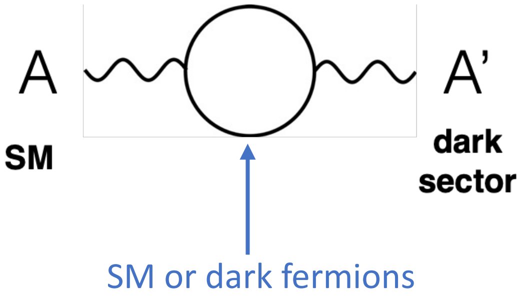
Looking forward to millicharged particles at the LHC

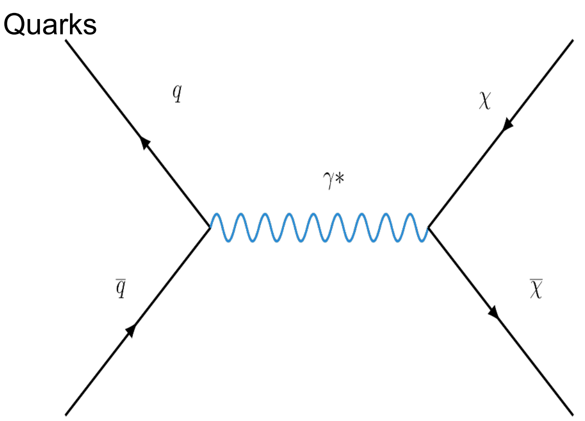
Jacob Steenis on behalf of the
FORMOSA Collaboration

What is compelling about mCPs?

- Currently no satisfying explanation for charge quantization…
  - No monopole discovery…
  - …charge could be **percentages** of e
  - (Hence "milli"-charged particle)

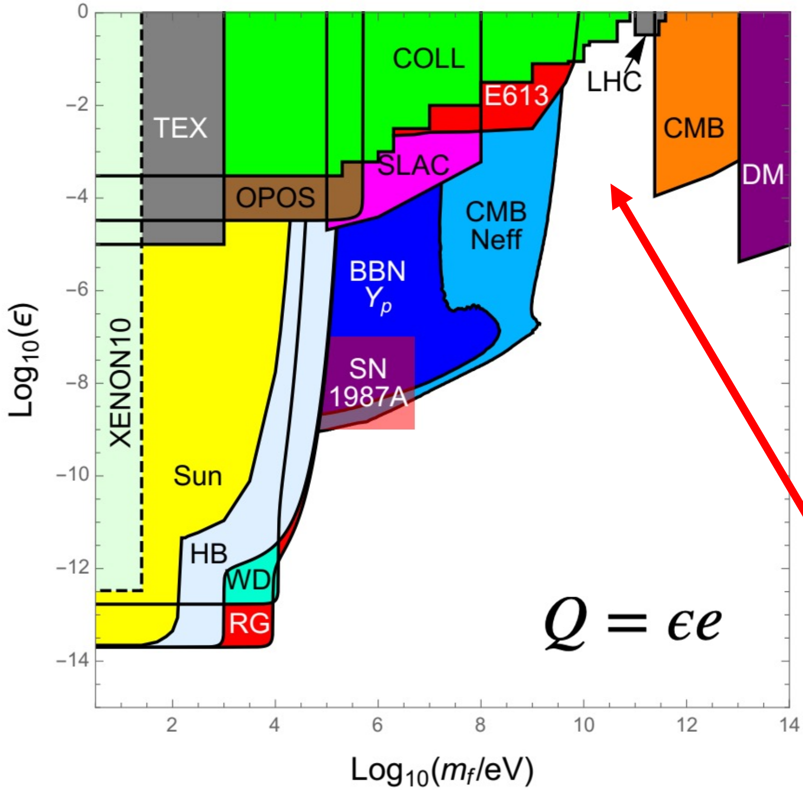


- mCPs arise in **dark photon theories**
  - Small kinetic mixing with SM photon gives dark sector fermions a "milli"-charge
  - Creates mechanism for communicating with dark sector



A phase space need…

arXiv:1511.01122



Potential sources of mCPs

- accelerators
  - Fixed-target collisions
  - **LHC collisions**
- reactors
- stars

Current LHC experiments lack substantial sensitivity to mCPs.

- **mCPs sail through matter easily due to small charge!**
- Limited to Q > 0.1e

Dedicated detectors are needed!

- Current: MilliQan (central region)
- Proposed: FORMOSA (forward region)

How can we detect millicharged particles?

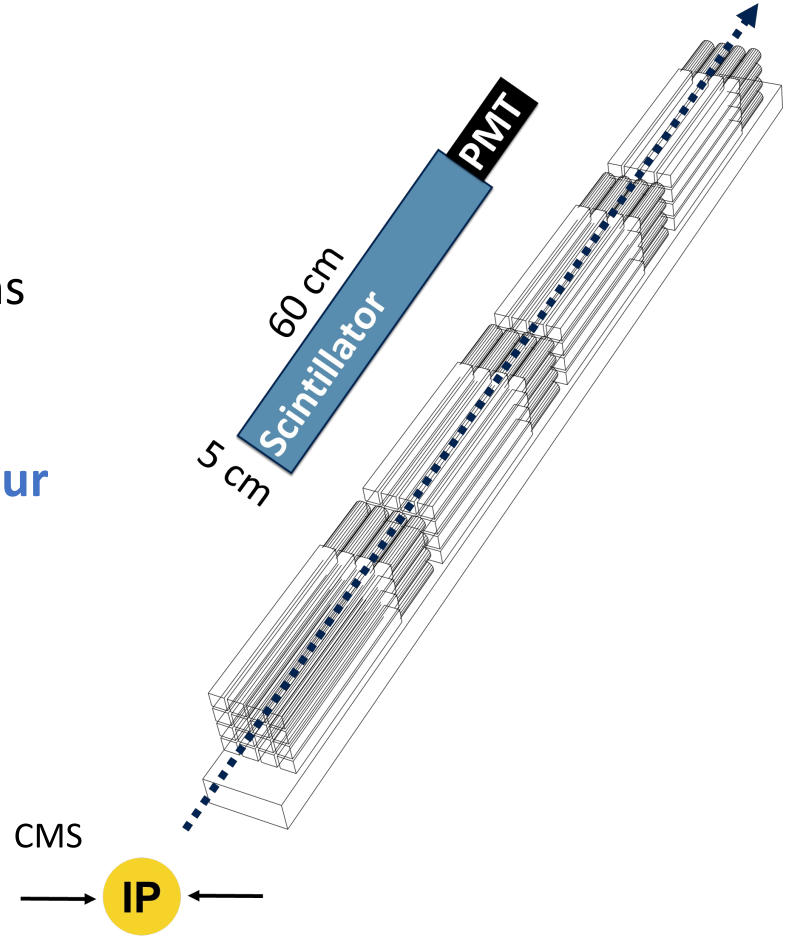
Follow the example of **MilliQan**!

Design requirements

- PMTs must be sensitive to single photons
- Need a substantial scintillation volume

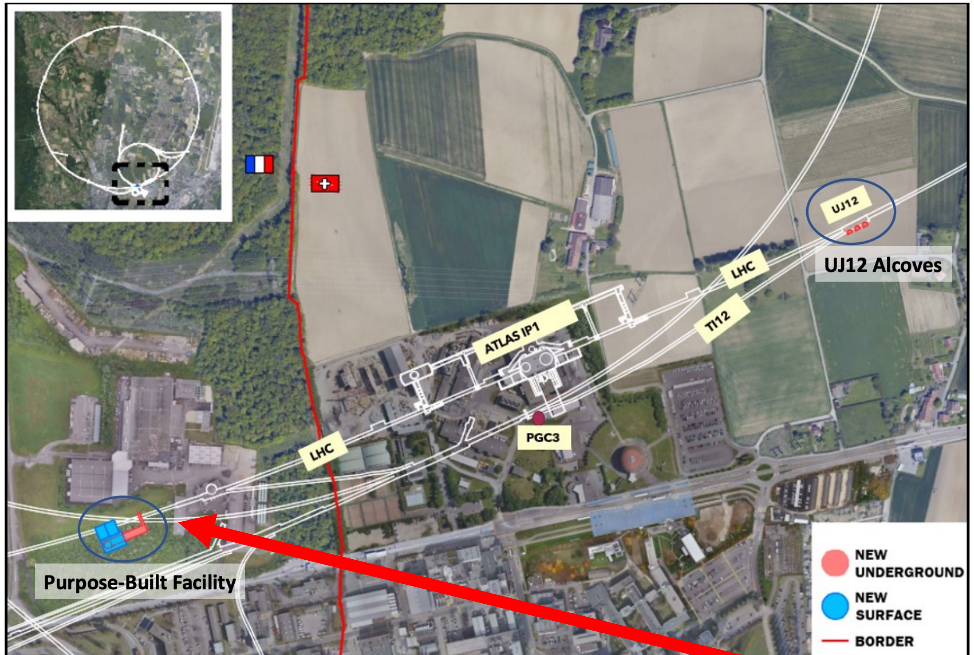
Expected signal is low-energy deposits in all four layers

- Requiring four layers hit within a small time-window makes uncorrelated backgrounds negligible



The FORMOSA Detector

~600m away from ATLAS

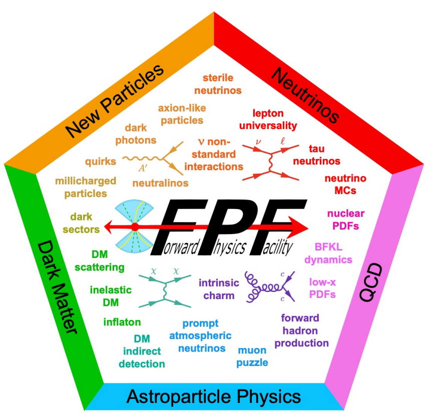


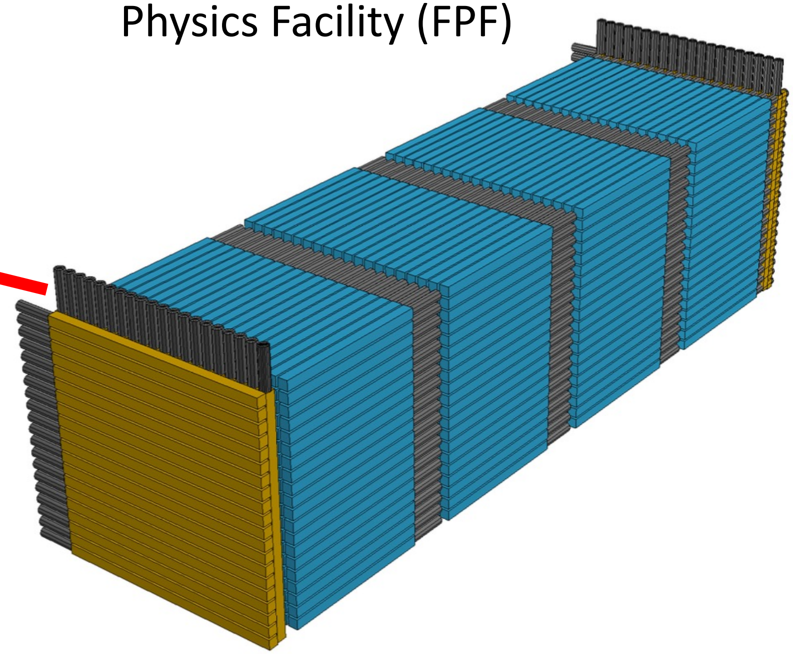
There's **~250x increase in production** rate in forward region relative to central region

- GeV-scale (and below) mCPs are produced evenly in pseudorapidity

FORMOSA is a proposed MilliQan-like detector **suitable for any location in the forward region**.

