milliQan and FORMOSA In Run 3 And Beyond

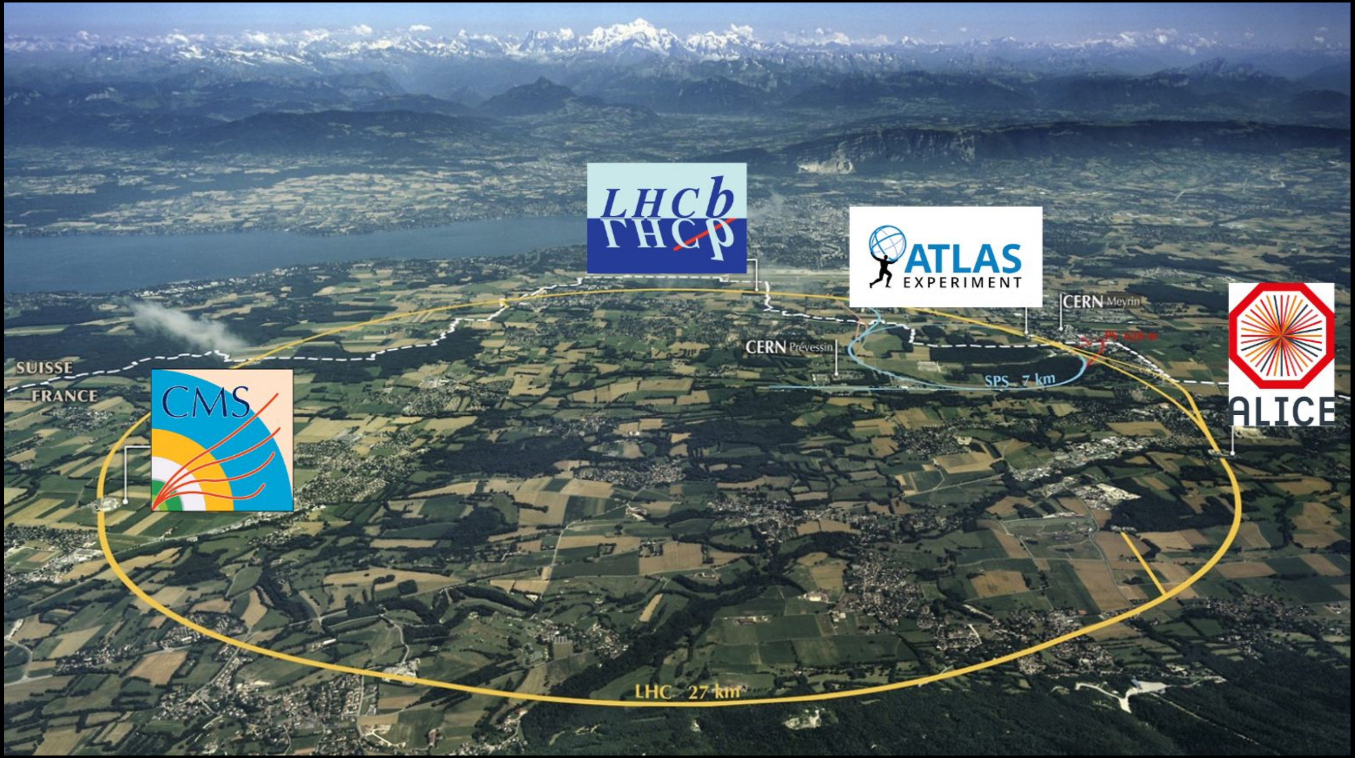
Ryan Schmitz (UCSB), 6/5/2024
On behalf of the milliQan and FORMOSA collaborations

Dark Matter in a Hidden Valley

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

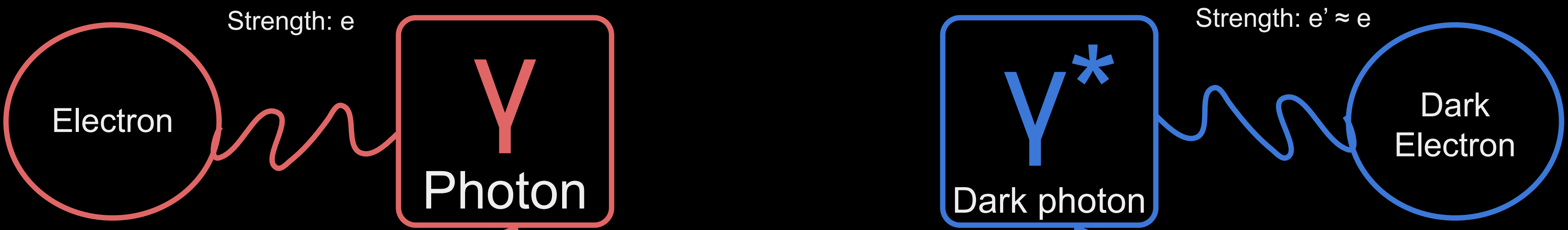
Where could it be hiding?

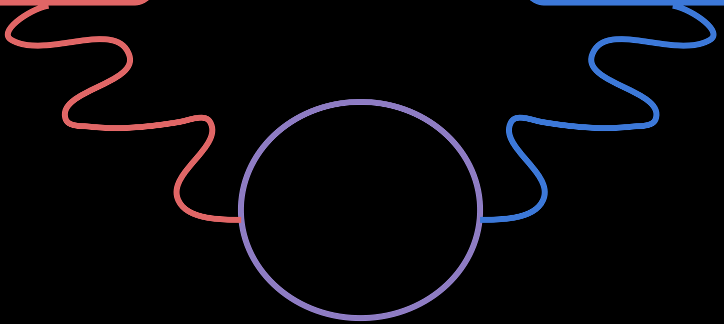
Dark matter gives biggest clue– many SM extensions include a dark or hidden sector



Dark sector mixing

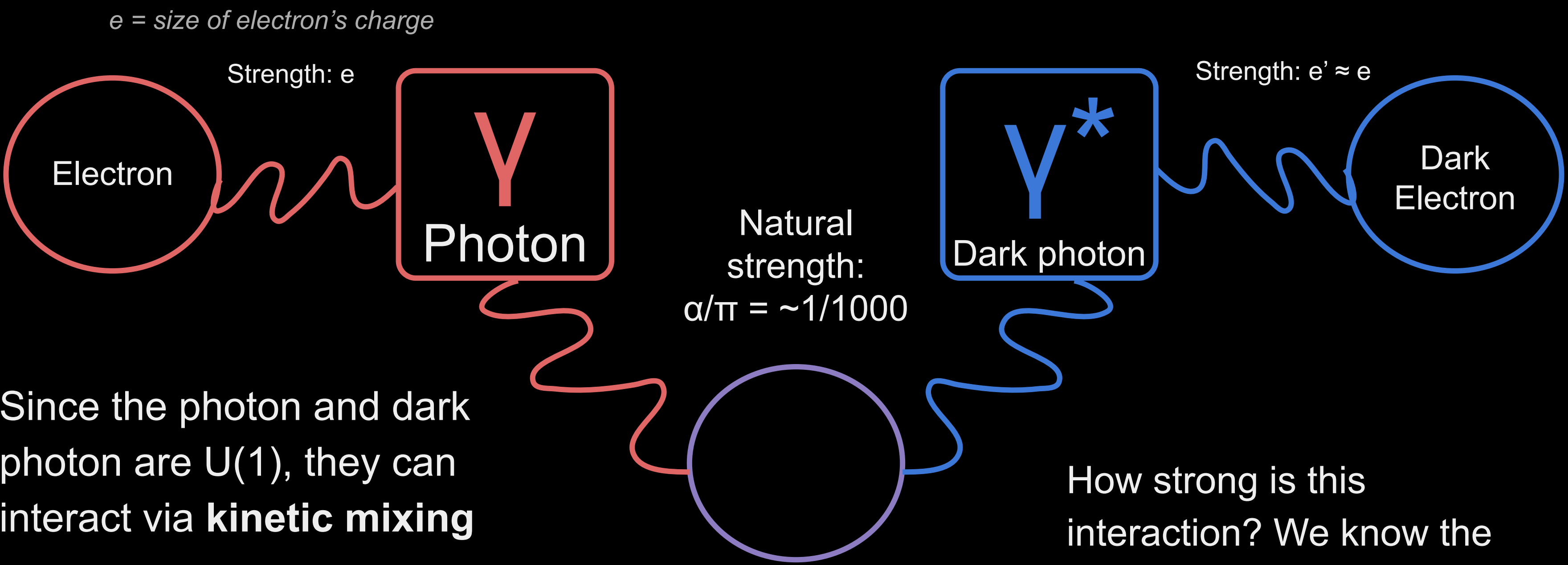
e = size of electron's charge





Since the photon and dark photon are U(1), they can interact via **kinetic mixing**

