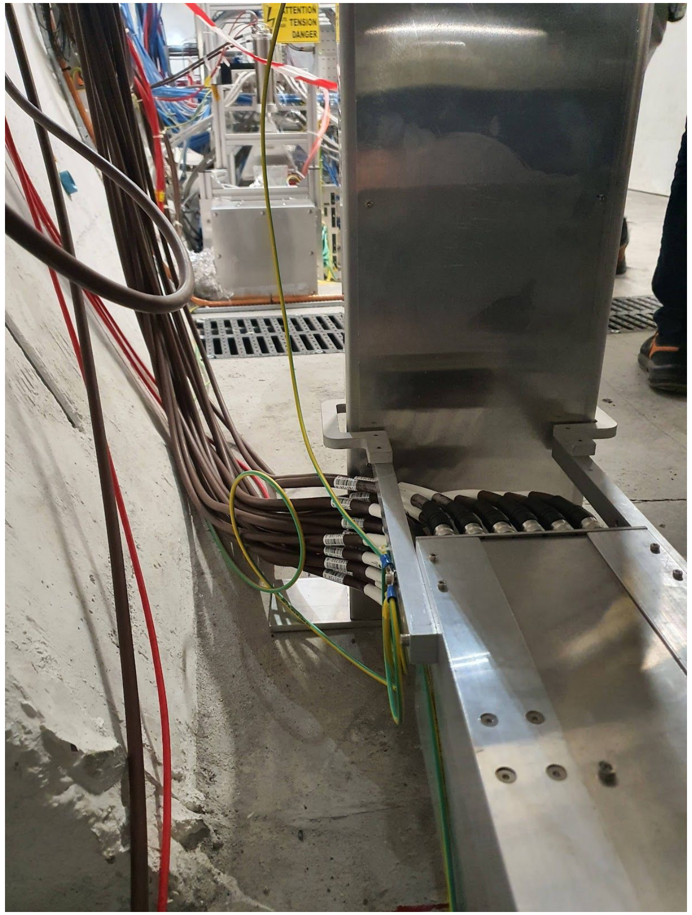
Internal cabling









We use a patch panel (which also doubles as an HV splitter) to completely run all the cables on the inside → The final structure is fully closed

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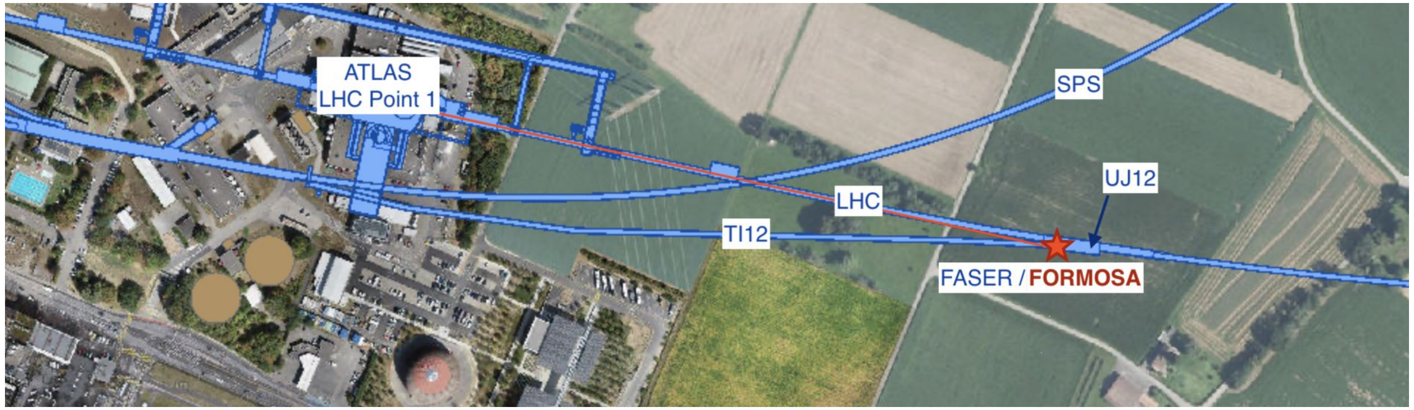
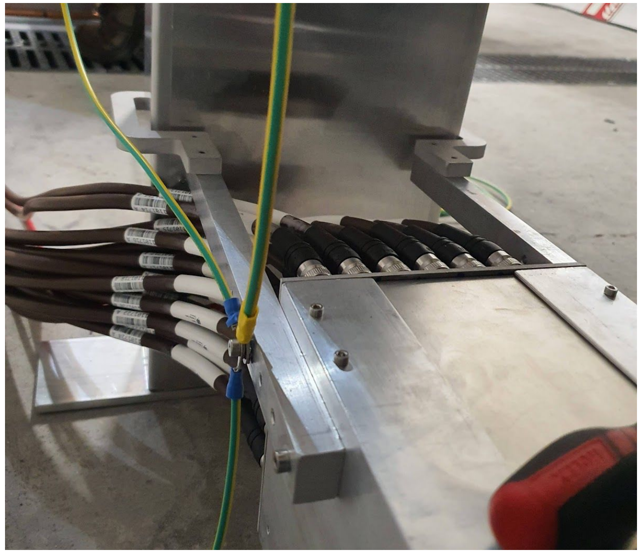
Installation completed a couple of weeks ago!