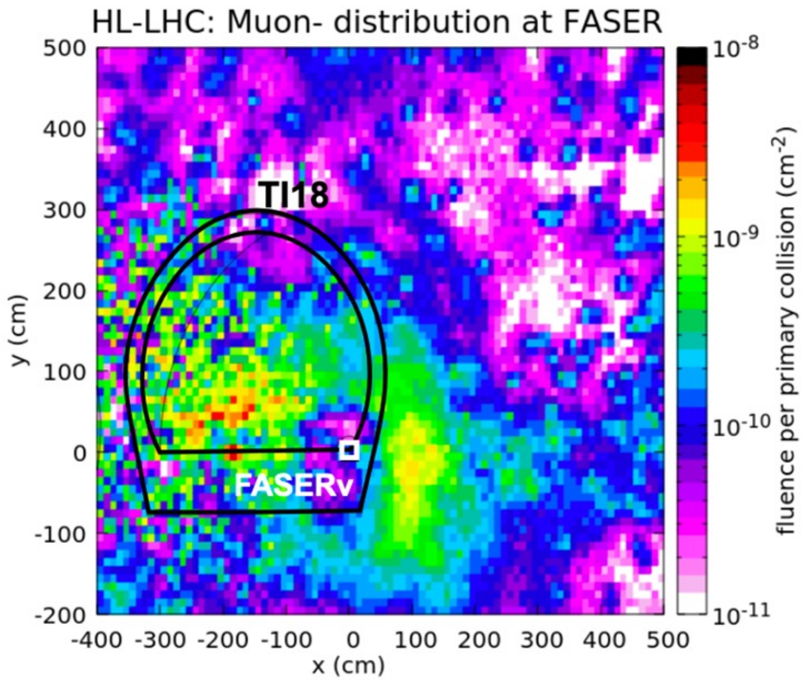
- Such as the proposed Forward Physics Facility (FPF)



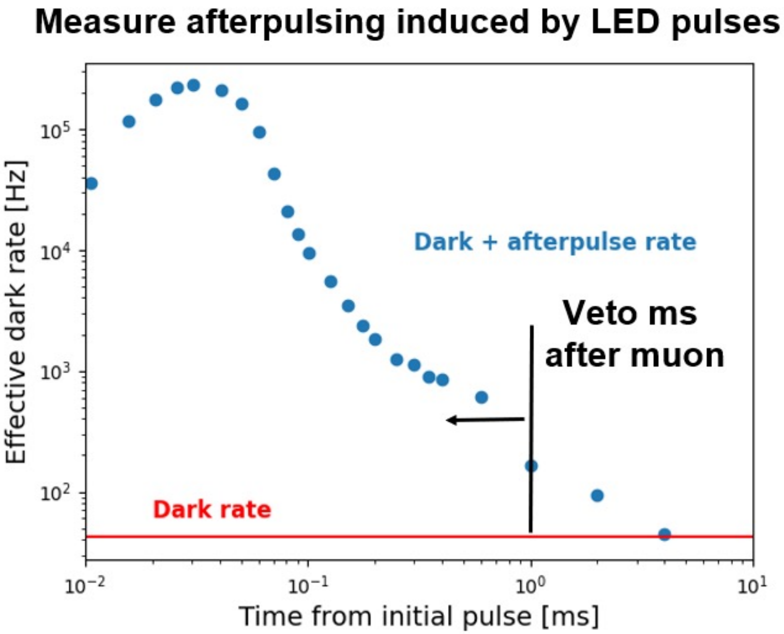


Targeted Background -- Afterpulsing

Muons generated at ATLAS

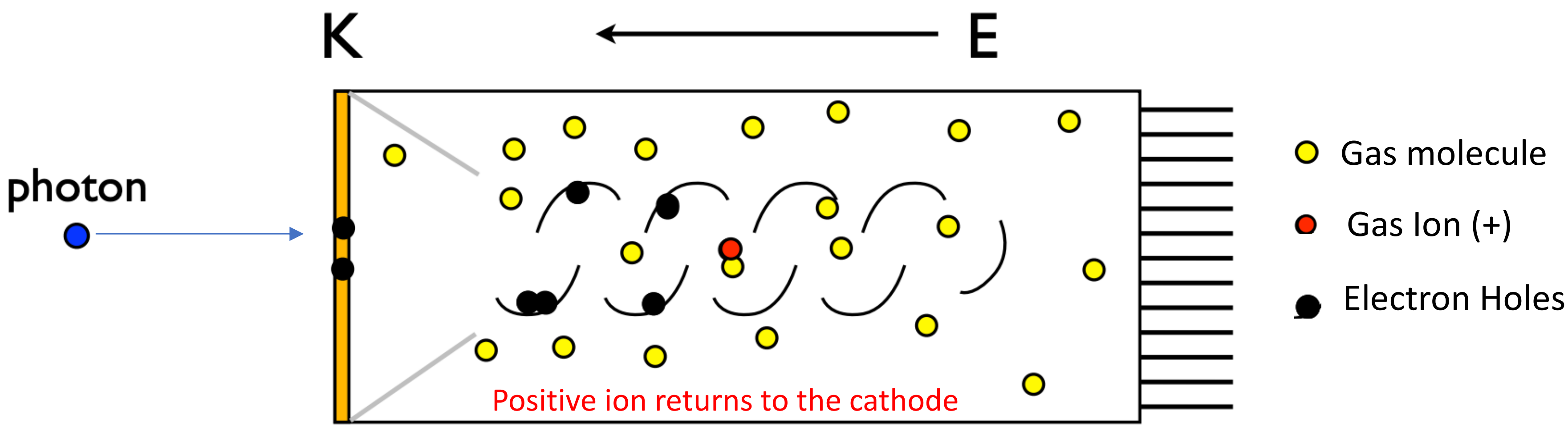


Afterpulsing in PMTs



The goal of the FORMOSA demonstrator is to demonstrate
we can eliminate the afterpulsing background!

Partners in crime: muons and afterpulsing



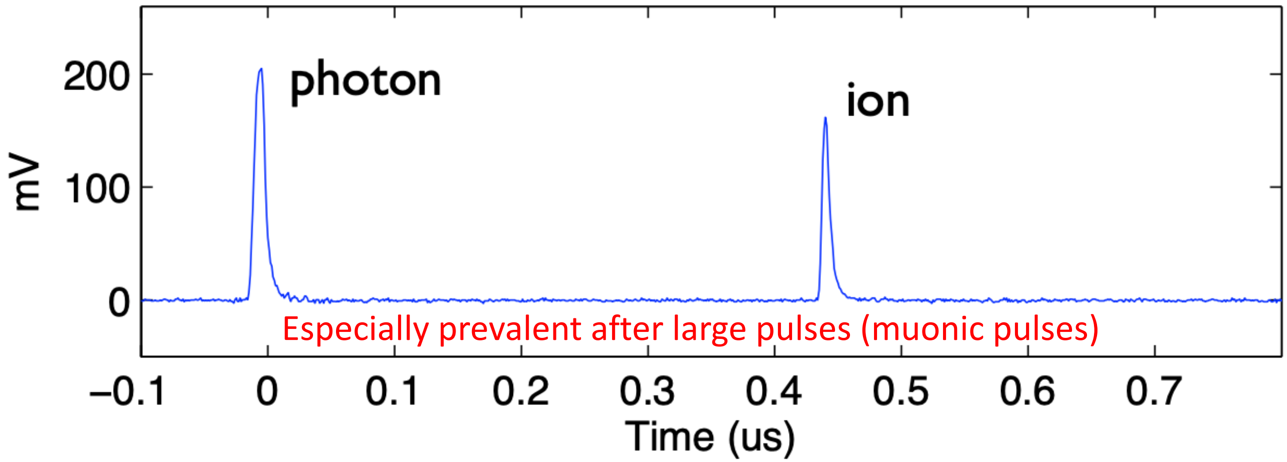
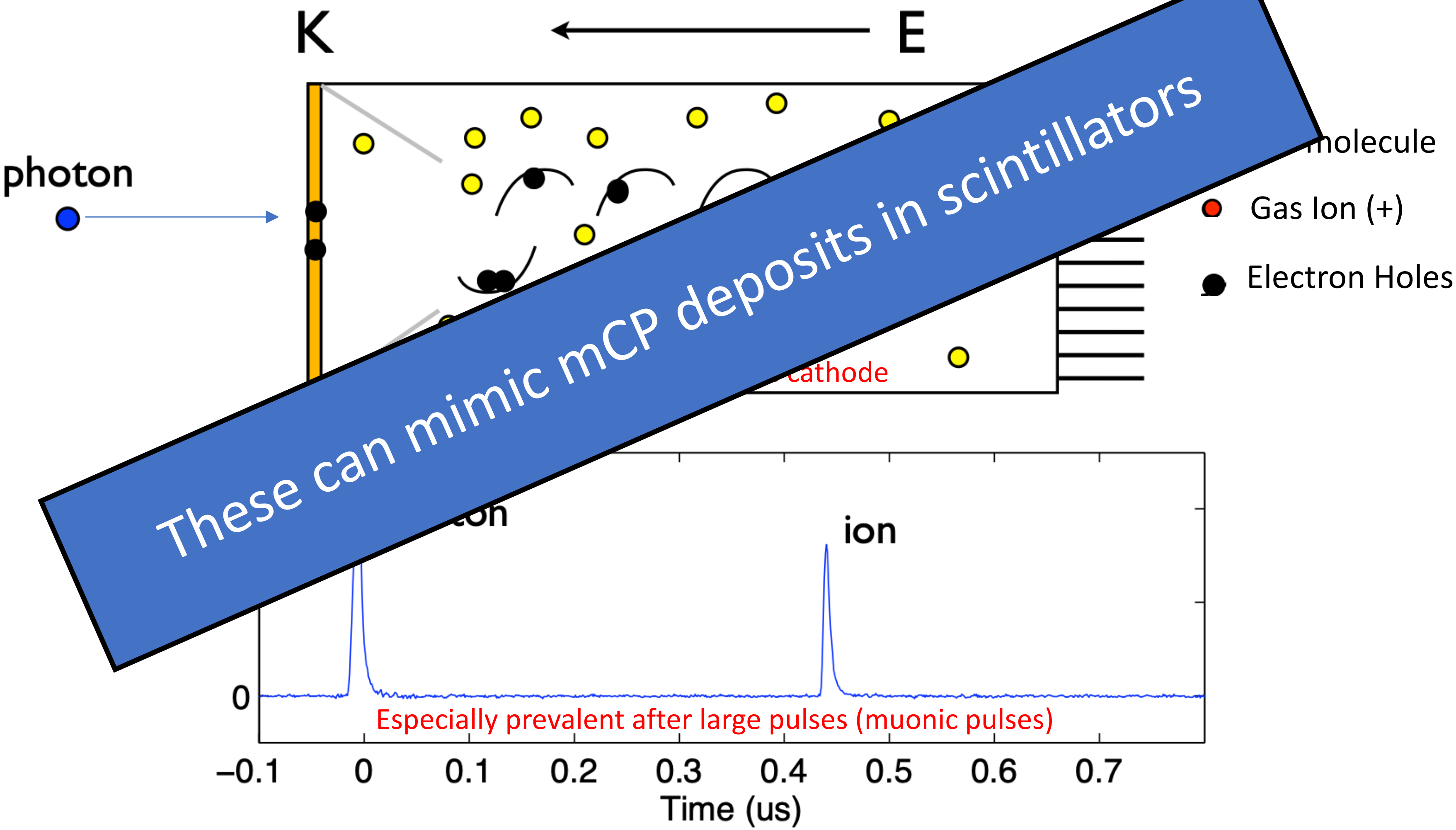


