FORMOSA

24.07.05

Juan Salvador Tafoya Vargas (UC Davis)
on behalf of the FORMOSA collaboration

LLP2024, Tokyo

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New physics and dark matter → Hidden Valley

No signs of new physics seen at the LHC (yet)

SM extensions that include dark (or hidden) sectors give the most plausible hint

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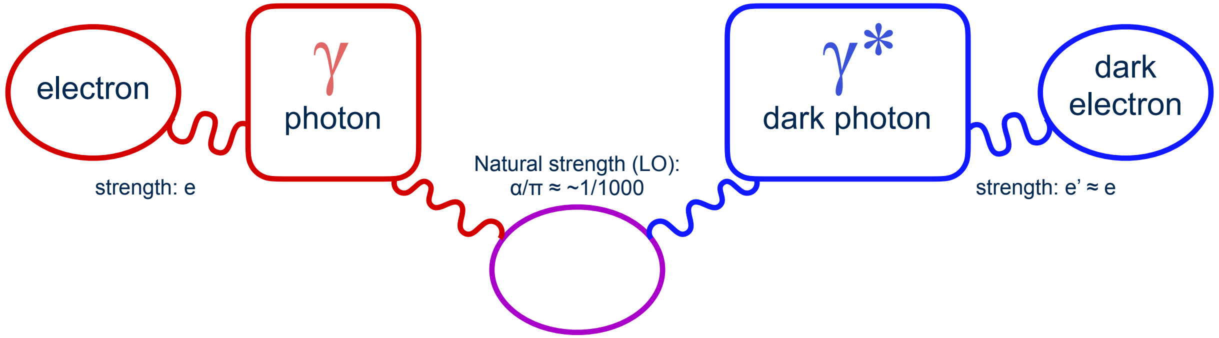

SM extensions that include dark (or hidden) sectors give the most plausible hint → Photons and dark photons are both U(1), they can interact via **kinetic mixing**

Interaction with dark electrons is around **1/1000 as strong as the standard model**

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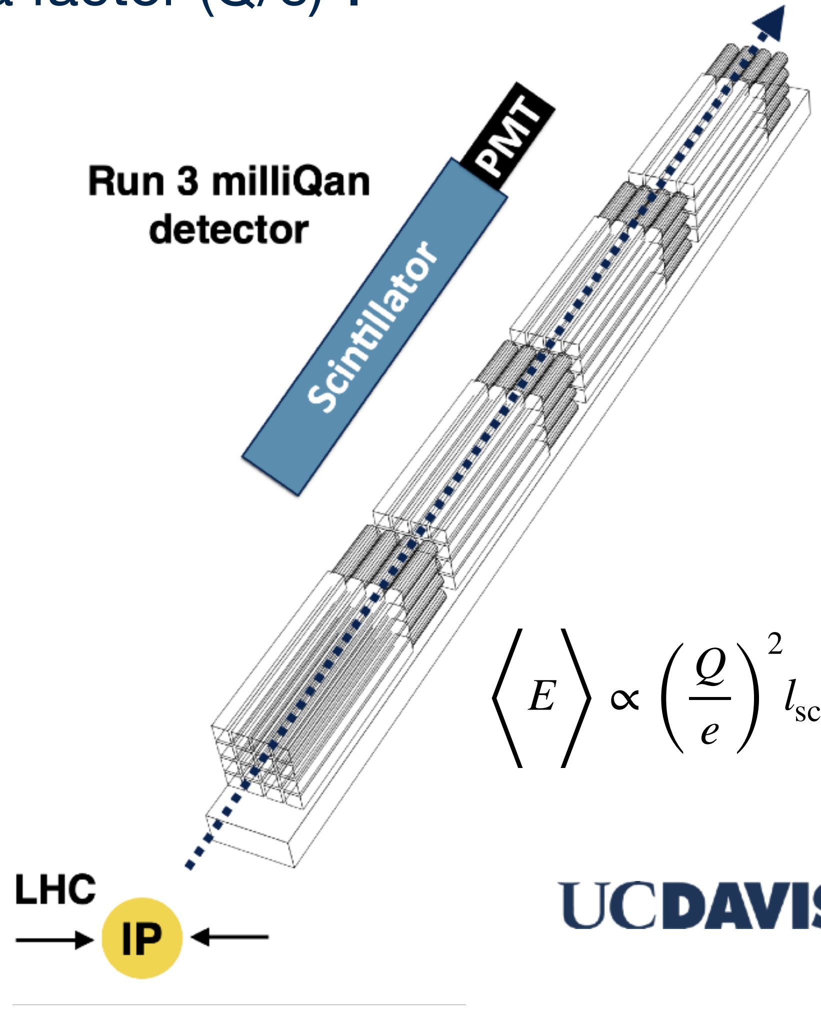
Direct millicharged particle searches at the LHC

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 long scintillator bars + PMTs to detect ionisation from MCPs.

Challenges:

- Expect few scintillation photons to be produced → must be able to detect single scintillation photons
- Well controlled backgrounds → "point" at the interaction point, triggering on sets of signals within small time windows (~15 ns)



$$\left\langle E \right\rangle \propto \left(\frac{Q}{e}\right)^2 l_{\text{scint}}$$

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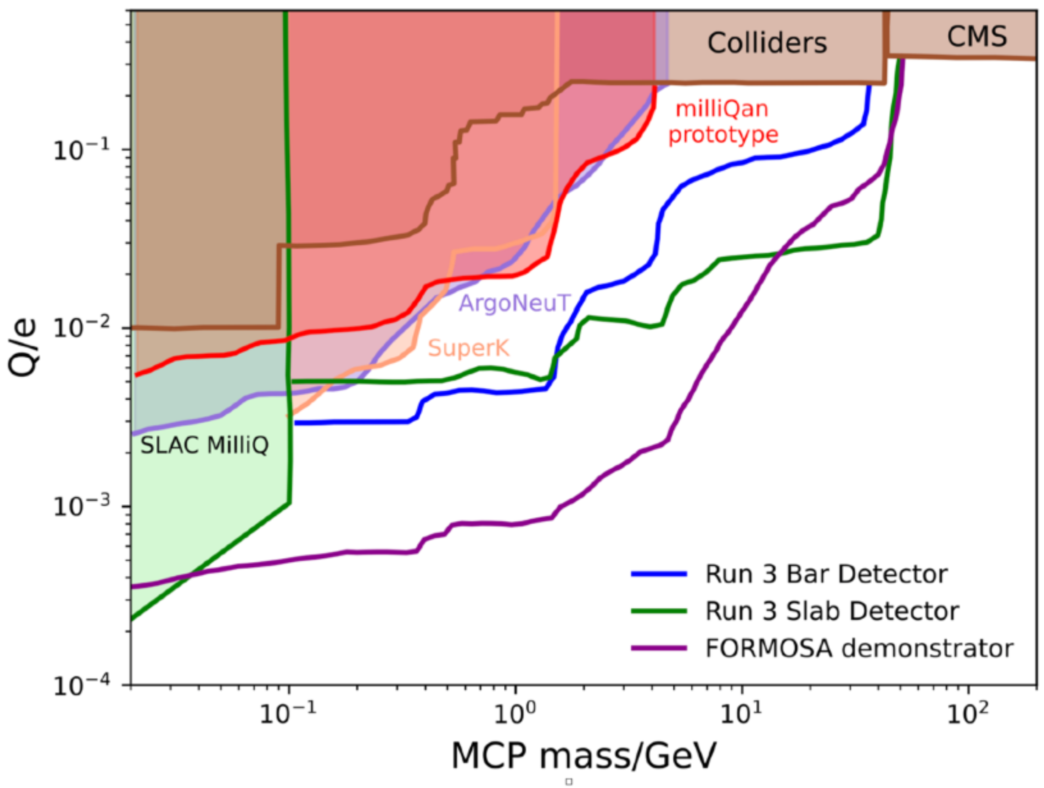
The milliQan experiment

Located in P5, looking at the central region of the CMS interaction point (see **Neha's talk**).

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**

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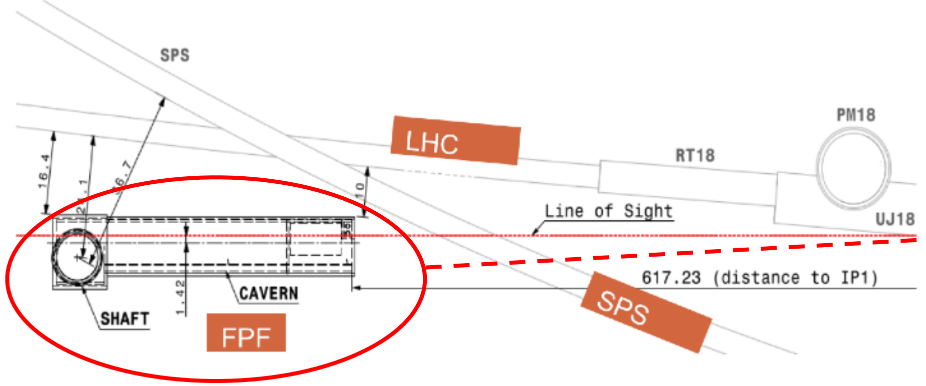
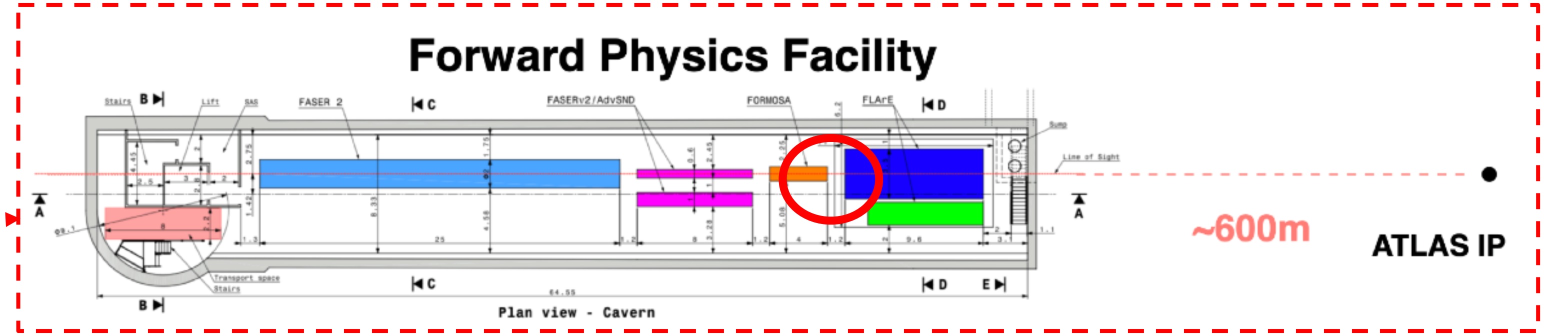
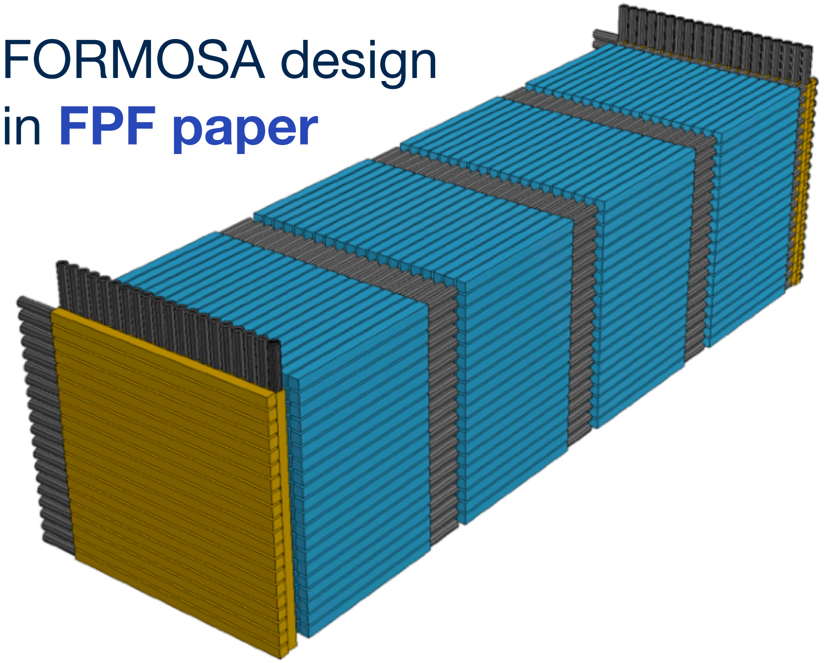
FORMOSA