Early February:
Electrical safety inspection passed.
We are good to run remotely!

Now: LHC tunnel closed for Run 3 preparations. **Commissioning FORMOSA!**

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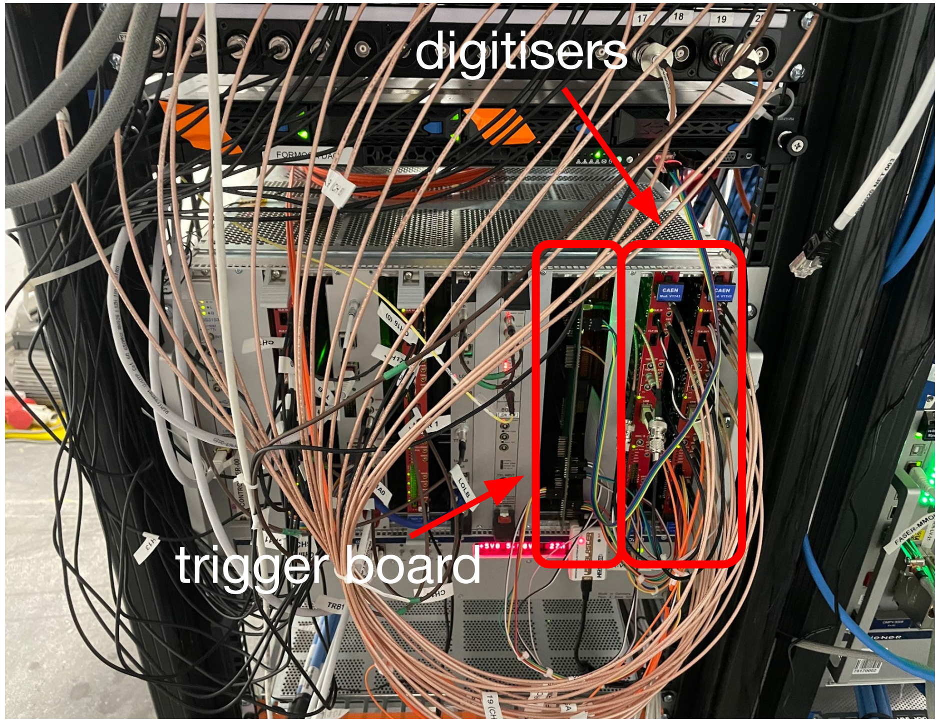
Readout and HV



- Similar readout to that of milliQan:

  CAEN digitisers + custom trigger board

  - **New**: muon veto implemented at trigger board level

- Using our own HV power supply, which powers up the entire demonstrator through our patch panel.

- Everything is installed on the FASER rack at TI12

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Calibration

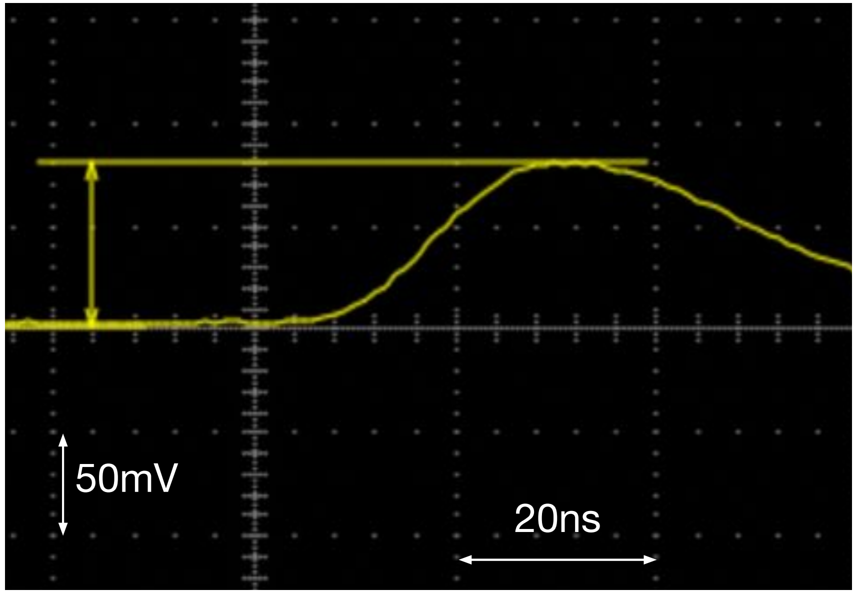
SPE = Single PhotoElectron i.e. physical electron emitted from the PMT's photocathode

MCPs produce just a **few scintillation photons**
→ we must be able to measure single photons
→ requires excellent calibration and identification of each PMT's SPE peak

PMT's signal grows linearly with the number of PE
 reaches saturation at 100ths or 1000ths of PE

Calibration runs:
Dark rate → measure SPE peak, can be done at any time
Source data → induce signal with a Cd109 radioactive source, done for each scintillator before installation.