Diagram and plot: Carlos Hernandez Faham

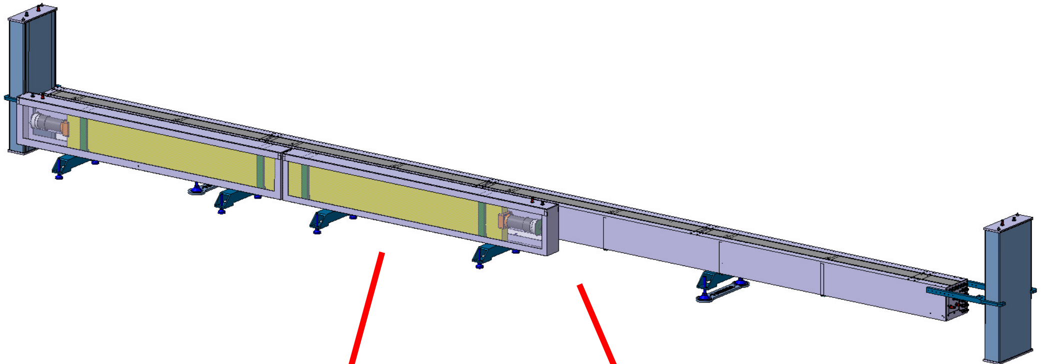
Partners in crime: muons and afterpulsing



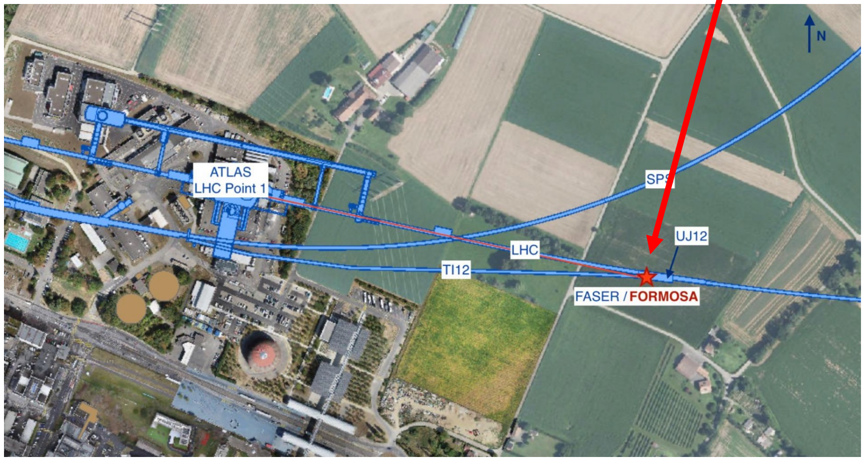
These can mimic mCP deposits in scintillators

Diagram and plot: [Carlos Hernandez Faham]

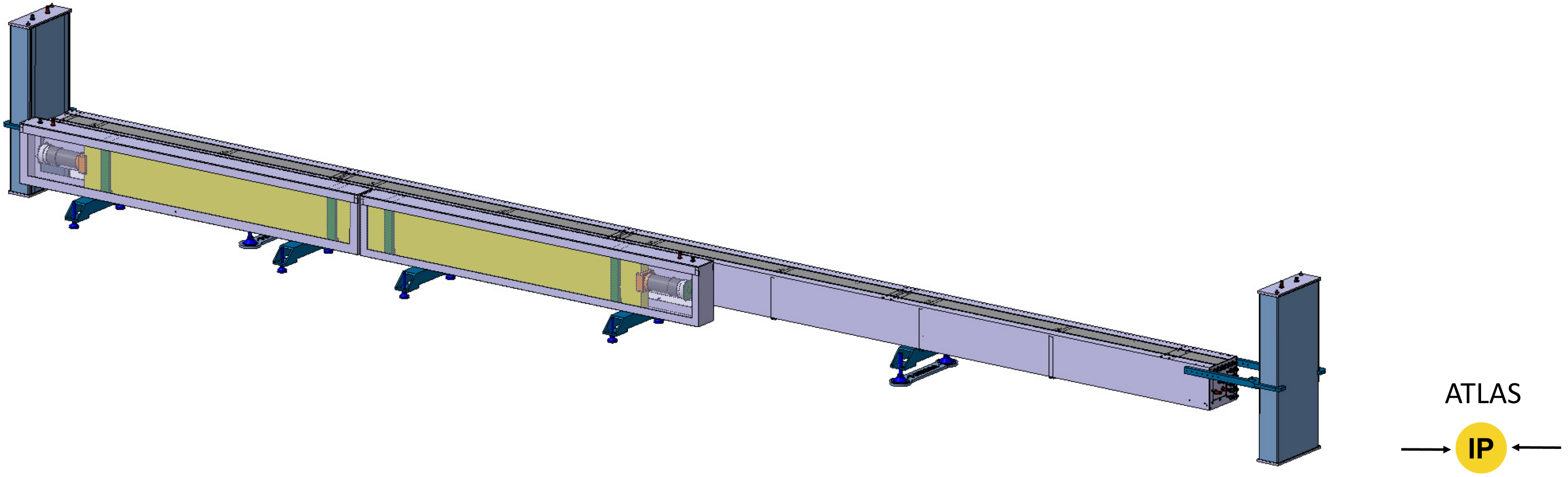
The FORMOSA Demonstrator



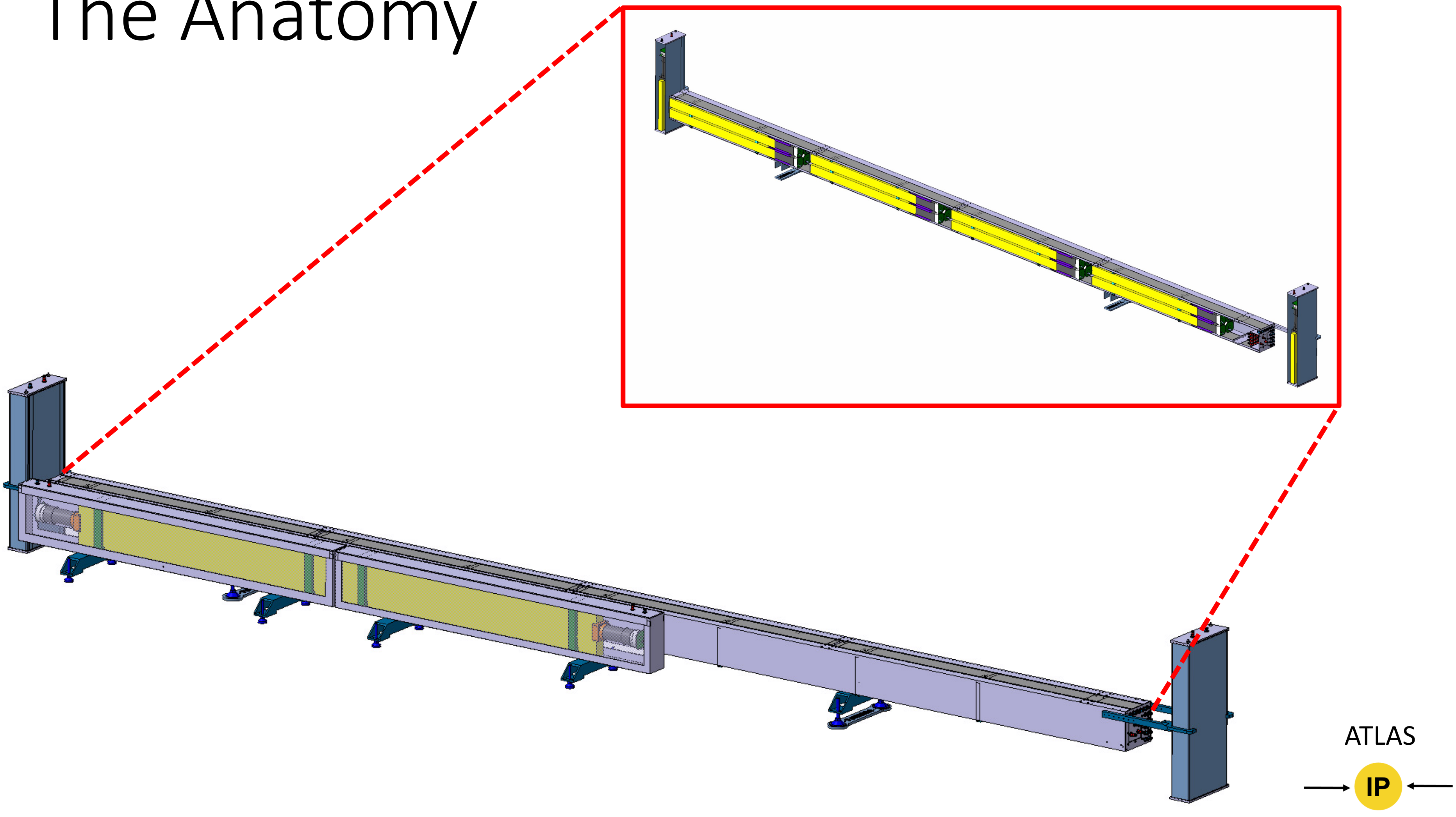
Forward region of ATLAS, ~600m away.