FORMOSA design in **FPF paper**



Aimed at the ATLAS IP, located in the very-forward region ($\eta > 9$)

Expect to see **~250x rate** of millicharged particle detection in the forward region compared to the central one (i.e. milliQan, $\eta \sim 0$)

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

Shielded from most SM particles produced at the IP by ~ **600m of rock**
Shielded from LHC beam-gas radiation by **>10m of rock**
Main background: beam muons → segmented beam-muon veto panels

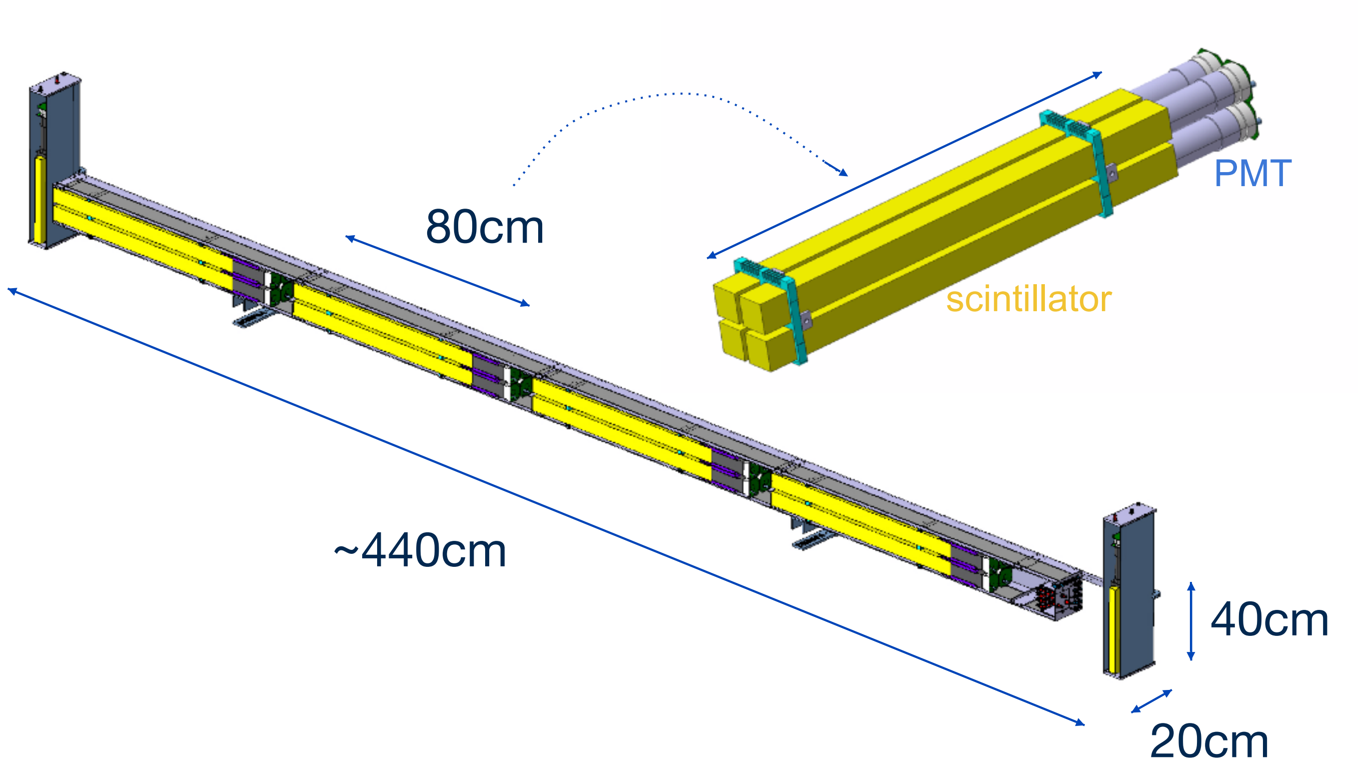
The FORMOSA demonstrator

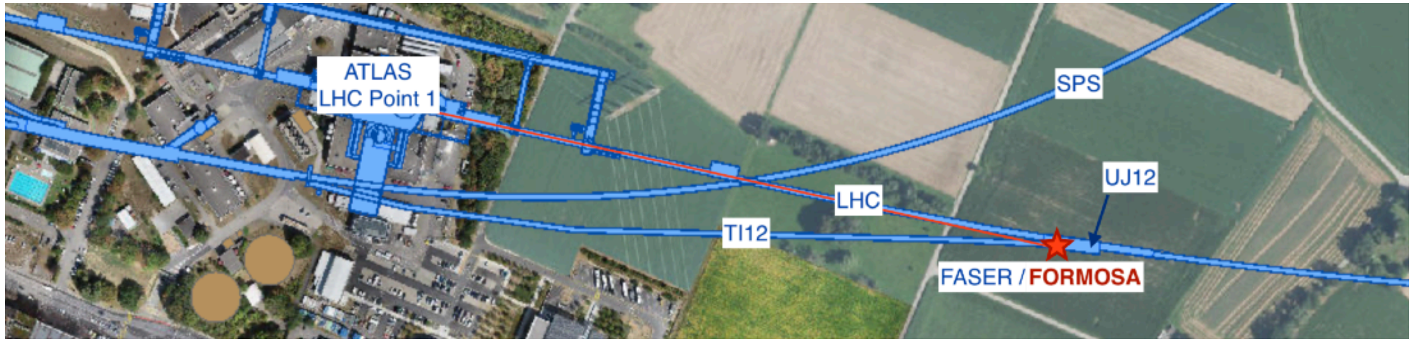
A small-scale version of the full FORMOSA was installed during YETS 2023

→ 2rows x 2columns x 4 layers

Located in the UJ12 cavern (behind FASER), in the opposite side of the to-be FPF

The demonstrator allows to **prove concept** and **target new phase space**





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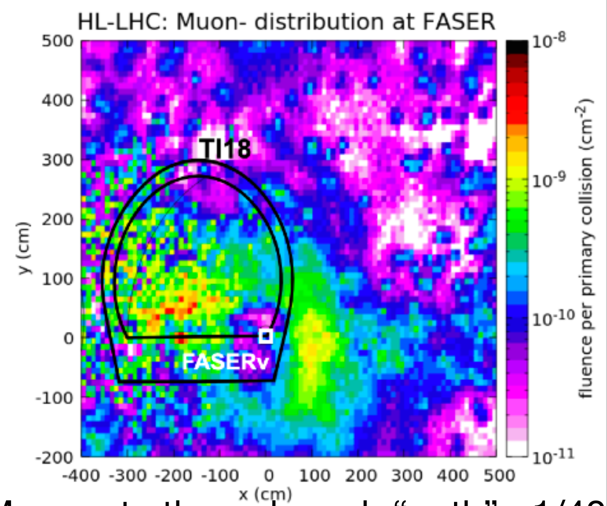
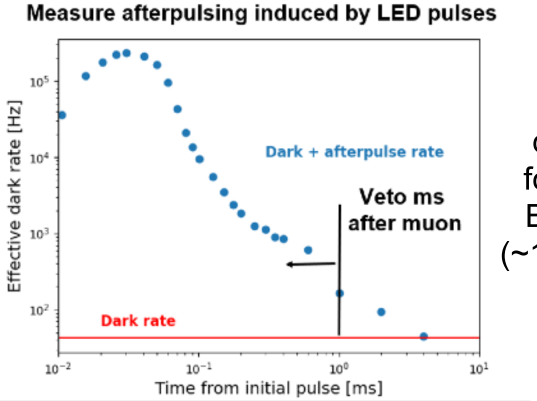
Main backgrounds at the demonstrator

Dominant expected background in the forward region:

afterpulses initiated by through-going muons



Muon rate through each “path” ~1/40ms



Can devote a ms of deadtime to cool down following a beam muon. But muons are frequent (~100Hz for demonstrator), so can’t wait too long

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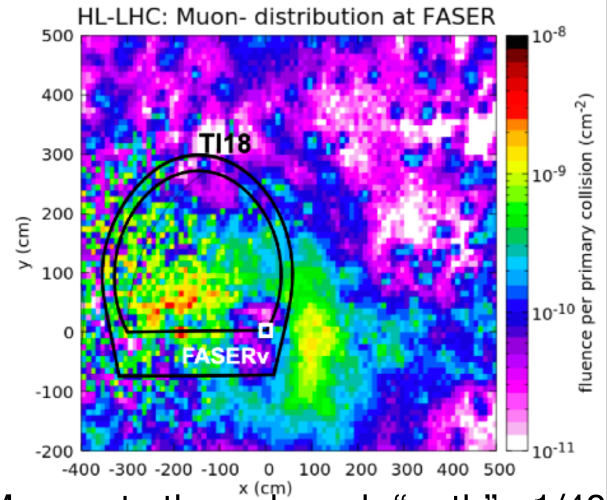
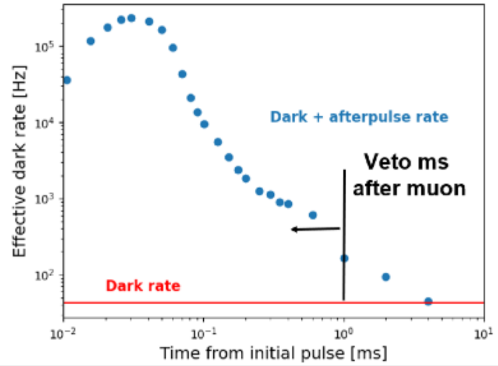