Dark sector mixing

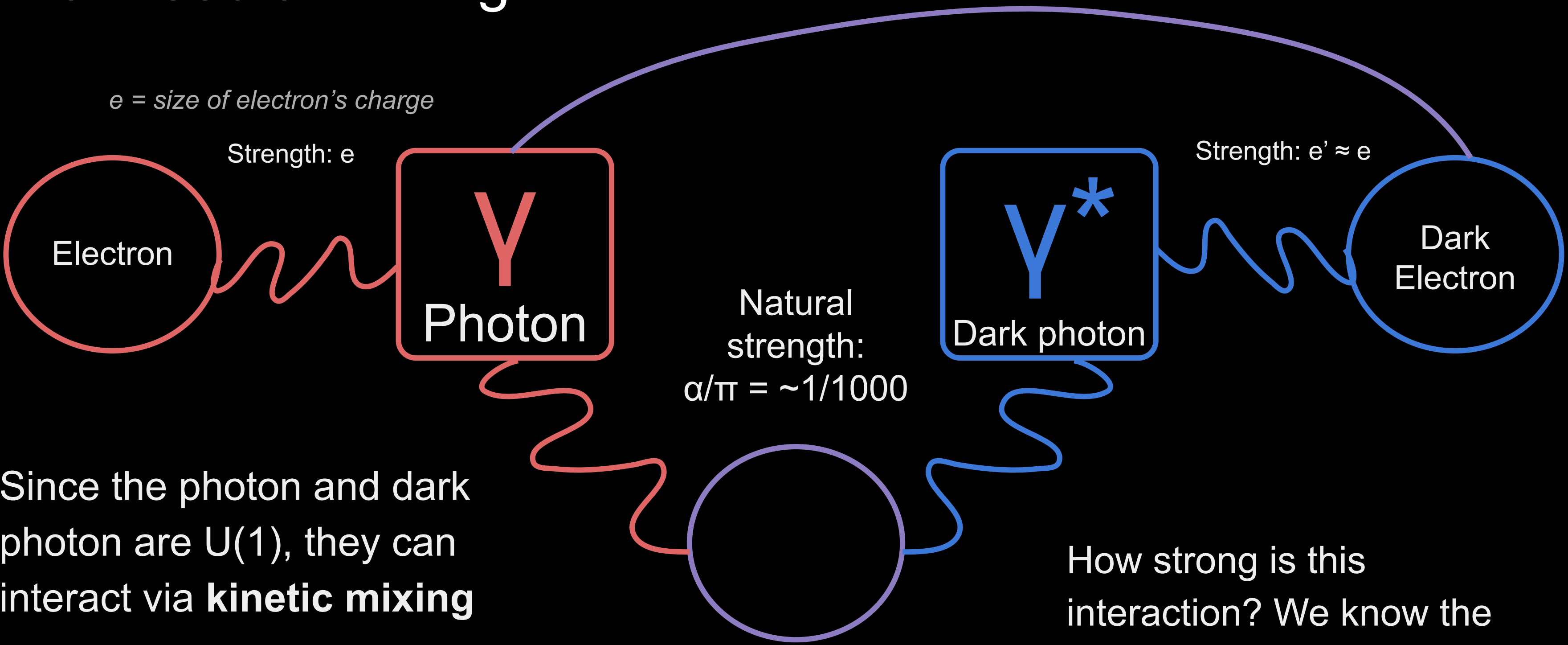


Since the photon and dark photon are U(1), they can interact via **kinetic mixing**

How strong is this interaction? We know the answer for the standard model: around 1/1000!

Dark sector mixing

The charge is just the strength of the two connections together. So these dark electrons have charge of 1/1000; millicharged particles!



Since the photon and dark photon are U(1), they can interact via **kinetic mixing**

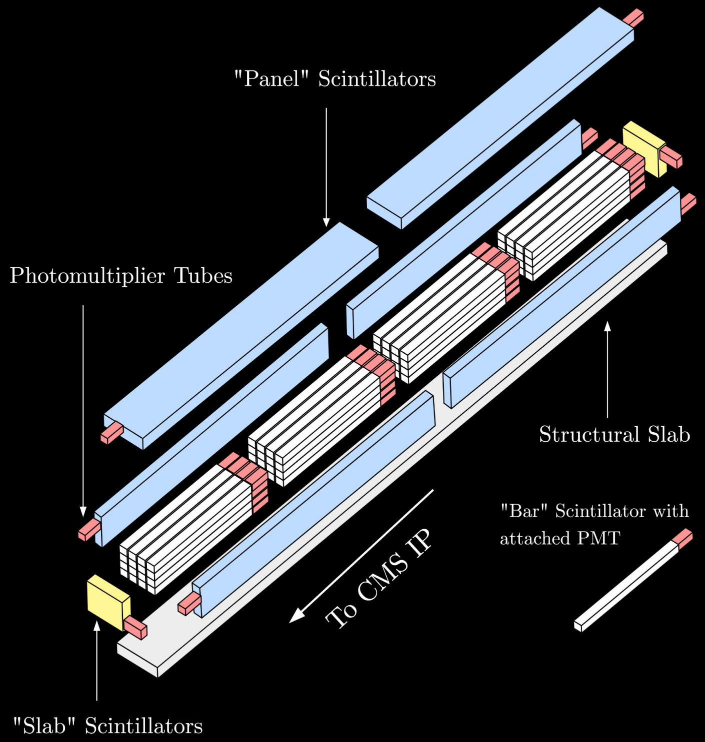
Let's use a millicharged particle detector to search for these!

How strong is this interaction? We know the answer for the standard model: around 1/1000!

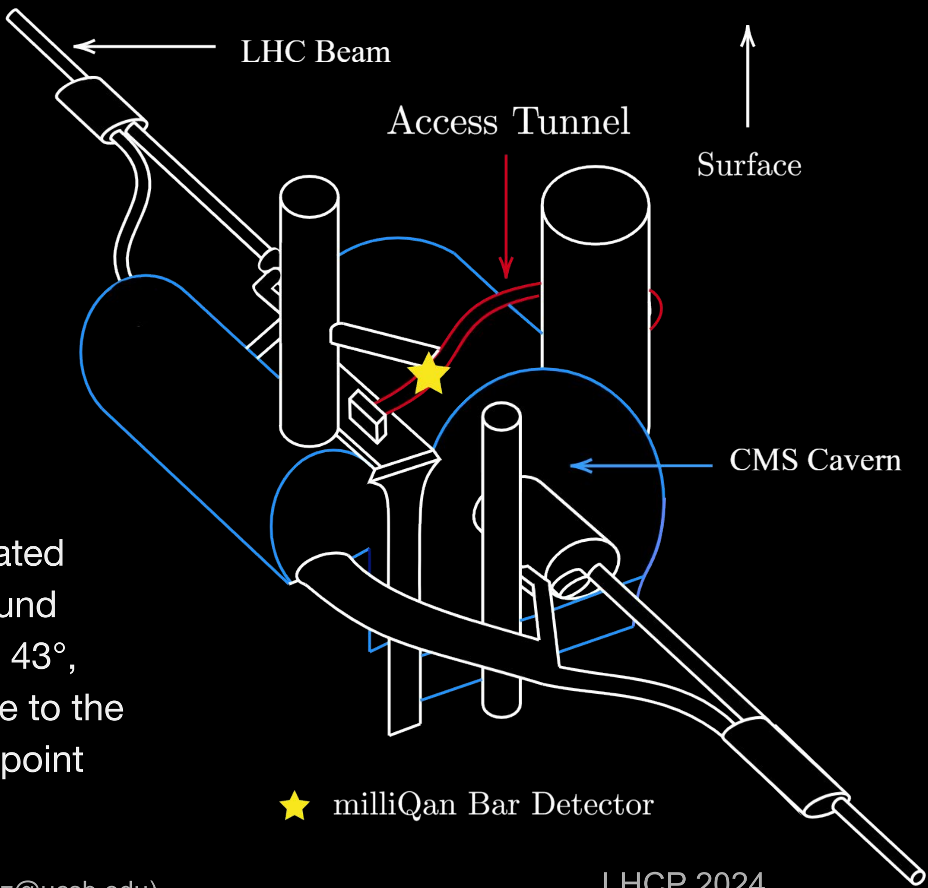
milliQan Run 3 Bar Detector

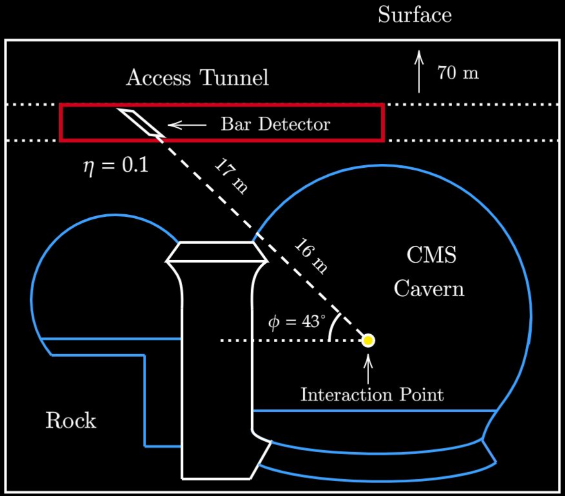
Basic design:

- 64 scintillator bars (60 x 5 x 5 cm) attached to PMTs arranged in 4 layers, pointed at CMS IP
- 6 Veto slabs on top and sides of detector to reject external backgrounds
  - Provide active and passive shielding
- 2 Veto panels on front and back of detector
  - Used to tag throughgoing muons



Detector Positioning



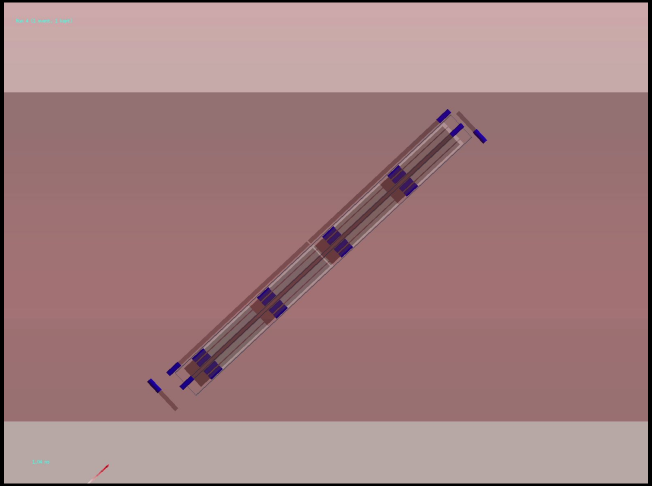


milliQan is located
80m underground
at η ~ 0.1, Φ = 43°,
r = 33m relative to the
CMS collision point

Beam Muon

Legend: μ, γ, mCP e⁻ optical photon

Q = e



When a charged particle passes through scintillator, it produces light, which we can detect