Example of SPE pulse



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Calibration

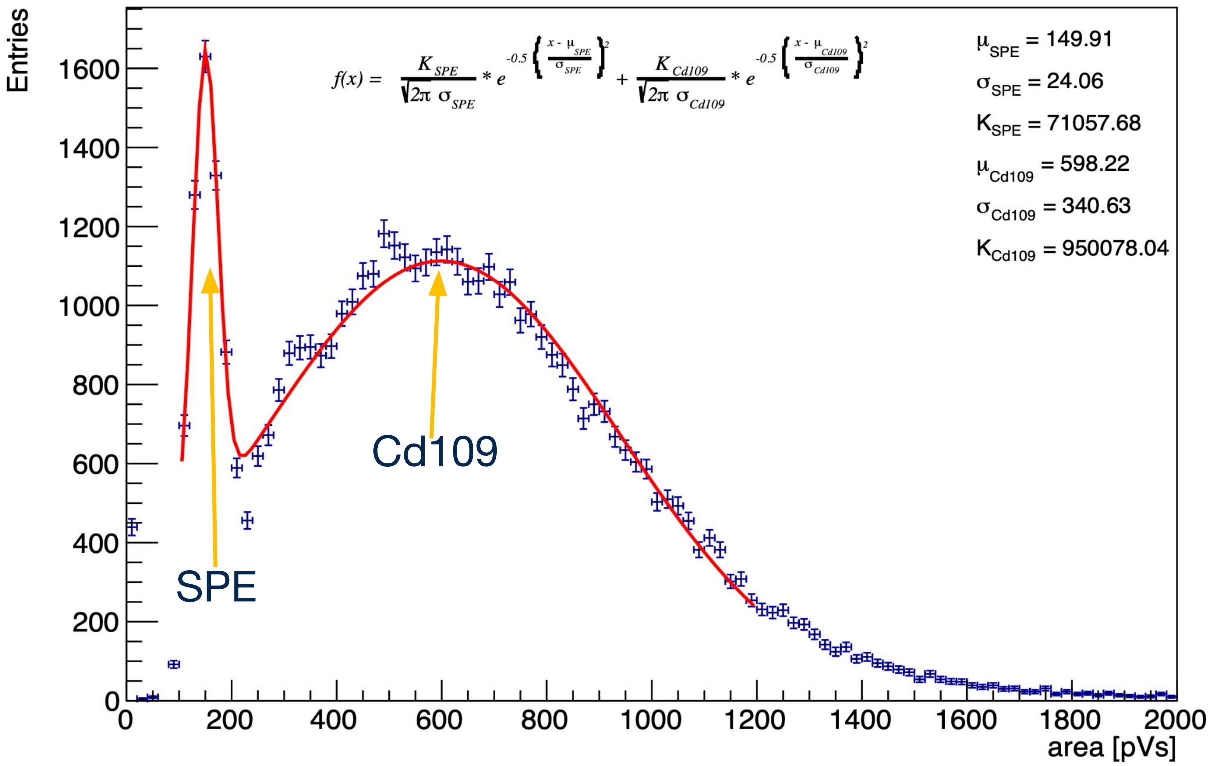
Nominal trigger threshold at 15mV

Bar PMT dark rates in the range of 3-5 kHz at 1500V
→ **good SPE peak definition**
→ SPE maxima at 30-60mV

Veto panel PMT dark rates of ~200Hz at 1100V
→ gain tweaked so that **cosmic muons** (~300photons/hit) **are below saturation**, foreseeing similar beam muon signals

Clear separation between SPE and source-induce signals → particularly true when looking at **pulse area**

FORMOSA bar 0



$$f(x) = \frac{K_{SPE}}{\sqrt{2\pi}\,\sigma_{SPE}} * e^{-0.5\left(\frac{x-\mu_{SPE}}{\sigma_{SPE}}\right)^2} + \frac{K_{Cd109}}{\sqrt{2\pi}\,\sigma_{Cd109}} * e^{-0.5\left(\frac{x-\mu_{Cd109}}{\sigma_{Cd109}}\right)^2}$$

We see compatible responses on the surface and underground
→ **no evident damage during transportation**