Muon rate through each "path" ~1/40ms

Measure afterpulsing induced by LED pulses



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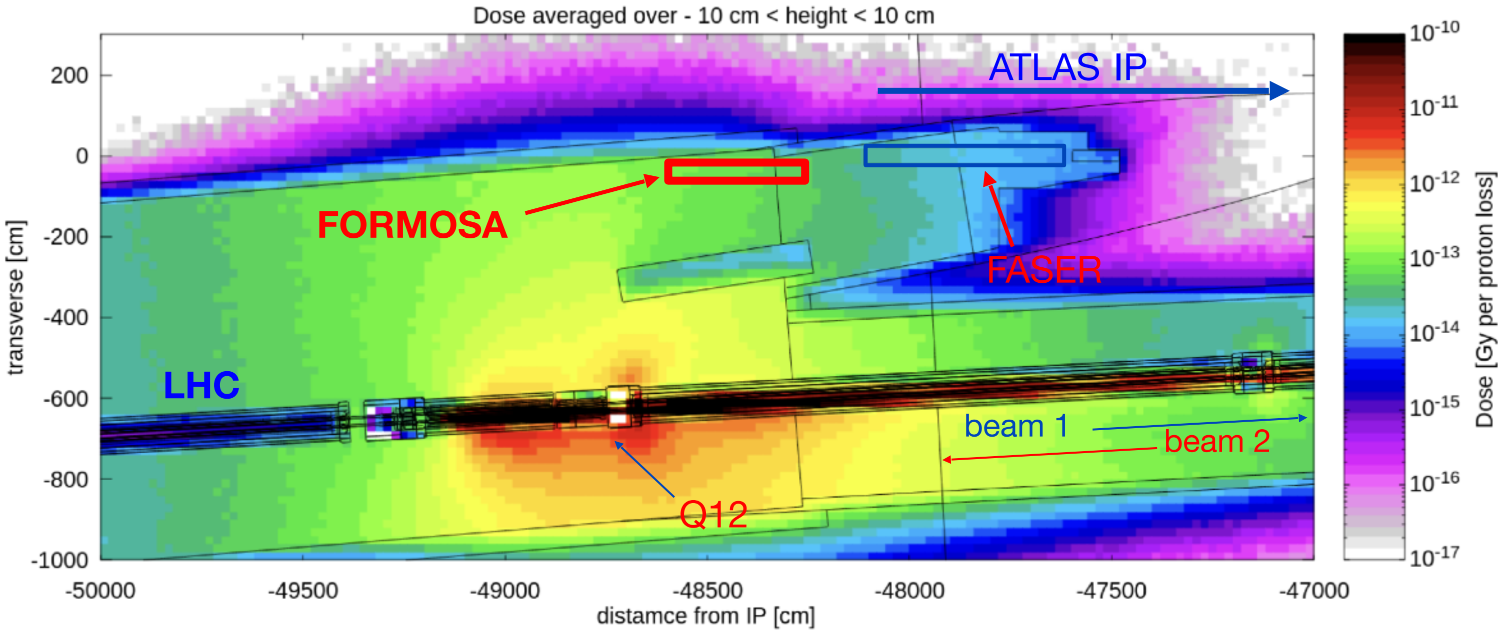
An additional challenge: **beam1-gas background**

(N.B. this background will NOT be present in the FPF)



Absolute average dose due to proton loses at Q12 (simulation provided by FASER)

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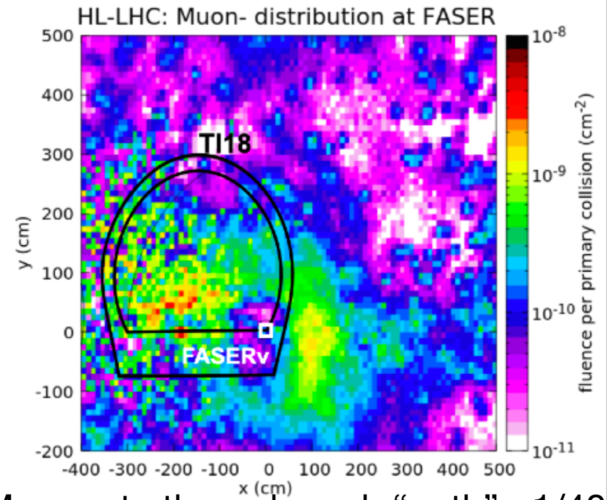

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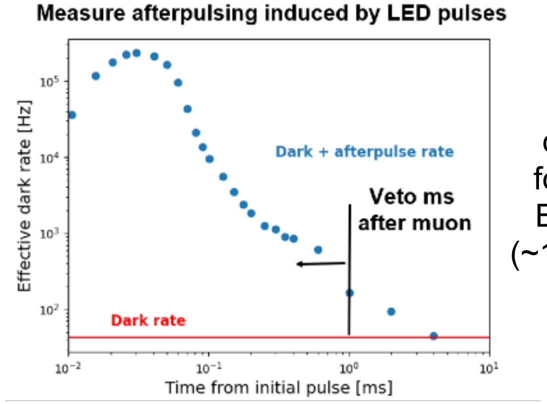

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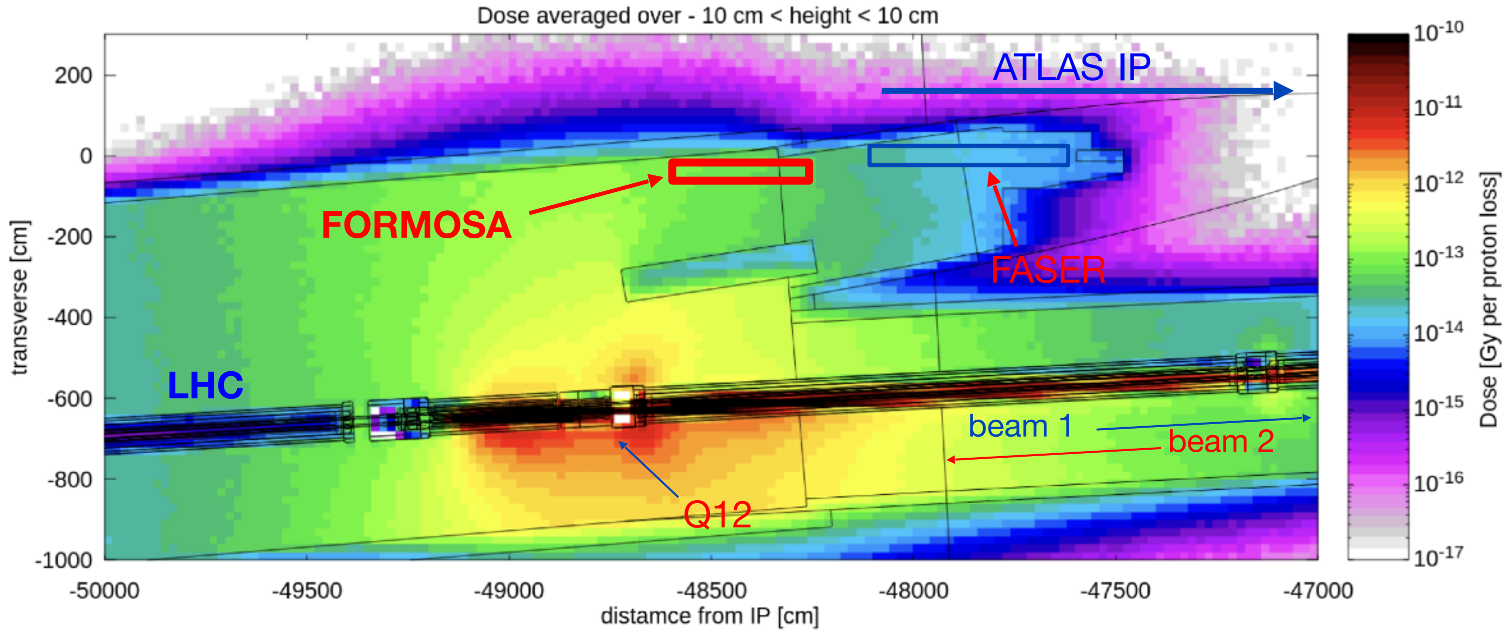

Absolute average dose due to proton loses at Q12 (simulation provided by FASER)

Side veto panels

Large front+back muon veto panels

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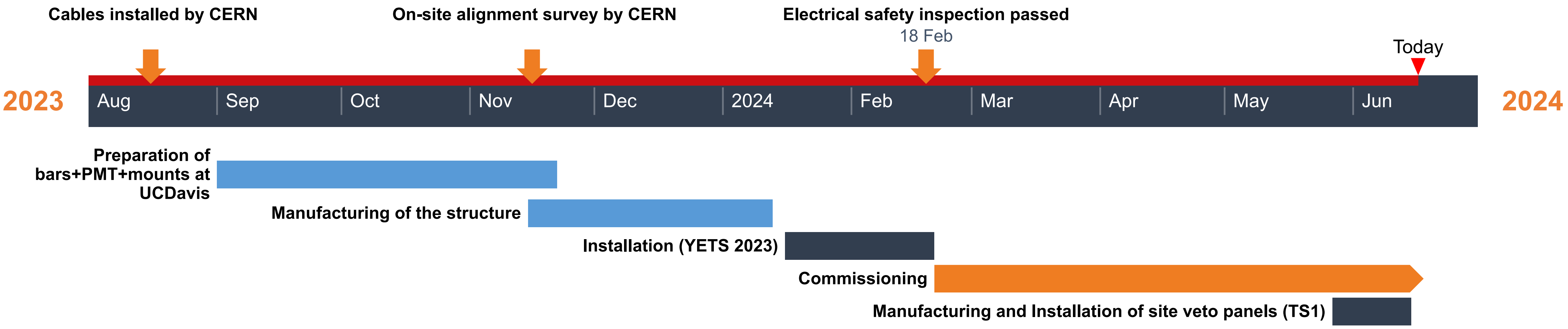
Manufacturing and installation

The demonstrator was built primarily by UC Davis hands!



The entire preparation and installation of the main body took about 7 months

(+2 weeks for the side veto panels)

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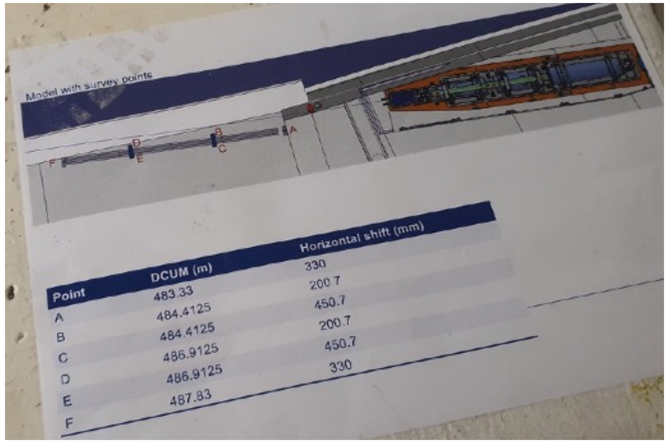
Undergrads: A.Gilotra, M. Legeard, L. Baillloeul, K. Sun, S. Arias-Obando, J. Zhu