Beam Muon

Legend: μ, γ, mCP e⁻ optical photon

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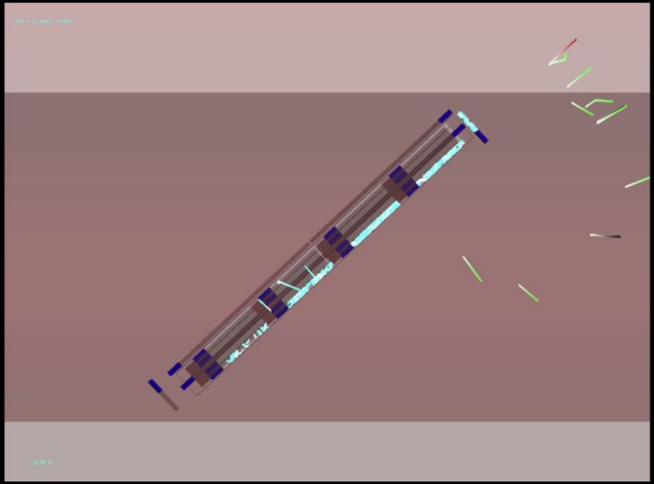
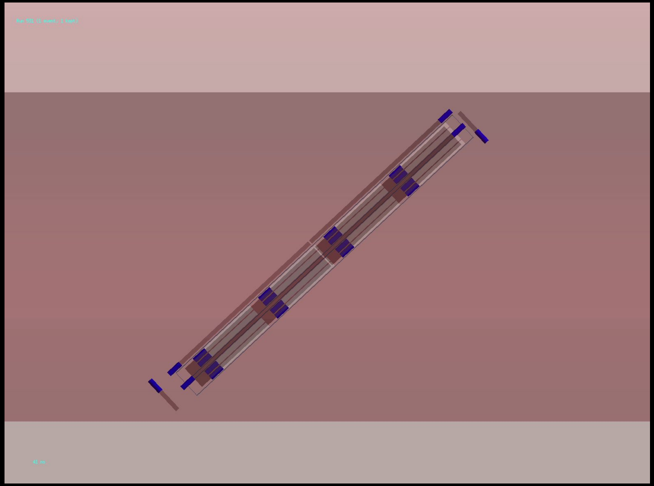


When a charged particle passes through scintillator, it produces light, which we can detect

mCP Signal

Legend: μ, γ, mCP e^- optical photon

Q = 0.01e



When a charged particle passes through scintillator, it produces light, which we can detect

Challenge: With e.g. Q = 0.01e, we see 10,000x less light than usual. So, we need to be able to detect individual photons to be sensitive to millicharged particles

mCP Signal

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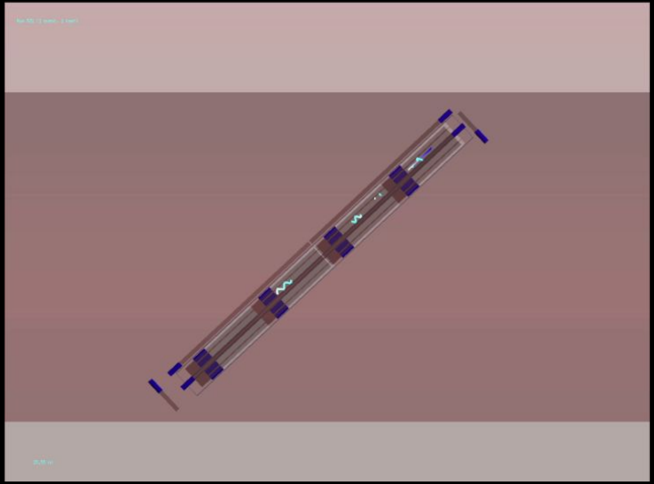


When a charged particle passes through scintillator, it produces light, which we can detect

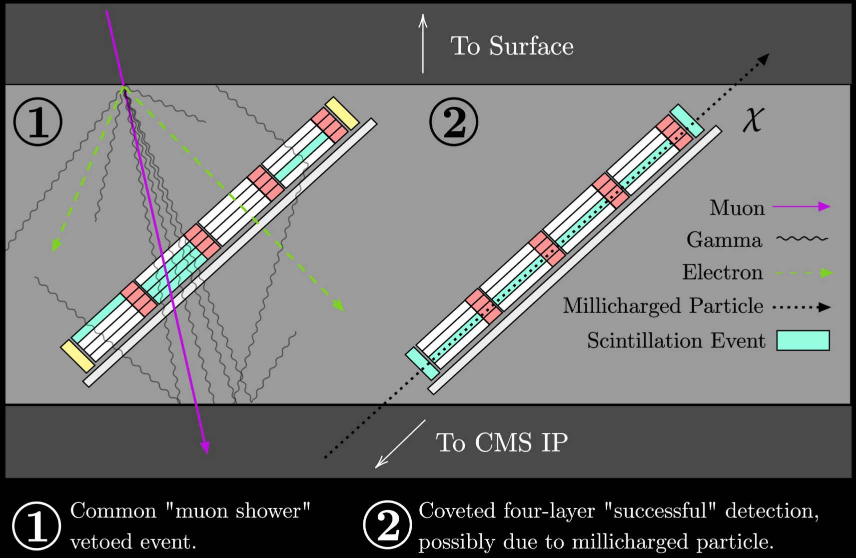
Challenge: With e.g. Q = 0.01e, we see 10,000x less light than usual. So, we need to be able to detect individual photons to be sensitive to millicharged particles

Backgrounds

Signal: ~few photons in one bar in each layer within 15ns, and no other activity

Backgrounds: Cosmic showers, PMT dark rates (~1 kHz per PMT)

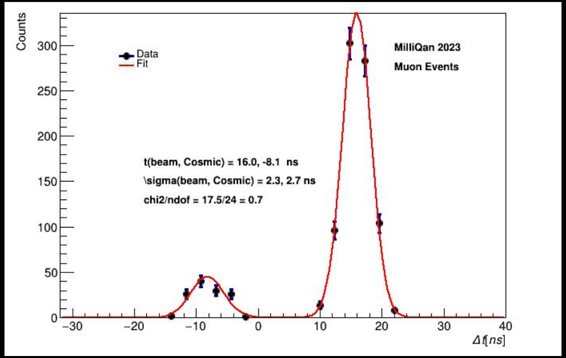
Simulations of the milliQan detectors have shown that with this signal selection, cosmic background rates are negligible (see arXiv:2104.07151)



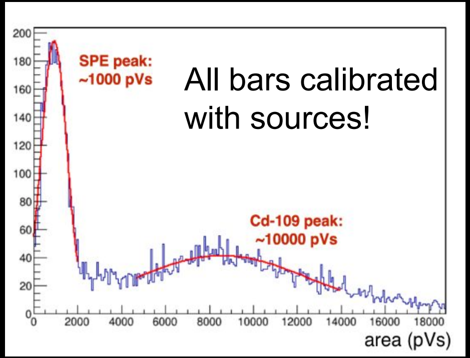
Bar Detector Status

Construction and response/timing calibration completed last year

Studies using beam and cosmic muon backgrounds ongoing

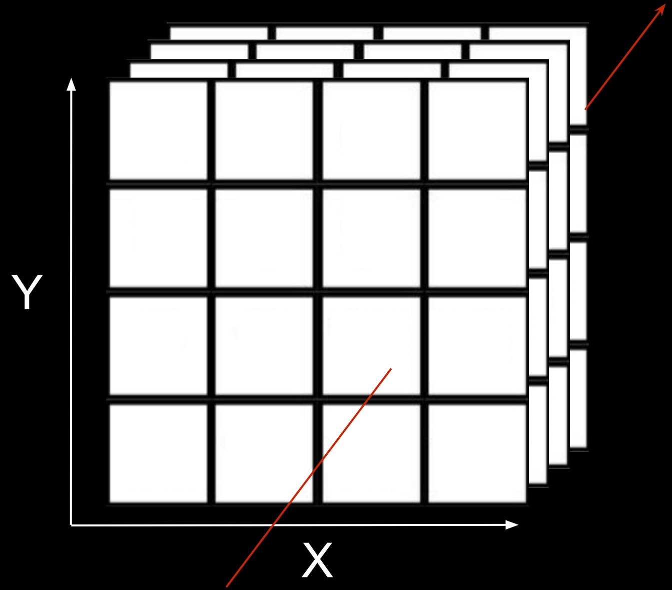


Muons passing through all layers are used for timing calibration

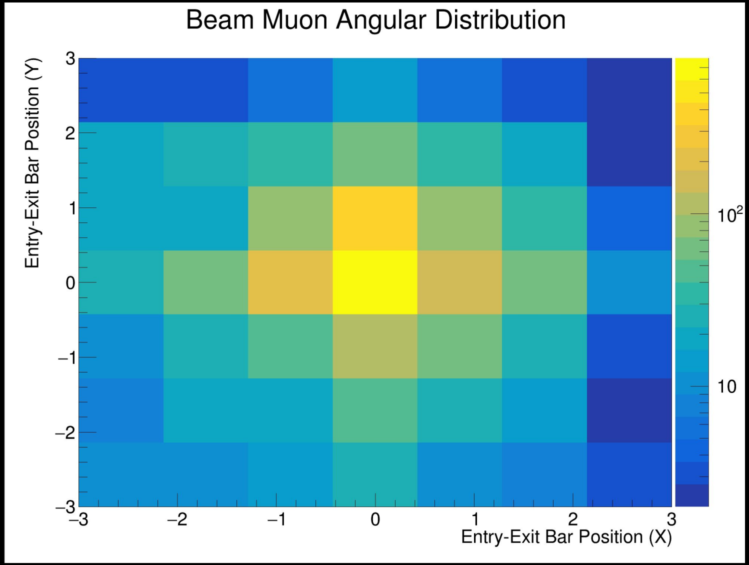


Comparing SPE and Cd109 peaks gives PMT response

Beam Muon Validation: Alignment



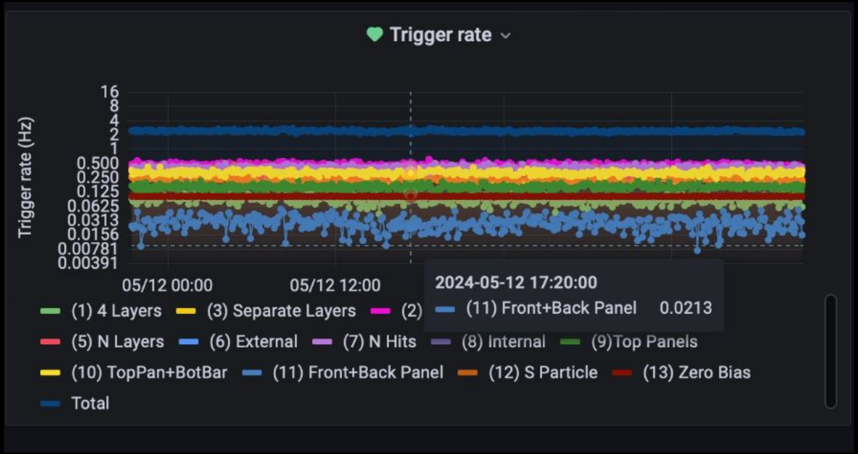
Muons (and mCPs) don't always follow a straight path through the detector. We can measure their paths!