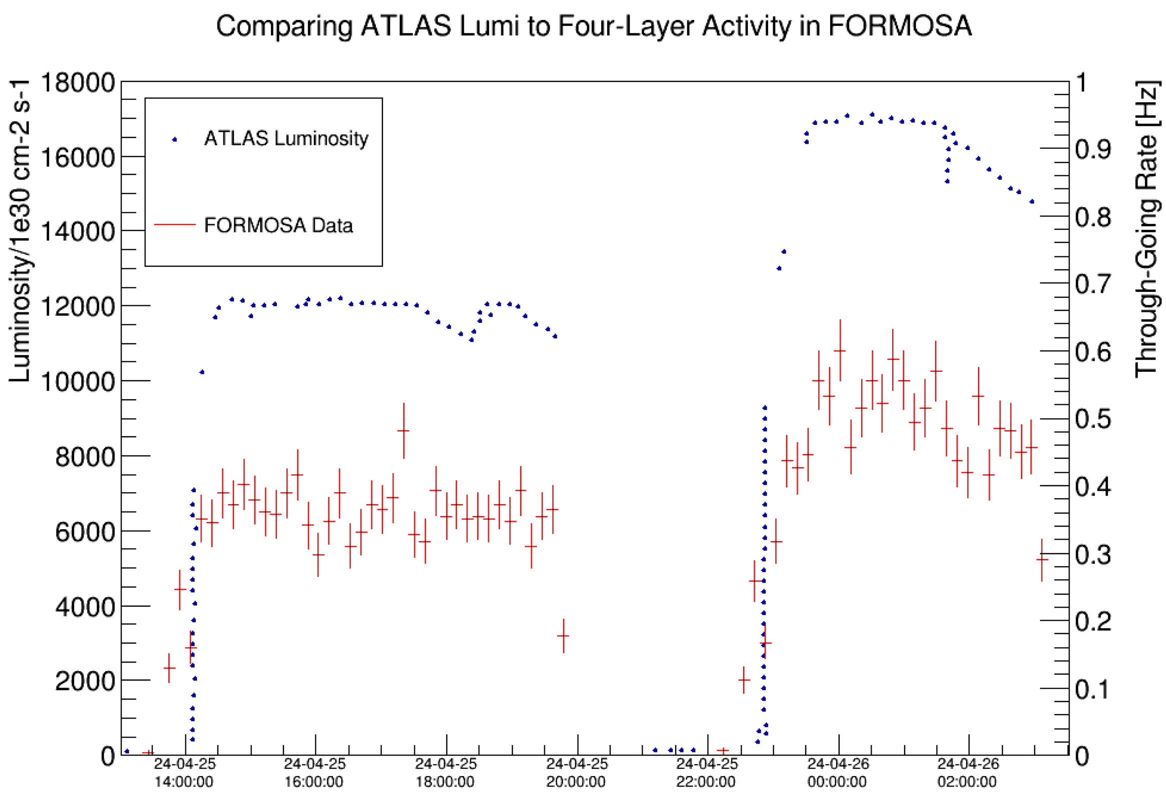
The Anatomy



The Anatomy



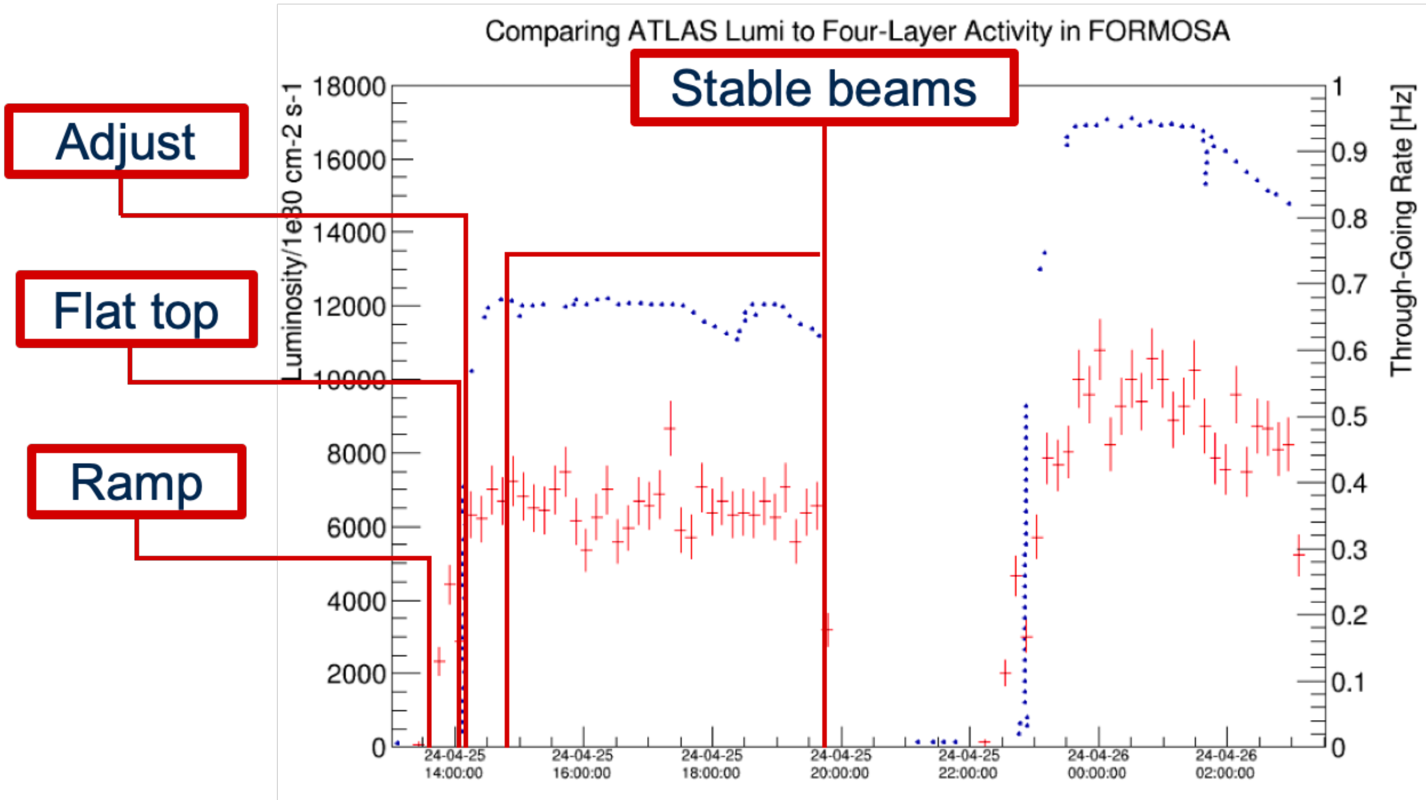
First look at data



We can select through-going activity (4 layers hit) in FORMOSA which aligns with ATLAS luminosity!

- Rate prescaled by ~1/500
- This offline plot roughly corresponds to expected muon rates

First look at data



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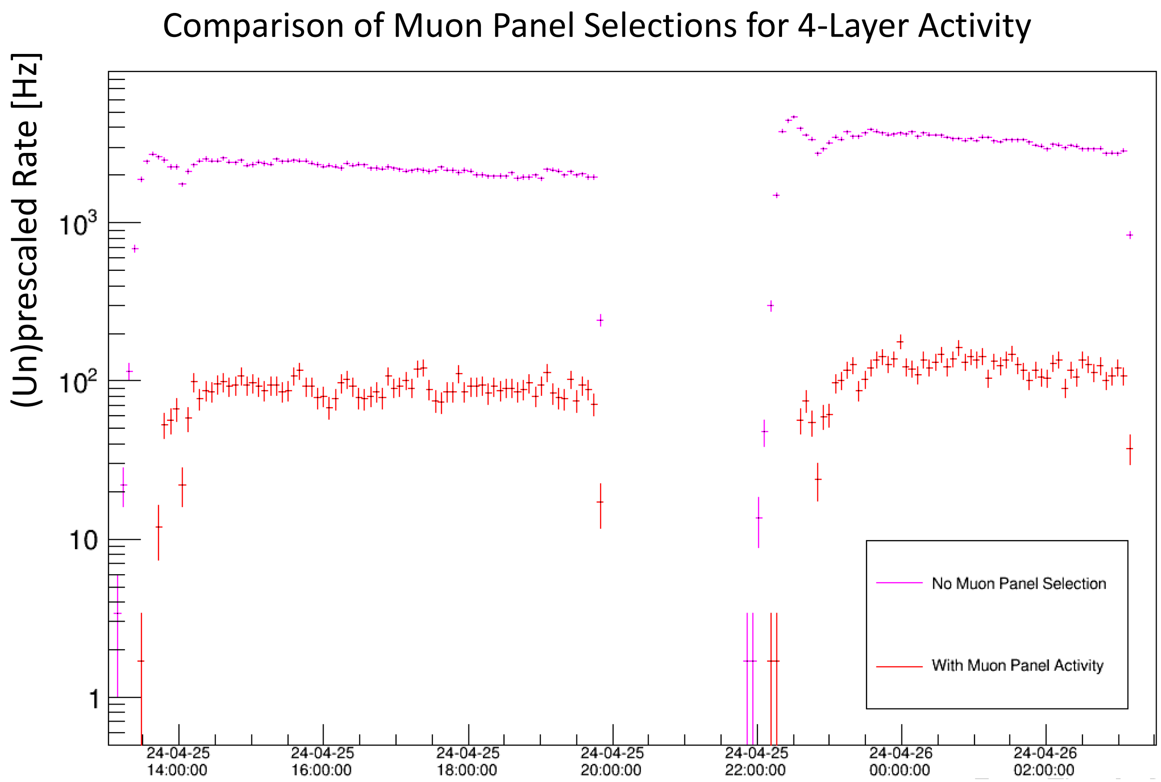
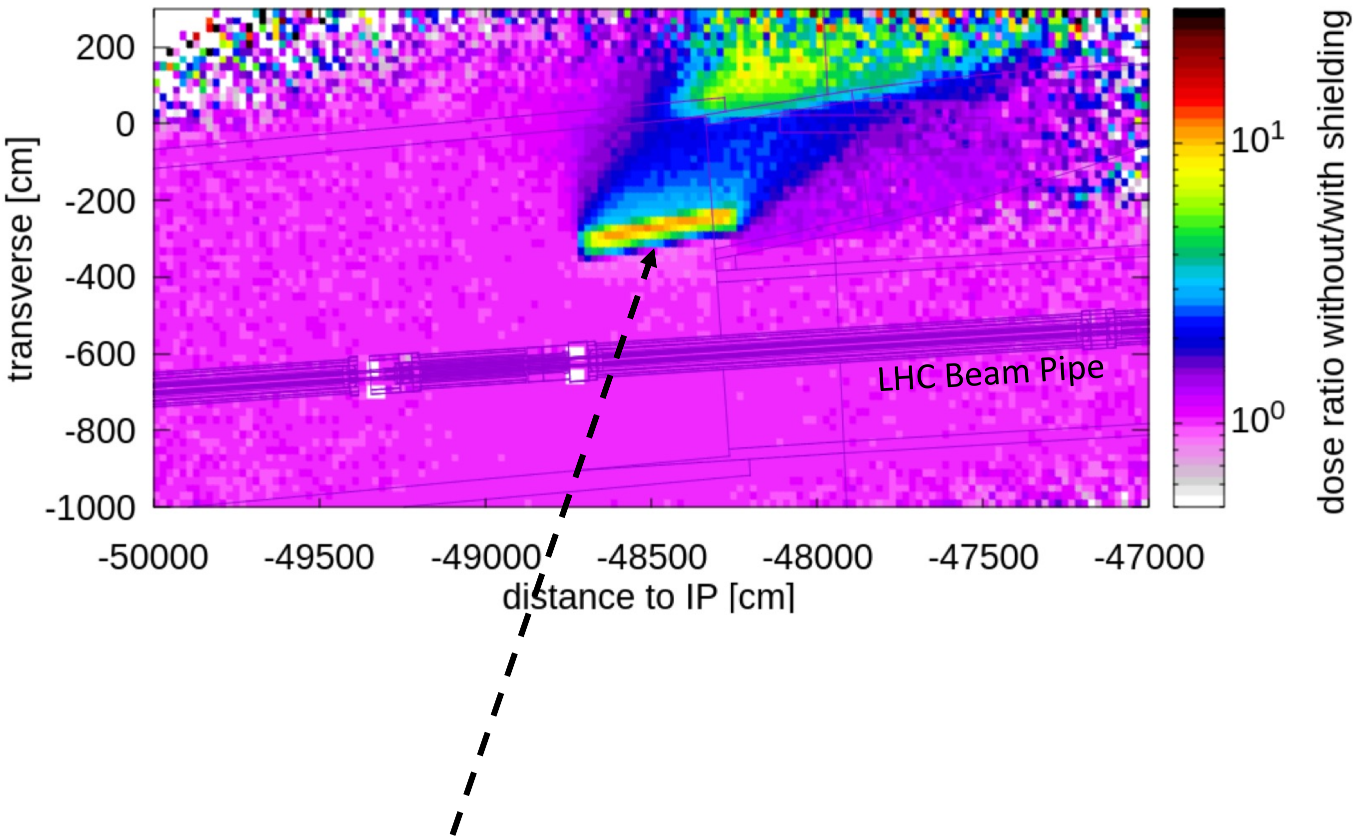