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

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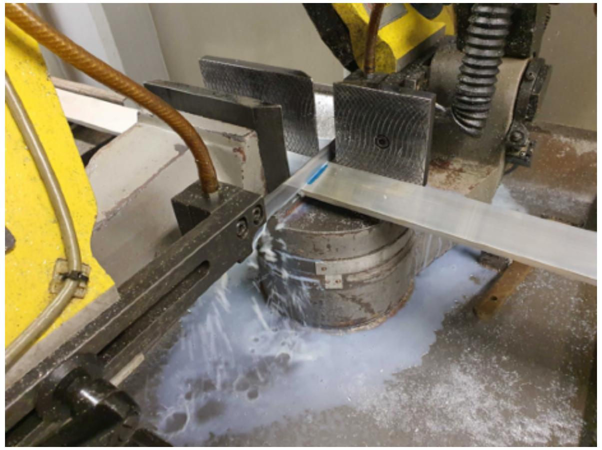
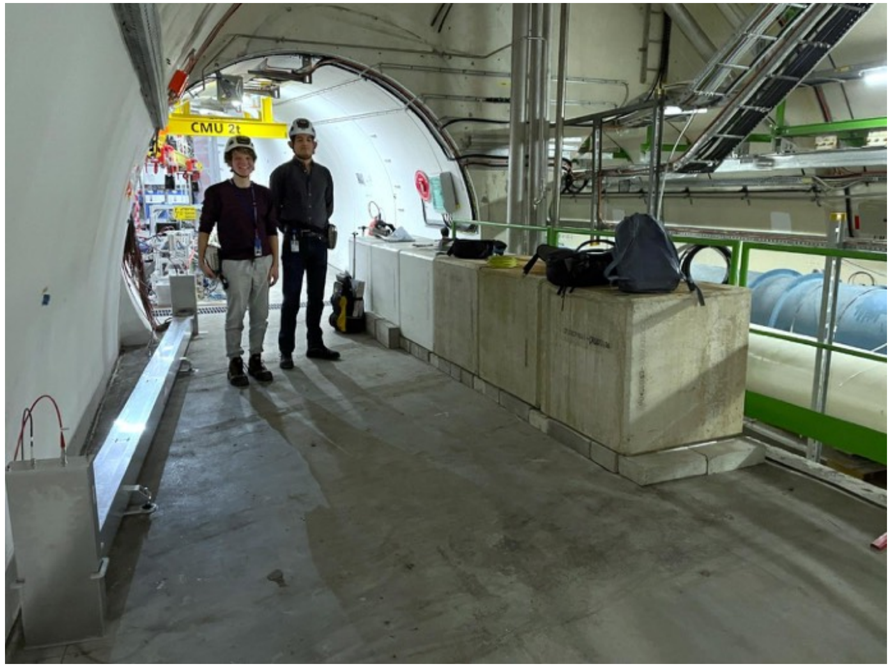
Machining, assembly and installation



November - Mid-January:
Machining the structure

Mid-January - Mid-February:
Installation



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

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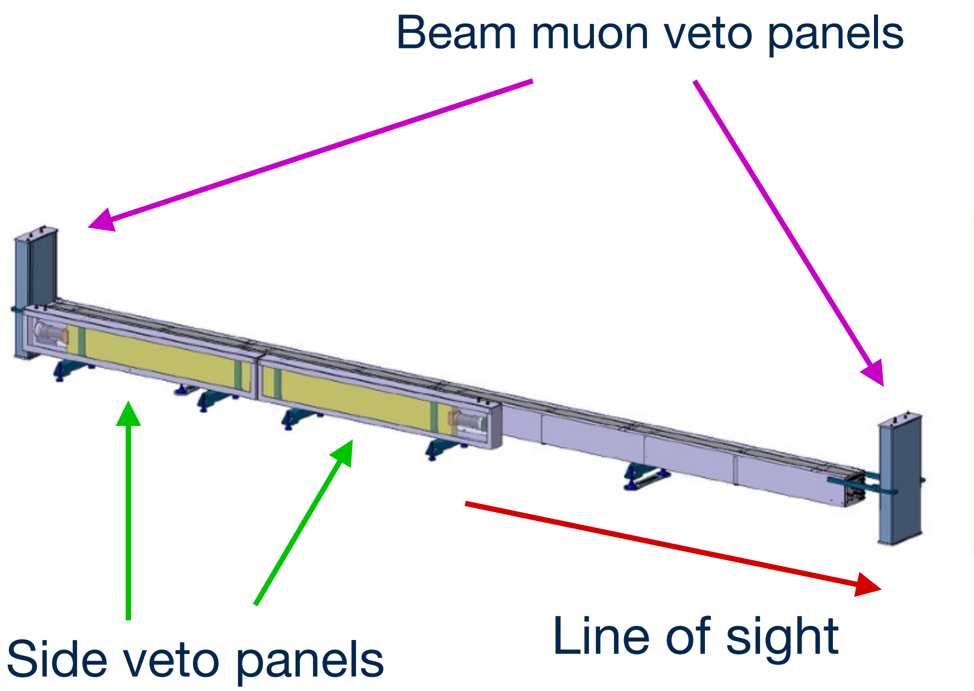
The demonstrator, as of the 14th of June 2024



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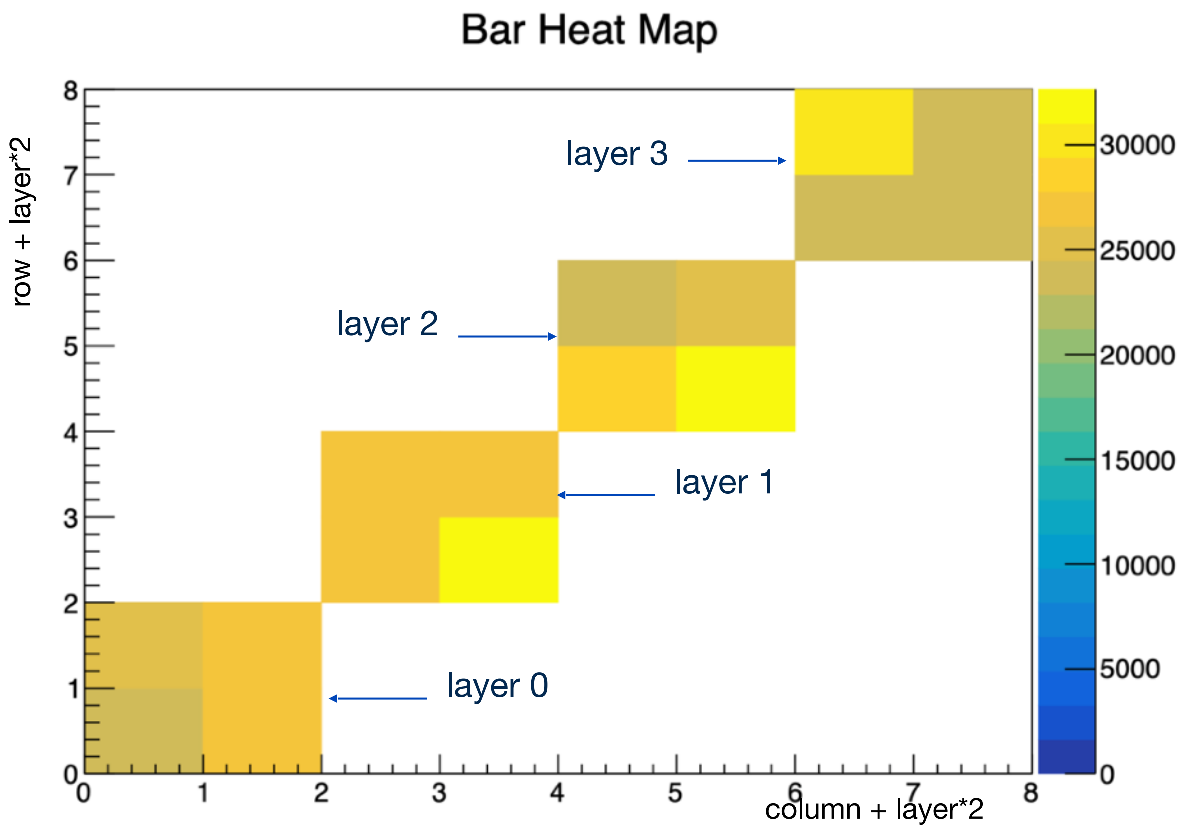
No-beam data

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

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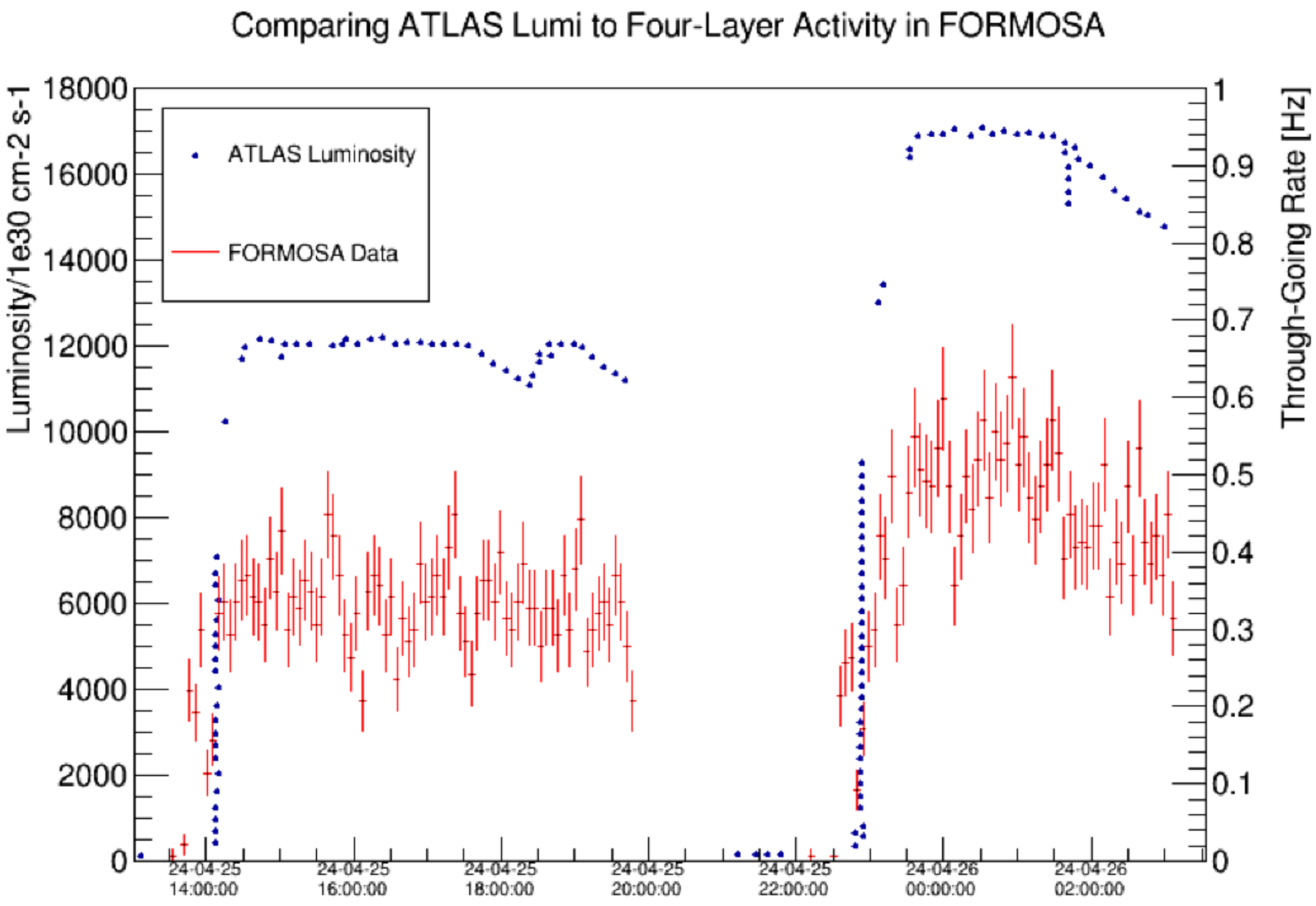
First look at data (prior side veto panels)