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Recorded data

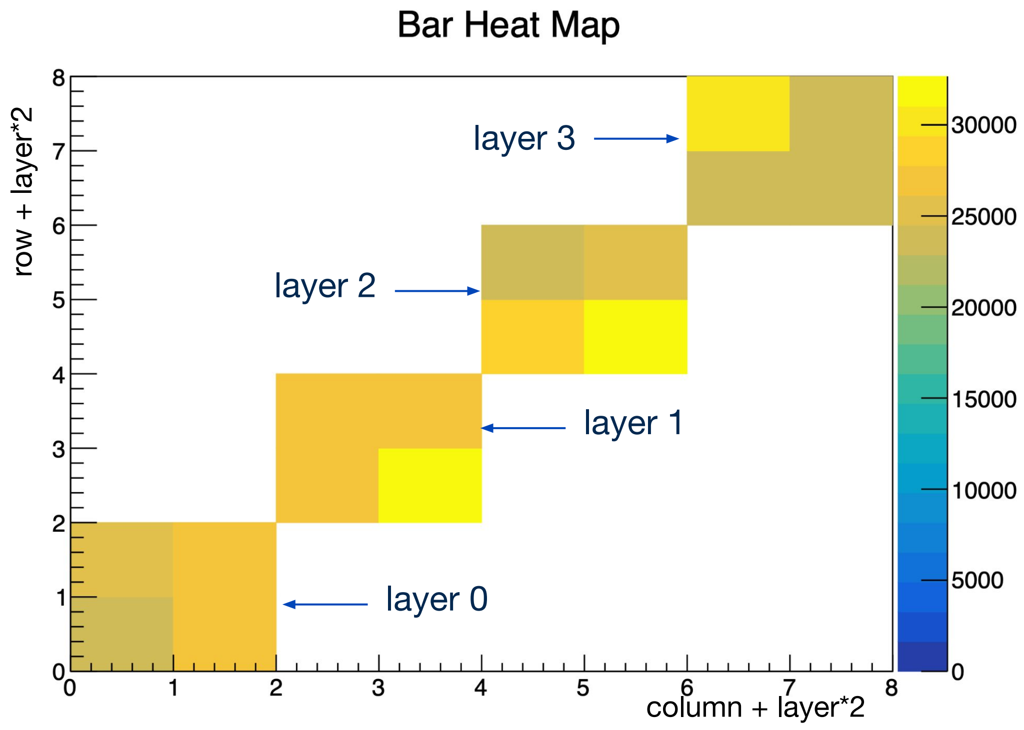
We have been running/testing for ~100 hours in total

Heat maps suggest correct activation on all the bars

Recorded data is consistent with that measured before the installation

In no-beam conditions, we've measured adequate recording rates:

- bars + veto panels: ~5 Hz



Measured from a day-long run taken on 2024/02/27

Current no-beam data and eventual beam data will help us better understand backgrounds, particularly afterpulsing

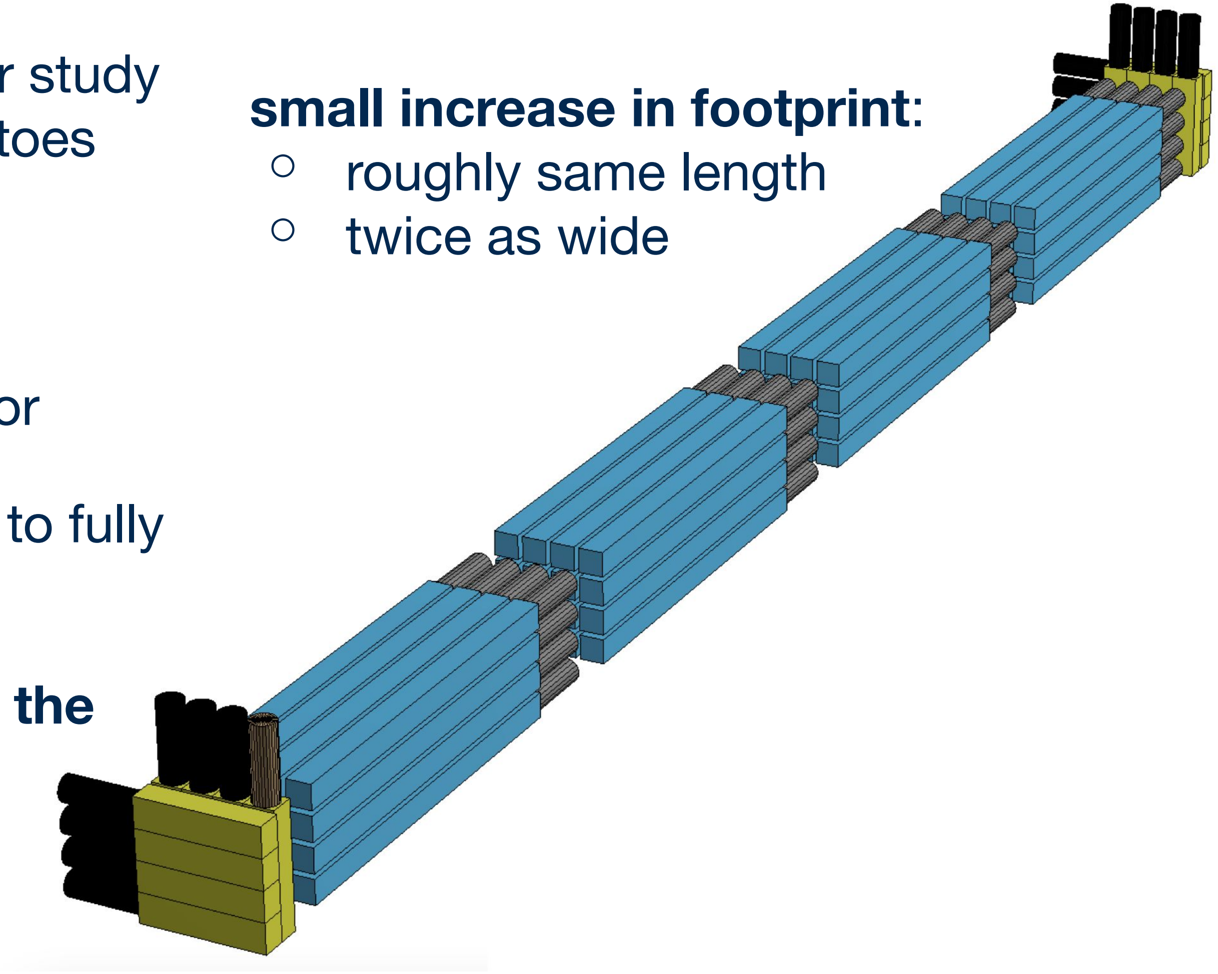
Possible iterations on the demonstrator

- Expand the cross section of the detector: 4bars x 4bars x 4layers
- Use segmented veto panels