If we remove offline cuts on the muon panels, it's clear that the un-prescaled rates can get very high

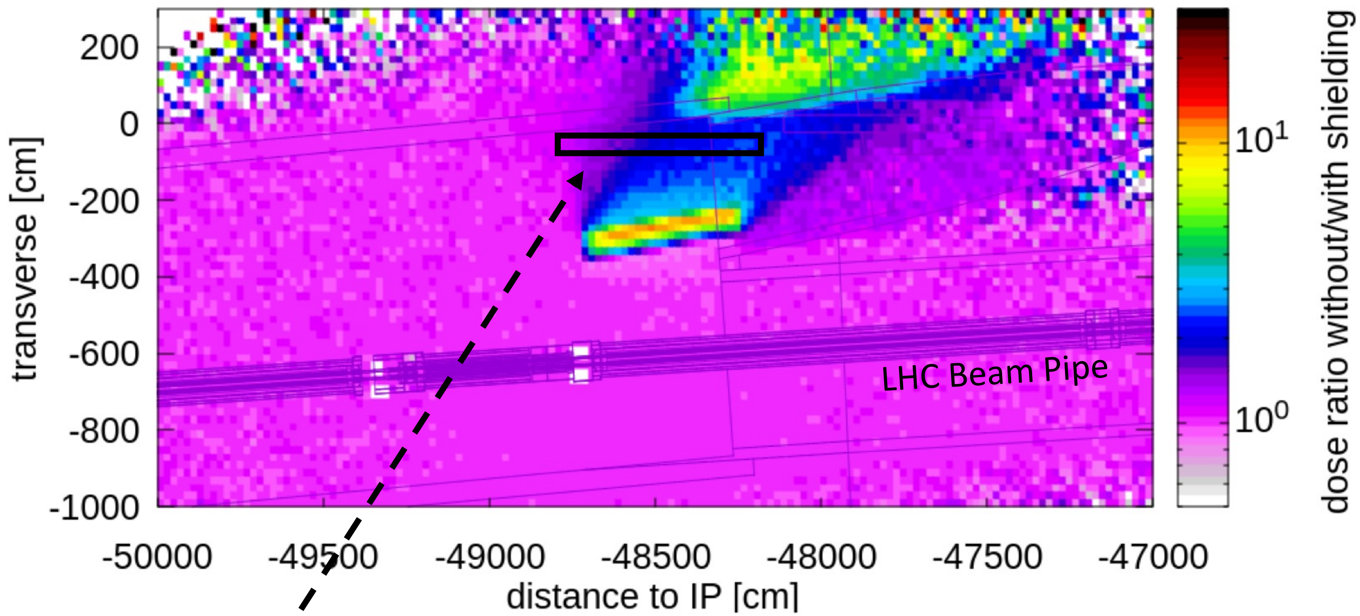
- **We need to study beam-related backgrounds**

Beam-related background



Concrete shielding

Beam-related background

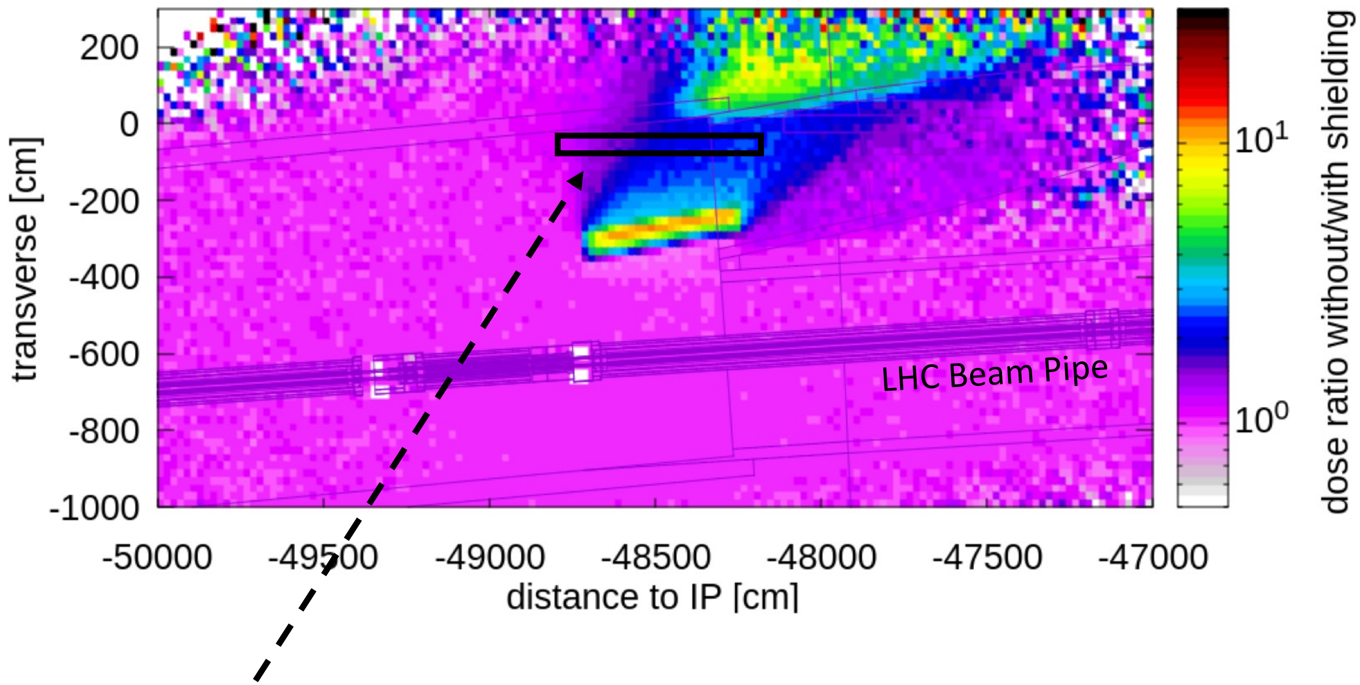


FORMOSA demonstrator

FORMOSA sticks out past the concrete shielding.

Added side-panels in recent intervention to mitigate this radiation.

Beam-related background

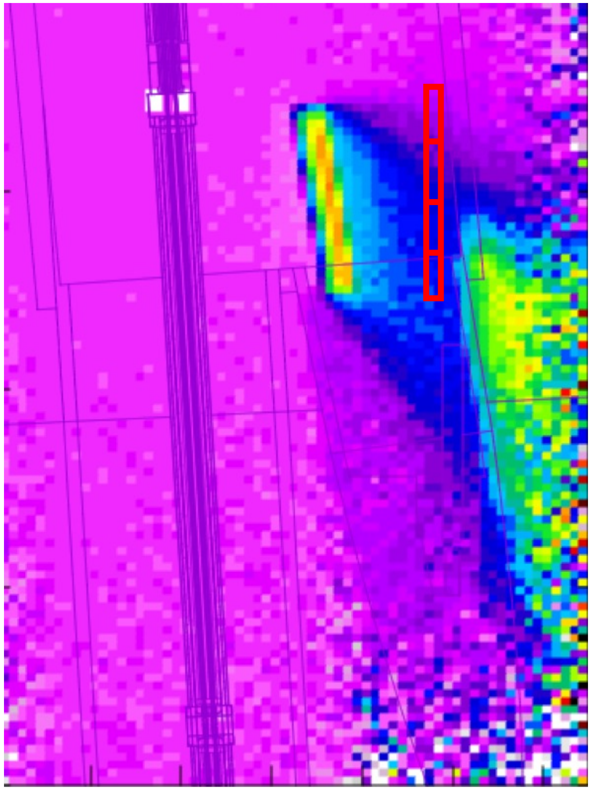


Such radiation backgrounds would not be an issue in a dedicated facility!

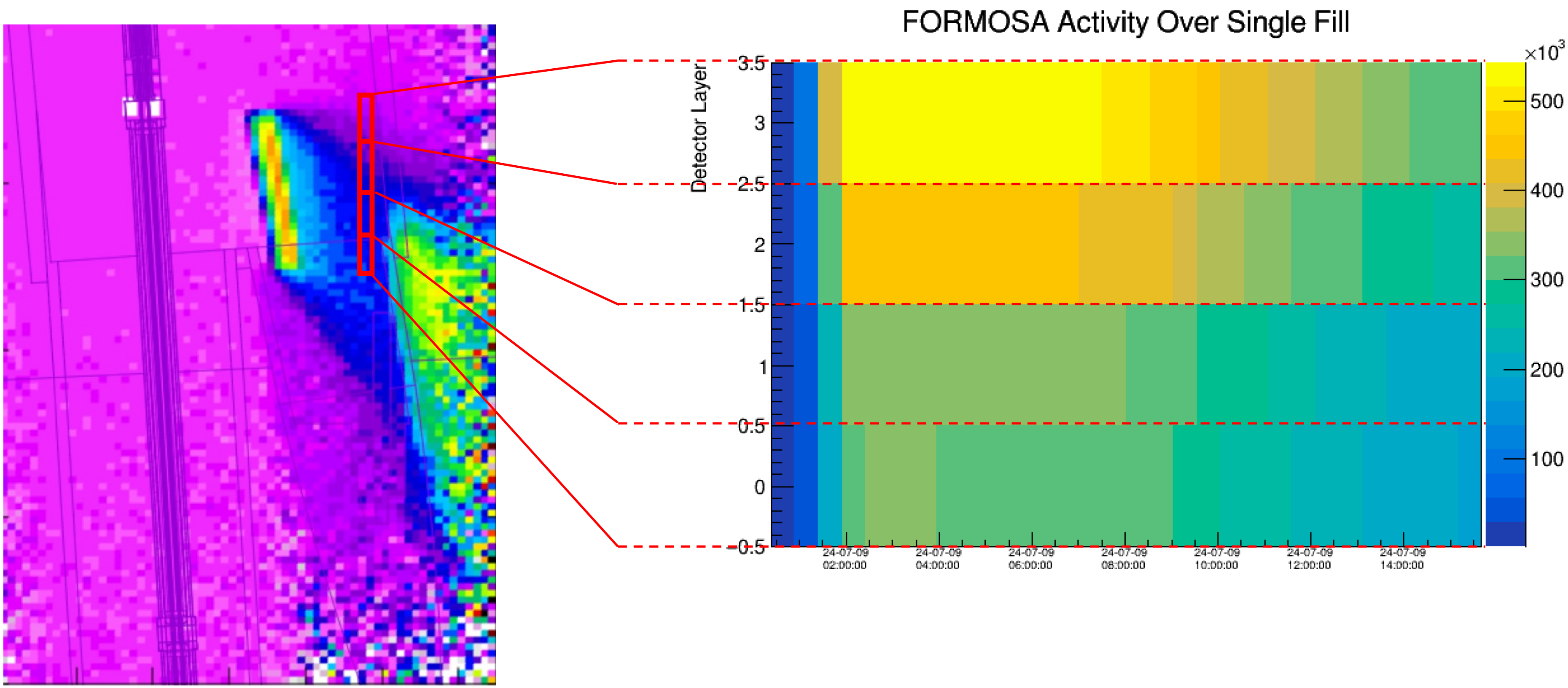
FORMOSA sticks out past the concrete shielding.