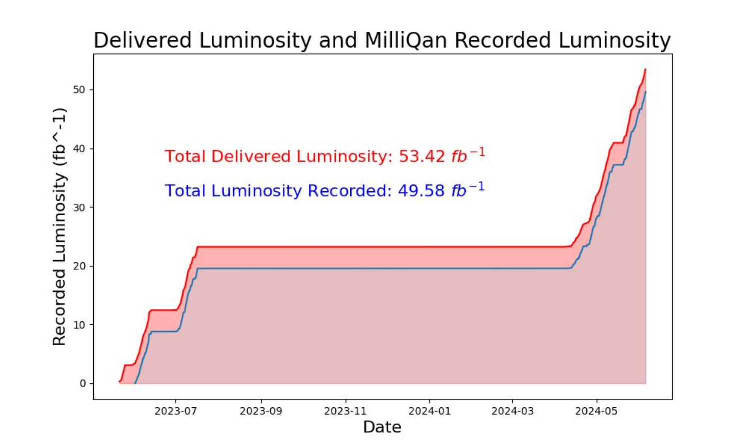
Measuring the tracks of beam muons allows for estimates of detector alignment and angular distributions

Data and Monitoring

- Currently taking physics data since June 2023!
- Web based monitoring and remote to help with remote shifting
- Recorded 50 fb^{-1} of collision data so far from LHC Run 3 and still running!



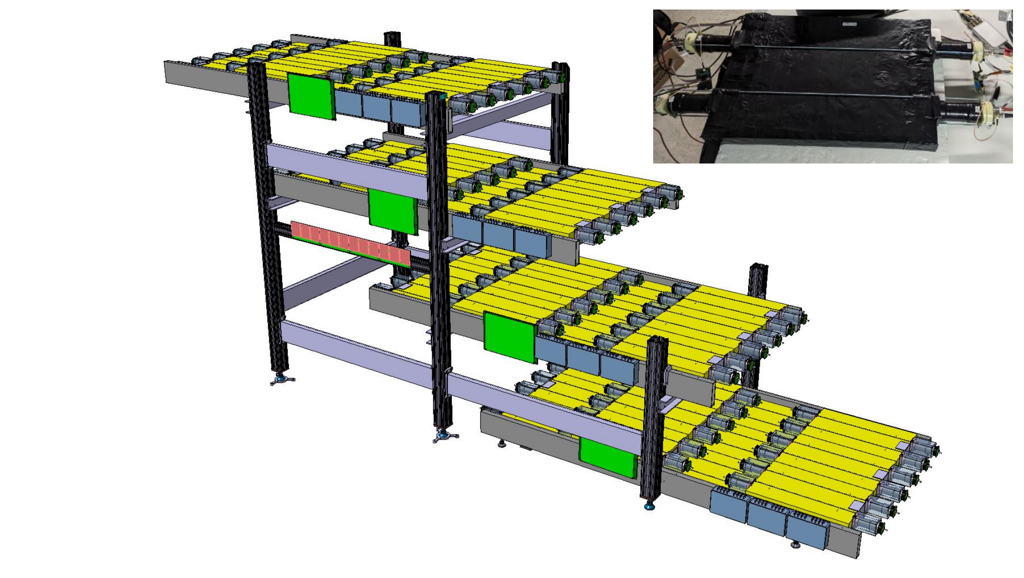
Web-based monitoring system allows for smooth datataking and early diagnosis of any problem



With high luminosity targets for 2024, will exceed 100 fb-1 later this year

Slab Detector Status

- Above 1.4 GeV, mCP production is rarer; acceptance is limiting factor
- “Slab Detector” uses four layers of twelve 40 x 60 x 5 cm plastic scintillator slabs
  - Surface area equivalent to ~1100 5 x 5 cm bars!
- Significantly improves acceptance for Q > ~0.01e



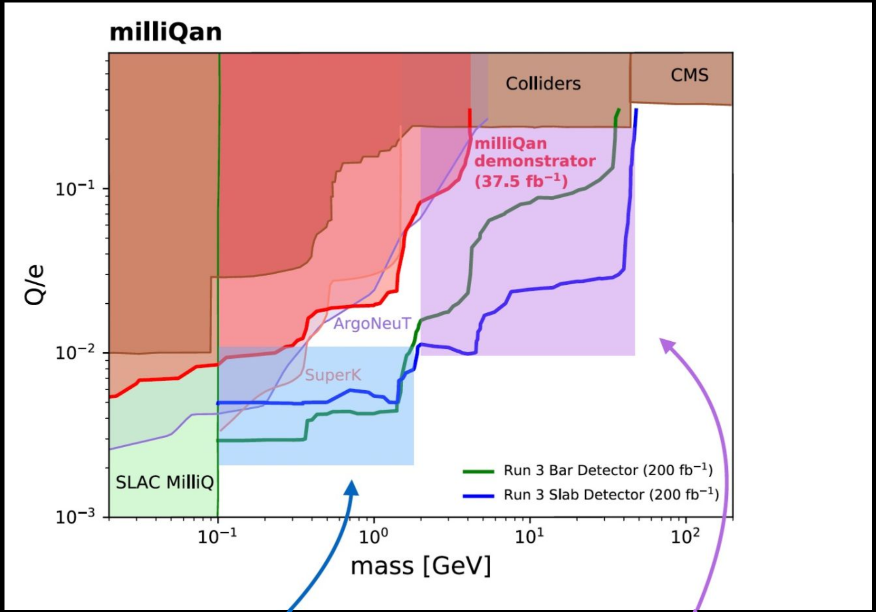
Slab Detector Commissioning

- All slabs calibrated and ready for installation
- DAQ system, ~half of slabs installed
  - Commissioning data already being collected
- Installation of remaining layers happening now!
  - Targeting full installation, physics data by end of June → Very soon!

milliQan Signal Sensitivity

- Bar detector → targets charge limited region
- Slab detector → targets acceptance limited region
- Expected combined sensitivity:
  - Charges ~0.001-0.1 e
  - Masses ~0.1-45 GeV

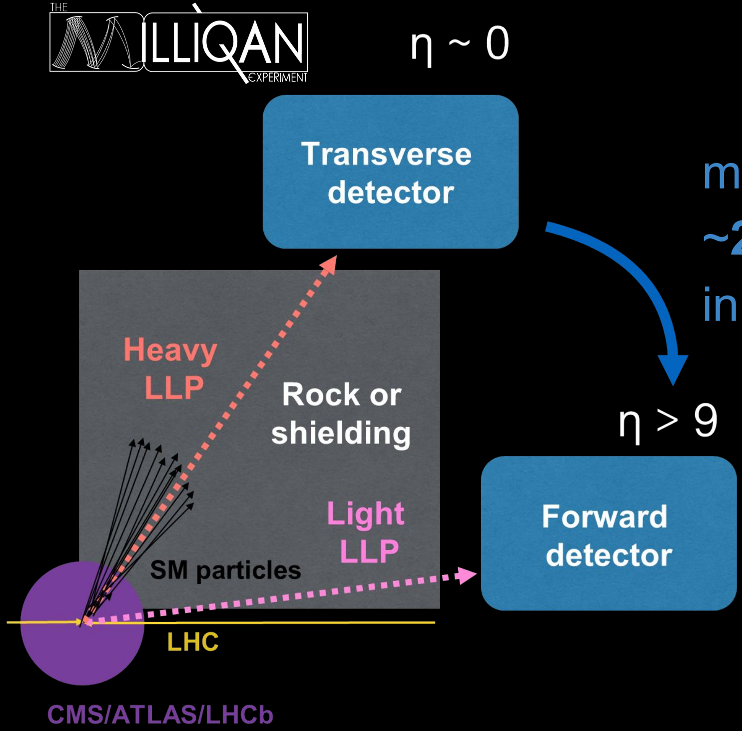
Full projections published in PhysRevD.104.032002



Charge limited region: very high mcp flux but low efficiency

Acceptance limited region: high efficiency but mcp flux is low

What's next?