- We see the increased activity in FORMOSA when beam circulates regardless of type
- During stable beams, there is a strong correlation between ATLAS luminosity and and 4-layer trigger rate

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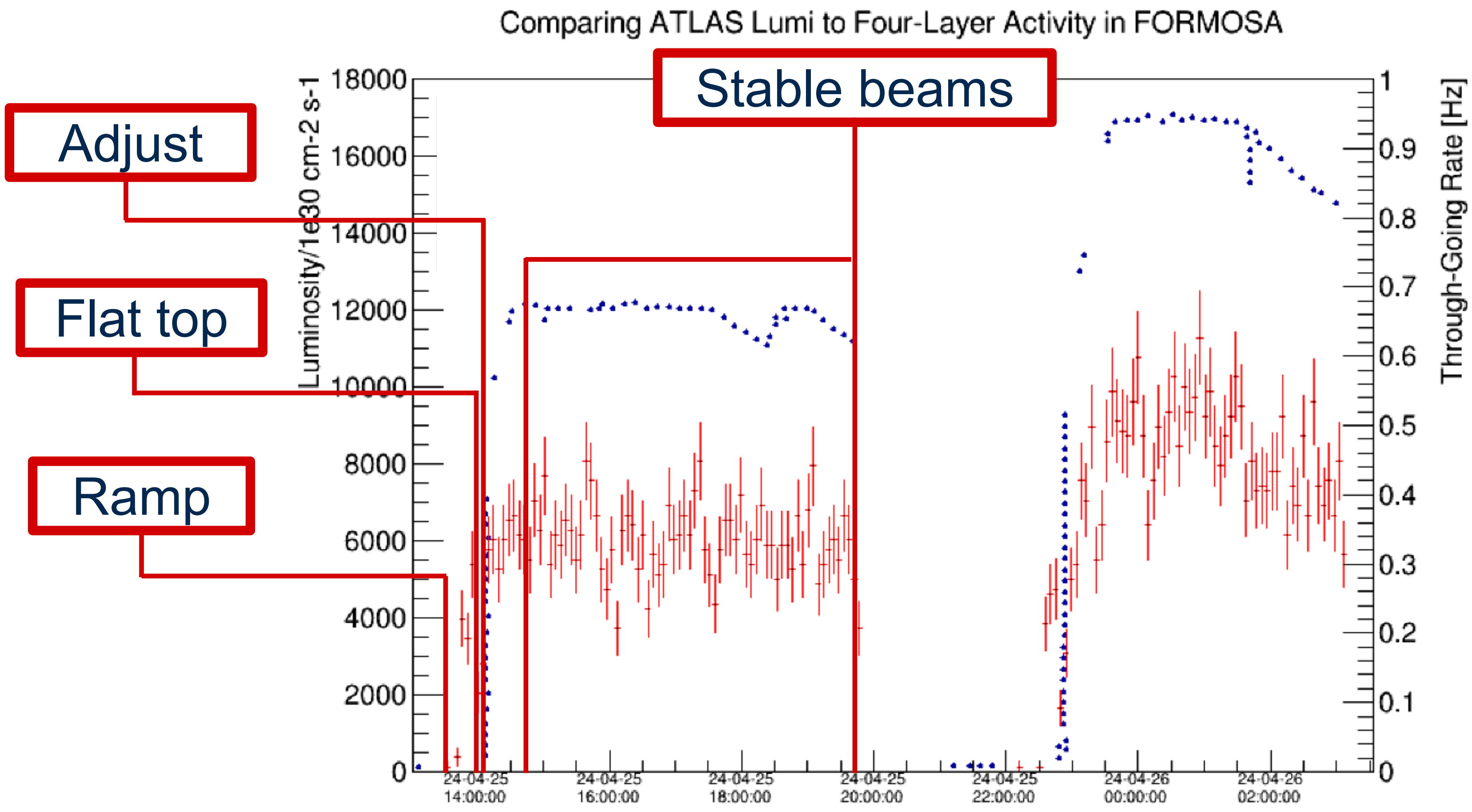

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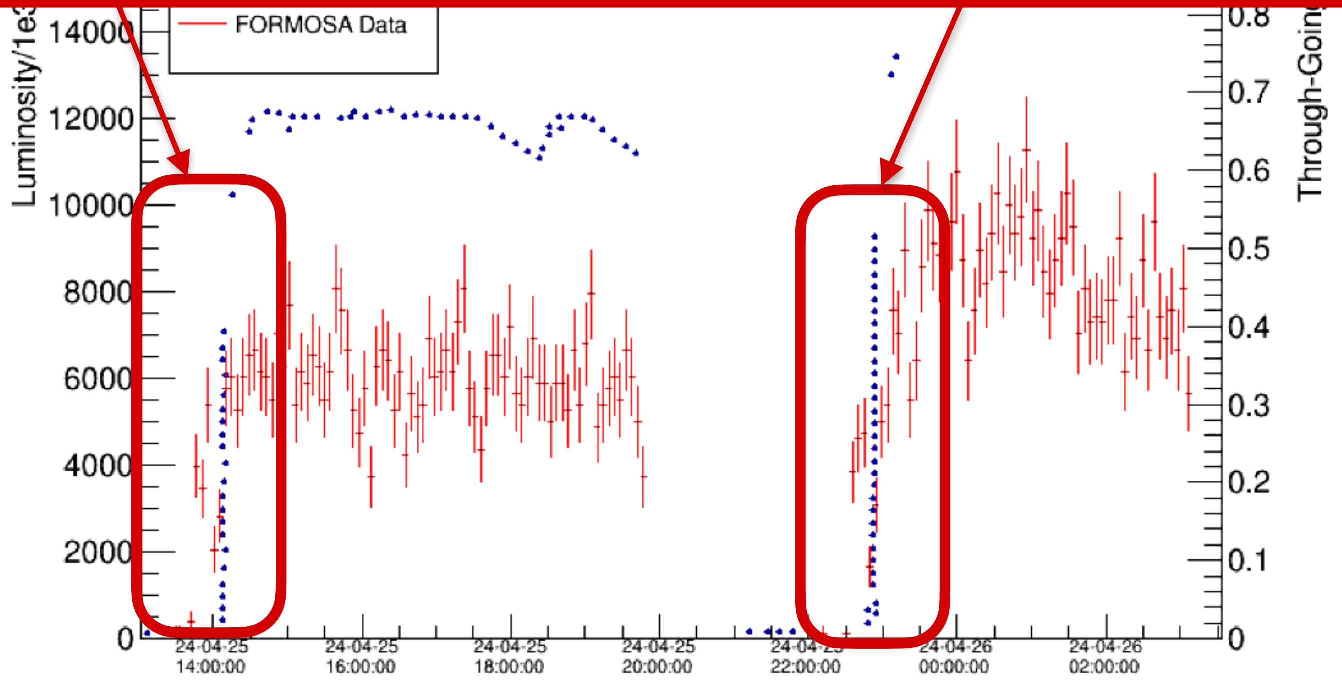
First look at data (prior side veto panels)

Expecting new side veto panels to improve the overall triggering rates, particularly pre-stable-beam detections (which certainly should be vetoed on).
Currently working on it!



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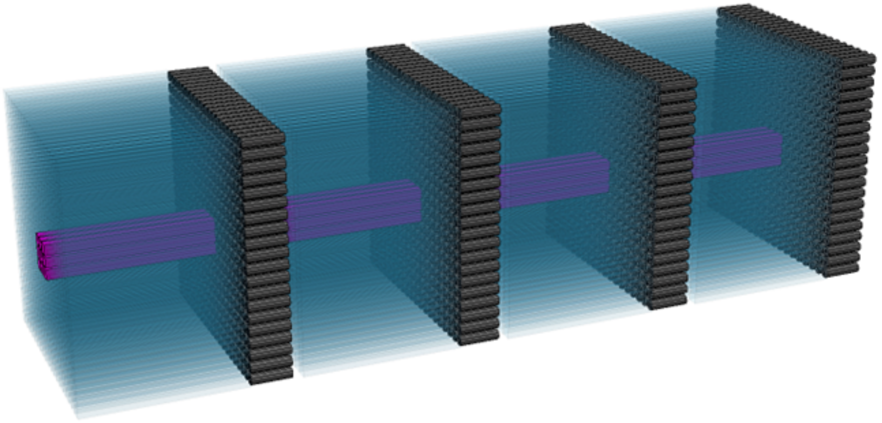
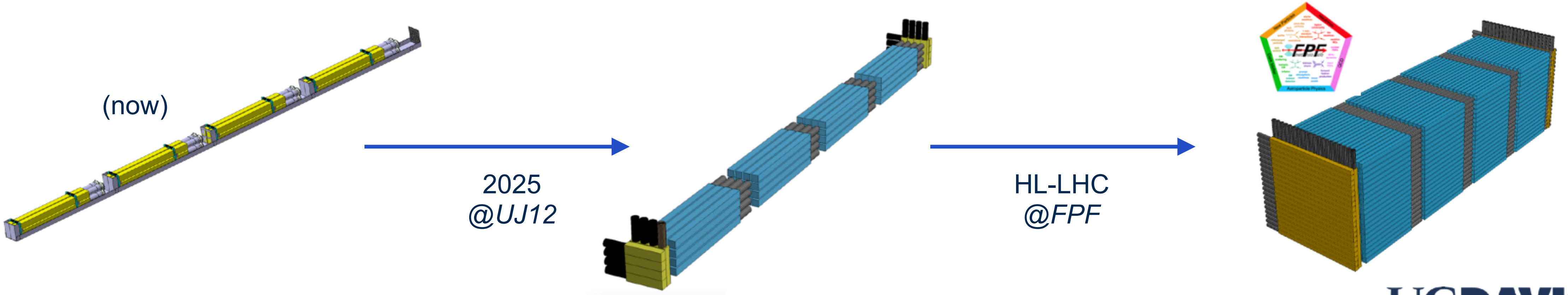
The future of FORMOSA

- Plan to expand the cross section of the detector:
  e.g. 4bars x 4bars x 4layers with segmented veto panels
  → Could allow initial search with new sensitivity to fully prove feasibility

- Consider smaller subdetector using CeBr3 in the full FORMOSA
  → Provides up to factor of ~4 improvement in low charge sensitivity (below $Q/e = 10^{-4}$!)