Added side-panels in recent intervention to mitigate this radiation.

Can we see the gradient of activity?

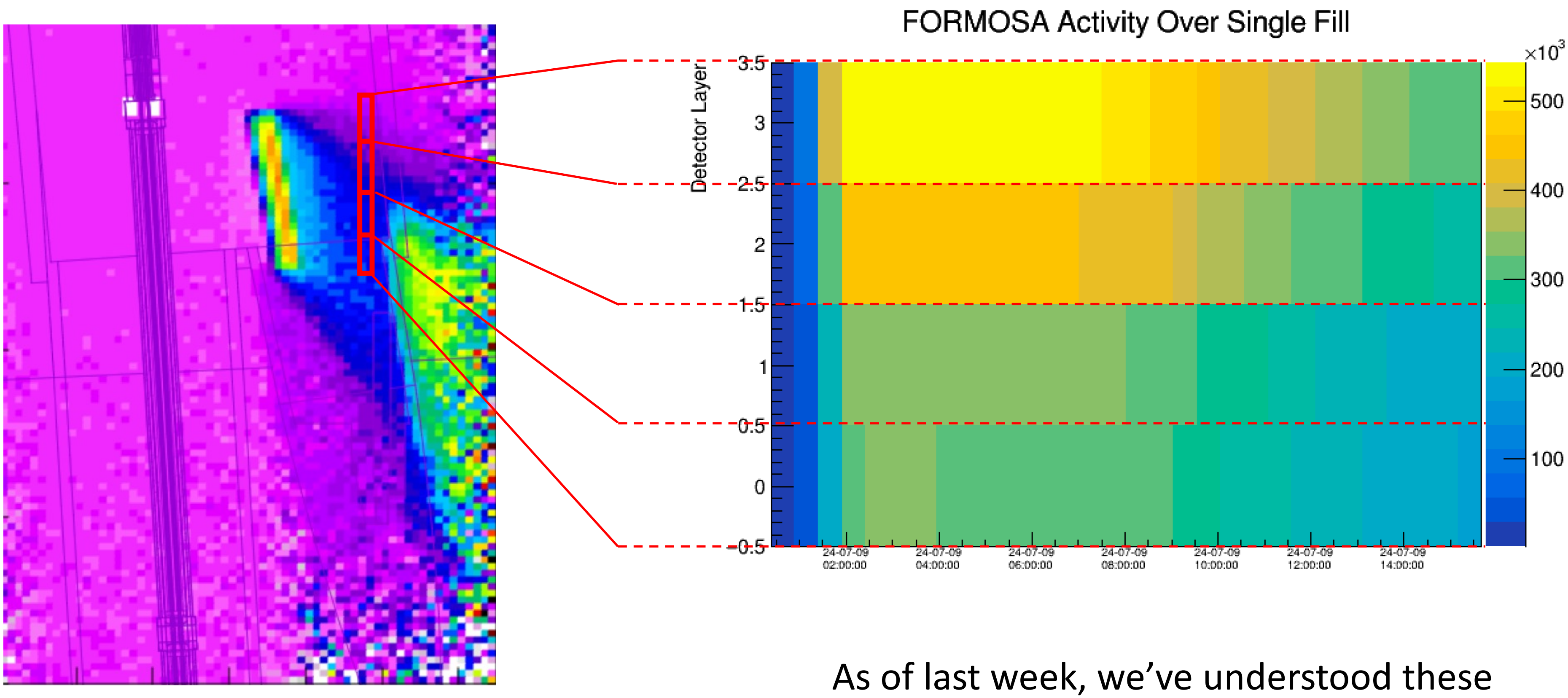


Can we see the gradient of activity?



Yes, there is a clear gradient

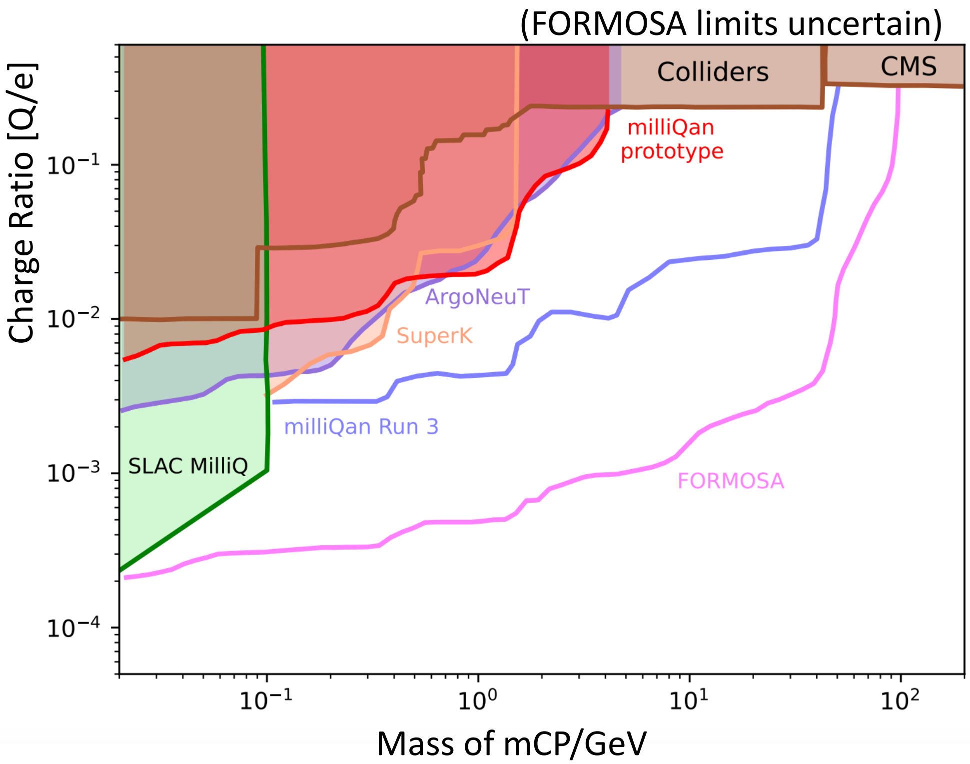
Can we see the gradient of activity?

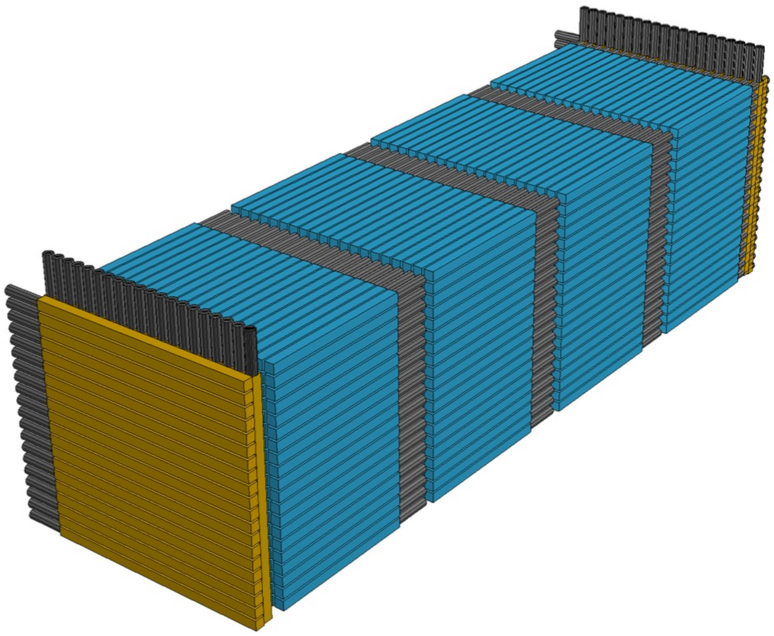


As of last week, we've understood these backgrounds sufficiently to **control the trigger rate** using savvy firmware!

Yes, there is a clear gradient

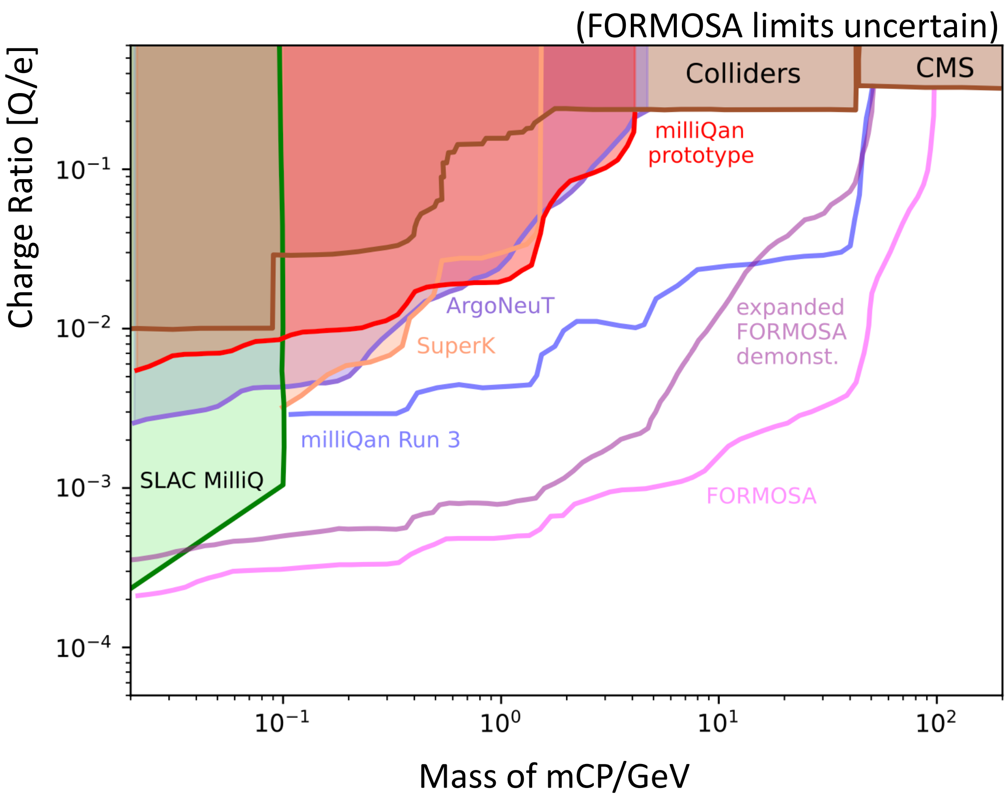
What’s the potential sensitivity of such a detector?