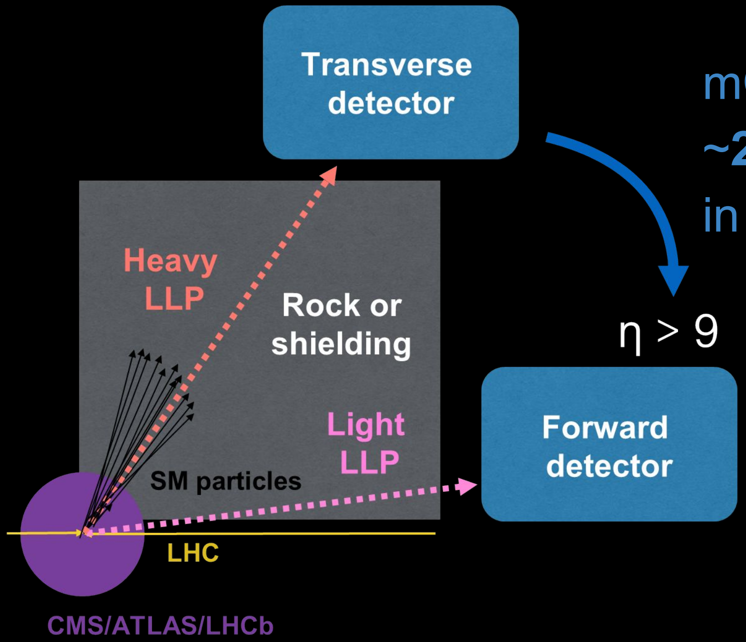


mCP flux over
~250 times larger
in forward region!

What’s next?

THE MILLIQAN EXPERIMENT

$\eta \sim 0$

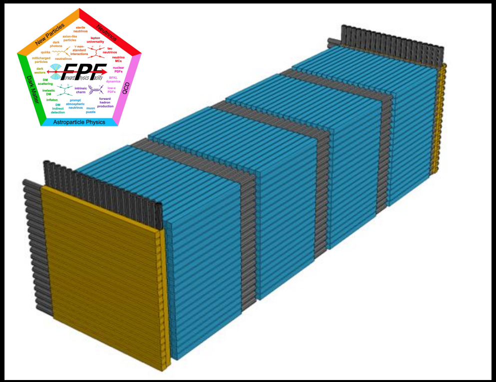


$\eta > 9$

mCP flux over **~250 times larger** in forward region!

FORMOSA

FORMOSA



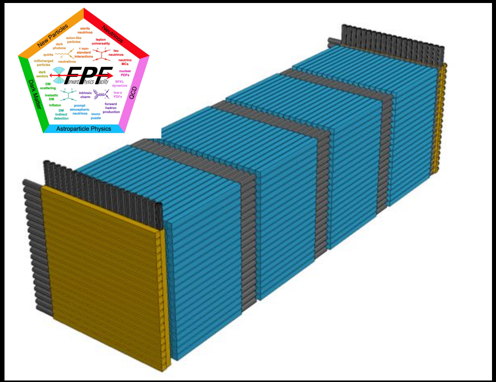
Let’s look **forward** for greatly increased production of light mCPs!

FORMOSA Detectors

- For FPF: Four 20 x 20 layers of scintillating bars coupled with PMTs, pointed to ATLAS IP

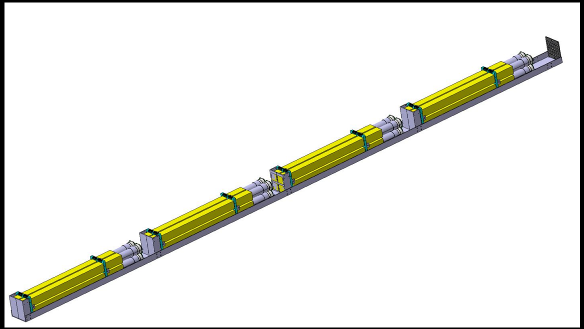
- Segmented beam-muon veto panels on front and back

- **Right now**: “FORMOSA Demonstrator” gives opportunity to prove concept and target new phase space



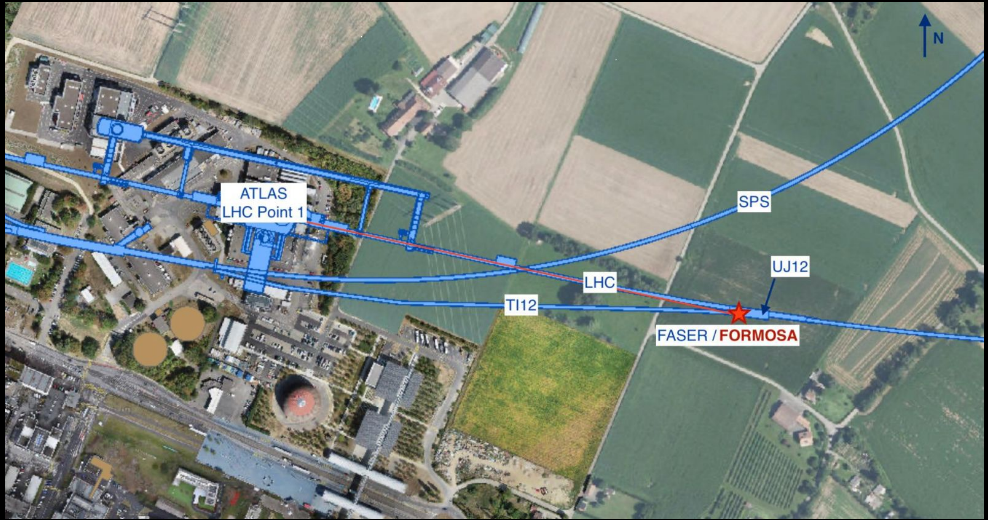
Full detector is a 20x20 array of scintillator bars

Demonstrator is a 2x2 array: a quarter-scale of milliQan



FORMOSA Demonstrator Installation

- Installation completed in early Feb
- LHC tunnel closed for Run 3 operations → Remote running and commissioning ongoing

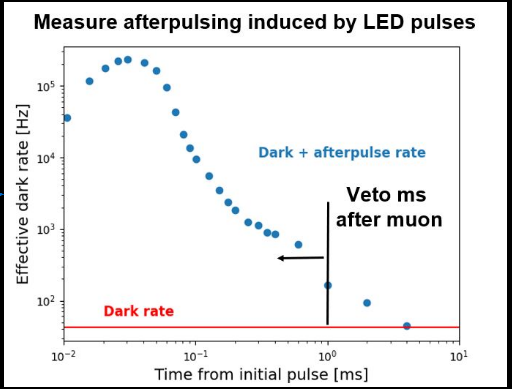


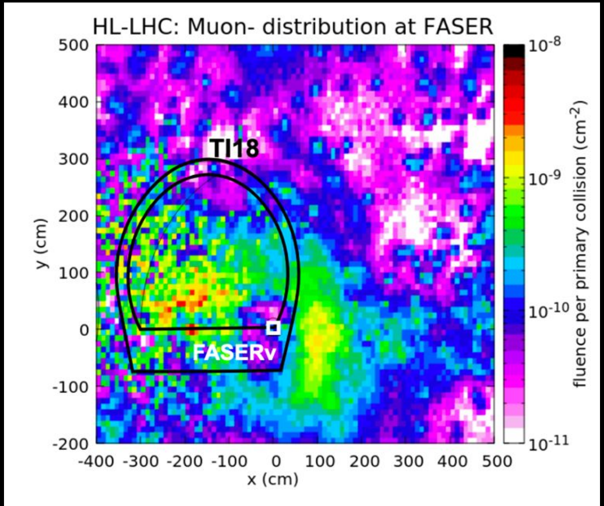
Background

Beam muons are dominant background:

- Through-going flux of ~1 Hz/cm²
- Causes frequent afterpulses
  - Can veto by cutting on time relative to initial pulse

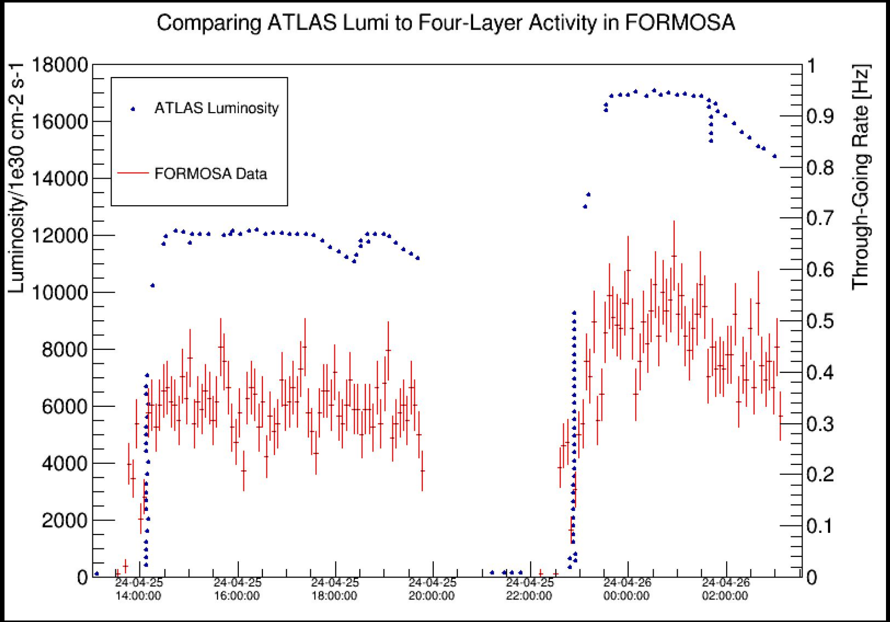
New challenges! Can prove feasibility with demonstrator





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

First look at data

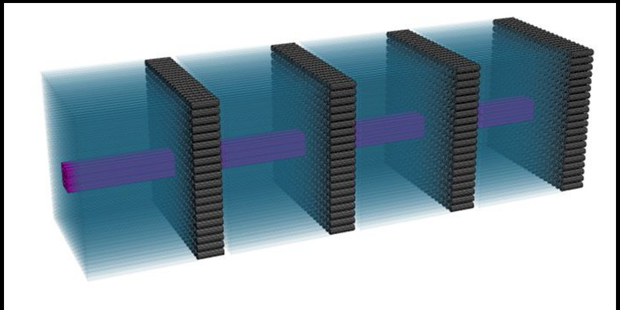


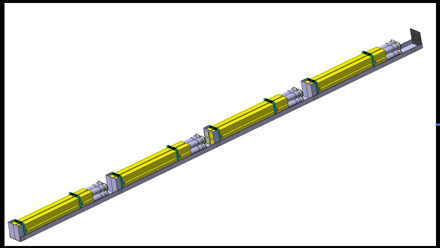
- We see the increased activity in FORMOSA when beam circulates regardless of type
- The 4-layer rate aligns with beam conditions

Looking Forward for FORMOSA

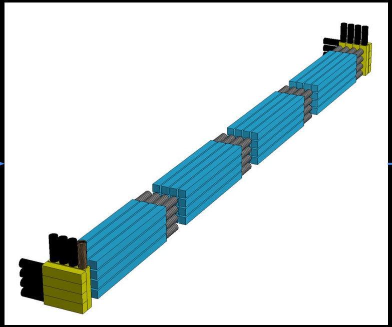
- Expand over time to full size FORMOSA detector
  - Learn from smaller iterations to optimize final form
  - 2x2 → 4x4 → 20x20
- Consider smaller subdetector using CeBr3
  - Provides up to factor of ~4 improvement in low charge sensitivity (below Q/e = 10^{-4}!)