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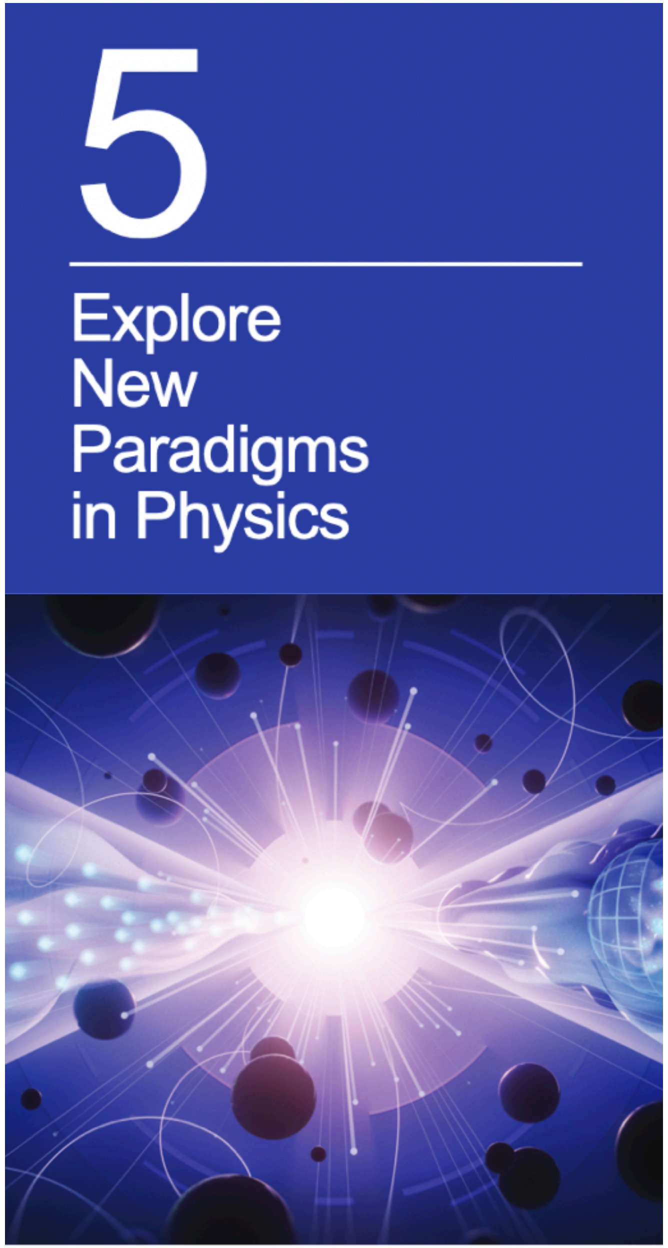
P5 outcomes and timeline

- 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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Outlook

- A small-scale version of FORMOSA was successfully installed at UJ12
- Beam data is already providing valuable information for the understanding of beam-muon backgrounds
- An additional background (beam-gas, not present at the FPF) affects data taking at UJ12. Already applying hardware- and software-based counter-measures.
- Opportunity to expand the demonstrator is being actively studied as we analyse current demonstrator data

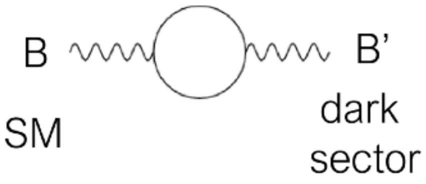
Backup

Why millicharged particles?

Standard motivation: Introduce new, hidden U(1) with a massless field A', a “dark photon” that couples to a massive “dark fermion” ψ’

$$\mathcal{L}_{\text{dark-sector}} = -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}'(\gamma^\mu\partial_\mu + ie'\gamma^\mu A'_\mu + iM_{\text{mCP}})\psi' - \frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu}$$

massless “dark photon” — “dark fermion” with mass M_{mCP} , charge *e’* — mixing term



$\kappa \sim 10^{-3} - 10^{-2}$
(naturally $\sim \alpha/\pi$)

- Ψ’ has mass M_{mCP} and charge under the new U(1) of e'
- Gauge transformation of $A'_\mu \to A'_\mu + \kappa B_\mu$ introduces coupling $\overline{\psi'}\kappa e'\gamma^\mu B_\mu \psi'$
- Conclusion: Coupling arises between dark fermion and SM photon of charge $\kappa e' \cos\theta_W$. **mCP parameters are entirely defined by their mass and charge**

see e.g. arXiv:2104.07151v2 for more details

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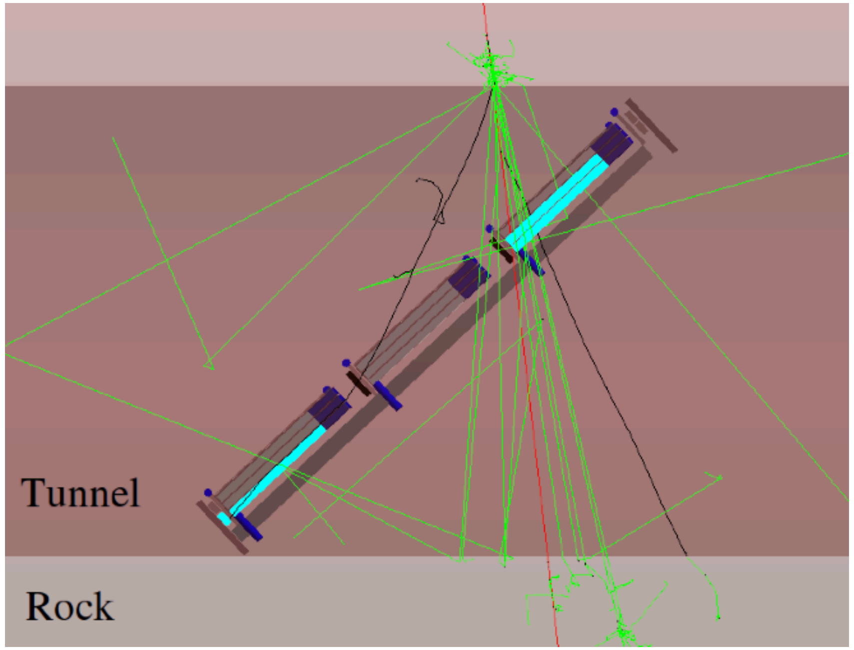
Collecting data

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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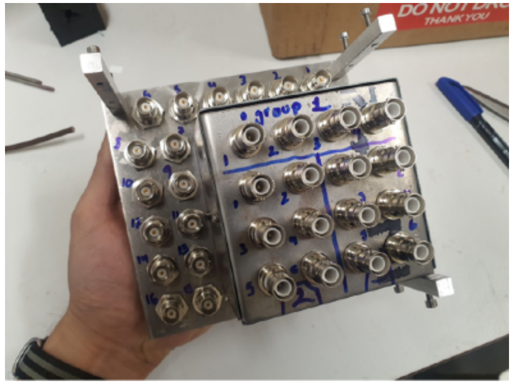
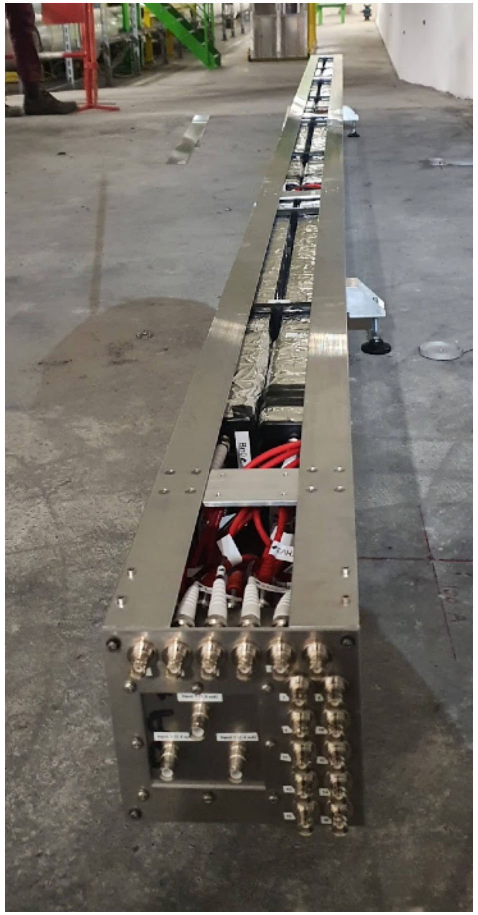
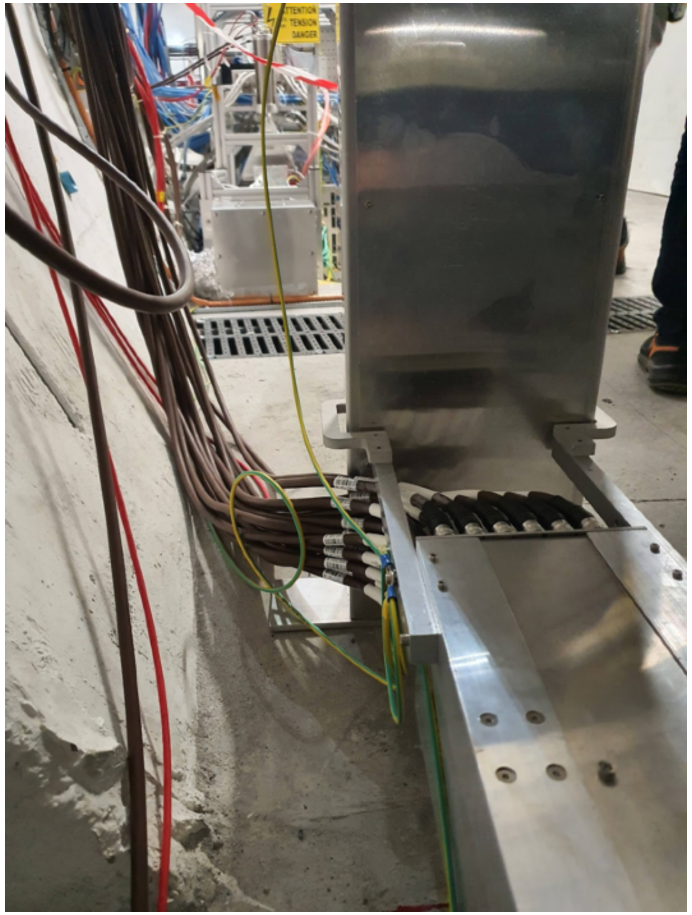
Internal cabling