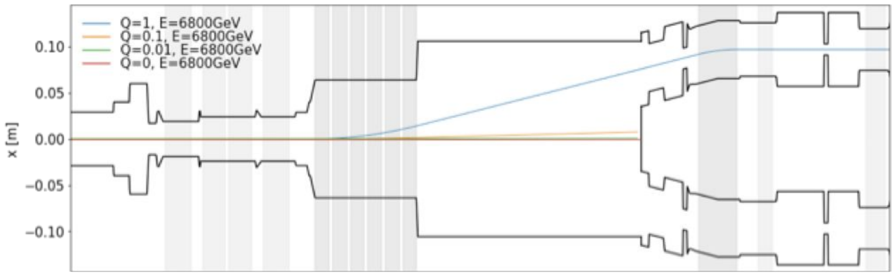
} allow for better study of active vetoes

- Structure can be manufactured quickly using stencils machined for the current demonstrator
- Could allow initial search with new sensitivity to fully prove feasibility
- **Could potentially be implemented towards the end of 2024**

small increase in footprint:
- roughly same length
- twice as wide

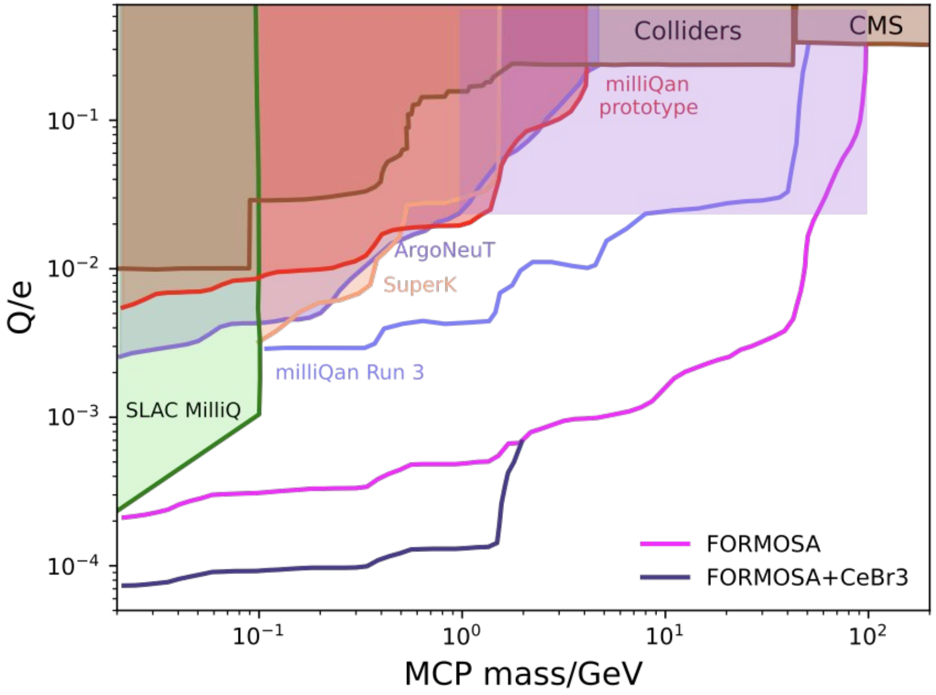


MCPs propagation



Field impact on
different charges (F. Kling)