CeBr3

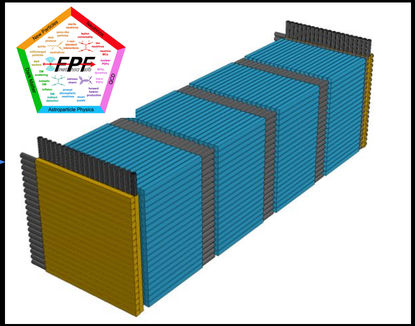




2025



HL-LHC

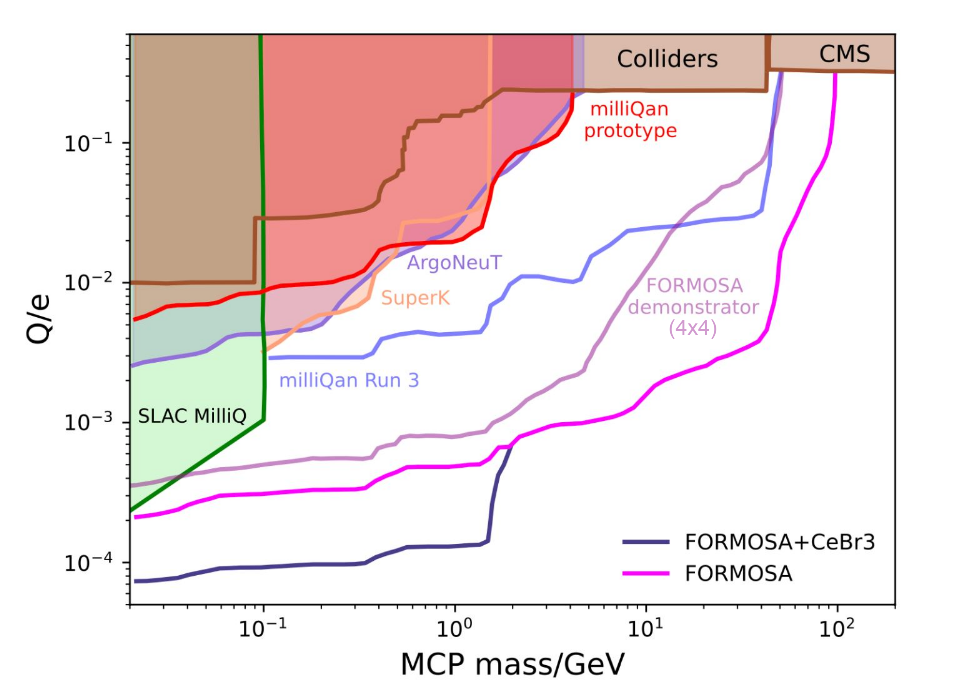


Expected Sensitivity

More details in initial paper:
[PhysRevD.104.035014]

- FORMOSA projections are very promising, even at the demonstrator level
  - Full FORMOSA can reach ~10^{-4} charge!

- Need to prove feasibility to achieve these projections. But much potential!

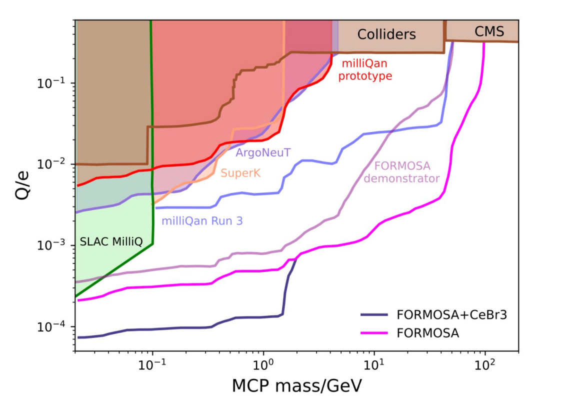


Outlook

- milliQan bar detector is on its way to 100 fb^{-1} of data this year

- milliQan slab detector and FORMOSA demonstrator will achieve first physics data soon

- Complementary approach yields stronger results and leading sensitivity in both the near and far future

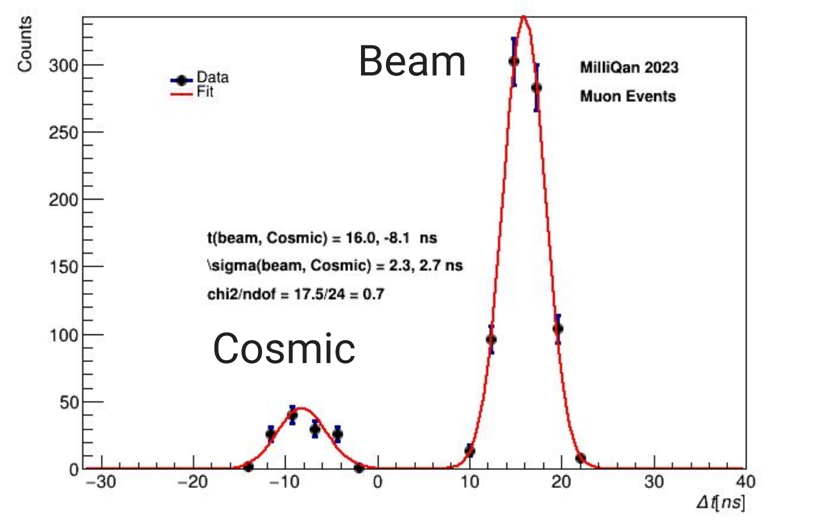


Backups

Beam Muon Validation: Timing Calibration

To study timing performance, we measure the time difference between the first and last layer in beam muon events

We can use this to calibrate the times for each layer and to set the width of the timing window for signal



This plot confirms we can see beam activity! The beam distribution also drops to zero when the beam is off, a good diagnostic tool

Background Prediction

Backgrounds were evaluated using this GEANT4 simulation, calibrated and validated against the four layer demonstrator, using selections motivated by the Run 2 demonstrator search

Together, these requirements reject backgrounds while maximizing signal efficiency

Key features of milliQan signal selections:

Exactly one bar hit per layer, in a line pointing towards the IP

Vetoing on muons + high energy background

Energy deposits consistent with a mCP

Detection timing consistent with a mCP originating from the IP

Cosmic Backgrounds

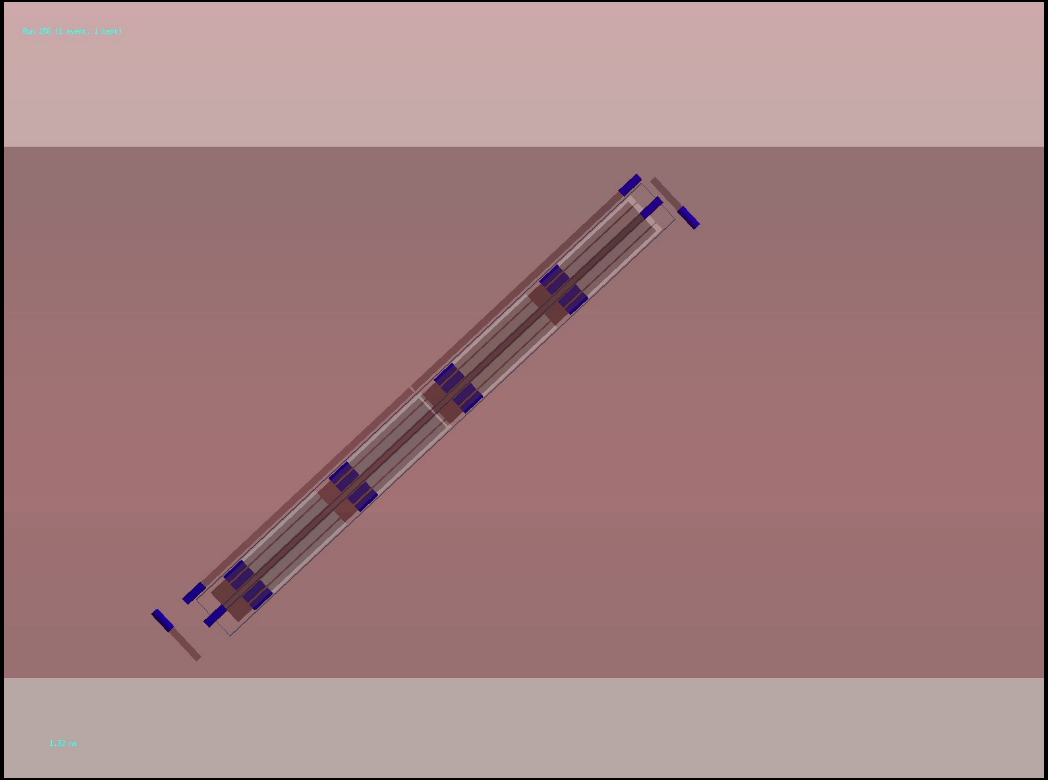
Selection	Run 3
≥ 1 per layer	8.1×10^5
$= 1$ Per Layer	6.0×10^3
Panel Veto	1.1×10^3
Slab Veto	780
Four In Line	0.19
Max n_{pe}/Min $n_{pe} < 10$	0.061
-15 ns $< \Delta t_{max} <$ 15 ns	0.012
Dark Rate	0.05