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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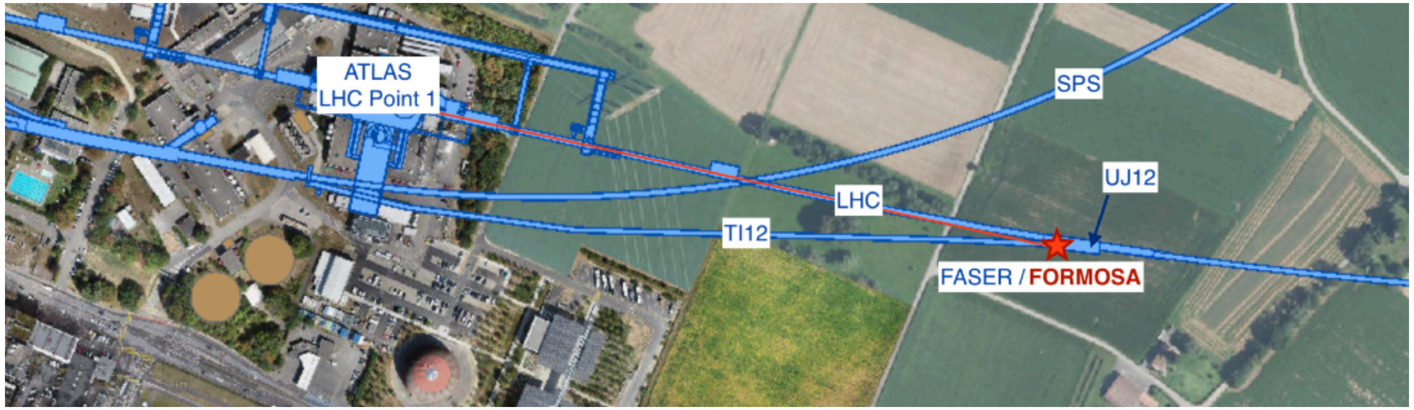
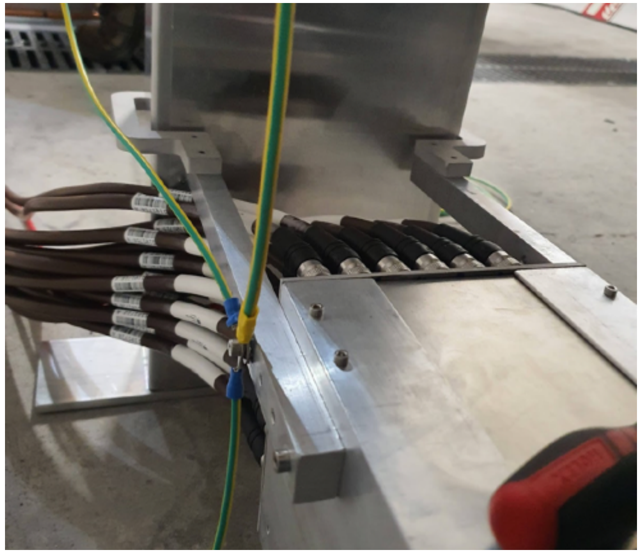
Installation completed in February!





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

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

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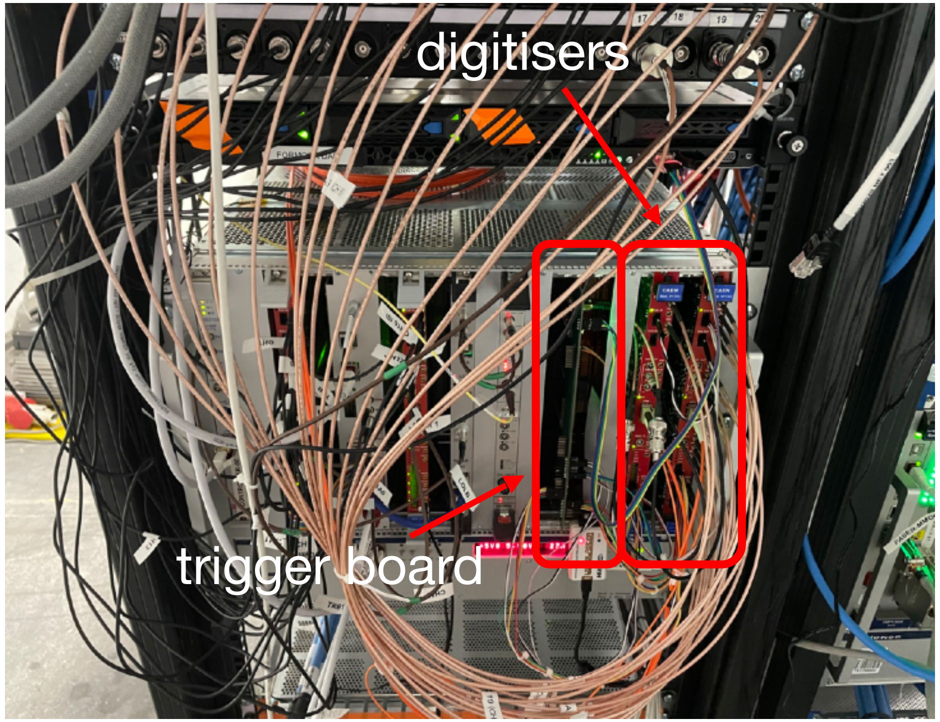
Readout and HV

- 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

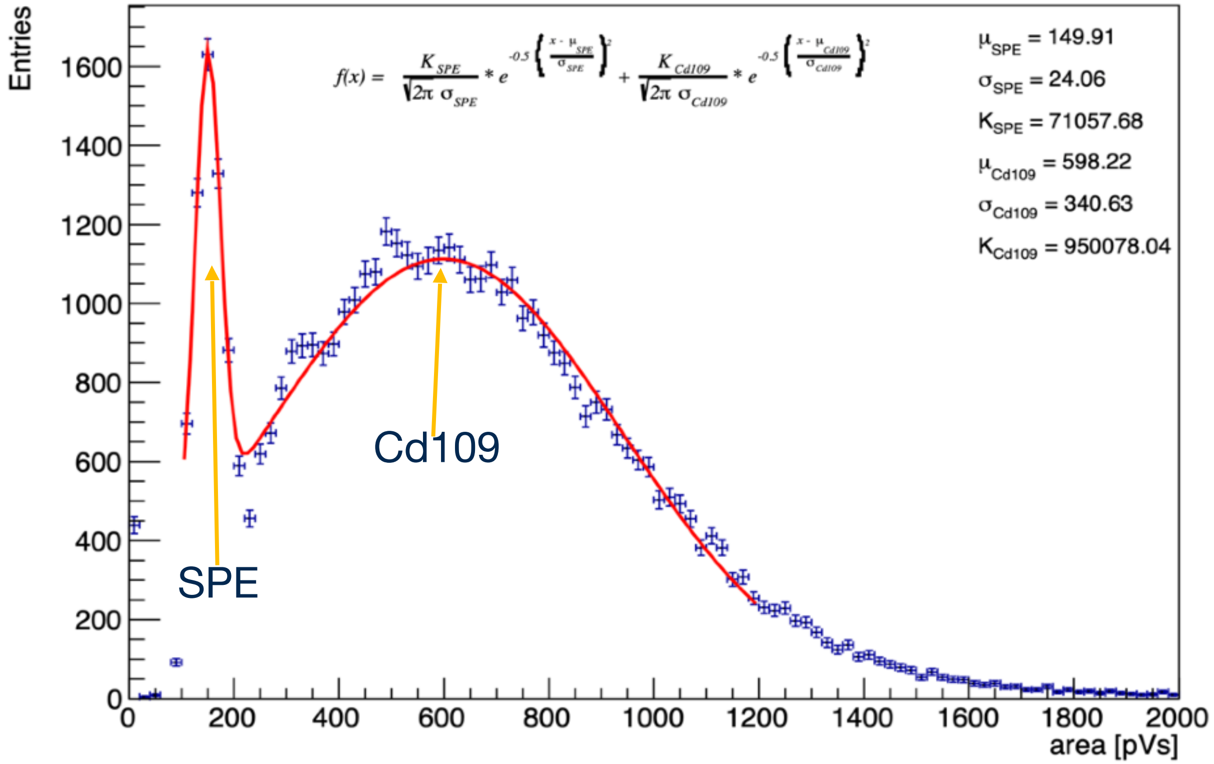
MCPs produce just a **few scintillation photons**
→ we must be able to measure single photons
→ requires excellent calibration and identification of each PMT's SPE peak

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

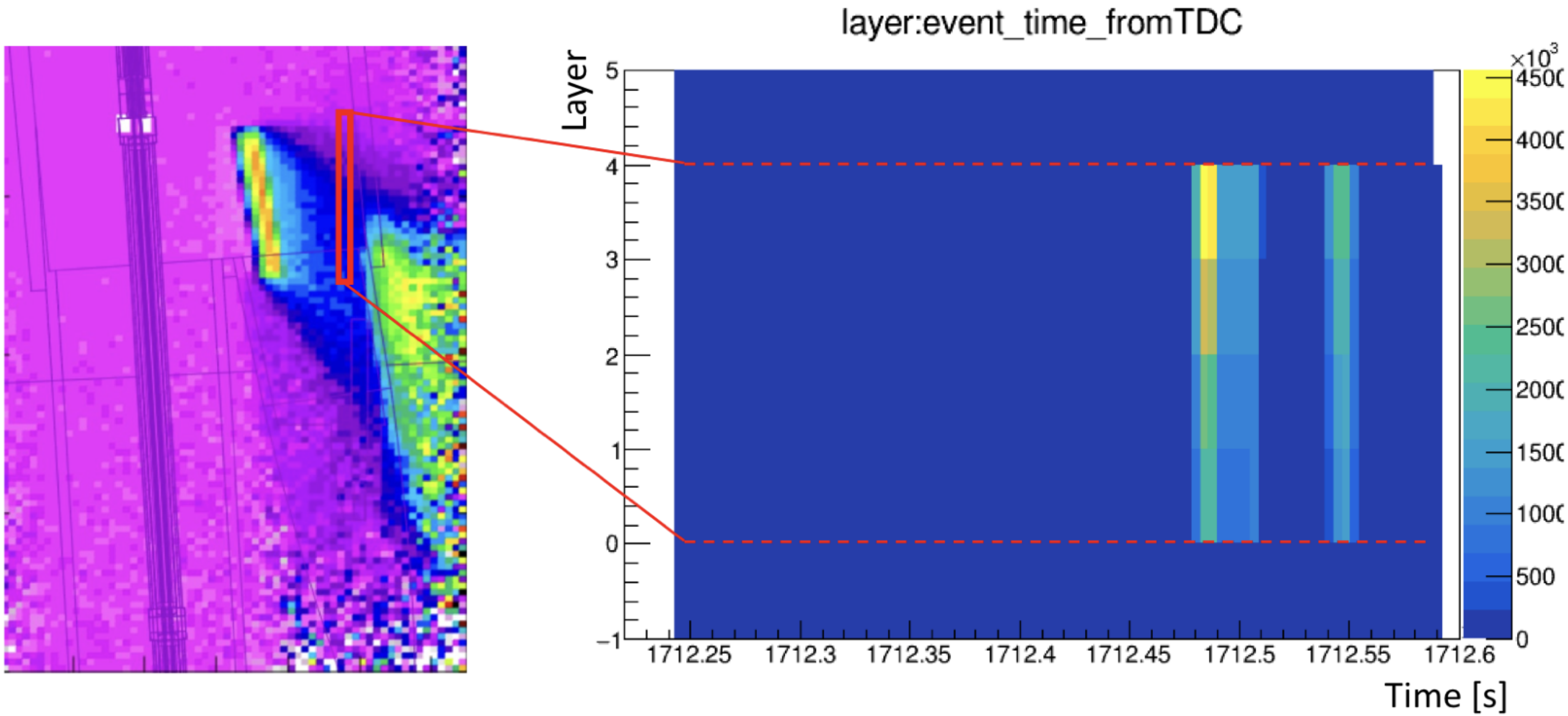
Calibration runs:
Dark rate → measure SPE peak, can be done at any time
Source data → induce signal with a Cd109 radioactive source, done for each scintillator before installation.