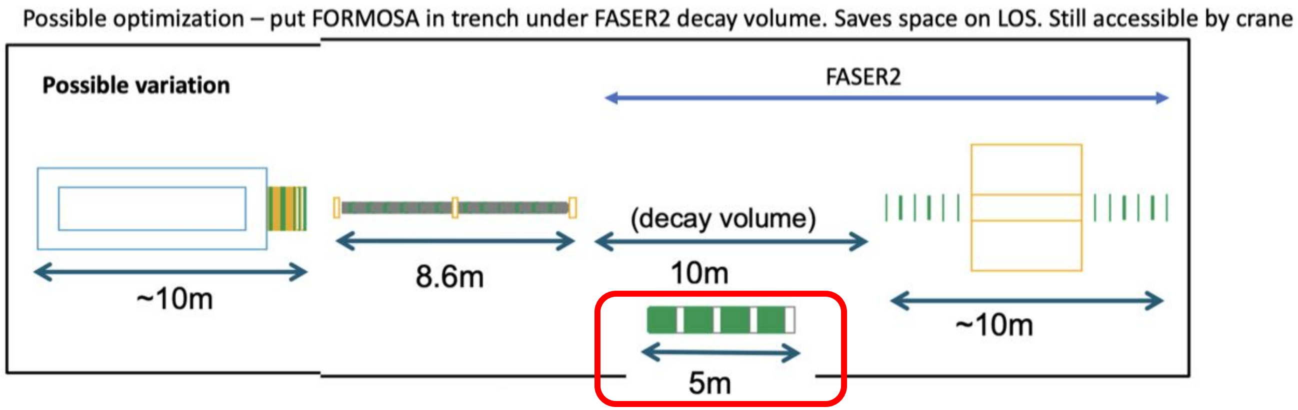
FORMOSA limit
uncertain here

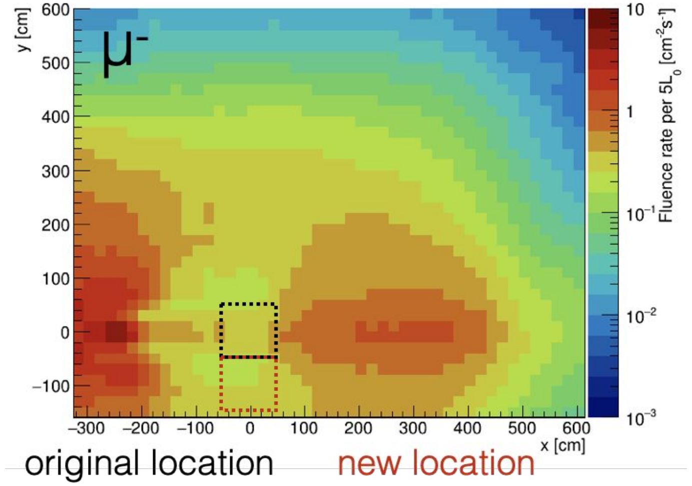


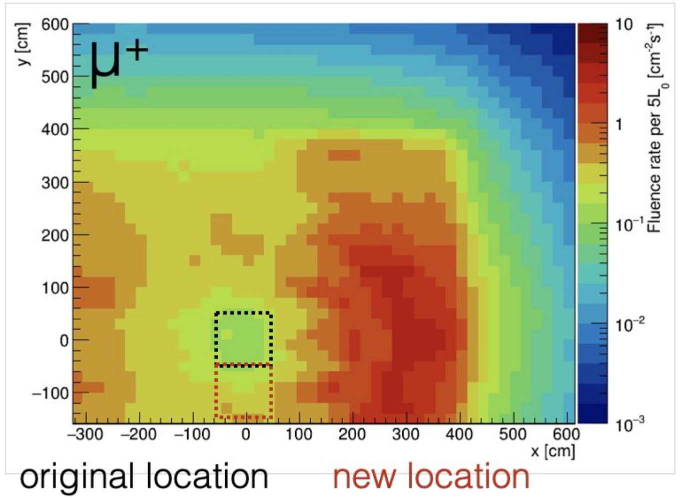
- Current exclusions assume **no impact** on MCPs from rock/LHC material/magnetic field
- Very reasonable for Q < ~0.1 but what about higher charges? → need to evaluate probability for MCPs to reach detector!
- Ongoing work: use FORESEE together with propagation tools developed for milliQan (updated with LHC BDSIM model) to evaluate reach for higher charges

Moving FORMOSA within the FPF

Matteo Vicenzi







Increase in flux for μ+ approx. balanced by decrease for μ-

- Studied impact of moving FORMOSA by 1 m under the LOS to increase available space
- **Negligible** change in signal acceptance
- Through-going muon flux increase **appears manageable** at ~10% (depends somewhat on FORMOSA z position and reliability of simulation)
- Practicalities and cost gains for cavern alterations (wider and/or longer) under study now