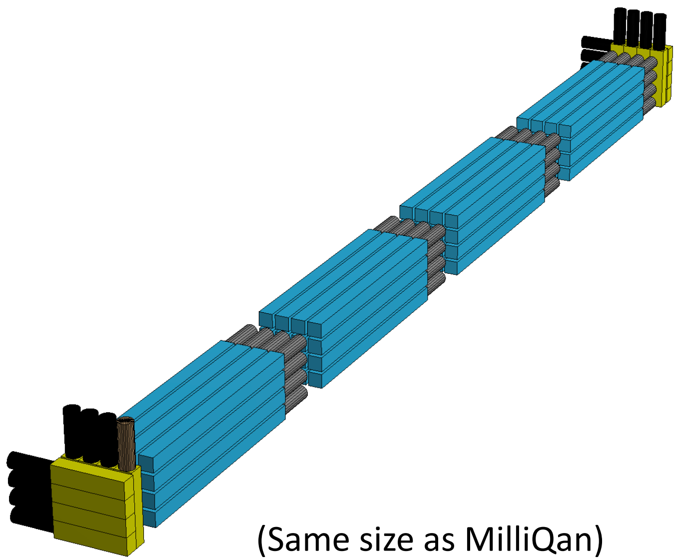




Sensitivity only depends on mass and charge of mCP

What if we expanded the demonstrator?





(Same size as MilliQan)

Sensitivity only depends on mass and charge of mCP

A year in review…

Achieved:

- Fabrication of structure
- Completion of PMT mounting/scintillator wrapping
- Above-ground testing and commissioning
- Detector **assembled** underground
- DAQ and triggering in a stable state
- **Calibration data obtained** underground
- **Manageable rates for signal triggers!**

Work in progress:

- Study **afterpulsing rates** in detector
- Further **optimize triggering** scheme


Thank you for listening!

A special thanks to Jamie Boyd, Brian Petersen, Claire Antel, and the **FASER collaboration**. Our work with FORMOSA could not have succeeded without you all!

The work of FORMOSA is built on the hard work and success of the **MilliQan collaboration**.

This speaker is supported with funding from the **Department of Energy**.

Backup

Lagrangians/Gauge Transformation

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} - \frac{\kappa}{2}A'_{\mu\nu}A^{\mu\nu}$$

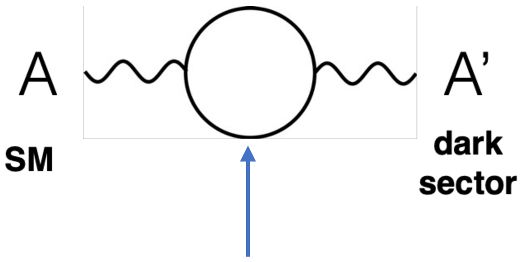
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} - \frac{\kappa}{2}A'_{\mu\nu}A^{\mu\nu} + i\bar{\psi}(\partial\!\!\!/ + ie'A' + iM_{mCP})\psi$$

$$A' \rightarrow A' - \kappa A$$

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}(\partial\!\!\!/ + i\kappa e'A + ie'A' + iM_{mCP})\psi$$

Theoretical Motivation

- Propose another electromagnetism in the dark sector
  - Suppose it's governed by a U(1) group, call it U'(1)
  - U(1) will have the standard charge (e)
  - **U'(1) will have some other fundamental charge (e')**
  - Fermions in this theory could have ±e, ± e', both, or neither
  - This gives a **coupling between our photon (A) and a new, dark photon (A')** via virtual pairs of fermions with both charges



- The Lagrangian:

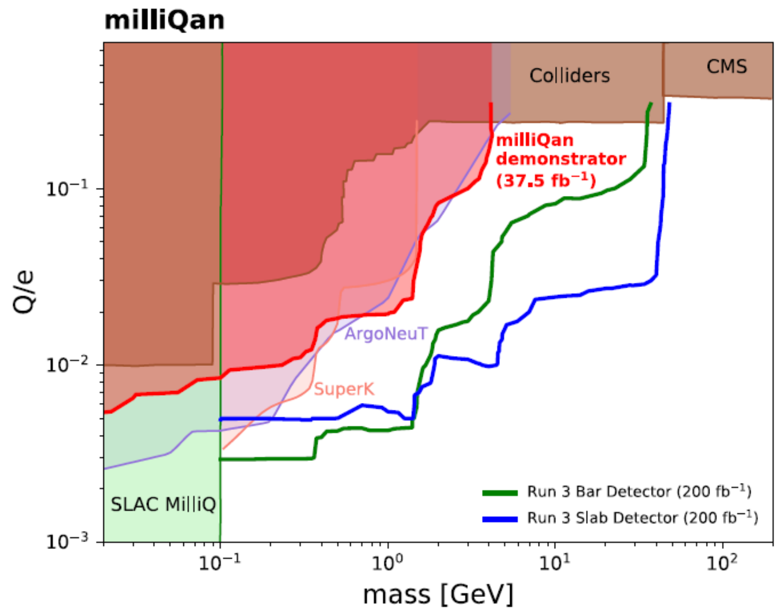
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}(\not{\partial} + i\kappa e' A + ie' A' + iM_{mCP})\psi$$

Millicharged coupling to the photon

Millicharged coupling to the **dark** photon

[Source: B. Holdom 1986]

The Sensitivity of MilliQan Detectors



Charge range: ~(0.001-0.1)e

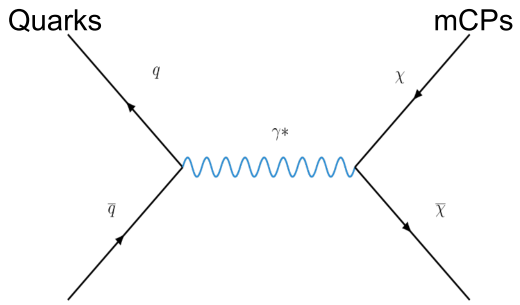
Mass range: ~(0.1-100)GeV

Bar Detector sensitive to a larger charge range.

Slab Detector sensitive to a larger mass range.

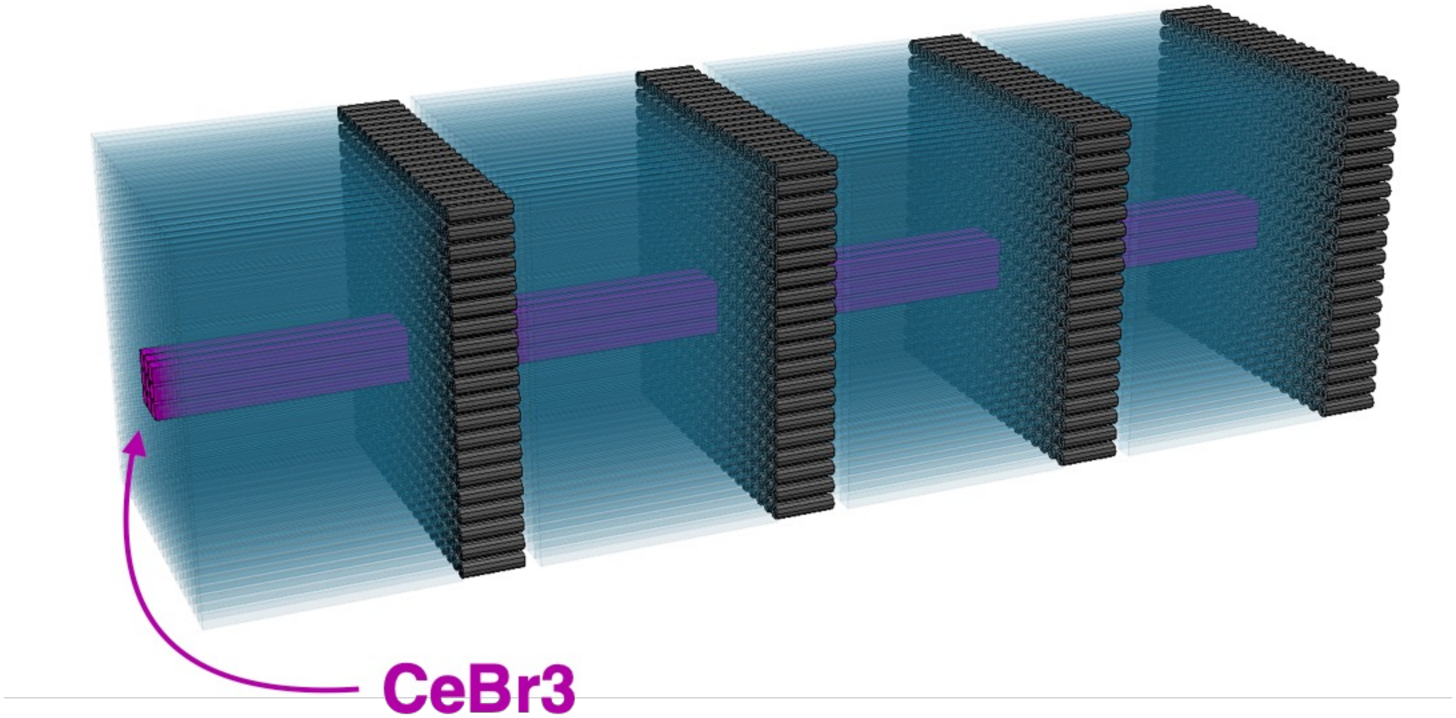
By what processes can we detect these?

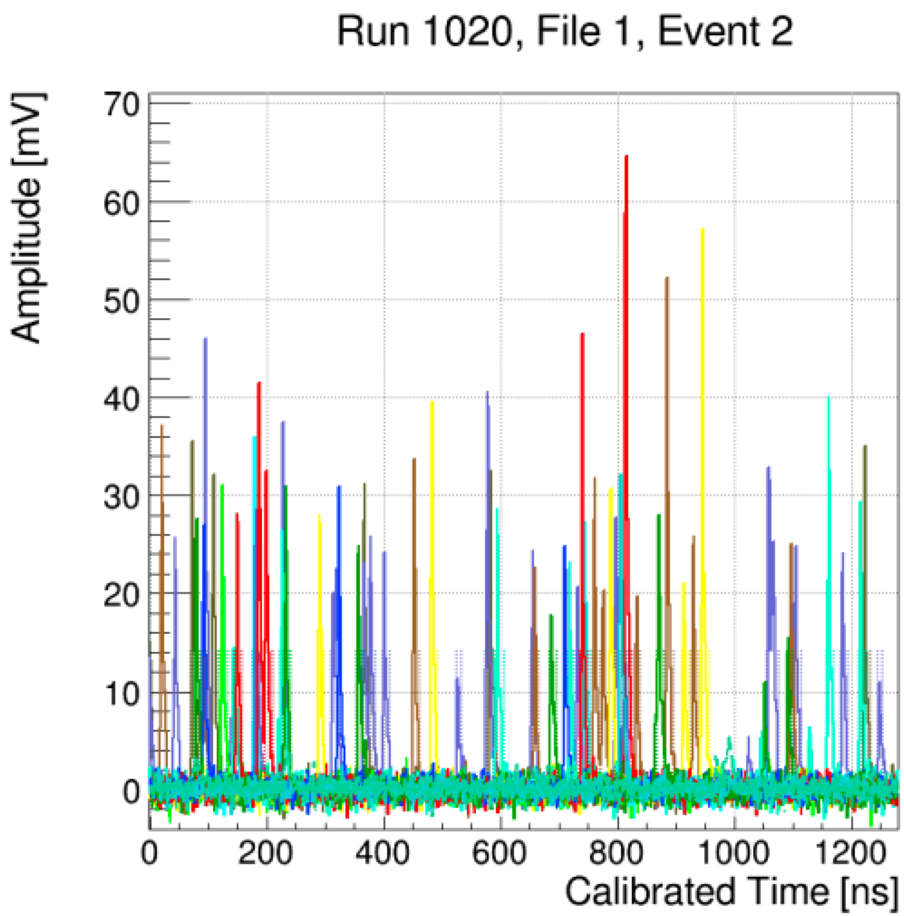
- Standard electromagnetic interactions!
- Millicharged particles couple electromagnetically to the standard model photon
  - Charge of κe
  - κ should be in the range of 0.1 – 0.001 otherwise current colliders would have found something (e.g. 0.5e)
  - https://cds.cern.ch/record/2841994/files/EXO-19-006-pas.pdf
- Thus, we can use standard charged-particle techniques!
- $\frac{dE}{dx} \sim Q^2$ for millicharged candidates with a mass greater than 100MeV
  - Ionization is the primary energy loss mechanism
  - Given by the Bethe-Bloch equation