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

FORMOSA bar 0



Detecting beam1-gas background



Study done by J. Steenis*. It clearly shows activation that follows a gradient as in the beam background simulation!*

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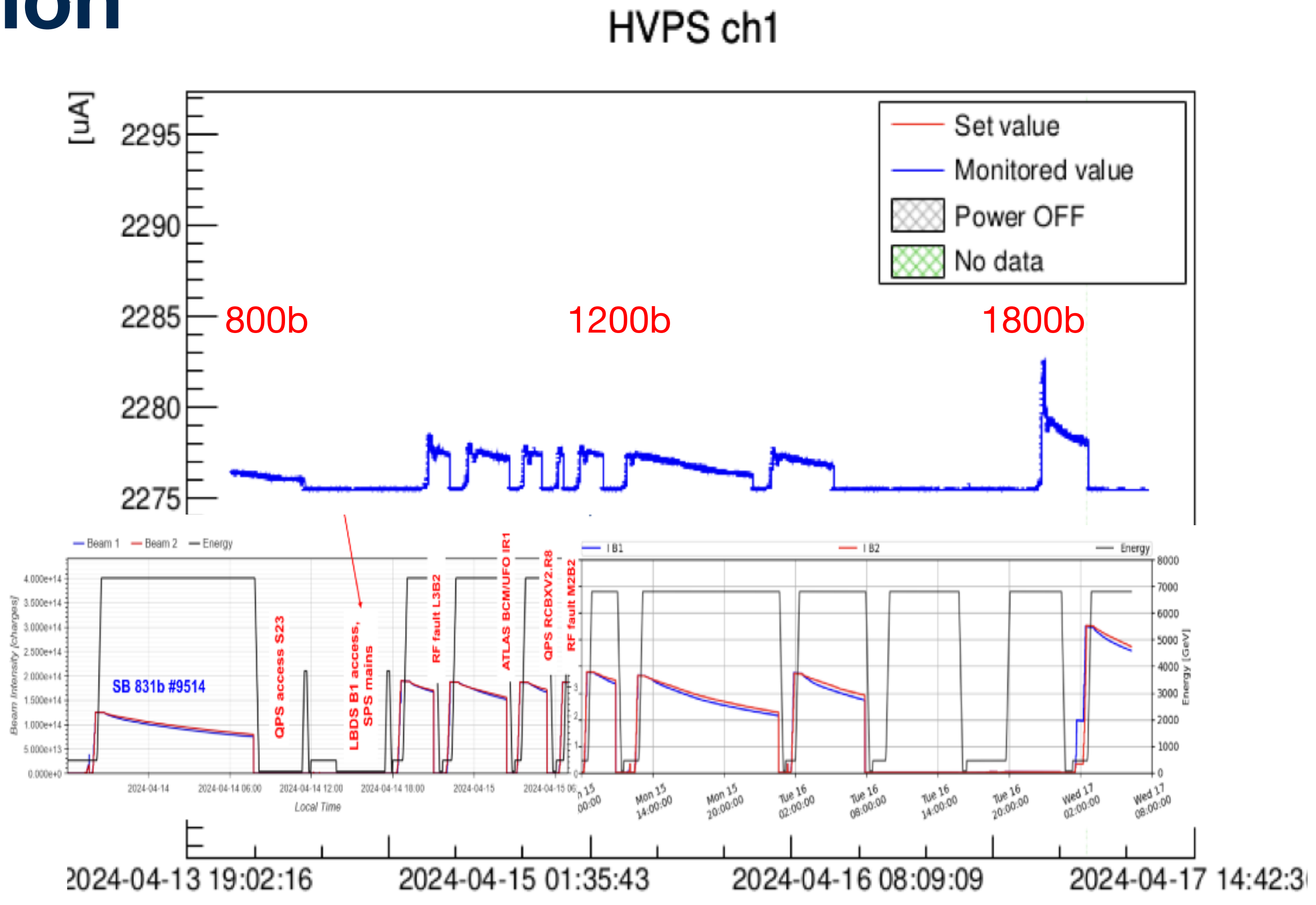
Beam-induced activation

We have measured activity at FORMOSA when the LHC circulates beam regardless of the type (scrubbing, VdM scans, stable beams).

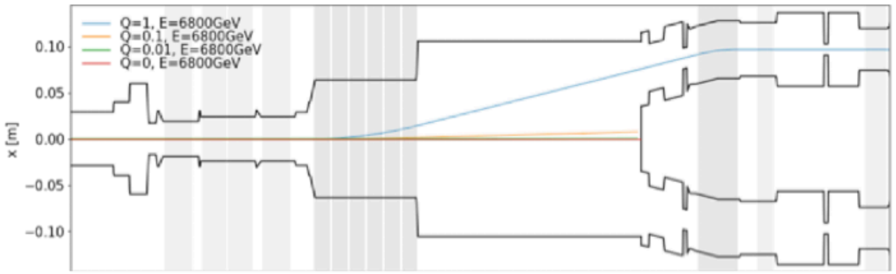
- An easy way to sense beam activity is by looking at the PMT's current draw: the more activation they get, the more current they consume.
- This is heavily correlated to the circulation of the beam itself.
- We are detecting **beam background**



Current draw of ch1 over several days, compared to LHC activity in the same period (LHC status recovered from the LHC morning meetings)

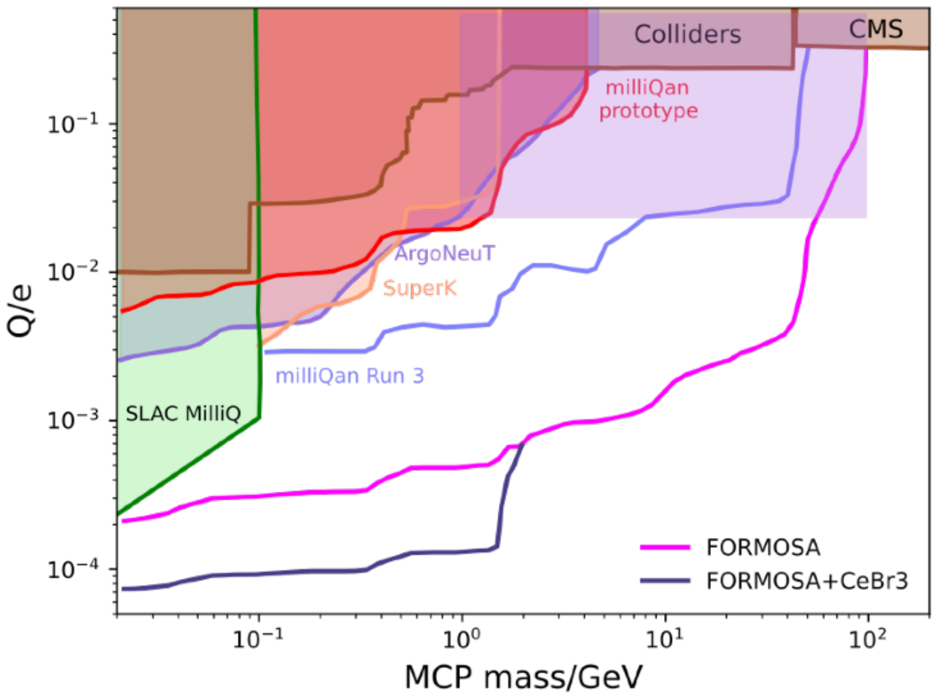
![UC Davis]

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

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Potential changes in the full FORMOSA

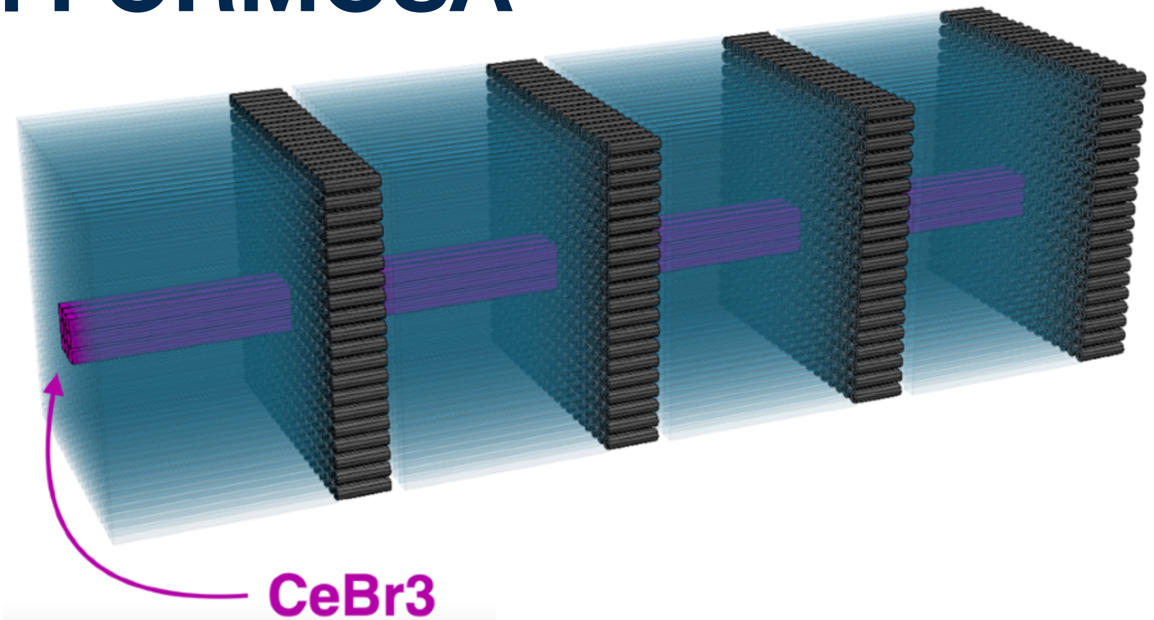
- Potential sub-detector made of CeBr3:

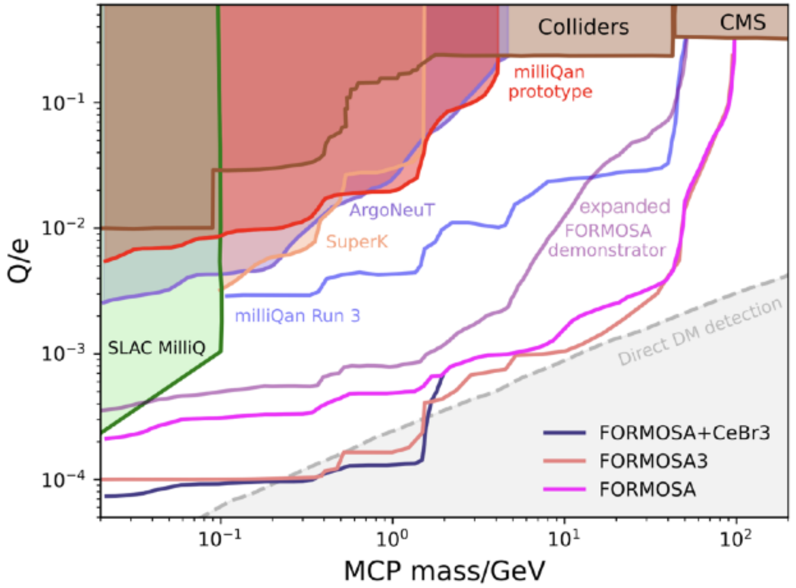
  ~35x more photons/cm compared to plastic scintillators, fast with low internal radioactivity

  → 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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Collaboration

The FORMOSA collaboration is comprised largely from the milliQan collaboration.

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