Cosmic background animation

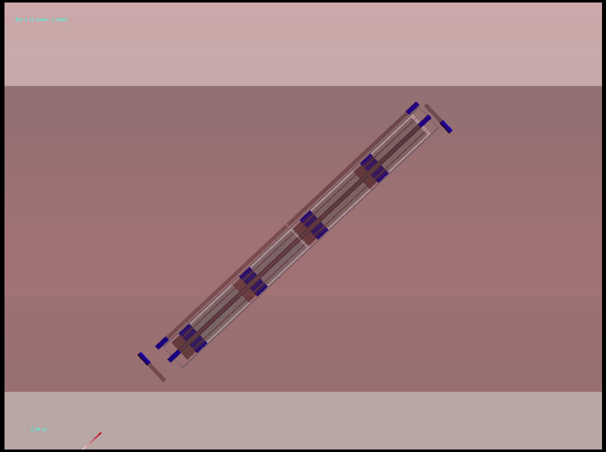
Secondary EM showers from cosmics entering into the cavern generate gammas and electrons

Electrons are vetoed by panels, but gammas can penetrate and possibly look like signal

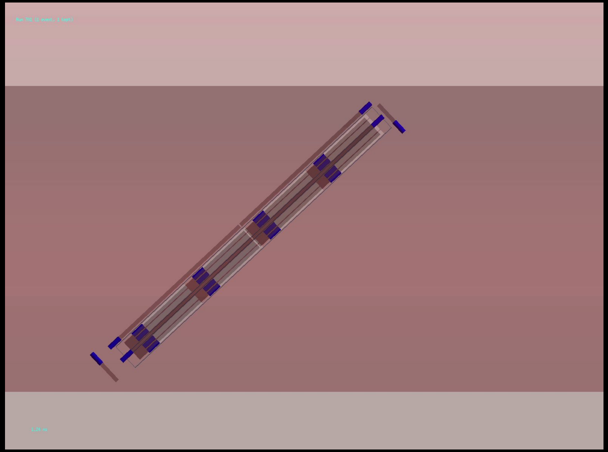
- Selections made cause backgrounds from cosmics to become negligible for bar detector



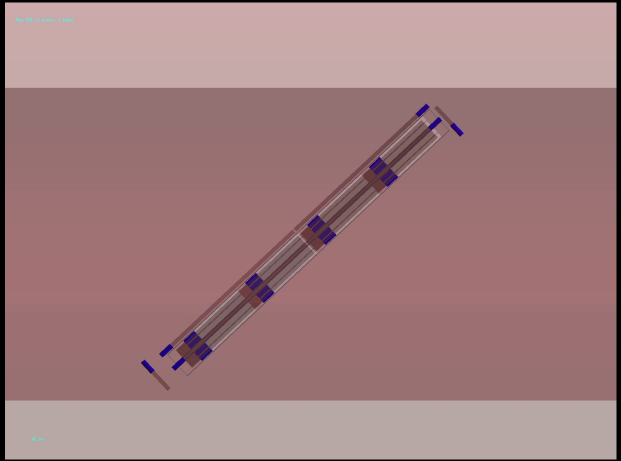
milliQan Simulation Animations



Beam muon

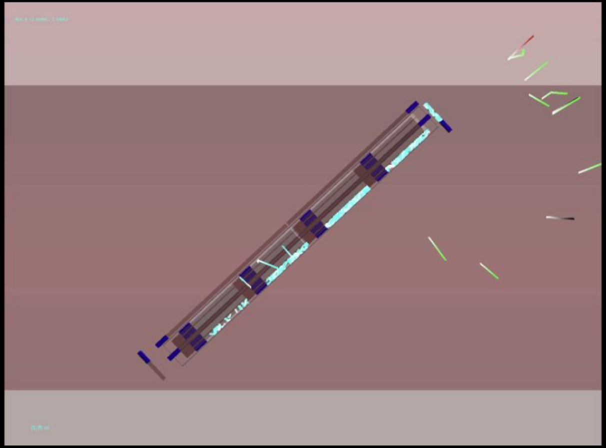


Cosmic shower

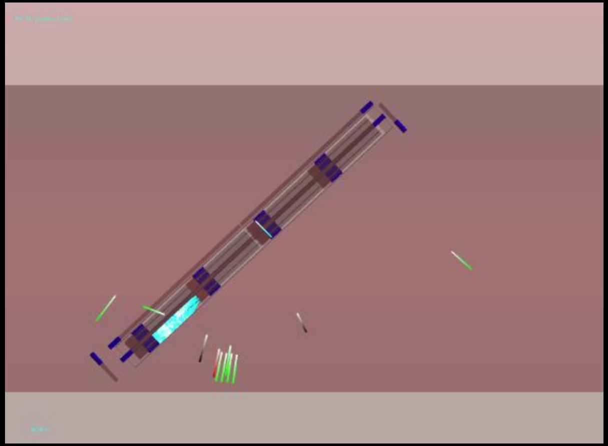


mCP (q=0.01e)

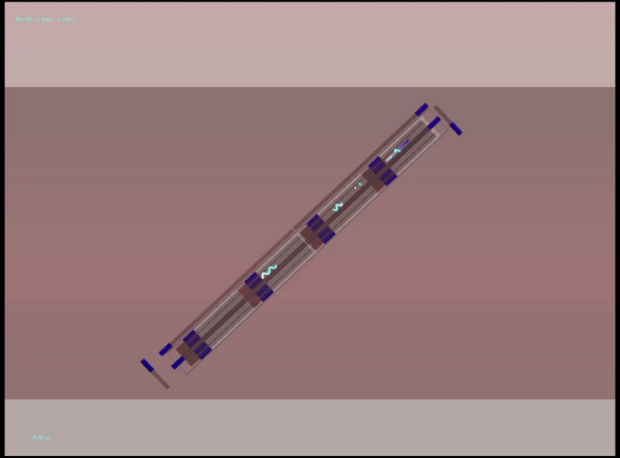
milliQan Simulation Images



Beam muon



Cosmic shower

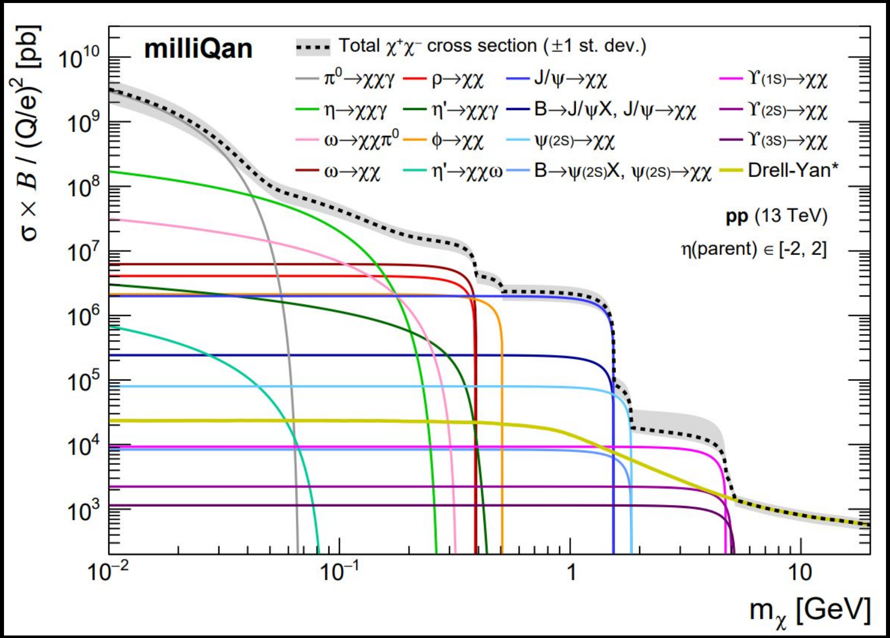


mCP (q=0.01e)

Limits on the phase space of mCPs

So, we'd like to look for millicharged particles (mCPs). **How are they produced?**

Every process that produces dilepton pairs (like two electrons, or two muons) can produce mCPs for the same reasons that cause mCPs have small charge



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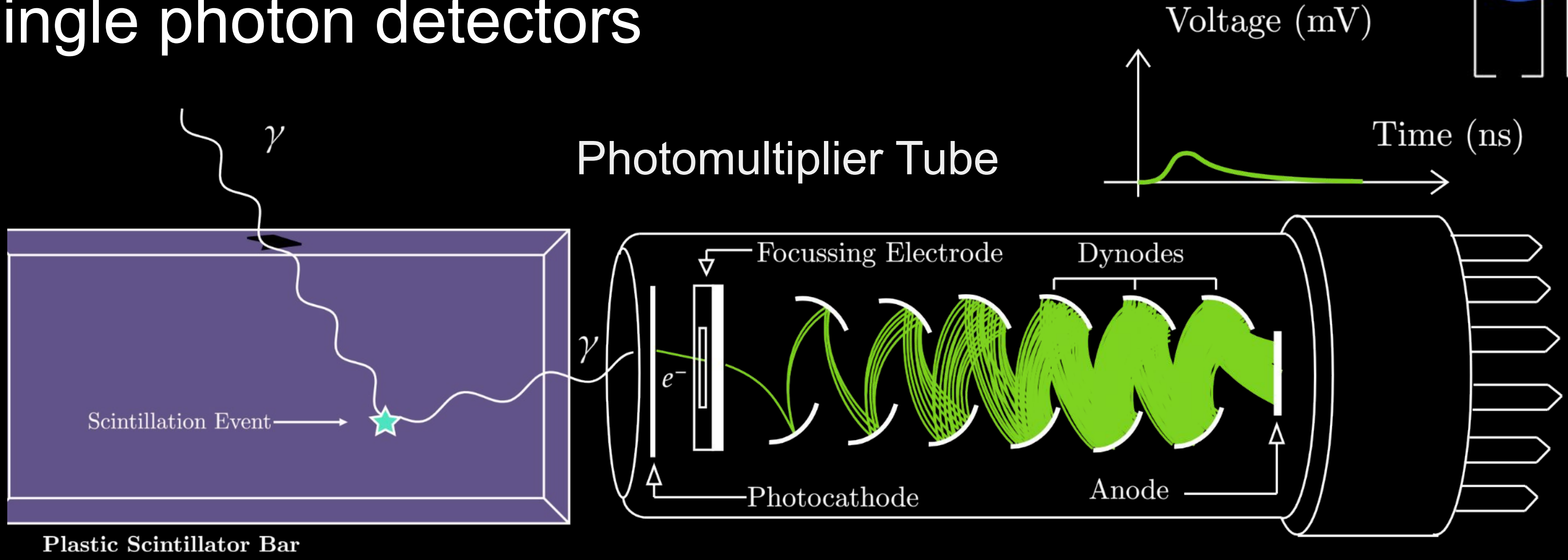
Single photon detectors