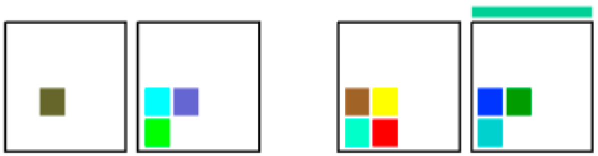


[Source: A. Haas et al. 2015]

CeBr3 Scintillator Added

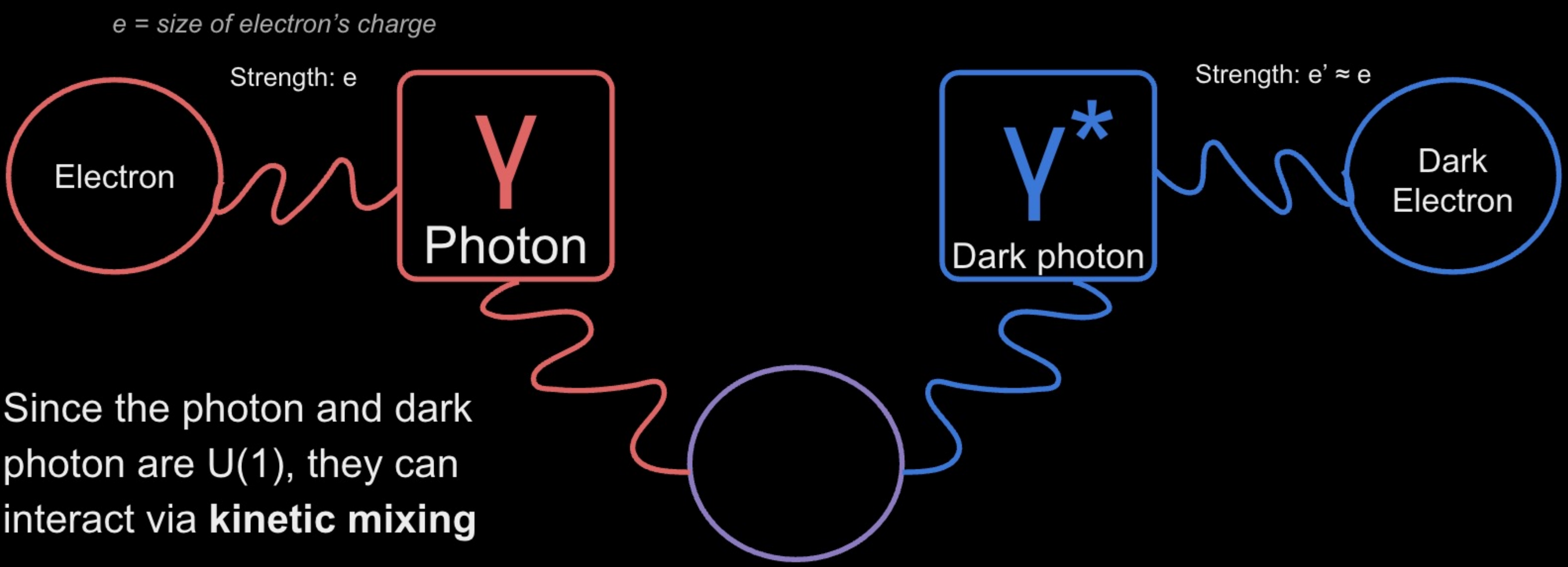






Channel 1, V_{max} = 35, N_{pulses} = 5
Channel 4, V_{max} = 36, N_{pulses} = 2
Channel 5, V_{max} = 46, N_{pulses} = 16
Channel 6, V_{max} = 31, N_{pulses} = 1
Channel 8, V_{max} = 52, N_{pulses} = 9
Channel 9, V_{max} = 57, N_{pulses} = 5
Channel 10, V_{max} = 40, N_{pulses} = 6
Channel 11, V_{max} = 65, N_{pulses} = 5
Channel 14, V_{max} = 31, N_{pulses} = 6
Channel 20, V_{max} = 32, N_{pulses} = 1

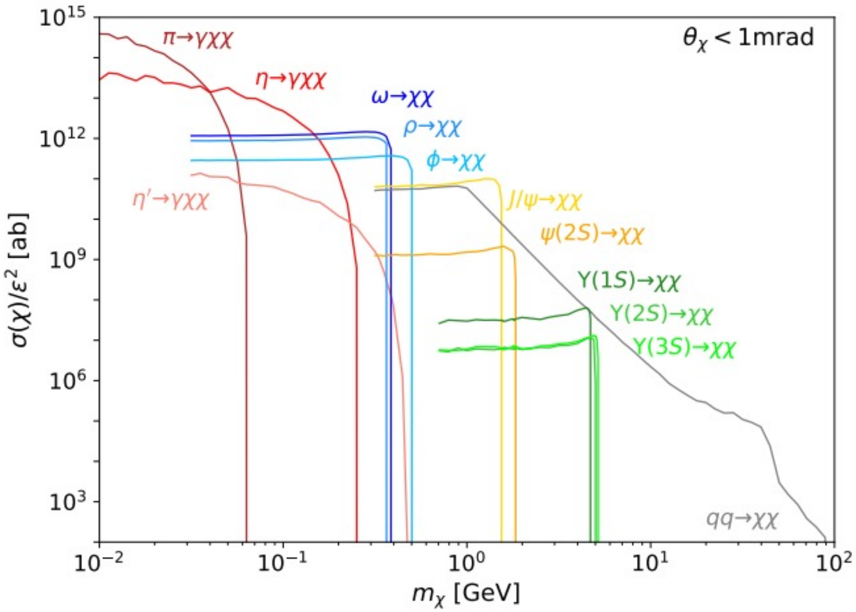
Dark sector mixing

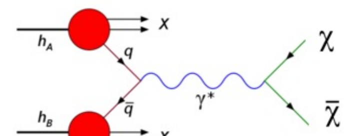


Since the photon and dark photon are U(1), they can interact via **kinetic mixing**

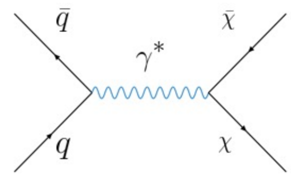
We can extend this sensitivity!

mCP Production Cross-Sections in the Forward Region

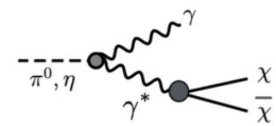




Drell-Yan



Meson decays

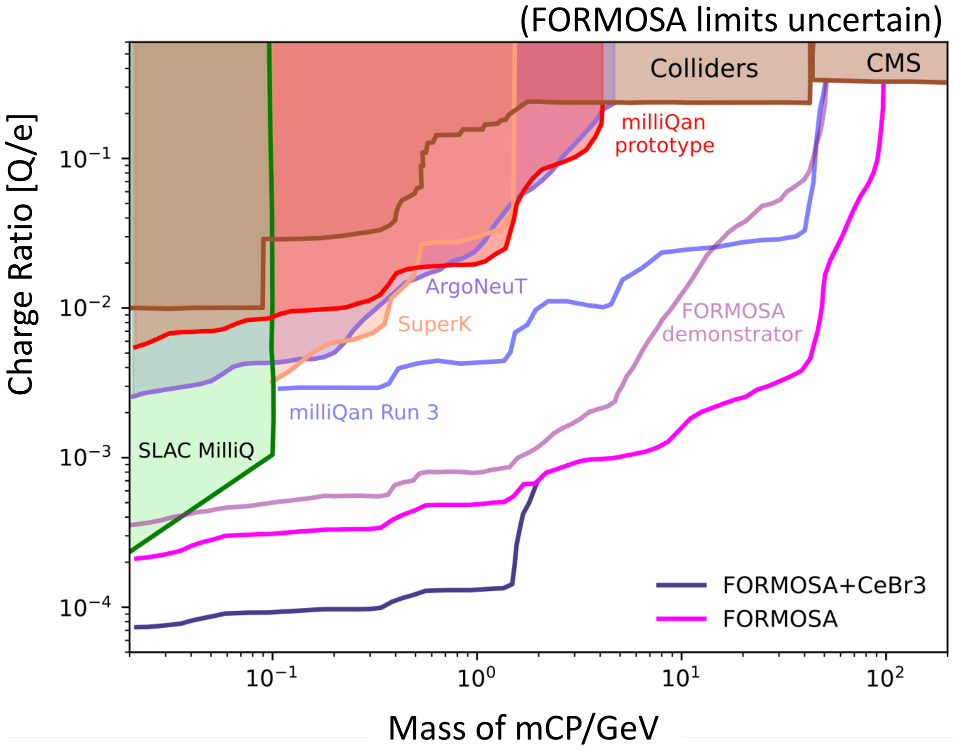


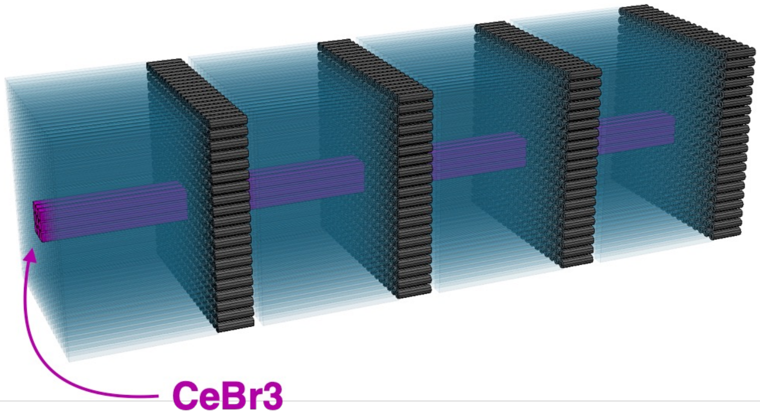
Dalitz decays

- A future detector in the forward region provides opportunity for substantial sensitivity extension
- GeV-scale (and below) mCPs are produced evenly in pseudorapidity
  - ~250x increase in production rate relative to central region

Plot: Forughi-Abari, Kling, and Tsai

An alternate design that includes CeBr3





Regions of the detector could be CeBr3

- 6x the light yield of plastic
- 5x the density
- Fast scintillation time constant
- Low intrinsic radioactivity
- More expensive…

Such a material could enhance low-charge sensitivity