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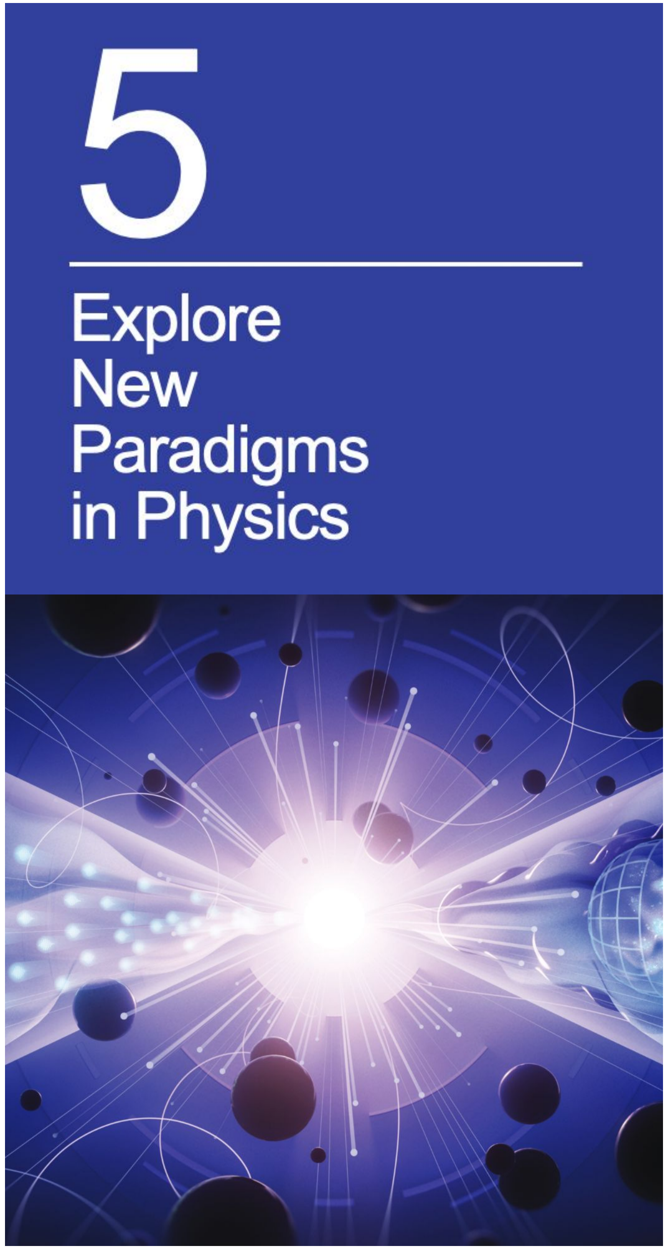
P5 outcomes and timeline

- FORMOSA fits P5 recommendation for new “agile” project portfolio (ASTAE)
  - From the P5 report: “Experiments at the proposed Forward Physics Facility at CERN like FASER2 and **FORMOSA** would be sensitive to the hidden sectors through the Vector and Heavy Neutral Lepton portals.”
- Timeline for experiment depends on when funding from ASTAE is realised (likely > 2026)
- We can build and commission FORMOSA in **~2-3 years** after construction funding is received



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Collaboration

The FORMOSA collaboration is comprised largely from the milliQan collaboration.

Lots (and in fact, most) of our experience is easily transferable to FORMOSA.

Summary

- Successful installation of the demonstrator at UJ12 concluded a couple of weeks ago
- Preliminary tests and calibration ongoing
- Initial studied with “no-beam” data and source tests look promising. We eagerly await stable beams!
- Opportunity to expand the demonstrator for 2025 running being actively studied as we analyse current demonstrator data
- We foresee construction and commissioning of the full detector to take ~2 years from funding

Backup

from arXiv:2104.07151v2

One can consider a dark sector containing a massless abelian gauge field, A', that couples to a new dark fermion, χ, with order one coupling, e'. A kinetic mixing, κ, can be introduced between the A' and SM hypercharge B. Under a convenient basis, A' is decoupled from the SM sector and the Lagrangian can be written as

$$\mathcal{L}_{\text{dark}} \subset -\frac{1}{4} A'_{\mu\nu} A'^{\mu\nu} + i\bar{\chi}\left(\partial\!\!\!/ + ie' A\!\!\!/' - i\kappa e' B\!\!\!/ + im_\chi\right)\chi$$

In this case, the χ acts as a field with hypercharge $\kappa \mathrm{e}'$. The new fermion is generically called a millicharged particle since a natural value for κ, and therefore the χ effective electric charge, of $\sim\alpha e/\pi \sim 10^{-3}\mathrm{e}$ arises from one-loop effects. The parameter space $1 < m_\chi < 100$ GeV, an ideal mass range for production at the LHC, is largely unexplored by *direct* searches.

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Collecting data

Measure MCPs, which produce few scintillation photons per bar

- Expect an MCP to come from the L.O.S. and interact with a bar in each layer pointing back to the IP

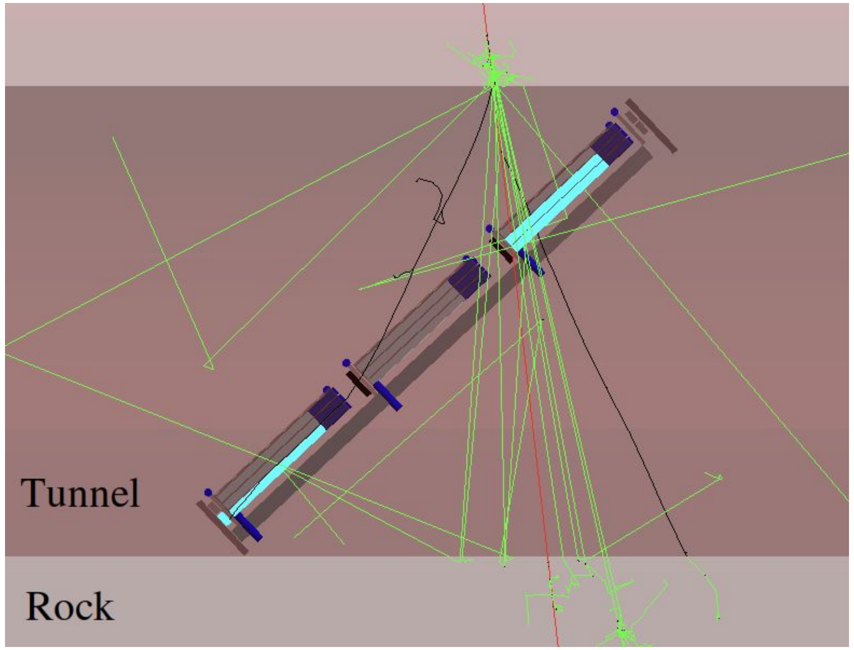
Cosmic background:

- Activation of multiple bars within the same layer

Beam muons:

- Apply dead time to the bars (i.e. to veto measurements) when the panels get activated
- Collect and labelling this data would also allow to better understand the effects of afterpulsing

Cosmic shower background, simulated for the milliQan demonstrator



Predicted rate of signal triggers ~ 1Hz
Predicted rate including all triggers ~4Hz

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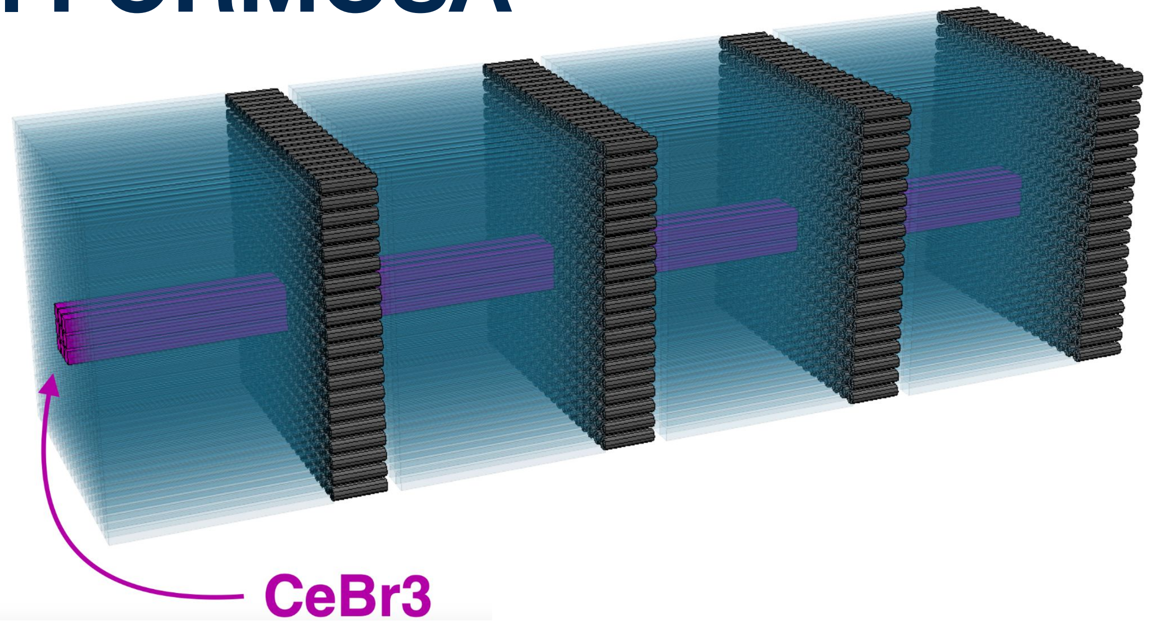
Potential changes in the full FORMOSA

- Potential sub-detector made of CeBr3:

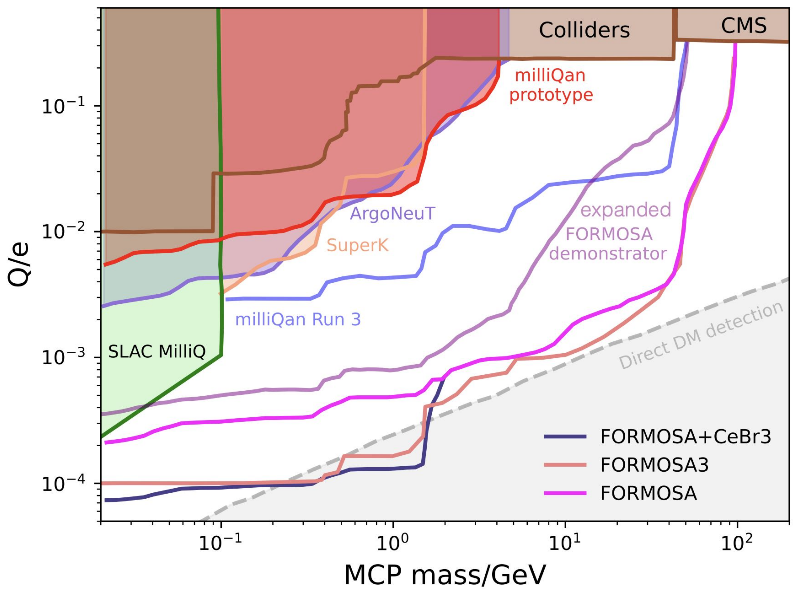
  ~35x more photons/cm compared to plastic scintillators, fast with low internal radioactivity

  → studying in lab



- Considering whether a 3 layer-FORMOSA would provide enough background rejection

- Explore the versatility of the veto panels



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