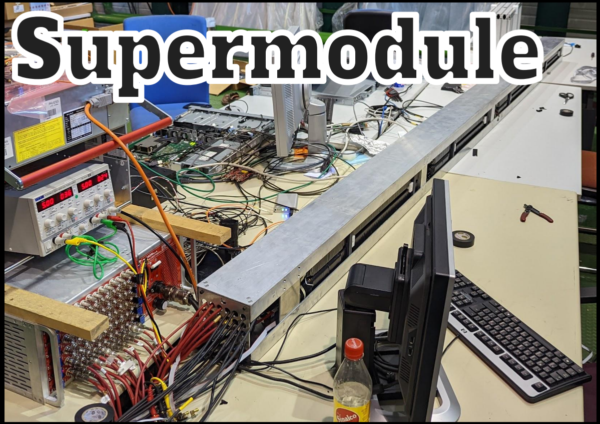
When scintillation photons strike a photomultiplier tube (PMT), the a process called the photoelectric effect absorbs the photon and emits an electron

The PMT has internal plates that are charged to a high voltage (1.5kV in milliQan). The electron accelerates to a plate, strikes it, and that collision ejects a few more electrons. The process is then repeated until a huge current arrives at the end of the tube. **This way, we detect single photons!**

Detector construction process

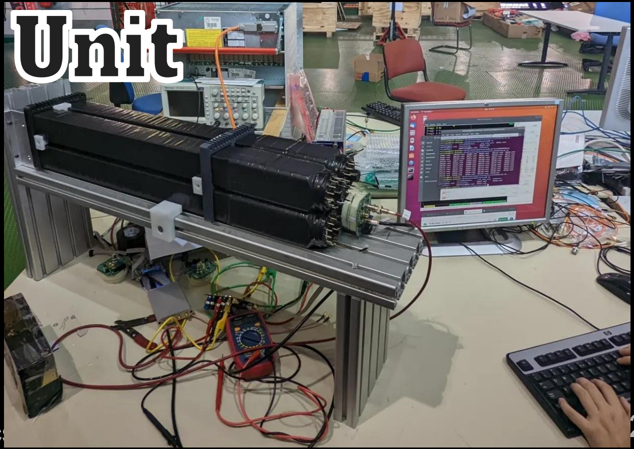
- 4 units make one supermodule, which is then re-tested.

x4



- 4 supermodules are placed into a structure, and make up the core of the detector

x4



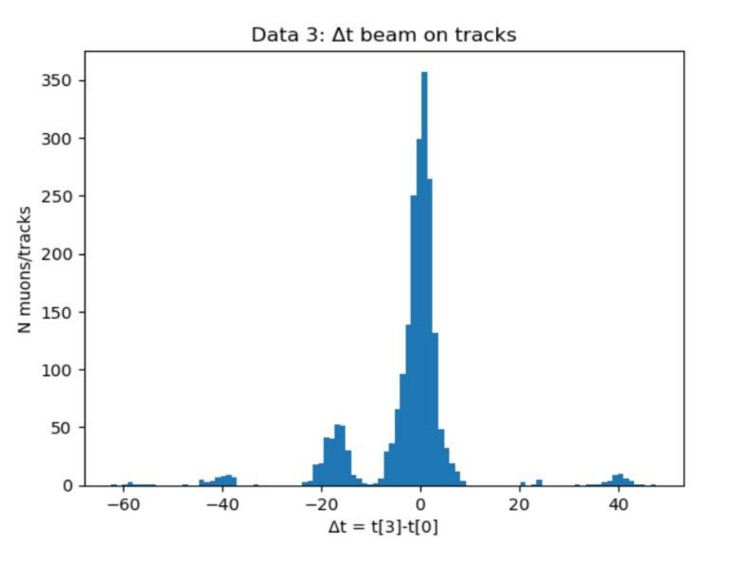
- 4 bars make one unit, which is then re-tested.

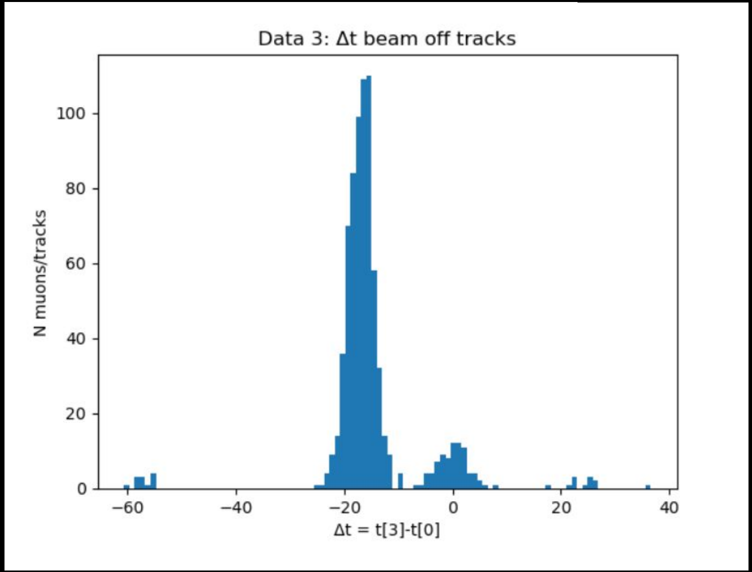
x4

Detector

- Extra shielding to block out cosmic ray backgrounds are added to the sides. Completed detector!

Beam on vs beam off, muon timing

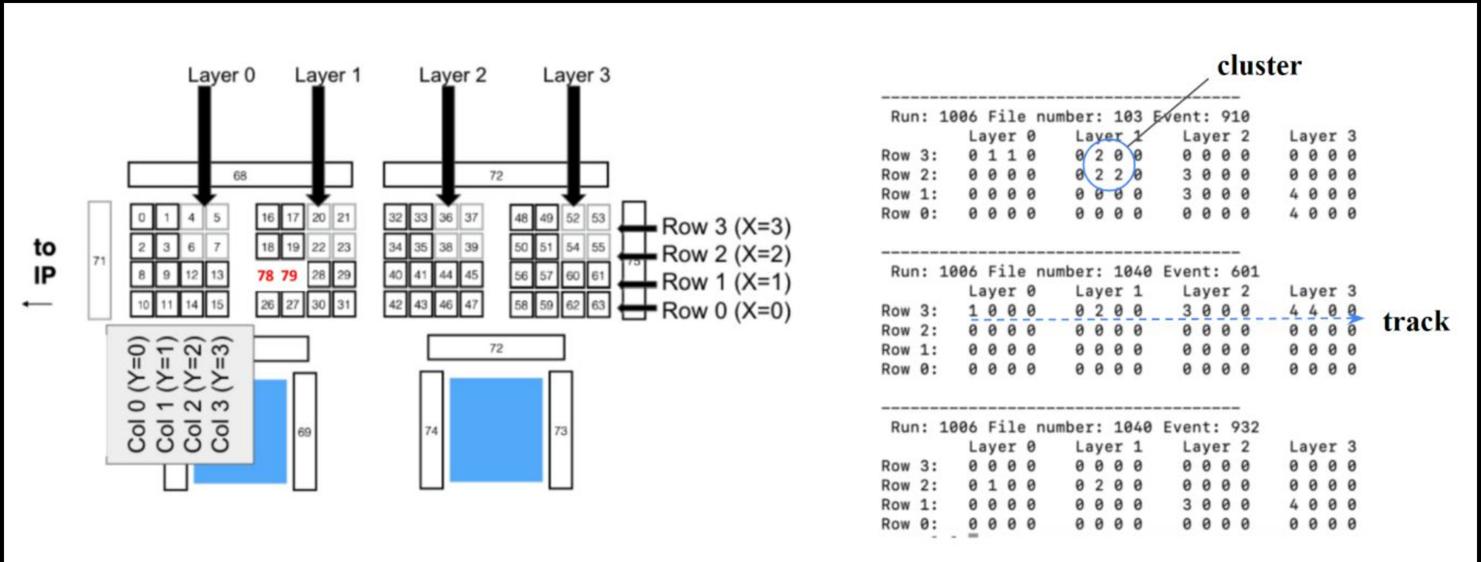




We can see beam muons appear with calibrated timing around zero when beam is on, and near -20 when the beam is off. So, we're seeing beam activity! This particular plot has a bug shifting some values by +/-30 ns, causing other clusters further out. The beam off sample may also have slight beam contamination

Muon Tracking Methodology

Track: a cluster at each of the detector's 4 layers, the centroid of which cannot move by more than one unit (in x and y direction)

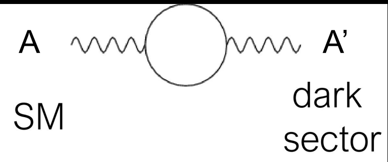


Why millicharged particles?

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 $\bar{\psi}'\kappa e'\gamma^\mu B_\mu \psi'$
- **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**